

A Strategic Vision for Understanding Inter-Hemispheric Asymmetries

A white paper for the 2024-2033 Solar and Space Physics Decadal Survey

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Summary:

Models for space weather forecasting will never be complete/valid without accounting for inter-hemispheric asymmetries in Earth's magnetosphere, ionosphere and thermosphere. This whitepaper is a strategic vision for understanding these asymmetries from a global perspective of geospace research and space weather monitoring. It includes both observation and modeling studies related to the topic. The importance of investigating inter-hemispheric asymmetries space physics research needs to be shown in the decadal survey. It is crucial to understand how each source of asymmetry interacts with each other and how asymmetric structures incorporate this information into real-time monitoring and predictive models of space weather impacts globally. Future challenges of inter-hemispheric asymmetries for Heliophysics investigations are discussed and so are potential solutions. Recently, interhemispheric asymmetry has gained significant interest with the community, both major funding agencies officially supporting relevant programs: the NSF Geospace Environment Modeling (GEM) is currently hosting a focus group "Interhemispheric Approaches to Understanding M-I Coupling (IHMIC)" for the years 2018-2023. A similar topic is also a focused science topic in NASA's Living With a Star (LWS) program, "Causes and Consequences of Hemispherical Asymmetries in the Magnetosphere-Ionosphere-Thermosphere System". The NASA's Drive Center program once hosted a center called "Center for Unified Studies for Interhemispheric Asymmetries (CUSIA)". The European agency, International Space Science Institute (ISSI), funded two international teams carrying out research focusing on the asymmetries (2014 and current). The community consensus, however, is that there are still extensive data gaps in the southern hemisphere and the current models do not sufficiently address the asymmetric features of the geospace environments.

1. Introduction: Understanding interhemispheric effects in geospace research and global space weather monitoring.

In Earth's Magnetosphere-Ionosphere-Thermosphere (M-I-T) system, northern and southern ionospheric and upper atmospheric regions are linked to the global magnetosphere. The interhemispheric asymmetries in these regions have, for example, major impacts on a number of processes including, large-scale convection and field-aligned currents, auroral signatures, substorm evolution, radiation belt dynamics, ion outflow, neutral dynamics and, importantly, coupling between these and other processes.

A number of Earth's geographic and/or geomagnetic topologies contribute to these effects, with perhaps the most important being, a) Earth's dipole tilt and offset, b) the ionizing role of sunlight on the upper atmosphere, and c) climate dynamics that control atmospheric temperature and winds (especially at high altitudes).

The combination of these effects is also important. For example, in spring and fall, the southern cusp remains in essentially constant sunlight, while the northern cusp in Longyearbyen, Svalbard undergoes daily variations of sunlight and darkness due to the Earth's dipole offset. Below, we provide a number of illustrative examples.

1.1 Auroral precipitation

Newell et al. [1996] used DMSP data in a comprehensive statistical study of auroral precipitation and determined that intense aurora occurs primarily when the background ionospheric conductivity is low. A larger-scale perspective of perhaps this same effect was published by *Papitashvili et al.* [2002] and is shown in Figure 1. Using data from the magnetometer chain along the west coast of Greenland from 1999-2000, they found that substorms in winter months (i.e., a dark ionosphere in Greenland) tend to propagate further poleward than in summer months.

1.2 Large-scale auroral forms

Differences in interhemispheric observations of auroral forms were studied by *Laundal and Østgaard* [2009] and are shown in Figure 2, which indicates that simultaneously observed aurora at 21:45 UT 12 May 2001 show completely different intensity distributions in different hemispheres. While they suggest that particle fluxes must be similar in each hemisphere, they note that “intense spots are seen at dawn in the Northern summer Hemisphere, and at dusk in the Southern winter Hemisphere”. The dramatic asymmetry is attributed to inter-hemispheric currents that would have a seasonal dependence.

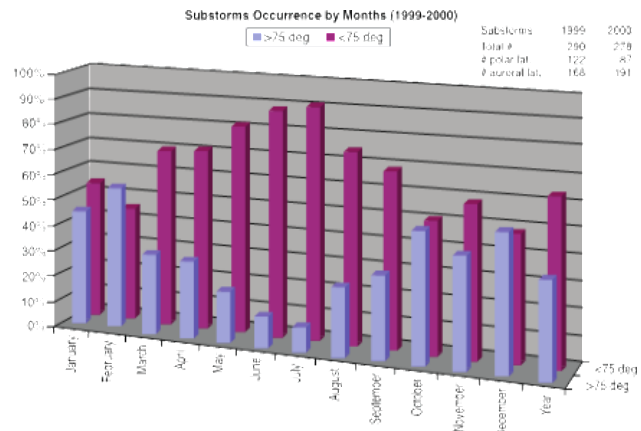


Figure 1 From *Papitashvili et al.* [2002], showing that substorms progress to higher latitudes in a dark ionosphere.

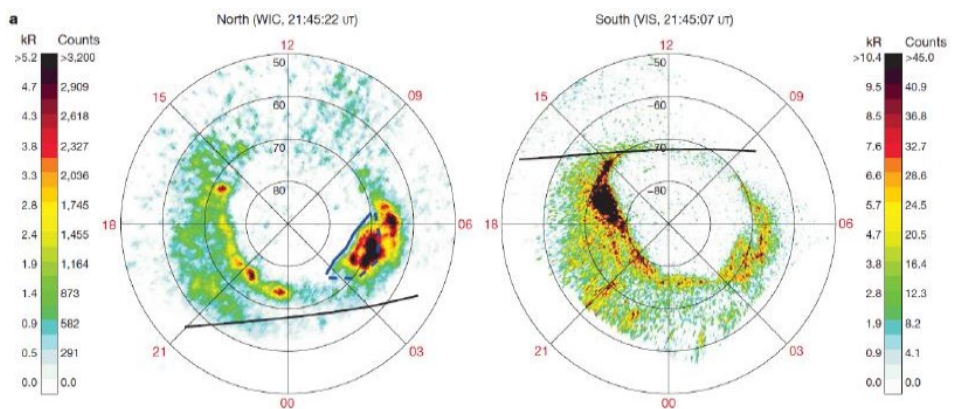


Figure 2. Adapted from *Laundal and Østgaard* [2009], images from the IMAGE (north) and the Polar satellite (south).

1.3 Asymmetries in large-scale currents

Theoretical work on large-scale interhemispheric currents have been studied by *Lyatskaya et al.* [2014]. The effect of the interhemispheric currents (IHCs) on the R1 FACs was investigated in the case of asymmetry in ionospheric conductivity between two hemispheres during summer-winter conditions and specific UT intervals. The results showed that any asymmetry in solar luminosity and, consequently, ionospheric conductivity in two hemispheres results in the generation of the IHCs flowing between two hemispheres. These IHCs can significantly affect the global 3-D current system in winter/summer conditions and some UT intervals.

The circuit analogy for magnetosphere-ionosphere current systems “current or voltage generators” was done to study dayside Transient High Latitude Current Systems (THLCS) [*Harteringer et al.* 2017] by using simulations and ground magnetometer observations from near conjugate locations in both hemispheres. The IHAs of magnetic field variations due to different spatial structure of the current systems in the high-latitude ground magnetic response during the 2015 storm [*Xu et al.* 2017] were done by using ground-based and satellite observations. These studies

show the asymmetries of auroral zone conductivity enhancements and Interplanetary Magnetic Field (IMF) conditions need to be taken into account in model simulations.

1.4 Thermospheric asymmetries

The geomagnetic field asymmetry can also result in stronger high-latitude convection and thermospheric neutral winds in the northern hemisphere [e.g., *Förster and Cnossen*, 2013]. The Earth's upper atmosphere is important for space weather investigations because of the human technologies operating in the region. *Oliveira et al.* [2017] found that the low altitude spacecraft such as CHAMP and GRACE measured asymmetric thermospheric responses to geomagnetic storms, concerning important space weather issues such as spacecraft drag.

1.5 Polar vortex Variability

The massive cyclone called the polar vortex, spanning from the lower stratosphere into the lower thermosphere, plays a pivotal role in our understanding of the entire global atmospheric circulation and ozone depletion. The lower temperature over the Antarctic leads to stronger polar vortices in the southern hemisphere. Such asymmetries in the polar vortices, in turn, potentially impacts the ionosphere-thermosphere system [e.g., *Pedatella and Harvey*, 2022]. Understanding the atmospheric asymmetries is, therefore, crucial for understanding global climate.

1.6 Dynamics and signatures of ULF waves

Mostly due to ionospheric conductivity (that depends greatly on solar insolation), ULF waves and/or their signatures are significantly affected by interhemispheric differences in conductivity. Numerous examples can be given, but we highlight two topics here.

First, recent work seeking to determine the extent to which EMIC waves in space (that are known to scatter radiation belt electrons) can be observed on the ground. *Noh et al.* [2022] compared observations of EMIC waves at GOES 13 to induction coil magnetometers on the ground at Sanikiluaq, Canada, the northern magnetic footpoint of GOES 13. They found a total of 295 coincident and 248 non-coincident EMIC wave events between GOES 13 and the SNK station, with the coincident events predominantly observed on the dayside, presumably related to ionospheric conductivity. This result is important because it implies that ground-based studies may not be able to observe nearly half of the waves observed at GOES 13.

At much lower frequencies, *Lysak et al.* [2020] used a numerical model to determine that, when one foot point of a field-line resonance is sunlit and the other is dark, the resonance will be one quarter of the full wavelength and will have a fundamental frequency of 2 lower. This is important because these waves are thought to energize radiation belt particles via a drift-bounce resonance, which is frequency dependent.

2. Interhemispheric effects in numerical models.

2.1 Current state of inter-hemispheric effects in numerical models

The current state of knowledge of existing numerical modeling capabilities concerning interhemispheric asymmetries is poor - we do not even know entirely what we can and cannot do. Most numerical models are, at least at some level, based on an assumption of symmetry. Sometimes this is explicit, as is the case with the Rice Convection Model (RCM) only coupling to northern hemisphere [*Toffoletto et al.* 2003], or the Comprehensive Inner Magnetosphere Ionosphere (CIMI) model using a dipole to calculate the loss cone [*Fok et al.* 2014]. Other times, it is implicit. As an example, the empirical conductance model used by the Ridley Ionosphere Model (RIM) was built only considering the northern hemisphere [*Ridley et al.* 2004]. It takes

expertise, time, and effort to fully realize interhemispheric asymmetries into contemporary models.

Despite limitations, models are indeed capable of capturing some large-scale asymmetries. Global magnetohydrodynamics (MHD), still the backbone of most global-level numerical investigations, can reproduce the large scale IMF By effects on ionospheric electrodynamics [e.g., *Korth et al.* 2004; 2011]. Global thermosphere models have done an excellent job of elucidating the impact of asymmetric high-latitude drivers [*Hong et al.* 2021]. Polar wind models have shown that outflow can become highly asymmetric [*Barakat et al.* 2015]. Overall, there is

capability, but the depth and limitations are poorly understood. Where models can and should be contributing is how asymmetries manifest on a system level. When heavy ion outflow becomes asymmetric? How does that affect the magnetosphere? The full IGRF field creates asymmetries in the loss cone and, therefore, ionospheric current closure and potential patterns. How does the global magnetosphere respond to these effects? Such investigations would open a wealth of knowledge on the physics underpinning asymmetries.

Ad-hoc couplings have provided an initial insight into the inter-domain dynamics of asymmetries. The global FAC patterns from MHD simulations are often used to investigate interhemispheric asymmetries. Even though these models use analytical expressions to estimate the ionospheric conductance values [e.g., *Knight et al.* 1973; *Ridley et al.* 2004], they can reproduce the

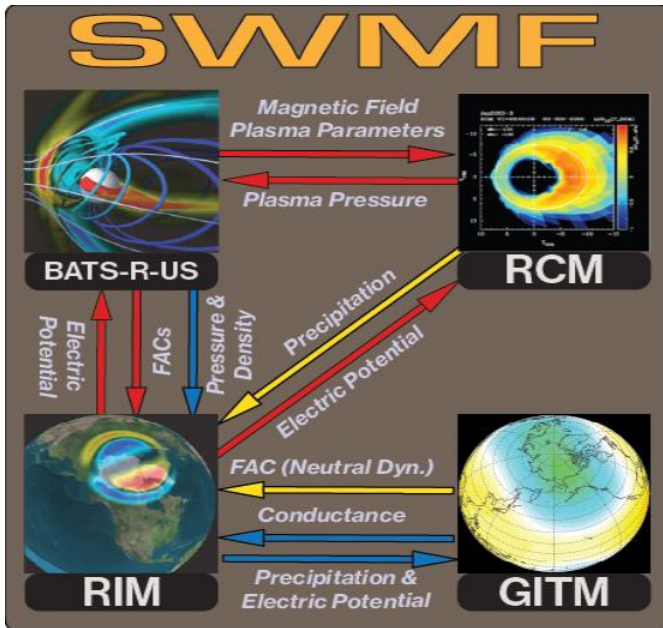


Figure 3. A proposed expanded M-I-T coupling scheme that would include greater feedback from the thermosphere to the ionosphere and magnetosphere.

interhemispheric asymmetries stemming from the external drivers (such as dipole tilt, IMF By). The FACs provide the electric potentials and the precipitation patterns necessary to specify upper boundary values for electromagnetic energy from the Magnetosphere to drive General Circulation Models GCMs). More recently, driving by AMPERE FAC observations has been incorporated to GCMs like TIE-GCM [*Maute et al.* 2021] and GITM [*Zhu et al.* 2022]. The asymmetries of Traveling atmospheric disturbance (TADs) and Traveling ionospheric disturbance (TIDs) from models are shown in *Zhu et al.*, 2022.

This study highlights the incomplete nature of such studies. It should be fully expected that interhemispheric asymmetries in the thermosphere should affect the ionosphere. This would, in turn, change global magnetospheric behavior as well. However, no global or coupled model system fully accounts for all these effects, leaving large gaps in our knowledge. Deeper model development is required to elucidate the global response to such asymmetries. A proposed study is outlined below in Figure 3. This diagram shows the Space Weather Modeling Framework (SWMF) coupling several models together, including the GITM. While the blue coupling paths between the ionosphere solver and GITM are established in the field, they have not been deeply employed to look at asymmetric feedback paths. The yellow coupling line, representing field

aligned currents (FACs) driven by neutral winds, represents a feature that is highly asymmetric between hemispheres but has never been explored in a self-consistent fashion. Funding and elevating such studies as critical tools for interhemispheric science is a deep need in heliophysics.

2.2 Future goals - model integration

Our overarching goal is to understand IHA in forcing from both above and below and to investigate their impacts on the global M-I-T system. Specifically, we propose to focus on the questions below:

- Where and under what conditions does IHA happen at different latitudes? What are the roles of multi-scale structures in IHA asymmetries?
- How large are IHA in the MI coupled system during quiescent and disturbed conditions? How effectively do these IHAs contribute to the asymmetries in the IT system?
- How large are IHA in lower atmospheric forcing and do they generate IHA in the upper atmosphere system?
- What is the importance of IHA associated with lower atmospheric forcing during quiescent times and meteorological disturbed times?

The community has insufficient understanding of the nature of interhemispheric asymmetries.

One obvious problem is our inability to make predictions due the observation gaps in the southern hemisphere. The thermosphere-ionosphere-magnetosphere-solar wind system is highly complex, dynamic, and heavily under sampled. Most numerical modeling tools are either not yet equipped to account for IHAs or inaccurately specify the related forcing. For example, in empirical models, north-south hemisphere asymmetries have been typically ignored and the data from two hemispheres have been binned together in data analysis and model development. The lack of IHA input into GCM models has prevented simulations from testing their impact on the global I-T system. In MHD and magnetospheric models, the default setup of the geomagnetic field is a pure dipole field, which can be far from reality. Recent simulations conducted by M. Fok show that the magnetic field configuration (dipole vs. IGRF) can strongly influence the particle precipitation distribution and energy flux. It is in an urgent need for the models to have the capability to account for the asymmetries imposed onto the geospace system. In addition, the role of multi-scale coupling is widely recognized among the community following the success of the NSF Geospace Environment Modeling (GEM) Focus Group on Magnetotail Dipolarizations and their Effects in the Inner Magnetosphere over the last four years. Cross-disciplinary multi-scale models are fundamental to further our understanding of interhemispheric asymmetries in the next decade.

3. Current state of interhemispheric observations and future needs.

Systematic, simultaneous observations that cover auroral and higher latitudes in both hemispheres are essential for addressing the problems of interhemispheric asymmetries. While spacecraft generally provide in-situ observations of both hemispheres (to varying degrees), ground-based observing platforms in the northern hemisphere are far more widespread and numerous than in the south. To a large degree, of course, this is due to logistical challenges in Antarctica although new technologies, described below, are very promising. These advancements have already been shown to be highly effective in support of remote observations, and are needed in the southern hemisphere to solve the challenges of interhemispheric asymmetries.

3.1.a Current capabilities of ground-based observations.

Magnetically conjugate ground-based observations provide the fundamental data that are needed to understand asymmetries. Although widespread arrays of magnetometers, all-sky cameras and other instruments exist in the northern hemisphere and span broad regions in magnetic local time, conjugate instrumentation in the southern hemisphere is very limited. Figure 4 shows the

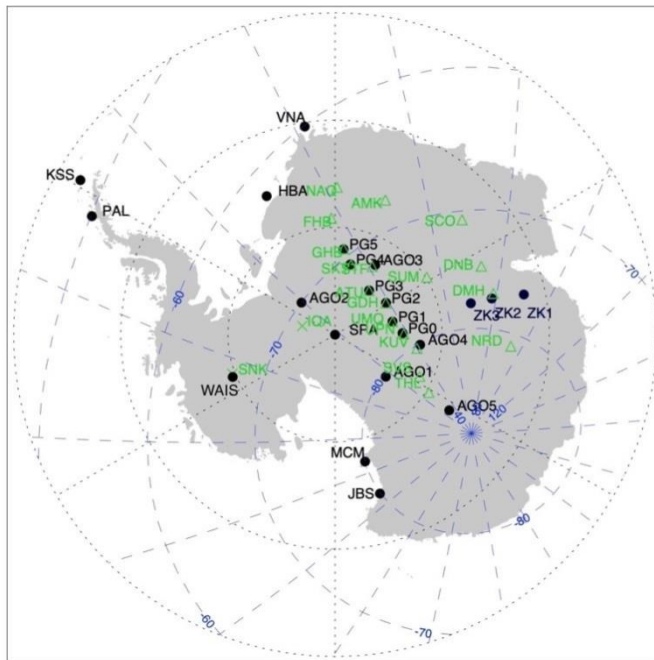


Figure 4. Map of Antarctica showing manned/ unmanned stations (black dots) with the Northern magnetically conjugate stations projected onto the map (green).

locations of various permanent stations, all located along the coast of Antarctica except for South Pole Station and WAIS Divide (not supported at this time). Very few of these sites have northern counterparts, largely because they were not established for this purpose. Still, many of these sites do support various instruments, notably McMurdo (MCM), Jang Bogo (JBS), Halley (HBA), Von Neumayer (VNA), King Sejong (KSS) and Syowa (not shown) stations. On the other hand, the unique West Greenland magnetometer chain is, by design, conjugate to AAL-PIP magnetometers on the East Antarctic Plateau, covering latitudes from the polar cap to the auroral zone along the 40-degree-magnetic meridian (labeled as stations “PG” in the figure). Aside from Syowa being roughly conjugate to Husafell, Iceland, which hosts a few instruments, there are no conjugate observing platforms in Antarctica.

3.1.b Current capabilities of spacecraft coverage

Satellite observations (THEMIS, Cluster, MMS, DMSP, GOLD, etc) can provide solar wind and magnetosphere conditions that are important for understanding the origins of the phenomena observed from the ground-based instruments and are important for interhemispheric studies. The Defense Meteorological Satellite Program (DMSP) spacecraft are perhaps the most useful tool that can provide particle and wave inputs into both high latitude ionospheres.

The future Geospace Dynamics Constellation (GDC) mission will measure the geomagnetic energy inputs and ionosphere-thermosphere (I-T) system over a broad range of spatial and temporal scales. One mission objective is to determine how hemispheric asymmetries in the Earth’s magnetic field, seasonal variations, and magnetospheric input affect the I-T system (GDC STDT Final Report).

3.2a Important future capabilities for ground-based observations

The development of improved remote observing platforms is essential for making Antarctic measurements. To date, existing technologies (e.g., Iridium communications and GPS navigation) have enabled the development of important new observing platforms, with three paths forward showing particular promise but each with its strengths and weaknesses. Small observatories like AALPIP [Clauer *et. al.* 2014] can support DASI-type observations, though the current platform is solar-powered with battery storage capabilities that extend its operation into darkness for a limited time. Efforts are underway to incorporate small wind generators, more advanced solar-

power and battery equipment, etc, which will enable year-round observations that, in principle, and can support auroral imaging (limited by Iridium bandwidth).

Robotic platforms have had good success in Antarctica with the use of ground-penetrating radar, supported by “Cool robots” [Ray *et al.*, 2014]. These are 70-kg four-wheel drive, solar-powered robotic platforms with GPS waypoint following, capable of towing or carrying payloads of over 40 kg. While the payload capabilities of these robots are impressive, their use is still limited to periods of sunlight. While their autonomous capability means that they can navigate to specific magnetic conjunction points to provide optimal interhemispheric measurements their routes might be constrained by crevasses and sastrugi, although Ray *et al.* [2014] report the successful completion of over 175 km of autonomous surveys. Data bandwidths using robots would be comparable to AALPIP because both use Iridium modems.

Advancements in drone technology suggests the possibility that they may provide another mechanism for DASI-type observations, though perhaps limited to very light payloads and not able to transmit data in real-time because the mass limitation likely not support Iridium operation. Still, successful operation of fluxgate magnetometers onboard drones has been enabled numerous magnetic surveys, including observations of ~ 5 nT perturbations [Yoo *et al.* 2021], sensitive enough to possibly detect field-line resonances and certainly adequate for observing substorm evolution. Like with robotic platforms, their operation would be restricted to periods of sunlight but they could also navigate to *specific* magnetic conjunction points to provide interhemispheric measurements.

3.2b Important future capabilities of satellite missions

While ground-based instruments can acquire conjugate data simultaneously and over extended regions, in-situ measurements are necessary because they provide information about the state of the ionosphere and thermosphere and also provide important data about energy inputs into the ionosphere and upper atmosphere. The availability of data from DMSP, NPOES and the future WSF-M missions has been highly valuable for studies of these regions, especially because the high-inclination of these spacecraft provides good coverage of the auroral zone and polar cap. On the other hand, the simultaneous interhemispheric observations shown in Figure 2 are quite a rare set of data. In order to understand even basic interhemispheric processes at high latitudes and the polar cap, large-scale conjugate images of aurora are essential for advancing the state of the field. Such a mission could consist of 2 small spacecraft in high-inclination elliptical orbits with apogees above the two poles.

4. The picture of inter-hemispheric asymmetries study in next decade

As modern space technology advances in the next decade, observations and models to monitor and predict the impacts of inter-hemispheric asymmetries will be crucial. Observations need to provide **3D coverage with meso spatial scale in both hemispheres**, especially in high latitude regions, to capture global and mesoscale system features. This includes satellite observations that globally cover from solar wind and IMF conditions to energy and particle inputs through magnetosphere, ionosphere, and thermosphere, and ground-based observations with multiple instruments at conjugate locations in both hemispheres. This could be achieved by the synergy and collaboration of interdisciplinary and international institutions. With better inter-hemispheric observations, models will be capable of **adapting multiple asymmetric mechanisms simultaneously and globally** and predicting the MIT coupling processes associated with the solar energy input and geospace feedback due to asymmetries. These advances will greatly improve our understanding of solar wind -magnetosphere-ionosphere -thermosphere coupling processes and real-time monitoring of space weather impacts.

Reference

- Barakat, A. R., Eccles, J. V., & Schunk, R. W. (2015). Effects of geographic-geomagnetic pole offset on ionospheric outflow: Can the ionosphere wag the magnetospheric tail? *Geophysical Research Letters*, 42(20), 8288–8293. <https://doi.org/10.1002/2015GL065736>
- Clauer, C. Robert, Hyomin Kim, Kshitija Deshpande, Zhonghua Xu, Daniel Weimer, Stephen Musko, Geoff Crowley, Chad Fish, Randall Nealy, T. E. Humphreys, J. A. Bhatti, A. J. Ridley, “Autonomous adaptive low power instrument platform (AAL-PIP) for remote high-latitude geospace data collection”, *Geosci. Instrum. Method. Data Syst.*, 3, 211-227, doi:10.5194/gi-3-211-2014, 2014.
- Engebretson, M., & Zesta, E. (2017). The future of ground magnetometer arrays in support of space weather monitoring and research. *Space Weather*, 15, 1433–1441.
- Fok, M. C., Buzulukova, N. Y., Chen, S. H., Glocher, A., Nagai, T., Valek, P., & Perez, J. D. (2014). The comprehensive inner magnetosphere-ionosphere model. *Journal of Geophysical Research: Space Physics*, 119(9), 7522–7540. <https://doi.org/10.1002/2014JA020239>
- Förster, M., and Cnossen, I. (2013), Upper atmosphere differences between northern and southern high latitudes: the role of magnetic field asymmetry, *J. Geophys. Res.*, 118, 5951-5966, doi:10.1002/jgra.50554
- Hartinger, M. D., Xu, Z., Clauer, C. R., Yu, Y., Weimer, D. R., Kim, H., Pilipenko, V., Welling, D. T., Behlke, R., and Willer, A. N. (2017), Associating ground magnetometer observations with current or voltage generators, *J. Geophys. Res. Space Physics*, 122, 7130– 7141, doi:10.1002/2017JA024140.
- Hong, Y., Deng, Y., Zhu, Q., Maute, A., Sheng, C., Welling, D., & Lopez, R. (2021). Impacts of Different Causes on the Inter-Hemispheric Asymmetry of Ionosphere-Thermosphere System at Mid- and High-Latitudes: GITM Simulations. *Space Weather*, 19(11). <https://doi.org/10.1029/2021SW002856>
- Knight, S. (1973). Parallel electric fields. *Planetary and Space Science*, 21(5), 741–750. [https://doi.org/10.1016/0032-0633\(73\)90093-7](https://doi.org/10.1016/0032-0633(73)90093-7)
- Knipp, D., Kilcommons, L., Hairston, M., & Coley, W. R. (2021). Hemispheric asymmetries in Poynting flux derived from DMSP spacecraft. *Geophysical Research Letters*, 48, e2021GL094781. <https://doi.org/10.1029/2021GL094781>
- Korth, H., Anderson, B. J., Wiltberger, M. J., Lyon, J. G., & Anderson, P. C. (2004). Intercomparison of ionospheric electrodynamics from the Iridium constellation with global MHD simulations. *Journal of Geophysical Research*, 109(A7), A07307. <https://doi.org/10.1029/2004JA010428>
- Korth, H., Rastätter, L., Anderson, B. J., & Ridley, A. J. (2011). Comparison of the observed dependence of large-scale Birkeland currents on solar wind parameters with that obtained from

global simulations. *Annales Geophysicae*, 29(10), 1809–1826. <https://doi.org/10.5194/angeo-29-1809-2011>

Laundal, K., Østgaard, N. (2009). Asymmetric auroral intensities in the Earth's Northern and Southern hemispheres. *Nature* 460, 491–493, 2009. <https://doi.org/10.1038/nature08154>

Lysak, R. L., Song, Y., Waters, C. L., Sciffer, M. D., & Obana, Y. (2020). Numerical investigations of interhemispheric asymmetry due to ionospheric conductance. *Journal of Geophysical Research: Space Physics*, 125, e2020JA027866. <https://doi.org/10.1029/2020JA027866>

Lyatskaya, S., Lyatsky, W., and Khazanov, G. V. (2014), Effect of Interhemispheric Field-Aligned Currents on Region-1 Currents, *Geophys. Res. Lett.*, 41, 3731– 3737, doi:10.1002/2014GL060413.

Maute, A., Richmond, A. D., Lu, G., Knipp, D. J., Shi, Y., & Anderson, B. (2021). Magnetosphere-ionosphere coupling via prescribed field-aligned current simulated by the TIEGCM. *Journal of Geophysical Research: Space Physics*, 126, e2020JA028665. <https://doi.org/10.1029/2020JA028665>

Newell, P. T., Feldstein, Y. I., Galperin, Y. I., and Meng, C.-I. (1996), Morphology of nightside precipitation, *J. Geophys. Res.*, 101(A5), 10737– 10748, doi:10.1029/95JA03516.

Noh, S.-J., Kim, H., Lessard, M., Engebretson, M., Pilipenko, V., Kim, E.-H., et al. (2022). Statistical study of EMIC wave propagation using space-ground conjugate observations. *Journal of Geophysical Research: Space Physics*, 127, e2022JA030262. <https://doi.org/10.1029/2022JA030262>

Oliveira, D. M., Zesta, E., Schuck, P. W., & Sutton, E. K. (2017). Thermosphere global time response to geomagnetic storms caused by coronal mass ejections. *Journal of Geophysical Research: Space Physics*, 122, 10,762– 10,782. <https://doi.org/10.1002/2017JA024006>

Papitashvili, V. O., and Rich, F. J., High-latitude ionospheric convection models derived from Defense Meteorological Satellite Program ion drift observations and parameterized by the interplanetary magnetic field strength and direction, *J. Geophys. Res.*, 107(A8), doi:10.1029/2001JA000264, 2002.

Pedatella, N. M., & Harvey, V. L. (2022). Impact of strong and weak stratospheric polar vortices on the mesosphere and lower thermosphere. *Geophysical Research Letters*, 49, e2022GL098877. <https://doi.org/10.1029/2022GL098877>

Ray, L., Adolph, A., Morlock, A., Walker, B., Albert, M., Lever, J. H., Dibb, J., (2014) Autonomous rover for polar science support and remote sensing, *IEEE Geoscience and Remote Sensing Symposium*, 2014, pp. 4101-4104, doi: 10.1109/IGARSS.2014.6947388.

Ridley, A. J., T. I. Gombosi, and D. L. DeZeeuw (2004), Ionospheric control of the magnetosphere: Conductance, *Ann. Geophys.*, 22(2), 567–584, doi:10.5194/angeo-22-567-2004.

Toffoletto, F., Sazykin, S., Spiro, R., Wolf, R., (2003) Inner magnetospheric modeling with the Rice Convection Model. *Space Science Reviews* 107, 175–196, 2003.
<https://doi.org/10.1023/A:1025532008047>.

Xu, Z., Hartinger, M. D., Clauer, C. R., Peek, T., and Behlke, R. (2017), A comparison of the ground magnetic responses during the 2013 and 2015 St. Patrick's Day geomagnetic storms, *J. Geophys. Res. Space Physics*, 122, 4023– 4036, doi:10.1002/2016JA023338.

Yoo, L.-S.; Lee, J.-H.; Lee, Y.-K.; Jung, S.-K.; Choi, Y. Application of a Drone Magnetometer System to Military Mine Detection in the Demilitarized Zone. *Sensors* 2021, 21, 3175.
<https://doi.org/10.3390/s21093175>

Zhu Q, Lu G and Deng Y (2022) Low and Mid-Latitude Ionospheric Response to the 2013 St. Patrick's Day Geomagnetic Storm in the American Sector: Global Ionosphere Thermosphere Model Simulation. *Front. Astron. Space Sci.* 9:916739. doi: 10.3389/fspas.2022.916739