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Editorial: Vertical coupling in the atmosphere-ionosphere-magnetosphere system

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Editorial on the Research Topic
Vertical coupling in the atmosphere-ionosphere-magnetosphere system

The Earth's ionosphere, a partly ionized plasma layer in the upper atmosphere extending from about 60 km to around 1,000 km, is not only a playground for many fascinating phenomena such as the aurorae or plasma bubbles, but also affects many technological systems: Ionosphere and Ionospheric perturbations affect the propagation of electromagnetic waves (precision and reliability of GNSS, over the horizon radars, radio communications), ionospheric currents cause changes in the geomagnetic field, leading to geomagnetically induced currents that pose a risk to power line transformers.

Ionospheric plasma is primarily generated by ionizing solar radiation. However, ionospheric dynamics and disturbances depend strongly on the interaction between the solar wind and the Earth's magnetosphere, which is tightly coupled to the ionosphere through field-aligned currents, electric fields, etc. In addition, the ionosphere is strongly linked to the neutral atmosphere, with which it partially merges and responds to processes that take place below in the neutral atmosphere. In particular, during geomagnetically quiet periods neutral atmosphere may account for 10%–15% of the ionospheric variability. Atmospheric gravity waves, generated by a variety of processes in lower atmosphere, are the key vertical coupling agent, transferring energy and momentum into middle/upper atmosphere and ionosphere. Atmospheric thermal tides, both migrating and non-migrating, are responsible for diurnal, semidiurnal and terdiurnal variabilities. There are also reports of multi-day variabilities, matching the periods of various planetary waves, though the origin of these variabilities is still debated. Changes in global atmospheric circulations, e.g., seasonal or caused by sudden stratospheric warmings, can influence middle/upper atmosphere and ionosphere. A downward coupling to lower atmosphere, due to atmospheric gravity waves being generated by Joule heating in the ionospheric E-region, has been also proposed.

Although the ionosphere has been studied for more than one hundred years, starting with the transatlantic transmission of radio signals, and the basic principles of ionospheric physics are well known, the relative role of various mechanisms and conditions that lead to the development of specific perturbations, instabilities and day-to-day variability needs to be further investigated because of the complex interactions with the layers below and above it. The papers in this Research Topic attempt to describe and explain some of these processes.

Prikryl and Rušin explores statistical connections between the occurrence of heavy floods in Canada and arrivals of solar wind high-speed streams (HSSs) emitted for solar coronal holes. Solar wind observations are statistically compared to the meteorological reanalysis data. The enhanced auroral energy deposition during HSSs is proposed as a mechanism for the generation of downward propagating atmospheric gravity waves (AGWs). As AGWs reach lower atmosphere, they may excite the conditional instability in the troposphere, thus leading to excessive precipitation. This downward influence from solar wind to troposphere could be considered as a direct link between solar variability and climate variability or trends.

Maetschke et al. suggest the generation process of auroral spirals, that remains a subject of long controversy. The process is illustrated using satellite observations in the tail of the Earth's magnetosphere during a specific geomagnetic substorm. It is shown that a chain of Kelvin-Helmholtz-type vortices in the magnetic field was triggered, leading to energetic electron injections into the Earth's upper atmosphere. The resulting auroral spiral was detected by ground optical cameras located in Tromsø, Norway.

Liu et al. examines changes of the total electron content (TEC) in local Asian sector during the period of a stratospheric sudden warming that occurred in Antarctica in 2019. Various well-known multi-day atmospheric periodicities are examined to distinguish between possible solar wind and geomagnetic forcing from above and forcing from lower atmosphere. The results suggest even a low-level geomagnetic activity could have certain impact on middle atmosphere and it should not be ignored when studying meteorological impacts on the ionosphere.

Szárnya et al. reports multi-instrument observations of a fireball that was recorded on 17 November 2019. The meteoroid had a velocity of 71.18 km/s and originated from the source radiant of the Leonid meteor shower. The meteor was recorded by the Czech fireball network cameras, and the produced ionization column was observed with a digisonde and with the Continous Doppler Sounding (CDS) at Průhonice and Sopron station. The meteor trail ionization was visible for more than 20 min in the digisonde data and CDS.

Knížová et al. describes the ionospheric response to severe tropospheric events in central Europe in July 2021 using multi-instrument observation of the ionosphere and mesosphere by ionosonde, continuous Doppler sounding and OH airglow cameras. It is shown that in addition to acoustic gravity waves, spread F was also observed.

Ikani et al. discusses observation of ionospheric irregularities over Nigeria using the rate of change index (ROTI) of the total electron content measured by receivers of the global navigation satellite signals. Latitudinal differences were found across Nigeria. The highest occurrence rate was around the March equinox. The second, less pronounced peak of occurrence rate was around the September equinox.

Aa et al. deals with a multi-instrument analysis of equatorial plasma bubbles in the American sector under a geomagnetically quiet period on 07–10 December 2019. Large day-to-day variability was found, which better corresponds to the activity of atmospheric gravity waves providing the seeding perturbation than to the estimated growth rate of the Rayleigh-Taylor instability.

Resende et al. describes atypical and spreading Sporadic E-layers (Es) observed by digisonde at low-latitude Brazilian station Cachoeira Paulista (22.41°S, 45°W, dip 35°) from 2016 to 2018. The authors conclude that the spreading Es layer, mainly during quiet times, is not necessarily formed by the particle precipitation in the South Atlantic magnetic anomaly region, but probably due to the turbulent wind shear affecting the evolution of the Es layer.

Buzás et al. investigates the effect of solar flares on the absorption of radio waves in the ionosphere using European digisondes DPS-4D. Amplitude changes at frequencies of 2.5 and 4 MHz were compared with changes in the minimum measured frequency fmin and the signal-to-noise ratio (SNR). The authors conclude that a combination of these three methods seems to be an efficient approach to monitor the ionospheric response to solar flares.

Gasperini et al. studies tides and planetary waves combining ICON MIGHTI wind data over the height ranges 93–106 km and 200–270 km (with day and night coverage), and *in-situ* topside F-region ion densities from IVMs onboard ICON near 590 km and the SORTIE CubeSat near 420 km. The study highlights the importance of simultaneous satellite measurements to analyze ion-neutral interaction and coupling via waves in the thermosphere–ionosphere system.

Kotov and Bogomaz is an opinion article that discusses an unconfirmed hypothesis on hot hydrogen atoms in the upper ionosphere (the exobase), and concludes that the hydrogen temperature is most likely consistent with that of other species.

Maute et al. examines the behaviour of migrating atmospheric solar tides simulated by TIE-GCM global circulation model, driven by tides fitted to ICON observations via the Hough Mode Extension method. It demonstrates that the SW2 tide unexpectedly changes it is latitudinal structure at 250 km from two peaks at mid latitudes to one broad low latitude peak. Other migrating tides undergo similar variations as SW2. The changes in tidal dynamics lead to substantial deviations of NmF2 and O/N_2 values from general seasonal behaviour.

Molina and Scherliess investigated the variability of thermospheric zonal winds at a height of about 250 km by applying a correlation analysis to GOCE zonal wind observations. GOCE observations were analyzed from −50°S to 50°N covering the low and mid-latitudes at dusk and dawn and during geomagnetic quiet conditions around the summer and winter solstice. Due to the GOCE orbit, only nonmigrating tidal components are found in the spatial and temporal correlations.

Molina and Scherliess presents an analysis of thermospheric zonal winds at 260 km altitude obtained from GOCE accelerometer data recorded from 2009 to 2012 during geomagnetically quiet times. Due to the orbit of GOCE measurements are always obtained at dusk and dawn around 6 and 18 LT. The longitudinal variability is assessed using a Fourier decomposition for the wavenumbers 1 to 5. This study summarizes the inter-year variability and seasonal differences concerning the different wavenumbers. Furthermore, the resulting wave activity for each wavenumber is compared to the Climatological Tidal Model of the Thermosphere (CTMT).

Berényi et al. examines the dynamics of ionospheric total electron content as well as the height and the peak density of the F region during the two large geomagnetic storms of the solar cycle

24. Additionally, SWARM and TIMED satellite data are examined. A method is proposed for the monitoring of the storm-time evolution of various known anomalies in sub-auroral, auroral and polar cap regions. The extreme plasma depletion is detected in connection to the equatorward expansion of the midlatitutde ionospheric trough.

Martinez and Lu investigates the short-term variability of the ratio between atomic oxygen and molecular nitrogen (O/N_2) measured by the geostationary GOLD satellite payload for over 3 years under various geomagnetically active conditions. Strong correlations between O/N_2 ratios and geomagnetic activity are found at high latitudes, while at low latitudes there also weak correlations. Strong seasonal dependence of these correlations is also reported. It is suggested that during geomagnetically quiet time the variability of O/N_2 ratios is substantially controlled by the influence from the lower atmosphere.

Kotov et al. investigates the impact of exosphere hydrogen density on the ionosphere-plasmasphere system. Satellite measurements in the topside ionosphere and in the plasmasphere are compared to a model constrained by ionospheric observations at both ends of the magnetic field line. It demonstrates that a factor of 2.75 increase in the hydrogen density increases the simulated plasma density in the afternoon plasmasphere up to ~80% and in the nighttime topside ionosphere up to ~100%, causing major errors.

Da Silva et al. explores the variability of energetic electron precipitations from the Earth's radiation belts in the atmosphere over auroral regions and over the near-equatorial South American Magnetic Anomaly. The particular focus is on electron losses from the radiation belts due to wave-particle interactions with plasma hiss waves during a specific geomagnetic event in Sept. 2017, caused by a high speed solar stream. Resulting precipitations of energetic electrons are shown to be the dominant mechanism for triggering the sporadic E layers.

Sobhkhiz-Miandehi et al. analyzes 11-year dataset of sporadic E layers, detected at mid and low altitudes by satellite radio occultation, and compares to ground observations from six ionosondes. It is demonstrated that at least in 20% of all cases, the ionosonde detections do not agree with radio occultation data. The authors conclude that ground and satellite occultation data agree best during daytime and local summer, when the E region has higher plasma concentration.

Author contributions

VB: Writing–review and editing. JC: Writing–original draft, Writing–review and editing. H-LL: Writing–review and editing. DP: Writing–original draft, Writing–review and editing. GS: Writing–review and editing.

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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