Magnetosphere-ionosphere-thermosphere coupling: differences and similarities between the two hemispheres

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Abstract

Disturbances in the solar wind and interplanetary magnetic field (IMF) affect the Earth's high-latitude thermosphere and ionosphere via coupling with the magnetosphere. To first order, one might expect these coupling processes to be symmetric between the two hemispheres. However, recent observations have shown that the upper thermospheric/ionospheric response to solar wind and IMF dependent drivers of the magnetosphere-ionosphere-thermosphere system can be very dissimilar in the Northern (NH) and Southern Hemisphere (SH). Statistical studies of both ground- and satellite-based observations show hemispheric differences in the average high-latitude electric field patterns, associated with magnetospheric convection, as well as hemispheric differences in ion drift and neutral wind circulation patterns. The cross-polar neutral wind and ion drift velocities are generally larger in the NH than the SH, and the hemispheric difference shows a semi-diurnal variation. The neutral wind vorticity is likewise larger in the NH than in the SH, with the difference probably becoming larger for higher solar activity. In contrast, the spatial variance of the neutral wind is considerably larger in the SH polar region. Simulations with the Coupled Magnetosphere-Ionosphere-Thermosphere (CMIT) model have recently demonstrated that these differences can be explained at least to some extent by asymmetries in the Earth's magnetic field, both in magnetic flux density and in the offset between the geographic and invariant magnetic poles in the two hemispheres [6]. However, the effects of this magnetic field asymmetry on the high-latitude thermosphere and ionosphere have to be investigated more systematically. In particular, the dependence of hemispheric asymmetries on altitude, season, IMF conditions, and solar activity level are not yet understood. We aim to address this through a combination of numerical model simulations and analyses of observations obtained with different methods, covering different spatial and temporal ranges. The proposed work is highly timely considering the recent launch of the Swarm mission, which will provide further observational material for our project.

1 Scientific Rationale

It is often assumed that the Northern Hemisphere (NH) and Southern Hemisphere (SH) are mirror images of each other because precipitating charged particles and magnetospheric electric generator sources follow magnetic field lines connecting both hemispheres. Such an assumption suggests implicitely a symmetric partitioning of energy and momentum transfer in the high-latitude upper atmosphere part of the global coupled magnetosphere-ionosphere-thermosphere (M-I-T) system under the influence of the external drivers. These are usually summed up as space weather effects and comprise the solar wind interaction with the magnetosphere and reconnection processes with the interplanetary magnetic field (IMF) at the magnetopause.

However, observations show evidence for asymmetries between various parameters of the NH and SH high-latitude ionosphere and thermosphere. Understanding these asymmetries better is important because they can give essential clues for a better scientific description of the complex M-I-T system. The hemispheric asymmetries also constitute a large-scale low-order aspect of the Earth's response to space weather. They concern the dynamics of the high-latitude plasma convection and the neutral wind dynamics in the upper atmosphere as well as the atmospheric mass density. Its closer study is therefore likely to be significant for

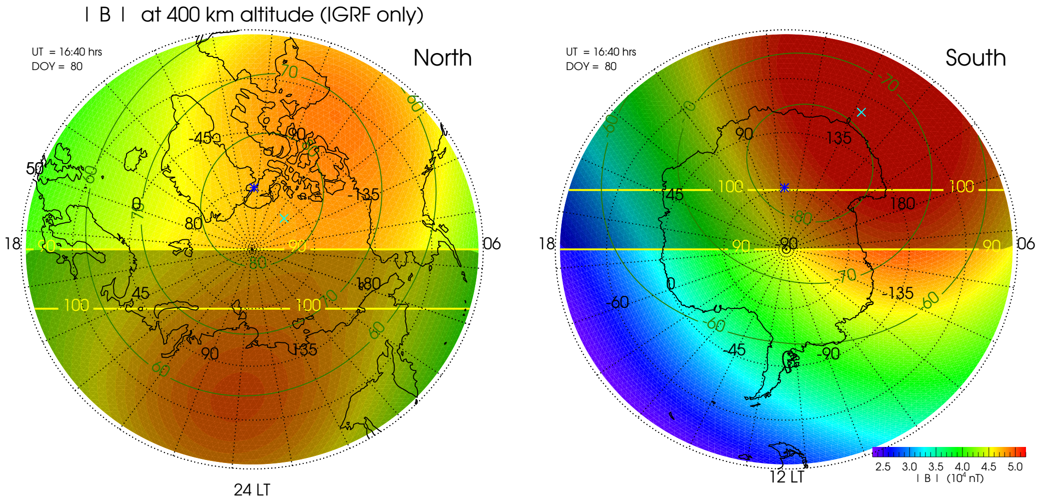

Figure 1: Geomagnetic IGRF flux density $|\vec{B}|$ at 400 km altitude for the present era over the Northern (left) and Southern polar regions (right), shown as colour-coded contour plots with the same scale (bottom right). The dipole axis orientation (geomagnetic poles) are indicated with dark-blue asterisks and the magnetic poles (or dip pole positions) with light-blue crosses. The green isolines show geomagnetic parallels of altitude-adjusted corrected geomagnetic coordinates (AACGM). The yellow solar zenith angle lines and the shading illustrate the solar illumination during equinox at 16:40 UT.

any problem that is sensitive to responses at these large scales as, e.g., the prediction of satellite orbits and reentry locations.

Initially, asymmetries of the M-I-T system were primarily thought to be related to seasonal differences between the NH and SH in the upper atmosphere and the corresponding disparity in the ionospheric conductivity at high latitudes. Early modelling efforts with global Thermospheric General Circulation Models (TGCMs) predicted a hemispheric asymmetry in terms of interhemispheric field-aligned currents (FACs) that should arise from seasonal as well as diurnal variations in conductivity [16, 1]. Also different neutral wind patterns associated with different solar illumination affect the FAC distribution [16].

Over the last decennium it has increasingly been recognized that the dynamic processes in the high-latitude upper atmosphere indeed do show hemispherically asymmetric features, both during particular event studies and in the statistical average sense, resulting from observations over longer periods. Simultaneous global UV imaging of the aurora in the two hemispheres demonstrated differences in the auroral intensity and the location of the polar cap during substorm events [12, 13]. The summer hemisphere was found to respond more promptly to changes in magnetospheric convection than the winter hemisphere. More recent global modelling studies on M-I-T coupling effects have shown that both the strength and the orientation of Earth's magnetic field can affect the coupling between the solar wind and magnetosphere, and thereby influence the ionosphere and thermosphere. The magnetic field configuration influences also the upper atmosphere itself, via its effect on ionospheric conductivity and plasma transport processes [3, 4].

Long-term observations of the cross-polar cap potentials (CPCP) with different observational methods that cover both hemispheres indicated slightly larger CPCP values in the SH than in the NH. This is reported both from advanced models of ground-based observations with the Super Dual Auroral Network (SuperDARN) during southward IMF [15, 5] as well as from satellite observations with the Defense Meteorological Satellite Program (DMSP) [14] and the Electron Drift Instrument (EDI) on board the Cluster mission [10, 8] with differences of the order of $\sim$10% and 7%, respectively. The CPCP difference poses the question about the nature of the large-scale magnetospheric generators, i.e., the relative importance of current versus voltage sources, and their resulting FAC system, which link outer magnetospheric processes with the near-polar upper atmosphere and the high-latitude plasma drifts [2].

Surprisingly, statistical analyses of the average cross-polar ion drift velocity within the polar cap region ($|\phi_m| > 80°$) showed larger ion drift magnitudes in the NH than the SH, with a similar ratio between them as was found for the CPCP [8]. The systematic NH–SH differences in the neutral wind and vorticity appear even larger. Based on CHAMP accelerometer data, [9, 7] showed that the average vorticity at high latitudes in the NH can exceed that in the SH by up to 30% during years of moderate to high solar activity.

The opposite behavior of the ion drift and neutral wind versus the driving electric field strength can be explained by the current near-polar geomagnetic flux density values. The geomagnetic main field is mostly dipolar at Earth's surface and above, but the non-dipolar contributions account for about 10% of its magnitude at ionospheric height. As shown in Fig. 1, they are particularly evident as differences in field strength and pattern shapes at high latitudes of both hemispheres. The $|\vec{B}|$ values at 400 km altitude are on average about 10% higher for the NH versus SH within the circumpolar region inside 80° magnetic latitude according to the International Geomagnetic Reference Field (IGRF). The horizontal gradients are likewise different and the NH exhibit two relative maxima while the SH has only one major $|\vec{B}|$ maximum. Also the offset between the invariant magnetic and the geographic poles is larger in the SH ($\sim 16°$) than in the NH ($\sim 8°$).

Using the Coupled Magnetosphere–Ionosphere–Thermosphere (CMIT) model [18], [6] made a first attempt to investigate the effects of the magnetic field asymmetry on the high-latitude thermosphere and ionosphere for equinox conditions with numerical simulations, and they compared the results with the observations of CHAMP. Their numerical simulation results gave first confirmations of the observed asymmetries of the plasma and neutral components. Further model studies are needed, to analyze the asymmetric hemispherical effects for different seasons and under varying solar activity conditions.

2 Scientific Goals

According to the previously mentioned complexity of the coupled M-I-T effects, we have identified several key scientific items that will be addressed by bringing together experts in the field of research both from the observational side as well as the global numerical modelling efforts. Advancing these items will lead toward an improved understanding of space weather effects on the near-Earth environment including practical application aspects (e.g., satellite drag).

1. **Use various observational data sets to systematically build a clear(er) picture of hemispheric differences.** The observations comprise measurements with Fabry-Pérot Interferometers (FPI) and satellite accelerometer records from CHAMP (Challenging Minisatellite Payload), GOCE (Gravity Field and Steady-State Ocean Circulation Explorer), and ESA's present "troika" near-Earth mission Swarm as well as SuperDARN and Cluster EDI ion drift measurements. Where the same area is covered for the same time period with different observations, these can be used to cross-check: do all observations show the same hemispheric differences? Where different observations cover different altitude ranges, these can be used to establish if/how hemispheric differences vary with altitude.
2. **Use available observations to sort with respect to IMF clock angle, season, and solar activity level to identify how hemispheric differences depend on each of these factors.**
3. **Use (at least) two different numerical models to test hypotheses to explain the observational findings.** The two models that will definitely be used are the Coupled Magnetosphere-Ionosphere-Thermosphere Model (CMIT) [18] and the Global Ionosphere Thermosphere Model (GITM) [17]. Further TIEGCM-type models can also be taken into account as, e.g., the latest version of the Coupled Middle Atmosphere and Thermosphere (CMAT2) model [11]. We would use these to investigate in particular how the differences in the magnetic field between the NH and SH interact with effects of different IMF clock angles, seasons, and solar activity and how these change with altitude. An analysis of the different momentum terms could be helpful in this respect. Several models are used so that results can be cross-checked: where they match, this gives more confidence in the results; where they don't match, this could reveal important clues to the relevant physics, which may be represented differently by different models.

3 Expected Outcomes

Results from investigations within the framework of the proposed project will be presented at various scientific workshops and international conferences. We seek to publish papers on specific aspects of the proposed project separately and aim to summarize them in a final review paper. Specific aspects could be modelling studies of the coupled M-I-T system under the restraining condition of near-to-real geomagnetic field conditions to cover

North-South asymmetries in this regard. Other specific aspects are the comparison of various data sets from different, both satellite and ground-based, observational techniques with regard to interhemispheric differences or the height dependences of the ion-neutral interaction within the upper atmosphere. The comparison will help to identify the basic parameters or conditions which cause hemispheric differences or which alternatively contribute in keeping a symmetric balance.

4 Added Value of ISSI

The proposed project brings together experts from all over the world with complementary expertise in numerical modeling of M-I-T processes and various observational techniques, both satellite-related and ground-based, which gather upper atmosphere parameters of the thermosphere (first of all neutral wind, mass density) and of the ionized components (ion drift). Such diverse expert knowledge is necessary due to the complex nature of the investigated subject and the diversity of techniques we aim to use. It is difficult to assemble such a team through other, conventional means and funding organisations. ISSI provides a unique opportunity in the area of basic environmental research (related to geophysics and space physics) to assemble these colleagues around one table that would be impossible otherwise. ISSI further provides a stimulating ambience for an open and wide-ranging discussion of all aspects of this complicated and complex matter and it constitutes a well-recognized forum for establishing further-ranging collaborations as well as for the publication of the results.

5 Participants

The proposed project team is composed of an international group of scientists with expertise in the high-latitude ionospheric convection, upper atmosphere dynamics, and magnetosphere-ionosphere-thermosphere couplings both from the observational point of view and with respect to physical-numerical modelling. It includes experts familar with ground-based observations (SuperDARN, FPI), satellite data analysis (CHAMP, GOCE, Swarm), and global numerical simulations (CMIT, GITM, CMAT2). These are the team members that have confirmed participation:

- Anasuya Aruliah, University College London, U.K.
- Gareth Chisham, British Antarctic Survey, Cambridge, U.K.
- Ingrid Cnossen, British Antarctic Survey, Cambridge, U.K.
- Mark Conde, Geophysical Institute, University of Alaska, USA
- Eelco N. Doornbos, Technical University Delft, The Netherlands
- Matthias Förster, GFZ German Research Centre for Geosciences Potsdam, Germany
- Stein E. Haaland, Birkeland Centre for Space Sci., Univ. of Bergen, Norway
- Aaron Ridley, University of Michigan, USA

Moreover we expect support from the following external experts (confirmed cooperation):

- Arthur Richmond, HAO, NCAR Boulder, USA
- Alexander A. Namgaladze, Murmansk State Technical University, Russia

6 Project Schedule

We plan to have two one-week meetings to be held in Bern. The first meeting should take place within the first four months after the start of the project and a second meeting a half to one year later. Prior to the first meeting we will agree on the observational data sets and their time span to be analysed for statistical analyses and probably also on 2–3 particular intervals for detailed study. Preliminary results from the observations and first model simulations will be presented and discussed at the first meeting in Bern. The second meeting will then focus on more detailed comparisons between the various observational data sets and model simulations, followed by the more fundamental discussion of the physical processed that contribute to asymmetries between the hemispheres. The preparation of individual papers on specific aspects of the topic or, preferably, a review paper that summarizes the new understanding of the differences and similarities in the frame of the global M-I-T coupling will also be conducted during the second final meeting.

7 ISSI Support

For the one-week meetings of our proposed team we would require a conference room with a beamer (projector) and internet access for the individual laptops. We request per diem and accommodation over the meeting periods in Bern for the team members and for external experts possibly invited ad hoc for particular occasions. We also request round trip travel expenses for the team leader to the meetings in Bern.

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