Abstract book

Long- and Short-Term Changes in Geospace Driven From Below and Need for Continued Observations

Marty Mlynczak

This is an incredibly exciting time to be a Geospace Scientist! We are at the dawn of the Geospace Climate era. Increasing carbon dioxide is demonstrably altering the thermal structure of the atmosphere from Earth's surface to the edge of Space. The consequences of this alteration will impact many facets of the global economy including the rapidly expanding space economy. It is now understood that long-standing problems such as space debris may be made more severe with the long-term greenhouse cooling of the mesosphere and thermosphere through increased debris lifetime. With literally hundreds of thousands of satellites predicted to be launched in the next decade alone, space climate will become an integral consideration in international space law, space policy, and for insuring space assets. To address these issues, a Geospace System Observatory (GSO) capable of measuring long term change with high statistical confidence is needed. The GSO must produce critical Geospace Data Records (GDRs) of sufficient quality and consistency for the derivation of multiple parameter trends. Design considerations for the future GSO including instrument and system requirements (e.g., parameter measurement accuracy and stability, algorithm stability, overlap of successive sensors, length of observation record, and orbit station keeping) will be discussed. Substantial understanding of these issues has been developed by the tropospheric science community for the measurement of climate trends and can help guide GSO development. A tremendous future of societally relevant measurement and discovery awaits! This is an incredibly exciting time to be a Geospace Scientist!

Outcome of the ISSI Forum on Space and Atmosphere Weather Linkages 2022

Michel Blanc

As an introduction to our ISSI workshop on "Physical links between weather in space and weather in the lower atmosphere", I will present on behalf of its participants an overview of the main findings of the Forum on "physical links between weather in space and weather in the neutral atmosphere", held from 14-16 November 2022 at ISSI Bern, which laid the foundations of the current workshop.
The first part of the forum was devoted to an inspection of the physical links connecting the upper atmosphere and ionosphere of the Earth to disturbance sources propagating from above (the Sun and interplanetary space) and from below (the lower atmosphere and solid Earth) at a variety of time scales, from short-term events to the scales of climate and geomagnetic field changes. Each contributor identified existing gaps in our current knowledge of these different phenomena.
In a second part, forum participants reviewed the diversity of observation tools, space-based and ground-based, that are currently available to explore these coupling mechanisms and their interactions. This exercise led to a preliminary identification of the most important needs for new modelling, observation and data analysis capabilities.

Finally, starting with a Strengths, Opportunities, Aspirations and Results (SOAR) critical analysis, forum participants formulated preliminary recommendations for the Way Forward: develop closer links between major agencies; develop a framework for the coordination of long-term observations; develop standards for access to and interoperability of data bases,…
The most important conclusion of the forum was to recommend the organisation of an ISSI workshop including a larger circle of experts to tackle together the many open science questions and observational gaps identified by the forum.

The Role of the Polar Vortex in Coupling the Atmosphere-Ionosphere System

Lynn Harvey

In the polar regions, the wintertime polar vortices play a critical role in both "bottom-up" atmospheric coupling via its modulation of planetary and gravity waves as well as "top-down" coupling via the transport of nitrogen oxides created by energetic particle precipitation. This talk will present the current state of understanding regarding the role of the polar vortex in coupling different atmospheric layers via both "bottom-up" and "top-down" processes. In particular, for "bottom-up" coupling, the polar vortices act to vertically couple the atmosphere from the troposphere to geospace by shaping the background wind field through which atmospheric waves propagate. For a variety of reasons, the geographic distribution of gravity wave (GW) activity depends on the strength and shape of the polar vortex. Vortex modulation of atmospheric GWs then impacts the abundance of traveling ionospheric disturbances. For "top-down" coupling, energetic particle precipitation (EPP) generates nitrogen oxides (NOx=N+NO+NO2) in the mesosphere-lower thermosphere polar regions. In the wintertime, the polar vortices play a key role in downward coupling the thermosphere to the stratosphere by focusing the descent of EPP-NOx within their cores. State-of-the-art global climate models severely underestimate EPP-NOx transport during disturbed Arctic winters. Recent advances in both "bottom-up" and "top-down" coupling will be presented. Outstanding questions and future directions will be discussed.

Local Mapping of Polar Ionospheric Electrodynamics: Using Different Datasets to Study Magnetosphere– Ionosphere–Thermosphere Coupling

Karl M. Laundal

The physical connection between space weather and the atmosphere takes place primarily in a narrow altitude region around 50-150 km. In particular, at 100-150 km the momentum exchange between ions and neutrals is significant due to collisions. But at high latitudes, the ion dynamics at this altitude depends most strongly on what happens much further away, in the magnetosphere. To understand the space weather-atmosphere connection, it is therefore crucial to understand magnetospheric dynamics. And furthermore, to understand global magnetospheric dynamics we rely on observations from the ionosphere. I will review this key role of the ionosphere, as the mediator of space weather-atmosphere coupling, and as a "screen" on which to observe magnetospheric dynamics. Two key questions must be answered: 1) How can we best make use of observations in the ionosphere to obtain a large-scale picture of the dynamics? And 2) What do observations in the ionosphere tell us about magnetospheric dynamics?

The Roles of Tides and Planetary Waves in Linking Terrestrial and Space Weather

Ruth Liebermann

The Ionosphere and thermosphere are significantly perturbed by waves propagating from below these regions. This presentation will consist of a brief review on the dynamics of tides and planetary waves, and the mechanisms by which these waves transmit signatures of tropospheric "weather" and stratospheric polar vortex evolution into the thermosphere and ionosphere. I will then present results from recent NASA missions that quantify thermospheric and ionospheric responses to tidal and planetary wave forcing.

Influence of the Boreal (Arctic) wintertime Polar Vortex on the variability of the Mesosphere, Thermosphere and Ionosphere

Tarique A. Siddiqui

It is now well established that the variability of boreal wintertime polar vortex can produce significant changes in the middle and upper atmosphere. Previous studies have demonstrated that the weakening of the wintertime polar vortex and subsequent sudden stratospheric warming (SSW) events can considerably impact the dynamics and chemistry of the mesosphere, thermosphere, and ionosphere. These upper atmospheric changes associated with the polar vortex weakening mainly result due to the modulation of vertically upward propagating gravity waves and tides. Recently, it has been found that the strengthening of the polar vortex can also produce appreciable changes in the middle and upper atmosphere with impacts largely opposite to those observed during SSWs. In this talk, a summary of past and recent studies mainly focusing on the atmospheric tidal changes associated with polar vortex variability will be presented from both observational and modeling perspectives. In addition, the physical mechanisms behind these tidal changes will also be discussed.

The Forcing from Below and the Longitudinal Dependence of Space Weather Impacts

Endawoke Yizengaw, Keith Groves, Paul Straus

The low-latitude region (within ±30º magnetic latitude) is confined entirely inside closed field lines and is relatively cutoff from magnetospheric and solar-wind drivers compared to mid- and high-latitude regions of the ionosphere. Hence, the occurrence of ionospheric scintillation at the low-latitude region is not fully dictated by magnetically active/storm conditions. Instead, intense scintillations that can disrupt radio (especially VHF and HF) links are often observed during magnetically quiet periods, indicating the disturbances are driven internally without any input from the solar transients' conditions. Therefore, to determine the driving mechanisms for the quiet time bubbles and its longitudinal and seasonal dependence, coordinated data from multi-instruments (VHF and GNSS receivers, Jicamarca radar, IVM and SABER instruments onboard LEO satellites) are utilized. This paper, using a one-to-one comparison between the tropospheric gravity waves (GWs) amplitudes (extracted from SABER temperature profiles) and irregularity occurrence distributions, demonstrated that the forcing from the lower atmosphere via GWs seeding plays a critical role for the formation and modulation of the longitudinal dependence of equatorial density irregularities. This denotes that understanding the forcing from the lower atmosphere is critically important to improve existing ionospheric correction models and avoid any disruption of radio links for several civilian and military applications during geomagnetically quiet times. The paper also reviewed additional impacts on radio signals from other unintended sources of radio frequency interference from the ground.

Effects of Small-Scale Waves in the Upper Atmosphere and Observing capabilities

Alan Liu

Small-scale waves play key roles in re-distributing energy, momentum, and minor species in the atmosphere, which have significant impact to the larger-scale waves, global circulation, energy budget, and chemical and electrodynamical processes. These waves are mostly generated in the lower atmosphere, but their impacts are most significant in the upper atmosphere and ionosphere. In this talk, I will present a few cases to demonstrate the effects of small-scale waves and follow up with a description of the current capabilities in the US for observing these small-scale waves, with focus on ground-based instruments and data infrastructure mostly supported by the US National Science Foundation. I will then share my thoughts on where the gaps are, and opportunities for future development and collaboration, in instrumentation, deployment, and data infrastructure to support open data access.

Atmospheric Gravity Waves and Atmosphere– Ionosphere–Magnetosphere Coupling

Alexander Kozlovsky

Atmospheric gravity waves are low-frequency transverse waves (periods larger than 10min) having frequencies low enough to be affected by gravity. The AGWs play an essential role in atmospheric dynamics, vertical energy transport, and the atmosphere-ionosphere coupling. The AGWs are generated in the lower atmosphere and propagate upward to the ionosphere where they produce irregularities of the electron density, which are observed as traveling ionospheric disturbances (TIDs). On the other hand, intense ionospheric electric currents and auroral precipitation in the auroral zone can cause AGWs which propagate downward to the mesosphere.
In the present study we focus on the medium-scale AGWs with periods 25-100 minutes. We use data from the Sodankylä Geophysical Observatory (SGO, 67°N, 27°E, Finland, MLAT ≈ 64°) located in the vicinity of the equatorial part of the nightside auroral oval. The AGWs at about 90 km altitude were inferred from the wind data of the Nordic Meteor Radar Cluster (Stober et al., https://doi.org/10.5194/amt-14-6509-2021) with spatial/height/time resolution 90km/5km/10min respectively. At the same time, TIDs were detected as variations of the electron density (critical frequency foF2) at the height of F2 maximum (hmF2, 200-350 km) in the data of SGO ionosonde operating with 1-min time resolution. We present 3-years (2020-2022) statistics of the collocated AGW and TID data to investigate propagation of the waves between mesosphere and ionosphere. In summer (April-September), the wave propagation is suppressed likely due to the strong zonal wind shear at the mesopause (near 90 km altitude). The most effective atmosphere-ionosphere interaction was observed in the dark ionosphere conditions, namely, in the night time in fall-winter (October-January). The results are discussed in association with the atmospheric dynamics and geomagnetic and auroral activity.

Observation of the upper Mesosphere / lower Thermosphere with hydroxyl airglow spectrometers and cameras and results concerning atmospheric dynamics

Sabine Wüst, Michael Bittner, Patrick J. Espy, W. John R. French, Frank J. Mulligan

Ground-based OH* airglow measurements have been carried out for almost 100 years. At some sites they are available for decades. Advanced detector technology has greatly simplified the automatic operation of OH* airglow observing instruments and significantly improved the temporal and, in the case of imagers, the spatial resolution of these measurements. Studies based on long-term measurements (i.e., ten years or more) or including a network of instruments were reviewed especially in the context of atmospheric dynamics. The results are presented. Furthermore, today's challenges are identified.

NASA's Geospace Dynamics Constellation and DYNAMIC Missions: Tracking Energy and Momentum Transfer Throughout the Middle and Upper Atmosphere on a Global Basis

Douglas Rowland

NASA is formulating two missions that will serve as strategic hubs for the Ionosphere-Thermosphere-Mesosphere Great Observatory: Geospace Dynamics Constellation (GDC, NASA strategic mission) and DYNAMIC (PI-led, competitively selected). GDC will study the response of the high latitude ionosphere-thermosphere to magnetospheric drivers, and the internal processes that redistribute mass, momentum, and energy on a global basis. DYNAMIC will focus on the forcing of the ITM from the lower atmosphere. Each will provide a critical perspective on the dynamics of the ITM system: GDC will explore the dynamics of the system at scales ranging from local (hundreds of kilometers) to global, with revisit times ranging from minutes to tens of minutes, providing key constraints on spatiotemporal scales of energy inputs from the magnetosphere. DYNAMIC will provide much higher temporal resolution of the variability in tidal and planetary variations, as welll as the orbit-to-orbit variations induced by magnetospheric and solar variability. GDC will measure magnetospheric energy inputs and I-T responses near 400 km, while DYNAMIC will provide vertically resolved measurements of the I-T system at lower altitudes. These missions are currently planned to operate simultaneously, with launch early next decade. This paper presents the system science approach of GDC, with some additional thoughts on how GDC+DYNAMIC will be able to address critical problems in understanding the ITM system.

The Changing-Atmosphere Infrared Tomography (CAIRT) Earth Explorer 11 candidate mission

Bernd Funke, Martyn Chipperfield, Quentin Errera, Felix Friedl-Vallon, Sophie Godin-Beekmann, Alex Hoffmann, Alizee Malavart, Scott Osprey, Inna Polichtchouk, Peter Preusse, Piera Raspollini, Björn-Martin Sinnhuber, Pekka Verronen, Kaley Walker

The Changing-Atmosphere Infra-Red Tomography Explorer (CAIRT) is currently in Phase A as one of two final candidates for ESA's Earth Explorer 11. As a Fourier transform infrared limb imager, CAIRT will observe simultaneously from the middle troposphere to the lower thermosphere at high spectral

resolution and with unprecedentedhorizontal and vertical resolution. With this, CAIRT will provide critical information on (a) atmospheric gravity waves, circulation and mixing, (b) coupling with the upper atmosphere, solar variability and space weather and, (c) aerosols and pollutants in the upper troposphere and lower stratosphere. In this presentation we will give an overview of CAIRT's science goals and the expected mission performance, based on latest results from feasibility studies performed during Phase 0. Special emphasis will be given to CAIRT's capacity to provide new insights on the coupling of the upper and lower atmosphere.

Optical Instrumentation for Auroral thermosphere-ionosphere observation and possible link with instrumentation for lower atmosphere

Mathieu Barthelemy, Robert Elisa, Lamy Hervé, Gael Cessateur, Bosse Léo

During the last few years, the Royal Belgian Institute for Space Aeronomy (BIRA-IASB), l'Institut de Planétologie et Astrophysique de Grenoble" (IPAG) and Centre Spatial Universitaire de Grenoble (CSUG) have conducted a number of optical auroral observations during several winter campaigns at the Skibotn Observatory, in partnership with the Tromsø Geophysical Observatory (TGO). These observations can be grouped in three types : imagery, polarimetric observations and spectroscopic observations. For polarimetric observations, a set of instruments has been developed: (a) IPAG produced the set of Cru instruments which are spectro-photo-polarimeters using sensitive PMs, narrow interference filters and a fast-rotating polarizer in front of the optics. It allows to measure the polarization of weak signals integrated over a 2° FOV at up to four different wavelengths (391.4, 427.8, 557.7 and 630.0 nm) simultaneously. (b) BIRA-IASB developed PLIP, the Polar Lights Imaging Polarimeter, which is an imaging polarimeter using 4 identical low-noise high-sensitive commercial cameras equipped with filter wheels and 3 narrow interference filters (427.8, 557.7 and 630.0 nm). Each camera is equipped with a fixed polarizer oriented at 0°, 45°, 90° and 135°. It has a very wide FOV (44° x 30°) but can only measure polarization of one wavelength at a time. The two instruments are complementary and have been used recently together on the same astronomical mount. For spectroscopic observations, we have recently re-used available material from a previous experiment, a Shamrock 303i spectrograph equipped with 3 gratings (300, 600 and 1800 lines/mm), and an iDus 2.3 CCD camera. They were combined with a small guiding lens and an optical fiber collimator in order to obtain low and high-resolution spectra of auroras in the pointing direction of our polarimetric instruments. Together with TGO, we installed this material permanently at the Skibotn Observatory pointing field-aligned with the aim of providing these data to the scientific community. In addition, ATISE is a Fourier transform spectrometer which allows to obtain the full spectrum from 380 to 900 nm in one exposure. It is based on a Fizeau concept. The FOV is small of the order of 1° x 1° but its sensitivity can be very high when using low noise camera. For the current version we used the Zwo 2600MM device. It is now used in campaign mode. All these ground-based observations will be linked with optical space instruments like AMICal Sat, ATISE, ATISE-Wind, SATIS and WFAI (ESA-Aurora mission).
Considering these different instruments, we will try to consider how we could transfer and modify such kind of devices for optical observation of the lower atmosphere especially for TLEs or use them directly.

Upper-Atmosphere–Ionosphere Observations: The Role of Geophysical Observatories and EISCAT

Thomas Ulich, Urban Brändström, Njål Gulbrandsen, Magnar Johnsen, Fred Sigernes, Kirsti Kauristie, Shin-Ichiro Oyama, Axel Steuwer and the EISCAT Staff

The Nordic Observatory Collaboration (NOC) is a joint effort of institutes operating observatory-grade instrumentation in - currently - Norway, Sweden, and Finland. Observations are considered observatory-grade, if they fulfil certain criteria. Most importantly, the observations have to be carried out continuously in consistent manner without time limit. They have to be well documented, maintained, as well as adhere to internationally agreed procedures. Thus, they serve as reference measurements.

The observatories represented here have been collaborating in some form for decades. With the go-ahead for the new EISCAT_3D incoherent scatter radar in 2017, and the advent of ever smaller and more cost-efficient satellite missions, the Nordic Observatory Collaboration was formally established and has thus far six signatories. The main objective is to provide a forum for planning and discussing future initiatives, share methods and procedures, exchange knowledge, co-ordinate measurement efforts, and apply jointly for funding.

This year, EISCAT_3D will gradually become operational and provide an unprecedented view of the upper atmosphere, lower thermosphere and ionosphere and near-Earth space over a large part of Northern Norway, Sweden and Finland.

The Nordic observatories together with EISCAT_3D situated in the unique high-latitude environment of the European Arctic, offer a huge wealth of ground-based measurements providing context for your space missions and space-situational awareness.

SuperDARN and the Atmosphere: I Have a Lot of Questions

Kathryn McWilliams, C. Ridley, L.B.N. Clausen

Variations of the heliospheric current sheet result in the Earth orbiting through sectors where the interplanetary magnetic field at Earth is directed primarily towards or away from the sun - i.e., orbiting through the undulating Parker Spiral. Ionosphere and thermosphere datasets have temporal variations consistent with the times when the heliospheric current sheet passes the Earth, i.e., as Earth passes into a different Parker Spiral regions. During the year 2003, the IMF direction at the Earth switched with a consistent periodicity of 12-15 days, leading to a long series of well-defined, repeated away/toward IMF sectors. While the IMF Parker Spiral orientation was very predictable and repeatable, the thermospheric neutral particle density, total electron content and SuperDARN echo occurrence rates had constant high and low offsets, depending on whether the Earth was located in away or towards IMF sectors. The thermosphere appeared to expand then contract every 12-15 days over the course of about 18 months, with other observations following the same trend. Possible links between the IMF polarity and thermosphere observations were investigated.

Effect of Lower Atmospheric Waves on the Thermosphere–Ionosphere System

Astrid Maute

In this presentation we use the over 2 years of TIEGCM-ICON simulations to evaluate the model by comparing primarily to ICON observations and examine the captured thermosphere-ionosphere variations. A special focus in our comparison will be on the daytime neutral wind driving the ionospheric electrodynamics, influencing the ion drift, and the plasma distribution. Using comprehensive data sets gives us an opportunity to quantify model biases and investigate potential causes. We will delineate during specific time periods the contributions due to lower atmospheric tidal forcing from the one due to solar and magnetospheric forcing. We will conclude with some thoughts on improvements in numerical modeling.
If there is time, we will show some ionospheric comparison of a new concept of operations (CONOPS) at the NOAA Space Weather Prediction Center of WAM-IPE with COSMIC-2 data highlighting the importance of the continuous evaluation and the challenges.

It's YES for NO, O/N2 and e: Gravity wave effects on middle and upper atmosphere transport

Han-Li Liu

WACCM-X has seen long-standing issues in its representation of several key constituents in the middle and upper atmosphere, including nitric oxide (NO) in the mesosphere and lower thermosphere (MLT), O/N2 in the thermosphere, and electron density in the ionosphere F-region: NO in WACCM-X is significantly lower than observed values, especially in the polar night region, while the column integrated O/N2 and F-region electron density are generally too large. These biases are thought to be related to transport, though the exact causes are not well understood. Recent high-resolution WACCM-X simulations show overall improvements in all three quantities. By analyzing the high-resolution simulation results and comparing with control simulations at regular resolution, we elucidate the effects of the resolved gravity waves on the transport from the MLT to the upper thermosphere, both through altering the mean circulation and wave mixing.

How can the effects of the middle atmosphere be taken into account to model the ionosphere accurately?

Aurelie Marchaudon and Pierre-Louis Blelly

The TRANSCAR ionosphere model family was initially developed for high latitudes. The IRAP Plasmasphere-Ionosphere Model (IPIM) has been extended in coverage to mid-latitudes, thanks to its interhemispheric resolution. An equatorial electrodynamics module is currently being developed to complete the coverage of IPIM at low latitudes and at the equator, in order to take into account the effects of Solar Quiet (Sq) currents, the equatorial electrojet and the equatorial fountain. By doing so, it becomes clear that the thermosphere, itself driven by the lower atmosphere, can have a significant effect on ionospheric dynamics, in particular, the day-to-day variability of the thermosphere has important consequences for ionospheric modelling at medium and low latitudes. As the IPIM model is fed with

inputs from empirical thermospheric models such as NRLMSISE-00 (density, temperature) and HWM-14 (wind), this day-to-day variability cannot currently be modelled.
In this presentation, we explore the first steps envisaged for taking this thermospheric variability into account. Since only scarce measurements of the thermosphere exist (local satellite measurements or Fabry-Perot interferometers at only a few locations on Earth), it is difficult to take this variability directly into account in the thermospheric inputs. To overcome this problem, we are exploring the possibility of analysing IPIM modelling sets with various atmospheric densities to obtain electron densities and ionospheric currents compatible with observation sets with good spatio-temporal coverage: GNSS measurements for total electron content (TEC), ground-based magnetometer measurements for magnetic disturbances and perhaps even HF radar measurements (such as SuperDARN or ionosonde) to gain direct access to certain ionospheric (fof2, hmf2) and thermospheric (density) quantities.
Finally, we will also discuss the paths explored for assimilating the above data directly into the IPIM model, for adjusting thermospheric inputs in the model in real time, for extending downwards the IPIM model to cover the 60-90 km range, and for defining new observables to be assimilated accordingly. The ultimate aim is to deduce information on coupling with the mesosphere and possibly the lower atmosphere.

Prospects and Challenges of Modelling the Whole Atmosphere with the Icosahedral Nonhydrostatic (ICON) Model

Claudia Stephan

The ICOsahedral Non-hydrostatic (ICON) general circulation model is a joint development by the Max Planck Institute for Meteorology and the German Meteorological Service. Its non-hydrostatic dynamical core is formulated on an icosahedral-triangular grid. The standard model version covers the atmosphere from the surface to approximately 80 km, while the upward extension of ICON has a lid at 150 km. The latter version employs deep-atmosphere dynamics and additional physics parameterizations to account for processes in the mesosphere and lower thermosphere (MLT). Science faces the challenge of better understanding the neutral dynamics, plasma physics and chemical processes in the MLT, their interactions, and their natural and anthropogenically forced variability. This calls for global whole atmosphere modelling to capture global tides and local extreme events at high resolution. As we are entering the age of exascale computing, global-scale simulations with horizontal grid spacings in the range of 1–10 km become available. Resolved orography and non-orographic gravity wave sources provide a realistic wave forcing of the overlying atmosphere with explicitly simulated vertical energy and momentum transport. Such high-resolution simulations have so far mainly focused on the troposphere and stratosphere, where ICON shows an unprecedented degree of realism in terms of representing gravity waves, both in regional models and global models. Expanding these efforts to the MLT requires model development. This presentation will summarize the latest success stories and give an outlook on promising plans for the future.

Science Drivers for Ground to Space (G2S) Modeling and Reanalysis: A Heliophysics Perspective

John McCormack

The extension of existing numerical modeling systems used for weather and climate applications to the upper atmosphere was initiated in the early 2000s. The motivation for this undertaking was to better understand measurements that characterize the transition region between Earth's atmosphere and space, and then develop this understanding into predictive capability for the near space environment that includes low-Earth orbit. Over the past two decades, improvements in whole-atmosphere modeling systems and the increasing volume of upper atmospheric observations from NASA missions (e.g., TIMED, AIM, GOLD, ICON) have demonstrated the possibility of developing a true "ground to space" environmental specification and prediction capability that combines global models with data assimilation. This presentation will review progress in this field to date and describe outstanding science topics that motivate development of a comprehensive "ground to space" reanalysis data set extending from troposphere to thermosphere. These topics include, e.g., space weather nowcasting and forecasting in response to both solar and terrestrial drivers, aiding future mission development through observation system simulations, orbital risk mitigation, atmospheric impacts of space vehicle reentry, and prediction of future near space environment conditions under current climate change scenarios.

ESA Heliophysics Working Group – Building Bridges

Matt Taylor , Piers Jiggens, Juha-Pekka Luntama, A. Strømme, Sebastien Vincent-Bonnieu

Heliophysics, the science of understanding the Sun and its interaction with the Earth and the solar system, has a large and active international community, with significant expertise and heritage in the European Space Agency and Europe. Several ESA directorates have activities directly connected with this topic, including ongoing and/ or planned missions and instrumentation, comprising an ESA Heliophysics observatory or more musically, a Heliophysics Orchestra. More specifically in ESA: The Directorate of Science with missions such as Ulysses, SOHO, Cluster, Solar Orbiter, SMILE etc, relevant payload components on missions such as JUICE, as well as hosting the Heliophysics archive; The Directorate of Earth Observation with Swarm and other Earth Explorer missions, as well as the ongoing ESA-NASA Lower Thermosphere-Ionosphere Science Working Group (EN-LoTIS-WG); The Directorate of Operations with the Vigil mission, the Distributed Space Weather Sensor System (D3S) and the Space Weather Service Network; The Directorate of Human and Robotic Exploration with many ISS and LOP-Gateway payloads and the Directorate of Technology, Engineering Quality with expertise in developing instrumentation and models for measuring and simulating environments throughout the heliosphere.
An ESA Heliophysics Working group has been appointed by several ESA Directors, under the direction of the ESA Director General, to work on optimizing synergies across directorates, and to act as a focus for discussion, inside ESA, of the scientific interests of the Heliophysics community, including the European ground-based community and data archiving activities.
This paper will present an overview of activities so far and where things are going.

Opportunities of Interdisciplinary Collaborative Activities in Polar Atmosphere Research

Lucilla Alfonsi

Not always scientists working in different scientific areas are aware of opportunities offered by joint deployment of instruments or by already existing observations. Many instruments, such as GNSS (GPS, GLONASS, Galileo, Beidou, etc.) receivers, can be used for multiple scientific purposes, if the scientific and technical requirements match the needs of the communities. This opens for mutual benefit, which can be a significant advance for polar science. Often, what is considered a noise in observations by one community can be an important signal for another. Thus, those communities can get further in removing (or mitigating) the noise and in accessing additional scientific information. This is the case of radioastronomy community that could take advantage in sharing data with atmospheric communities providing them precious information on lower and upper atmosphere parameters (e.g. TEC and PWV) and exploiting their expertise to mitigate the atmospheric "noise".
Due to heavy logistics the optimization of the measurement campaigns and the data sharing is crucial for making good science at the poles. Moreover, the interdisciplinary approach is always a formidable opportunity to discover new insights.
In this framework a new initiative, titled AGATA (Antarctic Geospace and ATmosphere research), is attracting international interest to gather into a unique platform atmosphere (from lower to upper) communities, radioscientists and astronomers working on polar regions.
AGATA is a Scientific Research Planning Group approved by SCAR in November 2022 (Scientific Committee on Antarctic Research) to run to become a new Scientific Research Programme (SRP). AGATA aims to significantly advance the current knowledge of the Antarctic atmosphere and geospace, in the bipolar, interhemispheric context. AGATA SRP will contribute to answering the outstanding scientific questions related to the whole-atmosphere coupling, space weather influences and whole atmosphere response to climate change. These questions will be addressed with a multi-disciplinary and multi-instruments approach, and by bringing together communities which investigate and study the polar atmosphere and geospace. While the understanding of physics of the neutral and ionized atmosphere has been significantly improved using both ground-based and space-based radio soundings, the questions that remain open need to be addressed with a synergistic approach. This requires active involvement of various research groups in the field.
AGATA was proposed by experts coming from 40 international institutions, taking advantage of existing and planned instrumentation in Antarctica and in the Arctic and satellite-based observations, and it aims to coordinate research efforts and data exchange. This bi-polar perspective allows the study of significant interhemispheric asymmetries in the atmospheric response observed in the polar regions.
To learn more: https://www.scar.org/science/agata/home/

Citizen Science: an Opportunity to Supplement Scientific Observations of the Upper Atmosphere

Maxime Grandin

In the recent years, several nightsky emission forms have been discovered and studied thanks to citizen science. Auroral photographers can notice optical structures which have never been investigated before and work hand in hand with researchers to improve our understanding of the complex mechanisms leading to those emissions in the upper atmosphere. Phenomena nowadays known as STEVE, the picket fence, the dunes and fragments have been studied thanks to photographs taken by citizen scientists, which can provide a great addition to observations from ground-based and satellite instruments. Other ways of engaging citizen scientists in scientific research can for instance be the classification of auroral forms from all-sky images for AI training, or the curation of collaborative databases of events identified in optical observations. We will review the current status of citizen science applied to space physics and aeronomy and discuss how it opens new opportunities for obtaining data from the upper atmosphere.

Relationship Between the Ionospheric Potential and the Ground-Level Electric Field in the Polar Cap (Vostok Station, Antarctica)

Renata Lukianova

The problem of the influence of the solar wind on the polar atmosphere and weather in the frame of the global electric circuit (GEC) paradigm is considered. GEC is a hypothesis that global thunderstorm activity draws current upward to the ionosphere and maintains an electric potential difference of ~250 kV between the ionospheric shell and the Earth's surface. Currents in the circuit are dispersed around the globe via the ionosphere to return eventually to the ground. In fair-weather regions, a downward directed geoelectric field of 100−200 V/m can be measured near the surface.
A hot topic of the Sun-climate connection is the influence of solar activity on GEC components, including variations in atmospheric conductivity, which possibly affects the efficiency of cloud formation and hence modulates the tropospheric weather.
Central (especially central-east) Antarctica is a unique place to search for possible manifestations of GEC because (1) the local atmospheric circulation formed by katabatic winds is one of the most persistent atmospheric phenomena on the Earth and the "fair weather" conditions are often met; (2) the overhead ionospheric electric potential variations are dominated by a specific convection pattern associated with the magnetospheric electric field and space weather; (3) the ionizing atmospheric effects of energetic particle precipitation are quite prominent.
The Vostok station (78.5S, 107◦E; 83.4 MLat) is located on the top of the Antarctic polar plateau. There, the vertical component of the ground-level atmospheric electric field (Ez) has been measured using an electrostatic mill since 1998 along with the standard meteorological observations. It is intended to review and discuss the following results obtained and some unresolved problems.
(*) Actually measured changes of Ez at the Vostok station represent a combination of the daily course of the tropic thunderstorms (described by "Carnegie curve") and deviations affected by the overhead ionospheric electric potential controlled by the solar wind.
(*) Variations in Ez and the overhead ionospheric potential (U) obtained from the SuperDARN or/and other convection models are highly correlated wrist the correlation are the local time dependent. During an individual magnetic storm, the Ez-U correlation becomes somewhat more complicated.
(*) Spectral analysis of the daily and hourly values of Ez and the air temperature reveals the periods which coincide with periods of gravity and planetary waves. There are some indications that during the prolonged periods of the southward IMF, katabatic winds may alter their prevailing direction.
(*) The existence of a meteorological response in the polar regions to fluctuations in the IMF azimuthal (By) component (so-called as Mansurov-effect revealed in 1970s at Vostok) has been previously established using the atmospheric reanalysis data but recently some issues has been questioned. Measurement from an individual (parent) station may capture these features in more detail.
(*) Comparison of the limited period of simultaneous interhemispheric observations of Ez at Vostok and Svalbard has shown a more complicated relationship between Ez and U in the northern auroral zone.

(*) Physical mechanism underlying the GEC-cloud hypothesis still not well understood. Also, some uncertancy still remains in the precise measurements of the cloud cover in the polar region. Good knowledge about the dedicated space missions is essential.
(*) In addition, among the interesting directions in the development of the GEC theory, the study of the seismic phenomena should be noted. Estimation of the efficiency of penetration into the ionosphere of quasi-static electric fields from sources localized on the Earth's surface shows that in the case of relatively large spot of ground-level Ez with a magnitude of about kV/m, horizontal fields up to several mV/m can appear in the ionosphere. These values are sufficient to induce variations in plasma density in the ionosphere which, as some case study demonstrated, can be observed by satellites.

Magnetosphere–Ionosphere Drivers and Responses to Large Subauroral Electric Fields

Bea Gallardo-Lacourt

The subauroral ionosphere, a captivating domain within Earth's upper atmosphere, intricately links the magnetosphere and thermosphere, exerting influence from high latitudes to the equatorial region. Manifestations of the subauroral electric field, a key player in this complex system, are often measured through large antisunward flow velocities. Utilizing both in-situ satellite observations and ground-based measurements, these flows, typically confined to narrow latitudinal bands (1-2 degrees), reach velocities of several kilometers per second.
Despite recent strides in measurement techniques, the subauroral region remains enigmatic, hindered by instrumental and observational limitations. Ground-based and in-situ studies have uncovered novel dynamics, reigniting scientific interest. Optical phenomena, including SAR arcs, STEVE, and the picket fence, have been linked to extreme subauroral plasma conditions characterized by large ion flow velocities (5-10 km/s) and elevated electron temperatures exceeding 6000 K. Intriguingly, these transformations occur rapidly, within mere minutes, challenging existing theories and instrumentation capabilities. This presentation will highlight the urgency for advancing in-situ and remote measurement technologies dedicated to the subauroral ionosphere.

Ground Based Observational capabilities for the Upper and Middle Atmosphere

Lisa Baddeley

I will provide a brief overview of the main instrumentation used by the upper and middle atmospheric communities, with a focus on the Scandinavian polar regions. In addition, the new EISCAT-3D radar will be coming online in the next few years whilst the current EISCAT Svalbard radar has probably less than 10 years operational lifetime left. I will discuss how the latter of these events could provide an opportunity for greater cross disciplinary collaboration in addition to challenges and issues in regards to instrument operations and data availability.

Eruptions on the Sun and their Consequences

Lucia Kleint

Eruptions on the Sun, called solar flares, are extremely powerful. Their violent nature and influence on Earth was realized in 1859 when English astronomer R. Carrington suddenly saw an unexpected brightening on the Sun. Lasting only a few minutes on the Sun, the event was followed by intense space weather with auroras seen as far south as Hawaii.
Research in flare physics has determined that the energy stored in the solar magnetic field is powering the eruptions. Particles accelerated during magnetic reconnection events precipitate into interplanetary space, but also towards the solar surface where they cause many observable phenomena, such as heating, mass motions, and emission in the whole electromagnetic spectrum. Large solar eruptions are the main causes of severe space weather events, which can affect satellites and communication. In this presentation, I will give a closer look on the origins of space weather and the current research of solar flares.

Impact of Energetic Electron Precipitation – Revisiting the Hypothesis of the Chemical Dynamical Coupling

Hilde Nesse

Energetic electron precipitation (EEP) connects the magnetosphere to the middle and lower atmosphere through ionization, chemical reactions, and modulation of winds. Evidence of a link to regional polar surface temperatures is provocative, where the sequence of events is still largely a black box, partly obscured by deficient EEP energy input and/or understanding of the atmospheric processes themselves. This presentation addresses recent advances and remaining challenges in respect to parameterizing EEP from the radiation belt into climate models. Moreover, to understand the importance of realistic EEP parameterization, the following questions are discussed: Which EEP energies and how strong fluxes are needed to modulate the atmospheric dynamics? And how to investigate the EEP effect if its impact depends on the dynamical preconditions of the atmosphere itself?

Assessing Ozone Variations in Response to Energetic Particle Precipitation: from Stratosphere to UMLT

Jia Jia

The enhancements of NOx and HOx resulting from Energetic Particle Precipitation (EPP) are recognized for inducing ozone loss in the mesosphere and upper stratosphere. However, in the lower stratosphere and the upper mesosphere/lower thermosphere (UMLT), the impact of NOx enhancement on ozone operates through a distinct mechanism. In the lower stratosphere, it is believed that the heightened NOx levels act to restrain ozone depletion by essentially 'locking' active chlorine and bromine species into reservoir forms (HCl/HBr and ClONO2/BrONO2). Contrastingly, in the UMLT, the chemical contribution of NOx faces competition from atomic hydrogen [H]. For an extended period, ozone was not anticipated to be influenced by EPP in this region. In this presentation, I will provide an overview of how ozone responds to EPP in the middle and upper atmosphere and touch the role of dynamical transport in contributing to these ozone responses.

Space Weather Effects on Cloud Processes via the Global Electric Circuit

Keri Nicoll and Giles Harrison

Clouds play a major role in the radiation budget of the Earth, the incomplete understanding of which contributes some of the largest remaining uncertainties in climate change. One potential mechanism by which clouds may be influenced by solar variations is via the Global Atmospheric Electric Circuit. Globally widespread electrification occurs at the upper and lower edges of layer clouds, from vertical conduction current flow in the Global Atmospheric Electric Circuit. This conduction current flow, Jc, is always present in fair weather, and is strongly modulated by solar activity through the flux of galactic and solar cosmic rays. This "global circuit coupling" which is based on well established classical physics, has been proposed as a physical coupling mechanism linking solar changes down through the lower atmosphere to the surface. The electrification of cloud droplets due to this mechanism can have implications for cloud microphysical processes, leading to changes in the large scale properties of clouds such as cloud height, opacity, and lifetime, which are important in controlling Earth's radiative balance. This presentation will review the evidence for the Global Atmospheric Electric Circuit effect on clouds. This will include discussion of in-situ cloud droplet charge measurements from balloon borne charge and cloud droplet sensors to quantify the charge on cloud droplets, discussion of the cloud microphysical processes affected by charge, and observations of changes in large scale cloud properties in response to Global Atmospheric Electric Circuit changes.

When and where can energetic electron precipitation contribute to atmospheric dynamics?

Lauren Blum

While our understanding of electron acceleration mechanisms in Earth's radiation belts has greatly increased over the past decade, quantitative physics-based understanding of loss mechanisms remains elusive. In particular, numerous questions remain regarding the contribution of electron precipitation into Earth's atmosphere to overall radiation belt losses. Here we present studies investigating when and where this high energy electron population typically trapped in the outer radiation belt can end up precipitating into the atmosphere. Understanding the properties of this MeV electron precipitation is critical to being able to account for their effects on atmospheric dynamics. Recent results from both event studies as well as statistical analysis reveal when, where, and for how long MeV electron precipitation events can occur, as well as their relationship to geomagnetic activity. Finally, we'll end by highlighting some recent and upcoming balloon campaigns aimed at capturing the effects of energetic electron precipitation on stratospheric Ozone.

Influence of solar energetic particles on stratospheric polar vortex and mesospheric ozone

Hui Li

Solar energetic particles (SEPs) play a significant role in influencing the Earth's atmosphere and climate. The polar region acts as a conduit for SEPs, leading to solar proton events (SPEs) and energetic electron precipitations (EEPs), which can ionize the atmosphere and contribute to ozone destruction. Utilizing data from the Aura satellite, substantial ozone depletion in the polar mesosphere during SPEs and EEPs has been observed, with more pronounced depletion at higher geomagnetic latitudes, particularly during EEPs. Ozone depletion is directly proportional to proton flux, and an increase in hydroxyl supports the ozone depletion mechanism. The study also indicates that protons have a greater impact on ozone compared to electrons, validating the link between the atmosphere and magnetosphere and enhancing our understanding of the solar influence on climate. Furthermore, recent studies suggest that SEPs, particularly intense solar proton events (SPEs), may modulate the dynamics of the stratospheric polar vortex (SPV), a crucial circulation pattern influencing weather and climate in the northern hemisphere. Analysis of 24 intense SPEs between January 1986 and March 2020 revealed that the wind speed of the SPV significantly increases at various altitudes during intense SPEs, with the magnitude of these enhancements positively correlated with the integrated flux of energetic protons. The strengthening of the SPV occurs 1-2 days before the onset of SPEs, suggesting that early increases in solar ultraviolet radiation may contribute to this intensification. However, partial correlation analysis indicates that solar energetic protons are likely the primary driver of SPV intensification, surpassing the influence of solar ultraviolet radiation. These findings advance our understanding of the complex interactions between solar activity and Earth's atmosphere and enhance climate modeling capabilities.

Ionosphere long-term trend patterns over Japan and Antarctic during 1948-2022

Huixin Liu

It is known that increasing CO2 concentration causes not only global warming in the troposphere but also significantly affect the thermosphere and ionosphere at similar time-scales. Although the thermosphere impact has been consistently revealed by both ground and satellite observations to be a cooling trend (though the magnitude varies), the impact on the ionosphere density shows contradicting results in the literatures due to complications in both physical processes and statistical analysis. Here in this study, we propose a new concept for the long-term trend, i.e. trend pattern instead of a single value in a certain period. This trend pattern is a 2-D pattern of the trend with dependence on local time and season. We have applied this new pattern-concept to long-term observations over Japan and the Antarctic and obtained interesting results.

These observation results find excellent agreement with model simulations, which uses completely different method for examining the trend caused by increasing CO2. This consistency demonstrates the reliability of the new concept. The patterns obtained with this concept provides more detailed information that can be applied to space weather operations in the future (e.g. maximum usable frequency, communication quality and distance, satellite signal scintillation), hence supports conceptual design and long-term planning of future space-borne and ground-based observing capabilities.

Observations of Long-Term Change in the Thermosphere, Challenges and Opportunities

Eelco Doornbos

One of the first scientific endeavours of the space age was the measurement of the density in the upper atmosphere and analysis of its drivers and variability. This could be done by analysing the orbital decay of the first artificial satellites and upper stages of their rockets. Coarse measurements of the drag acceleration on these objects could be obtained by recording the orbital period from optical or radio tracking, even if the missions were not specifically designed for this purpose. Later on, more precise tracking systems and dedicated accelerometer instruments on satellites have resulted in higher resolution and precision acceleration measurements. We therefore now have a near continuous record of satellite drag observations over decades, although with a great degree of inhomogeneity in terms of sampling resolution and accuracy. Together with in-situ mass spectrometer and remote sensing observations, these data enable the investigation of upper atmosphere climate and weather variability, which is not only important because the upper atmosphere is a boundary region for the entire Earth system, but also because knowledge of upper atmosphere variability is required to continue to operate in the crowded space environment in a safe and sustainable manner.

However, historic measurements were often processed on a project-by-project basis, and processing was done based on varying assumptions and at varying levels of quality resulting in data in a variety of formats. To be able to compare measurements made by different projects in different locations and link them to drivers requires further modelling and processing steps. To help to enable this, we have recently started to incorporate historic thermosphere data in the KNMI space weather timeline viewer.