International Council for Science

SCAR report

No 24
August 2005

Contents

Published by the

SCIENTIFIC COMMITTEE ON ANTARCTIC RESEARCH

at the

Scott Polar Research Institute, Cambridge, United Kingdom

SCAR Report

SCAR Report is an irregular series of publications, started in 1986 to complement SCAR Bulletin. Its purpose is to provide SCAR National Committees and other directly involved in the work of SCAR with the full texts of reports of SCAR Standing Scientific Groups and Group of Experts meetings, that had become too extensive to be published in the Bulletin, and with more comprehensive material from Antarctic Treaty meetings.

SCAR Bulletin

SCAR Bulletin, a quarterly publication of the Scientific Committee on Antarctic Research, carries reports of SCAR meetings, short summaries of SCAR Standing Scientific Groups, Action Groups and Groups of Experts meetings, notes, reviews, and articles, and material from Antarctic Treaty Consultative Meetings, considered to be of interest to a wide readership.

Printed by The Panda Press, 1 The Hollands Centre, Hollands Road, Haverhill, Suffolk, CB9 8PR, United Kingdom

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Proposal for a SCAR Scientific Research Programme on Antarctic Climate Evolution (ACE)

An international research initiative to study the climate and glacial history of Antarctica through palaeoclimate and ice-sheet modelling integrated with the geological record.

ACE Scientific Programme Planning Group, July 29 2004
Revised November 9. 2004.

http://www.ace.scar.org/

This proposal was prepared using guidelines provided the 'Implementation of the SCAR Review, June 2002'.

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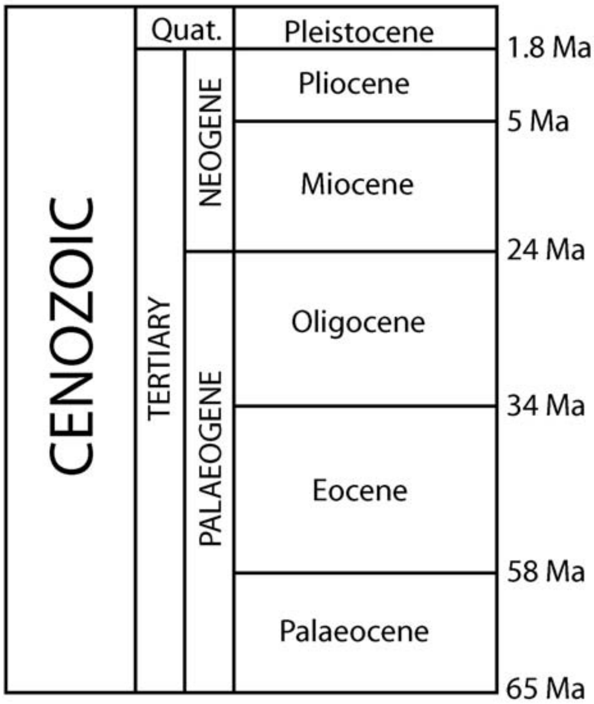
List of acronyms used in this document

AABW	Antarctic Bottom Water
ACC	Antarctic Circumpolar Current
ACE	Antarctic Climate Evolution
AGCS	Antarctica and the Global Climate System
ANDRILL	Antarctic Drilling Consortium
ANTEC	SCAR Group of Specialists on Antarctic Neo-Tectonics
ANTIME	Antarctic Ice Margin Evolution
ANTOSTRAT	Antarctic Offshore Stratigraphy Project
AP	Antarctic Peninsula
ATCM	Antarctic Treaty Consultative Meeting
DSDP	Deep Sea Drilling Project
EAIS	East Antarctic Ice Sheet
EBM	Energy Balance Model
EMICS	Earth Models of Intermediate Complexity
EPICA	European Project for Ice Coring in Antarctica
GCM	Global Climate Model
GLOCHANT	Antarctic Global Change Program
IMAGES	International Marine Global Change Study
IODP	Integrated Ocean Drilling Program
IPCC	Intergovernmental Panel on Climate Change
LGM	Last Glacial Maximum
PANGEA	A project focusing on super-continent accretion and dispersal from the Carboniferous to the Jurassic, when much of Pangea's climate appeared to be disposed in an icehouse mode
PB	Prydz Bay
RCM	Regional Climate Model
RS	Ross Sea
SALE	SCAR Group of Specialists on Subglacial Antarctic Lake Exploration
SCAR	Scientific Committee on Antarctic Research
SDLS	Seismic Data Library System
SHALDRIL	Shallow Drilling along the Antarctic Continental Margin
SPPG	Scientific Programme Planning Group
SRP	Scientific Research Programme
TAM	Transantarctic Mountains
THC	Thermohaline Circulation
WAIS	West Antarctic Ice Sheet & programme called The West Antarctic Ice Sheet Initiative
WAISCores	Part of WAIS to study two ice cores in West Antarctica.
WDC	World Data Centre
WL	Wilkes Land
WS	Weddell Sea

The Cenozoic



Proposal for a SCAR Scientific Research Programme on Antarctic Climate Evolution (ACE)

Executive Summary

ACE is a new international initiative that promotes the exchange of data and ideas between research groups focussing on the evolution of Antarctica's climate system and ice sheet. ACE will exist to facilitate scientific exchange between the modelling and data acquisition communities for the purposes of project development and hypothesis testing. The broad outcomes of the programme will be: (1) quantitative assessment of the climate and glacial history of Antarctica; (2) identification of the processes which govern Antarctic change, and those which feed back this change around the globe; (3) improvements in our technical ability to model past changes in Antarctica; and (4) precisely documented case studies of past changes, which models of future change in Antarctica can be tested against.

The Southern Ocean plays a lead role in the development and maintenance of the Earth's climate system. Equator-to-pole heat transport through the ocean and atmosphere is largely controlled by the latitudinal thermal gradient, which in turn is mostly a function of polar temperatures.

Past variability in Antarctic temperatures and the extent of glacial and sea ice thereby impacts climate systems throughout the globe. The Antarctic ice sheet is the largest reservoir of fresh water on Earth and exerts an influence on global sea levels and hydrology, as well as ocean chemistry. The seas surrounding Antarctica contain the world's only zonal circum-global current system wherein mixing occurs between water masses from all the ocean basins. Circumpolar flow maintains the thermal isolation of Antarctica from warmer surface waters to the north and has been linked to the development of continental glaciers and a dynamic sea ice regime. The Southern Ocean impacts the global thermohaline circulation as a major site of bottom and intermediate water formation. The southern seas are also important for ventilation of CO2 between the atmosphere and the ocean, by virtue of large-scale processes of upwelling, downwelling, and isopycnal mixing in a region of cold surface waters and strong winds. Antarctica, thus, has a key position in global climate processes now and in the past. To understand these processes it is necessary to examine their role in documented past climate change. The ACE programme aims to do this by formulating geological-based hypotheses on past changes in Antarctica and testing them using coupled climate/ice-sheet models.

1. Science aims/outcomes & rationale for their quality, importance & feasibility

ACE is a new, international research initiative to study the climate and glacial history of Antarctica through palaeoclimate and ice sheet modelling investigations, purposefully integrated with terrestrial and marine geological and geophysical evidence for past changes (Fig. 1).

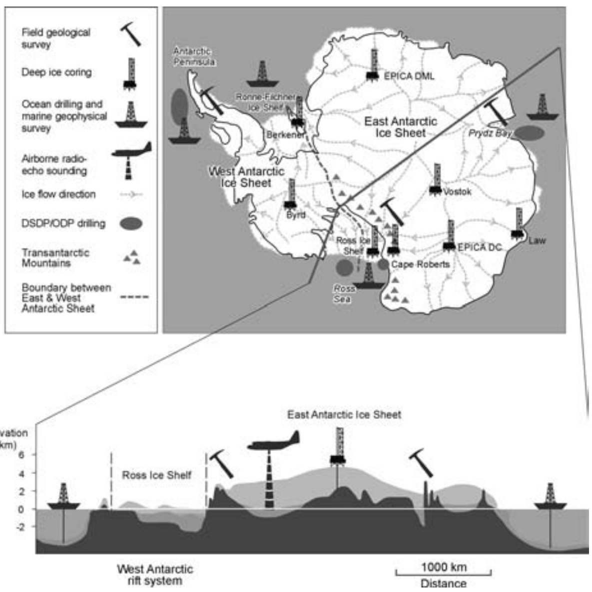


Figure 1. Recent geological and Glaciological field activities in Antarctica, illustrating the variety and spatial extent of exisiting and forthcoming datasets useful to the ACE programme.

Antarctica has been glaciated for approximately 34 million years, but its ice sheets have fluctuated considerably and have been one of the major driving forces for changes in global sea level and climate throughout the Cenozoic Era. The spatial scale and temporal pattern of these fluctuations has been the subject of considerable debate. Determination of the scale and rapidity of the response of large ice masses and associated sea ice to climatic forcing is of vital importance because ice-volume variations lead to (1) changing global sea levels on a scale of tens of metres or more and (2) alteration to the capacity of ice sheets and sea ice as major heat sinks/insulators. It is thus important to assess the stability of the cryosphere in the face of rising CO2 levels (IPCC, 2001), particularly as modelling of the climate shifts from a warm, vegetated Antarctica to a cold, ice-covered state 34 Myrs ago has shown the powerful influence of trace gases on the Earth's climate systems (DeConto and Pollard, 2003a). Concern is justified when CO2 levels are compared with those of the past. As Antarctica is a major driver of Earth's climate and sea level, much effort has been expended in deriving models of its behaviour. Some of these models have been successfully validated against modern conditions.

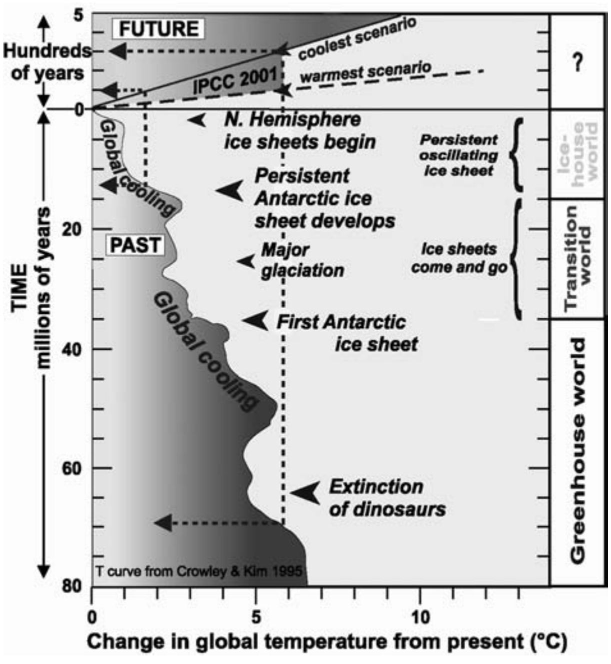


Figure 2. Variation in the Earth's temperature during the last 80 million years, based on reconstructions from deep-marine oxygen isotope records. Note the general cooling trend from 50 million years ago. Also note the abrupt"climate threshold events". For example at 34 million years ago when abrupt global cooling led to the first ice sheets developing on Antarctica. Future atmospheric temperature scenarios, based on IPCC greenhouse trace gas projections, are shown at top of diagram. Given the worst case scenario, in 100–300 years planetary temperatures could increase to a level where, according to our knowledge of previous Antarctic glaciations, ice cover on Antarctica could not be sustained.

Modelling the past record of ice-sheet behaviour in response to changes in climate (inferred from ice cores, sedimentary facies, and seismic data), palaeoceanographic conditions (inferred from palaeoecology and climate proxies in ocean sediments) and palaeogeography (as recorded in landscape evolution) is the next step.

The ACE programme aims to facilitate research in the broad area of Antarctic climate evolution over a variety of timescales. The programme will link geophysical surveys and geological studies on and around the Antarctic continent (Fig. 1) with ice-sheet and climate modelling experiments. ACE is designed to determine both climate conditions and climatic changes during the recent past (i.e., the Holocene prior to anthropogenic impacts, as well as at the last glacial maximum and other Quaternary glaciations, when temperatures were cooler than at present) and the more distant past (i.e. the pre-Quaternary, when global temperatures were several degrees warmer than today). This new cross-disciplinary approach, involving climate and ice sheet modellers, geologists and geophysicists, will lead to a substantial improvement in the knowledge-base on past Antarctic climate, and our understanding of the factors that have guided its evolution. This in turn will allow us to build hypotheses, examinable through numerical modelling, as to how Antarctic climate is likely to respond to future global change. Equally important, the development of data-driven models for Antarctic climate will allow us to extend our results to the analysis and prediction of global climate variability. Details of the specific outcomes and deliverables of ACE are provided in Section 4, p21.

A previous SCAR programme, ANTOSTRAT (ANTarctic Offshore STRATigraphy project), focused principally on developing a stratigraphic framework for the Cenozoic Antarctic margin through seismic stratigraphy and direct sampling through offshore drilling and coring. In addition, the goals of the short-lived SCAR initiative ANTIME (Antarctic Ice Margin Evolution) were transferred to ACE following the termination of GLOCHANT (Antarctic Global Change Program) in 2002. During the lifetime of ANTOSTRAT, significant advances were made to ice sheet and climate models in terms of their ability to replicate the modern environment and to reconstruct former conditions. As yet, there has been no concerted effort to employ such models to determine the Cenozoic climate evolution of Antarctica. The ACE programme will build on the achievements of ANTOSTRAT by focusing on linking palaeoenvironmental records, from current and future drilling and coring, with new ocean-ice sheet-climate modelling efforts in order to provide both constraints and tests for this new generation of models.

The science plan we propose will necessarily depend on outcomes from a range of regional programmes for

Programme (and year)	Location	Type of data
Ocean Drilling Program Leg 178 (1998)	Pacific margin of Antarctic Peninsula	Cores and down-hole logs for last 10 m.y. from outer shelf and rise
Cape Roberts Project (1997-1999)	Coastal south Victoria Land	Cores and down-hole logs for 34 to 17 Ma from inner shelf
Ocean Drilling Program Leg 188 (2000)	Prydz Bay	Cores and down-hole logs from outer shelf (90 and 30-36 Ma), slope (0-2 Ma) and rise (0-22 Ma)
Ocean Drilling Program Leg 189 (2000)	Tasman Sea	Cores and down-hole logs for the Eocene and Oligocene
ANDRILL (2003-2011)	McMurdo Sound (initially)	Several cores up to 1000 mbsf from Palaeogene to Quaternary-age strata
SHALDRIL (2003-)	Weddell margin of Antarctic Pen (initially)	Many cores to 200 mbsf for sampling thick dipping sedimentary sections and expanded Holocene sections. May become an IODP alternative platform
SALE (2000-)	Central Antarctica	Sediment cores to depths of several hundred m in subglacial lakes beneath EAIS. Bedrock samples to constrain age of subglacial terrain
IMAGES (2004-2007)	Continental rise around Antarctic margin Drake Passage	Many giant (up to 80 m) piston cores from late Quaternary drift deposits, basin fill, and older sediments in outcrop
IODP (2005 -)	Ross Sea and Wilkes Land	Proposals to drill in these areas are developed and, if funded, would contribute to the database useful for ACE research
ANTIME (1997- 2001) – now part of ACE	Antarctica	Determine the Late Quaternary sedimentary record of the Antarctic margin
ANTEC (2000-)	Antarctica	Determine Antarctic neotectonics and understand the nature of c oupling between tectonics, climate and erosion
WAIS (incl. WAIS-cores) (1990-)	West Antarctica	West Antarctic ice sheet initiative to study rapid climate change and future sea level
EPICA (1996 -)	Dome C and Dronning Maud Land, East Antarctica	Establishing palaeoclimate records for the last few glacial-interglacial cycles in East Antarctica
AGCS (SCAR SPPG) (planned 2004-)	Antarctica, and global processes	Antarctica and the Global Climate System, concerned with the troposphere, stratosphere and higher levels, where they affect the conditions near the surface. The programme will focus primarily on the last 2000 years and out to 100 years in the future, but will extend back several glacial cycles where necessary.

Table 1. List of programmes and projects generating data useful for research within the science plan of ACE.

gathering field data (Fig. 1). Some of these have been completed, while others are now in progress or are still in the planning stage (Table 1). The role of ACE will be to organise theme-based meetings and workshops to review past work and develop volumes for publication in international journals, and to promote planning and international collaboration for future field programmes. The themes that ACE will focus on are listed in Table 2.

Most Antarctic Earth science research is necessarily regional in character, with different countries normally operating in relatively limited sectors of the continent. Even multinational programmes typically focus on one particular area of the continent. Understanding climate evolution calls not only for a continent-wide view of past records of Antarctic climate change, but also for an understanding of the connections between continental margin and deep-sea processes and their separate but related histories. Progress in making these connections can only succeed through international collaboration that SCAR has mandated.

The rationale for the ACE programme, outlined herein, was developed and refined before, during, and after an Antarctic Earth science symposium in Erice, Italy in September 2001 (Cooper *et al*., 2002; Florindo and Cooper, 2001) and at the EUG/EGS/AGU meeting in Nice (April, 2003). Over 100 scientists gathered in Erice, almost all presenting posters or papers, and reflecting the interest and enthusiasm of the scientists who are active in this field. We believe that this enthusiasm can be maintained and fostered through well-planned programmes of international interest and relevance. Such programmes should be considered and set up in a timely fashion as a dedicated group (i.e. ACE) to continue the momentum gained from existing science initiatives.

2. Approach to implementation

We propose that the Scientific Research Programme be led by a committee of 10-12 persons. We consider this to be large enough to cover the range of disciplines, scientific and technical expertise and experience that we consider necessary for the successful implementation of the programme, but small enough to ensure that each member has a significant and clearly identified role. We believe that the proposed programme has attracted sufficient interest among scientists to allow these requirements to be met, and indeed we have taken these points into account in the formation of the Scientific Programme Planning Group (SPPG). We propose that two people in the committee be identified as convener and deputy convener. The committee would meet formally once a year, and conduct the rest of its business remotely. Members would serve for a 3-year term, with the possibility of extension depending on contribution and performance.

The committee should have knowledge of thematic issues and have appropriate regional (field) and technical/logistical experience. Eight members would focus principally on thematic issues (to cover the areas of palaeoclimate modelling, ice-sheet and sea ice modelling, ice-sheet history, chronostratigraphy, biostratigraphy, Southern Ocean history, subglacial and marine sedimentary processes, and glacial processes). Two further members would focus principally on regional and technical issues to provide expertise on the Antarctic Seismic Data Library (SDLS), regional working group activities/coordination, rock and ice drilling systems/operations, seismic-reflection systems/operations, data access and archiving, workshops/symposia and publications coordination. Members selected for the thematic component would come from a geoscience discipline. They would assist members selected for the regional/technical component in workshop/symposia and publications, who may come from either a geoscience background (with regional/technical experience) or from a technical background (with regional geoscience experience). In addition, we propose to have an advisory group of up to six senior researchers from the geoscience community who would agree to assist the committee on request.

An appropriate model for the individual expertise of the committee is as follows:

Thematic components

1. Geophysics (sea-floor morphology, multi-resolution seismic stratigraphy, regional structure and basin analysis, etc.)
2. Sedimentology (glacial/interglacial sequences and processes onshore and offshore, high resolution stratigraphy, etc.)
3. Palaeoceanography (ocean-basin history, water mass processes, sediment-ocean-air interfaces, etc.)
4. Geochemistry (tracer geochemistry, biogeochemistry, carbon cycle, provenance, etc.)
5. Geochronology and palaeomagnetism (age-dating techniques, rock-magnetic properties, chronostratigraphy, etc.)
6. Palaeontology (biostratigraphy, palaeoecology, evolution of polar biota, palaeoenvironmental proxies)
7. Ice sheet modelling (used to 'test' hypotheses derived from interpretation of the geological record AND establish glacial-interglacial accumulation patterns by integrating results to internal ice-sheet layers identified by ice-penetrating radar)
8. Palaeoclimate modelling (ice-sheet models coupled with atmosphere-ocean General Circulation Models (GCM's) to examine glaciation feedback mechanisms will be used to examine physical processes responsible for ice sheet configurations outlined in component 7)
9. Tectonics and climate change (interactions between climate change, the ice sheet, and Antarctic tectonism).

Regional/technical components

10. Data management (geologic and geophysical data)

11. Technological development (drilling/coring/sampling systems, geophysical data acquisition).

We appreciate fully that it is the responsibility of SCAR to appoint personnel onto the Scientific Research Programme's committee.

3. Proposed functions of the programme

The main function of the programme lies in the acquisition and compilation of "ground truth" geoscience data, and the use of these data in developing a suite of palaeoclimate models (both continent-wide, Southern Ocean-based, and sectorial) for the Antarctic region for significant periods of climate change through Cenozoic times. These periods, detailed in thirteen subsections below, and outlined in Table 2, include:

- late Eocene-early Oligocene cooling,
- Oligocene-Miocene boundary (Mi-1 glaciation)
- middle-late Miocene cooling,
- Pliocene warm periods,
- Pliocene-Pleistocene cooling,
- Quaternary periods of unusual warmth and extreme cold,
- warming since the Last Glacial Maximum,
- Holocene "stable" period, insolation seasonality maximum.

While these activities will concentrate on periods

Themes	Notes
3.1 Modelling themes	**Work in all themes to be constrained/checked by geological data on continent-wide and regional basis.**
3.1.1 Ice sheet modelling	Field-led. Will test hypotheses established from geological interpretations.
3.1.2 Coupled ice sheet and climate modelling	Process-led. Will in time be extended to coupled ice sheet-climate-ocean-sea ice modelling.
3.1.3 Coupled ice sheet and sediment modelling	Process-led. To constrain glacial dynamics and glacier characteristics from the sedimentary record. Compare to observed offshore sediment record.
3.2 Time-based themes	**Themes relating to the stratigraphic record, which will then be linked to ice sheet and climate modelling for each period to p rovide constraints and tests for both stratigraphic and ocean-ice sheet-climate models.**
3.2.1 Eocene-Oligocene transition	This key interval includes the major global cooling event in the Cenozoic era, likely representing an important expansion of Anta rctic ice volume. The stratigraphic record is needed from more areas with accessible older strata, as the record is not known well at present, and needs to b e related to tectonic reconstructions of the critical ocean gateways (Drake Passage and South Tasman Rise region).
3.2.2 Oligocene-Miocene boundary	Node in obliquity – Mi-1
3.2.3 Middle Miocene record	Isotopes show a shift to cooler climates at ~14 Ma, which may represent the intensification of Antarctic Circumpolar Current and thermal isolation of Antarctica from the rest of the globe. This shift is still not well understood and needs to be correlated with proximal palaeo-environmental records from Antarctica and tectonic reconstructions.
3.2.4 Pliocene record	The early Pliocene includes an interval of significant global warming. Consensus on this much-debated period (i.e., proposed major reduction in ice volume involving significant melting of ice sheets in some areas) requires new offshore proximal records integrated with advanced modelling. The late Pliocene also requires investigation, as it in cludes an abrupt cooling that is associated with a major increase in the size of northern hemisphere ice sheets. This introduced a new major control on sea level that may have significantly affected subsequent Antarctic ice sheet fluctuations.
3.2.5 Pleistocene intervals of extreme warmth and cold	Work based primarily on Ocean Drilling Program cores has led to the recognition of several stages within the Pleistocene characterized by extreme warmth (e.g. Stage 11, ~400 kyrs B.P.) when global ice volume was at a minimum, or cold (e.g. Stage 16, ~600 kyrs B.P.) when the ice sheets were larger than during our most recent glacial maximum. Understanding ice sheet behaviour at these times may help us understand the feedbacks that influence the gain of the cryospheric response to Milankovitch forcing.
3.2.6 Last glacial cycle	Integration of ice core, internal ice-sheet layer, and Antarctic margin sediment records is required for full documentation of Antarctic Ice Sheet behaviour through a glacial cycle.
3.2.7 Holocene	Records from shelf basins indicate large changes in sea ice conditions and ice shelf extent during a period of negligible anthropogenic greenhouse gas emissions. This provides an opportunity for understanding natural sources of modern background variability.
3.3 Process-oriented themes	**Themes that concern geologic and climatic processes known to be important in the evolution of Antarctic climate. Better knowledge of these themes can be incorporated into models.**
3.3.1 Terrestrial landscapes	Using chronological techniques available only in the last decade.
3.3.2 Influence of tectonics on the behaviour of the ice sheet	Involving tectonic evolution, uplift of mountain ranges, changes in heat flow, displacements of landmasses, and isostatic and flexural response to changing ice and sediment loads.
3.3.3 Change in ocean topography & circulation	Involving the history of ocean-basin morphology, opening of gateways and movement of water masses.
3.3.4 Climatic influences on development of the sedimentary record	Tracing transport pathways, from the ic e sheet to deep sea, and from interior basins into subglacial lakes and examining interglacial/glacial margins proximal to deep-sea sedimentary processes.

Table 2. Themes and sub-themes of interest condensed from those identified by the ACE community at the 2001 Erice meeting.

subsequent to the Palaeocene, it should be noted that ACE will also encourage and support palaeoenvironmental data collection from earlier periods that allow us to understand the immediate pre-glacial history of Antarctica. For example, drilling in the Bellingshausen Sea and the Larsen Basin may provide key evidence for the Palaeocene thermal maximum, which would be of direct relevance to ACE in terms of the pre-glacial climate setting of Antarctica.

We have identified the following main programme functions for ACE as:

1. Encouraging and facilitating communication and collaboration among research scientists working on any aspect of the evolution of Antarctic climate. This would be achieved by organizing workshops and symposia to present new results, exchange ideas, share/compile information and coordinate/plan laboratory and field operations. These would be coordinated with the activities of autonomous programmes such as ANDRILL and IMAGES;
2. Advising the research community on the types of geoscience data required for palaeoclimate modelling and effective model-data intercomparison, and critical locations (and ages) for which such data are needed;
3. Providing advice/assistance as needed on technical issues related to geoscience field and laboratory programmes and to palaeoclimate modelling studies (it should be noted that the project will not, and cannot, oversee or manage national or international field or laboratory projects or facilities (other than to help guide the SDLS));
4. Promoting data access and data sharing (and data-contributions to the SDLS, Antarctic data centres, and World Data Centres [WDC]) to facilitate and expedite data syntheses needed for developing new field programmes and enhancing palaeoclimate models. This function includes direct guidance of the Antarctic Treaty-mandated SDLS; and
5. Summarizing and reporting the results of these efforts to the scientific and wider community on an ongoing basis at workshops and symposia. A formal report would be made and presented to SCAR after a 6-year period.

3.1 Modelling Themes

Numerical modelling of former climate and glacial processes is central to the ACE programme. We envisage projects within three areas of glaciological modelling: ice sheet modelling; coupled ice, climate and ocean modelling; and coupled ice and sediment transport modelling.

3.1.1 Ice sheet modelling

Changes to the Antarctic ice sheet affect climate by direct modification to the hypsometry of the Earth's surface and its albedo and by regulating the transfer of fresh water to and from the oceans. The Antarctic Ice Sheet is also one of the Earth's major heat sinks. In addition, ice sheets are agents of large-scale erosion and deposition. Therefore, the ice cover of Antarctica acts in numerous ways to affect the environment of our planet's past, present and future. Because of this, the ability to model the Antarctic Ice Sheet numerically is valuable not only to glaciologists but also to Earth Science in general.

Numerical ice sheet models are usually organised as a 2-D grid or mesh (comprising many individual cells) over the area of ice sheet. Calculations of ice flow are made at each cell based on well-established physical principles. The interaction of ice flux between grid cells describes the time-dependent evolution of the ice sheet to changes in (a) imposed surface mass balance (the inputs and outputs of the ice sheet) and (b) mechanisms internal to the ice sheet. The most important data used as boundary and forcing conditions in an ice-sheet model are subglacial topography and surface mass balance.

Ice-sheet models typically comprise three main components. These are: the temporal evolution of ice thickness, which also incorporates the areal expansion and contraction of the ice sheet; a reduced model of how stresses and velocities vary within an ice mass (the key assumption is that longitudinal stresses are minimal and therefore that a local stress balance exists); and the temporal evolution of the internal temperature field of the ice sheet. In addition, there are many subsidiary models for effects such as isostasy (the deflection of underlying lithosphere to the load of an ice sheet); basal slip of the ice over its underlying substrate; the pattern of snow accumulation on and ice/snow melt from the upper ice-sheet surface; and the effect of temperature on the viscosity of ice.

A second category of large-scale ice-flow models is that of ice shelves (floating ice) and fast-flowing ice streams (which are thought to have many of the features of ice shelves). The physics controlling the flow of ice shelves and streams is more complex than that controlling ice-sheet flow. In particular, longitudinal and transverse stresses are often the dominant components of the force balance. Stress and velocity fields must therefore be determined simultaneously throughout the entire ice mass (as opposed to the local stress balance discussed above for ice sheets). Longitudinal and transverse stresses are important because ice shelves and streams are characterised by reduced (or, in the case of shelves, zero) basal traction.

A feature of all large-scale ice flow models is the extreme non-linearity of the underlying equations that they attempt to solve. This is a consequence of the empirical law thought to govern ice flow, in which strain rates vary with the cube of applied stress. In addition, there are several other features that introduce non-linearity into the system. For instance, the exponential relationship between the viscosity of ice and its temperature, and the coupling between ice flow and temperature via frictional heat generation.

Ice sheet models are perhaps most well known in the context of predicting ice-sheet response to climate change. In particular, much work has been done on the response of the present-day Greenland and Antarctic Ice Sheets to anthropogenic warming in the coming millennia, and to past changes over the last glacial-interglacial cycle. These models can also be used to examine ice sheet changes much further back in time, although they have yet to be used extensively for this purpose.

Use of numerical ice sheet models to test geologically-derived hypotheses concerning the Antarctic ice sheet is novel and timely given the ability of the models and the abundance of geological data now available.

3.1.2 Coupled Ice Sheet Climate and Ocean Modelling

Most prior modelling studies of ancient Antarctic ice sheets have used empirical parameterizations based on modern climatologies to provide meteorological input (surface mass balance forcing) for the ice sheet model (Huybrechts, 1990; Huybrechts, 1993). While this approach is well suited to testing the sensitivity of Antarctic ice sheets to changes in bedrock topography and/or different temperature and precipitation scenarios, it does not explicitly test the response of the coupled climate-cryosphere system to evolving boundary conditions and climatic forcing over long, geologically relevant time scales. An alternative approach uses a climate model, responding to changes in palaeogeography, bedrock elevation, atmospheric CO2, and orbital cycles to provide the ice sheet model mass balance forcing.

Several coupled climate/ice-sheet modelling schemes have been developed and tested. Until recently, however, these models have mostly been applied to the Northern Hemisphere Quaternary glacial cycles. One approach uses a climate model component that is computationally efficient enough to run continuously over long time intervals. Energy Balance Models (EBMs) can be run continuously for millions of model years, but they provide only simplistic representations of climate. For example, there is no explicit simulation of precipitation, which is of obvious importance to understanding long-term ice sheet dynamics. Another scheme uses Earth Models of Intermediate Complexity (EMICS), with a more sophisticated representation of the atmosphere and a dynamical ocean component. EMICS are extremely stripped-down Global Climate Models (GCMs) with very coarse spatial resolution. Although they have been successfully coupled to ice sheet models, they may be too coarse for some palaeoclimate problems, and their ability to adequately represent precipitation for Antarctic ice sheet studies has yet to be determined.

GCMs provide a much more detailed representation of climate and can be coupled with dynamical ice sheet models. GCM modelling of the present climate over Southern Oceans and Antarctica has improved considerably in the last decade, with better model physics and higher resolution (today's GCMs have an average spatial resolution of ~2°). The best GCM simulations of annual temperature and precipitation generally agree with observations. Despite some seasonal deficiencies around

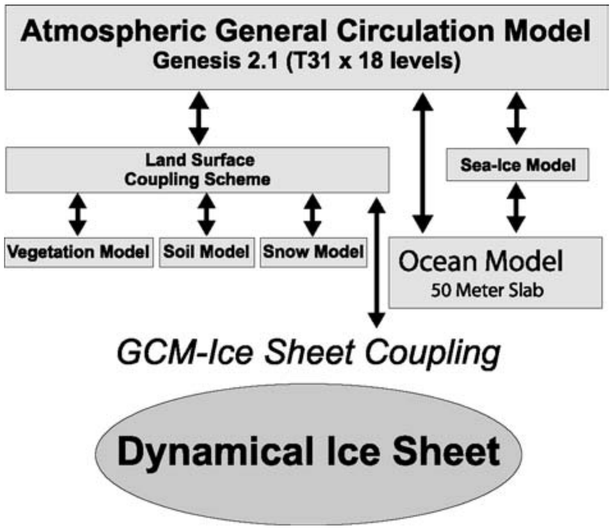


Figure 3. Schematic representation of the coupled GCM-ice sheet modelling scheme used by DeConto and Pollard (2003a) in their simulations of Paleogene East Antarctic ice sheets.

the coast, these models are capable of producing realistic mass-balance over Greenland and Antarctica, and can be used to model the three dimensional response of polar climate to a wide range of forcing scenarios. Regional Climate Models (RCMs) offer even higher resolution than GCMs (a few tens of km), with the potential to resolve regional-scale variations around the coast and the margins of ice sheets. RCMs are now being applied over present Antarctica, and they have great potential to solve regional palaeoclimatic problems. However, at the scale of Antarctica, they approach the computational limits of GCMs. Because they represent a restricted spatial domain, they do not account for the effects of global-scale climate change/forcing unless it is prescribed or provided by a prior GCM simulation.

Although GCMs can be coupled with dynamical ice sheet models, even those GCMs with simple, non-dynamical (slab) ocean components are too computationally demanding to run for more than a few decades at a time. For time-continuous problems over orbital or longer timescales, asynchronous GCM-ice sheet coupling scheme can be used to capture the important feedbacks between the Antarctic ice sheet and the atmosphere, while maintaining the computational efficiency required to run long (104-106 year) simulations. In most asynchronous coupling methods, the ice sheet model is run continuously while the GCM is run just often enough to capture the essence of the relevant forcing (i.e., every several thousand years to account for changing orbital cycles). Some methods use a "matrix" of prior GCM simulations, using canonical combinations of boundary conditions spanning the full range anticipated in the long-term simulation. Interpolated climatologies from the suite of GCM simulations are then used to drive continuous ice sheet simulations. These techniques have recently been successfully used to simulate the initial (Paleogene) history of the East Antarctic Ice Sheet (Figs.

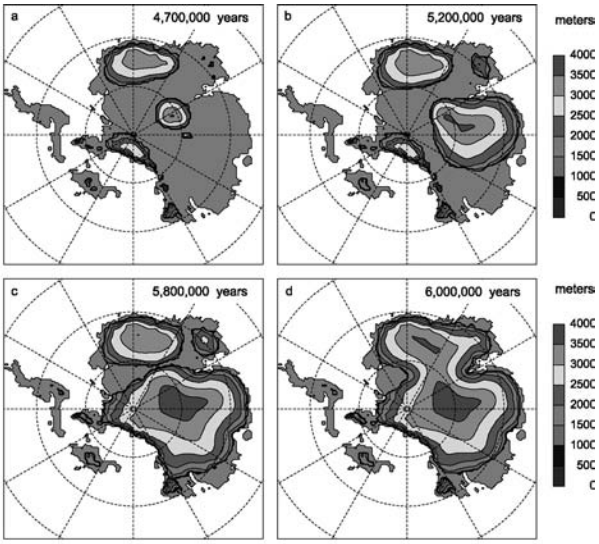


Figure 4. The simulated initiation of East Antarctic glaciation in the earliest Oligocene, using a coupled GCM-ice sheet model (from DeConto and Pollard, 2003a).

3 and 4) and are now being applied to other time periods throughout the Cenozoic.

These models offer an unprecedented opportunity to test the possible response of the Antarctic climate-cryosphere system to evolving boundary conditions and climatic forcing. However, rigorous comparison with the geologic record will be required to verify the results and place them in the context of actual palaeo-climatic and palaeo-environmental changes. In addition, detailed and accurate boundary conditions, based on geologic and geophysical data, will be required for many different time periods in the geologic past. These include reconstructions of global and Antarctic palaeogeography (plate position, shorelines, topography, bathymetry and vegetation). One role of ACE is to facilitate both the compilation of boundary conditions to be used for the latest generation of climate-ice sheet models, and to provide data for the validating the model output.

3.1.3 Coupled ice sheet and sediment modelling

Conditions at the base of continental ice sheets can be important in the long-term evolution of ice and bedrock, and may be critical in explaining some aspects of ice-sheet behaviour. Two main factors are basal hydrology and the presence of deformable sediment between bedrock and ice. Widely distributed deforming sediment may play significant roles in the large-scale morphology and long-term evolution of ice sheets (Alley *et al*., 1987a,b; Alley, 1991; MacAyeal, 1992; Clark, 1994; Clark *et al*., 1996; Clark and Pollard, 1998). Deforming sediment is observed today below many mountain glaciers (Boulton, 1996) and fast-moving West Antarctic ice streams (Kamb *et al*., 2001), where the lubrication due to sediment enables extremely high velocities compared with the surrounding ice.

Furthermore, sediment drifts around the margins of major ice sheets are one of the few surviving indicators of past ice sheet history. The observed Cenozoic deposits on continental shelves and slopes around Antarctica (Cooper *et al*., 1995; Barker *et al*., 1998; Davey *et al*., 2001; Naish *et al*., 2001) provide opportunities for very rich data-model comparisons for the period since the onset of major Antarctic glaciation in the Oligocene. Some of the broader questions amenable to this approach are as follows:

1. Did basal sediment influence the sizes and profiles of early Antarctic ice caps and the growth and subsequent variations of continental-scale ice sheets?
2. What is the long-term continental inventory of sediment for Antarctica? How much of the off-shore drifts are composed of pre-existing regolith vs. ice-quarried bedrock till? Do the offshore sediment drifts represent the bulk of the sediment transported to the coast since the Oligocene, or only a small fraction with the rest dispersed to the deeper ocean? These questions address long-term erosion rates and landscape evolution caused by Antarctic glaciation, with consequences for weathering and CO2 drawdown (Robert and Kennett, 1997). An analogous inventory for North American ice sheets and Atlantic deposits of the last 3 Ma has been made by Bell and Laine (1985).
3. Has the distribution of sediment affected patterns of erosion of Antarctic bedrock and thus the observed bedrock morphology today?

Co-evolution of Antarctic ice and sediment can be modelled over continental or regional domains by a coupled climate-ice sheet-sediment model. A model of deforming subglacial sediment can be coupled to the ice sheet model to account for bulk sediment thickness and transport by horizontal shear, induced by the basal-ice shear stress when basal temperatures are at the melt point. New till can be accounted for by the quarrying action of ice on bedrock. In ice-free regions, the model till can be eroded and transported fluvially following the steepest downhill path to the coast.

A weakly non-linear rheology has been used for subglacial deforming sediment (Clark and Pollard, 1998; Jenson *et al*., 1996), although a more nearly plastic rheology has been deduced recently under West Antarctic ice streams (Kamb *et al*., 2001), which (just like its non-linear counterpart) may yield substantial sediment transport due to the vertical migration of the failure plane (Tulaczyk, 1999). Sediment can also be transported via entrainment into the lower ice layers, but the relative contribution of this process is uncertain (Hildes, 2001).

In addition to deformation within the subglacial till layer, transport of sediment as suspended or bed load by subglacial streams or channels can contribute significantly to the overall sediment flux, especially near the margins of ice sheets and glaciers in summer, when surface melt provides a plentiful supply of meltwater to the base. This process can dominate the sediment flux at the snouts of temperate glaciers discharging into the fjords and Gulf of Alaska today (Hunter *et al*., 1996a; 1996b). We will add simple model components for basal hydrology regimes and subglacial fluvial sediment transport, and investigate their role versus subglacial till deformation over long time scales, and whether each regime leaves recognizable depositional signatures in the observed marginal sediments. This analysis should be very significant for periods during the early phases of ice sheet history when it is thought to have been temperate and then, later, polythermal (Powell *et al*., 2000; 2001).

The ice sheet-sediment model can span the entire Antarctic continent using a ~40 km polar stereographic grid, or can be run regionally for particular drainage basins with resolutions down to ~10 km. The finer resolution is necessary for the western Ross Sea region to assess ice transport from East Antarctica through deep Transantarctic Mountain valleys.

Coupled ice sheet and sediment modelling is particularly potent as a glaciological tool when model results are linked to measurements. Such model-data comparisons can be used to determine the locations of major sediment accumulation, predict Cenozoic age-depth relations, identify sediment provenance, clay mineralogy and grain sizes, assess orbital-scale variations within the sedimentary record, explain observed present-day bed roughness, and predict amounts and persistence of sediment in the locations of major subglacial lakes such as Lake Vostok (see link with SALE programme, p22).

3.2 Time-Based Themes

Several long-term drilling programmes of 10 to 20 years are necessary to answer the open questions concerning Antarctic climate/ice sheet evolution. The ANTOSTRAT Program started this long-term drilling program with the submission of five drilling proposals. The successor to the ANTOSTRAT Programme, the ACE Programme, will continue to encourage the two remaining IODP proposals to drill the Wilkes Land and Ross Sea margins.

The ACE programme will also promote and encourage new drilling expeditions using both IODP and mission specific platform technologies, such as shallow drilling (SHALDRIL) or sea ice and ice shelf-based drilling (ANDRILL) techniques, now in the testing stages. In sectors of the Antarctic continental shelf, such as the Wilkes Land margin, prograding foreset strata outcrop at the seafloor allowing older strata to be cored. A transect of shallow (50-150 m penetration) sites across the Wilkes Land continental shelf could achieve the objectives related to obtaining the record of the timing of glacial onset (Eocene-Oligocene?), and the record of large fluctuations in the glacial regime (Miocene?). Other locations around the Antarctic continental margin need to be identified for a coordinated drilling effort.

Earth Science research along the Antarctic continental margin has concentrated on the areas traditionally visited by ship, such as the Antarctic Peninsula, Ross Sea and Prydz Bay regions, or areas easily accessible by aircraft from the different international bases. Limited access to many sectors of the Antarctic margin has resulted in areas having only reconnaissance-type data sets. ACE will promote, encourage and, when necessary, coordinate the collection of data by different national programs in less explored sectors of the Antarctic margin that show potential for identification of new Eocene-Oligocene and mid-Oligocene targets. Work will be encouraged in areas where the potential exists for older strata at shallow depths both on the continental shelf and deep sea, and where there may also be continuous seismic reflectors across the margin that favour the connections between the proximal and the distal records.

The central goal of ACE is to coordinate the integration of improved geological data and Antarctic palaeoclimate modelling at different time slices, including the Eocene-Oligocene onset of glaciation and the mid-Oligocene transition.

ACE will be active in searching for new drilling platforms and capabilities. ACE will follow the development of a proposal by the European Polar Board of ESF to construct a deep-drilling research ice-breaker, the Aurora Borealis, dedicated to polar research. Presently the ice-breaker is scheduled to operate in the central Arctic Ocean all seasons of the year. ACE should take an active role in promoting the inclusion of Antarctic margin expeditions in icebreaker operations.

3.2.1 Eocene-Oligocene events

The Eocene and Oligocene epochs are key time intervals in the development of the Antarctic Ice Sheet. Based on deep-sea "proxy" records (e.g., oxygen isotope, global sea-level, ice-rafted debris, etc.), the Eocene and Oligocene represent a time of global cooling that culminates in the development of the first Antarctic ice sheet and an important expansion of Antarctic ice volume. The Eocene (~52 to ~34 Ma) is characterized by a global cooling trend that culminates at the Eocene-Oligocene (~34 Ma) boundary with global cooling during the remainder of Cenozoic era. The mid-Oligocene transition (~30 Ma) represents another major cooling event, which is associated with a major eustatic fall that likely represents a large Antarctic ice sheet expansion.

The ACE program envisions the following questions to be of first-order interest with respect to the Eocene-Oligocene transition:

1) What is the time of first arrival of grounded ice along different segments of the Antarctic shelf?
2) What is the temporal and spatial evolution of the Antarctic ice sheet through the Oligocene Epoch and across the mid-Oligocene transition?
3) Under what boundary conditions did the ice sheet reach the continental shelves around Antarctica?
4) Under what boundary conditions did the ice sheet expand during the mid-Oligocene transition?
5) What is the history of water mass evolution during Eocene-Oligocene and mid-Oligocene times?

3.2.2 Oligocene-Miocene boundary Mi-1 glaciation

The Oligocene-Miocene boundary marks a significant transition in the development of the Antarctic cryosphere, where small dynamic ice sheets of the late Oligocene rapidly expanded to continental scale in the early Miocene. The transition is recorded in benthic foraminiferal d18O records as a positive 1.0 per mil shift, representing the first of the Miocene glaciations (Mi 1). Mg/Ca reconstructions imply little or no change in temperature and that the ice volume increase was equivalent to 90m of sea level lowering (based on a Late Quaternary calibration). Sediment cores recovered in Western Ross sea indicate orbital modulation of the ice sheet during the transition, and corroborate proxy ocean records (Naish *et al*., 2001). It is argued that the Mi-1 event occurred as a consequence of a unique set-up of orbital parameters during an interval of declining CO2 that led to a prolonged period of cold summer orbits, during which time a large ice sheet established. This has important implications not only for modelling the climate drivers, but also for timescale development, as the orbital configuration has been used to astronomically calibrate the age of the Oligocene-Miocene boundary (Shackleton *et al*., 2000). However, a new calibration based on an integrated chronology for western Ross Sea drill-cores seems to preclude the use of astrochronology. Future work in this area includes:

- Regional correlation of the Mi 1 event along the Transantarctic Mountain front in Victoria Land Basin through integration of drillcore and newly acquired seismic data.
- Analysis of the vegetation records in sedimentary cycles spanning the Mi1 event to constrain terrestrial climate changes.
- Ice sheet dynamics across the Oligocene-Miocene boundary will be modelled using coupled GCM-Ice Sheet model and the sensitivities of CO2 and orbital configuration assessed.

3.2.3 Middle Miocene record

The middle-to-late Miocene period represents a time of significant ice sheet expansion in Antarctica. The Zachos *et al*. (2001) deep sea stable isotope record shows a mid-Miocene “climatic optimum” centred at about 15 MA, followed by strong enrichment of oceanic d18O over the next 6 Myrs. It is during this interval that East Antarctic glacial ice is thought to have evolved into a major and permanent ice sheet. One outstanding question revolves around the notion that this transition represents ice sheet development in East Antarctica. New seismic-stratigraphic data from the Ross Sea reveals at least 5 major intervals of ice shelf advance and retreat in the middle Miocene (Chow and Bart, 2002). Much of this ice is sourced in West Antarctica, suggesting the presence of a large and dynamic ice sheet in a part of Antarctica that is conventionally thought to be of lesser importance at this time. The presence of significant and dynamic ice in East versus West Antarctica in the middle and middle-to-late Miocene is a question that ACE participants plan to answer via a combination of modelling coupled with geophysical and geological analysis.

One of the most vexing questions concerns the stability of Antarctic climate and ice during the late Miocene. A variety of indicators from the McMurdo Dry Valleys suggest the maintenance of stable, hyper-arid, cold-desert conditions since 13 MA (Marchand *et al*., 2002). However, microfossil studies in the Transantarctic Mountains, and sedimentological work within Antarctic fjords is suggestive of significant climatic dynamism extending from the late Miocene through the Plio-Pleistocene. A degree of heterogeneity in climate response is expected considering the size and diverse landscapes of Antarctica. Yet the existing state of knowledge is sufficiently contradictory that the community has evolved into two camps when it comes to describing late Neogene conditions in Antarctica: the stabilists and dynamicists. This is another obvious target for dedicated analysis using a combination of climate and ice sheet simulations with careful assessment of the paleontologic and sedimentologic data from around Antarctica.

3.2.4 Pliocene record

The Pliocene Epoch is a critical time for understanding the nature of the Antarctic ice sheet as IPCC projections of global temperature rise suggest that we will reach Pliocene levels within the next hundred years. Geological evidence combined with modelling is needed to determine the size of the ice sheet and its dynamic behaviour. Indirect evidence, such as sea level changes and ocean floor sediments, suggest that ice volumes were subject to cyclical variability. It is believed that, since Northern Hemisphere ice sheets were not fully developed, sea level changes were driven by fluctuations of the Antarctic Ice Sheet. Many scientists believe that it was the relatively unstable West Antarctic Ice Sheet (WAIS) that was responsible for these changes, but the role of the much larger East Antarctic Ice Sheet (EAIS) remains controversial.

Key to this argument is the timing of the transition of the EAIS from a polythermal, dynamic condition to a predominantly cold stable state. Two opposing and vigorously defended views prevail. The long-standing view is that the EAIS became stable in mid-Miocene time, evidence of which is primarily from the longevity of the landscape and well-dated surfaces and ash deposits in the Dry Valleys region along the western border of the Ross Sea. Another controversial view is that terrestrial glacial deposits, known as the Sirius Group, scattered through the Transantarctic Mountains, indicate dynamic ice sheet conditions as recently as Pliocene time, based on diatom biostratigraphy and preserved vegetation. The latter viewpoint is supported by work on deposits known as the Pagodroma Group along the flanks of the largest outlet glacier, the Lambert, on the continent. Each argument is internally consistent and the biggest challenge is to reconcile the differing views. If the EAIS was indeed subject to major fluctuations until Pliocene time then, taking into account IPCC projections, we have cause to be concerned about the possibility of the EAIS becoming unstable within the next century.

The Pliocene question is best addressed by (1) identification of suitable near-shore late Miocene-Pliocene sedimentary basins to gain a high-resolution record of ice sheet fluctuations, as is currently planned in the McMurdo Sound area by ANDRILL; (2) improved dating of the controversial Sirius Group glacial deposits onshore; (3) discrimination of glacial processes and products under different climatic and tectonic regimes; and (4) ice sheet numerical modelling taking advantage of known ice sheet limits at critical times.

3.2.5 Pleistocene glacial cycles and intervals of extreme warmth and cold

Studies of Antarctic ice cores show that Pleistocene climate variability in the different sectors of the southern high latitudes has occurred out of phase (Masson *et al.*, 2000; Steig *et al.*, 1998). This raises questions about the response of the southern high latitudes to external climate drivers, such as orbital insolation, solar variability, and internal amplifiers such as thermohaline circulation and carbon-cycle changes (Rahmstorf, 2002) that operate at both Milankovitch and millennial-decadal time scales. These questions highlight a need for appropriate time series of climate variability from all sectors of the Southern Ocean. Recovery of sediment sequences with expanded Pleistocene sections, such as those from beneath the McMurdo Ice Shelf as proposed by the ANDRILL programme, will permit the study of the structure and timing of glacial and interglacial cycles in the Southern Ocean at millennial timescales that extend well beyond the last four major climate cycles. In addition, several groups organized under the IMAGES programme have proposed to collect long piston cores for Pleistocene research from several different sectors of the Southern Ocean. With new high resolution Pleistocene time series from both the Antarctic margin and offshore sites, we can determine if the abrupt climate changes that have been documented from the Atlantic and Indian sectors (e.g. Cortese and Abelmann 2002, Kanfoush *et al.* 2002, Kunz-Pirrung et al. 2002, Mazaud *et al.*, 2002, Bianchi and Gersonde, in press), and in polar ice cores (e.g., Dansgaard *et al.* 1993) have also occurred in the Pacific basin.

During the last decade, many palaeoceanographic studies focused on millennial climate variability. They show that the thermohaline circulation underwent instabilities (Charles *et al.*, 1996; Vidal *et al*, 1997) linked to climate variability. The palaeoceanographic record documents mainly the North Atlantic Ocean, and modelling experiments have explored the variability of North Atlantic Deep Water formation forced by fresh water flux from ice surge events (Stocker and Wright, 1991; Manabe and Stauffer, 1997; Ganopolski and Rahmstorf, 1998, 2001). However, Keeling and Stephens (2001) emphasise the importance of Southern Ocean sea-ice during glacial periods and suggest that the glacial "on/off" modes of global circulation were linked to a very different deep-water formation in the Southern Ocean. This conceptual approach is consistent with Last Glacial Maximum isotopic data indicating a strong bathyal front between intermediate and deep waters (Kallel *et al.*, 1988; Herguera *et al.*, 1992; Slowey and Curry, 1995) and deep-water temperatures that were near the freezing point (Duplessy *et al.*, 2002; Schrag *et al.*, 2002). At the moment there are only a few records that document deep Southern Ocean variability during glacial stages 2 and 3 (Ninneman and Charles, 2002). Additional cores to address these issues at this time period will be recovered as part of the IMAGES and ACE science plans.

Work proposed under IMAGES and ACE will also help us document the Pleistocene stability of the West Antarctic Ice Sheet (WAIS) as well as areas of the East Antarctic Ice Sheet (EAIS) that are grounded below sea level. We will reconstruct meltwater events based on reconstructing salinity and sedimentological analyses (grain-size, ice-rafted debris distribution) from sites sensitive to the stability of the WAIS and EAIS. This will improve our understanding of the vulnerability of the ice sheet during Pleistocene climatic optima and its potential impact on 1) global thermohaline circulation as a southern source of melt water discharge (e.g., Mikolajewicz, 1998), and 2) sea level rise well beyond present sea level stand, e.g. during marine isotope stages 9 and 11 (Rohling *et al.*, 1998). A draw-down of the WAIS would increase sea level by 5-7 m and thus have a major impact on life on Earth. This estimate ignores possible contributions from less stable portions of the EAIS.

3.2.6 Last Glacial Cycle and Deglaciation

There are currently 3 different ideas about the onset of deglaciation: 1) changes in the water balance of the North Atlantic, the source region for much of the global thermohaline circulation, serve to propagate the deglacial signal worldwide (e.g., Bender *et al.*, 1994); 2) changes in the Southern Ocean, as recorded in some ice cores, lead deglaciation as seen in Greenland ice (e.g., Blunier *et al.*, 1998); and 3) synchronicity in the timing of high latitude climate change in both hemispheres, and with some tropical records suggests that tropical forcing is a key initiator of deglaciation (e.g., Denton *et al.*, 1999; Seltzer *et al.*, 2002; Visser *et al.*, 2003). It may seem surprising that this controversy has not already been settled. The most important confound for establishing synchronicity, or its absence, among the available palaeoclimate records revolves around chronology development. It is notoriously difficult to date LGM ice layers and sediments to an accuracy of better than 1 to 2 kyr. It is also difficult to separate local climate or geomorphic signals from large transformations that are regionally or globally important. For example, based on sediment records from lakes Titicaca (Bolivia) and Junin (Peru), Seltzer *et al.* (2002)

suggest that southern tropical warming began up to 5,000 years before significant deglacial warming in the Northern Hemisphere and in Antarctica. If correct, this is strong evidence for a tropical trigger. However, Clark (2002) suggests that the Andean lake records cannot be appropriately compared with most North American lake records of deglaciation because the early formation of pro-glacial lakes in the Andes traps sediment and obscures the timing of all subsequent deglacial activity in the Junin and Titicaca basins. What is needed to resolve the deglacial synchronicity issue are better records from rapidly-deposited deglacial sequences across a range of longitudes and latitudes in the Southern Ocean, that use sedimentary or glacial outlet indicators to directly track regional climate systems. Currently there are too few precisely dated records of the LGM from the Southern Ocean.

3.2.7 The Holocene

The global instrumental record establishes the existence of a relatively small number of fundamental modes of coupled air-sea interaction that are collectively responsible for most known climate variability (or instability) at interannual to multi-decadal timescales. Chief among these coupled modes are the El Niño-Southern Oscillation (ENSO) system, Pacific Decadal Oscillation, Arctic Oscillation, North Atlantic Oscillation, Tropical Atlantic Dipole, and Southern Ocean (or Antarctic Circumpolar) Wave. All of these climate systems involve ocean thermal anomalies, atmospheric feedbacks, and significant climate responses on land. Although the instrumental record informs us about the existence and modern expression of these coupled ocean-atmosphere systems, it is not sufficient to resolve past changes in their dynamics and impacts or the relative importance of centennial to millennial climate phenomena. The palaeoclimate record is the only known source of information on the long term behaviour of these climate pacemakers. However, existing knowledge of Holocene variability is heavily biased towards terrestrial archives. There is very little information about the global ocean background climate state against which we observe and define the recent dramatic warming trends, particularly in the Southern Ocean. Nevertheless, rapidly accumulating deposits exist along the continental margin of Antarctica, and a few sites further north, that are suitable for reconstructing Holocene ocean conditions at decadal and possibly interannual timescales. The science issues to be addressed include the following:

- Many researchers now believe that the link between high and low latitude climate change on interannual and decadal timescales is best expressed as the so-called "Circumpolar Wave", an apparent propagation of sea surface temperature anomalies and atmospheric pressure patterns forced by tropical ocean variability. Existing instrumental records of this possible mode of global climate variability are too short to provide meaningful insights about the mechanisms involved. Long, annually resolved sediment records are required to test the idea that the tropics and high latitudes are connected through the same basic physical processes that govern ENSO cycles.
- How does solar forcing influence the distribution of sea ice and primary production in the Southern Ocean? Pronounced solar cycles with periods of 200 and 80 years have been identified in cores from the Antarctic Peninsula. The cause is not yet known, nor is the full aerial extent of their manifestation.
- Although some ice cores show only minor variability in the mid-Holocene, many terrestrial sites and some polar marine sites show large excursions during the mid-Holocene. In some cases these excursions, due presumably to changes in insolation seasonality, are larger than the full glacial to interglacial excursion. Southern Ocean sea ice and winds appear highly sensitive to insolation forcing and IMAGES cores can be used to examine forcing and response during periods of the Holocene when atmospheric pCO2 levels varied only slightly.

3.3 Process-Based Themes

3.3.1 Terrestrial landscapes

The landscape evolution of ice-free areas, backed up by recently developed geochronological techniques, opens up a new window on the climatic and glaciological processes associated with the evolution of the Antarctic Ice Sheet. The record, extending back to the Eocene/Oligocene transition, is based on argon/argon dating (40Ar/39Ar) of glass shards in volcanic ash in surficial deposits and surface exposure dating using cosmogenic isotopes, mainly in the Dry Valleys of the Transantarctic Mountains (Sugden *et al*., 1995; Nishiizumi *et al*., 1991). The latter technique has demonstrated that some landforms, and even till-covered glacier ice, are relict from Miocene time (Marchant *et al*., 2002). The technique also has the potential to date ice sheet thinning during the Holocene (Stone *et al*., 2003).

Most detailed work has been carried out in Victoria Land in the Ross Sea sector of the Transantarctic Mountains, where the terrestrial record agrees well with the offshore CIROS and Cape Roberts Project cores. It is now important to establish how representative this record is, and to extend the approach to other sectors of Antarctica with exposed mountains and coasts. In East Antarctica priorities might include the Lambert basin, the Atlantic and Indian Ocean coastal sectors and the Transantarctic Mountains bounding the Weddell Sea embayment. In West Antarctica, priorities are mountains in the Ross Bellingshausen Sea sectors, the Ellsworth Mountains and the Antarctic Peninsula.

Focus on terrestrial landscape evolution can provide climatic and environmental constraints at different times. The existence of pre-glacial fluvial landforms with superimposed tills reflecting the advance of small, warm-based local glaciers into beech forests, as is the case of Sirius Group deposits, may well reflect the transition to glaciation of Antarctica at the Eocene/Oligocene transition.

The geochemistry of regolith and the nature of tundra polygons pre-dating ice sheet glaciation tell of conditions during the growth of the maximum mid-Miocene Antarctic ice sheet. Landforms, striations and meltwater channels on mountain summits constrain the thickness, direction of flow and the basal thermal regime of this maximum ice sheet. Pliocene deposits in several coastal areas of East Antarctica and the tip of the Antarctic Peninsula constrain relative sea level and climate at the time. Mountains protruding through the thinner margins of the ice sheet can be used as dipsticks to constrain the morphology of the ice sheet during Pleistocene maxima, a point of particular relevance to establishing the thickening associated with the grounding of the Ross and Filchner-Ronne ice shelves (Stone *et al*., 2003). Finally, the terrestrial record can establish the history of Holocene thinning or variability of individual glacier basins and ice shelves, thus providing essential information on the Holocene trajectory of sea level and the Antarctic Ice Sheet against which to judge modern changes. The exciting prospect is of a firmly dated and spatially-extensive terrestrial record of landscape evolution for use in the development of models of ice sheet dynamics and evolution.

3.3.2 Influence of tectonics on the behaviour of the ice sheet

Modelling of Oligocene and Miocene climates requires accounting of tectonic evolution, including events such as opening of ocean gateways and uplift of mountain ranges. A widespread idea is that ice sheet development on Antarctica has been associated with the opening of ocean gateways that have enabled the Antarctic Circumpolar Current to isolate the continent. The critical gateways lie to the south of Tasmania and in Drake Passage (Barker and Burrell, 1977; Shipboard Scientific Party, 2001). Published estimates suggest that the Tasman gateway opened at the end of the Eocene (~34 Ma) and that a deep-water pathway through Drake Passage was established at the end of the Oligocene (~23 Ma), but further work is needed to refine and improve constraints on these estimates.

The Transantarctic Mountains, with maximum elevations >4 km, buttress the modern East Antarctic Ice Sheet and form the boundary between it and the West Antarctic Ice Sheet. However, when considering ancient ice sheets it is important to take account of changes in elevation of this 2000 km-long mountain range. Another important mountain range extends along the spine of the Antarctic Peninsula, which has a central plateau at an elevation of about 2 km along most of its 1000 km length. This mountain range forms an important climatic divide, with temperatures about 6°C warmer on the Pacific margin compared with points at the same latitude on the Weddell Sea margin (Reynolds, 1981). Topographically-forced snow accumulation over the Antarctic Peninsula results in a net surface mass balance that is more than three times the Antarctic average (Vaughan *et al*., 1999), and highlights the possibility that the Transantarctic Mountains might have been a focus for accumulation and ice sheet nucleation in past climates that were warmer and wetter than today. Apatite Fission Track data suggest that exhumation (and probably uplift) of the Transantarctic Mountains began at about 55 Ma, probably at a rate of about 200 m/Myr for the first 10-15 Myr (Fitzgerald, 1992; 2002). The timing of uplift of the Antarctic Peninsula remains uncertain (Elliot, 1997). Further work that better constrains the timing and rates of uplift of these mountain ranges, and others such as the Gamburtsev Mountains in central East Antarctica, would contribute to the objectives of ACE.

There is increasing evidence that subglacial geology has an important influence on the location of fast glacial flow pathways (e.g. Retzlaff *et al*., 1993; Larter *et al*., 1997; Bell *et al*., 1998; Anandakrishnan *et al*., 1998). There is also debate about the extent to which subglacial tectonic and volcanic events affect the basal conditions and stability of the West Antarctic Ice Sheet (Blankenship *et al*., 1993; Bentley, 1993). Thus, geophysical investigations that improve knowledge of subglacial and continental shelf geological features also contribute to ACE objectives.

Accurate models of Quaternary ice sheets need to take into account the flexural response of the lithosphere to changes in ice load. On longer time scales models also need to take into account changes in loading due to erosion and deposition of sediments (ten Brink *et al*., 1995). To model the flexural response of the lithosphere correctly, estimates of regional variations in its effective elastic thickness are required. In the absence of any direct evidence (e.g. measured flexure in response to a volcanic load of known age) such estimates must usually be based on studies of the tectonic and thermal history of the lithosphere (e.g. Stern and ten Brink, 1989).

3.3.3 Tectonics and climate: the influence of palaeo-seaways

Almost three decades ago Kennett (1977) proposed that a major cause of the Cenozoic evolution of both Antarctic glaciations and global palaeoceanography was the tectonic opening of Drake Passage and a passage south of Australia, which were necessary for the initiation of Antarctic Circumpolar Current (ACC) (Lawver and Gahagan, 1998). This dramatic climate shift is marked by an abrupt change in _18O during the Eocene-Oligocene transition at about 33 Ma that led to the first ice sheets developing on Antarctica. The opening of these seaways occurred during the Early Oligocene, although the precise timing is not well constrained. The associated magnetic anomaly observed in the Scotia Sea is chron C10 (29 Ma), but there is a significant segment of the ocean floor between this anomaly and the continental margins without magnetic anomalies (Tectonic Map of the Scotia Sea, 1995). Whereas the oceanic circulation during the Mesozoic was tranquil under the influence of equitable climates and oceanic thermohaline homogeneity, Cenozoic climate and oceanic circulation increasingly deteriorated (Berggren and Hollister, 1977). A latitudinal thermal heterogeneity caused by high latitude cooling and accelerated surface and bottom water circulation in the oceans characterizes the Cenozoic climate.

The real influence of Antarctic tectonics through the opening and closing of seaways on this climatic evolution is still a subject of debate. Prior to the development of permanent Antarctic ice sheets, a shallow seaway may have existed between East and West Antarctica in Early Cenozoic, although its ability to influence circulation patterns is not well established (Lawver and Gahagan, 1998). A primitive passage may have also existed through the northern tip of the Antarctic Peninsula into Powell Basin before the opening of Drake Passage (Lawver *et al.*, 1992). The tectonic fragmentation of the continental bridge that existed between South America and the Antarctic Peninsula was, however, the most probable cause for the development of deep seaways and the set-up of the ACC. The timing and significance of these tectonics events is still a subject of debate, but most authors agree that in had profound effects on the evolution of the Cenozoic climate. One important objective within ACE will be to investigate the change scenarios of Cenozoic palaeo-seaways around Antarctica and to assess the influence of this on the climate evolution.

3.3.4 Climatic influences on development of the sedimentary record

Although our knowledge about glacial and glacimarine sedimentary processes has advanced significantly over the past 15-20 years, quantitative sedimentological models for glacimarine systems remain rare. Those that are available involve relatively simple algorithms that describe a particular process such as: sediment deformation in a subglacial bed, subglacial water flow (and recently, supercooling), submarine jet discharge, particle settling from turbid overflow plumes, turbidity currents, debris flows, ice shelf and iceberg rafting, and debris incorporation into sea ice with subsequent rafting (e.g. Iverson *et al.*, 1998; Alley, 1992; Gordon *et al.*, 2001; Alley *et al.*, 1998; Morehead and Syvitski, 1999; Harris and Wiberg, 2001; Hill *et al.*, 1998; Mohrig *et al.*, 1999; Dowdeswell and Murray, 2000). None of the glacimarine models are integrated and few, if any, are linked to forcing variables such as glacial processes, marine currents, and variability in biogenic productivity, climatic changes, tectonism, etc. Furthermore, many other processes are still unaccounted for, and appropriate input variables, sediment fluxes, magnitudes and rates of processes, and feedbacks and leads or lags are unknown or poorly constrained. If we are to gain a better understanding of the past environmental changes in Antarctica, we need to establish reliable models based on a strong understanding of glacial and marine processes and how they interact spatially and temporally to construct those records.

Other branches of marine sedimentology and stratigraphy are in the process of establishing quantitative modular models, experimental scaled models and larger-scale sequence stratigraphic models (e.g. Paola *et al.*, 2001). The models are being designed so that ultimately they can be used with climatic input variables and have an output that constructs a sequence stratigraphic package on a continental margin. The glacial and glacimarine communities, specifically those conducting research in Antarctica, need to start such model construction. By doing so, in the future, real sedimentary architecture and stratigraphy of the continental shelf may be compared with that generated synthetically using known input variables so as to better constrain how the real succession may have formed. The models could also help (i) constrain glaciological and hence climatic models, (ii) constrain interpretations of glacial fluctuations on "high" resolution timescales, and (iii) predict the best drilling sites/targets for future drilling initiatives, which ultimately will provide the data to constrain the models more reliably.

It is only by using these types of modelling capabilities that we can hope to discriminate eustatic signals from glacial signals in continental shelf successions. That is because these types of continental margins are very complex in the factors that force and drive marine sedimentary packages (Powell and Cooper, 2002). In this setting accommodation space, package geometries and facies motifs are dependent on the temporal and spatial interaction of tectonic subsidence, glacial isostatic loading and unloading, changes in two base-levels of glacial advance-retreat and sea level rise-fall cycles, glacial and non-glacial erosion, sediment fluxes and accumulation rates, and the relative rates, and lead and lag times of each of these factors.

4. Time-line and milestones

Advance scheduling of workshops and symposia, and special sessions at major conferences, is important for fostering collaboration, exchange of ideas and further planning. The ACE steering committee will develop and maintain a schedule of such meetings extending forward at least 3 years. We have already undertaken five of the nine meetings proposed in our outline bid (assessed by SCAR XXVII in Shanghai):

1. June 2002; ACE workshop on palaeoclimate modelling, Amherst, USA.
2. July 2002; Antarctic palaeoclimate session at Western Pacific AGU meeting, Wellington, New Zealand.
3. July 2002; Symposium at SCAR XXVII in Shanghai, China.
4. December 2002; ACE session at Fall AGU meeting in San Francisco, USA.
5. April 2003; ACE outreach meeting EUG-AGU-EGS in Nice, France (ACE flyer distributed).
6. April 2003; ACE working group meeting after EUG-AGU-EGS in Nice, France.
7. December 2003; ACE session at Fall AGU meeting in San Francisco, USA (convened by Tony Payne, David Pollard, Martin Siegert and Robert DeConto).

The schedule for the year (prior to ACE becoming a Scientific Research Programme) will include the following meetings:

Theme	2005	2006	2007	2008	2009
MODELLING - nested regional & continental models	Workshop on the use of ice sheet and climate models, in Boston.	Completion of first regional model (Prydz Bay).	Completion of regional model (TAM-McMurdo).	Linked sectorial and continental model for EAIS.	Publish state-of-the art report on data and modelling AIS history and behaviour from a perspective of both long term (10^3-10^6 years and short-term (1 to 10^2 years) climate change over the last 5 million years.
MODELLING – significant events in time	Completion of Eocene-Oligocene shift modelling.	Completion of modelling Oligocene climate and ice sheet behaviour	Completion of modelling of mid-Miocene climate shift.	Completion of modelling warm events in Pliocene-Quaternary.	
TIME – Holocene/last glacial cycle/Quaternary	Internal layers, ice flow and accumulation reconstruction.	Complete review of Antarctic ice sheet – ice shelf – Southern Ocean record	Review of data collected by IMAGES and ANDRILL projects.	Assess reviews of Quaternary and Pliocene in li ght of new data from S Ocean and sub-Ross IS core.	
TIME – Pliocene	Continue review of sedimentary cores from Legs 178 and 188 (plus sediment cores from national programs). Continue fostering IODP proposals for Wilkes Land and Ross Sea.	Continue review of sedimentary cores from Legs 178 and 188.	Complete review of on-land and offshore record. Revise IODP proposals for Wilkes Land and Ross Sea. Develop proposals using SHALDRIL and ANDRILL technologies.		
TIME – Middle Miocene	Continue review of sedimentary cores from Leg 188. Continue fostering IODP proposals for Wilkes Land and Ross Sea	Complete review of offshore record – revise IODP proposals for Wilkes Land and Ross Sea. Develop proposals using SHALDRIL and Cape Roberts (ANDRILL) technologies.	Revise IODP proposals for Wilkes Land and Ross Sea.		Publish state-of-the art report that includes new data from ANDRILL, SHALDRIL, IMAGES and IODP integrated with modelling AIS history and behaviour for the period from 50 to 10 Ma ago.
TIME – Oligocene-Miocene boundary					
TIME – Eocene-Oligocene	Continue review of sedimentary cores from Leg 188. Continue fostering IODP proposals for Wilkes Land and Ross Sea.			Assess reviews in light of new ANDRILL, SHALDRIL and IODP data.	
PROCESSES-Terrestrial landscapes	Note: Develop in conjunction with Edinburgh group. Case for 15 Ma old cold MDV well made by Summerfield et al. (1999) and needs extending		Complete review of terrestrial landscape development.		
PROCESSES - Influence of tectonics	Note: Develop in conjunction with ANTEC.				
PROCESSES-Sediment transport paths and sediment processes	Continue review of sedimentary cores from Legs 178 and 188. Investigate glacial/interglacial processes in marginal areas and deep-sea, to be developed in conjunction with WAIS.	Complete review of icebergs as transport agents.	Complete review of subglacial sediment transport by grounded ice.	Complete review of transport across marine ice grounding line.	Complete integrated model for polar sediment transport by ice.

Table 3. Outline of tasks, deliverables and timelines for work to be carried out under the aegis of the ACE programme from 2005 to 2009.

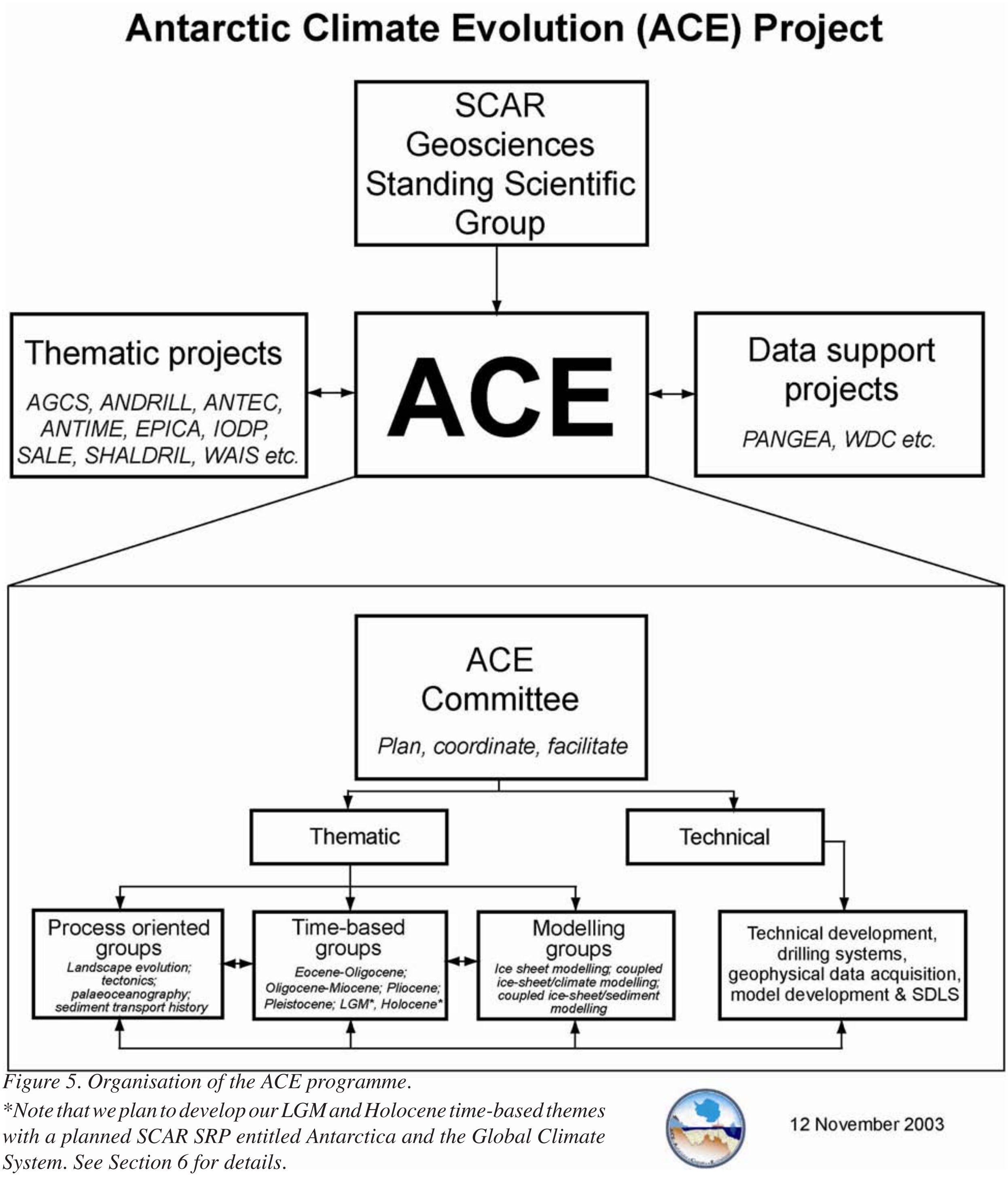


Figure 5. Organisation of the ACE programme.

**Note that we plan to develop our LGM and Holocene time-based themes with a planned SCAR SRP entitled Antarctica and the Global Climate System. See Section 6 for details.*

8. July 2004; ACE contributions to the SCAR XXVIII Open Science Meeting. Bremen, Germany.
9. July 2004; ACE workshop at Bremen SCAR Meeting (1-day). This workshop follows the SCAR Open Science Meeting and will allow the geosciences community to respond to recommendations and to begin to prepare group science proposals to pursue ACE activities.
10. December 2004; ACE session at Fall AGU meeting in San Francisco, USA.

The tasks, deliverables and time-lines we envisage are outlined in Table 3. This should be viewed as a guide, as it is difficult to be prescriptive in charting future progress in research.

5. Logistic requirements and costs

A programme of this scale will require a significant time commitment from the committee members, which will have to be covered by them personally and their home institutions. The costs we request here are basic operational costs to allow the committee to meet once a year (though they will undoubtedly meet additionally at other scheduled meetings), and to provide seed funding for two workshops or symposia each year. Our estimate of the annual budget request from SCAR for ACE is as follows:

- Travel and accommodation for committee members $ 1500/person for 10 persons $ 15,000
- Seed funding for workshop expenses (e.g., publication of report, some travel assistance) $ 8,000
- Costs for website and newsletter $ 2,000

TOTAL $ 25,000

Note: Supplemental funding requests (above the base monies requested) over the years will be for: inviting experts to SALE meetings; covering the expenses related to convening topical workshop and inviting key participants; funding the development of specialized educational and promotional material; allowing for smaller meeting of the ACE program management on a more frequent basis; and paying the expenses for the ACE Chief Officer to attend and present ACE activities at important international meetings.

6. Links with other SCAR activities

The ACE proposal has formal links with three other SCAR SRP proposals. The first is Subglacial Antarctic Lake Environments (SALE), the second is Antarctica and the Global Climate System (AGCS) and the third is Evolution and Biodiversity in Antarctica (EBA).

ACE and SALE will interact in two ways. First, the palaeoclimatic record contained in subglacial lake sediments will provide important new information from the interior of the continent. ACE and SALE will collaborate on the acquisition of such records. Second, the ice sheet history quantified through numerical modelling as part of the ACE programme will offer important constraints on the formation and development of subglacial lake environments. ACE will provide SALE with model results in order for the history of subglacial lakes to be established in the context of ice sheet and climate evolution.

Investigating Antarctic history over glacial-interglacial periods is appropriate to the study of both modern and ancient environments. ACE and AGCS aim to investigate this history as a component of much broader and distinct science plans. Further, each SPPG has compatible yet discrete specialisms that are well suited to studying the glacial-interglacial history of Antarctica. ACE contains expertise in ice-sheet/climate modelling, marine and terrestrial geology, marine geophysics and radio-echo sounding. AGCS includes expertise in atmospheric modelling and ice coring. This combined expertise covers the full suite of knowledge required to build a sub-programme on the Quaternary history of Antarctica. We propose that an action group, made up of appropriate personnel from both ACE and AGCS, be established to run this sub-programme.

It should be noted that while ACE and AGCS have compatible interests in Quaternary studies of Antarctica, the remaining components of each respective science plan differ markedly.

ACE and EBA have mutual interests in understanding past environments. For ACE such work is central to its programme of work. For EBA it is critical to evaluating how and why the present distribution and form of biota exists in Antarctica. Palaeoclimate information, collected and modelled through ACE will be made available to EBA. In addition, EBA will be invited to interpret palaeontological data collected through ACE activities. Members of EBA are encouraged to attend ACE meetings to discuss results and inform the ACE community about the various inputs the EBA programme requires.

7. Links with the International Polar Year (IPY)

The IPY provides a unique opportunity to plan, fund and undertake international collaborative research in the polar regions. By the time of IPY (2007-8), the ACE programme will be fully functioning. It is therefore highly appropriate that ACE, as an existing major international Antarctic research programme, seeks to become involved in IPY research in order to fulfil the ambition of this intense period of investigation. The plan for IPY activities is divided into five themes. The ACE programme is directly relevant to one of these themes, and will make major contributions to two others. Details of how ACE activity will contribute to the IPY are provided below.

The ACE programme will result in scientific findings directly relevant to Theme #2 of IPY: *To quantify, and understand, past and present environmental and human change in the polar regions in order to improve predictions*. The ACE programme will provide answers to the following two questions that will be asked in this theme: (1) How has the planet responded to multiple glacial cycles? and (2) What critical factors triggered the cooling of the polar regions? The proposed function of the ACE programme will allow the investigation of past changes in Antarctica during several time slices. Question 1 will be answered as part of the ACE investigation into the *Pleistocene glacial cycles and intervals of extreme warmth and cold (Section 3.2.5) and the Last Glacial Cycle and Deglaciation* (Section 3.2.6). Question 2 will be addressed in ACE through analysis of *Eocene-Oligocene events* (Section 3.2.1), and the *Oligocene-Miocene boundary Mi-1 glaciation* (Section 3.2.2), and also in the process-based theme on *Tectonics and climate* (Section 3.3.3).

Further, ACE findings will contribute to two other IPY themes. In IPY Theme #3, processes relating to global teleconnections will be investigated. To understand contemporary processes, models (both conceptual and numerical) need to be built and tested against the known record of past changes. To this end, ACE will provide the necessary process-based information concerning the causes and consequences of past changes in Antarctica at a variety of timescales relevant to IPY Theme #3. Two questions within IPY Theme #4 (*To investigate the unknowns at the frontiers of science in the polar regions*) are of direct relevance to ACE. The first concerns the character of the sub-ice and deep-ocean ecosystems. Such systems exist as a consequence of the modern environment and past environmental changes. The ACE programme will allow subglacial conditions to be evaluated through the Cenozoic, which will allow us to predict the long-term history of, for example, Lake Vostok (as discussed in Section 6; links with the SALE programme). The second question will determine the effect of the solid earth on ice sheet dynamics. ACE ice sheet modelling investigations of the *Influence of tectonics on the behaviour of the ice sheet (Section 3.3.2)* will have a direct input to this question.

As is evident in these brief details, the ACE programme will have explicit and purposeful links with IPY plans. Consequently, a successful ACE programme will lead to a significant component of the IPY ambition being fulfilled.

8. Outreach and education

ACE will endeavour to support and encourage the next generation of Antarctic scientists in three ways. First, an online lecture series paralleling the findings and outcomes of the ACE programme will be made available to schools, colleges and universities via the ACE website. These lecture materials will comprise downloadable power-point presentations, and will match ACE's scientific programme (detailed in Section 3). Second, we will encourage young scientists to take part in ACE workshops by offering bursaries for travel and subsistence. Although the level and number of the bursaries will be dictated by funds available, it is hoped that at least two bursaries will be available for each workshop/meeting. The condition of each bursary will be a report by the holder about their research and workshop experiences, which will be posted on the ACE website. Third, we will facilitate an exchange scheme between our respective institutions to allow young scientists to take part in fieldwork and to sample the research culture of other nations. Similar schemes operate within, for example, the Worldwide University Network, and it is anticipated that external funds (from such schemes) will be used to support the exchanges arranged through ACE.

9. Achievements to date

ACE was awarded SPPG status following SCAR XXVII in Shanghai (July 2002). Since its creation, ACE has undertaken a series of meetings and symposia as we hope SCAR would expect of a SPPG. Furthermore, the scientific programme within ACE is already underway, with the first papers directly related to the ACE science plan published in Nature in January 2003 (DeConto and Pollard, 2003a; Barrett, 2003) and in Geology in March 2004 (Taylor *et al.*, 2004). The following is a timeline of achievements, which testifies that ACE is already becoming an active programme of research, which facilitates world-class scientific investigation.

- June 2002; ACE workshop on palaeoclimate modelling, Amherst, USA. A workshop report is available from the ACE website (http://www.ace.scar.org//wkrpt.pdf)
- June 2002; Submission to SCAR of the ACE SPPG proposal.
- July 2002; ACE website launched (www.ace.scar.org). The site is maintained at the University of Massachusetts by Robert DeConto.
- July 2002; SCAR award Scientific Programme Planning Group status to ACE.
- December 2002; A full day ACE session at Fall AGU meeting in San Francisco, USA. The sessions comprised 14 talks and 8 poster presentations, with contributions from Peter Barrett, Robert DeConto, David Pollard, Martin Siegert, Ross Powell, David Harwood, and Robert Dunbar.
- January 2003; Publication of the first ACE papers in Nature (DeConto and Pollard, 2003a; Barrett, 2003).
- April 2003; ACE meeting at the EGU/AGU Spring meeting in Nice, France.
- May 2003; Submission to SCAR of the ACE SRP proposal.
- October 2003; Report from the SCAR Executive meeting (Brest, France July 2003), in GeoReach 2.4, detailing the recommendation of the Executive Committee to fund ACE as a SRP.
- March 2004. Publication of ACE paper in Geology (Taylor *et al.*, 2004).
- April 2004. Full session at the EGU, Nice entitled "Antarctic cryosphere and Southern Ocean climate evolution (Cenozoic-Holocene)" chaired by Fabio Florindo and Rainer Gersonde.
- Forthcoming, special issue of Global and Planetary Change (edited by Fabio Florindo and David Harwood).
- Forthcoming, Fabio Florindo and Peter Barrett will be chairing a session entitled 'Cenozoic Antarctic Glacial History' at the International Geological Congress, Florence August 2004.

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11. Concluding Statement

This proposal was prepared by the SCAR Scientific Programme Planning Group, consisting of the following scientists:

Martin J. Siegert –University of Bristol, UK, co-chair

Robert B. Dunbar – Stanford University, USA, co-chair

Robert M. DeConto University of Massachusetts, USA

Carlota Escutia, University of Granada, Spain

Fabio Florindo, Istituto Nazionale di Geofisica e Vulcanologia, Italy

Thomas Janecek, Florida State University, USA

Robert Larter, British Antarctic Survey, UK

Tim Naish, Institute of Geological and Nuclear Sciences, New Zealand

Ross D. Powell - Northern Illinois University, USA with advice and contributions from Peter Barrett (Victoria University, New Zealand), Alan Cooper (Stanford University, USA), Michael Hambrey (University of Wales, Aberystwyth), Alan Haywood (British Antarctic Survey), David Sugden (University of Edinburgh), David Pollard (Penn. State University), Rainer Gersonde (AWI), Jane Francis (University of Leeds), Gary Wilson (University of Otago), David Harwood (University of Nebraska, Lincoln), Andrés Moldonado (University of Granada), Antony Payne (University of Bristol).

Further details, including short biographies, of those listed above are provided in Appendix A.

Appendix A.

Short biographies of those who have contributed to the ACE proposal are provided below.

Peter Barrett. Antarctic Research Centre, Victoria University of Wellington, New Zealand. (email peter.barrett@vuw.ac.nz). Peter Barrett is Professor of Geology and Director, Antarctic Research Centre, at Victoria University of Wellington. He earned his Ph.D. for the stratigraphy and environmental history of the Beacon Supergroup in the central Transantarctic Mountains in 1968 from the Ohio State University. He sailed as sedimentologist on the RV GLOMAR CHALLENGER in 1972 for the first drilling for glacial history off the Antarctic margin. Since then he has led a several drilling projects in McMurdo Sound for their climatic and tectonic record (most recently the Cape Roberts Project), as well as carrying out field studies of contemporaneous deposits on land, and facies analogues in New Zealand.

Alan Cooper is emeritus geophysicist at U.S. Geological Survey and Consulting Professor at Stanford University Department of Geological and Environmental Sciences (email: acooper@usgs.gov). He earned his Ph.D. in Geophysics in 1974 from Stanford University and has worked on framework geology of continental margins around the Pacific Ocean. He spent the past 20 years conducting offshore geophyiscal and drilling operations to ivestigate the geology and paleoenvionmental history of the Antarctic margin. In 1989, he initiated and thereafter coordinated the Antarctic Offshore Stratigraphy Project (ANTOSTRAT), which laid the groundwork for the ACE project.

Robert DeConto. Department of Geosciences, University of Massachusetts, USA (email: deconto@geo.umass.edu). Rob DeConto is a Professor of Geosciences at the University of Massachusetts. He earned his Ph.D. in climatology and Earth system modeling from the University of Colorado and the National Center for Atmospheric Research in 1996. Rob's research is focused on new ways of combining numerical climate and ice sheet modeling with geological and geophysical observations to better understand the climate and ice sheet variability of Antarctica over a wide range of timescales. He is active in both the theoretical/modeling and field aspects of Antarctic research and is a Principal Investigator of ANDRILL.

Robert Dunbar. School of Earth Sciences, Stanford University, USA (email: dunbar@pangea.stanford.edu). Rob Dunbar is Professor of Geological and Environmental Sciences at Stanford University. His research interests link oceanography, climate dynamics, and geochemistry. Prof. Dunbar's research group works on topics related to global environmental change, with a focus on the coastal ocean, air-sea interactions, and polar processes. In January, 2004, he was named the J. Frederick and Elisabeth B. Weintz University Fellow in Undergraduate Education. This fellowship is in recognition of teaching and mentoring of Stanford undergraduates.

Carlota Escutia, Instituto Andalúz de Ciencias de la Tierra (Consejo Superior de Investigaciones Científicas), Spain. (email cescutia@ugr.es). Carlota Escutia is a research scientist at the Instituto Andalúz de Ciencias de la Tierra. She earned her Ph.D. in marine sciences in 1992 from the Universidad Politécnica de Cataluña-Universidad de Barcelona. From 1992 to 2002 she worked as a postdoctoral fellow and visiting scientist at the USGS Menlo Park (California) and as an Assistant Research Scientist-Staff Scientist at the Ocean Drilling Program-Texas A&M University (Texas). She works on the broad subject of seismic stratigraphy and sedimentology of siliciclastic continental margins. Her research focuses on sedimentary margin architecture and sedimentary processes with the main objective of understanding global environmental change, geohazards and resource assessment. With these objectives in mind she has been conducting studies in Antarctica, the Mediterranean, Atlantic Gulf of Cadiz, and Lake Baikal (Russia). She coordinated the ANTOSTRAT Wilkes Land working group, chaired numerous committees and presently serves as a member of one the IODP advisory panels: the Site Survey Panel.

Fabio Florindo. Istituto Nazionale di Geofisica e Vulcanologia (INGV), Rome, Italy (e-mail florindo@ingv.it). Fabio Florindo is Senior Scientist at the INGV from 2001. He hearned his Ph.D. in Palaeoceanography from the University of Southampton (U.K.). His research focuses in palaeomagnetism and environmental magnetism wih applications to palaeoclimate and palaeoceanography. In the last few years most of his research focused on increasing the resolution of understanding of ice sheet and climate history and their role in the evolution and development of climate. He is one of the lead proponents of the multinational ANDRILL (ANtarctic DRILLing) project.

Jane Francis is Professor of Palaeoclimatology and director of the Centre for Polar Science at the University of Leeds. Her research uses fossil plants as a tool for climate interpretation and information about past floral biodiversity and its response to climate change. Her current work focuses on understanding past climate change during both greenhouse and icehouse periods, particularly in Antarctica. She was awarded the Polar Medal for her polar research in 2002.

Michael Hambrey, Institute of Geography & Earth Sciences, University of Wales, Aberystwyth, UK (email mjh@aber.ac.uk), where he is Director of the Centre for Glaciology. He obtained a PhD in 1974 from the University of Manchester on the structural glaciology of Norwegian glaciers. His work has focused primarily on glacial processes and reconstructing earth's glacial record (Precambrian and Cenozoic) in the Polar Regions. His Antarctic interests, from 8 field seasons, are concerned with the Cenozoic glacial sedimentary record in the Transantarctic Mountains, the Prince Charles Mountains and James Ross Island.

David Harwood, Department of Geosciences, University of Nebraska-Lincoln, Lincoln, NE 68588-0340, USA (email dharwood1@unl.edu). David Harwood is a professor of micropaleontology and stratigraphy at the University of Nebraska. He earned his Ph.D. in Antarctic micropaleontology and stratigraphy at The Ohio State University in 1986. He has been investigating the history of Antarctic Cenozoic glaciation from terrestrial deposits, glacial marine deposits in outcrop and drillcore and from Southern Ocean drillcore sites and is the Director of the ANDRILL Science Management Office.

Alan Haywood. Geological Sciences Division, British Antarctic Survey, Cambridge, UK (email ahay@bas.ac.uk). Alan Haywood is currently Principal Investigator of the British Antarctic Survey's GEACEP Programme (Greenhouse to Ice-house Evolution of the Antarctic Cryosphere & Palaeoenvironment). He earned his Ph.D. in numerical climate modelling and palaeoenvironmental reconstruction in 2001 from the University of Reading and has worked on modelling past climate and environmental change since that time. His research focuses on the reconstruction of past climates (particularly for the Neogene) and on evaluating the outputs of advanced numerical climate models against proxy climate and environmental data. He is currently a member of the UK High Performance Computing steering committee.

Robert Larter. British Antarctic Survey (BAS), Cambridge, UK. (email r.larter@bas.ac.uk). Robert Larter earned his Ph.D. in Antarctic marine geophysics in 1991 from the University of Birmingham. He has extensive experience in application of marine geophysical techniques to studying the glacial history of, and effects of glacial processes on, the Antarctic continental margin. His research focuses on the Pacific sector or the Antarctic margin. He has participated in 11 Antarctic and sub-Antarctic marine geoscience cruises since 1984, including two cruises as an invited scientist on foreign vessels. He has been Chief Scientist on three research cruises on the BAS vessel RRS James Clark Ross.

Tim Naish, Geological Time and Past Environments Section, Institute of Geological and Nuclear Sciences (GNS), NZ (t.naish@gns.cri.nz). Tim Naish is leader of the Antarctic paleoclimate progreamme at GNS. He earned his PhD in sequence and cyclostratigraphic analysis of Quaternary sea-level changes in shallow-marine continental margins in 1995 from the University of Waikato, NZ and continued this research during a post-doctoral research fellowship at James Cook University, Queensland. His current research focuses on the analysis of glacial and sea-level signatures in ice-marginal marine environments. He will co-lead the ANDRILL programe drilling of the Ross Ice Shelf site, and is a member of the ANDRILL Science Steering Committee.

Tony Payne. School of Geographical Sciences, University of Bristol, UK. (email a.j.payne@bristol.ac.uk). Tony Payne is Proleptic Reader at the University of Bristol and co-director of the Centre for Polar Observation and Modelling (a NERC-funded Centre of Excellence). He has a Ph.D. in ice sheet modelling (Edinburgh 1988). His research is concerned primarily with modelling the response of ice masses to climate change, although he has wider interests in the numerical modelling of environmental systems.

David Pollard received his bachelor's degree in Mathematics from Cambridge University in 1973, and a master's degree in Aeronautics from the California Institute of Technology in 1974. He then joined the Division of Geological and Planetary Sciences at Caltech, and received his Ph.D. in planetary meteorology in 1979. He worked on Earth energy-balance climate and ice-sheet models as a postdoctoral associate at Caltech and Oregon State University in Corvallis, then worked from 1983 to 1988 as a commercial project-management software developer and in JPL quality assurance, gaining experience in large software systems. He rejoined academia in 1988 as a research associate at NCAR in Boulder, Colorado, where he worked for 9 years on all aspects of the GENESIS global climate model. In 1997 he moved to the Earth System Science Center at Penn State as a research associate, and continues to work on global and regional climate and ice-sheet model development and applications.

Ross Powell. Department of Geology and Environmental Geosciences, Northern Illinois University, USA. (email ross@geol.niu.edu). Ross Powell a Professor of Geology at Northern Illinois University. He earned his Ph.D. in glacial sedimentological processes in 1980 from the The Ohio State University and has worked on many process- and stratigraphic/palaeoclimatic-related studies in Antarctica and other high-latitude areas since that time. His research focuses on quantifying the processes that go to make a stratigraphic record in environments where glaciers, rivers, and sea and lake waters interact, and how such ancient records may be interpreted relative to glacial and climatic changes. He is currently a US representative to the GSSG, he is on the SALE and ACE SPPGs, and the Permafrost Action Group of the GSSG; formerly he was a member of two Groups of Specialists - GLOCHANT and SALEGOS.

Martin Siegert. School of Geographical Sciences, University of Bristol, UK. (email m.j.siegert@bristol.ac.uk). Martin Siegert is Professor of Physical Geography at the University of Bristol. He earned his Ph.D. in numerical ice sheet modelling in 1993 from the University of Cambridge and has worked in the broad subject of Antarctic glaciology since this time. His research focuses on the use of radar to the identify and characterise subglacial processes, and the investigation of the long-term history of the Antarctic ice sheet. He is co-Chair of the Subglacial Antarctic Lake Exploration (SALE) SPPG.

Gary Wilson, Department of Geology, University of Otago, NZ. (email gary.wilson@otago.ac.nz). Gary Wilson is a Senior Lecturer in physical stratigraphy and paleomagnetism and director of the Otago Palaeomagnetic Research Facility. He earned his PhD in sedimentology in 1993 from Victoria University of Wellington, NZ. His primary research interest is in paleoclimatology and the role of Antarctica in the role of the global climate system. Science graduating, he has held the Byrd Fellowship at the Ohio State University and a lectureship at the University of Oxford, UK. He is convenor of the McMurdo ANDRILL (Antarctic Drilling) Science implementation committee (MASIC)

Science Plan for a SCAR Programme on Antarctica and the Global Climate System (AGCS)

Submitted by the SCAR Physical Sciences Standing Scientific Group

Expected Duration of programme: 6 years

Estimated SCAR Funding Required: $90,000 Over the Lifetime of the Programme. But options are presented for additional expenditure if greater levels of funding become available

Programme Summary

This proposal outlines a programme of research to investigate the nature of the atmospheric and oceanic linkages between the climate of the Antarctic and the rest of the Earth system, and the mechanisms involved therein. This work is a high priority and will require a combination of modern instrumented records of atmospheric and oceanic conditions, and the climate signals held within ice cores to understand fully past and future climate variability and change in the Antarctic as a result of natural and anthropogenic forcings. The primary time period to be considered will be approximately the Holocene (about the last 10,000 years) to 100 years in the future, but records that capture abrupt climate change over earlier periods will also be used as necessary.

The programme will make use of existing deep and shallow ice cores, satellite data, the output of global and regional coupled atmosphere-ocean climate models and in-situ meteorological and oceanic data to understand the means by which signals of tropical and mid-latitude climate variability reach the Antarctic, and high latitude climate signals are exported northwards. The emphasis will be on synthesis and integration of existing data sets and model output, although some new ice core and oceanographic data will be collected.

There will be four major, closely linked themes of research. (1) Decadal time scale variability in the Antarctic climate system, which will investigate ocean-atmosphere coupling, the role played by radiative processes and the role of the El Niño-Southern Oscillation in modulating the Antarctic climate. (2) Global and regional climate signals in ice cores to establish better quantitative relationships between ice core data and measures of tropical, mid- and high latitude climate variability (3) Natural and anthropogenic forcing on the Antarctic climate system, including the production of regional-scale estimates of expected climate change over Antarctica during the next 100 years. (4) The export of Antarctic climate signals, to examine the means by which climate changes in the Antarctic can influence conditions at more northerly latitudes

The programme will be a valuable contribution to the International Polar Year planned for 2007-2008, especially their Themes 1, 2 and 3 dealing respectively with environmental variability, change, and teleconnections. We plan to use the IPY as a Special Observing Period to test models and high-low latitude climate signal transfer functions.

As part of the programme we will create a new web-based inventory of data extracted from Antarctic ice cores to complement the SCAR READER data base of mean in-situ meteorological data. The future climate scenarios produced will be of great value to the Life Sciences SSG in their consideration of how the Antarctic biota will evolve over the next century.

1. Programme Objectives

The goals of this programme are to gain insight into the linkages between the Antarctic and the rest of the global climate system. Specifically, we will address a number of key questions concerning extra-polar/Antarctic coupling:

- How does variability in tropical and mid-latitude atmospheric and oceanic conditions modulate the Antarctic climate?

- Does variability in Antarctic climate perturb tropical and mid-latitude atmospheric and oceanic conditions?
- What are the mechanisms that transfer the tropical signals to the Antarctic?
- What are the relative roles of the ocean and atmosphere in this transfer?
- What controls the stability of coupled atmosphere-ocean phenomena, such as the Antarctic Circumpolar wave and the Southern Hemisphere Annular Mode?
- What are the quantitative relationships that reflect the non-linear linkages between climate signals in ice cores, Antarctic sea ice and the Antarctic atmospheric circulation, and the varying extra-polar signals?
- Why do the teleconnections between the tropics and the Antarctic vary on decadal timescales?
- How has the development of the Antarctic ozone hole affected these teleconnections?
- What has been the impact on the Antarctic environment of changes in the El Niño-Southern Oscillation over recent decades?
- How will Antarctic climate conditions change on regional and continent-wide scales over the next century as a result of various greenhouse gas emission scenarios and other human source emissions into the atmosphere?

Within this programme we will also:

- Work with climate modellers to improve the representation of the Antarctic atmosphere, ocean and cryosphere in global and regional models.
- Assemble a new data base of Antarctic ice core information.
- Work with life scientists to investigate the impact of recent and possible future changes in climate on Antarctic ecosystems.
- Where necessary establish linkages with the deep ice core records of pre-Holocene climatic conditions.

2. Scientific background

Our understanding of the role of the Antarctic in the global climate system has advanced dramatically in recent years as new atmospheric, oceanographic and cryospheric data sets have become available. We now know that ice-albedo feedbacks and radiative processes (mainly related to clouds) are extremely important over the continent and in the sea ice zone, explaining why the inter-annual variability of temperatures is so large at high latitudes. Great advances have also been made in our understanding of ocean processes, such as the role of the Antarctic Circumpolar Current (ACC) in linking the ocean basins, allowing the global-scale thermohaline circulation to exist.

At the time of IGY the Antarctic was thought of as rather isolated from conditions at more northerly latitudes, but studies using the new observational data sets and sophisticated Atmosphere-Ocean General Circulation Models (AOGCMs) have shown the close couplings that exist between different elements of the system and the feedbacks that are operating.

The Antarctic is the main heat sink in the Southern Hemisphere and there is a southward flux of heat in response to the radiatively-induced Equator to Pole temperature difference. The bulk of the heat (80%) is carried by the atmosphere, but with the ocean transporting the remaining 20%. The circumpolar channel is important in inhibiting the poleward flux of heat via the ocean and plays an important role in the glaciation of the continent.

In the atmosphere the transient eddies (depressions) over the Southern Ocean play a greater role in the thermal advection when compared to their counterparts in the Northern Hemisphere, as a result of the simpler orography in the Southern Hemisphere. The track and frequency of these eddies is a function of the thermal gradient over the Southern Hemisphere and provides a means for climatic signals in the tropics and mid-latitude regions to reach the Antarctic. But the more active role of the eddies complicates the southward transfer of tropical climate signals as they have to cross the belt of strong westerlies. High-low latitude teleconnections in the Southern Hemisphere are therefore less robust than north of the Equator.

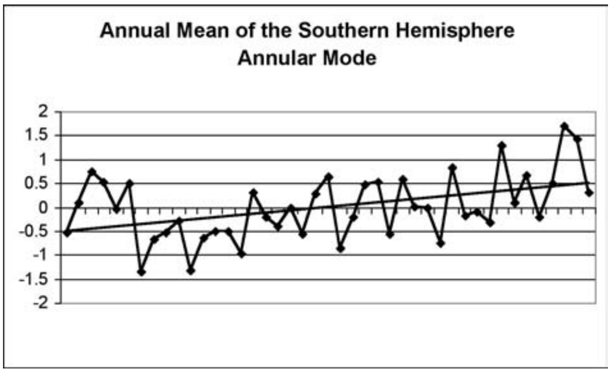

Figure 1. The annual mean value of the Southern Hemisphere Annular Mode (SAM) with linear regression line.

Ocean eddies are also of great importance in heat and momentum transport in the Southern Ocean and are likely to play an important role in controlling the strength of the Circumpolar Current. These systems typically have a horizontal length scale of 20-100 km and present challenges to modellers and those concerned with the collection of observational data.

Over recent decades part of the Antarctic have experienced major climate change, with near-surface temperatures on the western side of the Antarctic Peninsula rising faster than anywhere else in the Southern Hemisphere. This region has also experienced the disintegration of a number of floating ice shelves. Over this period significant advances have been made in understanding climatic cycles in the Antarctic and the role that extra-polar forcing and internal mechanisms, such as cloud radiative effects, plays in this variability. One of the first indications of high-low latitude coupling was the semi-annual oscillation (SAO). This was identified in the mean sea level pressure (MSLP) observations from the stations around the coast of the Antarctic and showed that pressures were at a minimum (maximum) during the autumn and spring (summer and winter) (van den Broeke, 1998). This was found to be associated with a southward movement and deepening of the circumpolar trough, which rings the Antarctic over 60-70o S. The circumpolar trough is present because of the large number of storms in the coastal region, with the systems having either developed in the strong thermal gradient at the edge of the Antarctic or having moved south from mid-latitudes. The SAO, which has no counterpart in the Arctic, occurs because of the different annual cycles of surface temperature over the Antarctic continent and mid-latitudes. As well as affecting the MSLP observations, a SAO is also found in the precipitation reports from the coastal region and will therefore be reflected in the sub-annual data in ice cores. Changes in the mid-latitude conditions therefore have the capacity to alter the Antarctic environment via the SAO. The oceanic circumpolar transport also shows a pronounced semi-annual signal, as a consequence of modulation of eastward wind stress by the SAO (Whitworth and Peterson, 1985; Meredith *et al.*, 1996), emphasizing the intimate coupling of atmospheric and oceanic dynamics around Antarctica. But the SAO is now known to exhibit inter-annual to decadal timescale variability, so complicating the investigation of Antarctic climate change.

Although the identification of the SAO was an important step in understanding the interactions between the mid- and high-latitude areas, recently it has been found that the SAO reflects, to a large extent, the Southern Hemisphere Annular Mode (SAM), which we now know is the principal mode of variability in the atmospheric circulation of the Southern Hemisphere extra-tropics and high latitudes. The SAM has a zonally symmetric or annular structure, with synchronous anomalies of opposite sign in Antarctica and the mid-latitudes, and is usually defined as the MSLP difference between 40o and 65o S. Over recent decades the SAM has been moving into its positive phase (Figure 1) with MSLP values decreasing across the Antarctica coastal zone and rising over the mid-latitude areas of the Southern Ocean. This has resulted in greater ascent of air around the continent and larger amounts of cloud and precipitation over the sea ice zone. The change in the SAM has also resulted in an increase in the westerly component of the wind around the continent and an increase in ACC transport. This has further given an increase in sea ice due to an increase in northward Ekman flow. There are indications that the changes in the atmospheric driving forces affect the ocean circulation and water mass properties of the source waters for deep and bottom water formation in the Weddell Sea, which contribute to the global thermohaline circulation (Fahrbach *et al.*, 2004).

The exact reasons for the change in the SAM are not understood fully, but model experiments have shown that the SAM is affected by changing levels of stratospheric ozone (Thompson and Solomon, 2002) and increasing

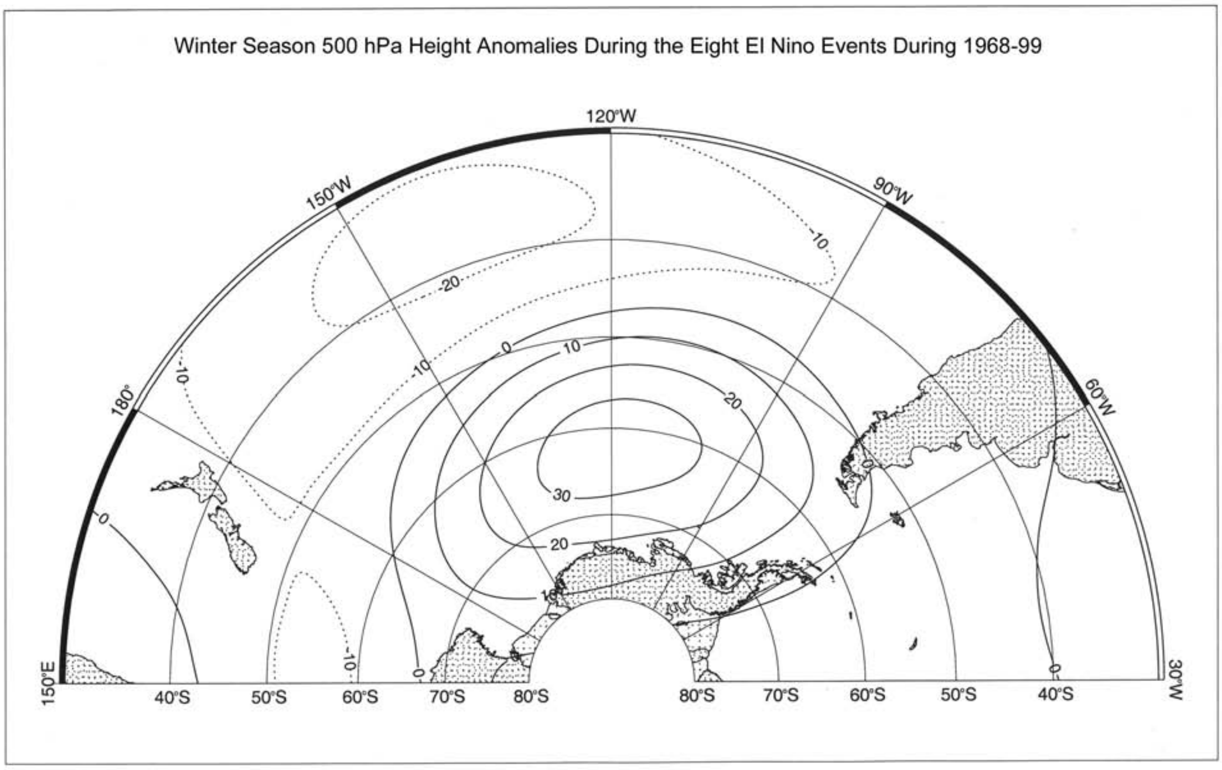

Figure 2. The 500 hPa height anomalies over the Amundsen-Bellingshausen Sea during the eight El Niño events between 1968-99.

amounts of greenhouse gases (Fyfe *et al.*, 1999). Ice core records capture annual to multi-decadal scale variability and dramatic changes in the large scale atmospheric circulation.

The circumpolarity of the Southern Ocean is a key factor in the global climate system, since it forms an important link between the other major oceans; the importance of this connectivity is further enhanced by the presence of the ACC, the world's largest current in terms of transport. It has been demonstrated recently that the SAM is an important mechanism controlling temporal variability in the circumpolar ocean transport around Antarctica on timescales up to seasonal (Aoki, 2002; Hughes *et al.*, 2003). The response of the ocean to the long-term trend in the SAM toward a higher index state has yet to be established, however Thompson and Solomon (2002) noted that this trend is strongly modulated by season, and recent ocean observations have revealed strikingly similar seasonal modulations in the ocean circumpolar transport (Meredith *et al.*, 2004a). This is suggestive of high latitude climate change (including possible ozone depletion) being transmitted to the ocean circulation, with possible global implications.

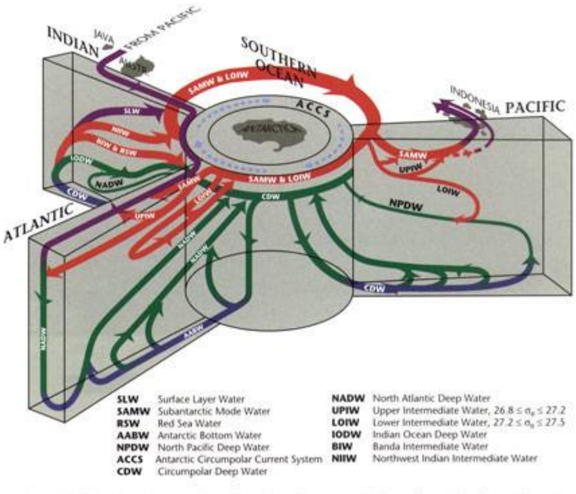

Figure 3. The thermohaline circulation. From Schmitz et al. 1995.

The El Niño-Southern Oscillation (ENSO) is the largest climatic cycle on Earth on the timescale of years to decades, and variations in the cycle have world-wide consequences. During El Niño events a Rossby wave train becomes established from the central, tropical Pacific across the South Pacific to the Bellingshausen Sea (Figure 2). On average, this results in colder, drier conditions over the Antarctic Peninsula, and warmer, temperatures and higher levels of precipitation over the coastal region of the southern Amundsen Sea during El Niño events (Turner, 2004). Ocean measurements during ENSO events are very scarce around Antarctica, however Meredith et al. (2004b) noted a deepened mixed layer and enhanced salinity at the western Antarctic Peninsula in response to increased ice production during the decay of the 1997/98 ENSO. This observation complements the previous observation of enhanced downslope convection of dense water from the tip of the Peninsula during 1998, again believed to be due to an ENSO-related modulation of the sea ice field (Meredith et al., 2003). There is, however, considerable variability in the nature of ENSO events even in the tropics and the extra-tropical response to this forcing is rather variable. For example, the 1982-83 El Niño event was the largest of the Twentieth Century, but it had a very anomalous signature in the Antarctic. This makes it very difficult to find consistent signals of ENSO events in atmospheric, oceanic and cryospheric parameters measured in the Antarctic. For example, signals of El Niño events have been detected in ice cores collected at the South Pole via the marine biogenic sulphur species methanesulphonate (Meyerson *et al.*, 2002) and the moisture flux into west Antarctic, and therefore the precipitation in this sector of the continent, was highly correlated with the ENSO cycle (Cullather *et al.*, 1996). But this latter study highlighted a change in phase of the ENSO/precipitation relationship between the 1980s and 1990s, pointing to a decadal timescale variability in some aspects of the tropical-high latitude teleconnections.

It has also been suggested that the ocean circulation can play a role in the southward transmission of ENSO signals via the Antarctic Circumpolar Wave (ACW) (White and Peterson, 1996). This could take place as SST anomalies develop in response to ENSO events along the Equator and move south into the western subtropical South Pacific, with the signals then spreading south and east into the Southern Ocean, where subsequent eastward propagation can take place via the Antarctic Circumpolar Current. However, Connolley (2003) has shown that the ACW was most pronounced during the 1980, but was less clear in earlier and later periods, again indicating decadal variability in the atmosphere-ocean interactions.

The above studies have highlighted the non-linear nature of many of the Antarctic-lower latitude teleconnections, suggesting that simple comparisons of ENSO measures (such as the Southern Oscillation Index) with environmental quantities measured in the Antarctic are only of limited value. A sounder approach will be to combine Antarctic observational studies and ice core records with modelling experiments and numerical analysis, which will give greater insight into the processes involved.

Although many of the studies concerned with teleconnections between the Antarctic and lower latitudes have considered the southward transfer of tropical signals, there are also important linkages out from the Antarctic. These have been most investigated in the ocean, with particular attention being paid to Antarctic Bottom Water (AABW) and the thermohaline circulation. This is the densest water mass in the open ocean; as such it constitutes the abyssal layer of the global overturning circulation (Figure 3). It has been hypothesised widely that changes in the production rate and/or properties of AABW could exert a long-term influence on global climate, though the precise nature and mechanisms involved are currently undetermined. The bulk of AABW formation requires dense shelf water as a precursor, with sea ice formation being a key process in adding salt to the ocean to raise its density. Consequenty, climatically-driven changes in sea ice production could play a profound role in altering AABW formation. Similarly, changes in the mass balance of the Antarctic ice sheets could affect the glacial freshwater contribution to the adjacent ocean, again with possible consequences for the production of AABW. Once formed, the components of AABW have to negotiate various topographic obstacles before reaching the major ocean basins to the north; this circulation (which is believed to be wind driven to some extent) is likely to exhibit temporal variability (e.g. Meredith *et al.*, 2001), but the details and extent of this are presently unknown.

As well as AABW, other Southern Ocean water masses are key in the global climate system. For example, Antarctic Intermediate Water (AAIW) and Subantarctic Mode Water (SAMW) form important parts of the "upper cell" of the global overturning circulation, and show properties that depend strongly on atmospheric forcings. In addition, these water masses are responsible for around 40% of the total uptake of anthropogenic carbon dioxide, and nutrients exported from the Southern Ocean in SAMW have been shown to support around 75% of global export production It is believed that such mode waters are very susceptible to atmospherically-driven climate change, and hence are strong markers of the oceans response to such changes (Banks and Bindoff, 2003). Furthermore, changing ocean conditions can be important drivers of Antarctic and global climate change. Recent observations indicate that Circumpolar Deep Water (CDW; the most prevalent water mass of the ACC) is warming at a much greater rate than the global oceans as a whole (Gille, 2002). In regions where CDW shoals and impinges on the continental shelves of Antarctica (e.g. the western Peninsula), this could be an important additional heat source that requires consideration in studies of future climate.

It is now timely for SCAR to undertake a programme of research into the links between the Antarctic climate and the rest of the Earth system as it is only in the last few years that sufficient high resolution in-situ data and ice core records have become available to investigate such connections and modelling tools have developed to the point where they can represent realistically the closely coupled atmosphere-ocean processes that are clearly important in long-term climate variability.

The climate of the Antarctic varies on a very wide range of time scales from the annual and sub-annual to the major ice ages. In order to keep the scope of the project manageable, the focus on recent and future climate variability and change, and to be able to examine atmospheric/oceanic processes in some detail, we propose to have the primary focus of the programme over the period of the Holocene out to the next 100 years. The second half of the Holocene was when the solar forcing was essentially the same as today and natural climate variability over this period will provide a reference against which we can compare variability and change in the period of anthropogenic influence. This is also a period during which the modern configuration of the Antarctic ice sheet began to evolve (Conway *et al.*, 1999), and it is upon these evolving boundary conditions that modern climate is superimposed. The next 100 years is also the period of interest to the Intergovernmental Panel on Climate Change (IPCC) and we propose to use some of the model data created as part of this activity in AGCS. The programme will also benefit from the involvement of several Antarctic deep ice core records that cover one or more glacial/interglacial cycles. These records offer case histories of a wider range of climate change than available over the Holocene and as such offer important opportunities for modelling climate extremes and abrupt climate change scenarios. We will also investigate the mechanisms controlling the duration and the variability of the warm periods.

We propose that the programme has four major, closely linked themes reflecting significant gaps in our knowledge:

a. Decadal time scale variability in the Antarctic climate system

This activity will focus on explaining the mechanisms responsible for variability in the Antarctic climate system on the scale of several years to a century. This is the timescale on which much of the ocean variability takes place and the changes observed in the atmospheric conditions and sea ice environment reflect the close coupling between the atmosphere and ocean in the high southern latitudes. Key targets will be to understand the variability of Southern Ocean water masses, including the warming of CDW, and the expression of the low frequency variability of ENSO in the Antarctic. Sea ice extent and concentration will also be examined, along with the reasons for changes in the SAM. The relative importance of the radiative processes in modulating the climate system will also be investigated.

b. Global and regional signals in ice cores

A large investment has been made in the collection of shallow and deep ice cores from the Antarctic, yet we still have an imperfect understanding of the means by which the signals of regional and global climate variability reach the coring sites and are locked into the ice record. To date most investigations of global and regional climate signals in ice cores have been based on the assumption that there will be linear relationships between measures of climate variability outside the Antarctic and quantities measured in ice cores. In this theme we will use diagnostic information from models and the re-analysis fields to establish better quantitative relationships between ice core data and measures of tropical and mid- high-latitude climate variability. The work with the re-analysis data sets and climate models will also be of value in identifying sites where ice cores could be collected in the future.

c. Natural and anthropogenic forcing on the Antarctic climate system

Elements of the Antarctic climate system have experienced major changes in recent decades, such as the marked warming on the western side of the Antarctic Peninsula since the 1950s. In addition, during the 1970s the total extent of Antarctic sea ice decreased; a change that was frequently attributed to humankind's activity. However, the ice extent recovered during the 1980s and the temperatures on the Peninsula have not changed significantly since about 1980. It has therefore proved difficult to separate natural climate variability from anthropogenic activity. As Antarctic sea ice is predicted to decrease over the coming century as a result of increases of greenhouse gases it is important to be able to distinguish natural variability from anthropogenic activity and to understand how global climate change will be expressed in the Antarctic.

d. The export of Antarctic climate signals

This theme will examine the means by which climate changes in the Antarctic can influence conditions at more northerly latitudes. Much of this is believed to happen via the ocean, with AABW escaping the subpolar gyres and traversing topographic obstacles to spread out into the world's ocean. The processes which control the transfer and spreading of the AABW require investigation, to determine the extent to which changes close to the Antarctic continent can influence the larger-scale ocean and climate. Processes close to the Antarctic can influence the production rate and properties of AABW and other water masses, such as intermediate and mode water. For example, removal of sea ice and glacier melt can both influence water mass production in the Antarctic coastal zone, thus influencing the shelf water properties that are key to the formation of AABW. Atmospheric changes that affect the ocean surface (heat and freshwater fluxes, wind-driven Ekman transports) are known to be important in setting the properties of intermediate and mode waters, and hence need to be included in the analyses. The long-term warming of CDW will have consequence fore formation and spreading of other water masses, since it is the oceanic source for all other waters that form around Antarctica. Thus consideration of this warming is important if our understanding of the Southern Ocean's role in global climate is to be usefully advanced.

3. Programme rationale/justification

The research proposed here is necessary in order to interpret correctly the climate signals in ice cores and to understand past and future climate variability and change in the Antarctic as a result of natural and anthropogenic forcing factors. As described above, the linkages between the different elements of the Antarctic climate system are highly non-linear and it is necessary to understand the atmospheric, oceanic and cryospheric elements of the system if past change is to be explained and we are to have confidence in future predictions.

SCAR is well placed to lead this activity as it has representatives from all the nations with major Antarctic research programmes and now has the structure of SSGs that brings together scientists with the necessary skills to undertake such a cross-disciplinary programme of research. It also has excellent links into the planning of Antarctic operations via COMNAP.

The work described here will build on successful SCAR activities that have already raised the profile of SCAR in the international community. The International Trans-Antarctic Scientific Expedition (ITASE) has the goal of understanding the last 200-1000 years of Antarctic climate and change in the chemistry of the atmosphere using ice core data. The ongoing collection of ice cores through ITASE will provide vital, high-resolution climate data extending back into the pre-industrial period. The SCAR REference Antarctic Data for Environmental Research (READER) project will continue to develop its high quality data base of mean in-situ mean meteorological data for investigation of climate variability at the research stations over the last 50 years. The Antarctic Tropospheric Aerosols and their Role in Climate (ATAC) Action Group is determining the influence of Antarctic tropospheric aerosols on the radiation budget and characterising and classifying the nature of Antarctic aerosols. Aerosols are transported to the Antarctic via the meridional atmospheric circulation and provide information on the sources of airmasses. ATAC will therefore become part of AGCS and contribute to the investigation of high-low latitude linkages.

This programme is also timely in that many of the tools, models and data analysis procedures required to carry out the work have only just become available. The ECMWF 40 year atmospheric re-analysis project (ERA-40) is just coming to a close and has produced the best time series of atmospheric conditions yet created, extending back to IGY. Although there are some questions regarding the quality of the analyses in the period before the mid-1970s when satellite sounder data became available, the fields are of high quality since that time. The data will be vital for investigating atmospheric variability, and will also allow the production of back trajectories for the investigation of signals arriving at the ice coring sites.

Early climate models were simple atmosphere-only models with poor horizontal and vertical resolution and no interactive ocean or sea ice. With prescribed ocean conditions they were not able to simulate the natural climate variability of the Earth. Later models were coupled to ocean models and had sea ice that simulated successfully the interactions between floes. The current generation of AOGCMs have developed to the point where they have sufficient horizontal and vertical resolution to successfully simulate most of the orography of the Antarctic, although they still have problems in handling areas such as the Antarctic Peninsula, which is a high, narrow barrier. A very recent innovation is the development of coupled atmosphere-ocean regional climate models that are better able to simulate the small-scale processes that are found in the Antarctic, and these will be used within AGCS. The results of AGCS will be of value to the modelling community and it is hoped that they will result in improvements to the high latitude element of global climate models.

There have also been great advances in the analysis of ice cores so that annual, and in some areas of high accumulation sub-annual, information can be retrieved. A broad range of environmental indicators are now available from ice cores allowing reconstruction of past content of gases, major and trace chemistry, radionuclides, isotopes, organics etc. These measurements allow reconstruction of past physical (temperature, precipitation, atmospheric circulation) and chemical climate through calibration with in-situ observations. That said, the opportunities and complexities inherent in such calibrations require significantly more focus and tighter connections between communities represented by SCAR, notably meteorologists, atmospheric chemists, solar physicists, biologists, and glaciologists. ITASE has dramatically advanced the number, quality, and calibration potential of ice core records. Further, through ITASE, ice core records can now be traced from site to site through tracking of time synchronous radar reflectors and into the atmosphere through aerosol collections. Deep ice cores collected by several SCAR nations have now successfully penetrated back 800, 000 years in the Antarctic revealing changes in the long term behaviour of climate and through comparison with Arctic deep ice cores reveal the global structure of abrupt climate change events. Efforts will be made with the International Partnerships in Ice Core Sciences (IPICS) to extend the record in time and to investigate during IPY where the longest records can be retrieved. With IPICS, surveys will be carried out of the best places on the edges of the Antarctic to establish a network of intermediate drillings with the aim of investigating the stability of this region over the last 20,000 years.

The International Polar Year (IPY) will be a major focus of Antarctic research, survey and logistical coordination during the period 2007-9. Over this time there will be additional observing systems deployed across the Antarctic and the Southern Ocean. The operational meteorological analyses, which will assimilate these data, will therefore be of high quality. But the enhanced observational data provides an ideal opportunity to carry out case studies of high-low latitude oceanic and atmospheric linkages. We will therefore use the IPY as a Special Observing Period within AGCS to test models and high-low climate signal transfer functions. We see AGCS as being a valuable SCAR contribution to the IPY, especially its Themes 1 “To determine the present environmental status of the polar regions by quantifying their spatial and temporal variability”, 2 “To quantify, and understand, past and present environmental and human change in the polar regions in order to improve predictions” and 3 “To advance our understanding of polar – global teleconnections on all scales, and of the processes controlling these interactions”.

We also see the results of this programme being of value to the IPCC and the Parties to the United Nations Framework Convention on Climate Change. Work is already well underway to produce the Fourth IPCC Assessment, which will be published in 2007. However, the trend is clear that users of the IPCC assessments require regional information on change rather than indications of global change. We see this programme as providing advise to IPCC for the Fifth Assessment, which we anticipate will need input towards the end of the programme. This may be one means for SCAR to have input to the assessment process. The long-term ice core record will also provide significant information for the chapter on palaeoclimatology in the next IPCC report.

Within SCAR itself we see the outcomes of this programme as being of great value to the SCAR Life Sciences SSG who require information on the climate evolution of the Antarctic over the next century based on various greenhouse gas emission scenarios. This will allow them to investigate possible changes in terrestrial and marine biota. We will also work closely with the SCAR Antarctic Climate Evolution (ACE) programme, which will be concerned with the Cenozoic period, over paleoclimatic data and modelling. In addition, we will collaborate with the SCAR Interhemispheric Conjugacy Effects in Solar-Terrestrial and Aeronomy Research (ICESTAR) programme regarding the possible role of solar and upper atmospheric changes in modulating the surface and tropospheric climate.

4. Methodology and preliminary implementation plan

This programme of research will be carried out through a close collaboration between meteorologists, climatologists, glaciologists, oceanographers and ice chemists, and will involve integration of observational and modelling activities. Such an approach will be essential as the programme will deal with subjects that are highly cross-disciplinary.

Preliminary implementation plans for the four research themes are presented below:

a. Decadal time scale variability in the Antarctic climate system

- Existing long, 1,000 year control runs of the pre-industrial climate from AOGCMs will be used to examine the natural climate variability of the Antarctic atmosphere and the oceanic conditions around the continent.
- As part of the above activity the ability of such models to represent Antarctic and Southern Ocean conditions will be verified thoroughly against existing atmospheric observations and analyses, and oceanographic ship and float data.
- Selected model parameters, such as precipitation and temperature across the Antarctic, will be compared

to the available ice core records to further assess the performance of the models. Such runs will provide an indication of atmosphere/ocean variability on a range of time scales and allow the determination of the robustness of high-low latitude teleconnections. Diagnostic information from the runs will provide insight into the mechanisms that are important in maintaining the teleconnections and the reasons for changes on the decadal timescale.

- The high quality re-analysis data sets, such as ERA-40, will be used to investigate atmospheric variability over recent decades. Case studies will be carried out of low-latitude – Antarctic linkages during different stages of recent ENSO events.
- Changes in water mass variability and other ocean properties will be carried out using existing cruise and float data. This work will also make use of the output from ocean and AOGCM runs.

b. Global and regional signals in ice cores

- Existing and new ice core data will be used in conjunction with re-analysis fields and selected lake sediment data to investigate how signals of change reach the cores. Back trajectory analysis will indicate the source regions of precipitation falling at the drilling sites.
- Blowing snow models will be used to investigate the mixing of snow on the surface, which provides a limit on the resolution of the data that can be identified in the cores. Output from the high resolution models that are becoming available will provide insight into the role of mesoscale processes in affecting the core data.
- A study will be carried out to determine the extent to which quantitative relationships can be developed between parameters measured in ice cores (or determined from ice core data) and measures of the atmospheric and oceanic circulation.
- The role of sea ice variability in modulating the atmosphere/ocean signals in ice cores will be determined.
- Study of the actual vertical aerosol distribution in the Antarctic troposphere, their transport pattern and life cycle, including air-snow transfer of aerosol in general, will be carried out to improve the ability to decipher the signals in the Antarctic ice core records of past climate (part of the ATAC project).
- The IPY will be used as a Special Observing Period for tracking airmasses arriving at ice core sites.
- A special focus will be ENSO variability as reflected in the cores.
- We will work closely with meteorologists and climatologists concerned with tropical climate variability and the export of such signals to higher latitudes.
- Links will be established with those concerned with change in the Arctic ice caps and high altitude glaciers.

c. Natural and anthropogenic forcing on the Antarctic climate system

- Using measures of the natural climate variability of the Antarctic climate system produced by Theme 1, we will use all available data to determine if the observed climate changes that have taken place over the last 50 years in certain sectors of the Antarctic are a result of anthropogenic activity. We will concentrate our investigation on the warming across the Antarctic Peninsula, the recent changes in sea ice extent and the role of the ozone hole in influencing tropospheric and oceanographic conditions and circulation. Regions of recent glacier change in East Antarctica will also be investigated notably Northern Victoria Land and the Lambert Glacier region. Throughout Antarctica evidence of changes in physical and chemical climate will be sought.
- Predictions will be produced of how the Antarctic climate is expected to evolve over the next century under different greenhouse gas scenarios. We will specifically use the predictions from the new generation of high resolution regional climate models that are becoming available.

d. The export of Antarctic climate signals

- Variability in AABW, AAIW, SAMW and CDW will be determined from cruise data and profiling float data.
- These data will be compared to such variability as represented in AOGCMs.
- The role of atmospheric and cryospheric forcing and variability on water mass production will be examined. Special emphasis will be placed on processes close to the Antarctic continent, including sea ice variability, iceberg calving and changes in freshwater release via glacial melt.
- The role of changing ocean abyssal circulation in regions of complex topography will be examined, with particular emphasis on understanding the mechanisms that control the northward export of AABW into the global overturning circulation.

In support of the above themes a central archive of ice core data will be created. Data derived from short and long ice cores will be essential to this programme with meteorologists, climatologists, sea ice experts, and ice chemists requiring access to these data. Projects such as ITASE, PAGES and EPICA have all produced extremely valuable paleoclimate data, but the data are scattered across institutes and data centres and not readily available to the broader research community. As a first step towards bring these data together, we will establish a web-based inventory of paleoclimate data derived from ice cores. Maps showing the locations where cores were collected will be created linking to information on who holds the data, the data derived and published papers that draw on these data.

5. Programme management and governance

We propose that the programme be managed and directed by a Steering Committee consisting of the chair of SSG/PS and leaders of the four themes. These will be distinguished scientists from the international community. The Steering Committee will meet for several days each year and review progress of the programme. They will be responsible for ensuring that the deadlines are met. Other scientists will be invited to the meetings of the Steering Committee as necessary in order to have external input to the planning and implementation of the programme. They will also meet at the biennial SCAR Science Meeting and present progress reports to the full SSG. Biennial reports will also be presented to the SCAR Delegates Committee on Science and the full Delegates meeting.

Each theme will be led by a distinguished scientist who will be responsible for coordination of the research within the theme. If approved a full implementation plan for the programme will be developed.

The Steering Committee, and particularly those involved in the themes will work closely with JCADM over the data management and data stewardship aspects of the programme.

With a programme of this scope it will be essential to maintain liaison with a number of international organisations and groups, and this will be the responsibility of the Steering Committee. We wish to stress that we see AGCS as being complementary to many existing programmes and not in competition with them, nor duplicating their activities. Programmes we will work closely with include:

- The WCRP CLIVAR programme
- CliC, and in particular the CLIVAR/CliC/SCAR Southern Ocean Panel, possibly by directly involving a member of the panel.
- IPCC
- SCOR

6. Deliverable outcomes from the programme, including public awareness

We anticipate that this programme would deliver:

- Greater insight into high/low latitude climate linkages.
- Papers in peer reviewed journals.
- Insight into Antarctic decadal timescale climate variability that will be of value to CLIVAR
- Advances in the representation of high latitude processes in climate models.
- High visibility for SCAR science to workers in tropical and mid-latitude climate studies.
- Valuable information on future climate scenarios will be provided to the SCAR Evolution and Biodiversity in the Antarctic programme and others biologists attempting to understand how Antarctic biota are affected by tropical conditions.
- Insight into the relative roles of the ocean and atmosphere in coupling the Antarctic and lower latitudes.
- Future climate predictions for the Antarctic under various greenhouse gas emission scenarios will be of value to other groups within SCAR, such as the marine and terrestrial life scientists.
- An AGCS web site will be created to describe the goals of the programme to scientists and the public, and to present research results.
- Data sets of Antarctic climate variability that will be of value to other workers.

7. Biennial milestones against which progress can be evaluated

Assuming that the programme starts in 2005 we would identify key biennial milestones as:

By the end of 2006

- Determine the natural climate variability of key elements of the Antarctic climate system from long climate model runs
- Preliminary assessment produced of atmospheric, and especially Southern Ocean, conditions in AOGCMs.
- Production of data on airmass origins reaching ice core sites

By the end of 2008

- Complete analysis of water mass variability from historical cruise and float data
- Study completed on quantitative relationships between ice core data and atmospheric/oceanic indices.
- Determine whether anthropogenic activity was responsible for the climate changes noted across the Antarctic over the last 50 years
- Complete study of atmospheric and cryospheric forcing on water mass production
- Initial data base of ice core data available
- Quantification of the Antarctic aerosol budget.
- Preparation of initial atmospheric and oceanic analyses for use within IPY

By the end of 2010

- Provide input to the Fifth IPCC assessment
- Completion of study on relationship between ENSO and Antarctic climate
- Complete analysis of Antarctic-tropical/mid-latitude links during IPY
- Output from high resolution models will provide insight into the role of local, regional and global signals in ice cores
- Production of regional and Antarctic-wide climate predictions for the Antarctic covering the next 100 years
- Supply regional climate scenarios covering the next 100 years to Life Sciences SSG

8. Success factors

- Obtaining funds for this work from the primary funding bodies.
- Papers published in peer reviewed journals
- Provide input to IPCC

- Influence the development of AOGCMs
- Develop methods that give insight into ice core data
- Outputs of AGCS used by other SCAR SSGs
- Obtain a higher profile for SCAR

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Supporting information

Programme proposers

Dr. John Turner, Chief Officer, SCAR Physical Sciences SSG

John Turner is a researcher at the British Antarctic Survey in Cambridge, UK where he leads a project investigating the climate of the Antarctic. He has a BSc in Meteorology/Physics and a PhD in Antarctic Climate Variability. From 1974 to 1986 he was employed by the UK Meteorological Office where he was in involved in the development of numerical weather prediction models and satellite meteorology. Since 1986 he has been at BAS working on high latitude precipitation, polar lows, teleconnections between the Antarctic and lower latitudes and weather forecasting in the Antarctic. From 1995 to 2003 he was the President of the International Commission on Polar Meteorology. He is currently the Deputy Secretary General of the International Association of Meteorology and Atmospheric Sciences. He is a member of the Steering Committee of the World Climate Research Programme's Climate and Cryosphere (CliC) project.

Prof. Paul Andrew Mayewski

Paul Andrew Mayewski is Director of the Climate Change Institute at the University of Maine. He has a PhD from the Institute of Polar Studies, Ohio State

University and PhD honoraris from Stockholm University. From 1975-2000 he was Director of the Climate Change Research Center at the Unversity of New Hampshire. He has led more than 40 scientific expeditions to the Antarctic, Arctic, and Himalayas/Tibetan Plateau. From 1987-1997 he served as Chief Scientist for the Greenland Ice Sheet Project Two (GISP2) and since 1989 has been chair of the International Trans Antarctic Scientific Expedition (ITASE) SCAR and IGBP activity. He has published extensively on the causes of climate change, abrupt climate change, and change in the chemistry of the atmosphere and has served on numerous national and international scientific committees.

Dr. Mike Meredith

Mike Meredith is a physical oceanographer with many years experience studying the changing circulation and water mass characteristics around Antarctica, in particular in relation to changing climatic forcing. He is currently a Theme Leader at the Proudman Oceanographic Laboratory, UK, where he leads a project concerned with long-term monitoring of circulation in high latitude regions. He has a BSc in Physics, an MSc in Oceanography, and a PhD in the Physical Oceanography of the Southern Ocean. Upon completing his doctoral research, he worked as a Senior Research Associate at the University of East Anglia before being awarded a prestigious NERC Research Fellowship to study ocean climate variability in the Antarctica. Following this, he worked as a physical oceanographer with the British Antarctic Survey, and then joined POL to lead their high-latitude oceans project.

Dr David Bromwich

David Bromwich is a senior research scientist and director of the Polar Meteorology Group at the Byrd Polar Research Center of Ohio State University. He is also a professor with the Atmospheric Sciences Program of the Department of Geography. Dr. Bromwich's research interests include: the climatic impacts of the Greenland and Antarctic ice sheets; coupled mesoscale-global circulation model simulations; the atmospheric moisture budget of high southern latitudes, Greenland, and the Arctic basin using numerical analyses; and the influence of tropical ocean-atmosphere variability on the polar regions. Dr. Bromwich has served on the National Research Council's Committee on Geophysical and Environmental Data and was previously a U.S. Representative of the Scientific Committee on Antarctic Research. He is a member of the American Meteorological Society, the American Geophysical Union, the Royal Meteorological Society, and the American Association of Geographers. Dr. Bromwich earned his Ph.D. in meteorology from the University of Wisconsin, Madison, in 1979.

The need for SCAR support

SCAR is in an excellent position to take the lead on this work as it is a focus for Antarctic scientists in all the necessary disciplines. Over recent years it has supported a number of activities that AGCS will build upon, including ITASE, ISMASS and READER. It has recently established links with SCOR which will be essential in undertaking the oceanic element of this programme.

Anticipated degree of national and international involvement

A high degree of international cooperation will be essential to carry out this programme. If approved, we will urge national SCAR committees to support this work through national initiatives. The involvement, and close cooperation with SCOR, CliC, CLIVAR and other international programmes with interests in the Antarctic and the Southern Ocean will be critical in the implementation of this programme. The IPY will also be a vital element in undertaking this research through the additional observational data that will become available over this period.

Indicative budget for the first 4 years of the programme

Undertaking a programme of research on this scale will require considerable funding for planning, coordination, discuss of results and liaison with other organisations. However, with the uncertainty over the level of funding that will be available from SCAR, we have presented a range of options below to give an indication of the activities that we would like to carry out if additional funds become available. The items indicated by three asterisks (***) will be carried out if additional funds are found.

Funding requirements for 2005-2008:

2005

- Annual meeting of the AGCS Steering Committee (Five people at $2K each = $10K)
- Development of the ice core data base ($2K)
- Workshop on the variability of the Antarctic climate system ($3K)
- Workshop on historical oceanographic data for the Southern Ocean ($5K)***
- Support for ASPeCT ($5K)*** and ITASE ($5K) ***

2006

- Annual meeting of the AGCS Steering Committee (Five people at $2K each = $10K)
- Development of the ice core data base ($2K)
- Workshop on the representation of the Antarctic and the Southern Ocean in models ($3K)
- Workshop of the origins of signals in ice cores ($5K) ***
- Workshop on Antarctic katabatic winds and their interaction with the ocean environment ($5K) ***
- Support for ASPeCT ($5K)*** and ITASE ($5K) ***

2007

- Annual meeting of the AGCS Steering Committee (Five people at $2K each = $10K)

- Workshop on Southern Ocean water mass variability ($5K)
- Workshop on anthropogenic forcing on the Antarctic climate ($5K) ***
- Workshop on airborne aerosol campaign in the Antarctic ($5K)***
- Support for ASPeCT ($5K)*** and ITASE ($5K) ***

2008

- Annual meeting of the AGCS Steering Committee (Five people at $2K each = $10K)
- Workshop on Antarctic climate prediction ($5K)
- Workshop on tropical-Antarctic climate linkages ($5K)
- Support for ASPeCT ($5K)*** and ITASE ($5K) ***

Evolution and Biodiversity in the Antarctic
Science Plan SCAR 2004

Programme Description

A1. Title: Evolution and Biodiversity in the Antarctic: the response of life to change

A2. Submitted by: Life Sciences Scientific Standing Group (LSSSG)

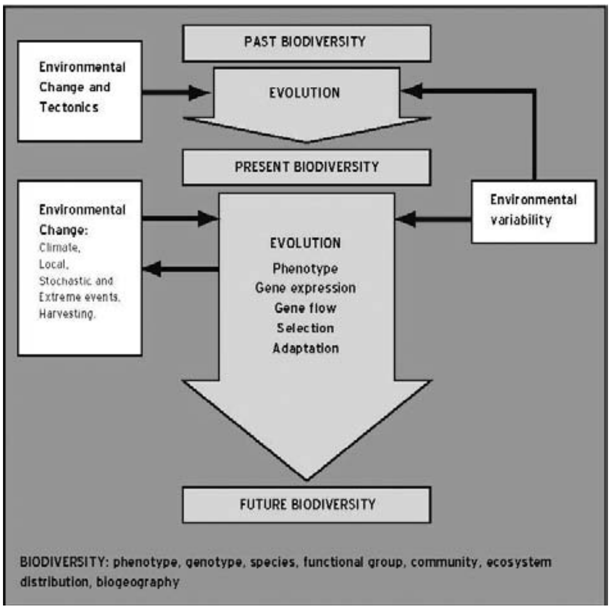
A3. Programme Duration: 8 years, January 1st 2006 – December 31st 2013 Six years of research and meetings and 2 years for synthesis and reporting. Final conference; SCAR Biology Symposium 2013.

A4. Estimated SCAR Funding: Total core programme $120 000 ($15 000/year) Expected total Supplemental Request: $64 000 ($8 000/year)

A5. Programme Executive Summary

This Scientific Research Programme (SRP) entitled Evolution and Biodiversity in the Antarctic (EBA): the response of life to change. EBA will use a suite of modern techniques and an interdisciplinary approach to explore the evolutionary history of selected modern Antarctic biota, examine how modern biological diversity in the Antarctic influences the way present-day ecosystems function, and thereby predict how the biota may respond to future environmental change. For the first time the scientific community will integrate understanding across the major realms of Antarctic biology (marine, terrestrial, freshwater, from molecules to ecosystems) into the cohesive picture that is a prerequisite of Earth System Science. EBA will advance evolutionary and ecological science using model systems and organisms from the Antarctic, facilitating interdisciplinary investigations of systems responses to change. To achieve these goals the broad objectives of this programme are to:

1. 1. Link with geoscientist to establish more clearly the evolutionary history of the Antarctic biota.
2. 2. Compare evolutionary adaptations to the Antarctic environment in a range of organisms and thereby determine general principles.
3. 3. Explore patterns of gene flow within, into and out from the Antarctic, and determine their consequences for population dynamics.
4. 4. Identify patterns and examine diversity of organisms, ecosystems and habitats in the Antarctic, together with the ecological and evolutionary processes that control these.
5. 5. Study the impact of past, current and predicted environmental change on biodiversity and the consequences for Antarctic marine, terrestrial and limnetic ecosystem function.



B. Proposed Details Programme Plan to date:

The biological community has held six meetings and produced two reports associated with the planning of this SRP:

Meeting 1: Shanghai China, July 2002
Meeting 2: Pontignano Italy
Meeting 3: Cambridge UK January 2003
Meeting 4: Varese Italy July 2003
Meeting 5: Eindhoven April 2004
Meeting 6: Paimpont July 2004
Meeting 7: Bremen July 2004

B 1. Objectives

The overall aim of the EBA programme is to understand the evolution and diversity of life in the Antarctic, to determine how these have influenced the properties and dynamics of present Antarctic and Southern Ocean ecosystems, and to make predictions on how organisms and communities will respond to current and future environmental change.

This programme involves an explicit integration of work on marine, terrestrial and limnetic ecosystems in a manner never before attempted. The science in this programme thus extends over an entire biome on Earth. By comparing the outcome of parallel evolutionary processes over the range of Antarctic environments, fundamental insights can be obtained into evolution and the ways in which life responds to change, from the molecular to the whole organism level and ultimately to biome level. The scientific and political environment of Antarctica offers a unique opportunity to address these globally significant scientific questions in the context of an interdisciplinary approach that is essential for understanding the structure and functioning of the Earth System. Most national programmes individually cannot attempt a study on such a bold scale, whereas the collaborative spirit of the Antarctic science community will provide a mechanism for achieving outstanding scientific success. Specific details and rationale of each of the objectives listed in the Executive Summary are provided below.

B 2. Scientific background and rationale (and details of objectives)

Nothing in biology makes sense except in the light of evolution. *Theodosius Dobzhansky, American Biology Teacher, 35: 125-129 (1973)*

Evolution is the most fundamental principle of biology, influencing all levels of biological organisation from molecules to ecosystems. It is best studied where its impact can be seen without interference from confounding factors. Evolutionary theory itself developed from insights gained in isolated, island systems, most notably Darwin's experiences in the Galapagos Islands and Wallace's travels through the Indo-West Pacific archipelago. Isolation is also a feature which makes the Antarctic an important natural laboratory for evolutionary work. The extreme nature of the physical environment allows us to probe evolutionary adaptation in rare detail. Important Antarctic discoveries such as the biosynthesis and evolution of antifreeze compounds in fish and terrestrial and limnetic invertebrates are now part of standard textbooks 1. The Antarctic is also an important laboratory because we know so much about the tectonic and climatic history that provides the context for evolution 2,3,4. Finally, the combination of isolation and climate change has lead to a biota rich in endemic taxa, and to a strong contrast between marine and terrestrial and limnetic realms, from apparently simple ecosystems on land to highly diverse marine benthic systems on the continental shelves 5,6 and in the Southern Ocean deep sea 7,8. An important feature of the EBA science programme is to seek an understanding of the reasons behind these striking differences in one of Earth's major biomes.

The western side of the Antarctic Peninsula is currently subject to one of the fastest rates of regional climate change on the planet. Climate change is having impacts on both marine, and terrestrial, and limnetic systems, and hence will influence future biological diversity. Our current understanding is that many Antarctic species are susceptible to this change 9 with those of the marine environment being particularly vulnerable 10. The critical examination of Antarctic ecosystems undergoing change allows EBA to provide a major contribution to the understanding of evolutionary processes that are of relevance to all life on Earth.

The history of the Antarctic biota

Over geological time environmental conditions and habitats in the Antarctic have changed dramatically. The fossil record, stretching back over 500 million years provides a broad outline of evolutionary history of the continent and its biota. Fossil evidence of Antarctic forests in the Cretaceous and Palaeogene poses interesting questions as to what adaptations in plants and animals evolved to cope with seasonal winter darkness, and the short summer season with continuous light.

After separation of the southern continents from Antarctica during the Cretaceous and Tertiary the earliest cold water marine faunas emerged some 35 million years ago. Since then, the shallow water marine fauna around Antarctica has been subjected to a steady decrease in seawater temperature, and an increasing influence of sea-ice. Conditions on land since the isolation of the Antarctic have fluctuated between cold and warm periods, but superimposed by an overall cooling since the Mesozoic, and terrestrial and limnetic biota, ice-cover and land availability have changed accordingly. However, some small areas of habitat now supporting terrestrial and limnetic biotas have been continuously available for periods of time ranging from the several million to only a few thousand years.

The study of biotic history is thus linked intimately to tectonic, climatic and palaeobiological studies and to biogeographic comparisons with other fragments of Gondwana. Critical to this work will therefore be research on land, freshwater, marine continental shelf and deep seas because all these environments are integral to the history of life since the break-up of Gondwana. Moreover, strong integration with other science programmes investigating climate and tectonic history are an essential feature of the work because intimate feedback between the living and abiotic environments have modulated both.

On shorter time-scales, the Antarctic biota has also experienced cycles of global environmental change driven by periodic glaciations, on which recent anthropogenic global warming and increased UV radiation resulting from ozone depletion have been superimposed 9. Regional scale and short-term climatic variations appear to have been more frequent and intense in recent years. Environmental change can affect every aspect of an organism's biology, from cellular physiology and biochemistry to population dynamics and food-web dynamics 11, 12. All organisms are susceptible to environmental change, but small and non-motile organisms are particularly vulnerable. Such organisms must alter their physiology and biochemistry to cope with environmental change. These responses may be a consequence either of genotypic (genetic) change or phenotypic (physiological) plasticity or both, with the time-scale of the former generally being longer 13.

B 2.1. What is the evolutionary history of Antarctic organisms?

How have past changes shaped modern biological diversity? Previous palaeobiological work in the Antarctic and other fragments of Gondwana has established many of the broad features of the evolutionary history of the Antarctic biota. For example, in the marine realm we now know that a shallow-water fauna has existed throughout its history. Palaeobiologists have established the broad history of cool-temperature and cold marine biotas that have evolved in a mid to high latitude setting. These faunas have typically been of lower diversity than contemporary faunas at lower latitudes 14. This poses the fundamental question, still unresolved, as to whether evolutionary processes differ between warmer and colder habitats (for example whether speciation or extinction rates might be higher in tropical or polar regions) 15,16.

The high diversity of the marine continental shelf fauna of Antarctica 17,18 has been variously explained in terms of a relatively homogenous physical environment, periodic disturbance by icebergs and the glacial history19. In particular periodic extensions of the Antarctic icesheet as far as the continental shelf edge will have fragmented the habitat and also driven many species down the continental slope. This is a classic mechanism for driving speciation and this so-called climate diversity pump, a variation of standard vicariance speciation models, has probably been a major evolutionary driver in the history of the Antarctic biota. Fluctuations in the size of the Antarctic icesheet are driven by orbital (Milankovitch) variability, first documented in Antarctica in the Eocene, and have continued through the Pleistocene to the present day.

The periodic extensions and contractions of the icesheet will have influenced speciation processes by limiting gene flow between isolated populations. Recently powerful insights into the evolutionary history of the Antarctic biota have been gained from modern molecular techniques. These have allowed divergence times between taxa to be dated, radiations such as those of the notothenioid fishes 20 to be related to climatic or tectonic events, and have also revealed a number of cryptic species hinting at a vast reservoir of undetected diversity (see 21,22). It is clear that the rapidly developing suite of molecular techniques offer enormous potential for potent insights into the evolutionary history of the Antarctic biota. Combining these approaches with our increasingly detailed understanding of the tectonic, climatic and glacial evolution of Gondwana offers a uniquely powerful opportunity to advance our understanding of how evolutionary processes are related to the physical setting.

The EBA programme cannot of itself undertake work on the tectonic, climatic or glacial history of the Antarctic. For this we must rely on other work both within and outside SCAR and cross-disciplinary meetings will thus be important for transfer of ideas and information. Molecular analyses of the Antarctic biota will, however, form a key component of the EBA programme. Key scientific areas will include:

1. 1. Cryptic species: to what extent may we have underestimated the diversity of the Antarctic biota?
2. 2. Radiations: when did the key radiations of the Antarctic taxa take place?
3. 3. Impact of glaciation: what are the evolutionary links between continental shelf and slope or deep-sea species?
4. 4. Phylogeography: how is the Antarctic biota geographically structured and related to that elsewhere?

B 2.2. Evolutionary adaptation to the Antarctic environment

The Antarctic is an extreme environment, both on land and in the sea. Studies of organisms living at extremes have been, and are central to developing our understanding of how life adapts to its environment, and work on Antarctic organisms has made a distinguished contribution to this work.

Two areas will form the basis of EBA work on evolutionary adaptation: organismal level ecophysiology and molecular studies (genomics and proteomics). Ecophysiology (including reproductive biology) has a long and proud history within SCAR biology, across marine and terrestrial and limnetic biomes. This work has been instrumental in developing our fundamental understanding of how organisms cope with environmental challenges on both long (evolutionary) and the shorter time scales relevant to understanding the impacts of climate change (see 23, 11). Ecophysiology will therefore continue as a major theme in the EBA programme, but strengthened by the insights and understanding to be gained from molecular techniques.

Important in this work are the very different environmental challenges set by marine and terrestrial and limnetic habitats in the Antarctic. In the marine realm the challenge is for organisms to function at the lowest seawater temperature on earth, but where seasonal variations are small (see 24). Similarly on islands close to the Antarctic Polar Frontal Zone air temperatures are extremely equable. In contrast on continental Antarctica, terrestrial and limnetic organisms must face enormous daily fluctuations in temperature, very low winter minima, extensive periods of freeze/thaw and long periods of low water availability 25. Another important ecological factor shaping Antarctic ecosystems is the marked seasonality in ice and snow cover, light regime and thus primary production. This resource limitation, especially at the lower trophic levels, has a strong impact on life cycle strategies and ecophysiological adaptations. Ecophysiological studies will be important in defining the limits to organism performance, trade-offs in reproductive and physiological activity, the energetic costs of coping with environmental challenges, and the consequences of these for population dynamics 26. Molecular studies will be important for elucidating the mechanisms underpinning the organismal level response, and the genetic mechanisms behind these

This combination is critical as neither ecophysiology nor molecular studies in isolation can provide a complete picture of evolutionary adaptation. The Antarctic biology community is unusual in having strong teams in both disciplines.

Key scientific areas to be investigated include:

1. 1. Limits to organism performance: to what extent does adaptation to the Antarctic environment constrain physiological performance?
2. 2. What are the physiological and genomic adaptations that allow organisms to survive in the Antarctic? Are these special to the Antarctic or simply variants of more general adaptations exhibited by organisms elsewhere?
3. 3. How well are Antarctic organisms able to cope with daily, seasonal and longer-term environmental changes?

B 2.3. Patterns of geneflow within, into and out of the Antarctic, and consequences for population dynamics

Isolation has been and remains a major factor in the evolution of Antarctic organisms. The Antarctic is isolated from the rest of the globe by the deep oceans separating it from other continents and by circulation patterns in the atmosphere and oceans. There are also barriers between populations within the Antarctic, in both terrestrial and limnetic and in marine environments. In the terrestrial and limnetic realms these barriers include ice sheets and oceans between land oases, and also atmospheric circulation patterns. In the marine environment barriers include deep water trenches between continental shelves, and isolating mechanisms such as oceanographic fronts and gyres.

This element of the EBA programme seeks to understand the extent of isolation of populations of Antarctic organisms both between the Antarctic and elsewhere and between populations within the Antarctic. In isolated populations evolution occurs through three major processes: genetic drift, mutation and natural selection. Gene flow between populations interrupts within-population evolutionary processes by diluting the effects of the above processes (review in 28). Theoretically gene flow can be active e.g. migration, or passive e.g. transport of propagules, through processes such as ocean currents, on birds and wind 29. Propagules are also transported by humans.

Understanding gene flow and associated population processes provides valuable insight into both fundamental and applied aspects of evolutionary biology in the Antarctic and within the biosphere. Antarctic ecosystems are experiencing increasing rates of environmental change driven mainly by global climate change, and also through major extraction industries both past and present (sealing, whaling and fisheries). It is of fundamental importance to global conservation and management strategies to understand the impact that this environmental change has on gene flow and hence the evolutionary control of the diversity of living organisms.

A key question in Antarctic biology is whether climate change will result in either relaxation of selection pressure on genomes, or tighter constraints and ultimately extinction of populations and species. With regard to sustainable fisheries management it is essential to understand population and stock structure and the extent of exchange of genetic information via transfer of individuals or propagules between populations. It is not understood for instance the extent to which the Antarctic krill population is structured, and this is a serious limitation to management of the fishery. Studies in this area will provide valuable information for CCAMLR management activities.

To determine patterns of gene flow requires the use of molecular techniques with the target molecules (proteins or DNA) and analytical protocol dependent upon the question being asked. Field samples of the organism need to be collected over suitable spatial and temporal scales, and returned to a laboratory, either in the Antarctic or outside, for molecular analysis. For interpretation these data need to be combined with studies of life history, population dynamics and dispersal. Collaboration with modellers and those working on oceanic and atmospheric dynamics will also be integral to success.

Key scientific areas to be tackled by this objective of the EBA programme include:

1. 1. Baseline population structure: how are populations of Antarctic organisms structured, what are their dynamics, and how do these differ from organisms elsewhere?
2. 2. Dispersal: how are organisms being transported to, within and out from the Antarctic? This will include examining the role of humans as vectors.
3. 3. Genetic structure of populations: is the genetic structure of populations of Antarctic organisms different from those elsewhere, and to what extent do these population structures reflect past evolutionary history?
4. 4. To what extent do populations of Antarctic organisms exist as a metapopulation?
5. 5. What is the role of advective processes in the gene flow and population structure of Southern Ocean organisms?

B 2.4. Patterns and diversity of organisms, ecosystems and habitats in the Antarctic, and controlling processes.

What is the present biodiversity in the Antarctic?

Present patterns of biodiversity and distribution are a consequence of factors and processes working on both evolutionary and ecological timescales 32, 33. In the

Antarctic there are a great many ecosystems, from highly complex suspension feeder communities to the strongly impoverished shallow water communities in the sea, and from the rich coastal areas of the subantarctic region to the very simple flora in the nunataks of the high Antarctic plains in the terrestrial and limnetic environment. However within this variety there are significant gradients that can be recognised, such as latitudinal, altitudinal, and depth.

Patterns of biological diversity are greatly different between land and sea in the Antarctic 5. In the marine realm the concept of the bell-shaped distribution of biodiversity with its peak in the tropics and low values at the poles has been shown to be an oversimplification 34. We now recognize that patterns of biodiversity in the Southern Hemisphere oceans are very different from those in the North, and the continental shelves of the Southern Ocean in particular have been shown to support a remarkably diverse fauna. This fundamental revision of our view of global patterns of marine diversity has been a result, almost exclusively from the work of SCAR marine ecologists. Of particular importance has been the recognition of taxa whose diversity decreases away from the Antarctic 35; for example some groups of amphipods 36, isopods 37 and pycnogonids (sea spiders)18.

In strong contrast terrestrial communities are relatively impoverished, partly the result of eradication of almost all biota at previous glacial maxima although recent work (including molecular diversity studies) has importantly, identified long-term refugia 38. Most terrestrial assemblages decrease sharply in diversity with latitude, for example in the insect order Diptera (true flies) has many representatives on the sub-Antarctic islands but only one species reaches high latitudes 25.

In marine, terrestrial, as well as limnetic systems some groups are very poorly represented, or even absent altogether. Examples on land include reptiles, amphibians, some insect groups and almost all higher plants. Examples in the sea include reptant decapods, stomatopods and many groups of fish. In contrast some marine groups are markedly species rich, examples including amphipods, isopods, polychaetes and pycnogonids. On land, even the most dominant groups are represented by relatively few species. In both realms a remarkably high proportion of taxa are endemic, reflecting a long period of evolutionary history in relative isolation (e.g. 38, 18).

Although most Antarctic biotic communities are recognisably related to those elsewhere, a few specific communities are unique to the Antarctic. Among these are the under-ice communities 39 and the epifaunal communities in the high Antarctic 40. The total lack of macroalgae in regions off the large ice shelves in the high Antarctic Weddell Sea contrasts with the rich macroalgae communities in the subantarctic regions 41, 42. Typical elements of the Southern Ocean system also include the marine top predators such as seals and penguins, with few species but playing a dominant role in the ecosystem 43. In the terrestrial and limnetic ecosystems the diversified vegetation of the subantarctic islands is replaced by moss and lichen communities in coastal maritime and continental Antarctica, and by endolithic communities in the high Antarctic. The terrestrial and limnetic fauna is characterised by the dominance of decomposers while herbivores and predators are few in the native fauna 44.

Although studies of biological diversity typically concentrate on species richness, other aspects of diversity are important. These include variety of life forms, trophic guilds and life histories. In the marine realm considerable progress has been made in these areas during the EASIZ programme elucidating, for example trophic diversity in amphipods and fish, and a range of population dynamics in fish and invertebrates. On land the RiSCC programme has elucidated the diversity of morphology and life history in both plants and invertebrates. Together these studies have overturned previous conceptions that the Antarctic environment only allowed the existence of a limited range of strategies; rather it is now clear that a great many strategies are possible and this contributes to the distinctive biological diversity of the Antarctic.

Work to date has concentrated in certain geographical areas, such as the Weddell and Ross Seas, or the Antarctic Peninsula for marine work, and sub-Antarctic islands, the maritime Antarctic and the McMurdo Dry Valleys for terrestrial and limnetic work. Many important areas and habitats remain almost completely unexplored, such as the Amundsen and Bellingshausen seas and many areas of the east Antarctic, including continental nunataks and some ice-free oasis on land. These almost completely unknown areas merit special attention in the EBA programme. Embedded in this objective is the Circum-Antarctic Census of Marine Life (CircAntCML) that will occur during the IPY.

Key scientific areas to be tackled in the EBA programme will include:

1. 1. Spatial and temporal variations in diversity: how does diversity vary from area to area within the Antarctic and within defined time frames? Current knowledge suggests that important comparisons, both on land and in the sea, will be the Antarctic Peninsula versus the high (or continental) Antarctic, and East Antarctica versus West Antarctica. Time-frames would include seasonal to interannual examination of selected sites.
2. 2. Latitudinal or environmental gradients: how does marine, and terrestrial, and limnetic diversity vary along gradients? Important areas to study here will be the Antarctic Peninsula and Victoria Land. Comparison with the Magellan area will be critical to this work.
3. 3. Evolutionary radiations: how recent are the key evolutionary radiations in the Antarctic?
4. 4. Unknown areas: what is the pattern of diversity and assemblage faunal composition in unexplored but important areas such as the deep-sea and inland nunataks and isolated islands?

5\. 5. Relations with elsewhere: how does diversity in key Antarctic groups compare with other Southern Hemisphere landmasses and oceanic islands?

B 2. 5. What is the impact of past, current and predicted future environmental change on biodiversity, and the consequences for Antarctic marine, and terrestrial and limnetic ecosystem function?

The principal physical factors, tectonic and climatic, influencing the evolution of the Antarctic biota have already been discussed, as have the consequences for present day diversity and evolutionary adaptation.

a). How are environmental changes driving evolution now?

Among the ecological factors controlling distribution patterns and biodiversity of the modern Antarctic biota, the most important are temperature, water availability in the terrestrial and limnetic ecosystem 25 , and ice cover, oxygen, light, UVB and wind in the marine systems 43. These factors are not constant, and all of them vary over a range of temporal scales from less than daily, through seasonal to interannual. The past two decades have seen a revolution in our view of variability in Antarctic systems, with the recognition that interannual variability is of fundamental importance to the dynamics of Antarctic ecosystems. Particularly important are subdecadal variations associated with ENSO, the Antarctic Oscillation and the circum-Antarctic progression of atmospheric and oceanographic variability manifest as the Antarctic Circumpolar Wave 45. Variability on this scale is important because it is of the same order as population dynamics and hence Antarctic organisms have been selected to cope with good and bad seasons within their lifespan. The system may, however, be disrupted if the pattern of environmental variability changes (for example through a change in the relative frequency of good and bad years, or of the extreme values).

Studies of sediment cores have also revealed variability on longer time scales, typically hundreds of years. It is possible that the Antarctic environment varies on timescales even longer, merging into that driven by Milankovitch orbital variability. These huge ranges of temporal scales of variability set a significant challenge to ecologists attempting to determine the effects of long-term secular environmental change. These difficulties are exacerbated by the way in which a combination of biotic properties and abiotic factors control processes which shape diversity and distribution patterns. For example, increased iceberg calving may lead to heavy iceberg scour of continental shelves all around the Antarctic which would result in temporal extinction of communities and generates processes of recolonisation and succession, which would produce distinct diversity patterns 46. In accordance with ecological theory (the intermediate disturbance hypothesis) this disturbance has been shown in the Antarctic to increase diversity on a regional scale 47. Life histories and dispersal capacity also greatly influence the colonisation abilities both in marine and terrestrial systems 25. The study of these processes is currently providing important information on the resistance and recoverability of Antarctic communities under present environmental conditions 17. The challenge now is to determine how changes to the physical drivers will effect the ecology of the Antarctic system.

b). The future

The most important anthropogenic changes currently affecting the Antarctic are accelerated global warming and increased levels of UVB, with further threats from fishing, and the introduction of alien species 47. In contrast to these widespread phenomena, pollution, and visitor pressure are causing only local effects on Antarctic diversity. Many of these changes have complex and interacting effects. For example an impact on the lowest or highest level in a food web can propagate through to affect other taxa indirectly. Thus UV impact on primary producers may affect consumers, and the removal of great whales has resulted in a very different trophic structure in the Southern Ocean. The recent explosive increase in the population of the Antarctic fur seal has led to extensive damage to vegetation and soil erosion.

The EBA programme will provide SCAR and the international scientific community with the best estimate possible of the possible consequences for the Antarctic of continued environmental change.

Key scientific areas to be tackled in the EBA programme will include:

1\. 1. What are the likely outcomes of interactions between introduced and indigenous species in selected environments given a climate of environmental change?

2\. 2. The nature of and extent to which interactions between changing abiotic conditions (temperature, UVB, water availability) change biotic responses (through synergy or interference) relative to single variable effects.

3\. 3. Modelling of interactions between environmental change and organism responses to facilitate predictions of change in the Antarctic biota.

4\. 4. Application of research findings for the development of conservation policy in the region in the face of changing environments and patterns of human use.

B 2.6. Integrating the study

The five main broad objectives outlined above are each clearly focused on a specific area of science. Each objective will provide useful outcomes however further value will arise from the connectivity between objectives. Furthermore, an explicit aspect of the EBA programme is to compare and where possible integrate results from the marine, terrestrial, and limnetic environments. This is a new venture for SCAR, for previous biology programme have always confined themselves to either the oceanic (BIOMASS, EASIZ, EVOLANTA [primarily]) or terrestrial and limnetic (BIOTAS, RiSCC) realms. Although land and sea are very different in terms of the relationship between physical forcing and biological response, there are important insights to be gained by intelligent comparisons. The differences, are of course, even more marked in the Antarctic than elsewhere because of the very different glacial history of the two realms.

The EBA programme is explicitly interdisciplinary in that it brings together a wide range of biological disciplines to tackle a series of sharply focused questions. These disciplines include molecular biology, taxonomy, biogeography, autecology, cellular and organismal-level ecophysiology, and community ecology. However many of the subjects to be tackled by the EBA programme will also require collaboration with other scientists, including palaeobiologists, oceanographers, geophysicists, glaciologists and modellers. This makes the EBA programme multidisciplinary to an extent that has only rarely, if ever, been achieved in SCAR to date. This multidisciplinary approach will allow the EBA programme to tackle a series of important science areas, including:

1. 1. Links between tectonics, climate evolution, glacial processes and evolution. In particular, we plan to continue to refine our understanding of how the present biota evolved, and why current patterns of biological diversity are what they are. For example, palaeobiological data can be used to assess the age of Antarctic habitats and species. These results can then be combined with molecular estimates of divergence time to provide a powerful two-pronged approach to understand Antarctic biotic evolution (as was used very successfully to determine the history of the notothenioid radiation by the ESF funded Network on the Biology of Antarctic Fishes). Palaeobiological data can also determine the nature and origin of latitudinal diversity gradients. Essential to this will be the interactions with SCAR's ACE and AGCS programmes.
2. 2. Links between the physical environment and gene flow. Models of oceanic and atmospheric circulation can be used to predict transport of propagules into (and out from) the Antarctic. Such models can also be used to elucidate advective processes in the Southern Ocean and their impact on gene flow and population dynamics. In the marine realm we will seek interactions with scientists working with the CCAMLR framework to inhance progress on his topic.
3. 3. EBA will have strong links with the SALE programme. The biological component of SALE and the EBA objectives are strongly compatible.
4. 4. Links with northern polar studies. Comparison of southern with northern polar processes can elucidate the significant evolutionary pressures and provide insight into gene selection.

B 3. Programme Rationale/ Justification

The largest challenge facing humankind is the management of the Earth System to ensure a sustainable human future. To this end, understanding of the functioning of the Earth System in the context of both natural and anthropogenic change is essential. The Antarctic, the Southern Ocean, and their biota are an instrumental part of the Earth System, not only influencing the pace and nature of environmental change, but also responding to it in an integrated system of biologically modulated teleconnections.

An important part of managing for a sustainable human future must include a thorough and profound knowledge of the way in which life has both evolved and the ways in which it is likely to change. Such knowledge can only be obtained by an integrated, interdisciplinary investigation of the structure and functioning of living systems. The Antarctic offers an immensely valuable regionally focussed approach to harness a wide range of international resources, both physical and intellectual. Its ecosystems offer examples of how both structure and function has evolved, and the likely responses of such species and ecosystems to change induced by a wide variety of both natural and anthropogenic processes, as well as the ways in which their responses feed back to influence these processes. In consequence, a programme that integrates research across a wide variety of fields, from functional genomics and molecular systematics, to ecosystem science and modelling, and which draws on and contributes information to a wide rage of related fields, such as climate modelling and tectonics, is required. The SCAR Evolution and Biodiversity in the Antarctic is just such a programme. Its major intention is to provide a platform for the kinds of interactions amongst disciplines and researchers that are essential to understand the evolution within, and responses and contributions of biodiversity to the earth system. In so doing, it will fill a major void in understanding of the role of biodiversity in the Earth System by providing the Antarctic context. No other programme has this as its major goal, nor has the human resources, expertise, and capability of doing so. As such, it is the premier route of contributing a major part of the information required to comprehend the functioning of the Earth System, which will enhance our ability to achieve a sustainable future for all life.

The programme is particularly opportune. Never before has there been such global interest in understanding the full complexity of the Earth System and its responses to change. The tools for comprehending interactions between organisms and their environments are also advanced to the stage where obtaining and managing information from the functional genomic to broad-scale spatial levels are reasonable straightforward, allowing integration of information across all levels in the ecological and genealogical hierarchies. Several international programmes, both within and outside SCAR have also laid the groundwork for the kinds of novel, interdisciplinary science being proposed here, and an equivalent number of proposed or recently initiated programmes will add considerable value to it. These include programmes such as Diversitas, Census of Marine Life, IMBER, CliC, EPICA, and many others that can provide the background to and information required for full integration of the work proposed here. This programme is also timely given increasing concerns expressed by the Antarctic Treaty System regarding the likely responses of Antarctic environments to natural and anthropogenic disturbances at a range of scales, and the request for information regarding ways in which these responses can be distinguished and mitigated to ensure long-term conservation of Antarctic environments and their biodiversity. Finally, by contributing a time-limited, burst of activity, that will leave a legacy of spatially explicit biodiversity information and tools for its exploration, the programme is in an excellent position to contribute to and raise the profile of Antarctic science in the context of the proposed International Polar Year.

B 4. Methodology and Implementation plan

B 4.1. Implementation

The structure of this programme will be based around a series of five major unifying key questions that are addressed across the realms of terrestrial, limnetic and marine environments. The programme will operate along the lines of a matrix of the key questions vs selected environments. A major marine focus will occur during the IPY. Each year the programme will run a series of workshops. There will be three types of workshops: a) defined themes, fostering cross-discipline interaction including joint workshops with the other SCAR programs, particularly ACE and AGCS; b) discipline based; c) environmental based. The workshop timetable will be defined at the EBA workshop during the SCAR Biology Symposium in Curitiba in 2005.

Additional to the workshops will be national and international field programmes. Such programs will be wide ranging, including subantarctic islands, inland to the most remote nunataks as well as northward to the Magallanes, and stretching across the Southern Ocean down to the deep ocean as well as the shelves. This wide range will need significant support from COMNAP and national programs. Already many nations have pledge support for the Census of Antarctic Marine Life (CAML) and co-ordination and securing of funds for this detailed study has already begun.

B 4.2. Timeline

- 2004: Delegates approve of EBA
- 2005: Planning phase including a) Planning meeting in Cambridge in March to draft an implimentation plan; b) SCAR Biology Symposium Theme – Evolution and Biodiversity in the Antarctic; c) International workshop on EBA where objective sub-committees will be appointed and specific milestone detailed; d) detailed planning of workshop structure and themes; e) IPY advanced planning, database construction and integration
- Year 1: 2006 Start of programme and continuation of workshops (one interdisciplinary with SCAR29). Participation in the Northern Hemisphere RiSCC major expedition
- Years 2 & 3: 2007-09 Major, time-limited push for Census of Antarctic Marine Life (CAML), IPY activities and workshops
- Year 4: 2009 First reporting of findings at the SCAR Biology symposium
- Year 5: 2010 Ongoing marine and terrestrial work, SCAR 31 interdisciplinary and other workshops
- Year 6: Last year of field work, with workshops including syntheses of marine/terrestrial system findings
- Year 7 & 8: Reporting years. Final reporting at SCAR Biology Symposium, 2013

B 4.3. Methodology

The EBA programme is wide-ranging and multidisciplinary. Because of this, and space constraints, it is not feasible to list specific methodologies in detail. However a few general points are worth emphasising.

1. 1. The programme will utilise state-of-the-art enabling technologies in molecular biology, ecophysiology, microbiology, taxonomy and organismal biology all of which are established and proven at the highest level in various national groups contributing to the EBA community.
2. 2. The programme will liaise with the relevant physical, geological and historical disciplines to ensure regular interaction and use of the most recent data and insights in interpreting the biological results.
3. 3. The programme will necessarily involve fieldwork and laboratory work, both in the Antarctic and in home institutions. In particular, the study of latitudinal gradients requires extensive international collaboration (as was achieved for the recent Victoria Land Transect study, which involved close collaboration between scientists from New Zealand, Italy and the USA, the IBMANT collaboration between European and Latin American countries on evolutionary connections between the Antarctic and South America, and ICEFISH 2004 a sub-Antarctic cruise with scientists from eight countries).
4. 4. Exploration of some areas will require new technologies (for example benthic landers or remotely operated vehicles for the deep-sea, autonomous underwater vehicles for work beneath ice shelves). Remote-controlled small aircraft for spectral sensing of terrestrial and limnetic environments.
5. 5. Importance will be attached to issues pertaining spatial and temporal scales in studies of gene flow, population dynamics, disturbance ecology and biological diversity.

B 4.4 Relationship with IPY

The International Polar Year activities will overlap with the timing of the EBA programme. Although the EBA and IPY activities were conceived in parallel, the IPY Initial Outline Science Plan (April 2004) indicates that the EBA will be able to make a significant contribution to IPY activities. By undertaking a time-limited, focussed initiative elucidating the spatial distribution of marine and terrestrial diversity, the EBA will leave a legacy of biodiversity information and the tools with which to explore it that is a hallmark of an IPY programme. Specifically the EBA will be in a position to contribute substantially to IPY Themes 1b, 2a-e, 4a-b, though with the major focus on 4b.

B 5. Programme management and governance

The EBA programme will be managed by a small Scientific Programme Group. This group will be selected to include expertise in a range of habitats, organisms and scientific disciplines. The SPG will work by electronic mail but will also meet once a year. An important aspect will be liaison with other scientific disciplines. This will be achieved by a series of multidisplinary workshops focused on specific topics. SIx steering groups will be formed to support each of the objectives as well as the Census of Antarctic Marine Life. EBA will schedule workshops to monitor the progress of the programme in an effective and democratic fashion.

We will work closely with JCADM with regard to data management and will rely heavily on marine data being integrated into MarBIN and terrestrial data integrated into the RiSCC Biodiversity database as well as relevant data centres and databases.

B 6. Deliverables

The main output from the EBA programme will be a significant step forward in our understanding of the Antarctic biota and its evolution. We anticipate that there will also be important contributions to fundamental understanding in a number of disciplines.

Specific output will include the following:

- Primary literature publications
- Conference proceedings (These would be particularly valuable where the symposium tackles a multidisciplinary theme in a focused manner)
- Input to databases (national/international e.g. GenBank, OBIS, GBIF)
- Advisory reports to ATCM and its instruments CEP, CCAMLR, COMNAP
- Input to, and feedback from international programmes (IPY, CoML, CAML, ACE, AGGS, APIS, CLIVAR, SO-GLOBEC, CLiC, ANDEEP, IBMANT, CPR, LGP, ICEFISH)
- Interactions with other SCAR programmes (ACE, AGCS, SALE)
- Trained PhD graduates
- Capacity development of students from developing Antarctic nations
- Outreach via National Programmes and in coordination with proposed SCAR Outreach Committee

B 7. Biennial milestones

- Programme Reports (detailing deliverables and success factors) and publications from workshops
- Four yearly SCAR biology conference proceedings

B 8. Success factors

The main success factor will be a significant improvement of our understanding of the Antarctic and its place in the Earth system. More specific items would include:

- Number of completed post-graduate degrees associated with the programme
- Number of papers citing EBA
- Citation profile indicating value of EBA science to the global science community
- The number of national programmes involved in EBA
- The number of scientists working in EBA

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C. Supporting Information

C 1. Special Programme Group

Dana Bergstrom (Australia, terrestrial) Angelika Brandt (Germany, Marine) Guido di Prisco (Italy, marine) Ad Huiskes (Netherlands, CO LSSSG)

C 2. SCAR Role

SCAR is the major organization coordinating research in the Antarctic and Southern Ocean region. With SCAR's support the EBA will facilitate a level of interdisciplinary interaction, in support of the integrated approach required for understanding the earth system, that will not be possible without the extensive network of representation that is SCAR, both in terms of its members and links to other organizations. Moreover, by feeding information back through SCAR, the EBA will enhance SCAR's ability to address key issues raised within the Antarctic Treaty System.

Furthermore SCAR and particularly the new SCAR platform of open science meetings will provide an opportunity for us to inform non- biological disciplines and of the ultimate necessity of the programme and their essential contribution towards understanding the impact of climate change on Antarctic ecosystems

C 3. National and International Involvement

It is anticipated that the majority of the SCAR nations will participate in this programme, that it will act as a major route for capacity building in new SCAR members and those with a comparatively reduced logistic and financial resource base, and that it will contribute to a wide variety of international programme, including potentially programme of the IGBP, WCRP, IPY, and other such as Diversitas, Census of Marine Life, and GBIF.

C 4. Indicative budget

2005

Item	**Amount**
EBA Manual	1,000
Terrestrial Database	9,000
MarBIN	5,000
Workshops	5,000
EBA-CAML Office	2,000
Total	**22,000**

2006

Item	**Amount**
SPG Meeting	5,000
Terrestrial Database	2,000
MarBIN	5,000
Workshops	10,000
EBA-CAML Office	2,000
Total	**24,000**

2007

Item	**Amount**
SPG Meeting	5,000
Terrestrial Database	1,000
MarBIN	5,000
Workshops	10,000
EBA-CAML Office	2,000
Total	**23,000**

2008

Item	**Amount**
SPG Meeting	5,000
Terrestrial Database	2,000
MarBIN	5,000
Workshops	10,000
EBA-CAML Office	2,000
Total	**24,000**

Annex 1

Acronyms

ACE - Antarctic Climate Evolution – an international research programme studying the climate and glacial history of Antarctica (SCAR programme)

AGGCS - Antarctica and the Global Cliamte System (SCAR programme)

ANDEEP- Antarctic benthic deep-sea biodiversity International Programme

APIS - Antarctic Pack Ice Seals Programme (SCAR programme)

ATCM - Antarctic Treaty Consultative Meeting

BIOMASS - Biological Investigations of Marine Systems and Stocks programme (past SCAR programme)

BIOTAS - Biological Investigations of Terrestrial Antarctic Systems (past SCAR programme)

CAML - Census for Antarctic Marine Life

CCAMLR - Committee for the Conservation of Antarctic Marine Living Resources

CEP - Committee for Environmental Protection

CLiC - Climate and Cryosphere Project – part of the World Climate Programme

CLIVAR –International research programme of climate variability and predictability climate change.

CoML - Census of Marine Life

COMNAP - Council of Managers of National Antarctic Programs

CPR- Continuous Plankton Recorder Programme Diversitas - an international programme of biodiversity science

EASIZ - Ecology of the Antarctic Sea Ice Zone (SCAR WG Biology) or Coastal-Shelf Easiz Programme on Sea-Ice

Ecology (recent SCAR programme)

EPICA - European Project for Ice Coring in Antarctica

EVOLANTA - Evolutionary Biology of Antarctic Organisms (recent SCAR programme)

GBIF - The Global Biodiversity Information Facility GenBank (R)- is a nucleic acid database produced by the National Institute of Health USA

IBMANT - Interactions Between the Magellan Region and the Antarctic – International Programme

ICEFISH 2004 – International Collaborative Expedition to collect and study Fish Indigenous to sub-Antarctic Habitats

IMBER - Integrated Marine Biogeochemistry and Ecosystem Research Project

IPY- International Polar Year

LGP- Latitudinal Gradient Programme – New Zealand based programme around the Ross Sea

OBIS - The Ocean Biogeographic Information System

RiSCC - Regional Sensitivity to Climate Change in Antarctic Terrestrial Ecosystems (recent SCAR programme)

SALE - Subglacial Antarctic Lake Exploration Project

SO-GLOBEC - Southern Ocean Global Ocean Ecosystem Dynamics

Science and Implementation Plan for a SCAR Research Programme ICESTAR: Interhemispheric Conjugacy Effects in Solar Terrestrial and Aeronomy Research

Submitted by the Standing Scientific Group on Physical Sciences

Expected Programme duration: 2005-2009

Expected SCAR funding: US$75,000

Programme Summary

A major challenge facing environmental science and policy is understanding the interactions between, and collective behaviour of, the many component parts of the Earth system, including the interaction between the natural environment and human society. This requires both the specification and prediction of the state of the system, involving the assimilation and integration of data from disparate sources (disparate instruments, sampling various locations, operated by different people and organizations). Near Earth space (geospace) is an integral part of the Earth system, providing the material link between the Sun and Earth, primarily through the polar regions, and posing a potential hazard to space-borne and ground based technology on which Society is increasingly dependent. Understanding of the complex geospace environment has matured to the level of being able to describe many of its component parts and a major goal now is to seek a unified framework that can specify and predict its global state and, therefore, "space weather". To enable this, this programme will establish a forum and working groups to provide a portal on the World Wide Web to all Antarctic geospace data and metadata, and tools for extracting and reducing these data into value added products, similar to those available or being developed in other areas of SCAR science.

Antarctica offers a privileged position to remotely sense the vast region of geospace (extending over millions kilometres from the planet) because the Earth's magnetic field focuses the effects of geospace into the polar regions and Antarctica has a land mass on which to base instruments at high latitudes, yet Antarctica has been underexploited relative to the Arctic. Recently there has been substantial investment by a number of countries in sophisticated instrumentation providing a grid of instruments over much of the Southern Polar Region. Further instruments are to be installed in the near future that will provide coverage equal to and in some cases better than that in the Northern Polar Region. There is now the capability to investigate conjugate relationships at an unprecedented level of detail. ICESTAR is designed to exploit this and one of the main results of the programme will be the enhanced visibility, accessibility, and usability of the Antarctic geospace data to enable whole system geospace research, including interhemispheric and ground space studies, and new cross disciplinary research such as teleconnections between the upper and lower levels of the atmosphere.

ICESTAR will have four working groups that will specifically focus on:

1. Quantifying and understanding the similarities and differences between the Northern and Southern polar upper atmospheres, under the varying influence of the solar electromagnetic radiation and of the solar wind.
2. Quantifying the effects on the polar ionosphere and atmosphere of the magnetospheric electromagnetic fields and plasma populations, from the radiation belts to the tail plasma.
3. Quantifying the atmospheric consequences of the global electric circuit and further understanding the electric circuit in the middle atmosphere as guided by the electric fields generated at the solar wind–magnetosphere interface.
4. Creating a data portal that will integrate all of the polar data sets and modeling results. This data portal will enable the research to be conducted by the other working groups.

We request funding to have yearly workshops, which will focus on the implementation of the data portal and updating the community on research which, has been conducted under this programme.

ICESTAR Programme Goals

ICESTAR is a new SCAR initiative striving for international coordination of interhemispheric research in the areas of solar terrestrial physics and polar aeronomy, promoting exchange of research ideas, and sharing experimental data from various arrays of geophysical instrumentation deployed over the Polar Regions and in near Earth space. The ICESTAR programme will specifically address several challenges articulated in the Decadal Research Strategy in Solar and Space Physics [Lanzerotti *et al.* 2003].

Since the International Geophysical Year (IGY, 1957-1958), almost fifty years of observations in space and over high latitudes of the Arctic and Antarctic have provided a good picture of the solar wind's dominating role in driving magnetospheric dynamics and the overall electro-dynamic coupling of the magnetosphere to the ionosphere. Nonetheless, important gaps remain in our understanding of the solar wind magnetosphere ionosphere interaction. We do not know enough about the changes and dynamics of the Earth's magnetosphere under extreme solar wind conditions, i.e., during strong geomagnetic storms. Much remains to be learned about how the solar forcing can affect the neutral atmosphere, especially at high latitudes where the solar wind driven processes are most influential. Possible influences of the changing Sun (i.e., its irradiance and magnetic moment) and geospace environment on polar climate and weather are also poorly understood.

However, recently there has been substantial investment by a number of countries in sophisticated instrumentation providing a grid of instruments over much of the Southern Polar Region. Further instruments are to be installed in the near future that will provide coverage equal to and in some cases better than that in the Northern Polar Region. There is now the capability to investigate conjugate relationships at an unprecedented level of detail.

The Initial Outline Science Plan for the International Polar Year 2007–2008, issued by the ICSU's IPY Planning Group in April 2004 (http://www.ipy.org), proposes five main science themes to address. Although the IPY main focus will be to determine the present environmental status of the Polar Regions and their connections to the potential global climate changes, the fifth theme calls "To use the unique vantage point of the polar regions to develop and enhance observatories studying the Earth's inner core, the Earth's magnetic field, geospace, the Sun and beyond". Thus, this theme is a major thrust of the proposed ICESTAR Scientific Research Programme.

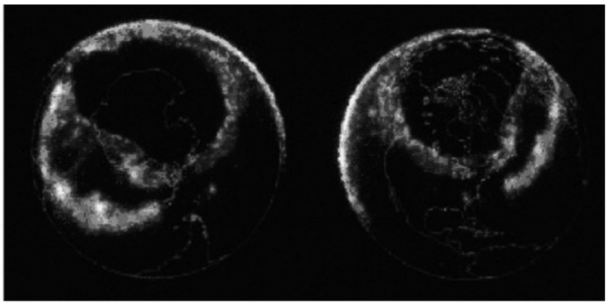

Figure 1: Satellite images of the Southern and Northern auroral ovals during a magnetic storm.

The ICESTAR Programme scientific goals are:

- To identify and quantify various mechanisms that control interhemispheric regional differences and commonalities in the electrodynamics and plasmadynamics of the Earth's magnetosphere-ionosphere coupling system, and in aeronomy of the upper atmosphere over the Arctic and Antarctic.
- To develop a "virtual" data portal that will link together a large number of globally distributed geophysical databases, including both data serving applications and visualization tools; this will enable a systems view of the polar upper atmosphere and geospace.

The polar ionosphere is often compared to a television screen displaying intimate processes of the solar wind magnetosphere interaction (Figure 1). We need deep understanding of various mechanisms responsible for energy transfer from the solar wind into geospace environment; this is impossible without simultaneous consideration of various geophysical phenomena occurring over both the Northern and Southern Polar Regions. The long acting solar forcing and short-term solar variability (activity) could also be significant in its influence on the polar terrestrial climate and weather.

Thus our focus and approach to interhemispheric research are important because: (a) Earth's dipole tilts and therefore, causes seasonal variations and north-south asymmetries that are not yet accurately understood to be included into various geospace models. Initial conjugate observations of auroras indicate that these models are inaccurate, so we do not yet understand well enough topology of the Earth's magnetospheric field; (b) We need to understand the total energy input into the upper atmosphere from the solar wind-magnetosphere coupling. Most of the geospace models are developed only from northern hemisphere observations, assuming symmetrical response of both the northern and southern Polar Regions to magnetospheric disturbances; (c) Polar climate effects could be different because of different circulation patterns in the two hemispheres.

Scientific Background

The near-Earth space environment commences at the top of the troposphere and continues out to the interface between the Earth's atmosphere and the Sun's atmosphere. In this region of space, temperatures range from 150 K up to over 1,000,000 K, flow speeds range from a few *m/s* to hundreds of *km/s*, and densities range from 1023 particles to 10^{-6} particles per cubic metre. In addition, above 600 km altitude, the ionospheric plasma becomes the dominant component of the atmosphere. This plasma is strongly tied to the magnetic field. Therefore, the proposed research programme will focus on some aspects of the atmospheric, ionospheric, and magnetospheric dynamics, specifically selected because of the possibility to maximize the Antarctic resources in their interhemispheric context.

Magnetospheric Dynamics

At the altitudes higher than approximately 100 km, the region of space that contains charged particles (i.e., the ionosphere) becomes quite important. The ionospheric plasma is intimately linked to the Earth's magnetic field, so one must also consider this. The Earth's magnetic field would extend to infinity if no other planet or star existed, but as that is not the case – it encounters the Sun's atmosphere. The Sun's atmosphere is extremely hot and therefore expands radially outward at supersonic speeds. In addition, the atmosphere becomes charged, so it is intrinsically tied to solar magnetic field lines. When the solar wind (i.e., the Sun's atmosphere near the Earth) encounters the Earth's magnetic field, it is diverted around the boundary, like a stream flowing around a rock. The cavity that is carved out is called the magnetosphere, and is dominate by earth's magnetic field as illustrated in Figure 2.

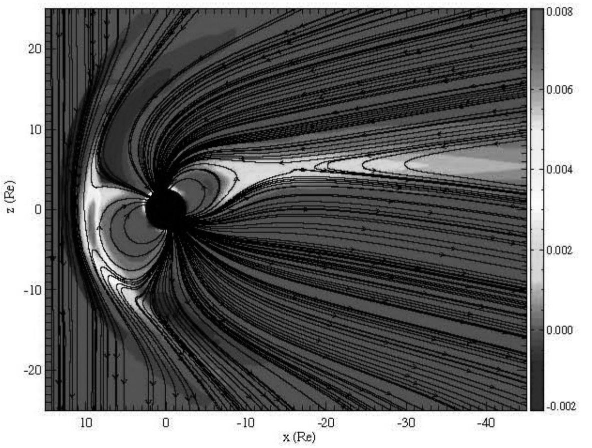

Figure 2: Traces of the magnetic field in the noon-midnight plane, over the magnetopause currents plotted in units of μA/ m2. The sun is off to the left, so the solar wind is streaming in from the left. Where the magnetic field lines start to bend in a semi-circle on the left is the bow shock. This figure illustrates a Northern summer solstice condition in at 16:45 UT, in which the Northern hemisphere magnetic pole is pointed towards the Sun.

We want to know the similarities and differences between the Northern and Southern polar upper atmospheres simply to fully understand how the entire planet responds to the varying influence of the solar electromagnetic radiation and of the solar wind. Most of the known geospace phenomena (including magnetic storms and substorms) develop in concert over both the Arctic and the Antarctic (Figure 1). High latitude geomagnetic field lines carry a load of field-aligned currents and electromagnetic waves from the magnetopause down to the ionosphere and atmosphere. During equinox, that load is about symmetrical over both Polar Regions, but it becomes quite asymmetric when either of the poles is tilted toward the Sun. In the latter case, the solar UV radiation becomes a controlling factor for the ambient ionospheric conductivity at high latitudes and this causes a great deal of asymmetry in the interhemispheric distribution of various ionospheric electrodynamic parameters, aurora borealis and australis, and even in influencing polar weather through the heating of the upper atmosphere by the aurora and friction between the ions and neutrals. The difference in the internal geomagnetic field strength over the Northern and Southern Polar Regions may cause fundamental differences in the energy deposition and create longitudinal asymmetry, for example, because of the South Atlantic magnetic anomaly.

The dynamic state of the inner magnetosphere is highly dependent on geomagnetic conditions. Magnetic storms are the most geodynamic phenomena occurring from the interaction of the solar wind with our magnetosphere. During the main phase of a magnetic storm the plasmasphere gets significantly depleted [Degenhardt *et al.*, 1977]. Then during and long after the recovery phase of the storm the plasmasphere slowly fills up again with new material, the main source region being upflowing ions from the ionosphere. However, it is still not clear how the energy from the solar wind during storm conditions penetrates deep to the inner plasmasphere and couples to the low altitude atmosphere.

Furthermore, continuous observations of the depletion and refilling of the plasmasphere are necessary inputs to models that track the development of the ring current during storms. Such questions can be investigated by remotely monitoring the density of the inner magnetosphere through the observation of field line resonant pulsations at geomagnetic latitudes ranging from 20° to 60° . Due to the fact that sufficient *in situ* measurements are not available from the inner magnetosphere, it has become essen-tial to develop good techniques of remotely and accurately monitoring it from the ground.

Very low frequency (VLF) whistler waves and ultra low frequency (ULF) waves have been used to remotely monitor the inner magnetosphere. The whistler dispersed frequency signature observed on the ground can be used to determine whistler wave's path and the equatorial density of the magnetic fluxtube (e.g., Helliwell [1965]). This method is accurate but not continuous because whistlers are not always present. They are excited by lightning in the lower atmosphere and they depend on the existence of an appropriate conducting material at those altitudes to keep the whistler field aligned.

More recently techniques for determining the local field line resonances have been used to successfully monitor the inner magnetosphere density variations. Once the local resonant frequency is known, the plasma mass density can be inferred if appropriate models of the magnetic field and the plasma density are assumed. According to Schulz [1996], the mass density at the equator can be inferred assuming that the observed pulsations represent oscillations of the field line at the fundamental, second, and third harmonic frequencies, and that the density falls off as $1/r^4$with radial distance.

The Antarctica Peninsula has the great advantage of covering low and mid magnetic latitudes, i.e., inner magnetosphere and plasmasphere, at a magnetic longitude that is reasonably well covered at all latitudes. The recent installation of SAMBA magnetometers on the Peninsula offers the opportunity of remotely monitoring the mass density of the inner magnetosphere. Most importantly, the SAMBA magnetometers are conjugate to the MEASURE chain magnetometers in North America, so determinations of the inner magnetospheric mass density can be done conjugately. Initial results indicate that such conjugate calculations will help restrain the models for inner magnetospheric density calculations.

Finally, the existence of the VLF antennas at Palmer and Vernadsky with SAMBA magnetometers being installed there offers a unique opportunity for the remote study of the inner magnetosphere. VLF whistler waves can determine the number density of the fluxtube, while ULF waves observed from magnetometers can determine the mass density of the same fluxtube so that estimates of the composition changes in the inner magnetosphere can be made.

Ionospheric Dynamics

Here we address the effects of the magnetospheric electromagnetic fields and plasma populations on the polar ionosphere and atmosphere. Sometimes the Sun bursts forth a significant amount of coronal plasma and then a huge magnetic cloud (many times larger than the Earth's magnetosphere) begins to propagate through interplanetary space. If this cloud hits the magnetosphere, it causes strong space storms. At times, the power transferred from the solar wind increases nearly two orders of magnitude, disturbing the entire magnetosphere, and disrupting satellite operations and communications. Due to that interaction, magnetospheric plasma particles energize and precipitate into the polar ionosphere causing magnificent aurora that illuminates the northern and southern polar skies (Figure 3). This precipitation, and the associated currents, can cause significant heating of the polar upper atmosphere.

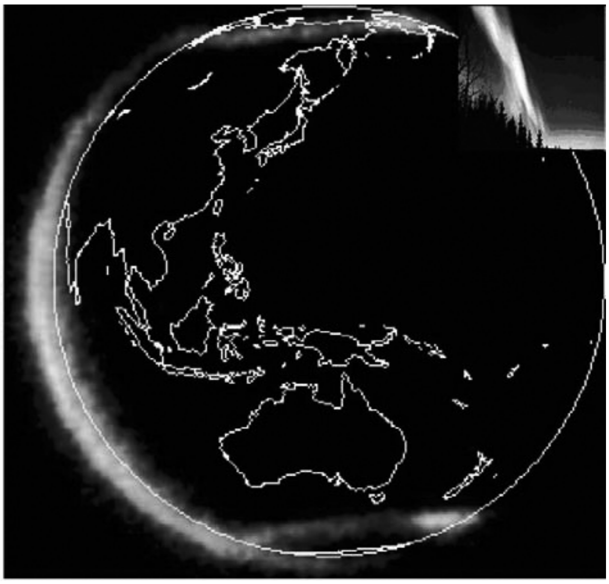

Figure 3: A global auroral substorm as observed by NASA's POLAR spacecraft and from the ground.

The heating of both polar atmospheres from the above could be quite asymmetric. This is because of the seasonal dependencies on the solar heating and the inherent asymmetry of the Earth's magnetic field. The geomagnetic asymmetry further introduces asymmetry in the distribution of aeronomical characteristics of the polar thermosphere and atmosphere. For example, asymmetry in the energy deposition from the magnetosphere into both polar ionospheres may cause different planetary gravity wave activity that may affect the strength of terrestrial weather fronts in both Polar Regions.

Atmospheric Dynamics

In this section, we address atmospheric consequences of the global electric circuit and further understanding of

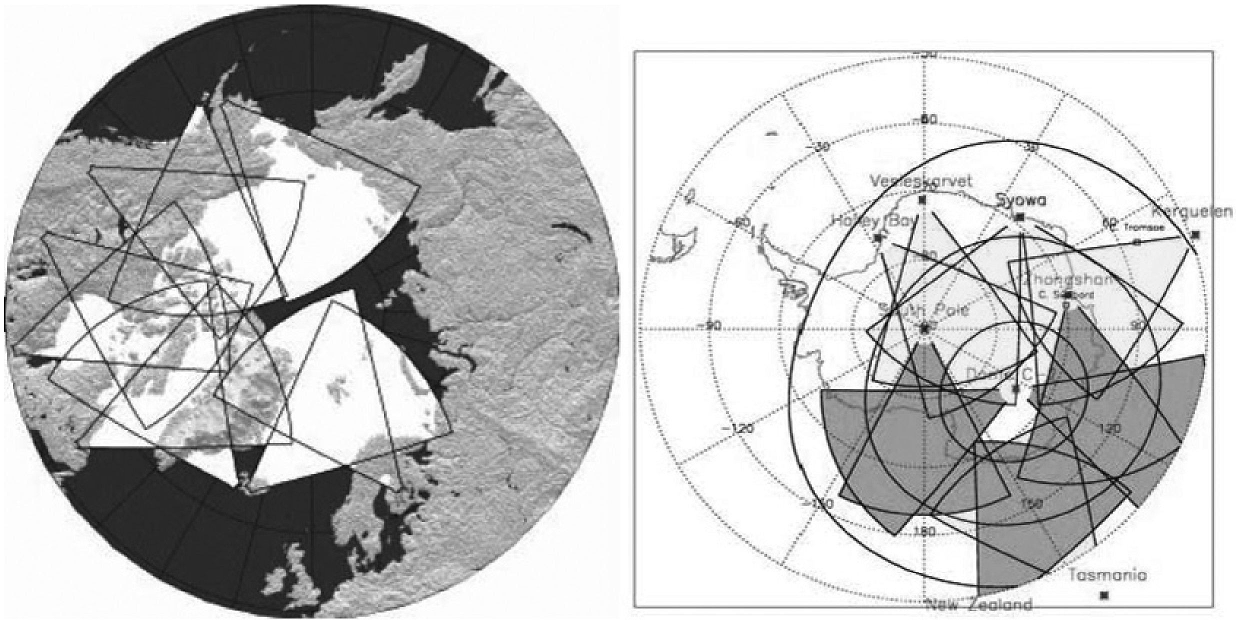

Figure 4: Maps of the Super Dual Auroral Radar Network (SuperDARN) arrays over the Northern (left) and Southern (right) polar regions. The Antarctic map shows fields-of-view for existing and planned radars, which will provide complete coverage of the southern polar region above 60° geomagnetic latitude.

the middle atmosphere as guided by the electric fields generated at the solar wind– magnetosphere interface.

The lower atmosphere is mainly driven by solar radiation inputs. The radiation is absorbed by water vapour in the troposphere and ozone in the stratosphere giving rise to a periodic heating of the atmosphere. This heating generates waves, called atmospheric tides, that propagate vertically transporting heat and momentum from the troposphere and stratosphere into the mesosphere and thermosphere. These waves are ubiquitous and globally coherent.

To quantify the effect of waves, such as atmospheric tides and gravity waves, on the geospace environment, distributed measurements of the neutral atmosphere fields of wind and temperature are required. Over the past decade a network of radar and optical systems have been deployed across Antarctica with the capability of measuring such parameters. This has been an international effort with instrumentation installed at Halley, Rothera, Syowa, Davis, Scott Base, McMurdo, and South Pole. To facilitate international cooperation and enhance scientific collaboration, the group of scientists responsible for this instrumentation have developed a memorandum of understanding. Similar efforts are taking place in the Arctic with a significant increase in the number of radar and optical systems over the past ten years. An Arctic chain of instrumentation now exists that includes Alaska, Canada, Greenland, and Russia, with collaborators from Japan, Germany, Australia, and the United Kingdom in addition to scientists from the host countries.

Because the Polar Regions are free as possible from thunderstorms, they are the best place anywhere in the world to investigate the "fair weather" art of the global atmospheric electric circuit. Regarding the DC circuit, the Polar Regions are excellent for studying three directly related quantities – vertical atmospheric electric current densities, variations of the ionospheric potential difference across the polar cap associated with the solar wind interaction with the magnetosphere, and variations of atmospheric conductivity associated with geomagnetic activity and/or Forbush decreases of the fluxes of incoming cosmic rays. Studies of Schumann resonances of the Earth-ionosphere wave guide excited by lightnings around the world are invaluable of the AC global circuit

Data Availability

An excellent example of the interhemispheric coordination is the Super Dual Auroral Radar Network (SuperDARN), which currently offers almost complete coverage of the northern polar region by the high frequency radars"fields of view". By tracking the ionospheric irregularities, the SuperDARN radars actually monitor the global ionospheric convection (electric field) pattern (Figure 4). Unfortunately, the northern SuperDARN is incomplete missing a pair of radars in the Russian Arctic. At the same time, SuperDARN operates four radars in the Antarctic, and in 23 years, the Antarctic Plateau will be completely covered by the radars proposed for the construction at the southern tip of New Zealand, Chinese Antarctic station Zhongshan, and at the U.S. and European Antarctic bases South Pole and Concordia. This will make the radar coverage superior in the southern polar region. The SuperDARN data are easily available via the Web site http://superdarn.jhuapl.edu.

Recent development in populating the Antarctic Plateau with many autonomous stations places the Antarctic solar terrestrial and aeronomy research into a lead position for the implementing the ICESTAR Programme. As shown in Figure 5, the centre of Antarctic Plateau is now well

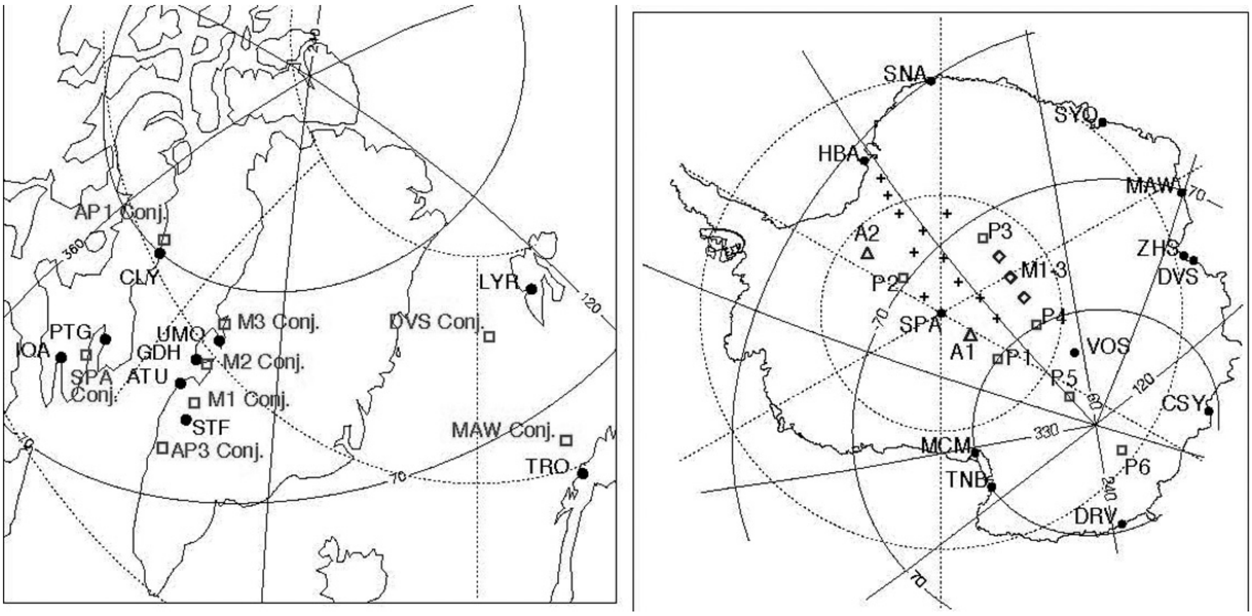

Figure 5: Arctic and Antarctic maps with geographic (geomagnetic) coordinates given by the dotted (solid) lines. Manned stations are shown by a three letter international station name code. U.S. AGO/PENGUIn sites are shown by P#. Recently deployed British low power magnetometers are shown by crosses. Proposed U.S. autonomous low power magnetometer (M1, M2, M3) sites are shown as blue diamonds and two proposed multi instrument ARRO sites are marked as A1 and A2. Conjugate locations of selected Antarctic sites are also depicted over the Arctic map.

covered with a network of autonomous low powered magnetometers and a number of automatic geophysical observatories. The U.S. Amundsen Scott South Pole Station is a critical component of this entire network: it is a very well equipped geophysical observatory located at the boundary between the southern auroral oval and polar cap. At the same time, this is a base from where many autonomous sites are easily accessible via air transport.

Another critical component of the Antarctic geospace array is the French Italian base Concordia, located in vicinity of the southern geomagnetic pole. The station will be opened for year round observations in 2005, and there are ambitious plans under development to turn this site into a well equipped geophysical observatory as well.

The Russian Antarctic base, Vostok, may also play a significant role in the overall operation of the Eastern Antarctic array of autonomous stations, as well as other coastal bases operated by SCAR member countries. Thus, three inland manned stations, more than a dozen of autonomous sites and another two dozens (including stations at the Antarctic Peninsula) of coastal bases make the “backbone” and “flesh” of the Antarctic Geospace Array, comparable (by its potential and resolution) to various geophysical networks deployed over Alaska, Greenland, Canada, and Scandinavia (Figure 5), such as MIR-ACLE (http://www.geo.fmi.fi/miracle/), CANOPUS (http://www.spagency.ca/www/), and CGSM (http://www.phys.ucalgary.ca/norstar/cgsm.html). INTERMAGNET (http://www.intermagnet.org) and WDC System (http://www.wdc.rl.ac.uk/wdcmain/) offer additional invaluable resources.

At last, studying the magnetosphere-ionosphere coupling, we need to collaborate with various satellite projects, for example, using the ISTP (http://wwwistp.gsfc.nasa.gov/istp/), CDAWeb (http://cdaweb.gsfc.nasa.gov), and OMNIWeb (http://cdaweb.gsfc.nasa.gov) resources for comparisons of the ground based and satellite observations.

One of the fundamental limitations to geospace research at present is the need to identify and visit many of distributed Web sites to get the datasets re-quired to address the increasingly interdisciplinary scientific problems. As a result, a fundamental tenet of this proposal is to establish a single “point of contact”: a data portal providing a distributed access to all high latitude geospace data. This would be a very significant contribution to research, that could be badged as a SCAR contribution. It is timely because the emergent GRID technology has now reached a level of maturity where this is possible, and it would be open to all nations because the Internet is now essentially available to all scientists.

Baker *et al.*[2004] have embarked on a concept of the electronic Geophysical Year (eGY, http://www.egy.org), which calls for deployment of virtual observatories in cyberspace as a natural extension of the worldwide network of physical observatories. ICESTAR will work together with the SCAR/COMNAP Joint Committee on Antarctic Data Management (JCADM; http://www.jcadm.scar.org) implementing the proposed approach.

Programme Rationale

The ICESTAR Programme will create an integrated, quantitative description of the upper atmosphere over Antarctica, and it’s coupling to the global atmosphere and the geospace environment. The reasons to embark on the endeavour now are:

The Emergence of New Datasets.

The volume of experimental data has been increasing significantly in recent years. In addition, many new datasets are expected to come online in the near future. At this time, there are new magnetometer chains, new polar orbiting satellites which, allow the simultaneous view of the Southern and Northern polar regions, new ionospheric (SuperDARN, AMISR, and EISCAT) radars, new mesospheric/thermospheric wind measurements (meteor radars, FPIs), new digisonde and TEC data. It is the right time to begin to create tools to examine the entire system as a whole utilizing all of the existing geospace data and preparing for the creation of many new datasets.

Emergence of Grid technology.

The "Grid" is just starting to be defined, and has yet to find a real niche. The seamless sharing of data is one possibility, and is one of the main goals of the ICESTAR programme. The creation of visualization tools that can utilize globally distributed data sets will push the limits of the current technologies and will spark the creation of new Grid functions. In addition, enabling the convergence of data and models is another strong goal of the Grid technology, which is synergistic with the Programme goals.

Enable Easy Access to Distributed Data.

Many research groups are creating data assimilation tools which require the use of as many data sources as possible. The creation of the ICESTAR data portal and use of the Antarctic Data Master Directory will enable these developments to grow significantly.

Uniqueness of Antarctica.

The Antarctic continent offers a unique vantage point for examining the near Earth space environment, spanning from the top of the troposphere, through the stratosphere, mesosphere, thermosphere and ionosphere, and into the magnetosphere. Here we underscore some of the similarities and differences between the Arctic and Antarctic:

(a) very different underlying neutral atmosphere, e.g., planetary waves and gravity waves morphology is very different, and more intense jet stream exists in the Antarctic;

(b) much larger displacement of the magnetic dip pole in the South than in the North (24° as opposed to 11°), which means it is much easier to separate effects that are controlled by solar radiation, i.e., ionospheric conductivity, from those caused by interactions of the solar wind; and

(c) the geomagnetic field is weakest in the South Atlantic sector, thus the flux of energetic particles is higher than anywhere else allowing to studying the atmospheric consequences of energetic particle precipitation. In addition, the Antarctic Peninsula allows to sample, geomagnetically, both the high and middle latitudes.

Focused Science.

The ICESTAR programme is intended to both enable and to conduct focused scientific research on the upper atmosphere above the Antarctic and how that region of space ties in with the global system. No other programme exists which is focused specifically on the quantitative understanding of the upper atmosphere above the Antarctic continent.

Tying Together the International Community.

Studies of the polar upper atmosphere fundamentally require international collaboration. First consider the deployment of instruments across Antarctica. These instruments are either located at manned bases or are remotely deployed and serviced from such bases. From a logistical and financial standpoint it is unfeasible to deploy a network of instrumentation in Antarctica without international collaboration. The problem is even more complex in the Arctic as individual countries there have control over portions of the region. With instruments being deployed and operated by different countries, international collaboration is essential so that data can be exchanged and integrated. Upper atmosphere scientists working with such data typically interact in a collaborative manner in an effort to solve open overarching science questions.

Summary of Science Objectives

The following key questions of the solar terrestrial physics and polar aeronomy provide a very sound scientific background for the ICESTAR Scientific Research Programme:

- How Earth's magnetosphere differs qualitatively and quantitatively under extreme, moderate, and quiet solar wind conditions?
- What is common and what is different in the solarterrestrial and aeronomical phenomena observed over both the Arctic and Antarctic.
- Does the auroral activity during substorms arise from instabilities in the ionosphere or does this aurora simply mirror plasma motions in the outer magnetosphere? How much do the dark and sunlit ionospheres control the polar substorm dynamics?
- To what extent are the ionized and neutral highlatitude upper atmospheric regions affected by mechanical and electrodynamic inputs from the lower atmosphere?
- How does the global electric circuit affect the ionosphere state? How this circuit is closed between the low and high latitudes?

Thus, it is important and timely to act now to study the Polar Regions in their interhemispheric context from observations in space and over the Arctic and Antarctic.

International Scope

As a well developed international scientific association, SCAR can naturally lead scientific programmes on interhemispheric research in various disciplines. Unlike the southern polar region where the Antarctic Treaty system governs international science activities, the Arctic constitutes a multinational environment where effective coordination of scientific activities and observational programmes is a challenging task. At the same time, it is obvi-ous that the joint, interhemispheric observational potential is very powerful allowing scientists to study largely (simultaneously and globally) various interhemispheric effects in high latitude magnetospheric and ionospheric processes and their consequences on upper atmospheric and aeronomical phenomena.

Although a significant body of international research exists in the described fields of solarterrestrial physics and polar aeronomy, ICESTAR will require extended international activities in collecting and coordinating corresponding datasets, models, and research efforts. The interest to ICESTAR has already been shown by a number of SCAR member countries such as Australia, Finland, France, Japan, Italy, P.R. China, Russia, Ukraine, United Kingdom, and the United States of America; other countries are welcome to join. Some of the SCAR member countries are active in the Arc-tic as well, and with their Arctic neighbours (e.g., Canada, Denmark, Norway, Sweden, Iceland) may participate in the ICESTAR programme studying interhemispheric aspects of the global magnetosphere-ionosphere coupling. Coordination and collaboration with international scientific organizations such as SCOSTEP (Scientific Committee on Solar Terrestrial Physics) will also be fostered. Their program on Climate and Weather of the Sun Earth System is of particular interest, and linkages between the upper and lower atmospheres can further be explored via ICESTSAR and the AGCS programmes.

Methodology and Implementation

To accomplish the program's ambitious research goals, we will:

- Create the ICESTAR data portal to facilitate the sharing and interpretation of global geospace datasets. This data portal will be linked to the Antarctic databases, which already ties together many data sets. The data portal will encourage the collaboration of researchers by sharing data and the interpretation of the results.
- Although many data sets are global in nature, they are run by many different institutions and countries. This creates a roadblock in the creation of a systems view of the geospace region. The creation of the data portal will break these barriers by allowing transparent and seamless integration of globally distributed similar datasets into a systems view. This will be true of magnetometer networks, image networks, and global radar networks.
- The ICESTAR programme will identify gaps in observation networks and instrumentation and will encourage individuals or groups of researchers to propose to the relevant funding agencies in an effort to acquire more funds to deploy key instrumentation thus allowing a complete understanding of the polar upper atmospheric system.
- The ICESTAR programme will coordinate joint studies on the scientific topics discussed in the preceding sections. In addition, it will hold annual workshops that will bring the community together to discuss these topics, focusing the community towards the programme goals.
- The ICESTAR will have three scientific working groups focused on the following areas:
    1. Quantifying the dynamics of the inner magnetospheric particles and fields and the consequences of those dynamics on the polar atmosphere.
    2. Quantifying the atmospheric consequences of the global electric circuit and further understanding the electric circuit in the middle atmosphere.
    3. Quantifying the general state of the Southern polar region upper atmosphere, ionosphere, and magnetosphere, and its similarities and differences with the Northern polar region. Because this focus area is so large, the working group will be lead by two co-chairs.
- The ICESTAR programme will have a Working Group dedicated to the creation and implementation of the data portal. This working group will have a chair and representatives from each of the other working groups to make sure that the portal is enabling research in each of the focus areas.

Program Management

The implementation of a programme of the proposed scale will require careful management and coordination internationally, as well as nationally. The overall management of the programme will be responsibility of the ICESTAR Steering Committee (810 members) led by two Co-Chairs and guided by the SSG/PS leadership ex officio. The SC will meet every year to determine the programme progress and outline the venues for international collaboration. ICESTAR will hold dedicated scientific workshops either separately or in conjunction with the biennial SCAR Science Meetings.

The above listed objectives will be the focus of four Thematic Action Groups (TAGs) established to coordinate activities:

TAG-A: Quantification of the coupling between the polar ionosphere and neutral atmosphere from the "bottom to top" and the global electric circuit.

TAG-B: Quantification of the inner magnetospheric dynamics using remote sensing techniques.

TAG-C:Quantification of the state of the upper atmosphere, ionosphere, and magnetosphere over the Antarctic continent and how it differs from the Northern hemisphere during a wide range of geophysical conditions.

TAG-D:Creation and management of the data portal to enable the ICESTAR programme and SCAR's SSG/PS.

Each TAG will establish and maintain liaison with the National Antarctic Programs through SCAR and its relevant scientific groups and committees: ADD (Antarctic Digital Database), MAGMAP (Magnetic Anomaly Map), and READER (Reference Antarctic Data for Environmental Research). The programme goals and objectives will be detailed together with the SSG/PS Expert Group on Solar Terrestrial Processes and Space weather (STEPS) and the relevant Action Groups APTIC (Antarctic Peninsula Troposphere-Ionosphere Coupling) and MADREP (Middle Atmospheric Dynamics and Relativistic Electron Precipitation).

Similar collaboration will be established with relevant projects of the International Arctic Science Committee (IASC; http://www.iasc.no).

The ICESTAR activities will also be coordi-nated with the Working Group on Polar Research of the International Association of Geomagnetism and Aeronomy (IAGA) and with the new international programme sponsored by SCOSTEP: Climate and Weather in the Sun-Earth System (CAWSES).

Finally, the proposed period for ICESTAR (2005–2009) overlaps the planned research activities in the framework of fourth International Polar Year (IPY, 2007/2008), which could make the programme one of the IPY's cornerstones.

Deliverables

The ICESTAR programme will deliver a wide variety of products ranging from a better scientific understanding of the polar atmosphere to a data portal that will enable scientists to create a systems view of the polar region. Specifically, the ICESTAR programme will focus on delivering:

I. A data portal linking together a large number of polar sites with diverse datasets. This data portal will have visualization and data translation modules that will allow users to examine the data and download it in formats that they can easily understand. The following data types will be provided to the portal by the associated groups: magnetometers, HF and MST radars, lidars, passive optical instrumentation, digisondes, riometers, VLF/ULF receivers, TEC measurements, and atmospheric electric field observations.

II. Quantification of the role of seasonal differences in polar ionospheric conductance and the effects on magnetospheric, ionospheric, and thermospheric dynamics.

III. Constraints on models based on conjugate remote sensing of inner magnetospheric dynamics.

IV. Characterization of the spatial and temporal properties of mesoscale convection in the ionosphere.

V. Characterization of the basic state of the polar middle atmosphere.

VI. Quantification of the AC and DC global atmospheric circuit and its effects on the ionospheric state.

Milestones

In order to achieve these ambitious goal, specific tasks have been identified:

1. Creation of the data portal (2005–2007):
   a. Identify all available geospace data sets to address the programme's scientific objectives and define architecture of the portal.
   b. Evaluate existing software that would be used for a portal.
   c. Identify nodes and implement data portal.
   d. Modify data portal according to community feedback received through workshop forum.
2. Identify and implement the necessary tools to analyze the data collected in the portal.
3. Identify the lack of instrumentation necessary to address scientific objectives and make recommendations to the community to fill the gaps.
4. Utilize the data portal tools to conduct scientific research and complete the list of deliverables.
5. Hold scientific workshops to verify that all participants are working towards to deliverables, access the state of the programme, and determine what needs to be modified to reach the goals of the programme.
6. Apply numerical models based on understanding gained by the previous milestones to provide an integrated, quantitative description of the upper atmosphere, ionosphere, and magnetosphere over Antarctica.

The ICESTAR programme will deliver a variety of products ranging from scientific papers in peer reviewed journals, presentations at international conferences, reports to SCAR, and most important – better understanding of interrelations between two polar regions through global empirical models of magnetosphere-ionosphere coupling.

One key product will be a data portal a Web based system of interfaces allowing scientists and the public to access various geospace datasets collected under the ICESTAR programme. This system will also provide access to a number of global models characterizing polar electrodynamics and plasmadynamics.

The proposed period for the ICESTAR programme is initially set for five years with possible extension for another five years. The proposed start date is January 1, 2005, pending approval by the XXVIII SCAR Delegates:

2005–2006:Start of ICESTAR Programme – Collect information and coordinate observations at the existing instrumental arrays in the Arctic and Antarctic aiming specifically at interhemispheric studies, including global development of the magnetic storms and substorms over the polar regions. Promote the deployment of new instruments where current gaps exist.

2007–2008:Main Phase (coincides with IPY) – Develop time dependent geospace models controlled by external (i.e., solar wind) drivers; couple these models with the potential input from atmospheric processes including the global electric circuit and thunderstorms.

2009–future: Closure or Renewal Phase – Consider termination or extension of the ICESTAR programme based on its progress and accomplishments.

Success Factors

The ICESTAR Programme success can be measured against abovementioned deliverables and periodic scientific reports at the ICESTAR Workshops and SCAR Science Meetings. The ICESTAR Steering Committee will also monitor the number of scientific papers published in refereed journals and elsewhere.

Surely, a key success measure will be the usage of the ICESTAR data portal if this is extensively used by all upper atmospheric scientists then it would be a great success.

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Supporting information

ICESTAR Steering Committee

The proposed ICESTAR Steering Committee consists of two Co-Chairs, five leaders of the Thematic Action Groups, 23 prominent Antarctic lead investigators, and an ex officio member of the SSG/PS leadership. The SC members will be rotated every other year.

- **Chairman, AllanWeatherwax (U.S.A.)** received a PhD in physics from Dartmouth in 1995 and subsequently joined the University of Maryland as a postdoc. He studied auroral radio emissions, radiowave propagation, and waveparticle interactions. In 1998, he was promoted a Research Scientist at Maryland and was part of the U.S. AGO/PENGUIn program. He is currently an Associate Professor of Physics at Siena College, NY. Dr. Weatherwax is an expert in the analog/digital equipment design and has extensive Arctic and Antarctic field experiences. Since 1999, he chairs the IAGA WG on Polar Research.
- **Co-Chairwoman, Kirsti Kauristie (Finland)** received a PhD in 1997. She studied the morphology and dynamics of auroras and auroral electrojets, working at the Finnish Meteorological Institute since 1988. During 1999-2003, she served as the PI of the international MIRACLE network of ground-based auroral instruments operating in the Fennoscandian sector; now she is a member of the MIRACLE Scientific Coordination Team. Within the ESA's Space Weather Pilot Project (2003-2005), she worked on the development of a real time auroral monitoring system. In basic research her interests are focused on the studies of mesoscale ionospheric electrodynamics.
- **TAG-A Leader, Martin Fullekrug(U.K.)** received a PhD from Goettingen University in 1994 and then spent three years in STARLab at Stanford University. In 1997, he became a Research Fellow in Frankfurt University, where he studied electrodynamics of lightning, sprites, and ionospheric phenomena in the context of the global atmospheric electric circuit, receiving the Habilitation in 2001. Max Planck Society awarded him a fellowship to join Tel Aviv University; ever since, he lectured in the Tel Aviv and Frankfurt Universities. In 2004, he joined the faculty of University of Bath.
- **TAG-B Leader, Eftyhia Zesta (U.S.A.)** received a PhD from Boston University in 1997. She built and integrated experimental systems for the Magnetometer Array for Cusp and Cleft Studies (MACCS) deployed in the Canadian Arctic. Studying transient ionospheric currents in polar latitudes, she won three AGU awards for best student presentations and a NRC postdoc position at the NOAA Space Environment Center. In 1998, she moved to UCLA, where she works ever since as an Associate Researcher. She is a PI of the SAMBA magnetometer chain deployed along Chile and in Antarctic Peninsula.
- **TAG-C CoLeader, Nikolai Østgaard (Norway)** received a PhD from University of Bergen in 1999. As a postdoc at University of Oslo and NASA/GSFC, he lead the in situ calibration of the PIXIE instrument at POLAR spacecraft and studied precipitating electron energy distributions deducted from Xray imaging. In 2001, he joined University of California, Berkeley as an Assistant Research Physicist and worked on the geocoronal imaging and FUV data form IMAGE spacecraft to study conjugate auroral phenomena. Since 2004, he is an Associate Professor at University of Bergen.
- **TAGC CoLeader, Scott Palo (U.S.A.)** received a Ph.D. from Univ. of Colorado in 1994. His thesis focused on radar observations and modelling of

global scale atmospheric perturbations. As a postdoc at NCAR, he worked on satellite data analysis and understanding the neutral atmosphere using a global circulation model. In 1997, he returned to Univ. of Colorado as a Research Associate; promoted to an Assistant Professor in 2001. He is an expert in the middle atmosphere, designing and deploying meteor radar systems in the Arctic and Antarctic.

- **TAG-D Leader, Aaron Ridley (U.S.A.)** received a PhD from University of Michigan in 1997. During graduate school, he won a fellowship through NCAR/HAO, where he used an ionospheric data assimilation technique and manipulated large, globally distributed datasets. As a postdoc at Southwest Research Institute, he created a real-time ionospheric specification technique and conducted research on the thermosphere and ionosphere. In 2000, Dr. Ridley returned to the University of Michigan, where he works with a global model of the magnetosphere and has created a global model of the coupled thermosphere and ionosphere.
- **Lead Member, Dr. Brian Fraser (Australia)** is a Professor of Physics at the University of Newcastle. His outstanding scientific career extends for more than 35 years and he is a renowned expert in the fields of geomagnetic pulsations and magnetospheric physics, mainly studying ULF waves and their generation mechanisms in the Earth's magnetosphere and beyond. He was first who suggested to use triangulation and polarization techniques on an array of ground-based magnetometers, discovered oxygen in the EMIC wave spectra and thus confirmed the presence of cold oxygen ions at geosynchronous orbit, and many more. Dr. Fraser's participation in the ICESTAR programme will help in identifying and studying bipolar effects of the magnetosphere-ionosphere coupling.
- **Lead Member, Dr. Natsuo Sato (Japan)** is a Professor and Head of the Computing and Communications Centre at the National Institute of Polar Research. In his 30+ years of the successful scientific career, he contributed significantly into the studies of conjugate auroral phenomena being a lead scientist of the Syowa-Iceland conjugate geomagnetic and auroral observation program. Dr. Sato is a Principal Investigator of the SuperDARN radars deployed at Syowa Station in Antarctica and an active member of SCAR. He also leads the Japan-China collaboration for the Syowa and Zhongshan Antarctic stations. Dr. Sato's contribution to the ICESTAR programme will cover many aspects of the magnetospheric and auroral physics.
- **Lead Member, Professor Ruiyuan Liu (P.R.China)** is a Council Member of the Chinese Society on Space Research, and a Fellow of the Chinese In stitution of Electronics. Graduating from the University of Science and Technology of China in 1963, he worked as a visiting scientist at the Rutherford Appleton Laboratory in the U.K. Returning to China, Dr. Liu served as a Deputy Director and a Professor of the China Research Institute of Radiowave Propagation, then as a Professor of the Polar Research Institute of China. He is an active member of SCAR and works in the fields of ionosphere, radiowave propagation, and upper atmospheric physics. His participation in the ICESTAR programme will enrich its international aspect bringing the wide experimental expertise and field operations.
- **SSG/PS Deputy Chair, ex officio, Maurizio Candidi (Italy)** has a spectacular 30+ years of scientific research in Italy and in the U.S. In 1990s, he served as a Director of the Instituto Fisica dello Spazio Interplanetario in Rome; currently he is an expert of the CNR and PNRA organizing the Italian research program in the fields of space physics and astronomy at the new European station Concordia in the Antarctic. Dr. Candidi has a long history serving SCAR as a Chair of the Working Group on Solar-Terrestrial and Astrophysical Research, and since 1992 – as a Deputy Chair of the SCAR's Standing Scientific Group on Physical Sciences.

Logistic Requirements

The ICESTAR will mainly be utilizing national resources in establishing, maintaining, and expanding geospace observations in the Arctic and Antarctic. SCAR is requested to provide a support for the initial development and maintenance of the data portal. In addition, the ICESTAR Programme requests supporting five scientific workshops focused on the activities of the Thematic Action Groups and the final phase of the overall programme.

The first workshop will be held with a small group of community members to help better clarify the programme goals, timeline, and methodology. In addition, the first workshop will solidify the implementation plan for the data portal. The following workshops will be open to the entire community. The third and fourth workshops will give the community an update on the goals of the programme and will have sessions devoted to examining the implementation of the programme and determining whether any modifications need to be made.

The final workshop will provide the community with the results of the programme activities and will have sessions aimed at determining whether the programme should continue, should be modified significantly, or should end

Indicative budget for 2005–2009

The ICESTAR will create an integrated, quantitative description of the upper atmosphere over Antarctica, and its coupling to the global atmosphere and geospace environment. In order to accomplish this goal, we will hold workshops focused on the data portal and the discussion of scientific goals.

In 2003-2004, the ICESTAR Planning Group used the support provided through SSG/PS to hold a programme planning workshop in Villefranche (Nice, France) in April 22-23, 2004 ($10,000). Because the creation of the data portal will require dedicated manpower, there is a budget of $30,000 (over the life of the programme) for the creation and upgrades to the data portal. In addition, there will be yearly workshops over the life of the programme focusing on the scientific goals of the TAGs.

Therefore, the ICESTAR Programme requests the following support for two SCAR budget cycles:

Budget cycle2004–2006: $30,000

Spring2005($10,000) - Data portal specification meeting, focusing on:

- Identification and metadata description of all available Antarctic data on the Internet for ICESTAR.
- Identification of available value added products on and offline and prioritization of the data and products based on their science merit.

Years2005–2006($10,000) Development and implementation of the ICESTAR metadata catalogue and “Virtual Data Portal”.

Summer 2006 ($10,000) ICESTAR Data Portal meeting, XXIX SCAR:

- Strategy for linking existing online sites together and providing online services for all known geospace data and products.

Budget cycle 2006–2009: $45,000

Spring 2007($15,000) - ICESTAR Science Community Workshop (coincides with IPY):

- Workshop centred on using ICESTAR metadata and the data portal to tackle selected problems/event studies in TAG AC science.

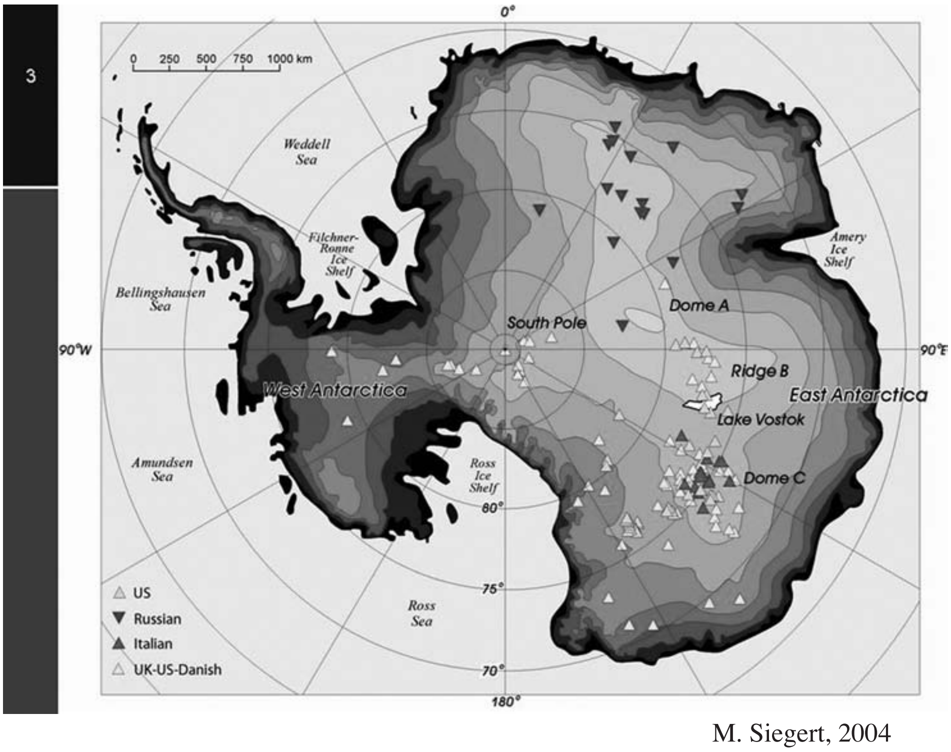
Summer 2008 ($15,000) - ICESTAR Special Session, XXX SCAR:

- Presentation of full ICESTAR data portal capabilities and science outputs from the community workshop.

Summer 2009 ($15,000) - ICESTAR “Forward Look” Workshop:

- Review ICESTAR achievements – the future.

Science and Implementation Plan for a SCAR Scientific Research Program (SRP) “Subglacial Antarctic Lake Environments (SALE)”



M. Siegert, 2004

by the SCAR Subglacial Antarctic Lake Exploration Group of Specialists (SALEGOS)

Submitted 6 November 2003; Revised and Resubmitted 6 August, 2004

Final Revision 15 November, 2004

Table of Contents

Proposal for a SCAR Scientific Research Program

Submitted 6 November 2003; Revised and Resubmitted 6 August, 2004

A. Program Description

A.1 Title:

Subglacial Antarctic Lake Environments (SALE)

A.2 Submission:

Through the Standing Scientific Groups for Life Sciences and Geosciences by the Subglacial Antarctic Lake Exploration Group of Specialists (SALEGOS). Endorsed by the LSSSG and GSSSG in Bremen, July, 2004.

A.3 Program Duration:

January 1, 2005 to December 31, 2013. Six years of meetings and planning with two years for final synthesis and reporting.

A.4 Estimated SCAR Funding :

Total Core Program: $200,000 ($25,000/year), Expected Total Supplemental Requests: $120,000 ($15,000/year)

A.5 Program Executive Summary:

It is proposed to form a Scientific Research Program (SRP) entitled "Subglacial Antarctic Lake Environments (SALE)" to serve as the international focal point of SCAR's activities to promote, facilitate, and champion cooperation and collaboration in the exploration and study of subglacial environments in Antarctica. SALE will be constituted for a period of eight years with twelve members' representative of the disciplines and expertise fundamental to subglacial lake exploration and study. SALE will:

- guide the development and implementation of the SRP's activities including changes in course as indicated by events and progress;
- encourage and facilitate communication and collaboration between scientists and technologists involved in subglacial lake environment exploration and research;
- advise the international community through SCAR on scientific and technology issues including addressing environmental concerns and proposing safeguards;
- promote partnerships, collaboration, data and sample access, common data management protocols and data sharing to facilitate and expedite the advancement of Antarctic science and knowledge;
- summarize and report results to the wider scientific community, policy makers, and the lay public in available venues;
- encourage adherence to the agreed guiding principles for subglacial environment stewardship, exploration, research, and data management;
- advocate subglacial lake environments exploration and research to National Committees, scientific communities, policy makers, and the lay public;
- establish scientific liaisons and logistics cooperation with other Antarctic entities and activities in close partnership and coordination with COMNAP;
- respond to requests from SCAR for expert advice in a timely manner including convening of expert groups when needed:
- maintain an up-to-date inventory of subglacial lakes, develop a standard identification scheme, and maintain a current bibliography;
- provide advice on minimization of contamination for entry, sensor package deployments, and sampling technologies and engage independent third party experts as needed for objective advice and guidance;
- organize and conduct workshops, scientific sessions, and symposia;
- provide a web site with links to activities related to subglacial lake environments including national programs, meetings, reports, and data repositories;

- convene and conduct scientific, methodological and technology workshops;
- provide a centralized focus for outreach efforts including promotional materials, an available speaker and topic list, creation of interactive tools for educating the public, meeting reports, regular press releases, and contact information for the media; and
- develop and promote common protocols and standards for data management to ensure access, quality and comparability across programs including the development of a portal to data repositories held by others.

The overarching scientific objectives of SALE are:

- To understand the formation and evolution of subglacial lake processes and environments.
- To determine the origins, evolution and maintenance of life in subglacial lake environments.
- To understand the limnology and paleoclimate history recorded in subglacial lake sediments.

The proposed SRP for SALE supports SCAR's mission, vision, and goals as outlined in the "First SCAR Long Range Strategic Plan" by providing a venue to ensure SCAR leadership in leading-edge interdisciplinary Antarctic exploration and science. SALE will facilitate and coordinate research among interested nations to develop greater scientific understanding of the nature and evolution of the Antarctic region and its processes, the role of Antarctica in the Earth System with particular reference to changing climate, and provide a basis for understanding the effect of global and human change by deciphering the past evolution of the continent and life over millions of years. The new knowledge gained about the workings of the Earth System will be communicated to policy makers and the lay public in understandable formats. SALE will be an advocate for environmentally sound subglacial lake environment exploration and research. While environmental, logistical and technological challenges are many, SALE will closely coordinate it efforts with COMNAP, national committees, and the ATCM to ensure that the best available knowledge is brought to bear on the varied issues that must be addressed. The SALE network will allow countries to participate at a level commensurate with available national resources while benefiting from a team effort intended increase the capacity of all of its members by sharing of collective expertise, experiences, and knowledge. Subglacial lake environments have already generated great public interest and SALE will capitalize on this interest with a vigorous outreach program that will assist in incorporating Antarctic sciences into the education process from "K-Gray" and communicate findings to the public.

Subglacial lake environments are emerging as a major new frontier theme of the International Polar Year in 2007-2009. The designation of SALE as a SRP will position SCAR to be a leader in the International Polar Year (IPY) in this topical area. SALE provides an international focal point for the exploration and study of subglacial lake environments. Initial plans have been agreed to form an international network of exploration and research programs under the auspices of SALE to coordinate activities during the IPY 2007-2009 and after [see Appendix D - SALE - UNified International Team for Exploration and Discovery (SALE-UNITED].

B. Program Plan

Over the past decade a series of international workshops, and meetings of a group of specialists; have developed an interdisciplinary science and technology plan for the exploration and study of subglacial lake environments. The Subglacial Antarctic Lake Exploration Group of Specialists (SALEGOS) was duly constituted by SCAR in Tokyo in the year 2000 and the membership was agreed upon. By the time of this proposal, SALEGOS will have held six meetings and produced meeting reports for each.

- Meeting 1: Bologna, Italy, November 2001.
- Meeting 2: New York, USA, May 2002.
- Meeting 3: Santa Cruz, USA, October 2002.
- Meeting 4: Chamonix, France, April 2003.
- Meeting 5: Bristol, UK, October 2003.
- Meeting 6: Bremen, Germany, July 2004.

SALEGOS members concluded that the group's Terms of Reference have been met fulfilling the mandate as originally envisioned. SALEGOS members recommended that the Group of Specialists be disbanded in July, 2004. SALEGOS members also recognized that SCAR has an interest in continuing to foster international cooperation in subglacial lake environment exploration and that an organization with the appropriate expertise is needed to continue to serve in an advisory role. As such, SALEGOS recommended the formation of a SCAR Scientific Research Program entitled "Subglacial Antarctic Lake Environments (SALE)".

B.1 Scientific Objectives

To understand the complex interplay of biological, geological, chemical, glaciological, and physical processes within subglacial lake environments an international, interdisciplinary plan for coordinated research and study is essential. The overarching scientific objectives that will guide subglacial lake environment exploration and research are:

- To understand the formation and evolution of subglacial lake processes and environments.
- To determine the origins, evolution and maintenance of life in subglacial lake environments.
- To understand the limnology and paleoclimate history recorded in subglacial lake sediments.

These objectives can only be accomplished by integrated and coordinated phases of discovery and hypotheses-driven research over at least a ten-year period (See Appendix B SALE Scientific and Technological Milestones). The scientific objectives will be addressed through a series of projects which form a comprehensive research program for the exploration of subglacial lake environments. Each research project will be defined by its own scientific objectives and requirements for logistics and technology. Together the portfolio of projects advances the overall program. The timing of individual projects, while interrelated, will ultimately be determined by the resources and technologies available and the priorities of individual National Antarctic Programs. The projects are not necessarily sequential and several may be pursued in parallel. However, some later objectives are dependent on the information, results, and technological advances provided by earlier phases of research. Below specific scientific objectives provided for each area of discovery. While there are disciplinary based objectives, in most instances, attainment of the objectives requires an interdisciplinary approach and team effort.

B.1.1 Functional Genomics and Phylogenetics

Examine organisms in terms of their genomes (their full DNA sequences), including gene function as well as their phylogenetic relationships; search for extinct and extant life signatures in the overlying ice sheet (glacial and accretion ice) to determine the possible origins of biotic constituents to the underlying lakes; and determine the genetic diversity in the water accumulations and benthic sediments of subglacial lake environments.

B.1.2 Limnology

Determine biogeochemical processes and metabolic activities in the water accumulations and sediments of subglacial lake environments and relate these to genomic data; measure vertical density gradients and use these to model water motion; examine the geochemical and isotopic composition of selected lake water constituents to determine their role in biological processes, water column stability, and to establish the age of subglacial lake environments water; and compute the hydrological budget for and hydrological linkages among subglacial lake environments.

B.1.3 Geophysics

Identify and measure subglacial lake surfaces using radio echo sounding; determine the bathymetry of subglacial accumulations of water and sediment thickness from seismic measurements; and understand the tectonic and ice sheet setting of subglacial lake environments through geological analysis of geophysical data.

B.1.4 Glaciology

Measure the flow of ice over subglacial lake environments through direct surface measurements and satellite data; understand the interrelation between ice sheet processes and water circulation; and Identify the formation and evolution of subglacial lake environments using numerical models of ice sheet history.

B.1.5 Geology and Cenozoic Paleoclimate

Understand the origin, transport and deposition of subglacial sediment and relate surface sediment in each sub-environment to extant process; use paleo-environmental data to determine water and ice sheet histories, and evaluate temporal changes in Cenozoic paleoclimate relative to those histories determined from Antarctic marginal sequences and global Cenozoic proxy records; and examine sediment mineral composition and chemistry and sample geological bedrock to establish the basinal tectonic setting and its temporal evolution. The importance and occurrence of subglacial lakes over geologic time will also be an area of research. "Paleo" considerations will be pursued in close collaboration with ACE (see Section B.4.1 Links with Other Proposed SCAR Activities).

B.2 Background

Beneath the thick East Antarctic Ice Sheet, water has accumulated over millennia forming subglacial environments ranging in size and form from Lake Vostok, an expansive body of water the size of Lake Ontario, to shallow frozen swamp-like features the size of Manhattan. Although similar in size to these more familiar landmarks, subglacial lake environments in Antarctica remain virtually unexplored and unknown. Over 145 features have now been identified suggesting that the subglacial environment may well be an immense interconnected, hydrological system that has previously gone unrecognized. Whereas the full extent and the interconnectedness of this major earth system are not yet fully known, the potential drainage systems identified are as extensive as large continental river basins. These environments have formed in response to a complex interplay of tectonics, topography, climate and ice sheet flow over millions of years and contain a previously unaccounted for reservoir of organic carbon. Sealed from free exchange with the atmosphere for possibly 10 to 35 million years, subglacial lake environments are analogous to the icy domains of Mars and Europa that hold the greatest promise for the presence of life beyond earth. Tantalizing evidence from studies of the overlying ice sheet indicates that unique life supporting ecosystems are likely locked within subglacial lake environments. Such life must have adapted to the temperatures, pressures, gases, and carbon and energy sources, which are akin to the deep ocean coupled with the inordinately slow delivery of constituents (nutrients, organic matter, gases) from the overriding ice sheet. These settings are probably the most oligotrophic on the planet and may harbor specially adapted organisms and ecosystems. Seismic, geochemical and genomic studies point toward the influence of local tectonics in setting boundary conditions under which these subglacial lake systems have evolved.

At about 35 million years ago, the climate of Antarctica shifted from a tree-covered continent to a region locked beneath ice. Recovery of a comprehensive record of this major climatic shift has remained elusive, especially for the interior of the continent. The region of highest subglacial lake density rings what is likely to have been one of the nucleation points of the East Antarctic Ice Sheet and has tremendous potential for containing paleo-records of these major shifts in climate. Numerous, targeted drilling efforts around the perimeter of the continent have thus far failed to recover continuous paleoclimate sedimentary records that are essential for understanding the evolution of global and regional climate. Subglacial lake environments may provide a signature of past climate as well as limnetic biogeochemical processes. In contrast to the East Antarctic Ice Sheet, the West Antarctic Ice Sheet may have responded dramatically to Quaternary environmental changes. Lakes beneath the West Antarctic Ice Sheet could contain unique records of ice sheet variability over the last few hundred thousand years, which could critically advance our understanding of ice sheet stability.

B.3 Enabling Technologies

Although SALE is structured as primarily a scientific program, the technological challenges and environmental stewardship issues are not underestimated. The stages of exploration, as detailed in the Cambridge workshop (1999), were seen as a useful starting point for further and more detailed consideration of the requirements for subglacial lake environment exploration (SALEGOS Meeting Report 1). Some technologies are already in place and can be used immediately if financial and logistical support is available (i.e., airborne radar, magnetic, and gravity and land based seismic surveys). Conversely, other technologies will require developmental efforts. Operational sensors that could be deployed within lakes exist for some of the more fundamental properties, whereas more complex sensor arrays will require development. Initial discussions suggest that standard oceanographic sensor arrays for pressure, temperature, conductivity, transmissometry (suspended particle detectors), fluorescence detection and current velocity have been developed to meet similar operational requirements of temperature and pressure. Other less mature in situ sensors are available for important parameters such as dissolved oxygen, nutrients and geothermal heat flux. More experimental sensor arrays would need to be developed for the detection of other dissolved gases (H2S, CH4, N2O, N2, Ar), major anions and cations, and bioreactive redox couples such as ammonium and dissolved manganese. Even available sensors will need to be field tested for compatibility with the expected temperature and pressure regimes of subglacial lake environments and environmental restrictions. Another requirement will be the suitability of the size of the sensor packages and the size of lake access holes. The limitations on the borehole size may require miniaturization of existing technologies.

Sample recovery has its own set of challenges. Again, standard oceanographic techniques for remote collection using water sampling bottles (e.g., Rosette Samplers with Niskin bottles) and sediment retrieval by coring devices (piston corers, gravity corers, box corers, grab samplers, etc.) may be compatible with subglacial environments. Other specialized techniques may need to be developed. One suggestion is the use of in situ filtering devices to process large volumes of water to concentrate particulates for analysis in a clean surface laboratory following retrieval of the device. Sediment trap technologies and other water particulate collection devices are adaptable to subglacial environments. The use of ROVs and associated sample collection abilities were discussed in an NSF sponsored workshop held on 27 March 2003 in Palo Alto, California and offered a promising way to sample certain environments over important spatial scales. As with sensor arrays, the size of the entry hole and compatibility with decontamination procedures are additional requirements for sampling devices including ROVs and other technologies. Geological drilling technologies remain to be fully developed; however the current Antarctic Geological Drilling (ANDRILL) Program is establishing technology and techniques (a 2000 m long drill string through up to 300 m thickness of floating ice on the sea) that are moving closer to what is required for subglacial lake sediment recovery.

A critical aspect of subglacial lake exploration and technology development is testing, verification and monitoring for potential contamination during all phases of the scientific program. There must deliberate and careful scrutiny of the methodologies employed, from ice drilling to sample recovery, both from an environmental stewardship and scientific standpoint. Stewardship issues include providing the maximum possible protection of subglacial lake environments by ensuring minimal alteration or change due to the planned scientific studies. From a scientific standpoint, it is essential that uncompromised samples be provided for study and that the presence of human-made devices does not bias the data collected. There is also concern that unusual or previously unknown biological agents be properly handled upon retrieval to avoid an unwanted release to the environment. Contamination may arise not only from the introduction of chemicals (toxic, nutritive, or otherwise) into the lake but also from the potential introduction of non-indigenous microorganisms. In addition, due to the presumed highly oligotrophic nature of the lakes, redistribution of water and sediments within the lakes must be minimized during any in situ operation. While these are difficult issues, much can be learned from the history of exploration of the McMurdo Dry Valley Lakes, the Ocean Drilling Program and NASA's experience in planetary protection. There is a need to test contamination procedures at all stages of processing and planetary protection rules serve as a guide for the development and testing of subglacial lake exploration technology.

The general approach of development and testing of technologies in more accessible and less environmentally sensitive analogue locations is crucial for environmental stewardship. Analogues include frozen lakes, ice shelves, and the upper portions of ice sheets in both the northern and southern hemispheres. Existing ice drilling techniques appear to be capable of meeting the field requirements for penetration of 4 or more kilometers of ice, penetrating low temperature (sub-zero) and high pressure regimes. The challenge for ice drilling is demonstration of the ability to do so with minimal and/or acceptable levels of contamination. For example, hot water techniques used with coiled tube drilling technology could replace chemical fluid-based drilling and still be able to maintain bore hole integrity for periods of time ample enough to conduct experiments, introduce sensor arrays and retrieve samples. Techniques are needed to ensure the purity of the drilling water fluid to avoid contamination from surface microbes. There may be solutions to this requirement in methods currently proposed to sterilize (UV radiation, ozonolysis) ballast waters in ships that prevent the introduction of non-indigenous species. And finally, decontamination techniques must be developed for any packages that would be delivered into a lake. The current approaches are sterilization by heat (autoclave) and/or chemical treatment (peroxide). Any instrument packages must be able to survive these decontamination protocols and maintain their operational specifications. The possible interconnection of subglacial systems will be considered in any assessment of the potential for compromising these environments during entry and sampling activities.

B.4 Program Justification

Over the past decade a series of international workshops and a Group of Specialists have been convened to develop an interdisciplinary science and technology plan for the exploration and study of subglacial environments. These planning efforts have been supported by the US National Science Foundation (NSF), the US National Aeronautic and Space Administration (NASA), the Russian Antarctic Expedition (RAE), the International Council for Science's (ICSU) Scientific Committee on Antarctic Research (SCAR), and others. Plans resulting from these efforts are extensive, well advanced, and detailed in scope and content. Within the next few years, current survey programs will be expanded to include intensive logistical efforts to survey, penetrate and sample the lakes. The phase of entry into these environments will require significant international collaboration, cooperation and coordination. The creation of a SCAR SRP to aid in facilitating these events and activities is critical and timely.

B.4.1 Links with Other Proposed SCAR Activities

The proposed SALE program will continue to build on past efforts and has elements and objectives that complement two other SRPs being proposed to SCAR; Antarctic Climate Evolution (ACE) and Evolution and Biodiversity in Antarctica (EBA).

The main objective of the ACE Program is the acquisition and compilation of "ground truth" geoscience data and the use of these data in developing a suite of paleoclimate models for the Antarctic region. ACE and SALE will interact in two ways. First, the paleoclimatic record contained in subglacial lake sediments will provide important new information from the interior of the continent. ACE and SALE will collaborate on the acquisition of such records. Second, the ice sheet history quantified through numerical modeling as part of the ACE program will offer important constraints on the formation and development of subglacial lake environments. ACE will provide SALE with model results in order for the history of subglacial lakes to be established in the context of ice sheet and climate evolution."

The proposed SCAR Program "Evolution and Biodiversity in the Antarctic (EBA)" aims to improve and expand fundamental understanding of the evolutionary history, current biology and biodiversity of Antarctic biota in both a climatic and tectonic context. The evolutionary process of life pervades all levels of biological organization from molecules to ecosystems. Subglacial lake environments offer a unique opportunity to examine biodiversity and evolutionary responses in isolated systems that provide analogues for life on early Earth and other planetary bodies. Novel responses to the environment are likely to be found in these lake systems, which are important end-members for biodiversity and polar community dynamics.

The objectives of ACE and EBA are complementary and supportive of many of the scientific objectives of SALE. The synergy among these SCAR programs will be encouraged and facilitated. Joint planning, meetings and coordination will be enured by appointing liaisons between the programs.

Subglacial lake environments have been identified as an area of scientific interest for the burgeoning efforts related to the IPY and IGY celebration in 2007-2009. The designation of SALE as a SRP is an important step for SCAR involvement in the IPY. SALE provides a focus for international efforts in subglacial lake environment exploration and study an important element of the IPY theme exploring new frontiers (see Appendix D).

B.4.2 Engaging Other Countries and Arctic Studies

Other countries' participation, especially smaller countries with limited resources, will be encouraged by inviting scientists to workshops and meetings, wide dissemination of information and data, and active promotion of partnerships among interested parties. Specific activities that are less resource intensive include modeling studies, sample analysis after retrieval, re-analysis of data, and sample sharing. The SCAR Executive will canvas all SCAR nations requesting indications of interest in the SRPs. SALE leadership will take these expressions of interest under advisement as the program develops. Initially SALE will also discuss policies and procedures for archiving the samples recovered and making them generally available to the community.

Relevant projects in the Arctic will be contacted and encouraged to share information with SALE. In particular, studies of life in ice will provide complementary and supporting information. A standing agenda item for SALE will be related or corollary studies and Arctic connections will be specially emphasized.

B.5 Preliminary Implementation Plan

An orderly transition from SALEGOS to SALE by 2005 is proposed:

- Submission of the transition plan to the SCAR Executive, May 2003 –Complete
- Transition plan considered by the SCAR Executive Committee, July 2003, Brest, France. - Approved for Final Proposal Submission.
- SALEGOS Meeting V October 14 and 15, 2003, Bristol, UK. – Complete.
- Revision of transition plan based on SCAR Executive Committee response, October 2003. - Complete
- SALEGOS Meeting VI to be held in conjunction with the SCAR Science Conference in Bremen, Germany, July 2004 (final meeting) - Complete
- Submission of the SRP Proposal to the SCAR Standing Scientific Groups (SSGs), endorsed by the LSSSG and GSSSG Bremen, July 2004. – Complete
- Revise SRP proposal according to new SCAR review criteria– Complete.
- SCAR Executive Committee and SSG recommendations to SCAR Delegates Meting, Bremerhaven, Germany, October 2004 –Complete
- First SALE meeting 2005.

B.6 Program Management

A detailed and specific plan for program management will facilitates wide participation, efficient operation, and the flexibility to evolve as the program matures. Responsibilities are clearly described to ensure that all components of the SALE mission and objectives receive adequate attention and focus. Subcommittees will be formed to concentrate efforts on issues of special importance, such as data management and outreach.

B.6.1 Scientific Steering Committee

The program will be managed by a Scientific Steering Committee (SSC) of twelve members with the scientific and technical expertise and experience necessary to successfully conduct the program. Each member will have a significant and clearly identified role related to a critical scientific discipline, environmental stewardship issues, and/or a technological challenge supportive of the overarching scientific objectives. At the inaugural SALE meeting a Convener, Deputy Convener and Secretary will be elected by the members. The committee would meet at least once a year and conduct the rest of its business electronically. Members would serve for a 4-year term, with the possibility of extension for a second term depending on contribution and performance. The committee membership should ensure the necessary breadth of knowledge to adequately address all relevant thematic/disciplinary/technological/environmental topics. This core of experts will be supplemented as needed by invitation of guest scientists and technologists to SALE meetings, regular review of SALE membership, and through liaison relationships with other organizations such as COMNAP, AEON, complementary SCAR SRPs, and others as appropriate. SALE will actively interact with EBA and ACE as to promote synergy and common interests. SALE will designate representatives to these other programs to ensure synergy, communication and collaboration.

SALE's initial membership should cover the following scientific and technological areas:

- limnology/ecology
- genomics/molecular ecology
- hydrodynamics
- geophysics and survey techniques
- glaciology
- geology/tectonics
- geochemistry
- Cenozoic paleoclimate
- ice drilling techniques/access
- observatories
- remotely operated and autonomous vehicles
- sample recovery and processing
- specialized analytical techniques
- environmental issues and clean technologies

Recognizing the budgetary limits on membership, guest speakers will be invited to committee meetings as needed when expertise beyond that of the committee is required to address an issue.

Table 1. Criteria for Membership on SCAR SRPs

- Appointment is by the SCAR Executive with approval of the Delegates.
- Primarily based on scientific expertise
- A mix of skills, experience, national representation, and gender should be maintained
- Terms are four years with the possibility of one four year extension
- A membership rotation scheme should be adopted that maintains program continuity
- A mix of expertise commensurate with the issues before the program should be maintained

Membership on the SALE SRP committee is open to all SCAR nations, targeting those with an interest in subglacial lake environments. The initial SALE membership should draw heavily on the current SALEGOS membership for continuity with a request for each interested National Committee to review its membership on the committee. Appointees should be selected based on a combination of national representation and expertise in relevant disciplines (as outlined below). We note that multiple persons from a single country may be appointed as members of SALE. Importantly, members should be enthusiastic proponents of subglacial lake environment exploration and research. Following the recommendations of SALEGOS, it is expected that each interested nation will form a National Scientific Steering Committee (NSSC). It is strongly recommended that SALE membership include liaisons with these national committees to improve communication, coordination, and collaboration.

B.6.2 Terms of Reference

SALE will operate under the general SCAR Terms of Reference (TOR) for Scientific Research Programs (SRPs) amended with program specific TORs:

- Oversee and guide the development and execution of the SRP's activities including changes in course as indicated by events and progress.
- Encourage and facilitate communication and collaboration between scientists and technologists world-wide involved in the exploration of subglacial lake environments while seeking support for the program through national and international mechanisms.
- Advise the international community through SCAR on scientific and technology issues relevant to subglacial lake exploration including environmental protocols, procedures, concerns and safeguards.
- Promote collaboration, data access and data sharing to facilitate and expedite the data syntheses needed to develop and revise the science and technology agenda for the exploration of subglacial lake environments.
- Summarize and report the results of these efforts to the scientific and wider community on an ongoing basis including regular reporting on the use of SCAR funds.
- Encourage adherence to the agreed guiding principles of exploration and research on subglacial lake environments, especially environmental stewardship.
- Be an advocate for exploration of subglacial lake environments in all venues including National Committees, scientific communities, and the public and establish scientific liaisons and logistics cooperation with other Antarctic entities and activities as appropriate.
- Respond to requests from SCAR for expert advice in a timely manner including convening of expert groups when needed (i.e., review of CEEs).
- Ensure the SRP activities are justified and supportive of the group's TOR.
- Interact and coordinate activities with other SCAR SRPs.
- Provide a centralized focus for outreach efforts including promotional materials, a web site, an available speaker and topic list, interactive tools for educating the public, a bibliography (including press releases and articles in the lay print and visual media), meeting reports, regular press releases, and contact information for the media.
- Develop and promote common protocols and standards for data management to ensure quality and comparability across programs.

SALE will neither oversee nor manage national or international field and laboratory projects or facilities other than to help guide and coordinate their development as requested. It is suggested that the first meeting of SALE review/revise the TOR for the program.

B.6.3 Plans for Data Management and Outreach

While SALE will not retain data, its web site will serve as a portal to member nations that do, making data widely available. SALE will develop a set of data management protocols and standards that all participants can agree to adhere to, to ensure comparability of data across all projects and programs. The standards will be developed by a SALE Subcommittee for Data Management Protocols and Standards in consultation with JCADM and other relevant organizations. To provide a focus for SALE outreach, a Subcommittee on Communication, Education, and Outreach will be formed to explore outreach and education options and develop a comprehensive communication, education, and information dissemination plan for SALE. SALE's outreach efforts will include, but not be limited to: the creation of promotional materials, developing an available speaker and topics list, creating interactive tools for educating the public, posting of meeting reports, and providing contact information for the media.

B.7 Deliverables

SALE will provide the following deliverables:

- maintain and make widely available an up-to-date inventory of subglacial lake features;
- a standard identification scheme for subglacial lake environments;
- a current bibliography of relevant articles from peer reviewed journals, meeting reports and the lay press;
- a website with links to all activities related to subglacial lake environments including national programs, meetings, and reports acting as a portal to data held by others;
- methodology and technology workshops in response to community needs;
- expert groups on clean sampling technologies and other environmental stewardship issues in response to community needs;
- workshops, scientific sessions, and symposia;
- review of CEEs for SALE projects and field activities as requested;
- advice on all aspects of SALE as requested by SCAR including convening of expert groups when additional expertise is needed;
- promotional materials, a web site, an available speaker and topics list, interactive tools for educating the public, a bibliography (including press releases and articles in the print and visual media), meeting reports, contact information for the media; and
- common protocols and standards for data management that ensure quality and comparability across programs.

B.8 Milestones

Workshops, symposia and special sessions at major conferences are important for fostering collaboration. The exchange of ideas in the furtherance of planning will be a primary mission of SALE.

- **Year 1** – Program Meeting - I; review/revise terms of reference, metrics of performance, scientific objectives, etc.; elect program officers; and report progress to SCAR.
- **Year 2** – Program Meeting - II; organize and hold a workshop; promote and organize SALE sessions at appropriate scientific meetings; develop a session for the SCAR Science Conference and report progress to SCAR.
- **Year 3** - Program Meeting - III; promote and organize SALE sessions at appropriate scientific meetings; develop a popular science article on SALE, and report progress to SCAR.
- **Year 4** - Program Meeting - IV; organize and hold a workshop; promote and organize SALE sessions at appropriate scientific meetings; develop a popular science article on SALE, develop a session for the SCAR Science Conference; and report progress to SCAR.
- **Year 5** – Program Meeting - V; promote and organize SALE sessions at appropriate scientific meetings, organize a major SALE international symposium.
- **Year 6** – Program Meeting - VI; promote and organize SALE sessions at appropriate scientific meetings; develop a popular science article on SALE, develop a session for the SCAR Science Conference; and report progress to SCAR.
- **Year 7** – Program Meeting - VII, organize publication of a SALE book, promote and organize SALE sessions at appropriate scientific meetings; develop a popular science article on SALE; and report progress to SCAR.
- **Year 8** – Program Meeting - VIII, publish the SALE book; develop a major keynote session for the SCAR Science Conference; and report progress to SCAR.

This timetable and the deliverables should be reviewed and revised as necessary at the first SALE meeting and reviewed at each subsequent meeting.

B.9 Metrics of Success

The measures of success of a program that serves primarily in an advocacy role are difficult to quantitatively define. However, it is important to develop metrics of performance that provide SCAR with some indication of a program's impact. The following are proposed as possible metrics of performance for the SALE SRP:

- workshops held, attendance, and reports produced;
- sessions focusing on exploration and research of subglacial lakes (number and quality) held at national and international meetings, attendance, and resulting proceedings publications;
- peer-reviewed publications each year (number and quality) related to subglacial lake exploration and research;
- articles in the popular press including numbers of interviews given by SALE members as well as website hits;
- formation of national scientific steering committees; and
- leverage of funds from other sources.

The SALE leadership will regularly canvas the community for these statistics and keep up-to-date records for annual performance reviews. It is proposed that during the first meeting of SALE that these metrics be revisited and a final set of performance criteria be agreed and communicated to the SCAR Executive for final approval.

B.10 References Cited

Report of the Subglacial Antarctic Lake Exploration Group of Specialists (SALEGOS): Meeting – 1. Bologna, Italy, 29-30 November 2001. 69 pp.

Report of the Subglacial Antarctic Lake Exploration Group of Specialists (SALEGOS): Meeting – 2. Lamont-Doherty Earth Observatory, USA, 23-24 May, 2002. 39 pp.

Report of the Subglacial Antarctic Lake Exploration Group of Specialists (SALEGOS): Meeting – 3. University of California at Santa Cruz, USA, 2-3 October, 2002. 19 pp.

Report of the Subglacial Antarctic Lake Exploration Group of Specialists (SALEGOS): Meeting – 4. Chamonix, France, 4-5 April 2003. 38 pp.

Report of the Subglacial Antarctic Lake Exploration Group of Specialists (SALEGOS): Meeting – 5. Bristol University, UK, 14-15 October 2003. 12 pp.

SALEGOS membership. An International Plan for Subglacial Lake Exploration. 2004. Polar Geography, In review.

SALEGOS membership. Subglacial Antarctic Lake Environments: International Planning for Exploration and Research. EOS, In review.

Appendix A
Subglacial Antarctic Lake Environments – UNified International Team for Exploration and Discovery (SALE-UNITED) in the IPY 2007-2009

ICSU and various national IPY planning committees include references to subglacial lake environments as a potential IPY 2007-2009 activity under the exploring new frontiers theme. To coordinate the multiple ideas submitted to ICSU and national committees as part of the IPY planning process, SALEGOS proposes that all nations with interests in subglacial lake environments join together under the auspices of the SCAR SALE SRP to promote international collaboration and partnerships. This alliance is referred to as SALE – UNified International Team for Exploration and Discovery (UNITED) and its mission and terms of reference are provided below.

Subglacial Antarctic lake environments are emerging as a premier, new frontier for exploration during the IPY 2007-2009. Several coordinated campaigns by various nations are in the early stages of planning and implementation. It is suggested that these efforts be coordinated under the auspices of the SCAR Scientific Research Program (SRP) - Subglacial Antarctic Lake Environments (SALE). Under the leadership of the SCAR SRP SALE, these programs would join together to promote and advance common scientific, technological, and logistical issues in close consultation with COMNAP. The coalition approach recognizes that the ambitious interdisciplinary objectives of SALE, as internationally agreed during a series of workshops, and extensive discussions of the SCAR Group of Specialists (SALEGOS), can only be realized by multiple exploration programs that will investigate exemplars of the diverse subglacial environments over the next decade or more. The IPY provides an opportunity for an intensive period of initial exploration that will advance scientific discoveries in glaciology, biogeochemistry, paleoclimate, biology, geology and tectonics, and ecology to a new level that could not otherwise be achieved by a single nation or program.

Each program will be an independently managed campaign with specific scientific objectives, logistical requirements, and management structure that will contribute to, and accrue added value from, a common international research agenda. Synergy is provided by the pooling of resources were appropriate, the sharing of experiences and expertise, the coordination of logistics and technological developments, and a shared vision. The SCAR SRP SALE will serve as the international science and technology steering committee with a subcommittee structure representing the major scientific disciplines and technological needs. The steering committee (SALE) will be comprised of the leaders of each program supplemented by international experts as needed.

The following are brief summaries of the projects being pursued by groups that have tentatively agreed to join SALE-UNITED:

- United Kingdom/US – UK researchers and partners are conducting a diverse set of projects that are expected to continue during and after IPY 2007-2009 including: numerical models of hydrological processes of subglacial environments; in collaboration with the US, studies of ‘accreted’ ice particles dynamics and origins in subglacial environments using models; studies of subglacial topography to establish basin origins; surveys and inventory of subglacial lakes continent-wide; and surveys of and entry into Subglacial Lake Ellsworth in West Antarctica to be conducted by a coalition of 9 UK universities and research institutions.
- US – ROV development for ice grounding studies including water and sediment sampling.
- US – AUV development for intra-lake surveys that include physical, chemical, and biological efforts.
- US – Geophysical surveys, lake evolution studies and modelling, ice sheet interactions concentrating on the Lake Vostok region, and accretion ice studies.
- US/France/Italy/Germany – Subglacial Lake Concordia will be a site for exploration and technology development including lake entry and sampling, and microbiological, geochemical, and genomic studies (in collaboration with the German IDEA traverse project),
- Russia – Over-snow geophysical studies (radar profiling and reflection/refraction seismic experiments) in the area of Lake Vosto. It will include subglacial lake bedrock, shoreline topography, ice sheet and water circulation modelling, and ice sheet/water interaction studies.
- Russia - Airborne geophysical surveys over the East Antarctic Highland between 75°E and 110°E.
- Russia - Lake Vostok accretion ice retrieval (3623 – 3700m) (further drilling towards lake and inclined core for repetitive analyses),
- Russia – Clean Lake Vostok drilling technology development, lake entry, water sampling, and eventual sediment sampling (implementation of this project will require a permit from the national Inter-Ministry Commission on Consideration of Applications of the Russian Physical Persons and Legal Entities on Activity in the Antarctic Treaty Area); development of the observatories and sampling devices that are ecologically clean. Technologies will be developed to transport equipment through the borehole drilling fluid of the borehole including full-scale trials.
- Russia – Deep ice core drilling for paleoclimate and Lake Vostok research in the northern part of Lake Vostok.

- Russia/France – Complex studies of Vostok ice core for microbiology/molecular biology, glaciology, ice chemistry and dynamics, and gas content.
- Russia/France/Denmark – Analogous lake (e.g. Radok) and ice (e.g. EPICA, North GRIP 'red ice') studies for microbiology and genomics,
- Italy – Detailed surveys and glaciological investigations of Dome C and the Dome C "Lake District".
- France/Italy – Dome C glaciology, chemistry and ice dynamics studies.
- France/Russia/Italy - Technology development for access hole for ice geophysics (temperature, inclinometry measurements) and bedrock sampling. Clean technology development for lake entry, permanent access and sediment collection in small sub-glacial lakes or lake-like features.

A common effort will be the development, implementation and promotion of environmentally benign procedures for subglacial lake environment exploration and research programs properly vetted through national and ATCM procedures. With proper planning and careful and methodical technology development and testing SALE can be an exemplar of environmental stewardship.

The concerted multi-target approach will assure the widest possible characterization of subglacial lake environments beneath the East and West Antarctic Ice Sheets. This will advance our understanding of the range of possible lake evolutionary histories; the character of the physical, chemical, and biological niches; the interconnectivity of subglacial lake environments; the coupling of the ice sheet, climate and the evolution of life under the ice; the tectonic setting; and the interplay of biogeochemical cycles. Research and exploration programs spanning the continent will allow for complementary investigations of subglacial lake environments of differing ages, evolutionary histories, and biogeochemical settings providing a holistic view of these environments over millions of years and under changing climatic conditions. While early discoveries and exciting findings are expected during the IPY 2007-2009, a long term sustained program of research and exploration will continue far beyond 2009.

To form a mutually beneficial network of programs, SALE–UNITED will operate under these guiding principles:

- Members retain autonomy to make decisions in the best interests of their program while taking into consideration the interests of other programs and the potential for synergies.
- Programs will pursue funding through their national procedures while looking for opportunities to develop joint funding across programs.
- Open and timely access to data and samples will be provided for other SALE-UNITED programs and the broader scientific community while protecting the intellectual property of individual investigators and programs.
- Participation in inter-comparisons and inter-calibrations of techniques and methodologies will be conducted to ensure quality and comparability of information across SALE-UNITED programs.
- Agreed data management protocols and standards will be adopted.
- Technological developments and "lessons learned" will be shared while protecting ownership and/or proprietary information.
- When appropriate joint publications and presentations will be encouraged when all involved stand to accrue benefits.
- Due consideration of "add-on" or "spin-off" projects by others will be provided when it does not compromise individual programmatic efforts but advances the common SALE-United mission.
- Assist in the promotion and communication of SALE-United goals, accomplishments, and findings.
- Respect and value the contributions of all SALE-UNITED members.

Appendix B.

SALE Scientific and Technological Milestones

SALE has put forward a comprehensive plan for facilitating and coordinating the exploration and study of subglacial lake environments. The scientific objectives will be accomplished by a network of independent but synergistic programs to be conducted by individual nations or teams of scientists from several nations. While the ultimate goal is entry, sampling and characterization of subglacial environments like Lakes Vostok, Concordia, Elsworth; analogue settings such as Dry Valley lakes, can provide valuable information and experiences to guide planning and implementation of the ambitious SALE agenda. In our planning activities related corollary and complementary programs and projects are included that will inform the work of SALE.

SALE involves technological challenges and objectives as well as scientific goals. A range of milestones have been developed that include specific activities as well as basic scientific questions. Since SALE is the continuation of SALEGOS, many activities and projects are already in progress and will be accomplished in the near term. Longer milestones will be dependent on securing funding and completion of field programs yet to be scheduled. Programs and technological development activities are listed in the year they start but many continue over a period of years with milestones being accomplished sequentially. More detailed timelines and milestones can be found in each program's planning documents. These milestones will be regularly revisited/revised and will assist in setting the agenda for future SALE meetings.

Scientific Milestones

2004/2005

1) Continuing studies to establish the organic carbon content and origins within the Vostok accretion ice to define carbon/energy sources for supposed microbial communities in the lake and test the hypothesis of ultra-low DOC content in Lake Vostok (Russia, US, France).
2) Continuing studies of solid (mineral) inclusions in the accretion ice to decode depositional conditions in the western shallow bay of Lake Vostok, mode of debris transportation to the lake bottom, the geological nature (rock composition and age) of the western lake coast and to test the hypothesis of a hydrothermal contribution to Lake Vostok (Russia).
3) Updated inventory of subglacial lakes (UK)
4) Further retrieval of additional Lake Vostok accretion ice (3623 – 3700m) for further characterization of ice chemistry and microbiology (Russia).
5) Over-snow radar profiling and reflection seismic experiments in the area of Lake Vostok to study lake boundaries, shore bedrock topography, lake bathymetry, sub-ice environments and to model ice sheet and water circulation, and ice sheet/water interaction (Russia).
6) Assess the biological contents preserved within East Antarctic Ice Sheet in relationship with past climate. Evaluate the potential of East Antarctic ice cores (e.g.: Vostok, Epica Dome C, Epica Droning Maud land) for providing records of the biological Aeolian input over period encompassing 1 million years. Expected outcomes: i) record of biological emission from ocean and continent (possible link with EBA), ii) estimate of the longest time limit for DNA survival in ice (France, Russia, Denmark).
7) Assess the biological content linked to the in-situ biological activity within the ice sheet and the basal ice of deep ice cores using microscopy and DNA-based methods. Test the hypothesis of biological activity in ice layers enriched with possible microbial gaseous by-products. (France, Russia, US, Denmark)
8) Assess the microbial content of Lake Vostok from accretion ice studies. Test the hypothesis concerning the sterility of Lake Vostok (main water body) sterility and the microbial thermophilic signatures and hydrothermal contribution to Lake Vostok coming from the bottom (France, Russia, US).
9) Assess the cycles of major chemical elements, organic carbon compounds, heavy metals, and gases for Lake Vostok. Evaluate the physical and chemical properties of accretion ice formed in shallow and deep waters over the lake as proxies of actual lake water properties. Test hypotheses concerning: i) the accumulation of atmospheric gases in Lake Vostok and specifically high oxygen tension, ii) potential hydrothermal contributions to Lake Vostok and iii) lake water contributions from a possible ancient evaporitic reservoir to Lake Vostok (France, Russia, US, Italy).
10) Assess Lake Vostok the heat and mass balance using water geochemical components such as : 2H, 18O, 3He, 4He. Conduct tests to determine if Lake Vostok is a closed system or part of an ice melt network. Constrain the geothermal heat flux, the exchanges of water and heat with the overlying glacier, and the water circulation (France, Russia, US, UK).
11) Assess the origin and evolution of Lake Vostok (link with ACE). Evaluating origin of the sediments trapped into the accretion ice. Evaluate the recent geological settings, thickness and coverage of sediments at the bottom of the lake. Estimate potential of sediment to depict episodes before the Antarctic glaciation (France, Russia, US)

2006/2007

1) Characterization of subglacial Lake Ellsworth morphology and geological setting by remote sensing (pending – UK)
   a. Mapping of lake extent and subglacial drainage basin, from radio-echo sounding; Determination of lake bathymetry, from seismic sounding; Measurement of lake-floor sediment thickness (and possible structure) from seismic sounding. These measurements will reveal the best cite within the lake for the exploratory mission, planned for 2008/9.
2) Continue geophysical observations (over-snow radar profiling and reflection/refraction seismic experiments) in the area of Lake Vostok to study lake boundaries, shore bedrock topography, lake bathymetry, sub-ice environments and to model ice sheet and water circulation, and ice sheet/water interaction (Russia).
3) Characterization of the origins of surface and basal ice recovered in the Vostok ice core using shallow cores and radars along the flow line (US/French-pending).
4) Continue investigations under items 6 to 11 from 2004-2005.

2007/2008

1) Characterization of ice flow (from surface GPS measured over two seasons, starting 2006-7) and ice accumulation (from surface measurements and snow pits, measured over two seasons, starting 2006-7) over subglacial Lake Ellsworth: Season 2 (pending – UK)
2) Determination of water circulation in Lake Ellsworth; using computational fluid dynamics modeling, and data acquired in 2006/7 as inputs and boundary conditions.
3) Airborne geophysical surveys over Princess Elizabeth Land (to the East of 75 degrees E) to study bedrock topography, sub-ice environments, subglacial lake distributions and crustal structure of this previously unstudied region of Antarctica (Russia)

2008/2009

1) Descriptions of the physical conditions in Lake Ellsworth from direct measurement (UK)
   a. Measuring whether the water in Lake Ellsworth is chemically and/or thermally stratified with respect to depth (using a CTD probe)
   b. Visualization of Lake Ellsworth (using a video probe)
2) Description of the geochemistry, microbiology and sedimentary records in Lake Ellsworth from direct sampling (UK)
   a. Characterization of particle size and lithology of lake-floor sediments, from sedimentological studies of lake-floor samples.
   b. Determination of the nature of the climate 'record' within lake-floor sediments (we will not know the nature of this until samples are returned)
   c. The identification of life, using life-marker chips in board probe, and using microbiological investigations of samples. The variability (through the water column) of life, and its relation to physical environment, will be measured in situ and through sample return (which will require subsequent laboratory work).
   d. Quantification of water currents in the lake, using electrochemical techniques.
3) Continuing airborne geophysical surveys over Princess Elizabeth Land and in the area to the north-east of Lake Vostok to study bedrock topography, sub-ice environments, subglacial lake distribution and crustal structure of this Antarctic region (Russia)
4) Continuing geophysical observations (over-snow radar profiling and reflection/refraction seismic experiments) in the area of Lake Vostok to study lake boundaries, shore bedrock topography, lake bathymetry, sub-ice environments and to model ice sheet and water circulation, and ice sheet/water interaction (Russia).

Technological Milestones

2004/2005

1) Development of a vibrating drill to sample the 20m thick ice cover of Lake Vida (McMurdo Dry Valleys) and search for life –funded (US).
2) Development of clean Lake Vostok drilling technologies (implementation of this project will require a permit from the national Inter-Ministry Commission on Consideration of Applications of the Russian Physical Persons and Legal Entities on Activity in the Antarctic Treaty Area). Technologies will be developed to transport equipment through the borehole drilling fluid of the borehole including full-scale trials (Russia).
3) Design a fast drill system with 4km capability to be applied to ice in Antarctica (France)
4) Design "clean technologies" for ice drilling. Selection of drill fluids compatible with sub-glacial environments (France)
5) Contribute to the inventory of ice-borne and ice-related DNA signatures in open gene databases. Continue to establish comprehensive bio-decontamination protocols and DNA-targeted methods adapted to the very low biological contents of deep ice cores samples in order to decipher in situ signals from artefacts and contaminants (All nations)
6) Development and construction of a ROV-AUV system, sediment coring system and oceanographic moored observatory for sub-ice shelf and subglacial lake exploration (US).
7) Development of an AUV to search for life beneath the ice of the dry valley lakes (US, proposal pending)

2006/2007

1) Development of clean Lake Vostok drilling technologies for lake entry and water sampling (implementation of this project will require a permit from the national Inter-Ministry Commission on Consideration of Applications of the Russian Physical Persons and Legal Entities on Activity in the Antarctic Treaty Area). Clean technologies will be developed to transport equipment through the borehole drilling fluid including full-scale trials (Russia).
2) Proof-of-concept field operation with the ROV-AUV through the Ross Ice Shelf (US)
3) Development of hot-water drill capable of melting a borehole through 3.5 km of ice in West Antarctica. (UK)
4) Development of equipment necessary for subglacial lake exploration (to include Conductivity/Temperature/Depth device, camera and lighting, life-marker chips, raman spectrometer, tuned laser diodes, microscope and sample chambers). (UK)
5) Construction of a subglacial lake exploration probe, with tether, communications system and winch, to include the apparatus described above. (UK)
6) Continuing design of a fast drill system with 4 km capability to be applied to ice in Antarctica (France).
7) Continuing design "clean technologies for ice drilling. Selection of drill fluids compatible with subglacial environments (France)

2008/2009

1) Development of clean Lake Vostok drilling technologies for sediment sampling (implementation of this project will require a permit from the national Inter-Ministry Commission on Consideration of Applications of the Russian Physical Persons and Legal Entities on Activity in the Antarctic Treaty Area - Russia).
2) Development of ecologically clean observatories and sampling devices that can be transported through

the borehole drilling fluid including full-scale trials (Russia).

3) Continuing design of a fast drill system with 4 km capability to be applied to ice in Antarctica (France).
4) Continuing design of a clean technological setting for ice drilling. Selection of drill fluids compatible with subglacial environments (France)

Related Studies

2004/2005

1) A study of the “pink” ice from the bottom of the NGRIP core – (pending – US, France, Denmark, UK)
2) A study of particles (biotic and abiotic) in the WAIS Divide core – (pending - US)
3) A study to examine life in icy soils – (pending - US)
4) A study of microbial contents and diversity in temperate glaciers (Illimani-Andes, Mont Blanc) (France)
5) Results of a Microbial Observatory program search for novel genomes and physiologies in the permanently ice covered lakes of the dry valleys (2004-2008 - US).
6) Findings from the McMurdo Dry Valley LTER (2004-2009) on biodiversity in Dry Valley lake ice and water columns (US)
7) US NAS NRC report on “Prevention of the Forward Contamination of Mars” sponsored by NASA through the Space Studies Board of NAS - 2005 (US)
8) Analogous lake (e.g. Radok) and ice (e.g. EPICA Dome C and Droning Maud land cores) studies for microbiology and genomics (Russia/France/Denmark)

2006/2007

1) Further findings from the McMurdo Dry Valleys LTER (2004-2009) on biodiversity in Dry Valley lake ice and water columns (US)
2) Further results of a Microbial Observatory program search for novel genomes and physiologies in the permanently ice covered lakes of the dry valleys (2004-2008 - US).
3) Further analogous lake (e.g. Radok) and ice (e.g. EPICA ice cores) studies for microbiology and genomics (Russia/France/Denmark)
4) Aerogeophysical studies of Gamburtsev Mountains and surrounding terrains for identification of additional lakes 2006-2009 (Australian/German/US)

2008/2009

1) Further findings from the McMurdo Dry Valleys LTER (2004-2009) on biodiversity in the Dry Valley lake ice and water columns (US)
2) Further results of a Microbial Observatory program (2004-2008) search for novel genomes and physiologies in the permanently ice covered lakes of the dry valleys (2004-2008 - US).