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Editorial: Coupled feedback mechanisms in the magnetosphere-ionosphere system

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Editorial on the Research Topic
Coupled feedback mechanisms in the magnetosphere-ionosphere system

The dynamics of the inner-magnetosphere and ionosphere are coupled through complex feedback mechanisms involving waves, DC electric fields, particle flows, and field aligned currents. A full understanding of the behavior of either the magnetosphere or ionosphere requires an account of the other. These magnetosphere-ionosphere (M-I) coupling processes and dynamics may be driven not only by the solar wind and its influence on the outer-magnetosphere, but from the thermosphere through the action of neutral winds. Today, current interests are brought on any processes contributing to the transport of energy into and out from the ionosphere. This includes general advection/convection in the ionosphere and inner-magnetosphere, and, particularly, meso-scale convective subauroral phenomena, including subauroral polarization streams (SAPS) and subauroral ion drifts (SAIDS). Luminous manifestations in the lower ionosphere such as Strong Thermal Emission Velocity Enhancement (STEVE), SAR arcs, diffuse electron and proton aurora, and discrete aurora, are key to the analysis and understanding the particle and fields dynamics. In this Research Topic, we have collected a wide variety of studies that contribute to understanding the magnetosphere-ionosphere-thermosphere as a coupled feedback system, from either satellite or ground-based data sets, theory, modeling, simulations, and studies involving machine learning. These studies are sorted according to the following sub-categories: radiation belts, mesoscale phenomenon, aurora, current systems, ion outflows and geomagnetic indices. Their main results are briefly contextualized and discussed in following.

Radiation belts

Convection, electric field, and boundary motion

Investigating the origins of the large-scale electric field and their dissymmetry causing observed radiation belt distortion, Lejosne et al. use the RCM model coupled with the Coupled Thermosphere-Ionosphere-Plasmasphere-electrodynamics (CTIPe) model. The objective is to assess whether or not neutral wind dynamo, i.e., dynamo electric fields produced by tidal motion of upper atmospheric winds (Richmond, 1989) that flows across the Earth's magnetic field lines, could cause these distortions and be at the origins of the local time asymmetry of the equatorial electron intensity occurring from dawn to dusk observed in the inner radiation belt (Selesnick et al., 2016). Measured equatorial electron intensity (100–400 keV) and *in-situ* electric field combined with wind dynamo modeling results lead to an estimation of 6–8 kV for the average dawn-to-dusk electric potential variation from neutral wind dynamo, making these fields main drivers of the drift shell distortion in the Earth's inner radiation belt. By tracing the drift of trapped energetic electrons (10–100 keV), Lejosne et al. further show electric field disturbances coherently transport radially this population over hundreds to thousands of kilometers in the inner belt. Results of the Rice Convection Model (RCM) (Toffoletto et al., 2003) code suggests that the electric field disturbances are likely greater than empirical estimates and that electron radial transport driven by prompt magnetospheric convection varies as L to the power 3, though the magnitude of this transport remains to be determined. Another study involving RCM (Priyadarshi et al.) investigates interactions between Earth's magnetotail and the inner magnetosphere, which play an important role in the transport of mass and energy in the ionosphere–magnetosphere coupled system. They simulate injection events and extract the flux-tube entropy parameter, the dawn-to-dusk electric field component, and the cumulative magnetic flux transport in the central plasma sheet. Recurrent neural networks are then trained to learn these results and to predict the solution for the successive tens of minutes. Predictions are successively and successfully validated against subsequent RCM simulation results. In Pierrard et al., the equatorward motion of the plasmapause projected in the ionosphere is related to the equatorward edge motion of the auroral oval that goes to lower latitudes during storms due to the geomagnetic perturbation as well as to the electron outer radiation belt. The links between these different regions are investigated during quiet periods, for which the plasmasphere is widely extended, as well as during geomagnetic storms; tremendous differences in flux associated with the pitch angle dependence are shown in both cases.

Electromagnetic waves

Electromagnetic waves produced by lightning strokes in the atmosphere and travelling through the ionosphere up to the magnetosphere produces the scattering of trapped particle in the inner belt. The propagation of these waves is studied from Earth to space in Ripoll et al. They find the electric field wave power decays with distance mostly quadratically in space, while the magnetic field wave power decays mostly linearly in space. These waves measured by the Van Allen Probes are rare on the dayside. Their mean wave-normal angle is 41.6° +/-24°, with a strong MLT-dependence. Their smaller refractive index during Northern hemisphere summer for L-shells above 1.8 is inconsistent with Chapman ionization theory and consistent with the so-called winter/seasonal anomaly (Liu et al., 2009). The wave normal angle and refractive index are found anti-correlated. High power attenuation is correlated with large refractive index and anti-correlated with small wave normal angle.

Microbursts are short-lived electron precipitation observed in the lower ionosphere by LEO satellites. They are thought to contribute significantly to the losses of energetic electrons in the outer radiation belt and to be caused by whistler mode chorus waves. The quantification of microbursts often relies on the assumption that chorus waves are ducted along the magnetic field line. Chen et al. develop a new nonducted chorus wave model integrated in the HOTRAY ray tracing code (Horne, 1989). Test particle simulations further show that nonducted waves tend to produce electron microbursts at lower energy, over a shorter duration, and over a broader L-shell region, and, as such, can trigger different resonance mechanisms.

Wave particle interaction and electron precipitation

The chemical imprint of the energetic electron precipitation on the atmosphere is a part of the natural forcing of the climate system (van de Kamp et al., 2016), with important questions on quantifying energetic electron precipitation flux in terms of timing and intensity. In that context, Nesse Tyssøy et al. create a new medium energy electron (MEE) (30–300 keV) flux proxy by accumulating the AE activity over multiple days and combining observations from NOAA/POES and EUMETSAT/MetOp spacecraft, as well as pitch angle diffusion by wave-particle interaction to estimate the precipitating fluxes. Their results indicate that AE based proxies can predict at least 70% of the observed MEE precipitation variance at all energies.

Intense precipitation observed at 37 km of altitude over Sweden from the Balloon Array for Radiation belt Relativistic Electron Losses (BARREL) are explained in Millan et al. by wave particle interaction occurring in dense plasma plumes at GEO orbits. In these plumes, whistler-mode hiss with electromagnetic power 3–4 times above the median power are found. The induced pitch angle scattering is far from equilibrium with short apparent decay rates of the electron flux in space of the order of ~12 min at 74 keV and persisting during ~30 min, exceeding by a factor ~10 the electron lifetime. The energy of the precipitating electrons is estimated to be ~50–100 keV. The prevalence of plasmaspheric plumes and detached plasma regions suggests whistler-mode hiss waves could be an important driver of electron loss even at high L-value (L~6), outside of the main plasmasphere. Pitch angle diffusion coefficients that are essential for computing precipitations can be embedded in a Deep Neural Network as done in Kluth et al. in order to create a parametrized model easily usable for simulating and predicting the effect of solar high-speed streams on the radiation belts. Pitch angle diffusion of protons, either produced by plasma-wave scattering or by field-line-curvature (FLC) scattering is further demonstrated by Borovsky et al. as better organized in a transformed coordinate system, called the "Mozer transform" from Mozer (1966).

Mesoscale and auroral phenomenon

Meso-scale structures in the plasma sheet and auroral oval play an important role in plasma transport. Lyons et al. test the 2-days structure of plasma sheet flow bursts predicted by the Rice Convection Model (RCM) using aurora and flow observations. They find that RCM predictions of the azimuthal spread of a low-entropy plasma sheet plasma and its associated field-aligned currents and flows give a realistic physical description of the structure of plasma sheet flow bursts. Lyons et al. examines a connection between such flow bursts and large-scale traveling ionospheric disturbances (LSTIDs). The observations show a direct connection between a group of streamers and flow channels to TIDs propagating equatorward from the equatorward boundary of the auroral oval. Ionospheric currents associated with the aurora, however, must be sufficiently large to result in LSTIDs. Garton et al. derives a neural network model fed by satellite observations of the magnetic field components to identify evidence of reconnection in the magnetosphere, based on a classification of the events as plasmoids, traveling compression regions, and dipolarization fronts. This model allows a full cataloging and examination of magnetic reconnection. Although it is initially built for Saturn, its method can generally be applied to any planet's magnetosphere.

Remote sensing techniques for aurora and energetic neutral atoms (ENA) have revealed fundamental plasma processes in the magnetosphere-ionosphere system. Gabrielse et al. present a new method that utilizes the 2D array of all-sky-imagers to estimate auroral scale sizes of intense precipitating energy fluxes and the associated Hall conductances. They find that mesoscale aurora contributes up to ~80% of the total energy flux immediately after onset during the early expansion phase of substorms. A sounding rocket mission by Rowland et al. investigated the factors leading to ion outflow following a geomagnetic substorm. ENA emissions were most intense in the auroral zone, and were dominated there by upgoing ENAs, indicating a strong interaction between the energetic ions and the neutral atmosphere. They suggest large regions of efficient wave particle heating up to a few keV. Adewuyi et al. presented temperature maps using satellite-based ENA observations of a storm event. In coordination with *in-situ* and auroral observations, they find that mesoscale features in the magnetotail are observed throughout the storm and suggested to be a dominant process that leads to pressure buildup in the inner magnetosphere.

Interaction between the magnetotail/aurora and inner magnetosphere is another key process in Geospace. Sorathia et al. investigate the relative importance of mesoscale flow structures and effects of ion non-adiabaticity on the ring current. Flow bursts produced by the simulation reproduce thermodynamic and magnetic statistics from *in-situ* measurements. Mesoscale bubbles, localized depleted entropy regions, and species-dependent particle gradient drifts are critical for ion transport. Pierrard et al. compared plasmapause positions measured by Van Allen Probes and a model. Inward motion of the outer radiation belt was related to the plasmapause erosion and equatorward edge motion of the auroral oval. Importance of the magnetic field topology and of convection electric field was suggested.

Ion outflows

Outflows from the ionosphere, and the general details of plasmasphere field-aligned flows, are very important processes as they can populate the inner magnetosphere with cold plasma, influencing many subsequent dynamic responses. Krall and Huba provide the latest in a long string of hydrodynamic and kinetic model investigations of plasmasphere outflows stretching back to SUPIM (Bailey et al., 1997) and FLIP (Young et al., 1980). Using the SAMI3 model from US Naval Research Laboratory the work examined all relevant topside species - H^+, He^+, N^+, and O^+ - and their thermal outflows during storm conditions. The study finds that counterstreaming cold ion populations occur in all cases as material streams outward from both hemispheres following large scale plasmasphere reconfiguration, with particular emphasis on afternoon/dusk sector counterstreaming in areas of large ring current heating. Zou et al. focus on the significant impact on ion outflows caused by another well-known mass transport stormtime signature, the storm enhanced density (SED) plume (Foster, 1993). During a moderate intensity storm, SED formation into the cusp fed the creation of polar cap patches anti-sunward, and these high-density structures triggered large cold ionospheric ion upward fluxes reaching 3 x 10^{14} m^{-2} s^{-1}. Such intense upward fluxes are important mechanisms for populating the inner magnetosphere with low energy ions.

Current systems

One of the major coupling mechanisms in the IM system are field aligned current systems. Hwang et al. use observations from the Cluster and MMS missions to identify solar wind driven Kelvin-Helmholtz (KH) vortices on the dusk and dawn flanks of the magnetosphere. The twisting magnetic fields result in field aligned currents that are upward from (downward into) the ionosphere, consistent that are with the Region-1 currents, ground and low-altitude spacecraft observations. Thus, showing that the KH vortices at the plasmapause are a driver of this current system. Sangha et al. presents a statistical study using AMPERE data of the bifurcation of the region-2 current system on the dawn and dusk sides. They show that this phenomenon exhibits seasonal and UT trends, with the bifurcated region two currents occurring preferably in the summer hemisphere at dusk, which may be due to enhanced ionospheric conductivity there. The authors point out a possible relation to SAPS. Field aligned currents play an important role in Zou et al. wherein they present a study using both remote and *in situ* observations of the ionosphere-thermosphere system, along with solar wind, IMF data and Sym-H index to demonstrate the crucial role that Storm Enhanced Densities (SED), structures of high ionospheric density, have in creating large upward ion fluxes. The FAC help contextualize the state of the magnetospheric driver in terms of its impact on the ionosphere.

Ionospheric currents, through their associated magnetic field induce current in the ground. Kikuchi et al. investigate the correlation of the measured surface magnetic field with ground induced currents (GIC) on various timescales from ~ 1 min to ~1 day. They show that the induced electric field calculated from the surface magnetic field and semi-infinite one- and two-layer conductivity models correlates well with the GIC for periods from 1 min to 24 h. These models, combined with global magnetospheric simulations, would allow for the prediction of GIC during space weather disturbances.

Geomagnetic indices

Geomagnetic indices are proxies for various magnetospheric/ionospheric current systems. Borovsky investigates the saturation, or non-saturation, of various geomagnetic indices, exploring the topics of whether the nature of the index matters, the relation of the saturation of the index to that of the polar cap potential, and any role the choice of solar wind driver function has. Borovsky shows, among other things, that the degree of saturation depends on the solar wind driver function, that different indices show different degrees of saturation, that the polar-cap function can sometimes correct for the saturation, and that the nature of the index measurement matters.

Geomagnetic indices can also serve as good proxies for other processes, such as precipitating MEE as described above (Nesse Tyssøy et al.) The link between the AE and MEE precipitation is likely to be the substorm dynamics, as these both crease the currents that produce the magnetic disturbances from which AE is determined, and directly inject both source and seed particles for MEE, some of which will precipitate.

As is clear from the above aggregation of the articles comprising this Research Topic, the processes, mechanism, and investigatory techniques used to further our understanding of the complex coupling in the magnetosphere-ionosphere-thermosphere system is an extremely rich area of research. The articles contained herein advance our knowledge of this very complex system-of-systems, and help point direction to promising avenues of exploration for future studies.

Author contributions

ST planned, wrote portions of, synthesized, and edited the manuscript. J-FR conceptualized, wrote parts of, and edited the manuscript, TN wrote portions of the manuscript and help in editing, PE wrote portions of the manuscript and helped with editing. Substantial contributions were made by all authors.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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