White Paper

Polar atmosphere and Geospace: Present knowledge, infrastructures and future research directions

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The growing instrumentation infrastructure since the 2000's in Antarctica and in the Arctic provides an opportunity for scientific research on the polar atmosphere and Geospace. Since 2012, the GRAPE Expert Group of SCAR has provided a unique international platform to exchange data and knowledge in this area. Now, the main challenges are to better understand the coupling between the neutral and the ionized layers of our atmosphere, and to be able to test the accuracy of the atmospheric correction given to end-users. Another challenge is to provide accurate monitoring of the integrated water vapor at polar latitudes, which is an essential parameter for meteorological monitoring and climate modelling. This SCAR White Paper details current infrastructures and knowledge and discusses their challenges and limitations and recommends key future directions in polar atmospheric research.

1. Introduction

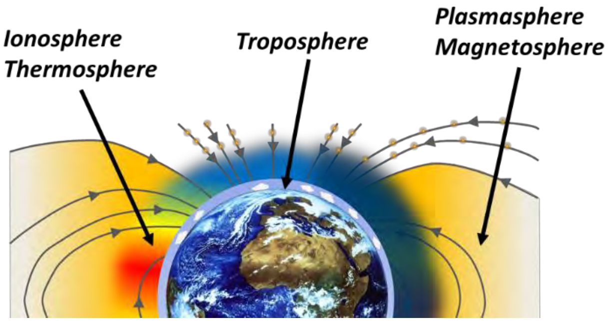

Figure 1: Schematic picture of the troposphere-thermosphere-ionosphere-plasmasphere system

Polar regions are Earth's windows to outer space. The Antarctic and Arctic regions provide a unique opportunity for scientific research that cannot be performed at mid- and low-latitude regions (Figure 1). The polar troposphere-thermosphere-ionosphere-plasmasphere system, is not as well understood as other regions due to the paucity of experimental observations. Furthermore, the different layers at high-latitudes and the auroral regions are much more dynamic at high-latitudes compared to other latitudes and featured by mechanisms not yet fully understood. To improve our knowledge of the atmospheric dynamics at polar region from troposphere up to plasmasphere, as well their coupling, it is of paramount importance to make an integrated multi-disciplinary investigation, making use of long-term multi-instrumentation observations, when possible, i.e. when national infrastructures are present.

Infrastructure at polar latitudes

The International Polar Year (IPY, Krupnik et al. 2011) and International Heliophysical Year (IHY, Davila et al. 2006) initiatives left an important heritage in terms of network instrumentation, data sharing, expertise exchange and increasing awareness of the current scientific capabilities. This lead to an increasing interest in ground networks of GNSS stations (e.g. POLENET, IGS Wilson et al. 2008, Dow et al. 2009), ionosondes and digisondes (e.g. GIRO, Reinisch and Galkin 2011), HF backscatter radars (e.g. SuperDARN, Greenwald et al. 1995, Chisham et al. 2007, Nishithani et al. 201), Ultra-High or High Frequency (UHF, HF) incoherent scatter radars (e.g. EISCAT, Rishbeth et al. 1985; RISR, Gillies et al. 2016), very low frequency (VLF) radio receivers, all-sky, medium and narrow field of view auroral imagers (e.g. ALIS, Brändström,1999), and magnetometers (INTERMAGNET and SuperMAG, Gjerloev 2009, Love and Chulliat 2013). The number of scintillation monitors (e.g. EDAS, Peng and Morton, 2013), VLF antennas (e.g. AWDAnet, Lichtenberger et al. 2008), High-power large aperture (HPLA) radars and Microwave humidity sounders are growing in the frame of both national and wider initiatives, and existing instrumentation is also being replaced or upgraded as the EISCAT-3D planned to become operational from 2022. In total,

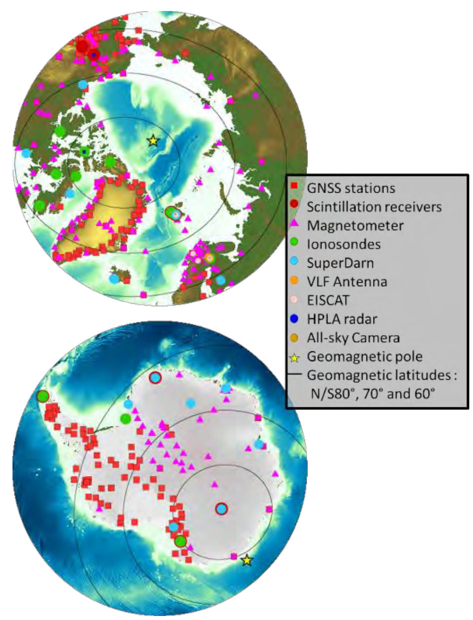

Figure 2: Scientific instrumentation infrastructure in Antarctica and Arctic regions.

nowadays close to 350 ground stations (Figure 2) are available and allow the estimation of tropospheric Integrated Water Vapor (IWV), Total Electron Content (TEC) and electron density in the ionosphere and plasmasphere, temperature of the ions and electrons, the geomagnetic field components, just to mention a few, as well as determination of the long-term trends in these geophysical parameters.

In this white paper, we highlight the main advances since the IPY 2007-2009 in the monitoring of these quantities and the improvement in the knowledge of the physics of the atmospheric-magnetospheric system.

2. Space Weather and Ionized components over polar regions

The investigation of the ionospheric behavior during geomagnetic storms allowed improving the knowledge about space weather responses of the upper atmosphere. Despite the investigations of ionospheric dynamics that have been done for decades there are still a number of open questions: how variable the ionospheric storm-time response is and how it is driven, and what are the reasons for its strong longitudinal and latitudinal asymmetries. In the last two decades, some strong geomagnetic storms occurred, impacting the ionosphere-thermosphere system. These events have been investigated using multi-instrument approaches leading to an improvement of our knowledge about electrodynamic processes of the ionosphere from low to high latitudes at different longitudinal sectors.

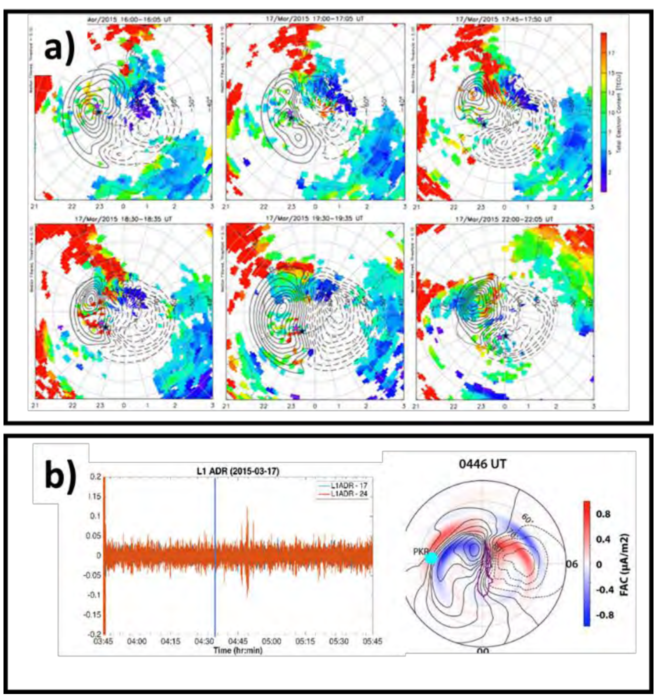

Figure 3: a) Electron content maps (South Hemisphere) and b) scintillations observations (North Hemisphere) during the Saint Patrick 2015 storm.

The St. Patrick's Day storm of 17 March 2015 was the largest storm in the 24th solar cycle (Dst reaching a minimum of -238 nT around 05:00 UTC). Figure 3a shows the Total Electron Content (TEC) maps of the southern polar region at selected times during the main phase of the storm. The TEC maps are overlaid with the SuperDARN convection pattern to facilitate the comparison with the TEC changes along the convection cells. At 16:00 UTC, no significant TEC enhancements were seen in the southern polar cap. At 17:00 UTC, a region of enhanced TEC forms at the magnetic noon sector. This region of enhanced TEC extends into the polar cap along the path of convection at later intervals of time. This tongue-like structure, known as the Tongue of Ionization (TOI), is an important feature in the storm time response of the polar ionosphere (Foster et al. 2005, Hernández-Pajares et al. 2020, Shreedevi et al. 2020) also captured during the October and November 2003 geomagnetic storms in the Northern Hemisphere (De Franceschi et al., 2008). Furthermore, the TOI fragmentates into patches as they traversed through the polar cap in response to the intensification of the ionospheric convection. This enhanced ionospheric convection and the associated formation of polar cap patches gave rise to intense scintillations in the polar cap ionosphere. Scintillations have been observed in the northern hemisphere using EDAS (GNSS Event-Driven Data Acquisition System). Figure 3b (left) shows a short-lived phase scintillation during the storm sudden commencement (SSC) observed by a receiver located at Poker Flat. The enhancement was observed starting at 04:45 UT and lasted about three minutes. This unique data and model combination reveal that the short-lived scintillation is due to the shock inducing field-aligned currents (FAC, Figure 3b, right) moving across Alaska (Zou et al. 2017). This type of impulsive phase variation is nicely captured by the EDAS high temporal resolution measurements. These multi-instrumental studies demonstrate their effectiveness to learn about the ionospheric dynamics driven by coupling processes involving the solar wind, the interplanetary magnetic field (IMF), and the magnetosphere, which results in electric fields, winds and composition changes. The induced electric fields are mapped along magnetic field lines to the high latitude ionosphere, but they also can cross the magnetic field lines and impact the electrodynamics of the of the low and mid latitude ionosphere, as a prompt penetration electric field (PPEF).

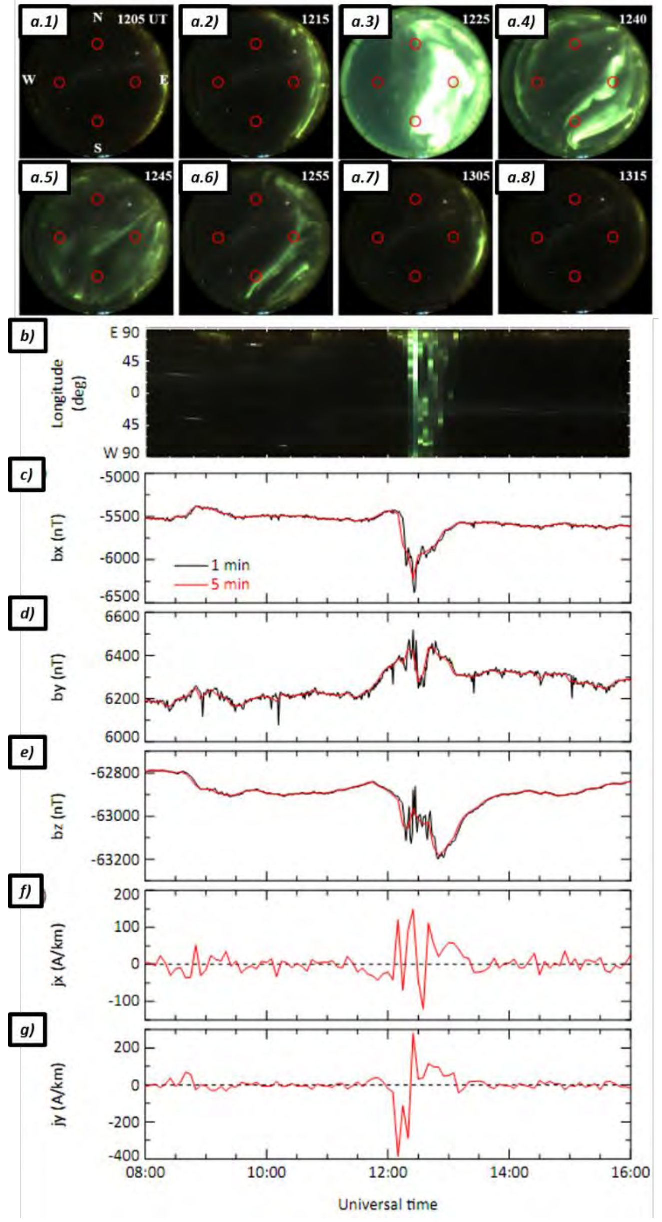

Figure 4: Multi-instrumental study of the geomagnetic storm occurred on May 11, 2019. 4a.1-a.8: The all-sky images observed by Aurora All-Sky Camera (ASC) at JBS during the geomagnetic storm occurred on May 11, 2019. The directions of image and observational time are presented on each image. The red circles indicate four-directions of line-of sight for interferometric observation. b) The keogram showing auroral activity in a zonal cross section from the A-ASC. (c)-(e) Temporal variations of the geomagnetic field measured by the magnetometer at JBS from 08:00 to 16:00 UT on 11 May 2019. The black and red lines in (c)-(e) indicate 1-min and 5-min averaged magnetic field, respectively. The time plots of ionospheric currents derived from magnetic field measurements in (f) north-south and (g) east-west directions

Another useful instrument to give information on the space weather inducing aurora activity is the all sky imager. This method follows the temporal developments of aurora during the geomagnetic storm. As an example, we show here (Figure 4, a1-a8) the auroral activity observed at 12:15 UTC on May 11, 2019 over Antarctica at Jang Bogo Station (JBS). The aurora begins to be observed at 12:15 UTC near the eastern horizon. At 12:25 UTC, the aurora is enhanced with broader spatial coverage over the station in association with poleward expansion of the auroral oval. Auroral structures seem to be dynamically varied with time during this interval, as shown in Figure 4.a4. At 12:55 UT in Figure 4.a6, the auroral intensity is diminished except for the eastern sky as the poleward expanded auroral oval begins to return to its normal location. After 13:00 UT, the auroral activity becomes too weak to be observed by the all-sky camera. To compare the auroral activity with the temporal variations of the ionospheric currents, a zonal keogram derived from the all sky imager and the magnetic field measurements are provided in Figure 4b-g (bottom). There is no auroral activity from 08:00 UTC to 12:15 UTC, but the aurora starts appearing at the eastern horizon and keeps expanding westward within an hour. Between 12:25 UTC and 13:00 UTC, a bright aurora covers the whole sky and turns back to the eastern horizon at 13:30 UTC. This temporal evolution of the auroral morphology is consistent with the variations of magnetic field measured by the magnetometer. The x-component (meridional) in Figure 4c shows obvious negative deviations from the background at the auroral breakup. When the aurora disappeared, the meridional component of magnetic field also returned to the background level.

These few examples of the multi-instrument approach to study the upper atmosphere clearly demonstrate its usefulness but show an important gap: the impossibility to date of performing a systematic inter-hemispheric comparison of such phenomena during quiet and disturbed geomagnetic periods due to lack of coverage.

3. Integrated water vapor over polar regions

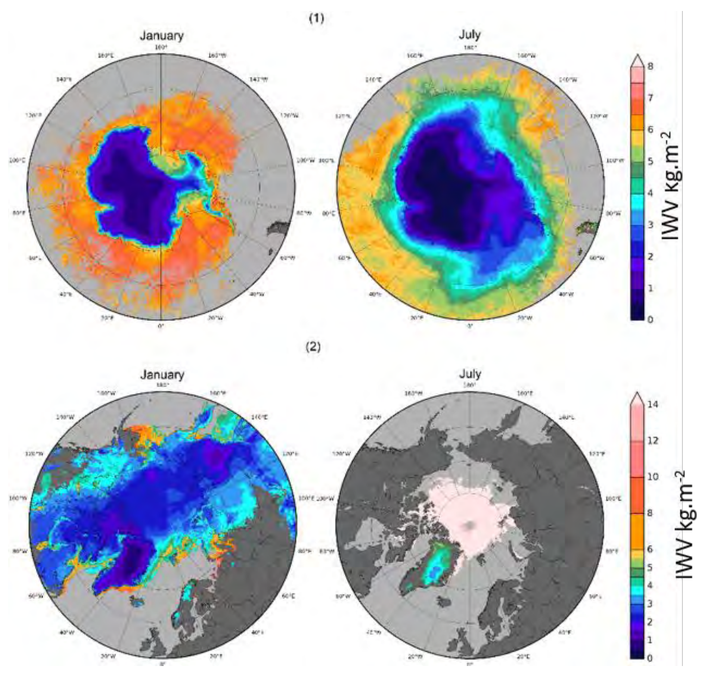

Figure 5: Monthly integrated water vapor means for representative months of summer and winter for (top) Antarctic and (bottom) Arctic, for the year 2007. Retrieval based on L1C NOAA-17 swath data, maps gridded to 0.25° x 0.25° using Gaussian weighting with 12.5 km search radius and 4 neighbors.

Being the most important natural greenhouse gas and responsible for the largest known feedback mechanism for amplifying climate change, the role of Integrated Water Vapour (IWV) is crucial in a warming climate. However, as the atmospheric water vapor is highly variable, both in space and in time, its measurement remains a demanding and challenging task. This is particularly true at high latitudes, where the amounts of water vapor are minimal (see e.g. Alraddawi et al., 2018) and difficult to measure. At the same time, the poles are particularly sensitive to the climate change. Different technics are nowadays used to monitor the IWV. As an example, the European Centre for Medium-Range Weather Forecasts (ECMWF) assimilated the GNSS COSMIC/FORMOSAT-3 Radio Occultation tropospheric data for the global weather model forecast (Ho et al. 2020) and for long-term reprocessing and reanalysis (Hersbach et al. 2020). There is also a growing importance of assimilating ground based GNSS measurements into a numerical weather prediction model at continental level (Rohm et al. 2019). Moreover, GNSS Reflectometry is a promising technique for land surface remote sensing from space including the polar regions (e.g. Li et al. 2020).

Thus, the interest in measuring the water vapor at those latitudes is highly of great importance. In the polar regions, the low water vapor content implies a poor determination of accurate profile and integrated values (Kuo et al., 1994). Afterwards, Miao et al. (2001) suggested a procedure to determine Antarctic vertically IWV column values up to 7 kg/m^2. Later, the method has been extended up to 15 kg/m^2 by Melsheimer and Heygster (2008) by including near 90 GHz observations and information about the relation between the emissivity at these frequencies (shown in figure 5). A more systematic usage of the humidity in polar regions from these sensors, which is based on the continuously available humidity sounders since 1999, requires a thorough validation with the retrievals based on surface observations, e.g. from radiosondes and GNSS observations. Until now, the diurnal cycle can only be observed at the few sites with GNSS stations, where the measurements are obtained continuously. Multi-instrumental studies are also necessary to validate the long-term trend in integrated water vapor over the polar region. The IWV time series (e.g. Figure 6) derived from the International GNSS Service (IGS) allow to provide the tropospheric product (Zenith Total Delays, ZTDs), homogeneously reprocessed from 1996 to 2010. The surface pressure and the weighted mean temperature above the GNSS sites, needed to convert the ZTDs to IWVs, are also taken from ERA-Interim (Uppala et al. 2008), but are corrected for an altitude difference between the model surface grid and the GNSS sites. From the combinations of these data sets/models, the main conclusion is that the Antarctic moistening seems to be dominantly driven by surface warming, while the Arctic IWV variability at the sites can be explained by the combination of surface temperature, tropopause temperature, precipitation, and in the North Atlantic, atmospheric circulations.

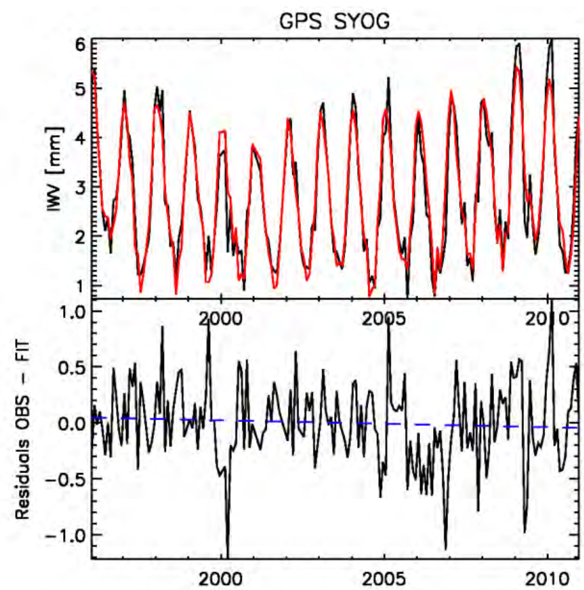

Figure 6: Examples of the stepwise multiple linear regression fits (in red) to the GNSS monthly mean IWV time series of SYOG (East Ongle Island, Antarctica). The lower panels show the residuals between the observations and fitted time series of the upper panels (black minus red), with a linear fit to the residuals in blue (negative trend, but not significant).

These data sets, used to monitor the IWV on a long-term basis, will be essential to constrain climatological prediction in the frame of the IPCC' reports (https://www.ipcc.ch/reports/). One of the main features not yet fully addressed by the atmospheric community is the coupling between the low and high atmosphere. This constitutes also a great challenge, especially for our understanding of gravity waves generated in the lower atmosphere and their impact on the formation of ionospheric travelling disturbances. But also to learn if the long-term (decades) ionospheric changes can be explained as (at least partially) due to climate change.

4. Questions which still need to be addressed

In 2014, the 1st SCAR Antarctic and Southern Ocean Science Horizon Scan assembled the world's leading Antarctic scientists, policy makers, leaders, and visionaries to identify the most important scientific questions that will or should be addressed by research in and from the southern Polar Regions over the next two decades (Kennicutt, et al., 2014). In that frame several questions were addressed in line with our activities. To effectively address these questions, the GRAPE expert group, which since 2012 permitted different research communities to share their knowledge, has the potential to aspire to more ambitious actions[1]. As an example, from the output of the GRAPE online Workshop (1-3 July 2020, grape.scar.org), the questions that should be addressed are:

1. What are the physical mechanisms ruling the coupling between the atmospheric neutral components and the ionized layer?
2. What are the coupling processes between the ionosphere and the plasmasphere at polar latitudes?
3. What is the plasmaspheric contribution to the Total Electron Content derived from GNSS at high latitudes?
4. What are the inter-hemispheric commonalities/differences in the ionospheric and plasmaspheric composition?
5. What is the role of the moving geomagnetic poles on the ionosphere-plasmasphere system and how does it impact the system on a long-term basis?
6. What is the role of the interplanetary magnetic field in the interhemispheric asymmetry of the ionospheric response to geomagnetic storms?
7. Which indices of ionospheric perturbation are best correlated with GNSS navigation errors in polar regions?

[1] The GRAPE EG members are proposing a new Scientific Research Program called RESOURCE (Radio Sciences Research on AntarctiC AtmosphereE).

8. How can we promote multi-instrumental observations to better understand the link between the electron content variation, auroral sky-imager as well as magnetic phenomena during geomagnetically disturbed periods?
9. What are the long-term trends in the ionosphere and plasmasphere, as seen from a bi-polar perspective, given that why the state-of-the-art products do not include updated information about the locations of the magnetic poles?
10. Are ionospheric scintillation events correlated with solar flares?
11. Could GNSS scintillation measurements be used to characterize magnetospheric and ionospheric dynamics related to radiation belt losses, particle precipitation, and solar flare activity as is routinely observed in broadband and narrowband VLF signal?
12. How can astronomical observations in the polar regions be improved through a better understanding of the upper atmosphere (neutral and ionized)?
13. How to improve the global atmospheric models (neutral and ionized) in a world where more and more radio-based studies are needed in polar regions?
14. How can we validate the models of the neutral, gas, and ionized atmospheric components for field applications such as communication, geo-localization …?
15. What is the trend in water vapor over the Arctic and Antarctic regions and how does this impact the global climate?
16. What is the accuracy of the integrated water vapor amounts derived from ground based GNSS receivers for the low absolute amounts of water vapor in the cold polar regions?

Finally, all the data sets on the ionosphere, plasmasphere, thermosphere and troposphere should be used to evaluating atmospheric global models such as the one from NCAR Whole Atmosphere Community Climate Model (WACCM-X 2.0, Liu et al. 2018) especially at high-latitudes.

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