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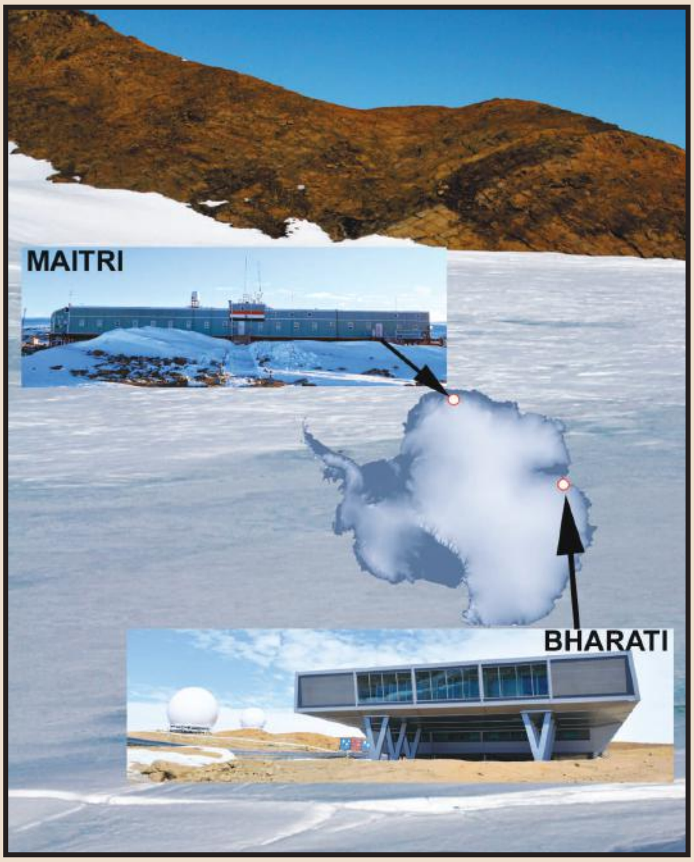

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Guest Editorial

Recent Antarctic Research in India: The National Committee Report to SCAR (2017)

Antarctica, the remote continent, having spectacular landscapes, has been playing major role in modulating global climate. During each winter, Antarctica grows nearly double to its size of summer, owing to an increase in seasonal sea ice extent. It has been recognized that the recent accelerated loss of ice over Antarctica can affect sea level as well as atmospheric and ocean circulations. India has been very active in Antarctica research since 1983, however it got a major boost during the last decade. During this period, the successful launch of the first expedition to the South Pole, setting up of the third station, 'Bharati' along with ground station for receiving satellite data at the Larsmann Hills on the East Antarctica coast, intensifying research in the Southern Ocean, and setting up advanced laboratories in the Antarctica and at ESSO-NCAOR, have resulted in improved understanding of Antarctica. Hence, this special issue was planned to look at the achievements, to identify gap areas and information needs. As the science agenda depend on information needs and thus this issue can help, both policy makers and researchers.

Considering the importance of the Antarctica, the Scientific Committee on the Antarctica Research (SCAR) had organized the 1st SCAR Antarctic and Southern Ocean Horizon Scan Retreat in 2014 to identify science questions to address the information and knowledge needs (Antarctic Science, 2014, 1-16, DOI:10.1017/S0954102014000674; Nature, 512:23-25). India had participated very actively and contributed significantly to develop the scientific questions, some of them are directly relevant to India.

The infrastructure available at 'Maitri' and 'Bharati' has enabled Indian researchers to contribute to many global research experiments planned under SCAR. The Indian Antarctic program is an example of long-term research efforts in a collaborative and coordinated manner. The major areas comprise, geoscience including paleoclimate, biology, oceanography, cryosphere studies, atmospheric and environmental sciences.

Antarctica was keystone of Gondwana and older super continents. Decoding history of the geological terrains hidden below ice is essential to understand how the super continent assembled and broke up in the past. The accurate topographical and geological mapping is the critical element for the advancement of many aspects of geo-science including this fragmentation process. High-resolution topographical and geological maps have been published for the Central Dronning Maud Land and Larsmann Hills. Geological studies conducted by India have helped to decipher the extension of the East African Orogeny in the Schrimacher Oasis and Humboldt Mountains based on the geochronology of granulated-facies rocks from the Schirmacher Oasis. Based on the GPS data collected from the Maitri (1997 onwards) and other sites on the Antarctica showed northward velocity of about 8 mm per year. At other places, the velocity varies between 4-20 mm per year and rotational movement has been estimated.

The study of proximal marine sediments revealed the geology of provenance, sedimentary processes on the continental rise and fluctuations of the East Antarctic Ice Sheet (EAIS) during Pliocene and late Miocene. The overall characteristics and composition of sediments in epi-shelf lakes of the Schhirmacher Oasis provided information on source rock composition, sediment transportation, depositional processes and weathering.

A focused Antarctica ice-core program was initiated since 2006 leading to recovery and study of several ice cores (up to 100 m) from coastal Antarctica. Ice-core proxy records provide information about climate variability at decadal,

**Author for Correspondence: E-mail: shailesh@moes.gov.in*

centennial and millennial scales. This study revealed a substantial warming of 0.6 to 1 degree C per century. The intimate relations between the Southern Hemisphere climate variability and Antarctic climate reconstructed from ice records - Southern Annular Mode (SAM) and ENSO played a major role in past changes in temperature, wind strength and sea ice extent. Integrating the proxy temperature data, it was observed that an overall cooing trend during last two thousand years. Such information is useful in validating climate models as well.

Lake sediments from the Schirmacher Oasis and Larsmann Hills offered great potential to reconstruct the past climate and environmental conditions. The lake sediments of the Schirmacher Oasis, indicated that this region has been ice-free for last 50,000 years or so. Paleo-climatic reconstruction from the Larsmann Hills and the Vestfold Hills revealed paleo-productivity fluctuations during the Holocene.

The use of various proxies such as microfossils (diatom and foraminifera), magnetic susceptibility, marine sedimentary records, oxygen isotopes, etc. have been handy to reconstruct the past productivity and ice-sheet dynamics. Such information is very useful in understanding atmospheric carbon dioxide variations.

The areas under snow and ice are least studied component of the Earth system due to paucity of observations, remoteness, challenging field conditions and limited time-window. Increasing imbalance in the mass budget has been observed during the last two decades. Accurate measurement of ice sheet and glacier features and variability lead to improved predictive modelling of ice loss. The monitoring of the snout of the Dakshin Gangotri (DG) and polar ice sheet along the Schirmacher Oasis showed continued recession. Many other glaciers show horizontal velocities varying between 1.9 to 10.9 m per annum to the north-north-East based on GPS measurements. The annual mass balance of glaciers is negative indicating impact of warming.

Digital elevation models for the Larsmann Hills and Schrimacher Oasis have been prepared using interferometric and photogrammetric techniques for monitoring ice sheets having an accuracy of ~ 25 cm. The use of such models for monitoring changes in the ice sheets are very useful.

An integrated study involving glaciology, bio-geochemical processes and ice core records from all polar regions was initiated for reconstructing, monitoring and predicting the variability of the global cryosphere system. An image album of the showing various cryosphere features using CARTOSAT-2 images have been made and further improved using RISAT-1 data. Using high-resolution temporal data, areas of snowmelt and freeze have been identified and monitored. Such information is very valuable as a baseline data.

Sea ice plays key role in modulating energy balance and thus impact atmospheric and oceanic circulations. Sea ice trend analysis using scatterometer (QUICKSAT and OSCAT) data and modelling have provided insight into sea ice response and forcing. The Antarctica sea ice shows both positive and negative anomalies, unlike Arctic which shows continuous retreat. These studies also revealed global tele connections - most frequently showing influence on the Indian monsoon and Indian Ocean Dipole. Sea ice variability is influenced by SAM and ENSO. A climatic dataset of Climatic Sea Ice Probability (SIOP) and sea ice type data generated based on microwave radio meter and scatterometers are routinely used for safe navigation as well as to understand variability in sea ice extent and likely causes.

The changes in polar atmosphere can alter planetary energy budget, moderate temperature gradient between the Equator and poles, and regulate variability in atmospheric circulation and thus influence global weather and climate. Studies of the Antarctic atmosphere are essential for the forecasting weather conditions and to understand the chemical processes taking place high in the stratosphere above Antarctica that result in ozone hole. Long-term continuous meteorological, electrical and ozone measurements at Maitri has provided a database on the Antarctic climate variability. Surface temperature, pressure, winds and blizzards show decreasing trend around the Maitri station.

Antarctica provide an excellent opportunity to study aerosols. Aerosol studies during last decade or so, revealed spatial heterogeneities associated with long-range transport and local influences. Energy balance studies at different snow/ice surfaces using remote weather station and satellite remote sensing revealed temporal and spatial heterogeneity. High sublimation rate of ice sheet has been attributed to high katabatic winds (8 m per second) and warmer temperatures. Most of the such studies had been short-term campaigns. Questions related to patterns and trends, and physical and chemical processes involved in phenomena have not been addressed. It is necessary to augment systematic, continuous, automated and long-term observations, followed by modelling.

Antarctica is one of the best places to study 'geospace' the region where the Earth's atmosphere interacts with the solar wind, a supersonic stream of charged particles emitted from Sun's corona. The interaction of the solar wind with Earth's magnetic field creates the aurora australis as well as a wide range of other effects including geomagnetic storms, disruption in short-wave radio communications and power surges in long electricity transmission lines. Two decades of experimental Geomagnetism revealed that Maitri is ideally suited for now casting geospace weather, inter-planetary weather as well as core-mantle processes. Cosmic noise absorption (CNA) measured using imaging rio meter provide insight into D-region ionospheric conditions and dynamics.

Antarctic life was earlier considered as simple and with with low diversity. Though, Antarctica has very harsh climate, during last decade, highly diverse several taxa and ecosystem were recorded. The Antarctic region has record of more than 1500 species of invertebrates and 200 species of vertebrates. Indian scientists have reported 7 new species, first records of 5 families, 25 genera and 92 species of both invertebrate and vertebrate groups. The systematic studies of monitoring seabirds and marine mammals revealed 49 species of sea birds and their abundance increased along higher latitudes. Four species of seals and two penguins were also recoded. Many nesting sites were discovered on the Islands around the Larsemann Hills. Algae, fungal, lichen and mosses are major floristic elements on Antarctica. 69 species of lichens, 109 species of cyanobacteria belonging to 30 genera and 9 families were recorded in the Schirmarcher Oasis and 25 species of lichens in the Larsemann Hills were identified. The discovery of Holocene Moss species, *Pholianutans*, preserved in lake sediments, dates back to 10000 years B. P.

Antarctic bacterial diversity has been studied from diverse habitats including soil, cyanobacterial mats, water, sediments, ephemeral streams, ice core, geothermal vents, orinthogenic soil, etc. Several new genera and species have been discovered. Molecular studies identified genes, responsible for the survival of bacteria at low temperatures. Enzymes from these bacteria have found applications in food processing to bioremediation.

The Southern Ocean plays a key role in the global climate system, being a medium through which critical exchanges of heat, salt, carbon, oxygen and nutrients take place between Antarctica and the rest of the world. The Antarctic Circumpolar Current (ACC) is the key system in the Southern Ocean. The zone of sink and ventilation of CO_2 have been identified in the Indian Sector of the Southern Ocean. Mesoscale eddies have been one of the factors leading to freshening of the Antarctic Intermediate Water (AAIW) and influence plankton community structure. Fast degree of warming and freshening of the Antarctic Bottom water (AABW) - could be due to southward meandering of the Antarctic Circumpolar Current (ACC) as well as glacier melting. Phytoplankton blooms in the coastal and open ocean due to the influence of this melt water. Knowing how the Southern Ocean marine ecosystem evolved will help us to understand evolutionary pathways including possible connection between the Antarctic deep sea benthos and benthic species in other deep oceans. The preliminary hydrographic measurements in coastal Antarctica identified upwelling zones, Circumpolar Deep Water (CDW) and cold fronts. Systematic, long term, multi-platform based observations on physical and biogeochemical processes are lacking and needs to be taken up with automated instruments.

India is a signatory and consultative party to the Antarctic Treaty, and has ratified the Protocol on Environmental Protection to Antarctica Treaty (Madrid Protocol) and carried out all research as per protocols of theTreaty. Maitri and Bharati stations are continuously monitored and many new treatment facilities have been created for maintaining the environmental health of the stations and proximities as per protocols. A study of carbon cycling in Antarctic snow and ice systems revealed that ice hosts significant and diverse type of carbon compounds attributed to microbial action and remote transport processes.

The interface between natural and social science is critical for the policy formulation as well as Antarctic governance. The issues related to the tourism, bioprospecting as well as impacts of climate are required to be addressed. The role of India in social science research needs to be enhanced.

It is important to understand how cryospheric processes contribute to the working of the Earth System and vice versa. The greater understanding of the pivotal role of the Polar regions in the Earth system and it's numerous connections with other physical and biological elements including space weather and Sun-Earth interactions has increased the importance of Polar research.

This is first such volume which provides a birds eye view of the Antarctic Research by India. We hope that these proceedings will help to identify future research areas to be undertaken on the pristine continent and surrounding waters.

Shailesh Nayak
Rahul Mohan
M Ravichandran
Naresh Pant
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Prof. Lakhotia, Chief Editor has readily agreed to our request of bring out this volume on the Antarctic Research. His editorial team have provided excellent support in this task. We are very thankful to them. Thanks to Ms Chinju Chandran and Shri Mahesh Kumar of my office who have assisted us in entire editorial work and carried out their duty with great dedication and sincerity.

Shailesh Nayak
Chair, National SCAR Committee & Guest Editor

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Review Article

Antarctic Palaeoclimatic Reconstruction Using Ice Cores: Indian Initiatives During 2008-2016

MELOTH THAMBAN*
ESSO – National Centre for Antarctic and Ocean Research, Headland Sada, Goa 403 004, India

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Study of ice core proxy records provide one of the most direct and accurate method to study the Antarctic climate change beyond the instrumental limits. Understanding the Antarctic climate variability on millennial, centennial to decadal level is crucial to our knowledge on the role and response of Antarctic ice sheets to the global climate variability. The Indian ice core studies have made significant contributions to the understanding of Antarctic climate variability and the various factors involved. The proxy environmental parameters used include temporal variability of stable isotopes, trace metal chemistry, ionic composition, dust particulates, and microbial components that are indicators of environmental change in the coastal Antarctica. Ice core proxy based reconstruction revealed significant changes in Southern Hemispheric climate during the past several hundreds of years. The study also revealed the utility of shallow ice cores in reconstructing the past changes in major climatic modes like the El Niño Southern Oscillation (ENSO) and Southern Annular Mode (SAM).

Keywords: ***Palaeoclimate*; Ice Core; El Niño Southern Oscillation; Southern Annular Mode; *Antarctica***

Introduction

The Antarctic climate system fluctuates widely on sub-annual to millennial time scales, in tandem with the global climate system. Since the time-series observations of climatic parameters were initiated only from the International Geophysical Year (1957-58), most of the instrumental records of Antarctic climate are only some decades old. Based on the available time series data, Antarctica seems to have undergone complex and significant temperature changes in recent decades (Turner *et al*., 2005 & 2006). While the largest annual warming trends are found on the western and northern parts of the Antarctic Peninsula (e.g., +0.56°C per decade at Faraday/Vernadsky station), many stations in East Antarctica and Amundsen-Scott Station at the South Pole in particular has shown a small cooling in the annual mean temperature of –0.05°C per decade (Turner *et al*., 2009). Notwithstanding these studies to understand the climate change in Antarctica, the spatial and temporal complexity of Antarctic climate are still poorly understood because of the limited and short periods of observational and instrumental data.

The north-to-south distribution of surface pressure around Antarctica is subject to remarkable variability in the intensity of the meridional pressure gradient and its zonal location. Due to the circumpolar nature of this variation, it is called the Southern Annular Mode (SAM), which is the principal mode of variability in the atmospheric circulation of the southern extratropics and high latitudes (see Trenberth *et al*., 2007). The SAM has a zonally symmetric or annular structure, with synchronous anomalies of opposite sign in high latitudes and midlatitudes (Lefebvre *et al*., 2004). The El Niño Southern Oscillation (ENSO) on the other hand, is the farthest reaching climatic cycle on Earth on decadal and sub-decadal time scales, affecting even the Southern Hemisphere (see Bromwich *et al*., 2000). The ENSO signals can be identified in the physical and biological environment of the Antarctic, although some of the links are not very robust and there can be large differences in the extra-tropical response to near-identical events in the tropics (see Turner, 2004).

**Author for Correspondence: E-mail: meloth@ncaor.gov.in*

Analysis of ice core records offer one of the most direct and accurate method to study the Antarctic climate change beyond the instrumental limits (Schneider *et al*., 2006; Mayewski *et al*., 2009). Ice core records from polar regions present continuous and highly resolved long-term records of reliable information on major atmospheric parameters like temperature, composition and trace gases. Among the various proxy variables used, the stable isotope ratios of oxygen ($\delta^{18}O$) and hydrogen (δD) offer the most critical information on the past changes in temperature. Owing to the differences in saturation vapour pressure and molecular diffusivity, isotopic fractionation takes place at each phase change of atmospheric water (Dansgaard, 1964). Since the heavy isotopes in precipitation decrease with the temperature of condensation, stable isotope ratios in ice cores provide quantitative proxy records of past temperature. However, factors such as temperature of the source from which moisture evaporated, subsequent cycles of condensation and evaporation, change in moisture source region and seasonality of precipitation make the interpretation of temperature from water isotopes difficult (Jouzel *et al.,* 2003).

Results and Discussion

During 2008-2016, several ice cores have been studied. The ice core drilling was carried out using an electromechanical drill system (GeoTecs Ltd, Japan; Model: Type D-2) during the austral summers. The retrieved ice cores (upto 101 m deep; diameter 10 cm) were cold-shipped and archived at the NCAOR cold room facility (–20ºC), until further processing in the laboratory. Processing of the ice core samples were carried out at the ice core processing facility at NCAOR. The ice core samples were first sub-sampled using custom-made bandsaw machines at the cold room (–15ºC) processing facility. Subsequently, the selected samples were manually decontaminated by removing the outer layer using microtome blades. Prior to analyses, samples were thawed at room temperature in a Class 100 clean room. Stable isotope ratios of the ice core samples were measured following standard methods using an 'Isoprime' (GV instruments) Isotope Ratio Mass Spectrometer (Naik *et al*., 2010 a). While two ice cores were extensively studied and published during this period, data from other cores under analysis and interpretation.

The ice core proxy based studies at revealed significant changes in Antarctic cryosphere and Southern Hemispheric climate during the past several hundreds of years (Laluraj *et al*., 2009, 2011 & 2014; Naik *et al*., 2010 a & b; Thamban *et al*., 2011a &b, 2013; PAGES 2k Consortium, 2013; Rahaman *et al*., 2016).

Palaeo-environmental Variability During the Past Five Centuries

High-magnification SEM-EDS study of micro-particles in the ice core of the 22nd IAE core revealed that these particles are mostly derived from volcanic eruptions relating to some of the major volcanic events. Studies also revealed that the tephra accreted during the Agung (1963) and Krakatau (1883) eruptions harbored microbial cells (both coocoid and rods), suggesting that volcanic ash particles could provide a significant micro-niche for microbes and nanobes in the accreted ice (Laluraj et al., 2009). Microbiological studies of polar ice at different depths of the above ice core also provided an important comparison, as they preserve records of microbial cells and past climate conditions (Antony *et al*., 2012). The bacteria identified from the different depth of the ice core might have been transported and deposited into ice along with dust particles and marine aerosols.

The nitrate (NO_3^-) profile of the IND-22/B4 core, which is considered to be a proxy for the zonal wind pattern over Antarctica, revealed synchronous changes in nitrate concentration with records of solar activity, showing relatively enhanced nitrate concentration during periods of reduced solar activity like the Dalton Minimum (~1790-1830 AD) and Maunder Minimum (~1640-1710 AD). The study suggest that the nitrogen species produced through processes such as solar activity, get associated with $nssSO_4^{2-}$ ions, get transported, deposited and preserved preferentially during very low temperature condition in Antarctica (Laluraj *et al*., 2011). The results revealed that multiple processes influenced its accumulation and preservation of nitrate (NO_3^-) at the study region. Correlation with the $nssSO_4^{2-}$ records reveal that sulphate aerosols of major volcanic eruptions activated the production of nitric acid, thereafter scavenged by ion-induced nucleation and transported to polar ice sheets. The correlation between the nitrate and $\delta^{18}O$ records further suggest a close link with the surface air temperatures, with lower temperature leading to higher nitrate preserved in the ice. Nitrate records preserved in the ice core appears to be influenced by production rates, processes in the atmosphere, as well as the temperature at the site of precipitation (Laluraj *et al.*, 2011).

Application of the $\delta^{18}O$-T spatial slope (1.31‰/°C) to the $\delta^{18}O$ profiles of IND-25/B5 and IND-24/B4 cores facilitated the estimation of surface air temperature in the study area (Naik *et al.*, 2010 a & b; Thamban *et al.*, 2011 a & b & 2013). The oxygen isotope ($\delta^{18}O$) records of the IND-22/B4 core supported significant changes in temperature during periods of solar activity as well a warming trend of 2.7°C for the past 470 years, with an enhanced warming during the last several decades (Thamban *et al.*, 2011 & 2013). The SAT record of IND-25/B5 exhibited high amplitude oscillations, with an average warming of 1°C for the entire century (1905-2005) with a trend of 0.1°C/10 years. However, the data revealed greatly enhanced warming trend of ~3°C during 1930-2005, with a warming of ~0.4°C/10 years. Based on the available instrumental data, it was demonstrated that while the western and northern parts of the Antarctic Peninsula is significantly warming, the East Antarctica in general and the South Pole in particular has shown a small cooling (Turner *et al.*, 2005 & 2006). Analysis of instrumental records from the coastal East Antarctic 'Novo' station also indicate a warming for the last ~50 years with similar temperature trend as found in the IND-25/B5 ice core (Naik *et al.*, 2010 b). Further support for such a warming derive from another coastal ice core from DML, which estimates a positive trend of the order of 0.12‰/decade for a similar time period (Divine *et al.*, 2009). Therefore, both the instrumental data as well as the proxy records confirms a significant warming during the past century at coastal DML region.

Antarctic Climate Variability and Its Linkages to SAM and ENSO

The El Niño-Southern Oscillation (ENSO) is linked to the Antarctic system through the Pacific South American pattern (PSA), which represents a series of positive and negative geopotential height anomalies initiated from tropical convection and extending from central equatorial Pacific to Australia, South Pacific near Antarctica, South America and then bending northwards towards Africa (Turner, 2004). During the ENSO events, the PSA pattern gives rise to geopotential height anomalies over the Amundsen-Bellingshausen seas and the Weddell Sea region. Studies have revealed that the Southern Annular Mode (SAM) significantly influences the Antarctic climate (Kwok and Comiso, 2002). The SAM, a hemisphere-wide atmospheric pattern, contributes to ~35% of variance in sea level pressure or geopotential height on a large range of time scales (Marshall, 2003). Several studies emphasised the crucial role of SAM on the recent climate changes across the Antarctic continent. Over the last 50 years, the SAM has shifted more into its positive phase with decreases of surface pressure over the Antarctic and corresponding increases at mid-latitudes (Marshall, 2003). The positive trend in the SAM seems to have resulted in a strengthening of the circumpolar westerlies and contributed to the spatial variability in Antarctic temperature change (Kwok and Comiso, 2002; Marshall, 2007). Most importantly, ENSO is also known to affect the SAM in a highly non-linear way. The two forcings can combine, partially offset or even enhance their influence on each other and the Southern Hemisphere as a whole (Gregory and Noone, 2008; Divine *et al.*, 2009; Turner *et al.*, 2009).

A detailed study was conducted on the regional atmospheric circulation changes associated with a reversal in the sign of the relationship between the SAM and near-surface temperatures in coastal parts of East Antarctica based on instrumental data from Halley station as well as an ice core from coastal Dronning Maud Land (Marshall *et al.*, 2009). The study revealed that the key factor affecting the regional SAM-temperature relationship is the relative magnitude of two climatological low pressure centres to the west and east of the area, which determines the source region of air masses advected into the locality. By integrating the proxy temperature data using ice cores and various proxy records across seven continental-scale regions, a global study revealed an overall cooling trend across nearly all continents during the last two thousand years (PAGES 2k Consortium, 2013). This cooling trend was reversed by distinct warming, beginning in some regions at the end of the 19th century. This cooling trend was reversed by distinct warming, beginning in some regions at the end of the 19th century.

In order to assess the temporal isotopic variability of ice cores as high-resolution quantitative proxy record of air temperatures and its relation to the southern hemispheric climatic modes, an ultra-high-resolution (>12 samples per year) ice core record was analyzed in relation to instrumental records (Naik *et al*., 2010 a & b). Comparison of the ice core $\delta^{18}O$ record with the reconstructed index of SAM for the period 1905 to 2005 was made after a 4-year low pass filtering of both data. Such a filtering could take care of the well known 4-5 yr variability within the SAM data (Thompson and Wallace, 2000). Although the correlations are low ($r^2 = -0.01$; $p = 0.1$), it is negative with high SAM corresponding to lower $\delta^{18}O$ and vice versa (Naik *et al*., 2010 a). This suggests that higher polarity of SAM corresponds to lower temperatures and vice versa. This is a component of the opposite relationship driven by SAM on surface air temperature over the west Antarctica (Gregory and Noone, 2008) and east Antarctica. SAM is also known to play an important role in driving decadal temperature changes in the Southern Hemisphere. A running decadal correlation between the annual $\delta^{18}O$ and SAM records also indicated an overall negative relationship, with certain periods (1918-1927; 1938-1947; and 1989-2005) showing absence of correlations or even weak positive relationships (Naik *et al*., 2010 b).

Relationships between the surface air temperature, SAM and ENSO in the study region were established using the ice core annual $\delta^{18}O$ data, the reconstructed SOI as well as the SAM indices. The analysis showed that for the period wherein the $\delta^{18}O$ and SAM relationship was insignificant or positive (1918-1927; 1938-1947 and 1989-2005), the relationships between the SOI and SAM are also in-phase (Naik *et al*., 2010 b). Interestingly, the above periods (1918-1927; 1938-1947 and 1989-2005) incorporate several El Niño and La Niña years. When the years of El Niño and La Niña events are omitted from the records, the relationship between the filtered $d^{18}O$ and SAM data became statistically significant ($r^2 = -0.2$; $p = 0.02$), suggesting that ENSO events weakens the SAM-temperature relationship during these periods (Naik *et al*., 2010 b). The results thus reveals that during the past century, the combined influence of ENSO-SAM modes have controlled the temporal changes in $\delta^{18}O$ values at the core site.

The dust record of IND-25/B5 ice core showed that dust deposition in East Antarctica followed the Southern Hemispheric climate change and doubled during the 20th century (Laluraj *et al*., 2014). Strong positive correlation observed between dust flux and the SAM suggests that the positive values of the SAM index are likely to be responsible for the recent increase in dust deposition over East Antarctica, through strengthening of westerly winds. The NCEP/NCAR reanalysis data reveals that the polar easterlies consistently strengthened since 1985 at the study region, leading to the sinking of dust materials brought by the stronger westerlies. Interestingly, the timing and amplitude of the insoluble dust flux matched remarkably well with the trace metal fluxes of Ba, Cr, Cu, and Zn, confirming that dust was the main carrier of airborne geochemical tracers to East Antarctica in the recent past (Laluraj *et al*., 2014). The observed doubling of dust and associated trace metal deposition in East Antarctica have wide-ranging implications for understanding the factors driving the inter-continental transportation of impurities and their environmental impact on Antarctica. These results have far-reaching implications for understanding the changes in temperature and dust levels and their impact on climate both in the recent past and future.

High resolution study of deuterium excess (d-excess), sea-salt sodium (ss-Na^+) and methane sulfonic acid (MSA) in the ice core IND-25/B5 from coastal Dronning Maud Land also revealed the history of moisture transport and sea ice condition during the last century (Rahaman *et al*., 2016). Sea ice extent (SIE) in the Weddell Sea was reconstructed based on Antarctic ice core records of stable oxygen ($\delta^{18}O$), hydrogen (δD) isotopes and sea-salt-Na^+. Among them, ss-Na+ flux record shows significant positive relationship with winter SIE in the Weddell Sea. Wavelet analysis of SAM index and SOI shows the highest common power in 4-8 year band during 1940-1960 and 1990-2000 overlapping with the period of higher SIE. This shows large variability during the last century (1905-2005 AD) which impacted moisture transport from various oceanic sectors to Antarctica. Cluster of backward wind trajectories shows that air parcels were mainly originated from the Weddell Sea with additional sources from the Ross Sea and the Bellingshausen-Amundsen Sea regions. Dramatic increase in SIE was observed in the Weddell Sea sector during 1940-1980. This study suggests that moisture source and sea ice variability in annual-decadal scale in Antarctica seems to be largely influenced by SAM and its teleconnection to ENSO. Further, the multifaceted scientific studies being carried out by Indian scientists in the realm of ice core palaeoclimatic research will contribute significantly to the global community's ongoing efforts to better understand the past climate variability during the Holocene and its implication to the changing environment.

Conclusions

During the 2008-2016, the Indian scientists have used a variety of proxy climatic records on ice cores from East Antarctica. Among the diverse types of studies undertaken, the ice core studies have generated large amount of knowledge basis on the Antarctic climate and its global/regional linkages. Ice core proxy based reconstruction revealed that the estimated surface air temperatures revealed significant warming during the past five centuries. The study also revealed the utility of shallow ice cores in reconstructing the past changes in major climatic modes like the El Niño Southern Oscillation (ENSO) and Southern Annular Mode (SAM).

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References

Antony R, Krishnan K P, Laluraj C M, Thamban M, Dhakephalkar P K, Anupama S and Shivaji S (2012) Diversity and physiology of culturable bacteria associated with a coastal Antarctic ice core *Microbiological Res* **167** 372-380

Bromwich D H, Rogers A N, Kallberg P, Cullather R I, White J W C and Kreutz K J (2000). ECMWF analysis and reanalysis depiction of ENSO signal in Antarctic precipitation *Journal of Climate* **13** 1406-1420, doi: 10.1175/1520-0442(2000)013

Dansgaard W (1964) Stable isotopes in precipitation *Tellus* **16** pp. 436-468.

Divine D V, Isaksson E, Kaczmarska M, Godtliebsen F, Oerter H, Schlosser E, Johnsen S J, van den Broeke M and van de Wal R S W (2009) Tropical Pacific-high latitude south Atlantic teleconnections as seen in d18O variability in Antarctic coastal ice cores *Journal of Geophysical Research* **114** D11112, doi: 10.1029/2008JD010475

Gregory S and Noone D (2008) Variability in the teleconnection between the El Niño-Southern Oscillation and West Antarctic climate deduced from West Antarctic ice core isotope records *Journal of Geophysical Research* **113** D17110, doi: 10.1029/2007JD009107

Jouzel J, Vimeux F, Caillon N, Delaygue G, Hoffmann G, Masson-Delmotte V and Parrenin F (2003) Magnitude of isotope/temperature scaling for interpretation of central Antarctic ice cores *Journal of Geophysical Research* **108**, 4361, doi: 10.1029/ 2002JD002677

Kwok R and Comiso J C (2002) Southern ocean climate and sea ice anomalies associated with the Southern Oscillation *Journal of Climate* **15** 487-501

Laluraj C M, Thamban M and Satheesan K (2014) Dust and associated geochemical fluxes in an ice core from the coastal East Antarctica and its linkages with Southern hemisphere climate variability *Atmospheric Environment* **90** 23-32

Laluraj C M, Thamban M, Naik S S, Redkar B L, Chaturvedi A and Ravindra R (2011) Nitrate records of a shallow ice core from East Antarctica: atmospheric processes, preservation and climatic implications *The Holocene* **21** 351-356

Laluraj C M, Krishnan K P, Thamban M, Rahul M, Chaturvedi A, Naik S S, D'Souza W, Ravindra R (2009) Origin and characterisation of microparticles in an ice core from the Central Dronning Maud Land, East Antarctica

Environmental Monitoring and Assessment **149** pp 377-383

Lefebvre W, Goosse H, Timmermann R and Fichefet T (2004) Influence of the Southern Annular Mode on the sea ice-ocean system *Journal of Geophysical Research* **109** C09005, doi:10.1029/2004JC002403

Marshall G J (2003) Trends in the southern annular mode from observations and reanalyses *Journal of Climate* **16** 4134-4143

Marshall G J (2007) Half-century seasonal relationships between the Southern Annular Mode and Antarctic temperatures *International Journal of Climatology* **27**: 373-383

Marshall G J, Battista S, Naik S S and Thamban M (2009) Analysis of a regional change in the sign of the SAM-temperature relationship in Antarctica *Climate Dynamics* DOI: 10.1007/s00382-009-0682-9

Mayewski P A, Meredith M P, Summerhayes C P, Turner J, Worby A, Barrett P J, Casassa G, Bertler N A N, Bracegirdle T, Naveira Garabato A C, Bromwich D, Campbell H, Hamilton G S, Lyons W B, Maasch K A, Aoki S, Xiao C and Tas van Ommen (2009) State of the Antarctic and Southern Ocean climate system *Reviews of Geophysics* **47** pp RG1003 1-38

Naik S S, Thamban M, Laluraj C M, Redkar B L and Chaturvedi A (2010a) A century of climate variability in the central Dronning Maud Land, East Antarctica and its relation to Southern Annular Mode and El Niño Southern Oscillation *Journal of Geophysical Research (Atmospheres)* **115** D16102, doi: 10.1029/2009JD013268

Naik S S, Thamban M, Laluraj C M, Redkar B L and Chaturvedi A (2010b) A century of climate variability in central Dronning Maud Land, East Antarctica, and its relation to Southern Annular Mode and El Niño; Southern Oscillation *Journal of Geophysical Research* **115** D16102, doi: 10.1029/2009JD013268, 2010, 1-12

PAGES 2k Consortium (2013) Continental-scale temperature variability during the last two millennia *Nature Geosciences* **6** 339-346

Rahaman W, Thamban M and Laluraj C M (2016) Twentieth Century sea ice variability in the Weddell Sea and its effect on moisture transport: Evidence from a coastal East Antarctic ice core record *The Holocene* **26** 338-349

Schneider D P, Steig E J, van Ommen T D, Bitz C M, Dixon D, Mayewski P A and Jones J M (2006) Antarctic temperatures over the past two centuries, from ice cores *Geophysical Research Letters* **33** L16707, doi: 10.1029/2006GL027057

Thamban M, Laluraj C M, Naik S S and Chaturvedi A (2011b) Reconstruction of Antarctic climate change using ice core proxy records from the coastal Dronning Maud Land, East Antarctica *Journal of Geological Society of India* **78** 19-29

Thamban M, Naik S S, Laluraj C M and Ravindra R (2011a) High resolution reconstructions of recent warming using instrumental and ice core records from coastal Antarctica *Mausam* **62** 665-672

Thamban M, Naik S S, Laluraj C M, Chaturvedi A and Ravindra R (2012) Antarctic climate variability during the past few centuries based on ice core records from coastal Dronning Maud Land and its implications on the recent warming. In: Earth System Processes and Disaster Management (Eds: R. Sinha and R. Ravindra) pp 239, Society of Earth Scientists Series, Springer, 2013, XII

Thompson D W J and Wallace J M (2000) Annular modes in the extratropical circulation. Part I: Month-to-month variability *Journal of Climate* **13** 1000-1016

Trenberth K E, Jones P D, Ambenje P, Bojariu R, Easterling D, Klein Tank A, Parker D, Rahimzadeh F, Renwick J A, Rusticucci M, Soden B and Zhai P (2007) Observations: Surface and Atmospheric Climate Change. In: Climate Change 2007 – The Physical Science Basis. Contribution of WG1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. Cambridge, U. K., and New York, NY, USA, 235-336

Turner J (2004) The El Niño-Southern Oscillation and Antarctica *International Journal of Climatology* **24** 1-31, doi: 10.1002/joc.965

Turner J, Bindschadler R, Convey P, di Prisco G, Fahrbach E, Gutt J, Hodgson D, Mayewski P and Summerhayes C (2009) Antarctic Climate Change and the Environment: a contribution to the International Polar Year. Scientific Committee on Antarctic Research, Cambridge, ISBN 978-0-948277-22-1

Turner J, Colwell S R, Marshall G J, Lachlan-Cope T A, Carleton A M, Jones P D, Lagun V, Reid P A, and Iagovkina S (2005) Antarctic climate change during the last 50 years *International Journal of Climatology* **25** 279-294

Turner J, Lachlan-Cope T A, Colwell S, Marshall G J and Connolley W M (2006) Significant warming of the Antarctic winter troposphere *Science* **311** 1914-1917.

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Review Article

Antarctic Glacier Monitoring

PRAKASH K SHRIVASTAVA*, SANDIP K ROY and HAMZA Y BHAI
Polar Studies Division, Geological Survey of India, Faridabad 121 001, India

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Polar ice is an important component of the natural system, affecting global climate on large as well as small scale. The Antarctic ice sheet has undergone significant changes in the past and governed the earth's climatic system. This ice sheet appears to have been very dynamic and yet, not much is known about the processes involved for this dynamism.

Glaciological studies in parts of Central Donning Maud Land (cDML) of East Antarctica include monitoring the changes of Antarctic ice sheet overriding the Schirmacher Oasis, measurement of snow accumulation on the ice sheet, study of subsurface topography and ice sheet dynamics. In the last three decades, Dakshin Gangotri (DG) glacier snout, which is a part of East Antarctic Ice sheet (EAIS) overriding Schirmacher Oasis shows continuous recession. There are major peaks of recession in every five year cycle. The higher average annual surface air temperature leads to the greater recession in the next year. Interestingly, this recessional trend of DG snout does not show perfect correlation with the meteorological parameters (such as surface air temperature, ground temperature, wind speed, etc.) of this area. This all reflect towards the existence of very complex equation for the recession of ice sheet and snow and ice characterization in this part of Antarctica. The vector component of ice sheet shows differential movement all along the southern edge of Schirmacher Oasis. The average annual recession of snout has shown positive correlation with the mean annual runoff and negative correlation with annual mass balance of the area.

Keywords: Recession; Snow Accumulation; Mass Balance; Schirmacher Oasis; East Antarctica

Introduction

An integrated approach has been adopted by the Geological Survey of India (GSI) for carrying out glaciological studies in the area surrounding Schirmacher Oasis in central Dronning Maud Land (cDML), East Antarctica (Fig. 1) since the inception of Indian Antarctic program in 1981. These studies include yearly measurements of the changes in polar glacier front and accumulation/ablation over ice sheet and ice shelf for obtaining information on the state of the polar ice sheet *vis-a-vis* the impact of climate change (Singh *et al*., 1988; Chaturvedi *et al*., 2009; Shrivastava *et al*., 2011; Swain *et al*., 2011, 2012). Ground Penetrating Radar surveys have been undertaken in selected areas to understand the subsurface ice characteristics and ground configuration (Dharwadkar *et al*., 2012). Dakshin Gangotri (DG) glacier snout was identified during the second Indian Antarctic Expedition and since then it is being monitored regularly by the GSI. The routine glaciological observations include monitoring of the DG glacier snout and its western flank along with recording of annual accumulation/ablation of snow on the ice shelf and on ice sheet. The snow accumulation/ablation study has been recently initiated in the Larsemann Hills area also. The present write up explains the overall glaciological observations taken by GSI in parts of cDML area, south of Schirmacher Oasis, East Antarctica.

Methodology

The overall work on glaciological studies in Schirmacher Oasis and Larsemann Hills areas by the GSI includes identification of area with the help of satellite images and available literature. This is followed by sub-surface characterization of ice sheet of the selected areas with the help of Ground Penetrating Radar (GPR). The GPR system

**Author for Correspondence: E-mail: pks.shri@gmail.com*

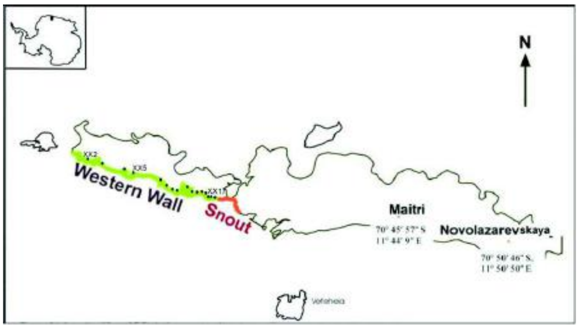

Fig. 1: Location Map of Dakshin Gangotri snout and Western wall in Schirmacher Oasis, East Antarctica

comprises a Subsurface Interface Radar (SIR) with a Toughbook, GPS, Survey wheel, cables and various antennas of 15, 20, 35, 40, 80, 100 and 200 MHz frequency. The system was run in continuous static mode generating a continuous subsurface profile along the traverse line. When running in continuous mode, the antennas were dragged at a constant speed and the profiles were pegged to ground surface using calibrated survey wheel as well as a handheld GPS unit. The dielectric constant for ice, confirmed by velocity analysis using the common midpoint survey, was kept at 3.0. The GPR study has been used to delineate the Land-Ice-Sea (LIS) interfaces. Regular monitoring of annual snow accumulation/ablation is being carried out by stake networks. The meteorological parameters of the area help in characterizing the annual changes of the part of ice sheet in East Antarctica. Calculation of vector components of ice body with D-GPS at different locations gives the idea about ice sheet dynamics. All these factors contribute in estimation of mass balance calculation.

DakshinGangotri Glacier Snout and Western Wall

The snout of DakshinGangotri (DG) glacier, overriding Schirmacher Oasis is being monitored every year since 1982. Since then, the snout has shown continuous recession. During the period 2014-15, the DG glacier snout has receded by 1.31 m with respect to its position from previous year (Tables 1 and 2). For the same period, the western wall has shown a recession of 2.37 m with respect to the previous year. The recessional data measured is the resultant of the advancement of the Polar ice sheet during Polar winter period and the net recession during the austral summer period show an increasing trend in the cumulative recession (Table 3). The meteorological data obtained for the Schirmacher Oasis were compared for annual average surface air temperature (AASAT), annual average air temperature (AAGT), Maximum surface air temperature (MSAT), annual average relative humidity (AARH), annual average precipitation (AAP), annual average wind speed (AAWS) and annual average total cloud cover (AATCC in tenths) (Swain and Raghuram, 2015). It is observed that meteorological parameters including higher average annual surface air temperature and higher wind speed results in greater recession of the snout of DG glacier snout. A similar phenomenon was observed with the relationship of annual average surface air temperature with the recession of DG glacier snout of the next year and vice versa (Shrivastava *et al*., 2011).

Glaciological studies conducted in the area around Schirmacher Oasis during the last three decades were helpful in deriving some meaningful patterns and charting a cause for future work. The annual recessional pattern of the DG glacier snout indicates that major recession in every five years with minor peaks at every 2-3 years interval between 1996-2010 period. But in the last five years the trend of the DG snout is different than the previous 15 years period (Fig. 2; Table 1). When the annual recession of the DG snout is compared with average annual surface air temperature, it does not show direct correlation, but when the recession is compared with the preceding average annual temperature, the correlation show little improvement.

Between the period of 1996 to 2011, nearly 4800 m^2 area has been vacated by the shrinking snout of this glacier. This recession has led to the disappearance of about 672 x 10^3 m^3 ice, which is equivalent to 576 x 10^3 m^3 of water. The average annual recession of the DG Glacier does not show any linear correlation with average annual surface air temperature, average annual ground temperature and average annual wind speed (Chaturvedi *et al*., 2009; Shrivastava *et al*., 2011, Shrivastava *et al*., 2014).The recession of DG snout has shown good positive correlation with mean annual runoff and has shown negative correlation with annual mass balance of the area (Fig. 3).

The Western wall includes 7 km (approx) long ice front (including ice wall and ramps) of the western

Table 1: DakshinGangotri glacier snout measurements (in meters) since 1996

OBS. PTS.	ORIG PTS FEB 1996	FEB -97	FEB -98	FEB -99	FEB -00	FEB -01	FEB -02	FEB -03	FEB -04	FEB -05	FEB -06	FEB -07	FEB -08	FEB -09	ORIG ORIG FEB 2009	FEB -10	JAN -11	JAN -12	JAN -13	JAN -14	FEB -15	FEB -16
1	2.00	2.66	3.35	3.02	3.70	3.56	3.22	3.91	4.80	7.81	7.95	8.05	11.62	12.05	1.72*	1.80*	—	—	10.33	—	—	—
2	4.50	4.93	7.40	9.10	10.80	11.10	11.25	12.19	13.94	15.65	15.86	14.50	17.85	16.87	1.65	2.09	2.17	1.98	3.00	2.76	4.55	6.42
2A	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2.39	2.30	—	6.15	6.89	8.7
3	1.00	1.28	1.90	2.20	2.33	2.69	3.10	3.7	4.20	4.86	5.44	6.72	7.11	7.29	1.36	1.61	2.39	2.30	2.84	2.93	3.42	3.46
4	2.00	1.80	2.83	3.40	3.72	4.01	4.35	4.66	5.33	5.63	6.29	6.52	6.80	6.92	2.00	2.02	2.40	2.55	2.76	2.74	2.99	3.34
4-A	2.00	2.19	2.60	2.85	3.10	3.46	3.90	4.27	4.45	4.65	4.83	5.24	5.63	5.84	2.00	2.37	2.89	3.05	3.80	4.19	5.52	5.8
4-B	2.50	2.70	2.95	3.00	3.40	3.74	4.05	4.43	4.33	4.15	5.27	5.20	5.63	5.67	1.78	2.25	2.80	2.90	4.10	4.54	5.69	5.7
5	7.00	7.16	8.10	8.70	9.30	8.32	8.53	8.56	11.75	11.65	11.3	11.48	11.08	14.42	2.86	2.64	3.30	3.55	4.27	4.32	10.26	9.63
5-A	1.10	1.49	1.51	1.92	1.50	1.99	2.30	3.09	3.08	3.35	4.10	3.90	4.04	4.17	1.65	1.93	2.33	2.38	3.09	3.24	3.37	4.68
5-B	1.10	1.42	2.05	2.60	3.00	3.04	3.45	4.08	4.37	4.39	5.04	4.55	5.63	5.66	1.21	1.60	2.16	2.30	3.18	3.78	5.17	5.31
6	1.50	1.36	1.80	1.96	2.08	2.92	4.10	5.06	6.97	8.55	10.98	11.55	14.35	14.70	2.20	3.13	3.72	3.30	5.60	5.80	6.31	6.61
7	1.50	1.72	3.10	3.84	4.24	5.15	6.00	8.14	9.44	10.95	12.45	12.90	14.10	15.33	2.90	2.72	3.10	4.00	4.80	5.53	5.94	6.37
8	5.00	5.09	6.40	6.20	6.98	6.98	7.96	8.71	8.00	9.15	9.52	10.35	11.09	11.22	4.22	4.22	4.36	4.08	4.87	4.72	5.32	5.1
9	2.00	3.49	4.50	5.56	6.54	7.25	8.35	10.52	10.01	10.92	12.43	12.50	12.97	13.31	2.62	4.15	4.68	5.14	5.40	5.30	5.55	5.76
10	4.00	4.10	4.43	4.47	6.04	6.61	6.59	8.32	8.45	9.05	9.71	10.20	10.94	12.32	—	—	—	—	13.6	12.54	14.66	15.5
10A	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1.81	5.23	5.80	5.62	—	—	—	6.43
11	2.00	2.09	3.66	3.71	4.46	5.20	4.83	5.46	6.30	6.25	6.46	7.90	8.52	8.66	2.30	1.10	2.71	3.42	4.33	4.54	6.07	7.04
12	3.50	5.01	6.15	6.68	7.01	7.33	7.99	8.94	9.88	10.79	11.34	12.15	14.36	15.13	1.82	1.32	3.30	3.58	3.62	3.69	5.44	—
13	1.00	1.84	3.25	4.26	5.15	5.83	5.85	7.99	7.86	10.15	11.31	12.51	14.22	15.06	4.01	1.34	2.93	3.25	4.50	4.96	5.97	6.91
14A	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	7.54	9.41	10.20	11.91	12.94	14.04
14	1.50	2.22	4.10	6.06	8.02	9.34	10.00	13.32	15.90	16.10	18.71	23.74	23.82	34.76	2.94	3.59	4.62	4.64	5.50	6.17	6.98	8.09
15	6.50	8.41	10.10	11.13	12.15	12.72	13.38	16.78	18.10	19.64	20.94	21.42	22.53	23.75	1.98	2.85	2.58	4.72	7.10	8.41	11.5	12.09

Table 2: Average annual recession/advancement of DakshinGangotri glacier since 1997 (in metres)

Year	1996 to 1997	1997 to 1998	1998 to 1999	1999 to 2000	2000 to 2001	2001 to 2002	2002 to 2003	2003 to 2004	2004 to 2005	2005 to 2006	2006 to 2007	2007 to 2008	2008 to 2009	2009 to 2010	2010 to 2011	2011 to 2012	2012 to 2013	2013 to 2014	2014 to 2015	2015 to 2016	1996 to 2016
1	0.66	0.69	-0.33	0.68	-0.14	-0.34	0.69	0.89	3.01	0.14	0.10	3.57	0.43	0.08	0.37	—	—	—	—	—	—
2	0.43	2.47	1.70	1.70	0.30	0.15	0.94	1.75	1.71	0.21	-1.36	3.35	-0.98	0.44	0.08	-0.19	1.02	-0.24	1.79	1.87	17.14
2A	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.21	—		0.74	1.81	2.76
3	0.28	0.62	0.3	0.13	0.36	0.41	0.60	0.50	0.66	0.58	1.28	0.39	0.18	0.25	0.78	-0.09	0.54	0.09	0.49	0.04	8.39
4	-0.20	1.03	0.57	0.32	0.29	0.34	0.31	0.67	0.30	0.66	0.23	0.28	0.12	0.02	0.38	0.15	0.21	-0.02	0.25	0.35	6.26
4-A	0.19	0.41	0.25	0.25	0.36	0.44	0.37	0.18	0.20	0.18	0.41	0.39	0.21	0.37	0.52	0.16	0.75	0.39	1.33	0.28	7.64
4-B	0.20	0.25	0.05	0.40	0.34	0.31	0.38	-0.10	-0.18	1.12	-0.07	0.43	0.04	0.47	0.55	0.10	1.20	0.44	1.15	0.01	7.09
5	0.16	0.94	0.60	0.60	-0.98	0.21	0.03	3.19	-0.10	-0.35	0.18	-0.40	3.34	-0.22	0.66	0.25	0.72	0.05	5.94	-0.63	14.19
5-A	0.39	0.02	0.41	-0.42	0.49	0.31	0.79	-0.01	0.27	0.75	-0.20	0.14	0.13	0.28	0.40	0.05	0.71	0.15	0.13	1.31	6.1
5-B	0.32	0.63	0.55	0.40	0.04	0.41	0.63	0.29	0.02	0.65	-0.49	1.08	0.03	0.39	0.56	0.14	0.88	0.60	1.39	0.14	8.66
6	-0.14	0.44	0.16	0.12	0.84	1.18	0.96	1.91	1.58	2.43	0.57	2.80	0.35	0.93	0.59	-0.42	2.30	0.20	0.51	0.3	17.61
7	0.22	1.38	0.74	0.40	0.91	0.85	2.14	1.30	1.51	1.50	0.45	1.20	1.23	-0.18	0.38	0.90	0.80	0.73	0.41	0.43	17.3
8	0.09	1.31	-0.20	0.78	0.00	0.98	0.75	-0.71	1.15	0.37	0.83	0.74	0.13	0.00	0.14	-0.28	0.79	-0.15	0.60	-0.22	7.1
9	1.49	1.01	1.06	0.98	0.71	1.10	2.17	-0.51	0.91	1.51	0.07	0.47	0.34	1.53	0.53	0.46	0.26	-0.10	0.25	0.21	14.45
10/10A	0.10	0.33	0.04	1.57	0.57	-0.02	1.73	0.13	0.60	0.66	0.49	0.74	1.38	3.42	-2.52	-0.18	1.10	-1.04	2.10	0.84	12.04
11	0.09	1.57	0.05	0.75	0.74	-0.37	0.63	0.84	-0.05	0.21	1.44	0.62	0.14	-1.20	2.20	0.12	0.91	0.21	1.53	—	6.43
12	1.51	1.14	0.53	0.33	0.32	0.66	0.95	0.94	0.91	0.55	0.81	2.21	0.77	-0.50	1.61	0.65	0.04	0.07	1.75	0.97	11.4
13	0.84	1.41	1.01	0.89	0.68	0.02	2.14	-0.13	2.29	1.16	1.20	1.71	0.84	-2.67	3.28	-1.37	1.25	0.46	1.01	—	15.25
14	0.72	1.88	1.96	1.96	1.32	0.66	3.32	2.58	0.20	2.61	5.03	0.08	10.94	0.65	1.03	0.02	0.86	0.67	0.81	-4.85	32.45
14A	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1.87	0.79	1.71	1.03	7.06	12.46
15	1.91	1.69	1.03	1.02	0.57	0.66	3.40	1.32	1.54	1.30	0.48	1.11	1.22	0.87	-0.27	2.14	2.38	1.31	3.09	0.59	27.36

*Positive values indicate recession; *Negative values indicate an advance

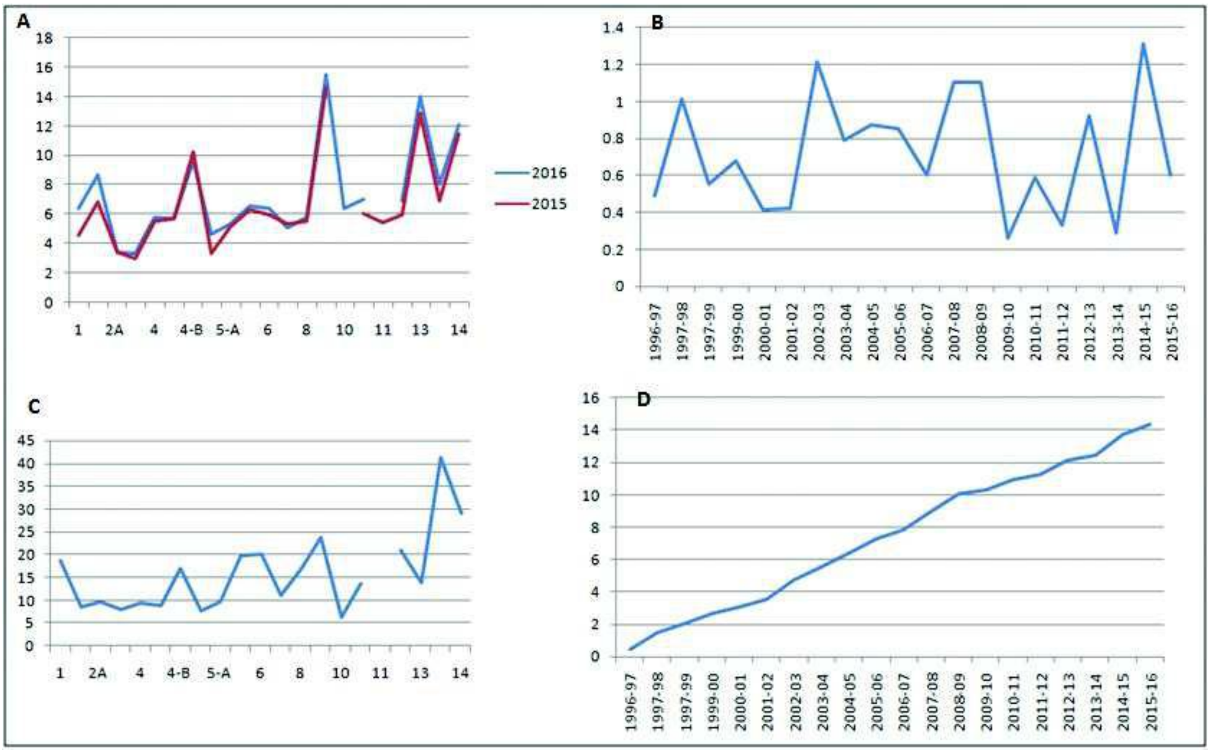

Fig. 2: Pattern of the DakshinGangotri (DG) glacier snout's recession. (A) Recession of the DG glacier in the years 2015 and 2016, (B) Recessional pattern since year 1996, (C) Total recession of DG snout since year 1996, (D) Cumulative curve for the recession of DG snout since 1996

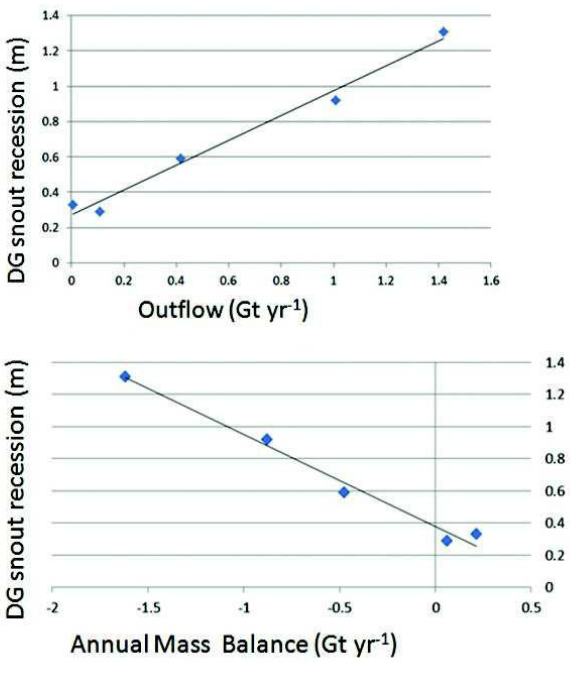

Fig. 3: Correlation between recession of DG snout with mean annual runoff and with annual mass balance of the area

Table 3: Cumulative recession of the DG glacier snout

Period	Recession (m)	Cumulative recession (m)
1996-97	0.49	0.49
1997-98	1.01	1.50
1998-99	0.55	2.05
1999-00	0.68	2.73
2000-01	0.41	3.14
2001-02	0.42	3.56
2002-03	1.21	4.76
2003-04	0.79	5.55
2004-05	0.87	6.42
2005-06	0.85	7.28
2006-07	0.60	7.88
2007-08	1.10	8.98
2008-09	1.10	10.08
2009-10	0.26	10.34
2010-11	0.59	10.93
2011-12	0.33	11.26
2012-13	0.92	12.18
2013-14	0.29	12.47
2014-15	1.31	13.78
2015-16	0.6	14.38

flank of DG snout. The wall lies on the higher ground compared to DG snout and receives maximum sun light throughout the day. This wall is being monitored continuously since 2001 with respect to fixed observation points located on the ground. The data on recessional pattern of Western wall has shown four advancements between 2007 and 2014 (Table 4 and 5). This pattern is totally different with the pattern of DG snout. Again after comparing with the average annual surface air temperature, the recession of Western wall does not show any direct correlation. The average annual recession between 2014 and 2015 is 2.37 m. Recession at different observation points vary in magnitude with the western points showing larger retreat which gradually reduces towards east (Fig. 4).

Snow Accumulation/Aablation on Ice Sheet

Snow accumulation and ablation is measured by stake networks fixed on the Antarctic ice sheet, south of Schirmacher Oasis and on ice shelf near the India Bay region. Stakes are fixed in a grid pattern with an interval of 50 m between two stakes. During the early phases of the austral summer period of 2014-15, a thick pile of snow accumulation took place in the study area. Unlike the data taken during the previous years, the measurements carried out in 2015 show that there was net ablation of 66.07 cm of snow from January 2014 to December 2014; the months January and February 2015 showed a net ablation of 9.40 cm and net accumulation of 7.61 cm, respectively (Fig. 5). The annual average accumulation / ablation data of this area (2014 to 2015) shows a net ablation of 66.20 cm. The past two years data shows annual accumulation of 56 cm for 2011-2012, 32.6 cm for 2012-2013, and 42.86 cm for 2013-2014. During the period of 2014 and 2015, a total of 66.20 X 10^4 kg of snow is ablated from the area encompassed by the stake network on the Polar ice sheet, making unit ablation of –16.55 kg/m^2. For the period of 2015-16 the larger area south of SchirmacherOasis shows 4±1cm mean ablation. The annual mass balance of

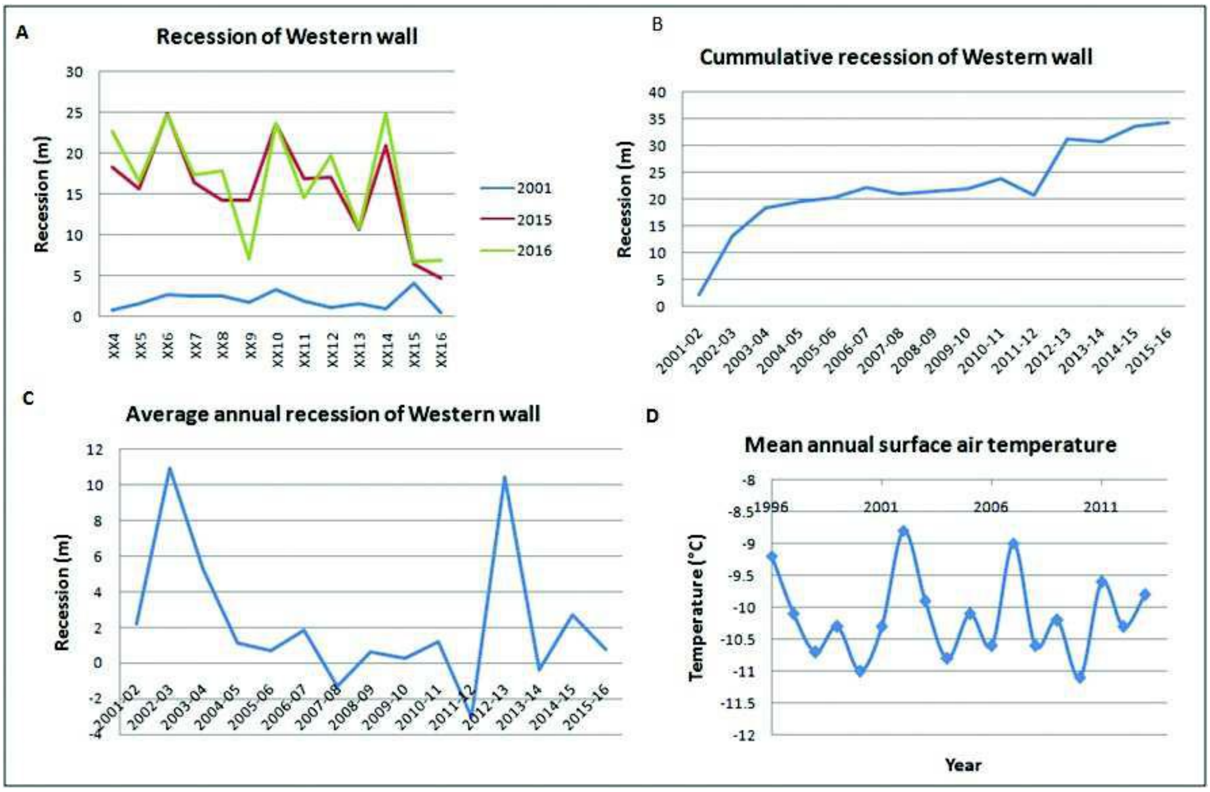

Fig. 4: Pattern of Western wall's recession. (A) Recession of Western wall in the years 2001, 2015 and 2016, (B) Cumulative curve for the recession of Western wall since 2001, (C) Recessional pattern since year 2001, (D) Average annual surface air temperature of the area

Table 4: Western Wall measurement (in meters) observation points since 2001

Fixed points	Latitude (S)	Longitude (E)	Feb-01	Feb-02	Feb-03	Feb-04	Feb-05	Feb-06	Feb-07	Feb-08	Feb-09	Feb-10	Feb-11	Feb-12	Feb-13	Feb-14	Feb-15	Feb-16
XX2	70^{0}44.603'	11^{0}26.390'	1.06	3.20	44.10	—	46.15	—	30.50	—	52.76	51.65	54.48	45.30	89.00	52.85	48.62	—
XX3	70^{0}44.621'	11^{0}26.529'	0.95	0.86	58.50	72.50	—	—	28.60	—	41.31	59.25	58.60	56.10	127.4	77.25	90.79	—
XX 4	70^{0} 44.729'	11^{0}27.660'	0.78	0.65	1.44	18.65	21.65	—	20.25	—	21.83	22.60	21.05	23.35	22.86	21.43	18.25	22.65
XX 5	70^{0}44.797'	11^{0}28.147'	1.53	—	—	—	—	13.95	14.15	—	16.28	16.60	16.90	10.40	13.44	15.11	15.69	16.55
XX 6	70^{0} 44.879'	11^{0}28.562'	2.67	—	7.78	15.00	—	—	21.20	—	30.00	27.85	24.20	—	13.66	16.41	24.85	24.74
XX 7	70^{0} 44.932'	11^{0}28.905'	2.53	5.01	5.24	6.80	—	8.56	11.13	—	18.45	11.87	12.20	12.34	13.78	13.84	16.38	17.43
XX 8	70^{0}45.225'	11^{0}31.120'	2.50	2.45	6.52	8.28	—	11.70	16.75	15.47	11.76	21.00	17.38	12.00	20.00	13.86	14.14	17.84
XX 9	70^{0} 45.268'	11^{0}31.401'	1.72	2.47	—	3.00	—	—	22.70	5.30	16.93	6.73	6.50	5.29	6.10	5.98	14.23	7.09
XX 10	70^{0}45.300'	11^{0}31.614'	3.30	16.71	8.91	17.63	17.00	19.12	20.05	18.72	4.96	21.08	21.35	21.11	21.80	23.8	23.60	23.59
XX 11	70^{0}45.417'	11^{0}33.135'	1.84	4.37	5.27	5.92	7.10	7.30	9.70	10.75	19.73	10.24	10.73	9.83	13.00	9.40	16.82	14.64
XX 12	70^{0} 45.428'	11^{0}33.289'	1.08	—	2.78	—	2.80	~3.35	5.90	9.76	10.94	10.40	8.42	13.23	15.92	15.35	16.97	19.76
XX 13	70^{0} 45.407'	11^{0}33.478'	1.58	1.86	2.96	3.10	4.70	4.73	6.10	7.96	11.55	6.20	18.90	7.53	8.63	8.54	10.66	10.78
XX 14	70^{0}45.403'	11^{0}33.619'	1.02	1.87	2.66	3.80	5.65	~6.50	8.20	12.5	9.21	14.85	15.92	-	-	20.88	20.86	24.82
XX 15	70^{0}45.424'	11^{0}33.733'	4.06	—	4.42	4.80	4.37	4.47	4.90	—	13.52	5.43	4.50	5.58	5.04	5.78	6.40	6.81
XX 16	70^{0}45.436'	11^{0}34.022'	0.53	—	—	0.01	1.55	2.60	4.40	—	4.86	2.44	14.90	4.54	5.48	5.82	4.66	6.98
XX 17	70^{0}45.631'	11^{0}34.739'	0.94	—	1.54	—	20.05	—	—	—	—	-	16.78	-	-			

"—" points not available/snow covered

the part of ice sheet, south of Schirmacher Oasis varies between –1.6 to 0.22 Gtyr^{-1} in last five years.

The runoff is mainly controlled by mean annual surface air temperature showing strong positive correlation and possibly due to geothermal component (Fig. 5). Horizontal movement of the melt water is neglected on the grounds that any liquid water owing down the slope of the ice sheet will generally encounter areas in which the firn is already saturated with water and will not refreeze. In the vertical movement, the water in excess of a prescribed volume fraction percolates to the lower layer. Once formed, the runoff is therefore assumed to reach the ocean. The mean annual runoff in the study area varies between 0.01 to 1.2 cubic meter per sq. meter.

The variation of the snow surface due to the annual snow accumulation and ablation pattern depend upon the dominant wind pattern. The calculation of the shifting of stakes located on the Polar ice sheet with the help of hand-held GPS shows that the Polar ice sheet is moving very slowly by 2.5 m per year towards N33E, as observed in the period between 2010-11 and 2014-2015 (Swain and Raghuram, 2015).

Subsurface Study by Ground Profile Radar (GPR)

Ground Penetrating Radar (GPR) technology offers the facility to delineate and map the subsurface features in three dimensions. The advantages of GPR include its non-destructive nature, higher resolution and rapid deployment. The ice-land interface in the south of Schirmacher Oasis and land-ice-sea

Table 5: Average annual recession/advancement of Western Wall (in meters) from observation points since 2001

Fixed points	(2001-02)	(2002-03)	(2003-04)	(2004-05)	(2005-06)	(2006-07)	2007-08)	(2008-09)	(2009-10)	(2010-11)	(2011-12)	(2012-13)	(2013-14)	(2014-15)	(2015-16)	(2001-16)
XX2	2.14	40.90	—	—	—	—	—	—	-1.11	2.83	-9.18	43.70	-36.15*	-4.23	—	47.56
XX3	-0.09	57.64	14.00	—	—	—	—	—	17.94	-0.65	-2.50	71.30	-50.15*	13.54	—	89.84
XX 4	-0.13	0.79	17.21	3.00	—	—	—	—	0.77	-1.55	2.30	-0.49	-1.43	-3.18	4.4	21.87
XX 5	—	—	—	—	—	0.20	—	—	0.32	0.30	-6.50	3.04	1.67	0.58	0.86	15.02
XX 6	—	—	7.22	—	—	—	—	—	-2.15	-3.65	—	—	2.75	8.44	-0.11	22.07
XX 7	2.48	0.23	1.56	—	—	2.57	—	—	-6.58	0.33	0.14	1.44	0.06	2.54	1.05	14.9
XX 8	-0.05	4.07	1.76	—	—	5.05	-1.28	-3.71	9.24	-3.62	-5.38	8.00	-6.14	0.28	3.7	15.34
XX 9	0.75	—	—	—	—	—	-17.40	11.63	-10.20	-0.23	-1.21	0.81	-0.12	8.25	-7.14	5.38
XX 10	13.41	-7.80	8.72	-0.63	2.12	0.93	-1.33	-13.76	16.12	0.27	-0.24	0.69	2.00	-0.20	-0.01	20.29
XX 11	2.53	0.90	0.65	1.18	0.20	2.40	1.05	8.98	-9.49	0.49	-0.90	3.17	-3.60	7.42	-2.18	12.8
XX 12	—	—	—	—	—	—	3.86	1.18	-0.54	-1.98	4.81	2.69	-0.57	1.62	2.79	18.68
XX 13	0.28	1.10	0.14	1.60	0.03	1.37	1.86	3.59	-5.35	12.70	-11.37	1.10	-0.09	2.12	0.12	9.2
XX 14	0.85	0.79	1.14	1.85	—	—	4.30	-3.29	5.64	1.07	—	—	—	-0.02	3.96	23.8
XX 15	—	—	0.38	-0.43	0.10	0.43	—	—	-8.09	-0.93	1.08	-0.54	0.74	0.62	0.41	2.75
XX 16	—	—	—	1.54	1.05	1.80	—	—	-2.42	12.46	-10.36	0.94	0.34	—	2.32	6.45
Average recession	**2.22**	**10.96**	**5.28**	**1.16**	**0.70**	**1.84**	**-1.28***	**0.66**	**0.27**	**1.19**	**-3.02***	**10.45**	**-0.37***	**2.70**	**0.78**	**21.73**

*Positive values indicate recession; *Negative values indicate an advance

interface along the northern margin of the Schirmacher Oasis has been carried out (Fig. 6) which is very crucial for the study of mass balance of this region. During expeditions, A 60 m line was surveyed (MLF at 35 MHz) at a distance of 90 m north of Baalsrudfjelletnunatak to 150 m distance north, showed that the variation in land-ice interface at a depth of 50 m to 90 m. Another 60 m profile obtained (MLF at 35 MHz) from 190 m north of this nunatak to 250 m north of it show the variation in land-ice interface at a depth of 140 m to 180 m. A combined profile from the base of Baalsrudfjelletnunatak to 250 m north shows a uniform and moderate slope of 280 till initial 70 m, followed by a steep slope of 380 till 250 m. Further GPR profiles obtained beyond these points show that the depth of the Land-ice interface increased to 300 m at a horizontal distance 500 m away from Baalsrudfjelletnunatakand at a distance of 750 m, a more or less uniform thickness of ice is observed for about 330-350 m till the point A7 of the Indianconvoy route. To observe still deeper part, two way travel time was increased to 6000 ns range, which is an equivalent to a depth of 440 m. Thereafter, the survey line followed the convoy route closely and subsurface data was recorded from A-7 (70°52.772' S: 12°8.550' E) to A-12 (70°50.393'S: 12°18.492'E). Data indicates that the polar ice thickness increases from 0 m near Baalsrudfjellet nunatak to about 380 m at point A-12 of convoy route (Dharwadkar *et al.*, 2012).

A possible loci for L-I-S (Land-Ice-Sea) interface was

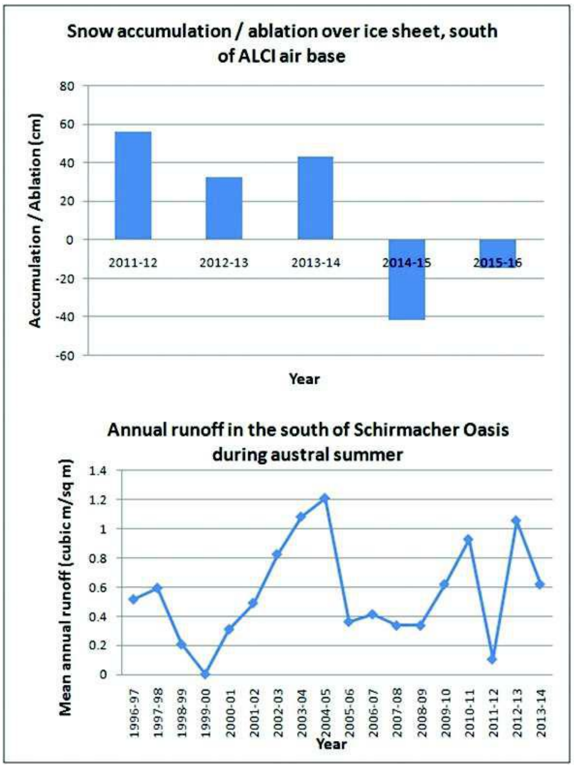

Fig. 5: Average annual snow accumulation/ablation and run-off, south of Schirmacher Oasis

detected at latitude 70°51.090'S and longitude 12°14.429'E that gets expressed as a steeply sloping land-ice interface juxtaposed against gently sloping sea-ice interface. This juxtaposition is observed at 340 m below the ice sheet that was later confirmed in a closely spaced profile line generated during 30th expedition. Convex nature of the bedrock has been observed in one profile north of the grounding line.

Glacial Inventory of the Wohlthat Mountains

A glacial inventory of the Wohlthat Mountains was prepared as per the guidelines of the Manual of Temporary Secreteriat (TTS) of World Glacier Inventory (Muller, 1977, 1978). The Wohlthat Mountain, located 110 km south of Schirmacher Oasis in Dronning Maud Land, comprises four blocks as (i) Gruber, (ii) Petermann, (iii) Humboldt and (iv) Orvin. There are total 122 glaciers in Wohlthat mountain chain. Out of this, more than 50% of the glaciers are oriented in NW and W directions. Most of the glaciers are smaller than 1 sq km. In general the glacier elevation varies between 700 to 2600 m above sea level. The glaciers are of mountain glacier type occurring in the form of ice aprons or flowing in simple basin. The general elevation of outlet glacier Oasiss from 1900 metre above sea level (masl) in the north in the Gruber block. Within the ambit of glacierisation of Gruber, 19 glaciers of different orientation and dimension were identified. The general elevation of the outlet glacier is 2300 msl in the south to 1000 msl in the north in Petermann block. There are 45 glaciers in this group. In Humboldt group the general elevation of outlet glacier (and ice sheet) is 2100 masl in the south to 1000 masl in the north. There are 41 numbers of glaciers in this group. In the Orvin group there are 17 glaciers and the general elevation 2100m to 1700m from south to north (Srivastava et at., 1988). Studies of recessional moraines indicate that the deglaciation in the eastern part of Wohlthat Mountain has taken place in three stages leading to the formation of dry valleys. The presence of ice sheet at 2000 m above sea level is indicated by polished surfaces and striations. These striations imply northwesterly flow of the glaciers.

Ice Sheet Dynamics

During 22nd (2002-03) and 24th (2004-05) Indian Antarctic Expeditions, study was carried out to understand the movement of glacier surrounding the Schirmacher Oasis in collaboration with Indian Institute of Geomagnetism (IIG), Mumbai (Fig. 7). The GPS network in the south of Schirmacher Range with 21 sites (Fig. 7) having 5 km inter-space networking was established to measure the horizontal movement of ice sheet. The base station (MAIT) was set up on exposed bedrock on Schirmacher Oasis. The GPS receivers in the field were powered by specially sealed 12V, 72 Ah charged batteries enclosed in non conducting boxes. All the sites were observed continuously for 48-72 hours duration with 30 s sampling interval and 15° elevation mask. The recorded GPS data organized into 24h segments, covered a Universal Time Coordinated (UTC) day and were analysed in three steps. In the first step the GPS carrier phase data were processed with the precise ephemeris from the International GPS Service (IGS) stations to produce position estimates. In the next step these data have been standardize with the help of daily solutions for station positions using GPS analysis Massachusetts Institute of Technology (GAMIT) and software (King and Bock, 2000). In

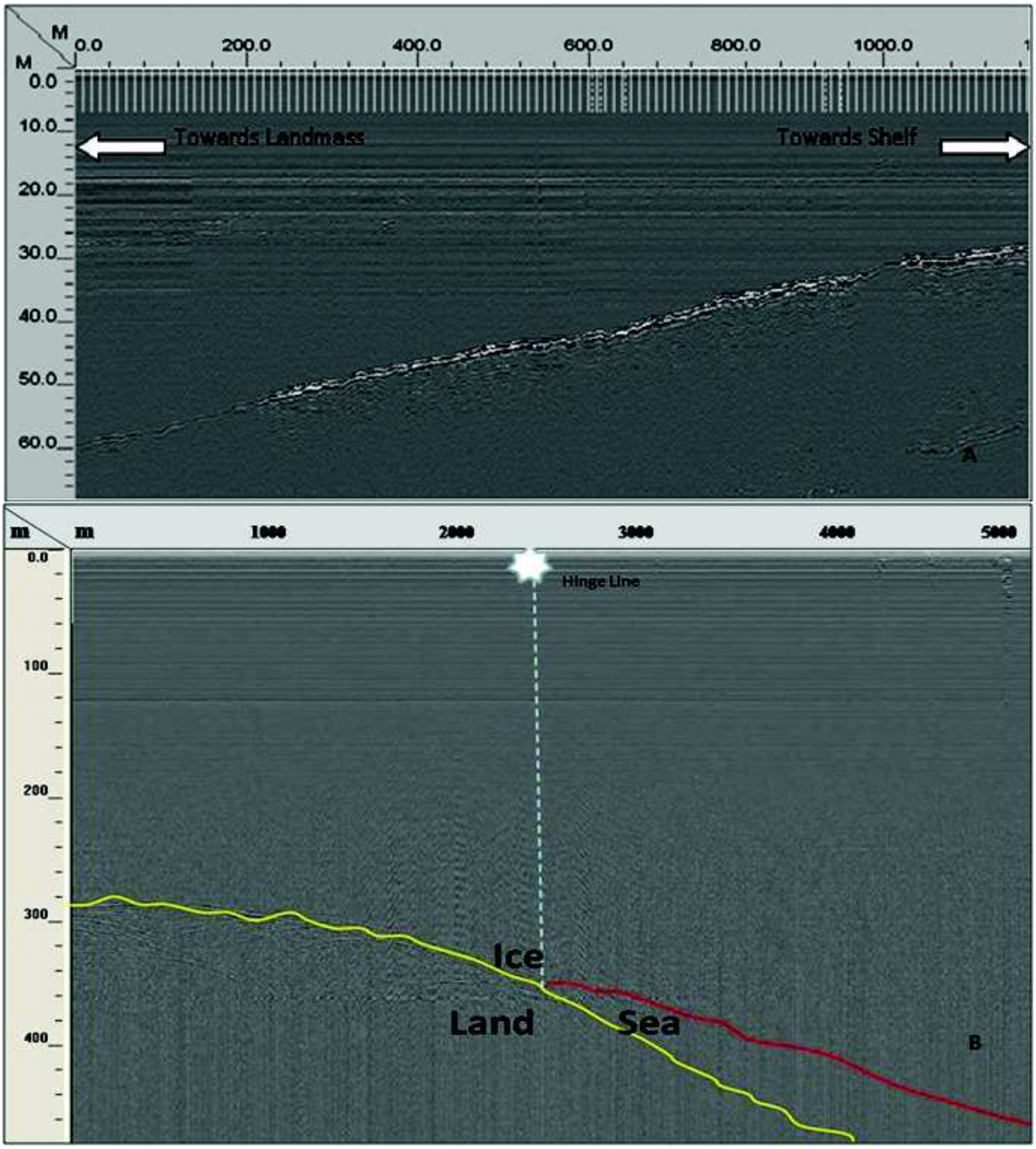

Fig. 6: (A) Interface between Ice and Land between Baalshrudnunatak and A-12 point, (B) Land-Ice-Sea interface, East of Schirmacher oasis

the third step station position and velocity vectors at each site were obtained.

For a complete description of the flow field of a glacier, both the horizontal and vertical components of the velocity are required. However, this study was confined to calculate the horizontal velocity components only by imposing tight constraints (1 cm/a) on the horizontal components of the base station. Horizontal velocities of the glacier sites lie between 1.89±0.01 and 10.88±0.01 m a-1 to the north-northeast, with an average velocity of 6.21±0.01 m a^{-1}. The

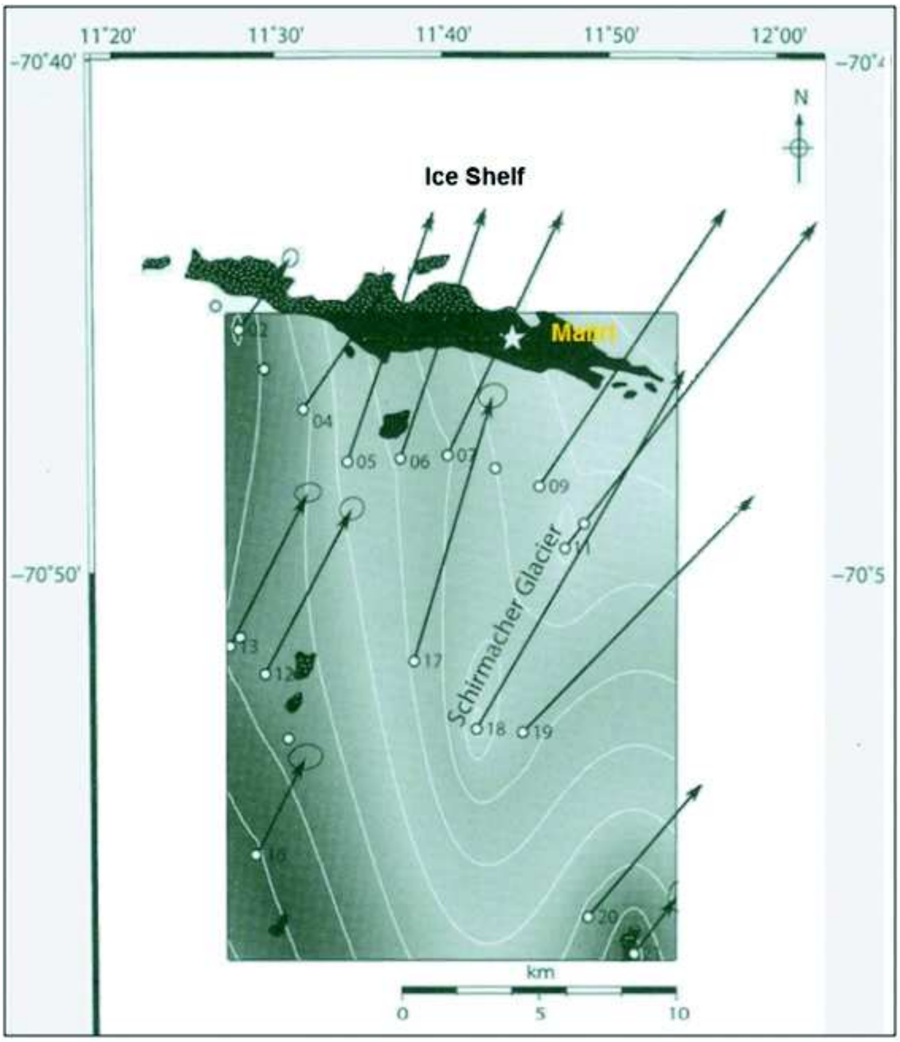

Fig. 7: Ice Sheet dynamics surrounding the Schirmacher Oasis, East Antarctica

principal strain rates provide a quantitative measurement of extension rates, which range from (0.11±0.01) & times 10-3 to (1.48±0.85) × 10-3 a-1, and shortening rates, which range from (0.04±0.02) × 10-3 to (0.96±0.16) × 10-3 a-1. The velocity and strain-rate distributions across the GPS network in the ice sheet, south of Schirmacher Oasis are spatially correlated with topography, subsurface undulations, fracture zones/crevasses and the partial blockage of the flow by nunataks and the Schirmacher Oasis (Sunil *et al*., 2007, 2010).

In a related study, the movement of ice sheet was also observed on year long basis through one polar winter. The vector movement of the glacier helps in bulging forward in the snout area of Dakshin Gangotri glacier. These extra bulged parts of the snout break down and melt away from the main glacial body during the polar summer resulting in a net retreat of the glacier (Chaturvedi *et al*., 1999, 2003 and 2004).

Discussions and Conclusion

The Dakshin Gangotri (DG) snout which is a part of EAIS, overriding Schirmacher Oasis, shows continuous recession since last three decades. During the period 2014-15, the DG glacier snout has receded by 1.31 m with respect to its position from previous year. For the same period, the western wall has shown a recession of 2.37 m with respect to the previous year. It is observed that meteorological parameters including higher average annual surface air temperature and higher wind speed results in greater recession of the snout of DG glacier snout in the succeeding year. The annual recessional pattern of Dakshin Gangotri glacier snout indicates that major recession in every five years with minor peaks at every 2-3 years interval between 1996-2010 period. But in the last five years (2011-16) the trend of DG snout is different than the previous 15 years period. The recessional pattern of Western wall is totally different with the pattern of DG snout. During the period of 2014 and 2015, there is unit ablation of -16.55 kg/m^2 over ice sheet, south of Schirmacher Oasis. The mean annual runoff in the study area varies between 0.01 to 1.2 m^3 per sq. meter. This mean annual runoff shows direct positive correlation with the average annual recession of the snout. The annual mass balance of the part of ice sheet, south of Schirmacher Oasis varies between -1.6 to 0.22 Gtyr^{-1} in last five years. The minor correlation between surface air temperature anomaly of Schirmacher region along with global (southern and northern hemisphere) temperature anomaly pattern provides space for some other factors such as effect of ocean current, albedo, isostacy and solar cycle, which may be contributing to the recession of this snout.

The ice-land interface in the south of Schirmacher Oasis indicates that the polar ice thickness increases from 0 m near Baalsrudfjellet nunatak (south east of Schirmacher Oasis) to about 380 m towards north-west of Schirmacher Oasis (70°50.393'S: 12°18.492'E). There are total 122 glaciers in Wohlthat mountain chain. Out of this, more than 50% of the glaciers are oriented in NW and W directions. Most of the glaciers are smaller than 1 sq km. These glaciers partly contribute to the part of ice sheet south of Schirmacher Oasis. Thermal profiling of ice sheet shows that the variations in the polar cold front penetrated up to a maximum depth of 25m. Beyond this depth, the temperatures remained uniform throughout the year. The highest temperatures were recorded at the bottom of the glacier. The zone of temperature-inversion was observed between 25m and 30m depth. Beyond this zone, the temperature gradually kept on rising till the borehole reached the bedrock. Horizontal velocities of the glacier sites lie between 1.89±0.01 and 10.88±0.01 m a^{-1} to the north-northeast, with an average velocity of 6.21±0.01 m a^{-1}.

References

Beg M J, Chaturvedi A, D'Souza M J and Asthana R (1997) Fluctuations in the Surface Profile of a part of Ice Shelf in Central Dronning Maud Land, East Antarctica Scientific report of Thirteenth Indian Expedition to Antarctica *Tech. Pub* **11** DOD, Govt of India, New Delhi, 221-226

Chaturvedi A, Singh A and Kaul M K (2001) Ice core drilling in polar continental ice at Tronstadhallet, Central Dronning Maud Land, Antarctica; Proc. Symp. Snow, Ice and Glaciers, March 1999 *Geolsurv Ind Spl Pub* **53** 403-408

Chaturvedi A, Singh A, Gaur M P, Krishnamurthy K V and Beg M J (1999) A confirmation of Polar Glacial Recession by monitoring the Snout of DakshinGangotri Glacier in Schirmacher Oasis. Scientific report on fifteenth Indian Expedition to Antarctica, Tech. Pub No. 13, D.O.D. Govt. of India, New Delhi, 321-336.

Chaturvedi A, Beg M J, Singh A and Ravindra R (2003) Two decades of obervations over polar ice cap margin in SchirmacherOasis of central Dronning Maud Land Antarctica, Abstract for 7th Int. Symposium of Antarctic Glaciology (ISAG-7) Milano, Italy

Chaturvedi A, Beg M J and Keshav Prasad A V (2004) Monthly patterns of Advance and Retreat of DakshinGangotri glacier snout in Schirmacher Oasis, Ninteenth Indian Expedition to Antarctica, Scientific Report, DOD *Tech Publ* **17** 21-31

Chaturvedi A, Shrivastava P K, Kaul M K, Chaturvedi S K and Mukerji S (2009) Recession of DakshinGangotri glacier snout in Schirmacher Oasis, East Antarctica *Ind Jour of Geosc* **63** 229-234

Dharwadkar A, Swain A K, Chaturvedi A, Mandal A, Roy S K and Kumar P (2012) Delineation of grounding line, quantification of the expanse and thickness of the ice shelf near Schirmacher Oasis, East Antarctica, RP/CHQ/IRHR/ 2006/008, Geological Survey of India Reporting, R. W. and Bock, Y., 2000: Documentation for the GAMIT analysis software, release 10.0, Massachusettes Institute of Technology, Cambridge

King R W and Bock Y (2000) Documentation for the GAMIT analysis software, release 10.0, Massachusettes Institute of Technology, Cambridge

King R W and Bock Y (2000) Documentation for the GAMIT analysis software, release 10.0, Massachusettes Institute of Technology, Cambridge

Muller F, Caflisch T and Muller G (1977) Instructions for the compilation and assemblage of data for a world glacier inventory, Zurich, Temporary Technical Secreteriat for World Glacier Inventory, Swiss Federal Institute of Technology

Muller F, Caflisch T and Muller G (1978) Instructions for the compilation and assemblage of data for a world glacier inventory, Zurich, Temporary Technical Secreteriat for World Glacier Inventory, Swiss Federal Institute of Technology, Suppliment identification glacier number

Ravindra R, Chaturvedi A and Beg M J (2002) Melt water lakes of Schirmacher Oasis – Their genetic aspects and classification. In Advances in Marine and Antarctic Science. Eds. Sahoo, D.B. and Pandey, P.C. New Delhi, 301-303

Shrivastava P K, Asthana R, Beg M J, Nath A K, Dharwadkar A, Swain A K, Roy S K and Mandal A (2013) Latitudinal shift in iceberg distribution as observed along the voyage route of Indian Antarctic Expedition *Indian Jour of Geosciences* **66** 149-158

Shrivastava P K, Asthana R and Roy S K (2011) The Ice Sheet Dynamics around DakshinGangotri Glacier, Schirmacher Oasis, East Antarctica *vis-a-vis* Topography and Meteorological Parameters *Jour Geol Soc of Ind* **78** 117-123

Shrivastava P K, Roy S K and Mallik R K (2014) Glaciological Studies in Central Dronning Maud Land, East Antarctica during the 33rd Indian Antarctic Expedition, GL/CHQ/M IV/2013/073, Geological Survey of India Report

Singh R K, Mukerji S, Srivastava D and Kaul M K (1988) Snow Accumulation and Ablation Pattern on Ice Shelf near DakshinGangotri, Antarctica and Development of Fast Ice off DakshinGangotri *Sci Rep of Fifth Indian Expedition to Antarctica Tech Pub* **5** DOD, New Delhi, 189-204

Srivastava D, Kaul M K, Singh R K, Mukerji S and Jayaram S (1988) Glacier inventory of Wholthat Mountain chain, Queen Maud Land, Antarctica *Scientific Report, Dept of Ocean Development, Tech Pub* **5** 235-245

Sunil P S, Reddy C D, Ponraj M, Dhar A and Jayapaul D (2007) GPS determination of the velocity and strain rate fields on Schirmacher Glacier, central Dronning Maud Land, Antarctica *Jour Glaciology* **53** 558-564

Sunil P S, Reddy C D, Dhar A, Ponraj M, Sevaraj C and Jayapaul D (2010) GPS derived velocity field and strain rates of Schirmacher Glacier, East Antarctica *Scientific Report, Tech Publ* **21** 115-126

Swain A K and Roy S K (2011) Glaciological work carried out during 27th Indian Antarctic Expedition. Unpublished report, Antarctica Division, (Mission IV) Geological Survey of India, pp 1-10

Swain A K and Mandal A (2012) Glaciological observations during the 30thIndianAntarctic Expedition.Unpublished report, Antarctica Division, (Mission IV) Geological Survey of India, pp. 1-10

Swain A K and Raghuram (2015) Glaciological studies in Central Dronning Maud Land, East Antarctica during the 34th Indian Antarctic Expedition, GL/CHQ/M-IV/2014/084, Geological Survey India.

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Research Paper

Recent Contributions to the Antarctic Geology - An Indian Perspective

NARESH C PANT[1],*, SANDIP ROY[2], V RAVIKANT[3] and RASIK RAVINDRA[4]
[1]*Department of Geology, University of Delhi, Delhi 110 007, India*
[2]*Geological Survey of India, NH 5P, NIT Faridabad 121 001, India*
[3]*Indian Institute of Technology-Kharagpur, Kharagpur 721 302, India*
[4]*Ministry of Earth Sciences, Prithvi Bhawan, New Delhi 110 003, India*

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Indian geoscientists have been studying Antarctic geology for three and a half decades in Antarctica. The studies were mainly carried out in campaign mode for long but have now assumed greater focus as these have started investigating scientific questions of global interests. Starting from early report of anorogenic magmatism in the central Dronning Maud Land (cDML), identification and description of magmatic charnockites representing a chemically distinct magma to characterizing and confirming the continuation of East African Orogen in Antarctica. These studies represent some of the key contributions besides providing the baseline geological maps of the cDML area. The establishment of permanent station at the Larsemann Hills has allowed wider India-Antarctica geological correlation.The land-sea-ice interface in the cDML and use of marine sediments as archives of ice-sheet fluctuations as well as providing clues to the sub-ice geology is demonstrated from the Wilkes Land sector in east Antarctica. These ice-sheet proximal deposits allow reconstruction of time-constrained advance and retreat of the east Antarctic ice sheet.

The contributions include study of Quaternary deposits, especially the lake deposits which have significant bearing on understanding the ice sheet behavior during late Quaternary. Increasing participation in global scientific programs, multidisciplinary studies and active involvement in Scientific Committee on Antarctic Research (SCAR) specially in geoscience augurs well for future progress of Antarctic geoscience studies in India.

Keywords: Dronning Maud Land; Larsemann Hills; Schirmacher; Wilkes Land; Geology

Introduction

Indian contribution to the Antarctic Geology has largely been confined to the central Dronning Maud Land (cDML) sector of the east Antarctica for nearly three decades (1981-2011). This was on account of the location of the first two stations, Dakshin Gangotri, located on the ice-shelf and Maitri, the second station on ice free Schirmacher Oasis, from which only limited access was possible. The studies which began as localized geological descriptions have assumed significance lately for two reasons- first recognition of cDML terrain as possible extension of the East African Orogen (EAO) in Antarctica and the significance of sub-ice geology in the context of understanding and predicting East Antarctic Ice Sheet (EAIS) behaviour, the largest single mass of fresh frozen water on planet earth. The studies were extended to the Larsemann Hill sector in eastern Antarctica after 2006,following the identification of site for the Bharati Station in the Grovenes Promontory. Indian contributions to Antarctic geology are described in following description for the three domains, namely, the cDML, the Larsemann Hills and the Wilkes Land sector.

Central Dronning Maud Land Sector

Geological Studies

The Wohlthat Massif, a rugged mountainous terrain located ~100km south of the Schirmacher Oasis, exposes large magmatic bodies. Indian geologists in pioneering studies recognized largely anorogenic

**Author for Correspondence: E-mail: pantnc@gmail.com*

nature of this magmatism which ranged from ultrabasic to acidic in composition besides establishing presence of a distinct charnockitic magma in the region (Kaul *et al*., 1991, Joshi *et al*., 1991, Joshi and Pant, 1995, Ravindra and Pandit, 2000). Ravikant (1998) presented a thermal model for one of the largest Proterozoic anorthosite massif located at the Gruber Mountains in cDML which was followed by petrological and geochemical studies of this Neoproterozoic magmatic intrusive (Ravikant *et al*., 2011). The inter-relationship between various magmatic bodies is debatable and requires further investigation. Compilation of several decades of geological data produced geological maps of Schirmacher Oasis (Geol. Survey. of Ind., 1998), Orvinfjella (Geol. Survey of Ind, 2006a), Muhlig-Hofmannfjella, (Geol. Survey of Ind., 2010), Wohlthat Massif (Geol. Survey of Ind., 1991) and Geomorphological map of the Schirmacher oasis (Geol. Survey of Ind., 2006b).

The shear zones of the Schirmacher oasis were studied in detail (Sengupta 1993, Roy *et al*., 2015a). The dominant shear zones have a NE-SW trend with a variable southerly dip. The stretching and mineral lineation associated the shear zone is a low 30° to sub horizontal from SE direction. The general movement sense is sinistral. The shear is a general shear with a pure to simple shear component in 45:55 ratio. The shear strain of $\gamma = 1.6$, calculated from deformed augen represents the cumulative strain suffered by these deformed rocks. The flow planes are parallel to regional foliation of rocks that define dominant fabric developed during the East African Orogeny. Based on the regional setting, nature and timing of this shear zones and its association with the retrogressive amphibolite-facies metamorphism (during the decompressive phase), these shear zones are inferredto be a part of the response of these rocks to the major exhumation phase (D'Souza *et al*., 2011). The mylonitic zones of the Schirmacher oasis are thought to have evolved during the late phase of D2/M2 to early D3/M3 tectonothermal event (Sengupta 1993, Bose and Sengupta 2003, D'Souza *et al*., 2011, Roy *et al*., 2015a).

An area of about 4 sq. km. was mapped on 1: 10,000 scale in the Baalsrudfjelletnunatak, southeast of the Schirmacher Range, during 31st Indian Antarctic expedition (2011-12). The lithological assemblage exposed in this nunatak consists of an interbanded sequence of quartzo-feldspathic gneiss, pyroxene granulite, metapelite with intrusives like lamprophyre and quartz veins. The country rock is represented by the quartzo-feldspathic gneisses with or without orthopyroxene and garnet. The melanocratic quartzo-feldspathic gneiss is rich in amphibole and biotite. The mineral assemblage of plagioclase + quartz + biotite + garnet + orthopyroxene + amphibole indicates granulite facies peak metamorphic conditions. Geochemical attributes of these orthogneissesindicate a syncollisional setting. The metapelite is represented by the mineral assemblage quartz + biotite + plagioclase + garnet + sillimanite. The peak metamorphism for metapelite is estimated at 635°C at 6-7Kbar assumed pressure (Roy *et al*., 2015b). Pyroxene granulite is one of the major rock types interbanded with the quartzo-feldspathic gneiss. It is composed of plagioclase + orthopyroxene + clinopyroxene + biotite + Ca-amphibole ± ilmenite. Two-pyroxene geothermometer indicates peak temperature of 730°C at intermediate pressure. The dominant pervasive fabric trends ENE-WSW. The map pattern of the nunatak is structurally controlled. The area underwent three phases of folding deformation (F_1, F_2 and F_3).The dome and basin structure is a result of the interference pattern of F_1 and F_2 folds. The ENE-WSW trending F_2 folds are the most dominant whereas the F_3 is of mild intensity. The lamprophyres are calc-alkaline in nature and are syn- to post-F_2 deformation. The oldest date obtained during the present studies from monazite within the metapelite of ~640Ma indicates that the area is a part of EAO marking the suture between east and west Gondwanaland and provides continuity of extension of EAO between Schirmacher and Wohlthat (Roy *et al*., in press). On the basis of lithotypes, petrography, structure and deformation fabrics, the Baalsrudfjelletnunatak shares geological continuity with the Schirmacher Oasis.

The complex metamorphic evolution of the cDML terrain has been a subject matter of intense studies by the Indian geosciences community. Central Dronning Maud Land, East Antarctica is a high grade polymetamorphosed and polydeformed terrain (Ravikant 2008, 2009; Ravikant *et al*., 2011). In several papers the Neoproterozoicage of metamorphism in the Schirmacher Oasis was demonstrated including the nature of the oceanic crust which allowed the authors to conclude that the proposed extension of EAO is likely to be within the Schirmacher Oasis (Ravikant *et al*., 2004, 2005, 2007; Ravikant 2005, 2006, 2008). It is significant as EAO in this terrain signifies the suture zone between the east and the west Gondwana blocks and is marked by the granulite grade rocks of ~650Ma age. In a detailed petrological study with geochronological constraints it was shown that the extension of EAO can be established further ~100km inland in the Humboldt Mountains in cDML (Pant *et al*., 2013a). Grain growth parameters and mineral zoning suggested an ~8km thick sequence regionally metamorphosed to granulite grade conditions (Pant and Verma, 1994). Calc-silicate rocks have been found to be intimately associated mainly with the metasedimentary units in the area. These rocks occur as zones exposing prominent marble bands and associated calc silicate rocks. The marble bands present in cDML have shown peak assemblages of forsterite-spinel-calcite-dolomite-plagioclase-biotite suggesting metamorphism at 750°-780°C under high XCO_2 (0.9) condition(D'Souza *et al*., 2012). The occurrence of granulites and enderbitic-charnockites, having anhydrous mineral assemblages may be related to this event. The calc-silicate rock shows scapolite-wollastonite-diopside-plagioclase assemblage with development of coronal garnet (D'Souza *et al*., 2012). The reaction textures present in the rock has helped constrain the P-T fluid history of calc silicate rock in particular and the metamorphism in cDML in general. The peak metamorphic temperature obtained through these textures is around 900°C under high pressure (~ 9kbar) conditions. The calc-silicate rocks and the marble have shown effect of amphibolite-facies retrogression under the influence of high H_2O content and reduced X_{CO2}value. Replacement of forsterite by clinohumite suggests at 650°C temperature and $X_{CO2} \sim 0.3$. The presence of clinohumite and diopside on other hand suggests further fall in X_{CO2}values and increased activity. This study shows the values obtained for calc silicate rocks to be higher than the estimates available from metapelite. However there are reported occurrences of UHT assemblages in cDML area (Grew 1983). The P-T fluid histories indicated for cDMLcalc-silicate rocks are strikingly similar to the calc silicate marbles reported from Ambasamudram area in of Kerela Khondalite Belt (KKB) and in Highland complex of Sri Lanka. These areas have been shown to be part of East African Orogen (EAO) associated with formation of Gondwana.

Geological evolution of the Schirmacher Oasis can be related to three temporally distinct tectonothermal events. Magnetic susceptibility studies indicate three phase deformation of these rocks (Pandit *et al*., 2008) which can be summarised as below:

- Structural evolution includes at least two folding events followed by intense shearing during the D_3 deformation phase.
- Observed magnetic susceptibilities are in the range of paramagnetic to mixed-type (paramagnetic + ferromagnetic) values with biotite and hornblende as the main carriers of magnetization.
- The magnetic fabric anisotropies define two groups characterized by prolate (linear) and oblate (planar) geometries, respectively. Anisotropies are higher for the oblate fabrics (P' 1.1 to 1.15) compared to the prolate ones (P'< 1.05). Oblate fabrics can be related to D_1 and D_2 fabrics while the prolate, lower-anisotropic geometries (SW-dipping magnetic lineations) are a result of D_3 shear overprint.

Quaternary Geology/Paleoclimate Studies

The Antarctic ice sheet is dynamic and continuously moving towards north under the influence of gravity. The portion of ice sheet, which floats over the sea, is called ice shelf. The loci of points where Land-Ice-Sea (L-I-S) meet, is called grounding line or hinge line and it has been demarcated for the area close to Schirmacher oasis through GPR profiling (Dharwadkar *et al*., 2012; Swain and Goswami, 2014). The grounding line is not fixed but keeps shifting in response to changes in environment. The location of grounding line is important in order to evaluate the dynamic processes occurring at the distal edge of ice sheet. Ground-penetrating radar (GPR) is a non-invasive, time and cost effective, environmentally safe technique for high-resolution geophysical mapping that is effectively used in the Polar Regions for subsurface mapping. During GPR data collection an-electromagnetic pulse (10-1000 MHz) is transmitted into the ground along a survey line. This pulse is reflected back to the surface from subsurface interfaces where dielectric properties of different mediums change and are recorded.

GPR profiles in a continuous stretch extending from the tip of Baalsrudfjelletnunatak, where the rocks are exposed, to the edge of ice-shelf and covering a distance of about 78 km were taken during 28th to 31st expeditions undertaken between 2008 and 2011. Data generated through these profiles has been used to demarcate the boundaries between land-ice-sea (Dharwadkar *et al*., 2012). This study has provided significant inputs to the mass balance of Antarctic ice and in estimating the vulnerability of the ice shelf to calving and affecting the land cargo routes between Maitri Station and the docking area of the ship carrying the supplies for Indian and Russian Stations. The continuous GPR profile from continent edge to the present day sea shore (~78 km) bring out the gradual changes in thickness of the ice sheet. The total volume of ice in this stretch is estimated to be about 7240 km^3 and assuming a uniform density of 0.85 for the ice, it amounts to about 6154 km^3 of water. The L-I-S interface occurs at 70°51'S: 12°14'E at a depth of 340 m below the surface along a north-south stretch east of the Schirmacher Range (Dharwarkar *et al*., 2012). During the present study a 30m high convex structure was detected north of the grounding line, but the presence of any subsurface mound could not be detected.

The sediments in the epi-shelf lakes of the Schirmacher Oasis represent a composite of source rock compositions, weathering, sediment transportation processes and depositional processes along with influence of the marine environment and have been used to decipher Quaternary climate evolution. SEM imaging of quartz grains selected at random, reveals a very high degree of mechanical abrasion characterized by features originating from glaciofluvial transport processes (Asthana *et al*., 2009, 2013; Shrivastava *et al*., 2012).

The palaeoclimate and deglaciation history of Schirmacher has been built by evidence from radiocarbon dates from the lake core sediments and a few glacial till samples. The data from earlier available record of geochronology of the sampleshave also been analyzed. The sediment cores collected from the L-49 (Priyadarshini Lake) have been dated.

The oldest dates obtained from the basal and near basal sections at 168 to 174 cm from the top have been dated at 30,640 years and 32,655 years BP. Cold conditions prevailed in the Schirmacher Oasis from 30,640-21,685 years B.P. having a low sedimentation rate of 0.005 mm/year. Warmer conditions existed between 32,655-30,640 years B.P. with a higher sedimentation rate of 0.015 mm/year. The ^{14}C dates of another core suggested a wet climate between 29,920-28,890 years B.P. with a sedimentation rate of 0.09 mm/year (Achyuthan *et al*., 2008).Reconstruction of the palaeoclimate history from the pollen spores present in the lichens and sediment samples of Priyadarshini Lake (L-49) by Bera (2006) and Bera *et al*., (2012). They showed that the region witnessed cold and dry climate during 10-9 ka B.P. followed by a long phase of warm and moist climate from 9-2.4 ka B.P. Subsequently from 2.4-1 ka B.P. onwards, dry and cold conditions set in the Schirmacher Oasis. However, the climate ultimately turned warm and moist beginning with 1 ka B.P. These alternating phases of climate were inferred on the basis of dominance of grasses, Cosmarium (fresh water algae) and Acritarch.

The lake history from 13 ka B.P. to the present has also been attempted by Phartiyal *et al.* (2014) by using the magnetic and geochemical properties of vertical sediment profiles along an east-west transect in theSchirmacher Oasis and with the help of AMS ^{14}C dates. These authors believe that from 13 to 12.5 ka B.P., the whole area was dominated by glaciers with plenty of glacial lakes which have been landlocked today. However, due to the onset of early Holocene warming conditions (~11.5 ka B.P.), the glaciers retreated leading to the formation of five large pro-glacial lakes which are located on the low lying valleys of the Schirmacher Oasis. Colder conditions prevailed in the Schirmacher Oasis between 13-12.5 ka B.P.; ~12-11.5 ka B.P. and 9.5-5 ka B.P. The radiocarbon dates obtained recently (Govil *et al*., 2012) from sediment cores (L-6) describe a time span of 10650, 9590, 3660, 2340 and 640 years BP for depths varying from 162 cm to about 8 cm.

The sedimentation rates for these depths as calculated indicate steep gradient of 18cm/K year to low gradient of 3 cm/K year for the basal sections and the segment just above, respectively. This indicates warmer climate between 9590 and 1065 years BP, followed by a cooler period for greater part of the period till about 4000 years BP. The dating of the glacial deposit debris also indicate gradual retreating trend of the ice sheet between 8942 years and 5471 years BP in four stages, the middle two periods being at 7,720 and 6,843 Years BP. Srivastava *et al*. (2013) undertook a study on samples collected from different glacial environments and found out a mineralogical control over the observed geochemical pattern and anomalies of these sediments that comprised essentially quartz, feldspar and heavy minerals and a small fraction of clay minerals. Asthana *et al*. (2009) also have given an account on paleoclimate of Schirmacher Oasis based microscopic structure on quartz grains while Warrier *et al*. (2014) have used environmental magnetism as proxy to work out glacial-interglacial variation in the Schirmacher Oasis. Thamban *et al*. (2012) have reconstructed palaeoclimate variation in Coastal Dronning Maud Land using ice core proxy records.

Geomorphological Studies

The low lying rocky mass of Schirmacher Oasis, disposed in the form of small hills, has been given rise to by the retreat of the ice cap and consequential uplifting of the landmass. The workers have cited examples such as, existence of comparatively higher relief of the structural hills on the northern periphery of the landmass than the central corridor, the steep escarpment at the northern margin and the indications of a fault running all along the northern margin in support of their arguments. The architectural pattern of the Schirmacher Oasis has evolved under the different depositional and erosional processes in a periglacial environment (Ravindra, 2001).

The excessive erosional phase is evidenced by absence of sharp peaks, shattering of rocks producing block fields, rolling topography, cavernous pits, glacial striations, polishing and en-echelon pattern of Roche Moutonees over a large area in the Oasis (Ravindra, 2013). Extensive development of patterned ground in the low gradient to near horizontal slopes has been mapped to indicate the fluctuations of the upper active layer of permafrost. Recent studies have shown possibilities of retreat of glaciers from Schirmacher much before the Holocene (Achyuthan, 2008). Geomorphological evolution of the Schirmacher oasis including that of the glacial lakes was discussed by Phartiyal *et al*. (2011).

The morphological studies on quartz grains, using SEM have shown multiple events of glacial crushing; grinding, conchoidal fractures, deep groves etc produced by attrition under high mechanical energy scenario. Removal of matter by wind action and chemical precipitation has also been recorded (Asthana *et al*., 2009; Shrivastava *et al*., 2012).

The surface textures and the morphological features indicate differential transportation under glacial regime as the angularities of the edges are still preserved and rounding/sub rounding typical of fluvial action as nearly absent.

Larsemann Sector

An area of 3 km^2 was mapped around Bhartistationin Grovness area of the Larsemann Hills, East Antarctica on 1: 2500 scale in order to establish correlation of crustal evolutionary history of this area with that of the Eastern Ghats, India. Based on the petrographic, mineral chemistry and petrochemical studies combined with field observations, four major rock types, representing three major suites of rocks, could be delineated, namely-pyroxene granulite and garnetiferous granite-granodiorite gneiss representing the metamorphosed igneous suite; sillimanite gneiss and metapelite (a. sillimanite + spinel + cordierite + magnetite ± garnet bearing and b. spinel + sillimanite/ kyanite (?) + magnetite ± cordierite ± garnet) representing the metamorphosed sedimentary suite and small patches of granitoids and migmatite representing the post tectonic intrusive igneous suit (Nath *et al*., 2011). The older relict amphibolite, garnetiferous mafic enclaves and diorite occur as rafts and enclaves within the garnetiferous granite-granodiorite gneiss country rock. Two prominent and persistent coplaner foliation planes, S1 and S2 were recorded in the study area trending ENE-WSW with a southerly dip varying from sub-horizontal to 45^o. The Larsemann Hills is affected by three progressive deformation events D1, D2 and D3 and a later NNE-SSW trending S2 layer parallel possible thrust component (D4?). Three generations of folds, namely the early relict, rootless, thickened hinged tight isoclinal recumbent F1folds; tight isoclinal to open upright to recumbent F2 mesofolds developed on S1 gneissosity/ schistosity and a D3 generated broad open warp F3 folds, were identified (Nath *et al.*, 2011). Two persistent joint planes J1 and J2 at high angle (~60°) were also noticed at many places across the litho-units, proving its late origin. These rocks had been put to a progressive metamorphic evolution from amphibolite-upper amphibolite to granulite grade, endorsed by conventional geothermobarometry. The prograde metamorphic dehydration melting reactions are defined by the inclusion assemblage of sillimanite in garnet and cordierite, amphibole in pyroxenes. This also indicates that the prograde P-T condition was well within the second sillimanite stability zone at the peak of metamorphism. The peak metamorphic P-T condition calculated by conventional geothermobarometry is 843°C at ~6 kb for the pyroxene granulites and 805°C at ~6 kb for the metapelites (Nath *et al.*, 2011). The retrograde path is defined by the isothermal decompression due to exhumation (uplift) after reaching the peak (granulite grade) followed by isobaric cooling to lower amphibolite grade metamorphic conditions (Nath *et al.*, 2011). An attempt has been made to correlate the crustal evolutionary history, with the available data generated from the study area during the previous expeditions, with that of the available literatures of the Eastern Ghats. It was observed that in the Anantagiri-Araku areas of the Eastern Ghats, thermobarometry indicates exsolution of pigeonite at ~950°C, of (100) clinopyroxene in orthopyroxene and vice versa at 750-820°C and formation of garnet at around 700-725°C, 7 kb, all in response to cooling of the rock. This shows a nearly isobaric cooling path subsequent to peak metamorphic conditions. Subsequently, the rock suffered nearly isothermal decompression to 5 kb. Hydration and K-metasomatism of the assemblage occurred at lower temperatures (~500°C) in the final phases. The study area is typically a Pan-African terrain where the peak metamorphic event, in 602±10Ma, and subsequent retrograde events occurred at lower temperature of ~523°C in 490±14Ma are quite evident from the P-T calculation and chemical dating of monazite. Similar Pan-African ages are also reported from various pockets of the Eastern Ghats.

Magnetic susceptibility studies in the Bharati Promontory of the Grovness Peninsula indicated that all the lithological units contain ubiquitous magnetite, however, with wide variation in the volume proportions that has resulted in a range of magnetic susceptibility values (10^{-4} to 10^{-2} SI units). Magnetic foliations show a correspondence with the general trend of lithounits (050° NE) and define a resulting geometry of mainly D_1 and D_2 foliations (Pandit and de Wall, 2014 and Pandit, 2016). The magnetic lineations show a preferred orientation with moderate easterly plunge (mean vector 093/36). The observations have implications for the magnetic field survey because such fabrics would impart a strong horizontal component of induced magnetization.

Geomorphological Studies

Geomorphological studies around the Bharati station on Grovenes promontory, in particular and the Larsemann Hills in general, commenced simultaneous with construction of the station during 2010-2012. The comparison of the physiographic elements, sedimentary processes, hydrochemistry and the lacustrine environments in two different polar peri-glacial milieu of the Schirmacher and areas of the Larsemann Hills such as Fisher IslandandBroknes Peninsula were attempted by Asthana *et al.* (2013). Ionic characters of lake water of the Bharati promontory have also been studied (Shrivastava *et al.*, 2012). Lakes of the Larsemann Hills have been studied in some detail. While Govil *et al.* (2012) established influence of grain size distribution on biological productivity in fresh-water ecosystems, Majumdar *et al.* (2013) inferred existence of cold-conditions during the Holocene period in freshwater lakes in the Vestfold Hills.

Princess Elizabeth Land (PEL) and Contiguous Areas

The first campaign of an international collaborative project, ICECAP-2 (International Collaborative Exploration of Central East Antarctica through Airborne geophysical Profiling), funded partially by a United Kingdom Global Innovation Award was undertaken in 2015-16 season. This season operations were hosted by Polar Research Institute of China (PRIC) and conducted from the Zhongshan Station with participation from USA, UK, China and India using airborne geophysical surveys for 44,000 line-km of ice sounding radar, laser altimetry, gravity and magnetic data collection. Following are some of the preliminary findings of this campaign (Sun *et al.*, 2016).

- PEL hosts an assortment of previously unidentified subglacial lakes and complex geomorphology
- Confirms the presence and extent of a 1,100 km-long system of canyons connecting the Lambert Rift to the Leopold and Astrid Coast
- A subglacial lake situated within the southern section of the canyon system, likely one of the largest known lakes in Antarctica

Corroborative geological field investigations are in progress.

Wilkes Land Sector

Examination of heavy mineral fraction of the marine sediments of Integrated Ocean Drilling Program (IODP) Expedition 318 off the coast of the Wilkes Land in east Antarctica (drillsite U1359) brought out the sourcing of sediments from the Precambrian hinterland constituting the east Antarctic shield as well as from the Palaeozoic Trans Antarctic Mountains and Ross Orogen (Pant *et al*., 2013b). The shield area is indicated to be a polymetamorphic terrain with a low-grade orogeny indicated by ~800Ma monazite within a biotite schist (Pant *et al*., 2016). This is the first report of signatures of a Neoproterozoic orogeny in this area and has significant bearing on the Australo-Antarctica reconstruction.

Clay mineral record was employed to reconstruct the fluctuations of the East Antarctic Ice Sheet (EAIS) during Mio-Pliocene and increased concentration of smectite suggested retreat of EAIS during 6.8-6.2, 5.8-5.5, ~4.5 and ~2.5Ma possibly coincident with the formation of Antarctic Bottom Water in Ross sea area (Verma *et al*., 2014). The period between 7-9 Ma at this depocenter marks the maximum concentration of Ice Rafted Debris (IRD) which include basaltic rock fragments sourced from the Ferrar Large Igneous Province towards east. This is also in conformity with the ice-retreat phases inferred using clay minerals at 7.4-7.3 and ~8.5 Ma (Verma *et al*., 2014).

Summary

The contributions of Indian geoscientists ranged from pioneering work in geological mapping and terrain definition in east Antarctica but were mainly concentrated in central Dronning Maud Land area and lacked collaboration with similar studies by other southern polar groups. In recent times, the field of activity has increased especially with the additional logistic support available in form of second permanent station at Bharati. The emphasis has shifted to collaborative studies as well as it is now well-diversified to address the current focus on paleoclimate, ice sheet evolution and integration of geophysics with geology. Further, the utilization of marine sedimentary archives to infer sub-ice geology is being utilized to bridge the crucial data gap in understanding ice sheet-bedrock interaction.

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References

Achyuthan H, Asthana R, Ravindra R and Eastoe C (2008) Radiocarbon dates and sedimentation within the Schirmacher Oasis, East Antarctica, SCAR Open Sc. Conf. St Petersburg, Russia

Asthana R, Shrivastava P K, Beg M J, Shome S and Kachroo K (2009) Surface microtextures of quartz grains from glaciolacustrine sediment core from Priyadarshini Lake, Schirmacher Oasis, East Antarctica as revealed under scanning electron microscope *Ind Jour of Geosc* **63** 205-214

Asthana R, Shrivastava P K, Srivastava H B, Beg M J and Kumar P (2013) Hydrochemistry and sediment characteristics of polar periglacial lacustrine environments on Fisher Island and Broknes Peninsula, East Antarctica *Advances in Polar Science* **24** 281-295

Bera S K (2006) Pollen Analyses of surface deposits and Holocene lake sediments of Schirmacher Oasis, Central Dronning Maud land, East Antarctica. Scientific Report of Twentieth Indian Antarctic Expedition

Bera S K, Phartiyal B and Sharma A (2012) Evidence of pollen – spores retrieved from lichen patches distributed in Schirmacher oasis and adjacent nunataks, East Antarctica: a case study of pollen transport over polar region *International Journal of Earth Sciences & Engineering* **5** 724-730

Bose S and Sengupta S (2003) High Temperature Mylonitization of Quartzofeldspathic Gneiss: Example from the Schirmacher Hills, *East Antarctica Gond Res* **6** 805-816

Dharwadkar A, Swain A K, Chaturvedi A, Mandal A, Roy S K and Kumar P (2012) Delineation of Grounding line Quantification of the expanse and thickness of the Ice shelf near Schirmacher Oasis, East Antarctica. Unpublished Geological Survey of India, report

Dharwadkar A, Roy S K and Kumar P (2013) Geological Studies in Baalsrudfjelletnunatak between Schirmacher Oasis and Wohlthat Mountains to establish continuation of East African Orogen (EAO) in cDML. Unpublished Geological Survey of India, report

D'Souza M J, Roy S K, Swain A K and Dharwadkar A (2011) Detailed study of Schirmachermylonites to determine formation time and stress, strain, temperature involved in their formation as an implication to exhumation history. Unpublished Geological Survey of India, report

D'Souza M J, Nath A K, Swain A K, Shrivastava P K, Mandal A and Dharwadkar A (2012) Modeling the Pan-African Calc Silicate rocks of Central Dronning Maud Land, East Antarctica with reference to CaO-Al2O3-SiO2-CO2 System. Unpublished Geological Survey of India, report

Geological Survey of India (1991) Geological Map of Schirmacher-Wohlthat Region, Central Dronning Maud land, east Antarctica. Scale 1:250,000

Geological Survey of India (1998) Geological Map of Schirmacher Oasis, Central Dronning Maud land, east Antarctica. Scale 1:25,000

Geological Survey of India (2006a) Geological Map of Orvinfjella, Central Dronning Maud land, east Antarctica. Scale 1:50,000

Geological Survey of India (2006b). Geomorphological Map of Schirmacher Oasis, Central Dronning Maud land, east Antarctica. Scale 1:25,000

Geological Survey of India (2010) Geological Map of Muhlig-Hofmannfjella, Central Dronning Maud land, east Antarctica. Scale 1:50,000

Govil P, Asthana R, Mazumder A and Ravindra R (2012) Grain Size Distribution and its Influence on Biological Productivity during Holocene in a Fresh Water Lake in Larsemann Hills, Antarctica *National Academy Science Letters* DOI 10.1007/s40009-012-0

Grew E S (1983) Sapphrine-garnet and associated paragenesis in Anarctica, In: Antarctic Earth Science, (Eds. R L Oliver, P R James and J B Jago) Australian Academy of Science, Canberra, 40-43

Joshi A and Pant N C (1995) Petrology, geochemistry and evolution of the Charnockite suite of the Petermann Ranges, East Antarctica. In: India and Antarctica during the Precambrian

(Eds. M Yoshida and M Santosh) *Mem Geol Soc Ind* **34** 241-258

Joshi A, Pant N C and Parimoo M L (1991) Granites of Petermann Ranges, East Antarctica and implications on their genesis *Jour Geol Soc Ind* **38** 169-181

Kaul M K, Singh R K, Srivastava D, Jayaram S and Mukerji S (1991) Petrographic and structural characteristics of a part of the East Antarctic Craton, Queen Maud Land, Antarctica. In: Geological Evolution of Antarctica. (Eds. Thomson M R A, Crame J A and Thomson J W), Cambridge Univ. Press, 89-94

Mazumder A, Govil P, Ravindra R and Khare N (2013) Indication of colder conditions within Holocene periodin a freshwater lake in Vestfold Hills area, east Antarctica region *Geosciences Journal* DOI 10.1007/s12303-013-0015-I

Nath A K, Dsouza M J and Mandal A (2011) Correlation of crustal evolutionary history of Larsemannhills, East Antarctica and Eastern Ghats, India, Unpublished GSI report

Pandit M K (2016) Magnetic fabric studies in Larsemann Hills, Prydz Bay region, East Antarctica. Report on 26th Indian Scientific Expedition to Antarctica (Ed. Jaypaul D), NCAOR publication (in press)

Pandit M K and de Wall H (2014) Preliminary magnetic susceptibility characteristics of the Bharati Promontory (Groveness Peninsula), Larsemann Hills, Prydz Bay region, East Antarctica *Journal of the Geological Society of India* **84** 163-173

Pandit M Kand de Wall H, Dharwadkar A and Nath A (2008) Magnetic fabric analysis of quartzo-feldspathic gneisses and amphibolites from Schirmacher area, Dronning Maud Land, East Antarctica. International Polar Conference, St. Petersburg, Russia (abstract)

Pant N C and Verma P K (1994) Grain growth parameters and mineral zoning: A comparative study from the Humboldt Mountains *East Antarctica Jour Geol Soc Ind* **44** 627-635

Pant N C, Biswas P, Shrivastava P K, Bhattachaya S and Verma K, Pandey M and IODP Expedition 318 Scientific Party (2013b) Provenance of Pleistocene sediments from Site U1359 of the Wilkes Land IODP Expedition- evidence for multiple sourcing from east Antarctic craton and Ross orogeny in Antarctic Palaeoenvironments and Earth-Surface Processes, (Eds. Hambrey M J, Barker P F, Barrett P J, Bowman V, Davies B, Smellie J L & Tranter M) *Geological Society of London* **381** 277-297 dx.doi.org/10.1144/SP381.11

Pant N C, Kundu A, Dsouza M J and Saikia A (2013a) Petrology of the Neoproterozoicgranulites from Central Dronning Maud Land, East Antarctica- implications for southward extension of East African Orogen (EAO) *Precambrian Research* **227** 389-408 dx.doi.org/10.1016/j.precamres.2012.06.013

Pant N C, Pandey M and Joshi S (2016) Polymetamorphic crust and a Neoproterozoic orogeny in the eastern Wilkes Land inferred from the marine sediments, Abstracts XXXIV SCAR Open Science Conference, Kualalumpur, p. 115

Phartiyal B (2014) Holocene paleoclimatic variation in the Schirmacher Oasis, East Antarctica: a mineral magnetic approach *Polar Science* **8** 357-369

Phartiyal B, Sharma A and Bera S K (2011) Glacial Lakes and geomorphological evolution of Schirmacher Oasis, East Antarctica, during Late Quaternary *Quaternary International* **235** 128-136

Ravindra R (2001) Geomorphology of Schirmacher Oasis, East Antarctica. Proc. Symp. On Snow, Ice and Glaciers, *Geol Surv India* **53** 379-390

Ravindra R (2013) Evolution of Rocky Oases in eastern Antarctica: Studies by Indian Scientists. In: Scientific and Geopolitical Interests in Arctic and Antarctic (Eds. Ramesh R, Sudhakar M, Chattopadhyay S), Proceedings of International Conference on Science and Geopolitics of Arctic and Antarctic, (iSaGAA), 296 LIGHTS, Research Foundation, New Delhi

Ravindra R and Pandit M K (2000) Geochemistry and geochronology of A-type granite from northern Humboldt Mountains, east Antarctica: vestiges of Pan-African event *Jour Geol Soc Ind* **56** 253-256

Ravikant V (1998) Preliminary Thermal Modelling of the Massif Anorthosite-Charnockitic Gneiss Interface from Gruber Mountains, Central Dronning Maud Land, East Antarctica *Jour Geol Soc Ind* **51** 287-300

Ravikant V, Golani P R, Dharwadkar A and Ravindra R (2011) Petrology and geochemistry of the Grubergebirgeanorthosite and marginal rocks, central Dronning Maud Land: further characterization of the Late Neoproterozoic magmatic event in East Antarctica *Journal of the Geological Society of India* **78** 7-18

Ravikant V (2005) Metamorphism of mafic and ultramafic enclaves within granulites, Schirmacher Oasis, East Antarctica *Journal of the Geological Society of India* **65** 279-290

Ravikant V (2006) Sm-Nd isotopic evidence for Late Mesoproterozoic metamorphic relics in the East African Orogen from the Schirmacher Oasis, East Antarctica *Journal of Geology* **114** 615-625

Ravikant V (2008) Late NeoproterozoicOrogenesis in the central Dronning Maud Land, East Antarctica: a review of tectonothermal events affecting rocks of the Schirmacher Oasis (~660–580 Ma) and Filchnerfjella (~570–530 Ma) *Geological Survey of India Special Publication* **91** Pan–African event in India and Antarctica**,** pp 156-170

Ravikant V (2009) Tectono-metamorphic events recorded in high-grade rocks from Filchnerfjella: further evidence for Pan-African reworking of the Grenville-aged crust in central Dronning Maud Land, East Antarctica *Indian Journal of Geosciences* **63** 1-12

Ravikant V, Bhaskar Rao Y J and Gopalan K (2004) Schirmacher Oasis as an extension of the East African Orogen into Antarctica: new Sm-Ndisochron age constraints *Journal of Geology* **112** 607-616

Ravikant V, Laux J H and Pimentel M M (2007) Sm-Nd and U-Pb isotopic constraints for crustal evolution during Late Neoproterozic from rocks of the Schirmacher Oasis: geodynamic evolution coeval with the East African Orogeny. In: Antarctica: A Keystone in a Changing world- Online proceedings of the 10th ISAES, (Eds. A K Cooper and C R Raymond) USGS Open-File Report 2007-1047, Short Research Paper 007, 5 p. doi: 10.3133/of2007-1047.srp007

Roy S K, Shrivastava P K and Malik R (2015a) Transect Geological Mapping (1:10000 Scale) in the central part of Schirmacher Range, East Antarctica to constrain its tectonometamorphic evolution and place in the Gondwana configuration Unpublished Geol Surv of India report

Roy S K, Pant N C, Dharwadkar A D and Kumar P K (2015b) Geological Studies in Baalsrudfjelletnunatak between Schirmacher oasis and Wohlthat Mountains to establish continuation of East African Orogen (EAO) in cDML, *Proc ISEAS Symp Goa, India* (Abstract).

Roy S K, Pant N C, Kundu A, Dharwadkar A D, Kumar P K, Joshi S, Raghuram, Mohd. Sadiq and Pandey M, Under review, Geological Studies in Baalsrudfjelletnunatak between Schirmacher oasis and Wohlthat Mountains to establish continuation of East African Orogen (EAO) in cDML, in press, Geological Society of London Special Publication on Crustal Evolution in India and Antarctica

Sengupta S (1993) Tectonothermal history recorded in mafic dykes and enclaves of gneissic basement in the Schirmacher hills *East Antarctica Precambrian Res* **63** 273-291

Shrivastava P K, Asthana R, Beg M J and Ravindra R (2011) Ionic Characters of Lake Water of Bharti Promontory, Larsemann Hills *East Antarctica Jour Geol Soc of Ind* **78** 217-225

Shrivastava P K, Asthana R, Roy S K, Swain A K and Dharwadkar A (2012) Provenance and depositional environment of epi-shelf lake sediment from Schirmacher Oasis, East Antarctica, vis-a'-vis scanning electron microscopy of quartz grain, size distribution and chemical parameters *Polar Science* **6** 165-182

Shrivastava P K, Mandal A, Kumar P and Dharwadkar A (2013) Glaciological studies in a part of East Antarctica During the Last Three Decades Unpublished GeolSurv of India report

Sun B, Greenbaum J, Blankenship D, Siegert M, Pant N, Guo J, Cui X, Wang B, Lindzey L, Li L, Arora D, Ng G and Richter T (2016) ICECAP-2 Aerogeophysical Observations of Princess Elizabeth Land, East Antarctica, Abstract, XXXIV SCAR Open Science Conference, Malaysia.

Swain A and Goswami S (2014) Continuous GPR survey using Multiple Low Frequency antennas – case studies from Schirmacher Oasis, East Antarctica *International Journal of Earth Science and Engineering* **7** 1623-1629

Thamban M, Naik S S, Laluraj C M, Chaturvedi A and Ravindra R (2012) Antarctic Climate Variability During the Past Few Centuries Based on Ice Core Records from Coastal Dronning Maud Land and Its Implications on the Recent Warming.EarthSystem Processes and Disaster Management (Chapter 5), (Eds. R Sinha and R Ravindra) Society of Earth Scientists Series 1, DOI 10.1007/978-3-642-28845-6_5, Springer-Verlag Berlin Heidelberg

Verma K, Bhattacharya S, Biswas P, Shrivastava P K, Pandey M, Pant N C and IODP Expedition 318 scientific party (2014) Clay mineralogy of the ocean sediments from the Wilkes Land margin, East Antarctica: implications on the palaeoclimate, provenance and sediment dispersal pattern *International J Earth Sci (GeolRundsch)* **103** 2315-2326, (DOI) 10.1007/s00531-014-1043-4

Warrier A K, Mahesh B S, Mohan R, Shankar R, Asthana R and Ravindra R (2014) Glacial; interglacial climatic variations at the Schirmacher Oasis: The first report from environmental magnetism *Palaeogeography Palaeoclimatology Palaeoecology* **412** 249-260.

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Review Article

Paleoclimatic Signals from the Proxy Records of the Southern Ocean : A Review

ABHILASH NAIR and RAHUL MOHAN*
Antarctic Sciences Division, National Centre for Antarctic and Ocean Research, ESSO, Ministry of Earth Sciences, Govt. of India, Headland Sada, Vasco-da-Gama 403 804, Goa, India

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Antarctic sea-ice extent and oceanic frontal systems are of primary importance to the marine biota since their marked meridional gradients in physical and chemical properties strongly regulate the phytoplankton contribution to primary productivity.Antarctic sea ice extent along with the Southern Ocean (SO) biological productivity varied considerably during glacial-interglacial periods, and both are known to have played a considerable role in regulating atmospheric CO_2 variations in the past. In the present review paper, we seek to understand the past latitudinal variability of the Southern Ocean frontal systems and Antarctic sea-ice extent based on a multi-proxy approach. The first aspect of this paper concentrates on the diatom based reconstructions of paleo sea-ice and hydrographic changes in the Southern Ocean and its impact on diatom sizes and productivity. Secondly, emphasis would be placed on the studies based on the morphology and isotopic composition of foraminifera and its paleoceanographic implication. The foraminifera shell preserved in the sediments provide unparalleled archives of morphological change, faunal variations, and habitat characteristics as a result of hydrographic changes. To sum up, the advantage of a mulitproxy approach including the magnetic, geochemical and sedimentological parameters have been discussed in understanding the Southern Ocean paleoclimate.

Keywords: **Southern Ocean; Sea-ice; Diatoms; Fronts; Productivity; Morphometry; Foraminifera; Magnetic Susceptibility**

Introduction

Southern Ocean (SO) is the least understood of the world's oceans, despite its vital role in the present climate system. It exchanges water with the other oceans and partly controls the CO_2 partitioning between the ocean and the atmosphere. In the modern SO, deep ocean waters with high CO_2 and nutrient content are brought to the surface by wind-driven upwelling. However, the scarcity of iron reduces phytoplankton growth (Martin *et al*., 1990; Boyd *et al*., 2000), and major macro nutrients are returned to the sub-surface before they are fully consumed. This incomplete utilization of nutrients allows the escape of the deeply sequestered pCO_2 back to the atmosphere, thereby contributing towards raising atmospheric pCO_2 levels (Sigman *et al*., 2010). Today, this CO_2 "leak" occurs mainly in the polar Antarctic zone as compared to the Subantarctic zone (greater nutrient consumption). However, data and models reveal that a combination of biological and physical processes contributed to lowering the atmospheric CO_2 during glacial times, whereby the Antarctic zone was more strongly stratified (Francois *et al*., 1997; Sigman *et al*., 2010) and productivity was higher in the Subantarctic during ice ages (Kumar *et al*., 1995; Kohfeld *et al*., 2005; Martinez-Garcia *et al*., 2009). Nonetheless it is plausible to presume that the Southern Ocean during different time period could have acted either as a source or a sink of atmospheric CO_2 by changes in the productivity regime or oceanic circulation, or both (Jaccard *et al*., 2013). Most of the SO is a high-nutrient, low-chlorophyll (HNLC) area. There are exceptions to this situation downstream of some of the islands, where surface water productivity is high. The main locations where this occurs are downstream of the Crozet and

*Author for Correspondence: E-mail: rahulmohan@ncaor.gov.in

Kerguelen Islands in the Indian sector of the SO. In the recent past quite a few attempts by Indian researchers have been made to understand this phenomenon which would be the prime focus of this paper.

Indian contribution in the field of SO paleoceanography has been largely limited to qualitative climatic reconstructions rather than quantitative studies. Nevertheless, recent advances in the field of SO paleoceanography have taken us a step closer to understanding the past climate variability at millennial and glacial-interglacial timescale. India made its first attempt in understanding the SO diatoms and its paleoceanographic implications by studying the latitudinal variation of diatoms in the surface sediment and nutrient availability in the Indian sector of the SO (Mohan *et al*., 2006). Similarly, planktic foraminifera assemblages preserved in the surface sediment and from water column were studied to understand its paleoceanographic implications (Mohan *et al*., 2015). This study from the Indian sector of the SO revealed higher shell weight of the planktic foraminifera from the sediments and the presence of heavier carbon isotopes in their tests as compared to specimens from water column indicating secondary calcification in foraminifera preserved in the sediments (Mohan *et al*., 2015). It has been suggested that the changes in terrigenous influx to this region were significantly influenced by the rhythmic glacial-interglacial fluctuations in bottom circulation and the position of the Atlantic Antarctic Polar Front (APF) (Thamban *et al*., 2005; Manoj *et al*., 2012). A recent study has also indicated that past changes in terrigenous input from Crozet islands (volcanic) may lead to glacial-interglacial variation in diatom productivity and size (Nair *et al*., 2015). The paleoproductivity records also reveal significant association with shifting nutrient regimes as a consequence of varying frontal zones (Manoj and Thamban, 2015; Nair *et al*., 2015).

An interesting application of the morphology of diatom as a proxy is to analyze if and how it varied over glacial to interglacial transitions at the Polar Front, as this may reflect millennial-scale shifts in the position of this front, and the associated high export of biogenic silica. Changes in the valve size of *F. kerguelensis* in deep-sea sediment cores from the Indian and the Atlantic sectors of SO were recently used to infer changes in diatom productivity, physiology and environmental conditions (Shukla *et al*., 2013; Nair *et al*., 2015). Shukla *et al*. (2013) suggested that variations in circum-polar upwelling were the main controlling factor in opal production during the last ~20,000 years. It was also hypothesized that high nutrient input from the Antarctic Peninsula during the last deglaciation may have exerted a strong control on *F. kerguelensis* valve size and opal export in the Atlantic sector of the Southern Ocean (Shukla *et al*., 2013).

Faithful retrieval and interpretation of high-quality ice-proximal sedimentary sequences from Antarctic margins and the Southern Ocean have made been possible by recent progress in drilling technology and climate proxy methods (Shevenell and Bohaty, 2012). These records provide valuable information about the histories of the East and West Antarctic Ice Sheets and related temperature change in the circum-Antarctic seas. In addition to the recent successes highlighting the value of ice-proximal records, further scientific drilling and climate proxy development are required to improve current understanding of Antarctica's complex paleoenvironmental history (Shevenell and Bohaty, 2012).

This paper provides the review of the work carried out by Indian researchers to understand the paleoclimate history of the Southern Ocean (Indian and Atlantic sector) as well as the applicability of the various proxies in paleoclimatic reconstructions.

Diatoms for Deciphering the Southern Ocean paleoclimate

Diatoms are unicellular algae with a siliceous skeleton called frustules which are found in almost every aquatic environment including fresh and marine waters. Their usefulness in the Southern Ocean paleoceanographic studies is because of their extreme sensitivity to changes in salinity, temperature, nutrient supply and other environmental factors. Diatoms contribute more than 70% of the primary production in the Southern Ocean and play a major role in global silica and carbon cycling. Diatom cell wall is composed of hydrated silica $[Si(H_2O)_n]$, and are well preserved in the sediments.

In polar oceans, 1-10% of the diatoms present in surface waters reach the ocean bed (Ragueneau *et al*., 2000). This percentage increases in shallow coastal areas compared to abyssal open ocean zones. Abiotic factors such as lateral transport and dissolution in the water column and at the water-sediment interface and biotic factors such as sedimentation type (single particles vs aggregates or fecal pellets, mass sedimentation events) are the main processes which determine the diatom flux to the sea-floor. These processes support the preservation of highly silicified diatoms as well as alter the geochemical signals embedded into the diatoms. It has however been shown that the residual diatom assemblages in the sediment can still indicate the prevalent surface conditions in different oceanic regions (eg. North Pacific,Sancetta 1992;Southern Ocean, Armand *et al*., 2005; Crosta *et al*., 2005; Romero *et al*., 2005). Diatoms can therefore be used as proxy to infer past oceanographic and climatic changes.

Mohan *et al*., (2006) studied the latitudinal variation of diatom in surface sediments of Southern Ocean (Indian sector) to understand its relationship with the changing nutrient availability and/or supply, and its utility in palaeoceanographic reconstruction. The study indicate that the spatial distribution of diatoms in surface sediments is well correlated with the frontal changes (SST and salinity) and related nutrient availability in the water column (Mohan *et al*., 2006). Similarly, the variation of Antarctic summer and winter sea-ice extent was well recorded in diatom abundance from the surface sediments in the Enderby Basin of Southern Ocean, thereby ascertaining the robustness of diatoms as a proxy for paleo sea-ice estimation (Mohan *et al*., 2011). Understanding the latitudinal variation of Antarctic sea-ice necessitates detailed information on the diatom assemblages preserved in the surface sediments from the sea-ice regime. In this context, a new species (*Trigonium curvatus*) of a diatom *Trigonium arcticum* from the Prydz Bay, East Antarctica has been described which could be possibly used as a sea-ice proxy for paleo sea-ice reconstruction (Nair *et al*., 2015).

Diatoms have been studied in consideration with past climate reconstruction and oceanographic settings from Southern Ocean.One such study by Shukla *et al*., (2013) involves the morphometric analysis of abundant diatom species (*F. kerguelensis*) in the SO (Fig. 1). As per the study, variations in circumpolar upwelling along with nutrient inputs from Antarctic Peninsula have exerted a strong control on *F. kerguelensis* valve size in the Atlantic and Indian sector of the SO. Size records from the Atlantic sector demonstrate larger valve sizes of *F. kerguelensis* during the Last Glacial Period, which is possibly related to greater iron availability through wider sea-ice coverage and higher eolian dust input (Shukla *et al*., 2013). But the scenario is different in the Indian sector

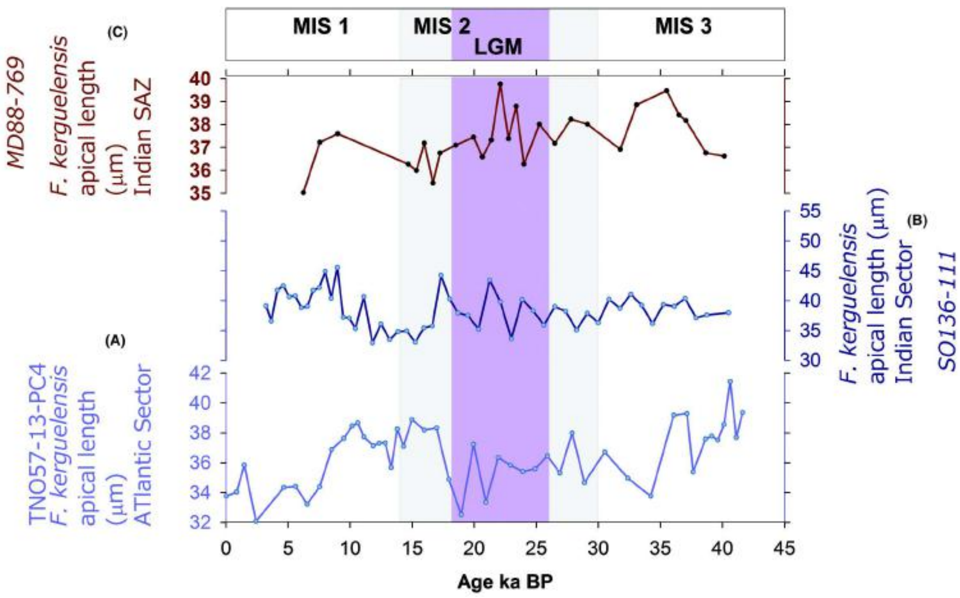

Fig. 1: Size variation of *F. kerguelensis* in the Indian sector vs Atlantic sector

of the SO where larger valve sizes of *F. kerguelensis* have been recorded in the Holocene sediments (Fig. 1). The Indian sector being far away from these iron sources as compared to the Atlantic could be the reason for the probably resultant lower diatom sizes during the last deglaciation. It was hypothesized that high nutrient input in the APF from the Antarctic Peninsula during the last deglaciation had a more important control on *F. kerguelensis* valve size and diatom physiology than the inferred increase in circum-polar upwelling (Shukla *et al*., 2013). During the Holocene period, due to iron limitation smaller *F. kerguelensis* valve size was found in the Atlantic APF and Indian SAF sediment cores, whereas the occurrence of larger *F. kerguelensis* size in the Indian APF core suggests high nutrient availability, especially iron through circum-polar upwelling (Shukla *et al*., 2013).

A recent paleoclimatic study using Southern Ocean (SO) sediment core (diatom records) from the Indian sector suggest a glacial shift in the Antarctic winter sea-ice limit and Polar Front, respectively up to the modern day Polar Frontal Zone (Nair *et al*., 2015). This study has revealed that glacial periods north of the Polar Front were characterised by high diatom productivity and larger *Fragilariopsis kerguelensis* (pennate diatom) and *Thalassiosira lentiginosa* (centric diatom) sizes (Fig. 2). *F. kerguelensis* and *T. lentiginosa* are the dominant components of the diatom assemblages, and most likely the main silica carrier in the iron-limited Southern Ocean. The larger and heavily silicified diatoms such as *F. kerguelensis* and *T. lentiginosa* may have effectively contributed to transporting biogenic silica and organic carbon to the sea bed during the last 42 ka BP. The northward shift in Antarctic winter sea-ice limit during the glacial period (Nair *et al*., 2015) is additionally supported by similar latitudinal changes in APF during the Last Glacial Maximum (LGM) deciphered using silicoflagellate and diatom assemblages (Shetye *et al*., 2013).

Foraminifera as Tracers of Past Oceanic Environments

Paleoceanography has always been closely linked with the study of planktic foraminifera. The high rate of production and excellent preservation of foraminiferal shells in deep sea sediments have produced probably the finest fossil record on earth, providing unparalleled archives of morphological

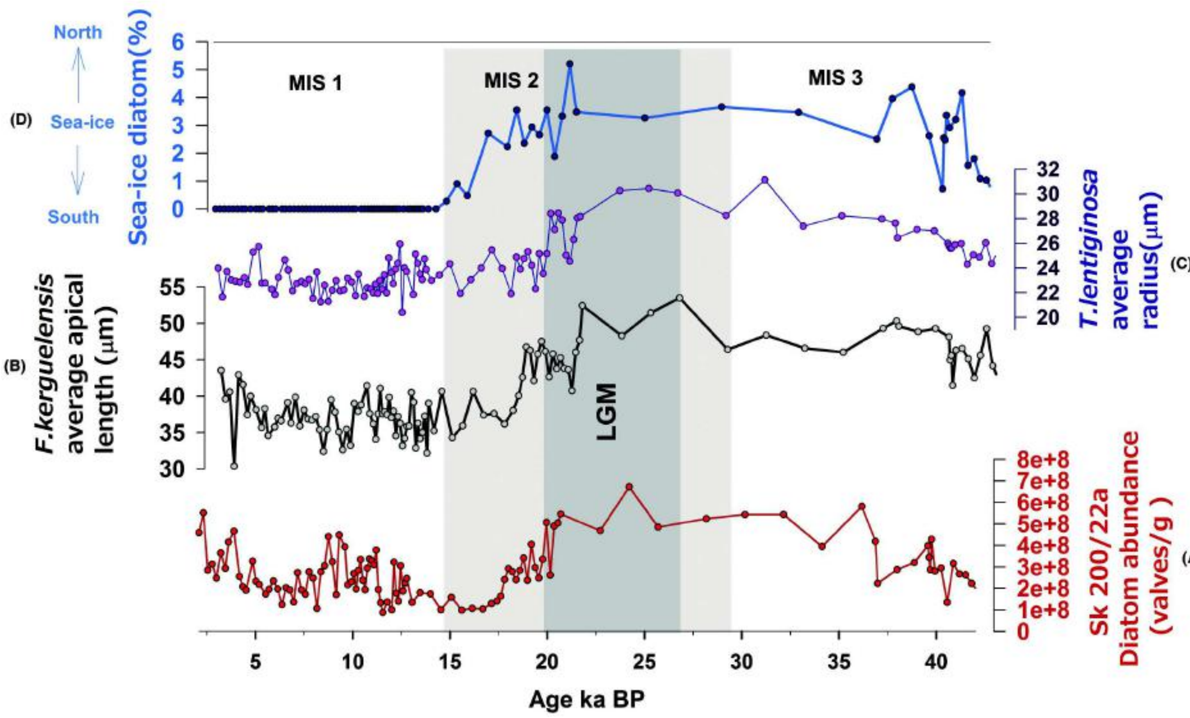

Fig. 2: Abundance and size variation of *F. kerguelensis* vs *T. lentiginosa* in the SO

changes, faunal variations, and habitat characteristics. Planktonic foraminifera are the most commonly used paleoceanographic proxies, be it through the properties of their fossil assemblages or as a substrate for extraction of geochemical signals. The steady flux of foraminiferal shells in the ocean is responsible for the deposition of a large portion of deep sea biogenic carbonate.

The isotopic composition of foraminifera has been used extensively to infer paleoclimatic and paleoceanographic variations (Sen Gupta, 1991; Waelbroeck *et al*., 2005). The seawater temperature for water depths ranging from 0-200 m in the southwestern Indian Ocean was estimated from *G. bulloides* $\delta^{18}O$ by using various paleotemperature equations (Saraswat and Khare, 2010). This study showed that the estimated seawater temperature matches well with the sea water temperature during the austral spring season suggesting that *G. bulloides* was abundant at that time (austral spring). The findings will help in paleoclimatic reconstruction studies based on characteristics of *G. bulloides*. Similarly, Khare and Chaturvedi (2012) studied the isotopic variation ($\delta^{18}O$ and $\delta^{13}C$) of *Globigerina bulloides* from the surface sedimentsof SO to understand the various frontal systems operating in the Indian sector.

Isotopic studies of *Globigerina bulloides* carried out from the water samples across the Southern Ocean between 10ºN and 60ºS reveals an interesting pattern of increase in the $d^{13}C$ value of the surface water DIC between 35ºS and ~60ºS, with a peak at ~42ºS, matching well with the variation of satellite obtained chlorophyll concentration. Such correlated distribution pattern (of $d^{13}C$ and chlorophyll) has been suggested to have been caused by increased organic matter production and associated removal (of $\delta^{13}C$) (Prasanna *et al*., 2016). Based on the similarities between the estimated and measured $\delta^{18}O$ values, the study concludes that the calcification depth of *G. bulloides* is confined to a depth of ~75-200 m between 10ºN and 40ºS latitude (Prasanna *et al*., 2016).

Studies based on the stable isotopic composition of planktic foraminiferal samples of plankton net and core top sediments collected during the first Indian expedition to the Southern Ocean (2004) provide vital insight into the foraminiferal preservation characteristics in the Indian sector of the Southern Ocean. Comparison between the measured and the predicted $\delta^{18}O$ values shows that the planktic foraminifera secrete their shells in isotopic equilibrium with seawater (Tiwari *et al*., 2011). Essentially the isotopic content of planktic foraminifera, from plankton net as well as core top sediment samples, is governed by the frontal structure of the Southern Ocean. Foraminifera from sediment samples faithfully record the frontal structures as revealed by the inter-comparison of the plankton net and sediment samples; hence it was suggested that the past fluctuations in the extent of various fronts can be reconstructed using down-core foraminiferal isotopic content in this region (Tiwari *et al*., 2011). It also possible to identify discrete water masses from the SO based on the oxygen isotope and sea-surface salinity and determine the paleosalinity from carbonate fossils from the sediment based on the salinity-oxygen isotope relation (Tiwari *et al*., 2013).

Several aspects of planktic foraminifera (morphology, assemblages, isotopes, elemental composition etc.) are used extensively to understand past oceanography. A study from the Indian sector of SO using planktic foraminifera assemblages from the surface sediment and the overlying water column revealed the dominance of symbiotic foraminiferal species in the subtropical region and non-symbiotic species in sub-Antarctic and polar frontal region (Mohan *et al*., 2015). An indication of secondary calcification in foraminifera preserved in the sediments was observed on the basis of higher shell weight of the planktic foraminifera from the sediments and the presence of heavier isotopes in their tests as compared to specimens from water column (Mohan *et al*., 2015).

Multi Proxy Studies on Late Quaternary Sediments from Southern Ocean

The magnetic parameters (magnetic susceptibility), in combination with other paleoenvironmental proxies such as ice rafted debris (IRD), calcium carbonate content and oxygen isotope records, are useful palaeoceanographic indicators in marine sedimentary records (Bloemendal *et al*., 1988, 1992). The lower and uniform values in magnetic concentration in the sediments of the sub-Antarctic region of the Indian sector of Southern Ocean during interglacial period have been used as a signature for reduced terrigenous input from the nearby volcanic islands (Manoj *et al*., 2012). In contrast, the periods of increased concentration of magnetic minerals in the Southern Ocean sediments have been attributed to enhanced terrigenous input and ice-rafting events. A comparison of the magnetic record with the *N. pachyderma* $\delta^{18}O$, IRD and carbonate records from a marine sediment core from Indian sector of SO reveals that the terrigenous influx, ice rafting, sea-surface temperature and carbonate productivity at the core site are apparently interrelated (Manoj *et al*., 2012). Changes in terrigenous sediment source and transport mechanism have also been investigated using magnetic susceptibility and sedimentological records (Thamban *et al*., 2005).

The records of IRD in the Southern Ocean sediments offer potential as proxy indicators to investigate the dynamic behaviour of Antarctic ice sheets and Antarctic climate (Hayes *et al*., 1975; Grobe and Mackensen 1992; Zachos *et al*., 1992). The concentration of IRD in the sediment core SK200/27 retrieved from Indian sector of SO (south of APF) was nearly twice that in the SK200/22a (north of APF, Fig. 3). Moreover, IRD was more abundant at the LGM in SK200/27 with its peak abundance preceding by nearly two millennia than the abundance in the core SK200/22a (Manoj *et al*., 2013). It seems that an intensification of Antarctic glaciation combined with a northward migration of the Polar Front during LGM promoted high IRD flux at SK200/27 and subsequent deglacial warming could have influenced the IRD supply at SK200/22a (Manoj *et al*., 2013).

To understand the functioning of the Southern Ocean biological pump in the past, it is crucial to reconstruct the paleoproductivity of the Southern Ocean. A high resolution multi-proxy (calcium carbonate, opal, total organic carbon, biogenic barium and planktonic carbon isotope ratios) approach would be ideal for reconstructing the Southern Ocean paleoproductivity. The palaeoproductivity studies carried out by Sruthi *et al*. (2012) and Manoj and Thamban, (2015) on a core from the Indian sector of SO reveal an inverse relationship between the calcium carbonate concentration and opal productivity, indicating the influence of shifting nutrient regimes in the Southern Ocean. To the north of APF, reduced calcite productivity during glacial period suggests an equatorial migration of the frontal regimes. In contrast to the south of APF, increased opal productivity during the interglacial period indicates a southward migration of APF (Manoj and Thamban, 2015). North of APF (Indian sector) was characterised by reduced carbonate productivity as compared to Holocene and the last deglaciation, as indicated by barium concentrations (Sruthi *et al*., 2012). The study also suggests enhanced sub-oxic conditions during LGM and oxygenated condition during the deglaciation and late Holocene. The suboxic conditions during LGM could be attributed to reduced ventilation resulting from a reduction in strength of the global thermohaline circulation at this time interval (Sruthi *et al*., 2012).

Plio-Pleistocene East Antarctic ice sheet dynamics was deciphered using clay mineralogy and carbon content analysis from a marine sediment core (IODP site U1359) off the eastern margin of the Wilkes Land sector (Verma *et al*., 2014). The distribution of clay minerals in the core could be a result of the interplay between illite and chlorite from local source, i.e. cratonic east Antarctic shield and smectite and kaolinite from easternmost sources (Verma *et al*., 2014). Poor crystallinity of illite corroborates the ice retreat condition. The ice retreat

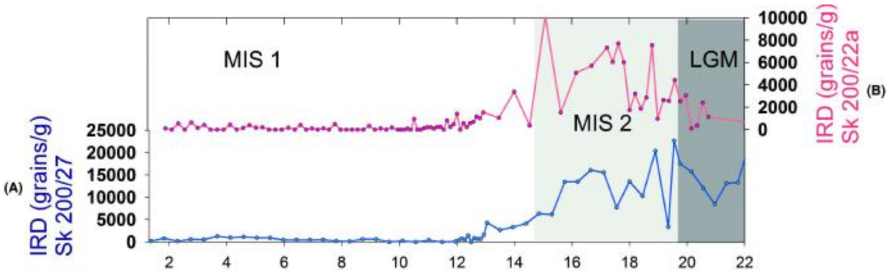

Fig. 3: IRD abandance of sediment core SK200/27 vs SK200/22a in the India sector of SO

condition as deciphered during 5.5-5.8 and 4.5 Ma coincides with the records from Antarctic Peninsula and Prydz bay suggesting continent-wide warming. This study suggests that in the eastern sector of Wilkes Land margin, warming started during late Miocene, i.e., during 6.8-6.2 Ma, much earlier than the other part of east Antarctica (Verma *et al*., 2014).

Scope for Future Research

Most of the Southern Ocean is a high-nutrient, low-chlorophyll (HNLC) area. There are exceptions to this situation downstream of some of the islands, where iron from the islands or surrounding shallow plateau fertilizes the mixed layer and causes a diatom bloom in spring and summer and therefore greater opal fluxes (Blain *et al*., 2007). The main locations where this occurs are downstream of the Crozet and Kerguelen Islands in the Indian sector of Southern Ocean. The oceanic waters around these volcanic islands could have been influenced by changes in terrestrial input during glacial-interglacial periods as a result of changing intensity of ACC (Manoj *et al*., 2012) and sea-level fluctuations, thus adding to the complexities of the oceanic processes. The aim in the future should be to look into such complex regions in order to unravel the local/regional influence from the global changes as lengthily studied in the Atlantic sector of the SO (Anderson *et al*., 2009; Martinez-Garcia *et al*., 2009; Jaccard *et al*., 2013). This will provide some clues on how certain regions of Southern Ocean acted as a sink or a source of atmospheric CO_2 during millennial events of the last glacial-interglacial periods. In addition, improved understanding about the SST and sea-ice variability in the Southern Ocean and northern North Atlantic during the glacial-interglacial timescale is imperative to assess the existence of teleconnections between the two hemispheres. Quantification of the past climate change in place of the earlier qualitative description is the evolving trend in the paleoceanographic research. Quantitative values in terms of sea surface temperature, salinity, sea ice, etc. are also vital for model validations. Such quantitative estimates coupled with accurate chronologies would help to better understand teleconnections between different components of the climate system.

Conclusions

The utility of diatoms, foraminifers, carbonate content, IRD etc. in the sediments has been known to exist since the last century but only in the last few decades the paleoceanographic and palaeoclimatologic studies are fairly well established. This article describes the applicability of different proxies (microfossils, magnetics, sedimentological and geochemical) in Southern Ocean paleoceanography studies. There are still few gaps in our knowledge of the robustness of different proxies used in providing quantitative and qualitative insight into past climatic conditions. From such a point of view, it is clear that none of the proxies can be universal and the simultaneous use of several proxies is necessary for a comprehensive perspective on the past ocean.

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References

Anderson R F, Ali S, Bradtmiller L I, Nielsen S H H, Fleisher M Q, Anderson B E and Burckle L H (2009) Wind-driven upwelling in the Southern Ocean and the deglacial rise in atmospheric CO2 *Science* **13** 1443-1448

Armand L K, Crosta X, Romero O and Pichon J J (2005) The biogeography of major diatom taxa in Southern Ocean sediments: 1. Sea ice related species. Palaeogeogr. Palaeoclimatol *Palaeoecol* **223** 93-126

Blain S. *et al*. (2007) Effect of natural iron fertilization on carbon sequestration in the Southern Ocean *Nature* **446** 1070-1071

Bloemendal J, Lamb B and King K W (1988). Paleoenvironmental implications of rock-magnetic properties of late

Quaternary sediment cores from the eastern equatorial Atlantic *Paleoceanography* **3** 61-87

Bloemendal J, King J W, Hall F R and Doh S J (1992) Rock-magnetism of late Neogene and Pleistocene deep-sea sediments: relationship of sediment source, diagenetic processes and sediment lithology *J Geophys Res* **97** 4361-4375

Boyd P W *et al*. (2000) A mesoscale phytoplankton bloom in the polar Southern Ocean stimulated by iron fertilization *Nature* **407** 695-702 doi: 10.1038/35037500

Crosta X, Romero O E, Armand L K and Pichon J-J (2005) The biogeography of major diatom taxa in Southern Ocean surface sediments: 2. Open-ocean related species *Palaeogeography, Palaeoclimatology, Palaeoecology* **223** 49-65

Francois R, Altabet M A, Yu E-F, Sigman D M, Bacon M P, Frank M, Bohrmann G, Bareille G and Labeyrie L (1997) Contribution of Southern Ocean surface-water stratification to low atmospheric CO2 concentrations during the last glacial maximum *Nature* **389** 929-935

Grobe H and Mackensen A (1992) Late Quaternary climatic cycles as recorded in sediments from the Antarctic continental margin, the Antarctic paleoenvironment: A perspective on global change *Antarctic Res Ser* **56** 349-376

Hayes D E, Frakes L A and Shipboard Party 1975 Deep Sea Drilling Project *Init Rep* **28** Washington DC 1017p

Jaccard S L, Hayes C T, Martínez-García A, Hodell D A, Anderson R F, Sigman D M and Haug G H (2013) Two Modes of Change in Southern Ocean Productivity Over the Past Million Years *Science* **339** 1419-1423 (doi: 10.1126/science.1227545)

Khare N and Chaturvedi S K (2012) Tracing the signature of various frontal systems in stable isotopes (oxygen and carbon) of the planktonic foraminiferal species Globigerina bulloides in the Southern Ocean (Indian Sector) *Oceanologia* **54** 311-323

Kohfeld K E, Le Quere C and Harrison S P (2005) Role of marine biology in glacial–interglacial CO2 cycles *Science* **308** 74-78, ISSN 0036-8075

Kumar N, Anderson R F, Mortlock R A, Froelich P N, Kubik P B, Diirich-Hannen and Suter M (1995) Increased biological productivity and export production in the glacial Southern Ocean *Nature* **378** 675-680

Manoj M C and Thamban M (2015) Shifting frontal regimes and its influence on bioproductivity variaiton during the Late Quaternary in the Indian sector of Southern Ocean *Deep Sea Res* Part II, doi: 10.1016/j.dsr2.2015.03.011

Manoj M C, Thamban M, Sahana A, Mohan R and Mahender K (2013) Provenance and temporal variability of ice rafted debris in the Indian sector of the Southern Ocean during the last 22,000 years *J Earth Syst Sci* **122** 491-501

Manoj M C, Thamban M, Basavaiah N and Mohan R (2012) Evidence for climatic and oceanographic controls on terrigenous sediment supply to the Indian Ocean sector of the Southern Ocean over the past 63,000 years *Geo Mar Lett* **32** 251 doi: 10.1007/s00367-011-0267-6

Martin J (1990) Glacial-interglacial CO_2 change: The iron hypothesis *Paleoceanography* **5** 1-13 doi: 10.1029/PA005i001p00001

Martínez-Garcia A, Rosell-Melé A, Geibert W, Gersonde R, Masqué P, Gaspari V and Barbante C 2009. Links between iron supply, marine productivity, sea surface temperature, and CO2 over the last 1.1 Ma *Paleoceanography* **24** PA1207 http://dx.doi.org/10.1029/2008PA001657

Mohan R, Shanvas S, Thamban M and Sudhakar M (2006) Spatial distribution of diatoms in surface sediments from the Indian sector of Southern Ocean *Current Science* **91** 1495-1502

Mohan R, Shukla S K, Patil S M, Shetye S and Kerkar K (2011) Diatoms from surface sediments of Enderby Basin of Indian Sector of Southern Ocean *Journal Geological Society of India* **78** 36-44

Mohan R, Shetye S, Tiwari M and Anil Kumar N (2015) Secondary Calcification of Planktic foraminifera from Indian sector of Southern Ocean *Acta Geologica Sinica* **89** 27-37

Nair A, Mohan R, Manoj M C and Thamban M (2015) Glacial-interglacial variability in diatom abundance and valve size: Implications for Southern Ocean paleoceanography *Paleoceanography* **30** doi: 10.1002/2014PA002680

Prasanna K, Ghosh P, Bhattacharya S K, Mohan K and Anilkumar N (2016) Isotopic disequilibrium in Globigerina bulloides and carbon isotope response to productivity increase in Southern Ocean *Nature* **6** 21533 | doi: 10.1038/srep21533

Ragueneau O, Treguer P, Leynaert A *et al*. (2000) A review of the Si cycle in the modern ocean: recent progress and missing gaps in the application of biogenic opal as a paleoproductivity proxy *Global Planet Change* **26** 317-365

Romero O, Armand L K, Crosta X and Pichon J J (2005) The biogeography of major diatom taxa in Southern Ocean sediments: 3. Tropical/Subtropical species *Palaeogeography, Palaeoclimatology, Palaeoecology* **223** 49-65 (this volume)

Sancetta C (1992) Comparison of phytoplankton in sediment trap time series and surface sediments along a productivity gradient *Paleoceanography* **7** 183-194

Saraswat R and Khare N (2010) Deciphering the Modern Calcification Depth of Globigerina Bulloides in the Southwestern Indian Ocean from its Oxygen Isotopic Composition *Journal of Foraminifer Research* **40** 220-230

Sen Gupta B K (1991) Modern Foraminifera: Kluwer Academic Publishers, Dordrecht, 371p

Shetye S, Mohan R and Nair A (2014) Latitudinal shifts in the Polar Front in Indian sector of the Southern Ocean: Evidences from Silicoflagellate assemblage *Geosciences Journal* 06/2014; DOI:10.1007/s12303-013-0061-8

Shevenell A E and Bohaty S M (2012) Southern exposure: New paleoclimate insights from Southern Ocean and Antarctic margin sediments *Oceanography* **25** 106-117 http://dx.doi.org/10.5670/oceanog.2012.82

Shukla S K, Crosta X, Cortese G and Nayak G N (2013) Climate mediated size variability of diatom Fragilariopsis kerguelensis in the Southern Ocean *Quat Sci Rev* **69** 49-58 doi: 10.1016/j.quascirev.2013.03.005

Sigman D M, Hain M P and Haug G H (2010) The polar ocean and glacial cycles in atmospheric CO2 concentration *Nature* **466** 47-55

Sruthi K V, Thamban M, Manoj M C and Laluraj C M (2012) Association of trace elements with various geochemical phases in the Indian sector of Southern Ocean during past 22,000 years and its palaeoceanographic implications *Current Science* **103** 803-809

Thamban M, Naik S S, Mohan R, Rajakumar A, Basavaiah N, Witty D'Souza, Sarita Kerkar, Subramaniam M M, Sudhakar M and Pandey P C (2005) Changes in the source and transport mechanism of terrigenous input to the Indian Ocean sector of Southern Ocean during the late Quaternary and its palaeoceanographic implications *J Earth Syst Sci* **114** 443-452

Tiwari M, Nagoji S, Thammisetti K, Drishya G, Parvathy R K and Sivaramakrishnan R (2013) Oxygen isotope-salinity relationships of discrete oceanic regions from India to Antarctica *vis-a-vis* surface hydrological processes *Journal of Marine Systems* **113-114** 88-93

Tiwari M, Mohan R, Meloth T, Naik S and Sudhakar M (2011) Effect of varying frontal systems on stable oxygen and carbon isotopic compositions of modern planktic foraminifera of Southern Ocean *Current Science* **100** 881-887

Verma K, Bhattacharya S, Biswas P, Shrivastava P, Pandey M and Pant N C, IODP Expedition 318 Scientific Party (2014) Clay mineralogy of the ocean sediments from the Wilkes Land margin, east Antarctica: implications on the paleoclimate, provenance and sediment dispersal pattern *International Journal of Earth Sciences* DOI 10.1007/s00531-014-1043-4

Waelbroeck C, Mulitza S, Spero H, Dokken T, Kiefer T and Cortijo E (2005) A global compilation of late Holocene planktonic foraminiferal δ18O: relationship between surface water temperature and δ18O: Quaternary *Science Reviews* **24** 853-868

Zachos J C, Breza J and Wise S W (1992) Earliest Oligocene ice-sheet expansion on East Antarctica: Stable isotope and sedimentological data from Kerguelen Plateau *Geology* **20** 569-573.

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Review Article

Lake Sediment Studies in Ice-Free Regions of East Antarctica – An Indian Perspective

ANISH KUMAR WARRIER[1,#,*], B S MAHESH[1] and RAHUL MOHAN[1]

[1]*National Centre for Antarctic and Ocean Research, Earth System Science Organisation, Headland Sada, Vasco-da-Gama, Goa 403 804, India*

[#]*Present address*: *Department of Civil Engineering, Manipal Institute of Technology, Manipal University, Manipal 576 104, Karnataka, India*

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Antarctica plays a vital role in controlling Earth's climate. Recent data indicates that there are widespread changes in Antarctica, especially the Antarctic Peninsula due to global warming. Therefore collecting past climatic information from ice-cores, marine and lake sediments are extremely important as the data can be utilized in the available models to plausibly model the future climate for the region. Lake sediments are widely found in Schirmacher Oasis, Larsemann Hills and Vestfold Hills in East Antarctica. During the period 2010-2015, considerable amount of work has been done on surficial sediments, water samples from the sediment-water interface and sediment cores from lakes of these regions for different environmental applications, such as provenance, bacterial diversity and paleoclimatic studies. Techniques such as environmental magnetism, geochemistry (organic and inorganic), sedimentology, clay mineralogy, scanning electron microscopy and geochronology have been employed on these sediments to decipher the past climate and environmental changes on different time-scales and to understand the provenance of these sediments. Few paleoclimatic studies are limited to the Holocene whereas a couple of studies document glacial-interglacial climatic variations in Schirmacher Oasis. These studies have a much better chronological framework when compared to the earlier studies. However, there are still issues with the temporal resolution of the data when compared with ice-cores which offers much better sample resolution. It is therefore crucial that future studies on lake sediments from these regions be made on a high-resolution interval which will allow the researchers to have a good correlation with other archives such as ice-cores, etc.

Keywords: Lake Sediments; Ice-free Regions; Paleoclimate; Schirmacher Oasis; Larsemann Hills; Vestfold Hills; East Antarctica

Introduction

The continent of Antarctica plays a crucial role in controlling the Earth's climatic system. Hence, it is equally important to study how climate has evolved in Antarctica during the geological past. The past climatic data can be used to predict the climatic patterns in the future. Recent studies have shown that the western part of Antarctica has warmed up considerably during the last 50 years, especially the Antarctic Peninsula, when compared with its eastern counterpart (Steig *et al.*, 2009; Vaughan *et al.*, 2003). In order to place observed and predicted 21st century climate change in perspective, reliable and highly resolved paleoclimatic data from Antarctica is essential (Kaplan and Wolfe, 2006). Unlike the *tropical* and *temperate* regions, past climate reconstruction in Antarctica is restricted to ice-cores, marine and lake sediments.

It is well established that lakes are "*sentinels of change*". They are sensitive and respond rapidly to changes in climate, integrating information about these changes in their sediments. Lakes, which record a host of paleoenvironmental conditions in their sediments not only serve as archives for their past-history but also record past environmental conditions of its surrounding region (Smeltzer and Swain, 1985)

**Author for Correspondence: E-mail: akwarrier@gmail.com*

and mechanisms of climate change. Lakes respond well to changes in environmental conditions such as seasonal temperature shifts, period of ice-free conditions, catchment runoff and input of glacial melt-water. These responses are reflected in the variation of sediment composition and associated proxy variables. The continent of Antarctica is bestowed with several ice-free regions namely, Larsemann Hills, Schirmacher Oasis, Bunger Hills, Vestfold Hills, etc. There are more than 100 lakes in Schirmacher Oasis and 150 lakes in Larsemann Hills which are classified into epishelf, pro-glacial and land-locked depending on their geomorphic characteristics (Ravindra, 2001). Similarly, Vestfold Hills contains more than 300 lakes which are either fresh or brackish depending on its proximity to the marine shoreline (Swadling *et al.*, 2001) According to Smol and Cumming (2000), the climatic information recorded in the sediments of these polar lakes offers tremendous potential in reconstructing the past climate and environmental changes.

India's early attempt on freshwater lakes in East Antarctica was in the austral summer of 1984-85 to describe the microfaunal component of freshwater habitats in Schirmacher Oasis (Ingole and Parulekar, 1993). Since then quite a few studies have been made on lake sediments from Schirmacher Oasis (Sharma *et al.*, 2007; Sharma *et al.*, 2000; Sinha *et al.*, 2000a; Sinha and Chatterjee, 2000) to decipher the past climate, long-distance transport of palynodebris and pollen (Bera, 2004; Sharma *et al.*, 2002) and presence of freshwater protozoans – *Arcellaceans* (Mathur *et al.*, 2006); Water samples from the lakes of Schirmacher Oasis have been utilized too for hydrogen and oxygen isotopic studies (Sinha *et al.*, 2000b); and quartz grains from surficial sediments of lakes in Larsemann Hills (Narayana *et al.*, 2010) and Schirmacher Oasis (Asthana and Chaturvedi, 1998) have also been studied to understand their provenance. In this paper, we have provided a review of work carried out in the three ice-free regions of East Antarctica (Fig. 1), namely Schirmacher Oasis, Larsemann Hills and Vestfold Hills since 2010-2011. The review is broadly based on work carried out on surficial sediments and sediment cores from the three regions.

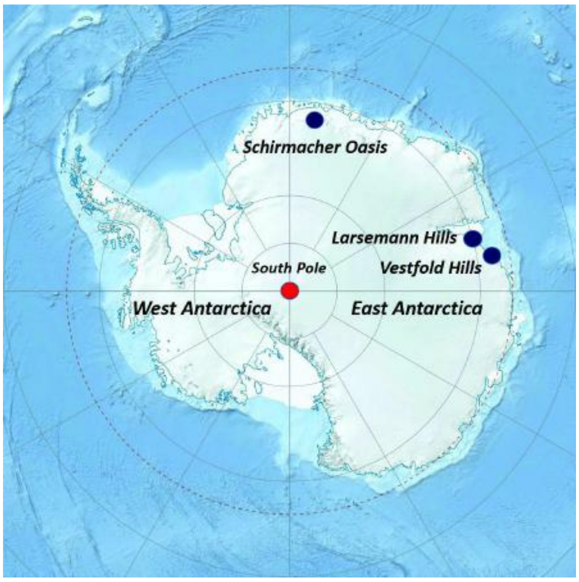

Fig. 1: General map of Antarctica showing the locations of Schirmacher Oasis, Larsemann Hills and Vestfold Hills

Studies on Surface Sediments and Sediment-Water Interface From Lakes

Table 1 provides a brief indication of the type of studies carried out on lake-bed sediments and water samples from sediment-water interface from lakes of Schirmacher Oasis and Larsemann Hills over the past few years. The techniques that have been employed on the surface sediments are sedimentology, geochemistry, scanning electron microscopic observations and clay mineralogy to understand the provenance of these sediments as well as the geological processes.

Srivastava *et al.* (2011) studied the clay mineralogical properties of glacial sediments found near the lakes of Schirmacher Oasis. The main aim of the study was to understand the origin of clay minerals in the sediments and decipher the paleoclimate. The clay content was separated from the sediment and studied for mineral identification using differential thermal analysis, thermogravimetric analysis and X-ray diffraction analysis. The results showed well-developed peaks of chlorite, illite, kaolinite, smectite and vermiculite. Most of the aforementioned clay minerals were formed due to weathering and alteration of igneous and metamorphic rocks of Schirmacher Oasis under cold climatic

Table 1. Details of studies made on surficial sediments from lakes of Schirmacher Oasis and Larsemann Hills

Sl.No.	Location	Studies made	Reference
1.	Schirmacher Oasis	Sedimentology, Mineralogy and Scanning Electron Microscopic observations of Quartz grains	Shrivastava *et al*. (2012)
2.	Schirmacher Oasis	Differential thermal analysis, Thermogravimetric analysis and X-ray diffraction analysis	Srivastava *et al*. (2011)
3.	Schirmacher Oasis	Geochemistry and Mineralogy	Srivastava *et al*. (2013)
4.	Schirmacher Oasis	Sedimentology	Srivastava *at al*. (2012)
5.	Schirmacher Oasis and Larsemann Hills	Sedimentology	Asthana *et al*. (2013)

conditions. Chlorite was formed due to the physical weathering of igneous and metamorphic rocks, whereas kaolinite - a product of chemical weathering of feldspar, was formed during relatively warmer climatic conditions. Smectite was interpreted to be of authigenic origin formed due to transformation of pyroxene, basalt and dolerite, whereas vermiculite was derived from the primary micas. The study provides good baseline data of clay minerals from the sediments of Schirmacher Oasis and can be ably used in studying the past climate.

In another study on surficial sediments, Shrivastava *et al*. (2012) investigated the sedimentological and mineralogical properties of surficial sediments from two epi-shelf lakes in Schirmacher Oasis. In addition, scanning electron microscopy observations were made on quartz grains from these sediments to evaluate the sedimentary provenance, modes of transport and weathering features. The study revealed that the quartz grains underwent different modes of physical weathering and chemical precipitation before they were deposited in these epi-shelf lakes as sediments. The sediments were mainly gneissic in composition as revealed by chemical analysis and saltation and suspension were believed to be the two dominant modes of transportation of the poorly sorted glaciofluvial sediments.

Srivastava e*t al*. (2012) made a detailed sedimentological investigation on sediment samples from different regions (polar ice, ice-free lakes, lakes and the coastal shelf area) in the Schirmacher Oasis. Basic stati-stical particle-size parameters like graphic mean, standard deviation, skewness and kurtosis were calculated for samples from the four locations. The results indicated that the Schirmacher Oasis is mainly characterized by glacial processes, including deposition and erosion of the sediments by glaciers, melt-water channels and winds, thus influencing the sediments in various ways. All the sediment samples were all poorly to very poorly sorted, fine-skewed to near-symmetrical and platykurtic to leptokurtic in nature.

Srivastava *et al*. (2013) also performed mineralogical and geochemical studies on glacial sediments collected from different locations in Schirmacher Oasis. Mineralogically, the sediments are predominantly made up of quartz and feldspar in higher proportion, and a large variety of heavy minerals: zircon, tourmaline, rutile, garnet, hornblende, hypersthene, enstatite, kyanite, sillimanite, andalusite, zoisite, lawsonite, chlorite, spinel, topaz, and opaques. The rare earth and trace elemental data relative enrichment in the coarse fraction as against fine fraction, indicating enrichment of heavy minerals in the coarse fraction. The sediments were mainly transported by melt-water streams and wind. However, transport under the influence of gravity and glacier action was also evident. The sediments underwent low degrees of chemical weathering (incipient to moderate) and the overall conclusion made through this study was that although there were minor differences amongst the sediments collected from different locations, they represented similar geochemical and mineralogical characteristics.

Asthana *et al*. (2013) studied the sedimentological properties of surface sediments from Schirmacher Oasis and Bharati Promontory, Larsemann Hills with an aim to understand the sedimentary and glacial processes taking place in the two regions. In addition to sedimentological data, scanning electron microscopic (SEM) observations on quartz grains were also made to strengthen the data. Field observations, sedimentological data and SEM of quartz grains from both the regions showed similar results. However, the extent and strength of glacial and glaciofluvial processes varied between the two regions. The field observations and SEM studies indicated that the effect of glaciers were quite prominent on quartz grains from Larsemann Hills, whereas, glaciofluvial activity played a dominant role in leaving its imprints on quartz grains from Schirmacher Oasis. The sedimentological data suggested that the sediments in both areas were poorly sorted and made up of pebble, sand, silt and minor clay fractions. Higher content of % sand was reported from both the regions. The silt + clay weight percentage was much less than that of sand in both the areas, which could have been removed by localized melting and fluvial action. A change in energy conditions was evident from the bimodal and polymodal distribution of sediments from both the study areas. The authors concluded that the periglacial environment of Schirmacher Oasis and Bharati Promontory, Larsemann Hills are characterized by a wide range of sedimentary and glacial processes, resulting in different combinations of erosional and depositional features.

In another study, Huang *et al.* (2013; 2010) characterised the bacterial diversity of water samples close to the sediment-water interface from Lake Tawani and Lake Untersee in Schirmacher Oasis. The objective of the study was to investigate the variety of bacteria present in the lakes of Schirmacher Oasis, especially those connected through surface channels and encompassed by valleys. The study would help in unraveling the dynamic nature of these unique seasonal, freshwater lakes, which potentially harbors highly adapted bacterial taxa with defined ecological functions. To this effect, the authors used culture-independent Bacterial Tag Encoded FLX Amplicon Pyrosequencing (bTEFAP), clone library construction, and culture-based analysis to target the eubacterial 16S rRNA gene. The results show the presence of around thirteen bacterial phyla and one-hundred and twelve genera. Bioinformatics analysis on the bTEFAP exhibited higher coverage of the bacterial composition in the waters of the Lake. When compared to other available methods, this method was able to detect different members of the phyla: *Chloroflexi, Gemmatimonadetes, Planctomycetes, Nitrospira*, and *Candidate Division TM7* due to the method's higher sensitivity. The authors finally propose the use of multiple approaches to identify more complete bacterial community rather than relying on any single technique.

Paleoclimate Reconstruction Using Lake Sediments and Paleo-Lake Deposits

Since 2010-2011, a number of studies have been made on lake sediments and paleo-lake deposits from Schirmacher Oasis, Larsemann Hills and Vestfold Hills to decipher the paleoclimate/paleoenvironment. A variety of techniques have been used for this purpose. For example, environmental magnetism, sedimentology, geochemistry, biogenic silica, diatoms etc. Table 2 provides details of paleoclimate studies (using various proxies) that have been carried out on sediment cores and paleo-lake deposits from the three regions.

Phartiyal *et al.* (2011) reconstructed the evolution history of Schirmacher Oasis from 13 cal ka B.P. to the Present by analyzing the magnetic susceptibility (MS) and loss-on-ignition (LOI) data for seven sediment profiles from five paleo-lake deposits. The LOI data suggested a very low organic content, whereas MS data helped in the reconstruction of changing detrital input. The presence of longer sediment profile (> 1 m thick) indicated the presence of five large lakes in the Schirmacher Oasis during the Holocene, which shrunk over a period of time leading to the occurrence of smaller lakes. The authors inferred that from 13 to 12.5 cal ka B.P., the whole of Schirmacher Oasis was dominated by glaciers with the present day land-locked lakes being the glacial lakes. The onset of Holocene warming at 11.5 cal ka B.P. led to the retreating of glaciers giving rise to five large proglacial lakes which occupied the low-lying valleys of Schirmacher Oasis. The drying of the landlocked lakes was attributed to several factors such as lack of water supply during summer months due to the recession of glaciers, reduced precipitation or snow accumulation, less melt-water streams, strong winds and sublimation of the lake due to prolonged ice-cover. On the other hand, the proglacial and the epishelf lakes continue to have a regular source of melt water from the continental ice sheet and the ice shelf, respectively. The authors inferred that although the clear cause of

Table 2. Details of paleoclimate studies made on sediment cores from lakes of Schirmacher Oasis, Larsemann Hills and Vestfold Hills

Sl.No.	Area of Study	Name of the Lake	Techniques used	Time-span	Reference
1.	Schirmacher Oasis	Paleo-lake deposits	Magnetic susceptibility, loss-on-ignition and geochronology	13 cal ka B.P. to the Present	Phartiyal *et al*., 2011
2.		Paleo-lake deposits	Environmental magnetism, geochemistry and geochronology	13 cal ka B.P. to the Present	Phartiyal, 2014
3.		Sandy Lake	Environmental magnetism, geochronology, sedimentology and scanning electron microscopy of quartz grains	42.5 to 1.16 cal ka B.P.	Warrier *et al*., 2014; Warrier *et al*., 2016
4.		Long Lake (L-27)	Organic geochemistry, sedimentology and geochronology	48 cal ka B.P. to the Present	Mahesh *et al*., 2015
5.		Lake L-6	Plant fossil	10.65 cal ka B.P.	Singh *et al*., 2012
6.	Larsemann Hills	Lake L-2	Sedimentology, biogenic silica, total organic carbon and geochronology	8.3 cal ka B.P. to the Present	Govil *et al*., 2011; Govil *et al*., 2012
7	Vestfold Hills	CD-01 Lat: 68°37' 26.7''S; Long: 77°58'14.6''E	Diatoms and geochronology	6.5 to 2.5 cal ka B.P	Mazumder *et al*. 2013a; Mazumder *et al*. 2013b; Mazumder and Govil, 2013

the lowering of water levels for these palaeolakes was not known, they could still serve as an important source of information for Quaternary researchers.

There are very few studies from Schirmacher Oasis wherein lake sediments have shown the potential of recording climatic variations on glacial-interglacial timescales. By analyzing the environmental magnetic and geochemical properties of sedimentary deposits of Schirmacher Oasis, Phartiyal (2014) reconstructed the climatic conditions during the past 13 cal ka B.P. Higher values of magnetic concentration-dependent parameters correspond to colder periods and low values reflect comparatively warmer lacustrine phases. Multivariate cluster analysis of the paleoclimatic data enabled the author to trace six phases of climatic fluctuations between 13 and 3 cal ka B.P. According to the author, Schirmacher Oasis experienced a short phase of relatively warmer climatic conditions during 12.5 cal ka B.P. (Late Pleistocene), 11-8.7 cal ka B.P. (Early Holocene Optimum) and 4.4-3 cal ka B.P. (Mid-Holocene Hypsithermal). This observation was made due to the decreased values of magnetic concentration-dependent parameters. Several major elements (Fe, Rb, Zn, Mo, Co, Pb, Mn, Cu and As) were observed in the sediments in order of decreasing abundance.

Based on the environmental magnetic properties of sediments deposited in Sandy Lake, glacial-interglacial climatic variation was reconstructed for the past 42.5 cal. ka B.P. (Fig. 2; Warrier *et al*., 2014). The magnetic minerals present in the sediments were not affected by the presence of authigenic greigite, bacterial and anthropogenic magnetite. The magnetic mineralogy was dominated by the presence of titanomagnetite as evident by scanning electron microscopic observations. Glacial periods were characterized by high magnetic mineral concentrations (high values of χ_{lf} and SIRM) and coarse SSD titanomagnetite (low χ_{ARM}/SIRM, χ_{ARM}/χ_{lf} and high S-ratio values). Extremely cold periods in the Schirmacher Oasis were recorded during 40.78, 36.08, 34.51, 29.03 and, 28.02–21.45 cal. ka B.P. Relatively warm periods were documented during 38.44–39.22 cal. ka B.P., 33.73–29.81 cal. ka B.P. and 28.52 cal. ka B.P. The LGM has documented the highest concentration of magnetic minerals, indicating widespread glaciation in the Schirmacher Oasis. The Holocene period was characterized by alternating phases of relatively warm (12.55–9.88 cal. ka B.P. and 4.21–~2 cal. ka B.P.) and cold (9.21–4.21 cal. ka B.P. and from ~2 cal. ka B.P. onwards) events. Many of the relatively warm and cold events discerned in this study were correlatable with other lake sediment and ice-core records from the Schirmacher Oasis and other ice-free areas in East Antarctica. This study

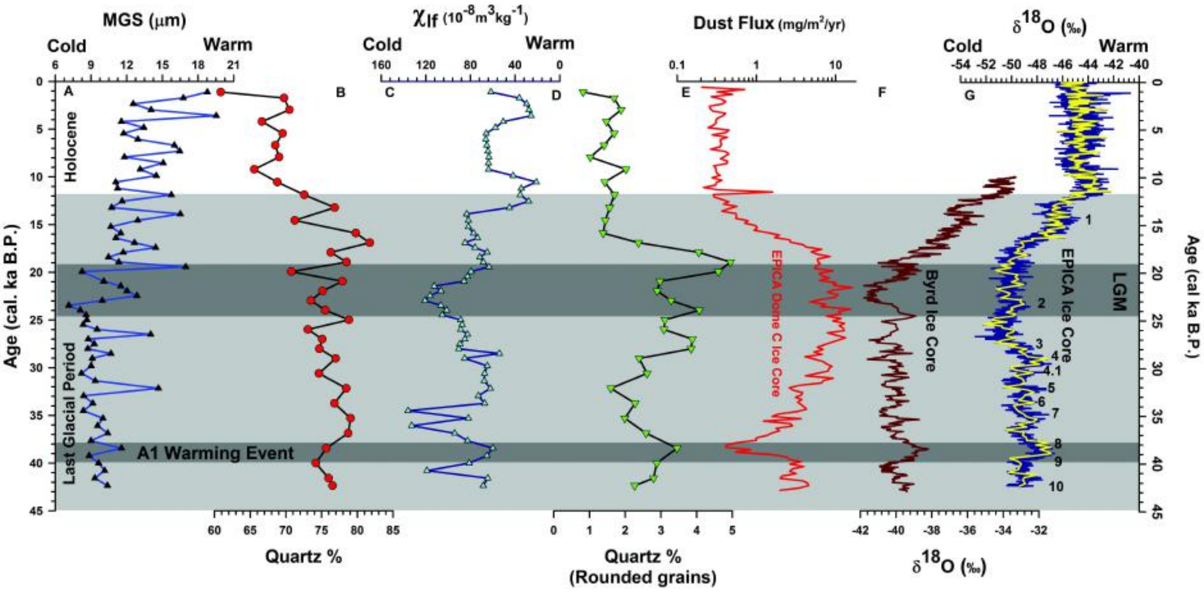

Fig. 2: Comparison of (A) mean grain size, (B) % quartz, (C) magnetic susceptibility ($\div_{lf}$), (D) % rounded quartz grains data of Sandy Lake sediments in Schirmacher Oasis (modified after Warrier *et al.*, 2014, 2016) with (E) dust flux (Lambert *et al.*, 2012) and oxygen isotopic data of ice-cores from (F) Byrd (Blunier and Brook, 2001) and (G) EDML (EPICA Community Members, 2006) station in the Dronning Maud Land, East Antarctica. A1 is one of the seven warming events reported in Antarctica during the past 90 cal. ka B.P. (Blunier and Brook, 2001)

provided environmental magnetic evidence for the Schirmacher Oasis escaping full glaciation during the past 40,000 years. This was the first report of a detailed environmental magnetic record of glacial–interglacial climatic variations from the Schirmacher Oasis.

Sediment particle size and quartz grains deposited in the sediments of Sandy Lake were used to understand their provenance and also the strength of the transporting medium during the past 42.5 cal ka B.P. (Warrier *et al.*, 2016). The poorly sorted and finely skewed sediments showed different modes of grain size distribution throughout the last 43 cal ka B.P. The statistical parameters of grain size data (sorting, skewness, kurtosis, mean grain size, D_{10}, D_{50}, D_{90} and SPAN index) indicated that the sediments were primarily transported by melt-water streams and glaciers. During the last glacial period, wind activity was strong as evident by the good correlation between rounded quartz data and dust flux data from EPICA ice-core data. The mean grain size values were low during the last glacial period indicating colder climatic conditions and the values increased after the last glacial maximum (LGM) which suggested an increase in the energy of the transporting medium, i.e., melt-water streams. Scanning electron microscopic (SEM) studies of selected quartz grains and analyses of various surface textures indicated that glacigenic conditions must have prevailed at the time of their transport. Semi-quantitative analyses of mineral (quartz, feldspar, mica, garnet and rock fragments & other minerals) counts suggested a mixed population of minerals with quartz being the dominant mineral. Higher concentration of quartz grains over other minerals indicated that the sediments were compositionally mature. The study revealed the different types of physical weathering, erosive signatures, and chemical precipitation most of them characteristic of glacial environment which affected these quartz grains before final deposition as lake sediments.

Organic geochemical and sedimentological data from sediments deposited in Long Lake (L-27), Schirmacher Oasis, provide a history of glacial-interglacial climatic variations during the last 48 cal ka B.P. (Mahesh *et al.*, 2015). The multi-proxy record (C_{org}, $\delta^{13}C$, C/N) gives evidence that the organic carbon analyzed from the lake is predominantly allochthonous. The lowest values of organic carbon during the last glacial and major part of Holocene indicated that the productivity was generally lower suggesting longer ice-cover period due to extreme cold conditions. The sustained Holocene warm conditions would have resulted in the lake experiencing longer ice-free conditions beginning at 6 cal ka B.P. as evident in the grain size variation. The particle size variation in the lake system is primarily governed by a combination of input through ice-melt water and aeolian action. The higher sand content during the Holocene than the glacial period indicates the warming conditions. The results show that Long Lake's response to Antarctic climate is reflected in its response to the ice-cover conditions which regulates the productivity and sedimentation in the lake system.

Singh *et al*. (2012) reported the presence of *Pohlia nutans* – moss species in a sediment core from Lake L6 in Schirmacher Oasis. The authors reported a radiocarbon date of 10.65 cal ka B.P. for the sediment layer (160-162 cm) from where the moss species was obtained. The preserved Holocene sub-fossil moss included delicate leaves, axes and rhizoids and perfectly matched the extant specimen of *P. nutans*. This was the first record of this sub-fossil from the central Dronning Maud Land (cDML), although the species is one of the most commonly found as part of the present-day flora in other parts of Antarctica. The current moss distribution data will be useful in monitoring the changes in its population and diversity in the Schirmacher Oasis region and also be helpful in reconstructing the past climate and environmental changes.

Govil *et al*. (2011) reconstructed the Holocene paleoenvironmental conditions by analysing the biogenic silica, sand and organic carbon concentrations in a sediment core from Lake L2 situated in the Grovnes, Larsemann Hills. The 78 cm sediment core represented a time-span of ~8.3 cal ka BP. The sediment core showed higher productivity values from ~8.3 to ~6 cal. ka B.P. High % sand suggested that sediments were deposited due to glacio-fluvial activity during ~8.3 to ~5 cal. ka B.P. Total organic carbon showed little variation throughout the sediment core, except in the upper ~10 cm (~4 cal. ka B.P.) part wherein it is comparatively high. The increased TOC in the upper part of the core possibly indicated the presence of algal mats due to exposure of the lake to the ice-free conditions. The BSi showed positive correlation with sand content during ~8.3 to ~5 cal ka BP and negative correlation from ~ 5 cal ka B.P. to the Present which was attributed to the high and low ratio of Al:SiO_2 (Govil *et al*., 2012).

Detailed study on diatom assemblage was carried out on sediments from an inland lake situated in Vestfold Hills, East Antarctica. AMS ^{14}C dates of the sediments of the lake extrapolate the time span of ~6500 to 2500 years BP. A total of thirteen diatom species were identified up to species level from the 47 cm length of the core. Eleven pennate forms (namely, *Achnanthes* aff. *Achnanthes groenlandica*, *A. taylorensis*, *Amphora ovalis*, *Cocconeis costata*, *Diploneis crabro*, *D. smithii*, *Fragilariopsis curta*, *F. ritscheri*, *Navicula directa*, *Navicula* sp. A and *Trachyneis aspera*) and two centric forms (namely, *Paralia sulcata* and *Thalassiosira anguste-lineata*) were identified. The variation of total diatom population and the abundance of salt crystal present in sediments suggest that the constant seawater influence (which was predominated in early Holocene) got weakened after ~5000 yrs BP till date (Mazumder *et al*. 2013a). Based on the abundance of icier condition indicator species *Fragilariopsis curta* along with other diatom assemblages (using unweighted pair group averaging method of Q-mode Cluster Analysis), it also can be concluded that Late Holocene experienced relative warmer climatic condition than its previous period (Mazumder *et al*. 2013b; Mazumder and Govil, 2013).

Scope for Future Work

A number of studies have been made on surface sediments and sediment cores from the three regions in East Antarctica. It can be seen that paleoclimate data obtained from sediment cores are quite little and also have a coarser temporal resolution with only a couple of studies extending back to glacial-interglacial timescale (~ 42.5 and ~ 48 cal ka B.P.; Warrier *et al.,* 2014, 2016; Mahesh *et al*., 2015). It is therefore necessary that future studies on lake sediments from Schirmacher Oasis, Larsemann Hills and Vestfold Hills be carried out with a clear aim of obtaining the longest possible sediment cores from the different types of lakes i.e., epishelf, pro-glacial and land-locked lakes. Closer interval sampling must be carried out to obtain high-resolution paleoclimate/paleoenvironment data. The high-resolution data will allow the researchers to have a good correlation with other archives such as ice-cores etc. Apart from closer interval sampling, newer proxies such as biomarkers, fossil pigments, glycerol dialkyl glycerol tetraether (GDGT) lipids etc. may also be used for getting quantitative estimates of past temperature variations.

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References

Asthana R, Shrivastava P K, Beg M J, Swain A K, Dharwadkar A, Roy S K and Srivastava H B (2013) Sedimentary processes in two different polar periglacial environments: Examples from Schirmacher Oasis and Larsemann Hills, East Antarctica *Spl Pub Geol Soc London* **381** 411-427

Asthana R and Chaturvedi A (1998) The grain-size behavior and morphoscopy of supraglacial sediments, south of Schirmacher Oasis, East Antarctica *Jour Geol Soc India* **52** 557-568

Bera S K (2004) Late Holocene Palaeo winds and climatic changes in Eastern Antarctica as indicated by long distance transported pollen spores and local microbiota in polar lake core sediments *Curr Sci* **86** 1485-1488

Blunier T and Brook E J (2001) Timing of millennial-scale climate change in Antarctica and Greenland during the last glacial period *Science* **291** 109-112

Community Members E P I C A (2006) One-to-one coupling of glacial climate variability in Greenland and Antarctica *Nature* **444** 195-198

Govil P, Mazumder A, Tiwari A K and Kumar S (2011) Holocene climate variability from the lake sediment core in Larsemann Hills, Antarctica *Jour Geol Soc India* **78** 30-35

Govil P, Asthana R, Mazumder A and Ravindra R (2012) Grain size distribution and its influence on biological productivity during Holocene in a fresh water lake in Larsemann Hills, Antarctica *Nat Acad Sci Lett* **35** 115-119

Huang J P, Swain A K, Thacker R W, Ravindra R, Andersen D T and Bej A K (2013) Bacterial diversity of the rock-water interface in an East Antarctic freshwater ecosystem, Lake Tawani(P)† *Aquat Biosyst* **9** 1-10 (http://www.aquaticbiosystems.org/content/9/1/4)

Huang J P, Hoover R B, Swain A, Murdock C, Andersen D T and Bej A K (2010) Comparison of the microbial diversity and abundance between the freshwater land-locked lakes of Schirmacher Oasis and the perennially ice-covered lake Untersee in East Antarctica *Proc of SPIE* 7819, 78190W1-W9

Ingole B S and Parulekar A H (1993) Limnology of Freshwater Lakes at Schirmacher Oasis, East Antarctica *Proc Indian Nat Sci Acad B* **59** 589-600

Kaplan M and Wolfe A 2006. Spatial and temporal variability of Holocene temperature in the North Atlantic region *Quat Res* **58** 223-231

Lambert F, Bigler M, Steffensen J P, Hutterli M and Fischer H (2012) Centennial mineral dust variability in high-resolution ice core data from Dome C, Antarctica *Clim Past* **8** 609-623

Mahesh B S, Warrier A K, Mohan R, Tiwari M, Anila B, Aswathi C, Asthana R and Ravindra R (2015) Response of Long Lake sediments to Antarctic climate: A perspective gained from sedimentary organic geochemistry and particle size analysis *Pol Sci* **9** 359-367

Mathur A K, Asthana R and Ravindra R (2006) Arcellaceans (thecamoebians) from core sediments of Priyadarshini Lake, Schirmacher Oasis, Eastern Antarctica *Curr Sci* **90** 1603-1605

Mazumder A and Govil P (2013) Signature of warmer Late Holocene around Vestfold Hills, East Antarctica *Canadian Jour Bas Appl Sci* **1** 33-43

Mazumder A, Govil P, Sharma S, Ravindra R, Khare N and Chaturvedi S K (2013a) A testimony of detachment of an inland lake from marine influence during the mid-Holocene in the Vestfold Hills region, East Antarctica *Limnol Rev* **13** 209-214

Mazumder A, Govil P, Ravindra R and Khare N (2013b) Indication of colder condition within Holocene period in a freshwater lake in Vestfold Hills area, East Antarctica region *Geosci Jour* **17** 235-239

Narayana A C, Mohan R and Mishra R (2010) Morphology and surface textures of quartz grains from freshwater lakes of McLeod Island, Larsemann Hills, East Antarctica *Curr*

Sci **99** 1420-1424

Phartiyal B (2014) Holocene paleoclimatic variation in the Schirmacher Oasis, East Antarctica: A mineral magnetic approach *Pol Sci* **8** 357-369

Phartiyal B, Sharma A and Bera S K (2011) Glacial lakes and geomorphological evolution of Schirmacher Oasis, East Antarctica, during Late Quaternary *Quat Int* **235** 128-136

Ravindra R (2001) Geomorphology of Schirmacher Oasis, East Antarctica. Proceedings, Symposium on snow, ice and glacier *Geol Surv India Sp Pub* **53** 379-390

Sharma C, Chauhan M S, Bera S K, Sinha R and Upreti D K (2000) Early Holocene sedimentological and palynological studies from Lake Priyadarshini, Eastern Antarctica. In: Vol. of Abstract, 10th International Palynological Congress, Nanjing, China, 151-152

Sharma C, Chauhan M S and Sinha R (2007) Studies on Holocene climatic changes from Priyadarshini Lake sediments, East Antarctica: the palynological evidence *Jour Geol Soc India* **69** 92-96

Sharma C, Bera S K and Upreti D K (2002) Modern pollen–spore rain in Schirmacher oasis, East Antarctica *Curr Sci* **82** 88-91

Shrivastava P K, Asthana R, Roy S K, Swain A K and Dharwadkar A (2012) Provenance and depositional environment of epi-shelf lake sediment from Schirmacher Oasis, East Antarctica, *vis-a-vis* scanning electron microscopy of quartz grain, size distribution and chemical parameters *Pol Sci* **6** 165-182

Singh S M, Ochyra R, Pednekar S M, Asthana R and Ravindra R (2012) A Holocene moss species preserved in lake sediment core and the present moss diversity at Schirmacher Oasis, Antarctica *Ant Sci* **24** 353-358

Sinha R and Chatterjee A (2000) Lacustrine sedimentology in the Schirmacher Range Area, East Antarctica *Jour Geol Soc India* **56** 39-45

Sinha R, Sharma C and Chauhan M S (2000a) Sedimentological and pollen studies of Lake Priyadarshini, Eastern Antarctica *Palaeobotanist* **49** 1-8

Sinha R, Navada S V, Chatterjee A, Kumar S, Mitra A and Nair A R (2000b) Hydrogen and oxygen isotopes analysis of Antarctica Lake waters, Schirmacher Oasis, East Antarctica *Curr Sci* **78** 992-995

Smeltzer E and Swain E B (1985) Answering lake management questions with paleolimnology. Pages 268-274 in Lake Reserves. Management - Practical Applications. Proceedings of 4th Annual Conference and Symposium (NALMS) 390

Smol J P and Cumming B F (2000) Tracking long-term changes in climate using algal indicators in lake sediments *J Phycol* **36** 986-1011

Srivastava A K, Ingle P S, Lunge H S and Khare N (2012) Grain-size characteristics of deposits derived from different glacigenic environments of the Schirmacher Oasis, East Antarctica *Geologos* **18** 251-266

Srivastava A K, Khare N and Ingle P S (2011) Characterization of clay minerals in the sediments of Schirmacher Oasis, East Antarctica: their origin and climatological implications *Curr Sci* **100** 363-372

Srivastava A K, Randive K R and Khare N (2013) Mineralogical and geochemical studies of glacial sediments from Schirmacher Oasis, East Antarctica *Quat Int* **292** 205-216

Steig E J, Schneider D P, Rutherford S D, Mann M E, Comiso J C and Shindell D T (2009) Warming of the Antarctic Ice-Sheet surface since the 1957 International Geophysical Year *Nature* **457** 459

Swadling K M, Dartnall H J G, Gibson J A E, Saulnier-Talbot E and Vincent W F (2001) Fossil Rotifers and the Early Colonization of an Antarctic Lake *Quat Res* **55** 380-384

Vaughan D G, Marshall G J, Connolley W M, Parkinson C, Mulvaney R, Hodgson D A, King J C, Pudsey C J and Turner J (2003) Recent rapid regional climate warming on the Antarctic Peninsula *Clim Change* **60** 243-274

Warrier A K, Mahesh B S, Mohan R, Shankar R, Asthana R and Ravindra R (2014) Glacial-interglacial climatic variations at the Schirmacher Oasis, East Antarctica: the first report from environmental magnetism *Palaeogeogr Palaeoclimatol Palaeoecol* **412** 249-260

Warrier A K, Pednekar H, Mahesh B S, Mohan R and Gazi S (2016) Sediment grain size and surface textural observations of quartz grains in late quaternary lacustrine sediments from Schirmacher Oasis, East Antarctica: Paleoenvironmental significance *Pol Sci* **10** 89-100.

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Review Article

India's Contribution to Geomagnetism and Allied Studies in Antarctica – A Review

ASHWINI K SINHA[1,*], AJAY DHAR[1], ANAND K SINGH[2], JAYANTA K BEHERA[1] and S GURUBARAN[1]

[1]*Indian Institute of Geomagnetism, Plot 5, Sector 18, New Panvel (W), Navi Mumbai 410 218, India*

[2]*ESSO-NCAOR, Goa, India*

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In this paper, we review the progress in Geomagnetism and allied areas based on the past thirty five Indian Antarctic expeditions and summarize the scientific results obtained in the last decade. Various dynamic processes in the near-Earth space environment, driven by the transient changes in geomagnetic field such as storms and substorms, severely affect the space weather over the Polar Regions. Magnetopsheric substorms lead to the intensification of ionospheric currents and auroral outbursts within the auroral oval, causing energetic charged particles in the auroral region to come down to D-region ionosphere, which is reflected as Cosmic Noise Absorption (CNA) as monitored by imaging RIOmeter at Indian Antarctic station, Maitri (Geog. 70.75° S, 11.73°E; Geom. 66.84°S, 56.29°E). A systematic rapid decline in The Earth's complex main magnetic field at Maitri (~110 nT/yr) is important for monitoring the evolution of reverse magnetic flux patches due to physical processes occurring in the outer core of the Earth. The Global Electric Circuit (GEC) studies were started to understand the solar-terrestrial relationship and associated changes in surface weather and the near-earth electrical environment. Schumann resonances (SRs), the AC part of GEC reveal a strong UT variation of amplitude in seasonal as well as yearly time scales. The observed diurnal variation is explained in terms of the dominant thunderstorm activity centered over the three convectively active regions, viz. Asia/Maritime Continent (Indonesia), South America and Africa.

The velocity and strain distribution of Schirmarchaer Glacier was investigated during two GPS campaigns in the year 2003 and 2004. The studies indicate that the horizontal velocity is in the range of 1.89-10.88 ma^{-1} with an average velocity of 6.21 ma^{-1}.

Keywords: Indian Institute of Geomagnetism (IIG); Indian Antarctic Research Stations; Geomagnetism; Global Electric Circuit; GPS; Environmental Magnetic Studies

Introduction

Antarctica is a region of great importance for studies of geomagnetism and allied fields. Present day geometry of the Earth's main magnetic field causes the high latitude region of the atmosphere to be directly affected by the increase in magnetospheric energy during geomagnetic storms and substorms. Intense energy input from the magnetosphere can result in visually spectacular aurora and changes in the ionosphere that affect HF (high frequency) communication (Detrick and Rosenberg, 1990). Increase in the convective electric field and auroral particle precipitation produce intense currents in the ionosphere, which are monitored through magnetic field measurements (Singh *et al.*, 2012; Behera *et al.*, 2015). Changes in the ionosphere are also monitored using an Imaging Riometer, which measures the strength of the 38.2 MHz galactic radio waves that impinge on the Earth's atmosphere, and thereby gives information on the changes in absorption of this signal due to changes in the ionospheric electron density (Browne *et al.*, 1995). Apart from the dramatic short term changes in the geomagnetic field recorded at Antarctica, which may be attributed to external causes, it has emerged that the Earth's complex main magnetic field, which has its origin in the fluid outer core of the Earth at a depth of about

**Author for Correspondence: E-mail: sinha.ashwini@gmail.com*

2900 km below the surface of the Earth, is also undergoing a systematic rapid decline as observed in the Antarctic region (Pathan *et al*., 2009). Indian Institute of Geomagnetism (IIG) started geomagnetic field measurements in Antarctica during the first Indian Antarctic Expedition in 1981-82. With the setting up of a permanent base at Dakshin Gangotri (DG) in 1983-84, observations were taken on a regular basis with Proton Precession Magnetometer (PPM), Fluxgate Magnetometer and an 30 MHz Analogue Riometer (Rajaram *et al*., 2001). After abandoning of Dakshin Gangotri Station and construction of new Station at Maitri in 1990, the observations were continued at Maitri and additional instruments were deployed. The Fluxgate Magnetometer was replaced by Digital Fluxgate Magnetometer (DFM) and the 30 MHz Riometer by a 38.2 MHz Imaging Riometer. The observations have indicated the importance of the location of Maitri, as a sub-auroral during magnetically quiet periods. However, during magnetically disturbed times auroral oval expands and the variations recorded are quite different from their quiet time variations. Large decrease in the main magnetic field observed at Maitri are now emerging to be important for monitoring the evolution of reverse magnetic flux patches due to physical processes occurring in the molten conducting outer core of the Earth. The study of Global Electric Circuit (GEC) provides a platform for understanding the solar-terrestrial relationship and associated changes in surface weather. Continuous measurements are carried out to understand the near-earth electrical environment. A link could be established between the surface electrical environment and space weather events (Panneerselvam *et al*., 2010; Jeni *et al*., 2015).

The Indian Antarctic Geomagnetic studies commenced with the launching of the first Indian Antarctic expedition in 1981-82. The first Indian base was set up in the Queen Maud Land region (Geog. 70° S latitude, 12° E longitude) of east Antarctic ice shelf. Nearly 10 days of magnetic data were collected with a PPM in January 1982. Since then, the stay and the observational period kept on increasing with setting up of permanent stations, Dakshin Gangotri (1983) and Maitri (1990). The third Indian Antarctic Station, Bharati (Geog. Co-ordinates ~69^0 S, 76° E) was commissioned at Larsemann Hills, East Antarctica in the year 2012. Over the past 35 years, the magnetic field is being continuously monitored, except for a few years gap in between. The geographic location of Dakshin Gangotri and Maitri has proved to be unique location from geomagnetic point of view, as will be elaborated in the results and discussions. With barely 2% of Antarctic Continent free from ice, Maitri is located on one such ice-free rocky area of Schirmacher Oasis - with number of fresh water lakes available within this area.

The present review on Geomagnetism and allied aspects is based on the past Indian Antarctic expeditions and summarizes the observations along with their scientific implications.

Experimental Facilities

IIG is participating in the Indian Scientific Expedition to Antarctic (ISEA) since its inception and fair numbers of scientists have visited Antarctica. The Institute is conducting geomagnetic, ionospheric, air-earth current and GPS measurements in Antarctica. The following instruments were operated for various geophysical studies as mentioned above:

i. Proton Precession Magnetometer (PPM) for recording of Total Magnetic Field (F) intensity
ii. Fluxgate Magnetometer (FM) to record variations in the three orthogonal components X, Y and Z. The Fluxgate Magnetometer was later replaced by a Digital Fluxgate Magnetometer (DFM) in 2003.
iii. 30 MHz Riometer to measure the strength of the cosmic radio noise that impinge on the Earth’s atmosphere, causing secondary ionization in the D region. The Riometer was replaced by an Imaging Riometer operated at 38.2 MHz to have a better understanding of the absorption processes
iv. Magnetometers at the vertices’s of a triangle to determine the velocity of small-scale auroral current systems over Maitri
v. Maxwell Current experiment to determine variations in air earth current system. The system was later expanded to record all three parameters of Global Electric Circuit (GEC), namely Conduction Current, Potential Gradient and Air-Earth Current. An Automatic Weather Station (AWS) was also operated to record Meteorological parameters used in analysis of GEC data
vi. Global Positioning System (GPS) for studies of crustal deformation and Glacier movement

vii. Induction Coil Magnetometer (ICM) for monitoring geomagnetic field variations in 0-32 Hz frequency range (geomagnetic pulsations). The Schumann Resonance frequencies estimated from the data set provide information about the global temperature and global change in temperature operated on a long-term basis.

Major Scientific Achievements

Comparative study of Quiet Day variations at Dakshin Gangotri (DC) and Novolazarevskaya (NOVO)

Regular geomagnetic measurements were started after establishing of Dakshin Gangotri Station during 1983-84. A comparative study of the quiet day features of the geomagnetic field at DG and nearby Russian Station, Novolazarevskaya was carried out to check the validity of data. The mean diurnal variation pattern of the three magnetic elements at the two stations (Fig. 1A) show that the two stations are in close conformity with the anticipated diurnal patterns for such geographical locations during local summer months close to solar minimum epoch. The range of variations at both stations is nearly the same.

However, the departures from total coincidence can be mainly attributed to the fact that the three

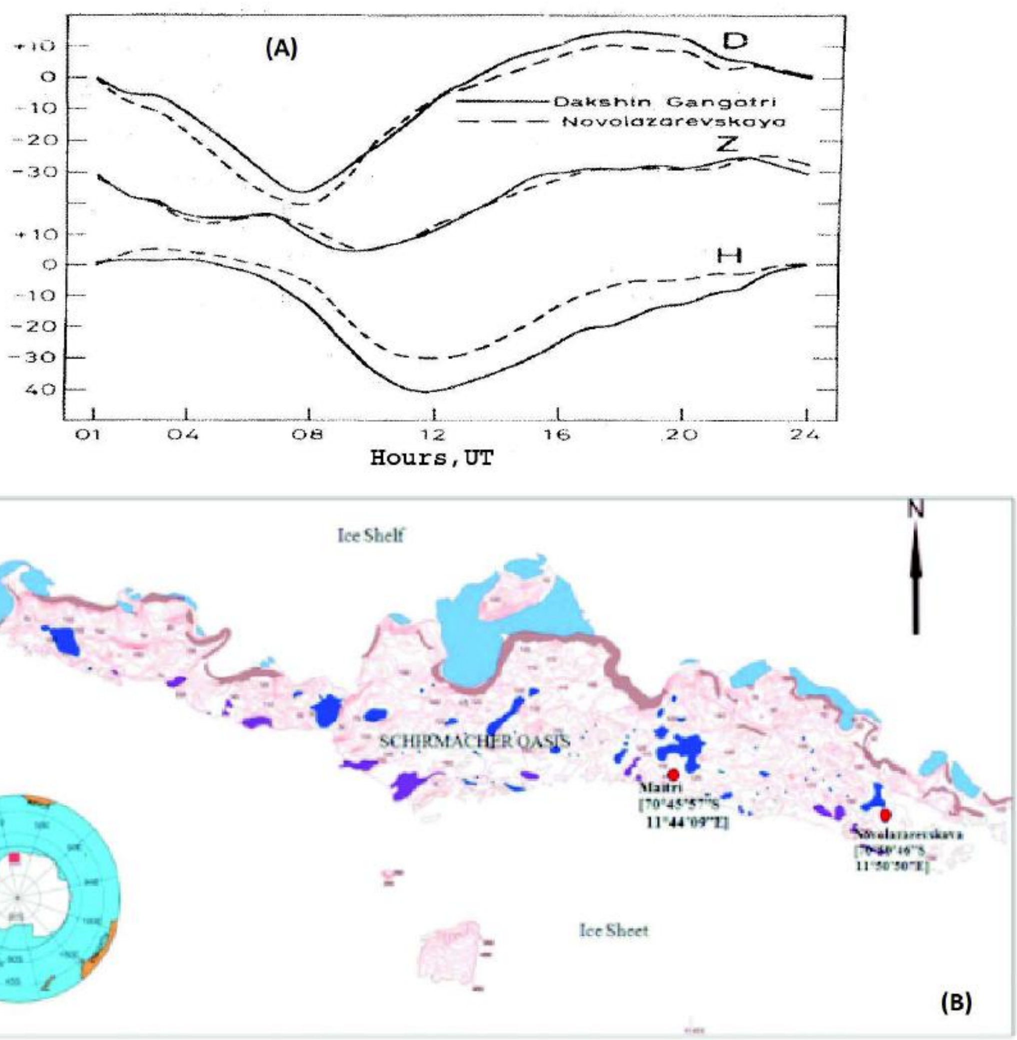


Fig. 1: **(A) shows mean diurnal variations in H, Z and D derived from records on quiet days at Dakshin Gangotri and Novolazarevskaya. (B) Shows geographic locations of Indian Antarctic station Maitri and Russian Antarctic station Novo in Schirmarcher Oasis. Though they are nearby stations, they do not exhibit identical geomagnetic variations**

dominant poles – Geographic, Dip and Corrected geomagnetic - are widely separated in Antarctic region, so that even two stations in close proximity geographically may show significant differences in the geomagnetic variations (Rangarajan and Dhar, 1988). The difference in geomagnetic variations between two geographically nearby stations is evident (Fig. 1 B).

The quiet-time ($\Sigma Kp \leq 3$) daily variations of the geomagnetic field at the Indian Antarctic station (refer Fig. 2), Maitri during two consecutive years of solar minimum was analyzed to investigate the characteristics of the solar quiet (Sq) current system and the signatures of the south limb of the Sq current loop of southern hemisphere over sub-auroral station. It was observed that Maitri behaves like a typical mid-latitude station during quiet magnetic conditions and seasonal variation of the Sq current strength over Maitri is strongest during summer months and weakest during winter months. In spite of the total darkness during winter months, Sq pattern is identified at Maitri.

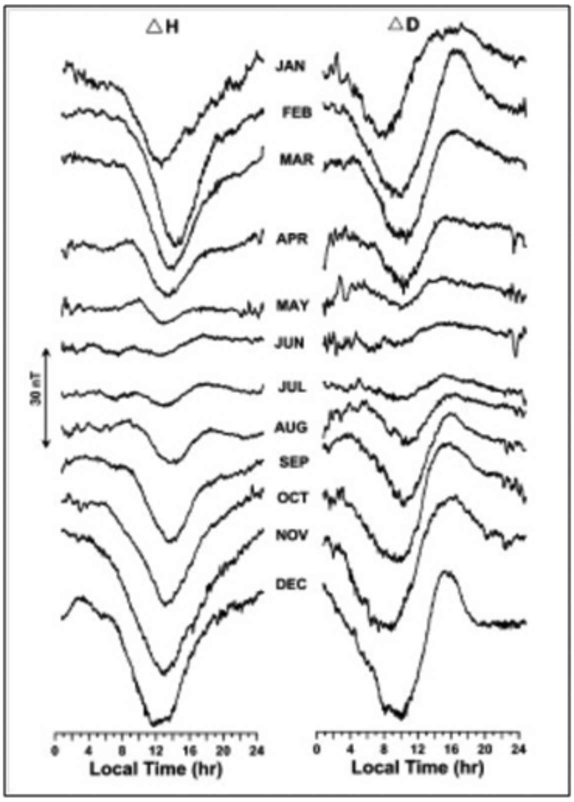


Fig. 2: *H*- and *D*-variations during various months averaged over quiet days (_*Kp* ≥ 3) of years 2009 and 2010

The range of horizontal field variation in the daily Sq pattern during summer is one order higher than that during winter. A sharp shift in the time of peak Sq current to later local times (> 1 hour per month) is observed during Jan-Feb and July-August, which may correspond to the transactions from complete presence or absence of sunlight to partial sunlight. The differences in the incoming solar UV radiation during such transactions can cause a sudden change in the local ionospheric conductivity pattern, and can also trigger some unusual thermo-tidal activity, that might be responsible for modifying the global Sq pattern (Vichare *et al*., 2012).

Geomagnetic Variations at Maitri in Relation to Space Weather

The auroral oval regions are dynamic in nature and they can shift polewards or equatorwards, depending on the degree of electromagnetic disturbance in geospace. With change in geospace disturbance, the sub-auroral locations are ideal to sense the rapid changes in space weather. DG and Maitri occupy such an important location and shift in and out of auroral oval with increasing magnetic disturbance (Banola *et al*., 1997). During quiet magnetic conditions, Maitri is situated to the north of auroral oval and is influenced by southern limb of Sq current system. With increasing charge particle precipitation in auroral oval, the auroral oval expands and overlaps the station. During such conditions, Maitri is influenced by auroral electrojet and behaves like a typical auroral zone station. Thus, Maitri becomes an ideal location for 'Space Weather' studies. "Weather in Space" refers to degree of electromagnetic disturbance in the Earth's Space Environment (Geomagnetosphere). The auroral regions of the Earth serve as ideal locations for the remote sensing of Space Weather. These regions map to Central Plasma Sheet (CPS) region of the magnetosphere. The CPS represents the region of magnetosphere where large amount of Solar-Terrestrial energy exchange takes place, and this energy ultimately finds its way into the auroral ovals of the Earth. Thus the magnetic variation recorded on ground in auroral regions provides clues to physical processes in the distant magnetosphere, and hence to those in the Interplanetary medium and on the Sun.

The past two decades of experimental

Geomagnetism at the Indian Antarctic station Maitri, using Magnetometer, Riometer, and observations of Optical aurora, has led us to the following conclusion:

Maitri is ideally suited for nowcasting Geospace Weather, and perhaps the Interplanetary Weather. The former refers to the degree of disturbance in electric and magnetic fields, and particle population in various regimes of the Earth's magnetosphere. The latter refers to the magnitude and direction of the solar magnetic field components, and the velocity, density and dynamic pressure of solar wind particles in interplanetary space.

Comparison of Y, X and Z variations and the Riometer absorption patterns at Maitri with the IMF variations and the interplanetary solar wind parameters measured by the WIND Satellite during 1999 (Fig. 3) show good agreement between the magnetometer and the Riometer variations and the southward component

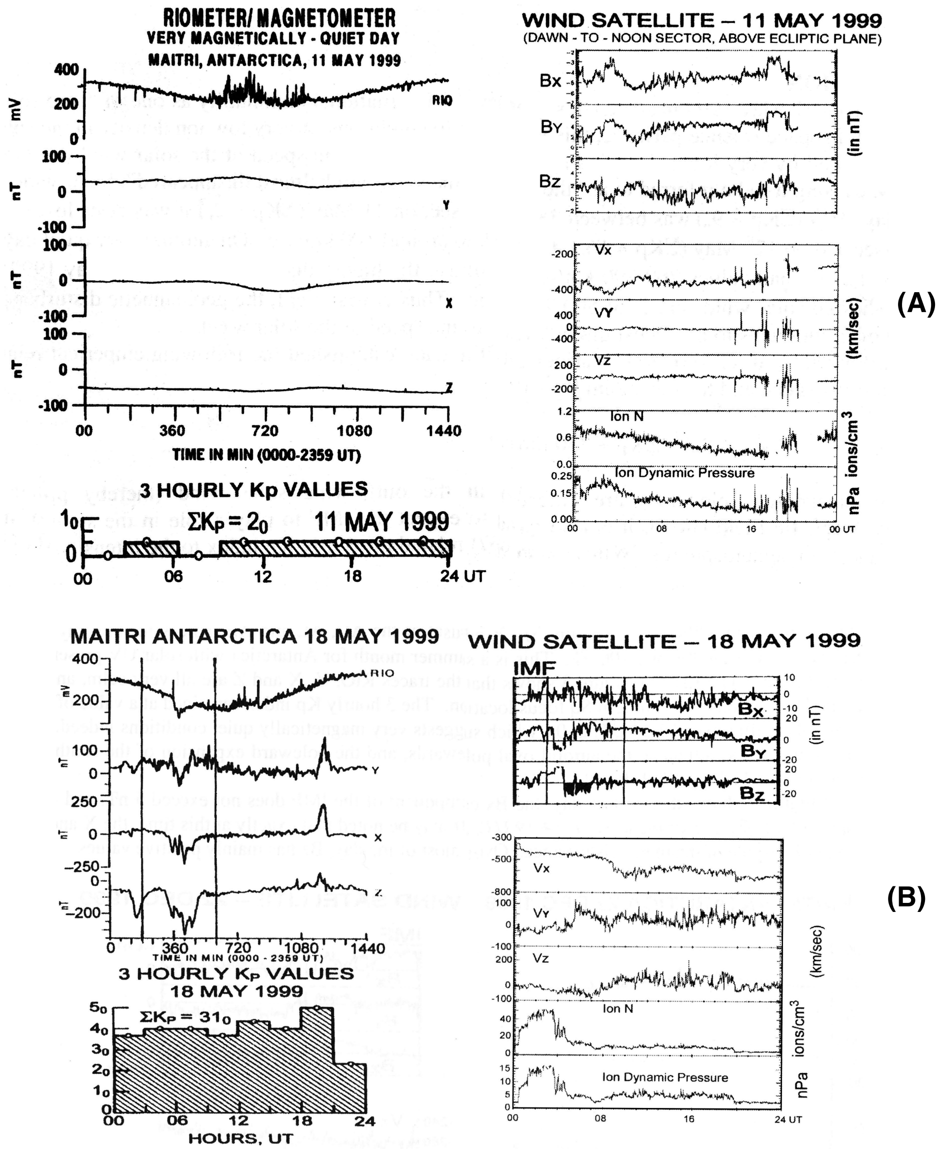


Fig. 3: (A) 30 MHz Riometer and geomagnetic Y, X and Z variations at Maitri for the disturbed day of 11 May 1999. Below is three hourly Kp values. The day the solar wind almost disappeared. IMF parameters for the same periods are shown on the right hand side for the comparison; (B) 30 MHz Riometer and geomagnetic Y, X and Z variations at Maitri for the disturbed day of 11 May 1999. Below is three hourly Kp values. The day the solar wind almost disappeared. IMF parameters for the same periods are shown on the right hand side for the comparison

of the IMF, its intensity, the speed of the solar wind, and the ion dynamic pressure of the solar wind. The changes recorded by a fluxgate magnetometer and a 30 MHz Riometer operating at Maitri during a splendid display of "aurora australis" on 4/5 March 1999 were interpreted in terms of currently – understood auroral physics. Interplanetary magnetic field and plasma parameters (Fig. 4) recorded by the WIND Satellite indicate very high solar wind velocities (>600 km/sec), and prolonged southward Bz of average value (<5 nT), during the auroral event. Ion density is however on an average 3-4/cm^3, and ion pressure only 2-3 nano Pascals during the event (Rajaram *et al*., 2002).

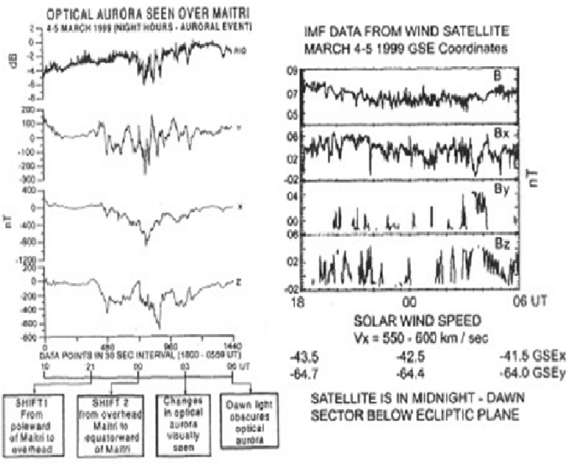


Fig. 4: Shift and change in the movement of optical aurora over Maitri and its ground geomagnetic signature from March 4, 18 UT to March 5, 06 UT 1999. Variations in IMF parameters are shown on right hand side for the same period

Observation from Conjugate Stations

Maitri does not have a conjugate location in the northern hemisphere as the field line originating from Maitri falls into Ocean (Fig. 5). In the absence of conjugate location for Maitri, magnetic data from Maitri was analyzed in corroboration with northern hemispheric two nearby stations LEIRVOGUR and NARSARSSUAQ, which fall on either side of the conjugate location of Maitri. LEIRVOGUR and NARSARSSUAQ are auroral zone stations and show the variations reflected by auroral electrojet and thus differed from the signatures recorded by Maitri during quiet magnetic conditions. During disturbed conditions, the variations however matched. This further confirmed the location of Maitri as sub-auroral (Dhar *et al*., 1993: Kalra *et al*., 1995).

Triangular Magnetometer Experiment Around Maitri

Magnetometers were operated at stations located at the vertices of a triangle around Maitri, with sides of 100-250 km to determine the presence and velocity of mobile, small-scale, auroral current systems over Maitri (Fig. 6). These currents while flowing over Maitri and surroundings, leave signatures over the ground based magnetometers. The velocities were determined from the time lags in these pulsations, The velocities of these mobile auroral current systems lie typically between 0.5 and 3.0 km/sec, and they tally well with the velocities obtained by various experimental groups in the northern auroral oval. During a particularly disturbed period of 28-31 Jan 1996, very large drift speeds of 3 to 18 km/sec were obtained from the time lags at the 3 stations, and this could be due to the presence of the eastward drifting Omega bands and westward traveling surges (Kalra *et al*., 1998; Dhar *et al*., 1999).

Rapid Declining of Geomagnetic Field at and Around Maitri

The dynamo process in the interior of the Earth generates a magnetic field that stretches up to the surface and beyond. The surface measurements of the geomagnetic field arise due to the internal field, however up to 10% contribution could be as a result of the ionospheric and magnetopsheric currents which are mainly controlled by the solar activity. The external currents vary at a much shorter scale (seconds to years) than the currents in the interior of the Earth. The long term variation in the geomagnetic field, arising due to the changes in the internal currents, is called as secular variation. The global secular variation suggests declining geomagnetic field intensity (Glatzmaier and Roberts, 1995; Pathan *et al*., 2009). The maximum rate of decline has been observed in the south Atlantic region. The Total Geomagnetic Field Intensity F measured at DG and later at Maitri, indicated a large drop between the year of 1987-1996 in the F values. When compared with the values of F for the geographic location of Maitri obtained from IGRF (International Geomagnetic Reference Field) for 1990, it showed a markedly decreasing trend for the years 1982, 1996, 1990 and 1996. Examination of the F values for 1922, 1951 and 1960 from earlier

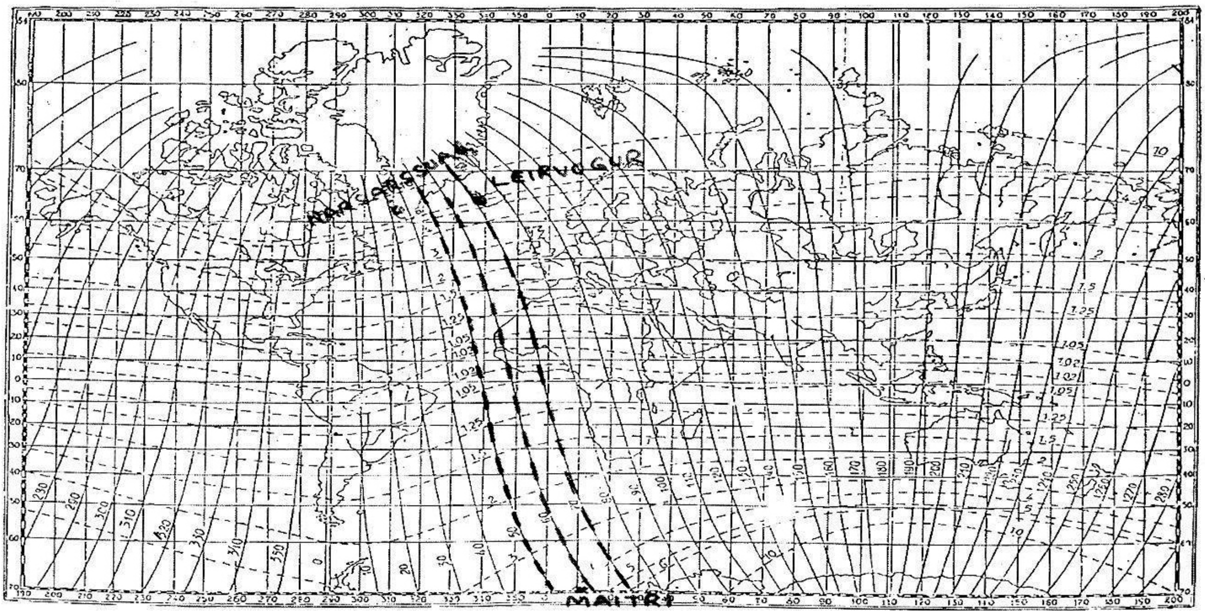


Fig. 5: In the absence of conjugate location for Maitri, magnetic data from two nearby stations LEIRVOGUR and NARSARSSUAQ was obtained and analyzed. These two stations fall on either side of the conjugate location of Maitri

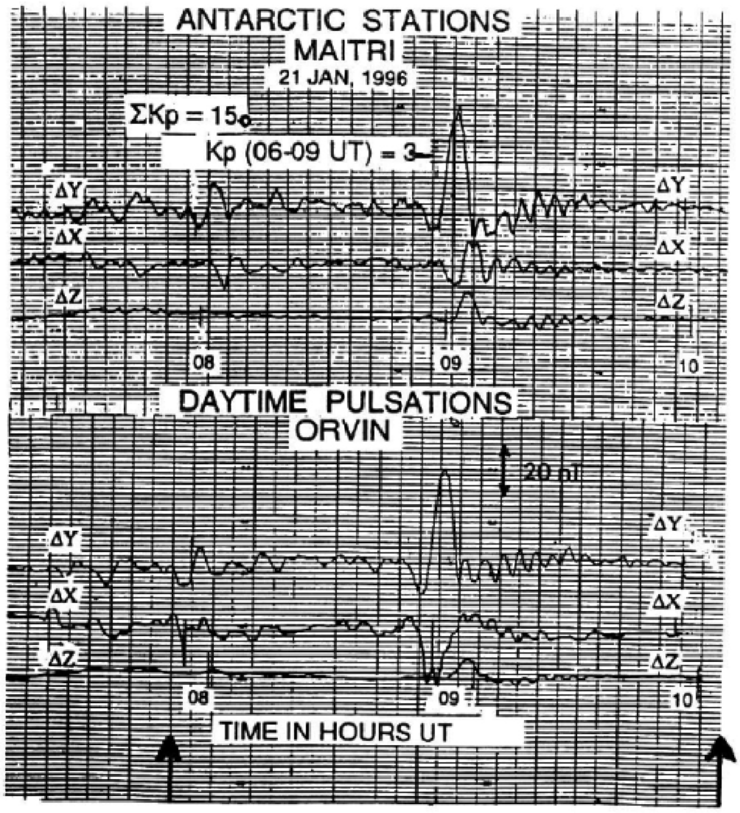


Fig. 6: Simultaneous geomagnetic pulsations at two locations MAITRI and ORVIN on 21 Jan 1996 between 0800 and 1000 UT. The drift speed of the small scale ionospheric current systems are estimated from the time lag in similar pulsations

Magnetic Charts for this location, the resulting curve suggested a drop of about 8000 nT in the past 75 years. A decrease of nearly 17% was observed since 1922, which is a considerable magnitude within 75 years (Arun *et al.*, 2000; Rajaram *et al.*, 2002; Pathan *et al.*, 2009). Recent observations of the magnetic field intensity at Maitri suggest annual decline rate has dropped about 60 nT/year, which is consistent with international geomagnetic reference field (IGRF) model (see Fig. 7).

An examination of total magmatic field (F) data from other stations (Figs. 8 and 9) in the northern and southern hemisphere suggested that this decrease was occurring only in the southern hemisphere. Bormann *et al.* (1995) had reported a decrease of about 100 nT/yr at Novolazarevskaya (Russian) and George Foster (German) stations, both the stations located in the vicinity of Maitri. The rate of decrease observed at southern hemisphere high latitude stations is as follows:

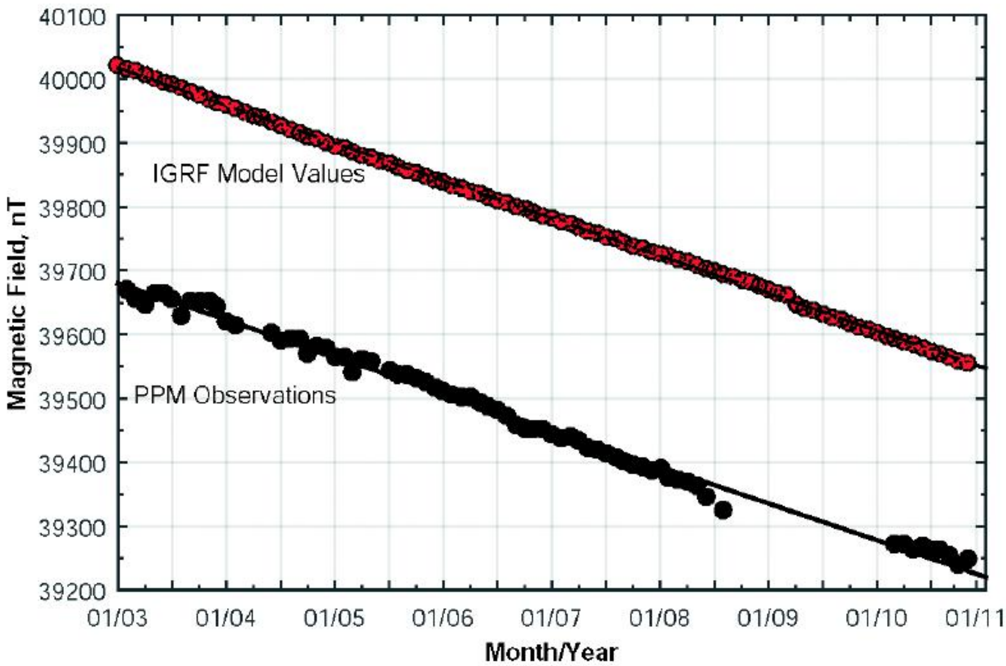


Fig. 7: Observed and modeled intensity of geomagnetic field at Maitri during years 2003-2010 show annual decline of about 60 nT/year

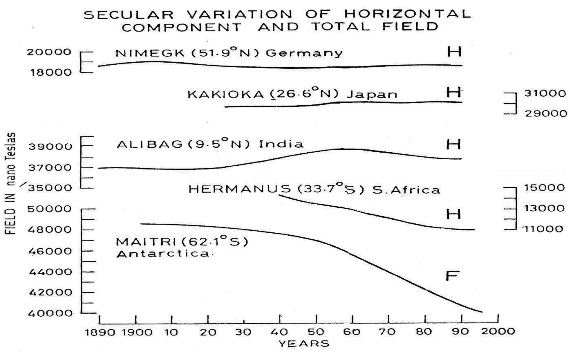


Fig. 8: Variation of the principal component of the geomagnetic field over the past century (1890-1996 A.D.) at northern hemisphere stations (Nemegk, Kakioka and Alibag) and at southern hemisphere stations (Harmanus and Maitri)

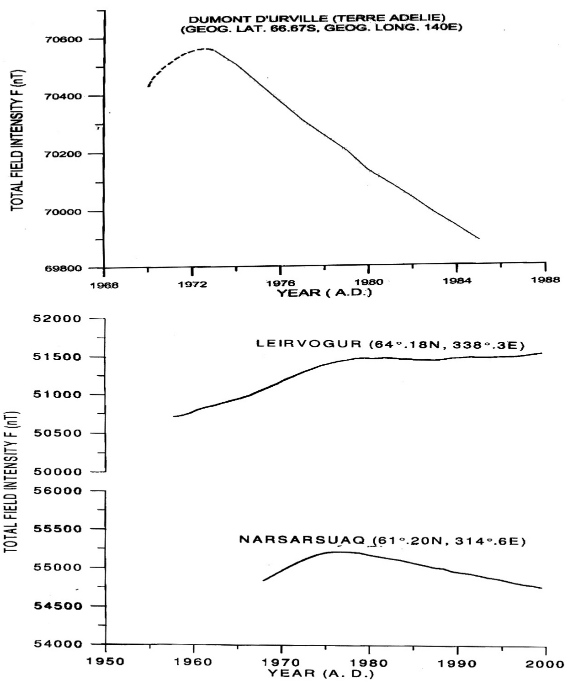


Fig. 9: GeomagneticTotal Field (F) variation at two northern hemisphere stations Narsarssuaq, Leirvogur and southern hemisphere station Demont D' Durville

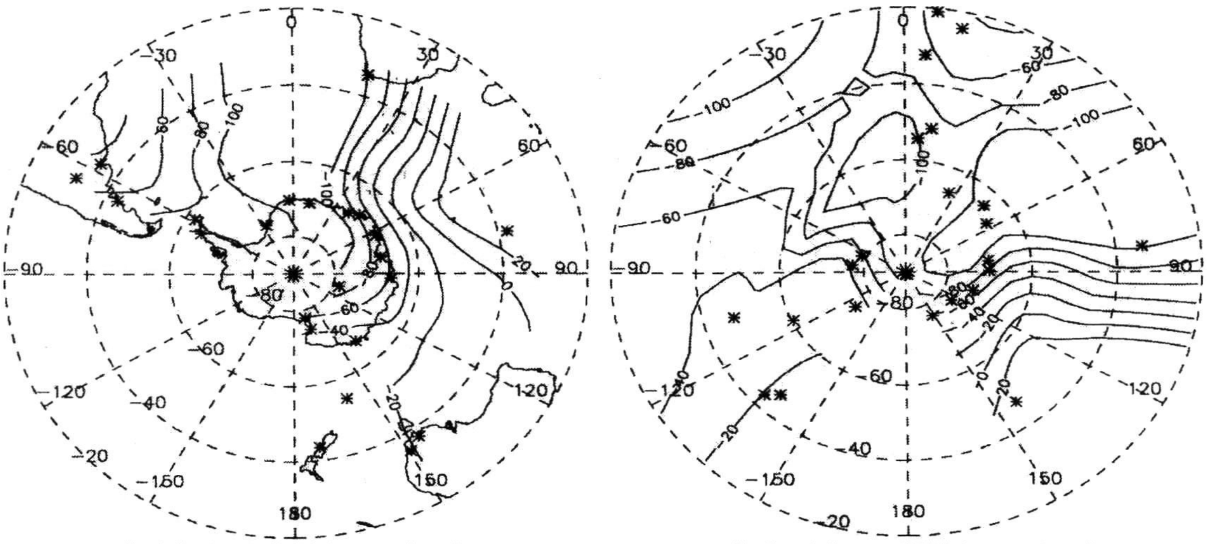
Novolazarevskaya: 108 nT/yr, Sanae: 108 nT/yr, Hermanus: 105 nT/yr, Argentine Island: 103 nT/yr, Syowa: 94 nT/yr, Halley Bay: 91 nT/yr, Davis: 73 nT/yr, Mawson: 72 nT/yr, Dumont d'Urville: 50 nT/yr (Rajaram *et al*., 2002).

Further analysis of magnetic data from high-latitude stations in northern and southern stations indicated that this rapid decline is confined to a narrow horse shoe shaped belt in the Antarctic region, encompassing Maitri (Arun *et al*., 2000). The rate of decline falls as one moves away in the poleward or equatorward direction. Gubbins (1988), defined these areas as 'Regions of Reverse Magnetic Flux'. Continuous monitoring of the F values as well as the efforts to modeling the decline will be useful in future. The Fig. 10 shows the contours of rate of average decrease in F (nT/yr) over the past five decades (1950-1999) for Antarctic and sub-Antarctic stations between 30°-90° S in geographic and geomagnetic coordinates. The locations of the stations considered are shown using star symbols.

Substorm Dynamics at Maitri and Bharati Stations in Antarctica

Continuously emanating charged particles from the Sun expand into the interplanetary space. The earthward directed stream of the solar wind confines the earth's magnetic field in a cavity like shape called as "magnetosphere". The dayside magnetosphere expends to about 8-10 R_E (where R_E is the radius of the Earth) on the dayside whereas it stretches beyond several 100s of R_E on the nightside in the form of a long tail known as "magnetotail". A fraction of the solar wind plasma and energy is stored in the Earth's magnetotail through magnetic reconnection process and ultimately released into the inner magnetosphere across the geomagnetic field lines and additionally diverted along the field lines to the polar regions during a process called as "substorm". Substorms manifest in the form for spectacular auroral displays, intense magnetic field variations, etc. (Rostoker *et al.*, 1980; Kellerman and Makarevich, 2011; Singh *et al.*, 2012; Murphy *et al.*, 2014). During intense events, precipitation of energetic charged particles into the polar atmosphere leads to enhanced cosmic radio noise absorption (Behera *et al.*, 2015), which influences the dynamics of the neutral atmosphere (Codrescu *et al.*, 1997) and even possibly the surface air temperature (Seppälä *et al.*, 2009). In addition to variations with local time, latitude and season, substorm characteristics vary over the solar cycle due to dominance of different solar wind drivers (Tanskanen, 2009; Tsurutani *et al.*, 2015).

Auroral latitudes (magnetic 60°-70°) are the most severely affected region due to substorm activity. Nevertheless, nearly all regions including the low latitudes undergo significant magnetic and electric field changes during substorms (McPherron *et al.*, 1973; Singh *et al.*, 2011). During the course of a substorm, extremely intense currents of the order of 10^6 A flow into the auroral ionosphere (Kamide and Kokubun, 1996), which can be easily monitored using satellite and ground based magnetometers. As a result of the short-lived, extremely intense auroral electrojets, the geomagnetic field could vary up to 10% of its total value. The direction and intensity of



GEOGRAPHIC COORDINATES GEOMAGNETIC COORDINATES

Fig. 10: Conditions of total magnetic field F variation in nT/yr for the period 1950-2000 AD, using data from stations located in the 30-90°S latitude region

the auroral electrojets mainly depend on the local times, for example, eastward current adds to the ambient geomagnetic field and is typically observed near dusk hours whereas westward current leads to a sharp depression near the local midnight (Rostoker *et al*., 1980). The intensification of the westward auroral electrojet is believed to be more closely related to the onset substorm.

Disturbances in the horizontal (H) components, observed at selected 10-12 longitudinally distributed auroral observatories in the northern hemisphere, have been used over several decades to derive auroral electrojet (AE) indices to monitor substorms (Davis and Sugiura, 1966). The auroral oval is often confined between 60°-70° magnetic latitude, however it expands equatorward and contracts poleward in accordance with changes in IMF, solar wind pressure variations and level of geomagnetic activity (Kamide and Akasofu, 1983). Moreover, there could be significant hemispherical asymmetry in the substorm characteristics (Newell *et al*., 2010; Singh *et al*., 2012).

Indian research bases - Maitri and Bharati in Antarctica (respectively at magnetic latitude 63°S and 75°S) are suitably located near the boundaries of the most dynamic auroral oval in the southern hemisphere. Years-long magnetic field observations in corroboration with other relevant data sets have been extensively used for the better insight of the substorm process and subsequent energy input into the upper atmosphere.

Morphology of Auroral Electrojets at Maitri Station: The local H, D and Z magnetic variations are generally sensitive to the east-west currents, field-aligned current and spatial gradient of the zonal (east-west) currents, respectively. Typical magnetic field components variation under the influence of the eastward and westward currents prevailing at different local times at Maitri are demonstrated in Fig. 11. It was inferred from the in-phase H and Z variations for the events that Maitri station being near the equatorward boundary of the auroral oval, the center of the eastward as well as westward electrojet for the events shown in Fig. 11 was poleward of our station (see Singh *et al*., 2012).

Identification of auroral electrojet onset over the years 2003-2008 was carried out using a customized automatic algorithm of Newell and Gjerloev (2011) (see Singh *et al*., 2016 for details). About 500 eastward electrojet events were identified whereas the number of events for the westward electrojet was about 3 times higher than the former. The auroral

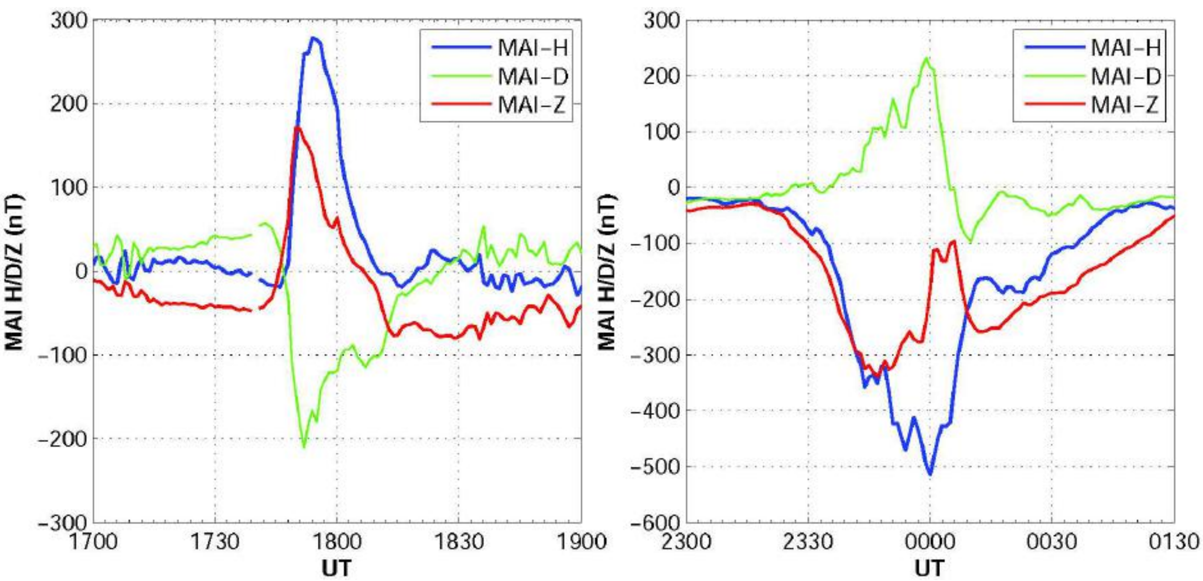


Fig. 11: Variations of the geomagnetic field components under the influence of eastward and westward auroral electrojets over Maitri. Positive H excursion (blue curve) represents dominance of eastward electrojet (left panel) whereas westward electrojet prevails around midnight (right panel)

electrojets at Maitri were observed to have profound solar cycle and local time variations as shown in Figs. 12 and 13. The yearly distribution of electrojet onsets have been shown in the Fig. 12. The thick red curve represents the yearly sunspot number. Occurrences of the auroral electrojets events varied in accordance with the solar activity as represented by the sunspot number, except for the year 2005 when several transient solar events were witnessed (Singh *et al*., 2015). During the deep solar minimum years 2007 and 2008, the auroral electrojet activity fairly subsided. However, the eastward and westward electrojet occurrences do not change in the same proportion thereby suggesting the fact that the drivers for the two auroral electrojets are not essentially same (Kamide and Rostoker, 2004).

The local time and magnetic local time are almost same as the universal time (UT) for Maitri station. Occurrence of the eastward electrojet maximizes around dusk hours (1800 h) whereas the westward electrojet peaks around midnight (0000 h) (please refer Fig. 13). However, there are notable differences in the local time distribution of the two electrojets, viz. the eastward electrojet regime spreads to a broader local time than the westward electrojet. The probability of occurrence of the eastward electrojet appears similar on either side of the dusk (1800 h) as shown in the left panel of Fig. 13, whereas for the westward

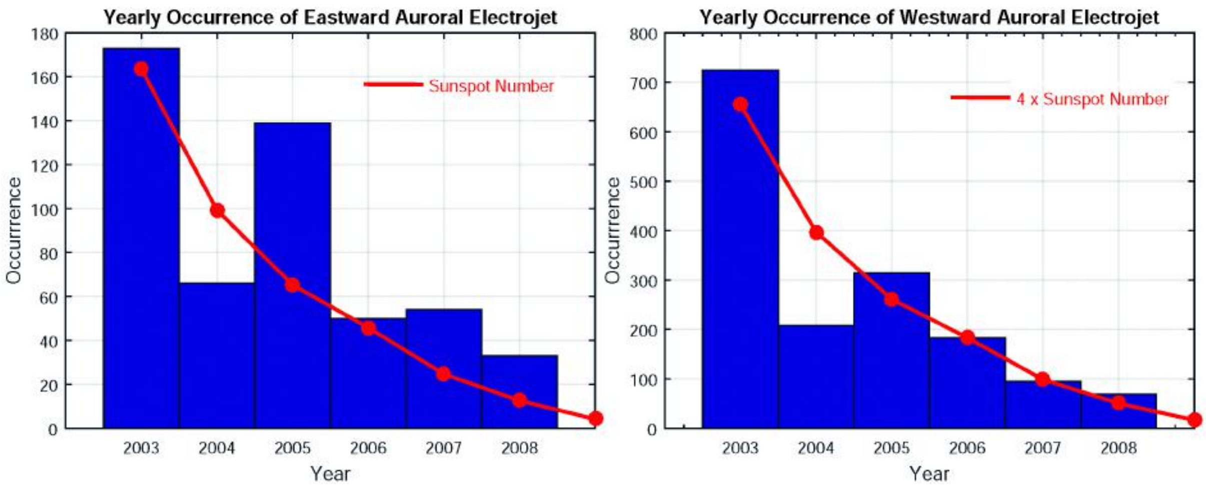


Fig. 12: Yearly occurrences of the eastward (left panel) and westward (right panel) auroral electojets over Maitri during years 2003-2008. The sunspot number is shown by the red curve

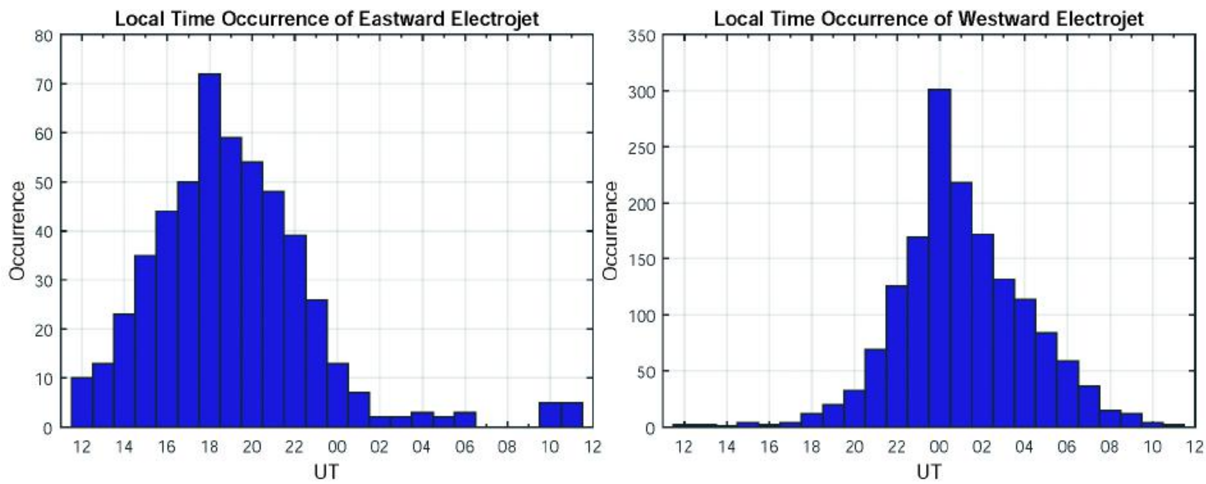


Fig. 13: Local time characteristics of the eastward and westward auroral electrojets at Maitri. The eastward electrojet maximizes around 1800 hrs (left panel) and westward electrojet peaks around the midnight (right panel)

electrojet the probability of occurrence is higher towards post-midnight than those occurring in the pre-midnight.

Substorm Dynamics at Very High Latitudes: Prolonged quiet geomagnetic conditions lead to the initiation of substorms at unusually high latitudes, which may go unnoticed at the standard auroral latitudes or in the AE indices. Bharati station (~75° magnetic latitude) is ideally located for observing such events. A typical event occurred on 02 March 2008 as shown in Fig. 14 when the substorm was localized at very high latitudes. The substorm signature was observed in both the hemispheres. Hornsund station (geographic location 77.0°N 15.6°E) forms a near conjugate pair with Bharati. A depression of about 500 nT was observed at Bharati and Hornsund in relation to the substorm event. No appreciable disturbance was observed at the standard auroral latitudes, nevertheless the substorm current wedge produced asymmetric magnetic field at the low latitudes (bottom panel of Fig. 14).

Analysis of about 100 days of magnetic data collected during years 2007-2010 in campaign mode at Bharati station suggested that the very high latitude substorms predominantly occur around midnight hours in a way similar to usual substorms (Fig. 15a). Majority of substorms were observed during the slow to moderate solar wind conditions (Fig. 15b) in contrast to the previous studies (Papitashvili *et al.*, 2002). Magnetic signatures of very high latitude substorms often observed were more pronounced in the winter hemisphere (at Hornsund station) than those observed in the summer hemisphere as shown in Fig. 15c. This could probably be due to differences in the ionospheric conductivities due to differential solar illumination.

Charged Particle Precipitation During Geomagnetic Disturbances

Precipitation of charged particles, especially electrons into the auroral latitudes during substorm activity and associated transient changes in high latitude ionosphere are also the important aspects of space weather research. Precipitation phenomena are even more significant as they link to Van allen radiation belts and Earth's atmosphere. Study of the precipitation process has recently got immense attention from the space and climate research point of view. Not only will it help us to understand dynamics of the radiation belts and related energetic electron flux evolution but also may provide a viable mechanism to explain the link between the atmospheric precipitation of solar energetic particles and polar climate Variability (S. Kirkwood *et al.*, 2015; Rodger *et al.*, 2013; Turunen *et al.*, 2009; Seppala *et al.*, 2007).

For many decades, Cosmic Noise Absorption (CNA) phenomena is possibly considered as the low

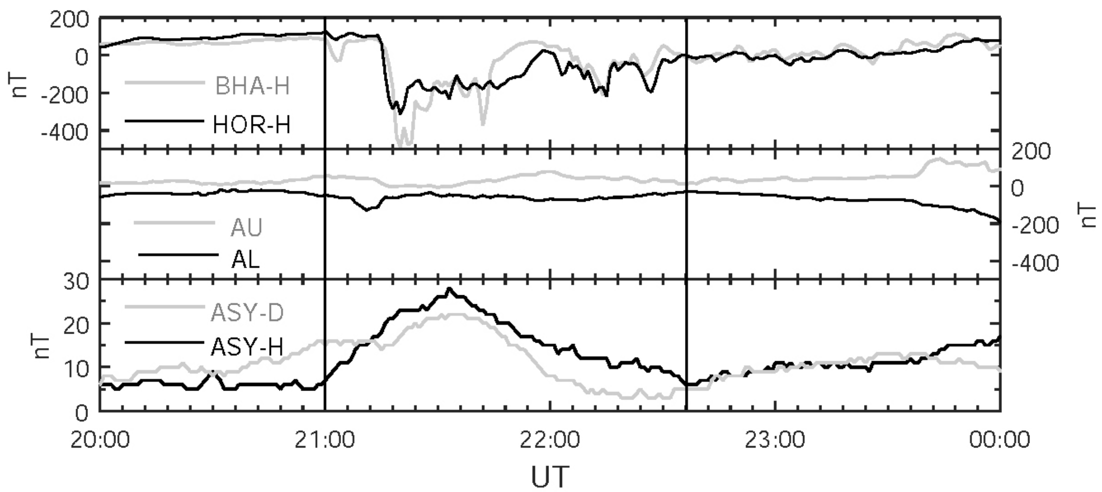


Fig. 14: Very high latitude substorm on 02 March 2008 leading to a depression of about 500 nT at Bharati and Hornsund station in the northern hemisphere (Fig.ure adapted from Singh *et al.*, 2012). No appreciable magnetic field variation was observed at the auroral latitude (middle panel), however noticeable asymmetry at the low latitude was evident (bottom panel)

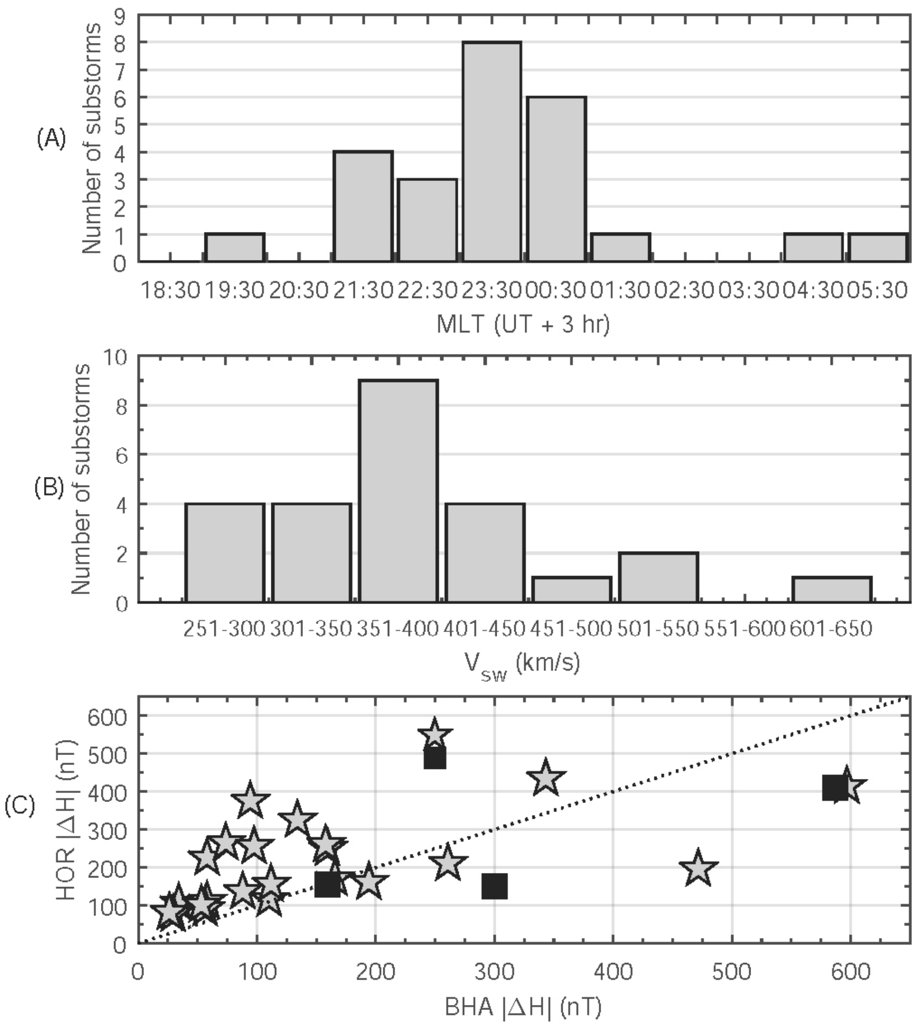


Fig. 15: Characteristics of very high latitude substorms observed over Bharati: (A) Occurrence in local time (B) dependence with speed of solar wind and (C) hemispherical asymmetry in the intensity of substorm. (Adapted from Singh *et al.*, 2012)

cost and handy proxy to decipher the energetic particle precipitation at high latitude Ionosphere, mostly in D-region (Little and Leinbach, 1959). The process of deposition is either in the open field line region at the day side of magnetosphere or in the closed field line region in the night side (Newell and Meng, 1992). However, the night side precipitations is mainly due to high energetic electrons in the energy range of (>20 Kev) inside the auroral region (Hargreaves, 1969). Softer electrons (<10 Kev) are responsible for auroral display and in some part for intensification of auroral electrojet in ionospheric E and F regions. Harder electrons such as 30 KeV to few MeV can penetrate deeper into the ionosphere and subsequently affect the composition of the middle atmosphere (Codrescu *et al*., 1997). Apparently, use of wide beam riometer for the particle precipitation could not provide the spatial information of the CNA pattern and later was replaced by advanced arrays of riometers forming different beams in 1990 and are called imaging Riometer (Detrick and Rosenberg, 1990).

First results from Imaging Riometer Installed at Maitri: An imaging Riometer (shown in Fig. 16) is installed at Indian Antarctic station Maitri (Geographic 70.75 degree S, 11.75 degree E; corrected geomagnetic 63.11 degree S, 53.59 degree E) in February 2010. Initial results from the imaging

Fig. 16: South-east view of the installed imaging Riometer at Maitri. It includes the antenna and the hut (yellow color hut) where the reciever unit is kept

Riometer data shows Sidereal shift of around 2 hours in the diurnal pattern which validate its data (Please refer Fig. 17). Also, the variation in the strength of cosmic noise signal with months is observed. This is apparently due to solar ionization of D-region ionosphere causing enhanced electron density where collision frequency is already high. The main objective of installing the imaging Riometer at Maitri is to study Magneotspheric-Ionospheric coupling during substorm processes. Hence, many typical examples of disturbed time CNA associated with storm-time and non-storm time substorm have been analyzed. Results reveal that CNA is more pronounced during storm-time substorm as compared to non-storm time substorm or, isolated. Further, initial results confirm that the level of CNA strongly depends upon the strengthening of convection electric field and the duration of south-ward turning of interplanetary magnetic field before the substorm onset (Behera *et al*., 2014).

Characteristics of Auroral Substorm Event During Substorm: Precipitations of energetic charged particles during the course of a magnetospheric substorm simultaneously affect upper and lower regions of the ionosphere. However, this depends on the energy of the charged particle flux in particular. Many previous studies (Frank-Kamenetesky and Troshichev, 2011; Kavanagh *et al*., 2002; Staunning *et al*., 1996) have reported that intense and short-lived CNA events associated with substorms are mostly observed in the midnight sector of the auroral oval. We have examined such type of CNA events as shown in Fig. 18 predominantly occurring during 0000-0600 UT (2300-0500 MLT) at Indian Antarctic station Maitri (corrected geomagnetic (CGM) coordinates 62.59^0 S, 53.59^0 E), which is located at the equator-ward edge of the auroral oval. Contrast to the earlier reports on the occurrences of auroral substorm absorption events, our study reveals that these kind of CNA's occur in the post midnight sector (~ 0200 UT). Identification of these events was done based on some strict criteria. Further, statistical study of such events show that absorption events related to isolated substorm and storm-time

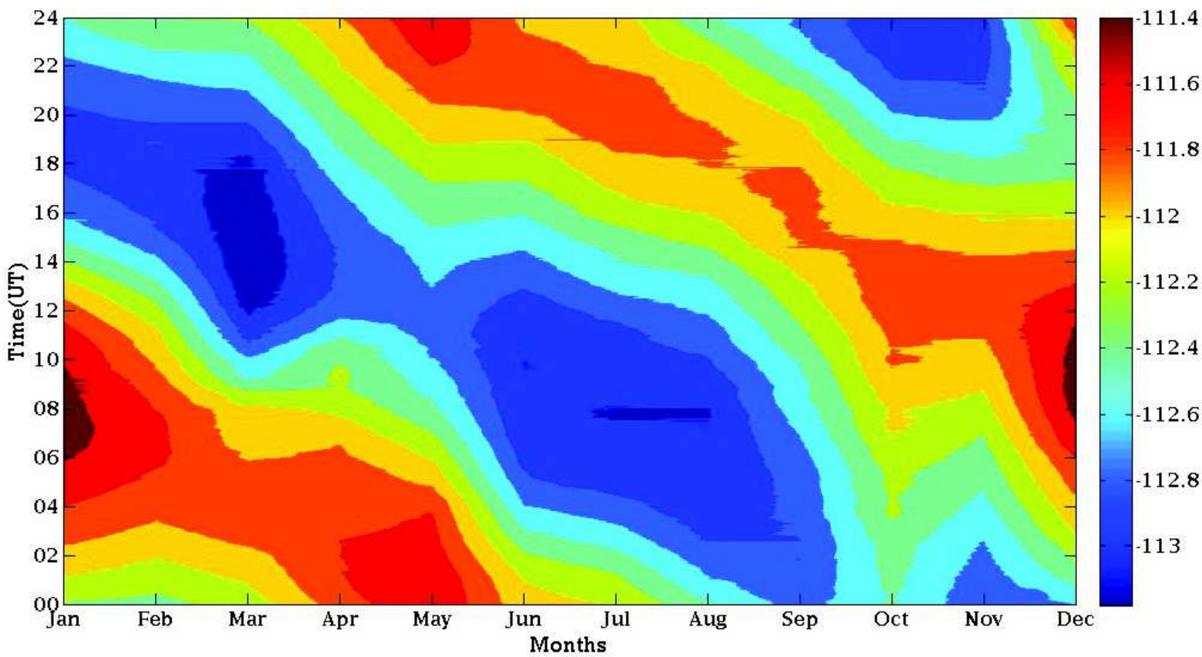


Fig. 17: Contour plot for Sidereal shift of maximum signal strength of Cosmic noise signal for consecutive months. For the month January to May, shift of ~ 10 hours (~ 10 UT to 00 UT) of maximum signal strength is seen. Similarly, for the month June to December, shift of ~14 hours (~24 UT to 10 UT) is seen

substorms exhibit distinct features in terms of their intensity and extent in latitude and longitude. Also, the statistical study suggests that the maximum intensity of CNA's depends on the interplanetary conditions as shown in Fig. 19, such as, the solar wind speed with correlation coefficient (r) of 0.5, southward component of IMF Bz (r = 0.75), and duskward component of IEF Ey (r = 0.85). The comparison showed that role of duskward component of IEF Ey is found to be more noteworthy than other interplanetary parameters.

Day Side Cosmic Noise Absorption Event Due to Eastward Propagating Kev Electron Flux: On 02 April 2011, a couple of cosmic noise absorptions (CNA) events were detected at Maitri, Antarctica (L=5, CGM 63.14^0 S, 53.69^0 E) confining to night and day times as shown in Fig. 20. One of the two events that occurred during night hours was caused due to auroral substorm onset. Our interest immediately went on to the later CNA event, which was recorded during daytime (1000-1300 MLT, At Maitri, MLT= UT-1). We refer to this CNA event as day side CNA (DCNA) event. Absence of westward electrojet during DCNA confirmed its dissimilarity from Auroral Substorm absorption events. Further, a comparison has been made between the DCNA event of 02 April 2011 with that of 14 July 2011, a day with substorm activity when Maitri is in day side but without DCNA event (Behera *et al.*, 2016). The comparison has been made in the light of interplanetary conditions, imaging Riometer data, ground magnetic signatures. Fig. 21 presents the GOES-13 satellite observation of electron fluxes with 40-475 KeV energy range showing clear enhancement during substorms on both the days (02 April, 2011 and 14 July, 2015) when Maitri was on the dayside. However, electron flux in the energy band of 150 and 275 KeV during DCNA day have increased by more than 2 folds compared to the day of 14, July, 2011. Also, the study showed that stronger prolonged eastward interplanetary electric field favored the occurrence of DCNA event. It is assumed that DCNA event is due to the gradient curvature drift of trapped non-relativistic electrons in the equatorial plane. Estimated energy of trapped electrons using azimuthal drift time for a set of ground stations within the auroral oval confirms the enhancement in electron fluxes in the same energy band as recorded by geostationary satellites GOES 13 and GOES 15. It is also noted that at Maitri, the peak to peak amplitude of these oscillation is 3-4 times larger during DCNA event

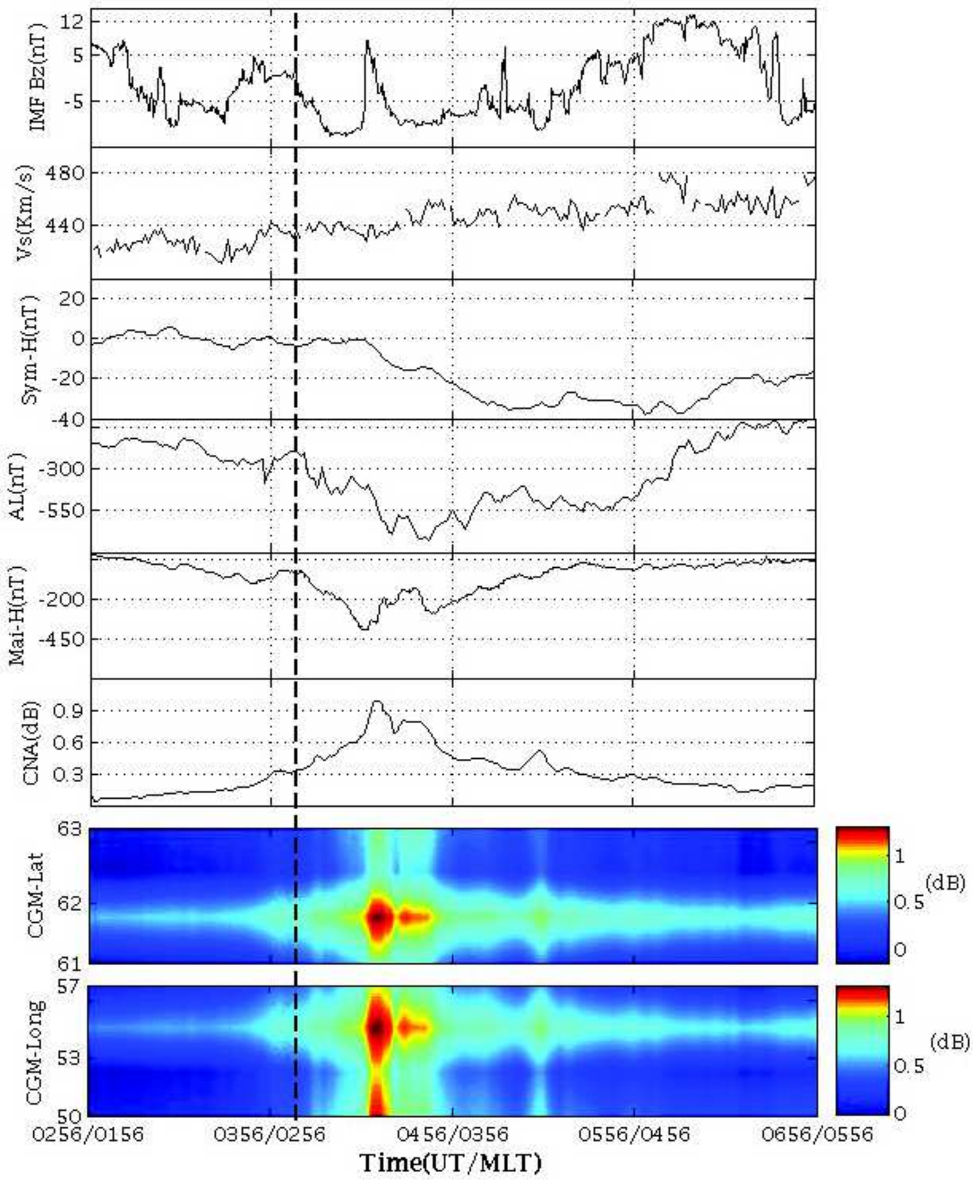


Fig. 18: CNA event at Maitri during an isolated substorm on 20 April 2011. IMF *Bz* and *Vsw* are shown in the top two panels. Next, SYM-H is shown (third panel). In response to the AL negative bay (fourth panel), westward electrojet and CNA were clearly observed (fifth and sixth panel). Last two panels show latitude and longitude extent of the absorption

(1100-1300 UT of 02 April, 2011) than those observed for non DCNA event (1000-1200 UT of 14 July, 2011) as depicted in Fig. 22. This indicates the presence of pronounced Pc5 oscillations at Maitri facilitates the growth of VLF chorus waves. Hence, the reason for precipitation of electrons is expected to be the loss cone scattering caused by wave-particle interaction triggered by ULF waves.

Studies on Global Electrical Circuit (GEC) from Maitri

Global thunderstorms in the tropical region are believed to maintain the global electric potential difference of ~300 kV between the ionosphere and the Earth's surface (Wilson, 1925). The fair weather electric field is directed from the ionosphere to the ground (Alderman and Williams, 1996). The atmospheric

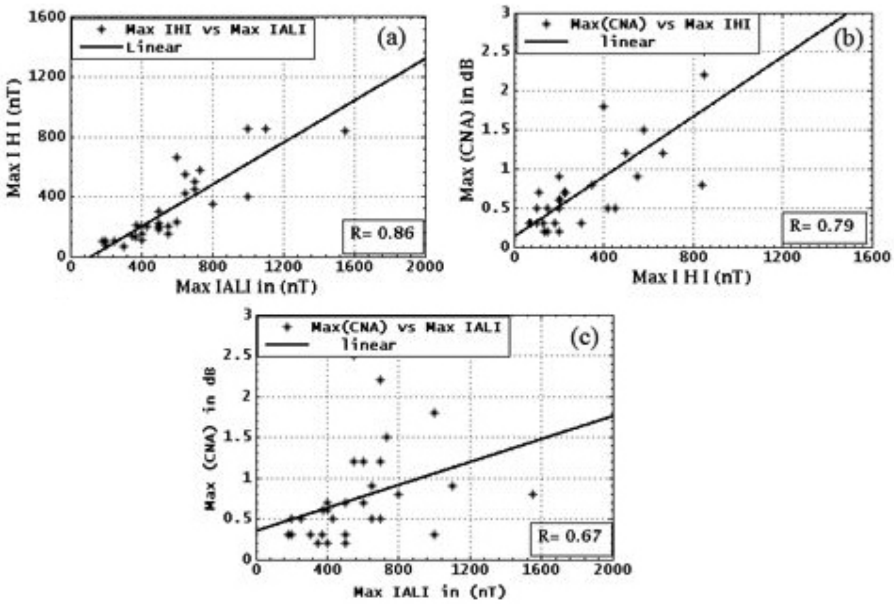


Fig. 19: Scatter plot of the maximum intensities of (a) *Vsw* vs CNA (correlation coefficient, *r* = 0.5), (b) southward IMF *Bz* vs CNA (*r* = 0.75) and (c) duskward IEF *Ey* vs CNA (*r* = 0.85) for selected events. CNA intensity at Maitri has strong dependence on IEF *Ey*

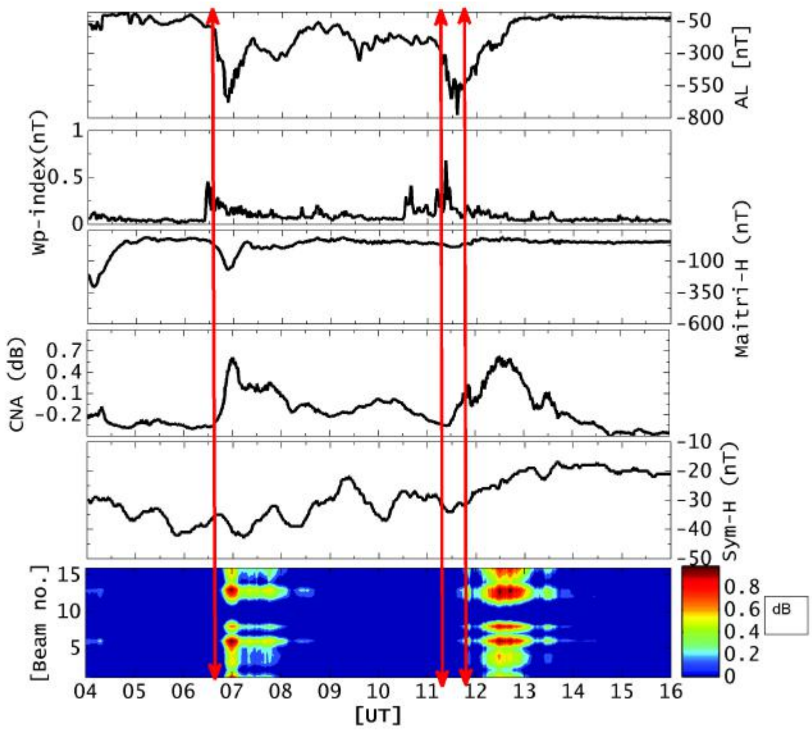


Fig. 20: Ground signatures of CNA events on 02 April 2011 at Maitri. The two upper most panels show AL-index and Wp-index, respectively. Third and fourth panels represent the variation in the horizontal component of geomagnetic field and wide beam CNA at Maitri , respectively. Sym-H has been plotted in the second bottom most panel and the last panel shows the keogram of the imaging Riometer. The extreme left solid line indicates the onset of auroral substorm absorption events where as middle solid line represent the onset of the second substorm and extreme right solid line shows the onset of CNA at Maitri. The delay between the onset of substorm and CNA onset at Maitri is a typical characteristics of DCNA

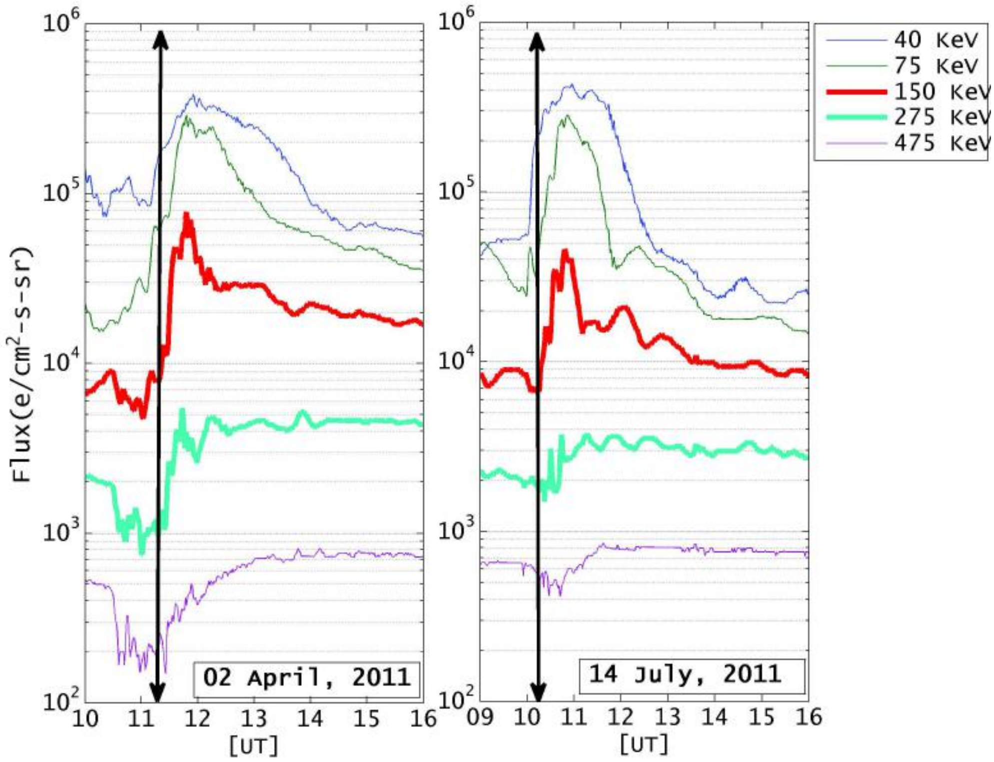


Fig. 21: 1 minutes resolution data of 40-475 KeV electron flux densities by GOES-13 for 02 April 2011 and 14 July, 2011. Solid bars both the panels indicate the onset of substorm for these days for example 1120 UT is the onset time of susbtom on 02 April, 2011 and 1010 UT is the onset time of substorm on 14 July, 2011

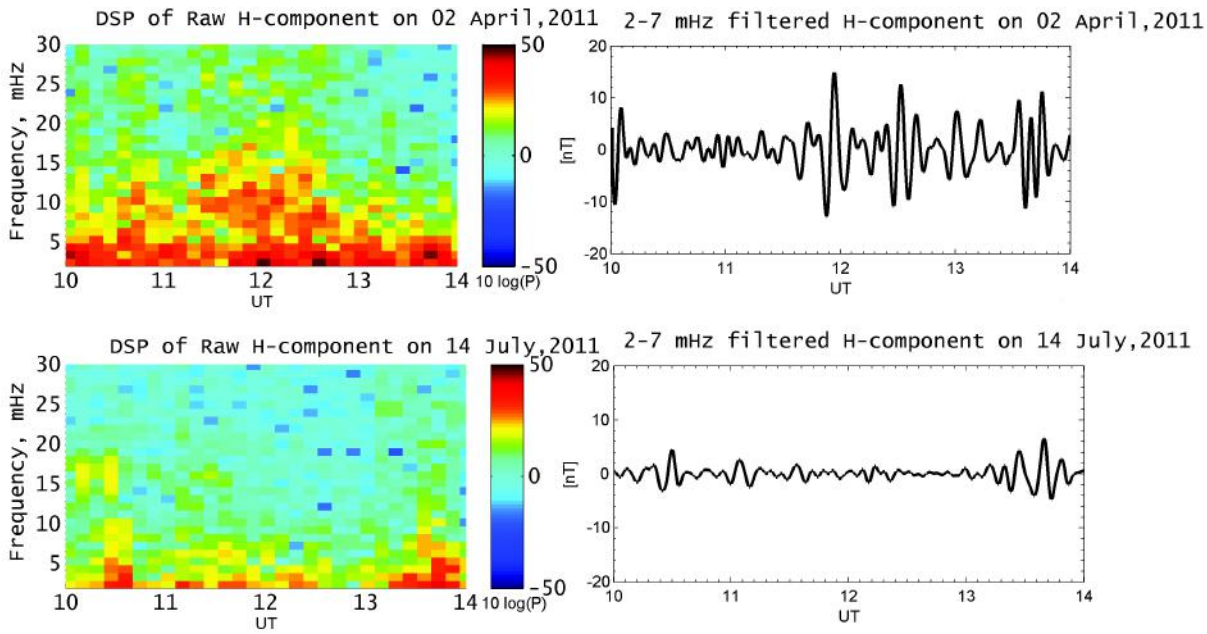


Fig. 22: (a) and (b) show the dynamics spectra of raw H-component at Maitri location on 02 April, 2011 and 14 July, 2011 respectively. (c) and (d) represent the filtered H component in Pc5 pulsation range (~1-7 mHz) on 02 April,2011 and 14 July, 2011 respectively

electrical parameters of concern to the global electric circuit are the vertical electric field, conductivity and total current density. GEC provides an excellent platform to explore interconnections and coupling of various regions of the atmosphere. It can also provide information on the solar-terrestrial weather relationship. The GEC is also useful in exploring one of the traditional scientific problems, namely, that of associating changes in surface weather with the solar output (Herman and Goldberg, 1978). The modern view of GEC incorporates solar wind-magnetosphere dynamo and ionospheric dynamo as sources other than global thunderstorm activity. In this context, studies on GEC provide us an opportunity to address environmental changes due to space weather activity, which include geomagnetic storms, magnetospheric substorms, solar proton events, etc.

For useful measurements of GEC parameters, the observing site is required to be free of atmospheric aerosols or anthropogenic activity and should be above the atmospheric boundary layer or where convective activity is negligible. Indian sites in Antarctica meet these requirements. Further, measurements from Antarctica also allow us to investigate meteorological effects, such as blizzards, wind turbulence, snowfall and clouds, on local electrical processes and enable us to understand the electrical climate of the Antarctic plateau (Cobb 1977; Kamra *et al*., 2009; Minamoto and Kadokura 2011; Siingh *et al*., 2013).

Initial studies have shown that during magnetically quiet and moderate conditions, the variations of measured atmospheric electrical parameters tend to be similar to the behaviour expected from the Carnegie curve, which was based on several cruise measurements carried out during 1920s (Panneerselvam *et al*., 2007). However, during geomagnetically disturbed conditions the diurnal pattern is often found to be different from the Carnegie curve and is modified by the ionospheric/ magnetospheric contributions. This study was carried out with the help of surface measurements of the atmospheric electrical parameters like Maxwell current, electric field and conductivity obtained from Maitri (117m MSL) during the austral summer from 2001 to 2004. Using long-term data sets, Jeeva *et al*. (2016) reported anomalous diurnal pattern of the atmospheric electric potential gradient and air-Earth current density on several days. This behaviour was ascribed to regional phenomena like katabatic winds bringing in space charge from the polar plateau.

Victor *et al*. (2015) discussed the variations of the atmospheric vertical electric field measured at Maitri and the polar station, Vostok (78.5ºS, 107ºE), during the geomagnetic disturbances on 25-26 January 2006. The departure of the field at Maitri, as observed in Fig. 23, during disturbed periods has been attributed to the magnetosphere-ionosphere coupled voltage generator. Digital Fluxgate Magnetometer data at Maitri were used to identify the presence of auroral electrojet (Fig. 24). Adopting the solar wind-magnetosphere coupling function (ε) as a measure for the energy and momentum transfer from the solar wind, Kumar *et al*. (2009) showed that the atmospheric electrical parameters are well correlated to the coupling function during geomagnetic disturbances (Fig 25). However, the correlation breaks down during minor storms and sub-storm events.

For the first time, studies have been carried out on the influence of a major geo-effective storm (Kp = 8) on 5 April 2010 on the atmospheric electrical parameters measured at three high-latitude stations in the Antarctic plateau (Victor *et al*., 2016). The objective was to identify the nature of the dawn-to-dusk convection cell and its impact on the electrical parameters monitored on the ground. Three consecutive substorms were identified from the

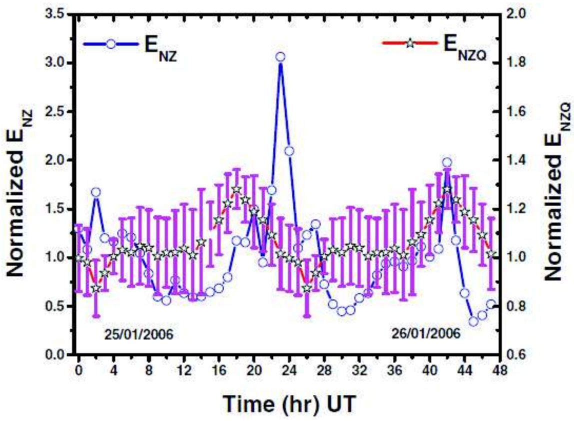


Fig. 23: Comparison of observed atmospheric electric filed (ENZ) on 25-26 January 2006 and E_{NZQ} at Maitri, Antarctica. Right side axis represents the normalized value for reference curve. Left side axis represents the normalized value of electric field at Maitri

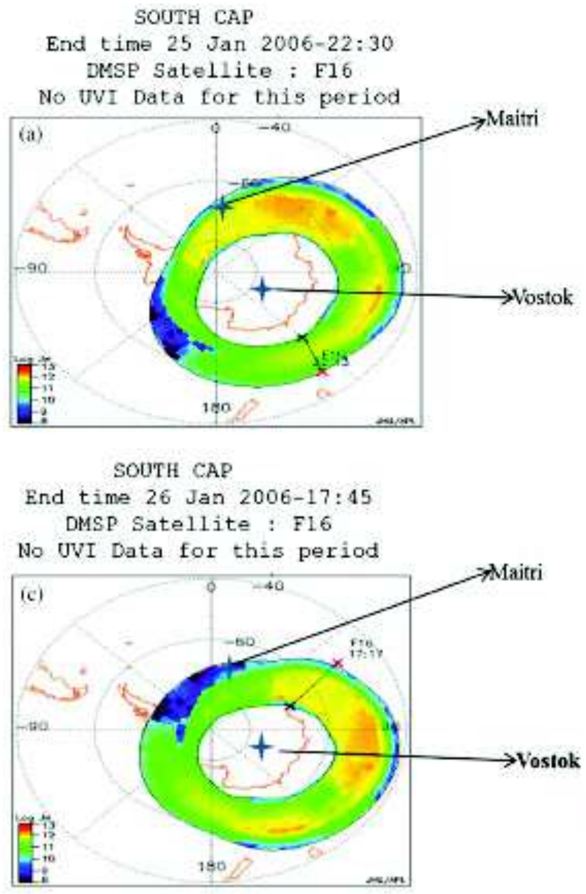


Fig. 24: The relative position of Maitri and Vostok compared to the auroral oval on 25–26 January 2006. (a) Auroral oval position over south polar cap at 22:30 UT on 25 January 2006; (b) at 00:00 UT on 26 January 2006; (c) at 17:45 UT on 26 January 2006; and (d) auroral oval position over south polar cap at 20:30 UT on 26 January 2006

magnetic records at Maitri. It was inferred that the variation in the amplitude of the potential gradient (PG) depends on the magnetic latitude during the substorm onset. During the substorm expansion phase, when the convection cell is overhead, PG is significantly enhanced due to the downward mapping of the ionospheric horizontal electric field. The deviation of PG with respect to the typical diurnal reference curves clearly indicates that the spatio-temporal variations of the ionospheric convective electric field significantly alter the atmospheric electric field measured over the three high latitude stations as shown in Fig. 26.

Schumann resonances (SRs) are the AC components of GEC and are excited by the lightning activity within the Earth–ionosphere waveguide. The study reveals a strong UT variation of amplitude in seasonal as well as yearly timescales. The diurnal trend in the amplitude is retained irrespective of seasons, whereas significant differences are noticed in the frequency behavior between the summer and winter seasons, especially in the EW component. The observed diurnal variation is explained in terms of the dominant thunderstorm activity centered over the three convectively active regions; Asia/Maritime Continent (Indonesia), South America and Africa. The diurnal variation in frequency depends not only on the location of the thunderstorm region with respect to the observer, but also on the ionospheric day/night conditions and the Earth-ionosphere cavity thickness (Manu *et al*. 2015).

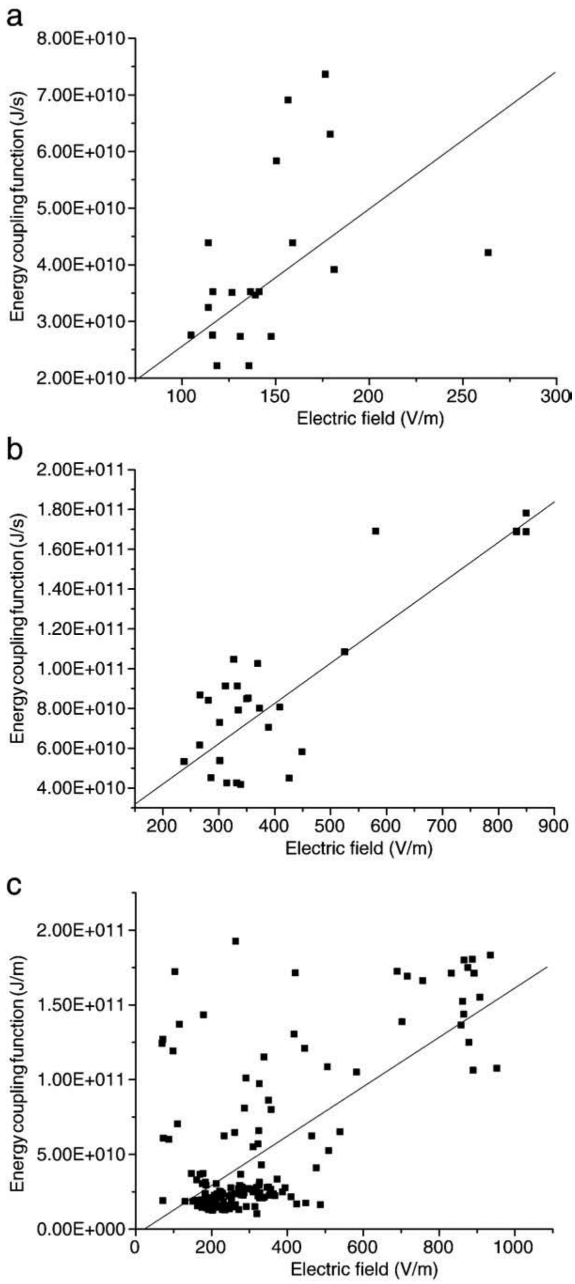


Fig. 25: (a, b, c) Electric field plotted against energy coupling function for magnetically disturbed days

GPS Measurements for Crustal Deformation, Mass Balance and Ice Dynamics of Nivlisen Ice Shelf and Tropospheric Studies

The satellite based navigation and surveying technique Global Positioning System (GPS) is a widely used tool to acquire measurements for Earth sciences as well as Atmospheric sciences. As a consequence of earthquake and plate tectonics, this space geodetic technique has a major impact on the study of problems of regional and local tectonics by making accurate measurements of the positions of point marks attached to earth. The aim of these types of observations is to determine the changes in the position of points on Earth's surface, determining the strain accumulation in the region, caused by seismic activities in the Earth's crust. Since the Antarctic Plate consists of divergent plate boundaries, broken by numerous large structures and Ice mass, this precise geodetic measurement can shed light on the deformation occurring in Antarctica.

GPS provides an opportunity to investigate many important dynamic processes in the troposphere. The tropospheric error is the effect of the neutral atmosphere on GPS signals. This error contains a dry and wet component. Assuming that the Earth's atmosphere is in hydrostatic equilibrium, the dry component only depends on the atmospheric pressure at the surface. For geodetics, the tropospheric effect is a disturbance that has to be removed from the measurements. But for meteorologists, this effect is an interesting signal that can give relevant information concerning the small-scale and short-term variations in the water vapor content (Braun *et al*., 2001).

Global positioning system (GPS) campaigns were conducted during two austral summer seasons to obtain insight into the velocity and strain-rate

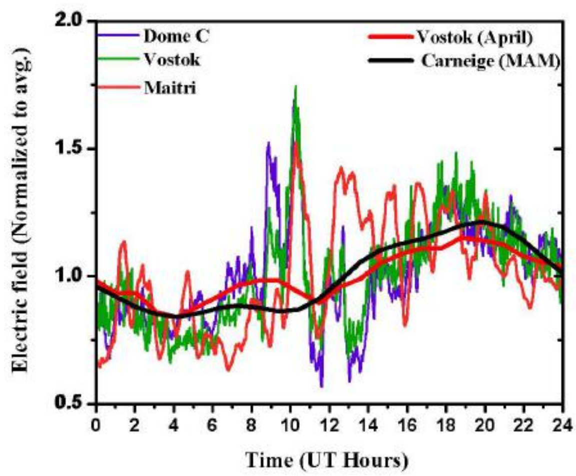


Fig. 26: Diurnal variation of normalized potential gradient for three highlatitude stations on 5 April 2010, intervals II and III are shaded. Averaged atmospheric electric field variation on April at Vostok and MAM period from Carnegie observation over plotted

distribution on Schirmacher Glacier, central Dronning Maud Land, East Antarctica (Fig. 27). GPS data collected at 21 sites was analyzed to estimate the site coordinates, baselines and velocities. The short term precession of the base station, MAIT, was estimated from the daily coordinates repeatability solutions. All GPS points on the glacier were constrained with respect to MAIT and nearby International GPS Service stations. Horizontal velocities of the glacier sites were estimated to lie between 1.89±0.01 ma^{-1} and 10.88 ±0.01 ma^{-1} to the north-northeast, with an average velocity of 6.21±0.01 ma^{-1}. The principal strain rates provide a quantitative measurement of extension rates, which range from (0.04±0.02) x 10^{-3} to (0.96±0.16) x 10^{-3} a^{-1}. The velocity and strain rate distributions across the GPS network in Schirmacher Glacier were spatially correlated with topography, subsurface undulations, fracture zones/crevasses and the partial blockage of the flow by nunataks and the Schirmacher Oasis (Sunil *et al.*, 2007).

Mass Balance and Ice Dynamics of Nivlisen ice Shelf in Antarctica: GPS were operated at equally distributed four sites over Nivlisen ice shelf. GPS data was collected and supplemented by GPR measurements (from other sources/institutes). The data was used to study the ice thickness distribution, velocity and mass balance of the ice shelf.

Using Global Positioning System (GPS) receiver, 19 days of continuous GPS data were collected from January 23 to February 10, during austral summer of 2005, in the frontal zone of Nivlisen Ice Shelf (NIS) of central Dronning Maud Land (cDML), East Antarctica. GPS data were analyzed to estimate the diurnal and semi-diurnal variations (Fig. 28). We

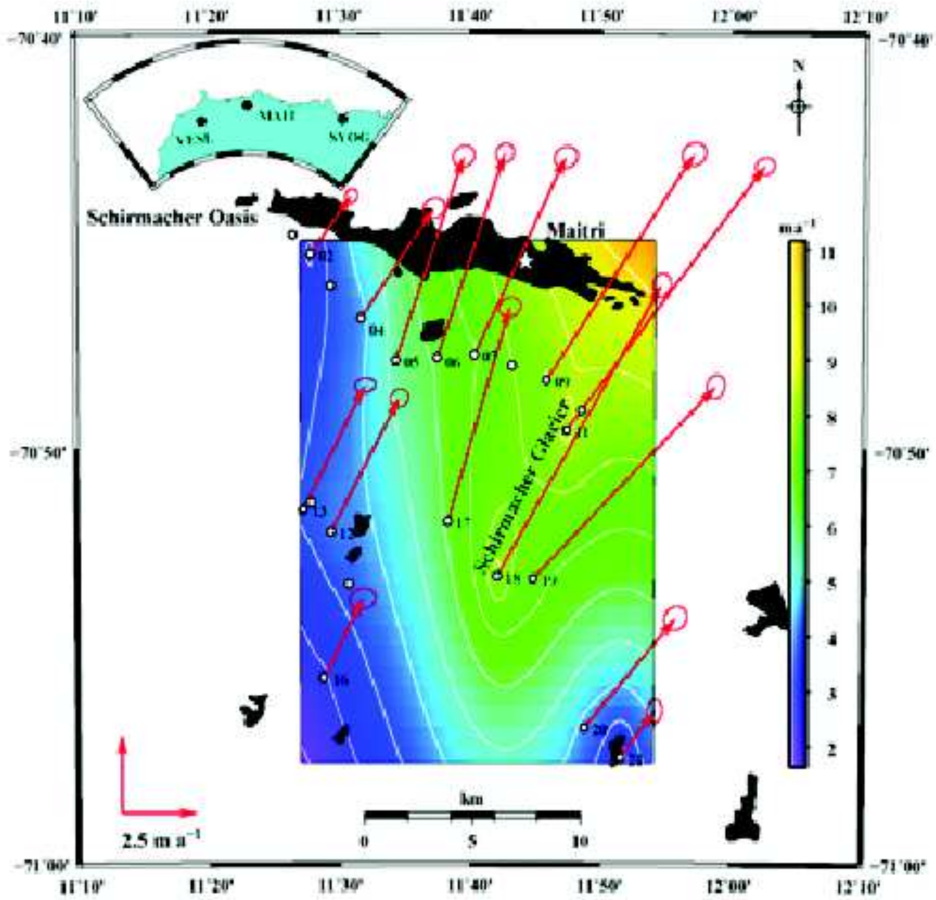


Fig. 27: Horizontal velocity vectors (with 95% confidence ellipses) for the GPS network on Schirmacher Glacier, superimposed on a shaded relief velocity-distribution map with 1m contour interval obtained from the GPS velocity field

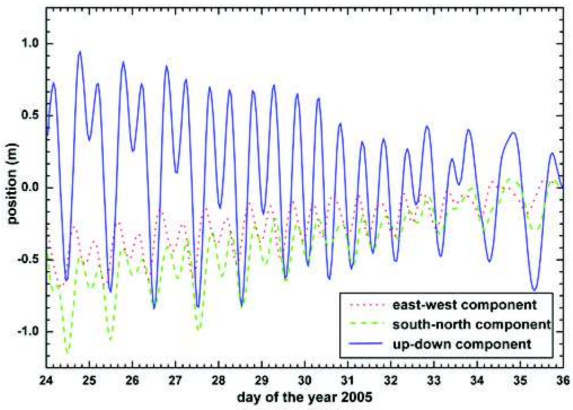


Fig. 28: Low-pass filtered position time co-ordinates of NIS GPS site at NIS

constrained the GPS sites at NIS with the base station MAITRI at Schirmacher Oasis and nearby International GNSS Service (IGS) stations. It is found that, the ice shelf motion in both horizontal and vertical were caused by the combination of ocean tidal effect, wind stress and ocean currents. The estimated horizontal velocity at NIS GPS site was 0.72 m/day towards north-northeast with an azimuth of 20.27°. Major constituents of the oceanic tide have been delineated from the hourly time series data by FFT analysis. The amplitudes of the diurnal and semi-diurnal estimated were ~1.25 m and 0.5 m, respectively. The results indicate not only the expected vertical tidal displacement but also a significant variation in the horizontal velocity of NIS. A phase shift with maximum forward velocity occurred about 3-4 hours after the maximum tidal height, suggests the additional role of ocean currents as one of the driving forces for the ice shelf movement. Further, this type of precise observations of diurnal and semi-diurnal tidal constituents can be assimilated in the models (Sunil *et al*., 2008).

Magnetic Anomaly Map of Bharati Promontory

A magnetic survey of Bharati promontory was carried out to compile a magnetic anomaly map of the area (Reddy and Dhar, 2007). It is observed that the high magnetic field anomaly regions are concentrated over some pockets which are located on high ridges. The causative source of the anomaly seems to be at very shallow depth as horizontal gradient of about 1000nT per 50 m were observed at some locations. The most likely candidate for the magnetic anomaly can be the magnetite bearing gneisses/amphibolitic gneisses which are present as NE-SW trending bands in the region. There are evidences of oxidation of iron rich material as seen in the form of limonitic surface exposures.

Environmental Magnetism

The Antarctic climatic and environmental variability can be studied by harnessing mineral magnetic techniques. Environmental magnetic measurements provide a means to accurately assess environmental variability at millennial to decadal timescales and to trace out the provenance (sediment source linkage) of the sediments deposited within and around the Antarctic region. The distribution of sediments within and around Antarctica is controlled by a tectonically active regime. This region has a prevalence of icebergs, glacial outwash and redistribution of bottom currents, transport and vertical rain-wash of biogenic and eolian material. Magnetic properties provide the potential for reconstructing ice sheet fluctuations both at millennial (~ short) and orbital (~ long) timescales (Loulergue *et al*., 2008).

Mineral magnetic study was carried out on sediment cores collected from two East Antarctica lakes such as Priyadarsini Lake (L49) and Schirmacher Oasis Lake (L6). Continuous, high-resolution measurements of rock magnetic parameters were measured at IIG Environmental Magnetism Laboratory to characterize the magnetic mineralogy and grain size, which are used to reconstruct depositional paleoenvironments and paleoclimate in the region. The magnetic analysis provided the means in terms of environmental magnetic techniques for core-correlation between Antarctica lake sites. Magnetic susceptibility and remnant magnetization measurements were done by using MFK1-FA Kappabridge and JR6 Spinner Magnetometer respectively. Frequency dependent susceptibility showed the presence of superparamagnetic (SP) grains in both the cores pointing at periods of lower glacial activity. Magneto mineralogical S-Ratio values showed the presence of Hematite in the upper part and Magnetite in the lower part of the cores. The influx of these magnetic minerals to the lakes is largely attributed to change in source of sedimentation derived from local glacial activities in and around these lake environments as well as sources remote from Antarctica continent. This environmental magnetic study has therefore proved to be potential for development of high resolution magnetic proxy data to reconstruct palaeoclimate changes during the past 20,000 years, beginning from Last Glacial Maximum from the least studied area like Antarctica (Ruddiman *et al*., 1976; Pant *et al*., 2005).

Conclusion

Indian Institute of Geomagnetism (IIG) is continuously contributing to polar research in India right from the launching of India's first scientific expedition to Antarctica. The role of IIG in the research of geomagnetic and allied field at Antarctica is significant. Contributions of field staff to be noted such as training, initiative, commissioning of several experiments and in data acquisition. The major findings such as rapid decline of total Magnetic field as observed at and near Maitri, SQ variations with season along with the experiments such as triangulation magnetometer study, conjugate geomagnetic observations etc., are significant. Researchers of IIG have significantly contributed to the substorm research with the help of magnetic data from Indian Antarctic stations viz. Maitri and Bharati. Dynamics of susbtorms as observed from Maitri and Bharati, morphological study of auroral electojet and study of susbtorms which lie poleward of the standard auroral oval are some of the important contributions to substorm research. The particle precipitation dynamics during geomagnetic activities resulting in auroral activity, can affect the HF communication and result in cosmic noise absorption to a greater extent. Data obtained from highly sophisticated Imaging Riometer operating in tandem with magnetometer along with supporting satellite data can throw light on the mechanism of wave-particle interaction responsible for particle acceleration and precipitation in the inner magnetosphere. The study of Global Electric Circuit (GEC) has been significantly strengthening our understanding of near Earth electrical environment at Antarctica and has been helpful in establishing a link between the surface electrical environment and space weather events. Furthermore, long data sets of AC part of the GEC obtained from inductioncoil magnetomaters operating at both the Antarctic stations can provide an estimate of global temperature and hence will be helpful in global climate study. Global Positioing System (GPS) is used as geodetic technique which has a major impact on the study of problems of regional and local tectonics by making accurate measurements

Global positioning system (GPS) campaigns conducted to obtain insight into the velocity and strain-rate distribution on Schirmacher Glacier, central Dronning Maud Land, East Antarctica from 21 sites indicated the horizontal velocities of the glacier sites to lie between 1.89±0.01 ma^{-1} and 10.88 ±0.01 ma^{-1} to the north-northeast, with an average velocity of 6.21±0.01 ma^{-1}. The principal strain rates provide a quantitative measurement of extension rates, which range from (0.04±0.02) x 10^{-3} to (0.96±0.16) x 10^{-3} a^{-1}. Such studies have been conducted for the first time in this region.

The GPS data collected from the frontal zone of Nivlisen Ice Shelf (NIS) of central Dronning Maud Land (cDML), East Antarctica to estimate the diurnal and semi-diurnal variations revealed that the ice shelf motion in both horizontal and vertical were caused by the combination of ocean tidal effects, wind stress and ocean currents. The results suggest the additional role of ocean currents as one of the driving forces for the ice shelf movement. Further, this type of precise observations of diurnal and semi-diurnal tidal constituents can be assimilated in the future models.

Mineral magnetic studies carried out on sediment cores collected from two East Antarctica lakes such as Priyadarsini Lake (L49) and Schirmacher Oasis Lake (L6) provided the means in terms of environmental magnetic techniques for core-correlation. The study has therefore proved to be potential for development of high resolution magnetic proxy data to reconstruct palaeoclimate changes during the past 20,000 years, beginning from Last Glacial Maximum from the least studied area like Antarctica. This part of studies are in pipeline and will be undertaken in near future.

Acknowledgments

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References

Adlerman E J and Williams E R (1996) Seasonal variation of the global electrical circuit *Journal of Geophysical Research: Atmospheres* **101** 29679-29688

Arun T, Patil A G, Dhar A and Rajaram G (2000) Rapid decrease in total magnetic field intensity at Indian Antarctic station Maitri in *J Indian Geophys Union* **4** 119-128

Banola S, Dhar A and Rajaram G (1997) Movement of Indian Antarctic station Maitri into Auroral Oval during Geomagnetic activity *Technical Report of Thirteenth Indian Expedition to Antarctica, Technical Publication* No. 11, Dept. of Ocean Development, New Delhi, pp. 91-105

Behera J K, Sinha A K, Singh A K, Geeta Vichare, Dhar A, Labde S and Jeeva K (2015) Substorm related CNA near equatorward boundary of the auroral oval in relation to interplanetary conditions in *Adv Space Res* **56** 28-37, DOI: 10.1016/j.asr.2015.03.036

Behera, J K, Sinha A K, Vichare G, Kozyreva O, Rawat R and Dhar A (2016) Dayside cosmic noise absorption at the equatorward boundary of auroral oval as observed from Maitri, Antarctica (L=5; CGM 62.45°S, 55.45°E), *J Geophys Res Space Physics* **121** 3198-3211 doi: 10.1002/2016JA022418

Behera, K Jayanta, Sinha A K, Singh A K, Rawat R, Vichare G, Dhar A, Pathan B M, Nair K U, Selvaraj C and Elango P (2014) First results from imaging riometer installed at Indian Antarctic station Maitri *J Earth Syst Sci* **123** 593-602

Bormann P, Schafer U, Kopsch C and Wagner S (1995) *Geophysical investigations*, *In:* The Schirmacher Oasis, Queen Maud land, East Antarctica and its surroundings, Gautha P. Bormann and D. Fritzsche (eds), Germany, Justus Perthes, 38-57

Braun J, Rocken C and Ware R (2001) Validation of line-of-sight water vapor measurements with GPS *Radio Science* **36** 459-472

Browne S, Hargreaves J K and Honary B (1995) An imaging riometer for ionospheric studies *Electronics & communication engineering journal* **7**(5) 209-217

Cobb W E (1977) *Electrical Process in Atmospheres* (eds) Dolezalek H and Reiter R (Darmstadt: Steinkopff) 161-167

Codrescu M, Fuller-Rowell T, Roble R and Evans D (1997) Medium energy particle precipitation influences on the mesosphere and lower thermosphere in *J Geophys Res* **102** 977-19,987

Codrescu M V, Fuller-Rowell T J, Roble R G and Evans D S (1997) Medium energy particle precipitation influences on the mesosphere and lower thermosphere *J Geophys Res* **102** 977-19 987

Davis T and M Sugiura (1996) Auroral electrojet activity index AE and its universal time *variations* in *J Geophys Res* **71** 785-801

Detrick D L and Rosenburg T J (1990) A Phased-Array Radio wave Imager for Studies of Cosmic Noise Absorption *Radio Sci* **25** 325-338

Dhar A, Kalra R, Jeeva K, Unnikrishnan K, Daga D M and Rajaram G (1993) *Changes in position and intensity of auroral electrojet inferred from conjugate area studies* Presented at INDO-RUSSIAN Symposium on 'Nature and Variations of the Geomagnetic Field' held at New Delhi

Dhar A, Patil A, Sankaran S and Rajaram G (1999) Three-station Magnetometer experiment at Antarctica during Jan-1996 to determine the velocity of disturbed-Time overhead Auroral current system (*In Scientific Report of Fifteenth Indian Expedition to Antarctica, Technical Publication No. 13, Dept. of Ocean Development, New Delhi*, pp. 1-20)

Frank-Kamentsky A and Troshichev O (2011) A relationship between the auroral absorption and the magnetic activity in the polar cap *Journal of Atmospheric and Solar-Terrestrial Physics* **77** 40-45

Glatzmaier G A and Roberts P H (1995) A three-dimensional self-consistent computer simulation of a geomagnetic field reversal *Nature* **377** 203-209

Gubbins D (1988) Thermal core mantle interactions and time averaged paleomagnetic field *Journal of Geophysical Research: Solid Earth* **93** (1988) 3413-3420

Hargreaves J K (1969) Auroral Absorption of HF Radio Waves in the Ionosphere: (1969) A Review of Results from the First Decade of Riometry *Proceedings of the IEEE* **57** 1348-1373

Herman J R and Goldberg R A (1978) Initiation of non-tropical thunderstorms by solar activity *Journal of Atmospheric and Terrestrial Physics* **40** 121-134

Jeeva K, Gurubaran S, Williams E R, Kamra A K, Sinha A K, Guha A and Dhar A Anomalous diurnal variation of atmospheric potential gradient and air Earth current density observed at Maitri, Antarctica *Journal of Geophysical Research: Atmospheres* **121** 593-12, 611, doi: 10.1002/2016JD025043

Kalra R, Dhar A, Unnikrishnan K, Jeeva K, Daga D M and Rajaram G (1995) Changes in Auroral Electrojet currents

Inferred from Geomagnetic Field variations at Maitri and Northern Conjugate stations *Scientific & Technical Report of Eleventh Indian Expedition to Antarctica*, *Technical Publication* **9** Dept of Ocean Development, New Delhi, pp. 87-101

Kalra R, Hanchinal A N, Sridharan M and Rajaram G (1998) Three station Fluxgate Magnetometer experiment to determine auroral current velocities over Indian Antarctic stations. *Scientific Report of Fourteenth Indian Expedition to Antarctica*, *Technical Publication* **12** Dept. of Ocean Development, New Delhi, pp. 47-55

Kamide Y and Rostoker G (2004) What is the physical meaning of AE index? *EOS Trans AGU* **85** 188-192

Kamide Y and Akasofu S-I (1983) Notes on the auroral electrojet indices in *Rev Geophys* **21** 1647-1656

Kamide Y and Kokubun S (1996) Two component auroral electrojet: Importance for substorm studies *Journal of Geophysical Research: Space Physics* **101** 13027-13046

Kamra A K, Siingh D and Pant V (2009) Scavenging of atmospheric ions and aerosols by drifting snow in Antarctica *Atmospheric Research* **91** 215-218

Kavanagh A J, Honary F, McCrea I W, Donovan E, Woodfield E E, Manninen J and Anderson P C (2002) Substorm related changes in precipitation in the dayside auroral zone – a multi instrument case study *Ann Geophys* **20** 1321-1334

Kellerman A C and Makarevich R A (2011) The response of auroral absorption to substorm onset: Superposed epoch and propagation analyses *Journal of Geophysical Research: Space Physics* **116**

Kirkwood S, Osepian A, Belova E, Urban J, Pérot K and Sinha K (2015) Ionization and NO production in the polar mesosphere during high-speed solar wind streams: model validation and comparison with NO enhancements observed by Odin-SMR. In *Annales Geophysicae* (Vol. 33, No. 5, pp. 561-572)

Kumar C A, Panneerselvam C, Nair K U, Jeyakumar H J, Selvaraj C, Gurubaran S and Venugopal C (2009) Apposite of atmospheric electric parameters with the energy coupling function (å) during geomagnetic storms at high latitude *Atmospheric Research* **91** 201-205

Little C G and Leinbach H (1959) The riometer-a device for the continuous measurement of ionospheric absorption *Proceedings of the IRE* **47** 315-320

Loulergue L, Schilt A, Spahni R, Masson-Delmotte V, Blunier T, Lemieux B and Chappellaz J (2008) Orbital and millennial-scale features of atmospheric CH4 over the past 800,000 years *Nature* **453** 383-386

Manu S, Rawat R, Sinha A K, Gurubaran S and Jeeva K (2015) Schumann resonances observed at Maitri, Antarctica: diurnal variation and its interpretation in terms of global thunderstorm activity *Current Science* **109** 784

McPherron R L, Russell C T, Kivelson M G and Coleman P (1973) Substorms in space: the correlation between ground and satellite observations of the magnetic field in *Radio Sci* **8** 1059-1076

Minamoto Y and Kadokura A (2011) Extracting fair-weather data from atmospheric electric-field observations at Syowa Station, Antarctica *Polar Science* **5** 313-318

Murphy K R, Mann I R, Rae I J, Walsh A P and Frey H U (2014) Inner magnetospheric onset preceding reconnection and tail dynamics during substorms: Can substorms initiate in two different regions? *Journal of Geophysical Research: Space Physics* **119** 9684-9701

Newell P T and Gjerloev J W (2011) Evaluation of SuperMAG auroral electrojet indices as indicators of substorms and auroral power *J Geophys Res* **116** A12211 doi:10.1029/2011JA016779

Newell P T, Sotirelis T and Wing S (2010) Seasonal variations in diffuse, monoenergetic, and broadband aurora in *J Geophys Res* **115** A03216, http://dx.doi.org/10.1029/2009JA014805

Newell P T and Meng C (1992) Mapping the day side ionosphere to the magnetosphere according to particle precipitation technique *Geophysical Research Letters* **19** Doi: 10.1029/92GL00404

Panneerselvam C, Kumar C P A, Dhar A, Nair K U, Selvaraj C, Gurubaran S and Pathan B M (2010) Instrumentation for the surface measurements of atmospheric electrical parameters at Maitri, Antarctica: First results *Earth, Planets and Space* **62** 545-549

Panneerselvam C, Selvaraj C, Jeeva K, Nair K U, Anilkumar C P and Gurubaran S (2007) Fairweather atmospheric electricity at Antarctica during local summer as observed from Indian station, Maitri *Journal of Earth System Science* **116** 179-186

Pant R K, Basavaiah N, Juyal N, Saini N K, Yadava M G, Appel E and Singhvi A K (2005) A 20 ka climate record from Central Himalayan loess deposits *Journal of Quaternary Science* **20** 485-492

Papitashvili V O, Clauer C R, Christiansen F, Kamide Y, Petrov V G, Rasmussen O, Watermann J F (2002) Near-conjugate magnetic substorms at very high latitudes observed by Greenland and Antarctic ground magnetometers and Ørsted satellite. In: R M Winglee (Ed.) *Proceedings of International Conference on Substorm-6* 110-114

Pathan B M, Dhar A, Asinker R L, Selvamurugan R and Hanchinal A N (2009) Declining magnetic field at Maitri, Antarctica in *Indian J Geosci* **63** 187-194

Rajaram G, Dhar A and Kumar A (2001) Response of Geomagnetic variations and 30MHz Riometer absorption, at Indian Antarctic Station Maitri, to conditions of "Zero" and "High" solar wind *Adv Space Res* **28** 1661-1667

Rajaram G, Arun T and Dhar A (2002) Diagnostics of Magnetosphere-Ionosphere coupling over Indian Antarctic Station Maitri, from Fluxgate Magnetometer and Riometer observations during the optical Auroral event of 4-5 March 1999 *Advances in Space Research* **30** 2195-2201

Rajaram G, Arun T, Dhar A and Patil A G (2002) Rapid decline in total magnetic field F at Antarctic Stations – its relationship to core – mantle features *Antarctic Science* **14** 61-68

Rangarajan G K and Dhar A (1988) A comparative study of Quiet day Variation of the Geomagnetic field at Dakshin Gangotri (India) and Novolazarevskaya (USSR) in Antarctica (1988) *Scientific Report on Fifth Indian Expedition to Antarctica* DOD publication No. **5**, pp. 353-361

Reddy C D and Dhar A (2008) Magnetic anomaly map for Bharati promontory, Larsemann Hills, East Antarctica *Current Science* **94** 25 March 2008

Rodger C J, Kavanagh A J, Clilverd M A and Marple S R (2013) Comparison between poes energetic electron precipitation observations and riometer absorptions Implications for determining true precipitation fluxes *Journal of Geophysical Research Space Physics* **118** 7810-7821

Rostoker G, Akasofu S-I, Foster J, Greenwald R, Kamide Y, Kawasaki K, Lui A, McPherron R L and Russell C T (1980) Magnetospheric substorms – definition and signatures in *J Geophys Res* **85** 1663-1668

Ruddiman W and McIntyre A (1976) Northeast Atlantic paleoclimatic changes over the past 600,000 years *Geological Society of America Memoirs* **145** 111-146

Seppälä A, Randall C E, Clilverd M A, Rozanov E and Rodger C J (2009) Geomagnetic activity and polar surface air temperature variability in *J Geophys Res* **114** A10312 doi: 10.1029/2008JA014029

Seppala A, Clilverd M A and Rodger C J (2007) Nox enhancements in the middle atmosphere during 2003 {2004 polar winter: Relative signi_cance of solar proton events and the aurora as a source *Journal of Geophysical Research: Atmospheres* **112**

Siingh D, Singh R P, Gopalakrishnan V, Selvaraj C and Panneerselvam C (2013) Fair-weather atmospheric electricity study at Maitri (Antarctica) *Earth, Planets and Space* **65** 1541-1553

Singh A K, Behera J K, Dhar A, Saini S, Panneerselvam C and Sinha A K (2016) Morphology of the auroral electrojets over Maitri station (magnetic latitude 63^{o}S) *Scientific Report of Antarctica XXVIII ISEA, Technical Report (submitted)*

Singh A K, Jayashree B, Sinha A K, Rawat R, Pathan B M and Dhar A (2011) Observations of near-conjugate high latitude substorms and their low latitude implications in *Current Science* **101** 1073-1078

Singh A K, Sinha A K, Rawat R, Jayashree B, Pathan B M and Dhar A (2012) A broad climatology of very high latitude substorms in *Adv Space Res* **50** 1512-1523 doi: 10.1016/j.asr.2012.07.034

Singh A K, Sinha A K, Saini S and Rawat R (2015) Auroral electrojets during severely disturbed geomagnetic condition on 24 August 2005 in *Adv Space Res* **55** 1349-1355

Stauning P (1996) Investigations of ionospheric radio wave absorption processes using imaging riometer techniques *J Atmosp Terr Phys* **58** 753-764

Sunil P S, Reddy C D, Ponraj M, Dhar A and Jayapaul D (2007) GPS determination of the velocity and strain-rate fields on Schirmacher Glacier, central Dronning Maud Land, Antarctica *Journal of Glaciology* **53** 558-564

Sunil P S and Reddy C D (2008) Tide-induced Nivlisen Ice Shelf Movement, East Antarctica, from GPS Observations (2008) *Proceedings, International Workshop on Snow, Ice, Glacier and Avalanches* **1** 122-129

Tanskanen E I (2009) A comprehensive high-throughput analysis of substorms observed by IMAGE magnetometer network: Years 1993–2003 examined in *J Geophys Res* **114** A05204 doi: 10.1029/2008JA013682

Tsurutani B T, Hajra R, Echer E and Gjerloev J W (2015) Extremely intense (SML $\geq$–2500 nT) substorms: isolated events that are externally triggered? in *Ann Geophys* **33** 519-524 doi: 10.5194/angeo-33-519-2015

Turunen E, Verronen P T, Seppala A, Rodger C J, Clilverd M A, Tamminen J, Enell C F and Ulich T (2009) Impact of different energies of precipitating particles on nox generation in the middle and upper atmosphere during geomagnetic storms *Journal of Atmospheric and Solar-Terrestrial Physics* **71** 1176-1189

Vichare G, Rawat R, Hanchinal A, Sinha A K, Dhar A and Pathan B M (2012) Seasonal evolution of S_q current system at sub-auroral latitude *Earth Planet Sp (2012)* **64** 1023. doi: 10.5047/eps.2012.04.007

Victor N J, Panneerselvam C and Kumar C P A (2015) Variation of surface electric field during geomagnetic disturbed period at Maitri, Antarctica *Journal of Earth System Science* **124** 1721-1733

Victor N J, Manu S, FrankKamenetsky A V, Panneerselvam C, Anil Kumar C P and Elango P (2016) Network of observations on the atmospheric electrical parameters during geomagnetic storm on 5 April 2010 *J Geophys Res Space Physics* **121** 2407-2417 doi: 10.1002/ 2015JA022080

Wilson C T R (1921) Investigations on lightning discharges and on the electric field of thunderstorms *Philosophical Transactions of the Royal Society of London. Series A, Containing Papers of a Mathematical or Physical Character* **221** 73-115.

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Review Article

Bacterial Biodiversity, Cold Adaptation and Biotechnological Importance of Bacteria Occurring in Antarctica

S SHIVAJI[1,2,*], G S N REDDY[1] and M K CHATTOPADHYAY[1]
[1]*CSIR-Centre for Cellular and Molecular Biology, Uppal Road, Hyderabad 500 007, India*
[2]*Prof. Brien Holden Eye Research Centre, L V Prasad Eye Institute. Banjara Hills, Hyderabad 500 034, India*

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Antarctica is the coldest, iciest, windiest and driest continent and defines the limits of temperature at which life forms can survive and divide. These cold loving microorganisms are known as psychrophiles and are present in all the unique habitats of Antarctica including permafrost and ice. Their distribution and abundance varies from habitat to habitat and several new genera and species have been discovered in the icy continent. They have several strategies by which they survive and divide at low temperature such as the ability to catalyze reactions and continue metabolism with cold-tolerant enzymes; ability to maintain optimum membrane fluidity at low temperature; occurrence of specific genes required for survival at low temperatures; presence of antifreeze–activity etc.. Enzymes from psychrophilic bacteria have been found to be useful for several purposes ranging from recombinant DNA technology to food processing. The ability of cold-tolerant organisms to degrade petroleum products and other environmental pollutants highlight them as potential candidates for bioremediation in extreme cold environments. The recently reported genome sequences of a number of novel cold-tolerant isolates are likely to provide some more insights into the mechanism of bacterial cryotolerance.

Keywords: Non-Cultivable Diversity; Cultivable Diversity; Novel Species; Cold Adaptation; Antarctica

Introduction

About 85% of the Earth's biosphere is permanently exposed to temperatures below 5ºC and these cold habitats span from the Arctic to the Antarctic, from high-mountains such as Himalayas to the deep ocean and also includes frozen soils (permafrost), glaciers and ice sheets, polar sea ice and snow (Deming and Eicken, 2007). A major fraction of this low temperature environment is represented by the deep sea which constitutes 71% of the Earth's area. Other cold environments include cold water lakes, cold soils (especially subsoils), cold deserts, and caves. All these permanently cold environments have been successfully colonized by a class of microorganisms known as psychrophiles (grow from subzero to 30ºC) (Morita, 1975; Helmke and Weyland, 2004; Laucks *et al.,* 2005). Among all the cold habitats, Antarctica is unique in that it is the coldest, driest, windiest and iciest (with ice covered at an average thickness of 1.9 Km) of all known habitats covering approximately 5.4 million square miles in area and is thus considered as one of the most extreme habitats of the world (Vincent, 1988; Claridge and Campbell, 1977; Campbell and Claridge, 2000; Smith *et al*., 1992). Despite the harsh climatic conditions, along with other life forms (such as mites, ticks, seals, penguins, mosses, lichens, bacteria, yeasts, algae etc) (http://www.globalclassroom.org/antarct6.html), psychrophilic bacteria dominate the continent and aid in nutrient recycling (Stokes and Redmond, 1966; Herbert and Bell, 1977; Tanner and Herbert, 1981; Delille and Legarde, 1974; Tanner, 1985; Voytek and Ward, 1995; Chessa *et al*., 2000; Kelly *et al*., 1978; Cavanagh *et al*., 1996; Denner *et al*., 2001; Cavicchioli and Thomas, 2000). Ekelof (1908 a and b) initiated studies on microbiology of the soil and air in Antarctica which was confirmed by Pirie (1904),

**Author for Correspondence: E-mail: shivas@ccmb.res.in; shivas@lvpei.org*

Gazert (1912), Tsiklinsky (1908) and McLean (1918 a and b). Later the emphasis was to enumerate and identify unique microorganisms from the continent of Antarctica (Boyd, 1962; Boyd and Boyd, 1962; Friedmann, 1980; Margni and Castrelos, 1963, 1965; Marshall and Ohye, 1966; Meyer *et al.*, 1962; Pfiser and Burkholder, 1965; Tsyganov, 1970). However with the advent of culture independent identification of microorganisms based on 16S rRNA gene metagenomics a greater diversity of microbes from various habitats of Antarctica was discovered. Browsing the NCBI (http://ncbi.nlm.nih.gov) database for 16S rRNA gene sequences indicated that about 6000 16S rRNA gene sequences of bacteria from Antarctica have been deposited in the database. Of these close to 210 sequences corresponded to the novel species so far described from Antarctica (Shivaji and Reddy, 2009; Chattopadhyay *et al.*, 2014; Reddy *et al.*, 2016).

Diversity of Antarctica as Studied by Non-cultivable Methods

Antarctic bacterial diversity has been studied by both cultivable and non-cultivable methods (using 16S rRNA gene sequence and certain other functional genes) from various habitats including soil, cyanobacterial mats, water, sediments, sub-glacial out flow, crypto-endolithic sand stones, anoxic meromictic sediments, sediment core, ephemeral streams, ice core, geothermal vents, ornithogenic soil, penguins, sponges and intestinal microbiota of Antarctic fish (for reviews see Reddy *et al.*, 2016; Shivaji and Reddy, 2009; Chattopadhyay *et al.*, 2014; Bottos *et al.*, 2014). The bacterial abundance from the above habitats of Antarctica ranged from 0.2×10^2 to 0.6×10^{12} cells/gram (Carpenter *et al.*, 2000; Priscu *et al.*, 1999; Karl *et al.*, 1999; Delille and Gleizon, 2003), 0.2×10^2 to 10^7 cells/ml (Takii *et al.*, 1986; Franzmann *et al.*, 1990; Lo Giudice *et al.*, 2012) and 8×10^6 to 2.4×10^7 cells/gram (Lanoil *et al.*, 2009; Stibal *et al.*, 2012) and 10^5 to 10^{10} cells/gm (Ramsay and Stannard, 1986; Aislabie *et al.*, 2009) for ice, water, sediment and soil, respectively. Antarctic soils are highly heterogeneous and the diversity varied with respect to soil type. For instance, Antarctic Peninsula soils were dominated by Proteobacteria (47.0%), where as in West Antarctic soils and Transantarctic mountain soils Actinobacteria and Bacteriodetes (42.0% and 31% repectively) (Bottos *et al.*, 2014) were dominant and in the Victoria Land soils Actinobacteria was dominant. Interestingly members of *Deinococcus-Thermus* are the third most dominating community (18.0%) in Transantarctic Mountain soils indicating that the bacterial communities across Antarctic soils vary significantly with geography, climate, soil physicochemical parameters and local biological influences. Further, unaffiliated clones associated with rare and unique taxa such as *Verrucomicrobia* and *Gemmatimonadetes* were also identified from Antarctic soils from Schirmacher Oasis (Shivaji *et al.*, 2004). In addition to above phylotypes Antarctic peninsula soils, west Antarctic soils and east Antarctic soils contain several unkown phylotypes (Shivaji *et al.*, 2004; Aislabie *et al.*, 2006; Yergeau *et al.*, 2007 a, b; Niederberger *et al.*, 2008; Aislabie *et al.*, 2009; Lee *et al.*, 2012; Tiao *et al.*, 2012; Bajerski and Wagner, 2013; Aislabie *et al.*, 2013).

Limited diversity studies on Antarctic sediments from Bratina island (Sjoling and Cowan, 2003), Ardley island (Li *et al.*, 2006), meromictic marine basin, Vestfold hills (Bowman *et al.*, 2000), Wright Glacier (Stibal *et al.*, 2012) revealed the dominance of phylotypes belonging to *Proteobacteria*, *Cytophaga–Flavobacterium–Bacteroides, Spirochaetaceae*, *Actinobacteria, Acidobacteria, Gemmatimonadetes, Firmicutes, Prochlorococcus, Cyanobacteria, Deltaproteobacteria* (specially the unique groups of *Desulfosarcina*, *Syntrophus* and *Geobacter*/*Pelobacter*/*Desulphuromonas* group), order Chlamydiales (Parachlamydiaceae), *Planctomycetes* and members of *Spirochaetales*. Carr *et al.* (2013) identified a total of fifty bacterial phyla from marine sediments beneath the Ross Ice Shelf and the predominant taxa reported were *Actinobacteria* (6.0%), *Bacteroidetes* (46.0), *Chloroflexi* (25.0%), *Firmicutes* (14.0%), and the subphyla Beta- (20.0%), Delta- (25.0%) and Gamma-*Proteobacteria* (8.0%). The Betaproteobacteria were represented by only two genera *Thiobacillus* and *Teptidiphilum* and there was unusually high proportion of *Chloroflexi* group. Bowman *et al.* (2000) demonstrated that anoxic marine sediments contained more than 200 distinct phylotypes with close to 31.0% belonging to the low G+C Gram-positives. Interestingly while studying the vertical distribution of bacterial phyla in fresh water sediment in which *Proteobacteria, Bacteroidetes, Actinobacteria and Firmicutes were dominant*. Shivaji *et al.* (2011)

identified a few clones belonging to *Caldiserica group, a* thermophilic candidate phylum from Antarctica.

Aquatic microbial diversity of Antarctica is limited as only 0.4% of the total ice area of Antarctica (12.3 9 106 km2) is seasonally ice free (Wilkins *et al*., 2013). Within this ice-free 50,850 Sq. Km area of Antarctica, the majority of bacteria belong to the phyla Proteobacteria representing 47.6% (*Alphaproteobacteria* [71.5%], *Betaproteobacteria* [18.8%], *Deltaproteobacteria* [2.0%] and *Gammaproteobacteria* [7.7%]) with dominating genera being *Rhodobacter* and *Sphingomonas* (Huang *et al*., (2013). Besides, *Bacteroidetes* (15.1%), *Actinobacteria* (14.8%), *Chloroflexi* (10.2%), *Acidobacteria* (6.7%), *Firmicutes* (3.6%), *Gemmatimonadetes* (1.3%) and *Verrucomicrobia* (0.2%) are minor components, while *Deinococcus-Thermus, Nitrospira, Planctomycetes,* and *Fusobacteria* were also present. The most common genera are *Sphingomonas, Caulobacter, Brevundimonas, Janthinobacterium, Duganella, Polaromonas, Variovorax, Rhodoferax, Flavobacterium, Pedobacter, Prevotella, Hymenobacter* and *Arcicella* (Wilkins *et al*., 2013). In general, shift in diversity was observed with depth of sediment wherein the predominance of *Bacteroidetes, Betaproteobacteria* and *Actinobacteria* in the surface are replaced by *Gammaproteobacteria* with depth (Archer *et al*., 2014). This is attributed to the tolerance to oxygen requirement of various members of the genera belonging to *Gammaproteobacteria*. The above observation was further supported by Kim *et al*., (2014) wherein deep waters contained a high proportion of unclassified *Bacteria* (10–20%) along with Proteobacteria. Interestingly, the surface water contained two major clades representing *Polaribacter* (20 to 64%) and uncultivated *Oceanospirillaceae* (7 to 34%) while *Pelagibacter* increased in abundance with depth (7 to 42%) (Kim *et al*., 2014). Response of bacterial community to hydrocarbon contamination also revealed a change in phylotypes profile. *Alphaproteobacteria, Gammaproteobacteria,* the *Cytophaga–Flavobacterium–Bacteroidetes* were major communities but genera *Psychrobacter, Arcobacter, Formosa algae, Polaribacter, Ulvibacter* and *Tenacibaculum* were detected only in hydrocarbon contaminated water and the abundance of *Sulfitobacter* group was high in sea water and decreased drastically by almost 9 folds in contaminated seawater (Prabagaran *et al*., 2007). The variation in marine and fresh water aquatic systems was evident in Atarctica. The fresh water ecosystems are dominated by groups such as *Flavobacterium, Pseudomonas* and *Polaromonas* (Michaud *et al*., 2012) while *Sulfitobacter, Thalassospira,* members of *Roseobacter, Gelidibacter, Polaribacter, Psychroflexus, Psychromonas* and *Pseudoalteromonas* were restricted to marine waters (Prabagaran *et al*., 2007; Guibert *et al*., 2012; Lo Giudice *et al*., 2012).

Sea ice, in general, is a dynamic, porous matrix that harbors a network of brine pores and channels that harbor active (Junge *et al*., 2004; Søgaard, 2010) and diverse (Brown and Bowman, 2001; Brinkmeyer *et al*., 2003; Maas *et al*., 2012) bacterial communities. The ice-associated community contains photosynthetic, chemoautotrophic and heterotrophic bacteria beside Archaea and several other eukaryotes. Approximately 36%, 25% and 25% were contributed by *Gammaproteobacteria*, *Alphaproteobacteria* and *Cytophaga-Flavobacterium* group while members of *Actinobacteria* were very rarely present. Among the *Gammaproteobacteria* species of the genera *Colwellia* and *Glaciecola* were the most abundant and *Marinobacter* spp. were rare. The *Alphaproteobacteria* were dominated by members of the *Roseobacter* lineage while CF group was centered on *Polaribacter* group (Bowman *et al*., 1997; Gosink *et al*., 1998; Brown and Bowman, 2001; Junge *et al*., 2002; Brinkmeyer *et al*., 2003; Kuhn *et al*., 2014; Lanoil *et al*., 2009). Besides, the occurrence of communities such as *Shewanella*, *Marinobacter*, *Planococcus*, *Alteromonas, Pseudoalteromonas*, *Psychrobacter*, *Halomonas*, *Pseudomonas*, *Hyphomonas*, *Sphingomonas*, *Arthrobacter*, *Planococcus*, and *Halobacillus* were also reported (Bowman *et al*., 1997). The temporal community analyses indicated a shift in community wherein *Paenisporosarcina* was reduced by 5 folds while *Bacillus* increased by 4 folds. In addition, *Acenetobacter* and *Cohnella* replaced *Paenibacillus* and *Jeotgalibacillus* in a span of two years (Doyle *et al*., 2013).

Diversity of Antarctica as Studied by Using Functional Genes

Besides the routine 16S rRNA based diversity, functional gene based diversity was also explored from Antarctic habitats and the genes used were basically targeted to look for the sulfate-reducing bacteria (SRB), photosynthetic bacteria, hydrocarbon degrading bacteria, chitinase and ketosynthase producing communities. Targeting the gene *dsrA* (dissimilatory sulfite reductase), diverse group of sulfate-reducing bacteria was detected in Antarctic habitats (Karr *et al*., 2005). Recently, Watanabe *et al*. (2013) detected phylotypes, based on *aprA* (adenosine-5'-phosphosulfate reductase alpha subunit) belonging to the genera *Thiocapsa, Sulfuricella, Desulfobacterium, Desulfofaba* and *Desulfotomaculum* from Antarctic fresh water lakes. While more than 70% of sulfur transformation in subglacial lake sediments was contributed by two genera *Sideroxydans* and *Thiobacillus* (Purcell *et al*., 2014). Further, the involvement of *Marinobacter*, *Roseovarius* and *Psychroflexus* in marine-derived hypersaline lake in the Vestfold Hills, Antarctica, that has the highest concentration of dimethylsulfide (DMS) in a natural body of water was reported (Yau *et al*., 2013). The above studies indicated the dominance and involvement of *Alphaproteobacteria* and *Betaproteobacteria* in sulfate reduction and also aerobic anoxygenic photosynthesis in Antarctic habitats. In addition, based on Polycyclic aromatic hydrocarbon ring-hydroxylating dioxygenase (PAH-RHD) gene, diverse groups belonging to Proteobacteria, Actinobacteria, Verrucomicrobia, Bacteroidetes, Firmicutes, Chloroflexi, Gemmatimonadetes, Cyanobacteria, Chlorobium, and Acidobacteria were reported from Antarctic soils and sediments. Among these the genera *Terrabacter, Mycobacterium, Diaphorobacter belonging to Gram-positives and Sphingomonas and Burkholderia of Gram-negatives were predominant* (Muangchinda *et al*., 2014). While 14 distinct phylotypes representing the genera *Rhodococcus*, *Mycobacterium*, *Nocardioides*, *Terrabacter* and *Bacillus* were identified from Antarctic sediments based on PAH-dioxygenases (Marcos *et al*., 2009). Diversity studies based on alkane monooxygenases (Alk) genes from a sediment sample indicated the predominance of unique genes that are differentially distributed between the two sites, the Admiralty Bay and King George Island of Peninsula Antarctica. The gene sequences identified the genera *Silicibacter*, *Gordonia*, *Prauserella*, *Nocardioides*, *Rhodococcus*, *Nocardia farcinica*, *Pseudomonas*, *Acidisphaer* and *Alcanivorax* (Kuhn *et al*., 2009). Besides, differential response of bacterial communities to hydrocarbon contamination was studied by Prabagaran *et al*. (2007). Studies based on chitinase genes (*chi67, chi69,chiA, chiB, chiF*) revealed the occurrence of *Janthinobacterium, Stenotrophomonas, Cytophaga, Streptomyces* and *Norcardiopsis* as the abundant genera from a 1600 year old sediment obtained from Ardley Island, Antarctica (Xiao *et al*., 2005). The phylogenetic analysis based on ketosynthase (KS) identified *Proteobacteria, Firmicutes, Planctomycetes, Cyanobacteria, Actinobacteria*, some uncultured symbiotic bacteria and five independent clades. Most of the identified KS showed below 80% identities at the AA level to their closest match revealing the great diversity and novelty of ketosynthase genes in Antarctic sediments (Zhao *et al*., 2008). Based on gene *pufM* (a gene coding for photosynthetic pigment-binding protein) 33 unique phylotypes related to *Rubrivivax, Acidiphilum, Rhodoferax* and *Roseateles* were detected from Antarctic sediments (Karr *et al*., 2003; Stibal *et al*., 2012). While studying the diversity of *psbA* gene from Lake Bonney, unique phylotypes of genera *Nannochloropsis*, *Ochromonas* and *Isochrysis* were identified (Kong *et al*., 2014). The *amoA* based diversity studies indicated the dominance of only two genera, the *Nitrosospira* and *Nitrosomonas,* as the ammonium oxidizing community in Antarctic habitats (Magalhães *et al*., 2014).

Diversity of Antarctica as Studied by Cultivable Methods

The cultivable bacterial diversity was explored extensively from various habitats such as soil (Miwa, 1975; Yi and Chun, 2006; Ruckert, 1985; Shivaji *et al*., 1988; 1989a; 1989b; 1991; Wery *et al*., 2003; Bozal *et al*., 2007), water (Lo Giudice *et al*., 2012; Michaud *et al*., 2012; Soller *et al*., 2000; Labrenz *et al*., 2000; Cristóbal *et al*., 2011), algal mats (Reddy *et al*., 2000; 2002; 2003a; 2003b; 2004; Van Trappen *et al*., 2002; Spring *et al*., 2003; Peeters *et al*., 2011), ice (Shivaji *et al*., 2004; Antibus *et al*., 2012; Bowmen *et al*., 1998) and sediments (Shivaji *et al*., 2011; Yu *et al*., 2011) and reviewed by Shivaji and Reddy (2009) and

Chattopadyay *et al*. (2014) from Antarctica. Among the habitats, water, soil and mats are more diverse compared to ice and sediments as evident from the absence and abundance of various communities. In all the habitats the most dominating communities are *Proteobacteria*, *Cytophaga-Flavobacterium-Bacteriodetes, Actinobacteria* and *Firmicutes* and communities belonging to *Deinococcus-thermus* and *Spirochaetes* are restricted, interestingly, only to soil (Hirsch *et al*., 2004; Antibus *et al*., 2012; Franzmann & Dobson, 1992; Chattopadyay *et al*., 2014). Among the Proteobacteria, Gammaproteobacteria leads in abundance in soil (3%) and water (0.6%) while members of Epsilonproteobacteria were absent (Reddy *et al*., 2016).

Relative percentage occurrence of cultivable bacteria from Antarctica indicated that the soils are dominated by *Firmicutes* (35%), *Actinobacteria* (25%) and *Proteobacteria* (18%), water is inhabited by *Proteobacteria* (42%), *Cytophaga-Flavobacterium-Bacteriodetes* (31%) and *Actinobacteria* (23%), algal mats are rich in *Proteobacteria* (40%), *Firmicutes* (28%) and *Cytophaga-Flavobacterium-Bacteriodetes* (24%), ice is abundant in *Proteobacteria* (48%), *Cytophaga-Flavobacterium-Bacteriodetes* (21%) and *Firmicutes* (19%) and finally the sediments communities are composed of *Proteobacteria* (50%) and *Actinobacteria* (29%) (Reddy *et al*., 2016). The above statistics clearly indicate that *Proteobacteria* is ubiquitously present in all the Antarctic habitats. Close to 500 cultivable bacteria isolated from Antarctica represent the above major groups of *Proteobacteria*, *Cytophaga-Flavobacterium-Bacteriodetes, Actinobacteria* and *Firmicutes* represented by 172 genera (38 novel genera) and 209 novel species.

Novel Species From Antarctica

Till date close to 209 bacterial species have been described based on polyphasic taxonomy (except, *Desulfovibrio* of *Deltaproteobacteria, Hymenobacter* species of CFB group and a few species of *Carnobacterium* and *Clostridium* of *Firmicutes*), from various habitats of Antarctica and these novel species belonged to the phyla *Alphaproteobacteria, Betaproteobacteria, Gammaproteobacteria, Deltaproteobacteria, Epsilonproteobacteria, CFB, Firmicutes, Actinobacter* and *Deinococcus-Thermus*. The relative frequency of the above isolates at the phyla level is shown in Fig. 1 and Table 1 (Bottos *et al*., 2014; Chattopadhyay *et al*., 2014; Reddy *et al*., 2016). The most common feature of the novel species of Antarctica is their psychrophilic growth wherein they grow from zero or subzero temperatures to 30ºC but not beyond. However, a few species like *Alicyclobacillus pohliae* (42-60ºC) (Imperio *et al*., 2008), *Aneurinibacillus terranovensis* (20-55ºC), (Allan *et al*., 2005), *Anoxybacillus amylolyticus* (45-65 ºC) (Poli *et al*., 2006), *Bacillus fumrioli* (25-55ºC) (Logan *et al*., 2000), *Brevibacillus levickii* (15-55ºC) (Allan *et al*., 2005), *Paenibacillus cineris* (8-50ºC) and *Paenibacillus cookie* (15-50ºC) (Logan *et al*., 2004) are moderately thermophilic and interestingly all these species were isolated from soil. The physiological characteristics with respect to the extracellular enzymes indicate approximately 79% of novel species secrete the enzyme phosphatase followed by protease (48.7%), lipase (48.5%), amylase (42%), β-glactosidase (32%) and urease (20%) (Fig. 2). Further, 68% of novel species described so far

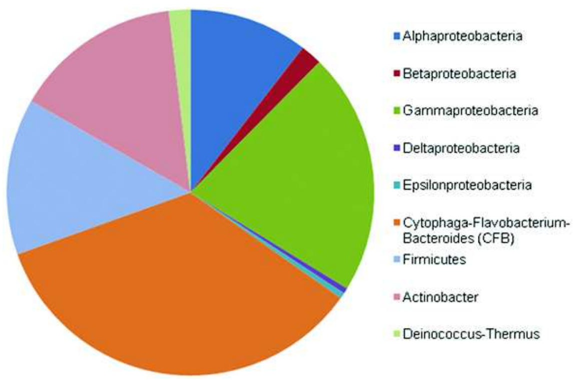

Fig. 1: Relative percentage of novel species described from various habitats of Antarctica

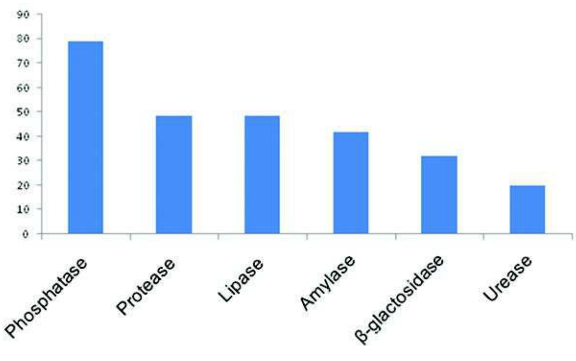

Fig. 2: Production of extracelluar enzymes by novel species from Antarctica

Table 1: Important characteristics of novel bacterial species from Antarctica

S.No.		Name of the species	A	C	L	P	U	BG	Ph	Pi	FA	MK	DA	G+C	Ca	O	H	Lipids	16S rRNA gene Acc. No
		Alphaproteobacteria																	
1	1	*Antarctobacter heliothermus**	-	-	-	+	ND	ND	ND	BY	18:1	Q10	ND	62.3	+	+	water	PG, PC	Y11552
2	2	*Constrictibacter antarcticus**	ND	ND	+	ND	ND	ND	+	-	18:1	Q10	ND	69.8	+	-	Rock	ND	AB510913
3	3	*Loktanella fryxellensis**	-	ND	-	-	-	+	+	PG	18:1ω7c	ND	ND	66	+	+	Mats	ND	AJ582225
4	4	*Loktanella salsilacus*	-	ND	-	-	-	+	+	Biege	18:1ω7c	ND	ND	60	+	+	Mats	ND	AJ440997
5	5	*Loktanella vestfoldensis*	-	ND	+	-	+	+	+	Pink	18:1ω7c	ND	ND	63	+	+	Mats	ND	AJ582226
6	6	*Polymorphobacter multimanifer**	ND	ND	-	-	-	-	+	Br	17:1ù6c	Q10	ND	68	+	+	Rock	PG, PE, SPL	AB649056
7	7	*Pseudorhodobacter antarcticus*	-	ND	+	-	-	-	+	Pink	18:1ω7c	Q10	ND	57.1	+	+	Sediment	PG, PC	FJ196030
8	8	*Pseudorhodobacter collinsensis*	-	+	-	+	+	+	+	Cream	18:1ω7c	Q10	ND	61	+	+	Ice cap	PC, PE, PG	KM978076
9	9	*Pseudorhodobacter psychrotolerans*	-	ND	-	+	-	+	+	Cream	18:1ω7c	Q10	ND	60.1	+	+	Soil	PC, PG, UL	KT163920
10	10	*Puniceibacterium antarcticum**	-	ND	-	-	-	-	+	PR	18:1ω7c	ND	ND	60.7	+	+	Water	PC, PE, PG	KP136797
11	11	*Rhodoligotrophos appendicifer**	ND	ND	-	-	-	-	-	Red	16:0	Q9	ND	61.1	+	+	Water	PE, PG	AB617575
12	12	*Robiginitomaculum antarcticum**	ND	ND	+	-	-	+	+	Rusty	18:1ω7c	Q10	ND	60.3	+	-	Water	ND	EF495229
13	13	*Roseibaca ekhonensis**	-	ND	-	-	ND	ND	ND	Red	18:1ω7c	Q10	ND	61	+	+	Water	PC, PE, PG, DPG	AJ605746
14	14	*Roseicitreum antarcticum**	-	ND	-	-	+	+	ND	Pink	18:1ω7c	Q10	ND	63.3	+	+	Sediment	PC, PE, PG	FJ196006
15	15	*Roseisalinus antarcticus**	-	ND	-	-	ND	ND	ND	Rose	18:1ω7c	Q10	mDap	67	+	+	Water	ND	AJ605747
16	16	*Roseovarius antarcticus*	-	ND	-	-	-	-	+	PY	18:1ω7c	Q10	ND	61	+	+	Bone	PC, PE, PG, DPG	KM347966
17	17	*Roseovarius tolerans**	-	ND	+	-	ND	ND	ND	Red	18:1	Q10	ND	64	+	+	Water	PC, PE, PG, DPG	Y11551
18	18	*Sphingomonas aerolata*	-	ND	-	-	ND	+	+	O	18:1ω7c	Q10	ND	65.4	+	+	Water	PC, PE, PG, DPG, SPL	AJ429240
19	19	*Sphingomonas aurantiaca*	-	ND	-	-	ND	+	+	O	18:1ω7c	Q10	ND	65	+	+	Water	PC, PE, PG, DPG, SPL	AJ429236

20	20	*Sphingomonas faeni*	-	ND	-	-	ND	+	+	O	18:1ù7c	Q10	ND	63	+	+	Water	PC, PE, PG, DPG, SPL	AJ429239
21	21	*Staleya guttiformis**	-	ND	ND	-	ND	ND	ND	-	18:1ù7c	Q10	ND	56	-	+	Water	PC, PE, PG	Y16427
22	22	*Sulfitobacter brevis*	-	ND	ND	-	ND	ND	ND	-	18:1ù7c	Q10	ND	58	-	+	Water	PC, PE,D PG	Y16425
23	23	*Thalassospira lohafexi*	-	ND	-	+	-	-	+	-	18:1ù7c	Q10	ND	53	+	+	Water	PE, PG	GU584152
		Betaproteobacteria																	
24	1	*Actimicrobium antarcticum** 2/4	ND	ND	+	-	-	-	+	-	16:1ù7c	Q8	ND	65.9	+	+	Water	PE, PG, UL	HQ699437
25	2	*Herbaspirillum psychrotolerans*	+	ND	ND	+	+	ND	ND	-	16:1ù7c	Q8	ND	62.5	+	-	Soil	PE, PG, DPG	JN390675
26	3	*Polaromonas vacuolata**	-	ND	+	-	+	ND	ND	-	16:1ù7c	ND	ND	52	+	+	Water	ND	U14585
27	4	*Rhodoferax antarcticus*	-	ND	ND	ND	ND	ND	ND	Peach	ND	ND	ND	61.5			Mat	ND	AF084947
		Gammaproteobacteria																	
28	1	*Alteromonas stellipolaris*	+	ND	+	+	-	+	++	Br	16:0	ND	ND	45	+	+	Water	ND	AJ295715
29	2	*Glaciecola Polaris*	+	ND	+	-	-	+	+	-	16:0	ND	ND	44	+	+	Water	ND	AJ293820
30	3	*Granulosicoccus antarcticus***	-	ND	+	+	-	+	-	-	16:1ù7c	Q8	ND	58	+	+	Water	ND	EF495228
31	4	*Granulosicoccus marinus*	-	-	+	+	-	+	+	-	18:1ù7c	Q8	ND	61	+	+	Water	ND	KF146345
32	5	*Hahella Antarctica*	ND	ND	-	-	-	-	+	Cr	16:1ù7c	Q9	ND	56.4	+	-	Water	ND	EF495227
33	6	*Halomonas alkaliantarctica*	-	ND	ND	-	-	ND	ND	-	18:1	Q9	ND	55	-	+	Water	PE, PG, DPG	AJ564880
34	7	*Halomonas glaciei*	-	ND	-	-	-	ND	-	-	18:1	Q8	ND	-	+	+	Water	ND	AJ431369
35	8	*Lysobacter oligotrophicus*	+	-	+	+	ND	+	ND	DB	i15:0	Q8	ND	66	+	+	Water	PE, PG, DPG	AB694977
36	9	*Marinobacter antarcticus*	-	ND	+	-	-	-	+	Br	16:1ù7c	ND	ND	55.8	+	+	Water	PE, PG, DPG	FJ196022
37	10	*Marinobacter guinea*	-	ND	+	-	-	-	+	-	16:1ù7c	Q9	ND	57.1	+	+	Sediment	ND	AM503093
38	11	*Marinobacter maritimus*	-	ND	+	-	+	-	+	Cr	18:1ù7c	Q9	ND	58	+	+	Water	ND	AJ704395
39	12	*Marinomonas Polaris*	-	ND	-	-	ND	+	+	-	18:1ù7c	ND	ND	41.2	+	-	Water	PE, PG	AJ833000
40	13	*Marinomonas ushuaiensis*	+	ND	-	-	-	ND	+	-	18:1ù7c	ND	ND	43.6	+	-	Water	ND	AJ627909
41	14	*Methylosphaera hansonii**	ND	ND	ND	ND	-	ND	-	Y	16:1ù7c	ND	ND	46	+	+	Sediment	ND	U67929
42	15	*Neptunomonas Antarctica*	-	ND	-	-	-	-	+	-	16:1ù7c	Q8	ND	46	+	+	Sediment	ND	FJ713802
43	16	*Oleispira lenta*	-	ND	+	-	-	-	+	-	16:1ù7c	ND	ND	43	-	+	Water	ND	EU980447
44	17	*Oleispira antarctica**	-	ND	+	-	-	ND	ND	-	16:1ù7c	ND	ND	42	+	+	Water	ND	AJ426420
45	18	*Pseudoalteromonas antarctica*	-	ND	+	+	-	-	+	-	16:1ù7c	ND	ND	42	+	+	Mud	ND	X98336

46	19	*Pseudoalteromonas prydzensis*	+	ND	+	+	+	-	+	-	16:1ω7c	ND	ND	39	+	+	Ice	ND	U85855
47	20	*Pseudomonas antarctica*	-	-	+	-	+	-	+	-	18:1	ND	ND	61	+	+	Mat	ND	AJ537601
48	21	*Pseudomonas deceptionensis*	-	ND	-	-	+	-	-	-	16:1	ND	ND	53.8	+	+	Sediment	PE, PG, DPG	GU936597
49	22	*Pseudomonas extremaustralis*	-	ND	ND	-	-	-	ND	-	16:1ω7c	ND	ND	ND	+	+	Water	ND	AF405328
50	23	*Pseudomonas guinea*	-	ND	+	-	-	-	+	-	16:0	ND	ND	58.5	+	+	Soil	ND	AM491810
51	24	*Pseudomonas meridiana*	-	-	+	-	+	-	-	-	16:0	ND	ND	63	+	+	Mat	ND	AJ537602
52	25	*Pseudomonas prosekii*	-	-	-	+	-	ND	ND	-	ND	ND	ND	ND	+	+	Soil	ND	JN814372
53	26	*Pseudomonas proteolytica*	-	-	+	+	-	-	-	-	18:1	ND	ND	58	+	+	Mat	ND	AJ537603
54	27	*Psychrobacter adeliensis*	-	-	-	+	-	-	-	-	18:1ω9c	ND	ND	45	+	+	Water	ND	AJ539105
55	28	*Psychrobacter aquaticus*	-	-	+	-	+	-	+	-	16:1	Q8	ND	43.6	+	+	Mat	PE, PG, DPG	AJ584833
56	29	*Psychrobacter fozii*	-	ND	-	-	+	ND	+	-	18:1ω9c	ND	ND	44	+	+	Sediment	ND	AJ430827
57	30	*Psychrobacter frigidicola*	-	ND	-	-	-	-	-	-	18:1ω9c	ND	ND	42	+	+	Water	ND	AJ609556
58	31	*Psychrobacter luti*	-	ND	+	-	-	ND	+	-	18:1ω9c	ND	ND	45	+	+	Soil	ND	AJ430828
59	32	*Psychrobacter nivimaris*	-	ND	+	-	ND	ND	ND	-	18:1ω9c	ND	ND	42	+	+	Org.Mate	ND	AJ313425
60	33	*Psychrobacter proteolyticus*	-	ND	+	+	+	-	+	-	18:1ω9c	ND	ND	43.6	+	+	Water	ND	AJ272303
61	34	*Psychrobacter salsus*	-	ND	-	-	-	-	-	-	18:1ω9c	ND	ND	44	+	+	Water	ND	AJ539104
62	35	*Psychrobacter urativorans*	-	ND	-	-	+	-	-	-	18:1ω9c	ND	ND	46	+	+	Water	ND	AJ609555
63	36	*Psychrobacter vallis*	-	-	+	-	-	-	+	-	18:1ω9c	Q8	ND	46	+	+	Mat	PE, PG, DPG	AJ584832
64	37	*Psychromonas antarcticus**	-	ND	ND	+	ND	ND	ND	-	16:1ω7c	Q8	ND	43	+	+	Soil	ND	Y14697
65	38	*Psychromonas kaikoae*	-	ND	ND	+	ND	ND	ND	-	16:1ω7c	Q8	ND	44	+	+	Sediment	PE, PG, DPG	AB052160
66	39	*Saccharospirillum impatiens**	+	ND	-	+	ND	ND	ND	-	18:1	Q8	mDap	55	+	+	Water	PE, PG, DPG	AJ315983
67	40	*Shewanella livingstonensis*	-	ND	+	+	-	+	+	-	16:1ω7c	MK7	ND	41	+	+	Water	PE, PG, DPG	AJ300834
68	41	*Shewanella frigidimarina*	-	ND	+	+	-	-	+	-	16:1ω7c	ND	ND	43	+	+	Ice	ND	U85903
69	42	*Shewanella gelidimarina*	-	ND	+	+	-	-	+	-	16:1ω7c	ND	ND	48	+	+	Ice	ND	U85907
70	43	*Shewanella vesiculosa*	-	ND	+	+	-	+	+	-	16:1ω7c	Q7	ND	42	+	+	Sediment	ND	AM980877
71	44	*Zhongshania antarctica**	-	ND	-	-	-	-	ND	-	17:1ω8c	ND	ND	52.5	+	+	Ice	ND	FJ889619
72	45	*Zhongshania guokunii*	-	ND	-	-	-	-	ND	-	17:1ω8c	ND	ND	51.8	+	+	Water	ND	FJ889678
		Deltaproteobacteria																	
73	1	*Desulfovibrio lacusfryxellense*	Not well characterized														Water		DQ767889

		Epsilonproteobacteria																	
74	1	*Campylobacter subantarcticus*	Not well characterized						B								ird		AM933371
		CFB																	
75	1	*Aequorivita antarctica*	+	ND	+	-	-	ND	ND	ND	i15:0	ND	ND	ND	+	-	Sea water	ND	AY027802
76	2	*Aequorivita capsosiphonis*	-	-	-	+	-	-	+	YO	I15:0	ND	ND	37	+	-	Algae	ND	EU290153
77	3	*Aequorivita crocea*	-	ND	+	+	-	-	+	Y	Ai15:0	ND	ND	34	+	-	Sea water	ND	AY027806
78	4	*Aequorivita lipolytica**	-	ND	-	+	+	-	+	Y	Ai15:0	ND	ND	36	+	-	Sea water	ND	AY027805
79	5	*Aequorivita sublithincola*	-	ND	-	-	+	-	+	O	Ai15:0	ND	ND	37	+	-	Sea water	ND	AF170749
80	6	*Algibacter psychrophilus*	+	-	-	-	-	-	-	Y	17:0 2OH	MK6	ND	33.5	+	+	Sediment	PE	KJ475138
81	7	*Algoriphagus antarcticus*	+	ND	-	-	-	-	+	O	Ai15:1ù10c	ND	ND	39	+	+	Mats	ND	AJ577141
82	8	*Antarcticimonas flava**	+	ND	+	+	-	+	+	Y	16:1ω7c	MK6	ND	37.3	+	-	Water	PE, UL	EF554365
83	9	*Bizionia algoritergicola*	-	ND	-	+	-	-	+	Y	Ai15:1ω10c	ND	ND	34	+	+	Ice	ND	AY694003
84	10	*Bizionia argentinensis*	-	ND	+	+	-	-	+	Y	Ai15:0 3OH	ND	ND	45	+	+	Ice	ND	EU021217
85	11	*Bizionia gelidisalsuginis*	-	ND	+	+	-	-	+	Y	Ai15:0 3OH	ND	ND	39	+	+	Ice	ND	AY694004
86	12	*Bizionia myxarmorum*	-	ND	+	+	-	-	+	Y	Ai15:0 3OH	ND	ND	43	+	+	Ice	ND	AY694002
87	13	*Bizionia saleffrena*	-	ND	+	+	-	-	+	Y	Ai15:0 3OH	ND	ND	40	+	+	Ice	ND	AY694005
88	14	*Cellulophaga algicola*	+	ND	+	+	-	+	-	YO	16:1ω7c	ND	ND	38	+	-	Ice	ND	CP002453
89	15	*Chryseobacterium frigidisoli*	+	ND	ND	+	-	ND	ND	Y	I15:0 2OH	MK6	ND	33.7	+	+	Soil	ND	JN390676
90	16	*Flavobacterium antarcticum*	-	-	+	+	-	-	+	Y	I15:0	MK6	ND	38	+	+	Soil	ND	AY581113
91	17	*Flavobacterium collinsense*	-	-	+	+	-	+	+	Y	I15:0	ND	ND	36.2	+	+	Soil	PE, UL	KM288594
92	18	*Flavobacterium degerlachei*	+	-	-	-	-	-	+	Y	I15:0 2OH	ND	ND	34.2	+	+	Mat	ND	AJ557886
93	19	*Flavobacterium faecale*	+	ND	ND	-	+	+	ND	Y	15:0	MK6	ND	37	+	+	Sediment	ND	KF214259
94	20	*Flavobacterium frigidarium*	-	-	+	+	+	+	ND	Y	16:1ω7c	ND	ND	35	+	+	Sediment	ND	AF162266
95	21	*Flavobacterium frigidimaris*	+-	-	-	+	ND	+	ND	Flexi	16:0	MK6	ND	34	+	-	Sediment	ND	AB183888
96	22	*Flavobacterium frigoris*	-	-	+	-	-	-	++	OR	I15:0 2OH	ND	ND	35	+	+	Mats	ND	AJ557887
97	23	*Flavobacterium fryxellicola*	-	-	+	-	-	-	++	YO	I15:0	ND	ND	36	+	+	Water	ND	AJ811961
98	24	*Flavobacterium gelidilacus*	+	ND	-	+	-	-	++	YO	I15:0	ND	ND	32	+	+	Water	ND	AJ440996
99	25	*Flavobacterium gillisiae*	+	-	+	-	-	-	ND	O	16:1ω7c	ND	ND	32	+	-	Sea ice	ND	U85889
100	26	*Flavobacterium gondwanense*	+	ND	+	-	+	+	+	O	A15:0	MK6	ND	39	+	+	Water	ND	M92278
101	27	*Flavobacterium hibernum*	+	-	+	+	-	+	ND	Y	I15:0	MK6	ND	34	+	-	Water	ND	L39067
102	28	*Flavobacterium micromati*	-	ND	-	-	-	-	++	OR	I15:0 2OH	ND	ND	33	+	+	Mats	ND	AJ557888

103	29	*Flavobacterium psychrolimnae*	+	-	-	-	-	-	++	Y	I15:0 2OH		ND	ND	34.5	+	+ Water	ND	AJ585428
104	30	*Flavobacterium segetis*	+	-	+	-	-	+	+	O	16:1ω7c	MK6	ND	41	+	+	Soil	ND	AY581115
105	31	*Flavobacterium salegens*	+	ND	+	+	-	+	+	Y	16:1ω7c	MK6	ND	41	+	+	Water	ND	M92279
106	32	*Flavobacterium tegetincola*	-	-	+	-	-	-	ND	Y	16:1ω7c	ND	ND	32	+	-	Mud pool	ND	U85887
107	33	*Flavobacterium weaverense*	+	-	+	-	+	-	+	Y	16:1ω7c	MK6	ND	37	+	+	Soil	ND	AY581114
108	34	*Gelidibacter algens**	+	ND	+	+	-	-	+	Y	A15:0	ND	ND	38	+	-	Sea ice	ND	U62914
109	35	*Gelidibacter gilvus*	-	ND	+	-	-	+	-	Y	A15:0	ND	ND	39	+	-	Sea ice	ND	AF001369
110	36	*Gelidibacter salicanalis*	-	ND	-	+	+	+	+	Y	a15:1ω10c	ND	ND	42	+	-	Sea ice	ND	AY694009
111	37	*Gillisia hiemivivida*	+	ND	+	+	+	-	+	Y	A15:0	ND	ND	34	+	+	Ice core	ND	AY694006
112	38	*Gillisia illustrilutea*	-	ND	-	-	-	-	-	Y	a15:1ω10c	ND	ND	32	+	+	Ice core	ND	AY694008
113	39	*Gillisia limnaea**	-	ND	-	+	-	-	+	Y	17:0 2OH	ND	ND	38	+	+	Mats	ND	AJ440991
114	40	*Gillisia sandarakina*	+	ND	+	+	-	-	+	O	i16:0	ND	ND	36	+	+	Ice core	ND	AY694007
115	41	*Hymenobacter algoricola*	Not well characterized							RP	16:1ω7c	ND	ND	ND	-	+	Gl. water	ND	EU155009
116	42	*Hymenobacter antarcticus*								RP	16:1ω7c	ND	ND	ND	-	+	Gl. Water	ND	EU155012
117	43	*Hymenobacter elongates*								RP	I17:1	ND	ND	ND	-	+	Gl. Water	ND	GQ454797
118	44	*Hymenobacter fastidiosus*								RP	16:1ω7c	ND	ND	ND	-	+	Gl. Water	ND	EU155015
119	45	*Hymenobacter glaciei*								RP	16:1ω7c	ND	ND	ND	-	+	Gl. water	ND	GQ454806
120	46	*Hymenobacter roseosalivarius**	+	-	+	+	-	ND	+	RP	16:1ω7c	MK7	ND	56	+	+	Soil	PE	Y18833
121	47	*Kordia Antarctica*	+	-	-	-	-	-	+	Y	16:1ω9c	MK6	ND	35	-	-	Sea water	PE, UL	JX456458
122	48	*Lacinutrix copepodicola**	-	ND	+	+	-	-	+	Y	I15:0	MK6	ND	32	+	+	Sea ice	PE	AY694001
123	49	*Lacinutrix jangbogonensis*	-	ND	+	+	-	-	+	Y	I15:0	MK6	ND	37	+	+	Sea ice	PE	KF977035
124	50	*Leeuwenhoekiella aequorea*	+	-	+	+	-	+	+	Y	17:1ω9c	MK6	ND	36	+	+	Sea ice	ND	AJ278780
125	51	*Leeuwenhoekiella polynyae*	+-	-	+	-	+	+		Y	I17:0 2 OH	MK6	ND	39	+	+	Water	PE, UL	KM101107
126	52	*Lewinella Antarctica*	+	-	-	+	-	+	+	O	16:1ω7c	MK7	ND	50	+	-	Water	ND	EF554367
127	53	*Maribacter antarcticus*	+	ND	+	-	-	-	+	O	I15:0	MK6	ND	37	+	+	Algae	PE	EU512921
128	54	*Muricauda Antarctica*	-	ND	-	+	-	+	+	Br	I17:0 3OH	MK6	ND	45	+	+	Sea water	PE	JN166984
129	55	*Nonlabens antarcticus*	-	-	-	+	-	-	+	O	Ai15:0	MK6	ND	38	+	+	Gl . core	PE	DQ660393
130	56	*Pedobacter ardleyensis*	+	ND	-	-	-	+	+	Red	I15:0	MK7	ND	40	+	+	Soil	PE, Sphingo lipid	KJ631640.
131	57	*Polaribacter filamentus*	+	-	ND	+	-	-	ND	Soh	I15:0 2OH		ND	ND	32	+	-Sea water	ND	U73726
132	58	*Polaribacter franzmannii*	+	-	ND	+	-	+	ND	O	I15:0 3OH		ND	ND	32	+	+ Sea ice	ND	U14586

133	59	*Polaribacter irgensii**	+	-	-	+	-	-	+	O	I15:0 3OH	MK6	ND	31	+	+	Sea water	PE	M61002
134	60	*Polaribacter sejongensis*	+	ND	+	+	-	+	+	Y	I15:0 3OH	MK6	ND	30	+	+	Soil	PE	HQ853596
135	61	*Pricia antarctica**	-	ND	-	-	-	-	+	Y	I15:0G	MK6	ND	44	+	+	Sediment	PE	FJ889677
136	62	*Psychroflexus lacisalsi*	+	ND	-	+	ND	-	+	O	A15:0	MK6	ND	35	+	+	Lake water	ND	AB381940
137	63	*Psychroflexus torques*	+	ND	+	+	-	-	+	O	A15:0	MK6	ND	33	+	+	Sea ice	ND	U85881
138	64	*Psychroserpens burtonensis**	-	ND	+	+	-	-	+	YO	15:1ω10c	ND	ND	29	+	-	Lake Water	ND	U62913
139	65	*Psychroserpens jangbogonensis*	+	ND	-	-	-	-	+	Y	20:4ω6c	MK6	ND	32.7	+	+	Sediment	PE	KJ475160
140	66	*Salegentibacter salegens**	+	ND	+	+	ND	+	+	Y	I15:0	MK6	ND	38	+	+	Water	ND	M92279
141	67	*Sejongia antarctica**	+	-	+	+	-	-	+	Y	17:1ω9c	MK6	ND	34	+	+	Soil	ND	AY553293
142	68	*Sejongia jeonii*	-	-	-	+	+	-	+	Y	A15:0	MK6	ND	36	+	+	Moss	ND	AY553294
143	69	*Sejongia marina*	+	ND	+	+	-	-	+	Y	A15:0	MK6	ND	35	+	-	Sea water	ND	EF554366
144	70	*Subsaxibacter broadyi*	-	ND	+	+	-	-	+	Y	A15:0	ND	ND	35	+	+	Cyano	ND	AY693999
145	71	*Subsaximicrobium saxinquilinus*	+	ND	+	+	-	-	+	O	I16:0 3OH	ND	ND	39	+	+	Cyano	ND	AY693998
146	72	*Subsaximicrobium wynnwilliamsii**	+	ND	+	+	+	-	+	O	A15:0	ND	ND	40	+	+	Cyano	ND	AY693997
147	73	*Ulvibacter antarcticus*	+	-	-	+	-	-	+	Y	I17:0 3OH	MK6	ND	37	+	+	Sea water	ND	EF554364
		Firmicutes 30																	
148	1	*Alicyclobacillus pohliae*	ND	ND	ND	ND	ND	ND	ND	Cream	15:0	ND	ND	55	-	-	Soil	ND	AJ564766
149	2	*Aneurinibacillus terranovensis*	+	ND	-	+	-	-	ND	Cream	A15:0	ND	ND	44.6	+		Soil	ND	AJ715385
150	3	*Anoxybacillus amylolyticus*	+	ND	-	-	-	ND	ND	-	I15:0	MK7	ND	43.5	+	-	Soil	ND	AJ618979
151	4	*Bacillus fumarioli*	-	ND	-	+	-	-	ND	BC	I15:0	ND	ND	40.7			Soil	ND	AJ250056
152	5	*Brevibacillus levickii*	+	ND	-	+	-	-	ND	Cream	A15:0	ND	ND	50.3	+		Soil	ND	AJ715378
153	6	*Carnobacterium alterfunditum*		Not well characterized							16:0	ND	ND	ND				ND	L08623
154	7	*Carnobacterium funditum*									16:0	ND	ND	34				ND	S86170
155	8	*Carnobacterium iners*									16:0	ND	mDap	34			Mats	ND	HE583595
156	9	*Clostridium bowmanii*									16:1ω9c	ND	ND	32				ND	AJ506119
157	10	*Clostridium frigoris*									16:1ω9c	ND	ND	32				ND	AJ506116
158	11	*Clostridium lacusfryxellense*									16:1ω9c	ND	ND	32				ND	AJ506118
159	12	*Clostridium psychrophilum*									16:1ω9c	ND	ND	31.8				ND	AJ297443

160	13	*Clostridium schirmacherense*									15:0	ND	ND	24				ND	AM114453
161	14	*Clostridium vincentii*									16:0	ND	ND	33				ND	X97432
162	15	*Exiguobacterium antarcticum*	+		-	+	-	+	+	O	16:0	MK7	ND	48.5	+	+	Soil	PG, DPG, PS, PI, PE, UL	DQ019164
163	16	*Exiguobacterium soli*	+		-	+	-	+	+	Y	15:0	MK7	ND	47	+		Soil	PG, DPG, PS, PI	AY864633
164	17	*Exiguobacterium undae*	+		-	+	-	+	+	O	16:0	MK7	ND	48	+	+	Soil	PG, DPG, PS, PI, PE, UL	DQ019165
165	18	*Jeotgalicoccus pinnipedialis*	ND	ND	ND	+	ND	-	-	-	15:0	MK7	ND	38.6	+	+		PG, DPG, PI	AJ251530
166	19	*Paenibacillus antarcticus*	+	ND	+	-	+	-	ND	-	a15:0	ND	ND	40.7	+	+	Sediment	ND	AJ605292
167	20	*Paenibacillus. cineris*	ND	ND	ND	-	-	+	ND	-	a15:0	ND	ND	51.5	+	+	Soil	ND	AJ575658
168	21	*Paenibacillus cookie*	ND	ND	ND	-	-	+	ND	Y	a15:0	ND	ND	51.6	+	+	Soil	ND	AJ250317
169	22	*Paenibacillus darwinianus*	+	ND	-	-	ND	ND	ND	-	a15:0	MK7	ND	55.6	+	-	Soil	PG, DPG, PE	KF264455
170	23	*Paenibacillus wynni*	+	ND	ND	-	-	+	ND	-	a15:0	ND	ND	44.6			Soil		AJ633647
171	24	*Planococcus antarcticus*	-	ND	+	+	-	+	-	O	a15:0	MK7,8	ND	41.5	+	-	Mat	PG, DPG, PE	AJ314745
172	25	*Planococcus maitriensis*	-	ND	-	+	-	+	-	O	a15:0	MK7,8	ND	39	+	+	Mat	ND	AF500007
173	26	*Planococcus mcmeekinii*	-	ND	-	+	ND	ND	ND	O	a15:0	MK7,8	ND	35	+	-	Brine	ND	AF041791
174	27	*Planococcus psychrophilus*	-	ND	+	+	-	+	-	O	a15:0	MK7,8	ND	44.5	+		Mat	PG, DPG, PE	AJ314746
175	28	*Psychrosinus fermentans*	Not well characterized					+	+	W							ater	ND	DQ767881
176	29	*Sporosarcina Antarctica*	-	ND		-	-	-	+	LY	a15:0	MK7	ND	39.2	+	+	Soil	ND	EF154512
177	30	*Sporosarcina macmurdoensis*	+	ND	-	+	-	-	+	-	a15:0	MK7	ND	44	+	-	Mat	ND	AJ514408
178		**Actinobacteria** 6/31																	
179	1	*Arthrobacter antarcticus*	+	ND	-	-	+	-	+	Y	a15:0	MK8	Lys-Glu	68	+	+	Sediment	DPG, PE	AM931709
180	2	*Arthrobacter ardleyensis*	-	-	+	+	ND	ND	ND	Y	a15:0	MK8	Lys-Ala-Glu	59.5	+	-	Sediment	ND	AJ551163
181	3	*Arthrobacter cryotolerans*	-	ND	ND	+	-	-	+	-	a15:0	$MK9H_2$	Lys-Glu	64.5	+	-	Soil	PG	GQ406812
182	4	*Arthrobacter flavus*	+	ND	-	-	-	ND	ND	Y	a15:0	$MK9H_2$	Lys-Thr-Ala_3	65	+	-	Mat	PE, PG, DPG	AB537168
183	5	*Arthrobacter gangotriensis*	-	ND	-	+	+	-	+	Y	a15:0	MK8	Lys-Glu	66	+	+	Soil	ND	AJ606061
184	6	*Arthrobacter kerguelensis*	-	ND	-	?	+	-	+	Y	a15:0	MK8	Lys-Glu	58	+	+	Sea water	ND	AJ606062
185	7	*Arthrobacter livingstonensis*	-	ND	ND	-	+	ND	ND	W	a15:0	$MK9H_2$	Lys-Thr-Ala	64.7	+	-	Soil	PG	GQ406811
186	8	*Arthrobacter psychrochitini-philus*	+	+	+	-	-	ND	ND	Y	a15:0	$MK9H_2$	Lys-Glu	58.5	+	-	Penguin	ND	AB588633
187	9	*Arthrobacter roseus*	-	ND	-	+	-	-	+	R	a15:0	$MK9H_2$	Lys-Thr-Ala_3	69	+	-	Mat	PE, PG, DPG	AJ278870
188	10	*Barrientosiimonas humi**	-	-	-	+	-	ND	ND	PY	a17:0	$MK8H_4$	Lys-Ser-Asp	68.4	+	-	Soil	PE, PG, DPG, UL	JF346171

189	11	*Curtobacterium psychrophilum**	+	ND	ND	-	ND	ND	ND	-	a15:0	MK10	Dab		65	+	-Soil	PG, DPG, UL	D45058
190	12	*Friedmanniella antarctica**	+	ND	+	-	+	ND	ND	O	a15:0	9H4	Lys-Gly		73	+	-Sand stone	PG, DPG, PI, UL	Z78206
191	13	*Friedmanniella lacustris*	-	ND	ND	+	-	ND	ND	O	a15:0	9H4	mDap	73	+	+	Water	ND	AJ132943
192	14	*Kocuria Polaris*	+	ND	+	-	-	-	-	O	a15:0	7H2	Lys-Ala$_3$		72.5	+	+Mat	PG, DPG, PI	AJ278868
193	15	*Leifsonia antarctica*	-	ND	-	+	-	+	+	Y	a15:0	MK10	Dab	-	+	+	Sediment	PG, DPG, PE	AM931710
194	16	*Leifsonia aurea*	-	ND	-	-	-	+	-	Y	a15:0	MK11	Dab	64	+	-	Mat	ND	AJ438586
195	17	*Leifsonia psychrotolerans*	+	ND	-	-	-	ND	ND	Y	a15:0	MK10	Dab	64.5	+	-	Soil	PG, DPG	GQ406810
196	18	*Leifsonia rubra*	-	ND	-	-	-	+	-	R	a15:0	MK11	Dab	66	+	-	Mat	ND	AJ438585
197	19	*Marisediminicola antarctica**	-	ND	-	-	-	+	-	Y	a15:0	MK10	Orn	67	+	-	Sediment	PG, DPG	GQ496083
198	20	*Micrococcus antarcticus*	+	ND	-	-	-	ND	ND	Y	a15:0	MK8	Lys	64.4	+	-	Soil	ND	EF154512
199	21	*Micromonospora endolithica*	+	-	+	+	ND	ND	ND	Orange	I16:0	MK10	mDap	70	+	-	Sand stone	PE, PI, DPG	AJ560635
200	22	*Modestobacter multiseptatus**	+	ND	-	-	-	ND	+	Pink	18:0	MK9H2	mDap	69.9	+	-	Soil	PE, PG, DPG, PI	Y18646
201	23	*Nesterenkonia lacusekhoensis*	-	ND	-	-	ND	ND	ND	Y	a15:0	MK7	Lys	66.1	+	-	Water	PC, PG, DPG	AJ290397
202	24	*Nocardioides antarcticus*	-	ND	+	+	-	-	+	Cream	i16:0	MK8H4	mDap	66.7	+	-	Sediment	PG, DPG, UL3	KM347967
203	25	*Nocardioides aquaticus*	+	ND	ND	+	ND	ND	ND	-	I16:1	MK8H4	mDap	69	+	-	Water	ND	X94145
204	26	*Nocardiopsis fildesensis*	-	ND	-	-	-	ND	ND	-	i16:0	MK9H4	mDap	76.8	+		Soil	PC, PG, PME	FJ853144
205	27	*Pseudonocardia antarctica*	+	ND	-	+	+	+	+	Brown	I16:0	MK8H4	mDap	71	+	+	Moraine	PC, PE, PI, PG, DPG	AJ576010
206	28	*Rhodoglobus vestalii**	ND	ND	ND	-	-	+	+	Red	a15:0	MK12	Orn	62	+	-	Water	ND	AJ459101
207	29	*Sanguibacter antarcticus*	-	ND	-	-	-	-	-	Y	a15:0	MK9H4	ND	69.5	+	-	Sea Sand	ND	EF211071
208	30	*Streptomyces fildesensis*	-	ND	+	ND	-	ND	-	YG	I16:0	MK9H6	mDap	70	+	-	Soil	PE, PI, DPG, PME	DQ408297
209	31	*Streptomyces hypolithicus*	-	-	ND	+	-	ND	ND	-	ND	ND	mDap	ND	ND	ND	Quartz	ND	EU196762
		Deinococcus Thermus																	
210	1	*Deinococcus antarcticus*	+	ND	+	+	ND	+	+	Pink	18:1ω7c	MK8	L-Orn	63.1	+	-	Soil	ND	KC494323
211	2	*Deinococcus frigens*	+	ND	ND	+	-	+	ND	P-O	16:1ω9c	MK8	L-Orn	65.5	+	+	Soil	ND	AJ585981
212	3	*Deinococcus saxicola*	+	ND	ND	+	-	-	ND	P-R	16:1ω9c	MK8	L-Orn	54.4	+	+	Soil	ND	AJ585984
213	4	*Deinococcus marmoris*	-	-	ND	+	-	+	ND	P-R	16:1ω9c	MK8	L-Orn	62.8	+	+	Soil	ND	AJ585986

*, Genus; **, Family; A, amylase; C, cellulase; L, lipase; P, protease; U, urease; BG, Beta-galactosidase; Ph, phosphatase; Ca, catalse; O, oxidase; Pig, pigment (o, orange; y, yellow; r, red; cr, cream; w, white); MK, quinine type; FA; Fatty acid methyl ester major; DA, diamino acid in peptidoglycan; GC, G+C content of the DNA; H, habitat (S, soil; Sd, sediment; Wf, fresh water; Ws, sea water; I, ice). ND = not determined; '+' = Present, '–' = Absent

are pigmented, indicating that pigmentation is a common phenomenon in Antarctic bacteria. Pigment is known to be involved in stress adaptation to low temperatures (Jaganadham *et al*., 1996; Jaganadham *et al*., 2000; Chattopadyay *et al*., 1997).

Alphaproteobacteria contributed 10.5% of total novel species isolated so far and the 23 novel species belonged to 16 genera of which 12 were novel genera described from Antarctic habitats (Table 1). Six of the novel species contained Bacterial chlorophyll (Liu *et al*., 2014; Labrenz *et al*., 1999; Labrenz *et al*., 2000; Labrenz *et al*., 2005; Labrenz *et al*., 2009; Yu *et al*., 2011) and could exhibit photoautotrophic type of growth. Majority of the species produced Alkaline phosphatase and â-galactosidase but none of them secreted amylase while only 3 and 5 species exhibited the activity for protease and lipase, indicating that this group is responsible for the availability of phosphate in Antarctic habitats. The presence of pigment is a common phenomenon in all except in case of *Constrictibacter antarcticus* (Yamada *et al*., 2011). All the species contained their respective generic characteristics and the major fatty acid was $C_{18:1}\omega 7c$ and the respiratory quinine was Q10.

Unlike *Alphaproteobacteria*, only very few species of *Betaproteobacteria* were isolated and the reason could be the inadequate information on conducive media conditions. So far four novel species belonging to 4 different genera were reported out of which 2 were novel genera. The genus *Polaromonas vacuolata* (Irgens *et al*., 1996) possessed intracellular gas vesicles. The genus *Rhodoferax antarcticus* contained bacteriochlorophyll (Madigan *et al*., 2000). All the species possessed their respective generic characteristics and the major fatty acid and respiratory quinone was $C_{16:1}\omega 7c$ and Q8 respectively.

Species belonging to *Betaproteobacteria* were the second largest group explored from Antarctic habitats. So far close to 44 novel species belonging to 18 genera were described of which 6 were novel genera. The genera *Oleispira* (Yakimov *et al*., 2003) and *Methylosphaera* (Bowman *et al*., 1997) were endemic to Antarctica. Further, novel family, *Granulosicoccaceae,* was reported from Antarctic water (Lee *et al*., 2007). Majority of species produce phosphatase (70%) and lipase (64%) while enzymes protease (37.5%), urease (23.7%), β-galactosidase (22%) and amylase (16.7%) are produced by less than 50% of the novel species (Table 1). Some of the novel species were interesting wherein *Pseudomonas prydzensis* produces chitinase (Bowman *et al*., 1998), *Oleispira antarctica* can degrade hydrocarbons (Yakimov *et al*., 2003), cells of species *Saccharospirillum* are microaerophilic (Labrenz *et al*., 2003), *Methylosphaera hansonii* is a methanotroph (Bowman *et al*., 1997) and *Alteromonas stellipolaris* produces buds (Van Trappen *et al*., 2004).

CFB group of bacteria dominated various habitats of Antarctica (Bottos *et al*., 2014) and constitute 35% of novel species from Antarctica. Interestingly all the novel species isolated were pigmented and yellow pigmented bacteria were the most common. So far 73 novel species belonging to CFB group were described and they belonged to 27 genera out of which 12 were novel genera. In addition, species belonging to the genera *Antarcticimonas, Pricia, Sejongia* and *Subsaximicrobium* were endemic to Antarctica. Among all the bacterial phyla from Antarctica, CFB group plays an important role in nutrient recycling as they produce phosphatase (91.5%), protease (64.7%, lipase (57.6%), amylase (58.8%), β-galactosidase (30.3%) and urease (15.4%). Species of the genus *Polaribacter* exhibited filamentous morphology while members of *Gelidibacter, Psychroflexus* and *Subsaximicrobium* exhibited gliding motility compared to other members of the phylum. Further, *Flavobacterium frigidimaris, F. gillisiae* and *F. gondwanense* were found to be rich in chitinase production. The yellow pigment found in majority of the species of CFB group is a carotenoid pigment and pigment involvement in low temperature adaptation was well established (Jaganadham *et al*., 2000). The occurrence of pigment could be an important characteristic for the dominance of CFB members in Antarctic habitats compared to other group.

Novel species belonging to Firmicutes or Low G+C Gram-positive group contributed 13.8% (29 species) to the total unique species from Antarctica and 12 genera were the most common. The most common habit was soil but cyanobacterial mats also contained members of this group. Though most of the species were psychrophilic, this group also contained few moderately thermophilic species, *Alicyclobacillus pohliae* (42-60ºC) (Imperio *et al.*, 2008), *Aneurinibacillus terranovensis* (20-55ºC), (Allan *et al.*, 2005), *Anoxybacillus amylolyticus* (45-65ºC) (Poli *et al.*, 2006), *Bacillus fumrioli* (25-55ºC) (Logan *et al.*, 2000), *Brevibacillus levickii* (15-55ºC) (Allan *et al.*, 2005), *Paenibacillus cineris* (8-50ºC) and *Paenibacillus cookie* (15-50ºC) (Logan *et al.*, 2004). Some members of this group were unique wherein *Anoxybacillus amylolyticus* produce significant quantities of EPS and amylase (Poli *et al.*, 2006), *Carnobacterium* species produces lactic acid (Franzmann *et al.*, 1991) and *Clostridium schirmacherense* secretes proteases (Alam *et al.*, 2006). Further, members of *Exiguobacterium* possess a variety of phospholipids in their cell wall wherein they contained PE, PG, PI, PS, DPG in addition to some unknown lipids (Frühling *et al.*, 2002; Chaturvedi *et al.*, 2008).

Close to 31 novel species representing 16 genera of *Actinobacteria* were reported from various habitats of Antarctica (Table 1). Out of the 16 genera, six novel genera were described of which three genera *Barrientosiimonas* (Lee *et al.*, 2013), *Marisediminicola* (Li *et al.*, 2010) and *Rhodoglobus* (Sheridan *et al.*, 2003) were endemic to Antarctica. Some of the novel species are unique wherein *Arthrobacter cryotolerans* (Ganzert *et al.*, 2011) produces H_2S, *Arthrobacter psychrochitiniphilus* (Wang *et al.*, 2009) secretes cold active extracellular chitinase and *Sanguibacter antarcticus* (Hong *et al.*, 2008) makes melanin. Interestingly, extracellular restriction endonuclease activity was detected in *Modestobacter multiseptatus* (Mevs *et al.*, 2000). Majority of Actinobacterial species from Antarctica were pigmented indicating the role of the pigment in their survival at low temperatures. Some of the species possess unique lipids in their cell wall wherein PME (phosphatidyl methylethanolamine) and PMI (2,6,10,15,19-pentamethylicosane) are synthesized by *Nocardiopsis fildesensis* (Xu *et al.*, 2014) and *Streptomyces fildesensis* (Li *et al.*, 2011) respectively. Among all the species *Leifsonia rubra* (0 to 18) (Reddy *et al.*, 2003b) and *Rhodoglobus vestalii* (-2 to 21) (Sheridan *et al.*, 2003) are unique in having the true psychrophilic growth temperature.

The coldest and driest environmental conditions persisting in Antarctica also supported the inhabitation of desiccation and radiation resistant bacterial communities such as *Deinococcus*. So far, four novel species of the genus *Deinococcus* were explored and they are radiation resistant. All the species were psychrophilic and are capable of growing from 9 to 18ºC while *Deinococcus antarcticus* is a mesophile with a growth temperature range of 20 to 40ºC. All the novel species are pink to red colored with L-ornithine as the cell wall diamino acid. All the species possessed unique and unidentified lipids belonging to phosphoglycolipids, glycolipids, phospholipids and lipids. These exceptional lipids can be explored for the further industrial applications and may also have a role in desiccation and radiation tolerance.

Some Unique Features of Bacteria from Extreme Environments

A majority of bacterial isolates from Antarctica shared many common features with respect to growth wherein the maximum growth temperature was below 30ºC with very few exceptions such as *Alicyclobacillus pohliae, Aneurinibacillus terranovensis, Anoxybacillus amylolyticus, Bacillus thermantarcticus* and *Brevibacillus levickii* (Lama *et al.*, 1996; Allan *et al.*, 2005; Poli *et al.*, 2006; Imperio *et al.*, 2008). Earlier studies also revealed that the G+C content of 16S rRNA gene correlated with the growth temperature in prokaryotes. An elongation of helix 17 was observed in five out of eight true psychrophilic species of the genus *Rhodoglobus* (An *et al.*, 2010) and *Leifsonia rubra* (Reddy *et al.*, 2003b) whose growth temperature was below 20°C. Occurrence of 16S rDNA operons with psychrotolerant signatures, the transitions from C and G to T and A, higher uracil content and G:U mismatches from mesophilic to psychrotolerant, was reported in the strains of *Bacillus* (Prüss *et al.*, 1999; Lauro *et al.*, 2007). Further swollen sporangia were observed in psychrophilic strains of the genus *Bacillus* compared to their nearest mesophilic counterparts (Reddy *et al.*, 2008; Abd El-Rahman *et al.*, 2002; Larkin and Stokes, 1967; Priest *et al.*, 1988). Recently, Reddy *et al.*, (2015) identified occurrence of an additional aromatic amino acid, proline, in the CspA protein of *Kocuria polaris* and assisting in adaptation to low temperature.

Cold Adaptation of Antarctica Bacteria

Various survival mechanisms at extreme low temperatures have been reported in Antarctica bacteria and reviewed earlier (Finegold, 1986; Ray *et al*., 1998; Shivaji *et al*., 2007; Shivaji and Prakash, 2010; Singh *et al*., 2014; Chattopadhyay *et al*., 2014). Differential phosphorylation of lipopolysaccharides (low phosphorylation at low temperature) occurs in *Pseudomonas syringae,* an Antarctic psychrophilic bacterium, to modulate the permeability of outer membrane (Ray *et al*., 1994a). In addition, a temperature dependent hosphorylation and dephosphorylation was also demonstrated in *Pseudomonas syringae* wherein a 65 kDa protein was found to be phosphorylated at low temperature while the 30 kDa protein gets phosphorylated at high temperatures (Ray *et al*., 1994b). Further, several cold active enzymes have been studied in Antarctic bacteria and demonstrated the higher catalytic activity at low temperatures (Ray *et al*., 1992). Several extracellular enzymes have been characterized from Antarctic bacteria which include a protease (Ray *et al*., 1992), ribonuclease (Reddy *et al*., 1994), alkaline phosphatase (Chattopadhyay *et al*., 1995; Rina *et al*., 2000), subtilisin (Davail *et al*., 1994), beta-lactamase (Feller *et al*., 1997), citrate synthase (Russell *et al*., 1998), RNA polymerase (Uma *et al*., 1999), DNA ligase (Georlette *et al*., 2000), β-galactosidase (Hoyoux *et al*., 2001) and lipase (de Pascale *et al*., 2008; Ali *et al*., 2013). All above enzyme were catalytically active at low temperature and were heat-labile. The flexibility in activity at low temperature for enzymes from Antarctic bacteria were due to their unique structural features wherein the enzymes exhibited fewer residues of proline or arginine, decrease in hydrophobic residues and disulfide bonds and increase in polar amino acids (Gerday *et al*., 2000; Metpally and Reddy 2009; D'Amico *et al*., 2002).

The survival of Antarctic bacteria was also due to the homeoviscous adaptation of membrane fluidity. At low temperatures the membrane fluidity was maintained by changing the fatty acid composition wherein the unsaturated fatty acids, short chained and branched fatty acids are synthesized in response to low temperature (Chintalapati *et al*., 2004). Further, the cold inducible desaturases that convert saturated fatty acids to unsaturated fatty acids were also responsible (Chintalapati *et al*., 2006; Chintalapati *et al*., 2007) for adaptation of Antarctic bacteria. In addition, the role of *cis-trans* isomerase was also implicated in maintaining the membrane fluidity in Antarctic bacteria (Kiran *et al*., 2005). Further, the increased syntheses of polar carotenoids were observed in maintaining the homeovisous status of the membranes (Jagannadham *et al*., 1991; Jagannadham *et al*., 1996; Chattopadhyay *et al*., 1997).

Besides several genes and promoters involved in cold adaptation of Antarctic bacteria were explored. An amino acyltransferase (Sundareswaran *et al*., 2010), trmE coding for GTPase (Singh *et al*., 2009), hutU operon (Janiyani and Ray, 2002), rpoS (Jovcic *et al*., 2008), RecBCD (Pavankumar *et al*., 2010) gene were known to be up regulated during the cold growth. In addition several cold inducible promoters resposnsible for regulation of genes at low temperature were identified (Duilio *et al*., 2004).

Our group has recently reported the genome sequence of a number of psychrophiles from different cold habitats like Antarctica (Sreenivas *et al*., 2014; Reddy *et al*., 2013; Kumar *et al*., 2013 a), Arctic (Shivaji *et al*., 2013a; 2013b; Kumar *et al*., 2013 b), Himalayan glaciers (Reddy *et al*., 2014) and Stratosphere (Shivaji *et al*., 2012). A comparative genome analysis of Csps in the psychrophilic *Sphingobacterium antarcticum*, *Oceanisphaera arctica* and *Exiguobacterium indicum* indicated that CspA was present in all of them, Csp C, D, E and G were present in at least one of the 3 isolates whereas Csp B and I were absent (unpublished). The implications of this observation with respect to cold adaptation warrant further studies. Comparative genome analysis of psychrophiles besides providing information on the role of specific genes in cold adaptation would promise insight into the adaptive response of bacteria to other stressors (viz high salt, high and low pH).

Biotechnological Potential of Antarctica Bacteria

Cold-active and/or thermolabile enzymes obtained from cold-tolerant organisms are of immense biotechnological importance. A thermolabile phosphatase, from an Antarctic bacterium has been used for restriction enzyme digestion, dephosphorylation, enzyme inactivation, and ligation or end-labelling. In addition cold-active proteases are suitable for food processing and in leather industries and are also useful in laundries for removal of stains. Cold-adapted bacteria are capable of degrading hydrocarbons (Margesin and Schinner, 2001; Powell *et al*., 2006; Shukor *et al*., 2009; Timmis *et al*., 2010) but some hydrocarbons like asphalt are recalcitrant in nature and resist microbial degradation (Kimes *et al*., 2014). Microorganisms having the capacity to degrade PCBs have also been isolated from both the Arctic and Antarctic regions (Master and Mohan 1998; De Dominico *et al*., 2004). Several strains are also known to produce lipases useful in lipase-mediated biodiesel production (Moreno and Rojo, 2014).

Conclusion

Microorganisms are a bioresource and the workhorses of biotechnology. Further extremophiles like the ones that survive under freezing temperatures are all the more important due to their ability to carry out biological processes under extreme freezing temperatures. This review focuses on the bacterial biodiversity of different habitats of Antarctica and explores their capability to survive under freezing condition and highlights their biotechnological potential.

References

Abd El-Rahman H A, Fritze D, Spröer C and Claus D (2002) Two novel psychrotolerant species, *Bacillus psychrotolerans* sp. nov. and *Bacillus psychrodurans* sp. nov., which contain ornithine in their cell walls *Int J Syst Evol Microbiol* **52** 2127-2133

Aislabie J M, Chhour K L, Saul D J, Miyauchi S, Ayton J, Paetzold R F and Balks M R (2006) Dominant bacteria in soils of Marble Point and Wright Valley, Victoria Land, Antarctica *Soil Biol Biochem* **38** 3041-3056

Aislabie J, Jordan S, Ayton J, Klassen J L, Barker G M and Turner S (2009) Bacterial diversity associated with ornithogenic soil of the Ross Sea region, Antarctica *Can J Microbiol* **55** 21-36

Aislabie J M, Lau A, Dsouza M, Shepherd C, Rhodes P and Turner S J (2013) Bacterial composition of soils of the Lake Wellman area, Darwin Mountains, Antarctica *Extremophiles* **17** 775-786

Alam S I, Dixit A, Reddy G S, Dube S, Palit M, Shivaji S and Singh L (2006) *Clostridium schirmacherense* sp. nov., an obligately anaerobic, proteolytic, psychrophilic bacterium isolated from lake sediment of Schirmacher Oasis, Antarctica *Int J Syst Evol Microbiol* **56** 715-20

Ali M S, Ganasen M, Rahman R N, Chor A L, Salleh A B and Basri M (2013) Cold-adapted RTX lipase from Antarctic *Pseudomonas* sp. strain AMS8: isolation, molecular modeling and heterologous expression *Protein J* **32** 317-25

Allan R N, Lebbe L, Heyrman J, De Vos P, Buchanan C J and Logan N A (2005) *Brevibacillus levickii* sp. nov. and *Aneurinibacillus terranovensis* sp. nov., two novel thermoacidophiles isolated from geothermal soils of northern Victoria Land, Antarctica *Int J Syst Evol Microbiol* **55** 1039-1050

An S Y, Xiao T and Yokota A (2010) Reclassification of *Leifsonia aurea* to the genus *Rhodoglobus* as *Rhodoglobus aureus* comb. nov., and emended description of *Rhodoglobus vestalii* Sheridan *et al*. 2003 *J Gen Appl Microbiol* **56** 53-5

Antibus D E, Leff L G, Hall B L, Baeseman J L and Blackwood C B (2012) Cultivable bacteria from ancient algal mats from the McMurdo Dry Valleys, Antarctica *Extremophiles* **16** 105-114

Archer S D, McDonald I R, Herbold C W and Cary S C (2014) Characterisation of bacterioplankton communities in the meltwater ponds of Bratina Island, Victoria Land, Antarctica *FEMS Microbiol Ecol* **89** 451-464

Bajerski F and Wagner D (2013) Bacterial succession in Antarctic soils of two glacier forefields on Larsemann Hills, East Antarctica *FEMS Microbiol Ecol* **85** 128-142

Bottos E M, Woo A C, Zawar-Reza P, Pointing S B and Cary S C (2014) Airborne bacterial populations above desert soils of the McMurdo Dry Valleys, Antarctica *Microb Ecol* **67** 120-128

Bowman J P, McCammon S A, Brown M V, Nichols D S and McMeekin T A (1997) Diversity and association of psychrophilic bacteria in Antarctic sea ice *Appl Environ Microbiol* **63** 3068-3078

Bowman J P, Gosink J J, McCammon S A, Lewis T E, Nichols D S, Nichols P D, Skerratt J H, Staley J T and McMeekin T A (1998) *Colwellia demingiae* sp. nov., *Colwellia hornerae* sp. nov., *Colwellia rossensis* sp. nov. and *Colwellia psychrotropica* sp. nov.: psychrophilic Antarctic species with the ability to synthesize docosahexanoic acid (22:6 omega 3) *Int J Syst Bacterial* **48** 1171-1180

Bowman J P, Rea S M, McCammon S A and McMeekin T A (2000) Diversity and community structure within anoxic sediment from marine salinity meromictic lakes and a coastal meromictic marine basin, Vestfold Hilds, Eastern Antarctica *Environ Microbiol* **2** 227-237

Boyd W L (1962) Comparison of soil bacteria and their metabolic activities in Arctic and Antarctic regions *Polar Rec* **11** 319

Boyd W L and Boyd J W (1962) Presence of *Azotobacter* species in polar regions *J Bacteriol* **85** 1121-1123

Bozal N, Montes M J and Mercadé E (2007) *Pseudomonas guinea* sp. nov., a novel psychrotolerant bacterium from an Antarctic environment *Int J Syst Evol Microbiol* **57** 2609-2612

Brinkmeyer R, Knittel K, J¨urgens J, Weyland H, Amann R and Helmke E (2003) Diversity and structure of bacterial communities in Arctic versus Antarctic pack ice *Appl Environ Microbiol* **69** 6610-6619

Brown M V and Bowman J P (2001) A molecular phylogenetic survey of sea-ice microbial communities (SIMCO) *FEMS Microbiol Ecol* **35** 267-275

Campbell I B and Claridge G G C (2000) In: Antarctic Ecosystems: Models for Wider Understanding, W. Davidson, C. Howard-Williams and P. Broady (eds.)

Carpenter E J, Lin S and Capone D G (2000) Bacterial activity in South Pole snow *Appl Environ Microbiol* **66** 4514-4517

Carr S A, Vogel S W, Dunbar R B, Brandes J, Spear J R, Levy R, Naish T R, Powell R D, Wakeham S G and Mandernack K W (2013) Bacterial abundance and composition in marine sediments beneath the Ross Ice Shelf, Antarctica *Geobiology* **11** 377-395

Cavanagh J, Austin J J and Sanderson K (1996) Novel *Psychrobacter* species from Antarctic ornithogenic soils *Int J Syst Bacterial* **46** 841-848

Cavicchioli R and Thomas T (2000) Extremophiles. ln. Encyclopedia of Microbiology. Second Edition (J. Lederberg, Ed.), Vol 2, p 317-337, Academic Press, San Diego

Chaturvedi P, Prabahar V, Manorama R, Pindi P K, Bhadra B, Begum Z and Shivaji S (2008) *Exiguobacterium soli* sp. nov., a psychrophilic bacterium from the McMurdo Dry Valleys, Antarctica *Int J Syst Evol Microbiol* **58** 2447-53

Chattopadhyay M K, Uma Devi K, Gopishankar Y and Shivaji S (1995) Thermolabile alkaline phosphatase from *Sphingobacterium antarcticus*, a psychrotrophic bacterium from Antarctica *Polar Biol* **15** 215-219

Chattopadhyay M K, Jagannadham M V, Vairamani M and Shivaji S (1997) Carotenoid pigments of an antarctic psychrotrophic bacterium *Micrococcus roseus*: temperature dependent biosynthesis, structure, and interaction with synthetic membranes *Biochem Biophys Res Commun* **239** 85-90

Chattopadhyay M K, Reddy, G S N and Shivaji S (2014) Psychrophilic bacteria: Biodiversity, Molecular basis of cold adaptation and biotechnological implications *Curr Biotech* **3** 100-116

Chessa J P, Petrescu I, Bentahir M, Van Beeumen J and Gerday C (2000) Purification, physico-chemical characterization and sequence of a heat labile alkaline metalloprotease isolated from a psychrophilic *Pseudomonas* species *Biochim Biophys Acta* **1479** 265-274

Chintalapati S, Kiran M D and Shivaji S (2004) Role of membrane lipid fatty acids in cold adaptation *Cell Mol Biol* (Noisy-le-grand) **50** 631-42

Chintalapati S, Prakash J S, Gupta P, Ohtani S, Suzuki I, Sakamoto T, Murata N and Shivaji S (2006) A novel Delta9 acyl-lipid desaturase, DesC2, from cyanobacteria acts on fatty acids esterified to the sn-2 position of glycerolipids *Biochem J* **398** 207-14

Chintalapati S, Prakash J S, Singh A K, Ohtani S, Suzuki I, Murata N and Shivaji S (2007) Desaturase genes in a psychrotolerant *Nostoc* sp. are constitutively expressed at low temperature *Biochem Biophys Res Commun* **362** 81-7

Claridge G G C and *Campbell* I B (*1977)* The salts in Antarctic soils, their distribution and relationship to soil processes *Soil Sci* **123** 377-384

Cristóbal H A, López M A, Kothe E and Abate C M (2011) Diversity of protease-producing marine bacteria from sub-antarctic environments *J Basic Microbiol* **51** 590-600

D'Amico S, Claverie P, Collins T, Georlette D, Gratia E, Hoyoux A, Meuwis M A, Feller G and Gerday C (2002) Molecular basis of cold adaptation. *Philos Trans R Soc Lond B Biol Sci* **357** 917-25

Davail S, Feller G, Narinx E and Gerday C (1994) Cold adaptation of proteins. Purification, characterization, and sequence of the heat-labile subtilisin from the antarctic psychrophile *Bacillus* TA41 *J Biol Chem* **269** 17448-53

Delille D and Lagarde E (1974) Contribution a!'etude ecologique des Milieux subantarctiques *V Rev lnst Pasteur Lyon* **7** 149-165

Deming J W and Eicken H (2007) Life in ice. In: Baross, J. and W. Sullivan (eds.*)* Planets and life – The emerging science of astrobiology, Cambridge University Press, Cambridge, p 292-312

De Domenico M, Lo Giudice A, Michaud L, Saitta M and Bruni V (2004) Diesel oil and PCB- degrading psychrotrophic bacteria isolated from Antarctic seawaters (Terra Nova Bay, Ross Sea) *Polar Research* **23** 141-146

Delille D and Gleizon F (2003) Distribution of enteric bacteria in

Antarctic seawater surrounding the Port-aux-Français permanent station (Kerguelen Island) *Mar Pollut Bull* **46** 1179-1183

Denner E B M, Mark B, Busse H J, Turkiewicz M and Lubitz W (2001) *Psychrobacter proteolyticus* sp. nov., a psychrotrophic, halotolerant bacterium isolated from the Antarctic Krill *Euphausia superba* Dana, Excreting a cold-adapted metalloprotease *Syst Appl Microbiol* **24** 44-53

de Pascale D, Cusano A M, Autore F, Parrilli E, di Prisco G, Marino G and Tutino M L (2008) The cold-active Lip1 lipase from the Antarctic bacterium *Pseudoalteromonas haloplanktis* TAC125 is a member of a new bacterial lipolytic enzyme family *Extremophiles* **12** 311-23

Doyle S M, Montross S N, Skidmore M L and Christner B C (2013) Characterizing microbial diversity and the potential for metabolic function at -15°C in the Basal ice of taylor glacier, antarctica *Biology* (Basel) **2** 1034-1053

Duilio A, Madonna S, Tutino M L, Pirozzi M, Sannia G and Marino G (2004) Promoters from a cold-adapted bacterium: definition of a consensus motif and molecular characterization of UP regulative elements *Extremophiles* **8** 125-32

Ekelof E (1908a) Bakteriologische studien wahrend der Schwedishen Sudpolar expedition 1901-1903. In: Wissenschaftiche Ergebnisse der Schwedischen sudpolar Expedition 1901-1903. 0. Nordenskjold (ed.) Lithogr. lnst.Generalstabs, Stockholm.210

Ekelof E (1908b) Studien uber den Bakteriengehalt der luft und des Erdbodeus der antarktishen Gegenden, ausgefiihrt wahrend der schwedischen sudpolar expedition 1901-1903. *ZHyg lnfekt* **56** 344-370

Feller G, Zekhnini Z, Lamotte-Brasseur J and Gerday C (1997) Enzymes from cold-adapted microorganisms. The class C beta-lactamase from the antarctic psychrophile *Psychrobacter immobilis* A5 *Eur J Biochem* **244** 186-91

Finegold L (1986) Molecular aspects of adaptation to extreme cold environments *Adv Space Res* **6** 257-64

Frühling A, Schumann P, Hippe H, Sträubler B and Stackebrandt E (2002) *Exiguobacterium undae* sp. nov. and *Exiguobacterium antarcticum* sp. nov *Int J Syst Evol Microbiol* **52** 1171-6

Franzmann P D, Deprez P P, MeGuire A J, McMeekin T A and Burton H R (1990) The Heterotrophic, Bacterial Microbiota of Burton Lake, Antarctica *Polar Biol* **10** 261-264

Franzmann P D, Höpfl P, Weiss N and Tindall B J (1991) Psychrotrophic, lactic acid-producing bacteria from anoxic waters in Ace Lake, Antarctica; *Carnobacterium funditum* sp. nov. and *Carnobacterium alterfunditum* sp. nov *Arch Microbiol* **156** 255-62

Franzmann P D and Dobson S J (1992) Cell wall-less, free-living spirochetes in Antarctica *FEMS Microbiol Lett* **76** 289-292

Friedman E 1 (1980) Endolithic microbial life in hot and cold deserts *Orig Life* 10 223-235

Ganzert L, Bajerski F, Mangelsdorf K, Lipski A and Wagner D (2011) *Arthrobacter livingstonensis* sp. nov. and *Arthrobacter cryotolerans* sp. nov., salt-tolerant and psychrotolerant species from Antarctic soil *Int J Syst Evol Microbiol* **61** 979-84

Gazert H (1912) Undersuchungen uber Meeresbakterien und chren Einfluss auf den Stoffwecksel im Meer. Deutschi biidpolar expedition. 1901-1903 Berlin, **7** 268-296

Georlette D, Jónsson Z O, Van Petegem F, Chessa J, Van Beeumen J, Hübscher U and Gerday C (2000) A DNA ligase from the psychrophile *Pseudoalteromonas haloplanktis* gives insights into the adaptation of proteins to low temperatures *Eur J Biochem* **267** 3502-12

Gerday C, Aittaleb M, Bentahir M, Chessa J P, Claverie P, Collins T, D'Amico S, Dumont J, Garsoux G, Georlette D, Hoyoux A, Lonhienne T, Meuwis M A and Feller G (2000) Cold-adapted enzymes: from fundamentals to biotechnology *Trends Biotechnol* **18** 103-7

Gosink J J, Woese C R and Staley J T (1998) *Polaribacter* gen. nov., with three new species, *P. irgensii* sp. nov., *P. franzmannii* sp. nov., and *P. filamentus* sp. nov., gas vacuolate polar marine bacteria of the Cytophaga-Flavobacterium-Bacteroides group and reclassification of *Flectobacillus glomeratus* as *Polaribacter glomeratus* comb. nov *Int J Syst Bacteriol* **48** 223-235

Guibert L M, Loviso C L, Marcos M S, Commendatore M G, Dionisi H M and Lozada M (2012) Alkane biodegradation genes from chronically polluted subantarctic coastal sediments and their shifts in response to oil exposure *Microb Ecol* **64** 605-616

Helmke E and Weyland H (2004) Psychrophilic versus psychrotolerant bacteria-occurrence and significance in polar and temperate marine habitats *Cell Mol Biol* **50** 553-561

Herbert R A and Bell C R (1977) Growth characteristics of an obligately psychrophilic *Vibrio* sp *Arch Microbiol* **113** 215-20

Hirsch P, Mevs U, Kroppenstedt R M, Schumann P and Stackebrandt E (2004) Cryptoendolithic actinomycetes from antarctic sandstone rock samples: *Micromonospora endolithica* sp. nov. and two isolates related to

Micromonospora coerulea Jensen 1932 *Syst Appl Microbiol* **27** 166-174

Hong S G, Lee Y K, Yim J H, Chun J and Lee H K (2008) *Sanguibacter antarcticus* sp. nov., isolated from Antarctic sea sand *Int J Syst Evol Microbiol* **58** 50-2

Hoyoux A, Jennes I, Dubois P, Genicot S, Dubail F, François J M, Baise E, Feller G and Gerday C (2001) Cold-adapted beta-galactosidase from the Antarctic psychrophile *Pseudoalteromonas haloplanktis Appl Environ Microbiol* **67** 1529-35

Huang Y, Zhang J and Zhu L (2013) Evaluation of the application potential of bentonites in phenanthrene bioremediation by characterizing the biofilm community *Bioresour Technol* **134** 17-23

Imperio T, Viti C and Marri L (2008) *Alicyclobacillus pohliae* sp. nov., a thermophilic, endospore-forming bacterium isolated from geothermal soil of the north-west slope of Mount Melbourne (Antarctica) *Int J Syst Evol Microbiol* **58** 221-225

Irgens R L, Gosink J J and Staley J T (1996) *Polaromonas vacuolata* gen. nov., sp. nov., a psychrophilic, marine, gas vacuolate bacterium fromAntarctica *Int J Syst Bacteriol* **46** 822-6

Jagannadham M V, Rao V J and Shivaji S (1991) The major carotenoid pigment of a psychrotrophic *Micrococcus roseus* strain: purification, structure, and interaction with synthetic membranes *J Bacteriol* **173** 7911-7

Jagannadham M V, Chattopadhyay M K and Shivaji S (1996) The major carotenoid pigment of a psychrotrophic *Micrococcus roseus* strain: fluorescence properties of the pigment and its binding to membranes *Biochem Biophys Res Commun* **220** 724-8

Jagannadham M V, Chattopadhyay M K, Subbalakshmi C, Vairamani M, Narayanan K, Rao C M and Shivaji S (2000) Carotenoids of an Antarctic psychrotolerant bacterium, *Sphingobacterium antarcticus*, and a mesophilic bacterium, *Sphingobacterium multivorum*. *Arch Microbiol* **173** 418-24

Janiyani K L and Ray M K (2002) Cloning, sequencing, and expression of the cold-inducible hutU gene from the antarctic psychrotrophic bacterium *Pseudomonas syringae Appl Environ Microbiol* **68** 1-10

Jovcic B, Bertani I, Venturi V, Topisirovic L and Kojic M (2008) 5' Untranslated region of the Pseudomonas putida WCS358 stationary phase sigma factor rpoSmRNA is involved in RpoS translational regulation *J Microbiol* **46** 56-61

Junge K, Imhoff F, Staley T and Deming J W (2002) Phylogenetic diversity of numerically important Arctic sea-ice bacteria cultured at subzero temperature *Microb Ecol* **43** 315-328

Junge K, Eicken H and Deming J W (2004) Bacterial activity at –2 to –20°C in Arctic wintertime sea ice *Appl Environ Microbiol* **70** 550-557

Karl D M, Bird D F, Björkman K, Houlihan T, Shackelford R and Tupas L (1999) Microorganisms in the accreted ice of Lake Vostok, Antarctica *Science* **286** 2144-2147

Karr E A, Sattley W M, Jung D O, Madigan M T and Achenbach L A (2003) Remarkable diversity of phototrophic purple bacteria in a permanently frozen Antarctic lake *Appl Environ Microbiol* **69** 4910-4914

Karr E A, Sattley W M, Rice M R, Jung D O, Madigan M T and Achenbach L A (2005) Diversity and distribution of sulfate-reducing bacteria in permanently frozen Lake Fryxell, McMurdo Dry Valleys, Antarctica *Appl Environ Microbiol* **71** 6353-6359

Kelly M D, Lukaschewsky S and Anderson C G (1978) Bacterial flora of Antarctic krill and some of their enzymatic properties *J Food Sci* **43** 1196-1197

Kim J G, Park S J, Quan Z X, Jung M Y, Cha I T, Kim S J, Kim K H, Yang E J, Kim Y N, Lee S H and Rhee S K (2014) Unveiling abundance and distribution of planktonic Bacteria and Archaea in a polynya in Amundsen Sea, Antarctica *Environ Microbiol* **16** 566-578

Kimes N E, Callaghan A V, Suflita J M and Morris P J (2014) Microbial transformation of the Deepwater Horizon oil spill-past, present, and future perspectives *Front Microbiol* **5** 603

Kiran M D, Annapoorni S, Suzuki I, Murata N and Shivaji S (2005) Cis-trans isomerase gene in psychrophilic *Pseudomonas syringae* is constitutively expressed during growth and under conditions of temperature and solvent stress *Extremophiles* **9** 117-25

Kong W, Li W, Romancova I, Prášil O and Morgan-Kiss R M (2014) An integrated study of photochemical function and expression of a key photochemical gene (psbA) in photosynthetic communities of Lake Bonney (McMurdo Dry Valleys, Antarctica) *FEMS Microbiol Ecol* **89** 293-302

Kuhn E, Bellicanta G S and Pellizari V H (2009) New *alk* genes detected in Antarctic marine sediments *Environ Microbiol* **11** 669-673

Kuhn E, Ichimura A S, Peng V, Fritsen C H, Trubl G, Doran P T and Murray A E (2014) Brine assemblages of ultra small microbial cells within the ice cover of Lake Vida, Antarctica *Appl Environ Microbiol* **80** 3687-3698

Kumar P A, Sreenivas A, Aditya Singh and Shivaji S (2013a) Draft genome sequence of *Winogradskyella psychrotolerans* RS-3T, isolated from the marine transect of Kongsfjorden, Ny-Ålesund, Svalbard, Arctic *Genome Announc* **1** e00630-13

Kumar P A, Aditya Singh, Sreenivas A, Begum Z, Reddy G S N and Shivaji S (2013b) Draft genome sequence of *Leifsoniarubra* CMS 76R T, isolated from a cyanobacterial mat sample from a pond in Wright Valley, McMurdo, Antarctica *Genome Announc* **1** e00633-13

Labrenz M, Collins M D, Lawson P A, Tindall B J, Schumann P and Hirsch P (1999) *Roseovarius tolerans* gen. nov., sp. nov., a budding bacterium with variable bacteriochlorophyll a production from hypersaline Ekho Lake *Int J Syst Bacteriol* **49** 137-47

Labrenz M, Tindall B J, Lawson P A, Collins M D, Schumann P and Hirsch P (2000) *Staleya guttiformis* gen. nov., sp. nov. and *Sulfitobacter brevis* sp. nov., alpha-3-Proteobacteria from hypersaline, heliothermal and meromictic Antarctic Ekho Lake *Int J Syst Evol Microbial* **50** 303-313

Labrenz M, Lawson P A, Tindall B J, Collins M D and Hirsch P (2003) *Saccharospirillum impatiens* gen. nov., sp. nov., a novel gamma-Proteobacterium isolated from hypersaline Ekho Lake (East Antarctica) *Int J Syst Evol Microbiol* **53** 653-60

Labrenz M, Lawson P A, Tindall B J, Collins M D and Hirsch P (2005) *Roseisalinus antarcticus* gen. nov., sp. nov., a novel aerobic bacteriochlorophyll a-producing alpha-proteobacterium isolated from hypersaline Ekho Lake, Antarctica *Int J Syst Evol Microbiol* **55** 41-7

Labrenz M, Lawson P A, Tindall B J and Hirsch P (2009) *Roseibaca ekhonensis* gen. nov., sp. nov., an alkalitolerant and aerobic bacteriochlorophyll a-producing alphaproteobacterium from hypersaline Ekho Lake *Int J Syst Evol Microbiol* **59** 1935-40

Lama L, Nicolaus B, Calandrelli V, Esposito E and Gambacorta A (1996) Xylanase produced by *Bacillus thermoantarcticus,* a new thermophilic bacillus *Enzyme Eng* **XIII** 284-286

Lanoil B, Skidmore M, Priscu J C, Han S, Foo W, Vogel S W, Tulaczyk S and Engelhardt H (2009) Bacteria beneath the West Antarctic ice sheet *Environ Microbiol* **11** 609-615

Larkin J M and Stokes J L (1967) Taxonomy of psychrophilic strains of *Bacillus J Bacteriol* **94** 889-895

Laucks M L, Sengupta A, Junge K, Davis E J and Swan-son B D (2005) Comparison of psychro-active Arctic marine bacteria and common mesophilic bacteria using surface-enhanced Raman spectroscopy *Appl Spectr* **10** 1222-1228

Lauro F M, Chastain R A, Blankenship L E, Yayanos A A and Bartlett D H (2007) The unique 16S rRNA genes of piezophiles reflect both phylogeny and adaptation *Appl Environ Microbiol* **73** 838-845

Lee K, Lee H K, Choi T H, Kim K M and Cho J C (2007) *Granulosicoccaceae* fam. nov., to include *Granulosicoccus antarcticus* gen. nov., sp. nov., a non-phototrophic, obligately aerobic chemoheterotroph in the order Chromatiales, isolated from Antarctic seawater *J Microbiol Biotechnol* **17** 1483-1490

Lee C K, Barbier B A, Bottos E M, McDonald I R and Cary S C (2012) The Inter-Valley Soil Comparative Survey: the ecology of Dry Valley edaphic microbial communities *ISME J* **6** 1046-1057

Lee L H, Cheah Y K, Sidik S M, Xie Q Y, Tang Y L, Lin H P, Mutalib N S and Hong K (2013) *Barrientosiimonas humi* gen. nov., sp. nov., an actinobacterium of the family *Dermacoccaceae Int J Syst Evol Microbiol* **63** 241-8

Li H R, Yu Y, Luo W and Zeng Y X (2010) *Marisediminicola antarctica* gen. nov., sp. nov., an actinobacterium isolated from the Antarctic *Int J Syst Evol Microbiol* **60** 2535-9

Li S, Xiao X, Yin X and Wang F (2006) Bacterial community along a historic lake sediment core of Ardley island west Antarctica *Extremophile* **10** 461-467

Li J, Tian X P, Zhu T J, Yang L L and Li W J (2011) *Streptomyces fildesensis* sp. nov., a novel streptomycete isolated from Antarctic soil.*Antonie Van Leeuwenhoek* **100** 537-43

Liu C, Zhang X Y, Su H N, Zhou M Y, Chen B, Li H, Chen X L, Zhao D L, Zhou B C, Shi M, Zhang Y Z (2014) *Puniceibacterium antarcticum* gen. nov., sp. nov., isolated from seawater *Int J Syst Evol Microbiol* **64** 1566-72

Logan N A, Lebbe L, Hoste B, Goris J, Forsyth G, Heyndrickx M, Murray B L, Syme N, Wynn-Williams D D and De Vos P (2000) Aerobic endospore-forming bacteria from geothermal environments in northern Victoria Land,Antarctica, and Candlemas Island, South Sandwich archipelago, with the proposal of *Bacillus fumarioli* sp. nov *Int J Syst Evol Microbiol* **50** 1741-53

Logan N A, De Clerck E, Lebbe L, Verhelst A, Goris J, Forsyth G, Rodríguez-Díaz M, Heyndrickx M and De Vos P (2004) *Paenibacillus cineris* sp. nov. and *Paenibacillus cookii* sp. nov., from Antarctic volcanic soils and a gelatin-processing plant *Int J Syst Evol Microbiol* **54** 1071-6

Lo Giudice A, Caruso C, Mangano S, Bruni V, De Domenico M and Michaud L (2012) Marine bacterioplankton diversity and community composition in an antarctic coastal environment *Microb Ecol* **63** 210-223

Maas E W, Simpson A M, Martin A, Thompson S, Koh E Y, Davy S K, Ryan K G and O'Toole R F (2012) Phylogenetic analyses of bacteria in sea ice at Cape Hallett, Antarctica *N Z J Mar Freshw Res* **46** 3-12

Madigan M T, Jung D O, Woese C R and Achenbach L A (2000) *Rhodoferax antarcticus* sp. nov., a moderately psychrophilic purple nonsulfur bacterium isolated from an Antarctic microbial mat *Arch Microbiol* **173** 269-77

Magalhães C M, Machado A, Frank-Fahle B, Lee C K and Cary S C (2014) The ecological dichotomy of ammonia-oxidizing archaea and bacteria in the hyper-arid soils of the Antarctic Dry Valleys *Front Microbiol* **5** 515

Marcos M S, Lozada M and Dionisi H M (2009) Aromatic hydrocarbon degradation genes from chronically polluted Subantarctic marine sediments *Lett Appl Microbiol* **49** 602-608

Margesin R and Schinner F (2001) Biodegradation and bioremediation of hydrocarbons in extreme environments *Appl Microbiol Biotechnol* **56** 650-663

Margini R A and Castrelos O D (1963) *Examenes bacteriologicos* de aire, rieve y suelo de carbo primaruera y Estacion cientifica Ellsworth *Inst Antarcti Argent Publ* **76** 1-15

Margini R A and Castrelos O D (1965) Las bacterias del Antarctico y su relacion con la epoca del ano contrib *Inst Antarct Argent* **141** 1-19

Marshall B J and Ohye D F (1966) *Bacillus macquariensis* sp. nov, a psychrotrophic bacterium from sub-antarctic soil *J Gen Microbiol* **44** 41-6

Master E R and Mohn W W (1998) Psychrotolerant bacteria Isolated from Arctic Soil that degrade polychlorinated biphenyls at low temperatures *Appl Environ Microbiol* **64** 4823-4829

McLean A L (1918a) Bacteria of ice and snow in Antarctica *Nature* **102** 35-39

McLean A L (1918b) Bacteriological and other researches Australian Antarctic Expedition 1911-1914 *Scient Rep* **7** 1-128

Metpally R P and Reddy B V (2009) Comparative proteome analysis of psychrophilic versus mesophilic bacterial species: Insights into the molecular basis of cold adaptation of proteins *BMC Genomics* **10** 11

Mevs U, Stackebrandt E, Schumann P, Gallikowski C A and Hirsch P (2000) *Modestobacter multiseptatus* gen. nov., sp. nov., a budding actinomycete from soils of the Asgard Range (Transantarctic Mountains) *Int J Syst Evol Microbiol* **50** 337-46

Meyer G H, Morrow M B, Wyss O, Berg T E and Littlepage J L (1962) Antarctica: The microbiology of an unfrozen saline pond *Science* **138** 1103-4

Michaud L, Caruso C, Mangano S, Interdonato F, Bruni V and Lo Giudice A (2012) Predominance of *Flavobacterium*, *Pseudomonas*, and *Polaromonas* within the prokaryotic community of freshwater shallow lakes in the northern Victoria Land, East Antarctica *FEMS Microbiol Ecol* **82** 391-404

Miwa T (1975) Clostridia in soil of the Antarctica *Jpn J Med Sci Biol* **28** 201-213

Moreno R and Rojo F (2014) Features of pseudomonads growing at low temperatures: another facet of their versatility *Environ Microbiol Rep* **6** 417-426

Morita RY (1975) Psychrophilic Bacteria *Bacteriol Rev* **39** 144-167

Muangchinda C, Chavanich S, Viyakarn V, Watanabe K, Imura S, Vangnai A S and Pinyakong O (2014) Abundance and diversity of functional genes involved in the degradation of aromatic hydrocarbons in Antarctic soils and sediments around Syowa Station *Environ Sci Pollut Res* **22** 4725-4735

Niederberger T D, McDonald I R, Hacker A L, Soo R M, Barrett J E, Wall D H and Cary S C (2008) Microbial community composition in soils of Northern Victoria Land, Antarctica *Environ Microbiol* **10** 1713-1724

Pavankumar T L, Sinha A K and Ray M K (2010) All three subunits of RecBCD enzyme are essential for DNA repair and low-temperature growth in the Antarctic Pseudomonas syringae Lz4W *PLoS One* **5** e9412

Peeters K, Hodgson D A, Convey P and Willems A (2011) Culturable diversity of heterotrophic bacteria in Forlidas Pond (Pensacola Mountains) and Lundström Lake (Shackleton Range), Antarctica *Microb Ecol* **62** 399-413

Pfiser R M and Burkholder P R (1965) Numerical taxonomy of some bacteria isolated from Antarctic and tropical sea waters *J Bacterial* **90** 863-872

Pirie J H H (1904) First Antarctic voyage of the Scotia *J Bacterial Scottish Geog Mag* **20** 129-132

Poli A, Esposito E, Lama L, Orlando P, Nicolaus G, de Appolonia F, Gambacorta A and Nicolaus B (2006) *Anoxybacillus amylolyticus* sp. nov., a thermophilic amylase producing bacterium isolated from Mount Rittmann (Antarctica) *Syst Appl Microbiol* **29** 300-307

Powell S M, Ferguson S H, Bowman J P and Snape I (2006) Using real-time PCR to assess changes in the hydrocarbon-degrading microbial community in Antarctic soil during bioremediation *Microb Ecol* **52** 523-532

Prabagaran S R, Manorama R, Delille D and Shivaji S (2007)

Predominance of *Roseobacter, Sulfitobacter, Glaciecola* and *Psychrobacter* in seawater collected off Ushuaia, Argentina, Sub-Antarctica *FEMS Microbiol Ecol* **59** 342-355

Priest F G, Goodfellow M and Todd C (1988) A numerical classification of the genus *Bacillus J Gen Microbiol* **134** 1847-1882

Priscu J C, Adams E E, Lyons W B, Voytek M A, Mogk D W, Brown R L, McKay C P, Takacs C D, Welch K A, Wolf C F, Kirshtein J D and Avci R (1999) Geomicrobiology of subglacial ice above Lake Vostok, Antarctica *Science* **286** 2141-2144

Prüss B M, Francis K P, von Stetten F and Scherer S (1999) Correlation of 16S ribosomal DNA signature sequences with temperature-dependent growth rates of mesophilic and psychrotolerant strains of the *Bacillus cereus* Group *J Bacteriol* **181** 2624-2630

Purcell A M, Mikucki J A, Achberger A M, Alekhina I A, Barbante C, Christner B C, Ghosh D, Michaud A B, Mitchell A C, Priscu J C, Scherer R, Skidmore M L and Vick-Majors T J, The Wissard Science Team (2014) Microbial sulfur transformations in sediments from Subglacial Lake Whillans *Front Microbiol* **5** 594

Ramsay A J and Stannard R E (1986) Numbers and viability of bacteria in ornithogenic soils of Antarctica *Polar Biol* **5** 195-198

Ray M K, Devi K U, Kumar G S and Shivaji S (1992) Extracellular protease from the antarctic yeast *Candida humicola Appl Environ Microbiol* **58** 1918-23

Ray M K, Kumar G S and Shivaji S (1994a) Phosphorylation of lipopolysaccharides in the Antarctic psychrotroph *Pseudomonas syringae*: a possible role in temperature adaptation *J Bacteriol* **176** 4243-9

Ray M K, Kumar G S and Shivaji S (1994b) Phosphorylation of lipopolysaccharides in the Antarctic psychrotroph *Pseudomonas syringae*: a possible role in temperature adaptation *J Bacteriol* **176** 4243-9

Ray M K, Kumar G S, Janiyani K, Kannan K, Jagtap P, Basu M K and Shivaji S (1998) Adaptation to low temperature and regulation of gene expression in Antarctic psychrotrophic bacteria *J Biosci* **23** 423-435

Reddy G S N, Rajagopalan G and Shivaji S (1994) Thermolabile ribonuclease from Antarctic psychrotropic bacteria: detection of the enzyme in various bacteria and purification from *Pseudomonas fluorescens FEMS Microbiol Lett* **122** 211-216

Reddy G S N, Agarwal R K, Matsumoto G I and Shivaji S (2000) *Arthrobacter flavus* sp. nov., a psychrotropic bacterium isolated from a pond in Mc Murdo Dry Valley, Antarctica *Int J Syst Evol Microbiol* **50** 1553-1561

Reddy G S N, Prakash J S, Matsumoto G I, Stackebrandt E and Shivaji S (2002) *Arthrobacter_roseus* sp. nov., a psychrophilic bacterium isolated from an antarctic cyanobacterial mat sample. *Int J Syst Evol Microbiol* **52** 1017-21

Reddy G S N, Matsumoto G I and Shivaji S (2003a) *Sporosarcina macmurdoensis* sp. nov. from a cyanobacterial mat samples from a pond in the McMurdo dry valley, Antarctica *Int J Syst Evol Microbiol* **53** 1363-1367

Reddy G S N, Prakash J S S, Srinivas R, Matsumoto G I and Shivaji S (2003b) *Leifsonia rubra* sp. nov. and *Leifsonia aurea* sp. nov. psychrophiles from a Pond in Antarctica *Int J Syst Evol Microbiol* **53** 977-984

Reddy G S N, Matsumoto G I, Shuman P, Stackebrandt E and Shivaji S (2004) Psychrophilic *Pseudomonas* from Antarctica: *Pseudomonasantarctica* sp. nov., *Pseudomonas meridianae* sp. nov. and *Pseudomonas proteolytica* sp. nov *Int J Syst Evol Microbiol* **54** 713-719

Reddy G S N, Uttam A and Shivaji S (2008) *Bacillus cecembensis* sp. nov., a bacterium isolated from the Pindari glacier of the Himalayan mountain ranges, India *Int J Syst Evol Microbiol* **58** 2330-2335

Reddy G S N, Ara S, Singh A, Kumar Pinnaka A and Shivaji S (2013) Draft genome sequence of *Psychrobacter aquaticus* CMS 56T, isolated from a cyanobacterial mat sample collected from water bodies in the McMurdo Dry Valley region of Antarctica *Genome Announc* **1** e00918-13

Reddy G S N, Sreenivas A and Shivaji S (2014) Draft genome sequence *Cryobacterium roopkundensis* strain RuGl7, isolated from a soil sample in the vicinity of Roopkund Lake, Himalayas, India *Genome Announc* **2** e01206-14

Reddy G S N, Sreenivas A and Shivaji S (2015) Draft genome of *Kocuria polaris* CMS 76or^{T}isolated from cyanobacterial mats, McMurdo Dry Valley, Antarctica: an insight into CspA family of proteins from *Kocuria polaris* CMS 76or^{T} *Arch Microbiol* **197** 1019-1026

Reddy G S N, Chattopadhyay M K and Shivaji S (2016) Biodiversity, Adaptation and Biotechnological importance of bacteria occurring in cold climates. In. Biotechnology of Extremophiles: Advances and Challenges. Ed. Pabulo H. Rampelotto (in press).

Rina M, Pozidis C, Mavromatis K, Tzanodaskalaki M, Kokkinidis M and Bouriotis V (2000) Alkaline phosphatase from the Antarctic strain TAB5. Properties and psychrophilic adaptations *Eur J Biochem* **267** 1230-8

Ruckert G (1985) *Myxobacteria* from Antarctic soils *Biol Fert Soil* **1** 215-216

Russell R J, Gerike U, Danson M J, Hough D W and Taylor G L (1998) Structural adaptations of the cold-active citrate synthase from an Antarctic bacterium *Structure* **6** 351-61

Sheridan P P, Loveland-Curtze J, Miteva V I and Brenchley J E (2003) *Rhodoglobus vestalii* gen. nov., sp. nov., a novel psychrophilic organism isolated from an Antarctic Dry Valley lake *Int J Syst Evol Microbiol* **53** 985-94

Shivaji S, Rao N S, Saisree L, Sheth V, Reddy G S N and Bhargava P M (1988) Isolation and identification of *Micrococcus roseus* and *Planococcus* sp. from Schirmacher Oasis, Antarctica *J Biosci* **113** 409-414

Shivaji S, Rao N S, Saisree L, Sheth V, Reddy G S N and Bhargava P M (1989a) Isolation and identification of *Pseudomonas* sp. from Schirmacher Oasis, Antarctica *Appl Environ Microbiol* **55** 767-770

Shivaji S, Rao N S, Saisree L, Reddy G S N, Seshu Kumar G and Bhargava P M (1989b) Isolates of *Arthrobacter* from the soils of Schirmacher Oasis, Antarctica *Polar Biol* **10** 225-229

Shivaji S, Ray M K, Kumar G S, Reddy G S N, Saisree L and Wynn-Williams D D (1991) Identification of *Janthinobacterium lividum* from the soils of the Island of Scotia Ridge from Antarctic Peninsula *Polar Biol* **11** 267-272

Shivaji S Reddy G S N, Prasad R A, Kutty R and Ravenschlag K (2004) Bacterial diversity of a soil sample from Schirmacher Oasis, Antarctica *Cell Mol Biol* **50** 525-536

Shivaji S, Kiran M D and Chintalapati S (2007) Perception and transduction of low temperature in bacteria. In: Physiology and biochemistry of extremophiles. Gerday C, Glansdor VN (Ed) ASM Press, Washington, 194-207

Shivaji S and Reddy G S N (2009) Chapter 2. Bacterial biodiversity of Antarctica: conventional polyphasic and rRNA approaches. In: Polar Microbiology: The Ecology, Biodiversity and Bioremediation Potential of Microorganisms in Extremely Cold Environments; Bej A K, Aislabie J, Atlas R M, Eds. Taylor & Francis group

Shivaji S and Prakash J S (2010) How do bacteria sense and respond to low temperature? *Arch Microbiol* **192** 85-95

Shivaji S, Kumari K, Kishore K H, Pindi P K, Rao P S, Radha Srinivas T N, Asthana R and Ravindra R (2011) Vertical distribution of bacteria in a lake sediment from Antarctica by culture-independent and culture-dependent approaches *Res Microbiol* **162** 191-203

Shivaji S, Ara S, Singh S K, Bandi S, Singh A and Pinnaka A K (2012) Draft genome sequence of *Bacillus Isronensis* strain B3W22, isolated from the upper atmosphere *J Bacteriol* **194** 6624-6625

Shivaji S, Ara S, Singh A and Pinnaka A K (2013a) Draft genome sequence of *Cyclobacterium qasimii* M12-11B T, isolated from an Arctic marine sediment *Genome Announc* **1** e00642-13

Shivaji S, Ara S, Prasad S, Manasa B P, Begum Z, Singh A and Pinnaka A K (2013b) Draft genome sequence of *Arcticibacter svalbardensis* MN12-7T, a member of the family Sphingobacteriaceae isolated from an Arctic soil sample *Genome Announc* **1** e00484-13

Shukor M Y, Hassan N A, Jusoh A Z, Perumal N, Shamaan N A, MacCormack W P and Syed M A (2009) Isolation and characterization of a *Pseudomonas* diesel-degrading strain from Antarctica *J Environ Biol* **30** 1-6

Singh A K, Pindi P K, Dube S, Sundareswaran V R and Shivaji S (2009) In the psychrophilic *Pseudomonas syringae*, trmE is important for low temperature growth *Appl Environ Microbiol* **75** 4419-4426

Singh P, Singh SM and Dhakephalkar P (2014) Diversity, cold active enzymes and adaptation strategies of bacteria inhabiting glacier cryoconite holes of High Arctic *Extremophiles* **18** 229-242

Sjöling S and Cowan D A (2003) High 16S rDNA bacterial diversity in glacial meltwater lake sediment, Bratina Island, Antarctica *Extremophiles* **7** 275-282

Smith R C, Prezelin B B, Baker K S, Bidigare R R, Boucher N P, Coley T, Karentz D, MacIntyre S, Matlick H A, Menzies D, Ondrusek M, Wan Z and Waters K J (1992) Ozone depletion: ultraviolet radiation and phytoplankton biology in Antarctic waters *Science* **255** 952-959

Søgaard D H, Kristensen M, Rysgaard S, Glud R N, Hansen P J and Hilligsøe K M (2010) Autotrophic and heterotrophic activity in Arctic first-year sea ice: Seasonal study from Malene Bight, SW Greenland *Mar Ecol Prog Ser* **419** 31-45

Söller R, Hirsch P, Blohm D and Labrenz M (2000) Differentiation of newly described antarctic bacterial isolates related to *Roseobacter* species based on 16S-23S rDNA internal transcribed spacer sequences *Int J Syst Evol Microbiol* **50** 909-915

Spring S, Merkhoffer B, Weiss N, Kroppenstedt R M, Hippe H and Stackebrandt E (2003) Characterization of novel psychrophilic clostridia from an Antarctic microbial mat: description of *Clostridium frigoris* sp. nov., *Clostridium lacusfryxellense* sp. nov., *Clostridium bowmanii* sp. nov., and *Clostridium psychrophilum* sp. nov., and reclassification of *Clostridium laramiense* as *Clostridium estertheticum* subsp. *laramiense* subsp. nov *Int J Syst Evol Microbiol* **53** 1019-1029

Sreenivas A, Reddy G SN and Shivaji S (2014) Draft genome sequence of a psychrophilic bacterium *Sphingomonas antarcticum* 4BY, isolated from the soils of Schirmacher oasis, Antarctica *Genome Announc* **2** e00696-14

Stibal M, Hasan F, Wadham J L, Sharp M J and Anesio A M (2012) Prokaryotic diversity in sediments beneath two polar glaciers with contrasting organic carbon substrates *Extremophiles* **16** 255-265

Stokes J L and Reymond M L (1966) Quantitative ecology of psychrophilic microorganisms *Appl Microbiol* **14** 74-78

Sundareswaran V R, Singh A K, Dube S and Shivaji S (2010) Aspartate aminotransferase is involved in cold adaptation in psychrophilic *Pseudomonas syringae Arch Microbiol* **192** 663-672

Takii S, Kondal T, Hiraishi A, Matsumoto G I, Kawano T and Torii T (1986) Vertical distribution in and isolation of bacteria from Lake Vanda: an Antarctic lake *Hydrobiologia* **135** 15-21

Tanner A C and Herbert R A (1981) Nutrient regeneration in Antarctic marine sediments *Kiel Meeresforsch Sanderh* **5** 390-395

Tanner A C (1985) The role of bacteria in the cycling of nutrients within the maritime Antarctic environment. Antarctic Nutrient Cycles and Food Webs (ed. W R Siegfried, P R Condy and Laws R M), Springer Verlag, Berlin, Heidelberg, p 123-127

Tiao G, Lee C K, McDonald I R, Cowan D A and Cary S C (2012) Rapid microbial response to the presence of an ancient relic in the Antarctic Dry Valleys *Nat Commun* **3** 660

Timmis K N, McGenity T J, Meer J R and deLorenzo V (eds.) (2010) Handbook of hydrocarbon and lipid microbiology. Berlin; Heidelberg: Springer Verlag. doi: 10.1007/978-3-540-77587-4

Tsiklinsky M (1908) La flore microbieene dans les regions due pole Sud. In: Expedition Antarctique Francais 1903-1905. **3** 1-33

Tsyganov V A (1970) Detection and morphological cultural characteristics of *Actinomycetes* from the antarctic *Mikrobiologia* **39** 821-826

Uma S, Jadhav R S, Kumar G S, Shivaji S and Ray M K (1999) A RNA polymerase with transcriptional activity at 0 degrees C from the Antarctic bacterium *Pseudomonas syringae FEBS Lett* **453** 313-7

Van Trappen S, Mergaert J, Van Eygen S, Dawyndt P, Cnockaert M C and Swings J (2002) Diversity of 746 heterotrophic bacteria isolated from microbial mats from ten Antarctic lakes *Syst Appl Microbiol* **25** 603-610

Van Trappen S, Tan T L, Yang J, Mergaert J and Swings J (2004) *Glaciecola polaris* sp. nov., a novel budding and prosthecate bacterium from the Arctic Ocean, and emended description of the genus Glaciecola *Int J Syst Evol Microbiol* **54** 1765-1771

Vincent C F (1988) Microbial ecosystems of Antarctica. Cambridge: Cambridge University Press 303

Voytek M A and Ward B B (1995) Detection of ammonium-oxidizing bacteria of the beta-subclass of the class Proteobacteria in aquatic samples with the PCR *Appl Environ Microbiol* **61** 1444-1450

Wang F, Gai Y, Chen M and Xiao X (2009) *Arthrobacter psychrochitiniphilus* sp. nov., a psychrotrophic bacterium isolated from Antarctica *Int J Syst Evol Microbiol* **59** 2759-62

Watanabe T, Kojima H, Takano Y and Fukui M (2013) Diversity of sulfur-cycle prokaryotes in freshwater lake sediments investigated using *aprA* as the functional marker gene *Syst Appl Microbiol* **36** 436-443

Wery N, Gerike U, Sharman A, Chaudhuri J B, Hough D W and Danson M J (2003) Use of a packed-column bioreactor for isolation of diverse protease-producing bacteria from antarctic soil *Appl Environ Microbiol* **69** 1457-1464

Wilkins D, Yau S, Williams T J, Allen M A, Brown M V, DeMaere M Z, Lauro F M and Cavicchioli R (2013) Key microbial drivers in Antarctic aquatic environments *FEMS Microbiol Rev* **37** 303-335

Xiao X, Yin X, Lin J, Sun L, You Z, Wang P and Wang F (2005) Chitinase genes in lake sediments of Ardley Island, Antarctica *Appl Environ Microbiol* **71** 7904-7909

Xu S, Yan L, Zhang X, Wang C, Feng G and Li J (2014) *Nocardiopsis fildesensis* sp. nov., an actinomycete isolated from soil *Int J Syst Evol Microbiol* **64** 174-9

Yakimov M M, Giuliano L, Gentile G, Crisafi E, Chernikova T N, Abraham W R, Lünsdorf H, Timmis K N and Golyshin P N (2003) *Oleispira antarctica* gen. nov., sp. nov., a novel hydrocarbonoclastic marine bacterium isolated fromAntarctic coastal sea water *Int J Syst Evol Microbiol* **53** 779-85

Yamada K, Fukuda W, Kondo Y, Miyoshi Y, Atomi H and Imanaka T (2011) *Constrictibacter antarcticus* gen. nov., sp. nov., a cryptoendolithic micro-organism from Antarcticwhite rock *Int J Syst Evol Microbiol* **61** 1973-80

Yau S, Lauro F M, Williams T J, Demaere M Z, Brown M V, Rich J, Gibson J A and Cavicchioli R (2013) Metagenomic insights into strategies of carbon conservation and unusual sulfur biogeochemistry in a hypersaline Antarctic lake *Int J Syst Evol Microbiol* **7** 1944-1961

Yergeau E, Newsham K K, Pearce D A and Kowalchuk G A (2007a) Patterns of bacterial diversity across a range of Antarctic terrestrial habitats *Environ Microbiol* **9** 2670-2682

Yergeau E, Bokhorst S, Huiskes A H, Boschker H T, Aerts R and Kowalchuk G A (2007b) Size and structure of bacterial, fungal and nematode communities along an Antarctic environmental gradient *FEMS Microbiol Ecol* **59** 436-451

Yi H and Chun J (2006) *Flavobacterium weaverense* sp. nov. and *Flavobacterium segetis* sp. nov., novel psychrophiles isolated from the Antarctic *Int J Syst Evol Microbiol* **56** 1239-1244

Yu Y, Li H R, Zeng Y X and Chen B (2011) Bacterial diversity and bioprospecting for cold-active hydrolytic enzymes from culturable bacteria associated with sediment from Nella Fjord, Eastern Antarctica *Mar Drugs* **9** 184-195

Zhao J, Yang N and Zeng R (2008) Phylogenetic analysis of type I polyketide synthase and nonribosomal peptide synthetase genes in Antarctic sediment *Extremophiles* **12** 97-105.

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Review Article

Faunal Diversity in Antarctica: Contributions of Zoological Survey of India

VISWA VENKAT GANTAIT* and KAILASH CHANDRA
Zoological Survey of India, M-Block, New Alipore, Kolkata 700 053, India

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Antarctica, the fifth largest continent of the planet covers an area of about 14 million square kilometres. Topographically it is divided into two geographic regions: West Antarctica and East Antarctica. It is also divided into three main ecological zones with distinctive climatic and biotic characteristics: the Continental, Maritime and Sub-Antarctic zone. Only about 2% of ice-free area; harsh climatic conditions; combinations of freezing temperatures, poor soil quality, lack of moisture and sunlight inhibit the faunal composition in the continent. Over 150 years of biological researches on Antarctic region recorded more than 1500 species of invertebrates and about 200 species of vertebrates. The major common groups of invertebrates known to occur are Protozoa, Acarina, Nematoda, Collembola, Rotifera and Tardigrada. Vertebrate fauna includes different species of fishes, birds, mammals etc. Though Indian Scientific Expedition to Antarctica started in 1981, Zoological Survey of India joined the mission of Antarctic Expedition in 1989. Since then, thirteen scientists successfully participated in thirteen different expeditions. Their sincere endeavour and zeal to work in the extreme inhospitable climatic conditions of the continent resulted in the description of 5 new species, first records of 5 families, 25 genera and 92 species of different invertebrate and vertebrate groups. Though some works have been done on taxonomic and ecological studies on different invertebrate groups by ZSI scientists, yet more studies are needed to explore the terrestrial and moss inhabiting invertebrate fauna from the continent.

Keywords: Antarctica; Faunal Diversity; New Species; New Records; Zoological Survey of India

Introduction

Antarctica is the southernmost pristine and beautiful continent of the earth, surrounded by three oceans: the Pacific Ocean, the Atlantic Ocean and the Indian Ocean. Practically it's a white icy continent of which 98% of its land area is covered by ice and remaining 2% is the exposed part, occupied by rocks and lakes of different sizes. This highest, coldest and windiest part of the planet is a unique place of the earth having six months continuous day and another six months continuous night in a year. Topographically, it consists of two parts: East and West Antarctica divided by the Transantarctic Mountain chain (Fig. 1). East Antarctica represents about two-third of the entire landmass of the continent and is more inhospitable than West Antarctica. The Antarctic region has been subdivided into three main ecological zones: the Continental Antarctic, the Maritime Antarctic and the sub-Antarctic with distinctive climatic and biotic characteristics.

The severe harsh climatic conditions do not allow the extensive vegetation in Antarctica, as well as inhibits the diversity of animal inhabitants in the continent. Marine animals remarkably outnumber the terrestrial animals in Antarctica. Most of the invertebrates occur in Antarctica *viz.* Protozoa, Mites, Nematodes, Collembola etc. live in the moss beds and melt water lakes. Nematodes occupy about 22% amongst the invertebrate fauna of the continent. The flightless midge *Belgica antarctica* is the largest purely terrestrial animal in Antarctica, measuring up to 6 millimeters in length. Marine invertebrates are dominated by sea anemones, star fishes and shrimp-like creatures called Krill. Antarctic vertebrates mainly

**Author for Correspondence: E-mail: v.gantait@rediffmail.com*

include Patagonian tooth fish, birds like Penguin, Skua, Albatross, Snow Petrel, etc. and mammals such as Seals, Whales, etc.

Faunal Diversity of Antarctica

Terrestrial animals of Antarctica are confined to microbes, a few groups of small invertebrates like Protozoa, Rotifera, Nematoda, Mites, etc. and some of the vertebrate groups like birds and mammals. A perusal of literature reveals that lakes of maritime and sub-Antarctic islands were more intensively surveyed than continental Antarctica. A total of 387 invertebrate fauna have so far been recorded in the sub-Antarctica, 127 in maritime Antarctica and 107 on the continent itself; mostly microscopic which were found in the soil, plant litter, moss, algae, lichen, peat, birds' litter and in the micro-climate under rocks (May, 1988, Laws, 1989). Block (1992) published a voluminous annotated bibliography of Antarctic invertebrates which include both terrestrial, as well as, freshwater species. That comprehensive bibliography of Antarctic invertebrate fauna covered over 1400 references and more than 1100 species of terrestrial and freshwater free-living animals and some ectoparasites from the maritime, sub-Antarctic and the continental Antarctic zones. Ingole and Perulekar (1987 and 1990) studied on composition and spatial distribution of micro-fauna of 10 freshwater lakes at Schirmacher Oasis, East Antarctica. Arif (1995) reported 137 species of Arthropods recorded from Schirmacher Oasis, which belongs to Acarina (70 species of mites), Mallophaga (37 species of biting lice), Collembola (20 species of springtail), Anoplura (5 species of sucking lice), Diptera (2 species of midges), Siphonoptera (1 species of fleas) and Coleoptera (2 species of beetles probably alien or known from islands near the Antarctic Peninsula). He also revealed that mites are the most diverse and well known group in the region. Acarina also included feather mites on Antarctic birds and a specialised group which live in the nasal passage of seals. Predator mite i.e. the fast moving yellow mite (*Gamasellus racovitzi*) and pink soil mite (*Nanorchestes antarcticus*) also occur in Antarctica (Laws, 1989).

Richter *et al*. (1990) reported some unidentified mites and springtail from Schirmacher Oasis. Hazra (1994) newly recorded five genera of nematodes from this region. Arif (1995) reported some groups of invertebrate fauna such as Earthworm, Nematode, Mite, Collembola, Diptera (adult and larvae) and Lepidoptera (moth). These collections were mostly made from soil and moss of lake areas, green houses of Russian and Indian stations. Richter (1907) recorded the terrestrial protozoa for the first time from the continent. Smith (1987) listed 124 Protozoan species from sub-Antarctic and maritime-Antarctic islands. Ingole and Perulekar (1987) were the first to report protozoa from Schirmacher Oasis. They also recorded only one species of ciliate, *viz., Oxytricha fallax* Stein and noted that protozoa are the most dominant fauna comprising 22.31% of the total lacustrine microfauna of this region. Mitra (1999) reported 16 species of Protozoa for the first time from this area. Rotifers, commonly called as 'wheel animalcules' or 'rotatoria', a group of small microscopic animals was also reported from Antarctica. The first Antarctic rotifer was recorded by Murray (1910). Sudzuki (1964) recorded 13 species of rotifers from moss. Mitra (1999) reported one rotifer species, *Philodina gregaria*, collected from 5 lakes and one swampy area of Schirmacher Oasis which is the first report of this from this region. Ramazotti (1972) revealed that seven species of rotifers, reported from Antarctica are also available in high altitude of Himalaya. Venkataraman (1995) recorded two Tardigrade species *viz., Hypsibius chilensis* and *Macrobiotus polaris* for the first time from Antarctica. Terrestrial nematodes were first described from the maritime Antarctic zone by De Man (1904) and from the sub-Antarctic zone by Jagerskjiold (1905). The first valid description of nematode from continental Antarctica was made by Steiner (1916). Tilbrook (1970) stated that 'the presence of nematodes in the maritime Antarctic region has been reported on many occasions, but nothing has been published on their taxonomy'. Spaull (1972) described the new genus *Antarctenchus* and new species *Antarctenchus hoperi* from the continent. Maslen (1980) recorded 40 species of nematodes from the Maritime zone of which 34 were endemic, 10 species recorded from Continental zone out of them seven were endemic and 22 species from Sub-Antarctic zone of which 12 were endemic to the region. Hazra (1994) recorded five nematode genera for the first time from Schirmacher Oasis. Ghosh *et al*. (2000) recorded two genera and two species of nematodes from Antarctic region and three genera and species from Continental Antarctica for the first time. Ghosh *et al*. (2005) described a new tylenchid nematode *Antarctenchus motililus* from Schirmacher Oasis. Bohra *et al*. (2010) recorded 5 new nematode species from East Antarctica. The first mite species discovered from the Antarctic region was a Cryptostigmatid, *Oribata Antarctica*, collected in the Belgica expedition during 1897-1899. Pugh (1993) opined that in the 100 years of Antarctic expedition 528 species of Acari have been reported from Antarctica and the southern Ocean. Three new mite species were described by Sanyal *et al*. (2002) from mosses and soil collected from the mainland Antarctica. Sanyal and Gupta (2005) described one new Acari species from the continent. The credit for the discovery of insect from Antarctica which included Collembola goes to Willem (1901). Block (1980) pointed that Collembola together with Acari have penetrated to terrestrial habitats further south than any other arthropods. Wallwork (1969) revealed that collembolan fauna encountered so far from Antarctica are endemic. Krills (*Euphausia superba*) perform a significant role in the Southern Ocean food web. Most of the larger animals in Antarctica are directly or indirectly so dependent upon krill for their food that without krill the entire Antarctic Ecosystem would totally collapsed. Antarctic vertebrates mainly include Patagonian tooth fish (Fig. 5), birds (Penguin, Skua, Albatross, and Snow Petrel etc.) and mammals (Seals, Whales etc.). There are 17 species of penguins in the world, six of which are found in Antarctica *viz*. Emperor (Fig. 6), Adelie, Chinstrap, Gentoo, Macaroni and Rock hopper penguins.

Contribution of ZSI to Antarctica Expeditions

In 1989, Professor Mohammad Shamim Jairajpuri, the then Director of the Zoological Survey of India (ZSI) was the first who thought to explore the faunal diversity of Antarctica. Total thirteen scientists of ZSI attended the expeditions till to date. Their sincere endeavour and zeal to work in the extreme harsh climate of the continent have resulted in documentation of fauna and discovery of few species of invertebrates from Antarctica.

During the expeditions, the scientists made extensive studies on taxonomy and ecology of different invertebrates as well as vertebrate groups in Schirmacher Oasis and Larshmann Hills of East Antarctica. Observations and monitoring on avian fauna were also done during voyage and in the mainland area. Five invertebrate species have been described; 43 invertebrates 44 vertebrate species have been reported from Antarctica (Table 1).

Major Contributions

Exploration of faunal diversity of moss, algae and lichen inhabiting terrestrial invertebrates of Schirmacher Oasis and Larsemann Hills of East Antarctica were studied by ZSI scientists. Studies relating to ecology of terrestrial nematodes, mites and collembola along with the effects of physico-chemical factors, *viz*., temperature, relative humidity, pH and organic carbon, nitrate and potassium, etc. were also conducted. During expeditions, soil samples and moss turfs from different locations of Schirmacher Oasis; different islands *viz*., Bharti, Fischer, McLeod, Broknes, Stornes, etc. in the Larsemann Hills were collected. Extensive surveys were also carried out at different lakes and water bodies for studies on aquatic fauna. As a result, four species of mites and one nematode species are described as new to science. Seventeen species of Protozoa, one Rotifera, two Tardigrada, 15 Nematoda, five Collembola, one Diptera and 12 Acari species of invertebrates were reported from the continent. Protozans are the most dominant invertebrate fauna in East Antarctica. The Protozoan species, *Difflugia lucida* was recorded for the first time from Antarctica (Barman, 2000). The dominance and diversity of five Testacean species (Protozoa: Rhizopoda), namely *Arcella arenaria* Greeff, *Arcella* sp., *Assulina muscorum* Greeff, *Assulina* sp. and *Corythion dubium* Taranek (Fig. 2) from eight lakes in Schirmacher Oasis were reported by Chatterjee *et al*. (2000). Hazra and Mitra (2002) reported that the genera *viz*., *Parmulina, Difflugia, Nebella, Oxytricha* and *Stylonychida* (Fig. 2) were found highly restricted in their distribution pattern; on the contrary *Arcella arenaria* and *Assulina muscorum* were the ubiquitous species. They also reported that the genus *Parmulina* is cosmopolitan in distribution, not only reported from Maritime Antarctica and Sub-Antarctic zone but also from other parts of the globe.

Hazra (1994) reported five genera of nematodes *viz*., *Tylenchorhynchus, Dorylaimellus,*

Table 1: Species described and reported by ZSI scientists

	Described species
Nematode	*Antarctenchus motililas* Ghosh *et al*., 2005
Mites	*Proctolaelaps antarcticus* Sanyal and Gupta, 2005
	Haplochthonius antarcticus Sanyal *et al*., 2002
	H. longisetosus Sanyal *et al*., 2002
	H. maitri Sanyal *et al*., 2002
	Reported species
Protozoa	*Arcella arenaria* Greeff, 1866
	Arcella catinus Penard, 1890
	Arcella sp.
	Assulina muscorum Greeff, 1888
	Assulina sp.
	Centropyxis aerophila Deflandre, 1929
	Centropyxis sp.
	Collopoda sp.
	Corythion dubium Taranek, 1871
	Difflugia lucida Penard, 1890
	Diplochlamys sp.
	Euglypha sp.
	Nebela sp.
	Oxytricha fallax Stein, 1859
	Parmulina sp.
	Stylonychia sp.
	Trinema sp.
Rotifera	*Philodina gregaria* Murray, 1910
Tardigrada	*Hypsibius chilensis* Plate, 1888
	Macrobiotus polaris Murray, 1910
Nematoda	*Aporcelaimellus* sp.
	Dorylaimellus sp.
	Dorylaimoides sp.
	Dorylaimus sp.
	Eudorylaimus sabulophilus Tjepkema, Ferris and Ferris, 1971
	Helicotylenchus diagonicus Darling and Thorne, 1959
	Helicotylenchus Dihystera (Cobb, 1893) Sher, 1961
	H. exallus Sher, 1966
	Helicotylenchus sp.
	Mononchus sp.
	Paramylonchulus sp.
	Plectus telekii Mulk and Coomans, 1978
	Rhabditis sp.
	Rotylenchus sp.
	Tylenchorhynchus sp.
Collembola	*Calx* sp.
	Cryptopygus antarcticus Willem, 1901
	Isotoma sp.
	Sphaeridia sp.
	Xenella sp.
Diptera	*Forcipemyia* sp.
Acari	*Acarus siro* Linnaeus, 1758
	Chelacaropsis moori Baher, 1949
	Hypoaspis oblonga Halbert, 1915
	Hypoaspis sp.
	Maudheimia petronia Wallwork, 1962
	Nanorchestes antarcticus Strandtmann, 1963
	Paratydeus sp.
	Pronematus sp.
	Pediculaster mongolichus Mahunked, 1970
	Raphignathus sp.
	Suidasia nesbitti Hughes, 1948
	Tyrophagus longior Grevais, 1862
Birds	*Aptenodytes patagonicus patagonicus* Miller, 1778 - (King penguin)
	A. forsteri Gray, 1844 - (Emperor penguin)
	Catharacta skua antarctica Brunnich, 1764 - (Antarctic skua)
	Catharacta skua maccormicki Saunders, 1893 - (South polar skua)
	Daption capense capense Linnaeus, 1758 - (Cape Petrel)
	Diomedea epomophora Forster, 1785 - (Royal Albatross)
	D. exulans exulans Linnaeus, 1758 - (Wandering Albatross)
	D. chlororhynchus Gmelin, 1789 - (Yellow-nosed Albatross)
	D. chrysostoma Forster, 1785 - (Grey-headed Albatross/ Grey-headed Mollymawk)
	D. immutabilis Rothschlid, 1893 - (Laysan Albatross)
	D. melanophris Temminck, 1828 - (Black-browed Albatross)
	Falco tinunculus objiurgatus Linnaeus, 1758 - (Indian Kestrel)
	Fulmarus glaciafoides Linnaeus, 1761 - (Antarctic Fulmar/Southern Fulmar)
	Holobaena caerulea Gmelin, 1789 - (Blue Petrel)
	Macronectus giganteus Gmelin, 1789 - (Southern Giant Petrel)
	Oceanites oceanicus oceanicus Kuhl, 1820 -

	(Wilson's Strom Petrel)
	Pachyptila belcheri Mathews, 1912 - (Thin-billed Prion)
	P. turtur Kuhl, 1820 - (Fairy Prion)
	P. vittata vittata Forster, 1777 - (Broad-billed Prion)
	Pagodroma nivea Forster, 1777 - (Snow Petrel)
	Pelecanoides urinator urinator Gmelin, 1789 - (Common Diving Petrel)
	Phaethon setheurus indicus Linnaeus, 1758 - (Short-tailed Tropic bird)
	Phalacrocorax atriceps nivalis King, 1828 - (Blue eyed Shag)
	Phoebetria fusea Hilsenberg, 1822 - (Sooty Albatross)
	P. palpebrata Forster, 1785 - (Light-mantled Sooty Albatross)
	Procellaria aequinoctialis aequinoctialis Linnaeus, 1758 - (White-chinned Petrel)
	P. cinerea Gmelin, 1789 - (Grey Petrel/Brown Petrel/ Pediunker)
	Pterodroma brevirostris Lesson, 1831 - (Kerguelen Petrel)
	P. mollis Gould, 1844 - (Soft-plumaged Petrel)
	Puffinus carnipes Gould, 1844 - (Flesh-footed Shear Water/Pale-footed Shear Water)
	P. gravis O'Reilly, 1818 - (Great Shearwater/ Greater Shearwater)
	P. griseus Gmelin, 1789 - (Sooty Shearwater)
	P. pacificus Gmelin, 1789 - (Wedge-tailed Petrel)
	P. puffinus puffinus Brunnich, 1764 - (Manx Sher Water)
	Pygoscelis adelie Homborn and Jacquinot, 1841 - (Adelie penguin)
	P. antarctica Forster, 1781- (Chinstrap penguin)
	Sterna vittata Gmelin, 1789 - (Antarctic Tern)
	Sula capensis Lichtenstein, 1823 - (Cape Ganet)
	S. dactylatra melanops Lesson, 1831 - (Masked Booby)
	Thalassoica antarctica Gmelin, 1789 - (Antarctic Petrel)
Mammals	*Delphinus delphis* Linnaeus, 1758 - (Common dolphin)
	Hydruga leptonyx Blainville, 1820 - (Leopard seal)
	Lobodon carcinophajus Homborn and Jacquinot, 1842 - (Crab-eater seal)
	Megaptera novaeangliae Borowski, 1781 - (Humpback whale)

Aporcelaimellus, Dorylaimoides and *Paramylonchulus* for the first time from Schirmacher Oasis. He also studied the population ecology of soil nematode fauna in relation to some edaphic factors in the region. The study showed that the nematode population was maximum (22.27%) in January and minimum (2.38%) in February, 1994. The genus *Tylenchorhynchus* was the most dominant one in comparison to others. Peak population of the nematodes was associated with higher levels of temperature, nitrate, organic carbon and relative humidity. During 1995-1996, five nematode genera *viz., Helicotylenchus, Mononchus, Dorylaimus, Rhabditis* and *Rotylenchus* were collected from 15 lakes and swampy areas in Schirmacher Oasis. Amongst them, two genera *viz., Rhabditis* and *Rotylenchus* were recorded for the first time from whole Antarctic region; the remaining three were recorded for the first time from Continental Antarctica (Ghosh *et al.,* 2000). Ghosh *et al.* (2005) described a new species *Antarctenchus motililas* (Fig. 4) from Schirmacher Oasis. Bohra *et al.* (2010) reported five nematode species *viz., Helicotylenchus dihystera, H. diagonicus, H. Exallus, Eudorylaimus sabulophilus* and *Plectus telekii* for the first time from East Antarctica.

Venkataraman (1995) recorded two species of Tardigrades *viz., Hypsibius chilenensis* and *Macrobiotus polaris* and a Rotifer species, *Philodina gregaria*. Three new mite species *viz., Haplochthonius antarctius, H. matri* and *H. longisetosus* belonging to the family Haplochthoniidae under the order Oribatida of the class Acarina were

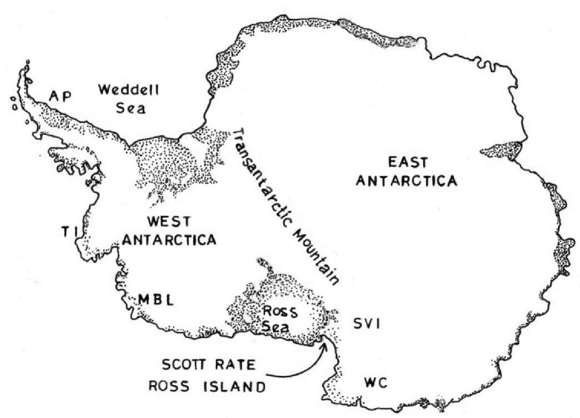


Fig. 1: East and West Antarctica

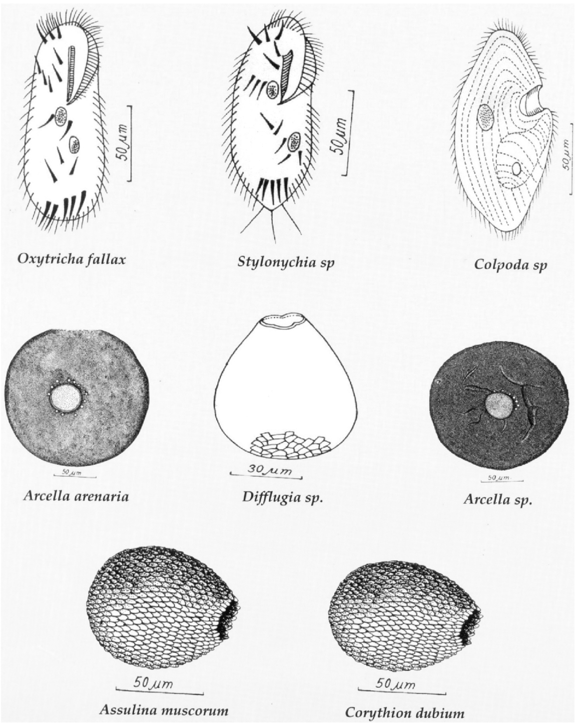
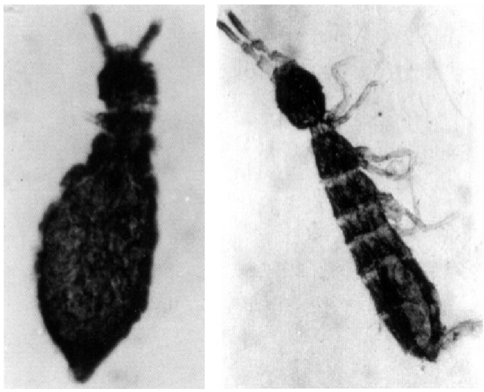


Fig. 2: Protozoa species

described by Sanyal *et al*. (2002) from mosses and soil collected from the mainland Antarctica. The family Haplochthoniidae was recorded for the first time from Antarctica. Sanyal and Gupta (2005) described one new Acari species, *Proctolaelaps antarcticus* (Mesostigmata: Ascidae) from Antarctic continent. The family Paratydeidae, six genera (*Chelacarposis, Pronematus, Paratydeus, Pediculaster, Suidasia, Proctolaelaps*) and seven species (*Chelacarposis moorei, Pronematus* sp., *Paratydeus* sp., *Pediculaster* sp., *Raphignathus* sp., *Suidasia nesbitti, Proctolaelaps antarcticus*) were also recorded for the first time from Antarctica. Sanyal and Hazra (2008) reported that the two arthropod groups *viz.,* Collembola (Insecta) and Mite (Acari) were found abundantly in moss-turf and soil in Sub-Antarctic and Maritime-Antarctic zones. The genus *Calx* of Collembola was newly recorded by them from Antarctica. The families, *viz.*, Cheylelidae, Pygmephoridae and Saproglyphidae and two genera, *viz.*, *Acarus* and *Hypoaspis* of mite were first recorded from the mainland Antarctica by them. Four genera *viz., Xenella, Isotoma, Calx* (Fig. 3) and *Sphaeridia*; one species, *Cryptopygus antarcticus* of Collembola were also recorded from East Antarctica.



Calx sp *Isotoma* sp

Fig. 3: Collembola species

Amongst vertebrates, 40 species of birds and four species of mammals were recorded from the continent by ZSI scientists. Observations on birds and mammals were also carried out during voyage to Antarctica. The details of observation and information on occurrence, abundance, distribution and behaviour of 46 birds were done by Chattopadhyay (1995) and maximum numbers of birds were observed between Latitude 47°S and 55°S. Venkataraman and Hazra (2005) studied on behaviour of skua using voice-recorder and found that when the recorded voices were played near the nest with chickens present, they started striking the tape recorder. When the voice of Adelie penguin was played, they started challenging with open wings raised over the back. Chandra (2007) presented the distribution, habit and abundance of 26 species of birds at various locations during his onward voyage to Antarctica between 50°19' to 69°51' Latitude (S) & 10°05' to 16°00' Longitude (E) and also return voyage from 68°07' to 37°58' Latitude (S) & 18°06' to 28°06' Longitude (E). The observations on South Polar Skua (Fig. 7) regarding their habit, nesting sites and population in Schirmacher Oasis, East Antarctica were also studied. Ultra structure studies of hairs of mammals and feathers of birds (*viz.,* Snow Petrel, Penguin and South Polar Skua) were also done (De and Mitra, 2010).

Conclusion

The terrestrial invertebrate fauna reported from West Antarctica including the Antarctic Peninsula are more in number than East Antarctica. East Antarctic fauna has been poorly studied during last 100 years, probably

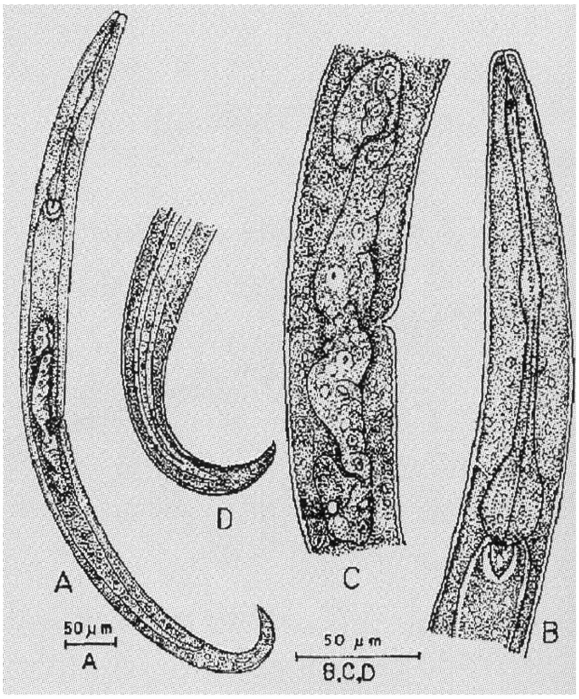


Fig. 4: ***Antarctenchus motililas*** **Ghosh** ***et al.*****, 2005**

Fig. 5: Patagonian tooth fish

Fig. 6: Emperor penguin with chick

Fig. 7: South Polar Skua

due to harsh and inhospitable climatic conditions of this part of the continent. Based on literature studies it was observed that among the terrestrial and freshwater invertebrate fauna, described and recorded so far from Antarctica, the mites are maximum in number (over 27%), followed by Diptera (19-20%), Protozoa (18-19%), Collembola (17-18%), Nematoda (10-11%), Rotifera (8-9%) and Tardigrada (7-8%).

References

Arif M (1995) Occurrence of invertebrate fauna in Schirmacher Oasis, Antarctica. Department of Ocean Development *Technical Publication* **9** 301-311

Barman R P (2000) Studies on the Moss-inhabiting terrestrial invertebrate fauna of Schirmacher Oasis, East Antarctica during the XVII Indian Scientific Expedition to Antarctica *Seventeenth Indian Expedition to Antarctica, Scientific Report, 2000*. Department of Ocean Development *Technical Publication* **15** 169-183

Block W (1980) *Terrestrial habitats in Antarctic Ecology* **I** (Ed R M Laws) 163-236

Block W (1992) An Annotated Bibliography of Antarctic Invertebrates (Terrestrial and Freshwater) *British Antarctic Survey* pp 263

Bohra P, Sanyal A K, Hussain A and Mitra B (2010) Five new records of nematodes from East Antarctica *Journal of Threatened Taxa* **12** 974-977

Chandra K (2007) Observations of Sea Birds during the XXI Indian Expedition to Antarctica (2001-2002) *Twenty First Indian Expeditions to Antarctica, Scientific Report,* Ministry of Earth Sciences *Technical Publication* **19** 135-153

Chatterjee P, Sinha J, Das A K and Mitra B (2000) Studies on some Antarctic testaceans (Protozoa: Rhizopoda): A

Community Analysis *Ecological Environment and Conservation* **6** 237-243

Chattopadhyay S (1995) On the avian fauna encountered during the eleventh Indian Scientific Expedition to Antarctica *Eleventh Indian Expedition to Antarctica, Scientific Report, 1995*. Department of Ocean Development *Technical Publication* **9** 163-197

De Man J G (1904) *Nematodes libres*, Result Voyages S Y Belegica *Zoologie* **8** 1-51

De J K and Mitra B (2010) Notes on the Zoo-geographical distribution of Antarctic birds based on the sighting of ZSI scientists during 15th and 22nd Indian Antarctic Expeditions *Rec Zool Surv India* **110** 107-112

Ghosh S C, Chatterjee A, Mitra B and De J K (2005) *Antarctenchus motililus* sp. n. (Nematoda: Tylenchida) from Schirmacher Oasis in East Antarctica *Journal of Interacademicia* **9** 367-371

Ghosh S C, Mitra B and Chatterjee A (2000) Distribution of Nematode Fauna in different lake water system in Schirmacher Oasis in East Antarctica *Journal of Interacademicia* **4** 420-425

Hazra A K (1990) Terrestrial invertebrate fauna of Antarctica. In: *Taxonomy in Environment and Biology* (Ed. Director, Zoological Survey of India) 229-242

Hazra A K (1994) A study on the population ecology of soil Nematode fauna in relation to some edaphic factors in Schirmacher Oasis, Antarctica *Ninth Indian Expedition to Antarctica, Scientific Report, 1994*. Department of Ocean Development, *Technical Publication* **6** 65-90

Hazra A K and Mitra B (2002) Diversity and colonization of the terrestrial intertebrate fauna at Schirmacher Oasis, East Antarctica *Rec Zool Surv India* **100** 145-159

Ingole B S and Parulekar A (1987) Microfauna of Schirmacher Oasis, Antarctica: I. Water moss communities *Scientific Report of Indian Expedition to Antarctica, Technical Publication* **4** 139-148

Ingole B S and Parulekar A (1990) Limnology of Pryadarshini lake, Schirmacher Oasis, East Antarctica *Proceedings of Natural Science Academy* **B59** 589-600

Laws R (1989) Antarctica: The Last Frontier, British Library Cataloguing in Publication Data, Italy. OFSA, S.P.A. for Boxtrene Ltd., London

Maslen N R (1980) Additions to the Nematode fauna of the Antarctic region with keys to taxa *Br Antarct Surv Bull* **49** 207-229

May J (1988) *The Green Peace Book of Antarctica (A new view of the seventh continent)* Dorling Kindersley Ltd., London

Mitra B (1999) Studies on moss inhabiting invertebrate fauna of Schirmacher Oasis *Fifteenth Indian Expedition to Antarctica, Scientific Report*. Department of Ocean Development *Technical Publication* **13** 93-108

Murray A (1910) Microscopic life at Cape Royds *British Antarctic Expedition, 1907-1909 Reports on the Scientific Investigations* **1** 17-22

Paugh P J A (1993) A synoptic catalogue of the Acari from Antarctica, the sub-Antarctic islands and the Southern Ocean *Journal of Natural History* **27** 323-421

Ramazotti C (1972) Phylum Tardigrada *Mem Inst Italiana Idrobiol* **28** 731

Richter W, Haendel D and Jughans P (1990) The animals of the Schirmacher Oasis (East ANtarctica) *Ant Res Proc Symp* Held at Potsdam GDR, **VII** 495-503

Richter F (1907) Die fauna der Moosrasen der Gaussebergs und emiger sudlicher Inseln *Dt Sudpol Exped* **9**(4) 259-302

Sanyal A K, Basak S and Barman R P (2002) Three new species of Oribatid Mites (Acarina: Oribatida: Haplochthoniidae) from the Antarctic continent *Acarina* **10** 57-63

Sanyal A K and Gupta S K (2005) Acari from Antarctic continent: One new species of Proctolaelaps (Mesostigmata: Ascidae) and some new reports (Prostigmata, Astigmata, Mesostigmata, Cryptostigmata) *Proceedings of Zoological Society* **58** 79-84

Sanyal A K and Hazra A K (2008) A review on studies on Collembola (Insecta) and Mite (Acari) in Schirmacher Oasis, East Antarctica *Bionotes* **10** 118-120

Smith H G (1987) The distribution and ecology of terrestrial protozoa of sub-Antarctic and maritime Antarctic islands *British Antarctic Survey Scientific Reports* **95** 1-104

Spaull V W (1972) Antarctenchus hooped n.g., n.sp. (Nematoda: Dolichodoridae) from Signy Island, South Orkney Islands Britisy *Antarctic Survey Bulletin* **33&34** 177-184

Steiner G (1916) Beitragezur geographischen verbreitung freilebenden Nematodon *Zool Anz* **46** 311-335

Sudzuki M (1964) On the microfauna of the Antarctic region. I. Moss-water community at Langhovde Biological Research of Japan *Ant Res Exp Ser* **19** 1-41

Tilbrook P J (1970) The terrestrial environment and invertebrate fauna of the maritime Antarctica *Antarctic Ecology* (Ed M W Holdgate). Academic Press, London and New York: 886-896

Venkatraman K (1995) Studies on phylum Tardigrada and other associated fauna, South Polar Skua and Bird and Mammal logging during 1994-1995 Expedition *Eleventh Indian Expedition to Antarctica, Scientific Report, 1995*. Department of Ocean Development, *Technical Publication* **12** 221-243

Venkatraman K and Hazra A K (2005) Studies on South Polar Skua (*Catharacta maccormicki*) in and around Maitri, Schirmacher Oasis *Rec Zool Surv India* **105** 139-145

Wallwork J A (1969) The zoogeography of Antarctic cryptostigmata. In: *Proceedings of 2nd International Congress of Acarology* Hungarian Academy of Sciences, Budapest: 17-20

Willem V (1901) Les Collemboles recueillis par 1 Expedition Antarctique Beige *Annals of the Society for Entomology of Belgium* **45** 260-262.

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Review Article

Physical Process Influencing the Ecosystem of the Indian Sector of Southern Ocean-An Overview

N. ANILKUMAR* and P. SABU
National Centre for Antarctic and Ocean Research (NCAOR), Earth System Science Organisation (ESSO), Healand Sada, Vasco-da-Gama, Goa 403 804, India

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The Antarctic Circumpolar Current (ACC) is the key current system in the Southern Ocean (SO) which connects three major oceans. The eastward flowing ACC in the Indian sector of SO (IOSO) influences by the southwest Indian ridge and Weddell gyre which results a southward shift of the core of ACC. This brings warm water to the coastal Antarctica and may cause glacier/sea-ice melting and further warming and freshening of bottom water masses. Additionally eddies in IOSO are the principal mechanism which transfer heat, salt, and carbon poleward across the zonal ACC and contribute to the mixing of water masses. The southward intrusions of Subtropical Surface Water as well as the upward movement of Antarctic Intermediate Water are attributed to the influence of anticyclonic and cyclonic eddies respectively. Presence of upwelling in the coastal waters of Antarctica (Prydz Bay), increased sea ice extant and subsequent enhanced melting in positive Southern Annular Mode (SAM) events causes high chlorophyll *a* in the coastal waters as well as south of Polar Front during austral summer, which perhaps makes the IOSO a potential site for CO_2 sink. Further, the bottom waters from this region may bring the dissolved CO_2 which is getting ventilated in subtropics. However detailed investigations covering seasons are required to be implemented using Models and Observations (Both satellite and in-situ) for a better understanding about the IOSO ecosystem and it's links to Tropical Ocean.

Keywords: Antarctic Circumpolar Current; Antarctic Bottom Water; Melt Water; Eddies; Chlorophyll; Southern Ocean

Introduction

Southern Ocean (SO) is a unique region which tends to have a global scientific relevance in terms of its circulation, water masses, other distinct physical, chemical and related biological processes and it's response to climate change. In the light of the above perspectives, the SO in general and the Indian Ocean sector of the SO (IOSO) in particular, is still an understudied region. Further the IOSO circulation is linked with the Indian Ocean circulation through Agulhas current, Antarctic Circumploar Current (ACC), West Australian current and South Equatorial current systems. Hence the exchange of heat and mass through these currents shall affect the variabilities of the Indian monsoon.

The major current in the SO is the ACC, which is the major conduit for inter ocean transport of heat and fresh water fluxes (Rintoul and Sokolov, 2001; Sokolov and Rintoul, 2002; Rintoul *et al*., 2002; Yuan *et al*., 2004). ACC transforms the hydrographic conditions in the SO, which is entrenched with copious circumpolar fronts, jets, high-speed filaments and eddies (Sokolov and Rintoul 2007; Lenn *et al*., 2011; Nowlin and Klinck, 1986; Stammer 1998; Hughes 2005). The IOSO has complex quasi-zonal frontal systems and the individual branches of these fronts often merge and diverge in response to interactions with the bathymetry (Sokolov and Rintoul 2007, 2009).

In some region of the IOSO the front allied with the Agulhas retroflection, known as Agulhas Return Front (ARF), merges with the Subtropical Front (STF) (Belkin & Gordon 1996; Lutjeharms and Ansorge 2001; Kostianoy *et al*., 2004) which is the boundary between subtropical and subantarctic waters (Deacon 1937; Hamilton 2006). The fronts southwards of STF

**Author for Correspondence: E-mail: anil@ncaor.gov.in*

are Subantarctic Front (SAF), Polar Front (PF), Southern ACC Front (SACCF) and southern boundary of the ACC (SB). These fronts extend through the water column since ACC is a deep-reaching barotropic current, (Belkin and Gordon 1996; Meijers *et al.*, 2010). The topographic influences and discrepancies in hydrographic as well as biological characteristics in various frontal systems have been reported (Orsi *et al.*, 1995; Belkin and Gordon 1996; Sparrow *et al.*, 1996; Holliday and Read 1998; Kostianoy *et al.*, 2004; Sokolov and Rintoul 2007; Swart *et al.*, 2008; Sokolov and Rintoul, 2009; Swart and Speich 2010). Also, previous studies in the Indian IOSO have reported frontal variability, water masses and their influence on the phyto- and zooplankton biomass during austral summer (Jasmine *et al.*, 2009; Gandhi *et al.*, 2012).

The IOSO encompasses several deep and intermediate water masses which ventilate the abyssal and intermediate depths of the world oceans. The major water masses in the IOSO are Subtropical surface Water (STSW), Subantarctic Surface Water (SASW), Mode Water, Antarctic Surface Water (AASW), Antarctic Intermediate Water (AAIW), Circumpolar Deep Water (CDW) and Antarctic Bottom Water (AABW). Among these AABW is one of the most significant water masses which brings the dissolved inorganic carbon (DIC) from the polar regions to tropics and causes the deterioration of DIC due to the occurrence of warm water. The high degree of freshening and warming of AABW has been reported by earlier investigators (Whitworth, 2002; Rintoul, 2007). Another peculiar feature observed in the IOSO is the presence of Winter Water (WW) which has a close relationship with the heat budget as well as the freshening due to ice melt in the SO and is a major source of micronutrients which regulates the Chlorophyll (Chl a) blooms (Deacon, 1937; Park *et al.*, 1998; Yuan *et al.*, 2004; Boyd and Ellwood, 2010).

With the existing knowledge of IOSO it is quite impractical to derive a proper understanding useful for scientific indulgent or societal benefits. Hence more systematic investigations are required to be carried out to study the atmospheric, physical, biogeochemical and palaeoclimatic processes in IOSO to understand its role in the global climate change scenario. In view of this, the Ministry of Earth Sciences (Govt. of India) has initiated a national scientific program in the IOSO since 2004 with National Centre for Antarctic and Ocean Research (NCAOR), Goa as the nodal agency. So far eight multi-institutional and multidisciplinary expeditions have been completed with the active participation from several national and international research organizations and universities. In the present review paper we discuss about the major results in the aspect of hydrodynamics of the IOSO published so far from the studies carried out by the Indian expeditions.

Data and Methods

The surveys were carried out along two meridional sections, one above the southwest Indian ridge (between 45°E and 48°E) and the other above a relatively flat bottom (57° 30′E). The observations were carried out as far south as 69°19'S to understand the hydrodynamics of the study region and for this the atmospheric and physical parameters were measured (Fig. 1). The observations were mainly concentrated between the subtropical (40°S) and coastal waters of Antarctica. Data and samples were collected during the austral summer (January-February) onboard ORV Sagar Kanya in 2004, Akademic Boris Petrov in 2006 and 2009 and ORV Sagar Nidhi, in 2010, 2011, 2012, 2013 and 2015. In

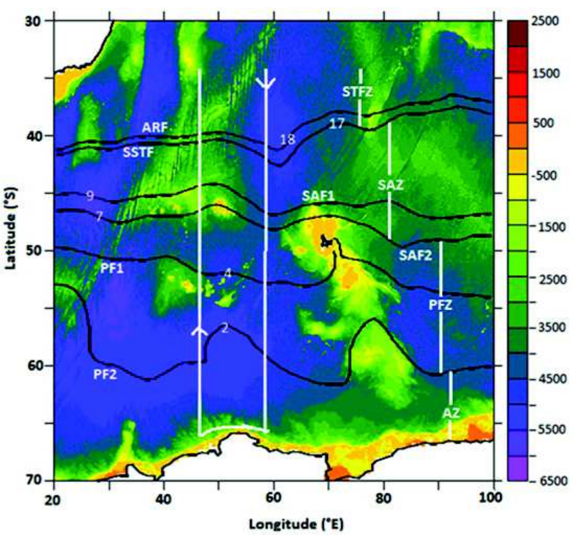

Fig. 1: IOSO study region. Fronts are marked using WOA climatology. Background colour represents the bathymetry of the study area from the high resolution ETOPO1 data [STFZ- Subtropical Frontal Zone, SAZ-Subantarctic Zone, PFZ-Polar Frontal Zone and AZ-Antarctic Zone]

2006 expedion, a time series observations were also carried out in the Prydz Bay (69°19'S, 76°E). During the above expeditions except in 2009, a CTD (Sea-Bird Electronics, USA) and XCTDs (Tsurumi-Seiki Co. TSK Ltd, Yokohama, Japan) were deployed to collect the temperature and salinity profiles. XCTD probes were launched at ~ 0.5° nautical mile intervals between the CTD stations. In 2009, a MARK III-B CTD (Neil Brown Instrument Systems) was used to collect the vertical profiles of temperature and salinity. The XCTD profiles were quality controlled by following the guidelines in the CSIRO Cookbook (1993). The salinity data from the CTD were calibrated against water samples analysed using a high-precision salinometer (Guildline AUTOSAL). Oceanic fronts were identified using the characteristic property indicators following the criteria listed by Belkin and Gordon (1996), Sparrow *et al*. (1996), Holliday & Read (1998) and Kostianoy *et al*. (2004). The thickness of the fresh water input in the surface layer relative to the WW in the study region was estimated using the formula of Park *et al*. (1998):

$$h = \frac{D_C(S_W - S^{bar})}{S_W}, S^{bar} = \frac{1}{D_C}\left[\int_{-D_C}^{0} Sdz\right],$$

where h is the thickness of the fresh water input per unit surface area, Dc is the WW depth, Sw is the WW salinity, and S^{bar} is the depth-averaged salinity between the surface and WW depth. Surface ocean currents from Ocean Surface Current Analysis–Realtime data (Bonjean and Lagerloef, 2002), monthly ASCAT wind stress (Bentamy and Fillon, 2012), Ekman current and AMSR-E ice coverage data from ERDDAP, (https://coastwatch.pfeg.noaa.gov/erddap), Argo data from the Coriolis Data Center (http://www.coriolis.eu.org/cdc) and sea surface height anomaly data AVISO (http://atoll-motu.aviso.oceanobs.com) were used. ECMWF (ORAS4,) reanalysis data (Balmaseda *et al*., 2013) was also used to understand the freshening of AABW in the study area.

Results and Discussion

Major Physical Processes in the IOSO

Frontal Variability: During southern summer, the position and structure of the SO fronts during austral summer 2004 (ARF, STF, SAF and PF) along 45°E has been discussed by Anilkumar *et al*. (2005). ARF was observed with a width of ~ 110 km in the region between 40°15' and 41° 15'S, the surface temperature ranges from 19° to 17°C and the depth of the 10°C isotherm ranges from 300 to 750m, contrary to narrower (44 and 73 km) ARF reported in an earlier study (Holliday and Read, 1998). However, STF identified between 41°15' and 42°15'S which was narrower (~ 110 km) compared to previous studies (> 220 km). On the other hand, the SAF was identified as a broader front (~ 500 km) between 42° 30' and 47°S compared to 165-275 km width reported by earlier studies (Holliday and Read, 1998; Lujeharms and Valentine, 1984). Between these latitudes, the surface temperature reduced from 9.7 to 6.3°C and surface salinity varied from 34.0 to 33.85. The differences in frontal positions based on the data from previous investigation are discussed by Anilkumar *et al*. (2005). The PF was identified as Surface PF (SPF) and Subsurface PF (SSPF), and the SPF was identified between 48 and 52°S, with a width of ~ 440 km, while the SSPF was identified by the northern limit of 2°C isotherm below 200 m. Anilkumar *et al*. (2014a) identified the positions of the Southern ACC Front and Southern Boundary of ACC between 60°S

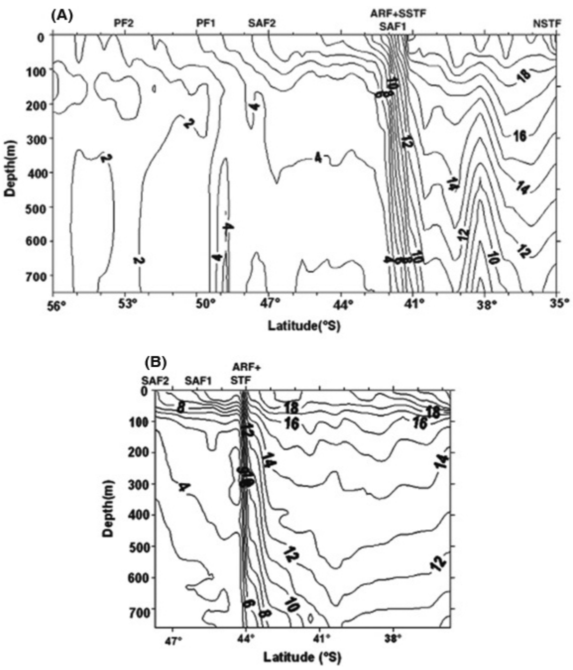

Fig. 2: Vertical structure of temperature (a) along 45°E and (b) along 57°30'E (1°C contour interval)

and 61°S and between 64°S and 64°30'S, respectively. A shifting of the merged fronts ARF+STF +SAF by >2° latitude towards south from 45°E to 57°30'E, has been demarcated (Fig. 2) by Anilkumar *et al*. (2006, 2007) and this shift could be due to the bottom topographic influence. The results of this analysis brought out the surface as well as subsurface manifestation of various oceanic fronts in IOSO, which was not intensively examined earlier.

Water Masses: The water masses in the IOSO have been demarcated (Fig. 3) by Anilkumar *et al*. (2006). STSW, SASW, and AASW were identified from 37 to 40°S, between 43° and 45°S and from 44° to 56°S respectively. STSW is characterized by relatively high temperature and salinity. The SASW always found near the southern boundary of the frontal zone and it is characterized by the lower temperature and salinity (9°C, <34). While nearing the PF region from the subtropics the surface water becomes colder and fresher indicating the presence of AASW. Cold and fresh Mode Water in a depth between 400 and 700 m from 31° to 41°S has also been reported by them and it as a subtropical Mode Water concurring with the earlier findings (Park *et al*., 1991 & 1993; McCartney, 1977). North of the ACC, this water mass is formed by deep winter convection and appears in summer sections as a pycnostad (or thermostad) beneath the seasonal thermocline (Park *et al*., 1993; Stramma and Lutjeharms, 1997). This Mode Water is not concatenated with the argument of McCartney (1977, 1982) who suggested all Mode Waters are associated with the circumpolar SAF. Between 31° and 41°S from ~1150 and ~1200 m depth, the features of AAIW characterized by its properties (q~ 4.4°C; salinity minimum ~ 34.42 and s_q ~ 27.24 kg m^{-3}) were identified which was reported earlier at 1100 m (Blindoff and McDougall, 1999) and 1300 m (Park *et al*., 1998). This could be due to impact of eddies present in this region as reported by Sabu *et al*. (2015). AAIW, as indicated by a salinity minimum at about 1000 m depth, spreads northward to about 10°S below the subantarctic Mode Water (Stramma and Lutjeharms, 1997) which has a strong circulation in the western Indian Ocean (Harris, 1972; Toole and Warren, 1993). Circumpolar Deep Water (CDW), occupies the depth range 2000-3800 m, has been identified with its remarkable feature (q~ 2°C; S~ 34.77 and s_q ~ 27.8 kg m^{-3}) in the IOSO, this concatenate with the characteristics of the North Atlantic Deep water (NADW) reported by Park *et al*. (1993), which rises sharply to shallower depths north of 45°S. The Antarctic Bottom water (AABW) was identified below CDW at 4100 to 4700 m depth. Along the deep western boundary of Madagascar (Warren, 1981), AABW enters the Madagascar Basin through the fractures in the Southwest Indian Ridge (Warren, 1978) and flows further north and this agrees with the characteristics of AABW identified upto 49°S.

Further Anilkumar *et al*. (2015) reported that AABW in the IOSO became warmer (~0.04°C) fresher (~0.01) and lighter (0.01 kg m^{-3}) in a time span of four years, from 2006 to 2010 (Fig. 4). A high degree of freshening was indicated by them from 2006 to 2010 in the IOSO (~0.01 in four years) compared to the freshening observed by Rintoul (2007) from 1990 to 2005 (~0.01 in 15 years). The increased influence of melt water from continental ice also may cause the freshening of bottom waters (Jacobs, 2002, 2006, Jacobs and Giulivi, 2010; Pritchard *et al*., 2012). In addition to the role of Amery Ice Shelf, indeed the nearby Cape Darnley Polynya was reported as a significant source of new bottom water (Ohshima *et al*., 2013). From the above discussions it can be noted that high degree of freshening and warming of AABW has been observed in the recent years could be due to the increased glacier melting as an impact of global warming.

Winter Water (WW): The WW is believed to be a key source of micronutrients (Boyd and Ellwood 2010), which controls the blooms of chlorophyll (Chl a) in the region. Freshwater layer thickness relative to the WW in 2010 and 2011 was compared (Fig. 5 and 6) and observed higher thickness and cooler WW during 2011 (Anilkumar *et al*., 2014a). This could be due to the increased presence of sea ice in the winter of 2010, which subsequently melted, resulting in the advection of melt water from the south and west of the study region. WW, temperature minimum layer in the subsurface, is the remnant of the mixed layer of the previous winter capped by seasonal warming and freshening (Deacon 1937; Park *et al*. 1998). The ocean surface is exposed to winds during the ice-free period, which augments the mixing, further this temperature minimum layer becoming mixed with the surface and subsurface layers, and subsequent changes shall be made in the heat budget of the region (Yuan *et al*., 2004).

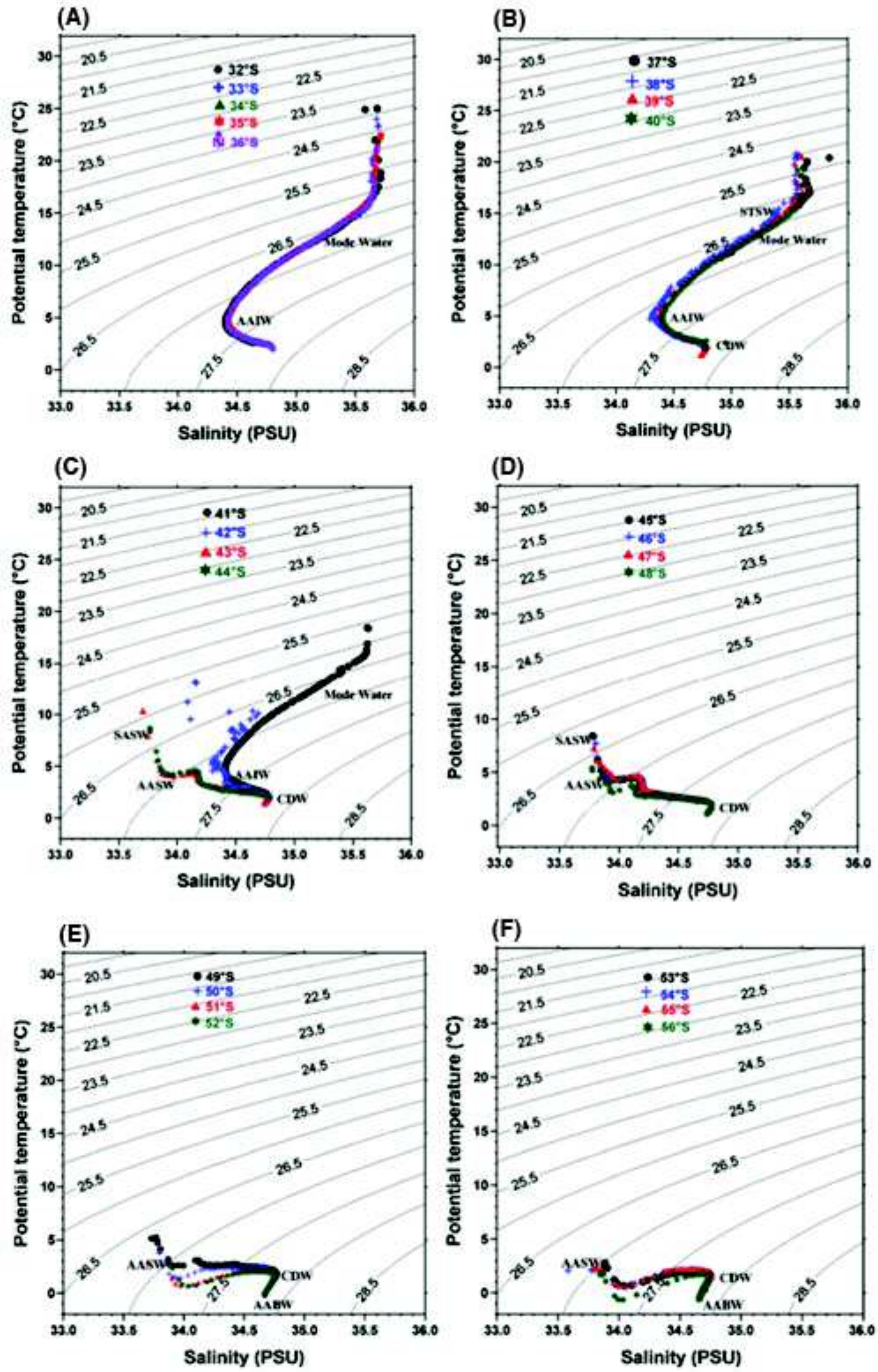

Fig. 3: TS diagram along 45°E. (a) 32–36°S, (b) 37–40°S, (c) 41–44°S, (d) 45–48°S, (e) 49–52°S, (f) 53-56°S (Anilkumar *et al*., 2006)

Eddies: The SO is one of the most energetic regions of the world ocean in terms of the eddy activity (Fu *et al*., 2010) in which mesoscale eddies play an important role in the dynamics and thermodynamics

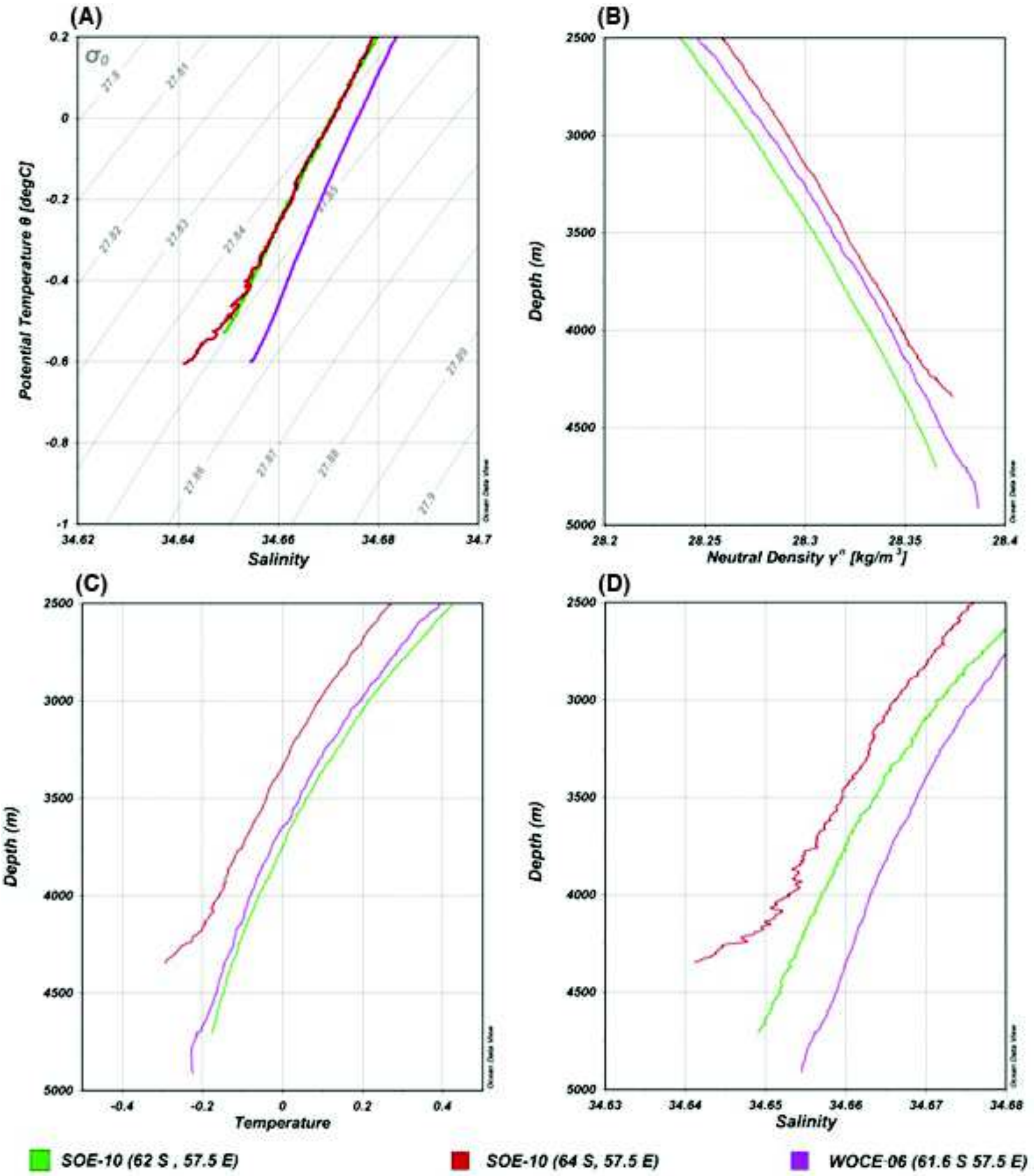

Fig. 4: Comparison between IOSO Expedition 2010 (SOE-10) and WOCE 2006 (a) è-S plot showing the presence of AABW (b) vertical structure of neutral density (c) vertical structure of temperature (d) vertical structure of salinity (Anilkumar *et al*., 2015)

(Marshall and Radko, 2003). Alternate cyclonic and anticyclonic eddies are common features in STF due to high mesoscale variability (Garrett, 1981). A southward shifting STSW in 2011 compared to 2010 (Fig. 7) is attributed to the dominance of eddies in 2011 (Chacko *et al*. 2014). The cyclonic eddy transports cold, fresh and deeper AAIW to much shallower depths (Fig. 8) but the anticyclonic eddy pushes the warm, more saline STSW to deeper depths (Sabu *et al*., 2015). Large change in water mass characteristics was noticed in the eddy regions which is more significant in the cyclonic eddy. STSW, Subtropical Mode Water, and AAIW were also significantly modified in the cyclonic eddy. It is

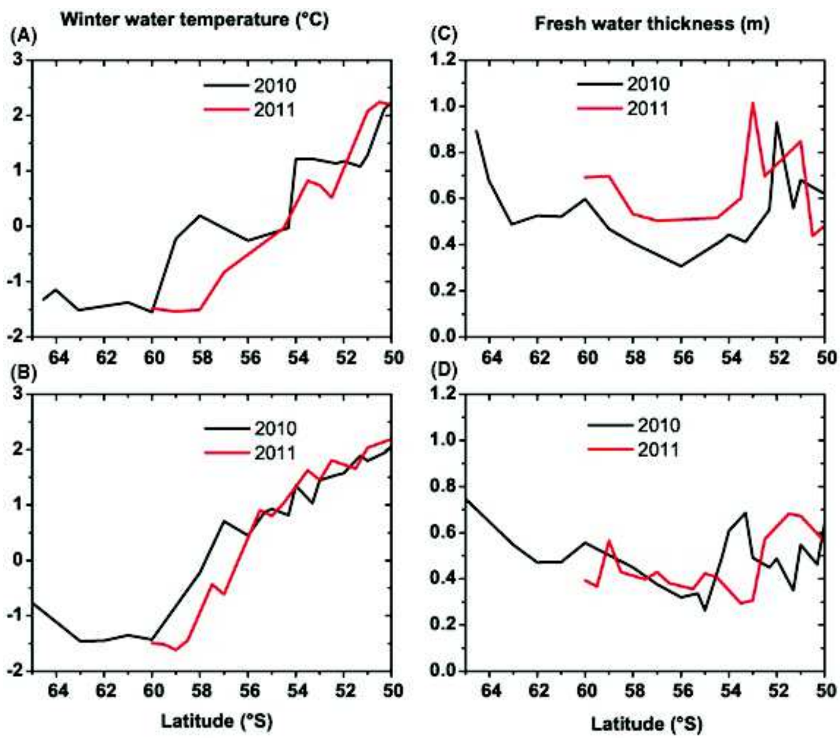

Fig. 5: (A) WW temperature (°C) in 2010 and 2011, along 47°E and (B), in 2010 and 2011 along 57°30'E (C) Freshwater thickness (m), in 2010 and 2011 along 47°E and (D), in 2010 and 2011 along 57°30'E

hypothesized that the freshening in the AAIW at a given depth in the cyclonic eddy is due to shoaling of the pycnocline, causing further intrusion of fresh saline water from deeper depths whereas the corresponding freshening in the anticyclonic eddy is due to the conservation of potential vorticity.

Costal Upwelling: Anilkumar *et al*. (2010) reported the signatures of coastal upwelling in the Prydz Bay (69°192 S 76°E) and its influence on the on phytoplankton abundance during the austral summer 2006 (Fig. 9). In earlier studies it was mentioned that Prydz Bay, is characterized by horizontal distributions of meltwater, suggesting a strong upwelling of warm water with the signatures of CDW, this causes the formation of sensible heat polynyas, perhaps it results in melting the existing ice and/or prevents new ice formation (Stagg *et al*., 1985; Cai *et al*., 2003; Flocco, 2005). Depends on oceanic conditions, the physical processes allied with the meltwater have varying impact on the growth of phytoplankton (Jansen *et al*., 2007). These studies signify the importance of upwelling processes on the phytoplankton community structure in the coastal waters of the Southern Ocean.

Physical Processes and Phytoplankton Bloom: Eventhough SO is considered as a high nutrient low-chlorophyll (Chl) region, the studies carried out by Sabu *et al*. (2014) and Anilkumar et.al. (2014a) showed the occurrence of an anomalous phytoplankton bloom in this area during the austral summer, 2011. The bloom, which formed in January 2011, intensified during February and weakened by March. High surface Chl concentrations (0.76 mg m^{-3}) were observed in the area of the bloom (60°S, 47°E) with a Deep Chlorophyll Maximum (DCM) of 1.15 mgm^{-3} at a depth of 40-60 m (Fig. 10). During 2011, both the concentration and spatial extent of sea ice were high on the western side of the bloom, between 0°E and 40°E, and enhanced freshwater influx was observed in the study area, as a result of ice-melt this probably causes the enhanced Chl *a* in the Antarctic Zone. A positive Southern Annular Mode and an intense La Nina during 2010-2011 are possible reasons for the high sea-ice. The presence of such blooms

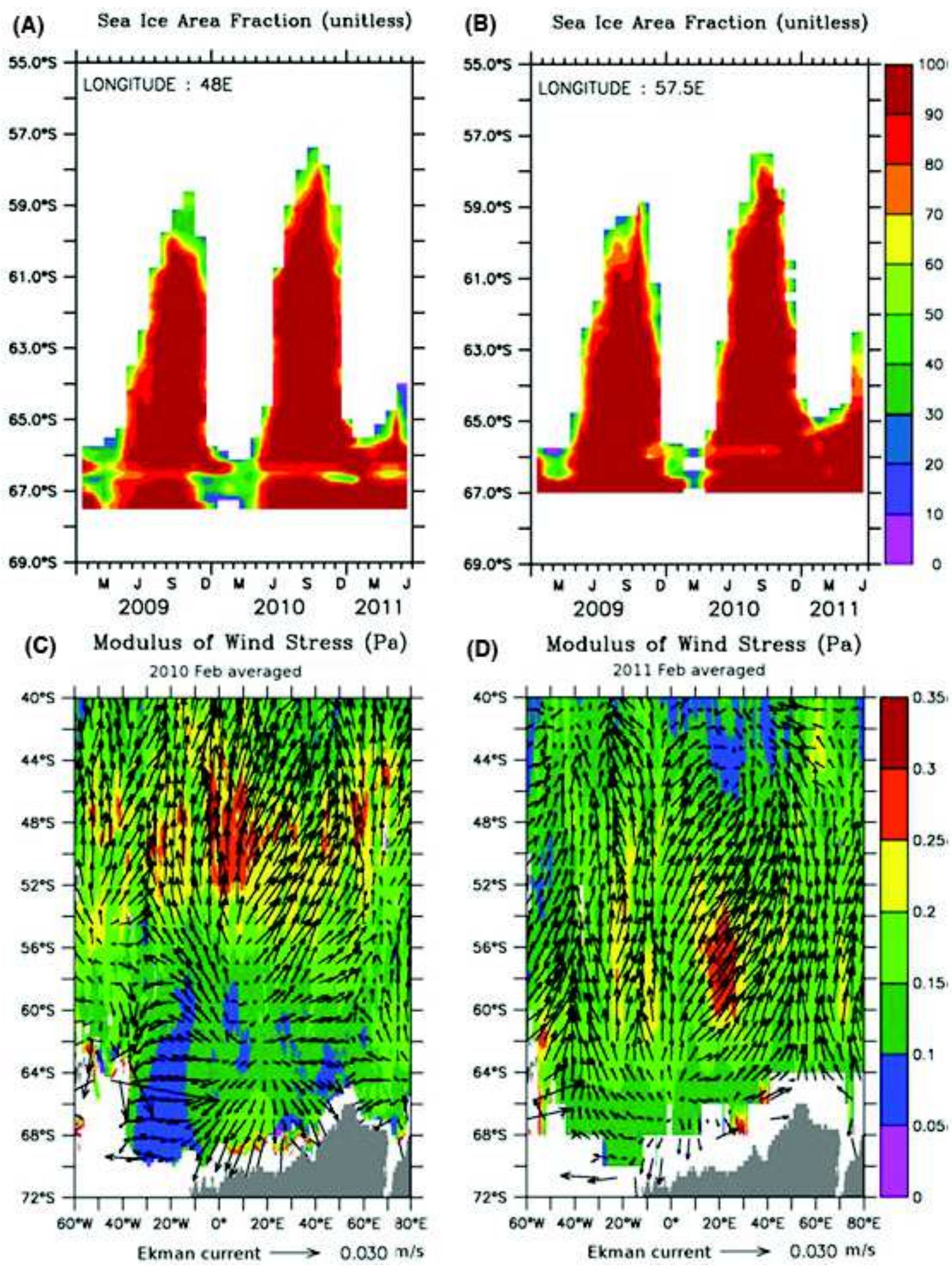

Fig. 6: Sea ice fraction derived from AMSRE along A, 48°E and B, 57°302 E; and wind stress (Pa) overlaid by Ekman currents (m s^{-1}) derived from ASCAT during C, February 2010 and D, February 2011 (Anilkumar *et al*., 2014)

can play major role in drawing down atmospheric CO_2, exporting carbon to the ocean interior, enhancing annual biological productivity, and influencing trophic dynamics and biogeochemical cycles of the IOSO.

CO_2 Ventilation: Dissolution and dissociation of bicarbonate ions are the factors controlling the CO_2 exchange south of 50°S, where the productivity is limited. Supply of deep water with high DIC content

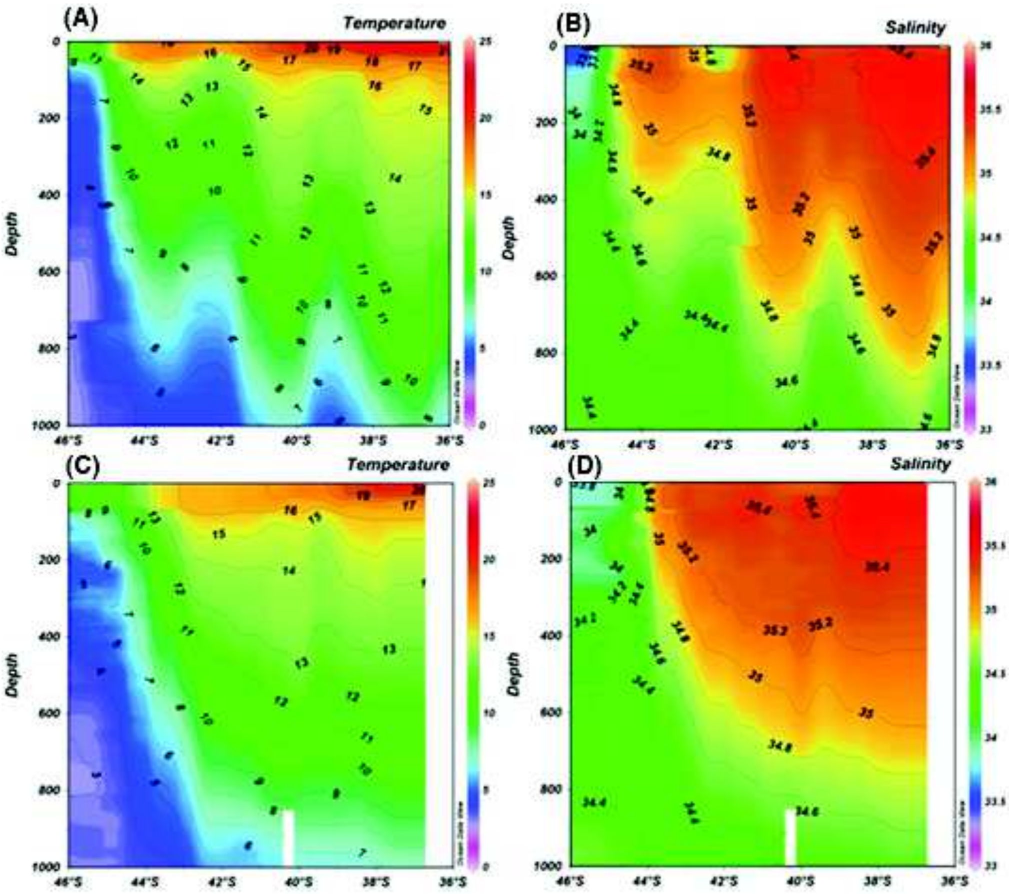

Fig. 7: Vertical section of temperature and salinity in 2011 (a, b) and 2010 (c, d) [Racheal *et al*., 2014]

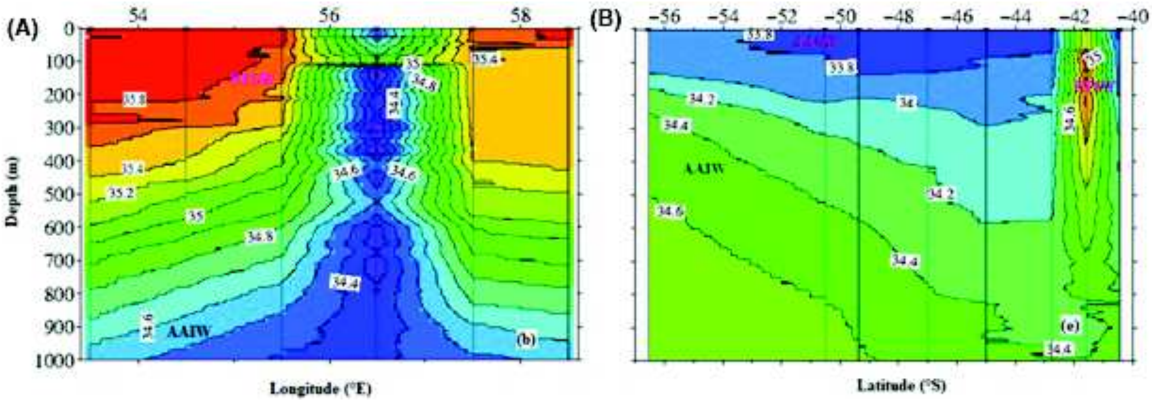

Fig. 8: Vertical section of salinity in the (a) cyclonic eddy along 40°S section and (b) anticyclonic eddy along 57° 30' E section. Black vertical lines in the figure represent the CTD locations [Sabu *et al*., 2015]

to the surface layer and then to the atmosphere (Fig. 11) is attributed to the occurrence of upwelling in the subtropical region and further to the deterioration of the dissolved inorganic carbon due to the occurrence of warm water (Prasanna *et al*., 2015). South of 44æ%S has been identified as major sink of global carbon in the SO region (Caldeira and Duffy, 2000; Fletcher *et al*., 2006) where one third of the total

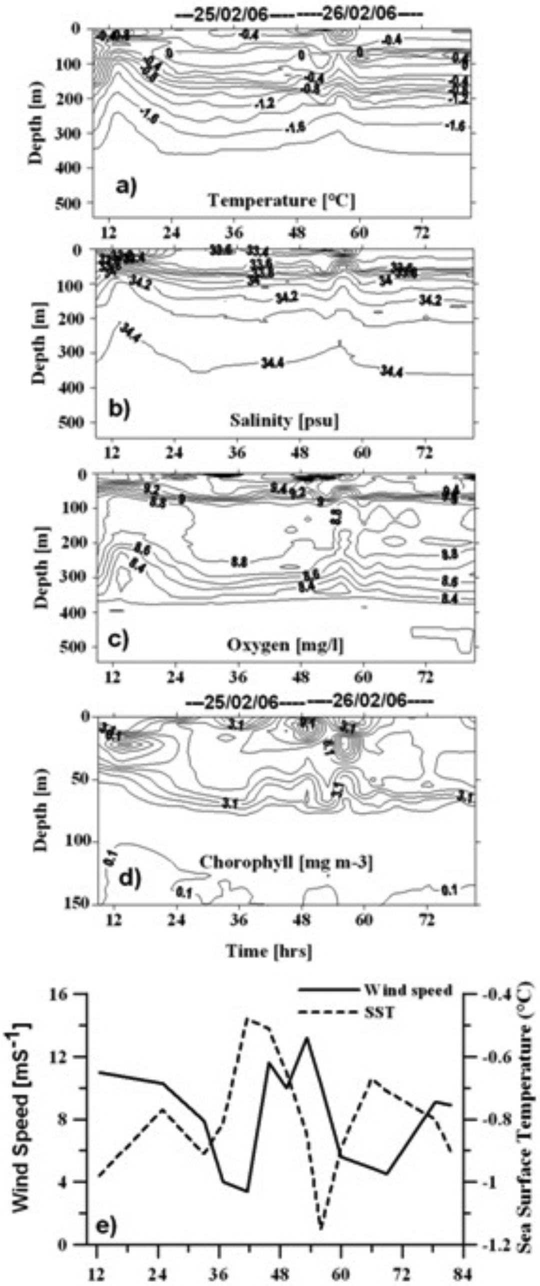

Fig. 9: Vertical structure of (*a*) temperature; (*b*) salinity; (*c*) oxygen; (*d*) chlorophyll and (*e*) wind speed and SST at 69°19'S, 76°E (Anilkumar *et al*., 2010)

global ocean uptake of anthropogenic CO_2 takes places (c.a. 0.7 PgC yr^{-1}) (Fletcher *et al*., 2006). Eventhough the efficiency of sinking of CO_2 reduces with time in SO predictions suggest that the region may remain as an important sink of atmospheric CO_2, (Roy *et al*., 2011) and it can be considered as a net sink for anthropogenic CO_2 (Takahashi *et al*., 2012). Although the role of temperature and wind in the CO_2 uptake process was renowned, the process of CO_2 uptake in SO is not completely understood (Longinelli *et al*., 2012). In the sub-Antarctic zone (SAZ) between 48°S and 51°S deep penetration of anthropogenic CO_2 (<1900 m) was observed with modest accumulation (<400 m) in south of 53°S (McNeil *et al*., 2001). In some particular zones in SO, the net flux of CO_2 is positive during summer time in an year although the SO has a net negative flux of CO_2 (Metzl, 2009) and these regions are significant to monitor in the event of climate change. To understand the factors responsible for the variability of CO_2 concentration in air and ocean, studies on physical and biological variables in this region are more significant (Valsala *et al*., 2012). Detailed observations on air and ocean CO_2 concentration in both the Indian Ocean and IOSO are imperative to link the prominent role of IOSO with the tropical climatic changes.

Way Forward

The IOSO behaves differently in terms of circulation due to its enclosure in the north with continental Asian landmasses hence anthropologically induced climate change is much faster. Hence future long term hydrodynamic studies (both Modeling and Observations) in the IOSO are imperative to address the following major scientific and societal questions.

- How the Southern Ocean circulation, thermohaline structure, bottom water masses, sea level and sea ice extent varies during different scales and how it is linked to Tropical Indian Ocean?
- What is the role of CO_2 dynamics/acidification rate, biogeochemistry and biodiversity of the Southern Ocean in modulating the physical characteristics of the water and vice versa?
- What are the atmospheric and ocean tele-connection between Southern Ocean and Tropical Ocean both in seasonal and inter-annual time scale? How these oceans responding to climate change?

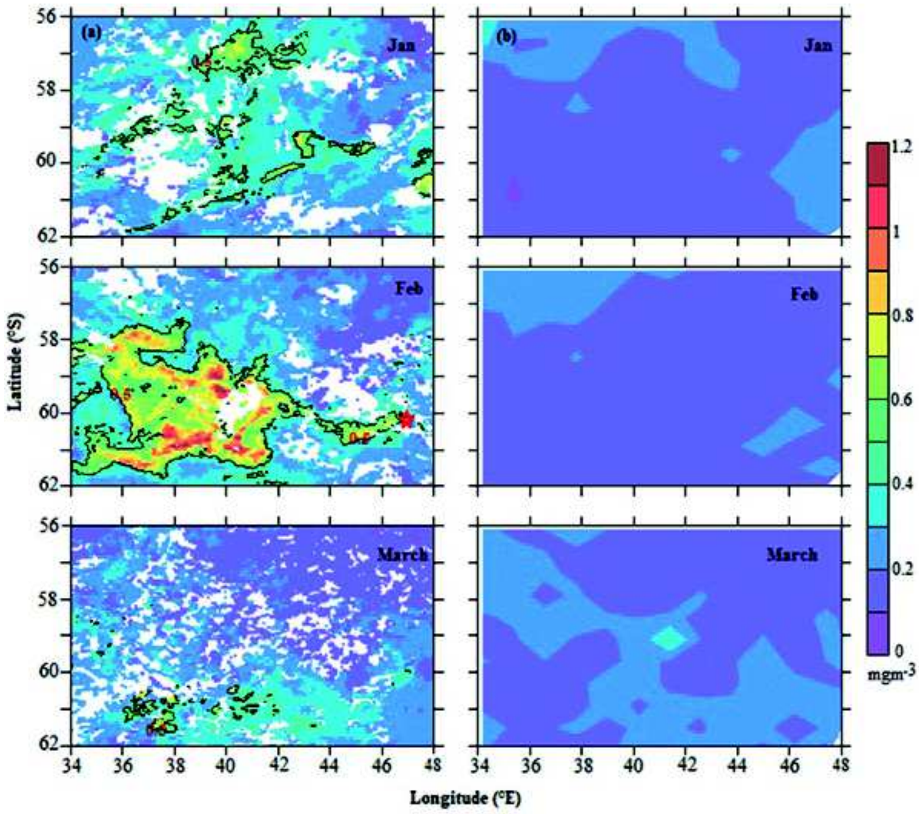

Fig. 10: Monthly variation of satellite Chl *a* during 2011(a) and long term mean (1997-2002) of Chl *a* (b) in the Indian sector of AZ [Sabu *et al*., 2014]

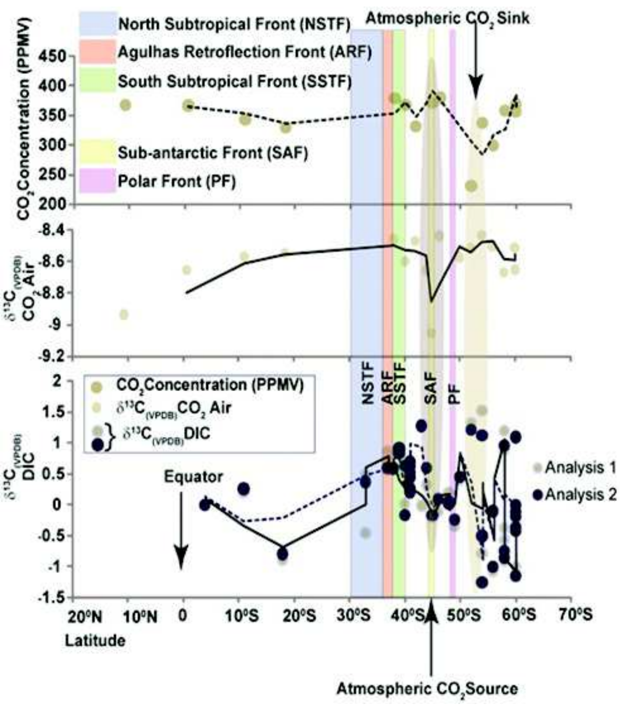

Fig. 11: A zone of CO_2 sink has been identified near 52°S, a zone of CO_2 ventilation has been identified near 45°S. Productivity being the main driving force for CO_2 sinking in southern ocean (Prasanna *et al*., 2015)

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References

Anilkumar N, Dash M K, Luis A J, Ramesh Babu V, Somayajulu Y K, Sudhakar M and Pandey P C (2005) Oceanic fronts along 45°E across Antarctic Circumpolar Current during austral summer 2004 *Current Science* **88** 1669-1673

Anilkumar N, Luis A J, Somayajulu Y K, Ramesh Babu V, Dash M K, Pednekar S M, Babu K N, Sudhakar M and Pandey P C (2006) Fronts, Water Masses and Heat Content Variability in the Western Indian Sector of Southern Ocean during Austral Summer 2004 *Journal of Marine Systems* **63** 20-34

Anilkumar N, Pednekar S M and Sudhakar M (2007) Influence of ridges on hydrographic parameters in the Southwest Indian Ocean *Marine Geophysical Researches* **28** 191-199

Anilkumar N, Rahul Mohan, Shukla S K, Pednekar S M, Sudhakar M and Ravindra R (2010) Signatures of coastal upwelling in Prydz Bay, East Antarctica during austral summer 2006 *Current science* **99** 1390-1394

Anilkumar N, George J V, Chacko R, Nuncio M and Sabu P (2014b) Variability of fronts, fresh water input and chlorophyll in the Indian Ocean sector of the Southern Ocean *New Zealand Journal of Marine and Freshwater Research* **49** 20-40

Anilkumar N, Chacko R, Sabu P, Honey Pillai U K, George J V and Achuthankutty C T (2014a) Biological response to physical processes in the Indian Ocean sector of the Southern Ocean, A case study in the coastal and oceanic waters *Environmental Monitoring and Assessment* **186** 8109-8124

Anilkumar N, Chacko R, Sabu P and George J V (2015) Freshening of Antarctic Bottom Water in the Indian Ocean Sector of Southern Ocean *Deep Sea Research II* **118** 162-169

Balmaseda M A, Mogensen K and Weaver A T (2013) Evolution of the ECMWF ocean reanalysis system *Quarterly Journal of the Royal Meteorological Society* **139** 1132-1161

Belkin I M and Gordon A L (1996) Southern Ocean fronts from the Greenwich Meridian to Tasmania *Journal of Geophysical Research* **101** 3675-3696

Bentamy A and Fillon D C (2012) Gridded Surface Wind Fields from Metop/Ascat Measurements *International Journal of Remote Sensing* **33** 1729-1754

Blindoff N L and McDougall (1999) Decadal changes along an Indian Ocean section at 32°S and their interpretation *Journal of Physical Oceanography* **30** 1207-1222

Bonjean F and Lagerloef G S E (2002) Diagnostic model and analysis of the surface currents in the Tropical Pacific Ocean *Journal of Physical Oceanography* **32** 2938-2954

Boyd P W and Ellwood M J (2010) The biogeochemical cycle of iron in the ocean *Nature Geoscience* **3** 675-682

Cai P, Huang Y, Chen M, Liu G, Qiu Y, Chen X, Jin D and Zhou X (2003) Glacial meltwater and sea ice meltwater in the Prydz Bay, Antarctica *Science in China* (*Series D*) **46** 50-61

Caldeira K and Duffy P B (2000) The role of the Southern Ocean in uptake and storage of anthropogenic carbon dioxide *Science* **287** 620-622

Chacko R, Nuncio M, George G V and Anilkumar N (2014) Observational evidence of the southward transport of watermasses in the Indian sector of Southern Ocean *Current Science* **107** 1573-1581

Deacon G E R (1937) The hydrology of the Southern Ocean *Discovery Reports* (15) 3-122

Fletcher S E M, Gruber N, Jacobson A R, Doney S C, Dutkiewicz S, Gerber M, Follows M, Joos F, Lindsay K, Menemenlis D, Mouchet A, Muller S A and Sarmiento J L (2006) Inverse estimates of anthropogenic CO_2 uptake, transport, and storage by the ocean *Global Biogeochemistry Cycles* **20** 2

Flocco D, Biggs N R T, Zambianchi E and Wadhams P (2005) An overview of the Antarctic polynyas and their impact on deep water production *Geophysical Research Abstracts* **7** 03513

Fu L-L, Chelton D B, LeTraon P-Y and Morrow R (2010) Eddy dynamics from satellite altimetry *Oceanography* **23** 14-25

Gandhi N, Ramesh R, Laskar A H, Sheshshayee M S, Shetye S, Anilkumar N, Patil S M and Mohan R (2012) Zonal variability in primary production and nitrogen uptake rates in the southwestern Indian Ocean and the Southern Ocean *Deep-Sea Research I* **67** 32-43

Garrett J (1981) Oceanographic features revealed by the FGGE drifting buoy array. In: Gower J F R (Ed) *Oceanography from Space*, Plenum Press, New York, pp. 61-69

Hamilton L J (2006) Structure of the Subtropical Front in the Tasman Sea *Deep-Sea Research I* **53** 1989-2009

Harris T F W (1972) Sources of the Agulhas Current in the spring of 1964 *Deep Sea Research* **19** 633-650

Holliday N P and Read J F (1998) Surface oceanic fronts between Africa and Antarctica *Deep-Sea Research I* **45** 217-238

Hughes C W (2005) Nonlinear vorticity balance of the Antarctic Circumpolar Current *Journal of Geophysical Research* **110** C11008

Jacobs S S, Guilivi C F and Merle P (2002) Freshening of the Ross Sea during the late 20th century *Science* **297** 386-389

Jacobs S S (2006) Observations of change in the Southern Ocean *Philosophical Transactions of the Royal Society A* **364** 1657-1681

Jacobs S S and Giulivi C F (2010) Large multi decadal salinity trends near the Pacific- Antarctic continental margin *Journal of Climate* **23** 4508-4524

Jansen D, Schodlok M P and Rack W (2007) Basal melting of A-38B: A physical model constrained by satellite observations *Remote Sensing Environment* **111** 195-203

Jasmine P, Muraleedharan K R, Madhu N V, Asha Devi C R, Alagarswamy R, Achuthan Kutty C T, Jayan Z, Sanjeevan V N and Sahayak S (2009) Hydrographic and productivity characteristics along 45°E longitude in the southwestern Indian Ocean and Southern Ocean during Austral summer 2004 *Marine Ecology Progress Series* **389** 97-116

Kostianoy A G, Ginzburg A I, Frankignoulle M and Delille B (2004) Fronts in the Southern Indian Ocean as inferred from satellite sea surface temperature data *Journal of Marine Systems* **45** 55-73

Lenn Y D, Chereskin T K, Sprintall J and McClean J L (2011) Near-surface eddy heat and momentum fluxes in the Antarctic Circumpolar Current in Drake Passage *Journal of Physical Oceanography* **41** 1385-1407

Longinelli A, Giglio F, Langone L, Moggio L, Ori C, Selmo E and Sgavetti M (2012) Atmospheric CO_2 concentrations and delta C-13 values between NewZealand and Antarctica, 1998 to 2010: some puzzling results *Tellus Ser B-Chem Phys Meteorology* **64**(December)

Lutjeharms J R E and Ansorge I J (2001) The Agulhas return current *Journal of Marine Systems* **30** 115-138

Lutjeharms J R E and Valentine H R (1984) Southern Ocean thermal fronts south of Africa *Deep-Sea Research* **31** 1461-1475

Marshall J T and Radko T (2003) Residual-mean solutions for the Antarctic circumpolar current and its associated overturning circulation *Journal of Physical Oceanography* **33** 2341-2354

McCartney M S (1977) Sub Antarctic Mode Water. In: Angel, MV (Ed) A voyage of Discovery. Pergamon, New York, 103-119

McCartney M S (1982) The subtropical recirculation of Mode Waters *Journal of Marine Research* **40** 427-464 (supplementary)

McNeil B I, Tilbrook B and Matear R J (2001) Accumulation and uptake of anthropogenic CO2 in the Southern Ocean, south of Australia between 1968 and 1996 *Journal of Geophysical Research-Oceans* **106** 31431-31445

Meijers A J S, Klocker A, Bindoff N L, Williams G D and Marsland S J (2010) The circulation and water masses of the Antarctic shelf and continental slope between 30 and 80°E *Deep Sea Research Part II* **57**(9) 723-737

Metzl N (2009) Decadal increase of oceanic carbon dioxide in Southern Indian Ocean surface waters (1991-2007) *Deep-Sea Research II* **56**(8-10) 607-619

Nowlin Jr, W D and Klinck J M (1986) The physics of the Antarctic Circumpolar Current *Review of Geophysics* **24** 469-491

Orsi A H, Whitworth T III and Nowlin W D Jr (1995) On the meridional extent and fronts of the Antarctic Circumpolar Current *Deep-Sea Research I* **42** 641-673

Ohshima K I, Fukamachi Y, Williams G D, Nihashi S, Roquet F, Kitade Y, Tamura T, Hirano D, Herraiz-Borreguero L, Field I, Hindell M, Aoki S and Wakatsuchi M (2013) Antarctic Bottom Water production by intense sea-ice formation in the Cape Darnley Polynya *Nature Geoscience* **6** 235-240

Park Y H, Gamberoni L and Charriaud E (1991) Frontal structure and transport of the Antarctic Circumpolar Current in the South Indian Ocean sector, 40°-80°E *Marine Chemistry* **35** 45-62

Park Y H, Gamberoni L and Charriaud E (1993) Frontal structure, water masses and circulation in the Crozet Basin. *Journal of Geophysical Research* **98** 12361-12385

Park Y H, Charriaud E and Fieux M (1998) Thermohaline structure of Antarctic surface water/winter water in the Indian sector of the Southern Ocean *Journal of Marine Systems* **17** 5-23

Prasanna K, Prosenjit Ghosh and Anilkumar N (2015) Stable isotopic signature of Southern Ocean deep water CO_2 ventilation *Deep Sea Research II* **118** 177-185

Pritchard H D, Ligtenberg S R M, Fricker H A, Vaughan D G, vanden Broeke M R and Padman L (2012) Antarctic ice-sheet loss driven by basal melting of ice shelves *Nature* **484** 502-505

Rintoul S R and Sokolov S (2001) Baroclinic transport variability of the Antarctic Circumpolar Current south of the Australia (WOCE repeat section SR3) *Journal of Geophysical Research* **106** 2815-2832

Rintoul S R, Sokolov S and Church J (2002) A 6-year record of baroclinic transport variability of the Antarctic Circumpolar Current at 140 degrees E derived from expendable bathythermograph and altimeter measurements *Journal of Geophysical Research* **107**

Rintoul S R (2007) Rapid freshening of Antarctic Bottom Water formed in the Indian and Pacific oceans *Geophysical Research Letters* **34** L06606

Roy T Bopp L, Gehlen M, Schneider B, Cadule P, Frolicher T L, Segschneider J, Tjiputra J, Heinze C and Joos F (2011) Regional impacts of climate change and atmospheric CO_2 on future ocean carbon uptake: a multimodel linear feedback analysis *Journal of Climate* **24** 5195-5195

Sabu P, Anilkumar N, George J V, Chacko R, Tripathy S C and Achuthankutty C T (2014) Air-sea-ice interaction on the anomalous phytoplankton bloom in the Indian Ocean sector of Antarctic Zone of the Southern Ocean during austral summer 2011 *Polar Science* **8** 370-384

Sabu P, George J V, Anilkumar N, Chacko R, Vinu Valsala and Achuthankutty C T (2015) Observations of watermass modification by mesoscale eddies in the subtropical frontal region of the Indian Ocean sector of Southern Ocean *Deep Sea Research II* **118** 152-161

Sokolov S and Rintoul S R (2002) Structure of southern ocean fronts at 140°E *Journal of Marine Systems* **37** 151-184

Sokolov S and Rintoul S R (2007) Multiple jets of the Antarctic Circumpolar Current south of Australia *Journal of Physical Oceanography* **37** 1394-1412

Sokolov S and Rintoul S R (2009) Circumpolar structure and distribution of the Antarctic Circumpolar Current fronts: 1. Mean circumpolar paths *Journal of Geophysical Research* **114** C11018

Sparrow M D, Heywood K J, Brown J and Stevens D P (1996) Current structure of the South Indian Ocean *Journal of Geophysical Research* **101** 6377-6391

Stagg H (1985) The structure and origin of Prydz Bay and Mac. Robertson Shelf, East Antarctica *Tectonophysics* **114** 315-340

Stramma L and Lutjeharms J R E (1997) The flow field of the subtropical gyre of the South Indian Ocean *Journal of Geophysical Research* **102** 5513-5530

Stammer D (1998) On eddy characteristics, eddy transports, and mean flow properties *Journal of Physical Oceanography* **28** 727-739

Swart S, Speich S, Ansorge I J, Goni G J, Gladyshev S and Lutjeharms J R E (2008) Transport and variability of the Antarctic Circumpolar Current south of Africa *Journal of Geophysical Research* **113** C09014

Swart S and Speich S (2010) An altimetry-based gravest empirical mode south of Africa: Dynamic nature of the Antarctic Circumpolar Current fronts *Journal of Geophysical Research* **115** C03003

Takahashi T, Sweeney C, Hales B, Chipman D W, Newberger T, Goddard J G, Iannuzzi R A and Sutherland S C (2012) The changing carbon cycle in the Southern Ocean *Oceanography* **25** 26-37

Toole J M and Warren B A (1993) A hydrographic section across the subtropical South Indian Ocean *Deep Sea Research* **40** 1973-2019

Valsala V, Maksyutov S and Murtugudde R (2012) A window for carbon uptake in the southern subtropical Indian Ocean *Geophysical Research Letters* **39** L17605

Warren B A (1978) Bottom water transport through the Southwest Indian Ridge *Deep Sea Research* **25** 315-321

Warren B A (1981) Trans-Indian hydrographic section at lat., 18°S: property distribution and circulation in the South Indian Ocean *Deep Sea Research* **28** 759-788

Whitworth T III (2002) Two modes of bottom water in the Australian-Antarctic Basin *Geophysical Research Letters* **29** 1073

Yuan X, Martinson D G and Dong Z (2004) Upper-ocean thermal structure and its temporal variability in the southeast Indian Ocean *Deep-Sea Research I* **51** 333-347.

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Review Article

Indian Contributions to Chemical Studies in the Indian Sector of Southern Ocean

MELENA A SOARES* and N ANILKUMAR

National Centre for Antarctic and Ocean Research, Earth System Science Organisation, Vasco-da-Gama, Goa 403 804, India

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Southern Ocean is a crucial oceanic regime for understanding the role of biogeochemical cycles in influencing the global climatic changes, as this is a region where signatures of global changes are more pronounced. For an Improved understanding of the link between Southern Ocean processes, biogeochemical cycles and the global climate, scientific research was commenced. Some remarkable research work has been accomplished by Indian Scientific community in the Indian sector of the Southern Ocean (ISSO). A total of six successful multi-disciplinary and multi-institutional expeditions were carried out from the year 2009 to 2015 in the ISSO, with the pilot expedition launched in the year 2004. During the last decade, an understanding of different aspects of the ocean processes has been achieved using chemical studies and proxies. Studies in the ISSO focused on shifts in the oceanic fronts, the carbon and nutrient dynamics, as well as the food web dynamics across the different fronts. The spatial-temporal variation of nutrients, dissolved oxygen, dissolved inorganic carbon and the factors regulating their distribution in the ISSO has also been addressed. Attempts were made to understand the atmosphere-ocean interaction of CO_2 and biogeochemical processes. Some experimental work have been undertaken to assess the nitrogen uptake and influence of micronutrients on phytoplankton. Similarly, stable isotope of oxygen has been used as a proxy in some early studies in the ISSO. Isotopic and molecular investigations have been commenced to understand the biogeochemical processes within the water column, as the biological pump and particulate organic matter (POM) have a major role to play in carbon sequestration and further influencing the global climate variability. Detailed studies on dissolved and particulate organic matter are being carried out to gain knowledge of the biological pump and the factors responsible for climate variability and ocean acidification.

Keywords: Indian Sector of Southern Ocean; Carbon; Oxygen Isotope; Stable Isotopes

Introduction

Southern Ocean (SO) is the largest and one of the most dynamic regions of the world Oceans. This is a regime influenced by the strongest winds and ocean currents. It is characterized by a well-defined frontal structure and supports transport and exchange of heat, salts, and other organic and inorganic components between the major ocean basins, through the Antarctic Circumpolar Current (ACC) (Jasmine *et al*., 2009; Anilkumar *et al*., 2006; Holliday and Read, 1998). The biogeochemical processes in this region have a major role in the global carbon cycle and climate change. The SO is a HNLC (High Nutrients Low Chlorophyll) region with high variability in the hydrographic and chemical characteristics (Martin *et al*., 2013). With a motive to understand this variability and the factors responsible, a pilot expedition in the Indian sector of the Southern Ocean (ISSO) was launched in the year 2004. From 2009 to 2015, six successful multi-disciplinary and multi-institutional expeditions were carried out in the ISSO. Some major national and international scientific institutions/ Universities have participated in these expeditions. With the launch of these expeditions, research in various sectors of oceanographic studies were commenced to understand the biogeochemical processes in the ISSO. Furthermore, the latitudinal variation of calcification depth of foraminifera (*G.bulloides*) was studied using stable oxygen

**Author for Correspondence: E-mail: smelena7@gmail.com*

isotopes. Investigations to identify the sources and processes governing the distribution of Suspended Particulate Matter (SPM) across the different frontal zones in ISSO are also being carried out. Studies addressing the variation of $\delta^{13}C$ and $\delta^{15}N$ of particulate organic matter (POM), and the factors controlling the isotopic signatures of POM in ISSO have been initiated to achieve knowledge of the biogeochemical processes and the biological pump in the ISSO. Some of the processes studied and the findings reported by using chemical proxies in the ISSO and coastal Antarctica have been discussed in this article.

Nutrients and Dissolved Gases

Documenting and understanding the trends of nutrient and dissolved gases, especially, carbon dioxide (CO_2) and CO_2 fluxes is important for providing insights into the biogeochemical processes in the ISSO and their role in the global climate changes. SO is a region characterised by low temperatures, strong winds, surface currents and mixing velocities. The role of temperature and wind stress in the process of CO_2 uptake and variations in CO_2 fluxes is documented in the SO (Anderson *et al.*, 2009; Longinelli *et al.*, 2012; Waugh, 2014). SO has been demarcated as a major sink of atmospheric CO_2 (Caldeira and Duffy, 2000; Fletcher *et al.*, 2006). However, studies have suggested that the strength of SO as a sink is decreasing and the intensity varies seasonally across different zones (Metzl *et al.*, 1991; Metzl, 2009). A deeper understanding of the carbonate system and the processes governing CO_2 uptake is of utmost importance to ascertain whether the entire regime acts as a source or sink for atmospheric CO_2. To gain better insights in this aspect, studies on total CO_2 (tCO_2) and partial pressure of CO_2 (pCO_2) in the ISSO were initiated.

A study to address the spatio-temporal variation of pCO_2 and its relation with nutrients and biological production in the ISSO along two transects (48°E and 57°30'E) was taken up during austral summer 2009 (Shetye *et al.*, 2012). This study reported low nitrate with higher nutrient utilisation in the Sub tropical front (STF) from 41°-43°S along 48°E and 43°-46°S along 57°30'E. Vertical mixing was assumed to have a major role in the supply of higher tCO_2 to the surface waters. The pCO_2 increased southwards along both the transects and this was attributed to the lower productivity (low TOC and Chlorophyll values) in the Polar Front (PF) region from 48°S to 57°S, during the study period. Based on a correlation analysis of different factors and temperature normalised pCO_2, this study postulated biological processes to be controlling the pCO_2 along 57°30'E transect and physical processes controlling the pCO_2 variation along 48°E transect. They proposed that SO acted as a sink but the area around Crozet Island behaved as a source likely because this region is prone to upwelling. pCO_2 increased southwards mainly due to low biological productivity. This study suggested that southwards the pCO_2 exhibited an increasing trend in the last decade and is associated with the Southern Annular Mode (SAM).

To fill the existing gaps concerning the knowledge of carbon cycle and pCO_2 variability in the ISSO, Shetye *et al.* (2015) studied the physical and biological processes controlling pCO_2 in the surface mixed layer during the transition period from summer to early winter. The authors used a one dimensional model by Louanchi *et al.* (1996), and describe the mixed layer carbon cycle, using in-situ data (January 2009, February 2010, March 2012) and satellite derived data to determine the relative contribution of biological activity, mixing, thermal and air-sea fluxes on pCO_2. Significant spatial and seasonal variation was observed in surface seawater pCO_2 across the frontal zones. An average increase of ~75μatm was reported in this study, from the STF (289 μatm) to the PF (364 μatm). It was also noted that the average pCO_2 estimated in the entire study area increased from 286 μatm in January to 337 μatm in March. A transition from pCO_2saturated waters (March 2009) to under saturated waters (January 2012) was observed during the study. In the month of January, the highest biological drawdown of pCO_2 was reported. This drawdown was associated with biologicalprocesses such as primary production, respiration and calcification, and was considered as the predominant controlling factors as compared to the physical processes like thermal variability, mixing and air-sea fluxes. This study concatenates the previous study (Shetye *et al.*, 2012) which addresses ISSO as a sink. The same study also reported that the average nutrients were highest in February, however silicate was maximum in March. A deviation from the Redfield's N/P ratio (16) was displayed with a variation, from an average of 6 to 9 increasing southwards, along the transect. The low N/P ratio indicated higher nitrate utilization. The N/P and Si/N ratios decreased from January to March.

A similar study was carried out in the Antarctic coastal waters and the Enderby basin to address the seasonal biogeochemical dynamics, pCO_2 variability and the air-sea flux through the different seasons (Shetye *et al.*, 2016). They found sea-ice plays a crucial role in driving biochemical changes and pCO_2 variability in the coastal Antarctica. Sea-ice changes caused a decrease in sea surface pCO_2 during summer, while it enhances pCO_2 during winter. This study documented a higher pCO_2 in March compared to that in January and February, however, most of the study area was under saturated with pCO_2. Based on the CO_2 fluxes estimated the study inferred, Enderby basin act as a strong sink in January, but a weak sink in other two months and proposed that different factors dominate during different months. The primary productivity, nutrient availability and sea ice were dominating in January but in February temperature played a major role, followed by primary productivity and sea-ice melting. However during March, nutrients, light availability and vertical mixing along with decay of organic matter were significant factors. The study also reported that the regions east of 55°E along the coastal Antarctica acted as a source of CO_2, while the western region acted as a sink for atmospheric CO_2 and associated this deviation with vertical mixing and biological processes.

Studies on nutrient distribution and DO in ISSO waters were initiated by Rajkumar *et al.* (2008). During the pilot expedition to SO, it was reported that the trend in nutrient distribution across the frontal zones matches with the hydrographic properties. The data (nutrient and oxygen) obtained during this study also provided insights of the changes in productivity.

Recently attempts have been made to understand the nutrient variability and nutrient utilisation across the frontals zones in the ISSO using geochemical tracers such as N*(nitrate utilisation) and Si*(Silicate utilisation).

N* and Si* was calculated as follows:

$N^* = NO_3 - 16PO_4$

$Si^* = Si(OH)_4 - NO_3$ (Sarmeinto *et al.*, 2004)

It was suggested that the utilization of nitrate was high in the northern region from 39°S to 44°S; whereas the silicate utilisation was higher in the south from 45°S to 52°S (Dessai *et al.*, 2011, Tech rep). The study ascertained that the nutrient dynamics across the fronts depends on the physical and biological processes.

Shetye *et al.* (2014) studied silica depletion under the Antarctic sea ice. They hypothesised that diatom bloom driven depletion of dissolved silica in the Antarctic under sea ice waters affect biomineralising organisms. They reported that surface dissolved silica (DSi) increased from subtropics towards the poles and was high all along the coast and also the dominance of diatoms resulted in high sediment organic carbon (3.5 %). They reported intense diatom dominated ice-edge plankton bloom in the Enderby basin causing severe depletion of DSi ($< 5\ \mu M$) under sea ice. This was supported by the presence of small spicules of sponges under Antarctic ice, also evidence for silica depletion from penecontemperorous dissolution was observed on small style spicules and the authors attributed thelow silica concentration under Antarctic sea ice to diatom bloom which is severely affected by the silicification in sponges.

Stable Isotopic Signatures of Carbon for Understanding CO_2 Exchange

A study to identify the region of CO_2 venting over the SO was carried by Prasanna *et al.* (2015). To achieve this, the atmospheric CO_2 concentration, the $\delta^{13}C$ of atmospheric CO_2, and the $\delta^{13}C$ of DIC was estimated in the sea surface waters across the latitudes in ISSO during 2011, 2012, 2013. They used Keeling's mixing model to trace the source of CO_2. The average $\delta^{13}C$ composition of the source of CO_2 was predicted to be –9.22±0.26 ‰ in the year 2011 and 2012 whereas it was predicted to be 13.49±4.07 ‰ in the year 2013, based on measured data. The end member value for 2011, 2012 was similar but did not match with the expected value of degradation of phytoplankton, thus the authors deduced dissolution of bicarbonates in the water column to be the source of CO_2 during the study period. They also proposed the degeneration of DIC to be favoured in warmer waters. However in 2013, the source of CO_2 was inferred to be degradation of organic matter and mixing of DIC present in seawater. The Keeling's component model identified the end member to have a composition of -36.7 ‰. Another finding from this study was that degassing of CO_2 to the atmosphere was favoured in coastal Antarctic region as this regime experience high wind speed and the surface waters have high DIC.

A recent report by Prasanna *et al.* (2016) addresses the effect of change in water mass properties with depth and latitudinal position on the incorporation of $\delta^{18}O$ and $\delta^{13}C$ in foraminifera (*G.bulloides*). The study also addressed the spatial distribution of $\delta^{13}C$ of DIC in surface waters. The $\delta^{18}O$ and $\delta^{13}C$ values of calcite at equilibrium, was calculated using the temperature and compared it with the isotopic composition of $\delta^{18}O$ and $\delta^{13}C$ in the water column. The measured $\delta^{18}O$ and $\delta^{13}C$ values were higher than the expected values by –2 ‰ and –1 ‰ respectively. They attributed the cause of disequilibrium south of 40°S to a process of mass dependent kinetic fractionation due to deeper depth habitat, partial dissolution, non-equilibrium calcification, oceanic Suess effect and genetic variability. An enrichment in $\delta^{13}C_{(DIC)}$ of surface waters was reported and this was attributed to an increase in organic matter production or its associated removal. Large inter-annual variation between the period of 2012 and 2013 was documented. They also proposed a model for production and export of organic matter. This model can be used to simulate $\delta^{13}C_{(DIC)}$ values for biologically productive regions in the SO. The model accounts for the $\delta^{13}C_{(DIC)}$ values in a given location based on the production rate of organic carbon, total organic carbon and the removal rate of organic carbon, it also demonstrates that a steady state of the carbon isotope ratio of water can be achieved in a relatively short time of ~5000 days. Beyond 50°S, the $\delta^{13}C_{(DIC)}$ values were low. The study ascertained that these $\delta^{13}C_{(DIC)}$ values are controlled by the nutrient supplied by Antarctic Bottom Water and upwelling.

Use of Stable Isotope of Oxygen ($\delta^{18}O$) and Hydrogen (δD) as a Proxy

$\delta^{18}O$ is generally used as a tracer to identify different water masses. δD values of seawater are sensitive to various processes of the hydrological cycle like evaporation, precipitation, and freezing. Therefore, study of δD and $\delta^{18}O$ along with salinity are unique and important to understand ocean surface processes.

A study was carried out by Tiwari *et al.* (2013) by coupling stable isotopes of oxygen and salinity in surface sea water to ascertain the ocean-atmospheric processes across the different fronts in the ISSO as well as to identify the water masses in this region. The study highlighted the relation between $\delta^{18}O$ and sea surface salinity pertaining to distinct water mass and confirmed the prevalence of evaporation/precipitation. The subtropical zone was dominated by evaporation/precipitation, whereas in the Antarctic zone, ice melting-freezing is dominant. The effect of continental ice melt was noted at the southernmost location (66.73°S). Using this stable isotope proxy the Subtropical and Polar fronts were identified at 44°S and 54°S respectively. This was succeeded by a study (Tiwari *et al.*, 2015) to document the $\delta^{18}O$ variability, the relation of $\delta^{18}O$ with salinity across the fronts in ISSO. The study also identified the origin, of the waters in the eddy encountered area. The slope of $\delta^{18}O$-salinity relation indicated that the warm core eddy was formed in a region dominated by evaporation and precipitation, while the waters surrounding the eddy are from a region dominated by freezing and melting. The role of eddies in the formation of intermediate waters in the SO was also explored in this study. The Antarctic Intermediate Waters (AAIW) with $\delta^{18}O$ values of 0.0 ‰ to 0.2 ‰, flowing below the Antarctic Surface waters which displayed the lowest temperature, salinity and $\delta^{18}O$ values (–0.4 ‰ to –0.2 ‰) were identified. The AAIW forms in the polar frontal waters, a region with the dominance of freezing/melting, however it was observed at a shallower depth which was possibly due to the influence of the eddy.

Experimental Work

To understand the nitrogen uptake and its role in limiting phytoplankton productivity, a few experiments have been carried out in the ISSO. Earlier studies have ascertained iron limitation in the SO and an addition of iron can increase primary productivity (Geider & Rocha, 1994; Hutchins *et al.*, 1995). However the effect on different N-substrate was unknown. One such initiative was a bottle scale ^{15}N tracer iron experiment carried out by Prakash *et al.* (2010) to assess addition of iron on the N-uptake rate and f-ratio in the ISSO. It was reported that iron addition not only enhance NO_3 uptake but also showed an increase in ammonia and urea uptake with insignificant effect on the f-ratio. The addition of iron did not enhance N-uptake based primary production at the initial stage but increased the uptake at a later stage.

Another mesocosm experiment was carried out by Dessai *et al.* (2011, Tech. Rep) to study the influence of iron and cobalt on phytoplankton community structure in the subtropical and polar front of the ISSO. It was reported that individually both the micronutrients stimulated growth when added individually but when added in combination it did not trigger much growth. It was also observed that diatom sustained longer in a cobalt enriched environment whereas the biomass was higher in the iron enriched environment.

Suspended Particulate Matter (SPM)

A study was taken up by Dessai *et al.* (2011) to gain insights into the spatial distribution of SPM and the associated trace metals and to identify its sources. The authors reported high SPM and low salinity in surface waters and also high SPM at 1000 m along with high iron and manganese in Antarctic zone. The study suggested that the particulate matter in the northern region especially the subtropical front was mainly of biogenic origin, with enrichment of calcium. It also stated that, temperature and salinity controlled primary production, has a major role in the SPM distribution of this region. Conversely, in the southern region SPM was of terrigenous origin and rich in iron and manganese. The inputs to the SPM in Southern region was proposed to be mainly from melt water and from a region with low productivity dominated by diatom. A similar study was carried out to understand the processes controlling the distribution of SPM across the frontal zones during austral summer 2010, wherein it was reported that the highest SPM was quantified in the Subantarctic zone followed by the Antarctic zone and this variability was attributed to the different biogeochemical processes dominating in the different zones of ISSO (Nayak & Noronha, Tech. rep., 2011)

Particulate Organic Matter (POM) in the Water Column

The ISSO being characterised by different oceanic fronts and influenced by eddies, this region is highly dynamic in terms of air-sea flux of CO_2 as well as the factors governing the fate of organic matter (production, remineralisation) and preservation. POM is a key component of the biological pump and it is known from earlier studies, that a major portion of POM is remineralised in the upper photic layer (Honjo *et al.*, 2008; Duforet-Gauier *et al.*, 2010). Therefore to understand the biogeochemical processes isotopic and molecular studies are important. The stable isotopic ratio of carbon and nitrogen of POM ($\delta^{13}C$ and $\delta^{15}N$) are often used to understand the conditions prevailing at the time of carbon fixation and to get insights of the processes related to organic matter cycling (Lourey *et al.*, 2003, 2004 & references within). Recently investigations to understand the biogeochemical cycle of POM using isotopic and molecular studies have been initiated.

One such study addressed the variation of $\delta^{13}C$ and $\delta^{15}N$ of POM, and the factors controlling the isotopic signatures of POM in surface waters in the ISSO (Soares *et al.*, 2015). In this study it was reported that in the ISSO, physical processes like temperature gradient and eddies as well as the biological processes contribute equally in the isotopic characterisation of POM, and these factors are responsible for the variation in $\delta^{13}C$ and $\delta^{15}N$ across the fronts in ISSO surface waters. During austral summer 2012, the $\delta^{13}C$ of POM in Subtropical front was enriched in $\delta^{13}C$ (average –22.81‰), relative to the $\delta^{13}C$ of colder Polar Front waters that displayed depleted values (average –25.82‰) similar to $\delta^{15}N$ that was enriched in the Subtropical front. It was postulated that the community structure had a major role in determining the isotopic signatures of POM with the dominance of dinoflagellates in the eddy prone, low nutrient Subtropical front waters with $\delta^{13}C$ enriched POM and diatoms dominated nutrient rich colder water displaying depleted $\delta^{13}C$ of POM.

Other Related Studies

Use of $\delta^{18}O$ as a Proxy in Planktonic Foraminifera Studies

Saraswat and Khare (2010) tried to ascertain the water depth at which the planktonic foraminiferal spp. *G. bulloides* calcifies its shell based on the stable isotopic composition of oxygen ($\delta^{18}O$) in its shells. A comparison of seawater salinity and temperature estimated from $\delta^{18}O$ of *G. bulloides* $\delta^{18}O$ show that calcification depth of *G. bulloides* varies latitudinally.

The study also stated that north of 43°S the calcification depth was deeper approximately 200 m, determined from the estimated temperature well matching the seawater temperature at 200 m. However, south of 43°S the calcification depth was shallower.

Subsequently, a study was carried out to evaluate the spatial variability of isotopic value of foraminifera across different frontal regimes (Tiwari *et al*., 2011). This study documented, planktonic foraminifera secrete their shell at isotopic equilibrium with seawater. Also, comparative analysis of $\delta^{18}O_{calcite}$ and predicted values $\delta^{18}O_{calcite}$ revealed a similar trend as that measured for the shells. They reported $\delta^{13}C$ values of plankton net samples and core top sediment samples increased southwards and attributed it to the productivity fluctuation which increase southwards due to the influx of nutrients from ice melt, since $\delta^{13}C$ variability appear to be governed mostly by primary productivity.

Recently, Mohan *et al*. (2015) demonstrated that there is a shift in the abundance of foraminifera from Subtropical Front to Polar Front and reported $\delta^{18}O$ in sediments is higher compared to towed plankton samples. The study proposed that some part of the shell precipitates in cooler deeper waters where secondary calcification occurs. This study suggested the absence of dissolution in the foraminifera from surface sediments and attributed it to low organic biomass.

Future Prospects

Although many studies have been carried out in the ISSO, the region is still understudied in terms of the biogeochemical processes. It is of utmost importance to understand the biogeochemical processes in the region as the SO have a strong global influence. Most important being the CO_2 dynamics, although studies are going on, they need to be extended on a larger scale and the system needs to be monitored to quantify the fluxes. It is essential to address Ocean acidification, which significantly influences the ocean biological community structure and other biochemical processes, consequently affecting the food web dynamics. Besides, detailed studies to understand the biological pump and processes like remineralisation within the water column are crucial, as the water masses formed in the ISSO can upwell at a different location causing degassing/flux of CO_2 to the atmosphere. As the carbon, nutrients and food web dynamics are all inter-linked and involve a complex interplay of varied physical, biological and biogeochemical processes which need to be studied in detail to understand and further predict the global climate variability.

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References

Anderson R F, Ali S, Bradtmiller L I, Nielsen S H H, Fleisher M Q, Anderson B E and Burckle L H (2009) Wind-driven upwelling in the Southern Ocean and the deglacial rise in atmospheric CO2 *Science* **323** 1443-1448

Anilkumar N, Luis Alvarinho J, Somayaluju Y K, Ramesh Babu V, Dash M K, Pednekar S M, Babu K N, Sudhakar M and Pandey P C (2006) Fronts, water masses and heat content variability in the Western Indian sector of the Southern Ocean during austral summer 2004 *J Mar Syst* **63** 20-34

Caldeira K and Duffy P B (2000) The role of the Southern Ocean in uptake and storage of anthropogenic carbon dioxide *Science* **287** 620-622

Dessai D V G, Singh K T , Mohan R, Nayak G N and Sudhakar M (2011) Reading source and processes from the distribution of suspended particulate matter and its selected elemental chemistry in the Southern and Indian Oceans *Current Science* **100** 1193-1200

Dessai D R G, Bhaskar P V, Anilkumar N, Krishnan K P and Achuthankutty C T (2011) Chemical Features *Southern Ocean expedition, Technical report 2011*, pp. 10-18

Duforet-Gaurier L, Loise L, Dessailly D, Nordkvist K and Alvain

S (2010) Estimates of particulate organic carbon over the euphotic depth from in situ measurements application to satellite data over the Global Ocean *Deep Sea Research I,* **57** 351-367

Fletcher S E M, Gruber N, Jacobson A R, Doney S C, Dutkiewicz S, Gerbe M, Follows M, Joos F, Lindsay K, Menemenlis D, Mouchet A, Muller S A and Sarmiento J L (2006) Inverse estimates of anthropogenic CO2 uptake, transport, and storage by the ocean *Global Biogeochemical Cycles* **20** 2

Geider R J and Roche J La (1994) The role of iron in phytoplankton photosynthesis and the potential of iron limitation of primary productivity in the sea *Photosynth Res* **39** 275-301

Holliday N P and Read J F (1998) Surface oceanic fronts between Africa and Antarctica *Deep Sea Reearch I* **45** 217-238

Honjo S, Manganini SL, Krishfield R A and Francois R (2008) Particulate organic carbon fluxes to the ocean interior and factors controlling the biological pump: A synthesis of global sediment trap programs since 1983 *Progress in Oceanography* **76** 217-285

Hutchins D A (1995) Iron and the marine phytoplankton community *Prog Phycol Res* **11** 1-49

Jasmine P, Muraleedharan K R, Madhu N V, Asha Devi C R, Alagarsamy R, Achuthankutty C T, Jayan Z, Sanjeevan V N and Sahayak S (2009) Hydrographic and production characteristics along 45°E longitude in the southwestern Indian Ocean and Southern Ocean during austral summer 2004 *Marine Ecology Progress Series* **389** 97-116

Longinelli A, Giglio F, Langone L, Moggio L, Ori C, Selmo E and Sgavetti M (2012) Atmospheric CO_2 concentrations and delta C-13 values between New Zealand and Antarctica, 1998 to 2010: Some puzzling results *Tellus Ser B-Chem Phys Meteorol* **64** (December)

Louanchi F, Metzl N and Poisson A (1996) A modeling the monthly sea surface fCO_2 fields in the Indian Ocean *Marine Chemistry* **55** 265-280

Lourey M J, Trull T W and Sigman D M (2003) Sensitivity of ä^{15}N of nitrate, surface suspended and deep sinking particulate nitrogen to seasonal nitrate depletion in the Southern Ocean *Global Biogeochemical Cycle* **17** 1081.http://dx.doi.org/10.1029/2002GB001973

Lourey M J, Trull T W and Tilbrook B (2004) Sensitivity of ä^{13}C of Southern Ocean suspended and sinking organic matter to temperature, nutrient utilization, and atmospheric CO_2 *Deep Sea Research I* **51** 281-305

Martin P, Loeff M R, Cassar N, Vandromme P, d'Ovidio F, Stemmann L, Rengarajan R, SoaresM, González H E and Ebersbach F (2013) Iron fertilization enhanced net community production but not downward particle flux during the Southern Ocean iron fertilization experiment LOHAFEX *Global biogeochemical cycles* **27** 871-881

Metzl N (2009) Decadal increase of oceanic carbon dioxide in Southern Indian Ocean surface waters (1991–2007) *Deep Sea Research II* **56** 607-619

Metzl N, Beauverger C, Brunet C, Goyet C and Poisson A (1991) Surface water pCO_2 in the Western Indian sector of the Southern Ocean: a highly variable CO_2 source/sink region during the austral summer *Marine Chemistry* **35** 85-95

Mohan R, Shetye S S, Tiwari M and Anilkumar N (2015) Secondary calcification of planktonic Foraminifera from the Indian sector of Southern Ocean *Acta Geologica Sinica* **89** 27-37

Nayak G N and Noronha C (2011) Suspended particulate matter in the Southern Ocean:An approach to understand source and processes *Southern Ocean expedition, Technical report 2011* pp. 41-45

Prakash S, Ramesh R, SheshshayeeM S, Mohan R and Sudhakar M (2010) Effect of high level iron enrichment on potential nitrogen uptake by marine plankton in the Southern Ocean *Current Science* **99** 1400-1404

Prasanna K, Prosenjit Ghosh, Bhattacharya S K, Mohan K and Anilkumar N (2016) Isotopic disequilibrium in *Globigerina bulloides* and carbon isotope response to productivity increase in Southern Ocean *Scientific Reports* **6** 21533 doi 10.1038/srep21533

Prasanna K, Prosenjit G and Anil Kumar N (2015) Stable isotopic signature of Southern Ocean deep water CO_2 ventilation *Deep Sea Research Part II* **118** 177-185

Rajakumar A, Alagarsamy R, Khare N, Saraswat R and Subramaniam M M (2008) Studies on the nutrient distribution in the Southern Ocean waters along the 45° E transect *Indian Journal of Marine Sciences* **37** 424-429

Saraswat R and Khare N (2010) Deciphering the modern calcification depth of *Globigerina bulloides* in the Southwestern Indian Ocean from its oxygen isotopic composition *Journal of Foraminiferal Research* **40** 220-230

Sarmiento J L, Gruber N, Brzezinski M A and Dunne J P (2004) High-latitude controls of thermocline nutrients and low latitude biological productivity *Nature* **427** 56-60

Shetye S S, Jena B and Mohan R (2016) Dynamics of sea-ice biogeochemistry in the coastal Antarctica during transition from summer to winter *Geoscience Frontiers* (In press)

Shetye S S, Mohan R, Patil S, Jena B, Chacko R, George J V, Noronha S, Singh N, Priya L and Sudhakar M (2015)

Oceanic pCO_2 in the Indian sector of the Southern Ocean during the austral summer–winter transition phase *Deep Sea Research Part II* **118** 250-260

Shetye S S, Mohan R, Jafar S A, Nair A, Patil S, Jawak S, Asthana R and Gazi S (2014) Diatom burst-driven silica depletion under the Antarctic sea ice: evidence from sponge spicules *Current Science* **107** 273-277

Shetye S S, Sudhakar M, Ramesh R, Mohan R, Patil S and Laskar A (2012) Sea surface pCO_2 in the Indian Sector of the Southern Ocean during Austral summer of 2009 *Advanced Geosciences* **28** 79-92

Soares M A, Bhaskar P V, Naik R K, Dessai D, George J, Tiwari M and Anilkumar N (2015) Latitudinal ä^{13}C and ä^{15}N variations in particulate organic matter (POM) in surface waters from the Indian ocean sector of Southern Ocean and the Tropical Indian Ocean in 2012 *Deep Sea Research Part II* **118** 186-196

Tiwari M, Nagoji SS, Divya David T, Anilkumar N and Rajan S (2015) Oxygen isotope distribution at shallow to intermediate depths across different fronts of the Southern Ocean: Signatures of a warm-core eddy *Deep Sea Research Part II* **118** 170-176

Tiwari M, Nagoji S S, Kartik T, Drishya G, Parvathy R K and Rajan S (2013) Oxygen isotope–salinity relationships of discrete oceanic regions from India to Antarctica *vis-a-vis* surface hydrological processes *Journal of Marine Systems* **113-114** 88-93

Tiwari M, Mohan R, Meloth T, Naik, S S and Sudhakar M (2011) Effect of varying frontal systems on stable oxygen and carbon isotopic compositions of modern planktic foraminifera of Southern Ocean *Current Science* **100** 881-886

Waugh D W (2014) Changes in the ventilation of the southern oceans *Philos Trans R Soc A —Math Phys Eng Sci* **372** 2019.

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Review Article

Progress in Southern Ocean Biology from the Indian Sector: Half-decadal (2009-13) Overview

S C TRIPATHY*, R K MISHRA and R K NAIK

National Centre for Antarctic and Ocean Research, Earth System Science Organization, Headland Sada, Vasco-da-Gama, Goa 403 804, India

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This manuscript reviews the scientific insight gained from biological studies performed during Indian Southern Ocean Expeditions (ISOE) in the last 5 years. India's research activities in the Southern Ocean (SO) region emphasize the importance of enhanced understanding of the SO processes, biogeochemical cycles, marine productivity and global climate change scenario. Under the aegis of Ministry of Earth Sciences, Government of India, concerted efforts are put in place by NCAOR to carryout research in Indian sector of the SO since 2004, with a primary focus to comprehend the role (response) of the SO in regional and global climate variability. The findings discussed here are based on of a wide array of biological data collected during different expeditions (4^{th} to 7^{th} expedition conducted during 2009-13) which highlights: causal mechanisms of variability in phytoplankton community structure and productivity among frontal regions (i.e., Subtropical Front (STF), Subantarctic Front (SAF) and Polar Front (PF)), patterns of phytoplankton biomass distribution within and among the fronts, role of diatoms in deciphering environmental change, food-web dynamics, bio-optical characterisation of water column, response of bacteria and phytoplankton to micronutrient amendments, biochemical profiling of squids, distribution of Antarctic krill, and occurrence of different marine mammals/birds in the above frontal regions. Here, we attempt to succinctly capture the findings of published literature engendered from ISOE to put forward our present perception of this lesser-understood region in the SO. This document is expected to contribute to an increased understanding of the Indian sector of SO, besides providing the much needed visibility to our ongoing scientific endeavours among the international community.

Key words: Southern Ocean; Indian Sector; Plankton; Productivity; Biogeochemistry; Climate Change

Introduction

Each oceanic region has different significance in influencing the global climate change scenario with their potential for drawing-down the atmospheric CO_2 (Sabine *et al*., 2004). In this context, the Southern Ocean (SO), being the world's largest high-nutrient low-chlorophyll (HNLC) regions, plays a significant role as a sink for atmospheric CO_2 via its solubility and prevailing biological pumps (Chisholm *et al*., 2001). It thus plays a pivotal role in the global carbon cycle and climatic regulations through biogeochemical fluxes of carbon, nutrients etc. from the ocean surface to the deep interior. The efficiency of the biological pump depends on a range of environmental and biological factors (such as type of phytoplankton/zooplankton inhabiting), which in turn are influenced by climate change. It is observed that the productivity in SO regions is closely related to the hydrodynamics across the fronts and convergence zones, thereby varying the phytoplankton, the prey-predator relationship and food-web structure and biogeochemical cycle (Pollard *et al*., 2002; Kostianoy *et al*., 2004).

The biogeochemistry and circulation of the SO are widely viewed to be sensitive to perturbation by climate change (Sarmiento *et al*., 1998). The SO ecosystems are structured broadly by latitude, or more precisely, by the quasi-zonal structure of the Antarctic Circumpolar Current (ACC) (Grant *et al*., 2006; Griffiths *et al*., 2009) and by the bottom topography/

**Author for Correspondence: E-mail: sarat@ncaor.gov.in*

depth. The plankton community of small flagellates, coccolithophores and small zooplankton prevail at the silica limited waters of the Subantarctic Front (SAF) and Subtropical Front (STF), and diatoms become increasingly dominant towards south in the HNLC waters at Polar Front (PF) and the coastal Antarctica, where primary production is believed to be limited by availability of trace nutrients (presumably iron). These aspects drew the interest of researchers from all over the world to study such dynamic ecosystem for climate change, thus resulting in several large scale experiments (i.e., SOIREE, SOFeX, EiFeX, LOHAFEX, WOCE, JGOFS, RACER, SO-GLOBEC and BROKE-West survey etc.) in Pacific and Atlantic sector of the SO; nevertheless, the Indian sector of SO remained underexplored.

In 2004, under the sponsorship and support of Ministry of Earth Sciences (MoES), Government of India, the National Centre for Antarctic and Ocean research (NCAOR), Goa initiated a national programme to study the Indian sector of SO (Fig. 1) for an improved understanding of the SO processes, biogeochemical cycles, marine productivity and its response to global climate change. Till date, eight multi-institutional and multi-disciplinary expeditions were undertaken to the SO during the austral summer. Standard methodologies were adopted for measurement and analyses for respective variables (for details please refer the relevant published article). Outcome of the expeditions are published in the technical/scientific reports published by NCAOR and in the peer-reviewed journals of national and international repute. The present article aims to summarize the significant scientific results obtained from biological studies conducted during different expeditions from 2010 to 2013 (Table 1).

Findings from Different Expeditions

Over the years different ISOEs were carried out in Indian sector (45°E-77°E, 40°S-69°S) of the SO during austral summer (January-March). Cruise tracks were designed to spatially cover meridional and zonal sections for sampling across and along the frontal regions, respectively. During some expeditions, time series measurements at particular locations were also conducted to resolve the temporal variations in SO biological processes. The multidisciplinary observations were mainly concentrated between the subtropical (40°S) and coastal waters off Antarctica. Findings pertaining to biological studies from 4th to 7th expedition are discussed hereunder:

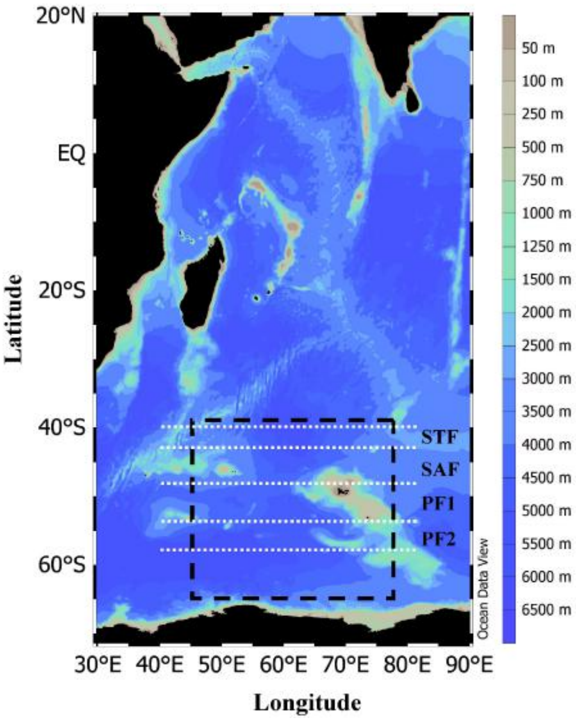

Fig. 1: Map showing boundary of the Indian sector of Southern Ocean (dashed-line rectangle box). The dotted white lines indicate the location of different frontals regions, whereas the colour bar indicates depth of the bottom topography

Findings from the 4th ISOE (2009-10)

This expedition was aimed at studying the Polar Front (PF) and coastal Antarctic zone (66°S) of the Indian sector of SO, which revealed interesting facts about the prevailing food-web dynamics, variability in phytoplankton biomass/chlorophyll a (Chl-a) and primary productivity (PP). Pavithran *et al.* (2012) observed contrasting pattern of Chl-a distribution within the PF (PF1: 52°S and PF2: 56°S), in spite of nutrients and light conditions not being limiting at both the regions. Hence, they attributed the reason for the observed contrasting pattern in Chl-a to the dominance of microbial food-web and conventional food-web at PF1 and PF2, respectively. Chl-a increased from 40°S to 52°S along the 52°30'E meridional transect except the 48°S. The subsurface chlorophyll maxima (SCM)

Table 1: General information about the Indian Southern Ocean Expeditions (ISOE)

Expedition	Duration	Study area*	Variables measured*	Sampled stations*
ISOE-4	12-Jan-2010 to 25-Mar-2010	40°S 66°S 47.5°E 57.5°E (PF1, PF2 & coastal Antarctica)	Phytoplankton pigment (chlorophyll a), primary production (^{14}C), phytoplankton/zooplankton taxonomy, bacterial carbon demand, Antarctic krill sampling for studying its distribution	21 stations
ISOE-5	24-Jan-2011 to 10-Mar-2011	40°S 60°S 47°E 57.5°E (Focus on STF+PF)	Phytoplankton pigments (HPLC), primary production (^{14}C), phytoplankton/zooplankton taxonomy, bio-optical studies, bacterial production and activity, marine mammals, seabirds, squid jigging	2 meridional transects along 57.5°E and 47°E including the STF and PF. Total 26 stations (2 time series: 1 each at STF and PF)
ISOE-6	23-Dec-2011 to 06-Feb-20	53.5°E 58.5°E 40°S 53°S (Focus on STF)	Phytoplankton pigments (HPLC), primary production zooplankton taxonomy, bio-optical studies, bacterial (^{14}C), phytoplankton/production and activity, squid jigging and biochemical evaluation. Observations on atmospheric CO_2 conc., atmospheric and dissolved $\delta^{13}C$ were started	09 stations (1 time series at STF)
ISOE-7	11-Jan-2013 to 27-Feb-2013	40°S 56.5°S 47.5°E 57.5°E (Focus on PF)	Phytoplankton pigments (HPLC), primary production (^{14}C, ^{13}C), ^{15}N-nitrogen uptake rates, phytoplankton/ zooplankton taxonomy, bio-optical studies, bacterial production and activity	19 stations (2 time series: 1 each at STF and PF)

*Some of the information (parameters measured, stations sampled) are restricted to biological sampling stations only. For sampling *ORV-Sagar Nidhi* was used for all expeditions and observations were made with prime importance to the frontal regions. For details please refer technical reports of the respective ISOE

depths varied from 50 m at 39°S to 10 m at 43°S. However, the column Chl-a concentration increased from 0.72 mg m^{-3} at 48°S to 5.38 mg m^{-3} at 52°S indicating that the colder water in the south was more productive compared to the waters of the north of Subantarctic Front (SAF) (Pavithran *et al*., 2014a). In the coastal region the Chl-a showed patchy and distinct variation between stations at the surface and varied from 0.39 to 4.9 mg m^{-3} and gradually increased from the west (51° 14'E) to east (53° 32'E). Based on scanning electron microscope studies, it was observed that the coccolithophores species *Emiliania huxleyi* was higher in abundance at the north of Subtropical Front (STF) and decreased its concentration towards south of SAF. Furthermore, it was found that the species survived better at a higher temperature (18.4-15.3°C), salinity (35.45-35.29) and low nutrients, high pH and high solar radiation conditions. The north-south trend of decreased calcification of *E. huxleyi* reflected the role of temperature and salinity as major factors for controlling the biogeographical distribution of coccolithophores (Patil *et al*., 2014). Shetye *et al*., 2014 observed that the diatom *Corethron criophilum* was the dominant species in the coastal region under low temperature (~1.5°C) and lower salinity 33. The authors suggested the possibility of a CO_2-driven shift in phytoplankton dominance in the future due to elevated CO_2 levels (decreased pH) in the SO.

During this period, PP varied from 0.03 to 20.20 (3.09 ± 4.89mg C m^{-3} d^{-1}) in the water column, and like Chl-a didn't show any north-south trend. The PP values for polar waters were higher than that of the offshore stations. The PP peak was observed at ~30 m, which did not coincide with the Chl-a peaks indicating that factors other than Chl-a were controlling PP in this region. Integrated PP (IPP) varied from 159-1083 mg C m^{-2} d^{-1}, with lowest values at 44°S (a typical HNLC region along with Si-limitation); whereas highest IPP was observed at the coastal region (66°S). High PP in the coastal region could possibly be due the influence of melt-water intrusion which brings the micronutrients (i.e., Fe, Co etc.), thus triggering an enhancement of biomass and productivity (Pavithran *et al*., 2014a). Comparison of Chl-a and PP data from PF and coastal Antarctic region indicated discrepancy in high Chl-a and relatively low PP in the coastal region by Tripathy *et al*., 2014. The authors depicted that large-sized phytoplankton (i.e., diatoms), dominant in coastal region, could package more intra-cellular pigments when compared to smaller phytoplankton (<10 μm), consequently there is decrease in their light-absorption/ photosynthetic efficiency (Fig. 2), resulting in lower surface PP, which is otherwise expected to be higher

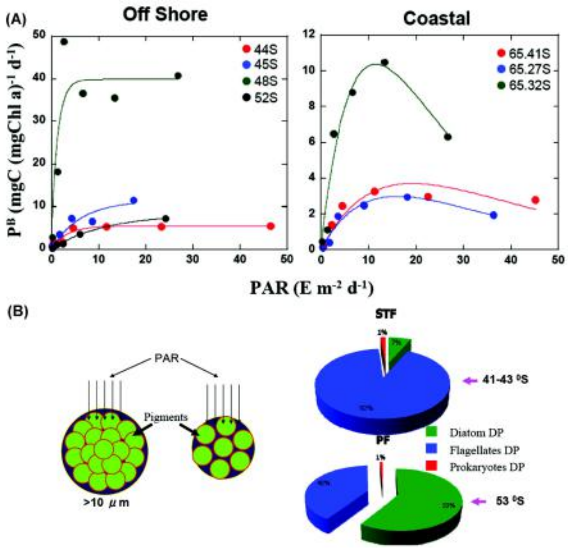

Fig. 2: (A) Photosynthesis (biomass-specific productivity)-irradiance curve in the water column showing inhibition in the surface layer in the coastal stations, (B) schematic of package effect (left panel) and percentage contribution of different diagnostic pigments at STF (41°-43°S) and PF (53°S)

in the presence of elevated Chl-a.

The mesozooplankton such as copepod and copepodites were dominant over all the fronts and zones sampled, however the salps were observed from surface to depth of 300 m and were distinct at south of PF region. In the offshore water both copepod and copepodites showed higher abundance at the mixed layer, and biomass increased towards PF compared to the SAF and STF region. Results indicated that increased phytoplankton biomass facilitated a higher increase of mesozooplankton biomass at PF than at SAF and STF (Pavithran *et al*., 2014a).

Like phytoplankton, bacterial carbon demand (BCD) varied significantly between the fronts (p = 0.03, df = 3) and depths (p = 0.003, df = 6) and ranged from 0.05 to 0.22 μg C l^{-1} h^{-1}. Similar to contrasting pattern of Chl-a, BCD was higher at PF1 (2.91 mg C m^{-2} h^{-1}) than at PF2 (1.55 mg C m^{-2} h^{-1}) implying that contribution of microbial loop (conversion of dissolved organic matter to secondary biomass) at PF2 was more pronounced due to lower bacterial respiration rate (0.83 mg C m^{-2} h^{-1}). Integrated bacterial growth efficiency was higher at PF2 (8.95) as compared to that of PF1 (7.42), further signifying the net contribution of PF2 to the microbial loop (Krishnan *et al*., 2014).

In SO food chain, the link between producers (phytoplankton) and higher animals are maintained by the krill. The krill is the largest euphausiid, widely distributed in SO and plays a key role in this ecosystem as a feed especially for whales, seals and birds. In the surface layers, three species of krill (*Euphausia lucens*, *E. frigida* and *Thysanoessa sp.*) were observed during the expedition (Manjebrayakath, 2014). No stage of the Antarctic krill (*E. superba*) was present in the surface layers suggesting that the species may not be migrating up to the surface during vertical migration. *E. frigida* (52%) was the most dominant species followed by *Thysanoessa sp.* (27%) and *E. lucens* (21%). The *Thysanoessa sp.* was restricted between 40°S and 46°S, whereas the *E. frigida* was abundant and widely distributed from 40°S and 66°S probably due to its wider tolerance to temperature.

Findings from the 5th ISOE (2010-11)

Two meridional sections (along 57.5°E and 47°E) including the STF and PF were covered during this expedition. Observations were also carried out along one zonal section (60°S). Between the two time series (72 h @ 3 h interval) stations, the PF was more productive than STF. Surface Chl-a was observed to be relatively low at STF (0.1-0.4 mg m^{-3}) compared to PF (0.2-0.45 mg m^{-3}). The water column-integrated Chl-a was also lower at STF (2.2-4.4 mg m^{-2}) compared to PF (4.2-7.3 mg m^{-2}). The southward increasing trend of phytoplankton biomass and shoaling of sub-surface chlorophyll maximum (SCM) was noticed between 40°S and 60°S. Chl-a values at SCM were in the range of 0.7 to 1.0 mg m^{-3} and the depth of SCM was always deeper than mixed layer depth (MLD). Along the transect 47°E surface distribution of Chl-a showed a southward increasing trend. The SCM at STF varied between 60 and 80 m with Chl-a ranging between 0.4 mg m^{-3} (40°S) and 1.2 mg m^{-3}

(60°S). On the other hand, at 57.5°E transect Chl-a ranged between 0.2 and 0.5 mg m^{-3} indicating lower Chl-a compared to the western margin (more productive). Surface Chl-a along 57.5°E was more uniform and the zonal variations across 60°S showed more productivity than the eastern margins (Pavithran *et al*., 2014b), which could be due to the availability of micronutrients because of proximity to the African continent. Phytoplankton diagnostic pigment-based analysis using CHEMTAX showed the cross-front distribution of phytoplankton communities and the relative contribution from major taxonomic groups to total biomass at STF and PF (Garcia *et al*., 2014; Mendes *et al*., 2015). Cyanobacteria and prochlorophytes dominated the total Chl-a in the STF, the haptophyes dominated the SAF region and diatoms were dominant at the PF. It was found that the spatial distribution of phytoplankton groups varied along ocean surface thermal gradients. Moreover, latitudinal differences in temperature, nutrients, variation in MLD, prevailing wind pattern and herbivory are probably the other parameters that distinguish the phytoplankton assemblages in this region (Mendes *et al*., 2015).

Time series measurements from this expedition highlighted the significance of deep chlorophyll maximum (DCM) in explaining the variability of IPP (Tripathy *et al*., 2015). At the PF, they observed a well-defined temperature minimum layer (TML), which was the winter residue of Antarctic Surface Water (AASW), between 50 and 320 m. The DCM at the PF (~ 75 m) was more prominent than that at the STF and coincided with the upper boundary of the TML. The elevated Chl-a in DCM is believed to result from the proliferation of the low-light adapted phytoplankton (shade flora) triggered by higher concentrations of micronutrients (presumably Fe) found in the winter remnant of the AASW than in the overlying mixed layer. Due to the presence of a strong DCM the average column-integrated Chl-a was nearly 2 times higher at the PF than at the STF yielding ~ 1.4 times higher IPP at the PF (211 mg C m^{-2} d^{-1}) compared to the STF (152 mg C m^{-2} d^{-1}). Higher Chl-a and PP at the PF was related to the dominance of diatoms. Owing to their higher sinking rate, the diatoms with sequestered CO_2, would generate substantial export production/flux, thereby making the PF region as a potential sink for atmospheric CO_2 (Tripathy *et al*., 2015).

Similar to the previous expedition the mesozooplankton showed clear diel variation in the STF and PF with a predominance of copepods (95%), indicating their adaptability to different environments and food availability (Pillai *et al*., 2014). A total of 18 and 12 taxa of copepods were observed at the STF and the PF, respectively, with more temporal variation in species abundance at STF than at PF. Vertical distribution of biomass at both STF and PF showed a decreasing trend from surface to deeper layer. An exclusive abundance of salps and cyclopoid copepod was also noticed in the STF, indicating a rare predator-prey relationship (between salps and sapphirina) existing in this region. Due to the abundance of salps, an exceptional increase in biomass was noticed occasionally at both the frontal regions by Pillai *et al*. (2014). They reported that (i) in both the transects (57.5°E: 37°S-60°S and 47°E: 42°S-60°S) a general increase in zooplankton biomass was observed towards southern latitudes, mainly due to occurrence and increase in density of macro-zooplankton components such as euphausiids, amphipods and salps; (ii) the higher abundance of meso-zooplankton observed at PF compared to STF was probably related to the seasonal phytoplankton availability in that area; (iii) the food-web structure appears to be more dynamic and multivorous at the STF comprising both conventional and microbial modes; whereas, the conventional food-web was more active at the PF, dominated by the herbivores.

Isolation and characterization of microalgae and bacteria were carried out from two transects (i.e., 45°S 57.30°E and 48°S 57.30°E). This study focused on hydrogen production and antibacterial activity against some gram-positive and gram-negative pathogenic bacteria by the isolated microalgae (Bandopadhyay *et al*., 2014). It was observed that isolates from 45°S and 57° 30' E at 45 m (P1) has more hydrogen producing capacity than isolates from 48°S and 57° 30' E at 30 m (P2). In the case of antibacterial activity chloroform and ethanol extracts of P1 have maximum activity against gram-positive bacteria than gram-negative bacteria. Ethyl acetate and ethanol extracts of P2 had maximum inhibition against pathogenic *E. coli*, a gram-negative bacterium. A total of 57 bacteria were isolated and found that some of the bacteria were pigmented and some were exopolysaccharide producing.

Bio-optical properties in the water column were studied by Shaju *et al*. (2014). They found a strong linear relationship between phytoplankton specific absorption (at 440 and 665 nm) vs Chl-a ($R^2 = 0.96$ and $R^2 = 0.94$) and opined that phytoplankton absorption can be largely explained/determined by phytoplankton biomass in this region. Absorption by coloured dissolved organic matter (CDOM) was relatively high in the blue regions at par with phytoplankton absorption. In contrast the CDOM absorption was less compared to the phytoplankton absorption. However the CDOM absorption variation did not show any change with respect to Chl-a or salinity implying that CDOM production may be mainly related to the microbial activity. The non-algal suspended particulate matter (SPM), CDOM and Chl-a co-varied indicating that occurrence of waters dominated by one or two of these absorbing component was highly improbable. Ternary diagram for absorption (at 440-560 nm) by three components (Fig. 3) showed that most samples (73%) located within the central zone, thus these three components co-vary to some extent. No clear separation of Case 1 and Case 2 waters could be done due to high contributions from CDOM in this region (Shaju *et al*., 2014).

For observations on atmospheric CO_2 concentration, the $\delta^{13}C$ in atmospheric CO_2 sampled in the glass flask and the $\delta^{13}C$ of dissolved inorganic carbon (DIC) in sea surface water samples collected

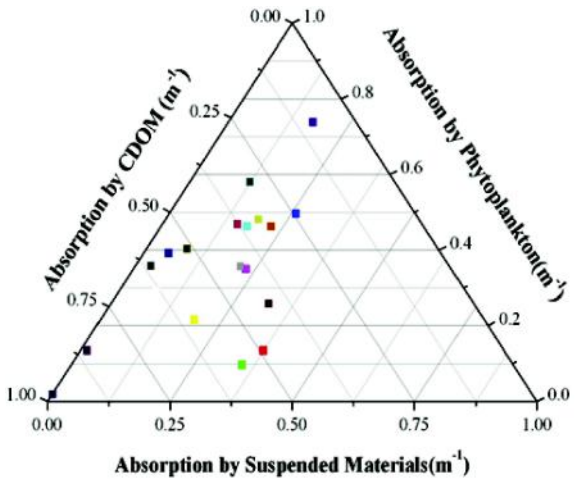

Fig. 3: Relative contribution of absorption by bio-optical substances in the Indian sector of Southern Ocean during 2010-11 austral summer

across the latitudes (Prasanna *et al*., 2014) have been carried out (Table 1). The study found that in the SO the region near south STF (46°S) was the zone of CO_2 source where photosynthetic activity was not enough to convert the CO_2 into primary production. The PFZ (52°S to 56°S) is the region of CO_2 sink where productivity is mainly responsible for the CO_2 uptake by the ocean. The different composition of CO_2 based on the source isotopic signature was identified based on this study. Furthermore, analysing three years (including this year) data Prasanna *et al*. (2015) showed that the major source of CO_2 degassed from the ocean is from the dissociation of DIC, which is mainly caused by ocean acidification, which is expected to be intensify in future.

Any change in environmental settings would likely exert an influence on the distribution of biological species, may it be plankton or higher animals, since there are links between oceanographic variables and the fauna like marine mammals, sea birds and squids, which being the top predators, play a crucial role in SO ecosystem. Opportunistic visual surveys of marine mammals were conducted (Jayabaskaran, 2014). During this expedition a pod (6) of Minke whales (*Balaenoptera bonaerensis*) and a pod (7) of Killer whales (*Orcinus orca*) were sighted. Though about 30 species of marine mammals have been reported from the SO region as whole, information from the Indian sector of SO is very limited and so far only 9 species of marine mammals have been reported by Indian scientists. About 18 species of sea birds (Albatross and Petrels which are common in the SO) between 40°S to 66°S and only one bird of Antarctic Brown Skua (*Stericorarius lonnbergi*) were sighted. The popular flying squid (*Todarodes filippovae*), having high economic value, were observed in the STF (35°S-38°S and 66°E-77°E) region. Bioaccumulation of heavy metals tested in *T. filippovae* tissues in the mantle of the species which are within the permissible limits recommended for human consumption. The cccurrence of coral fragment indicated the presence of cold water coral, especially in Ob and Lena seamounts regions.

Findings from the 6th ISOE (2011-12)

During this expedition the STF was studied extensively with meridional transect and time series observations. Total Chl-a varied from 0.03 to 1.19 mg m^{-3} and both these values were observed at the STF. The taxonomic composition of phytoplankton community showed dominance of flagellates at the STF and it decreased towards higher latitudes and switched to dominance of diatoms at the PF, whereas photosynthetic prokaryotes were almost below detectable level at the PF (Naik *et al*., 2015a). The marked variation of community at the STF and the PF were linked to the environmental settings at respective stations and the variation was also explained by canonical correspondence analysis (CCA) which indicated the preference of environmental variables for each group (Fig. 4). The

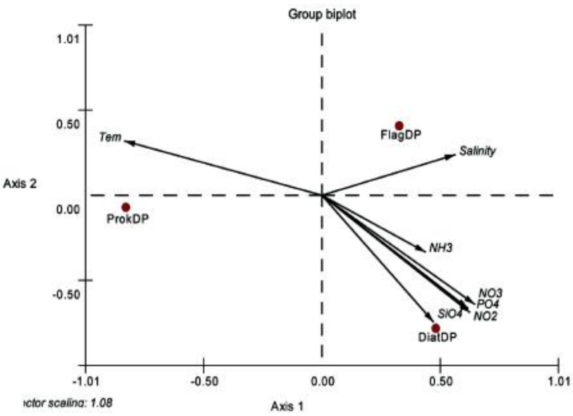

Fig. 4: Canonical correspondence analysis ordination diagram group biplot explaining the relationship between phytoplankton group (based on diagnostic pigment indices) and environmental variables at STF and PF

prokaryotes showed the preference for temperature and diatoms for elevated nutrients, whereas the flagellates preferred intermediate temperature and salinity condition. The water column stability also played a role in phytoplankton distribution. Column stability was high at the STF (shallow MLD) with lower nutrient levels and low at the PF (deep MLD) with high nutrient levels supporting flagellates at the STF and diatoms at the PF, respectively. Diagnostic pigment indices and CHEMTAX was used to analyse the time series (48 h) samples from the STF, which depicted oscillation in phytoplankton community structure at 6 hourly intervals at 120 m depth. The oscillation between flagellates (nanoplankton) to prokaryotes (picoplankton) and then to diatoms (microplankton) coincided with significant variation in nitrate and phosphate concentrations, along with an increase in abundance of grazer community. The observed small interval variation in phytoplankton community was controlled passively by bottom-up factors due to weak dissipation rate and actively by top-down factors due to the presence of ciliates and heterotrophic dinoflagellates (Naik *et al*., 2015b).

The PP was estimated both at the STF and the PF along 57° 30'E, which showed noticeable spatial variation at the STF with high surface and sub surface values at both 41°S (3.01 mg C m^{-3} d^{-1}) and 43°S (3.28 mg C m^{-3} d^{-1}). The STF was shown to be three fold more productive than the PF by Haridevi *et al*. (2015). They observed high variability in PP within the STF at longitudes 53° 30'E and 57° 30'E along 43°S latitude, which could be ascribed to variation in composition of phytoplankton group. Diatoms and dinoflagellates were dominant in earlier and later sampling, respectively. Photosynthesis-Irradiance (PI) experiment carried out at the same stations for 10 m and 50 m samples showed higher uptake rate at 53° 30'E than at 57° 30'E. Extended day length was found to influence the PP. Towards the dusk a secondary peak in PP (0.32 mg C m^{-3} h^{-1}) was observed, which could be attributed to the production after photo-repair or due to the existence of low-light adapted phytoplankton capable of fixing CO_2 at dim light.

The micro-zooplankton abundance was more dominant at the STF (avg. 764×10^3 ind.m^{-2}) than at the PF (avg. 471×10^3 ind.m^{-2}). The composition also differed significantly between the two regions with heterotrophic dinoflagellates and ciliates being dominant at the STF. In contrast to the high micro-zooplankton abundance at the STF the meso-zooplankton biovolume was higher at the PF (PF: avg. 0.245 ml.m^{-3}; STF: avg. 0.105 ml.m^{-3}). However, the diversity of meso-zooplankton was more at the STF (12) compared to the PF (8), indicating disparity in the food-web structure between the two fronts (Minu *et al*., 2015). Copepods were predominant at all depths in both the frontal regions with occasional appearance of salps and euphausiids. Time series observations showed significant diurnal variations of the meso-zooplankton standing stock in the mixed and thermocline layer compared to the deeper layers of the STF. High standing stock was observed early in the morning and late night depicting the effect of light on vertical migration of the zooplankton.

Using the *ex-situ* experimental approach the response of bacteria and phytoplankton to micronutrient amendments (i.e., Co, Cu, Fe and their mixture) were studied at the STF. Results indicated that availability of micronutrients, particularly Fe, affects the bacterial abundance and community composition, but not the phytoplankton growth at the STF (Ramaiah *et al*., 2015a). Preponderance of only a few bacterial prototypes was observed on amendment of micronutrients and this could be due to preferential and/or versatile utilisation of exogenously added micronutrient. In addition to this, biochemical characteristics and numerical profiling analysis using 16S rRNA marker gene yielded several clusters. This analysis revealed the prevalence of only few prototypes such as *Firmicutes* (~90%) and *Gammaproteobacteria* (~10%) in the DCM zone of this STF location (Ramaiah *et al*., 2015b).

Squid jigging operations carried out during this expedition explained the discontinuity length-weight relationship in the species *Sthenoteuthis bartramii* (Pravin *et al*., 2015). The morphometric measurements were taken for understanding the relationship between species from different geographical areas. A total of 56 specimens were identified, out of which 19 were male and their length ranged between 21.2-32.8 cm (avg. 29 cm) and weight from 230-1020 g (mean 698 g). The length of females ranged from 19.4-44.9 cm (mean 31 cm) and weight from 115-2410 g (mean 847 g). The results confirm that both male and female *S. bartramii* showed an isometric growth pattern. The observed fluctuation in the growth might be due to the variation in ecology, geographic conditions and food availability. Two flying squids such as *Todarodes filippovae* and *Ommastraphes bartramii* were observed for biochemical evaluation for nutritional properties. Except the moisture content, the ash, protein and fat were higher in *T. filippovae* than *O. bartramii*. Biochemical profiling of squids indicated that omega-3 polyunsaturated fatty acids were high in both *O. bartramii* and *T. filippovae*, which are commonly found in the SO (Remyakumari *et al*., 2015).

Findings from the 7th ISOE (2012-13)

This expedition encompasses observations along the regular meridional track (57° 30'E) and in the PF region. Chl-a ranged from 0.2 to0.9 mg m^{-3} and increased from STF to PF1 and then decreased at the PF2, indicating PF1 as more productive than other frontal zones. Variation in DCM was observed in various fronts and it was 50 m at the STF and SAF, whereas, it was 75 m and 100 m at the PF1 and PF2, respectively. These variations in DCM could be linked to the variation in MLD of the respective fronts that can alter the nutrient flux along with photic depth. The diagnostic pigment indices showed highest abundance of diatoms at the PF1 and PF2, while the flagellates and prokaryotes were predominant at the STF and SAF regions, respectively. Unlike the diatoms and flagellates, the prokaryotes were found low in concentration, especially at the PF. These results indicate the niche preference of specific groups (Mishra *et al*., 2016). However, the diatoms abundance was always lower at the surface water compared to the depth in the frontal regions. Abundances of phytoplankton community at different depths might be the consequence of phytoplankton adaptations to the environmental conditions of the region. The flagellates abundance showed opposite trend to the diatoms both at the surface and water column. The prokaryotes decreased from STF to PF2 at the surface and showed their abundance at a depth of 30 m in the STF and 100 m at SAF, PF1 and PF2. Such information on group distribution and its percentage contribution with respect to region and related environmental conditions would provide refined knowledge on phytoplankton community dynamics and its role in biogeochemistry of the given area. Combined analysis of *in situ* and satellite-based phytoplankton pigment data for the period 1998-2014 indicated that the diatoms abundance increased at the STF and decreased at the SAF and the PF. On the other hand Mishra *et al*. (2015) showed that the chlorophytes abundance increased at STF, SAF and PF, revealing a shift in phytoplankton communities along the fronts. They suggested that the diatom community in the SO was adapted to a wide range of temperature at various frontal regions, indicating the mechanism of cold adaptation. On the other hand, the chlorophytes growth was restricted at the PF due to lack of cold adapted species in the community.

Daily integrated surface photosynthetically active radiation (PAR) showed clear latitudinal variation and ranged from 16.58 to 65.99 (39.82 ± 14.52 E m^{-2} d^{-1}). Although, overall decreasing trend (R^2 = 0.56) was observed from lower (0.12°S) to higher

(56.58ºS) latitudes, intermittent higher values of daily PAR were also recorded at higher latitudes, especially in the STF and SAF regions (Tripathy *et al*., 2016). Irregular variation of daily PAR could mainly be ascribed to the overcast sky. Towards south, the overcast condition was more prevalent, particularly in the PF region. The variation of column-integrated PP (IPP) showed clear distinction among fronts with higher values at STF and SAF compared to PF region. The IPP ranged from 29.17 to 325.54 (124±86.34 mg C m^{-2} d^{-1}) in these regions. No clear relationship was observed between daily PAR and corresponding daily IPP and column-integrated Chl-a (Chl_{int}) indicating that factor(s) other than surface light contributing towards IPP and Chl_{int} variation in the study area. In the PF region, especially at 50º.75'S and 52º.43'S despite high Chl_{int} the IPP was low, which could be ascribed to cloud-induced very low daily PAR (18.31 and 18.59 E m^{-2} d^{-1}, respectively) at those locations. Moreover, IPP and corresponding Chl_{int} did not show any correlation between them, thereby corroborating the hypothesis proposed by Tripathy *et al*. (2014), that high biomass does not always lead to high PP in the study area. The relationship between surface PP (PP_0) and daily PAR did not show light limitation. PP_0 showed moderately strong positive relationship (R^2 = 0.63) with surface Chl-a (Chl_0) signifying that ~60% of the variance in PP_0 can be explained by phytoplankton biomass only. From the present observations the authors inferred that (1) very low surface PAR resulted in low IPP, otherwise light limitation is unlikely during clear sky conditions of the austral summer, (2) intensity of surface PAR had a reasonable control on surface PP; whereas it had inconsequential effect on water column-integrated productivity.

During the investigation, a total of 47 species of zooplankton (copepods were dominant) were recorded from all stations which includes calanoida (27), cyclopoida (9), poicelostomatoida (4), harpacticoida (3), chaetognatha (2) and appendicularins (2). Species diversity and dominance ranged from 0.12 to 1.05 and from 0.1 to 0.88, respectively (Fig. 5). Maximum species diversity was found at PF2 and the minimum at PF1. Calanoida (56%) followed by cyclopoida (38%) represented the total zooplankton community at the STF; whereas, at the SAF cyclopoida (65%) and Calanoida (25%) were the dominant groups. On the other hand at PF1 and PF2 calanoida and

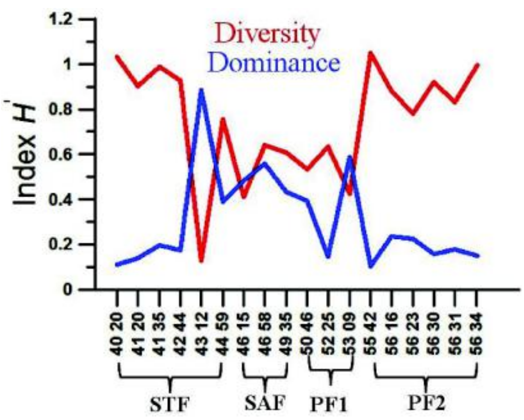

Fig. 5: Variation of zooplankton species diversity and dominance at different frontal regions of the Indian sector of SO

cyclolpoida comprise 50% and 45% of the total zooplankton community, respectively (Venkataramana *et al*., 2016). The higher abundance of zooplankton observed at PF2 coincided with the peak of phytoplankton density. Presence of high zooplankton biomass at PF2 might lower the level of Chl-a. In this region, grazing pressure might be higher than the phytoplankton growth rate in presence of high nutrients. Highest Chl-a concentration was observed at PF1 coinciding with low zooplankton biomass, indicating that control of autotrophic production was mainly depending on either presence of high nutrients and/or zooplankton abundance. Macro-zooplankton were often second only to copepods in abundance and biomass. Their population density was low due to their inability to adapt to the prevailing environmental conditions. The predominant species were *Mesosagitta minima*, *Sagitta* sp., *Oikopleura gracillis* and *O. labradoriensis*.

In continuation to *ex-situ* experiment conducted by Ramaiah *et al*. (2015) at STF, a similar approach was used to study the response of bacterial and phytoplankton community to micronutrient amendments at the PF. Results indicated a significant increase in phytoplankton biomass in all micronutrient amendments as compared to the control. Furthermore, it was observed that autotrophic process in the PF was not only limited by Fe, but also by Co and Cu (Jain *et al*., 2015).

The absorption coefficients of phytoplankton specific absorption at 440 nm, a^*_{ph} (440) were within the limits reported earlier. The study reported, Chl-a specific phytoplankton absorption, $a^*_{ph}(440)$ for microphytoplankton between 0.03-0.26 $m^2 mg^{-1}$, nano-fractions between 0.029-0.135 $m^2 mg^{-1}$ and for total phytoplankton between 0.008-0.17 $m^2 mg^{-1}$ (Minu *et al*., 2016). This study showed that in the red region $a^*_{ph}(665)$ were quite higher than the earlier reports. This high a^*_{ph} could be a result of pigment packaging. Absorption by picophytoplankton showed typical spectra similar to that of total particulate matter except in the case of distinct peaks of Chl-a. Pico fractions had a negligible amount of Chl-a concentration which may have resulted in low absorption by Chl-a in the 440 nm range. Phycoerythrobilins have absorption peaks at 540-546 nm and around 615-645 nm. Phaeophytin and phaeophorbide have maximum absorption at 665 nm apart from Chl-a. It is suggested that cyanobacteria of pico size dominating with phycoerythrobilins and phaeophytins may have constituted the fractions in the study region. The absorption coefficients of detritus were lower for size fractions examined than reported earlier. The authors suggested that, as this region is isolated from any kind of terrestrial influence the possible ways of detritus input in the study area could be from autochthonous source.

Summary

The SO plays a fundamental role in the functioning of the earth system, influencing climate, sea level, biogeochemical cycles, and biological productivity on a variety of scales. Usually an ecosystem would be dictated, in the first instance, by the sensitivity of thriving organisms to the changing physical environment. The overall dynamics of the system would then be determined by the influence of affected species on other species in the food-web, whether that influence is as predators, prey, competitors, ecological succession or in some other role. In SO along with seasonal variability, inter-annual variability is a natural feature of the region, including variability in the Southern Annular Mode, strength of the ACC, maximum sea ice extent, and productivity. The combination of these factors can give rise to large variations in ecological changes over time. However, attributing ecological change(s) as impacts of climate change is a challenging task, faced by the modern oceanographic fraternity, because results between regions and across years are variable and, often ambiguous.

In this context, scanty information on the Indian sector of SO are available on particular aspects of ecosystems, such as controls on variability in phytoplankton and zooplankton community, food-web dynamics, primary production, in-water constituents that compete with phytoplankton for utilisation of light, the distribution of Antractic krill, copepod lifecycles, grazing pressure and other predator foraging and life cycles. Outcomes from the Indian Southern Ocean Expeditions conducted during 2009 to 2013 certainly forms a good first hand baseline dataset to get an overall preliminary picture of the Indian sector of SO processes that are responsible for modulating the biological productivity and biogeochemistry of this region. It summarizes by considering the general nature of SO food-webs and the regional/frontal differences in the ecosystems. The study area extended between the 40ºS to 66ºS along the meridional transect between 47ºE and 57º 3'E, wherein point sampling and time series observations were carried out. Biomass and community structure of plankton, primary productivity, carbon flux, food-web dynamics, bacterial phylogenetic diversity, biochemical composition of krills and squids, and survey of mammals and birds were some of the major areas of investigation. However, no studies have been initiated to investigate benthic life forms, benthic-pelagic coupling and its role in carbon cycle.

The SO ecosystem is generally assumed to be controlled by the supply of macro and micro-nutrients and light that are essential for phytoplankton photosynthesis. This bottom-up control suggests that the ecosystem would be sensitive to changes in physical forcings that influence the light and nutrient environment experienced by phytoplankton (upwelling, varying MLD, melt/spread of sea ice). The phytoplankton performs essential role in controlling the biological fluxes and export of carbon and nutrients from the ocean surface to the deep interior. In addition, predators exert controls on ecosystem structure and function (top-down control), which contribute to ecosystem variability. To differentiate between bottom-up and top-down controls, further integrated observations of physics, chemistry and biology across multiple trophic levels are required, which would in turn facilitate better understanding of the biogeochemical process of the Indian sector of SO.

Considering the overall results from above expeditions (only those variables which were repeated in all the expeditions), we can infer that the Indian sector of SO has marked temperature gradient zonation from STF to PF. These zones provide different environmental settings that will have an influence on the biota present in that region. It's evident that the phytoplankton community structure follows the similar pattern of dominance in all the observations carried out in different expeditions. The flagellates being dominated at STF and diatoms at PF. Similarly, the primary productivity results indicated the PF being more productive as compared to STF (Table 2). Whereas, zooplankton community was dominated with copepod in both the fronts, however, the microzooplankton community was dominant at STF as compared to PF. The results on food web dynamics indicate that the STF was influenced by microbial food web and conventional food web whereas; PF was mainly by conventional food web. The variation of such food webs and the phytoplankton biomass was complimenting vice versa role of the predator-prey relationship. However, the long-term satellite and NOBM data indicates the break in the pattern of phytoplankton community dominance albeit the results need to be validated with *in situ* observations those will be carried out in future expeditions.

Since the ISOE time is limited to austral summer (January-March) only, there is non-availability of data on the variability in the *in situ* conditions during rest of the seasons. Thus, to bridge the gap of *in situ* data collection on oceanographic variables, year-round mooring, simulation/modelling of the study area is a prerequisite for effective monitoring and assessment of current and future climate change impacts. Necessarily, the design of the field program would benefit from the current understandings about how the SO ecosystem is responding to alterations in climate change. Plans are under process to deploy sensors attached to autonomous ocean profiling floats (such as Argo), line mooring, and autonomous underwater vehicles (glider) so as to increase spatial as well as temporal observations of oceanic realm, which would facilitate validation of observation from space-borne ocean color sensors.

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Table 2: Comparison of phytoplankton productivity at different frontal zones of the Indian sector of SO

Frontal Zone	Primary productivity (PP)			Remarks	Reason
	a	b	c		
STZ (north of STF)	200 mgC m^{-2} d^{-1}	~ 185 mgC m^{-2} d^{-1}	–	Low PP	Nutrient Limitation, High stability due to stratification
STFZ (zone between SSTF & ARF)	300-400 mgC m^{-2} d^{-1}	210 mgC m^{-2} d^{-1}	152 mgC m^{-2} d^{-1}	Low PP	Nutrient Limitation
SSTF	> 900 mgC m^{-2} d^{-1}	> 900 mgC m^{-2} d^{-1}	–	High PP	Supply of nutrients along with key micro-nutrients (e.g., Fe) from the Antarctic bottom water. An additional supply of some key micronutrients by the ARC from the African continent and the presence of the Crozet Island
PFZ (zone including PF and SAF)	< 200 mgC m^{-2} d^{-1}	340 mgC m^{-2} d^{-1}	210 mgC m^{-2} d^{-1}	Low PP	Grazing by zoo-plankton and Fe limitation. However the persistent TML supports relatively higher column PP than STF
ANZ (zone between Antarctic continent & PF)	–	~ 190 mgC m^{-2} d^{-1}	387 & 1083 mgC m^{-2} d^{-1}	Relatively low PP	Light limitation, and pigment packaging effect in large plankton

*a: Jasmine *et al*. (2009); b: Gandhi *et al*. (2012); c: Tripathy *et al*. (2014, 2015)

References

Bandopadhyay R, Shukla P, Gupta P and Singh N (2014) Isolation and Molecular Characterization of Novel Microalgal Species from Southern Ocean towards Exploring their Metabolic Potential and Biological Variability In: Technical Report of the 5th Indian Southern Ocean Expedition (Eds. Anilkumar N and Achuthankutty CT) ISBN: 978-93-5156-520-8 pp 53-56

Chisholm S W, Falkowski P G and Cullen J J (2001) Discrediting Ocean Fertilization *Science* **294** 309-310

Gandhi N, Ramesh R, Laskar A H, Sheshshayee M S, ShetyeS, Anilkumar N, Patil S M and Mohan R (2012) Zonal variability in primary production and nitrogen uptake rates in the southwestern Indian Ocean and the Southern Ocean. *Deep-Sea Research I* **67** 32-43

Garcia R A, Fearns P R C and Mckinna L I W (2014) Challenges in detecting trend and seasonal changes in bathymetry derived from HICO imagery: a case study of Shark Bay, Western Australia *Remote Sens Environ* **147C** 186-205

Grant S A, Constable B, Raymond and Doust S (2006) Bioregionalisation of the Southern Ocean *Report of Experts Workshop* WWF-Australia and ACE CRC Hobart pp 48

Griffiths H J, Barnes D K A and Linse K (2009) Towards a generalised biogeography of the Southern Ocean benthos *J Biogeogr* **36** 162-177

Haridevi C K, Naik R K and Achuthankutty C T (2015) Photosynthetic efficiency of phytoplankton in the Indian sector of Southern Ocean during austral summer 2012. In: Technical Report of the 6th Indian Southern Ocean Expedition (Eds. Anilkumar N and Achuthankutty CT) ISBN: 978-93-5212-562-3 pp 19-24

Jain A, Meena R M, Naik R K, Gomes J, Bandekar M, Bhat M, Mesquita A and Ramaiah N (2015) Response of polar front phytoplankton and bacterial community to micronutrient amendments *Deep Sea Res II* **118** 197-208

Jasmine P, Muraleedharan K R, Madhu, N V, Asha Devi C R, Alagarswamy R, Achuthankutty C T, Jayan Z, Sanjeevan V N and Sahayak S (2009) Hydrographic and productivity characteristics along 45°E longitude in the southwestern Indian Ocean and Southern Ocean during Austral summer 2004 *Mar Ecol Prog Ser* **389** 97-116

Jayabaskaran S (2014) Relationship between Oceanographic parameters and Deep Sea Megafauna and Marine Mammals of Southern Ocean In: Technical Report of the 5th Indian Southern Ocean Expedition(Eds. Anilkumar N and Achuthankutty CT) ISBN: 978-93-5156-520-8 pp 63-70

Kostianoy A G, Ginzburg A I, Lebedev S A, Frankignoulle M and Delille B (2003) Fronts and mesoscale variability in the southern Indian Ocean as inferred from the TOPEX/POSEIDON and ERS-2 altimetry data *Oceanology* **43** 632-642

Krishnan K P, Sinha R K, Nair S, Noronha S B, Chacko R and Anilkumar N (2014) Carbon demand utilization and metabolic diversity of bacterioplankton in the frontal regimes of the Indian sector of Southern Ocean *Ann Microbiol* DOI 10.1007/s13213-014-0948-2

Manjebrayakath H (2014) Role of Antarctic krills in the biogeochemical cycle in the Indian sector of Southern Ocean In: Technical Report of the 4th Indian Southern Ocean Expedition (Eds. Anilkumar N and Achuthankutty CT) ISBN: 978-93-5156-583-3 pp 63-66

Mendes C R B, Kerr R, Tavano V M, Cavalheiro F A, Garcia C A E, Dessai D R G and Anilkumar N (2015) Cross-front phytoplankton pigments and chemotaxonomic groups in the Indian sector of the Southern Ocean *Deep Sea Res II* **118** 221-232

Minu P, Souda V P, Mishra R K, Anilkumar N and Ashraf M P (2016) Size fractionated phytoplankton and its optical properties in the Indian sector of Southern Ocean In: Technical Report of the 7th Indian Southern Ocean Expedition (Eds. Anilkumar N and Tripathy SC) ISBN: 978-93-5267-057-4 pp 48-57

Minu R L, Gopalakrishnan T, Asha Devi C R, Pillai H U K, Sanjeevan V N and Achuthankutty C T (2015) Micro and mesozooplankton community structure at the Suptropical and Polar Fronts during austral summer 2012 In: Technical Report of the 6th Indian Southern Ocean Expedition (Eds. Anilkumar N and Achuthankutty CT) ISBN: 978-93-5212-562-3 pp 25-29

Mishra R K, Naik R K and Anilkumar N (2016) Phytoplankton community distribution along the frontal regions of Indian Ocean Sector of Southern Ocean during Austral summer 2013 In: Technical Report of the 7th Indian Southern Ocean Expedition (Eds. Anilkumar N and Tripathy SC) ISBN: 978-93-5267-057-4 pp 22-26

Mishra R K, Naik R K and Anilkumar N (2015) Adaptations of phytoplankton in the Indian Ocean sector of the Southern Ocean during austral summer of 1998-2014 *Front Earth Sci* **9** 742-752

Naik R K, Bhaskar P V and Achuthankutty C T (2015a) Biological components In: Technical Report of the 6th Indian Southern Ocean Expedition (Eds. Anilkumar N and Achuthankutty CT) ISBN: 978-93-5212-562-3 pp 11-18

Naik R K, George J V, Soares M, Devi A, Anilkumar N, Roy R, Bhaskar P V, Murukesh N and Achuthankutty C T (2015b) Phytoplankton community structure at juncture of the

Agulhas Return Front and subtropical front in the Indian Ocean sector of Southern Ocean: Bottom-up and top-down control *Deep Sea Res II* **118** 233-239

Patil S M, Mohan R, Shetye S, Gazi S and Jafar S (2014) Morphological variability of *Emilianiahuxleyi* in the Indian sector of the Southern Ocean during the austral summer of 2010 *Mar Micropaleontol* **107** 44-58

Pavithran S, Pillai H U K, Bhaskar P V, Anilkumar N and Achuthankutty (2014b) Biological productivity and food-wed dynamics In: Technical Report of the 5th Indian Southern Ocean Expedition (Eds. Anilkumar N and Achuthankutty CT) ISBN: 978-93-5156-520-8 pp 19-21

Pavithran S, Pillai H U K, Nanjkar M, Tripathy S C and Achuthankutty C T (2014a) Biological productivity of Indian sector Southern Ocean In: Technical Report of the 5th Indian Southern Ocean Expedition (Eds. Anilkumar N and Achuthankutty CT) ISBN: 978-93-5156-520-8 pp 13-18

Pavithran S, Anilkumar N, Krishnan K P, Noronha S B, George J V, Nanajkar M, Chacko R, Desai D R G and Achuthankutty C T (2012) Contrasting pattern in chlorophyll a distribution within the Polar front of Indian Sector of Southern Ocean during Austral summer *Curr Sci* **102** 899-903

Pillai H U K, Pavithran S, Tripathy S C and Achuthankutty C T (2014) Time series observation of mesozooplankton at STF and PF In: Technical Report of the 5th Indian Southern Ocean Expedition (Eds. Anilkumar N and Achuthankutty CT) ISBN: 978-93-5156-520-8 pp 24-27

Pollard R T, Bathmann U, Dubischar C, Read J F and Lucas M (2002) Zooplankton distribution and behaviour in the Southern Ocean from surveys with a towed optical plankton counter *Deep Sea Res II* **49** 3889-3915

Prasanna K, Ghosh P and Anil Kumar N (2015) Stable isotopic signature of Southern Ocean deep water CO_2 ventilation *Deep Sea Res II* **118** 177-185

Prasanna K, Ghosh P, Anil Kumar N and Dessai D R G (2014) CO_2 uptake by Southern Ocean during austral summer of 2011 In: Technical Report of the 5th Indian Southern Ocean Expedition (Eds. Anilkumar N and Achuthankutty CT) ISBN: 978-93-5156-520-8 pp 28-33

Pravin P, Aneeshkumar K V and Mennakumari B (2015) Squid Jigging Operations in the Indian Ocean Sector of Southern Ocean In: Technical Report of the 6th Indian Southern Ocean Expedition (Eds. Anilkumar N and Achuthankutty CT) ISBN: 978-93-5212-562-3 pp 47-52

Ramaiah N, Jain A, Meena R M, Naik R K, Verma R, Bhat M, Mesquita A, Nadkarni A D, Souza S E, Ahmed T, Bandekar M and Gomes J (2015b) Response of bacteria and phytoplankton from a subtropical front location Southern Ocean to micronutrient amendments *ex situ*, *Deep Sea Res II* **118** 209-220

Ramaiah N, Jain A, Meena R M, Naik R K, Verma R, Bhat M, Mesquita A, Nadkarni A, D'Souza S E, Ahmed T, Bandekar M and Gomes J (2015a) Bacterial responses to nutrient alterations *ex-situ* and their phylogenetic diversity from subtropical front of Indian sector of Southern Ocean In: Technical Report of the 6th Indian Southern Ocean Expedition (Eds. Anilkumar N and Achuthankutty CT) ISBN: 978-93-5212-562-3 pp 30-46

RemyaKumari K R, Asha K K, Aneeshkumar K V, Suseela M, Pravin P and Lakshmanan P T (2015) Biochemical Profiling of two Species of Squids (*Ommastraphes bartramii*) (Lesucur 1821) and *Todarodes filippovea* (Adam 1975) from the Indian Ocean sector of Southern Ocean In: Technical Report of the 6th Indian Southern Ocean Expedition (Eds. Anilkumar N and Achuthankutty CT) ISBN: 978-93-5212-562-3 pp 53-56

Sabine C L, Feely R A, Gruber N, Key R M, Lee K, Bullister J L, Wanninkhof R, Wong C S, Wallace D W R, Tilbrook B, Millero F J, Peng T H, Kozyr A, Ono T and Rios A F (2004) The Oceanic Sink for Anthropogenic CO_2 *Science* **305** 367-371

Sarmiento J L, Hughes T M C, Stouffer R J and Manabe S (1998) Simulated response of the ocean carbon cycle to anthropogenic climate warming *Nature* **393** 245-249

Shaju S S, Minu P, Ashraf P M and Beenakumari B (2014) Measurements of bio-optical parameters of Southern Ocean In: Technical Report of the 5th Indian Southern Ocean Expedition (Eds. Anilkumar N and Achuthankutty CT) ISBN: 978-93-5156-520-8 pp 34-40

Shetye S and Mohan R (2014) Investigation-III: Silicoflagellates as Paleoclimatic indicators: A case study from the Indian sector of Southern Ocean In: Technical Report of the 4th Indian Southern Ocean Expedition (Eds. Anilkumar N and Achuthankutty CT) ISBN: 978-93-5156-583-3 pp 28-30

Tripathy S C, Haridevi C K and Mishra R K (2016) Latitudinal distribution of surface PAR and its relation with phytoplankton biomass and productivity In: Technical Report of the 7th Indian Southern Ocean Expedition (Eds. Anilkumar N and Tripathy SC) ISBN: 978-93-5267-057-4 pp 27-29

Tripathy S C, Pavithran S, Sabu P, Pilai H U K, Dessai D R G and Anilkumar N (2015) Deep chlorophyll maximum and primary productivity in Indian Ocean sector of the Southern Ocean: Case study in the Subtropical and Polar

Front during austral summer 2011 *Deep Sea Res II* **118** 240-249

Tripathy S C, Pavithran S, Sabu S, Naik R K, Noronha S B, Bhaskar P V and Anilkumar N (2014) Is phytoplankton productivity in the Indian Ocean sector of Southern Ocean affected by pigment packaging effect? *Curr Sc* **107** 1019-1026

Venkataramana V, Tripathy S C, Pillai H U K and Santhosh Kumar C (2016) Distribution of copepod community structure in frontal systems of the Indian Ocean sector of Southern Ocean In: Technical Report of the 7th Indian Southern Ocean Expedition (Eds. Anilkumar N and Tripathy SC) ISBN: 978-93-5267-057-4 pp 30-36.

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Review Article

Environmental Monitoring Around Indian Antarctic Stations

ANOOP KUMAR TIWARI*

ESSO-National Centre for Antarctic and Ocean Research, Headland Sada, Vasco da Gama, Goa 403 804, India

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Environmental monitoring is integral part of Environmental Impact Assessment (EIA). Continuous efforts of Scientific Committee on Antarctic Research (SCAR), Committee for Environmental Protection (CEP), Council of Managers of National Antarctic Programme (COMNAP) and establishment of Convention for Conservation of Marine Living Resources (CCAMLR) has given impetus to establish scientific approach towards environmental monitoring thus formed a core part of Antarctica Treaty System (ATS).

Adoption of Madrid Protocol in 1998 brought forward guidelines for environmental monitoring and environmental impact assessment defining indicators for assessment of contamination in the environment due to anthropogenic activities. Continuous presence of human and activities in Antarctica no longer justify the meaning of "Sustainable Development" in order to safeguard the pristine nature of continent.

Indian scientists successfully laid the foundation of scientific research in Antarctica during the maiden expedition in 1981-82. Owing to prevailing requirement, Environmental Monitoring of Maitri station carried out by, the Bhabha Atomic Research Centre, Mumbai (BARC) in air, water, terrestrial and biological environment during austral summer of VIII, IX and X- Indian Antarctic Scientific Expeditions in the year 1988, 1989 and 1990, respectively. Comprehensive environmental monitoring carried out at Maitri station in year 1999, in which air, water, noise, soil and biological indicator selected to form baseline as well as to compare individual indicators, with those assessed in the past from same locations.

Black carbon concentration at site showed the range of carbon concentration as 26.5±16.2 ng/m^3 at Bharati station while average concentration recorded was 13±5 ng/m^3 at Maitri station. $PM_{2.5}$ values recorded in the range of 1.0-7.0 μg/m^3, whereas Suspended Particute Matter (SPM) variation recorded in the range of 7.7±6.0 μg/m^3 at Maitri station.

Keywords: Antarctica; Monitoring; Environmental Impact Assessment; Contamination; Madrid Protocol; Antarctica Treaty; Maitri; Bharati

Introduction

Antarctica is the last vast wilderness on the planet and it is an important part of Earth's system. By acting as a global heat sink, it helps controlling our climate and weather. Recent development in Antarctica has changed the concept of the pre-International Geophysical Year (IGY) of 1957-1958 of being insignificant in scientific exploration and thereafter represented a major turning point for research in Antarctica. IGY provided a sound foundation for the development of Antarctic scientific activity in a wide range of disciplines, including glaciology, atmospheric sciences and medicine (Gerson, 1958; Walton and Morris, 1990).

Human presence in Antarctica started way back in year 1900, which slowly picked up as other countries started taking interest noticing unique place for conducting science, observing source of probable minerals and hydrocarbons (Blanchette *et al*., 2004). Apart from scientific interest, commercial and tourism activities also started flourishing in Antarctica since last few decades. More recently, the International Polar Year (IPY) has generated platform for scientific and public interest in the 'white continent', and

**Author for Correspondence: E-mail: anooptiwari@ncaor.gov.in*

inevitably given further impetus to human activity in and around the continent (Tin *et al*., 2009). As interest grown it also added logistics in many folds to support the all kind of interests. Though in year 1959, while Antarctica Treaty had been signed and Antarctica remained the place for science and peaceful purpose while claims and exploration activities were frozen, yet other activities continues. Antarctic Treaty, signed on 1st of December 1959 by twelve nations and entered into force on 23rd June 1961, establishes the legal framework for the management of Antarctica. At present there are 57 treaty member nations including India in which 29 nations have consultative status and a few more countries are in the process to join for consultative status.

Environmental Protocol, which is also known as "Madrid Protocol" was adopted in 1991 in response to proposals that the wide range of provisions relating to protection of the Antarctic environment should be harmonized in a comprehensive and legally binding form. Article 8 of the Protocol introduces the term Environmental Impact Assessment (EIA) and provides three categories of environmental impacts (less than, equal to and more than minor or transitory), according to their significance. The Article also requires that assessment of planned activities to be undertaken in Antarctica, subject to the procedures set out in Annex I. It draws on and updates the agreed Measures as well as subsequent Treaty meeting recommendations relating to protection of the environment, as part of the Antarctic Treaty System (ATS). It provides for comprehensive protection of the Antarctic environment and dependent and associated ecosystems (ATS, 2002). Article 6 of Protocol emphasize on Co-operation and states; "Each Party undertakes, to the extent possible, to share information that may be helpful to other Parties in planning and conducting their activities in the Antarctic Treaty Area, with a view to the protection of the Antarctic environment and dependent and associated ecosystems".

Madrid Protocol has been underpinned with six annexes which have to be followed and abide by all treaty parties; (a) Annex I - Environmental Impact Assessment, (b) Annex II - Conservation of Antarctic fauna and flora (c) Annex III - Waste disposal and waste management (d) Annex IV - Prevention of marine pollution (e) Annex V - Area protection and management and (f) Annex VI - Liability arising from environmental emergencies. Until 1980-1990, the waste at most Antarctic stations was simply dumped in conveniently located landfill sites close to the station, or alternatively, disposed into the sea or burnt in the open air. The Protocol provided strict guidelines for environmental management and protection, and established the obligation to clean-up abandoned work sites. Adoption of Madrid Protocol in 1998, brought forward guidelines for environmental monitoring and EIA, defining indicators for assessment of contamination in the environment due to anthropogenic activities (Bargagli, 2008; Budhavant *et al*., 2015; Clarke and Harris, 2003; Clarke, 1988).

In accordance with the recommendation XV-5 of the Fifteenth Antarctic Treaty Consultative meeting, held in Paris in 1989, there are a series of activities that should be monitored. Through continuous monitoring the environmental change can be observed which would setup valuable benchmark to evaluate the state of Antarctic environment. According to the Protocol on Environmental Protection (article 8 and annex I), EIA procedure has been developed for activities undertaken in the Antarctic (Harris and Meadows, 1992; Lyons *et al*., 1999; Pineschi, 2001).

Environmental monitoring is integral part of EIA therefore continuous efforts of Scientific Committee on Antarctic Research (SCAR), Committee for Environmental Protection (CEP), Council of Managers of National Antarctic Programme (COMNAP) and establishment of Convention for Conservation of Marine Living Resources (CCAMLR) has given impetus to establish scientific approach towards environmental monitoring thus formed a core part of ATS. This paper represents the environmental monitoring and post-EIA conducted after establishment of Indian permanent stations "Maitri" and "Bharati" in Antarctica.

Indian Antarctic Stations – Area of Study

Realizing the importance of Antarctica in terms of Scientific knowledge, first winter-over station, "Dakshin Gangotri" was established in year 1983 on ice-shelf of Princess Astrid coast ($70^0$05'37" S Latitude, $12^0$0'00" E Longitude). Then it got abandoned in year 1989, as it started sinking in snow due to internal heat stress and snow accumulation in periphery of station. Second permanent Indian station was established on rock terrain of Schirmacher Hills in east Antarctica, in year 1988-89, on the nunatak Vassfjellet close to the ice shelf, about 80 km from the ice shelf edge (Fig. 1). Maitri is situated in an area of base rock and surrounded by a number of small lakes. A glacier to the south of station covers parts of the nunatak and ends about 400 meters from the main building. Maitri station can accommodate 25 persons inside main building and approximate 50 persons in summer huts, located nearby main structure.

Bharati station is also all year round station which became functional in year 2012, located in Larsemann hills area at Grovnes on the rocky terrain in east Antarctica, nearly 2500 km away from Maitri station (Fig. 2). Bharati station can accommodate 15 persons during winter and 35 persons during summer period. Bharati station is located very close to sea, nearly 300 meters away from the edge of sea-peninsula conjunction.

The scientific investigations being carried out since first expedition includes but not limited to, studies on meteorology, geomagnetism, environmental science, radio-wave propagation, geology, glaciology,

Fig. 1: Maitri Station in Schirmacher Hills, East Antarctica

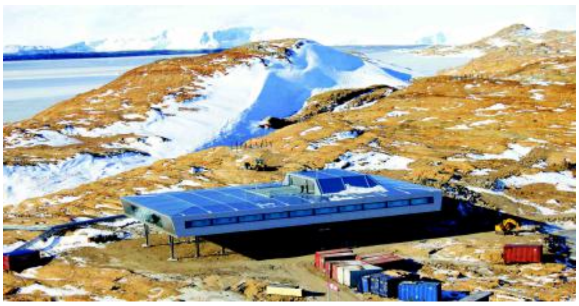

Fig. 2: Bharati Station in Larsemann Hills, East Antarctica

chemistry, physical sciences and microbiology of the Antarctic ice and the study of freshwater lakes. Since then scientific studies were carried out in various disciplines and valuable results are extracted which have proven to understand a lot about icy continent.

Environmental Monitoring

Need for environmental monitoring arises while Parker and Vince Howard (1977) carried out first environmental impact monitoring of drilling project in Antarctica referring the procedure developed by Leopold *et al*. (1971). Kennicutt Ii (1990), also brought forward the need of monitoring and conservation of oil spill to protect the pristine Antarctic Environment. Signing of Madrid Protocol in year 1991 by the treaty parties further emphasized environmental monitoring due to human impact in collaborative manner to highlight the urgent need for decision makers (Walton and Morris, 1990; Walton and Shears, 1994).

Environmental Monitoring of Indian Stations in Time Scale

Environmental monitoring of Indian stations, Dakshin Gangotri and Maitri had been conducted by the Bhabha Atomic Research Centre (BARC, Mumbai) in 1988, 1989 and 1990. During year 1994, 1995, 1996, 1999 and 2000, environmental monitoring had been carried out by National Environmental Engineering Research Institute (NEERI, Nagpur). Veermata Jijabai Technological Institute (VJTI) undertook environmental monitoring in the year 2002 around Maitri station. Baseline monitoring information during year 2007, 2008, 2009 and 2010 for the new Indian research station (Bharati) as well as Maitri has been collected by Shriram Institute of Industrial Research (SIIR, New Delhi). ESSO-National Centre for Antarctic and Ocean Research (NCAOR, Goa) entrusted with EIA and environmental monitoring starting from year 2003, 2006 and 2012 to 2015-16, for Maitri and Bharati stations.

Environmental Indicators

CEP and COMANP developed guideline to choose parameters of relevance which are presented in Table 1. These indicators are subjective and should be selected based on the geography, activities undertaken, likely impact on environment including short-term and long-term assessment, future activities

Table 1: An overview of some potential indicators and parameters for use in monitoring programmes in Antarctica

Indicator	Parameter
"Footprint"	Area subject to human activity, e.g. spatial coverage of buildings and associated impact including roads, pipes etc; number and location of field expeditions
Air quality	SO_2, particulates
Soil quality	Erosion (e.g. footpaths), metals, TPH, PAH
Sea water quality	TSS, DO, BOD, COD, pH, conductivity
Fresh water quality	TSS, DO, BOD, COD, pH, conductivity
Snow and ice quality	Metals, TPH, particulates
Vegetation quality	Spatial extent, metals
Wildlife health	Population size, breeding success
Fuel handling	Amount consumed, number of spills, size and location of spills
Aircraft/vehicle operations	Distance travelled, number of landings, fuel consumed
Solid and liquid waste	Waste types (including hazard), volume/weight
Waste water	TSS, DO, BOD, COD, pH, conductivity, faecal coliforms, volume
Field activities	Number of person days in field, location of field camps
Introduced organisms	Species, distribution, population size
EIA/permit compliance	Number of breaches recorded

as well as wilderness values (COMNAP, 2005). Since, in Antarctica unified emission standards are yet to be developed and implemented, best practice and stringent standards may be adopted. To achieve results in practical sense, state-of-the-art instrument and equipment may be implied to record and monitor observations and should be calibrated according to standard protocol.

Environmental study, under Indian Antarctic Programme carried out since first expedition in year 1981-82 when hydro-chemical studies of polynya in Antarctica and fresh water lakes conducted by CSIR-National Institute of Oceanography (NIO) Goa. Environmental Monitoring of Maitri station started before the Protocol put on force in year 1998. Owing to prevailing requirement, environmental monitoring of Maitri station carried out by BARC, for air, water, terrestrial and biological environment during austral summer of VIII, IX and X-Indian Antarctic Scientific Expedition (ISEA) in the year 1988, 1989 and 1990, respectively. BARC, collected background baseline data on natural radioactivity and trace heavy metal concentrations in air, water and rock samples and also measured background gama dose rate in air and tritium levels in the ocean as well as in Antarctic fresh water Lakes around Maitri station (Ramachandran and Balani, 1998; Sathe, 1994).

During XIII to XVI-ISEA (austral summer of 1993-95), environmental monitoring programme undertaken by, NEERI, an organisation under Council of Scientific and Industrial Research (CSIR), Government of India, organization. Observations carried out selecting relevant and important environmental indicators, i.e., Suspended Particulate Matter (SPM) Sulfur dioxide (SO_2) and Oxides of Nitrogen (NOx). Simultaneously samples were collected of water, wastewater, and soil and then analyzed for various physicochemical (i.e. pH, temperature, conductivity, turbidity, alkalinity, total hardness, chloride, sulphate, sodium, potassium, nitrate, nitrite, ammonical nitrogen, total phosphate, dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), oil and grease, hydrocarbon and heavy metals like cadmium, copper, chromium, lead, iron and zinc) as well as for biological parameters. Emission from the stacks of boilers, incinerators and exhaust of vehicles were also monitored (Ghosh *et al*., 1997a; Ghosh and Ramteke 1997; Ghosh *et al*., 1997b). Referring to guidelines, comprehensive environmental monitoring carried out at Maitri station in year 1999-2000, in which air, water, noise, soil and biological indicator selected to form baseline as well as to compare individual indicators, with those assessed in the past from same location (Tiwari *et al.*, 2006).

Air Environment

Use of fossil fuel in Antarctica is required for survival, as modern material are also required to sustain in adverse climatic condition, however use of fuel and material, generates emission and waste. Estimation and measurement of aerosol particles are important to understand effect on climate variability as well impact on the human health. It also becomes imperative to classify particles into natural and anthropogenic source and origin (Anonymous, 1981; Buettner, 1962; Kondratyev *et al.*, 1986). Kallenborn *et al.* (2015), also agree that, long term monitoring data are useful for in-depth interdisciplinary research on contaminant pattern profiles, spatial and temporal trend studies, environmental fate and distribution modeling, and understanding of regional transport pathways in the future.

SPM in air is usually very irregular in shape. While liquid particles present in mists and sprays tend to be spherical, the solid particles making up most dust and fumes fall into one of the three general classes: granular, flaky and needlelike. $PM_{2.5}$ collected during December 2014-March 2015 at Maitri station at upwind and downwind direction analyzed to observe the variation. The upwind concentration has mean value of 2 ± 1.8 µg/m^3. The downwind concentration ranges from a minimum of 1 µg/m^3 to 7 µg/m^3 with the mean value of 3 ± 2.2 µg/m^3 (Fig. 3). This increase in the concentration can be attributed

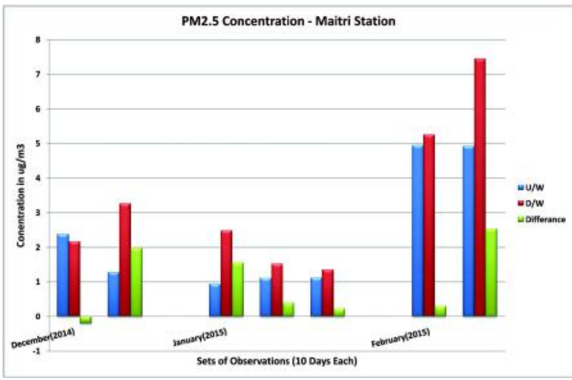

Fig. 3 :$PM_{2.5}$ Concentration Showing results of Upwind and Downwind of Maitri Station

to the local activities carried out near the station (Pande, 2015). Ghosh and Ramteke (1997) reported oxygen content in the exhaust of various stacks attached with incinerator, boiler and generator in between 12-14%, whereas CO_2 varied from 0.6 to1.2% at Maitri station, suggested need of tuning of machineries being operated in station.

Ambient air quality at the site in Larsemann Hills before setting up station Bharati carried out for Respirable Particulate Suspended Matter (RSPM), SO_2, NOx and Carbon monoxide (CO), during austral summer for three consecutive years (2007-2010) by SIIR. Concentration values shows RSPM varied from 11 to 37%. However, increase in concentrations of SPM and RSPM were noticed due to site preparation activities. SO_2 concentration varied from <1 to 3.9 μg/m^3, whereas NOx varied form 4.1-7.4 μg/m^3 (Khandal *et al.*, 2010; Ravindra *et al.*, 2011).

Year round measurement of the NOx, carried out in year 2013-14 at Maitri station. Normal values were recorded in range of 0.14, 0.12, 0.02 ppb of NOX, NO_2 and NO respectively. Particular episodes were also recorded 7.2, 6.04 and 1.52 ppb against the normal values during winter period while concentration recorded for few hours in many folds of normal occurrence of NOx (Fig. 4). It may be the chemical processes taking place in the upper atmospheric region is coupled to the lower atmospheric region and modifies the weather parameters as well the electric environment and thus the monitoring of the atmospheric electric parameters can be a tool to understand the coupling processes between the space weather events and the meteorological weather events. The mechanism behind those observations may be production of NOx in the upper atmospheric region, due to the particle precipitations or the transportation of Lightning NOx (LNOx) from the tropic and sub tropic region to the polar region through the general global circulation and descending from the upper atmosphere (Environmental Monitoring of Indian Antarctic Stations, unpublished observations by A K Tiwari).

Aerosol Black Carbon (BC) is a unique tracer for combustion emissions: it has no non-combustion source. It is inert and long-lived in the atmosphere, and can be transported over great distances. Average concentration of black carbon at Maitri station, due

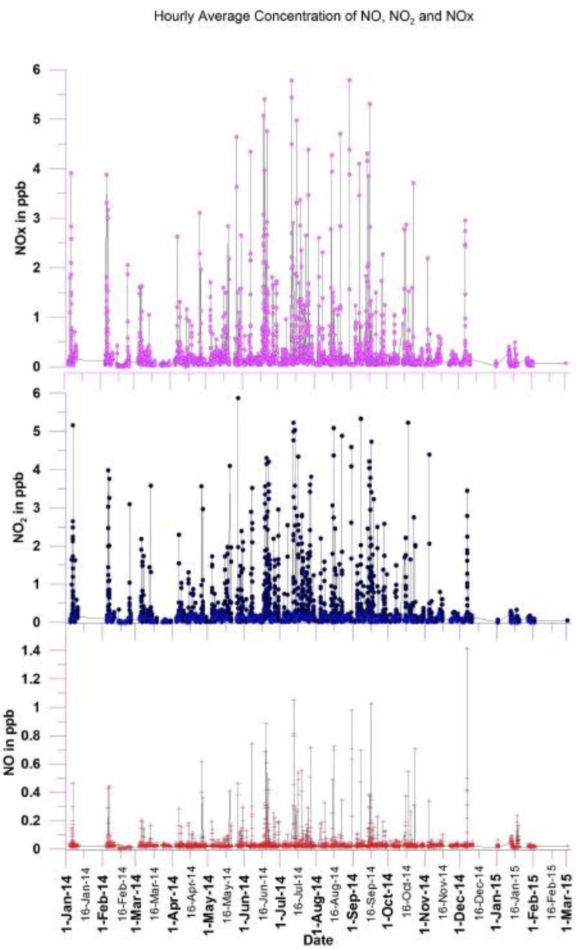

Fig. 4: Year round NOx measurement at Maitri Station in Antarctica

to long range transport, recorded was 13±5 ng/m^3. Aethelometer was operated, at the Grovnes before establishment of Bharati station during XXVII-ISEA to obtain black carbon concentration at site. Results showed the range of carbon concentration as 26.5±16.2 ng/m^3 (Chaubey *et al*., 2010).

Aethelometer measurements deployed to elucidate the variations of combustion-related aerosol emissions at Maitri station. Black carbon concentrations varied both as a function of wind direction and source strength over the diurnal cycle. Average concentration of black carbon aerosol varies in the range of 10-100 ng/m^3, as depicted in continuous measurement at Maitri station since year 2013-14, which includes contribution from local source also. Higher concentrations are recorded due to prolong high wind thus ablation of snowpack which has resulted mixing of deposited back carbon in the air during winter period while vortex formation, acts as barrier for transfer of long range transport of aerosol from other continent (Environmental Monitoring of Indian Antarctic Stations, unpublished observations by A K Tiwari).

Mercury is toxic chemical which introduced into our environment naturally as well as through man-made sources. Human sources may include incinerators, coal burning, certain industrial process, batteries and some electrical items (Witherow and Lyons, 2008). Elemental mercury plays an important role in cycle of mercury in the atmosphere and ocean (Brooks *et al*., 2008; Cossa *et al*., 2011). During, austral summer of XXXII and XXXV-ISEA, Total Gaseous Mercury (TGM) measured at Maitri station and found to be in range of 1.0-3.5 ng/m^3 in ambient air except the particular episodes while concentration of TGM exceeded 5 ng/m^3 during and after occurrence of blizzard (Tiwari and Qureshi, 2016).

Water Environment

There are more than 105 lakes (epi-shelf, pro-glacier and land-locked) identified in Schirmacher Hills within 35 km^2 area. Multi-year assessment (2011-2015) of water quality in term of physico-chemical parameters shows, most of lakes are indicating slight acidic pH and deprived of minerals, even one or two lakes shown pH lower than 5. However traces of zinc and iron and other heavy metals have been noticed in Zub-Lake (Priyadarshini Lake). This is being attributed to occasional seepage of waste water from collection pond and mixing in the stream connected as in-feed to Zub-Lake as well as water circulation though iron pipeline, however other wind-blown as well as left-out metallic articles are seen at the bottom of lake (Unpublished observations by A K Tiwari). The water quality of the lake has not changed by the intrusion of small quantity of wastewater through seepage water channel from possibly due to maintained high dilution ratio as well as augmentation with replenish of water from the glacial melt water of approximate 61000 m^3 feeding Zub lake every year, however volume may vary depending upon the ambient temperature of particular year (Tiwari and Nayak, 2007). Conductivity, heavy metals and ionic characteristics (Fig. 5) varies in terms of special and temporal change, however characteristics of lakes

(A)

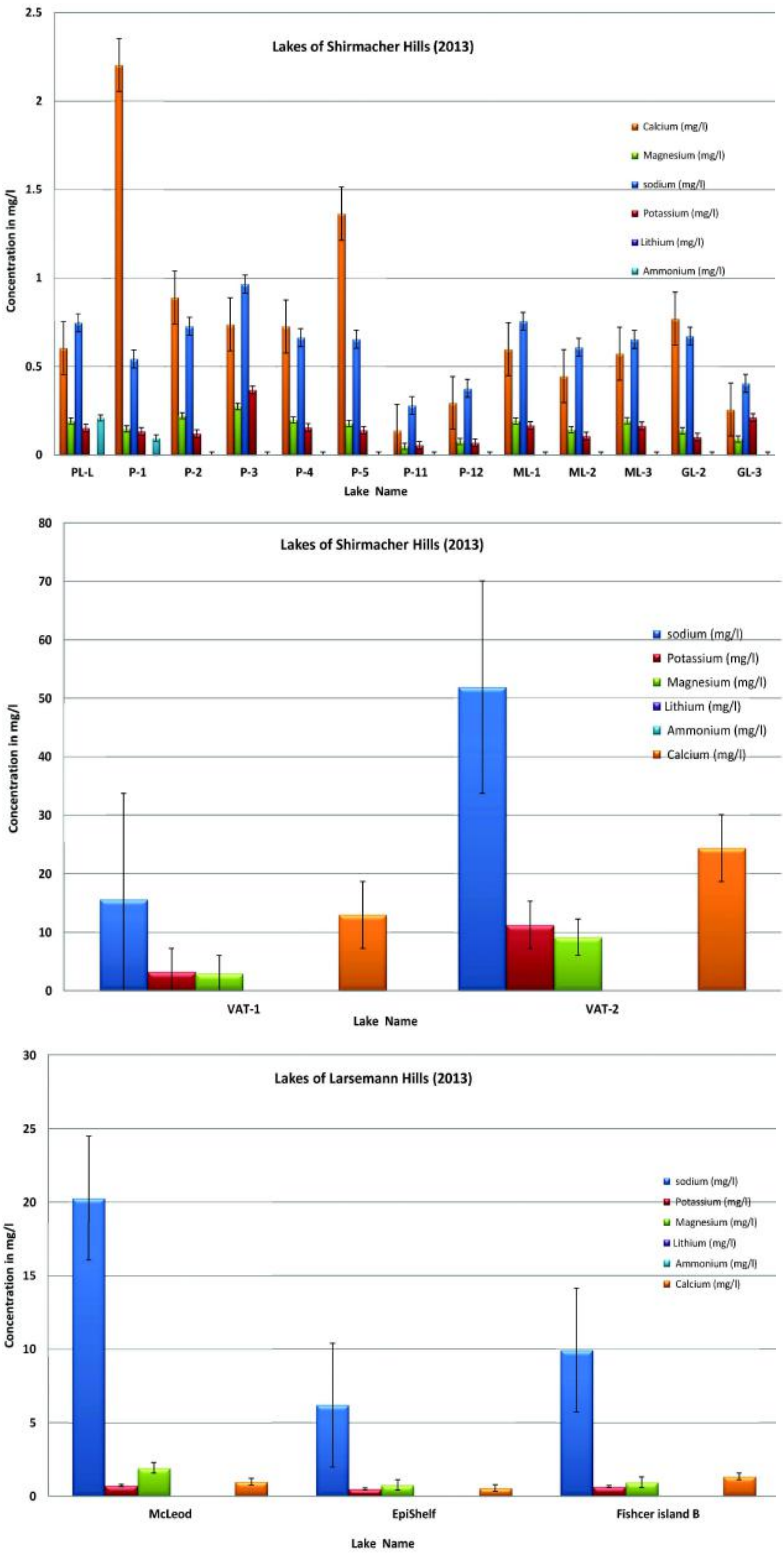

Fig. 5 : Cation Distribution in the Lakes of Shirmacher and Larsemann Hills

are still comparable without any significant change with water quality of 38 lakes had been carried out by Kumar *et al*. (2002) during XVIII-ISEA, ascertaining various physico-chemical parameters.

Water quality monitoring carried out by SIIR, during XXVII to XXIX-ISEA in Grovnes, Stornes and Broknes peninsula. Water quality parameters did not show significant variations. However, some parameters showed marginal inter-annual variations between lakes. For instance, chloride values in all lakes were within the range of freshwater, but in two Lakes results shows 58-836 mg/l and 351-353 mg/l the values varied widely and also indicated saline water influence. Most of the metals analysed were showing values from below detectable to very low values. Nutrient parameters such as PO_4 and NO_3, though varied marginally between lakes, showed lower values, suggesting that the lake in Larsemann Hills are not subjected to organic or inorganic pollution (Khandal *et al*., 2010; Ravindra *et al*., 2011).

Waste Water Treatment

The Rotating Biological Contactor (RBC) are a range of complete self-contained sewage treatment plants which are designed for small communities and manufactured in different range of sizes (Connor, 2008). These units are ideal for single house, small housing developments, hotels, public houses and small commercial developments. The units are compact, self-contained, single-piece treatment plants that utilize natural biological processes to effectively break down domestic and commercial waste water (Hiras *et al*., 2004). RBC is most preferred biological treatment system in Antarctica to treat grey water generated from the station. Two RBC were installed at Maitri station in year 1989-90 to treat the grey water generated from kitchen, laundry and bathrooms. Efficacy assessment also has been carried out during various expeditions, considering appropriate indicators. The performance of RBC is evaluated in terms of BOD, COD and Ammonia nitrogen (NH_3-N). During year 2011-12, efforts were made to improve the efficacy of RBC to tune it to meet design parameters. Performance evaluation of RBC was carried out to assess the treatment efficiency of bio-discs. It was noticed that the treatment efficiency of B3- RBC was 27.8% in terms of BOD and 41.3 % in terms of COD. Whereas, B1-RBC was working with efficiency of 66.7% in terms of BOD and 68.9% in terms of COD (Tiwari *et al*., 2009). A laboratory experiment of tertiary treatment of wastewater is carried out using activated carbon method, which gave the BOD removal up to 84%. Bharati station has been augmented with advance wastewater treatment system comprising Membrane Bio Reactor (MBR). System is functioning and meeting most of the time designed effluent standards, except when over loading of influent observed. Wastewater outfall at Maitri and Bharati station have been analysed for presence of pathogens and results found positive in few samples, presented in Table 2 (personnel communication, unpublished data by S Kerkar).

Noise Environment

Numerous study conducted worldwide shows that increased noise due to machinery or aircraft/helicopter impart health impact as well as annoyance. Noise barrier and Personal Protective Equipment should be used at high noise level area (Babisch *et al*., 2009; Baldauf *et al*., 2008). High noise level can lead to sleep deprivation which can affect physical and mental health (Douglas and Murphy, 2016; Murphy *et al*., 2009). Noise level monitoring conducted in year 2012-13 around Maitri station shows Leq values varied in range of 48 to 63 dBA (with wind effect), whereas electrical generators produced 108 dBA and helicopter take off generated 103 dBA of noise levels (Unpublished observations by A. K. Tiwari). These results are close to earlier monitored by Ghosh and Ramteke (1997) and Tiwari and Kulkarni (2004) which indicated that in and around Maitri station noise level varied from35-57 dBA, whereas near operation of various machineries it varies in range of 66 to 105 dBA. Antarctica being unique place more appropriate indicators should be developed to limit the exposure time and duration of noise levels,

Biological Environment

Antarctic lakes possess relatively short and simple food chain, Kok and Grobbelaar (1978) states that the zooplankton occupies the top of the food chain due to the absence of fish. They found a significant correlation between average primary production rates measured by Grobbelaar (1974) and zooplankton biomass in various water bodies, and concluded that zooplankton rely heavily on algal production and play an important role as consumers of primary producers.

Study on phytoplankton at ice edge was carried out by NIO during III-IASE (Sengupta, 1983). Micro fauna of the Priyadarshini Lake of Schirmacher Hills were studied with the objectives; evaluation of environmental characteristics, faunal density and distribution. Bacteria and Yeasts of Antarctica are studied by Centre for Cellular and Molecular Biology (CCMB), Hyderabad, during IV-IASE to investigate the molecular biology of microorganisms with a view to understand the molecular mechanism of adaptation in extreme cold conditions (Alam *et al*., 2005). Shivaji *et al*. (1989), were the first to report *Planococcus* species from the Antarctic habitat. Alam *et al*. (2003), isolated a new member of the genus *Planococcus,* from a cyano-bacterial mat sample collected in the

Table 2: Heterotrophic and pathogenic counts at Maitri and Bharati station's wastewater outfall

Stations	Nutrient Agar	Zobell Marine Agar	Mac Conkey Agar	SS Augur	TCBS Agar	EMB
Maitri	2.31×10^5cfu/mL	1.98×10^5cfu/mL	0.45×10^5cfu/mL	0.75×10^5cfu/mL	0.35×10^5cfu/mL	0.49×10^5cfu/mL
Bharati	4.31×10^6cfu/mL	3.86×10^6cfu/mL	0.3×10^6cfu/mL	0.8×10^6cfu/mL	0.23×10^6cfu/mL	0.77×10^6cfu/mL

vicinity of Maitri, the Indian station, in Schirmacher Hills, Antarctica. Based on phenotypic and genotypic data, they concluded that the new isolate merits separate species status, and therefore, proposed the name *Planococcus maitriensis* for strain S1.

A profiling underwater radiometer was used in the water around Maitri during thirteen IASE by NIO and it was concluded that greater productivity in the Antarctic waters is due to higher quantum of light received. The bacterial and fungal population of Antarctica atmosphere was monitored and it was found that bacterial population was dominated by Gram positive rods and fungal population by *Penicillium* species (Lokobharathi and Krishnakumar, 1997). Bryophytes collected in Schirmacher oasis represents, nine species of mosses under five genera and four families. Around 19 Lichen flora of Schirmacher hills is collected and studied by the National Botanical Research Institute (NBRI), Lucknow along with heavy metal analysis of lichen (Bera, 2012). Algal flora diversity study was carried out in fresh water streams of Schirmacher Hills by Banaras Hindu University (BHU), which recorded over 30 species of algae predominantly belonging to cyanobacteria (Pandey and Kashyap, 1998).

Ghosh *et al*. (1997b), estimated the Shannon weaver diversity index values of the phytoplankton present in various lakes around Maitri station, which varied between zero and 2.54 indicating poor productivity and, less number and uneven distribution of the species. Zub Lake represented, rotiferans, cladocerans and copepodids, the lakes at western side of Maitri station, contained only one species of nematode. Altogether eight varieties of zooplankton were recorded in surface water samples Diversity index values varying from nil to 1.37 for zooplankton indicate nonproductive water bodies.

The bacterial population in some brackish water lakes of Larsemann Hills was enumerated by Krishnan *et al*. (2009), shows that both freshwater and saline bacteria were encountered in the lakes. These lakes were also found to harbor a large number of manganese oxidizing bacteria, predominantly belonging to the genera *Shewanella*, *Pseudomonas* and an unclassified genus in the family Oxalobacteriaceae. During the XXVIII to XXX-ISEA, bacterial population in some lakes of Larsemann Hills was enumerated. No pathogenic population such as Coliform, *Salmonella, Staphylococcus* and *Psedomonas* was encountered (Khandal *et al*., 2010). However, during XXXIII-ISEA (2013-14), water sample collected from lakes of Schirmacher and Larsemann Hills as well as from the seashore near Bharati station, processed to isolate 208 bacteria which includes; psychrophiles, heterotrophs and pathogens. Few lakes at Broknes shown presence of suspected E.Coli; *Enterobacter, Shalmonela, Shigella, and Staphylococcus species* (personnel communication, unpublished data by S Kerkar).

Alien Species: Threat to Ecosystem

The rapid global warming can affect an ecosystem changes to adopt naturally. Pollution of water of ponds, lakes and Oceans is increasing day to day which threatened the future course of life. The invasion of native ecosystems by non-native or alien organisms; weeds, pathogens, predators, etc., is now widely regarded as a top threat to biological diversity worldwide. Of the many non-native species that may be introduced to a native ecosystem, some act as competitors, predators, pathogens, or disrupters of key ecological processes (nutrient cycling, flood or fire regimes, etc.). Others exhibit no clear negative impacts, or may enhance the habitat for certain native species while harming other native components. Invasive species are described as “critical”, “widespread”, or “among the top” sources of stress to conservation targets. Thus there is urgent need of conservation to find ways of maintaining the high levels of biological diversity that are seen in today’s world. The synonymous terms was used to describe aliens species are: introduced, exotics, non-natives. The, “invasive alien” has been widely used since the 20th century (McGeoch *et al*., 2015; Tiwari *et al*., 2006; Walton, 1987). SCAR and ATCM have developed various guidelines and recommended measures to be adopted in order to avoid introduction of alien species in Antarctica (WP-25, 2012; WP-53, 2011). Logistic operation including cargo, ship, aircraft and transport vehicle, may act as carrier to invasive alien species if proper measures are not adopted. Detailed study on identification of alien species at Indian stations is to be initiated soon.

Initial Environmental Evaluation (IEE)

Activities to be undertaken (Scientific and Logistics) in Antarctica Treaty area should be assessed for less than minor, minor or transitory and more than minor or transitory according to Article 8 of Environmental Protocol. Assessment procedure as mentioned in Annex-1 of Protocol should be followed (ATS, 2002). Lamers *et al*. (2014) also in opinion that experiences in the use of strategic thinking and strategic environmental assessment tools in and outside of Antarctica represent exemplars that can be adopted by stakeholders in an Antarctic setting and can be scaled up to the Antarctic region as a whole. A more strategic approach to environmental governance in Antarctica should consist of different components, including strategic thinking, planning, decision making, implementation and monitoring.

Proposed activities at Maitri and Bharati station have been carefully examined to prepare IEE for placement of shelter hut (IP-002, 2007), installation of earth station (IP-026, 2008), wind energy generators (IP-021, 2009; IP-049, 2008), approach path (IP-001, 2010) and ground station (IP-075, 2013). Preparation of IEE is useful tool to adopt environmental measures during project implementation.

Environmental Impact Assessment

Research undertaken in Antarctica mainly focused on chemical fingerprinting, elucidation of biogeochemical process and pathways, ecological assessment and remediation research, though they are process-oriented (Tin *et al*., 2009) Human activity attributes to chemical contamination through exhaust gases and fuel spills which is noticeable among other sources (Bargagli, 2008) .

According to the Monitoring of Environmental Impacts from Science and Operations in Antarctica (Bonner and Angel, 1987) the monitoring improvement is to be carried out and implemented which is the intact part of the Post- Environmental Impact Assessment study. Environmental Impact assessment study initiated at Maitri station during austral summer of XIX-ISEA in year 1999-2000, selecting indicators for ambient air (SPM, SO_2 and NO_x). Essential physico-chemical parameters for analysis of water and wastewater defined and then analysed including biological study of phytoplankton and zooplankton in lake water. Ambient noise levels were monitored on the basis of day-night (Leq) as well as machine noise levels. Soil samples were also collected to assess the particle size distribution, bulk density, water holding capacity, porosity, calcium, sodium, potassium, magnesium, oil and grease and hydrocarbons contamination in the soil.

Air quality prediction carried out employing air quality model, Industrial Source Complex Short Term Version-3 (ISCST-3) for Bharati (Tiwari *et al*., 2007) and Maitri station and mixing height is calculated based on the radiosonde dada available from the nearby Russian station, Novolazevskaya. Depth of Zub Lake (source of drinking water), which is also known as Priyadarshini Lake, was measured at various places and depth area relationship is obtained to find out the total quantity of water available and also the during summer the total quantity of water melted and stored in Zub lake is also measured form day to day basis of height increment and surface area relationship. An environmental management plan was prepared to mitigate the adverse impact including health and safety of the occupants (Tiwari and Kulkarni, 2004; Tiwari *et al*., 2006).

Waste Management

Station has the systems to collect and segregate the waste as per nature of the waste i.e. bio degradable and non-biodegradable. Further, biodegradable waste is also segregated as papers, rags and food waste. Paper rags etc., are burnt in a closed room by incinerator and ash is collected in the drums similarly the human excreta is incinerated and the ash are collected into the drum and all the solid waste is removed from the Antarctica and bring to country for safe disposal. During 1996-97, comprehensive environmental cleaning put into force and around 20 metric ton of waste removed from in and around Maitri station (Ravindra, 2000) . Similar exercise carried out in year 2013-14 and 15 ton of waste has been removed which included used oil barrels, vehicle parts, etc.

Conclusion

Research undertaken in Antarctica mainly focused on chemical fingerprinting, elucidation of biogeochemical process and pathways, ecological assessment and remediation research, though they are process-oriented (Acosta-Martínez *et al*., 2015; Formenti *et al*., 2011). Holistic environmental monitoring programme at the Indian scientific permanent station, Maitri was started in year 1988. Awareness in environmental monitoring programme has resulted into generation of noticeable database for future comparison. Indian team members are worked also in close cooperation with other country, i.e. Peru, Germany, Iran, France, Russia and South Africa.

Black carbon concentration at Maitri and Bharati stations varied in range of 13±16.2 ng/m^3 to 26.5±16.2 ng/m^3 is being attributed by long range transport, however local anthropogenic activities are also contributing nearly 1-3 μg/m^3 of $PM_{2.5}$. Station operation and maintenance require huge amount of fossil fuel to operate various life supporting machineries and transport vehicles. Generators, incinerators and boilers being operated in stations are the main source of emission to attribute in environment, which may have noticeable impact on the surrounding environment as well as changing albedo of snow cover enriching it with carbon particles (Weller *et al*., 2013). Fossil fuel burning is main source of NOx and SO_2 emission, though maximum-average ambient concentration of NOx has been recorded in nearly 0.14 ppb at Maitri station, installation of state-of-the-art silent generators based on Combined Heat and Power (CHP) concept would mitigate further environmental impact (Fumo *et al*., 2011; Tiwari *et al*., 2007). Presence of mercury is largely attributed to long-range transport, however abrupt change in the concentration of the mercury soon after blizzard is a particular phenomenon that has to be further explored through experiments and observations.

Consumption of water from the lakes for routine need and drinking purpose ultimately produces wastewater and treated effluent also accumulate in the environment or joins water cycle thus enriching soil and sediment with heavy metals, organic and inorganic constituents. Low treatment efficacy of RBC (recorded less than 50% of BOD and COD removal) is a matter of concern and seepage from wastewater has potential to contaminate downstream lake water, thus in few location concentration of NO_3, PO_4, Cl and Na have been recorded higher in Zub lake, then natural concentrations of similar elements, recorded in other lakes at Schirmacher Hills. The analysis of data do not shows the significant change in environmental indicator (heavy metal) except the increment of iron in drinking water and presence of biological indicator, which is attributed to use of old iron pipe and seepage of treated wastewater in Zub lake during summer. Presence of E-Coli and pathogens in nearby lakes of stations indicates careful examination of anthropogenic activities, however birds also acts as vector to transport organic ingredient and dropping into lake water, which may also have been attributed presence of pathogens in lake water (Barbosa and Palacios, 2009; Grimaldi *et al*., 2014).

Realizing the environmental issues projected through environmental indicators the efficiency of bio-disc is improved and new advanced wastewater treatment system with UV filtration has been commissioned. Measures are taken to block the seepage treated water by layering the pond with reinforced polypropylene liner.

Every year around 80-100 scientists/logistics personel reach to Antarctica to stay and work in Indian Antarctic stations. There may be risk of introduction of invasive alien species in the area where they work and stay. However this threat from Antarctica to India is almost not possible due to difference in climatic conditions and survival of microorganisms. Array of measures are required to be implemented at Indian Antarctic stations as well as other stations which do exists in Antarctica. These comprises, year-round environmental monitoring, targeted scientific research, measures on non-native species as well as regulations on non-scientific activities including tourism. Environmental impact due to some human activity are irreversible and it is matter of research and monitoring to distinguish between natural and anthropogenic pollution attributed by local or long – range source. ATCM, CEP and COMNAP are further updating guideline on environmental monitoring with inclusion of recent measures, resolution and decisions adopted during recent ATCMs. Stringent measures and standards will improve the present scenario of stations and activities to protect pristine Antarctic environment.

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References

Acosta-Martínez V, Van Pelt S, Moore-Kucera J, Baddock M C and Zobeck T M (2015) Microbiology of wind-eroded sediments: Current knowledge and future research directions *Aeolian Research* **18** 99-113. doi:10.1016/j.aeolia.2015.06.001

Alam S I, Dube S, Reddy G S N, Bhattacharya B K, Shivaji S and Singh L (2005) Purification and characterisation of extracellular protease produced by Clostridium sp. from Schirmacher oasis, Antarctica *Enzyme and Microbial Technology* **36** 824-831 doi: http://dx.doi.org/10.1016/j.enzmictec.2005.01.011

Alam S I, Singh L, Dube S, Reddy G S and Shivaji S (2003) Psychrophilic Planococcus maitriensis sp.nov. from Antarctica *Syst Appl Microbiol* 26 505-510 doi: 10.1078/072320203770865792

Anonymous (1981) The atmospheric aerosol. In: Meszáros E (ed) *Studies in Environmental Science* **11** Elsevier, pp 91-132 doi: http://dx.doi.org/10.1016/S0166-1116(08)70765-9

ATS (2002) Handbook of Antarctic Treaty System. Ninth edn. Department of State, United States

Babisch W, Houthuijs D, Pershagen G, Cadum E, Katsouyanni K, Velonakis M, Dudley M-L, Marohn H-D, Swart W, Breugelmans O, Bluhm G, Selander J, Vigna-Taglianti F, Pisani S, Haralabidis A, Dimakopoulou K, Zachos I and Järup L (2009) Annoyance due to aircraft noise has increased over the years—Results of the HYENA study *Environment International* **35** 1169-1176 doi: http://dx.doi.org/10.1016/j.envint.2009.07.012

Baldauf R, Thoma E, Khlystov A, Isakov V, Bowker G, Long T and Snow R (2008) Impacts of noise barriers on near-road air quality *Atmospheric Environment* **42** 7502-7507 doi: http://dx.doi.org/10.1016/j.atmosenv.2008.05.051

Barbosa A and Palacios M J (2009) Health of Antarctic birds: a review of their parasites, pathogens and diseases *Polar Biology* **32** 1095 doi:10.1007/s00300-009-0640-3

Bargagli R (2008) Environmental contamination in Antarctic ecosystems *Science of the Total Environment* **400** 212-226 doi: http://dx.doi.org/10.1016/j.scitotenv.2008.06.062

Bera S K, Phartiyal B and Sharma A (2012) An Evidence of Pollen – Spores Retrieved from Lichen Patches Distributed in Schirmacher Oasis and Adjacent Nunataks, East Antarctica: a Case Study of Pollen Transport Over Polar Region *International Journal of Earth Sciences & Engineering* **5** 724-735

Blanchette R A, Held B W, Jurgens J A, Aislabie J, Duncan S and Farrell R L (2004) Environmental pollutants from the Scott and Shackleton expeditions during the Heroic Age of Antarctic exploration *Polar Record* **40** 143-151 doi: 10.1017/s0032247403003334

Bonner W N and Angel M V (1987) Conservation and the Antarctic environment: The working group reports of the joint IUCN/SCAR Symposium on the scientific requirements for Antarctic conservation *Environment International* **13** 137-144

Brooks S, Arimoto R, Lindberg S and Southworth G (2008) Antarctic polar plateau snow surface conversion of deposited oxidized mercury to gaseous elemental mercury with fractional long-term burial *Atmospheric Environment* **42** 2877-2884 doi: http://dx.doi.org/10.1016/j.atmosenv.2007.05.029

Budhavant K, Safai P D and Rao P S P (2015) Sources and elemental composition of summer aerosols in the Larsemann Hills (Antarctica) *Environmental Science and Pollution Research* **22** 2041-2050 doi: 10.1007/s11356-014-3452-0

Buettner K J K (1962) Human aspects of bioclimatological classification. In: Tromp S W (ed) Biometeorology.

Pergamon, pp 128-140. doi:_http://dx.doi.org/10.1016/B978-0-08-009683-4.50026-7

Chaubey J P, Moorthy K K, Babu S S, Nair V S and Tiwari A (2010) Black carbon aerosols over coastal Antarctica and its scavenging by snow during the Southern Hemispheric summer *Journal of Geophysical Research* **115** doi: 10.1029/2009jd013381

Clarke A and Harris C M (2003) Polar marine ecosystems: Major threats and future change *Environmental Conservation* **30** 1-25 doi: 10.1017/S0376892903000018

Clarke A D (1988) Aerosol physical chemistry in remote marine regions *Journal of Aerosol Science* **19** 1195-1198 doi: http://dx.doi.org/10.1016/0021-8502(88)90134-6

COMNAP (2005) Practical Guidelines for Developing and Designing Environmental Monitoring Programmes in Antarctica. Antarctic Environmental Officers Network (AEON)

Connor M A (2008) Wastewater treatment in Antarctica *Polar Record* **44** doi: 10.1017/s003224740700719x

Cossa D, Heimbürger L E, Lannuzel D, Rintoul S R, Butler E C V, Bowie A R, Averty B, Watson R J and Remenyi T (2011) Mercury in the Southern Ocean *Geochimica Et Cosmochimica Acta* **75** 4037-4052 doi: 10.1016/j.gca.2011.05.001

Douglas O and Murphy E (2016) Source-based subjective responses to sleep disturbance from transportation noise *Environment International* **92-93** 450-456 doi: http://dx.doi.org/10.1016/j.envint.2016.04.030

Formenti P, Schütz L, Balkanski Y, Desboeufs K, Ebert M, Kandler K, Petzold A, Scheuvens D, Weinbruch S and Zhang D (2011) Recent progress in understanding physical and chemical properties of African and Asian mineral dust *Atmospheric Chemistry and Physics* **11** 8231-8256 doi 10.5194/acp-11-8231-2011

Fumo N, Mago P J and Jacobs K (2011) Design considerations for combined cooling, heating, and power systems at altitude *Energy Conversion and Management* **52** 1459-1469 doi: http://dx.doi.org/10.1016/j.enconman.2010.10.009

Gerson N C (1958) From Polar Years to Igy. In: Landsberg H E and Mieghem J V (eds) *Advances in Geophysics* **5** Elsevier, pp 1-52. doi:http://dx.doi.org/10.1016/S0065-2687(08)60074-6

Ghosh T K, Muley R D, Ghode R and Ramteke D S (1997a) Water and Wastewater Management at Indian Station Maitri in Antarctica. In: Technical Publication No 11, Scientific Report, Thirteenth Indian Expedition to Antarctica, Department of Ocean Development, New Delhi. pp 301-311

Ghosh T K and Ramteke D S (1997a) Environmental Status at Maitri, Indian Permanent Station in Antarctica : Preliminary Studies. In: Technical Publication No 11, Scientific Report, Thirteenth Indian Expedition to Antarctica, Department of Ocean Development, New Delhi, pp 267-280

Ghosh T K, Salgonkar L N and Kotangale J P (1997b) Biotic Features of Selective Surface Water Bodies around Indian Station Maitri in Schirmacher Oasis, Antarctica. In: Technical Publication No 11, Scientific Report, Thirteenth Indian Expedition to Antarctica, Department of Ocean Development, New Delhi, pp 294-303

Grimaldi W W, Seddon P J, Lyver P O B, Nakagawa S and Tompkins D M (2014) Infectious diseases of Antarctic penguins: current status and future threats *Polar Biology* **38** 591-606 doi: 10.1007/s00300-014-1632-5

Grobbelaar J U (1974) Primary production in freshwater bodies of the sub-Antarctic island Marion *S Afr J Antarctic Res* **4** 40-45

Harris C M and Meadows J (1992) Environmental management in Antarctica Instruments and institutions *Marine Pollution Bulletin* **25** 239-249 doi: http://dx.doi.org/10.1016/0025-326X(92)90676-W

Hiras D N, Manariotis I D and Grigoropoulos S G (2004) Organic and nitrogen removal in a two-stage rotating biological contactor treating municipal wastewater *Bioresour Technol* **93** 91-98 doi: 10.1016/j.biortech.2003.06.005

IP-001 (2010) Initial Environmental Evaluation for Development of Approach Path at Proposed New Indian Research Station at Larsemann Hills, East Antarctica. India, ATCM-XXXIII, Urguay

IP-002 (2007) Initial Environmental Evaluation for Placement of Shelter Huts at the proposed site of new Indian Research Base, Larsemann Hills, East Antarctica. India, ATCM XXX, India

IP-021 (2009) Initial Environmental Evaluation for Installation of Wind Energy Generators (WEG) at Proposed New Indian Research Base at Larsemann Hills, East Antarctica. India, ATCM-XXXII, USA

IP-026 (2008) Initial Environmental Evaluation for Installation of Earth Station at Maitri, Schirmacher Oasis, Antarctica. India, ATCM-XXXI, Ukraine

IP-049 (2008) Initial Environmental Evaluation for Installation of Wind Energy Generators (WEG) at Maitri, Schirmacher Oasis, Antarctica. India, ATCM-XXXI, Ukaraine

IP-075 (2013) Initial Environmental Evaluation for Establishment of the Ground Station for Earth Observation Satellites at the Indian Research Station Bharati at Larsemann Hills, East Antarctica. India, ATCM-XXXVI, Belgium

Kallenborn R, Hung H and Brorström-Lundén E (2015) Chapter 13 - Atmospheric Long-Range Transport of Persistent Organic Pollutants (POPs) into Polar Regions. In: Eddy Y- -Z (ed) Comprehensive Analytical Chemistry, vol Volume 67. Elsevier, pp 411-432. doi: http://dx.doi.org/10.1016/B978-0-444-63299-9.00013-2

Kennicutt Ii M C (1990) Oil spillage in Antarctica *Environmental Science and Technology* **24** 620-624

Khandal R K, Verma V K, Niyogi U K, R K S, Sharma B, Pal N, Kumar M and P K (2010) Longterm Environmental Monitoring and Impact Assessment Stidies at New (Upcoming) Indian Scientific Base, at Larsemann Hills (East Antarctica). Shriram Institte of Industral Research, New Delhi

Kok O B and Grobbelaar J U (1978) Observations on the crustaceous zooplankton in some freshwater bodies of the sub-antarctic island marion *Hydrobiologia* **59** 3-8

Kondratyev K Y, Ivanov V A, Pozdnyakov D V and Prokofyev M A (1986) Natural and Anthropogenic Aerosols: A Comparative Analysis. In: Marini-Bettòlo G B (ed) Studies in Environmental Science, vol Volume 26. Elsevier, pp 281-303 doi: http://dx.doi.org/10.1016/S0166-1116(08)71801-6

Krishnan K P, Sinha R K, Krishna K, Nair S and Singh S M (2009) Microbially Mediated Redox Transformations of Mangnese (II) along with Some Other Trace elements: A Study from Antarctic Lakes *Polar Biology* **32**1765-1778

Kumar P, Shokri M R and Mehrotra I (2002) Water Quality: Lakes of Schirmarcher Oasis, Antarctica. In: Technical Publication No.16, Eighteenth Indian Expedition to Antarctica, Scientific Report, Department of Ocean Development, New Delhi, pp 272-292

Lamers M, Liggett D and Tin T (2014) Strategic thinking for the antarctic environment: The use of assessment tools in governance. In: Antarctic Futures: Human Engagement with the Antarctic Environment. Springer Netherlands, pp 307-327. doi:10.1007/978-94-007-6582-5_14

Leopold L B, Clarke F E, Henshaw B B and Balsley J R (1971) A Procedure for Evaluating Environmental Impact. Circular, US Geological Survey, vol 645

Lokabharathi P A and Krishnakumari L (1997) UV Radiation and Primary Production in the Antarctic waters. In: Scientific Report on Thirteenth Indian Expedition to Antarctica, Technical Publication No. 11. Department of Ocean Development, New Delhi, pp 323-324

Lyons W B, Welch K A and Bonzongo J C (1999) Mercury in aquatic systems in Antarctica *Geophysical Research Letters* **26** 2235-2238

McGeoch M A, Shaw J D, Terauds A, Lee J E and Chown S L (2015) Monitoring biological invasion across the broader Antarctic: A baseline and indicator framework *Global Environmental Change* **32** 108-125 doi: http://dx.doi.org/10.1016/j.gloenvcha.2014.12.012

Murphy E, King E A and Rice H J (2009) Estimating human exposure to transport noise in central Dublin, Ireland *Environment International* **35** 298-302 doi: http://dx.doi.org/10.1016/j.envint.2008.07.026

Pande A S (2015) Satellite and Ground based Monitoring of Air Quality at Indian Antarctic Base " Maitri" and Two Indian Cities. M.Tech.Dissertation, Centre for Environmental Science and Engineering, Indian Institute of Technology, Mumbai

Pandey K D and Kashyap A K (1995) Diversiy of Algal Flora in Six Freshwater Streams of Schrimacher Oasis, Antarctica. In: Scientific report on Tenth Indian Expedition to Antarctica, Technical Publication No 8, Department of Ocean Development, New Delhi. pp 219-230

Parker B C and Vince Howard R (1977) The first environmental impact monitoring and assessment in Antarctica. The dry valley drilling project *Biological Conservation* **12** 163-177 doi: http://dx.doi.org/10.1016/0006-3207(77)90014-3

Pineschi L (2001) Chapter 15 - The duty of prior environmental impact assessment of Antarctic activities under the Madrid Protocol and its implementation in the Italian legal system A2 - Walton, Sergio CaroliPaolo CesconDavid W.H. In: Environmental Contamination in Antarctica. Elsevier Science, Amsterdam, pp 363-380 doi: http://dx.doi.org/10.1016/B978-008043199-4/50016-2

Ramachandran T V and Balani M C (1998) Report on the Participation by the Bhabha Atomic Research Centre in the Tenth Indian Expedition to Antarctica. In: Technical Publication No 8, Scientific Report, Tength Indian Expedition to Antarctica, Department of Ocean Development, New Delhi. pp 159-180

Ravindra R (2000) Report of the Environmental Task Force. In: Sixteenth Indian Expendilion to Antarctica, Scientific Report, vol Technical Publication No. 14. Department of Ocean Development, New Delhi, pp 1-36

Ravindra R, Tiwari A K, Achuthankutty C T and Rai K N (2011) Final Comprehensive Environmental Evaluation of New Indian Research Station at Larsemann Hills, East

Anatrctica, XXXIV-Antarctica Treaty Consultative Meeting,IP-006. Argentina

Sathe A P (1994) Baseline Data on Natural Radioactivit and Metal Concentration in Natural Antarctic Samples. In: Ninth Indian Epedition to Antarctica, Technical Publication No. 6. Department of Ocean Development, New Delhi, pp 251-258

Sengupta R and Qasim S Z (1983) Chemical Studies on the Ice shelf, in a Fresh Water Lake and in a Polynya at Princess Astrid Coast, Dronning Maud Land, Antarctica. In: Scientific Report on First Indian Expedition to Antarctica, Technical Publication No. 1. Department of Ocean Development, New Delhi, pp 62-68

Shivaji S, Rao N S, Saisree L, Sheth V, Reddy G S and Bhargava P M (1989) Isolation and identification of Pseudomonas spp. from Schirmacher Oasis, Antarctica *Appl Environ Microbiol* **55** 767-770

Tin T, Fleming Z L, Hughes K A, Ainley D G, Convey P, Moreno C A, Pfeiffer S, Scott J and Snape I (2009) Impacts of local human activities on the Antarctic environment *Antarctic Science* **21** 3-33 doi: 10.1017/ S0954102009001722

Tiwari A K and Kulkarni S (2004) Environmental Status at Indian Polar Research Station Maitri - A Comprehensive Study. In: A. C (ed) Ninteenth Indian Expedition to Antarctica, Scientific Report, vol Technical Publication No 17. National Centre for Antarctic and Ocean Research through NISCAIR, CSIR, New Delhi, pp 189-221

Tiwari A K, Kulkarni S, Ramteke D S and Nayak G N (2006) Environmental Quality at Maitri Station in Antarctica *Journal of Environmental Science and Engineering* **48** 191-198

Tiwari A K and Nayak G N (2007) Water Abundance and Effect of Glacier Melting at Priyadarshini Lake in Antarctica *Journal of Institution of Engineers India (Environmental Engineering)* **88** 27-32

Tiwari A K, Nayak G N and Pandey P C (2009) Wastewater Fate at Maitri in Antarctica *Journal of Institution of Engineers India (Environmental Engineering)* **90** 49-54

Tiwari A K and Qureshi A (2016) Mercury Assessment at Indian Antarctic Stations in Antarctica – A Preliminary Study. In: Society for Environmental Toxicology and Chemistry - Asia Pacific, Singapore, Singapore, 2016

Tiwari A K, Ravindra R, Rajan S, Khare N and Saxena A (2007) Draft Comprehensive Environmental Evaluation of New Indian Research Base at Larsemann Hills, Antarctica. XXX Antarctica Treaty Consultative Meeting. New Delhi

Tiwari A K, Singh S M and Pandey P C (2006) Invasive Alien Species : Threat to Antarctic Biodiversity and Control Mechanism. In: Rai L C and Gaur J P (ed) Invasive Alien Species and Biodiversity in India. Gautam Printers, Varanasi, India, pp 160-168

Walton D W H (1987) Antarctic terrestrial ecosystems *Environment International* **13** 83-93 doi: http://dx.doi.org/ 10.1016/0160-4120(87)90046-8

Walton D W H and Morris E M (1990) Science, environment and resources in Antarctica *Applied Geography* **10** 265-286 doi: http://dx.doi.org/10.1016/0143-6228(90)90035-N

Walton D W H and Shears J (1994) The need for environmental monitoring in antarctica: Baselines, environmental impact assessments, accidents and footprints *International Journal of Environmental Analytical Chemistry* **55** 77-90 doi: 10.1080/03067319408026210

Weller R, Minikin A, Petzold A, Wagenbach D and König-Langlo G (2013) Characterization of long-term and seasonal variations of black carbon (BC) concentrations at Neumayer, Antarctica *Atmospheric Chemistry and Physics* **13** 1579-1590 doi: 10.5194/acp-13-1579-2013

Witherow R A and Lyons W B (2008) Mercury deposition in a polar desert ecosystem *Environmental Science and Technology* **42** 4710-4716. doi:10.1021/es800022g

WP-25 (2012) Guidelines to minimise the risks of non-native species and disease associated with Antarctic hydroponics facilities. Australia and France, XXXV-ATCM, Hobart

WP-53 (2011) Measures to reduce the risk of non-native species introductions to the Antarctic region associated with fresh foods. SCAR,XXXIV-ATCM, Buenes Aires.

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Research Paper

Polar Ice Sheet and Glacier Studies – Indian Efforts in last Five Years

PRAVEEN K THAKUR, ARPIT CHOUKSEY, S P AGGARWAL and A SENTHIL KUMAR*
Indian Institute of Remote Sensing, Indian Space Research Organisation, Dehradun 248 001, India

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Indian scientists have been involved in studies of cryosphere in Polar Regions from past 35 years. For continuous monitoring and expanding research in the fields of atmospheric science, geosciences, glaciology, environmental sciences, etc. specific to these regions, the ESSO - National Centre for Antarctic and Ocean Research (ESSO-NCAOR) has established three permanent research stations in Antarctica. This paper addresses efforts by Indian scientists in last five years in cryospheric studies on the Antarctica using remote sensing data. Inventories of Antarctic glaciers and ice sheet features prepared by Indian researchers have facilitated for detailed long-term studies on glacier dynamics, sea ice, fluctuations of the continental ice margin and snouts of glaciers. For safe and optimal navigation of ships, a sea ice advisory has been also set up. This paper also addresses recent efforts of using high-resolution earth observation satellite data which were acquired for geospatial mapping of cryospheric features and glacial landforms and for delineation of wind induced snow deposition zones in part of the Antarctica. Spatiotemporal dynamics of surface melting over Antarctic was further studied by using moderate resolution satellite data.

Keywords: Glaciers; Ice Sheet Features; Remote Sensing; Cryospheric Features

Introduction

After the oceans, the cryosphere is the second largest component of the climate system that holds around 69% of the global freshwater resource (Shiklomanov, 1993). Various components of the cryosphere (snow, lake ice, sea ice, glaciers, ice caps, ice shelves and ice sheets) contribute to short-term climate changes, whereas the ice shelves and ice sheets also contribute to long-term changes including the ice age cycles. Thus, monitoring the changes in the cryosphere regions is very essential. Antarctic region plays an important role in the global climate change. Indian researchers have been carrying out observations on major components of the global cryosphere in the Himalayas, Antarctic and Arctic regions. Ice sheets are the greatest potential source of global freshwater ice, holding approximately 99% of the global total. This corresponds to 64 m of world sea-level equivalent, with Antarctica accounting for 90% of this rise. This paper highlights the studies carried out by Indian scientists using high – resolution optical well as microwave data in Antarctic region only during last 5 years.

This paper is organised as follows: In Section 2, application of satellite based remote sensing techniques by ISRO and ESSO-NCAOR on Antarctic studies is described. Our conclusions are given in Section 3.

Satellite-based Remote Sensing for Antarctic Studies

With high-resolution sensors on-board and high revisiting capability over the Polar Regions, the Polar orbiting satellites are best suited for Antarctic studies. Currently, three major Indian institutions involved in utilizing the satellite data for Antarctic surface and subsurface data analysis are (i) ESSO-National Centre for Antarctic and Ocean Research (ESSO-NCAOR), (ii) Geological Survey of India (GSI), and (iii) Indian Space Research Organisation (ISRO). Some of the salient outcomes of the studies carried out by ISRO are as follows:

Ship Navigation Advisory Efforts

Sea Ice advisory and utilization of RISAT-1 and

*Author for Correspondence: E-mail: senthil@iirs.gov.in

SARAL AltiKa derived free-board Climatic Sea Ice Occurrence Probability (SIOP) and sea ice type data has been operationalized for safer ship navigation by ISRO, Ahmedabad (Maheshwari *et al*., 2015; Rajak *et al*., 2014; Rajak *et al*., 2015). Results of these studies can be visualised on the website (SAC, 2015). The major highlights in this web portal are sea ice advisory and RISAT-1 CRS based 36m mosaic for Antarctic region.

Indian satellite RISAT-1 C-band imagery was used for geospatial mapping of cryospheric surface features in the Antarctic environment (Jawak *et al*., 2015a). Geospatial mapping of vegetation in the Antarctic environment using very high resolution WorldView-2 data was also done by Indian researchers (Jawak and Luis, 2014). Mapping of shoreline of more than 100 lakes on Larsemann hills and 10 lakes on Schirmacher Oasis with an accuracy of 1 meter, as a reference data for validation of algorithms for semi-automatic extraction of lake features using satellite data was completed (Jawak and Luis, 2014; Jawak *et al*., 2015b; Jawak *et al*., 2015c). Ice calving and deformation from ice margins and spatio-temporal change detection were detected using RISAT-1 SAR data. Large scale disintegration was reported at two prominent glacier tongues namely Polar Record Glacier and Polar Times Glacier. The results were verified by observations made during 33rd Indian Scientific Expedition to Antarctica (ISEA).

High-Resolution Satellite Data Applications

ESSO-NCAOR has produced the first operational digital elevation models (DEMs) for Larsemann Hills and Schirmacher Oasis, East Antarctica, using interferometric and photogrammetric techniques. To improve the DEM quality further, a precise DEM was generated by interactive synthesis of multi-temporal elevation datasets. Due to improved vertical accuracy compared to existing Antarctic DEMs, these indigenous DEMs have gained a significant attention (Jawak and Luis, 2014). An enhanced digital elevation model (DEM) of the Larsemann Hills region, east Antarctica, is constructed synergistically by using highly accurate ground-based GPS measurements, satellite-derived laser altimetry (GLAS/ICESat) and Radarsat Antarctic Mapping Project (RAMPv2) DEM-based point elevation dataset. This DEM has a vertical accuracy of about 1.5 times better than RAMPv2 DEM and seven times better than GLAS/ICESAT-based DEM. The accuracy was improved by validating the RAMPv2 DEM elevation by supplementing with GLAS/ICESat and DGPS survey data, when compared to that of DEM constructed by using GLAS/ICESat or RAMPv2 alone. With the use of accurate GPS data as ground control points based reference elevations, the DEM extracted is much more accurate with least mean Root Mean Square Error (RMSE) of 34.5 m than that constructed by using a combination of GLAS/ICESat and RAMPv2 as true reference. The newly constructed DEM achieves highest accuracy with the least average elevation difference of 0.27 m calculated using 46 ground reference points. Available DEMs of Antarctic region generated by using radar altimetry and the Antarctic digital database indicate elevation variations in the range of 50-100 m, which necessitates the generation of local DEM and its validation by using ground truth. This was first attempt of fusing multi-temporal, multi-sensor and multi-source elevation data to generate a DEM of any part of Antarctica, in order to address the ice elevation change to infer the ice mass balance. This hybrid approach focuses on the strengths of each elevation data source to produce an accurate DEM (Jawak and Luis, 2014).

Recently, a study has been done by ISRO, Dehradun to identify and map the various ice sheet features and glacier landform in part of Antarctic using high resolution optical Cartosat-2 (resolution~1m) and RISAT-1 FRS1 (resolution~3m) datasets (Kumar *et al*., 2015). This work was done for Princess Astrid area of the coast of Queen Maud Land lying between 5° and 20° E. The study has used CARTOSAT-2 and Landsat optical datasets for its analysis and mapping. A total of 264 CARTOSAT-2 scenes from time period of December 2014 and February 2015 were acquired from ISRO in geotiff format in transverse Mercator projection on user request from 2014-15 Indian Antarctic expedition by scientists of the ESSO-NCAOR, Goa under the Ministry of Earth Sciences (MoES). All datasets were ortho-rectified with Aster GDEM (30m) in polar stereo graphic projections systems taken from Landsat 8 datasets. In first part of this work an image album has been made highlighting some of the major ice sheet features and glacier landforms present at Antarctica using ISRO's high resolution satellite CARTOSAT-2. In second part, RISAT-1 FRS1 and some MRS data has been used

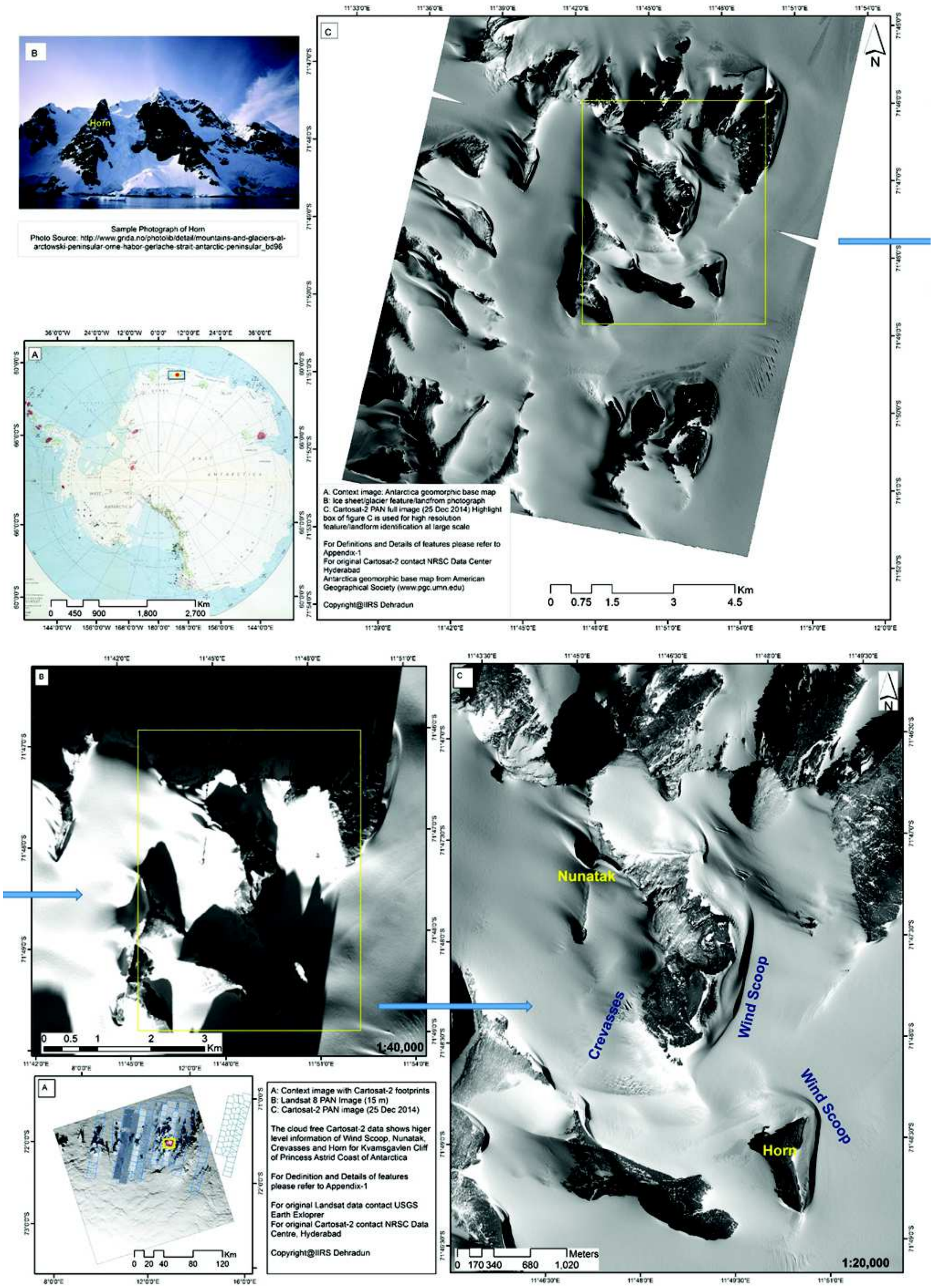


Fig. 1: Identified ice sheet features and glacier landforms in study area example from Antarctica image album showing one full map set (full cartosat-2 image and highlighted part)

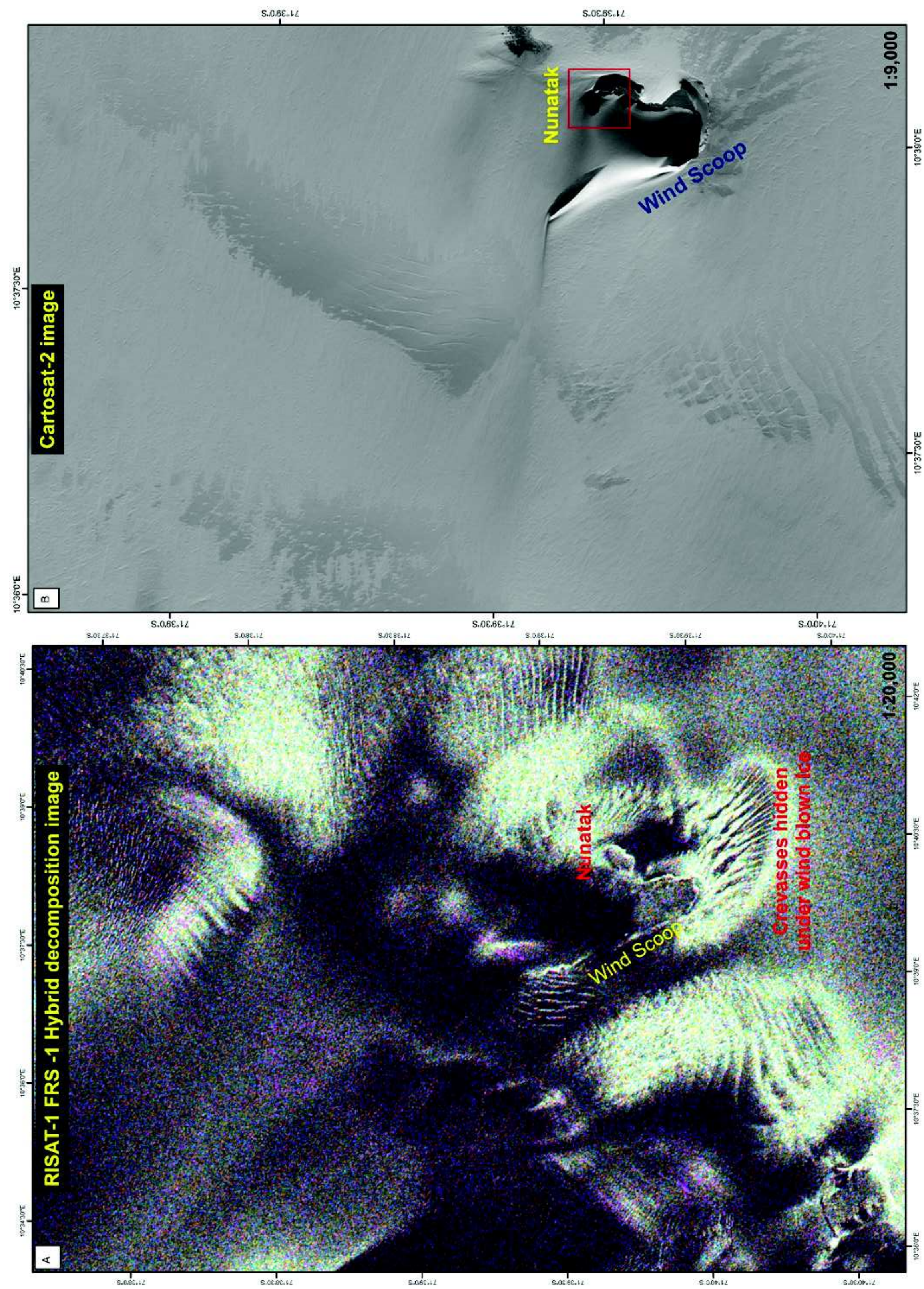

B
Cartosat-2 image
Nunatak
Wind Scoop
1:9,000
A
RISAT-1 FRS -1 Hybrid decomposition image
Nunatak
Wind Scoop
Crevasses hidden under wind blown ice
1:20,000

Fig. 2: A

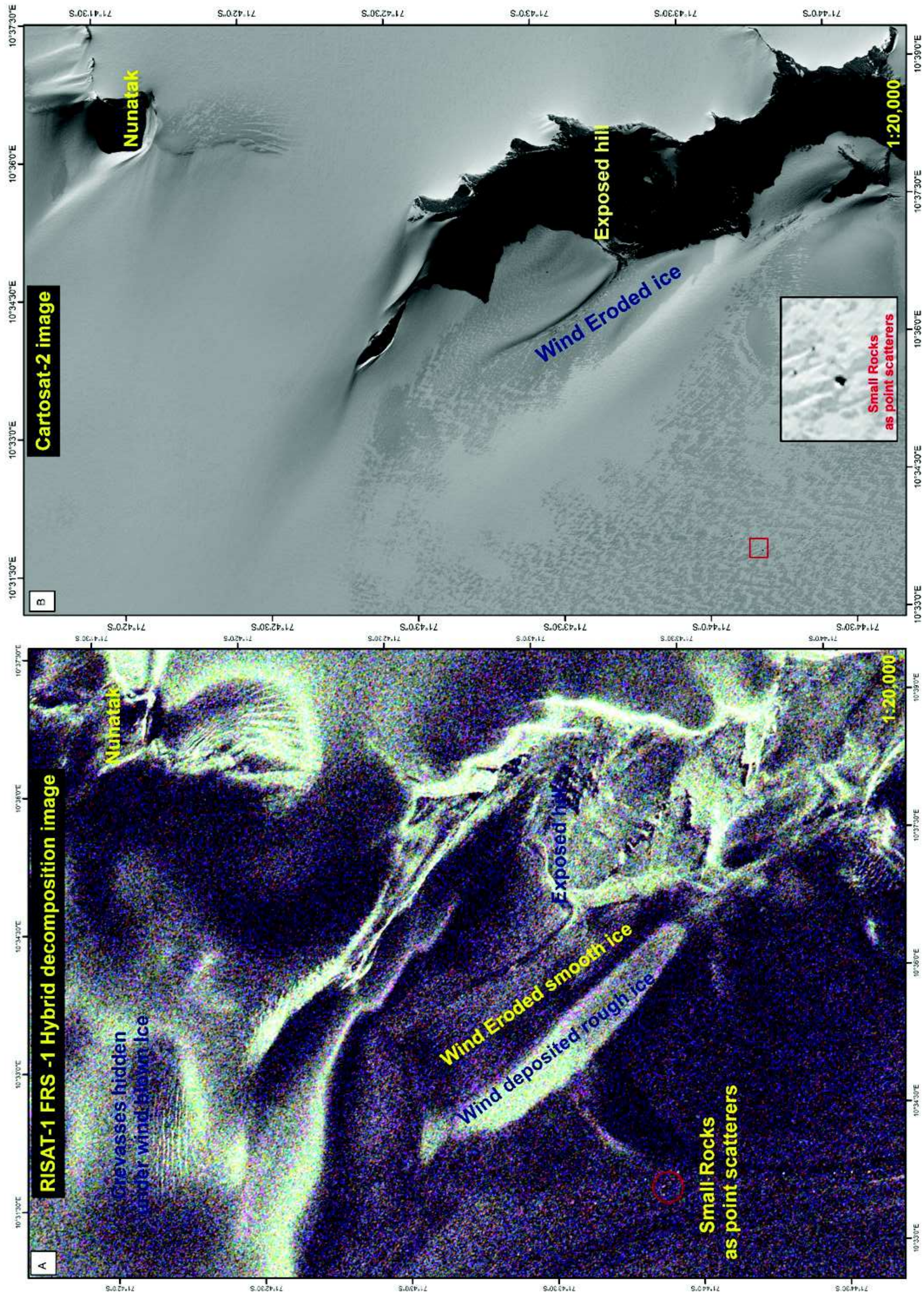
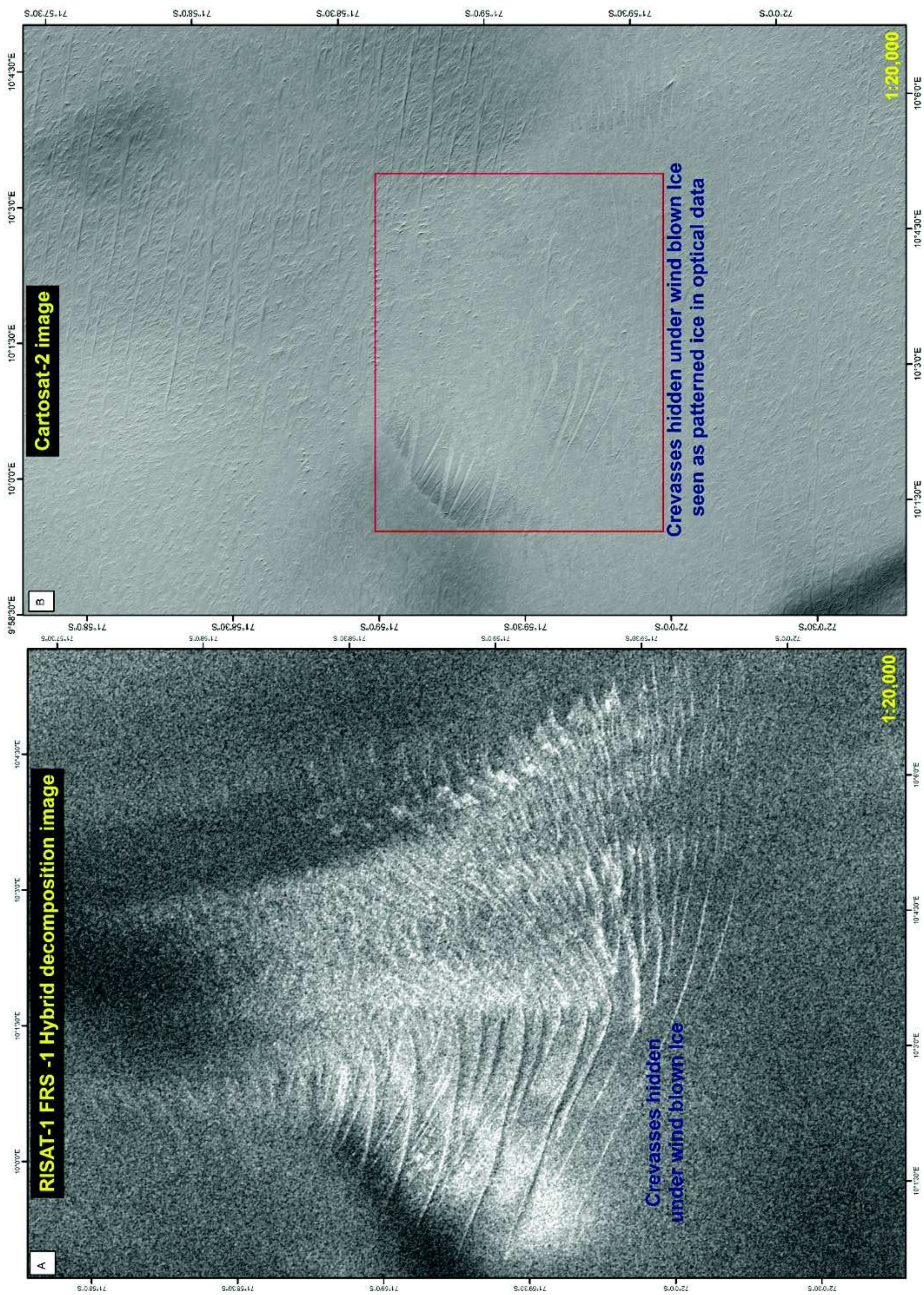

Cartosat-2 image
Nunatak
Exposed hill
Wind Eroded ice
Small Rocks
as point scatterers
1:20,000
B
RISAT-1 FRS -1 Hybrid decomposition image
Nunatak
Exposed hill
Wind Eroded smooth ice
Wind deposited rough ice
Small Rocks
as point scatterers
1:20,000
A

Fig. 2: B



B
Cartosat-2 image
Crevasses hidden under wind blown ice
seen as patterned ice in optical data
1:20,000
A
RISAT-1 FRS -1 Hybrid decomposition image
Crevasses hidden
under wind blown ice
1:20,000

Fig. 2: C

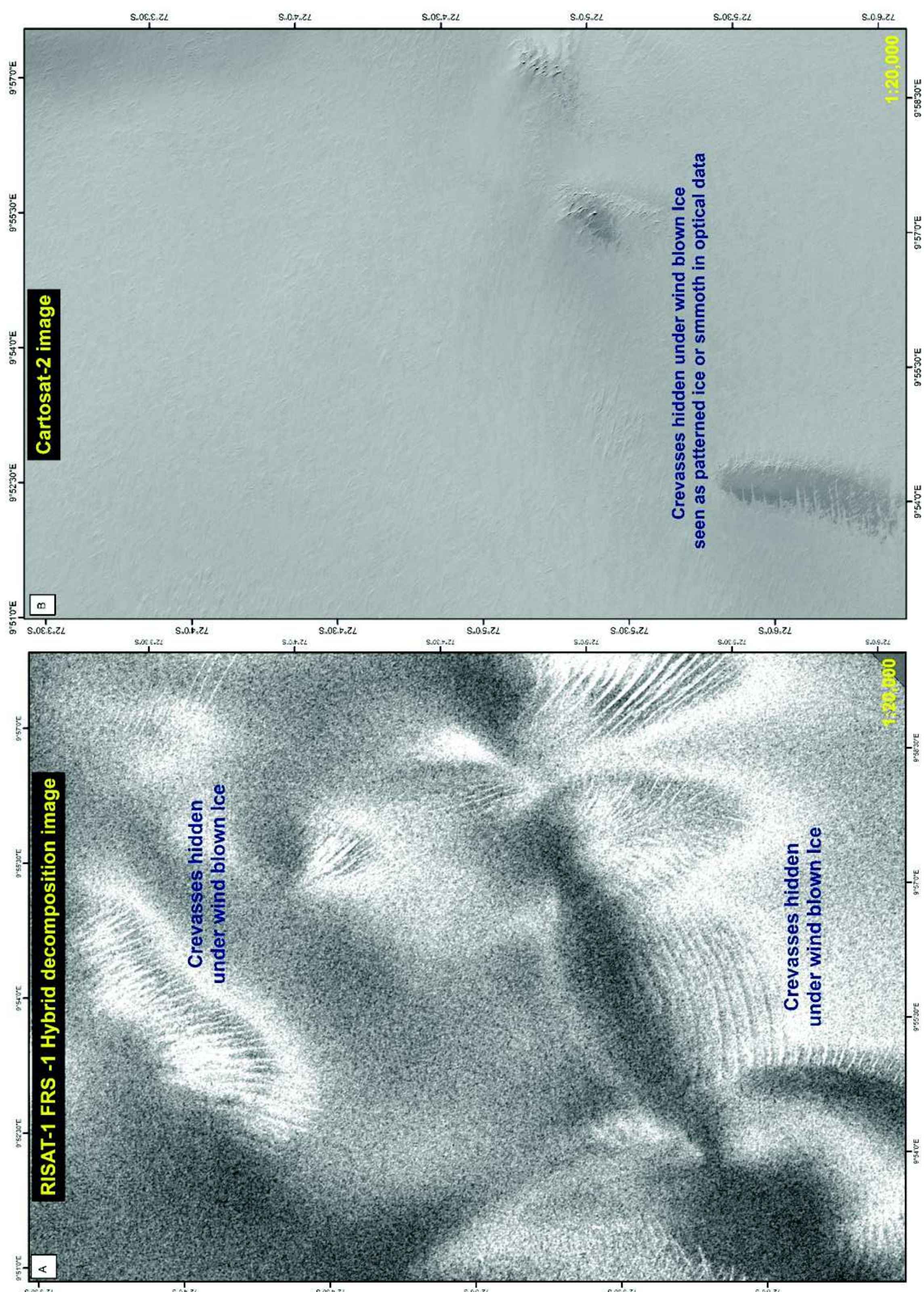


Fig. 2: D

Fig. 2: (A-D): Comparison of ice sheet feature identified using RISAT-1 FRS-1 (3m) and CARTOSAT-2 (< 1m) high resolution satellite for common areas near Princess Astrid coast, Antarctica

to identify additional ice sheet and glacier features which were not detected by optical data (Thakur *et al*., 2016). The CARTOSAT-2 high resolution images were used to identify and map some of the unique ice sheet and glacier features such as crevasses, sastrugi, nunatak, ice ridges, wind scoops, rim lines, moraines, blue ice area (BIA) and deposited snow (Fig. 1). Quantification of geomorphic parameters such as size, shape, length, area were carried out using orthorectified CARTOSAT-2 and RISAT-1 FRS1 images.

In addition, some of the ice sheet features such as crevasses and sastrugi, which are not clearly visible in optical sensor data due to wind induced snow deposition, are clearly visible in RISAT-1, FRS1 data. Mapping of such features deposited under snow is feasible only in SAR datasets due to penetration capability of C-band SAR in dry snow packs (Fig. 2A-D). Spatio-temporal changes in these features due to wind and glacier movement is quantified by utilizing time series of cloud free orthorectified Landsat 8 Images. Support Vector Machine (SVM) based supervised classification techniques have been used with Landsat-8 datasets of year 2013 and 2014 for mapping some of these features and overall classification has given satisfactory results of the mapped features with overall accuracy of 91 to 94%. Further, to quantify and understand wind dynamics, wind speed and direction vector mapping was done using 10 km resolution Antarctic Mesoscale Prediction System (AMPS) datasets for the selected areas during the period of May 2013 to June 2015 on daily to monthly mean basis. These winds maps are generated to analyse the movement of winds with reference to erosional and depositional processes in the selected areas. The above study and analysis has explained the process of erosion and deposition by the wind with reference to its movement and velocity. Wind speed in this area is very high, ranging from 9.14 to 16.72 m/s. Mountainous barriers and Nunatak creates the katabatic winds that generate the huge wind scoops approximately 15m wide around Nunataks. Also the longitudinal glacier flow-strips are mapped from CARTOSAT-2 image and RISAT-1 data between the area of Wohlthat Mountains and Orvin Mountains of East Antarctica. Mapping of the flow lines of the Glaciers between the above mountains was generated to study the pattern of glacier flow lines for Somovken glacier and its flow directions with respect to its depositional and erosional processes.

Additionally, Jawak and Luis (2014) evaluated the potential of 8-band high resolutionWorldView-2 (WV-2) panchromatic (PAN) and multispectral image (MSI) data for the extraction of polar geospatial information. In this study, they introduced a novel method based on a customized set of normalized difference Spectral Index Ratios (SIRs), incorporating multiple bands, to improve the accuracy of land-cover mapping. Most recently available WV-2 data are classified into land-cover surfaces such as snow/ice, water bodies, and landmass using the customized normalized difference SIRs. Jawak *et al*. (2015d) also reviewed various methods for deriving bathymetry information using remote sensing technologies.

Indian scientists have extensively used remote sensing techniques to complement the ground surveys and Geographical Information Systems (GIS) to study the physiography, mass balance of glaciers and other polar studies. ISRO used over forty scenes of NOAA AVHRR data in two formats, local area coverage (LAC) and SCRIPPS to construct a 1km three-band Antarctic mosaic in year 2009 (NRSC, 2015). This paper demonstrates the strengths of Indian researchers to extract and study various information about Antarctic region.

The Ice Sheet Dynamics around Dakshin Gangotri Glacier, Schirmacher Oasis, East Antarctica was studied by Shrivastava *et al*. (2011). Recession of the snout of Dakshin Gangotri glacier in the western part of Schirmacher Oasis, East Antarctica has been recorded over two decades. The notable difference in the rate of recession in different parts of the Dakshin Gangotri glacier overriding Schirmacher Oasis can be attributed to combined effect of natural factors, including meteorological parameters, ice sheet dynamics and geomorphology of that area. Global positioning system (GPS) campaigns were conducted during summer seasons to obtain insight into the velocity and strain-rate distribution on Schirmacher Glacier, central Dronning Maud Land, East Antarctica. GPS data were collected at 21 sites and analysed to estimate the site coordinates, baselines and velocities (Sunil *et al*., 2007). The velocity and strain-rate distributions across the GPS network in Schirmacher Glacier were spatially correlated with topography, subsurface undulations, fracture zones/crevasses and the partial blockage of the flow by Nunataks and the Schirmacher Oasis (Fig. 3).

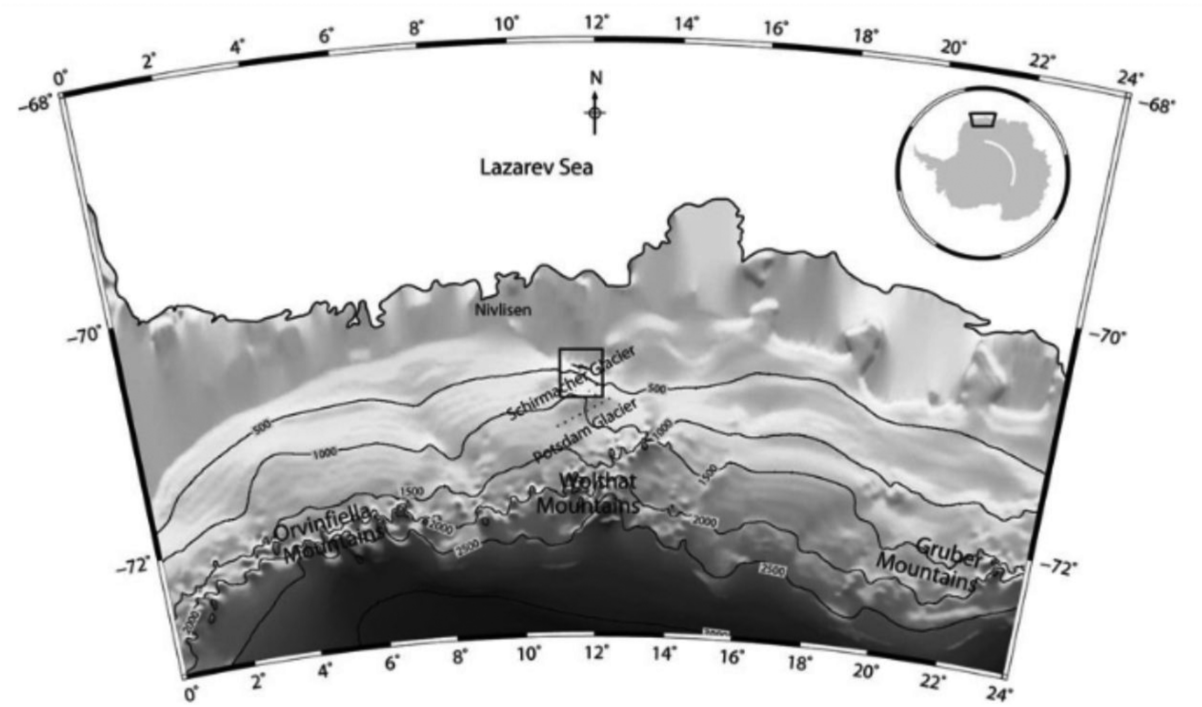


Fig. 3: Location map of central Dronning Maud Land, East Antarctica, showing the study area of Schirmacher Glacier (rectangle) superimposed on a shaded relief map of GTOPO30 digital elevation model with 500m elevation contour interval. Sunil *et al*. (2007)

During Indian Antarctic Expeditions, monitoring of iceberg is an important programme of GSI since very beginning (GSI, 2015). Iceberg monitoring in the Antarctic waters done by Asthana *et al*. (2013) during onward voyage of 24th Indian Antarctica Expedition has revealed concentration of icebergs in two well defined zones separated by an iceberg free zone. They found large variations in the size and shape of the icebergs. They also observed a continuous shift of icebergs position in north-east direction between 50°S to 54°S latitudes and can be related with the Sub-Antarctic front (SAF) and Antarctic Circumpolar Current (ACC).

Melt-Freeze Study of Antarctic using Moderate Resolution Satellite Data

Scientists from ISRO, Ahmedabad and Hyderabad studied the spatiotemporal dynamics of surface melting over Antarctica and developed a methodology to detect and monitor snowmelt and freeze from microwave scatterometer data as this is of importance in understanding the response of ice shelves to climate change (Oza *et al*., 2011; Bothale *et al*., 2015). The association of scatterometer backscatter observations with the snow-pit observations helped in the investigation of inter-annual variations in surface melting was first carried out using space-borne scatterometer data (Oza *et al*., 2011). In next study, K_u band scatterometer based normalised radar backscatter was used, which is sensitive to the water content of snow. In this study, QuikSCAT and OSCAT Enhance Resolution Image data available at, http://www.scp.byu.edu/, in slice mode at 2.225 km resolution were studied. All passes of HH resolution data has been used in the study. Analysis has been done for data from 2001 to 2014. Both the sensors provide daily data for Polar Regions in 13.6GHz. The crossing time for QuikSCAT is 10:30 AM for descending and 10:30PM for ascending pass. Similarly the crossing time for descending pass of OSCAT is 11:30AM and 11:30PM for ascending pass. With the increase in the liquid water content in the snow, there is a sudden decrease in the backscatter from radar. This was used as the basis of melt detection. An adaptive threshold based classification using austral winter mean and standard deviation of HH polarization radar backscatter data is considered. Spatiotemporal dynamics of snow melt in Antarctica from 2001 to 2014 using microwave scatterometer data from OSCAT and QuikSCAT is generated at 2.25 km resolution at daily interval, and derived snow melt and freeze maps. The high correlation between melt duration, obtained from satellite data and the Positive Degree day (PDD) calculated with in-situ data from Automatic Weather Stations at Antarctica, validates the efficacy of the melt algorithm used in the analysis and sensitivity of scatterometer data in detecting presence of water due to melt (Bothale *et al*., 2015).

Conclusions

With the growing concern about the global climate change and its impact, study of the physical and environmental parameters in Polar Regions has become crucial. The Indian Antarctic programme has been established for long-term monitoring of Antarctic glaciers and ice sheet features by establishing 3 stations with advanced facilities. This program is strongly supported by remote sensing community in India. Some of the recent studies carried out with very-high-resolution optical and microwave sensor data depict their potential in identifying and mapping many unique ice sheet and glacier features.

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References

Asthana R, Shrivastava P K, Beg M J and Ramar R (2013) Monitoring of icebergs in Antarctic waters during the 24th Indian Antarctica Expedition *Tech pub* **22** MoES, pp 265-271

Bothale R V, Rao P V N, Dutt C B S, Dadhwal V K and Maurya D (2015) Spatio-temporal dynamics of surface melting over Antarctica using OSCAT and QuikSCAT scatterometer data (2001-2014) *Current Science* **109** 25

GSI (2015) Geological survey of India http://www.portal.gsi.gov.in/, links therein. Accessed in December 2015

Jawak S D and Luis A J (2014) A semiautomatic extraction of Antarctic lake features using WorldView-2 imagery *Photogrammetric Engineering & Remote Sensing* **80** 939-952, DOI: 10.14358/PERS.80.10939

Jawak S D, Bidawe T G and Luis A J (2015a) A review on applications of imaging synthetic aperture radar with a special focus on cryospheric studies *Advances in Remote Sensing* **4** 163-175

Jawak S D, Devliyal P and Luis A J (2015b) A comprehensive review on pixel oriented and object oriented methods for information extraction from remotely sensed satellite images with a special emphasis on cryospheric applications *Advances in Remote Sensing* **4** 177-195

Jawak S D, Vadlamani S and Luis A J (2015c) A synoptic review on deriving bathymetry information using remote sensing technologies: Models, methods and comparisons *Advances in Remote Sensing* **4** 147-162

Jawak S D, Kulkarni K and Luis A J (2015d) A review on extraction of lakes from remotely sensed optical satellite data with a special focus on cryospheric lakes *Advances in Remote Sensing* **4** 196-213

Kumar A S, Thakur P K, Aggarwal S P, Dixit A, Dadhwal V K, Nagaraja R, Aparna N and Ratnakumar K V (2015) Glimpse of Antarctica Ice sheet features and glacier landforms - As viewed by Cartosat-2. Image album published by Indian Institute of Remote Sensing (IIRS), Dehradun and National Remote Sensing Centre (NRSC), Hyderabad, 54

Maheshwari M, Mahesh C, Singh R K K, Jayaprasad P, Rajak D R, Oza S R, Kumar R and Sharma R (2015) Estimation of sea ice freeboard from SARAL/AltiKa data *Marine Geodesy* **38** 487-496

NRSC (2015) Spatio-temporal dynamics of surface melting over Antarctica using scatterometer data, internal report by Bothale and Rao, NRSC-ECSA-ACSG-NOV-2015-TR-769, 13p

Oza S R, Singh R K K, Vyas N K and Sarkar A (2011) Study of Inter-annual variations in surface melting over Amery Ice Shelf, East Antarctica, using space-borne scatterometer data *J Earth Syst Sci* **120** 329-336

Rajak D R, Singh R K K, Maheshwari M, Jayaprasad P, Oza S R, Beg M J, Sharma R and Kumar R (2014) Sea ice advisory using Earth observation data for ship routing during Antarctic expedition. Scientific Report, Space Applications Centre (ISRO), Ahmedabad, India. Doi: 10.13140/ RG.2.1.5073.8725

Rajak D R, Singh R K K, Jayaprasad P, Oza S R, Sharma R and Kumar R (2015) Sea ice occurrence probability data and its applications over the Antarctic *J Geomatics* **9** 193-197

SAC (2015) Space Application Centre.http://www.sac.gov.in/ Vyom/index.jsp/, links therein. Accessed on December 22, 2015

Shiklomanov I A (1993) World Fresh Water Resources, in Gleick H P (Ed): Water in Crisis: A Guide to World's Water Resources, New York: Oxford University Press, 473 pages

Shrivastava P K, Asthana R and Roy S K (2011) The Ice Sheet Dynamics around Dakshin Gangotri Glacier, Schirmacher Oasis, East Antarctica *vis-a-vis* Topography and Meteorological Parameters *Journal of Geological Society of India* **78** August 2011

Sunil P S, Reddy C D, Ponraj M, Dhar A and Jayapaul D (2007) GPS determination of the velocity and strain rate field on Schirmacher Glacier, central Dronning Maud Land, Antarctica *Journal of Glaciology* **53** pp 558-564

Thakur P K, Dixit A, Chouksey A, Aggarwal S P and Kumar A S (2016) Ice sheet features identification, glacier velocity estimation and glacier zones classification using high resolution optical and SAR data *Proc SPIE 9877, Land Surface and Cryosphere Remote Sensing III*, 987719 (5 May 2016), doi: 10.1117/12.2224027.

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Research Paper

Advances in Antarctic Sea Ice Studies in India

SANDIP R OZA[1], D R RAJAK[1], MIHIR K DASH[2], I M BAHUGUNA[1,*] and RAJ KUMAR[1]
[1]*Space Applications Centre, Ahmedabad 380 025, India*
[2]*Indian Institute of Technology Kharagpur, Kharagpur 721 302, India*

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Sea ice cover plays a key role in regulating the Earth's climate by influencing the global atmospheric and oceanic circulation through various feedback mechanisms. The only viable source for the continuous monitoring of sea ice cover, its variability and characterization in the vast and remote polr region is the utilization of data acquired by orbiting satellites supported by Ship based observations. India has been contributing significantly in the development of techniques for extraction of sea ice from state-of-art Indian sensors and other international missions. Significant progress has been made towards understanding sea ice variability in the Antarctic region. Based on various studies in polar regions, it has been observed that during last few decades, Arctic is showing the consistent decline of summer sea ice cover, in contrast to Antarctica which is showing regional anomalies with positive and negative trends. Role of sea ice concentration in Indian monsoon has also been examined. Relation of El Nino Southern Oscillation (ENSO) and sea ice extents have been studied. A climatic dataset of Sea Ice Occurrence Probability (SIOP) generated for the Antarctic region was used to compare the climatic sea ice growth and melt patterns in the eastern and the western regions of the Antarctic.This paper reviews the recent contributions mainly by Indian scientists in the studies of sea ice with inclusion of a few international scientific contributions.

Keywords: Antarctic; Sea Ice; Remote Sensing; Microwave Radiometer; Scatterometer; SAR

Introduction

Antarctic and Southern Ocean science is vital to understand natural climate variability, the processes that govern global change and the role of humans in the Earth and climate system (Kennicut II *et al*., 2015). Sea ice is an integral part of polar ocean-climate system. Sea ice dynamics and thermodynamics play an important role in the polar climate, which in turn influences the global oceanic and atmospheric circulation. The extent of global sea ice cover over the polar regions varies between 16.6×10^6 and 27.5×10^6 km^2 at any given time, which corresponds to around 3–6% of the earth's total surface area (Comiso, 2010). For instance, while the Arctic Ocean shows a 2-2.5 times increase in its sea ice cover from summer to winter, the Antarctic shows a five- to six-fold increase (Zwally *et al*. 1983; Gloersen *et al*. 1993, Simmonds, 2015). Monitoring of fluctuations of the Antarctic sea ice indicate an increase of about 2.4 % per decade. (Nayak, 2008). More specifically, Satellite passive-microwave data for the period November 1978-December 2010 reveal an overall positive trend in the ice extents of 17 100$\pm$2300 km^2/year (Parkinson and Cavalieri, 2012). Such changes are primarily driven by the seasonal variation in atmospheric and oceanic conditions. The only viable source for the continuous monitoring of sea ice over the vast and remote polar region is the utilization of satellite remote sensing data.

In the past one decade India has contributed significantly to an increased understanding of the ice variability around Antarctica using space-borne data. Availability of data from Indian sensors like MSMR Multi Scanning Microwave Radiometer (launched on 26 May 1999 onboard OceanSat-1), OSCAT Ku band pencil beam Scaterrometer (launched on 23 September 2009 onboard OceanSat-2) and SCATSAT Ku band pencil beam Scaterrometer (launched on 26 September 2016 onboard SCATSAT-1) have made it possible to contribute in the understanding of Sea Ice extents and variability in the Northern and

*Author for Correspondence: E-mail: imbahuguna@sac.isro.gov.in

Southern polar regions. This paper presents an overview of the country's contribution specially in Antarctic sea ice studies.

Development of Techniques for Sea Ice Characterization

Teleti and Luis (2013) have extensively discussed the evolution of remote sensing sensors technologies with emphasis on their suitability for observing the polar regions. The study of the extents of sea ice and its variability on a seasonal to longer timescale necessitates global earth observation systems with high temporal coverage. However, such systems compromise on the spatial resolution. Nonetheless, sensors orbiting the earth have been one of the main sources of data collection on the sea ice extent and its spatial and temporal variability. An initial attempt to characterize the sea ice over Antarctica was made by Indian scientists utilising MSMR data onboard Oceansat-1 (Bhandari *et al*., 2005; Bhandari and Khare, 2009; Dash *et al*., 2001; Vyas *et al*., 2003). An atlas of sea ice cover over Antarctica (Fig. 1) is a key outcome of the studies made by Vyas *et al*. (2004).

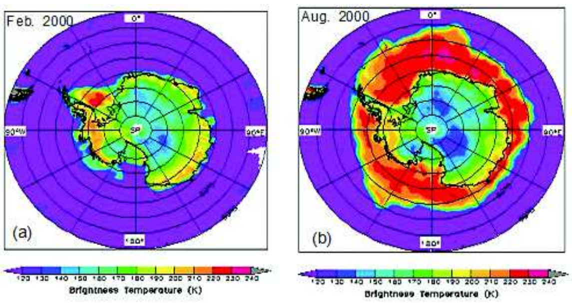

Fig. 1: Antarctic sea ice cover derived from Oceansat-1 MSMR 18 GHz brightness temperature data; (a) summer sea ice cover and (b) winter sea ice cover

Subsequent studies on sea ice detection has come from the use of OSCAT Scaterrometer data onboard Oceansat-2 (Oza *et al*., 2011a). Discrimination between sea-ice and ocean is ambiguous in the Scaterrometer observations under the high wind and/ or thin/scattered ice conditions. Oza *et al*. (2011b) developed an algorithm to distinguish ocean winds from the sea ice in both the hemispheres using spatio-temporal coherence techniques, in addition to backscatter coefficient and the Active Polarization Ratio (API). These authors found that the threshold API value of –0.025 was optimum for sea-ice and ocean discrimination. They compared their results with the operational sea-ice products and found that overall sea-ice identification accuracy achieved was of the order of 95 per cent, ranging from 92.5% (during December in the Southern Hemisphere) to 98% (during March in the Northern Hemisphere). This algorithm was used to mask the sea ice area in operational ocean wind product using OSCAT data.

Singh *et al*. (2015) have synergistically utilized the Ka-band SARAL AltiKa data along with Ku-band OSCAT Scaterrometer data to improve the sea ice discrimination from other ice and ocean features.

After discrimination of sea ice from satellite images, further classification of sea ice is required for many purposes which also includes ice routing to serve Ship navigation. Zhu *et al*. (2016) have used Radarsat-2 dual-polarization satellite images to develop an algorithm to classify Antarctic sea ice based on conditional Random Fields (CRF) approach by including multiple features from sea-ice concentration, gray-level co-occurrence matrix textures, polarization ratio, backscatter coefficients and intensity data.

Detection of sea Ice floes in polar region has been demonstrated by use of RISAT-1 SAR data (Srisudha *et al*., 2013). This detection is useful for the analysis of ice floes size distribution which has implications in ice motion dynamics and polar species habitat in the sea ice zone.

Worby and Cosimo (2004) have validated the Passive microwave derived ice edge locations in the Antarctic using in situ observations from ships between 1989 and 2000 (Worby and Cosimo, 2004). They reported the better correlation during growth season compared to that observed during melt season, which could be due to low concentration and saturated nature of ice.

Besides ice cover or extent, ice thickness is much more important parameter which needs to be retrieved from satellite data. Towards the development of a technique for the estimation of sea ice thickness, studies have been carried out by Singh *et al*. (2011) for thin sea ice using 89 GHz AMSRE brightness temperature data and by Maheshwari *et al*. (2015) for the estimation of sea ice freeboard using data from AltiKa altimeter launched by India in SARAL mission.

These techniques have been developed for the Arctic and needs validation for their use in the Southern polar region as well.

Antarctic sea ice thickness has also been retrieved by using Ice Cloud and land Elevation satellite (ICEsat) elevation measurements to retrieve sea-ice (with snow cover) freeboard in the Weddell Sea Antarctica (Kern and Spreen, 2015). They have also discussed the uncertainties involved in measurements.

It is worth mentioning here, that ship-based observations have been used to describe regional and seasonal changes in the thickness distribution and characteristics of sea ice and snow cover thickness around Antarctica (Worby *et al*., 2008). Their data set comprises 23,373 observations collected over more than two decades of activity and has been compiled as part of the Scientific Committee on Antarctic Research (SCAR) Antarctic Sea Ice Processes and Climate program (ASPeCt). The results show seasonal progression of the ice thickness, surface ridging, snow cover and local variability for each region and season. The long-term mean and standard deviation of the total sea ice thickness (including ridges) is reported as 0.87+0.91m, which is 40% greater than the mean level ice thickness of 0.62m.

One of the important contribution in the understanding of sea ice are the Sea Ice temperature products produced from Earth Observation System (EOS) Moderate Resolution Imaging Spectroradiometer (MODIS) onboard both the Terra and Aqua satellites (Hall *et al*., 2004). Daily sea ice extent and ice surface temperature (IST) products are available at 1- and 4-km. resolution.

Sea Ice Modelling and Trend Analysis

Sea Ice Modelling

Rana *et al*. (2011) introduced an image processing-based model called active contour model (also known as Snake model) and non-rigid motion estimation techniques to predict sea ice edge in the Antarctic. Recently Deb *et al*. (2016) have used state-of-art Ocean General Circulation Model known as Nucleus for European Modelling of the Ocean (NEMO) coupled with Louvain-la-Neuve Sea Ice Model, version 2 (LIM2) to study the impact of dynamical Southern Annular Mode forcing to a non-annular response in sea ice cover over the Indian Sector of the Southern Ocean.

Long-term Analysis

Trend Analysis: Sreenivasan and Mujumdar (2006) have used SSM/I passive microwave data, to map sea ice around Antarctica during its depletion phase (November 2001 to January 2002).

In another study by Rai and Pandey (2006), Antarctic sea ice edge variability in recent years and its relationship with Indian ocean sea surface temperature based on 23 years of satellite passive microwave observations (1982-2004). Sea ice edge anomaly averaged around Antarctica shows nearly zero trend in the time domain.

Scaterrometer based studies of sea ice variability suggest significant decline of summer (September) sea ice in the Arctic, whereas the Antarctic sea ice shows strong positive trend in the Ross sea sector and statistically significant negative trend in Amundsen and Bellingshausen seas (ABS) sector (Fig. 2). As

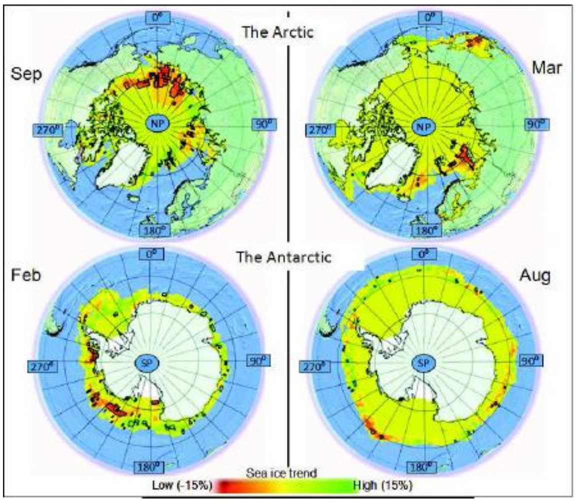

Fig. 2: Summer minimum and winter maximum sea ice trends (1) Chukchi, (2) Okhotsk, (3) East Siberian, (4) Laptev, (5) Barents, (6) East Greenland, (7) Weddell, (8) Indian Ocean sector, (9) Ross (10) Amundsen, (11) Bellingshausen (Oza *et al*., 2012)

observed in Fig. 3, the pattern of scaterrometer-derived observations closely follows the pattern of passive microwave based observations, which is indicative of the validity of the scaterrometer derived estimates.

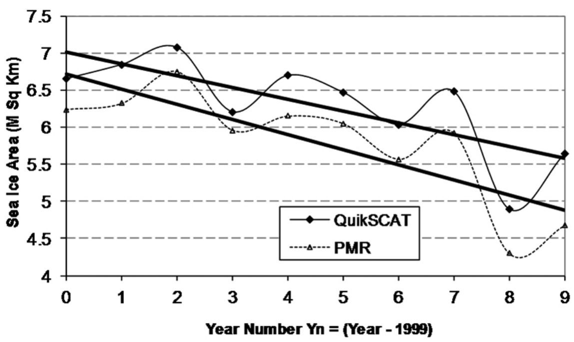

Fig. 3: Comparison of Scaterrometer derived sea ice trend with the passive microwave radiometer (PMR) based estimates obtained from www.nsidc.org

Detailed investigation of these trends and regional anomalies have been discussed in various research publications (Oza *et al*., 2010; 2011a, 2012). Monthly trend analysis data is available on the web portal (vedas.sac.gov.in) of Visualisation of Earth Observation Data and Archival System (VEDAS) of the Space Applications Centre (SAC).

Studies based on observations from passive microwave radiometers by Prabhu *et al*. (2011) showed that the sea ice cover in the ABS (Amundsen and Bellingshausen Seas) sector exhibit a strong decreasing trend. This could possibly be due to the increasing SST trends in this sector and decreasing trends in the Ross Sea sector (Maheshwari *et al*., 2013).

Climatic dataset of Sea Ice Occurrence Probability (SIOP) : A climatic dataset of Sea Ice Occurrence Probability (SIOP) generated for the Antarctic region was used to compare the climatic sea ice growth and melt patterns in the eastern and the western regions of the Antarctic (Rajak *et al*. 2015). The SIOP product developed from a long-term (1978-2012) passive microwave daily-averaged Sea Ice Concentration (SIC) gives the probability of sea ice occurrence for each date from January 1 through December 31. Two of the demonstrated potential applications of this dataset are (i) generation of sea ice majority mask, and (ii) assessment of the climatic intra-seasonal SIOP growth and decay gradients over the eastern and western regions of the Antarctic.

Analysis of the temporal gradients of SIOP growth (indicative of sea ice refreezing rate) and decay (indicative of sea ice melting rate) indicated different rates of sea ice growth and refreezing over the eastern and western parts (Rajak *et al*., 2015). It was also observed that while the sea ice decay gradient is higher compared to growth gradient in the east Antarctic region; the growth gradient is higher than the decay gradient in the western region. It indicates faster melting than refreezing in the east Antarctic while faster refreezing than melting in the west Antarctic. SIOP Data set is available on the mosdac.gov.in and vedas.sac.gov.in web portals; e.g. see Fig. 4.

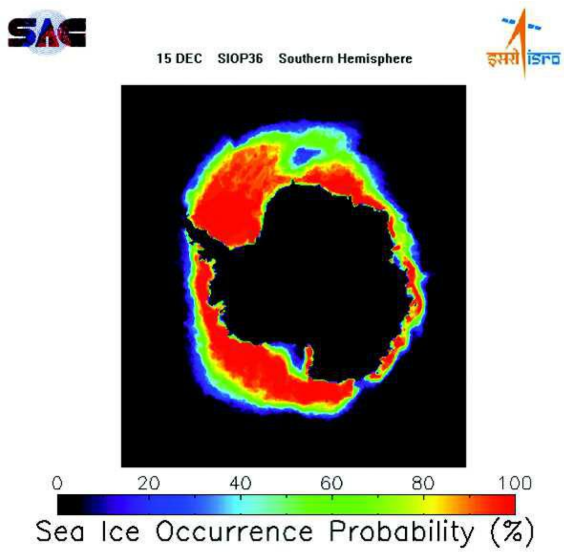

Fig. 4: SIOP data for 15th of December (source: mosdac.gov.in)

Assessment of Sea Ice Melting : Sea ice affects the ocean-atmosphere dynamics through various feedback mechanisms, such as ice-albedo. Srivastava *et al*. (2011) have assessed the impact of the ice albedo feedback mechanism on the Antarctic sea ice melting rates using DMSP SSM/I sea ice monthly concentration data (1988-2006). The melting rate obtained from the SSM/I data was compared with the theoretical melting rate obtained by differentiating a theoretical curve, based on the effect of seasonal cycle of solar irradiance. Further research is required in the assessment of albedo as a consequence of effect of various oceanic features. Albedo is directly connected to heat balance and mass balance of sea ice.

A study by Istomina *et al*. (2015) reveals that melt pond fractions in Arctic affects the energy balance of Arctic ocean in summer. An algorithm to retrieve melt pond fraction and sea ice albedo from Medium Resolution Imaging Spectrometer (MERIS) data is validated against aerial, ship borne and in situ campaign data.

Role of Westerlies and Thermohaline Structure on the Sea Ice Extent : Nuncio and Luis (2011) studied satellite-derived sea ice extent during November 1978 to December 2006 in the Indian Ocean Sector of the Southern Ocean in relation to atmospheric forcing and oceanic thermohaline structure. The study revealed that the sea ice extent increased when the ocean exhibited higher stability.

Sea Ice and Its Global Teleconnection

On the relation of Antarctic sea ice and monsoon variability, Dugam and Kakade (2004), carried out a study to statically evaluate the relation between satellite derived Antarctic sea ice extent and Indian Summer monsoon variability over the various homogeneous regions of India. Analysis was carried out for 22 years (1979-2000). It is observed that deficient monsoon years are preceded by more than normal sea ice extent, and in excess or normal monsoon years the sea ice extent is less than the normal.

Studies by Prabhu *et al*. (2009, 2010, 2011, 2015) indicate the role and impact of Antarctic sea ice on the All-India summer monsoon (AISM). These authors found a coherent propagating pattern between the ASI extent and AISM, as well as the rainfall over most of the homogeneous geographical regions of India. Furthermore, their study reveals that the sea-ice extent (SIE) of the western Pacific Ocean sector in the month of March has a strong association with that of the AISM in the same year. Using SSMR-SSM/I based sea ice products (1979-2009) these authors reported that the SIE over the Bellingshausen and Amundsen Sea Sector (BASS) during the austral summer (October–December) has an inverse relationship with the all AISM of the following year. Furthermore, the sea surface temperature and the upper tropospheric meridional transport of heat over the southeast Pacific, during the period preceding the monsoon season, show contrasting behavior with respect to the extremes of AISM. These authors have also demonstrated that a positive (negative) SAM during February–March is favorable (unfavorable) for the ensuing summer monsoon rainfall over the Indian sub-continent.

Dash *et al*. (2013) studied the teleconnection between ENSO and the sea ice extent (SIE) in the Weddell Sea (South Atlantic) and the Bellingshausen–Amundsen Sea (South-Eastern Pacific) sectors of the Southern Ocean and found that the relationship between the tropical expression of ENSO and the SIE in these two areas has undergone a phase shift around 1992 (Fig. 5). The phase shift is attributed to the contrasting features of the structure and strength

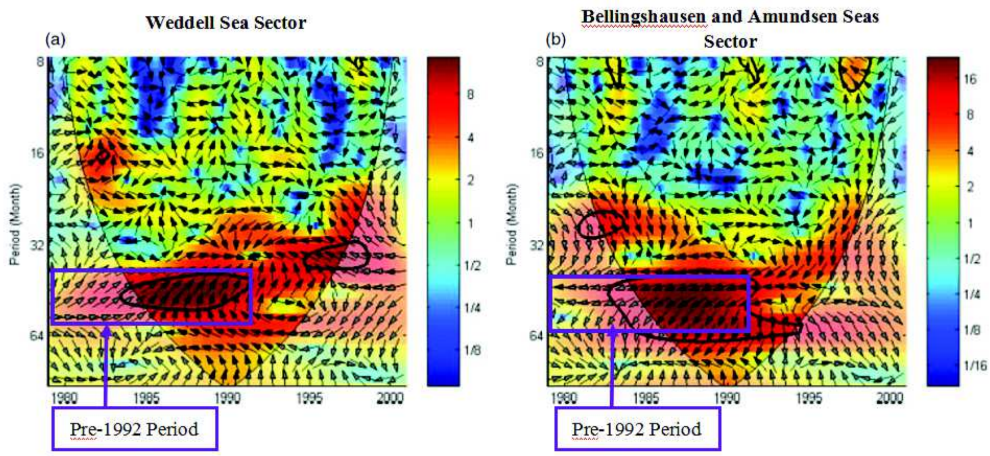

Fig. 5: The wavelet covariance (shaded) and phase difference (vector) between SOI and the sea ice extent anomalies in the cone of influence and 5% significance level contour (thick dark line) is overlaid on the covariance. The vectors indicate the phase difference and the lead/lag relation between the two-time series. (Source : Dash *et al*., 2013)

of the RFC before and after 1992 in both, the South Atlantic and the South-Eastern Pacific.

Deb *et al*. (2014) studied the effect of ENSO on the sea ice behavior in the Indian Sector of the Southern Ocean (ISSO). Their investigation found that sea ice in the eastern part of ISSO (i.e. 50º-80ºE) is negatively correlated with ENSO (Fig. 6). Also, they demonstrated that the ENSO induced variabilities in the sea ice area of the ISSO are mainly controlled by (1) the thermodynamics of the region (surface air temperature and sea surface temperature changes due to modulation of the local pressure gradient), (2) dynamics of the sea ice, and (3) the alteration of mean meridional heat flux primarily due to changes in the RFC.

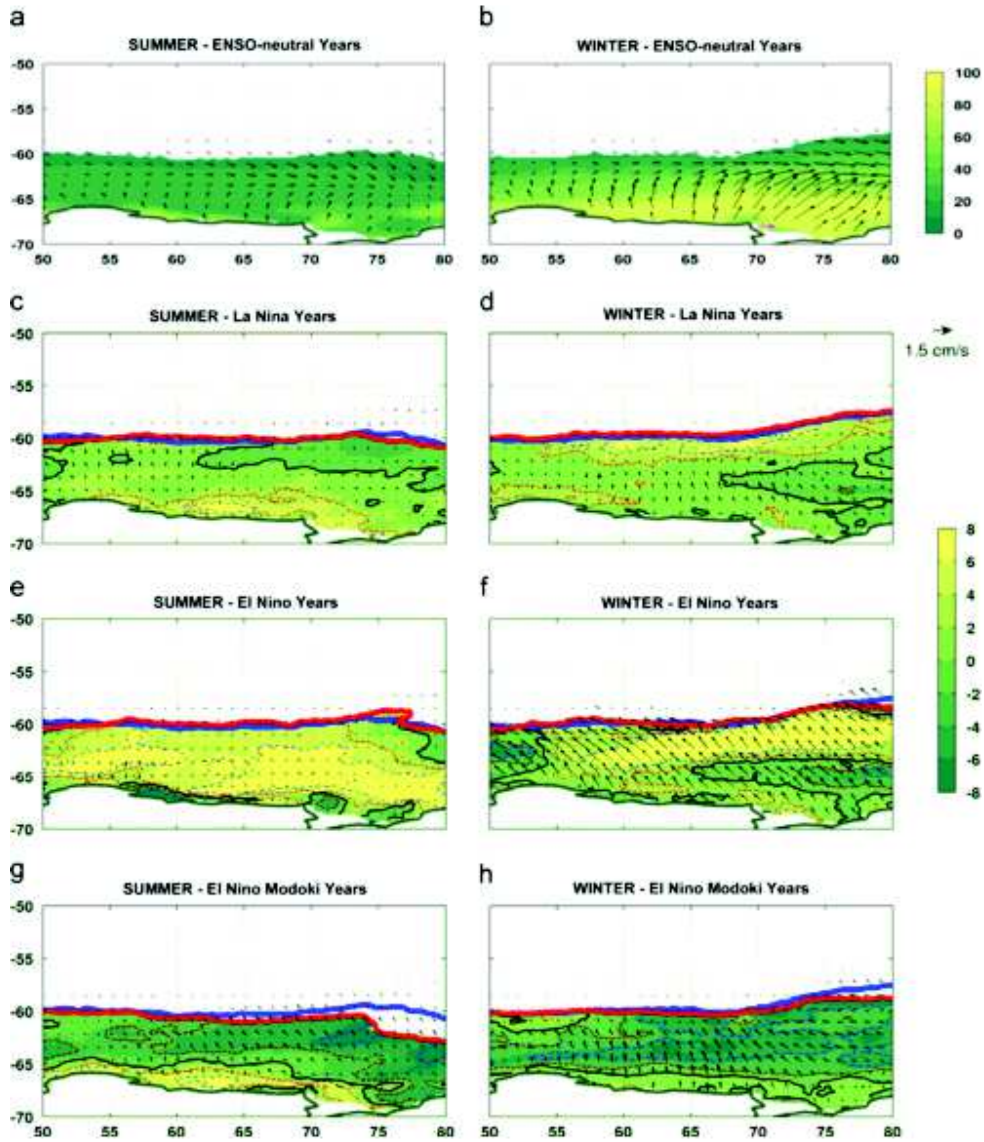

Fig. 6: Distribution of mean sea ice concentration (SIC) during normal/ENSO-neutral years (a) summer and (b) winter. Composite of SIC anomalies for La Niña years (c) summer (d) succeeding winter; for El-Niño years (e) summer (f) succeeding winter and for El-Niño Modoki years (g) summer (h) succeeding winter. Composites of sea ice motion vectors (cm/s) for corresponding seasons are overlaid on them. Red dashed contours and blue dot–dashed contours represent SIC anomalies greater than one and two sigma levels respectively, solid black contours represent zero values. The thick blue contours represent the average sea ice edge for the ENSO-neutral years. The thick red contours represent the composite sea ice edge during corresponding seasons (Deb *et al*., 2014)

Conclusions

During the past one decade, Indian scientists have demonstrated their capability to design and launch of state-of-the-art remote sensing satellites that provide products to study the land- and sea-ice. Advanced techniques have been developed for the sea ice characterization, which have also been utilized for the long-term analysis of sea ice variability. Long-term/climate-scale studies carried out in the Antarctic region have provided valuable insights into the polar ice processes and the changes. Value added products derived using space-borne data requires further validation in the Antarctic region.Studies carried out so far need to be further expanded with development of more advance instruments onboard satellites and development of algorithms for advance analysis of data. Continuity of missions is required for generation of long term database of sea ice extent, types and thickness. The contrast in the nature of growth and decay of sea ice in Arctic and Antarctic region needs to be thoroughly examined. Modeling is required to understand the effect of sea ice variability in the ocean circulations and sea ice-atmosphere energy balance studies. Monitoring Sea Ice drift is one of the potential area of remote sensing applications in the studies of sea ice using advance image processing techniques.

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References

Bhandari S M and Khare N (2009) Investigations of the seasonality oscillating sea-ice edge over the Southern Ocean based on Oceansat-1 MSMR and QuikSCAT observations in *Indian Journal of Geoscience* **63** 221-228

Bhandari S M, Dash M K, Vyas N K, Khanolker A, Sharma N, Khare N and Pandey P C (2005) Intercomparison of simultaneous MSMR and SSM/I observations for sea ice estimation over Antarctic region in *International Journal of Remote Sensing* **26** 3123-3136

Comiso J C (2010) Variability and Trends of the Global Sea Ice Cover, In: Sea Ice (Eds: Thomas D N and Dieckmann G S) pp 205-246, Oxford, U.K.: Wiley-Blackwell

Dash M K, Bhandari S M, Vyas N K, Khare N, Mitra A and Pandey P C (2001) Oceansat MSMR Imaging of the Antarctic and the Southern Polar Ocean in *International Journal of Remote Sensing* **22** 3253-3258

Dash M K, Pandey P C, Vyas N K and Turner J (2013) Variability in the ENSO-induced southern hemispheric circulation and Antarctic sea ice extent in *International Journal of climatology* **33** 778-783

Deb P, Dash M K and Pandey P C (2014) Effect of Pacific warm and cold events on the sea ice behavior in the Indian sector of the Southern Oceanin *Deep-Sea Research*–I **84** 59-72

Deb P, Dash M K, Dey S P and Pandey P C (2016) Non-annular response of sea ice cover in the Indian sector of the Antarctic during extreme SAM events, in *International Journal of Climatology* DOI: 10.1002/JOC.4730

Dugam S S and Kakade S B (2004) Antarctic Sea ice and Monsoon variability in *Indian Journal of Radio and Space Physics* **33** 306-309

Gloersen P, Campbell W J, Cavalieri D J, Comiso J C, Parkinson C L and Zwally H J (1993) Satellite passive-microwave observations and analysis of Arctic and Antarctic sea ice, 1978–1987 in *Annals of Glaciology* **17** 149-154

Hall D K, Key J R, Casey K A, Riggs G A and Cavalieri D J (2004) Sea ice Surface temperature product from MODIS, in *IEEE transactions on Geoscience and Remote Sensing* **42** 1076-1087

Istomina L, Heygster G, Huntemann M, Schwarz P, Birnbaum G, Scharien R, Polashenski C, Perovich D, Zege E, Malinka A, Prikhach A and Katsev I (2015) Melt pond fraction and spectral sea ice albedo retrieval from MERIS data-part 1: Validation against in-situ, aerial and ship cruise datain *The Cryosphere* **9** 1551-1566

Kennicutt I I M C, ChownS L, Cassano J J, Liggett D, Peck L S, Massom R, Rintoul S R, Storey J, Vaughan D G, Wilson T J, Allison I, Ayton J, Badhe R, Baeseman J, Barrett P J, Bell R E, Bertler N, Bo S, Brandt A, Bromwich D, Cary S C, Clark M S, Convey P, Costa E S, Cowan D, Deconto R, Dunbar R, Elfring C, Escutia C, Francis J, Fricker H A, Fukuchi M, Gilbert N, Gutt J, Havermans C, Hik D, Hosie G, Jones C, Kim Y D, Le M Y, Lee S H, Leppe M, Leitchenkov G, Li X, Lipenkov V, Lochte K, López-Martínez J, Lüdecke C, Lyons W, Marenssi S, Miller H, Morozova P, Naish T, Nayak S, Ravindra R, Retamales J, Ricci C A, Rogan-Finnemore M, Ropert-Coudert Y, Samah A A, Sanson L, Scambos T, Schloss I R, Shiraishi K,Siegert M J, Simões J C, Storey B, Sparrow M D, Wall D H, Walsh J C, Wilson G, Winther J G, Xavier J C, Yang H and Sutherland W J (2015) A road map for Antarctic and Southern Ocean science for the next two decades and beyond in *Antarctic Science* **2 7**3-15

Kern S and Spreen G (2015) Uncertainties in the sea-ice thickness retrieval from ICEsat in *Annals of Glaciology* **56** DOI: 10.3189/2015AoG69A736

Maheshwari M, Mahesh C, Singh R K K, Jayaprasad P, Rajak D R, Oza S R and Rajkumar (2015) Estimation of Sea Ice freeboard from SARAL-AltiKa data in *Marine Geodesy in* **38** 487-496

Maheshwari M, Singh R K K, Oza S R and Rajkumar (2013) An Investigation of the Southern Ocean Surface Temperature Variability Using Long-Term Optimum Interpolation SST Data in ISRN Oceanography, Article ID 392632, DOI: http://dx.doi.org/10.5402/2013/392632

Nayak S (2008) Polar research in Indiain *Indian Journal of Marine Sciences* **3 7**352-357

Nuncio M and Luis A J (2011) Role of Westerlies and Thermohaline structure on sea-Ice extent in the Indian Ocean sector of Antarctica in *Journal of Geological Society of India* **78** 211-216

Oza S R, Singh R K K, Vyas N K and Sarkar Abhijit (2012) An atlas of the Arctic and the Antarctic sea ice trends (1999-2009) - derived from QUIKSCAT scatterometer data, *Scientific Report : Space Applications Centre Ahmedabad*, No. SAC/EPSA/AOSG/OSD/SR/04/2012

Oza S R, Das I M L, Singh R K K, Srivastava A, Dash M and Vyas N K (2011a) Inter-annual variations observed in winter and summer Antarctic sea ice extent in recent decade in *Mausam* **62** 633-640

Oza S R, Singh R K K, Vyas N K, Gohil B S and Sarkar Abhijit (2011b) Spatio-temporal coherence based technique for near-real time sea-ice identification from scatterometer data in *Journal of Indian Society of Remote Sensing* **39** 147-152

Oza S R, Singh R K K, Vyas N K and Sarkar Abhijit (2010) Recent trends of arctic and antarctic summer sea-ice cover observed from space-borne scatterometer in *Journal of Indian Society of Remote Sensing* **38** 611-616

Parkinson C L and Cavalieri D J (2012) Antarctic sea ice variability and trends, 1979-2010 *The Cryosphere* **6** 871-880

Prabhu A, Kripalani R H, Preethi B and Pandithurai G (2015) Potential role of the February–March Southern Annular Mode on the Indian summer monsoon rainfall: A new perspective; Climate Dynamics DOI: 10.1007/s00382-015-2894-5

Prabhu A, Mahajan P N and Khaladkar R M (2011) Trends in the polar sea ice coverage under climate change scenarioin *Mausam* **62** 609-616

Prabhu A, Mahajan P N, Khaladkar R M and Bawiskar S (2009) Connection between Antarctic sea-ice extent and Indian summer monsoon rainfall in *International Journal of Remote Sensing* **30** 3485-3494

Prabhu A, Mahajan P N, Khaladkar R M and Chipade M D (2010) Role of Antarctic circumpolar wave in modulating the extremes of Indian summer monsoon rainfall in *Geophysical Research Letters* **37** L14106 DOI:10.1029/2010GL043760

Rai S and Pandey A C (2006) Antarctic sea ice variability with Indian Ocean Sea Surface Tempereture in *Journal of Indian Geophysical Union* **10** 219-229

Rajak D R, Singh R K K, Jayaprasad P, Oza S R, Sharma R and Raj Kumar (2015) Sea ice occurrence probability data and its applications over the Antarcticin *Journal of Geomatics* **9** 193-197

Rana P K, Dash M K, Routray A and Pandey P C (2011) Prediction of sea ice edge in the Antarctic using GVF Snake model in *Journal of the Geological Society of India* **78** 99-108

Simmonds I (2015) Comparing and contrasting the behavior of Arctic and Antarctic sea ice over the 35 year period 1979-2013 in *Annals of Glaciology* **56** 18-28 DOI: 10.3189/2015/SAoG69A909

Singh R K K, Maheshwari M, Jayaprasad P, Rajak D R, Kumar R and Oza S R (2015) Concurrent use of OSCAT and AltiKa to characterize Antarctic Ice Surface Features in *Marine Geodesy* **38** 497-509

Singh R K K, Oza S R, Vyas N K and Sarkar Abhijit (2011) Estimation of Thin Ice Thickness from the Advanced Microwave Scanning Radiometer-EOS (AMSR-E) for a Coastal Polynya in the Chukchi and Beaufort Seas in *IEEE Transactions on Geoscience and Remote Sensing* **49** 2993-2998

Sreenivasan G and Majumdar T J (2006) Mapping of Antarctic Sea Ice in depletion phase: An indicator of climate change? In *Current Science* **90** 851-857

Srisudha S, Kumar S, Jain D S and Dadhwal V K (2013) Detection and size distribution analysis of ice floes near Antarctic using RISAT-1 imagery in *Current Science* **105** 1400-1403

Srivastava A, Das I M L, Oza S R, Mitra A, Dash M and Vyas N K (2011) Assessment of sea ice melting rates in the Antarctic from SSM/I observations in *Mausam* **62** 601-608

Teleti P R and Luis A J (2013) Sea ice Observations in Polar Regions: Evolution of Technologies in Remote Sensing in *International Journal of Geosciences* **4** 1031-1050

Vyas N K, Bhandari S M, Dash M K, Pandey P C, Khare N, Khanolkar A and Sharma N (2004) An Atlas of Antarctic Sea Ice from OCEANSAT-1 MSMR , SAC-NCAOR-01-2004, National Centre for Antarctic and Ocean Research (DOD), Goa, India

Vyas N K, Dash M K, Bhandari S M, Khare N, Mitra A and Pandey P C (2003) On the secular trend in sea ice extent over the Antarctic region based on OCEANSAT – 1 MSMR Observations in *International Journal of Remote Sensing* **24** 2277-2287

Worby A P and Cosimo J C (2004) Study of Sea ice edge and ice extent from satellite and ship observations in *Remote Sensing of Environment* **92** 98-111

Worby A P, Geiger C A, Paget M J, Van Woert M L, Ackley S F and Deliberty T L (2008) Thickness distribution of Antarctic sea ice *Journal of Geophysical Research* **113** C05S92, doi:10.1029/2007JC004254

Zhu T, Li F, Heygster G and Zhang S (2016) Anatarctic Sea–Ice classification Based on Conditional Random Fields from RADARSAT-2 Dual polarization satellite Imagesin *IEEE Journal of Selected topics in Applied Earth observations and Remote Sensing* **9** 2451-2467

Zwally H J, Comiso J C, Parkinson C L, Campbell W J, Carsey F D and Gloersen P (1983) Antarctic Sea Ice, 1973-1976: Satellite Passive–microwave Observations, NASA SP–459, National Aeronautics and Space Administration, Washington, D. C. 206p.

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Research Paper

Antarctica Plate Motion

SAPNA GHAVRI[1], JOSHI K CATHERINE[1], A AMBIKAPATHY[2], AMIT KUMAR[1] and VINEET K GAHALAUT[2,*]

[1]*CSIR-National Geophysical Research Institute, Hyderabad 500 007, India*

[2]*National Centre for Seismology, Ministry of Earth Sciences, New Delhi 110 003, India*

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We have analysed GPS measurements of site motion from fifty sites in the Antarctica, including the one set up by us at Maitri. The Maitri site exhibits a predominantly northward velocity of ~8 mm/year. Elsewhere on the Antarctica plate the site velocity estimates vary from 4 to 20 mm/year and exhibit spectacular rotation of the atlantic plate. The estimated pole of the Antarctica plate is located on the plate itself and thus the plate, surrounded by mostly the divergent plate margins, appear to spin along this pole. Large seasonal variations are seen in displacement time series from sites which are located closer to the pole.

Keywords: Antarctica; Maitri; Plate Motion; GPS Measurements

Introduction

The Antarctica, which is the fifth largest of the seven continents on Earth, was the part of the supercontinent Gondwana more than 170 million years ago. Over time Gondwana broke apart and Antarctica was formed around 35 million years ago. The area of Antarctic plate is 61 million km^2, which is almost five times that of the Indian plate. The Antarctic plate has a unique geodynamic setting since it is almost completely (87%) surrounded by mid-oceanic ridges, divergent or conservative margins which are formed due to interaction of the Antarctic plate with the South America plate, Africa plate, Australia plate, Pacific plate and Nazca plate (Fig. 1). Only a small part of it abuts the subduction zone, which is formed due to interaction of the South America plate, Scotia plate and Antarctic plate. Seismicity in the Antarctica plate interiors is generally low. Most of the seismicity is concentrated on the plate boundary. A few earthquakes occur in the volcanic region in the western Antarctica and peninsular region (Reading, 2007). The continental interior shows suppression of crustal failure due to ice loading causing low seismicity. Ice quakes occur in the continental shelf region due to ice shelf breakoff.

CSIR-National Geophysical Research Institute (NGRI) with the support from ESSO-National Centre for Antarctic and Ocean Research (NCAOR) established a permanent GPS station in the year 1997 at the Indian base station Maitri. Majority of data from this site were acquired in campaign mode. However, over the years, the site became unstable. The results from this site have been reported earlier (Ghavri *et al*., 2015). A new station MAIT was established at Maitri in 2013 (Fig. 2). In this article, we report on the Antarctic plate motion through GPS measurements.A few attempts have been made earlier (Argus *et al*., 2014; Bouin and Vigny, 2000; Dietrich *et al*., 2004; Donnellan and Luyendyk 2004), however, the number of GPS sites used to estimate the plate motion in these studies were small. Our study involving data from 48 sites provides the most comprehensive analysis so far.

GPS Measurements and Analysis

We analysed the data from Maitri station (MAIT) along with forty seven other GPS stations from UNAVCO (University NAVSTAR Consortium) and SOPAC (Scripps Orbit and Permanent Array Center). We used GAMIT-GLOBK software (Herring *et al*.,

**Author for Correspondence: E-mail: vkgahalaut@yahoo.com*

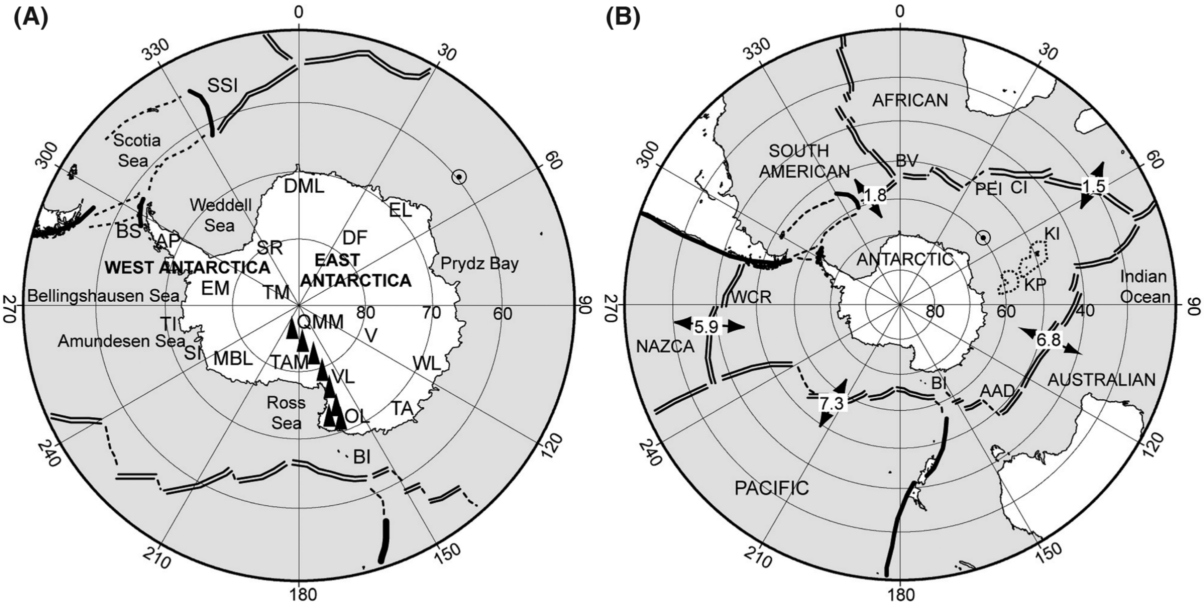

Fig. 1: (A) Geographical Locations and major physiographic features of Antarctica. SSI-South Sandwich Islands, BS-Bransfield Strait, AP-Antarctic Peninsula, TI-Thurston Island, SI-Siple Island, MBL-Marie Byrd Land, TAM-Transantarctic Mountains, VL-Victoria Land, OL-OatesLand, V-Vostok, Lake Vostok, TA-Terre Adelie, WL-Wilkes Land, EL-Enderby Land, DF-DomeFuji, DML-Dronning Maud Land, SR-Shackleton Range, TM-Thiel Mountains, EM-Ellsworth Mountains; (B) The Antarctic Plate and surrounding Plates. BV-Bouvet Triple Junction, WCR-West Chile Rise, BI-Balleny Islands, AAD-Australian-Antarctic Discordance, KP-Kerguelen Plateau, KI-Kerguelen Islands, CI-Crozet Islands, PEI-Prince Edward Islands. Numbers indicate divergence rates in cm/year. Plate margins are: divergent-double line, convergent-single thick line, other-dotted line. The dot and circle in each panel represents the anti-pole of the Antarctica plate, estimated in this study. Modified after Reading (2007)

Fig. 2: GPS site at Maitri, Antarctica, established in 2013

2010a, b; King and Bock, 2006) to process GPS data in ITRF08 reference frame. The estimated velocity is less about 4 mm/yr in the eastern part of East Antarctica and about 20 mm/yr in the western part of West Antarctica and Antarctic Peninsula. We observed that the Antarctic Plate is moving towards the South American Plate (Fig. 3). The estimated velocity at Maitri is predominantly towards north with a rate of 8±1 mm/yr.

We found that the site motion in Antarctica is spectacular in the sense that the plate appears to rotate. Such a motion is not observed for any other plate on the globe. We use the site motion data to estimate the Euler pole of rotation. The Euler Pole, estimated by considering Antarctic Plate as a single plate is at 58.69±0.41°N latitude, 130.18±0.41°W longitude and is rotating with an angular velocity of 0.2153±0.0021°/myr. Such a pole will cause rapid variations in the plate velocity, which is evident from that estimated from GPS measurements. As discussed earlier, that the Antarctica plate is mainly surrounded by the mid-oceanic ridges, the convergent plate margins, and only a small part of it joins the subduction zone, south of South America plate. On the other hand, majority of the other plates are surrounded by both divergent as well as convergent plate margins and hence those plates move largely in one direction. However, unique plate margin boundaries setting of the Antarctica plate causes a spinning type of motion of this plate.

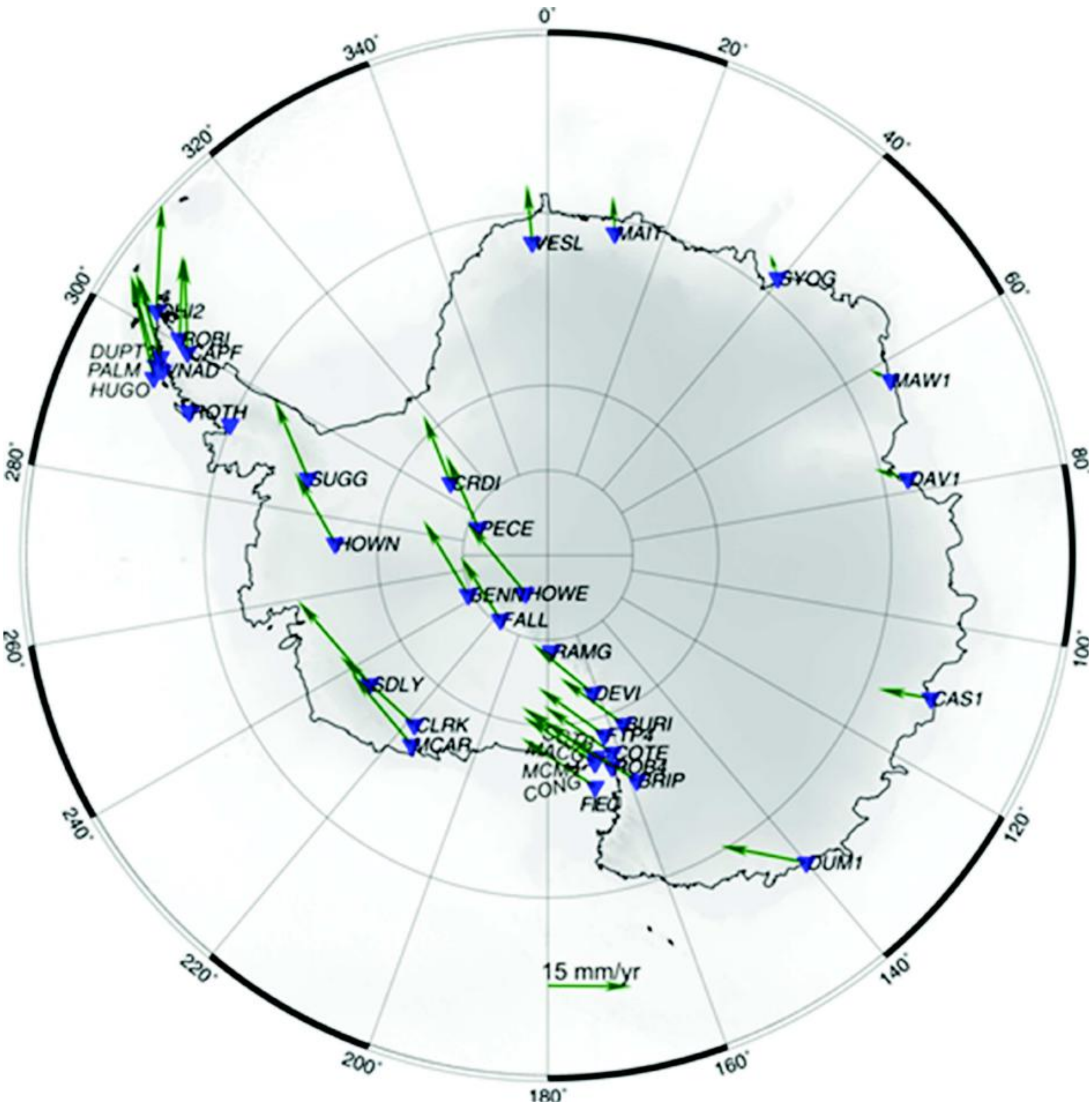

Fig. 3: ITRF08 velocity for the 48 sites on the Antarcticacontinent. Indian GPS site at Maitri is shown as MAIT

Seasonal Variations in the Plate Motion and Internal Deformation of the Plate

There is large velocity variations at sites in the Antarctica plate. The systematic large variations in the site velocity are primarily due to the fact that the Euler antipole of the plate is located on the plate itself. The volcanic province in the western Antarctica also causes some variations in the site motion. In the peninsular Antarctica, the variations in the site motion is primarily due to the proximity of the suduction zone. There is also possibility of some internal deformation, as evident from the presence of high topographic feature, the Trans-Antarctic mountains. Such deformation is very small, less than a couple of mm/year. Quantifying of such deformation by using longer time series data has been taken up. Low internal deformation in the Antarctica is consistent with the general absence of earthquakes in the Antarctica plate region.

Besides variations in the site motion, there are seasonal variations at some sites. Seasonal variations, daily as well as annual, in Antarctica are mainly because of the fact that it is a polar region. Daily and annual variations in the equatorial regions of Antarctica (away from pole) probably occur due to change in temperature, total electron content during and day and night condition, humidity, pressure, and precipitation. At sites in the Antarctica polar region, such changes are more prominent and are annual and show variations in the horizontal motion up to ~3 cm and in vertical as much as ~5 cm. To understand these changes, modelling the effect of each sources is being contemplated.

Conclusions

We analyse GPS measurements in the Antarctica region to constrain its motion. Our site at Maitri shows a predominantly northward motion of ~8 mm/year. The motion of the plate is predominantly towards South American plate and it appears to be spinning. Such a spinning motion is primarily due to the fact that is it is surrounded by the divergent or conservative plate boundaries. This is also consistent with the derived pole of rotation for this plate, which is located on the Antarctica plate itself. There are large seasonal variations in the motion which may be mainly due to the polar conditions.

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References

Argus D F, Peltier W R, Drummond R and Moore A W (2014) The Antarctica component of postglacial rebound model ICE-6G_C (VM5a) based on GPS positioning, exposure age dating of ice thicknesses, and relative sea level histories *Geophysical Journal International* **198** 537-563

Bouin M N and Vigny C (2000) New constraints on Antarctic plate motion and deformation from GPS data *Journal of Geophysical Research: Solid Earth (1978-2012)* **105** 28279-28293

Dietrich R, Rülke A, Ihde J, Lindner K, Millerd H, Niemeiere W, Schenkef H.-W and Seeber G (2004) Plate kinematics and deformation status of the Antarctic Peninsula based on GPS *Global and Planetary Change* **42** 313-321 doi: 10.1016/j.gloplacha.2003.12.003

Donnellan A and Luyendyk B P (2004) GPS evidence for a coherent Antarctic plate and for postglacial rebound in Marie Byrd Land *Global and Planetary Change* **42** 305-311

Ghavri S, Catherine J K and Gahalaut V K (2015) First estimate of plate motion at Maitri GPS site, Indian Base station at Antarctica *Journal Geological Society of India* **85** 431-433

Herring T A, King R W and McClusky S C (2010a) Documentation of the GAMIT GPS Analysis Software release 10.4. Department of Earth, and Planetary Sciences. Massachusetts Institute of Technology, Cambridge

Herring T A, King R W and McClusky S C (2010b) GLOBK, Global Kalman filter VLBI and GPS analysis program, version 10.4. Department of Earth, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge

King R W and Bock Y (2006) Documentation of the GAMIT GPS analysis software. Massachusetts Institute of Technology, Massachusetts

Reading A M (2007) The seismicity of the Antarctic plate, In Stein S and Mazzotti S ed, Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues *Geological Society of America Special Paper* **425** 285-298 doi: 10.1130/2007.2425(18).

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Research Paper

Aerosol Studies on and Around Antarctica

S SURESH BABU*
Space Physics Laboratory, Vikram Sarabhai Space Centre, Thiruvananthapuram 695 022, India

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Antarctica provides an excellent environment to examine the natural and background aerosols in the atmosphere over snow and ice. The Indian efforts (metrological measurements) at Antarctica were initiated with the establishment of the first Antarctic station in Eastern Antarctica during the first Indian Scientific Expedition to Antarctica (ISEA) in 1981. The detailed and systematic characterization of physical and optical properties of coastal Antarctic aerosols over Indian Antarctic stations Maitri and Bharati were initiated during the International Polar Year (IPY) 2007 to 2009. Since then, several scientific publications were emerged from the Indian side on Antarctic aerosols. This article provides a brief review of the Indian efforts on Antarctic aerosols.

Keywords: Antarctic Aerosols; AOD; Black Carbon; Size Distribution; Snow Scavenging

Introduction

Antarctica provides an excellent environment to examine the natural and background aerosols in the atmosphere over snow and ice. Besides that, the large ice sheet of the Antarctic continent affects atmospheric circulation patterns over this region, which affects the transport and removal of the aerosol particles (Shaw, 1979). In the recent years, with the increase in human interventions (exploratory, scientific and tourism) in Antarctica, there is an increase in the emissions of anthropogenic species (including aerosols) (Shaw, 1979; Tomasi *et al*., 2007). Overall, aerosol over Antarctica consists mainly of the transported components either from the Oceans or from the surrounding continents. It mainly consists of aged aerosols. Large variations in the columnar aerosol loading over Antarctica are also reported during the periods of strong volcanic eruption of El Chichon (1982) and Mt. Pinatubo (1991), which also justifies the teleconnection of Antarctica with other regions of the world from transport at higher altitudes and their subsequent influence on the Antarctic aerosols system (Herber *et al*., 1993; Tomasi *et al*., 2007).

Antarctic aerosol system is studied by several investigators from different countries which include the aerosol properties such as their chemical nature (Savoie *et al*., 1993; Minikin *et al*., 1998; Wagenbach *et al*., 1998; Kerminen *et al*., 2000), their total number, mass concentrations and size distributions (Samson *et al*., 1990; Jaenicke *et al*., 1992; Mazzera *et al*., 2001; Koponen *et al*., 2003) their role as cloud condensation nuclei (De Felice *et al*., 1997); and their chemical mass size distributions (Harvey *et al*., 1991; Gras, 1993; Ito, 1993; Teinila *et al*., 2000; Rankin and Wolff, 2003). As far as the columnar aerosol optical depths (AODs) are concerned, Antarctica presents a pristine environment. The first measurements of AOD performed in Antarctica using a Sun photometer were in 1968/69 (Sakunov and Rusin, 1980), while regular measurements have been recorded at South Pole (USA) since 1976 (Bodhaine *et al*., 1986). AOD over Antarctica at 500 nm varies between 0.01 and 0.06 for the coastal and low-latitude sites and further lower values are reported at the high-latitude sites (Six *et al*., 2005). Aerosol concentrations varied from few particles cm^{-3} to few thousands particles cm^{-3} (Hogan, 1975). While fine particles of sulphate are most abundant over the Antarctic continent, coarse particles of sea-salt are major contributor to aerosols in the coastal Antarctic regions (Hall and Wolff, 1998;

**Author for Correspondence: E-mail: s_sureshbabu@vssc.gov.in, sureshsplvssc@gmail.com*

Wagenbach *et al*., 1998; Kerminen *et al*., 2000). The cyclonic storms revolving around the continent over the oceans bring the marine aerosol in to the Antarctic continent.

Concerning the global distribution and importance of black carbon (BC) aerosols, there is a major lack of observations of BC at Antarctica, especially in the Indian oceanic sector of eastern Antarctica (Hara *et al*., 2008). The first long term (from December 1986 to November 1987) measurements of BC over Antarctica was made by Hansen *et al*. (1988) which provided the background value of BC at South Pole. These measurements are important when we consider the recent increase in the ship borne Antarctic tourism activities during Austral summer (Graf *et al*., 2010). Impact of local pollution and growing combustion derived emissions from ship borne activities in the oceans surrounding Antarctica have strong relevance for BC concentrations (Weller *et al*., 2012).

All these studies have pointed out the importance of long term measurements of physical and optical properties of aerosols for complete characterization of the Antarctic aerosols on the spatial and temporal scales from different regions of Antarctica with the following objectives. They are: (1) Delineation of long term changes in the physical, chemical and optical properties of aerosols in Antarctic atmosphere, quantification of the effect of long range transport and estimation of radiative impact (2) Estimation of snow scavenging of aerosols and deposition of black carbon on ice and to characterise the physical, chemical and optical properties of aerosols in Snow and the corresponding changes in snow albedo and (3) Quantification of the anthropogenic influence in Antarctic atmosphere to delineate local and long-range transport.

Indian Efforts on Aerosol Studies Over Antarctica

The Indian efforts (meteorological measurements) at Antarctica were initiated with the establishment of the first Antarctic station (Dakshin Gangotri) in Eastern Antarctica during the first Indian Scientific Expedition to Antarctica (ISEA) in 1981. While the meteorological measurements are carried out continuously in each ISEA, the aerosol measurements are limited to few days of the expedition and are discontinuous. During January 1997 to February 1998, NPL team has carried out measurements of columnar ozone, water vapour and aerosol optical thickness at 1020 nm at Maitri (Tripathi *et al*., 2002). While limited measurements of number concentrations and size distributions (Lal and Kapoor, 1989; Pant *et al*., 2011), columnar aerosol optical depth (AOD) and mass concentrations (Gadhavi and Jayarman, 2004, Chaubey *et al*., 2010, 2011, 2013), aerosol conductivity (Kamra *et al*., 2009) are carried out during different years, a comprehensive multi parameter aerosol measurements were not available from Indian side till the International Polar Year (IPY) of 2007.

During the southern hemispheric summer of International Polar Year (IPY) 2007 to 2009, a detailed characterization of physical and optical properties of coastal Antarctic aerosols has been carried out over Indian Antarctic station Maitri, and for the first time over 3rd Indian Antarctic station Bharati, before the station has been established (Chaubey *et al*., 2010; 2011). During this study the first time measurements of black carbon (BC) and semi-quantitative effects of scavenging of aerosols by snow were carried out from Maitri and Bharati.

The mean AOD at 500 nm over Maitri (0.034 ± 0.005) and Bharati (0.032 ± 0.006) during IPY (2008) were found to be comparable, showing the spatial homogeneity in columnar aerosol properties over the Antarctic atmosphere (Chaubey *et al*., 2011). Spectral variations of AOD over Bharati differ significantly from those over Maitri. Estimated α_{AOD} (Angstrom wavelength exponent) showed an increased fine mode dominance at Maitri ($\alpha_{AOD} \sim 1.2$) compared to Bharati ($\alpha_{AOD} \sim 0.7$).Based on the measurements from Maitri during 2001, Gadhavi and Jayaraman (2004) have reported a mean AOD value of 0.036 ± 0.018 at 400 nm. Based on the measurement during December 2004 to February 2005, Devara *et al*. (2011) have reported a mean AOD value of 0.042 at 500 nm over Maitri with an Angstrom exponent of 0.24 indicating the abundance of coarse particles during the study period. On the other hand, AOD measured at these stations were significantly lower than that measured over the oceanic regions surrounding Antarctica (Chaubey *et al*., 2013). The AOD at 500 nm measured during different expeditions by the Space Physics Laboratory is shown in Fig. 1.

The distinct geographical features of Maitri and Bharati, despite being in the Antarctic Circle, might be, at least partly, responsible for the distinct

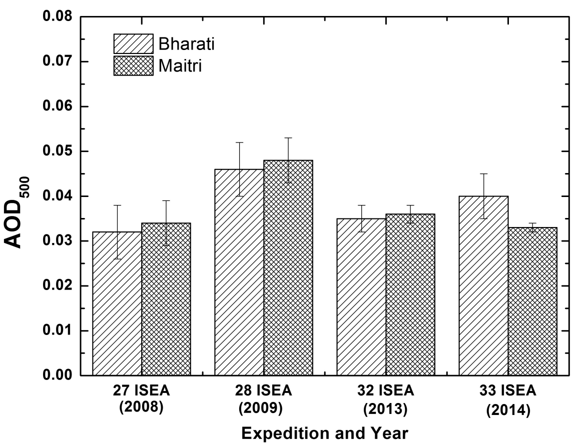

Fig. 1: Aerosol Optical Depth at 500 nm measured from Maitri and Bharati during different summer expeditions. The AOD is in general comparable over both stations except in 2014

differences seen in the aerosol characteristics. Maitri is a continental station under moderate anthropogenic influence while Bharati is rather pristine and is more under the influence of marine environments. The two main mechanisms which might be contributing to the variabilities in aerosol properties at Maitri are (i) marine particles (sea salt) and dust particles from the oasis both produced and transported by the winds, and (ii) those produced by the local activities at Maitri and nearby stations. Moreover, as the coarse mode sea salt particles get settled faster in comparison to the fractionated sea salt aerosols, the marine airmass reaching Maitri would be strongly deprived of the coarse mode component. On the other hand, Bharati being very near to and surrounded by the open Ocean (free from sea ice) and having a low elevation, is conducive for being influenced by the (local) wind generated sea salt particles much more than Maitri. This would also explain the difference in α_{AOD} between the two stations.

In comparison to AOD, most of the near surface aerosol parameters depicted larger day to day variations at Maitri and Bharati indicating the spatial heterogeneities associated with long range transport and local influences. Based on the measurements during the summer of 2007-2008, Chaubey *et al.* (2011) have reported that the total mass concentration of composite aerosols (M_T) depicted fairly large day-to-day variation at Maitri, from a minimum value of 4.4 $\mu g\ m^{-3}$ to a maximum of 14.7 $\mu g\ m^{-3}$, with a mean value of 8.25 ± 2.87 $\mu g\ m^{-3}$. Comparatively lower values are found at Bharati where it varied from 4.58 $\mu g\ m^{-3}$ to 8.53 $\mu g\ m^{-3}$ with a mean value of 6.03 ± 1.33 $\mu g\ m^{-3}$, implying better pristine conditions (Chaubey *et al.*, 2011). Based on the measurements over Maitri, Gadhavi and Jayaraman (2004) reported that the total aerosol mass concentration at surface level is of 7 $\mu g\ m^{-3}$ for the PM10 particles with significant (day-to-day) variations. Based on the measurement during the 2009-2010, Budhavant *et al.* (2015) reported that the mean mass concentration for PM10 aerosols over southern ocean was found to be 13.4 $\mu g\ m^{-3}$ and over coastal Antarctica near Bharati was found to be 5.13 $\mu g\ m^{-3}$. They further reported that the elements of anthropogenic origin (Eg. Zn, Cu, Pb …) were highly enriched with respect to crustal composition. Based on the observations during 11 January 2009 to 21 March 2009 and 09 December 2009 to 09 January 2010, Ali *et al.* (2015) have reported that the total suspended particulate matter (TSPM) over Larsemann hills (where the present-day Bharati station is established) reduced from 7.6 $\mu g\ m^{-3}$during Jan to Mar, 2009 to 2.4 $\mu g\ m^{-3}$ during Dec 2009 to Jan 2010. The TSPM reported over Maitri during December 2009 to January 2010 was 9 $\mu g\ m^{-3}$. They also reported that the TSPM over both Maitri and Larsemann hills are acidic in nature with a PH value of 5.56 at Larsemann hills and 5.28 at Maitri. The acidic nature of TSPM is due to the absence of sufficient alkaline minerals. Based on the snow sample collected over coastal Antarctica near to Maitri and Larsemann Hills during December 2009 to March 2010, Budhavant *et al.* (2014) reported that the pH of surface and fresh snow were 6.03 and 5.64 respectively.

Based on the measurement over Maitri, Kamra *et al.* (2009) have shown that the ion concentrations of all categories and the air-earth current simultaneously decrease by approximately an order of magnitude as the wind speed increases from 5 to 10 m s^{-1}. This reduction is due to the scavenging of atmospheric ions and aerosols by the drifting snow particles. Based on the measurements over Maitri during January-February, 2005, Siingh *et al.* (2013) showed that the diurnal variations in positive ion concentrations and the surface temperature are almost parallel to each other on fair weather days and the rate of increase of positive ion concentrations is linked to the freezing point. However, the exact mechanism for the formation of intermediate ions, which is also responsible for the formation of new particles, is yet to be identified. Pant *et al*. (2010) have studied the number concentration and size distributions of aerosol particles during the passage of cyclonic storms (revolving around the Antarctic continent)close to the Maitri station during February 2005. They reported that as a storm approached Maitri, concentration of coarse particles increased by an order of magnitude and the number size distribution frequently showed a coarse mode at ~ 2 μm, a broad Aitken mode from 0.04 to 0.1 μm and, once in a while, a nucleation mode at 0.018 μm. All these modes exist with a slight change in the mode diameter while the storm is going away from the Maitri station. In addition to this, Pant *et al*. (2011) have also shown that at Maitri, total number concentrations of coarse and fine particles vary from 0.1 to 0.8 and from 100 to 2000 particles cm^{-3} respectively, during the southern summer months of January and February, 2005 at Maitri. Maitri is situated on an oasis and experiences a fair amount of local station activities during the summer period. Moreover, advection from the neighbouring stations lying upwind, movement of men and transport of goods (more frequent during Antarctic summer at all the stations) also contribute to the local (regional) aerosols and to the day-to-day variations in the near-surface aerosol characteristics.

Prior to IPY (2007-2009), direct measurements of BC mass concentrations did not exist over Maitri and Bharati. The BC values measured over Larsemann Hills (Bharati) and Maitri during the summer expedition in 2009 are shown in Fig. 2. The mean BC mass concentration at Maitri and Bharati observed during the IPY period were respectively 75 ± 33 ng m^{-3} (which is on the higher side of the background concentration and values reported at other coastal Antarctic locations) and 13 ± 4 ng m^{-3} (which is comparable to the values reported for the other few coastal Antarctic locations), respectively (Chaubey *et al*., 2010). The BC values reported in this study over Bharati were measured even before the establishment of the permanent Indian station at Larsemann hills (Bharati). BC contributed very little to the mass concentrations of composite aerosols over both stations during the study period; being 2 % at Maitri and 0.2 % at Bharati. The BC, produced by the activities over Antarctica, is found to contribute to the high concentration at Maitri. The Angstrom

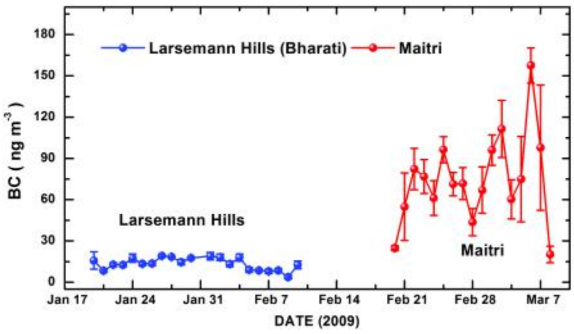

Fig. 2: BC mass concentration over the Indian stations Bharati (Larsemann Hills) and Maitri during the summer expedition, 2009. The BC measurements were made at Larsemann hills before the establishment of the permanent station, Bharati. The day to day variability in BC is mainly due to the snow scavenging associated with blizzards (Chaubey *et al.*, 2010)

exponent (α_{ABS}) for absorption estimated from the spectral values of absorption coefficients (β_{ABS}) is found to vary from 0.5 to 1, indicating a high BC/OC ratio typical of BC of fossil fuel origin (Chaubey *et al*., 2010).

One of the major removal mechanisms of BC from the polar atmosphere is through snow scavenging. It is found that the mass concentrations of BC were reduced to half of the normal day values during snow fall event but recovered rapidly to the normal day's values shortly after the cessation of the episode (Chaubey *et al*., 2010). BC scavenged or dry-deposited on snow and ice can produce large climatic and radiative implications.

Air mass back trajectories computed for the summer period (1 December 2007 to 31 March 2008) showed that, aerosol properties over both Maitri and Bharati are modified by the wind coming from the high latitude polar regions (Chaubey *et al*., 2010). Based on the analysis of snow samples collected from two regions in East Antarctica, Mahalinganathan and Thamban (2016) have reported the presence of calcium nitrate aerosols transported from the southern South American regions. With the increased tourism and scientific activities during summer, there can be a large day to day variability in the aerosol characteristics at coastal Antarctica due to the air mass coming at the stations from inland continental stations.

Aerosol Properties Over Southern Oceans

The scientific expeditions from India to Antarctica also provide an excellent opportunity to study the aerosol properties over different oceanic regions in the Indian longitude sector from the Arabian Sea to the southern oceans. During the 16^{th} ISEA, Deshpande and Kamra (2002) has made measurements of aerosol size distributions over the oceanic regions en route to Maitri. They have reported the presence of nucleation mode particles in great abundance up to 30°S. Perhaps the first of its kind measurements of BC over Southern Ocean was made by Moorthy *et al*. (2005), on board Sagar Kanya, during its first pilot expedition to Southern Ocean from January to April, 2004. They reported a steady BC values (~ 50 ng m^{-3}) over southern ocean which exponentially increases to 2000 ng m^{-3} over Arabian Sea. Based on the measurements over oceans during January-April, 2006 onboard R/V Akademik Boris Petrov from the Antarctic coast to Indian coast, Vinoj *et al*. (2007) reported extremely low (< 0.1) and steady AOD over southern ocean which increases nearly exponentially to 0.7 in the northern Arabian Sea. Based on the measurements of various aerosol properties, such as spectral AOD, total aerosol mass concentration as well as BC mass concentration, on board SagarKanya during its first pilot expedition to Southern Ocean Babu *et al*. (2010) reported that the aerosol radiative forcing at surface level over southern ocean in the range –4 to –5 Wm^{-2} increases to –10 to –23 Wm^{-2} over the ocean north of equator. Compiling the dataset from various expeditions to southern ocean as well as to Antarctica, Chaubey *et al*. (2013) have reported the seasonality in latitudinal gradient in aerosol properties over the oceanic regions and the role of long range transport in the observed seasonality.

Conclusion

Scientific literatures on the aerosol measurements from Indian side over Antarctic regions are available from the 6^{th} Indian Scientific Expedition to Antarctica onwards. Most of these measurements were happened in random years and focussed on one or two aerosol parameters only. Systematic measurements on various aerosol parameters were initiated after the International Polar Year (2007-2008). These measurements were also in campaign mode and the data duration over Antarctic region was very limited. It is important to have a dedicated atmospheric science laboratory at the Bharati station for the continues and long term observation of aerosols, gases and other atmospheric parameters which will be useful not only for the assessment of long term changes in the back ground aerosol properties but also for the scientific understanding of various process responsible for aerosol - Cryosphere interaction.

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References

Ali K, Trivedi D K and Sahu S (2015) Physico-chemical characterization of total suspended particulate matter over two coastal stations of Antarctica and adjoining ocean *Atmospheric Environment* **122** 531-540, doi.org/10.1016/j.atmosenv.2015.10.021

Babu S S, Moorthy K K and Satheesh S K (2010) Latitudinal gradient in aerosol properties overthe Indian and Southern Oceans during the austral summer *Current Science* **99**(10) 1384 -1389

Bodhaine B A, Deluisi J J, Harris J M, Houmere P and Bauman S (1986) Aerosol measurements at the South Pole *Tellus B* **38B** 223-235, doi: 10.1111/j.1600-0889.1986.tb00189.x

Budhavant K, Safai P D and Rao P S P (2015) Sources and elemental composition of summer aerosolsin the Larsemann Hills (Antarctica) *Environ Sci Pollut Res* 2041-2050, DOI 10.1007/s11356-014-3452-0

Budhavant K, Rao P S P and Safai P D (2014) Chemical Composition of Snow-Water and Scavenging Ratios over Costal Antarctica *Aerosol and Air Quality Research* **14** 666-676 doi: 10.4209/aaqr.2013.03.0104

Chaubey J P, Moorthy K K, Babu S S and Nair V S (2011) "The optical and physical properties of atmospheric aerosols over the Indian Antarctic stations during southern hemispheric summer of the International Polar Year 2007-2008" *Annales Geophysicae* **29** 1-13

Chaubey J P, Moorthy K K, Babu S S, Nair V S and Tiwari A (2010) "Black carbon aerosols over coastal Antarctica and its scavenging by snow during the Southern Hemispheric summer" *J Geophys Res* **115** D10210, doi: 10.1029/ 2009JD013381

Chaubey J P, Moorthy K K, Babu S S and Gogoi M M (2013) Spatio-temporal variations in aerosol properties over the oceanic regions between coastal India and Antarctica *Journal of Atmospheric and Solar-Terrestrial Physics* **104** 18-28

De Felice T P, SaxenaV K and Yo S (1997) On the measurements of the cloud condensation nuclei at Palmer station, Antarctica *Atmos Environ* **31** 4039-4044

Deshpande C G and Kamra A K (2002) Aerosol size distributions in the north and south Indian ocean during the northeast monsoon season *Atmospheric Research* **65** 51-76

Devara P C S, Sonbawne S M, Dani K K, Saha S K and Ernest Raj P (2011) Characterization of aerosols and pre-cursor gases over Maitri during 24th Indian Antarctica Expedition *International Journal of Remote Sensing* **32** http:// dx.doi.org/10.1080/01431161.2010.507681

Gadhavi H and Jayaraman A (2004) Aerosol characteristics and aerosol radiative forcing over Maitri Antarctica *Current Science* **86**(2) 296-304

Graf H F, Shirsat S V, Oppenheimer C, Jarvis M J, Podzun R and Jacob D (2010) Continental scale Antarctic deposition of sulphur and black carbon from anthropogenic and volcanic sources *Atmos Chem Phys* **10** 2457-2465

Gras J L (1993) Condensation nucleus size distribution at Mawson, Antarctica: microphysics and chemistry *Atmos Environ* **27** 1417-1425

Hall J S and Wolff E W (1998) Causes of seasonal and daily variations in aerosol sea-salt concentrations at a coastal Antarctic station *Atmos Environ* **32** 3669-3677

Hansen A D A, Bodhaine B A, Dutton E G and Schnell R C (1988) Aerosol black carbon measurements at the South Pole: Initial results, 1986 1987 *Geophys Res Lett* **15** 1193-1196

Hara K, Osada K, Yabuki M, Hayashi M, Yamanouchi T, Shiobara M and Wada M (2008) Measurement of black carbon at Syowa station, Antarctica: Seasonal variation, transport processes and pathways *Atmos Chem Phys Discuss* **8** 9883-9929

Harvey M J, Fisher G W, Lechner I S, Issac P, Flower N E and Dick A L (1991) Summertime aerosol measurement in the Ross sea region of Antarctica *Atmos Environ* **25** 569-580

Herber A, Thomason L W, Radianov V F and Leiterer U (1993) Comparison of trends in the tropospheric and stratospheric aerosol optical depth in the Antarctic *J Geophys Res* **98** (D10) 18441-18447

Hogan A W (1975) Antarctic aerosols *J Appl Meteoro1* **14** 550-559

Ito T (1993) Size distribution of Antarctic submicron aerosols *Tellus B* **45** 145-159

Jaenicke R, Dreiling V, Lehmann E, Koutsenoguii P K and Stingl J (1992) Condensation nuclei at the German Antarctic station "Georg von Neumayer" *Tellus Ser B* **44** 311-317

Kamra A K, Siingh D and Pant V (2009) Scavenging of atmospheric ions and aerosol by drifting snow in Antarctica *Atmos Res* **91** 215-218

Kerminen V M, Teinila K and Hillamo R (2000) Chemistry of sea-salt particles in the summer Antarctic atmosphere *Atmos Env* **34** 2817-2825

Koponen I K, Virkkula A, Hillamo R, Kerminen V M and Kulmala M (2003) Number size distributions and concentrations of the continental summer aerosols in Queen Maud Land, Antarctica *J Geophys Res* **108** 4587 doi: 10.1029/ 2003JD003614

Lal M and Kapoor R K (1989) Certain meteorological features of submicron aerosols at Schirmacher oasis, East Antarctica *Atmos Environ* **23** 803-808

Mahalinganathan K and Thamban M (2016) Potential genesis and implications of calcium nitrate in Antarctic snow *The Cryosphere* **10** 825-836

Mazzera D M, Douglas H L, Chow J C, Watson J G and Grubisic V (2001) PM10 measurements at McMurdo Station, Antarctica *Atmos Env* **35** 1891-1902

Minikin A, Legrand M, Hall J, Wagenbach D, Kleefeld C, Wolff E, Pasteur E C, Ducroz F (1998) Sulfur-containing species (sulfate and methanesulfonate) in coastal Antarctic aerosol and precipitation *J Geophys Res* **103** 10975-10990

Moorthy K K, Satheesh S K, Babu S Sand Saha (2005) Large latitudinal gradients and temporal heterogeneity in aerosol black carbon and its mass mixing ratio over southern and northern oceans observed during a trans-continental cruise experiment *Geophys Res Lett* **32** L14818 doi:10.1029/ 2005GL023267

Pant V, Singh D and Kamra A K (2011) Size distribution of atmospheric aerosols at Maitri, Antarctica *Atmos Environ* **45** 5138-5149

Pant V, Siingh D and Kamra A K (2010) Concentrations and size distributions of aerosol particles at Maitri during the passage of cyclonic storms revolving around the continent of Antarctica *J Geophys Res* **115** D17202, doi: 10.1029/ 2009JD013481

Rankin A and Wolff E (2003) A year-long period record of size-segregated aerosol composition at Halley, Antarctica *J Geophys Res* **108** 4775 doi:10.1029/2003JD003993

Sakunov G G and Rusin N P (1980) Background characteristic of atmospheric transparency regime in the Antarctic (in Russian), in Studies of Antarctic Climate, pp. 20-26, Gidrometeoizdat, St. Petersburg, Russia

Samson J A and Barnard S C, Obremski J S, Riley D C, Black J J and Hogan A W (1990) On the systematic variation in surface aerosol concentration at the South Pole *Atmos Res* **25** 385-396

Savoie D L, Prospero J M, Larsen R J, Huang F, Izaguirre M A, Huang T, Snowdon T H, Custals L and Sanderson C G (1993) Nitrogen and sulfur species in Antarctic aerosols at Mawson, Palmer station and Marsh (King George Island) *J Atmos Chem* **17** 95-122

Shaw G E (1979) Considerations on the origin and properties of the Antarctic aerosol *Rev Geophys* **17** 1983-1998

Siingh D, Pant V and Kamra A K (2013) Temperature-dependence of the positive intermediate ion concentrations at Maitri, Antarctica *Journal of Atmospheric and Solar-Terrestrial Physics* **104** 67-74

Six D, Fily M, Blarel L and Goloub P (2005) First aerosol optical thickness measurements at Dome C (East Antarctica), summer season 2003-2004 *Atmos Environ* **39** 5041-5050

Teinila K, Kerminen K M and Hillamo R (2000) A study of size-segregated aerosol chemistry in the Antarctic atmosphere *J Geophys Res* **105** 3893-3904

Tomasi C *et al*. (2007) Aerosols in Polar Regions: A historical overview based on optical depth and in situ observations *J Geophys Res* **112** D16 205, doi: 10.1029/2007JD008432

Tripathi O P, Jain S L and Arya B C (2002) Monitoring of ozone, water vapour and aerosol optical thickness at Maitri Antarctica *Advances in Marine and Antarctic Science* ISBN 81- 7648-347-8 Page no. 32-349

Vinoj V, Anjan A, Sudhakar M, Satheesh S K, Srinivasan J and Moorthy K K (2007) Latitudinal variation of aerosol optical depths from northern Arabian Sea to Antarctica *Geophys Res Lett* **34** L10807, doi: 10.1029/2007GL029419

Wagenbach D, Ducroz F, Mulvaney R, Keck L, Minikin A, Legrand M, Hall J S and Wolff E W (1998) Sea-salt aerosol in coastal Antarctic regions *J Geophys Res* **103** 961-10, 974

Weller R, Minikin A, Petzold A, Wagenbach D and Konig-Langlo G (2012) Characterization of long-term and seasonal variations of black carbon (BC) concentrations at Neumayer, Antarctica *Atmos Chem Phys Discuss* **12** 25355-25387, doi: 10.5194/acpd-12-25355.

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Research Paper

Six Years Observations ond Analysis of Radiation Parameters and Surface Energy Fluxes on Ice Sheet Near 'Maitri' Research Station, East Antarctica

ASHWAGOSHA GANJU and H S GUSAIN*

Snow and Avalanche Study Establishment, Research and Development Centre, Chandigarh 160036, India

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In the present study, radiation parameters incoming shortwave radiation flux, reflected shortwave radiation flux, albedo have been observed on ice sheet near 'Maitri' research station, East Antarctica. Surface energy fluxes have been estimated using snow-meteorological parameters. Air temperature, surface temperature, relative humidity, wind speed, atmospheric pressure, incoming shortwave radiation flux, reflected shortwave radiation flux, albedo were recorded using automatic weather station installed on ice sheet about 1 km from 'Maitri' research station. Radiation parameters and energy fluxes were obtained for six years from March 2007 to January 2013. Mean incoming shortwave radiation flux, reflected shortwave radiation flux and albedo were observed to be 124 Wm^{-2}, 80 Wm^{-2} and 0.64, respectively, during six years. Daily average air temperature at the observation site varies from 4.6°C to –28.6°C with six years mean of –10.2°C. High katabatic winds are observed at the site with six years mean wind speed of 8.4 ms^{-1}. Net shortwave radiation flux and sensible heat flux were observed to be heat source for the ice sheet with mean values of 44 Wm^{-2} and 28 Wm^{-2}, respectively, while net long wave radiation flux and latent heat flux were observed as heat sink with mean values of –49 Wm^{-2} and –62 Wm^{-2}, respectively. Sublimation of the ice sheet at the rate of 0.017 cm/day has been observed. Results of the present study were also compared with other studies in Antarctica. It has been observed that present study site near 'Maitri' research station has comparatively warmer temperatures, low relative humidity, high wind speed and low albedo compared to other coastal stations in Antarctica. High sublimation rate of the ice sheet at the present study location may attribute to high katabatic winds and warmer temperatures.

Keywords: Radiation Flux; Cryosphere; Transfer Coefficient; Katabatic Winds; Diurnal Variation

Introduction

Solar radiation is the driving force for weather and climate on planet Earth. Absorption, reflection, scattering, evaporation, sublimation, melt, freezing, condensation and other physical phenomena at the earth's surface drives the interaction between earth's surface and atmosphere. These physical processes exchange energy between earth's surface and atmosphere above. The surface energy balance is an essential element of the climate in any region of the world. It has an added significance in the snow/ice covered cryospheric regions, as small changes can affect cryospheric regions largely. In order to study the long term effect of the climate on the snow/ice fields, it is important to understand the variability of radiation parameters and different surface energy fluxes on temporal and spatial scales. The components of the surface energy fluxes are net shortwave radiation flux, net longwave radiation flux, sensible heat flux, latent heat flux and sub-surface conductive heat flux (Paterson 1994, Vihma 2011). These energy fluxes at the surface determine the ablation and accumulation processes (Lewis *et al*., 1998). Quantification of these fluxes can contribute to better understanding of the mass exchange at the surface and subsequently the health of the glacier/ice sheet (Gusain *et al*., 2009). Incoming and reflected shortwave radiation fluxes, down welling and upwelling longwave radiation fluxes are components

**Author for Correspondence: E-mail: gusain.hs@gmail.com*

of the radiative energy flux (King and Turner 1997) while sensible and latent heat fluxes are turbulent energy fluxes.

Many studies have been conducted all over the globe on estimation of surface energy fluxes of snow cover (Gustafsson *et al*., 2001; Fierz *et al*., 2003; Datt *et al*., 2008), glaciers (Wagnon *et al*., 2003; Giesen *et al*., 2008; Sicart *et al*., 2008; Azam *et al*., 2014), ice sheet (Reijmer and Oerlemans 2002; Van den Broeke *et al*., 2004a; Van As *et al*., 2005; Town and Walden 2009; Gusain *et al*., 2011), sea ice (Vihma *et al*., 2009) and lake ice (Doran *et al*., 1996) using *in situ* observations. Different components of surface energy flux differ in contribution to the net surface energy balance. The relative contribution of these energy fluxes strongly depends on the prevailing meteorological, topographical and surface conditions. Radiative energy fluxes are generally observed directly using pyranometers or pyrgeometers. A few parametrization schemes (Berliand 1960, Laevastu 1960, Zillman 1972, Maykut and Church 1973, Brutsaert 1975, Jacobs 1978, Moritz 1978, Marks and Dozier 1979, Dozier 1980, Idso 1981, Bennett 1982, Iqbal 1983, Plüssand Ohmura 1996, Prata 1996, Dilley and O'Brien 1998,Niemelä 2001a, 2001b) are also in vogue to estimate different radiative energy fluxes using *in situ* meteorological observations. Turbulent energy fluxes can be measured directly using eddy covariance system or scintillometers. However, in most of the studies, these energy fluxes have been estimated using bulk transfer technique (Oke 1970, Moore 1983; Schneider 1999; Wagnon *et al*., 2003; Munneke *et al*., 2009; Gusain *et al*., 2014; Azam *et al*., 2014). Bulk transfer equations use meteorological variables over the surface and at screen level height above the surface as input to estimate turbulent energy fluxes (Deardorff, 1968; Oke, 1970; Moore, 1983). Contribution of sub surface heat flux in net energy balance is generally very low compared to radiative and turbulent energy fluxes and can be estimated using temperature measurements at different vertical levels inside the snowpack or ice. Sub-surface heat flux can also be measured directly using heat flux sensors placed inside snow/ice. Present study focuses on estimation of long term surface energy fluxes of the ice sheet near 'Maitri' research station and analyses the temporal variation of energy fluxes during different months of the year.

Study Area and Data

'Maitri' research station is situated in Schirmacher oasis which lies between the latitude S 70°44′ to 70°46′ and longitude E 11°24′ to 11°54′. Schirmacher oasis is located about 70Km inland from Prinsesse Astrid Kyst in Dronning Maud Land, East Antarctica. Continental ice sheet south of Schirmacher oasis is known as Schirmacher glacier. An automatic weather station (AWS) of make Sutron was installed on ice sheet at 70°46′05.1″S, 11°42′12.2″E, at an altitude of 142m. AWS site is about 1 km from 'Maitri' station. Figure1 shows the location of 'Maitri' research station in East Antarctica and automatic weather station installed on ice sheet. Automatic weather station was equipped with the following calibrated sensors:

1. AT/Rh sensor to measure air temperature and relative humidity. It measures air temperature in the range of +50°C to –50°C with an accuracy of $\pm$0.3°C and relative humidity with an accuracy of $\pm$3% from 0% to 90% and $\pm$4% from 90% to 100%.
2. Wind speed and wind direction sensor (Propeller Vane type) of make RM YOUNG for measuring wind speed and direction. Sensor is capable of measuring wind speed in the range of 0-50 ms^{-1} with an accuracy of $\pm$0.3 ms^{-1} and gust survival of 60 ms^{-1}. Sensor can measure wind direction with accuracy of $\pm$3 degrees and range 360 degrees.
3. Pressure transducer located in the enclosure can measure atmospheric pressure from 400mb to 1100mb with an accuracy of 0.5 mb.
4. Upward and downward looking pyranometers of make Kipp and Zonen measures incoming and outgoing shortwave radiation in the wavelength range of 305-2800nm with cosine error of $\pm$1% from 0 to 70° zenith and $\pm$3% from 70° to 80° zenith angle.
5. IR-based snow surface temperature sensor measures snow surface temperature in the range of +50°C to –50°C with an accuracy of $\pm$0.3°C.

The automatic weather station record hourly observations of air temperature, relative humidity, wind speed and direction, incoming and reflected shortwave radiation, atmospheric pressure and snow

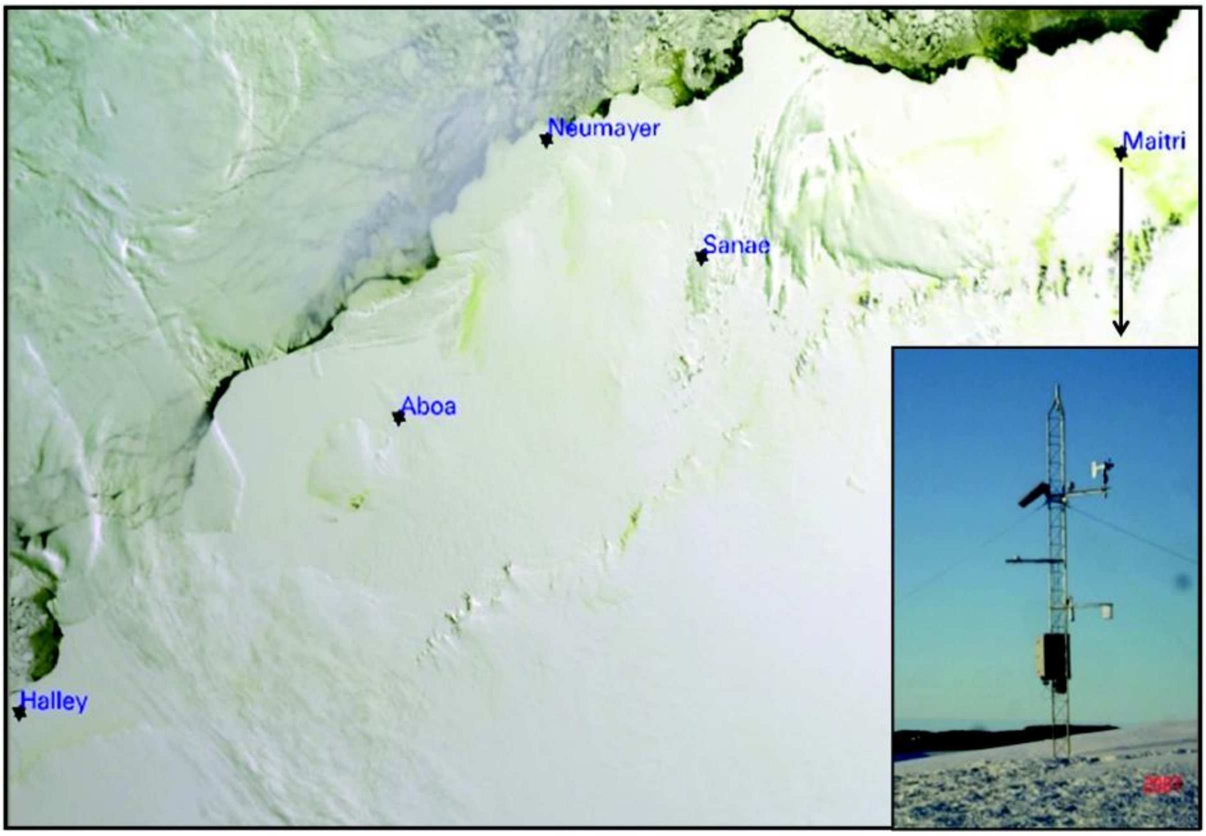

Fig. 1: Study area near 'Maitri' research station

surface temperature. All the sensors of AWS were powered by 100 Ampere-Hour battery and recharged from solar panel. Calibrated heat flux plates were also used to measure sub surface heat flux during summer period. Cloud amount and type had been observed conventionally at 'Maitri' research station.

Methodology

Detailed methodology of estimation of surface energy fluxes are given in Gusain *et al*. (2009) and Gusain *et al*. (2014) and summarized here. Net shortwave radiation flux was estimated using following equation,

$$SHW_{net} = SHW\downarrow - SHW\uparrow \tag{1}$$

Where, $SHW\downarrow$ is incoming shortwave radiation flux and $SHW\uparrow$ is reflected shortwave radiation flux. These fluxes were recorded directly using pyranometer sensor.

Net longwave radiation flux was estimated using following equation,

$$LW_{net} = LW\downarrow - LW\uparrow = \varepsilon_m \sigma T_a^4 - \varepsilon_s \sigma T_s^4 \tag{2}$$

Where, T_a is atmospheric temperature, T_s is ice surface temperature, ε_m is emissivity of the air, ε_s is emissivity of the ice surface and σ is the Stephan Boltzmann constant (5.67 x 10^{-8} W m^{-2} K^{-4}). Air emissivity was calculated using the model given below (Prata, 1996),

$$\varepsilon_m = 1 - (1+w) \exp\{-(1.2+3.0w)^{1/2}\} \tag{4}$$

Where, w is precipitable water content and estimated using air temperature and vapourpresuure as,

$$w = 46.5 (e_a/T_a) \tag{5}$$

Clouds affect the net longwave radiation flux significantly (Ganju *et al*., 1999). In the presence of clouds, net longwave radiation flux was estimated by the following equation,

$$LW_{net} = (\varepsilon_m \sigma T_a^4 - \varepsilon_s \sigma T_s^4)(1-rN) \tag{6}$$

Where, r is coefficient and depends on type and height of clouds. Experimental values reported by US Army Corps of Engrs (1956) are r = 0.76 for low clouds, r = 0.52 for medium clouds and r = 0.26 for high clouds. N is the amount of cloudiness in terms of fraction of sky covered.

Sensible heat flux (SHF) and latent heat flux (LHF) was estimated using bulk aerodynamic method and given as,

$$SHF = (C_p \rho_0/P_0)\, K_n\, P\, u\, (T_a - T_s) \quad (7)$$

$$K_n = k^2 / [\log(z_a/z_0)]^2 \quad (8)$$

Where ρ_0 is the density of air (1.29Kg m^{-3}) at the standard atmospheric pressure P_0 (1.013x10^5Pa), K_n is a dimensionless transfer coefficient, P is mean atmospheric pressure at the measuring site, and u and T_a are measured wind speed and air temperature.k is von Karman's constant (0.41), z_a is sensor height above ground and z_0 is aerodynamic roughness length and a value of 0.001m is adopted for an ice surface (Van de Wal and Russell 1994; Bintanja1995; Konzelmann and Braithwaite 1995).

$$LHF = L_v\, (0.623\rho_0/P_0) K_n\, u\, (e_a - e_s) \quad (9)$$

Where L_v is the latent heat of vaporization, e_a is the atmospheric vapour pressure and e_s is the saturation vapour pressure at the glacier surface. The latter is a function of the surface temperature and is 611Pa for a melting surface (Paterson, 1994). For distinguishing sublimation and condensation, guidelines given by Ambach and Kirchlechner (1986), and Greuell and Konzelmann (1994), has been followed. For condensation Lv = 2.514 $MJKg^{-1}$, and for sublimation L_v = 2.849 $MJKg^{-1}$. When $(e_a - e_s)$ is positive, and T_s = 0deg, water vapour condenses as liquid water on the melting glacier surface with Lv = 2.514$MJKg^{-1}$, when $(e_a - e_s)$ is negative, there is sublimation with Lv = 2.849 $MJKg^{-1}$. Also, when $(e_a - e_s)$ is positive and $T_0 <$ 0 deg, there is deposition from vapour to solid ice with Lv = 2.849 $MJKg^{-1}$. The equations of Sensible and Latent heat fluxes are applicable for neutral atmospheric conditions. In Antarctica, the atmospheric conditions above ice sheet are rarely neutral and so the equations can be applied with stability corrections for the transfer coefficient K_n in terms of Richardson number (Ri). For unstable conditions (Ri<0) transfer coefficient is given by Kw2 = K_n.(1-10R_i). For Ri = 0, Kw2 = K_n; and for stable conditions (Ri>0), Kw2 = K_n/(1+10R_i) (Price and Dunne, 1976). Sub surface heat flux was observed directly using sub surface heat flux plates. Heat flux plates was placed inside the ice sheet at a depth of 10 cm from the surface to record the flow of heat from surface to ground below as well as from ground to the surface (Datt *et al*., 2015).

Results and Discussion

Figures 2 and 3 show daily average surface temperature and daily average air temperature, respectively. Strong annual cycle has been observed for the surface temperature and air temperature during the data period. Large short term variation can also be seen during the annual cycles for these parameters. Daily average surface temperature varied from –30.0°C to 0°C and 6 years average was observed to be –11.3°C. Lowest daily average surface temperature was recorded for 26-July-2012. Daily average air temperature varied from –28.6°C to 4.6°C and 6 years average was observed to be –10.2°C. Lowest and highest daily average air temperature was recorded for 25-July-2009 and 8-November-2007, respectively. In the annual cycle higher temperature was observed during summer season due to radiative heating and temperature dips down during winter in the absence of shortwave radiation. Temperature remains low till the month of September as ice sheet continuously losses heat due to longwave radiation. October onwards as incoming shortwave radiation flux increases, air and surface temperature also increase till the summer months January and February. February onwards again temperature starts decreasing and annual cycle was repeated for each year. Short term variations in the annual cycle are due to change in daily weather and cloud conditions.

Figure 4 shows daily variation in relative humidity (RH) during 6 years. Annual cycle with large short term variations can be observed in the figure. Daily average relative humidity (RH) varied from 26% to 97% and 06 years mean was observed to be 50.8%.Relative humidity was observed high during summer months January and February while low during winter months July, August and transition period from winter to summer September, October. Days with average relative humidity more than 80% corresponds to snowfall days and such events are frequent in coastal region of Antarctica. High relative

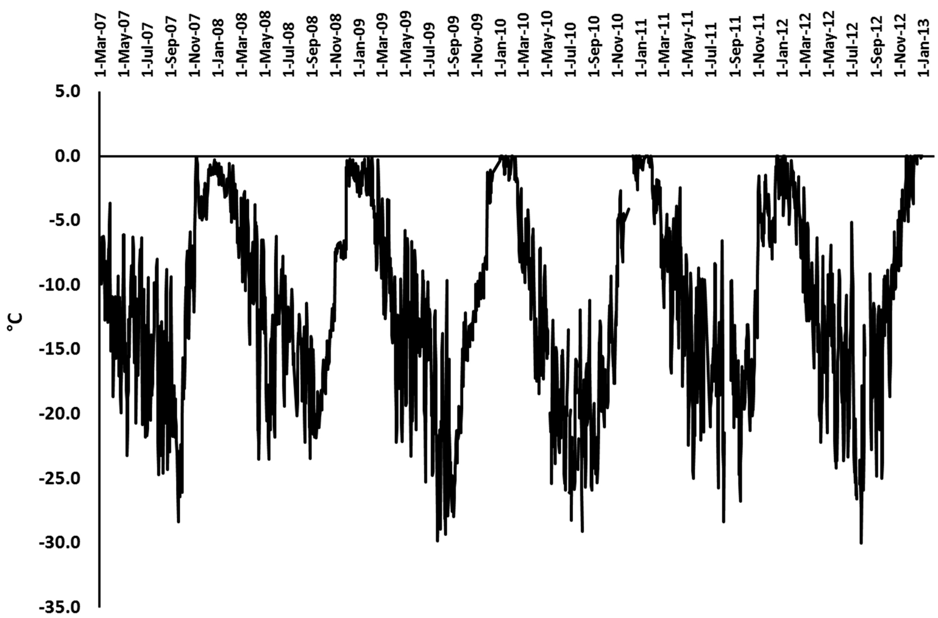

Fig. 2: Daily average surface temperature

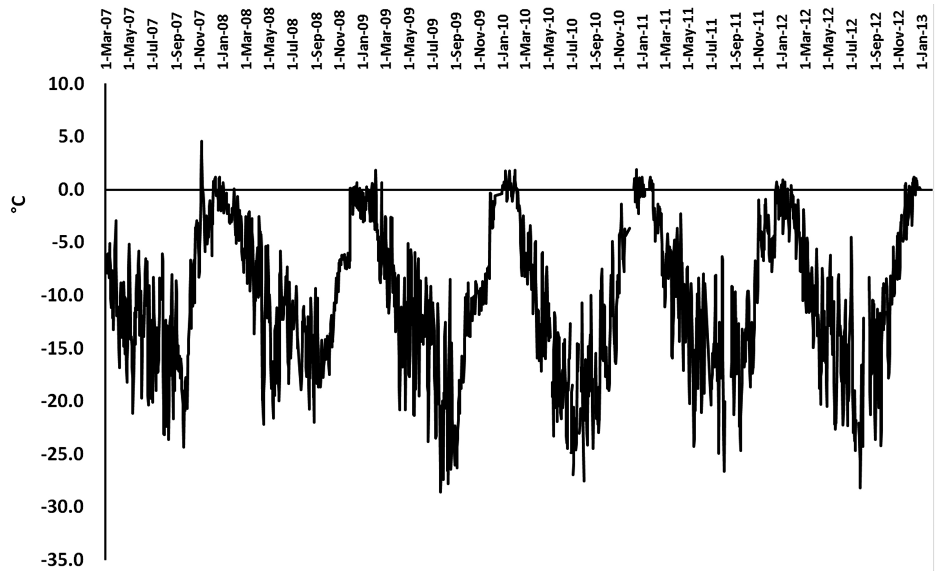

Fig. 3: Daily average air temperature

humidity during summer months is because of warm air advection.

Figure 5 shows daily average wind speed. Daily average wind speed varied up to 32 ms^{-1}. Annual cycle was observed in wind speed with higher winds during winter season and low winds during summer. Strong katabatic winds are observed at the study location with six years mean of 8.4 ms^{-1}. High katabatic winds are due to steep slope at the location from the Antarctic Plateau. Katabatic winds are gravity driven winds blowing down the slope towards periphery of Antarctic continent from the inland high Antarctic plateau. Major wind directions observed at the locations are East, South-East and South. The wind is characterized by short period of light wind followed by a period of high wind. High wind events

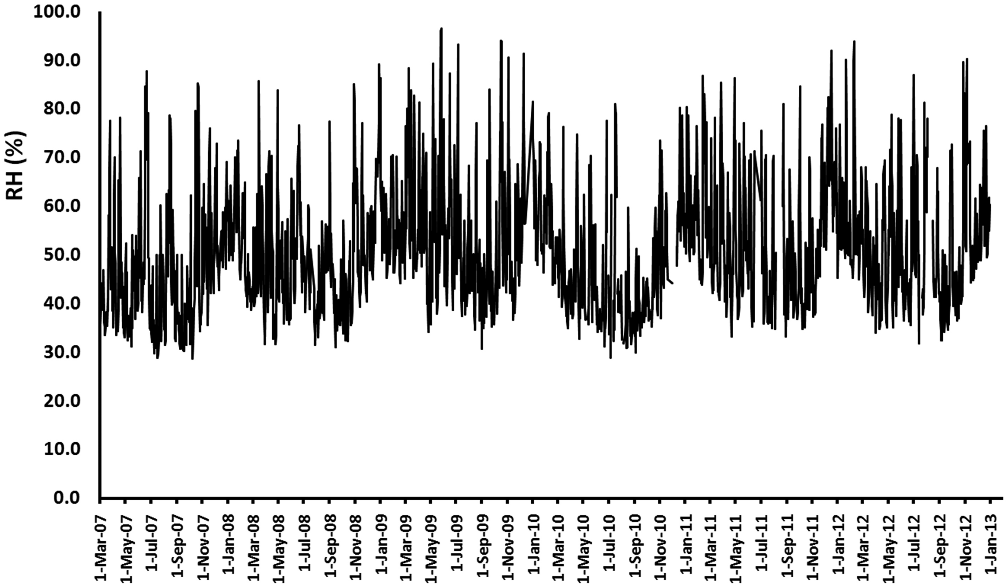

Fig. 4: Daily average relative humidity

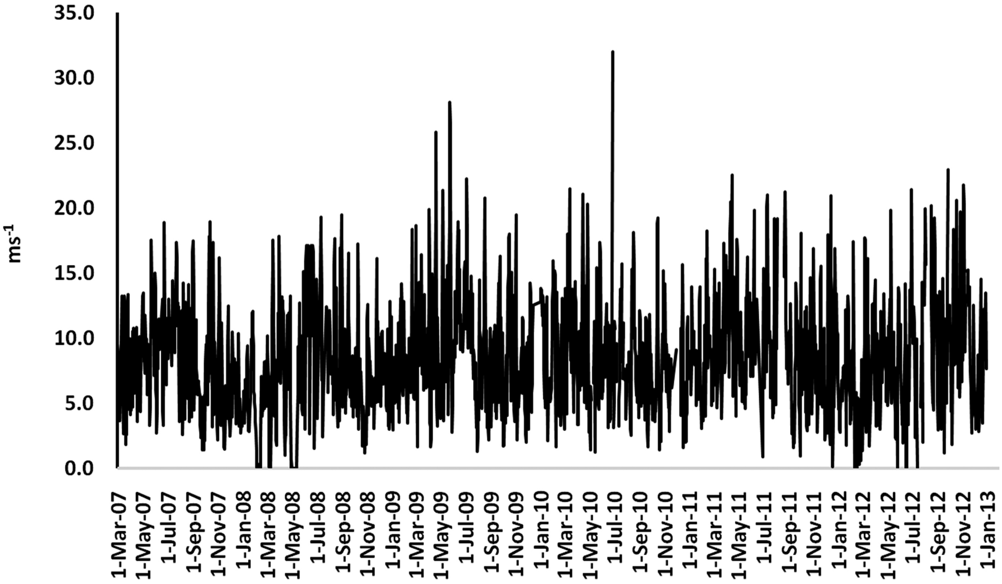

Fig. 5: Daily average wind speed

are generally correspond to passage of low pressure systems at the observation site (Tyagi *et al.*, 2007). Low pressure systems are frequent in the coastal Antarctica due to proximity of Antarctic sea.

Figures 6 and 7 shows the incoming shortwave radiation flux and outgoing shortwave radiation flux. High annual and seasonal variability was observed in the incoming and outgoing shortwave radiation fluxes. Incoming shortwave radiation flux is observed highest during summer, it gradually decreases during transition period from summer to winter and then become zero during peak winter months. Again after winter months, incoming shortwave radiation flux increases during transition period from winter to summer and reaches at highest during peak summer months. The cycle

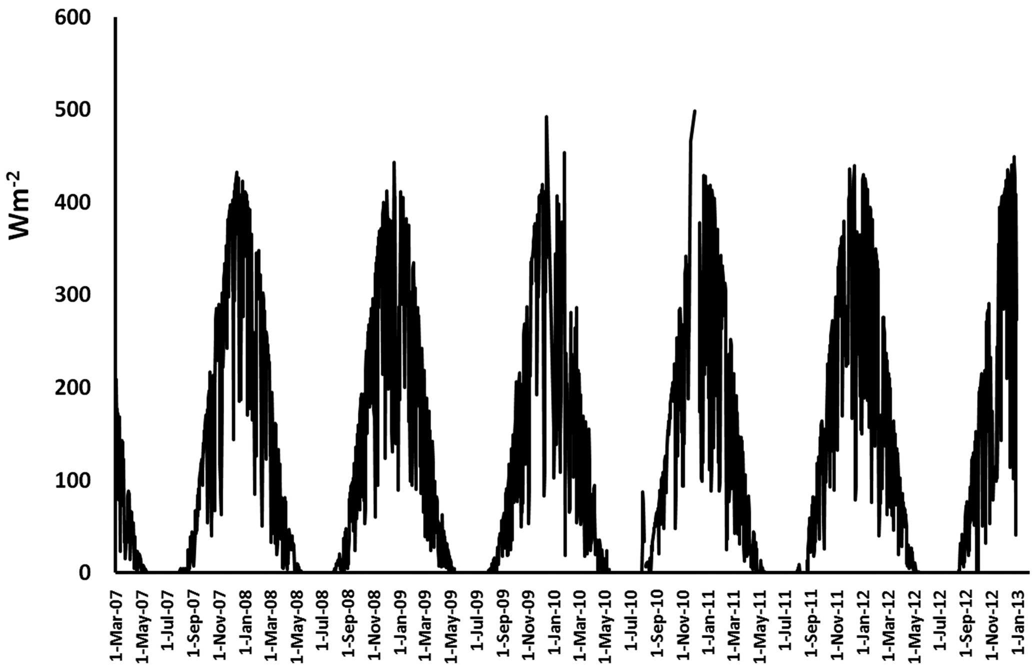

Fig. 6: Daily average incoming shortwave radiation flux

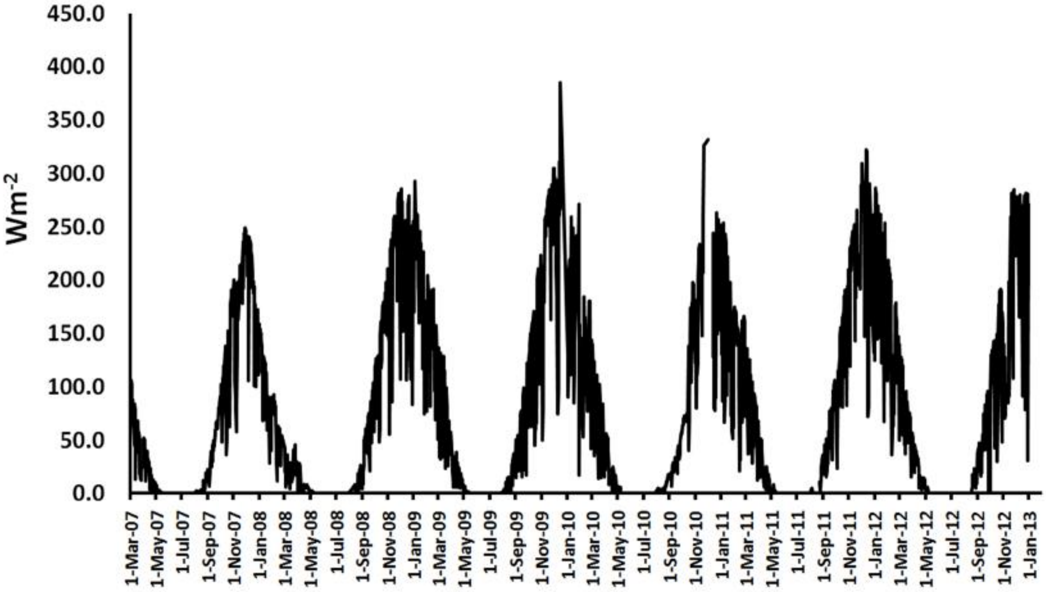

Fig. 7: Daily average outgoing shortwave radiation flux

repeats every year. Seasonal variation in incoming shortwave radiation flux is mainly due to variation in solar zenith angle. Mean solar zenith angle varies from 52° to 88° during summer days while solar zenith angle is ~90° during winter days. For the days of transition period, e.g. March, April, September and October months, solar zenith angle varies between 67.8° to 90°. Daily mean incoming shortwave radiation flux at the observation site was observed up to 500 Wm^{-2}. Six years mean incoming shortwave radiation flux was observed to be 124 Wm^{-2}. Daily average outgoing shortwave radiation flux was observed up to 385 Wm^{-}

^{2} and six years mean was obtained 79.7 Wm^{-2}. Inter-diurnal variation in incoming and outgoing shortwave radiation flux was due to frequent passage of frontal systems and clouds (Van den Broeke *et al.*, 2004b). Daily mean albedo of the glacier surface varied from 0.19 to 0.93 with mean albedo of 0.64 during 6 years.

Temporal variation of net shortwave radiation flux, net longwave radiation flux and net radiation flux. Daily average net shortwave radiation flux varied from 0 Wm^{-2} during winter to 272 Wm^{-2} during summer.As surface temperature approaches 0°C during summer, pronounced melting of the ice sheet was observed. Water layer over ice reduces the albedo of the surface and net shortwave radiation flux increases. Net shortwave radiation flux for the summer months of 2007-08 was high compared to other years. During this particular summer season albedo values observed were low compared to other summer seasons. A rise in daily average air temperatureup to 4.6°C during first week of November 2007 started early melting of the ice sheet and triggered a positive feedback loop of albedo causing excessive melting during the season (Gusain *et al.*, 2009). Net shortwave radiation flux was observed to be the source of heat for the ice sheet with 06 years average of 44.3 Wm^{-2}. Daily average net longwave radiation flux varied from –12 Wm^{-2} to –86 Wm^{-2} during the data period. Antarctic ice sheet continuously losses heat in the form of longwave radiation. Clouds affect longwave radiation flux significantly and less loss of heat from ice sheet is observed during cloudy days. Net longwave radiation flux was observed to be heat sink with 06 years mean of –49.2 Wm^{-2}. Net radiation flux varied from –86 Wm^{-2}during winter to 198 Wm^{-2} during summer and 06 years mean was obtained –4.9 Wm^{-2}. Net radiation flux was observed to be positive during summer months and negative during winter months. During summer net radiation flux act as heat source to the ice sheet while during winter it becomes heat sink. During transition months from summer to winter e.g. March, April, Net radiation flux changes from positive to negative. Similarly, during transition months from winter to summer e.g. September, October, net radiation flux again changes from negative to positive. Net radiation flux line in Fig. 8 cuts the x-axes (representing 0 Wm^{-2}) twice a year. At these points net radiation flux is zero and net shortwave radiation flux equals the net longwave radiation flux. Above these points net shortwave radiation flux dominates net longwave radiation flux and glacier surface absorbs radiation. Absorbed radiation increases the glacier surface temperature and melting start when the surface temperature reaches 0°C. Below these points net longwave radiation flux dominates the net shortwave radiation flux and the glacier surface loses energy, tending to decrease the surface temperature.

Figure 8 shows temporal variation in sensible heat flux and latent heat flux. Strong seasonal and annual cycle was observed in the sensible heat flux during the data period. Sensible heat flux was low during the summer months November, December, January and February as the difference in surface and air temperature was obtained low for these months, resulting into less flow of heat from air to surface or vice versa. Sensible heat flux was comparatively higher during the months March, April, May, June, July and August. Higher values attributed to high rate of heat transfer from air to surface or surface to air due to higher difference in temperature and comparatively high wind speed. Highest sensible heat flux was obtained during the September and October months as air temperatures are much higher compared to surface temperatures during these months. Daily average sensible heat flux varied from –208 Wm^{-2} to 309 Wm^{-2} with 06 years average of 28 Wm^{-2} and act as source of heat to the ice sheet throughout the year.

Latent heat flux has also shown seasonal variation. Lowest values were obtained for winter months and transition period from winter to summer, i.e. during September and October months. Highest values were obtained for summer months, i.e. November, December, January and February. Highest latent heat flux during summer attributed to high rate of sublimation of ice at higher temperatures. Sublimation and evaporation processes slow down due to low temperatures, which attributed to low latent heat flux during winter and transition period. Wind also plays an important role in sublimation and evaporation process. High wind accelerates the process, resulting into higher latent heat flux during windy days. Daily average latent heat flux varied from –260.4 Wm^{-2} to 41.3 Wm^{-2} with 06 years mean of –62.1 Wm^{-2}. Latent heat flux was observed as heat sink to the ice sheet throughout the year and sublimation at the rate of 0.017cm/day is observed at

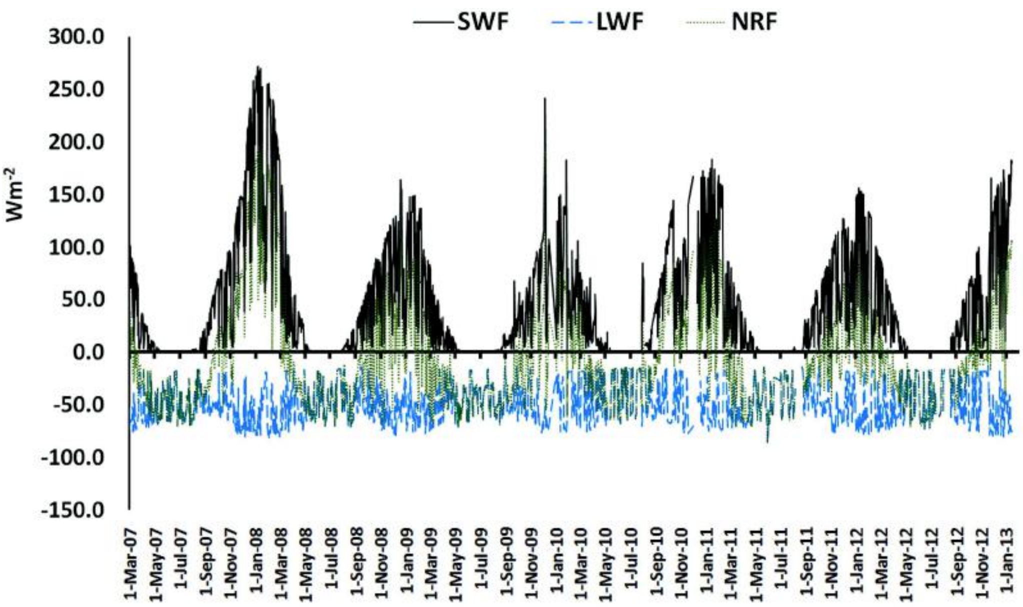

Fig. 8: Daily average sensible and latent heat flux

the observation site.

Figure 9 shows diurnal variation in net radiation flux and net sub surface heat flux at the observation site during summer. Net subsurface heat flux varied from –11.5 Wm^{-2} to 11.3 Wm^{-2}in diurnal variation with mean value of –0.12 Wm^{-2}. Net subsurface heat flux was observed to be less than 1% of net radiation flux during summer.

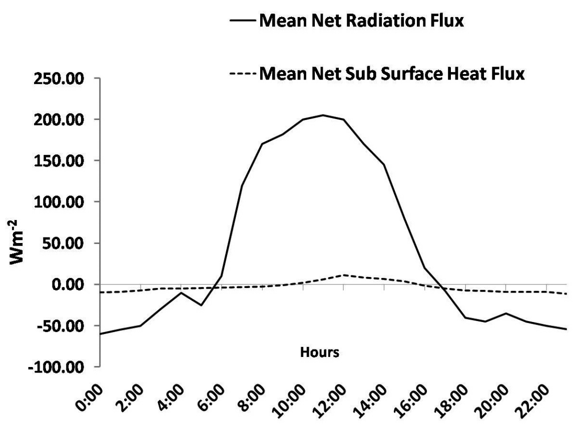

Fig. 9: Diurnal variation in net radiation flux and net sub surface heat flux at observation site during summer

Conclusion

In this paper we have reported 6 years observations and analysis of radiation parameters and surface energy fluxes of ice sheet near Indian research station 'Maitri' in East Antarctica. Daily average air temperature varied between 4.6°C to –28.6°C and 6 years mean air temperature obtained was –10.2 °C. Mean relative humidity at the site was 50.8% and mean wind speed was 8.4 ms^{-1}. Frequent low pressure systems were observed at the site, as site is located in the coastal region of Antarctic continent and has proximity to Antarctic sea. Daily average incoming shortwave radiation flux varied from 0 to 500 W m^{-2} with 06 years mean of 124 W m^{-2}. Similar values of incoming shortwave radiation flux has been reported in other coastal region of Antarctica. Albedo at the site varied from 0.19 to 0.93 and mean albedo was 0.64. Albedo value of 0.19 corresponds to melting glacier during summer while 0.93 corresponds to fresh snow over ice surface. Mean albedo obtained at the present site is low compared to other glacier site of Antarctica reported earlier. Low values of outgoing shortwave radiation flux (6 years mean 79.7 W m^{-2}) obtained at the site were due to low albedo values. Strong seasonal cycle was obtained in different surface energy fluxes, which attributed to seasonal cycle in solar radiation and meteorological parameters at the site. Seasonal cycle in solar radiation attributed to seasonal variation in solar zenith angle. Net shortwave radiation flux obtained was the main source of heat to the ice sheet during summer while net longwave radiation flux and latent heat flux were the main heat sink, as ice sheet continuously losses heat due to longwave radiation and sublimation process. Sensible heat flux became main heat source to the ice sheet during winter and transition period. Mean net sub surface heat flux was obtained –0.12 W m^{-2} during summer and contributed less than 1% of the net radiation flux to the net energy balance of the ice sheet. Mean values of net shortwave radiation flux, net longwave radiation flux, sensible heat flux and latent heat flux were obtained 44.3 W m^{-2}, –49.2 W m^{-2}, 28 W m^{-2} and –62.1 W m^{-2}, respectively during 6 years. Latent heat flux observed at the site is equivalent to the sublimation rate of 0.017cm/day. Mild temperature, low relative humidity and high katabatic wind compared to other Antarctic coastal locations cause high latent heat flux of the ice sheet near 'Maitri' research station.

Acknowledgement

Authors are thankful to the Scientists/Technical Officers and technical staff of SASE for valuable data collection in Antarctica. Authors are also thankful to ESSO-National Centre for Antarctic and Ocean Research (NCAOR) for logistic support to the technical team of SASE.

References

Ambach W and Kirchlechner P (1986) Nomographs for the determination of meltwater from ice and snow surfaces by sensible and latent heat *Wetter Leben* **38** 181-189

Azam M F, Wagnon P, Vincent C, Ramanathan A L, Mandal A and Pottakkal J G (2014) Processes governing the mass balance of ChhotaShigri Glacier (Western Himalaya, India) assessed by point-scale surface energy balance measurements *The Cryosphere Discussion* **8** 2867-2922

Bintanja R (1995) The local surface energy balance of the Ecology Glacier, King George Island, Antarctica: Measurements and modelling *Antarctic Science* **7** 315-325

Bennett T J (1982) A coupled atmosphere–sea ice model study of the role of sea ice in climatic predictability *Journal of Atmospheric Science* **39** 1456-1465

Berliand T C (1960) Method of climatological estimation of global radiation *Meteorologiyai Gidrologiya* **6** 9-12

Brutsaert W (1975) On a derivable formula for long wave radiation from clear skies *Water Resource Research* **11** 742-744

Datt P, Gusain H S and Das R K (2015) Measurements of net subsurface heat flux in snow and ice media in Dronning Maud Land Antarctica *Journal Geological Society of India* **86** 613-619

Datt P, Srivastava P K, Negi P S and Satyawali P K (2008) Surface energy balance of seasonal snow cover for snow-melt estimation in N-W Himalaya *Journal of Earth System Science* **117** 567-573

Deardorff J W (1968) Dependence of air-sea transfer coefficients on bulk stability *Journal of Geophysical Research* **73**(8) 2549-2557

Dilley A C, O'Brien and D M (1998) Estimating downward clear sky long-wave irradiance at the surface from screen temperature and precipitable water *Quaterly Journal of Royal Meteorological Society* **124** 1391-1401

Doran P T, Mckay C P, Meyer M A, Andersen D T, Wharton J R, R A and Hastings J T, (1996) Climatology and implications for perennial lake ice occurrence at Bunger Hills Oasis, east Antarctica *Antarctic Science* **8** 289-296

Dozier J (1980) A clear sky spectral solar radiation model for snow-covered mountainous terrain *Water Resource Research* **16** 709-718

Fierz C, Riber P, Adams E E, Curran A R, Föhn P M B, Lehning M and Plüss C (2003) Evaluation of snow-surface energy balance models in alpine terrain *Journal of Hydrology* **282** 76-94

Ganju A, Satyawali P K, Sing A and Sethi D N (1999) Snowcover simulation model - A review *Defence Science Journal* **49** 419-436

Giesen R H, Van den Broeke M R, Oerlemans J and Andreassen L M (2008) Surface energy balance in the ablation zone of Midtdalsbreen, a glacier in southern Norway: Interannual variability and the effect of clouds *Journal of Geophysical Research* **113** D21111 doi: 10.1029/2008JD010390, pp.1-17

Greuell W and Konzelmann T (1994) Numerical modelling of the energy balance and theenglacial temperature of the Greenland ice sheet: calculation for the ETH-camp location (West Greenland, 1155 m a.s.l) *Global and Planetary Change* **9** 91-114

Gusain H S, Mishra V D and Arora M K (2014) A four-year record of the meteorological parameters, radiative and turbulent energy fluxes at the edge of the East Antarctic ice sheet, close to Schirmacher Oasis *Antarctic Science* **26** 93-103

Gusain H S, Mishra V D and Negi A (2011) Comparative study of the radiative and turbulent energy fluxes during summer and winter at the edge of the Antarctic ice sheet in Dronning Maud Land –East Antarctica *MAUSAM* **62** 557-566

Gusain H S, Singh K K, Mishra V D, Srivastava P K and Ganju A (2009) Study of surface energy and mass balance at the edge of the Antarctic ice sheet during summer in Dronning Maudland, East Antarctica *Antarctic Science* **21** 401-409

Gustafsson D, Stähli M and Jansson P-E (2001) The surface energy balance of a snow cover: comparing measurements to two different simulation models *Theoretical and Applied Climatology* **70** 81-96

Idso S B (1981) A set of equations for full spectrum and 8- to 14-ìm and 10.5- to 12.5- μm thermal radiation from cloudless skies *Water Resource Research* **17** 295-304

Iqbal M (1983) *An Introduction to Solar Radiation*, Academic Press, 390 pp

Jacobs J D (1978) Radiation climate of Broughton Island, Energy budget studies in relation to fast-ice breakup processes, In: Davis Strait (Ed.). *Occas. Pap., FULL FORM* vol. **26**, *Institute of Arctic and Alpine Research*, University of Colorado, Boulder, United States, pp. 105-120

King J C and Turner J (1997) *Antarctic Meteorology and Climatology*, Cambridge University Press, UK, pp. 409

Konzelmann T and Braithwaite R J (1995) Variations of ablation, albedo and energy balance at the margin of the Greenland ice sheet, Kronprins Christian Land, eastern north Greenland *Journal of Glaciology* **41** 174-182

Laevastu T (1960) *Factors affecting the temperature of the surface layer of the sea*, Academic Book Store, Helsinki, 136 pp

Lewis K J, Fountain A G and Dana G L (1998) Surface energy balance and melt water production for a Dry Valley glacier, Taylor Valley, Antarctica *Annals of Glaciology* **27** 603-609

Marks D and Dozier J (1979) A clear-sky long wave radiation model for remote alpine areas *Archive fur Meteorologie Geophysik und Bioklimatologie* **27** 159-178

Maykut G A and Church P F (1973) Radiation climate of Barrow, Alaska, 1962-66 *Journal of Applied Meteorology* **12** 620-628

Moore R D (1983) On the use of bulk aerodynamic formulae over melting snow *Nordic Hydrol*ogy pp. 193-206

Moritz R E (1978) A model for estimating global solar radiation, Energy budget studies in relation to fast-ice breakup processes in Davis Strait. *Occasional Paper of University of Colorado, Institute of Arctic and Alpine Research* **26** 121-142

Munneke P K, Van Den Broeke M R, Reijmer C H, Helsen M M, Boot W, Schneebeli M and Steffen K (2009) The role of radiation penetration in the energy budget of the snowpack at Summit, Greenland *The Cryosphere* **3** 155-165

Niemelä S, Räisänen P and Savijärvi H (2001a) Comparison of surface radiative flux parameterizations Part I. Longwave radiation *Atmospheric Research* **58** 1-18

Niemelä S, Räisänen P and Savijärvi H (2001b) Comparison of surface radiative flux parameterizations Part II. Shortwave radiation *Atmospheric Research* **58** 141-154

Oke T R (1970) Turbulent transport near the ground in stable conditions *Journal of Applied Meteorology* **9** 778-786

Paterson W S B (1994) *The physics of glaciers* 3rd edition Elsevier, Oxford, 480

Plüss C and Ohmura A (1996) Longwave radiation on snow-covered mountainous surfaces *Journal of Applied Meteorology* **36** 818-824

Prata A J (1996) A new longwave formula for estimating downward clear-sky radiation at the surface *Quarterly Journal of the Royal Meteorological Society* **122** 1127-1151

Price A G and Dunne T (1976) Energy balance computation of snowmelt in a sub Arctic area *Journal of Resource* **12** 686-694

Reijmer C H and Oerlemans J (2002) Temporal and spatial variability of the surface energy balance in Dronning Maud Land, East Antarctica *Journal of Geophysicacl Research* **107** 4759, doi: 10.1029/2000JD000110, 1-12

Schneider C (1999) Energy balance estimates during the summer season of glaciers of the Antarctic Peninsula *Global and Planetary Change* **22** 117-130

Sicart J E, Hock R and Six D (2008) Glacier melt, air temperature and energy balance in different climates: The Bolivian Tropics, the French Alps, and northern Sweden *Journal of Geophysical Research* **113** D24113, doi:10.1029/2008JD010406, 1-11

Town M S and Walden V P (2009) Surface energy budget over the South Pole and turbulent heat fluxes as a function of an empirical bulk Richardson number *Journal of Geophysical Research* **114** D22107, doi: 10.1029/2009JD011888, 1-15

Tyagi A, Singh U P and Mohapatra M (2011) Weather & weather systems at Schirmacher Oasis (Maitri) during recent two decades – A review *MAUSAM* **62** 513-534

U S Army Corps of Engineers (1956) *Summary report on the snow investigations - snow hydrology*, Portland, OR: North Pacific Division, Corps of Engineers, US Army, 434p

Van As D, Van Den Broeke M and Van De Wal R (2005) Daily cycle of the surface layer and energy balance on the high Antarctic Plateau *Antarctic Science* **17** 121-133

Van de Wal R S W and Russell A J (1994) A comparison of energy balance calculations, measured ablation and melt water runoff near Sondre Stromfjord, West Greenland *Global and Planetary Change* **91** 29-38

Van Den Broeke M, Reijmer C H and Van De Wal R S W (2004a) A study of the surface mass balance in Dronning Maud Land, Antarctica, using automatic weather stations *Journal of Glaciology* **50** 565-582

Van den Broeke M, Reijmer C and Van de Wal R (2004b) Surface radiation balance in Antarctica as measured with automatic weather stations *Journal of Geophysical Research* **109** D09103, doi: 10.1029/2003JD004394, pp. 1-17

Vihma T (2011) Atmosphere-snow/ice interactions, Encyclopedia of Snow, Ice and Glaciers (Eds: Vijay P. Singh, Pratap Singh and Umesh K. Haritashya), Springer, 1253

Vihma T, Johansson M M and Launiainen J (2009) Radiative and turbulent surface heat fluxes over sea ice in the western Weddell Sea in early summer *Journal of Geophysical Research* **114** 1-18

Wagnon P, Sicart J E, Berthier E and Chazarin J P (2003) Wintertime high-altitude surface energy balance of a Bolivian glacier, Illimani, 6340 m above sea level *Journal of Geophysical Research* **108** D6, doi:10.1029/ 2002JD002088, 1-14

Zillman J W (1972) *A study of some aspects of the radiation and heat budgets of the southern hemisphere oceans*, Meteorological Study No. 26, Commonwealth Bureau of Meteorology, Canberra, Australia, pp. 562.

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Research Paper

Progress in Meteorological Studies Around Indian Stations in Antarctica

V K SONI*, M SATEESH, ANAND K DAS and S K PESHIN
India Meteorological Department, Earth System Science Organisation, New Delhi 110 003, India

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The study of climate of Antarctica and its role in the Earth system is critically important as the region experiences change that has global implications. The climate of the continent and the surrounding ocean are closely coupled to other parts of the global environment by the ocean and the atmosphere. Subjects of immediate interest are forecasting of weather and climate and understanding the effects and likely impacts of climate change. India Meteorological Department is taking part in Indian Scientific Expeditions to Antarctica since the very first expedition during 1981-82. The meteorological data collected at Maitri station for the period 1990-2015 have been analyzed. The long term analysis of temperature record showed a cooling trend at Maitri station. The trend analysis of pressure, wind and blizzards during the period 1990-2015 is also discussed. Recently, the India Meteorological Department has established manned permanent meteorological observatory at Bharati station with the objective to collect data on meteorological parameters, solar radiation and ozone so as to understand the Antarctic atmospheric processes and dynamics. WMO has enlisted Meteorological Observatory at Bharati, and assigned WMO Index number 89776. A GPS-based ozonesonde system has also been installed at Bharati for measurement of vertical profile of ozone. IMD provides weather forecast of Maitri and Bharati stations.

Keywords: Antarctica; Blizzard; Temperature; Pressure; Wind

Introduction

Antarctica is an important part of our climate system and its sensitivity to climate changes, however, very few meteorological measurements are available. In order to address this issue, the World Meteorological Organization (WMO) strongly recommended that all research station should set up a meteorological observatory and data be provided through the Global Telecommunication System.

IMD's Antarctic Meteorological Programme continues to be an integral part of the Indian Scientific Expedition to Antarctica since the very first expedition during 1981-82. During 2nd expedition (1982-83), surface meteorological observatory was established at DakshinGangotrion an ice-shelf about 20 km from the coast. A Permanent station "DakshinGangotri" and a year round meteorological observatory was established during the third Indian expedition in 1983-84. This was the first time the Indian team started over wintering in Antarctica to carry out scientific programme. In February 1983, ozone soundings were initiated. During 4th expedition (1984-85) trial Data Collection Platform (DCP) was commissioned for down loading INSAT IB data and during 5th expedition (1985-86), Data Collection Platform (DCP) was made fully functional. Measurement of global solar radiation was started during 1984-85. Observational program continued till Jan 1990 at DakshinGangotri until this station was decommissioned. DakshinGangotriis now non-functional due to its complete burial under the ice.

The Second station "Maitri" was established in 1989. Meteorological observation Programme of IMD was started from January, 1990 (from 9th expedition) and is continuing till date without any break. Automatic weather station was setup at Maitri during 26th expedition. Recently IMD has implemented Polar WRF model for Maitri and Bharati region at the horizontal resolution of 15 km using initial and boundary conditions of the IMD GFS T-382.Daily Forecasts for next 48 hours are produced based on available

**Author for Correspondence: E-mail: soni_vk@yahoo.com*

observations, satellite images of NOAA and synoptic charts provided by Weather Service of South Africa.

Maitri is located in the valley of central part of Schirmacher Range, Dronning Maud Land, East Antarctica. The Schirmacher Range lies between the Wolthat Mountains about 80 km to the south and the tip of the shelf ice that is about 100 km to the north. The northern boundary of the Schirmacher oasis has an abrupt and steep fall towards the shelf ice. Maitri is affected by the eastward moving depressions that are synoptic scale frontal systems. These systems move in the circumpolar trough zone that lies between 60º and 66º S meandering north and south between seasons. The large amplitude cloud bands in association with these systems move across the station, producing dramatic variation in cloud cover. The cyclonic circulation associated with these low-pressure systems is frequently seen on the 500 hPa chart. These systems bring warm and moist air to the coastal areas of the Antarctic continent from northern latitudes. Therefore, when a depression approaches the station, pressure starts falling continuously and temperature starts rising. The rise in temperature, which can be of the order of 10ºC during a blizzard, is also due to the fact that the low level inversion is broken because of turbulence caused by increase in wind speed. After the system moves away, often pressure increases steeply, temperature falls, wind becomes light or calm and the sky clears. On some occasions when small low pressure system move at relatively higher latitudes, the skies are overcast with stratus clouds and calm or light wind prevails. Such situations result in heavy snowfall at the station.

Antarctica is mainly divided into three regions namely, West Antarctica, East Antarctica and Antarctic Peninsula. A mountain range known as Transantarctic Mountains in Antarctica extends across the continent from Cape Adare in northern Victoria Land to Coats Land with some interruptions in between. These mountains divide East Antarctica and West Antarctica. Sharp contrast in temperature trends are observed by many researchers in East Antarctica and West Antarctica. The southern hemisphere (SH) annular mode (SAM), also known as Antarctic Oscillation (AAO) is the principal mode of variability of the SH extra-tropical atmospheric circulation (Thompson and Wallace, 2000). The SAM is defined as the zonal mean atmospheric pressure difference between the mid-latitudes (~40ºS) and high latitude (~65ºS) (Marshall, 2003). SAM alters the north-south movement of westerly wind belt that circles the Antarctic. During positive phase of SAM, pressures are lower than normal over Antarctica, and westerly winds are stronger than normal over the Southern Ocean.

Observations and Analysis

The surface meteorological observation data, i.e. maximum and minimum temperature, mean sea level pressure, wind collected by the India Meteorological Department at Maitri for the period 1990-2015 have been analyzed in this paper. The observers also keep record of blizzards at Maitri. The trend in frequency of Blizzards and their maximum duration is also examined. The definition of blizzard may vary from region to region (e.g., Bluestein, 1993; Wild, 1995; Branick, 1997). The following criterion is used by IMD to define the blizzard:

1. Blowing snow with or without snowfall.
2. Visibility less than 1 km
3. Wind speed greater than or equal to 23 kts.

Depending on the situation to call a meteorological condition ‘a blizzard’, sometimes any one of the above criteria is waived off. For example, copious snowfall is recorded for two days at a stretch followed by winds, as low as 10 to 15 knots can cause a severe blizzard with visibility less than 10 meters as the area covered by snowfall sometimes exceed several hundred square kilometers in Antarctic regions. At times even in very high winds (around 60 to 70 kts) the visibility may not decrease to 1 km level due to little snowfall or very low temp. Such cases are also considered as blizzard. Even light to moderate winds upto 15 knots can cause moderate to intense blizzards if fresh snow is present on the ground. Such blizzards sometimes last for periods beyond 12 hours as the ground level snow is swept across the station from far off places, as far as 200 km continuously. Visibility of less than 10m is quite common during such blizzards. Reasonably good vertical visibility is an indicator of such blizzards.

Results and Discussion

Surface Air Temperature Trends

The air temperature of Antarctic is not controlled mainly by insolation. The very slant angle of solar radiation (low angle of incidence), very high albedo of snow/ice surface, low atmospheric turbidity, absence of vegetation and no major landmass nearby makes the Antarctica a very cold region on the Earth. During the dark period in the austral winter when sun does not rise above the horizon, there continues to be heat loss to space, but there is no input insolation. This causes temperatures to drop to their lowest point of the year. Furthermore the air in Antarctica is very dry and because of this very little heat emitted by ground is retained by the atmosphere. Temperature is influenced more or less by the heat transport mechanisms, wind and weather phenomena which perturb radiation. Persistent clear sky with light wind also lead to lower temperature of Antarctica region. On cloudy days, diurnal variation of temperature was found to be very low as compared to that on clear sky days as expected. Similarly night temperature used to drop considerably during cloud free nights.

Turner *et al*. (2005) examined surface temperature trends from 19 Antarctic stationswith long records. The spatial pattern of temperature change can be broadly summarized as rapid warming at stations on the Antarctic Peninsula and little change, or modest cooling at stations along the coast of East Antarctica. Nicolas and Bromwich (2014) observed statistically significant annual warming in the Antarctic Peninsula and virtually all of West Antarctica, but no significant temperature change in East Antarctica during 1958-2012. There is sharp contrast in temperature change on either side of the Transantarctic Mountains which divides East and West Antarctica. Several researchers examined the surface air temperature data of past several decades and observed that the Antarctic Peninsula and Western Antarctica are among the most rapidly warming regions of southern hemisphere (Turner *et al*., 2005, Chapman and Walsh 2007, Steig *et al*., 2009, Bromwich *et al*., 2013, Nicolas and Bromwich, 2014). In contrast, East Antarctica has experienced an insignificant, cooling trend (Schneider *et al*., 2012, Nicolas and Bromwich 2014). Smith and Polvani (2016) also observed annually averaged warming of the Antarctic Peninsula and West Antarctica while very small trends over East Antarctica. They further found that this asymmetry is because of highly significant warming of West Antarctica in austral spring and a cooling of East Antarctica in austral autumn. This large spatial asymmetry in temperature trends between West and East Antarctica is not yet understood clearly. Some researchers have attributed the cooling of East Antarctic and the warming of the Peninsula to positive trend in the Southern Annular Mode (Thompson and Solomon 2002, Nicolas and Bromwich 2014). Nicolas and Bromwich (2014) examined the influence of the southern annular mode (SAM) on Antarctic temperature trends. They suggested that the trend of the SAM toward its positive phase in austral summer and fall since the 1950s has had a statistically significant cooling effect not only in East Antarctica but also in West Antarctica (only in fall). Smith and Polvani (2016) examined the relationship between the SAM and Antarctic temperature trends and conclude that SAM is most likely contributor to the observed temperature trends in austral autumn but natural climate variability can be likely contributor to the recent warming of West Antarctica and of the Peninsula.

Monthly mean variation of maximum, minimum and average surface air temperature is shown in Fig. 1. The surface air temperature over the Maitri has a seasonal variation with peak observed during local summer (December and January). The peak during summer is due to solar energy warming up the surfaces. The temperature gradually decreases from January onwards up to August. From August to September temperature rises slightly and thereafter increases sharply from October. The surface air

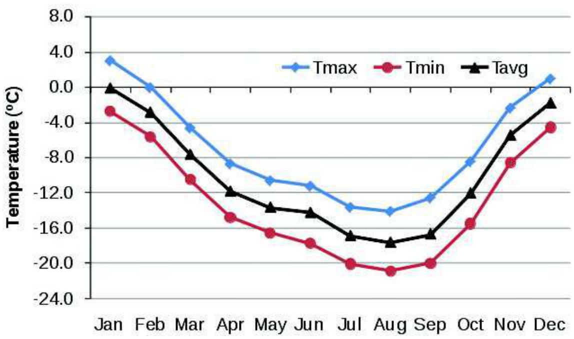

Fig. 1: Monthly mean (1990-2015) variation of maximum, minimum and average temperature

temperature rises slightly form from May to June. This may be due to the frequent movement of extra-tropical low pressure systems which causes the warm and moist air drawn from lower latitudes and mixed with dry and cold continental air thus causes increase in temperature. Generally during the blizzard period, a rise in the temperature was observed due to the same reason. The highest mean monthly maximum and minimum temperature is found in January. The lowest maximum (–14.1°C) and lowest minimum temperature (–20.9°C) is witnessed in August. There are incidences when the surface air temperature enhances due to the presence of a blocking polar high, it is observed primarily during local winter season. The average annual temperature is around –10±0.8°C. The winter air temperatures are observed in April and stay around –12°C to –17°C during the succeeding months. By the temperature regime, the winter season continues for six months from April to September. July/August is the coldest month with mean temperature aroud –17°C. Summer is warm and continues for two months from December to January when average monthly temperature is close to zero. The highest temperatures are recorded during the summer solstice. During this period, rapid snow and ice melting occurs and numerous relief depressions are filled with water. Based on the temperature, two other seasons can be categorized as spring (October-November) and autumn (February-March).

Long-term data for the period 1990-2015 available from Maitri is used to study the temporal trend in maximum, minimum and average temperature (Figs. 2, 3, 4A and 4B). The trends were computed using a standard least-squares method, with the Mann Kendal test used to calculate the significance levels. Statistically significant trend at –0.053°C year^{-1} over

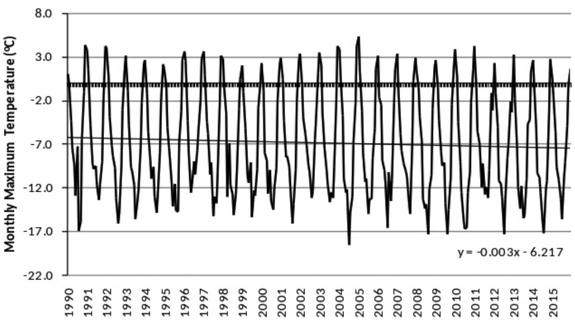

Fig. 2: Long-term variation in Monthly mean maximum temperature (1990-2015)

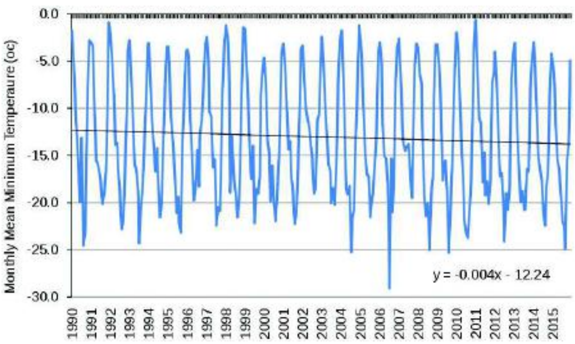

Fig. 3: Long-term variation in Monthly mean minimum temperature (1990-2015)

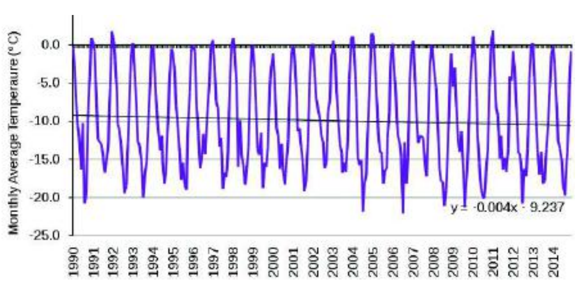

Fig. 4: (A) Long-term variation in Monthly mean average temperature (1990-2015)

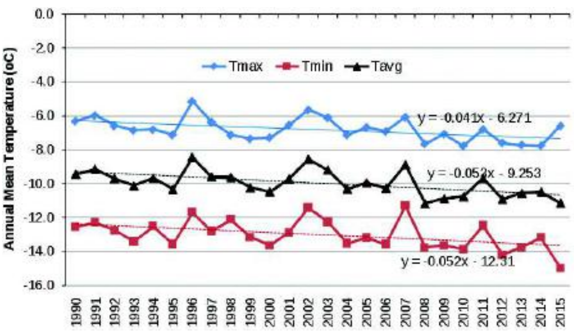

Fig. 4: (B) Long-term variation in annual mean temperatures (1990-2015)

1990-2015, a figure that is significant at the <5% level. The temperature trends observed at Maitri are similar to that observed at neighboring Russian station Novolazarevskaya during 1990-2015.

Mean Sea Level Pressure Trends

The mean monthly variation of mean sea level pressure during the period 1990-2015 is depicted in Fig. 5. Annual variations of atmospheric pressure, similar to the other Antarctic stations have two maximums (in June and January) and two minimums (in March and

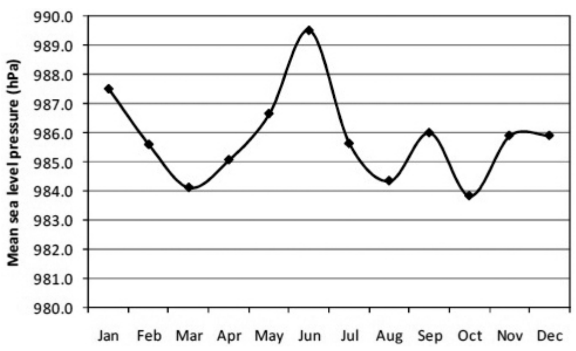

Fig. 5: Monthly variation of mean sea level pressure (MSLP)

October). One peak in the month of June has mean value of 989.5 hPa and the other in January with value of 987.5 hPa. The MSLP pressure fell to a low value of 984 hPa in March and then steadily increases till June.

Monthlymean sea level pressure (MSLP) trend for the Maitriduring 1990-2015 is depicted in Fig. 6. A consistent decrease of pressure at Maitri of –0.002 hPa year^{-1} was observed during 1990-2015 at Maitri. Turner *et al*. (2005) observed decreases in pressure

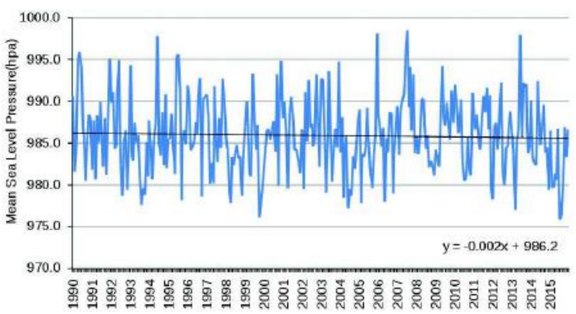

Fig. 6: Long-Term variation of monthly mean sea level pressure (MSLP)

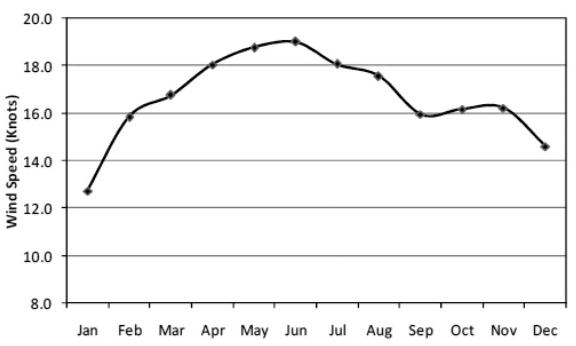

Fig. 7: Monthly variation of mean wind speed (knots)

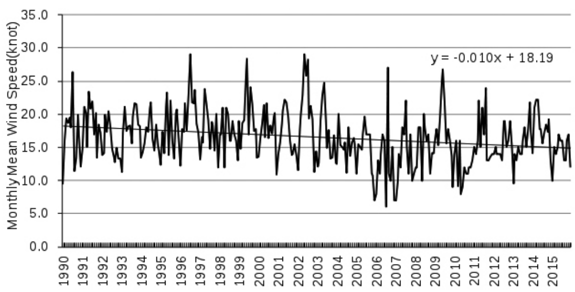

Fig. 8: Long-Term variation of monthly mean wind speed (knots)

in all sectors of the Antarctic, with the most negative trends being at Molodezhnaya (statistically significant at the 1% level) and Mirny station.

Surface Wind Speed Trends

Antarctica is a dome of ice with a 4000m high plateau in its interior sloping towards its perimeter at coast. The surface wind at Maitri is mainly katabatic in nature predominantly from south-east direction. The katabatic wind refers to cold and relatively dense air near the surface moving downhill due to gravity. As the cold heavy wind moves towards sea, it gathers speed to very high value. The winds at Maitri are predominantly easterly and south-easterly. The confluence zone east, south-east and south is a zone of convergence at Maitri which enhance supply of radiative cooling of air near surface along the coastal slopes as a result katabatic winds become stronger and more persistence (Kumar and Gupta, 2007). The winter months are the windiest months at Maitri with mean wind speed around 18 knots (Fig. 5). Minimum mean wind speed is observed during summer ranging from 12 to 14 knots. The weak winds during summer are due to less cyclonic activities. The trends in near-surface wind speed for the Maitri is presented in Fig. 10. Declining trend of 0.13 knots year^{-1} is observed at Maitri for the period 1990-2015. The declining trend in mean wind speed can be attributed to decreasing trend in the frequency of cyclonic disturbances affecting Maitri station.Further, A decrease in wind speed would result in a more stable boundary layer and colder conditions at the surface, which would explain the trend towards colder surface air temperature.

Long Term Variation in Frequency of Blizzards

Blizzards at Maitri are usually warm, moist and are associated with eastward moving cyclone situated north or northeast of Maitri station (Rasal, 2003). Mainly the blizzards are observed during June to September. Tyagiand co-workers (2011) found that due to cyclonic activities, warm air masses are transported toward Schirmacher Oasis which causes rise of temperature at Maitri. The longer duration of blizzard depends on slow moving blocking anticyclone situated east of Maitri station at lower latitude. The blocking high is the high pressure system which remains at the station for several days in the area where zonal flow prevails. This high pressure system plays a blocking role in slowing the cyclone. The long term variation in frequency of blizzards and duration of longest blizzard is presented in Figs. 9 and 10, respectively. The frequency of blizzards is decreasing at a rate of 0.29 blizzards year^{-1}. Durations of longest blizzard is also found to be decreasing.

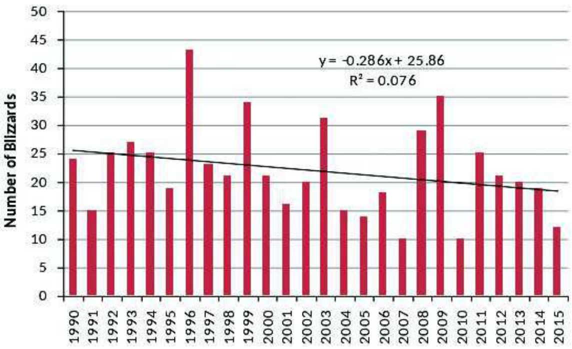

Fig. 9: Frequency of Blizzards at Maitri during 1990-2015

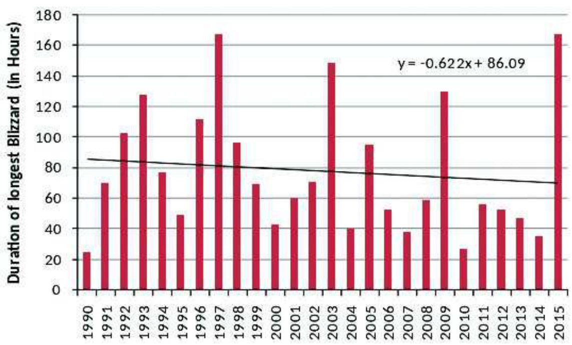

Fig. 10: Longterm variation of the duration of longest Blizzard each year

Conclusions

This paper has examined the temporal variability and change in some of the key meteorological parameters around Maitri station. The temperature trends showed cooling over Maitri during 1990-2015 which is consistent with the trend at nearby Russian station Novolazarevskaya during the same period. The wind speeds at the station have decreased at a statistically significant level. A decrease in wind speed would result in a more stable boundary layer and colder conditions at the surface, which explains the trend towards colder surface air temperature. The clear decrease in mean sea level pressures at the Maitri station over the period 1990-2015 of the station data is indicative of the SAM moving towards a high-index state in recent decades.

Acknowledgement

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References

Bluestein H B (1993) Synoptic-Dynamic Meteorology in Midlatitudes, Vol. 2: Observations and Theory of Weather Systems 594 pp Oxford Univ Press, New York

Branick M L (1997) A climatology of significant winter-typeweather events in the contiguous United States 1982-94 *Weather Forecasting* **12** 193-207

Bromwich D H, Nicolas J P, Monaghan A J, Lazzara Ma, Keller L M, Weidner Gaand Wilson A B (2013) Central West Antarctica among the most rapidly warming regions on Earth. Nature Geoscience **6** 139-145 DOI 10.1038/ngeo1671

Chapman W L and Walsh J E (2007) A Synthesis of Antarctic Temperatures *J Clim* **20** 4096-4117 DOI 10.1175/JCLI4236.1

Kumar A and Gupta V B (2007) Mathematical modeling of katabatic winds over Schirmacher region East Antarctica *JRSP* **36** 204-212

Marshall G J (2003) Trends in the Southern Annular Mode from observations and reanalyses *J Clim* **16** 4134-4143

Nicolas J P and Bromwich D H (2014) New Reconstruction of Antarctic Near-Surface Temperatures: Multidecadal Trends and Reliability of Global Reanalyses *J Clim* **27** 8070-8093

Rasal A S (2003) Blizzards – A case study of longest blizzard over Maitri (Antarctica) during 2006 *Mausam* **54** 743-752

Schneider D P, Deser C and Okumura Y (2012) An assessment and interpretation of the observed warming of West Antarctica in the austral spring *Clim Dyn* **38** 323-347 DOI 10.1007/s00382-010-0985-x

Smith K L and Polvani L M (2016) Spatial patterns of recent Antarctic surface temperature trends and the importance of natural variability: lessons from multiple reconstructions and the CMIP5 models *Clim Dyn* doi 10. 1007/ s00382-016-3230-4

Steig E J, Schneider D P, Rutherford S D, Mann M E, Comiso J C and Shindell D T (2009) Warming of the Antarctic ice-sheet surface since the 1957 International Geophysical Year *Nature* **457** 459-62, DOI 10.1038/nature07669

Thompson D W J and Wallace J M (2000) Annular modes in the extratropical circulation. Part I: Month-to-month variability *J Climate* **13** 1000-1016

Thompson D W J and Solomon S (2002) Interpretation of recent Southern Hemisphere climate change *Science* **296** 895-899

Turner J, Colwell S R, Marshall G J, Lachlan-Cope Ta, Carleton A M, Jones P D, Lagun V, Reid Pa and Iagovkina S (2005) Antarctic climate change during the last 50 years *Int J of Clim* **25** 279-294 DOI: 10.1002/joc.1130

Tyagi A, Singh U P and Mohapatra M (2011) Weather and weather systems at Schirmacher Oasis (Matri) during recent two decades – A review *Mausam* **62** 513-514

Wild R (1995) Definition of the British blizzard *Weather* **50** 327-328.

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Research Paper

Contributions to the Floral Diversity of Schirmacher Oasis and Larsemann Hills, Antarctica

SHIV MOHAN SINGH[1,*] and SANJEEVA NAYAKA[2]

[1]*National Centre for Antarctic and Ocean Research, Earth System Science Organisation, Headland Sada, Vasco-da-Gama, Goa 403 804, India*

[2]*CSIR-National Botanical Research Institute, Rana Pratap Marg, Lucknow 226 001, Uttar Pradesh, India*

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In continental Antarctica, algae, fungi, lichen and mosses are the major floristic elements. To understand their distribution and diversity pattern in ice free areas of Schirmacher Oasis and Larsemann Hills investigations were conducted during various Indian Antarctic Expeditions. Due to the extreme environmental conditions in Antarctica, lichens and bryophytes undergo sever morphological changes and occur in mostly in sterile condition that makes them difficult group to identify. A total of 69 species of lichens were encountered in the Schirmacher Oasis and 25 species in the region of Larsemann Hills. Most lichens known from these two areas are microlichens. The ecophysiological studies on lichens indicated *Rhizoplaca melanophthalma* as the most desiccation tolerant species in Schirmacher Oasis. The studies on moss flora contributed only 12 species under eight genera and five families from Schirmacher Oasis. The sub-fossil moss *Pohlia nutans* of Holocene period was recorded from lake sediment cores from Schirmacher Oasis. There are several studies on algal flora of Schirmacher Oasis and in one of the studies a total of 109 species of cyanobacteria belonging to 30 genera and 9 families were recorded from Schirmacher Oasis. Similarly, a total of 19 species of fungi belonging to 13 genera and seven families were recorded from Schirmacher Oasis soils and 5 species of yeasts were recorded from Larsemann Hills. Furthermore, *Thelebolus microsporus* was characterized for adaptation strategies and biotechnological potentials.

Keywords: Schirmacher Oasis; Larsemann Hills; Algae; Fungi; Moss; Lichens; Antarctica

Introduction

Antarctica is a region that has extreme environmental conditions for the existence of any form of life. The extremes include low temperature, long periods of darkness, frost and snow cover, frequent winds, bright sun light along with UV radiation. Only 0.3% of the area of Antarctica is ice-free during summer period and Antarctic life is mainly confined to this ice-free areas of coastal outcrops, offshore islands, nunataks, mountain ranges and oases. The occurrence of life in Antarctica can be directly attributed to their adaptation to the stress. Therefore, assessment of terrestrial biodiversity is a thrust area of research for understanding the survival strategy in extreme environment and for the prospect of biotechnology in Antarctica. Indian researchers have contributed immensely to the terrestrial biodiversity of Antarctica since their first expedition to the continent during the year 1981. Their area of operation is mainly centered on Schirmarcher Oasis and Larsemann Hills in east Antarctica. In the present communication we summarize the Indian contribution to terrestrial biodiversity of Antarctica with emphasis on algae (including Cyanobacteria), fungi, moss and lichens.

Contributions to the Lichenological Studies

Lichen is a symbiotic association between an alga and a fungus. The extraordinary ability of the lichens to thrive in freezing temperatures, UV exposre and oligotrophic soils and highly diffused sunlight gives

**Author for Correspondence: E-mail: smsingh@ncaor.gov.in*

them the edge over the other flora in colonizing one of the world's most inhospitable continents. The dry and sterile rock surfaces where other group of plants unable to grow the lichens colonizes successfully on them (Fig. 1A). Therefore, the ecology, taxonomy and adaptation biology of lichen are always been a subject

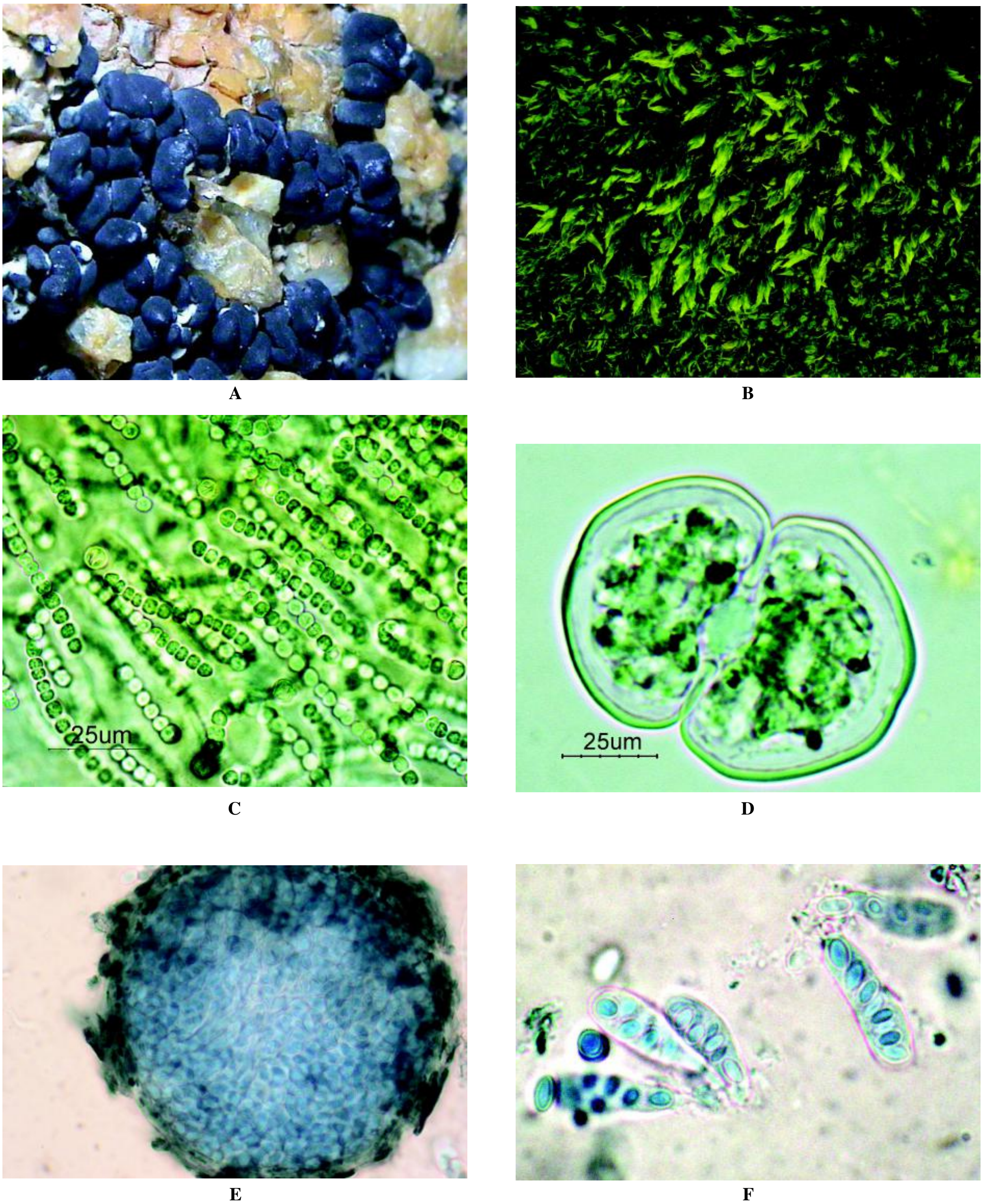

Fig. 1: (A) *Lecidea* (lichen), (B) *Bryum* (Moss), (C) *Nostoc* (Cyanobacteria), (D) *Cosmarium* (green alga) and (E-F) *Thelebolus* (fungi)

Table 1: Lichens flora of Schirmacher Oasis & Larsemann Hills, Antarctica

Species	Contributors
Acarospora sp. A. Massal	Wafar & Untawale, 1983; Upreti 1997
Acarospora flavocordia Castello & Nimis	Olech & Singh, 2010
Acarospora gwynnii Dodge & Rudolph	Upreti & Pant 1995; Upreti 1997; Singh *et al*., 2007; Olech & Singh, 2010
Acarospora williamsi Filson	Upreti & Pant 1995; Olech & Singh, 2010
Amandinea coniops (Wahlenb.) M. Choisy ex Scheid	Olech & Singh, 2010
Amandinea punctata (Hoffm.) Coppins & Scheid	Olech & Singh, 2010
Alectoria minuscula	Upreti & Pant 1995
Arthonia lapidicola (Taylor) Branth & Rostr.	Singh *et al*., 2007
Arthonia molendoi (Frauenf.) R. Sant.	Olech & Singh, 2010
Arthonia rufidula (Hue) D. Hawksw., R. Sant. & Øvstedal	Olech & Singh, 2010
Bacidia johnstonii C. W. Dodge	Olech & Singh, 2010
Bacidia stipata I. M. Lamb	Olech & Singh, 2010
Buellia darbishirei I. M. Lamb	Olech & Singh, 2010
Buellia frigida Darb.	Upreti 1997; Singh *et al*., 2007; Olech & Singh, 2010
Buellia grimmiae Filson	Upreti & Pant 1995; Upreti 1996; Singh *et al*., 2007; Olech & Singh, 2010
Buellia grisea C. W. Dodge & G. E. Baker	Olech & Singh, 2010
Buellia illaetabilis I.M. Lamb	Nayaka & Upreti 2005; Singh *et al*., 2013
Buellia lignoides Filson	Olech & Singh, 2010
Buellia pallida C. W. Dodge & G. E. Baker	Upreti & Pant 1995; Upreti 1996; Olech & Singh, 2010
Buellia papillata (Sommerf.) Tuck.	Olech & Singh, 2010
Buellia pycnogonoides Darb.	Olech & Singh, 2010
Buellia subfrigida May. Inoue	Olech & Singh, 2010
Caloplaca athallina Darb.	Singh *et al*., 2007; Olech & Singh, 2010
Caloplaca citrina (Hoffm.) Nordin	Singh *et al*., 2007; Olech & Singh, 2010
Caloplaca frigida Søchting	Olech & Singh, 2010
Caloplaca isidioclada Zahlbr.	Upreti & Pant 1995
Caloplaca lewis-smithii Søchting & Øvstedal	Singh *et al*., 2007; Olech & Singh, 2010
Caloplaca saxicola (Hoffm.) Nordin	Singh *et al*., 2007; Olech & Singh, 2010
Candelaria murrayi Poelt	Olech & Singh, 2010
Candelariella flava (C. W. Dodge & G. E. Baker) Castello & Nimis	Upreti 1997; Singh *et al*., 2007; Olech & Singh, 2010
Carbonea assentiens (Nyl.) Hertel,	Nayaka & Upreti 2005; Singh *et al*., 2013
Carbonea capsulate (Dodge & Baker) Hale	Upreti & Pant 1995; Upreti 1996
Carbonea vorticosa (Flörke) Hertel (Flörke) Hertel	Singh *et al*., 2007; Olech & Singh, 2010; Singh *et al*., 2013
Huea coralligera (Hue) C.W. Dodge & G.E. Baker	Singh *et al*., 2007
Lecania cf. racovitzae (Vain.) Darb.	Olech & Singh, 2010
Lecanora cf. mawsonii C. W. Dodge	Olech & Singh, 2010
Lecanora expectans Darb.	Upreti 1997; Singh *et al*., 2007; Olech & Singh, 2010
Lecanora fuscobrunnea C. W. Dodge & G. E. Baker	Upreti & Pant 1995; Upreti 1997; Olech & Singh, 2010
Lecanora geophila (Th. Fr.) Poelt	Nayaka & Upreti 2005; Singh *et al*., 2007; Olech & Singh, 2010; Singh *et al*., 2013
Lecanora mons-nivis Darb.	Olech & Singh, 2010
Lecanora orosthea (Ach.) Ach.	Olech & Singh, 2010; Singh *et al*., 2013
Lecanora sverdrupiana Øvstedal	Olech & Singh, 2010
Lecidea andersonii Filson	Olech & Singh, 2010; Singh *et al*., 2013
Lecidea cancriformis C. W. Dodge & G. E. Baker	Upreti & Pant 1995; Upreti 1996; Singh *et al*., 2007; Olech & Singh, 2010
Lecidea cf. placodiiformis Hue	Olech & Singh, 2010
Lecidea siplei R. Filson	Upreti & Pant 1995; Upreti 1996
Lecidella siplei (C. W. Dodge & G. E. Baker) May. Inoue	Olech & Singh, 2010; Singh *et al*., 2007
Lecidella patavina (A. Massal.) Knoph & Leuckert	Singh *et al*., 2007
Lecidella stigmatea (Ach.) Hertel	Nayaka & Upreti 2005; Olech & Singh, 2010; Singh *et al*., 2013
Lepraria cacuminum (A. Massal.) Lohtander	Olech & Singh, 2010; Singh *et al*., 2013
Lepraria membranacea (Dicks.) Lett.	Upreti & Pant 1995
Leproloma cacuminum	Nayaka & Upreti 2005; Singh

(A. Massal.) J.R. Laundon	*et al*., 2013
Pertusaria sp.	Upreti & Pant 1995
Physcia caesia (Hoffm.) Fürnr.	Upreti & Pant 1995; Olech & Singh, 2010; Singh *et al*., 2007
Physcia dubia (Hoffm.) Lettau	Singh *et al*., 2007; Olech & Singh, 2010
Pleopsidium chlorophanum (Wahlenb.) Zopf	Olech & Singh, 2010
Polycaulina murrayi Dodge	Upreti & Pant 1995
Porpidia sp.	Upreti & Pant 1995
Pseudephebe minuscule (Nyl. Ex Arnold) Brodo & D. Hawksw.	Singh *et al*., 2007; Olech & Singh, 2010; Singh *et al*., 2013
Rhizocarpon flavum Dodge & Baker	Upreti & Pant 1995; Upreti 1996
Rhizocarpon geminatum Körb.	Olech & Singh, 2010
Rhizocarpon geographicum (L.) DC.	Olech & Singh, 2010
Rhizocarpon nidificum (Hue) Darb.	Nayaka & Upreti 2005; Singh *et al*., 2013
Rhizoplaca melanophtalma (Ram.) Leuckert & Poelt	Upreti 1997; Singh *et al*., 2007; Olech & Singh, 2010
Rinodina endophragmia I. M. Lamb	Nayaka & Upreti 2005; Olech & Singh, 2010; Singh *et al*., 2013
Rinodina olivaceobrunnea C. W. Dodge & G. E. Baker	Upreti & Pant 1995; Upreti 1997; Singh *et al*., 2007; Olech & Singh, 2010
Rinodina peloleuca (Nyl.) Mull. Arg.	Singh *et al*., 2007
Rinodina petermanii (Hue) Darbishire	Upreti & Pant 1995
Sarcogyne privigna (Ach.) A. Massal.	Nayaka & Upreti 2005; Singh *et al*., 2007; Olech & Singh, 2010; Singh *et al*., 2013
Umbilicaria africana (Jatta) Krog & Swinscow	Nayaka & Upreti 2005; Olech & Singh, 2010; Singh *et al*., 2013
Umbilicaria antarctica Frey & I. M. Lamb	Olech & Singh, 2010
Umbilicaria aprina Nyl.	Upreti & Pant 1995; Olech & Singh, 2010; Singh *et al*., 2013
Umbilicaria decussta (Vill.) Zahlbr.	Upreti & Pant 1995; Singh *et al*., 2007; Olech & Singh, 2010; Singh *et al*., 2013
Usnea antarctica Du Rietz	Singh *et al*., 2007; Singh *et al*., 2013
Verrucaria holizoa Leight.,	Nayaka & Upreti 2005; Singh *et al*., 2013
Xanthoria candelaris	Singh *et al*., 2013
Xanthoria elegans (Link) Th. Fr.	Upreti & Pant 1995; Upreti 1997; Singh *et al*., 2007; Olech & Singh, 2010
Xanthoria mawsonii C. W. Dodge	Singh *et al*., 2007; Olech & Singh, 2010

of investigation to Antarctic researchers. In the past few decades a large number of lichenological investigations on Antarctic lichens were carried out that provided clear picture of diversity and distribution of lichens in the continent with 439 taxa (Øvstedal and Smith 2001, 2004). In Indian context, for the first time Wafar and Untawale (1983) reported the occurrence of *Acarospora* sp. at Antarctica. However, lichens from Schirmacher Oasis have been collected since the 1970s. Golubkova and Simonov (1972) published the first comprehensive list of 21 lichen taxa from Schirmacher Oasis. Thereafter, detailed lichenological investigations in Schirmacher Oasis were carried out by Ritcher (1990a, 1995), researchers at CSIR-National Botanical Research Institute, Lucknow and ESSO-National Centre for Antarctic and Ocean Research, Goa. Upreti & Pant 1995; Upreti (1996, 1997) and Nayaka *et al*. (2009, 2011) systematically compiled and enumerated a total of 48 lichen taxa so far reported from Schirmacher Oasis. Meanwhile a monograph containing a comprehensive account of the taxonomy, ecology and distribution of lichens in the Schirmarcher Oasis has been published, according to which the region shelters a total of 54 lichenized and lichenicolous fungi (Olech and Singh, 2010). Upreti and Nayaka (2011) while reporting the affinities of Indian subcontinent lichen flora with that of Antractica mentioned that a total of 69 lichen taxa are so far known from Schirmacher Oasis. The species of lichen genus *Buellia* dominates the area with 10 species, followed by 9 species of *Lecanora*, 5 species each of *Caloplaca* and *Umbilicaria*. The crust forming species dominates the area with 54 species, while only 9 species are foliose, 4 are fruticose and single species of leprose form.

In the recent times India has extended its scope research at Larsemann Hills, in Prydz Bay area, East Antarctica. Singh *et al*. (2007) reported a total of 25 lichen species from McLeod island of Larsemann Hills 12 of which were new records to the area. The lichen biota of McLeod Island was dominated by crustose lichens with 19 species and *Buellia frigida* Darb. was the most dominant lichen. Singh *et al*. (2013) presented the consolidated checklist of lichens from both Schirmacher Oasis and Larsemann Hills. The check-list of lichen flora has been given in Table 1.

The lichens have ability that they can accumulate

Table 2: Bryoflora of Schirmacher Oasis, Antarctica

Species	Contributors
Bryum archangelicum Bruch & Schimp.	Ochyra & Singh 2008
B. argenteum Hedw.	Singh & Semwal 2000
B. argenteum Hedw. var. *muticum* Brid.	Ochyra & Singh 2008
B. orbiculatifolium Cardot & Broth.	Ochyra & Singh 2008
B. pseudotriquetrum (Hedw.) Gaertn.	Singh & Semwal 2000; Ochyra & Singh 2008
Bryoerythrophyllum recurviroste (Hedw.) Chen	Singh & Semwal 2000
Ceratodon purpureus (Hedw.) Brid., Bryol. Univ.	Singh & Semwal 2000; Ochyra & Singh 2008
Grimmia sp.	Singh & Semwal 2000
Grimmia plagiopodia Hedw.	Singh *et al*., 2012; Kurbatova & Ochyra 2012
Hennediella antarctica (Ångstr.) Ochyra & Matteri	Singh *et al*., 2012; Kurbatova & Ochyra 2012
Hennediella heimii (Hedw.) R.H. Zander	Singh *et al*., 2012
Leptobryum pyriforme (Hedw.)	Tewari & Pant 1986
Orthogrimmia sessitana (De Not.) Ochyra & Ż arnowiec	Ochyra & Singh 2008
Plagiothecium orthocarpum Mitt.	Singh *et al*., 2012
Pohlia nutans (Hedw.) Lindb.	Singh *et al*., 2012
Pottia heimii (Hedw.) Hamp.	Singh & Semwal 2000
Schistidium antarctici (Cardot) L.I. Savicz & Smirnova	Singh *et al*., 2012
Syntrichia sarconeurum Ochyra & R.H. Zander)	Singh *et al*., 2012

Table 3: Diatom flora of Schirmacher Oasis, Antarctica

Species	Contributors
Achnanthes minutissima (Kuetz.) Grunov.	Palanisamy 2010; Singh *et al*., 2013
Achnanthes exigua Grunov.	Palanisamy 2010; Singh *et al*., 2013
Diadesmis contenta (Grunov. Ex Heurck) D.G. Mann	Palanisamy 2010; Singh *et al*., 2013
Fragilaria intermedia Grunov.	Palanisamy 2010; Singh *et al*., 2013
Fragilaria intermedia Grunov. Var. *robusta* Venks	Palanisamy 2010; Singh *et al*., 2013
Fragilaria virescens Ralfs.	Palanisamy 2010; Singh *et al*., 2013
Gomphonema lanceolatum Ehrenb.	Palanisamy 2010; Singh *et al*., 2013
Hantzschia amphioxys (Ehrenb.) Grun.	Palanisamy 2010; Singh *et al*., 2013
Hantzschia sp.	Kashyap *et al*., 1988; Singh *et al*., 2013
Melosira sp.	Kashyap *et al*., 1988
Navicula cryptocephala Kuetz.	Palanisamy 2010; Singh *et al*., 2013
Navicula muticopsis Van Heurck.	Kashyap *et al*. 1988; Singh *et al*., 2013
Navicula radiiosa Kuetz.	Palanisamy 2010; Singh *et al*., 2013
Navicula sp. A & B	Singh *et al*., 2013
Nitzschia obtusa Gruan/W. Smith	Kashyap *et al*., 1988; Palanisamy 2010; Singh *et al*., 2013
Pinnularia borealis Ehrenb	Kashyap *et al*., 1988; Singh *et al*., 2013
Stauroneis anceps Ehrenb	Palanisamy 2010; Singh *et al*., 2013
Synedra ulna (Nitzsch.) Ehrenb.	Kashyap *et al*., 1988; Palanisamy 2007; Singh *et al*., 2013

Table 4: Cyanobacterial flora of Schirmacher Oasis, Antarctica

Anabaena sp.	Kashyap *et al*., 1988; Pandey *et al*., 2013
Anabaena cylindrica Lemm.	Singh *et al*., 2008
Aphanothece caldariorum Richter, P.	Singh *et al*., 2008
Aphanothece clathrata W. et. G. S. West	Singh *et al*., 2008
Aphanocapsa delicatissima W. et. G. S. West.	Singh *et al*., 2008
Aphanothece heterospora Rabenh.	Singh *et al*., 2008
Aphanocapsa montana Cramer	Singh *et al*., 2008
Aphanothece muscicola (Menegh.) Wille	Kashyap *et al*., 1988; Pandey *et al*., 1992; Singh *et al*., 2008
Aphanothece nidulance Richter	Kashyap *et al*., 1988
Aphanothece pallida (Kütz.) Rabenhorst	Singh *et al*., 2008
Aphanothece saxicola Nägeli.	Singh *et al*., 2008
Calothrix crustacea Thuret.	Singh *et al*., 2008
Calothrix cylindrica Fremy	Singh *et al*., 2008
Calothrix gelatinosa (Böcher) V. Poljanskij	Singh *et al*., 2008
Calothrix gracilis Fritsch.	Kashyap *et al*., 1988; Pandey *et al*., 1992
Calothrix parietina Thuret ex. Born et. Flah	Kashyap *et al*., 1988; Pandey *et al*., 1992; Singh *et al*., 2008
Calothrix braunii Born et. Flah.	Singh *et al*., 2008
Calothrix brevissima West	Kashyap *et al*., 1988; Pandey *et al*., 2013
Chamaesiphon subglobosus (Rostaf.) Lemm.	Kashyap *et al*., 1988; Pandey *et al*., 2013; Singh *et al*., 2008
Chlorococcum humicolum (Naeg.) Rabenh	Kashyap *et al*., 1988
Chroococcus aeruginosus Nag.	Kashyap *et al*., 1988; Pandey *et al*., 2013; Singh *et al*., 2008
Chroococcus limneticus var. *elegans* (Lem.) Hollerbach	Singh *et al*., 2008
Chroococcus minimus (Keissler) Lemm.	Singh *et al*., 2008
Chroococcus minutus (Kütz.) Näg.	Pandey *et al*. 2013; Singh *et al*., 2008
Chroococcus pallidus Näg.	Kashyap *et al*., 1988; Pandey *et al*., 2013; Singh *et al*., 2008
Chroococcus varius Braun	Singh *et al*., 2008
Chlorogloea microcystoides Geitler.	Singh *et al*., 2008
Cosmarium leave Riabenh	Kashyap *et al*., 1988
Cosmarium turgidum Breb	Kashyap *et al*., 1988
Cosmarium turpini Breb	Kashyap *et al*., 1988
Gloeocapsa sp.	Kashyap *et al*., 1988; Pandey *et al*., 1992
Gloeocapsa alpina (Näg.) Brand.	Singh *et al*., 2008
Gloeocapsa atrata (Turt.) Kütz.	Singh *et al*., 2008
Gloeocapsa fusco-lutea (Näg.) Kütz.	Singh *et al*., 2008
Gloeocapsa granosa (Berk.) Kütz.	Singh *et al*., 2008
Gloeocapsa kuetzingiana Näg.	Kashyap *et al*., 1988; Pandey *et al*. 2013; Singh *et al*., 2008
Gloeocapsa luteofusca Martens.	Singh *et al*., 2008
Gloeocapsa magma (Bréb.) Kütz.	Kashyap *et al*., 1988; Pandey *et al*. 1992; Singh *et al*., 2008
Gloeocapsa montana Kütz.	Singh *et al*., 2008
Gloeocapsa polydermatica Kütz.	Singh *et al*., 2008
Gloeocapsa ralfsiana (Harv.) Kütz.	Kashyap *et al*., 1988; Pandey *et al*., 1992; Singh *et al*., 2008
Gloeocapsa rupestris Kütz.	Singh *et al*., 2008
Gloeothece samoensis Wille.	Singh *et al*., 2008

Gloeocapsa sanguinea (Ag.) Kütz.	Singh *et al*., 2008
Lyngbya aestuarii Liebm. Ex Gomont	Kashyap *et al*., 1988; Pandey et al., 1992; Singh *et al*., 2008
Lyngbya attenuata Fritsch.	Kashyap *et al*., 1988; Pandey *et al*., 2013; Singh *et al*., 2008
Lyngbya aerugineo-coerulea (Kütz.) Gom.	Singh *et al*., 2008
Lyngbya confervoides Ag. ex. Gomont	Singh *et al*., 2008
Lyngbya infixa Fremy.	Singh *et al*., 2008
Lyngbya sp.	Singh *et al*., 2008
*Lyngbya lutea (*Ag.) Gom	Singh *et al*., 2008
Lyngbya martensiana Menegh.	Singh *et al*., 2008
Lyngbya nigra C. Ag. ex. Gomont.	Singh *et al*., 2008
Lyngbya semiplena (C. Ag.) J. Ag.	Singh *et al*., 2008
Microcoleus sociatus West et. West	Singh *et al*., 2008
Microcoleus vaginatus (Vauch.) Gom.	Singh *et al*., 2008
Nostoc sp.	Kashyap *et al*., 1988; Pandey *et al*., 1992
Nostoc antarcticum W. et G.S.West	Singh *et al*., 2008
Nostoc commune Vaucher ex Born et Flah	Kashyap *et al*., 1988; Pandey *et al*., 1992; Singh *et al*., 2008
Nostoc kihlmanii Lemm.	Singh *et al*., 2008
Nostoc pruniforme (Kütz.) Hariot.	Kashyap *et al*., 1988; Pandey *et al*., 2013; Singh *et al*., 2008
Nostoc sphaericum Vauchr	Pandey *et al*., 2013
Nostoc verrucosum Vaucher	Singh *et al*., 2008
Nodularia harveyana (Twaites) Thuret.	Singh *et al*., 2008
Myxosarcina chroococcoides Geitler	Singh *et al*., 2008
Oscillatoria agardhii Gomont.	Kashyap *et al*., 1988; Pandey *et al*., 2013
Oscillatoria anguina (Bory) Gom.	Singh *et al*., 2008
Oscillatoria animalis Agardh.	Singh *et al*., 2008
*Oscillatoria bornet*i var. *tenuis* Zukal	Singh *et al*., 2008
Oscillatoria brevis (Kütz.) Gomont.	Singh *et al*., 2008
Oscillatoria granulata Gardner	Singh *et al*., 2008
Oscillatoria irrigua Kütz.	Singh *et al*., 2008
Oscillatoria kuetlizii Lemm.	Kashyap *et al*., 1988; Pandey *et al*., 2013
Oscillatoria limosa Ag. Ex Gomont.	Kashyap *et al*., 1988; Pandey *et al*., 2013
Oscillatoria limnetica Lemm	Kashyap *et al*., 1988
Oscillatoria ornata Kütz.	Singh *et al*., 2008
Oscillatoria pseudogemminata Schmid.	Singh *et al*., 2008
Oscillatoria temuis Ag.	Kashyap *et al*., 1988
Phormidium automnale (Ag.) Gom	Kashyap *et al*., 1988
Phormidium fragile (Menegh) Gom	Kashyap *et al*., 1988
Phormidium frigidum Fritsch.	Kashyap *et al*., 1988; Pandey *et al*., 1992
Phormidium laminosum Gomont	Singh *et al*., 2008
Phormidium pristleyi F. E. Fritsch.	Singh *et al*., 2008
Phormidium molle	Singh *et al*., 2008
Phormidium mucosum Gardner.	Singh *et al*., 2008
Phormidium subincrustatum Fritsch and Rich.	Singh *et al*., 2008
Phormidium subfuscum Kütz. ex. Gomont	Singh *et al*., 2008

Phormidium tenue (Menegh.) Gomont	Singh *et al*., 2008
Phormidium uncinatum (Ag.) Gom	Singh *et al*., 2008
Phormidium viride (Vaucher) Lemm.	Singh *et al*., 2008
Plectonema gracillimum (Zopf) Hansgirg	Singh *et al*., 2008
Plectonema terebrans Born. et Flah.	Singh *et al*., 2008
Plectonema sp.	Pandey *et al*., 1992
Pleurocapsa minor Hansg.	Singh *et al*., 2008
Porphyrosiphon notarisii (Menegh.) Kütz.	Singh *et al*., 2008
Psudanabaena constricta (Szafer) Lauterb.	Singh *et al*., 2008
Rivularia minutula (Kütz.) Born et. Flah	Singh *et al*., 2008
Scenedesmus acutus Fritsch	Kashyap *et al*., 1988
Schizothrix antarctica F. E. Fritsch.	Singh *et al*., 2008
Schizothrix vaginata (Näg.) Gom.	Singh *et al*., 2008
Schizothrix sp. I & II	Kashyap *et al*., 1988; Pandey *et al*., 2013
Scytonema myochrous (Dillw.) Ag. ex. Born. et. Flah.	Pandey *et al*., 2013; Singh *et al*., 2008
Scytonema sp.	Kashyap *et al*., 1988; Pandey *et al*., 1992
Spirulina jenneri (Stiz.) Geitler	Singh *et al*., 2008
Stigonema minutum (Ag.) Hass. Ex Bornet et Flah.	Kashyap *et al*., 1988; Pandey *et al*., 1992; Singh *et al*., 2008
Synechococcus aeruginosus Nägeli.	Kashyap *et al*., 1988, Pandey *et al*., 1992; Singh *et al*., 2008
Synechocystis aquatilis Sauv.	Singh *et al*., 2008
Synechococcus cedrorum Sauv.	Singh *et al*., 2008
Synechococcus major Schröter.	Singh *et al*., 2008
Synechocystis pevalekii Erceg.	Singh *et al*., 2008
Synechocystis sallensis Skuja	Singh *et al*., 2008
Tolypothrix conglutinata Borz.	Kashyap *et al*., 1988; Pandey *et al*., 2013
Tolypothrix distorta (Kütz.) Born et Flah.	Singh *et al*., 2008
Tolypothrix byssoidea (Hass.) Kirchner ex Bornet et Flah.	Singh *et al*., 2008
Ulothrix sp.	Kashyap *et al*., 1988
Uronema sp.	Kashyap *et al*., 1988
Xenococcus sp. UN1	Singh *et al*., 2008

large amount of heavy metals in their thalli and act as an effective monitor of both for background and enhanced levels of heavy metals of the area. Antarctic lichens are also utilized for monitoring air pollution around Maitri by analyzing the heavy metals accumulated in them (Upreti and Pandey 1999). Heavy metal concentration in *Umbilicaria aprina* and *U. deccussata* growing luxuriantly were estimated for iron, copper, lead and chromium levels. The presence of lead in lichen samples collected near Russian station is quite interesting as it is mainly derived from man-made pollution, transported to the polar atmosphere owing to its use as an antiknock petrol additive. In one of the study pollen grains carried away by wind currents to Antarctica and deposited on moss and lichens tufts were analyzed that helped in tracing the direction of wind currents together with past climatic condition of the area. The encounter of different pollen and spore types reflected their long distance transport ranging from tropical to temperate floristic regions around Antarctica mainland which is devoid of any higher plant taxa, except for members of Poaceae and Caryophyllaceae (Sharma *et al*., 2002). In another study the carotenoid contents in lichens collected from Antarctica were also carried out by column and thin layer chromatography which revealed the presence of 21 carotenoids (Czeczuga *et al*., 1996). The total concentration of carotenoids

Table 5: Fungal flora of Schirmacher Oasis & Larsemann Hills, Antarctica

Species	Contributors
Schirmacher Oasis	
Acremonium antarcticum (Speg.) Howksw	Sharma 2000; Singh *et al*., 2013
Acremonium psychrophilum Moller & Gams	Sharma 2000; W. Singh *et al*., 2013
Acremonium zonatum (Swada) W. Gams	Singh *et al*., 2013
Arthrobotrys ferox Onofri & Tosi	Sharma 2000; Singh *et al*., 2013
Arthrobotrys robusta Duddington	Singh *et al*., 2013
Aspergillus fumigatus Fresenius	Singh *et al*., 2013
Bullera alba	Ray *et al*., 1989; Shivaji *et al*., 1994
Candida humicola	Ray *et al*., 1989; Shivaji *et al*., 1994
Candida famata	Ray *et al*., 1989; Shivaji *et al*., 1994
Candida ingeniosa	Ray *et al*., 1989; Shivaji *et al*., 1994
Candida auriculariae	Ray *et al*., 1989; Shivaji *et al*., 1994
Cephalosporium sp.	Singh *et al*., 2013
Cladosporium herbarum (Pers.) Link	Singh *et al*., 2013
Cryptoococcus friedmanii Vishniac	Singh *et al*., 2013
Cryptoococcus sp.	Sharma 2000; Singh *et al*., 2013
Cladosporium sp.	Singh *et al*., 2007
Dacrymyces sp.	Singh *et al*., 2013
Exidia sp.	Singh *et al*., 2013
Fusarium sp.	Singh *et al*., 2007
Hormoconis resinae Lind.	Singh *et al*., 2013
Mortierella antarctica Linne	Singh *et al*., 2013
Phoma exigua Desm.	Singh *et al*., 2013
Phoma herbarum Westd.	Sharma 2000; Singh *et al*., 2013
Rhodotorula rubra	Ray *et al*., 1989; Shivaji *et al*., 1994
Thelebolus microspores (Berk & Br.) Kim.	Singh *et al*., 2013
Trichoderma sp.	Singh *et al*., 2007
Torulopsis psychrophila	Sharma 2000; Singh *et al*., 2007; Singh *et al*., 2013
Torulopsis sake Goto	Singh *et al*., 2013
Larsemann Hills	
Cryptococcus albidus	Singh *et al*., unpublished
C. antarcticus	Singh *et al*., unpublished
Mrakia blollopis	Singh *et al*., unpublished
Rhodotorula sp.	Singh *et al*., unpublished
Thelebolus microsporus	Singh *et al*., 2013

raged from 23.25 to 123.50 μg^{-1} dry wt. The type of carotenoids in Antarctic lichens may provide the clue for the adaptation of lichens to harsh climatic condition.

During 28th Indian Antarctic Expedition, lichens of Schirmacher Oasis were studied in detail for their physiological adaptation to Antarctic environment. The water relation, carbon isotope discrimination and climate changes studies were conducted. According to the parameters of Pressure Volume Curve derived from Thermocouple Psychrometric technique *Rhizoplaca melanophthalma,* a squamulose lichen growing over soil in dry, exposed areas can be considered as highly desiccation tolerant species (Nayaka and Upreti, 2011). The detailed report of 28th expedition is under publication.

Contributions to the Bryophyte Flora

The bryophytic flora of Antarctica comprises about 85 species with dominance of moss with 70 taxa (Seppelt 1986). The bryophytes in the continent are confined to warmer regions such as peninsula and maritime region, while continental Antarctica is poorly represented. After lichens bryophytes are the better adapted plant groups to Antarctic conditions. The mosses (Fig. 1B) in Antarctica act like keystone species providing shelter to several other organisms such as micro-invertebrates, fungi, algae and lichens. Mosses are also sensitive to changes in the cryosphere. Their presence is an indicator of short term climatic and aerodynamic stability or the dynamics of snow and ice in the rock deserts of Oasis (Richter 1990b).

A large number of moss samples were collected from Schirmacher Oasis during 16th and 19th Indian Antarctic Expeditions which resulted in six species of bryophytes (Singh *et al*., 2013). Remarkable morphological variation and infertile condition makes identification of mosses difficult. Probably this is the reason why number of taxa are reduced to six from nine originally identified by Singh and Semwal (2000) from Schirmacher Oasis. Meanwhile, three remarkable new moss species (*Bryum argenteum, B. orbiculatifolium*, *B. archangelicum*) were added to terrestrial flora of Oasis (Ochyra and Singh, 2008). Recently, Singh *et al*. (2012) conducted a systematic survey and collected moss specimens from different terrestrial locations and lake sediments of Schirmacher Oasis which resulted in 12 species belonging to eight genera and five families. The check-list of moss flora has been given in Table 2. Also, the same study encountered a 10.65 kyr BP old sub-fossil moss *Pohlia nutans* preserved in the lake sediment at about 160-162 cm depth. The preserved Holocene sub-fossil moss includes delicate leaves, axes and rhizoids and matches perfectly the extant specimens of *P. nutans*.

Contributions to the Cyanobacteria and Algal Flora

Algae are most common biological elements in Antarctica exhibiting their presence in water bodies, wet soil, even on ice, in association with moss and lichens. About 700 algal taxa are known from the Antarctic continent and off-shore islands (Hirano 1965). Studies on the algal flora in Schirmacher Oasis was initiated by Richter (1995) who reported 209 taxa. There after several studies on algae (Fig. 1C,D) were under taken in the Oasis on both florist as well as ecophysiological aspects. However, studies on diatoms of the area ware meager and was carried out during 6th, 10th, 11th 18th, 23rd and 25th Indian Antarctic Expeditions. The study resulted in 18 diatoms belonging to 10 genera and five families. Of these *Diadesmis contenta, Fragellaria intermedia, Gomphonema lanceolatum, Navicula radiosa, Synedra ulna* and *Stauroneis anceps* are new records to Schirmacher Oasis (Kashyap *et al*., 1988; Palanisamy 2007; Palanisamy 2010; Singh *et al*., 2013). The check-list of diatom flora has been given in Table 3. The diatoms are found frequently associated with Cyanobacteria in the Oasis. The algae in Antarctica are also found growing in association with bryophytes as epiphytes to withstand the extreme climatic conditions. In one such studies 14 microalgae belonging to class Cyanophyceae, Bacillariophyceae and Chlorophyceae have been recorded growing in rhizodal zones of moss genera *Bryum* and *Pottia* (Singh *et al*., 2013). The other general studies on algae include Shukla *et al*. (1999) reporting 16 taxa and Singh (2000) reporting 33 taxa under Cyanophyceae, Chlorophyceae and Bacillariophyceae.

The Cyanobacteria (Fig. 1C) are oxyphototrophic prokaryote ubiquitous in all major ecosystems of the world including Antarctica. They are adapted to the Antarcitc environment in terms of temperature, freezing and thawing cycle, photoprotection, light acquisition or photosynthesis, low humidity and prolonged period of darkness. Earlier studies indicate that Cyanobacteria are most dominant component of flora in the regions of Antarctica that are ice-free (Broady 1982, 1989, Pandey *et al*., 1992, 1995). The having ability to fix nitrogen Cyanobacteria are most important organism in Antarctica making soil suitable for the growth of other plants. Therefore, study of Cyanobacteria in Schirmacher Oasis and Larsemann Hills is very essential to understand the plant diversity in Antarctica and their response to changes in environmental condition and climate change. Kashyap *et al*. (1988, 1991) recorded 34 cyanobacterial taxa including unicellular, filamentous, non heterocystous and heterocystous forms in streams, lakes, associated with mosses and on soils of Schirmachar Oasis and reported *Stigonema minutum*, *Nostoc commune* and *Gloeocapsa* sp. as most common species. Pandey *et al*. (1995) studied the cyanobacterial flora of six fresh water streams of Schirmacher oasis and reported 30 species. Further, Singh and Elster (2007) reviewed cyanobacteria in Antarctic lake environment and highlighted their diversity, distribution and ecology. The diversity and distribution of cyanobacteria from the hydro-terrestrial and lake habitats of Schirmacher Oasis were mapped and a total of 109 species from 30 genera and 9 families were recorded (Singh *et al*., 2008). Recently, Pandey *et al*. (2013) enumerated a total of 35 Cyanobacteria from different habitats in Schirmacher Oasis and nearby nunataks. The check-list of cyanobacteria and green algal flora has been given in Table 4. In one of the studies it is found that nitrogen fixation by Cyanobacteria-moss association was highest in comparison to cyanobacteria found alone in soil near lake. However, Cyanobacteria were dominant flora (90%) of the soil surface in Schirmacher Oasis (Pandey *et al*., 2013).

Contributions to the Fungal Flora

The fungi are less hardy and more widely distributed organism in Antarctica in comparison to mosses and lichens. Their diversity increases with the availability of water and energy. They can withstand extremes of temperatures and severe desiccations. Yeast probably dominates and the majority of the microfungi reported from this place belong to cosmopolitan Hypomycetes (Singh *et al*., 2013). Six basidiomycetous yeasts were reported from Schirmacher oasis (Ray *et al*., 1989; Shivaji *et al*., 1994). The studies on the mycological flora of

Schirmacher Oasis were carried out during 17th Indian Antarctic Expedition onwards. Sharma (2000) reported nine species of fungi from the Schirmacher region. These include *Arthrobotrys ferox* on moss, *Torulopsis psychrophila* and *Phoma herbarum* on bird excreta, *P. herbarum* on skeletal remains, *Acremonium antarcticum* and *A. psychrophilum* on lichens and species of *Torulopsis psychrophila* and *Cryptococcus* on ornithogenic soils. Recently, Singh *et al*. (2013) enumerated a total of 19 species of fungi belonging to 13 genera under seven families from Schirmacher Oasis. The check-list of fungal flora has been given in Table 5. Except for *Dacrymyces* and *Exidia* all the species were recorded for the first time from Schirmacher Oasis. Melt water streams originating from glacier supported the luxuriant growth of lichens and moss cushions which served as potential source for fungal isolation.

In subsequent years, biodiversity of psychrophilic fungi (*Acremonium*, *Aspergillus*, *Cladosporium*, *Fusarium* and *Trichoderma*) from Schirmacher Oasis (Singh *et al*., 2006) and 5 species of yeasts (*Cryptococcus albidus*, *C. antarcticus, Mrakia blollopis Rhodotorula microsporus*, *Thelebolus microspores*) from Larsemann Hills were also assessed (Singh *et al*., unpublished). A cold-tolerant fungal strain *Thelebolus microsporus* was investigated for the first time for its pigment and fatty acid production from Larsemann Hills (Singh *et al*., 2014). Recently, an exopolysaccharide (EPS) was isolated, purified and characterized which is the first ever report on bioactive EPS thelebolan from *Thelebolus* sp. (Fig. 1E-F) (Mukhopadhyaya *et al*., 2014).

Conclusion

Though Schirmacher Oasis and Larsemann Hills among the most extensive ice-free areas of continental Antarctica, yet, knowledge of the terrestrial biology of these areas are still fragmentary and needs detailed investigations in year to come. While much of the contribution on the diversity and distribution of algae, fungi, lichens and bryophytes is available for Schirmacher Oasis not much information is available for Larsemann Hills on these aspects. Therefore, there is tremendous scope for conducting biological diversity study in this area. However, documentation of biodiversity and understanding the basis of their adaptation to harsh conditions of Antarctica have become routine activities, but now the time has come to translate our basic knowledge into bioprospection for the benefit of mankind. Antarctic biodiversity may serve as potential genetic resources for life saving drugs or to protect our skin from harmful ultra-voilet rays or cultivate economically important plants and animals in cold conditions. Isolation of antifreeze glycoproteins from various species of Antarctic fish is a best example in this respect where scientists are looking for ways to improve farm-fish production in cold climates, extend the shelf life of frozen food and enhance the preservation of tissues to be transplanted. The bioprospecting activities in Antarctica are increasing and several patents are already been filed based on biodiversity of Antarctica. During the year 1988-2003 of the 18 companies that have applied for Antarctic based patents, most applicants are Japanese-based companies, followed by German ones (Lohan and Johnston 2005). At present prospecting Antarctic bioresources for commercial application has restricted due to existence of Antarctic Treaty System. However, ambiguity in Antarctic Treaty such as ownership of genetic resources, legitimate access to bioresources, benefit sharing, environmental impact assessment etc. need to be readdressed so that novel genetic wealth of Antarctica can be used for betterment of human life.

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References

Broady P A (1982) Ecology of non-marine algae at Mawson Rock, Anartica *Nova Hedwigia* **36** 209-229

Broady P A (1989) Survey of Algae and other terrestrial biota at Edward VII Peninsula, Marie Byrd Land *Antarctic Science* **1** 215-224

Czeczuga B, Inoue M and Upreti D K (1996) Carotenoids in lichens from the Antarctic *Nankyoku Shiryo (Antarctic Record) National Institute of Polar Research, Tokyo* **40** 247-254

Golubkova N S and Simonov I M (1972) Lishayniki Oazisa Shirmakhera *Trudy Sovet Skoy East Antarkti Cheskoy Eksfeditsii Leningrad* **60** 317-327

Hirano M (1965) Freshwater algae in the Antarctic regions. In van Meighem F, van Dye P and Schell J (eds.) Biogeography and Ecology in Antarctica *The Hague* 127-193

Kashyap A K, Gupta R K and Pandey K D (1998) Check-list of Cyanobacteria occurring in Schirmacher Oasis, Antarctica *Journal of Scientific Research BHU, Varanasi* **47** 171-179

Kashyap A K, Pandey K D and Gupta R K (1991) Nitrogenase activity of the Antarctic Cyanobacterium *Nostoc commune*: Influence of Temperature *Folia Microbiologica* **36** 557-560

Kurbatova L E and Ochyra R (2012) Two noteworthy additions to the moss flora of the Schirmacher Oasis in the continental Antarctic *Cryptogamie Bryologie* **33** 159-167

Lohan D and Johnston M (2005) *UNU-IAS Report – Bioprospecting in Antarctica* United Nation University, Yokohama

Mukhopadhyaya S K, Chatterjeea S, Gauria S S, Dasa S S, Mishraa A, Moumita Patraa M, Ghosha A K, Dasa A K, Singh SM and Dey S (2014) Isolation and characterization of extracellular polysaccharide Thelebolan produced by a newly isolated psychrophilic Antarctic fungus *Thelebolus Carbohydrate Polymers* **104** 204-212

Nayaka S and Upreti D K (2005) Schirmacher Oasis, East Antarctica, a lichenologically interesting region *Current Science* **89** 1069-1071

Nayaka S, Upreti D K and Bajpai R (2009) Diversity and adaptive response of lichens in Antarctica with special reference to Schirmacher Oasis. In Sridhar K R (ed.) *Frontiers in fungal ecology, diversity and metabolites*. I.K. Internataional Publishing House Pvt. Ltd., New Delhi. Pp. 107-123

Nayaka S, Upreti D K and Singh R (2011) Water relation of some common lichens occurring in Schirmacher Oasis. In J Singh and H N Datta (eds.) *Antarctica: The Most Interactive Ice-Air-Ocean Environment* Science Publishers, Inc. Pp. 163-172

Ochyra R and Singh S M (2008) Three remarkable moss records from Dronning Maud Land, Continental Antarctica *Nova Hedwigia* **86** 497-506

Olech M and Singh S M (2010) *Lichens and lichenicolous fungi of Schirmacher Oasis, Antarctica*. Monograph. National Centre for Antarctic and Ocean Research. Pp 1-140.

Øvstedal D O and Smith R I L (2001) *Lichens of Antarctica and South Georgia. A guide to their identification and ecology*. Cambridge University Press, U.K.

Øvstedal D O and Smith R I L (2004) Addition and corrections to the lichens of Antarctica and South Georgia *Cryptogamie, Mycologie* **25** 323-331

Palanisamy M (2007) *Synedra ulna* (Nitzsch) Ehrenberg: A new generic record in Schirmacher Oasis, Antarctica *Current Science* **92** 179-181

Palanisamy M (2010) Studies on Diatom Flora of Schirmacher Oasis, East Antarctica. *Twenty Third Indian Antarctic Expedition, Ministry o f Earth Sciences, Technical Publication* **21** 173-190

Pandey K D, Kashyap A K and Gupta R K (1992) Nitrogen fixation by Cyanobacteria associated with moss communities in Schirmacher Oasis, Antarctica *Isr J Botany* **41** 187-198

Pandey K D, Kashyap A K and Gupta R K (1995) Nutrient status, algal and cyanobacterial flora of six fresh water streams of Schirmacher Oasis, Antarctica *Hydrobiologia* **299** 83-91

Pandey K D, Giri D D, Singh R, Gupta R K, Shukla S P, Shukla P N and Kashyap A K (2013) Cyanobacteria in Schirmacher Oasis, Antarctica: Status Review. In Tripathy S C, Mishra R K, Mohan R and Khar N (eds.) *Studies in biological sciences and human physiology. Three decades of Indian scientific activities in Antarctica*. CSIR-NISCAIR, New Delhi. National Centre for Antarctic and Ocean Research, Vasco da Gama. Pp. 83-116

Ray M K, Shivaji S, Rao N S and Bhargava P M (1989) Yeast strains from the Schirmacher Oasis, Antarctica *Polar Biology* **9** 305-309

Ritcher W (1990a) The lichens of the Schirmacher Oasis (East Antarctica). *Geodätische und Geophysikalische Veröffentlichungen, Reihe 1, Berlin* **16** 471-488

Ritcher W (1990b) The bryoflora of Schirmacher Oasis, East Antarctica in relation to hydrosphere and cryosphere. In Peach H J and Fritzsche D (eds.) *Antarctic Research Proc Symp Postdam, GDR*. Pp. 489-494

Ritcher W (1995) Biology. In Bormann P and Fritzsche D (eds.)

The Schirmacher Oasis, Queen Maud Land, East Antarctica and its surroundings, Germany Pp. 321-347

Seppelt R D (1986) Bryophytes of Vestfold hills. In Pickard J (ed.). *Antarctic Oasis. Terrestrial environments and the history of Vestfold hills* Sydney Pp. 220-244

Sharma JR. (2000) Mycological studies at Antarctica. Seventeenth Indian Expedition to Antarctica, *Scientific Report, Department of Ocean Development, Technical Publication* **15** 165-168

Sharma C, Bera S K and Upreti D K (2002) Modern pollen-spore rain in Schirmacher Oasis, East Antarctica *Current Science* **82** 88-91

Shivaji S, Chattopadhyay M K and Ray M K (1994) Bacteria and yeasts of Schirmacher Oasis, Antarctica: Taxonomy, Biochemistry and Molecular Biology *Proc NIPR Symp Polar Biology* **7** 173-184

Shukla S P, Gupta R K and Kashyap A K (1999) Algal Colonisation of Schirmacher Oasis, Antarctica. *Scientific Report - Fifteenth Indian Expedition to Antarctica. Department of Ocean Development, Technical publication* **13** 109-116

Singh S C (2000) Ecological study of Algal flora of Schirmacher Oasis of Antarctica. *Scientific Report - Seventeeth Indian Expedition to Antarctica. Department of Ocean Development, Technical publication* **15** 221-231

Singh D K and Semwal R C (2000) Bryoflora of Schirmacher Oasis, East Antarctica: A preliminary Study. *Scientific Report - Sixteeth Indian Expedition to Antarctica. Department of Ocean Development, Technical publication* **14** 173-182

Singh D K, Sharma J R, Gupta R K and Palnisamy M (2013b) Plant diversity in Schirmacher Oasis, East Antarctica with special reference to bryophytes, fungi and diatoma. In Tripathy S C, Mishra R K, Mohan R and Khar N (eds.) *Studies in biological sciences and human physiology. Three decades of Indian scientific activities in Antarctica*. CSIR-NISCAIR, New Delhi. National Centre for Antarctic and Ocean Research, Vasco da Gama. Pp. 117-138

Singh S M and Elster J (2007) Cyanobacteria in Antarctic lake environments: A mini-review In Joseph S (ed.) *Cellular origins, life in extreme habitats and astrobiology* **11** Springer. Pp. 303-320

Singh S M, Puja G and Bhat D J (2006) Biodiversity of Psychrophilic fungi from Schirmacher Oasis of East Antarctica *Current Science* **90** 1388-1392

Singh S M, Nayaka S and Upreti D K (2007) Lichen communities in Larsemann Hills, East Antarctica *Current Science* **93** 1670-1672

Singh S M, Singh P and Thajuddin N (2008) Biodiversity and distribution of Cyanobacteria at Dronning Maud Land, East Antarctica *Acta Botanica Malacitana* **33** 17-28

Singh S M, Ochyra R, Pednekar S M, Asthana R and Ravindra R (2012) A Holocene moss species preserved in lake sediment core and the present moss diversity at Schirmacher Oasis, Antarctica *Antarctic Science* **24** 353-358

Singh S M, Nayaka S and Upreti D K (2013b) Contribution to the lichen flora of Schirmacher Oasis and Larsemann Hills, Antarctica. In Tripathy S C, Mishra R K, Mohan R and Khar N (eds.) *Studies in biological sciences and human physiology. Three decades of Indian scientific activities in Antarctica*. CSIR-NISCAIR, New Delhi. National Centre for Antarctic and Ocean Research, Vasco da Gama. Pp. 139-155

Singh S M, Singh P N, Singh S K and Sharma P K (2014) Pigment, fatty acids and extracellular enzyme analysis, of a fungal strain *Thelebolus microsporus* from Larsemann Hills, Antarctica *Polar Record* **50** 31-36

Tewari S D and Pant G (1996) Some moss collections from Dakshin Gangotri, Antarctica *Bryological times* **91** 7

Upreti D K and Pant G (1995) Lichen flora in and around Maitri region, Schirmacher Oasis, East Antarctica *Scientific Report - Eleventh Indian Expedition to Antarctica. Department of Ocean Development, Technical publication* **9** 221-231

Upreti D K (1996) Lecideoid Lichens from the Schirmacher Oasis, East Antarctica *Willdenowia* **25** 681-686

Upreti D K (1997) Notes on some crustose lichens from Schirmacher Oasis, East Antarctica *Feddes Repertorium* **108** 281-286

Upreti D K and Nayaka S (2011) Affinities of Indian lichen flora *vis-a-vis* Antarctic and Schirmacher Oasis in: Singh J and Datta H N (eds.) *Antarctica: The most interactive ice-air-ocean environment*. Science Publishers, Inc., New Delhi. Pp. 149-161

Upreti D K and Pandey V (1999) Determination of heavy metals in lichens growing on different ecological habitats in Schirmacher Oasis, East Antarctica *Spectroscopy Letters* **33** 435-444

Wafar S and Untawale A G (1983) Flora of Dakshin Gangotri in Antarctica. *Scientific Report-First Indian Expedition to Antarctica. Department of Ocean development, Technical Publication* **1** 182-185.

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Research Paper

Monitoring Wildlife and their Habitats in the Southern Ocean and Around Indian Research Stations in Antarctica

ANANT PANDE, K SIVAKUMAR, S SATHYAKUMAR*, R SURESH KUMAR, J A JOHNSON, SAMRAT MONDOL and VINOD B MATHUR

Wildlife Institute of India, Chandrabani, Dehradun, Uttarakhand 248 001, India

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Antarctica and its surrounding ocean are at the centre stage of rapid and extreme environmental events due to prevailing global climate change, which in turn necessitates long-term monitoring of wildlife and their habitats in this region. Systematic monitoring of seabirds and marine mammals were carried out during five austral summers (2008-09, 2009-10, 2013-14, 2014-15 and 2015-16). Vessel-based surveys for pelagic seabirds in the southern Indian Ocean, aerial surveys for seals and penguins and field surveys for locating nesting sites of Antarctic birds were conducted at Indian area of operation in Antarctica. Forty-nine species of seabirds were observed during the vessel-based surveys. Species richness peaked in the mid-latitudes but species abundances increased along higher latitudes towards Antarctica. Planktivorous species in the lower latitudes were replaced by mixed prey dependent species in the higher latitudes. Aerial surveys recorded a total of four species of seals viz. Weddell seal, Crabeater seal, Leopard seal and Ross seal and two penguin species viz. Emperor penguin and Adelie penguin. Out of 15 islands in Larsemann hills that were surveyed on-foot, the presence of nesting sites of seabirds is reported from 13 islands. The preliminary results from our study provide the baseline data for ecologically important species within Indian area of operation in Antarctica and will help design future research activities.

Keywords: **Larsemann Hills; Schirmacher Oasis; Prydz Bay; India Bay; Aerial Survey; Nest Monitoring**

Introduction

Global warming has been identified as a major driver of change in the Antarctic ecosystem, some areas in the continent warming more rapidly than other parts of the world (Hansen *et al*., 1999). Though, there are marked variations in the responses of the Antarctic terrestrial and marine communities to the annual climatic variations (Walther *et al*., 2002), more information is needed on understanding the sensitivity of key ecological species to primary biological and physical driving forces in the continent. These temporal variations in the Antarctic environment are considered to play a major role in the primary production, benthic recruitment rates and vertebrate population dynamics. Modifications in the cold climate of southern ocean and Antarctica will affect the community composition of primary producers, thereby affecting the higher trophic levels (Croxall *et al*., 2002; Agusti *et al*., 2010; Constable *et al*., 2014).

Marine vertebrates, being ecologically important and threatened with climatic change (Sydeman *et al*., 2015), have long been identified as ecosystem sentinels. They are influenced by oceanographic processes which play a large role in determining their abundance and distribution (Abrams 1985; Bost *et al*., 2009; Ribic *et al*., 2011; Commins *et al*., 2013). However, population trends are known for only a few marine mammal species (Constable *et al*., 2014), and for seabirds the effects of climatic change have not been studied in depth for most of the species. Seabird species from southern ocean such as penguins have been demonstrated to respond dramatically to sea-ice variations over the past century (Smith *et al*., 1999; Ainley *et al*., 2003). However, the underlying processes linking climate variation to these top predators remains unclear (Sydeman *et al*., 2015; Trathan *et al*., 2015).

**Author for Correspondence: E-mail: ssk@wii.gov.in*

Long-term monitoring of seabird and marine mammal populations is thus needed to provide crucial information about any kind of fluctuations over a period of time. Conventions in the Antarctic treaty, i.e., Convention on the Conservation of Antarctic Seals (CCAS) and the Convention for the Conservation of Marine Living Resources (CCAMLR) also stress the importance of ecosystem monitoring through such species.

In this context, the Wildlife Institute of India (WII), Dehradun, has been monitoring seabirds, mammals and their habitats in the southern ocean and around the Indian Research Stations in Antarctica since the early 1990s (Sathyakumar 1995; Bhatnagar and Sathyakumar 1997; Hussain and Saxena, 2008).

WII initiated Phase-I of the monitoring program titled "Long-term monitoring of wildlife and habitats in Antarctica and Southern Ocean" from 2008-10 (Sivakumar and Sathyakumar 2012; Kumar and Johnson, 2014) followed by a phase-II from 2013-2016 (Pande *et al.*, 2014). This program was undertaken to ascertain the status of key species of the southern ocean and Antarctica and establish a protocol for long-term monitoring of key indicator species around Indian research stations. The present study presents a preliminary assessment of the data compiled during these past five Indian Scientific Expeditions to Antarctica (InSEA).

Study Area

Southern Indian Ocean (African Sector) and Southern Ocean

The voyage route of Indian Scientific Expedition to Antarctica (InSEA) from Cape Town, South Africa (S 33° 55' 25.59" E 18° 25' 24.04") to Larsemann hills, east Antarctica (68°54'92.1" S, 75°30'40.2" E) to Indian barrier (India Bay), Princess Astrid Coast (S 70° 7' 47.34" E 12° 23' 51.9") and back to Cape Town (Fig. 1) was used for seabird and marine mammal monitoring. The voyage covered a latitudinal stretch of southern Indian Ocean from 38° S to 60° S and southern ocean from 60° S to 70° S. The longitudes covered were from 9° 37'E to 76° 50'E.

Larsemann Hills, Prydz Bay, Antarctica : Larsemann hills (69° 20'S to 69° 30'S Latitude; 75° 55'E to 76° 30'E Longitude), East Antarctica, are a group of islands at Prydz Bay (Fig. 2). It is an ice-free oasis on the Ingrid Christensen Coast, Princess Elizabeth Land, located approximately midway between the eastern extremity of the Amery Ice Shelf and the southern boundary of the Vestfold Hills, flanked on both sides by two large peninsulas, the western Stornes and the eastern Broknes, which enclose a group of variously sized islands and peninsulas. Together the islands form the second largest group of four major ice-free oases found along East Antarctica's 5000 km long coastline spread over an area of about 50 km^2 (Hodgson *et al.*, 2009). India's 3rd permanent research station in Antarctica, BHARATI, is located on Grovnes peninsula. Four other Antarctic stations, viz. the Progress I & Progress II (Russia), Law- Racovita (Australia-Romania) and Zhongshan (China) are located along the edge of the Broknes peninsula.

Schirmacher Oasis, Central Dronning Maudland

The Schirmacher Oasis is situated on the Princess Astrid coast of Dronning Maud Land, Antarctica between the Fimbul ice shelf and continental icecap (Fig. 3). This ice-free land is spread across an area of about 34 km^2 between the coordinates 70° 46' 04"-44' 21" S and 11° 49' 54"-26' 03" E (Singh *et al.*, 2012). Second permanent Indian research station MAITRI is located on the south-eastern part of the oasis.

India Bay, Princess Astrid Coast

India Bay, as it is called by the Indian expeditioners, is part of the Haakon VII sea next to the Fimbul ice shelf where Indian expedition activities are conducted (69°47'-69° 48' S and 10° 3'-12°58' E (Fig. 4).

Methods

Vessel-based Surveys

We conducted vessel-based surveys on the voyage route of Indian expedition vessels in the Southern Indian Ocean and Southern Ocean. These surveys were conducted onboard ice-class vessels chartered by the ESSO - National Centre of Antarctic & Ocean Research (NCAOR), Ministry of Earth Sciences, Government of India onboard MV Emerald Sea (2008-09; 28th InSEA) and M V Ivan Papanin (2009-10, 2013-14, 2014-15 & 2015-16; 29th, 33rd, 34th & 35th

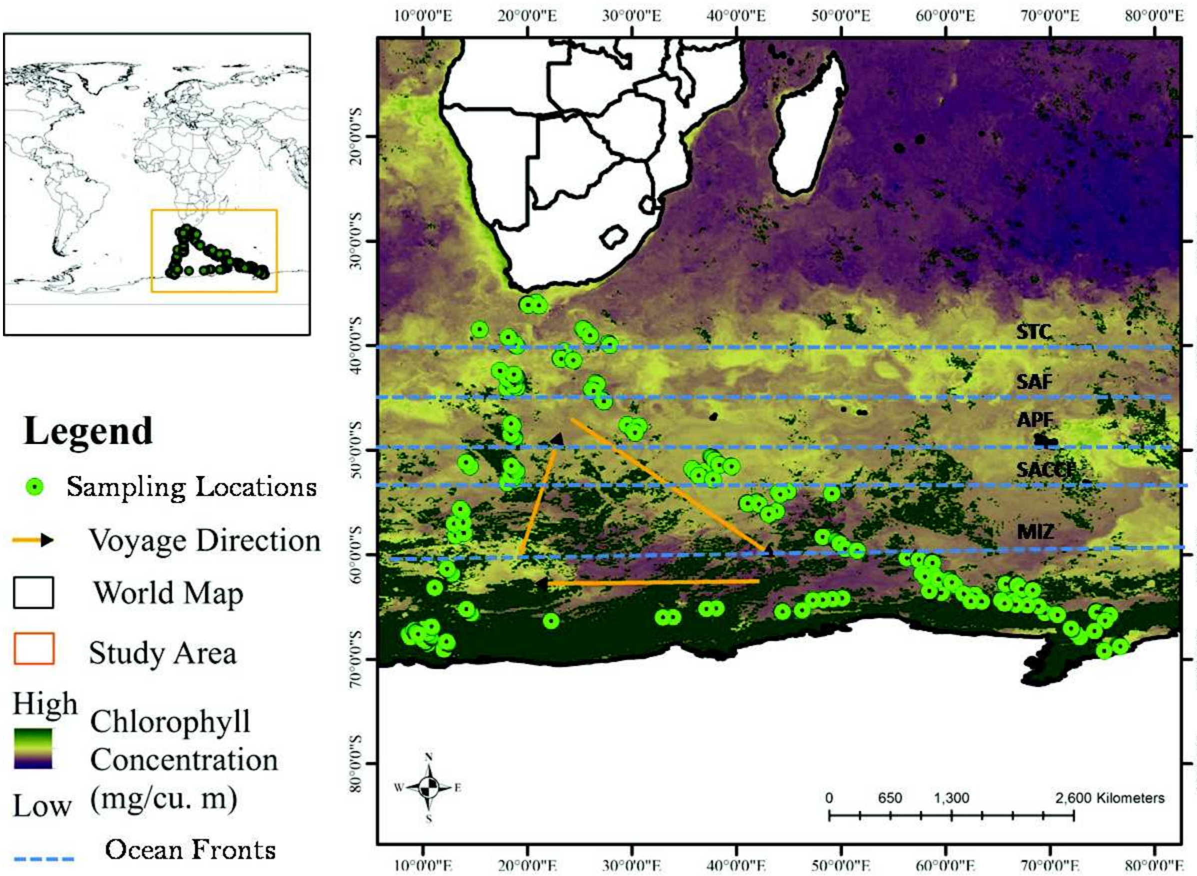


Fig. 1: Sampling route for the vessel-based surveys in the Indian Scientific Expedition to Antarzctica in the Southern Indian Ocean. STC – Sub-tropical Current, SAF – Sub-Antarctic Front, APF – Antarctic Polar Front, SACCF - Southern Antarctic Circumpolar Current Front, MIZ – Marginal Ice Zone (front abbreviations from Commins *et al*. 2013). Average chlorophyll values of December 2013 taken from NASA Earth Observations http://neo.sci.gsfc.nasa.gov/

InSEA respectively). Observations for oceanic birds and marine mammals were carried out from the bridge of these vessels (approx. height from sea level ~ 40 m) in appropriate weather days to estimate their abundance and distribution pattern along the voyage route.

All the seabirds, flying across the bow of the ship, up to 300 m from the ship or visible to naked eye, were counted during the daylight hours (Tasker *et al*., 1984) and a visual estimation was made of their perpendicular distance from the ship route. Only those birds were counted which could be seen without any ocular aid, although, once sighted the identity was confirmed with the help of binoculars. Birds which were foraging together be within 2-5 m of each other were considered to be as one cluster. Marine mammals seen from the bridge of the ship were identified based on their spout pattern, dorsal fin shape, diving pattern and tail fluke shape with the help of binoculars.

Observations were also made during the ship's movement through pack ice, when the cruising speed was at least 6 Knots or more. Observations were not conducted when the sea state was more than 5 (Beaufort scale 0 to 12) and during foggy days (visibility < 300m). Morning and evening glare were avoided by shifting to the side of the ship (starboard or port) opposite to the Sun.

Aerial Surveys

Aerial surveys were conducted at Larsemann hills and India Bay (Princess Astrid Coast) region to estimate the distribution and population of ice-breeding seals and penguins in the Indian sector of operation in

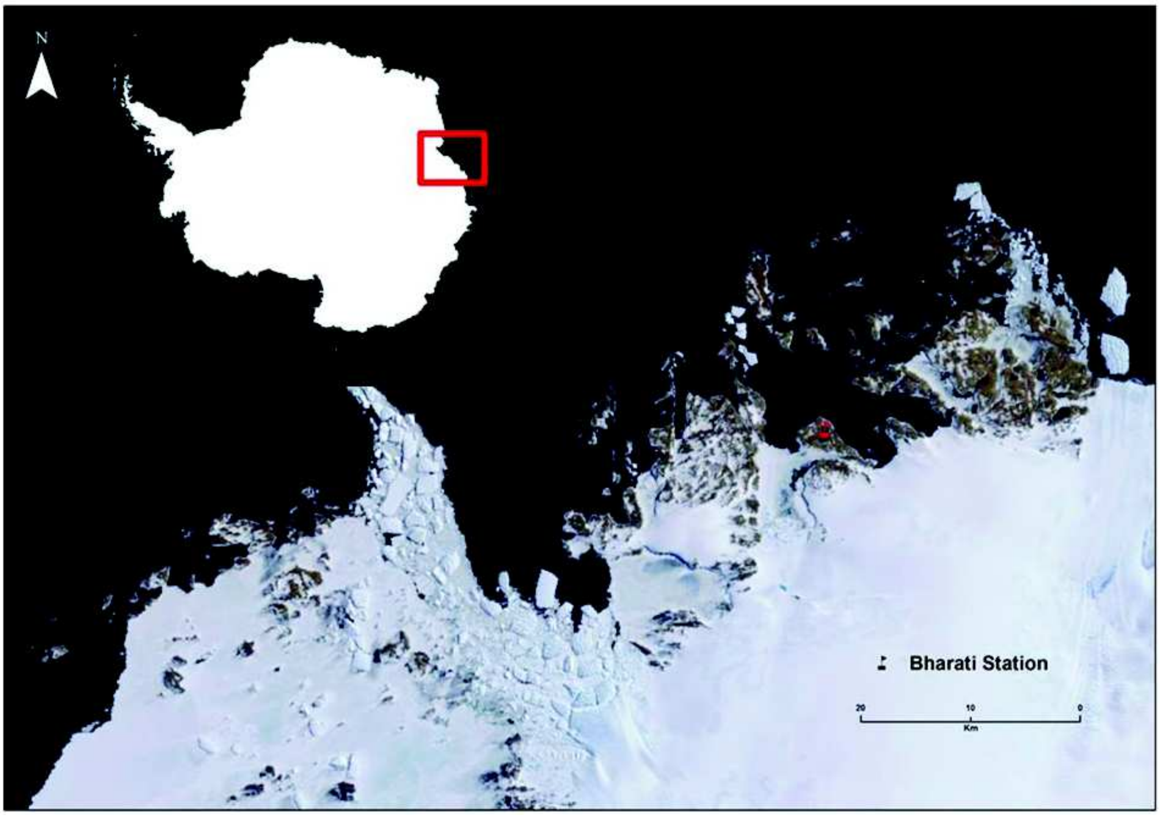


Fig. 2: Larsemann hills, east Antarctica, and site of Indian research station Bharati

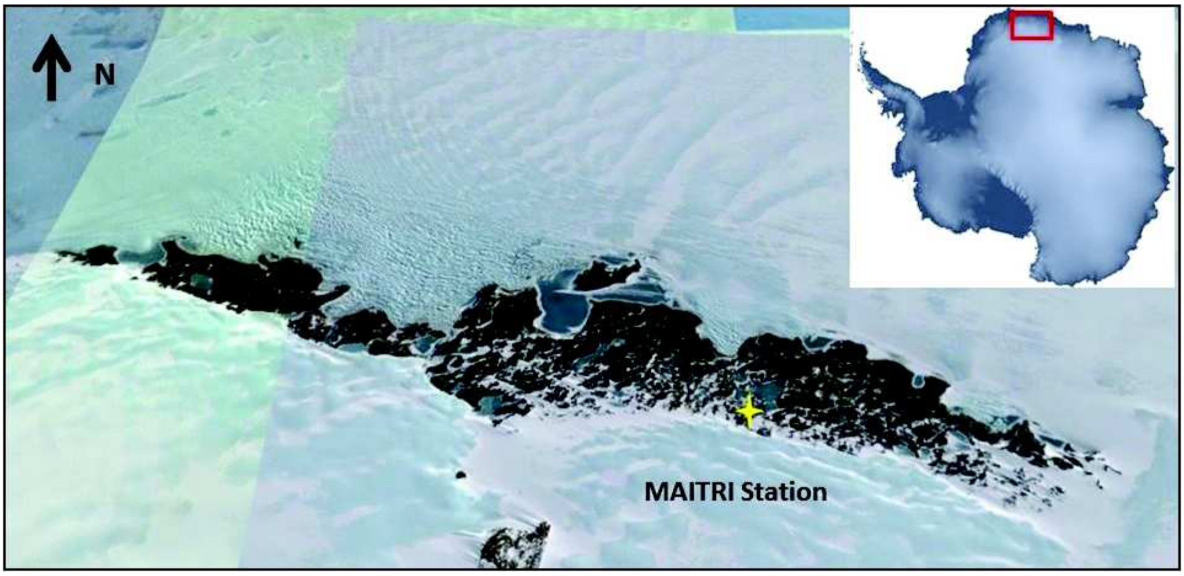


Fig. 3: Schirmacher oasis, central Dronning Maud Land, site of Indian research station Maitri

Antarctica. Aerial sorties were made on the Bell or Squirrel type helicopters in four expeditions' viz. 28th, 29th, 33rd and 35th InSEAs. The methodology varied between expeditions due to modification of objectives in the last two expeditions. In the first two expeditions, surveys followed a pattern of flying along the contour

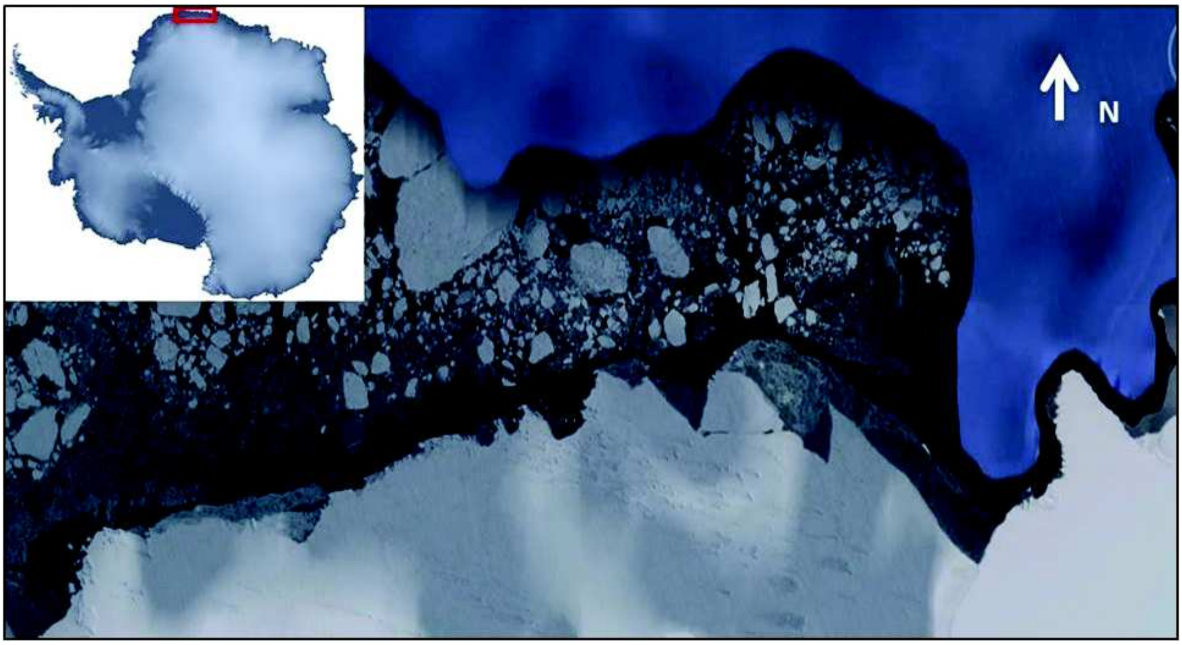


Fig. 4: India Bay, Princess Astrid coast

of the coastline, pack ice and fast ice (Sivakumar and Sathyakumar 2012; Kumar and Johnson 2014). In the last two, transects were laid, perpendicular from the coastline up to the edge of fast ice. A slight modification was made in the 35thInSEA where high resolution video-documentation was employed to record ice-breeding seals in Larsemann hills region. All identified major coastal habitats, i.e. pack ice, fast ice, ice-free islands and near ice shelf zones were surveyed. In both methods, two observers scanned up to a visually estimated distance of 300 m on either side of the helicopter for hauled-out seals. The helicopter was flown at a uniform ground speed of 80 km h^{-1} at an altitude of around 100 m above sea surface. Information on species, number, age class (adult or pup/chick), time, approx. distance from the transect line, reaction to the noise of helicopter, GPS location, etc. were subsequently recorded on each sighting. The sightings were also supplemented by aerial photography with Nikon D300 DSLR camera with Nikkor 70-300 mm zoom lens.

On-foot Surveys

Several islands at Larsemann hills were surveyed on foot to determine presence of any animal use. The smaller islands (< 2 sq. km) were surveyed completely while straight line transects were conducted on larger islands to maximize efforts. This intensive area search method was also employed in, Schirmacher oasis which was surveyed on foot for detecting any animal presence. GPS locations were taken of seabird nest sites, feeding sites (in case of South Polar Skua), Adelie penguin moulting sites, direct sighting, dead remains and related information on species, habitat etc. were duly collected.

Nest Monitoring

Seabird species such as snow petrel *Pagodroma nivea*, south polar Skua *Stercorarius maccormicki* and Wilson's storm petrel *Oceanites oceanicus* were selected for long-term nest monitoring. The monitoring planned to cover all phases of nesting of the species which starts from November (egg-laying) and ends in February-March (fledging).

Snow petrel colonies were identified from on-foot surveys conducted at the islands based on presence of nests cavities with egg/chick/broken egg shells. Selected nesting sites were chosen for intensive monitoring of nesting behavior on the basis of their accessibility.

Study plots, each of 3 x 3 m, enough to cover many cavities which average about 0.2 m^2 in entrance area (Einoder *et al*., 2014), were placed at fixed intervals along lines running diagonally from the bottom to the top of the colony (Mehlum *et al*., 1988). Each potential nest cavity within the study plot was marked using non-toxic paint and its geographic co-ordinates were recorded on a handheld GPS unit.

Intensive study plots (3 x 3 m) were chosen from differently sized colonies to study nest cavity characteristics. The cavities were classified as occupied and unoccupied on the basis of presence of the bird. Physical characteristics such as nest depth, entrance height, entrance width and nest chamber volume were manually measured.

Results

Seabird and Marine Mammal Observation Surveys

A total of 15 vessel-based surveys resulted in ~ 384 hours of observation in the aforementioned sectors during the Indian expeditions (Table 1) conducted over periods of Jan-Mar. 2009, Dec 2009-Mar. 2010, Dec. 2013-Apr 2014, Jan. 2015-Mar. 2015 and Feb. 2016. Forty-nine species of pelagic seabirds were recorded during the study period spread across the five expeditions (Table 2). Amongst the recorded species, four species such as Atlantic petrel, Grey-headed Albatross, Sooty Albatross and Indian Yellow-nosed Albatross are enlisted as endangered (IUCN 2016). Some seabird species were recorded only once, far from their actual distribution ranges, which could have been misidentified from morphologically similar species (Pande *et al*., 2014). Observations recorded were split into High Antarctic (60° to 70° S), Sub-Antarctic (50° to 60° S), Temperate (40° to 50° S) and Sub-tropical (north of 40° S) oceanographic zones as per previous studies (Ribic *et al*., 2008; Commins *et al*., 2013). Encounter rates (birds seen/ km) for the pelagic seabirds were found consistent for all the major oceanographic zones surveyed (Table 3). Bird densities peaked during the sub-Antarctic zone during early summers which shifted to high Antarctic zone during late summers (Fig. 5; Pande *et al*., 2015). The frequency of occurrence (%) of species in the sub-Antarctic and high Antarctic zone varied considerably within the austral summer season (Fig. 6).

Table 1: Voyage survey details for the Indian Scientific Expeditions to Antarctica

Expedition	Voyage ID	Time period	Sector covered	Effort (in hours)
28th InSEA	V1	Jan 2009	CT-LH	65.5
	V2	Feb 2009	LH-IB	36.0
	V3	Mar 2009	IB- CT	36.2
29th InSEA	V4	Dec 2009	CT-LH	44.0
	V5	Feb 2010	LH-IB	16.0
	V6	Mar 2010	IB-CT	40.6
33rd InSEA	V7	Dec 2013	CT-LH	19.5
	V8	Jan 2014	LH-IB	15.7
	V9	Feb 2014	IB- CT	24.7
	V10	Feb 2014	CT-LH	10.7
	V11	Mar 2014	LH-IB	12.0
	V12	Apr 2014	IB- CT	26.3
34th InSEA	V13	Jan 2015	CT-LH	25.5
	V14	Mar 2015	IB- CT	2.2
35th InSEA	V15	Feb 2016	LH-IB	8.7

CT = Cape Town, South Africa, LH = Larsemann Hills, Antarctica, IB = Indian barrier (India Bay), Princess Astrid Coast

Sixteen species of marine mammals were observed during vessel-based surveys in the southern Indian ocean. Out of these, about 11 species were seen exclusively in the High Antarctic zone (60-70 °S) while two species (Humpback whale *Megaptera novaeangliae* and Sperm whale *Physeter macrocephalus*) were also seen north of 60 °S (see Table 4). Balaenopterids (baleen whales) formed the largest group (49%) amongst all marine mammals dominated by Humpback whale (see Fig. 7).

Aerial surveys at Larsemann hills and India Bay

Aerial strip transects (n = 27, effort ~ 30 hours) resulted in a total of 1738 sightings (Table 5). 8822 individuals of four species of seals (Crabeater seal *Lobodon carcinophaga*, Leopard seal *Hydrurga leptonyx*, Ross seal *Ommatophoca rossii* & Weddell seal *Leptonychotesweddellii*) and two penguin species (Adelie penguin *Pygoscelis adeliae* & Emperor penguin *Aptenodytes forsteri*) were counted. Sightings were dominated by Weddell seal (58.2 % of overall sightings) at both India Bay and Larsemann hills survey areas (Fig. 8.1 & 8.2). There was only one Ross seal sighting during the aerial surveys while pair of them was once seen hauled out on fast ice during voyage from Larsemann hills to India Bay (Kumar and Johnson, 2014).

Table 2: Pelagic seabird species recorded during vessel-based surveys in the five InSEAs

S.No	Common name	Scientific name	IUCN status	Pop_ trend	2008-09	2009-10	2013-14	2014-15	2015-16	Zone
1	Antarctic Fulmar	*Fulmarus glacialoides*	LC	stable	1	1	1	1	1	T,SA,HA
2	Antarctic Petrel	*Thalassoica antarctica*	LC	stable	1	1	1	1	1	T,SA,HA
3	Antarctic Prion	*Pachyptila desolata*	LC	stable	0	1	1	1	1	T,SA,HA
4	Antarctic tern	*Sterna vittata*	LC	unknown	1	0	1	0	0	HA
5	Arctic tern	*Sterna paradisaea*	LC	decreasing	0	1	0	1	0	HA
6	Atlantic Petrel	*Pterodroma incerta*	EN	decreasing	1	0	1	0	0	T,SA
7	Black Petrel	*Procellaria parkinsoni*	VU	stable	0	1	0	0	0	ST,T,SA,HA
8	Black-bellied Storm Petrel	*Fregetta tropica*	LC	decreasing	1	0	1	1	0	T,SA
9	Black-browed Albatross	*Thalassarche melanophris*	NT	decreasing	1	1	1	0	0	ST,T,SA
10	Blue Petrel	*Halobaena caerulea*	LC	stable	1	1	1	1	1	T,SA,HA
11	Broad-billed Prion	*Pachyptila vittata*	LC	decreasing	1	0	1	1	0	ST,T,SA,HA
12	Brown Skua	*Catharacta antarctica*	LC	stable	1	0	1	0	0	T,HA
13	Cape Gannet	*Morus capensis*	VU	decreasing	1	1	1	1	0	ST,T
14	Cape Petrel	*Daption capense*	LC	stable	1	1	1	1	1	T,SA,HA
15	Common Diving Petrel	*Pelecanoide surinatrix*	LC	decreasing	1	0	1	1	0	T,SA,HA
16	Cory's Shearwater	*Calonectris borealis*	LC	unknown	1	1	1	0	0	ST,SA,SA
17	Fairy Prion	*Pachyptila turtur*	LC	stable	1	0	1	0	0	T,SA,HA
18	Flesh-footed Shearwater	*Ardenna carneipes*	LC	stable	1	0	1	0	0	ST
19	Great Shearwater	*Ardenna gravis*	LC	stable	0	0	1	0	0	ST
20	Great-winged Petrel	*Pterodroma macroptera*	LC	decreasing	1	1	1	1	0	ST,T,SA,HA
21	Grey Petrel	*Procellaria cinerea*	NT	decreasing	1	1	1	0	0	T,SA,HA
22	Grey-backed Storm Petrel	*Garrodia nereis*	LC	decreasing	1	0	0	0	0	T
23	Grey-headed Albatross	*Thalassarche chrysostoma*	EN	decreasing	1	1	1	1	1	ST,T,SA,HA
24	Indian Yellow-nosed Albatross	*Thalassarche carteri*	EN	decreasing	1	1	1	0	0	ST,SA
25	Kerguelen Petrel	*Aphrodroma brevirostris*	LC	stable	1	0	1	1	0	T,SA,HA
26	Laysan Albatross*	*Phoebastria immutabilis*	NT	stable	1	0	0	0	0	ST
27	Leach's Storm Petrel*	*Hydrobates leucorhous*	LC	stable	1	0	0	0	0	ST
28	Light-mantled Albatross	*Phoebetria palpebrata*	NT	decreasing	1	1	1	1	1	T,SA,HA
29	Little Shearwater	*Puffinus assimilis*	LC	decreasing	0	0	1	0	0	ST,T
30	Northern Giant Petrel	*Macronectes halli*	LC	increasing	0	1	1	1	1	T,SA,HA
31	Salvin's Albatross*	*Thalassarche salvini*	VU	unknown	1	0	0	0	0	ST
32	Salvin's Prion	*Pachyptila salvini*	LC	stable	0	1	1	0	0	T,SA
33	Short-tailed Shearwater	*Ardennate nuirostris*	LC	decreasing	0	0	1	0	0	ST,T,SA,HA
34	Slender-billed Prion	*Pachyptila belcheri*	LC	stable	1	0	1	1	0	T,SA,HA
35	Snow Petrel	*Pagodroma nivea*	LC	stable	1	1	1	1	1	HA
36	Soft-plumaged Petrel	*Pterodroma mollis*	LC	stable	1	1	1	1	0	ST,T,SA
37	Sooty Albatross	*Phoebetria fusca*	EN	decreasing	1	1	1	1	0	ST,T,SA,HA
38	Sooty Shearwater	*Ardenna grisea*	NT	decreasing	1	1	1	0	0	ST,T,SA,HA
39	South Polar Skua	*Catharacta maccormicki*	LC	stable	1	1	1	1	1	ST,T,SA,HA
40	Southern Giant Petrel	*Macronectes giganteus*	LC	increasing	1	1	1	1	1	ST,T,SA,HA
41	Southern Royal Albatross*	*Diomedea epomophora*	VU	stable	1	0	1	1	0	ST,T,SA,HA
42	Wandering Albatross	*Diomedea exulans*	VU	decreasing	1	1	1	1	0	ST,T,SA,HA
43	Wedge-tailed Shearwater*	*Ardenna pacifica*	LC	decreasing	0	0	1	0	0	SA
44	Westland Petrel*	*Procellaria westlandica*	VU	stable	0	0	1	0	0	SA
45	White-bellied Storm Petrel	*Fregetta grallaria*	LC	decreasing	1	1	0	0	0	ST,T,SA
46	White-capped Albatross*	*Thalassarche steadi*	NT	decreasing	1	0	0	0	0	ST,T,SA
47	White-chinned Petrel	*Procellaria aequinoctialis*	VU	decreasing	1	1	1	1	1	ST,T,SA,HA
48	White-headed Petrel	*Pterodroma lessonii*	LC	decreasing	1	1	1	1	0	ST,T,SA,HA
49	Wilson's Storm Petrel	*Oceanites oceanicus*	LC	stable	1	1	1	1	1	ST,T,SA,HA

1 – Recorded, 0 – Not recorded, ST = Sub-tropical, T – Temperate, SA – Sub-Antarctic, HA – High Antarctic, EN – Endangered, LC – Least Concern, NT – Near Threatened, VU – Vulnerable (Threat categories of IUCN Red List), *Probably misidentified or vagrant
#Source: IUCN Red List accessed on 15th July 2016

Table 3: Encounter rates (birds/km) for the seabirds recorded in major oceanographic zones in the southern Indian Ocean in the past five expeditions

InSEA	High antarctic	Sub-antarctic	Temperate	Sub-tropical
28	0.16 ± 0.52	0.15 ± 0.34	0.07 ± 0.1	0.09 ± 0.23
29	0.30 ± 0.61	0.36 ± 0.78	0.11 ± 0.2	0.04 ± 0.03
33	1.30 ± 3.32	1.07 ± 2.74	1.51 ± 10.61	0.63 ± 1.13
34	1.13 ± 2.42	2.99 ± 7.93	0.28 ± 0.17	0.32 ± 0.18
35	0.69 ± 1.46	ND	ND	ND

Table 4: Marine mammal species seen during vessel-based surveys in the southern Indian ocean. Percentage abundance of each species is for the particular zone where it was sighted. This does not include the unidentified sightings

Zone	Species	% Abundance
Sub-tropical	Sperm Whale	0.84
	Long-finned Pilot Whale	35.49
Temperate	Dusky Dolphin	0.84
	Sperm Whale	0.21
	Long-finned Pilot Whale	1.67
Sub-Antarctic	Antarctic fur seal	0.21
	Humpback Whale	0.63
High Antarctic	Blue whale	0.21
	Leopard Seal	0.21
	Ross seal	0.21
	Southern bottlenose whale	0.21
	Minke Whale	1.67
	Sei Whale	1.67
	Weddell Seal	2.09
	Sperm Whale	2.30
	Killer whale	3.76
	Antarctic Minke Whale	4.59
	Fin whale	5.64
	Crabeater Seal	10.65
	Humpback Whale	26.93

Distribution of Wildlife Around Indian Stations

Bharati station, Larsemann Hills: Foot surveys carried out in the Larsemann Hills region revealed presence of five bird species, viz. Adelie penguin, emperor penguin, snow petrel, south polar Skua and Wilson's storm petrel (Pande *et al*., 2014). In all, 15 island/peninsula were surveyed for the presence of habitat use by the birds, of which, nesting sites were detected in 14 islands (Table 6).

Maitri Station, Schirmacher Oasis: Six breeding pairs of south polar Skua were observed in the eastern part of the oasis. Dead remains of two species, Adelie penguin and snow petrel were also found in this area. There was also a single sighting of the Wilson's storm petrel in the area north of the station. The total Skua population on the eastern side of Maitri could be somewhere around 12-15 individuals. Most of these individuals were habituated to human presence and were found to roost near the Indian and Russian stations in the oasis. Four south polar Skua individuals were also ringed with colored leg bands for long-term monitoring of breeding pairs near Maitri station.

Preliminary Results From Nest Monitoring

Over 200 nests of snow petrel were marked and measured for long-term monitoring at Larsemann hills during the last two austral summers (2014-15 & 2015-16). Initial analysis from the cavity parameters classified nest cavities of snow petrels in three types viz. boulder, crack and slab (Pande *et al*., 2015). Out of these three, slab type cavity was the preferred site for nesting accounting for close to 60% of the nests. The cavities with breeding pairs were also lower in volume and narrower compared to the unoccupied cavities (Fig. 9 A & B).

Table 5: Aerial surveys conducted during the Indian Scientific Expeditions to Antarctica*

Expedition	Aerial surveys (n)	Time period	Sector covered	Effort (in hours)
28^{th}InSEA	7	Jan-Feb 2009	Larsemann Hills &Princess Astrid coast	6.69
29^{th}InSEA	6	Dec 2009-Feb 2010	Larsemann Hills &Princess Astrid coast	10.67
33^{rd}InSEA	11	Dec 2013-Mar 2014	Larsemann Hills &Princess Astrid coast	9.55
35^{th}InSEA	3	Jan-Feb 2016	Larsemann Hills	2.99

*No aerial surveys were conducted in 34^{th}InSEA (2014-15) due to unavailability of helicopter support

Table 6: Status of seabirds in islands of Larsemann hills

S.No.	Island/Peninsula	Adelie Penguin	Snow Petrel	South Polar Skua	Wilson's Storm Petrel
1	Betts	M	N	N	+
2	Grovnes	M	N	N	N
3	Breadloaf	-	N	+	-
4	Broknes	-	N	+	N
5	Butler	M		N	N
6	Easther	M	N	+	N
7	Fisher	M	N	+	N
8	Harley	M	-	-	-
9	John	-	-	N	-
10	Manning	M	N	N	N
11	Solomon	M	-	-	N
12	Cook	M	N	-	N
13	Osmar	M	-	+	-
14	Sandercock	-	-	N	-
15	McLeod	M	N	N	N

+ = present but no nesting, - = Not detected, M = Moulting, N = Nesting (updated from Pande *et al*., 2014)

Discussion

Population Assessments

This study generated baseline data on key seabird and marine mammal species in the southern Indian ocean and especially in Prydz bay and India bay. The seabird counts from the vessel-based surveys indicate higher bird species richness in the sub-Antarctic zone gradually declining towards the high Antarctic. However, the bird abundance displayed an increasing trend as expected towards the continental waters (Fig. 5). The increase in bird abundance in the high Antarctic during late summers is attributed to the retreating sea ice towards the coastal shelf areas (Commins *et al*., 2013). Birds which are abundant in the high Antarctic zone had a relatively higher frequency of occurrence during late summer observations (Fig. 6). Birds such as Arctic tern *Sterna paradisaea*, blue petrel *Halobaena caerulea*, snow petrel *Pagodroma nivea* and light-mantled albatross *Phoebetria palpebrata* moved towards open waters south of 60° S in the late summers. Arctic terns are known to forage in the high Antarctic zone from December to March (Egevang *et al*., 2010) whereas surface-seize feeders such as blue petrel, snow petrel and light-mantled albatross prefer foraging in open water polynyas within the sea ice zone (Ainley *et al*.,

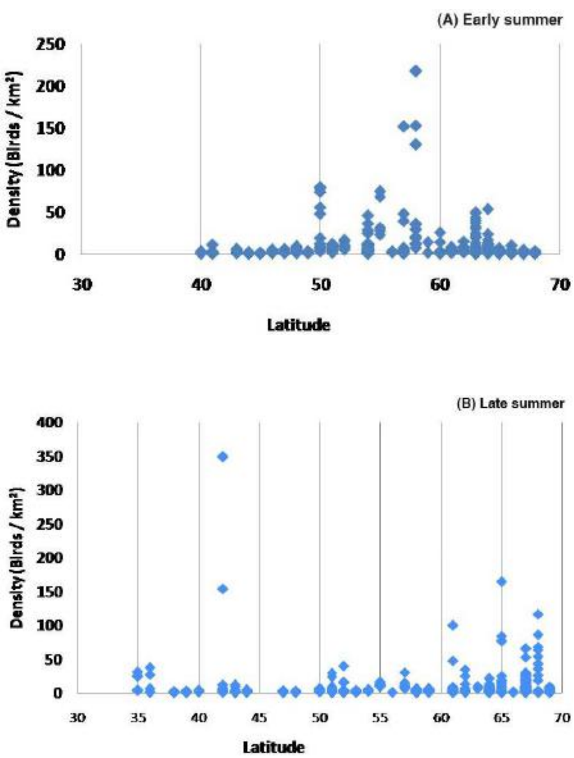


Fig. 5: Density of pelagic seabirds during the austral summers. (A) early summer, (B) late summer (Pande *et al*., 2015)

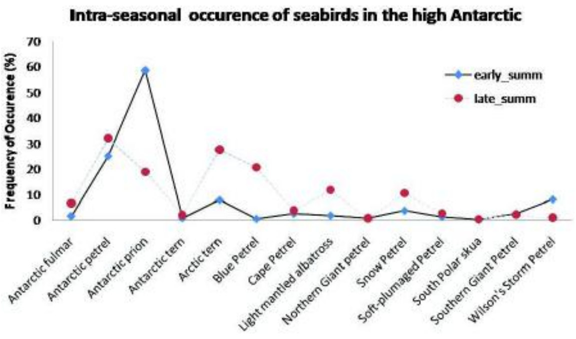


Fig. 6: Intra-seasonal occurrences of key pelagic species in the high Antarctic (60-70°S)

2003; Ribic *et al*., 2008). In the high Antarctic zone, mixed feeders increased in proportion as compared to the plankton, fish and cephalopod feeders (Pande *et al*., 2014). This change is duly attributed to Antarctic petrel and Antarctic prion which were seen in large flocks during the voyage surveys. Similarly, baleen whale species such as Humpback whales spend considerable amount of time foraging in the nutrient-rich waters of the southern ocean during the austral summer (Robbins *et al*., 2011; Constantine *et al*., 2014) to feed on abundant Antarctic krill swarms (Siegel *et al*., 2013). Species-specific distribution maps would be helpful in understanding seabird movements in relation to retreating sea ice. A comprehensive monitoring protocol for the seabirds during In SEAs will be prepared after complete analysis of data gaps.

Weddell seal was found to be the dominant species of the fast ice areas of the Indian sector of operation in Antarctica. The estimates derived from previous counts (Sathyakumar 1995; Bhatnagar and Sathyakumar 1997; Hussain and Saxena 2008) were higher in comparison to past five years data (Table 7). This is probably due to a change in methodology and the area covered by the aerial surveys. Counts of Weddell seals in Larsemann hills were higher than that on Princess Astrid coast due to persistent fast ice in embayment areas in the Prydz bay which accounted for more number of seals hauled out during the surveys (Sivakumar and Sathyakumar 2012; Kumar and Johnson 2014).

Habitat Assessments

Surveys to determine habitat use by seabirds in Larsemann hills covered all major islands and peninsulas except Stornes. Stornes peninsula (69°25'S, 76°6'E) being an Antarctic Specially Protected Area no. 174 (ATS 2014) was not sampled for seabird distribution. Islands/peninsulas like McLeod, Manning and Broknes which are comparatively larger in size could not be covered entirely due to time constraint and inaccessibility. South polar Skua nesting and feeding sites were found in close proximity to snow petrel colonies in islands such as Easther. However, only spatial mapping would reveal any significant relationship between habitat useof these two species. In Schirmacher oasis, the nesting of south polar Skuas was observed to be positively influenced by human presence. Further monitoring of skua breeding pairs is needed using radio-telemetry to understand their movement patterns and territoriality during the breeding period. Dead remains of Adelie penguin suggest the movement of penguins from one colony to another through the oasis which can be confirmed using molecular analysis or radio-telemetry of passing individuals.

Conclusion

Several studies in the past have highlighted the role played by seabirds and marine mammals in maintaining the Antarctic ecosystem health (Croxall *et al*., 2002; Weimerskirch *et al*., 2003; McMahon & Burton 2005). The CCAMLR Ecosystem Monitoring Program (CEMP) also emphasizes the importance of monitoring key seabird and marine mammal species to serve as a basis for the conservation of Antarctic marine living resources and understand the physical and biological drivers of population changes. With data available from several years of monitoring identified species and habitats, we would be better able to understand sensitive species and populations to environmental fluctuations and changes in ecological parameters (such as breeding phenology) over time. Baseline data generated from this study would form the bedrock of the future detailed investigations on demographic assessments, genetic studies and ecosystem monitoring.

In summary, data on distribution patterns of oceanic birds, seals and penguins in the Indian sector of operation would help in preparing monitoring protocols in view of changing climate. The nest monitoring study backed by past survey data will help

Table 7: Abundance estimates of some key species based on wildlife monitoring studies done by Wildlife Institute of India in Indian area of operation in Antarctica

	Weddell Seal			Crabeater Seal			Adelie Penguin			Emperor Penguin		
	SC	ER	GS	SC	ER	GS	SC	ER	GS	SC	ER	GS
*Sathyakumar 1995	-	-	-	17.8	1.04±0.51	-	34.8	1.80 ±1.62	-	47.2	3.16 ±2.75	-
*Bhatnagar & Sathyakumar 1997	-	1.1±1.1	-	-	1.1±0.6	-	-	1.9±1.0	-	-	3.5±2.3	-
Hussain & Saxena 2008	90.2	6.57±1.27	6.0±1.2	8.3	-	1.82±0.1	30.0	12.28±4.97	10.6±7.8	70.0	29.5±7.3	34.0±20.4
#Sivakumar & Sathyakumar 2012	[a]90.0^ [b]53.0^	1.99±1.41^	6.32±7.75	[b]8.0^	0.10±0.10^	1.69±1.20	[a]6.0^ [b]9.0^	[a]24.0±21.0[b] 23.0± 19.0	13.0±10.0	5.35±8.43 5.32±7.89	[a]1.0^ [b]17.0^	[a]2.0±1.0[b]
#Kumar & Johnson 2014	97.0	4.02±2.95	4.71±5.50^	1.7	0.001± 0.002	1.46±0.76^	9.77	0.44±0.33^	4.96±5.51^	23.15	1.05±0.84^	0.0±21.3^
#Pande *et al*. 2014	42.2	0.47±0.48^	2.58±2.64	18.9	0.15±0.16^	2.96±3.14	26.8	0.92±2.1	2.77±3.28^	1.8	0.04±0.03^	2.14±1.86
$This study (2008-2016)	54.0	8.52±8.20	4.68±5.81	2.0	0.51±0.53	1.68±1.66	11.0	2.31±1.75	4.25±5.16	17.0	2.50±2.63	8.61±17.60

SC - Species composition (% abundance), ER - Encounter rates (individuals seen/km) ± SD, GS - Group Size ± SD

^unpublished data, [a]Larsemann hills, [b]India Bay,

*Studies conducted in India bay, #Studies conducted in both Larsemann hills and India bay sectors

$Combined estimates of studies conducted in the past four expeditions i.e. 28th, 29th, 33rd & 35th

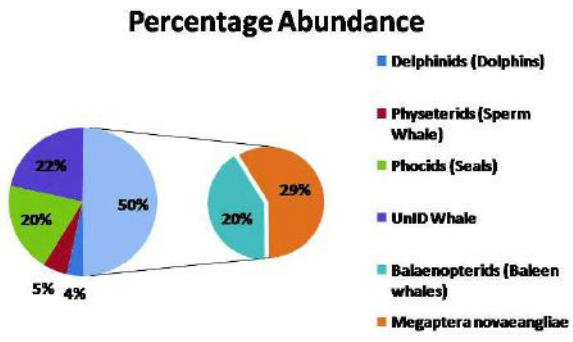
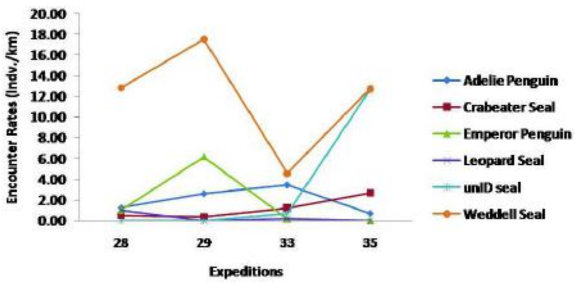
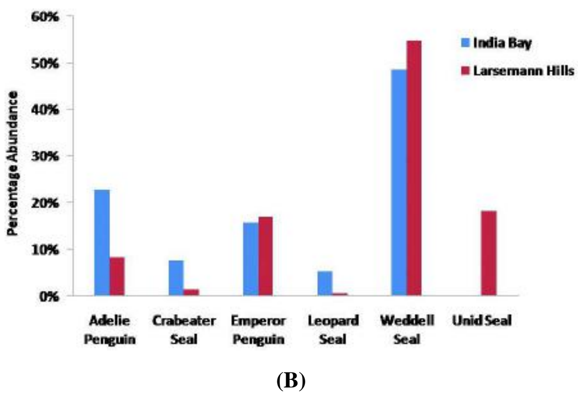


Fig. 7: Percent composition of marine mammals seen during vessel-based surveys



(A)

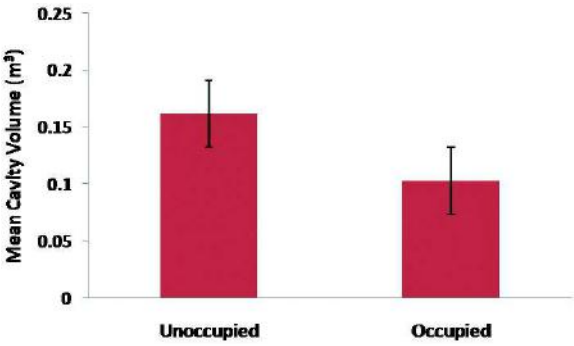
Fig. 8: (A) Encounter rates of vertebrate species sighted during aerial surveys (combined for Larsemann and Princess Astrid coast). The higher number of unidentified seal sightings in the 35th In SEA was due to a new approach employed to count seals using high resolution video-documentation (Anant Pande *unpublished data*)



(B)

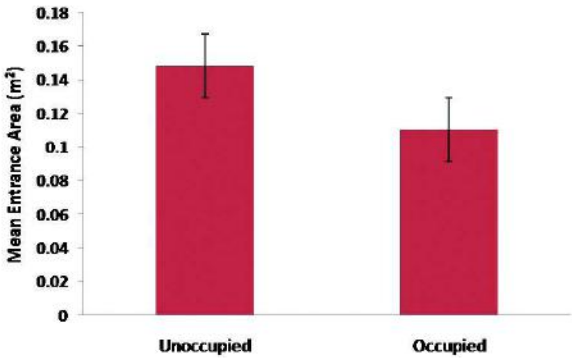
Fig. 8: (B) Percentage abundance of vertebrate species in Larsemann hills and India Bay (Princess Astrid coast) region

in demarcating ecologically important areas near Indian research stations. A spatial mapping of habitat use by the key vertebrate species is under preparation



(A)

Fig. 9: (A) Nest cavity volume of snow petrel nests marked in Larsemann hills for long-term monitoring



(B)

Fig. 9: (B) Nest entrance area of snow petrel nests marked in Larsemann hills for long-term monitoring

Plate 1: Seabird species occurring in Larsemann hills, Prydz bay, Antarctica. Clockwise from top left: Snow petrel, Wilson's Storm petrel, Emperor penguin, Adelie penguin, South polar Skua

to inform station activity planning and establish monitoring protocols for further studies on behaviour, genetic structuring and population monitoring.

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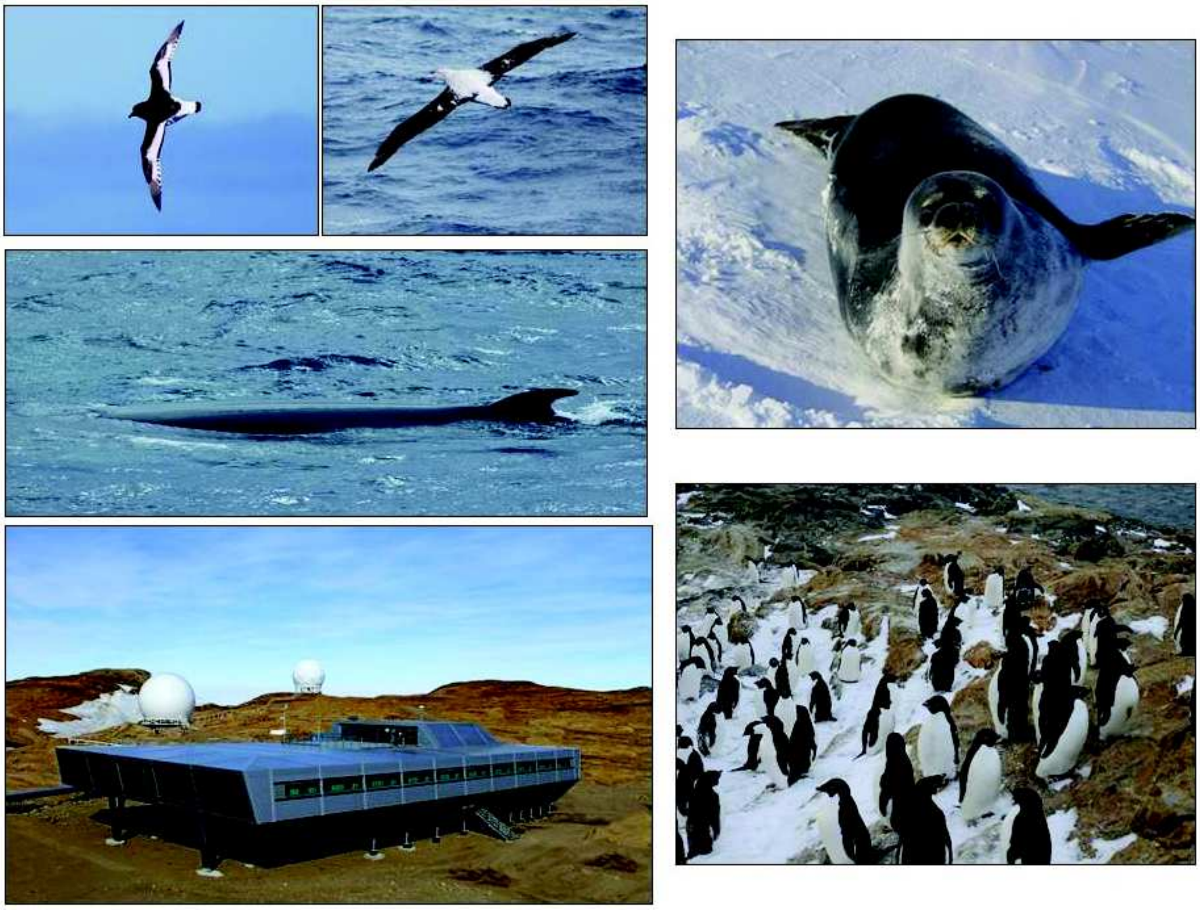

Plate 2: Some commonly seen species during Indian Antarctic expeditions. Clockwise from top left: Antarctic petrel, Wandering Albatross, Weddell seal, Adelie penguin aggregation; Bharati research station at Larsemann hills, Antarctica; and Antarctic Minke whale

References

Abrams R W (1985) Environmental determinants of pelagic seabird distribution in the African sector of the Southern Ocean *J Biogeo* 473-492

Ainley D G, Tynan C T and Stirling I (2003) Sea ice: a critical habitat for polar marine mammals and birds. In Thomas DN, Diekman GS (Eds) Sea Ice: An Introduction to its Physics, Biology, Chemistry and Geology. Blackwell Science, London, pp 240-266

ATS (2016) - Measure 2 (2007) Annex B Management Plan for Antarctic Specially Managed Area No. 6 Larsemann hills, east Antarctica http://www.ats.aq/documents/recatt/Att358_e.pdf- Accessed on 20 July 2016

Agustí, Sejr M K and Duarte C M (2010) Impacts of climate warming on polar marine and freshwater ecosystems *Polar Biol* **33** 1595-1598

Bhatnagar Y V and Sathyakumar S (1999) Daily monitoring and aerial census of penguins and seals in Antarctica.Technical Publication *Department of Ocean Development* **13** 165-182

Bost C A, Cotté C, Bailleul F *et al*. (2009) The importance of oceanographic fronts to marine birds and mammals of the southern oceans *J Marine Syst* **78** 363-376

Coetzee B W and Chown S L (2015) A meta analysis of human disturbance impacts on Antarctic wildlife *Biol Rev* **91** 578-596

Commins M L, Ansorge I and Ryan P G (2013) Multi-scale factors influencing seabird assemblages in the African sector of the Southern Ocean *Antarct Sci* **26** 38-48

Constable A J, Melbourne Thomas J, Corney S P *et al*. (2014) Climate change and Southern Ocean ecosystems I: how changes in physical habitats directly affect marine biota

Glob Chang Biol **20** 3004-3025

Constantine R, Steel D, Allen J *et al*. (2014) Remote Antarctic feeding ground important for east Australian humpback whales *Marine Bioly* **161** 1087-1093

Croxall J P, Trathan P N and Murphy E J (2002) Environmental change and Antarctic seabird populations *Science* **297** 1510-1514

Egevang C, Stenhouse I J, Phillips R A *et al*. (2010) Tracking of Arctic terns *Sterna paradisaea* reveals longest animal migration *PNAS* **107** 2078-2081

Einoder L D, Emmerson L M, Southwell D M and Southwell C J (2014) Cavity characteristics and ice accumulation affect nest selection and breeding in snow petrels (*Pagodro manivea*), *Marine Ornith* **42** 175-182

Hansen J E, Ruedy R, Glascoe J and Sato M (1999) GISS analysis of surface temperature change *J Geophys Res* **104** 30 997-31 022

Hodgson D A, Verleyen E, Vyverman W *et al*. (2009) A geological constraint on relative sea level in Marine Isotope Stage 3 in the Larsemann Hills, Lambert Glacier region, East Antarctica (31 366-33 228calyrBP) *Quat Sci Rev* **28**) 2689-2696

Hussain S A and Saxena A (2008) Distribution and status of Antarctic seals and penguins along the Princess Astrid Coast, East Antarctica *Indian J Marine Sci* **37**(4) 455-461

IUCN (2016) IUCN Red List –http://iucnredlist.org/ - Accessed on 15th July 2016

Kumar R S and Johnson J A (2014) Aerial surveys for pack-ice seals along the Ingrid Christensen and Princess Astrid Coasts, East Antarctica *J Threat Taxa* **6**(9) 6230-6238

McMahon C R and Burton H R (2005) Climate change and seal survival: evidence for environmentally mediated changes in elephant seal, *Mirounga leonina*, pup survival *Proc R Soc Lond B Biol Sci* **272** 923-928

Mehlum F, Gjessing Y, Haftorn S and Bech C (1988) Census of breeding Antarctic Petrels Thalassoicaantarctica and physical features of the breeding colony at Svarthamaren ,Dronning Maud Land, with notes on breeding Snow Petrels *Pagodroma nivea* and South Polar Skuas *Catharacta maccormicki Polar Res* **6** 1-9

Pande A, Sivakumar K, Sathyakumar S and Mathur V B (2014) Long-term monitoring of wildlife and their habitats in Antarctica: Vertebrate surveys near Indian research stations, Unpublished Technical report submitted to National Centre for Antarctic and Ocean Research for the 33rd Indian Scientific Expedition to Antarctica, Wildlife Institute of India, Dehradun, pp. 21

Pande A, Sivakumar K, Sathyakumar S, Mondol S and Mathur V B (2015) Sentinels of south: seabird monitoring in southern ocean and Antarctica, Conference presentation at XV Annual Research Seminar, 1- 4 Sept, 2015, Wildlife Institute of India, Dehradun

Ribic C A, Chapman E and Fraser W R (2008) Top predators in relation to bathymetry, ice, and krill during austral winter in Marguerite Bay, Antarctica *Deep-Sea Res II* **55** 485-499

Robbins J, Dalla Rosa L, Allen J M *et al*. (2011) Return movement of a humpback whale between the Antarctic Peninsula and American Samoa: A seasonal migration record *Endanger Species Res* **13** 117-121

Sathyakumar S (1995) Developing a long-term monitoring programme for birds and mammals in the Indian Ocean and Antarctica using GPS and GIS technologies, Technical Publication, Department of Ocean Development **12** 207-219

Siegel V, Reiss C S, Dietrich K S *et al*. (2013) Distribution and abundance of Antarctic krill (*Euphausiasuperba*) along the Antarctic Peninsula *Deep Sea Res I* **77** 63-74

Singh S M, Ochyra R, Pednekar S M *et al*. (2012) A Holocene moss species preserved in lake sediment core and the present moss diversity at Schirmacher Oasis, Antarctica *Antarct Sci* **24** 353-358

Sivakumar K and Sathyakumar S (2012) Climate Change and its impact on the distribution of birds in Southern Indian Ocean and Antarctica. In: G. K. Saha (Ed) Climate Change: Man and Environment. Daya Publishers, Delhi. pp. 300

Smith R C, Ainley D, Kaber K *et al*. (1999) Marine ecosystem sensitivity to historical climate change in the Antarctic Peninsula *Bio Science* **49** 393-404

Sydeman W J, Poloczanska E, Reed T E and Thompson S A (2015) Climate change and marine vertebrates *Science* **350** 772-777

Tasker M L, Jones P H, Dixon T and Blake B F (1984) Counting seabirds at sea from ships: A review of methods employed and a suggestion for a standardized approach *The Auk* **101** 567-577

Trathan P N, García Borboroglu P, Boersma D *et al*. (2015) Pollution, habitat loss, fishing, and climate change as critical threats to penguins *Conserv Biol* **29** 31-41

Walther G R, Post E, Convey P *et al*. (2002) Ecological responses to recent climate change *Nature* **416** 389-395

Weimerskirch H, Inchausti P, Guinet C and Barbraud C (2003) Trends in bird and seal populations as indicators of a system shift in the Southern Ocean *Antarct Sci* **15** 249-256.

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Research Paper

Hydrographic Characteristics of a Coastal Antarctic Transect in the Indian Ocean Sector

ALVARINHO J LUIS* and VINIT R LOTLIKAR
Earth System Science Organization (ESSO), National Centre for Antarctic and Ocean Research (NCAOR), Headland Sada, Goa 403 804, India

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We address results of the hydrographic measurements obtained from Expendable CTD (XCTD) probes deployed along a coastal Antarctic transect between Prydz Bay and India Bay during austral summer of 2013. The thermal structure indicated two upwelling zones: one centered at 38°E and another at 60°E; these entrain Circumpolar Deep Water (CDW) to shallow depths. The two bays are influenced by cyclonic circulation adjacent to the Amery Ice Shelf and in the Weddell Sea. The former promotes a cold front at 70°E which extends to deeper depths, while the latter promotes a cold front at 40°E in the upper 400 m. We encountered deep mixed layer (> 100 m) in low weak wind speed condition. The temperature and salinity profiles capture signatures of super cooled water in the Prydz Bay between 90-164 m and Antarctic Bottom Water at deeper depths (> 900m). CDW is the voluminous water mass detected in the study area. The research work, which is first of its kind pertaining to the coastal Antarctic sector by deploying XCTDs, will serve as benchmark for planning a detail survey in this region using a dedicated research vessel for deeper penetration of hydrographic recording instruments for a broader and 3-dimensional picture of the circulation and water mass transformation.

Keywords: **XCTD Observations; Water Masses; Thermohaline Structure; Mixed Layer Depth; Coastal Antarctica**

Introduction

The Southern Ocean (SO) has a profound influence on the world's ocean and the global climate system (Deacon, 1937). It connects global oceans and acts as a major conduit for ocean circulation (Rintoul *et al*., 2001; Iudicone *et al*., 2008). The Antarctic Bottom Water (AABW), which is one of the most important water masses of the global ocean, is formed at a few regions of the Antarctic shelf. AABW descends the shelf and flows northward, together with the Antarctic Intermediate Water and the Lower Circumpolar Deep Water, both of which are generated within the SO. They constitute the counter-clockwise part of the Meridional Overturning Circulation (MOC) and have significant effects on the ventilation and heat transport at abyssal and intermediate depths of the world's oceans. The southward flux of the MOC is driven by the North Atlantic Deep Water (NADW).

The dense AABW, which refers to several varieties of bottom waters produced and exported around the Antarctic continental margins, is generated around some areas of the Antarctic shelf (Orsi *et al*., 1999; Gordon *et al*., 2004). The different varieties of bottom waters are the Weddell Sea Bottom Water formed in the Weddell Sea, the Ross Sea Bottom Water formed in the western Ross Sea, and the Adélie Bottom Water formed along the Adélie coast of Wilkes Land (Orsi *et al*., 1999, 2002). AABW formation is rather complicated as it involves poorly understood shelf processes and mixing of different water masses (Gill, 1973; Foster and Carmack, 1976). During austral winter, sea ice is formed within the Antarctic coastal polynyas due to convection facilitated by cold and strong offshore winds (Arrigo and Van Dijken, 2003), leaving behind high salinity dense water (brine). The brine sinks, driving deep convection bringing water with high nutrients and CO_2 to the surface (Arrigo *et al*., 2008). Finally, on

**Author for Correspondence: E-mail: alvluis@ncaor.gov.in; alvluis1@gmail.com*

Antarctic shelf, the Circumpolar Deep Water (CDW) mixes with younger waters of local origin, producing ventilated water which is known as Modified Circumpolar Deep Water (mCDW; Withworth *et al*., 1998). It is injected into mid-depths and contributes to the formation of the different types of AABW. Sea ice formation within the Antarctic shelf converts local upper waters like the Antarctic Surface Water (AASW) or the shoaling mCDW into the densest Shelf Water (SW) (Whitworth *et al*., 1998). The SW is divided into Low Salinity Shelf Water (LSSW), and High Salinity Shelf Water (HSSW), which are discriminated by salinity of 34.6 psu (Smith *et al*., 1984). The HSSW is recognized by its core salinity of ~34.8 (Orsi *et al*., 2002).

The region between the eastern limb of the Weddell Sea and western edge of the Prydz Bay (black contour labeled by letter 'A' in Fig 1) is the focus of this study because of the following reasons: (i) this region is the site of an important confluence between the region west of Weddell-Enderby Land, Kerguelen Plateau to the north and the Australian-Antarctic Basin to the east. As a consequence, the resulting signature of water masses, circulation and biogeochemistry of this area is significantly influenced by this confluence. (ii) The Prydz Bay has been widely suggested as a region for AABW formation (Jacobs and Georgi, 1977; Orsi *et al*., 1999; Yabuki *et al*., 2006), thereby meriting a investigation of hydrographic features and the role of adjacent cyclonic circulation in the Weddell Sea and circulation adjacent to the Amery Ice Shelf on vertical thermohaline structure. The oceanographic features are cursory in the region from 10° to 77°E, so we address the water masses distribution and thermohaline structure during the austral summer period of 2013. The hydrographic data was collected using eXpendable CTD (XCTD) probes deployed during the Indian Scientific Expedition to Antarctica. Though the results are preliminary in nature, they help to gain insight into the oceanographic features of the study area, as well as in facilitating the development of sampling strategy using a dedicated oceanographic vessel in the near future.

Oceanographic Features of the Study Area

The study area extends from 9.55°E to 76°E, from India Bay, the berthing site which is about 100 km north of the Indian Research base Maitri to Prydz Bay (the region marked by letter 'A' in Fig. 1). The region lies inside the Weddell-Enderby basin, with the Kerguelen Plateau to the north-east and the shallowest point of the Princess Elizabeth Trough (PET) to the east of Prydz Bay. The survey area can broadly be divided into two regimes: the region west of 50°E, which is dominated by the eastward extension of the Weddell Gyre (Gordon, 1998; Park *et al*., 2001), while to the east of 50°E, the Antarctic Circumpolar Current (ACC) and its southern fronts, comprising southern ACC front (sACCF) and Southern Boundary (SB) (Orsi *et al*., 1995), influence the region from the north. The fronts are forced southward by the Kerguelen Plateau, and flow eastward through the PET. The Amery Ice shelf is also an important feature, feeding shelf and ice-shelf water into the study region.

Two important features that are identified at the margin of Antarctica are the Antarctic Slope Front

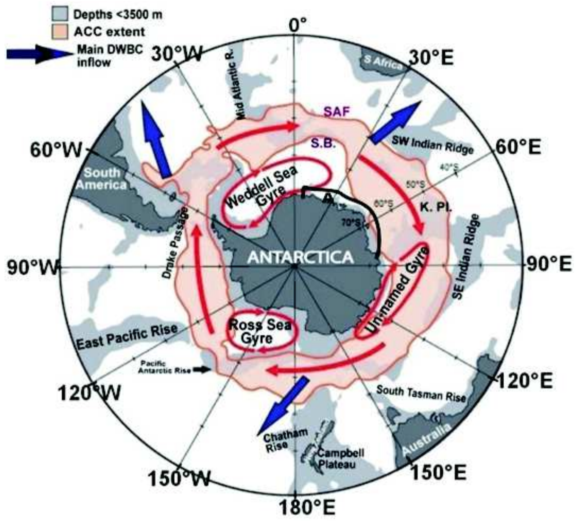

Fig. 1: The main oceanographic elements of the Southern Ocean including: (i) the ACC contained by the Subantarctic Front (SAF) and southern limit of southern boundary (SB) or Upper Circumpolar Deep Water; (ii) the Ross, Weddell and unnamed subpolar gyres; and (iii) the main exit points of deep western boundary currents from the Southern Ocean (deep blue arrows). The general path for the ACC is from Orsi *et al*. (1995) with modifications based on Heath (1985) and Morris *et al*. (2001). The coverage of the XCTD sampling area lies within the black contour indicated by letter 'A'. Bathymetric elevations are Annotated as R - ridge; and K. Pl.- Kerguelen Plateau. The base chart is modified from Orsi and Whitworth (2005)

(ASF) and the Antarctic Coastal Current (ACoC). The ASF defines the boundary between cold, relatively fresh waters encountered at the Antarctic continental shelf and the warmer, more saline waters farther offshore, which are found below the near-surface layer (Jacobs, 1991). It is associated with a westward transport around Antarctica, which is considered be a consequence of the prevailing westward winds near the Antarctic continent, which induce an Ekman transport of cold, relatively fresh surface water toward the continent, thereby setting up a geostrophic westward flow around Antarctica (Deacon, 1937; Sverdrup, 1953). This flow is constrained to the continental slope depths of 500–1000 on the eastern side of the Antarctic Peninsula (Muench and Gordon, 1995). The ACoC is a fast, shallow flow over the continental shelf, which is often associated with the front of the ice shelf (Jacobs, 1991). The transport of the ACoC, and that associated with the ASF, is important for the advection of nutrients and krill, for preconditioning the shelf waters for the formation of AABW through their associated heat and freshwater fluxes, and for supplying waters beneath ice shelves, thus melting the underside of the ice shelf (Heywood *et al*., 2004).

In the Indian Ocean sector, negative wind stress curl associated with the Antarctic Divergence promotes cyclonic oceanic sub-structure. Zeverev (1963) reported the presence of a series of cyclonic gyres between 20° and 100°E, while Smith *et al*. (1984) showed that the subsurface cyclonic eddies of 500 km diameter were located at 67° and 80°E, along 65°S. Other researchers reported the presence of cyclonic eddies at 67°, 100°, and 115°E, and the zonal diameter of the eddies was estimated to be about 500 km (Wakatsuchi *et al*., 1994). In the present study area, the Antarctic Divergence is located relatively close to the continent and some stations are placed hundreds of kilometers away from the coast, and so the topographic features of the continental shelf and slope could influence the water mass properties (Wakatsuchi *et al*., 1994).

Data Processing

The XCTD deployments were carried out from 19th-25th February, 2013 (Fig. 2), from the Indian Antarctic Expedition vessel M V Ivan Papanin plying between Prydz Bay and India Bay. The hydrographic stations

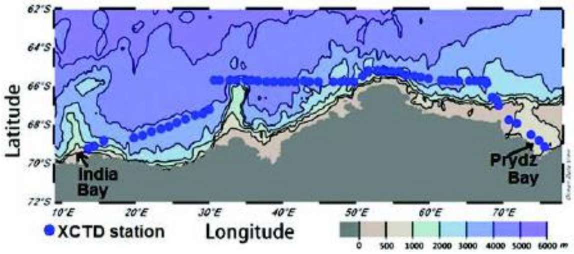

Fig. 2: The XCTD sampling locations during 19th-25th February, 2013. The bathymetry is shown in the background

were spaced 30-32 nautical miles apart. The XCTD probes (make: Tsurumi Seiki Company Limited, Japan; type: XCTD-3; terminal depth: 1000 m; temperature/ salinity accuracy: ± 0.02 °C/± 0.03 mS cm^{-1}) were deployed at every degree longitude to record temperature and salinity in the upper 1 km of the ocean. A comparison of the XCTD-3 data and Sea Bird CTD profiles reveal that the former is consistent with temperature and salinity accuracy specified by the manufacturer (Mizuno and Watanabe, 1998), and that the fall rate for the XCTD probes show no systematic bias in the fall equation provided by the manufacturer (Kizu *et al*., 2008). The temperature profiles were quality-controlled by following the standard procedures (Bailey *et al*., 1993; Uchida *et al*., 2011). High frequency noise in the salinity profiles was minimized by using a median filter with a 15-m (Xiaojun *et al*., 2004). We also used ECMWF interim daily for quantifying the net heat flux at surface and surface wind speed (Berrisford *et al*., 2011)

Results

Criteria used in this study to identify the water masses in the coastal Antarctic domain are listed in Table 1. The most important of these are Antarctic Surface water (AASW), Circumpolar Deep Water (CDW) and AABW. The Winter Water (WW) is one of the components of Antarctic Surface Water (AASW), the other being Summer Surface Water (SSW). WW, which forms a temperature minimum layer below the SSW, is characterized by temperature of –1.87°C and salinity of 34.34. It is a remnant of the surface water formed by winter convection (Wong *et al*., 1998), which spreads northwards by winds away from the continent. SSW has a temperature <4°C and the salinity range of 33.5 to 34 psu. These water masses

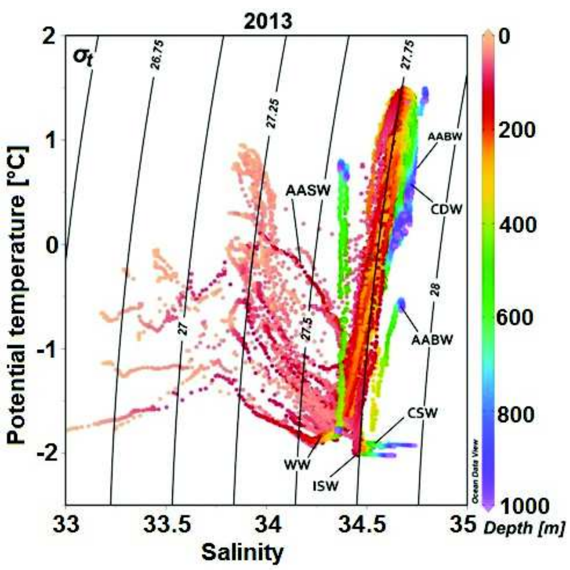

Fig. 3. ***θ-S*** **diagram prepared using the XCTD data collected during period 19th-25th February, 2013**

are representative of freezing and melting in the study area. Winter mixed layer are usually remnant of the previous winters. WW is usually under-saturated due to non-conservative processes of organic matter in surface layer and entrainment of warm CDW water into mixed layer during winter when sea ice cover mitigates the wind effect.

Below WW, the Continental Shelf Water (CSW) (θ: –1.85°C and salinity: 34.56 psu) was detected in the Prydz Bay. CSW is relatively salty and denser than the surface waters and is found in the subsurface region. Mixing over the shelf occurs throughout the water column unlike in the open sea. Convection supports sea ice formation and brine rejection leading to the genesis of these cold saline waters. The voluminous water mass in the study area is CDW (θ: 0.61°C and salinity: 34.68 psu). It is involved in the formation of all other water masses through vertical and lateral mixing induced by polar easterlies at the Antarctic slope and shelf regions (Whitworth *et al*., 1998). This high saline warm water is driven from the sub-Antarctic region to the Antarctic region, where it keeps the region ice free during winter.

The CDW was detected below 75 m, between 32° and 42°E, and at a deeper depth (> 180 m) between 58° and 68°E (Fig. 4). Our profiles captured traces of AABW at deeper depths (>900m), which is probably due to truncation of the profiles at 1000 m. Previous time series study carried out using portable CTD data during 24-27 February, 2006 could not detect either CDW or AABW in this region (Anilkumar *et al*., 2010). Supercooled water having temperature and salinity ranges of –2.14 to –1.96°C and 34.39 to 34.46, respectively, have been detected in the region north of the Amery Ice Shelf (Shi *et al*., 2011). These are caused by melting beneath the sea ice where the freezing point is very low due to high pressure (Shi *et al*., 2010). From Fig. 4 the signatures of the supercooled water was found in the Prydz Bay at 70.9°E, between 90-167 m, at 71.8°E, between 99-139 m, and at 73.7°E, between 123-164 m.

In the Prydz Bay, up-sloping of isohalines and presence of low temperature (<0 °C) densest water >27.7 σ_t at surface are detected (Fig. 4). The melt water is contributed by the Amery Ice Shelf and three glaciers located nearby the Larsemann Hills, *viz*. Fisher (~75°S, 65°E), Lambert (~73°S, 70°E) and Polar Record glaciers (~70°S, 73°E) (Anilkumar *et al*, 2010). The fresh water which is marked by low salinity (<34) in the upper 30 m pushes the high salinity dense water below 50 m (Fig. 4). The winter time observations of Middleton and Humphries (1989) indicate that the Prydz Bay shelf is occupied by water of salinity slightly higher than 34.6 psu, the minimum salinity required for the formation of AABW. Our section provides an evidence for shelf water descending down the continental slope to deeper depth (Fig. 4).

The mixed layer depth (MLD) varies from 20 m at 15.6°E to 122 m at 50°E. The deepening of the MLD is found to be unrelated to the surface wind speed or net heat flux. The deeper MLD on the eastern side of the transect can be attributed to large influx of fresh water from adjacent Amery Ice Shelf and glaciers, which forms a thick layer at the surface. On the other hand, intrusion of cold and fresh water from the Weddell Sea is evident in the temperature and salinity structure on the western side of the transect. The wedge structure in the temperature isotherms up to 40°E, where it forms a strong thermal front, is interrupted by the upwelling CDW; it is a clear indication of the confluence of Weddell Sea circulation with the study area. Likewise, three stations in the Prydz Bay capture a front at 70°E,

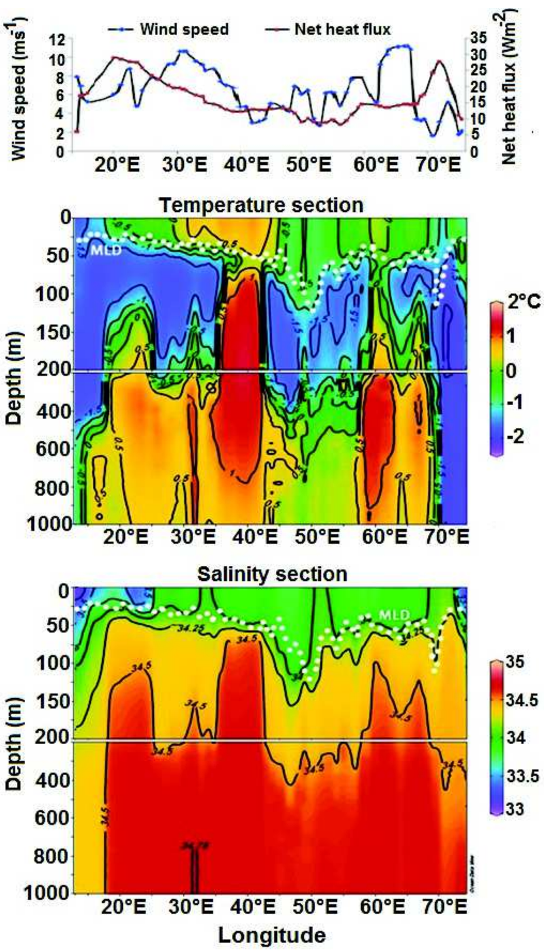

Fig. 4: Vertical temperature and salinity structures prepared from XCTD observations recorded during 19th-25th February, 2013. Mixed layer depth (represented by white dots) has been calculated as the depth where density change of 0.03 kgm^{-3} is encountered from surface value (Dong *et al.*, 2008). Surface meteorological parameters were derived from ECMWF interim forecast (Berrisford *et al.*, 2011)

which is formed due the influence of the cyclonic circulation adjacent Amery Ice Shelf.

The thermal structure indicates two upwelling zones; one centered on 38°E and the other at 60°E, which carries CDW to lower depths. India Bay and Prydz Bay experience strong downwelling whose signature is evident up to 1000 m. These characteristic features of the two domains are influenced by Weddell Sea gyre and cyclonic gyre adjacent to the Amery Ice Shelf. We note that satellite chlorophyll-a images indicate high chlorophyll-a bloom in austral summer in the Prydz Bay promoted by strong stratification resulting from melt water discharged from the Amery Ice Shelf, supplemented by net heat influx (~30 Wm^{-2}) into the ocean (Fig. 4).

Table 1: Criteria for identification of the principal water masses (after Smith and Tréguer, 1994)

Water mass	θ (°C)	S
WW	–1.87	34.34
CDW	0.61	34.68
CSW	–1.85	34.56
Ice Shelf Water (ISW)	–2.00	34.50
AABW	–0.51	34.66
AASW	–1 to 1	34-34.6

Conclusions

In this preliminary study, the results pertaining to water masses and their distribution along a coastal section between Prydz Bay and the India Bay occupied during the austral summer of 2013 are discussed. A data set consisting of temperature and salinity profiles recorded by deploying XCTD has been used to highlight the principal water masses and the vertical thermohaline structure in the study area, and to elucidate the role of the Weddell Sea and cyclonic gyre adjacent to the Amery Ice Shelf and the possible role of surface meteorological parameters on the evolution of the vertical thermohaline structure. The data indicates that the Weddell Sea circulation promote a front at 40°E in the upper 400 m, while influence of the cyclonic gyre adjacent to the Amery Ice Shelf promotes a front at 70°E which extends down to deeper depths. Deep mixed layer (> 100 m) are encountered in conditions of weak wind speed. Signature of super cooled water was found in the Prydz Bay between 90-164 m. The profiles capture signatures of AABW at deeper depths (>900 m). CDW is the voluminous water mass that is detected in the study area.

Acknowledgements

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References

Anilkumar N, Mohan R, Shukla S K, Pednekar S M, Sudhakar M and Ravindra R (2010) Signature of coastal upwelling in Prydz Bay, East Antarctica during austral summer 2006 *Current Science* **99** 1390-1394

Arrigo K R and Van Dijken G L (2003) Phytoplankton dynamics within 37 Antarctic coastal polynyas *J Geophys Res* **108** 3271 doi: 10.1029/2002JC001739

Arrigo K R, van Dijken G L and Bushinsky S (2008) Primary production in the Southern Ocean, 1997-2006 *J Geophys Res* **113** C08004, doi: 10.1029/2007JC004551

Bailey R, Gronell A, Phillips H, Meyers G and Tanner E (1993) CSIRO Cookbook for Quality Control of Expendable Bathythermograph (XBT) Data, CSIRO Marine Laboratories Report 221, CSIRO, Hobert

Berrisford P, Dee D P, Poli P, Brugge R, Fielding K, Fuentes M, Kållberg P W, Kobayashi S, Uppala S and Simmons A (2011) The ERA-Interim archive version 2.0. European Centre for Medium Range Weather Forecasts, Shinfield Park, Reading, Berkshire RG2 9AX, United Kingdom

Deacon G E R (1937) The hydrology of the Southern Ocean, Discovery Rep. 15, pp. 1-24, Inst. of Oceanogr. Sci., Southampton, UK

Dong S, J Sprintall, S T Gille and L Talley (2008) Southern Ocean mixed-layer depth from Argo float profiles *J Geophys Res* **113** C06013, doi: 10.1029/2006JC004051

Foster T D and Carmack E C (1976) Frontal zone mixing and Antarctic Bottom Water formation in the southern Weddell Sea *Deep Sea Res* **23** 301-307

Gill A E (1973) Circulation and bottom water production in the Weddell Sea *Deep Sea Res* **20** 111-140

Gordon A L (1998) Western Weddell Sea thermohaline stratification, ocean, ice, and atmosphere: interactions at the Antarctic continental margin *Antarctic Research Series* **75** 215-240

Gordon A L, Zambianchi E, Orsi A, Visbeck M, Giulivi C F, Whitworth III T and Spezie G (2004) Energetic plumes over the western Ross Sea continental slope *Geophys Res Letters* **31** L21302 doi: 10.1029/2004GL020785

Heath R A (1985) A review of the physical oceanography of the seas around New Zealand – 1982 *N Z J Mar Freshwater Res* **19** 79-124

Heywood K J, Naveira A C, Garabato D P, Stevens and Muench R D (2004) On the fate of the Antarctic Slope Front and the origin of the Weddell Front *J Geophys Res* **109** C06021 doi: 10.1029/2003JC002053

Iudicone D, Madec G, Blanke B and Specih S (2008) The role of Southern Ocean surface forcings and mixing in the global conveyor *J Physical Oceanography* **38** 1377-1400

Jacobs S and Georgi D (1977) Observations on the southwest Indian/Antarctic Ocean *Deep Sea Research* **24** 43-84

Jacobs S S (1991) On the nature and significance of the Antarctic Slope Front *Mar Chem* **35** 9-24

Kizu S, Onishi H, Suga T, Hanawa K, Watanabe T and Iwamiya H (2008) Evaluation of the fall rates of the present and developmental XCTDs *Deep-Sea Res Part 1* **55** 571-586

Middleton J H and Humphries S E (1989) Structure and mixing in the region of Prydz Bay Antarctica *Deep-Sea Research* **36** 1255-1266

Mizuno K and Watanabe T (1998) Preliminary results of in situ XCTD/CTD comparison test *J Oceanogr* **54** 373-380

Morris M, Stanton B R and Neil H L (2001) Subantarctic oceanography around New Zealand: Preliminary results from an ongoing survey *N Z J Mar Freshwater Res* **35** 499-519

Muench R D and Gordon A L (1995) Circulation and transport of water along the western Weddell Sea margin *J Geophys Res* **100** 503-515 18

Orsi A H, Smethie Jr J and Bullister J L (2002) On the total input of Antarctic waters to the deep ocean: A preliminary estimate from chlorofluorocarbon measurements *J Geophysical Res* **107** 3122 doi: 10.1029/2001JC000976

Orsi A H and Whitworth III T (2005) Hydrographic atlas of the World Ocean Circulation Experiment (WOCE). In: M. Sparrow, P. Chapman, & J. Gould (Eds). Southern Ocean. International WOCE Project Office, Southampton, UK, vol. 1, ISBN 0-904175-49-9

Orsi A, Johnson G and Bullister J (1999) Circulation, mixing and production of Antarctic bottom water *Progress Oceanography* **43** 55-109

Orsi A H, Whitworth III T and Nowlin W D Jr (1995) On the meridional extent and fronts of the Antarctic Circumpolar Current *Deep Sea Res* **42** 641-673

Park Y-H, Charriaud E, Craneguy P and Kartavtseff A (2001) Fronts, transport, and Weddell Gyre at 30E between Africa and Antarctica *J Geophys Res* **106** 2857-2879

Rintoul S R, Hughes C W and Olbers D (2001) The Antarctic Circumpolar Current system. In: G Siedler J, Church and J Gould (Eds). Ocean Circulation and Climate: Observing and Modelling the Global Ocean. Academic Press, London, pp. 271-302

Shi J, C Yaoyao, J Yutian and Jiaqiang H (2011) Supercooled water in austral summer in Prydz Bay, Antarctica *Chinese Journal of Oceanology and Limnology* **29** DOI: 10.1007/s00343-010-0011-5

Smith N and P Tréguer (1994) Physical and chemical oceanography in the vicinity of Prydz Bay, Antarctica, In the Southern Ocean Ecology: The BIOMASS Perspective, S. Z. El-Sayed, ed. Cambridge Uni. Press, Cambridge, pp 25-43

Smith N R, D Zhaoqian, K R Kerry and S Wright (1984) Water masses and circulation in the region of Prydz Bay, Antarctica *Deep Sea Res* **31** 1121-1147

Sverdrup H U (1953) On conditions for the vernal blooming of phytoplankton. Journal du Conseil *International pour l'Exploration de la Mer* **18** 287-295

Uchida H, Shimada K and Kawano T (2011) A method for data Processing to obtain high-quality XCTD data *J Atmosph and Ocean Technol* **28** 816-826

Wakatsuchi M, K I Ohshima, M Hishida and M Naganobu (1994) Observations of a street of cyclonic eddies in the Indian Ocean sector of the Antarctic Divergence *J Geophys Res* **99** 417-20, 426

Withworth III, Orsi A H, Kim S-J, Nowlin Jr, W D and Locarnini R A (1998) Water masses and mixing near the Antarctic Slope Front. In: Jacobs, SS., Weiss, R.F. (Eds), Ocean, Ice and Atmosphere: Interactions at the Antarctic Continental Margin. AGU, Washington, DC, pp. 1-27

Wong A P S, Bindoff N L and Forbes A (1998) Ocean–ice shelf interaction and possible bottom water formation in Prydz Bay, Antarctica. In: Jacobs S S and Weiss R F (Eds.), Ocean, Ice and Atmosphere: Interactions at the Antarctic Continental Margin : *Antarctic Research Ser* **75**. AGU, Washington D.C., pp. 173-187

Xiaojun Y, Douglas G M and Zhaoqian D (2004) Upper ocean thermohaline structure and its temporal variability in the southeast Indian Ocean *Deep-Sea Res Part 1* **51** 333-347

Yabuki T, Suga T, Hanawa K, Matsuoka K, Jiwada H and Watanabe T (2006) Possible source of Antarctic Bottom Water in Prydz Bay region *J Oceanography* **62** 649-655

Zeverev A A (1963) Currents in the Indian sector of the Antarctic *Tr Sov Antarkt Eksped* **17** 144-155.

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Research Paper

Indian Contributions to Antarctic Social Sciences

SANJAY CHATURVEDI*
Centre for the Study of Geopolitics, Panjab University, Chandigarh 160 014, India

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The term 'social sciences' encompasses a diverse group of disciplines and fields of study and not simply the study of politics and policy. The Scientific Committee on Antarctic Research (SCAR) Humanities and Social Sciences Experts Group (HASSEG), the body representing the Antarctic social scientists, is an outstanding example of emphatic acknowledgment –in this case by SCAR—of critically important interface/interaction between natural sciences and social sciences. In case of India, both the Ministry of Earth Sciences (MoES), New Delhi and the National Centre for Antarctic and Ocean Research (NCAOR), Goa have welcomed and encouraged not onlypolicy-oriented, critically-informed social science research on a range of issues related to Antarctic governance (e.g. bioprospecting, climate change, tourism) but also the presence of social scientists in Indian delegations to the Antarctic Treaty Consultative Meetings (ATCMs). The presence and participation of an Indian social scientist in the Executive Committee of HASSEG, representing the field of Geopolitics, has opened up valuable space for India to engage in innovative, cutting edge international collaborative research in Antarctic social sciences. This article provides a synoptic overview of Antarctic social science research in India over past decade or so thematically rather than chronologically.

Keywords: Antarctic Governance; Antarctic Tourism; Bioprospecting; Climate Change; Global Knowledge Commons; Post-Colonial Engagement; SCAR HASSEG

Introduction

It is difficult to find a view or policy perspective 'from nowhere'. It is least surprising that the overarching intellectual context as well as the thrust of Indian social science engagement with the complex and compelling question of 'Antarctic governance' (its past, present and future) remains firmly anchored in the notion of 'post-colonial' (Chaturvedi 2009a; Chaturvedi, 2013a; Dodds, 2006). India's quest for a 'genuine' post-colonial engagement with the Antarctic, as described in Indian social science literature, also revolves around the ethical and the geopolitical aspects of knowledge production and knowledge sharing. The dominant sense in which the term 'knowledge' is deployed here appears akin to German scholar Nico Stehr's definition of knowledge as 'a capacity for action' (Stehr, 1994; 2016).

Nico Stehr would like to "characterize knowledge not as something that is so but as a generalized *capacity to act* on the world, as a model for reality, or as the ability to set something in motion" (Adolf and Stehr, 2014:1). In his view, "knowledge is not passive knowledge –as the first step toward action and changes of reality, it is also capable of legitimizing, defending and sustaining social condition or to organize resistance against the forces of reality" (Stehr, 2016: 19). It is critically important, therefore, to acknowledge that the search for new knowledge (e.g. about the Southern Polar Region) is dictated not only by the desire to turn the "unknown into familiar" but also by "the desire to expand the volume of existing possibilities for action" (Ibid.).

The Context and Texts of 'Post-Colonial' Indian Engagement with Antarctica: Challenges and Opportunities

One of the key policy concerns of India's post-colonial engagement, from a critical social science perspective, relates to the legal freezing of the colonial geopolitical map of competing territorial claims and counter-claims under Article IV of the Antarctic Treaty. The position

**Author for Correspondence: E-mail: csgiorg@gmail.com, sanjay@pu.ac.in*

adopted by India with regard to non-recognition of this colonial-imperial legacy is both unambiguous and firm. The notes sent by the Permanent Mission of India to the United Nations Division for Ocean Affairs and the Law of the Sea (between 13 July 2005 and 31 August 2009), in response to submissions made by Australia, Argentina and Norway to the Commission on the Limits of Continental Shelf happen to be the most emphatic expression of India's non-recognition of territorial claims and counter-claims to date. For example, the note sent by India in response to the Australian submission (Republic of India, 2005) stated:

> India recalls the principles and objectives shared by the Antarctic Treaty and the United Nations Convention on the Law of the Sea, 1982 [Convention] and the importance of harmony between the Antarctic Treaty and the Convention and the continuing cooperation, security and stability in the Antarctic area. India while referring to Article IV of the Treaty, wishes to inform that it does not recognize any State's right or claim to territorial sovereignty in the Antarctic area and consequently over the seabed and subsoil of the submarine areas adjacent to the continent of Antarctica. (Emphasis given)

The note further said:

> Acknowledging with appreciation Australia's request to the Commission for not taking any action on the portion of its submission relating to the areas of the seabed and subsoil adjacent to Antarctica, India requests the Commission not to take any action accordingly (Ibid.).

Equally firm and clear is India's commitment to the provisions of the Antarctic Treaty of 1959, its underlying principles, and various instruments of governance collectively termed as the Antarctic Treaty System (ATS). But this unwavering commitment of India to peaceful uses of Antarctica in the best interests of humankind is tempered with the realization that 'democratization' of Antarctic governance is a work in progress and needs to be further broadened and deepened. This would entail, among other things, a brutally frank acknowledgement, on the one hand, of the enviable 'knowledge'(*capacity to act*) of a relatively small number of Antarctic Treaty Consultative Parties (ATCPs) to draft and drive the agenda of Antarctic governance, and equally lamentable lack of such capacities on the part of a vast majority of ATCPs, on the other hand. The latter further calls for a close and critical self-reflection on the part of major actors in the ATS like India with regard to persisting power-knowledge asymmetries within the ATS, which become most glaring on the floor of the ATCMs. Indian social science research (see Chaturvedi, 2013b) continues to raise and address following questions in self-introspection mode.

How can India further broaden and deepen its post-colonial engagement with Antarctica so as to proactively and effectively contribute to further democratization of Antarctic governance? What are the reasons behind persisting mismatch between Asia's –and for that matter India's—growing physical-scientific presence on the continent of Antarctica and the knowledge-power driven geopolitical influence within the ATS? What has been the level of Indian commitment and participation in the ATCMs? What are the geopolitical as well ethical implications of inadequate 'burden sharing' in terms of setting agendas and joint knowledge production at the ATCMs?

One of the key findings of research focusing on 'post-colonial' engagement with the question of increasingly complex and crowded agenda of Antarctic governance is that India, along with other Asian countries, will have to collectively and proactively engage with Antarctic science diplomacy especially in emerging issue-areas of critical universal importance such as biological prospecting and climate change. Failure to do so could result in wide-ranging implications for both the ATS and the role that India aspires to play as a rising and responsible power in world affairs (Chaturvedi, 2013a; Chaturvedi 2013b).

Some new research findings and insights have been added to India's first post-colonial engagement with the question of Antarctic governance dating back to 1950s; a decade of critical importance for newly independent India's engagement with both domestic and foreign policy agenda. Chaturvedi (2013c) has revisited the Indian intervention in the UN on the 'Question of Antarctica' during 1956-1957, on the basis of recently de-classified files in the National Archives of India. In his view, even though considerable grounds have already been covered on various aspects of the Indian intervention (Howkins, 2008), a key puzzle remains largely unanswered, especially in the context of a rather complex value-interests interface that confronted political leadership of post-colonial and post-partition India during 1950s. Why did the Indian intervention fall short of a genuine post-colonial engagement with Antarctica, by choosing not to directly question the colonial legacy of territorial claims on the "white" continent?

Chaturvedi argues that Nehru's approach to the 'Question of Antarctica' during the first decade of India's independence, coinciding with the east–west cold war, was a part of what he perceived as India's 'Tryst with Destiny'. It was from a high moral ground that Nehru would approach various 'pragmatic' issues at both home and abroad. One of the key factors responsible for the rise and fall of a rather short but significant Indian intervention was the interplay between Nehru's worldview (in which the Question of Antarctica joined a host of other important foreign policy calculations) and complex labyrinth of domestic and external factors that surfaced during the tumultuous decade of 1950s and early 1960s. An equally important role was played by the ways in which Indian foreign policy and diplomacy came to be institutionally conceived and conducted during this period with a few eminent personalities at the helm of affairs.

The Indian intervention in the UN General Assembly during 1950s on the 'Question of Antarctica' was largely dictated and driven by the geopolitical visions of Jawaharlal Nehru and a handful of close associates such as Krishna Menon in the then nascent and overstretched foreign policy establishment confronting wide ranging internal as well as external challenges. The ideal-normative thrust of de-colonization agenda was often tempered, if not outrightly overtaken, by the hard-core power-political considerations of the cold war agenda. The Indian intervention in the UN on the 'Question of Antarctica' could not prove an exception to the rule but it did create a space for alternative imaginations of Antarctic geopolitics of peace and international cooperation.

Antarctica as 'Global Knowledge Commons': The Challenge of Bio-Prospecting

With highly 'capitalized actors' and forces of the 'globalized economy' arriving on the scene (Bush, 2001: 139), Antarctica is now being re-located, slowly but surely, on the new maps of global supply chains (Khanna, 2016) and getting increasingly integrated into international geopolitical economy. The technological, political and attitudinal transitions and transformations unfolding in the wider international system (Hemmings, 2007) are also impacting the science-geopolitics interface in the Antarctic that has been conceived, constructed and privileged over the past five decades by the ATCPs, largely through the mechanism of the ATCMs. Particularly noteworthy is the new revolution in the field of biotechnology, with industries of the future increasingly targeting the materials and processes in plants, animals and microorganisms.

Mindful of such a complex and dynamic context, Indian social scientists (see Chaturvedi, 2009b) turned their attention, early on, to the implications of market-driven search for bioactive components in living organisms for the legitimacy, authority and effectiveness of the ATS. It was further noted that in global commons areas such as the Antarctic and the high seas, geopolitical considerations of access and ownership are also combined with issues of sovereignty and jurisdiction. It is this entanglement of perceptions and priorities that makes bioprospecting and related matters so complex. The following critical issues have been identified as worthy of special attention. Firstly, commercialization of publicly funded science is likely to impose 'inappropriate' limits on freedom of scientific investigation in both the Antarctic and in the high seas. Secondly, in order to ensure that benefits are shared equitably by the entire humanity in global commons, mutually agreed limitations on ownership rights over biological resources would be required. Finally, consensus will have to be negotiated and sustained by various stakeholders on how best to regulate bioprospecting in areas outside national jurisdiction of Antarctic biodiversity.

Indian social science research (Chaturvedi, 2009b) on bioprospecting has once again found the question of knowledge absolutely central to both the ethical and the geopolitical implications of this new frontier of economic-commercial exploitation in the Antarctic; yet another problematic example of 'peaceful activities'. Integral to biological prospecting is the search for knowledge in the domain of diverse biological and genetic resources. Whether or not such knowledge qualifies as 'public good', in contrast to ‘private knowledge’, would depend largely on the extent to which it is available (or *made* available) in a manner that is non-rival and non-exclusive in terms of *access* as well as consumption (Herber, 2006). It is important to be reminded that the Preamble to the Antarctic Treaty of 1959 emphatically points out that: “it is in the interest of all mankind that Antarctica shall continue for ever to be used exclusively for peaceful purposes and shall not become the scene or object of international discord.” This in turn imposes certain moral and geopolitical obligations on the part of those already engaged—and those likely to be engaged—in this ‘peaceful activity’ in the Antarctic Treaty area. One such obligation amounts to an unambiguous assurance to the effect that even those who are not directly involved in the ATS or in this commercial activity in the Antarctic Treaty area – south of 60 degrees South—enjoy the benefits of such knowledge. In other words, a private good principle is not only at odds with the dominant ethos of the ATS, it is also against the principle of global knowledge commons.

Apparently, innovations make use of previously accumulated knowledge, that is, each innovation draws upon the ‘global commons of pre-existing knowledge’. One important question that assumes both further significance and complexity in the case of the Antarctic is the following: how much of the returns to the innovation should be credited to the innovator and how much would be allocated to the use of the global knowledge commons? After all, in the case of Antarctica, scientific research has historically been characterized by publicly funded and internationally open knowledge, a classic example of global public good.

One of the key findings of the Indian social science research on bioprospecting is that although the nature and extent of the physical impact of bioprospecting on the Antarctic eco-systems and biodiversity is being currently addressed by the ATCPs, the task of putting into place by consensus a sound legal-political arrangement marked by principles of equity and fairness is likely to be far more complex than often assumed. The objective of developing sound and sustainable measures on bioprospecting in the Antarctic can be accomplishedonly when some basic consensus prevails on the kind of regulation and the type of management system that are desirable, practical, and most importantly, equitable. Given that bioprospecting is an activity with potentially both environmental and resource implications, the ATCPs need to work out a more comprehensive policy imagination in the first instance. Equally important would be to ensure that steadily growing, and so far unregulated, corporate bid to access and exploit the rich biodiversity of the Southern Ocean does not eclipse the first order value enshrined in the 1961 Antarctic Treaty, namely the freedom to pursue scientific research. Close cooperation with SCAR and COMNAP, and coordination with other international legal for a would be an inevitable aspect of the formation of a comprehensive Antarctic bioprospecting policy regime, anchored in the norms of equality and equity in terms of both access and benefit sharing. India is yet to articulate its official position clearly on bioprospecting at the ongoing discussions at the ATCMs. This seems to have taken at least those by surprise who have observed India vociferously championing the cause of equity and benefit sharing in relation to the Convention on Biological Diversity (CBD), along with countries like Brazil. Again, in the overarching context of post-colonial engagement, it is a matter of when rather than whether India would be presenting a working paper on this complex but increasingly compelling issue-area at one of the future ATCMs.

The Challenge of Climate Change and the Future of Antarctic Governance

Indian scholars writing on the multifaceted implications of climate change for the Antarctic (Chaturvedi, 2012) have noted that it is at a crucial juncture in the evolution of the ATS that climate change issue has surfaced on the ATCM agenda. The ATS is confronted with a complex, crowded and compelling agenda (e.g. tourism and biological prospecting) and its overall capacity to deliberate and deliver legally binding measures to regulate growing commercialization of ‘peaceful’ uses of the Antarctica seems to be under considerable stress. The voluntary restraint enshrined in Article IV of the Antarctic Treaty on the claims and counterclaims/rights over territorial sovereignty also stands considerably challenged in the wake of more recent assertions of claims to extended continental shelves (Rajan, 2011).

Chaturvedi (2012) has discussed at some length the nature and implications of what he terms as Antarctic 'climate security dilemma' for the future of Antarctic governance. His major argument is that climate change will make Antarctica and its resource endowment both geographically more accessible and geopolitically more galvanizing to the world, especially in the wake of growing scarcities of resources (both real and imagined) and clean environment interests. Trends such as these will put to severe test the authority and effectiveness of the ATS. At the heart of contestation that might follow could be the intricate question of 'securing' on the one hand the southern polar region and its 'polar attributes' and 'Antarctic values' (e.g. historical/heritage, geopolitical, environmental, scientific, intrinsic/aesthetic) and the 'Antarctic regime' on the other, against perceived threats of climate change. Some of the key questions with far reaching policy implications that need to be answered are the following: What would a perceived inability to address climate change mean for the credibility of science–both as a value and policy guide—globally and in the Antarctic? Is climate change only a matter of physicality and physical-ecological transformations, as largely framed and explained by climate science? What does the notion of security imply in the Antarctic-specific context of climate change? What is it that is being secured against the threats posed by climate change and by whom: instruments of governance, values enshrined in the Antarctic Treaty, national interests and alignments, colonial geographies of various territorial claims and rights?

In the decades ahead, the Antarctic climate security dilemma is likely to acquire greater complexity as well as visibility. Even the most innovative Antarctic-specific responses to the 'management' of climate change in the 'Antarctic Treaty Area', both in terms of intentions and outcomes, will not be able to conceal the fact that the 'white continent' remains at the receiving end of the total quantum of green house gases being released into the atmosphere by the ATCPs themselves. Can the Antarctic governance be quarantined from the complex and compelling issues related to the ethics and the geopolitics of climate change on the agenda of 'global' climate change diplomacy; including the critical question of who is polluting the atmosphere more, where, and why?

The ATCPs no doubt are confronted with difficult choices. If they choose not to engage with normative-ethical issues related to climate change, they might somehow be able to deter highly contentious 'North-South' debate from entering into the domain of Antarctic governance and thereby threaten the principle of consensus on which the security of Antarctic regime rests. On the other hand, a willful decision to disengage from more contentious ethical issues could make the ATCPs look like an accomplice to the 'business as usual' attitudes and actions (including their own in some cases) north of 60 degrees south. Consequently this might also seriously undermine the physical-ecological integrity of the 'natural reserve devoted to peace and science' that the ATCPs, as the first order value, are committed to secure in the wake of climate change.

Even a cursory glance at the key recommendations of the SCAR Antarctic Climate Change and the Environment (ACCE) report would show that despite great progress made in Antarctic climate change research in recent years, "there are still major gaps in our knowledge and many areas where we require additional instrumental data gathering and model development" (SCAR, 2009: 389). Such gaps no doubt would demand and deserve much greater attention and collective-collaborative-proactive action on the part of the ATCPs.

Apparently, it is the mismatch between 'securing the Antarctic' (both continent and the Southern Ocean in terms of physicality and physical impacts) and 'securing the Antarctic regime' and its core values that gives rise to the Antarctic dilemma of climate security. At the heart of this mismatch remains the question of who represents Antarctica, including its values, and for whom? The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), ATCMs and the Committee on Environmental Protection (CEP) are challenged in various ways with an issue area that demands holistic, coordinated, proactive and effective responses. Given that there is both a complex and contested spatial-geography (both material and symbolic) underlying the question of who or what is at 'risk', where, when, and how, the challenge of realizing a comprehensive climate security for the southern polar region, in the best interest of humankind, will remain rather daunting.

Regulating Antarctic Tourism: Indian Contribution to the 38th ATCM Debate (IP 104)

The decision to include Information Paper (IP) 104, presented by India at the 38th ATCM, held in Sofia, Bulgaria from 1-10 June 2015, in an article providing an overview of recent advances made by Indian social sciences in Antarctic studies demands some explanation. The reason is two-fold. Firstly, the IP 104, entitled 'Towards a Comprehensive, Proactive and Effective Antarctic Tourism Policy: Turning Recommendations into Action'is the outcome of extensive collaborative research and dialogue between researchers and policy makers. Secondly, IP 104 was very well received and appreciated at the Sofia ATCM in terms of its policy-orientation and has provided further impetus to interdisciplinary, policy-oriented research in India on issues related to the regulation of Antarctic tourism. What follows next is a brief summary of IP 104.

IP 104 is based on the assumption that the 'institutional memory' (who said, what, when and why at various ATCMs) is critically important for making the on-going dialogue on how to regulate Antarctic tourism more focused, less repetitive and action oriented. What IP 104 chooses to do therefore is to selectively map out the origins and evolution of ATCM dialogue on 'regulating' Antarctic tourism, highlighting the recommendations (formal and informal) made in this regard by the three categories of stakeholders; Regulators, Organisers and Monitors. It is hoped that this exercise will shed some light on durability and consistency of various issue-areas as perceived, framed and flagged by various stakeholders over a rather long time.

IP 104 borrows the useful classification deployed by a seminal study on Antarctic tourism (Liggett *et al.*, 2011) to identify key Antarctic tourism stakeholders. These are: (a) *Regulators*: 'government representatives directly involved in Antarctic policy'; (b) *Organizers*: 'tour operators and industry representatives'; and (c) *Monitors*: 'representatives of environmental NGOs and Antarctic tourism researchers'. While acknowledging the overall usefulness of this classification, IP 104 points out that (i) there prevails a remarkable diversity of perspectives and priorities within each category of stakeholder, which in turn carries significant implications for Antarctic tourism policy; (ii) the texts adopted by various stakeholders from time to time have been dictated to a large extent by the wider regional and global geopolitical, geoeconomic and legal contexts; and (iii) the Antarctic tourism policy environment is increasingly shaped by the forces of globalization, flows and networks operating both within and across state actors.

It is the peculiar and challenging geographical legal-geopolitical setting of the region that makes Antarctic tourism different from tourism in other parts of the globe. Despite the remarkable improvement in technology and logistics in recent years, it is the physical geography of the area (environmental constraints) that dictates the when and where of the Antarctic tourism. As a result, tourists tend to visit the most accessible parts of the Antarctic (as such, the Ross Sea region, and particularly the Antarctic Peninsula and the Subantarctic or peri-Antarctic islandsand coincide --even clash-- with the most productive period for scientific research, the Antarctic summer. In the prevailing circumstances, it is clear that regulation of Antarctic tourism will continue to take place at (1) the ATS level, (2) the governmental level and (3) the tourism industry level. All three have their own contributions to make to Antarctic tourism policy.

One of the key arguments made in the IP 104, reflecting India's position, is that the 'strategic vision' of regulating Antarctic tourism (Tourism with a Difference) is integral to the kind of ' common futures' that the Antarctic Treaty parties would want to visualize and realize in the best interest of humankind. It looks like many issue-areas, such as the port state control, demand and deserve a far more robust and regular engagement than has been possible thus far. Many such issue-areas have remained on (and for some time off) the agenda of the ATCMs for a long time and have invited rich and rewarding interventions by delegations to the ATCMs.

One of the key conclusions of IP 104 is that a large number of issue-areas related to the regulation of Antarctic tourism have remained on the ATCM agenda over decades and in some cases repeatedly discussed and highlighted. At the same time the contexts in which some of these 'enduring concerns' were discussed have also changed. With both the numbers of stakeholders and their concerns fast multiplying, a building-block approach to the 'Strategic Vision' of Antarctic tourism would necessitate in the first place making good use of the institutional memory to avoid duplication of debate on certain issues on the one hand, and to underline the urgency to continue to discuss several such issues in their fast changing contexts, on the other. It appears that it is not so much a question of whether but when the ATCPs would turn to a more focused discussion of how best to formalize, institutionalize and operationalize the insights, resolutions, recommendations and measures that have accumulated over the decades at various ATCMs. There is not an iota of doubt that the major onus of responsibility/accountability/action lies on the part of Antarctic tourism *Regulators* since there are obvious (at times not very obvious) limits to self-regulation by the *Organizers*, as also pointed out by many *Monitors* from time to time.

IP 104 concludes by drawing attention to the fact that according to the United Nations World Tourism Organization (UNWTO, 2014), "Despite occasional shocks, international tourist arrivals have shown virtually uninterrupted growth —from 25 million in 1950 to 278 million in 1980, 528 million in 1995, and 1087 million in 2013" (Ibid.2). According to the UNWTO's long-term forecast 'Tourism Towards 2030', "international tourism arrivals worldwide are expected to increase by 3.3% a year from 2010 to 2030 to reach 1.8 billion by 2030" (Ibid.).Again, it is not a question of *whether* but *when* (more likely sooner than later) some of the ATCPs from Asia would find themselves far more engaged and involved with the challenge of Antarctic tourism regulation; as increasing number of Asians from some of the fastest growing economies in the world would be heading to the Southern Polar Region as tourists. A political economy perspective on tourism in the era of climate change and 'resource scarcities' compels all the three categories of Antarctic tourism stakeholders to ensure continuity of a multi-sectoral, multi-disciplinary research, dialogue and constructive critique on the one hand, and a robust science-diplomacy directed at implementing and enforcing legally binding measures on the other.

Conclusions

The domain of Antarctic social sciences is steadily expanding (Steel, 2015). It is largely from a critical post-colonial perspective that Indian social science contributions to Antarctic studies have evolved during the past decade or so, with new issue-areas such as bioprospecting and climate change being added to research agenda. The policy orientation of this research has become more pronounced with regard to Antarctic tourism issues, especially as articulated in IP 104 presented by India at the 38th ATCM held in Sofia. It is quite obvious from the sources cited in this synoptic overview that the nature and scope of social science research in India on the Antarctic is still quite narrow and needs to be broadened and deepened. Participation of Indian researchers in international collaborative research on various social science issues (Hemmings *et al*., 2015), including the question of Antarctic values, also needs to be further enlarged and encouraged.

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Disclaimer

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References

Adolf M and Stehr N (2014) Knowledge, Routledge

Bush W (2001) The next 40 years: The Challenge of economic globalisation and 21st century security threats. In: The Antarctic Past, Present and Future (Eds: Jabour-Green J and Howard M) pp. 126-146, Cooperative Research Centre for the Antarctic and Southern Ocean

Chaturvedi S (2009a) Antarctica. In: International Encyclopedia of Human Geography, (Eds: Thrift N and Kitchin R) pp. 132-139, Elsevier

Chaturvedi S (2009b) Biological prospecting in the southern polar region: science-geopolitics interface. In:Final Frontiers or Global Laboratories? The Interface between Science and Politics in the International Polar Year (Eds: Tenberg M and J Shadian) pp 171-188, Ashgate.

Chaturvedi S (2012) The Antarctic 'climate security' dilemma and the future of Antarctic governance. In: Antarctic Security in the Twenty First Century (Eds: Hemmings AD, Rothwell DN and Scott K N) pp 257-283, Routledge

Chaturvedi S (2013a) India and Antarctica: towards post-colonial engagement. In: The Emerging Politics of Antarctica (Ed: Brady A M) pp50-74, Routledge

Chaturvedi S (2013b) Antarctic as 'Global Knowledge Commons': Geopolitics, Science and Trusteeship. In: Scientific and Geopolitical Interests in Arctic and Antarctic (Eds: Ramesh, D, Sudhakar M and Chattopadhyay S) pp 11-32, LIGHTS

Chaturvedi S (2013c) Rise and Decline of Antarctica in Nehru's Geopolitical Vision: Challenges and Opportunities of the 1950s in *The Polar Journal* **3** 301-315

Dodds K (2006) Post-colonial Antarctica: an emerging engagement in *Polar Record* **42** 59-70

Government of India (2005) Republic of India: Permanent Mission of India to the United

Nations: 'Notification Regarding the Submission Made by Australia to the Commission

on the Limits of the Continental Shelf', 5 July 2005 [Accessed 21 August 2016] http://

www.un.org/depts/los/clcs_new/submissions_files/aus04/clcs_03_2004_los_ind.pdf

Hemmings A (2007) Globalization's cold genius and the ending of Antarctic isolation. In: Looking South: Australia's Antarctic Agenda (Eds: Kriwoken L K, Jabour J and Hemmings A. D.) pp. 176-190, Federation Press

Hemmings A, Chaturvedi S, Leane E, Liggett D and Juan Francisco Salazar (2015) Nationalism in Today's Antarctic in *The Yearbook of Polar Law*7531-555

Herber B P (2006) Bioprospecting in Antarctica: the search for a policy regime in *Polar Record* **42** 139-46

Howkins A (2008) Defending polar empire: opposition to India's proposal to raise the 'Antarctic Question' at the United Nations in 1956 in *Polar Record* **44** 35-44

IP 104 (2015) Towards a Comprehensive, Proactive and Effective Antarctic Tourism Policy: Turning Recommendations into Action. Presented by India at the 38th ATCM, Sofia, 1-10 June.

Khanna P (2016) Connectography: Mapping the Future of Global Civilization. Random House

Liggett D, McIntosh A, Thompson A, Gilbert N and Storey B (2011) From frozen continent to tourism hotspot? Five decades of Antarctic tourism development and management, and a glimpse into the future' *Tourism Management* **32** 357-366

Rajan S (2011) Antarctic continental shelf and the law of the seas: A future winter of discontentment? In: Science & Geopolitics of Arctic and Antarctic *Proceedings of SaGAA National Conference* pp 32-38

SCAR (2009) Antarctic Climate Change and the Environment (ACCE) Review Report (accessed 20 October 2016) http://www.scar.org/scar_media/documents/publications/acce/ACCE_25_Nov_2009_sm.pdf

Steel G D (2015) Polar, social, science: A reflection on the characteristics and benefits of the polar social sciences in *The Polar Journal* **5** 1-7

Stehr N (2016) Information, Power, and Democracy. Cambridge University Press

Stehr N (1994) Knowledge Societies. Sage

UNWTO (2014) Tourism Highlights, World Tourism Organization United Nations, pp. 1-16.

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Cover: Operational Indian Research bases, Maitri (on ice-free rocky area in the Schirmacher oasis) and Bharati (between Thala Fjord & Quilty bay, east of Stornes Peninsula), at Antarctica; background is an area of Larsemann Hills (Photographs: Bharati by Subrata Moulik, Maitri by Gopal and the background by Rakesh Rao; design by Dr. Swati Nagar).

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