Foreward: Special issue on “Effects of the solar wind and interplanetary disturbances on the Earth’s atmosphere and climate”

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Abstract

The special issue “Effects of the solar wind and interplanetary disturbances on the Earth’s atmosphere and climate” discusses the effects of solar wind and interplanetary disturbances on the Earth’s atmosphere and climate. After a brief introduction to the solar wind and its geoeffective agents, the results presented in the special issue are highlighted, which include both statistical studies aimed at the identification of atmosphere and climate response to external solar forcing, and attempts to identify responsible physical mechanisms and include some of them in climate models are.

Introduction

Understanding the contribution of various factors, both natural and anthropogenic, to past and future climate changes, is necessary in order to make better future projections. The natural factors can be internal to the Earth’s system, like continental drift, plate tectonics, volcanic activity, ocean variability, etc. As the terrestrial system is an open system, it is also subjected to the influence of various external factors: solar irradiance, solar wind, galactic cosmic rays, supernova explosions, passage through interstellar dust or galactic shoulders, etc.

The papers collected in this special issue address recent theoretical and empirical results concerning the effects of solar wind and interplanetary magnetic field (IMF) disturbances on the Earth’s atmosphere and climate. They bring new insight into the different ways in which the Sun affects the terrestrial system and contribute to the more complete accounting the role of the Sun in climate change.

This special issue is partly resulted from the activities of two International Space Science Institute research teams: “Effects of Interplanetary Disturbances on the Earth’s Atmosphere and Climate” and “Specification of Ionization Sources Affecting Atmospheric Processes”, and of the COST ES1005 action TOSCA (“Towards a more complete assessment of the impact of solar variability on the Earth’s climate”).

Solar wind and its geoeffective agents

Sun is the most significant source of energy in the vicinity of the Earth, and its effects on the Earth much exceed the effects of all other external factors. Sun, as many other stars, is a variable star: its energy output varies on timescales from milliseconds to millennia. These variations in the energy output and the related variations in the

appearance of the Sun are known as solar activity. The best known manifestation of solar activity are the sunspots – dark spots on the solar surface whose number and total area cyclically vary with a period of ~ 11 years, superposed on a longer, centennial variation. Very big sunspots can be seen with naked eye, and have been observed since ancient times, but systematic observations of sunspots began after the inventory of the telescope in the early 17th century. The sunspot number is the longest instrumental solar data series, and has been extensively used as a measure of solar activity for studying solar influences on the Earth's atmosphere and climate.

With the launch of space-borne instruments, it was found that the total solar irradiance (the solar electromagnetic radiation integrated over all wavelengths, received at the top of the atmosphere per unit area per unit time), previously known as the “solar constant”, is not constant but varies in phase with the sunspot number (Willson and Hudson, 1981). Variations with the sunspot cycle were also found for the radiation in different wavelength ranges (“spectral solar irradiance”). The correlations between the number of sunspots and solar irradiance made it possible to produce a number of reconstructions of the variations of total and spectral solar irradiance over the four centuries of instrumental sunspot observations, and further back in time based on solar activity proxies. They all agree on the 11-year sunspot cycle and centennial variations in solar irradiance, though the estimated amplitudes of the variations are quite different (Solanki et al., 2013, their Figure 10).

The disturbances of the Earth's magnetic field, known as “geomagnetic activity”, can also serve as an indicator of the solar influences on the terrestrial system. An important indication about the solar activity agents affecting the Earth's atmosphere and climate is the finding that various meteorological parameters correlate better with geomagnetic activity than with the sunspot number (e.g. Bucha and Bucha, 1998). Therefore, the identification of solar activity agents leading to geomagnetic disturbances is important not only for space weather and its effects on technological systems, but also for the better understanding of the role of the Sun in weather and climate.

Solar flares were the first solar activity phenomenon found after the sunspots. On September 1, 1859, while observing a complex sunspot region, the amateur astronomer Carrington saw in white light a localized brightening of the solar surface lasting a few minutes – a solar flare. This flare, observed independently by Hodgson, was followed 17 hours later by the most powerful geomagnetic storm registered so far (Carrington 1859; Hodgson 1859). After the statistical investigations that followed on the correspondence between solar flares and geomagnetic disturbances, the paradigm was established that geomagnetic storms are caused by solar flares. This belief survived until the late 20th century, when the famous paper appeared with the meaningful name “The solar flare myth” (Gosling, 1993), presenting evidences that coronal mass ejections (CMEs), rather than solar flares, drive the strongest geomagnetic disturbances. A solar flare is by definition a confined, sudden, rapid, and intense variation in brightness, while a CME involves an outburst of solar plasma with embedded magnetic fields. Actually, flares and CMEs often though not always occur together, with almost all big flares accompanied by CMEs, and almost all powerful CMEs accompanied by flares (Gopalswamy, 2016). Flares and CMEs are both due to explosive release of magnetic energy stored in the corona, a proxy for which is the number of sunspots (e.g. Wheatland and Litvinenko, 2001), therefore their number and intensity are correlated with the sunspot number.

However, geomagnetic activity variations on the time scale of the solar cycle are poorly correlated with the number of sunspots. On shorter time-scales, it was noticed already by the end of the 19th century that there are geomagnetic storms not associated with any visible activity on the solar surface. The specific signature of these geomagnetic storms is that they are “recurrent” – regularly occurring every 27 days, which associates them with the solar rotation period. Further, it was found that only moderate geomagnetic storms are recurrent, while major storms (caused by CMEs as we know now) are sporadic. The sources of the recurrent storms were named “M-regions” – regions on the Sun supposedly emitting beams of charged particles that sweep the Earth like a garden hose, and produce geomagnetic disturbances each time they turn into geoeffective position (Cliver, 1994). With the launch of Mariner-2 spacecraft it was proved that recurrent geomagnetic storms are indeed caused by recurring high-speed solar wind streams (HSS), and observations from Skylab indicated that the source regions of HSS are solar “coronal holes” – unipolar regions of open magnetic field lines in the solar corona, with unusually low density and low temperature (Zirker, 1977).

CMEs and HSS both interact with the Earth’s magnetosphere and cause geomagnetic disturbances, but in different ways. A CME drives a region of compressed solar wind ahead of it (so called “sheath”) with large-amplitude interplanetary magnetic field and dynamic pressure fluctuations, which may enhance the solar wind-magnetosphere coupling (Kilpua et al., 2013). The ejecta itself, especially if it contains a magnetic cloud, characterized by an enhanced and smoothly rotating magnetic field, provided prolonged periods of Bz negative component. This, according to Dungey’s theory of magnetic reconnection, is the necessary condition to connect the geomagnetic field to the interplanetary magnetic field, allowing energy, mass, and momentum to be transferred from the solar wind into the magnetosphere and thence down into the ionosphere and thermosphere (Lockwood, 2016). The geoeffectiveness of HSS, on the other hands, is due to the interaction of the fast flow with the upstream slower flow, leading to the appearance of a region with strongly fluctuating magnetic field Bz component in Alfvén waves (e.g. Crooker, 2000). As these two geomagnetic activity drivers are different, the disturbances they cause are also of different types (Borovsky and Denton, 2006): CME-generated storms are stronger, but of shorter duration and sporadic, while HSS-generated storms, though moderate as a rule, are longer lasting and recurrent. As a result, the HSS provide the main contribution to the average yearly geomagnetic activity (Richardson et al., 2002).

The interaction of CMEs and HSS with the Earth’s magnetosphere leads to precipitation of energetic particles into the high latitude atmosphere, especially in the mesosphere lower thermosphere (MLT) region. The efficiency of both HSS and CME peaks in the declining phase of solar activity cycles, and the dominant factor affecting the precipitation is the solar wind speed (Asikainen and Ruopsa, 2016). Even in the lack of any CMEs and HSS, there still is some non-zero geomagnetic activity due to the fact that the Earth is continuously bathed by the background solar wind in which CMEs and HSS are embedded. Parker (1958) was the first to theoretically predict the existence of the solar wind: the lack of hydrostatic equilibrium, in the solar corona (the outermost part of the solar atmosphere), when gravity is not sufficient to balance the thermal expansion, results in its continuous expansion which fills the whole Solar system with a flow of plasma and embedded magnetic field from the Sun – the background solar wind. This background solar wind continuously interacts with the magnetosphere leading to particle precipitation, which is almost always present, not only in disturbed periods. It was recently found that the parameters of the background solar wind have long-term, cycle to cycle variations (Kirov et al., 2015), which should lead to long-term variations

of the quiet time precipitation, on top of which storm-time precipitation is added leading to an increase by several orders of magnitude.

The solar wind also modulates the flux of galactic cosmic rays, which are the principal source of atmospheric ions in the troposphere away from the continental boundary layer and below the middle stratosphere. The solar wind dynamic pressure and orientation of the IMF carried by the solar wind are known to affect the state of the Earth's magnetosphere leading to the changes in the ionosphere, mainly at high latitudes. Cosmic rays, solar proton events and energetic precipitating particles can also alter the atmospheric conductivity. Solar wind-induced changes in ionospheric potential and in atmospheric conductivity modulate the flow of current density in the global atmospheric electric circuit (GEC).

Problems discussed in the special issue

Traditionally, solar irradiance variations are the only solar activity agent considered when evaluating the solar variability effects on climate (e.g., IPCC, 2013). Total and spectral irradiances are included in most of the modern climate models. The effects of the solar wind and interplanetary magnetic field (IMF) disturbances effects on the atmosphere are much less well understood and are not accounted for in the majority of climate models, though they are the main driver of geomagnetic disturbances which, as noted, is better correlated with atmospheric parameters. The papers gathered in this special issue are devoted to the effects of different solar wind agents on the atmosphere and climate.

Figure 1 illustrates the main processes involved in the propagation of the solar wind and interplanetary disturbances through the atmosphere. The influence of the solar wind/IMF disturbances on the climate can be established by direct statistical analysis of the time series (problem 1). For example, Morozova and Barlyaeva (2016) applied different statistical techniques and established the contribution of different climate forcings to the temperature variations in Portugal and discovered strong bidecadal cycles, which can be related to solar impact.

Zhou et al. (2016) have found out a statistically significant correlation between solar wind speed and sea surface temperature in the North Atlantic modulated by B_z (the IMF component parallel to the Earth's magnetic dipole). Although the statistical analysis does not provide all necessary information about underlying physical processes it can give some hints on the presence of such connections and potential mechanisms involved in the transformation of the signal. Lam and Tinsley (2016) present a detailed review of recent progress in this direction and convincing evidences of the link between IMF disturbances and atmospheric dynamics obtained from the analysis of observations. They also suggest that this link should be related to GEC changes caused by IMF disturbances followed by the altering of the cloud droplets life cycle, the cloud and planetary waves properties (problem 2). The treatment of this mechanism in the climate models constitutes a notable challenge because of oversimplified representation of the cloud microphysics in the majority of the global climate models, but it can be addressed when new cloud schemes are developed. Slightly different mechanism explaining obtained correlations between solar wind and extra-tropical cyclones is suggested by Prikryl et al. (2016). They hypothesized that the magneto-hydrodynamic waves initiated by the high-speed solar wind streams are able to generate atmospheric gravity waves transferring energy from the auroral region to the troposphere initiating convection and altering the distribution of the cloud and precipitation bands (problem 3). Magnetic

storms caused by solar wind or IMF disturbances are definitely important for the ionosphere (see Blagoveshchensky and Sergeeva, 2016) and such a process can definitely takes place, but its efficiency should depend on the background state of the atmosphere, because the vertical propagation of the waves strongly depends on the zonal wind properties. This fact is also supported by the results of Veretenenko and Ogurtsov (2016) who find strong modulation of the correlation between solar activity and low cloud anomalies by the state of the polar vortex. They showed that negative correlation between solar activity and low clouds observed in 1980s-1990s has been reversed in earlier 2000s because of noticeable weakening of the polar vortices. Similar conclusions have been presented by Roy et al.(2016). Using long term observation of sea level pressure and multiple regression analysis they find out that a stronger geomagnetic activity during the periods of intensified solar wind speed leads to the enhancement of the pressure difference between Azores and Iceland resulting in positive phase of the North-Atlantic oscillation (NAO) with important implications for winter European climate. They also show that this process is initiated by geomagnetic activity but also depends on the phase of Quasi Biannual Oscillation (QBO), which implies the location of the triggering mechanism in the stratosphere and the propagation of this perturbation down to the troposphere.

Figure 1. Main processes involved in the propagation of the solar wind and interplanetary disturbances throughout the atmosphere and problems considered in this special issue.

The chain of the processes responsible for this effect starts from the energizing of magnetospheric particles by the enhancement of the solar wind leading to their precipitation, ionization of the Earth's atmosphere below 110 km (problem 4) and producing reactive nitrogen and hydrogen oxides (Mironiova et al., 2015). As it was established in many publications (e.g., Rozanov et al., 2012) the transport of the active nitrogen oxides down to the high latitude stratosphere during the polar night leads to the ozone destruction followed by the cooling of the vortex interior, acceleration of the zonal winds and refraction of the vertically propagating waves equator ward with

implications for the meridional circulation and wave pattern in the troposphere resembling positive NAO phase (problem 5). While the theoretical aspects of this chain are mostly well understood the exact treatment of all components in the climate models still renders difficult. One missing process in the previous modeling efforts is the ionization by middle range energy electrons. Arsenovic et al. (2016) have added the production of nitrogen and hydrogen oxides by the precipitating electrons with energies from 30 to 300 keV to atmosphere-ocean-chemistry-climate model SOCOL-MPIOM and illustrated the functioning of the entire chain of early-mentioned physical processes connecting the ionization by particles with ozone layer and climate change. The authors concluded that the influence of the middle range energy electrons should not be neglected. Another problem is related to extremely powerful particle precipitation events, which are not covered by satellite measurements. To partially fulfill this gap Makhmutov et. al (2016) presents a catalogue of the precipitating electron events from the 1960s to the present day and estimate their energy spectra. The catalogue contains more than 500 events when enhanced X- ray fluxes were detected from the ground level up to 30-35 km over polar latitudes during the period 1961-2014. Normally electrons do not penetrate into the atmosphere deeper than 50 km due to high ionization and radiation energy losses. However, they can generate X-rays via bremsstrahlung, which reaches altitudes of about 20 km and lower. Balloon and rocket observations of X-ray precipitation began in 1950-1960s and since the mid 1950s, consistent long-term balloon observations of ionizing particles in the atmosphere have been undertaken by scientists from the Lebedev Physics Institute in Russia. The results of these observations contain unique data on X-ray bursts generated in the polar stratosphere by precipitating magnetospheric electrons.

Lower energy precipitating electrons and protons can be measured by satellite, but their energy spectrum is not perfectly known from the observations and it should be approximated for the calculations of ionization rates. Wissing et al. (2016) applied different fits of energy spectra of precipitating protons to calculate ionization rates. The calculated ionization rates were used in chemistry-transport model to evaluate the range of uncertainty caused by inaccuracy of the energy spectrum parameterizations. They showed that the spectrum fit could be responsible for the up to 8% error in the calculated ozone mixing ratio, while in extreme cases the error could reach 50%. This conclusion is important for the evaluation of the model results against observations. Another problem with the ionization rate calculations is related to the treatment of particles with wide range of energies. At present time several models of ionization rate calculations (e.g., Fang et al., 2010) are able to treat electrons and protons with energies less then 500 MeV. These models have been successfully validated for the upper atmosphere to the altitude above 60 km and applied for the study of the effect of energetic particles but the absence of highly energetic particles may lead to a significant underestimation of the ionization rates below 60 km. At the moment there is no model that could properly treat whole energy range of the precipitating particles. One such model (CRAC:EPII (Cosmic Ray Atmospheric Cascade: Electron Precipitation Induced Ionization) has been developed by Artamonov et al. (2016a) and Artamonov et al. (2016b) present its first evaluation and comparison with an analytical parameterization of Fang et al. (2010). The agreement between two models is found to be good in the mesosphere, but in the stratosphere the absence of secondary X-rays generation (Bremsstrahlung) in the parameterized model leads to substantial deviation of the ionization rates.

Conclusions and outlook

The papers in this special issue are based on the observation data analyses and modeling results. They demonstrate that the understanding of the solar wind and IMF disturbances influence on different climate parameters is growing. The analysis of the observation data performed in several papers provides more indications of the surface climate response to solar variability, however the identification of the exact pathway of the solar signal throughout the atmosphere still remains unresolved. On the one hand the climate response to the solar wind driven geomagnetic activity resembles positive phase of the North Atlantic oscillation, which points to the location of the initial impact in the middle atmosphere and downward propagation of the response (Arsenovic et al., 2016; Roy et al., 2016; Prikryl et al., 2016). On the other hand the evolution of the climate response to IMF showed that the primary impact should locate in the troposphere (Lam and Tinsley, 2016 and references therein) and can be probably connected to the changes of global electric circuit induced by solar wind variability. The former mechanism is much easier to investigate because the availability of several relatively simple parameterizations describing primary chemical impact makes it possible to introduce energetic particles to practically any climate models. Moreover, Matthes et al. (2016) have already prepared and described all components of the forcing related to energetic particle precipitation and here the challenge is rather to convince climate community to apply this data set for the future model experiments. This task is more complicated because complete theoretical explanation of the so-called “top-down” mechanism is not yet available. The latter mechanism is difficult to address because at the moment there are no climate models, which are capable to treat cloud microphysics with reasonable level of complexity to describe the influence of GEC. We hope that our special issue will inspire new and more extensive studies in all described directions.

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