Effects of interplanetary disturbances on the Earth's atmosphere and climate

Team Leader: **Prof. Katya Georgieva**

Research domain: Solar-Terrestrial Sciences

Abstract:

Traditionally only the solar irradiance changes are considered when evaluating the solar variability effects on climate. However, the Earth is also influenced by the effects of the continuously varying solar wind, the flow of plasma and embedded magnetic field from the Sun. Earlier studies have identified significant atmospheric effects due to solar wind disturbances. The suggested mechanisms are versatile, but mostly not quantitatively tested.

The largest interplanetary disturbances, in particular the coronal mass ejections (CME) and the high-speed solar wind streams (HSS) are known to cause dramatic effects in the near-Earth space, accelerating magnetospheric (in particular, auroral and ring current) particles to higher energies and enhancing particle precipitation into the atmosphere, especially in the mesosphere-upper thermosphere (MLT) region. Moreover, magnetospheric particle precipitation maintains and produces electric currents and fields that also affect the charged and neutral atmosphere below. The solar wind dynamic pressure is suggested to affect large-scale wave activity in the atmosphere, the circulation in the stratosphere and troposphere, and the coupling between the atmospheric layers. The effects are found to depend on the nature of the interplanetary disturbance and to be very different for CMEs and HSSs.

The aim of the Team is to summarize the present level of knowledge and to critically discuss new ideas about the effects of interplanetary disturbances on the Earth's atmosphere and climate, and the mechanisms by which these influences are transmitted from the top to the bottom of the atmosphere.

An expected output of the Team is a review paper to comprehensively and critically present and discuss the various mechanisms and effects that the charged environment has upon the neutral atmosphere and climate. One of the novelties not covered in any earlier reviews is to take into account the possibly different affects of the above mentioned two main solar wind drivers.

The core team consists of experts covering a versatile range within solar-terrestrial sciences, including heliospheric physics, observations of energetic particles and the properties of the atmosphere at different altitudes, as well as modeling of atmospheric chemistry, dynamics and climate, as well as modeling of atmospheric chemistry and climate.

We plan to have two meetings of about 10-15 experts within July 2013 to December 2014 time frame.

Scientific rationale, goals, and timeliness of the project

Scientific rationale

The global and regional climatic changes observed in the last century have raised questions about the attribution of these changes, the evaluation of their further evolution, and the measures needed for their prevention and/or mitigation. While all experts agree that human activity plays a role in changing climate, it is also clear that the terrestrial atmosphere is affected by natural factors as well, the most important and persistent of which is undoubtedly the activity of the Sun as the biggest energy source in the vicinity of the Earth (http://www.ipcc.ch/). However, the different mechanisms by which solar variability influences the near-Earth environment are still poorly understood, and therefore the quantification of the solar contribution to climate change still remains incomplete.

Solar variability is a result of the magnetic activity of the Sun, maintained by the action of the solar dynamo which transforms the solar poloidal field prevailing during sunspot minimum into toroidal field with a maximum at sunspot maximum, and back into poloidal field with the opposite magnetic polarity during the next sunspot minimum, similar to a simple harmonic oscillator transforming kinetic and potential energies into each other (Parker, 1955; Choudhuri, 2011). The different solar and heliospheric manifestations of solar variability are related to these two faces of solar magnetism: sunspots, solar flares, variations in total and spectral solar irradiance, coronal mass ejections and magnetic clouds – to the solar toroidal field, and slow solar wind from the solar equatorial streamer belt, coronal holes and the high speed solar wind streams emanating from them – to the solar poloidal field (Feynman, 1982). The two types of solar magnetic activity are not independent as they are both produced by the action of the solar dynamo, but their long-term evolutions may not be identical, and during a given period the one or the other may have the main impact to the terrestrial system (Georgieva et al., 2012).

These different manifestations of solar activity have different impacts on both geomagnetic activity (Boberg et al, 2005; Borovsky and Denton, 2006) and atmospheric processes (Georgieva et al., 2012), resulting from different physical mechanisms. However, these impacts are not thoroughly studied, and the mechanisms are not yet clear enough.

Today, most of the research activities concentrate on the solar radiative forcing. Most General Circulation Models (GCMs) use the total solar irradiance dominated by the visible wavelengths reaching the Earth's surface with variations of the order of 0.1% in the 11-year sunspot cycle, and the irradiance in the shorter wavelengths which are fully absorbed in the higher layers of the atmosphere whose sunspot cycle variations are one to two orders of magnitude larger (Ermolli et al., 2012) as sole solar inputs, whereas the effects of the variations of the solar wind, interplanetary magnetic field and energetic particles are practically neglected. As a result, even the most complete GCMs at present only include a fraction of the many solar inputs into the terrestrial atmosphere, and therefore may not correctly describe and quantify the impact of solar variability on climate.

The proposed ISSI team will not deal with the solar radiative forcing, but will instead concentrate on the other manifestations of solar activity and their effects on climate.

Geoeffective manifestations of the solar toroidal magnetic field, other then the solar irradiance, are solar flares, coronal mass ejections, and magnetic clouds. The solar flares, apart from bursts of electromagnetic radiation, including X-rays, UV, visible light and radiowaves which lead to changes in the Earth's upper atmosphere, can also produce streams of highly energetic particles, known as solar proton events, and are often though not always associated with coronal mass ejections and magnetic clouds. Coronal mass ejections are huge eruptions of plasma and embedded magnetic fields from the corona which interact with the Earth's magnetic field. Magnetic clouds, considered a subclass of CMEs, are eruptions of plasma characterized by high magnetic field amplitude and consequently low plasma beta (ratio between the plasma and the magnetic pressure), and a smooth rotation of the magnetic field inside the structure, and are associated with the most intense geomagnetic storms.

The manifestations of the solar poloidal magnetic field are the slow solar wind in which the Earth is embedded all of the time, and the recurrent fast solar wind streams from long-lived solar coronal holes prevailing during the declining and minimum phase of the sunspot cycle. An important parameter quantifying the solar wind influence on the terrestrial system is the solar wind dynamic pressure.

The geomagnetic activity, as the most obvious result of the solar wind interaction with the Earth's magnetosphere, follows the variations of the solar poloidal field manifestations – slow and fast solar wind streams, rather that the solar toroidal field manifestations – CMEs and magnetic clouds (Richardson et al., 2002). Moreover, the increase in the geomagnetic activity since the beginning of the twentieth century is supposed to be due to the fact that CMEs and recurrent high-speed streams at the beginning of the twentieth century must have been embedded in a background of slow solar wind that was less geoeffective (having, for example, lower IMF strength and/or flow speed) than its modern counterpart (Richardson et al., 2002). The long-term variations in the parameters of the slow and fast solar wind and their effects on the terrestrial atmosphere, are not accounted for in any GCM, though they may potentially have a serious impact on the long-term variations of atmospheric circulation which is shown to be better correlated with geomagnetic activity ruled by these solar poloidal field manifestations than with solar irradiance (Bucha and Bucha, 1998).

Energetic particles produced during solar flares and/or CMEs can have a significant impact on the atmosphere, with the effects being focused on the polar regions (Krivolutsky and Repnev, 2012). Some level of energetic particle precipitation (EPP) is nearly continuously present, and during solar storms the level of EPP into the atmosphere can increase by several orders of magnitude. EPP causes enhanced ionization in the middle atmosphere (20-100 km) leading to increased production of HOx and NOx which participate in catalytic ozone destruction. HOx has a short-lived effect on the atmosphere; NOx on the other hand is mainly destroyed by photodissociation, therefore during polar winter, when little or no sunlight is present, NOx impact on the atmosphere can be long lasting. For example, following a series of solar storms in 2003, NO_2

enhancement of several hundred per cent and tens of per cent ozone depletion were observed between 36 and 60 km, an effect which lasted for several months after the events (Seppala et al., 2004). Dynamical coupling mechanisms between atmospheric layers can further provide coupling between this form of space weather and lower atmosphere. Analyses of meteorological data and chemistry-climate model results indicate that during the winter season polar surface temperatures show variability depending on the level of NOx produced by EPP (Baumgaertner, 2011). For exceptionally strong solar proton events, model simulations show a significant decrease of the free tropospheric and surface air temperatures of more than 3 K, and significant zonal winds change by 3-5 m/s in the upper troposphere - lower stratosphere region (Calisto et al., 2012).

Understanding this link between particle forcing from the Sun and climate requires a close examination of the dynamical and chemical coupling mechanisms connecting particle forcing driven changes in the atmosphere to changes in climate variables.

The effect, however, is not linear, and it is found that the impacts of EPP on the atmosphere depend on the strength of the stratospheric polar vortex (Randall et al., 2006). On the other hand, the strength of the polar vortex depends upon the solar wind dynamic pressure which has solar cycle as well as long-term variations: when the winter time solar wind dynamic pressure is high, the polar vortex is stronger and the sub-tropical jet in the upper to middle stratosphere is weaker (Lu et al., 2008).

The strength of the polar vortex is in itself an important factor determining the prevailing large-scale atmospheric circulation and surface temperature anomalies (Kolstad et al., 2010), and is suggested as a link between solar activity and circulation of the lower atmosphere (Veretenenko and Ogurtsov, 2012).

Another manifestation of the solar wind influences on climate can be through the global electric circuit. Variations in the downward ionosphere-Earth current density Jz due to changes in the cosmic ray flux and other energetic space particle fluxes, and at high magnetic latitudes from solar wind electric fields, affect the production of space charge in layer clouds, with the charges being transferred to droplets and aerosol particles. Variations in Jz affect the production of space charge in layer clouds, with the charges being transferred to droplets and aerosol particles affecting the atmosphere's transparency and therefore modulating the solar irradiance reaching the Earth. Proxies for climate change in the same stratified depositories show strong correlations of climate with the inferred global circuit variations (Tinsley, 2008).

In summary, the impact on climate of solar activity agents is complex and far from being understood. Solar total and spectral irradiance, though very important for climate, is just one of many manifestations of solar activity affecting the Earth's system in general and climate in particular. The different manifestations of solar magnetic activity have different short-term and long-term evolution, and different (sometimes even opposite) effects on the terrestrial atmosphere. The understanding of the origin, long-term variations and terrestrial effects of these different solar activity agents would help to better understand the impacts on and the long-term variations of terrestrial climate.

Goals of the Team

Not only general public but also some researchers understand solar variability as only variations in the solar radiative output which is the only parameter used to quantify the solar impact on climate in most of the existing models. The main reason for this is that the mechanisms by which other manifestations of solar activity influence the terrestrial atmosphere are not quite clear. The goal of the Team is to summarize what is known and what is not known of the terrestrial effects of different solar wind structures, with a critical analysis of the suggested mechanisms of their influences on the terrestrial atmosphere. The immediate outcome is expected to be a review paper on this subject. The long-term outcome is hoped to be a guide for researchers in the area of solar-climatic influences which would help them in realizing that the "solar activity" has many faces, all of which should be understood and considered when evaluating solar influences on climate.

Timeliness of the project

The influence of solar activity on the Earth's climate is a matter of high scientific as well as practical importance – not only because the chain of coupling processes from the Sun through the interplanetary medium to the Earth's magnetosphere, ionosphere and various atmospheric regions is a challenge to our present understanding of the underlying physical mechanisms, but also because the global warming observed in the last century requires an objective estimation of natural versus anthropogenic factors for climate change in order to adopt the most appropriate strategies for environmental behavior with far reaching economical, political and societal consequences.

What added value does ISSI provide for the implementation

Many teams have developed strong expertise on specific aspects or regions in the Sun-Earth system (Sun, solar wind and interplanetary magnetic field, Earth's magnetosphere, ionosphere, upper, middle and lower atmosphere), but not many scientists are aware of the key issues in adjacent areas and their relevance for assessing the system as a whole. ISSI provides the meeting facilities and financial support for an interdisciplinary international team to work together toward a more complex assessment of the effects of interplanetary disturbances on the Earth's atmosphere and climate.

List of confirmed members

Katya Georgieva (Bulgaria) – team leader

Alan Aylward (United Kingdom)

Timo Asikainen (Finland)

Radan Huth (Czech Republic)

Boian Kirov (Bulgaria)

Alexei Krivolutsky (Russia)

Mai Mai Lam (United Kingdom)

Hua Lu (United Kingdom)

Kalevi Mursula (Finland)

Dora Pancheva (Bulgaria)

Eugene Rozanov (Switzerland)

Annika Seppala (Finland)

Pekka Verronen (Finland)

Facilities required

We will need a meeting room with a large-table for seating 12-14 people. Participants will bring their own laptops. A computer projector and screen will be required and a black board/white board would be useful. Internet connection (preferably wireless) will be needed for all team members. Communication between members' laptops can be handled via the internet (email) and via portable storage media that individual members will bring. Coffee/Tea/Snacks for refreshment during the discussions and for breaks will also be needed.

Financial Support requested

We request per diem for 13 participants plus two additional young scientists that we hope to add to the team at a later date in accordance with the proposal guidelines. Per diem will be needed for 6-7 days for each participant for each of the two meetings. We also request round trip airfare for the team leader.

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