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Editorial

A review of Space Climate and an introduction to the papers of the JASTP special issue on Space Climate

The Sun is a typical G-type star in the middle of its main sequence lifetime. The radiative, magnetic and particle output of the Sun varies at time scales from stellar evolutionary time scales to the decadal time scales of the renowned solar cycle and to the much shorter forms of activity like solar flares. Solar variability forces the whole heliospheric environment and all planetary atmospheres, including that of Earth, characterizing what is now known as Space Climate. Space Climate is therefore an interdisciplinary line of research encompassing a vast number of topics ranging from physics of solar variability, solar wind, cosmic rays, and planetary atmospheres to climate, with an emphasis on understanding the long-term evolution and processes that interconnect the heliospheric system.

This special issue of the Journal of Atmospheric and Solar–Terrestrial Physics (JASTP) presents 27 papers dealing with the different aspects of Space Climate. Most papers were presented in the Third Space Climate Symposium organized at Saariselkä, Finnish Lapland, in March, 2009. The main results included in these papers, with appropriate background information from the respective subfields of Space Climate, are summarized below.

1. Solar activity and solar dynamos

Early drawings and images of sunspots form the scientific foundation of our understanding of solar variability at centennial time scales. There is a long and painstaking tradition of scrutinizing a part of this information in terms of indices called sunspot numbers. However, there is much more information hidden in the details of these early drawings and images, which has mostly been neglected so far. Therefore, efforts that aim to recover this valuable information are highly motivated. Clette describes the ongoing efforts at SIDC to digitize sunspot drawings made at the Uccle station and reviews their future plans. Cristo, Vaquero, and Sánchez-Bajo present an automatic program to read and analyze historical drawings of solar images in the pre-photographic era and to use them to verify the evolution of the sunspot butterfly diagram in the mid-18th century during parts of cycles 0 and 1.

It is well known by now that a magnetohydrodynamic dynamo mechanism is responsible for the origin and evolution of sunspots and the whole solar magnetic field. Thus, understanding the solar dynamo mechanism is an important aspect of Space Climate research. However, long-term variability of the solar magnetic field and episodes such as the Maunder minima (1645–1715 AD), when sunspots were hardly observed, still lack a well-established explanation. Low-order dynamo models have proven useful in illuminating certain aspects of solar variability. Passos and Lopes use such a model to study under which conditions the Maunder-like grand minima can occur. Recently, dynamo models have been increasingly used not only to understand past activity but in predicting future activity. Charbonneau and Barlet studied the scientific basis of dynamo-related solar cycle precursor schemes based on solar surface magnetic field observations. In all stochastically driven models, the poloidal magnetic field has a precursor value only in the case of sufficient field feedback into the dynamo, emphasizing the importance of accurate determination of the magnetic budget of solar polar fields. Georgieva and Kirov relate the two solar cycle maxima of geomagnetic activity to the solar toroidal and poloidal fields and studied their long-term variation. They extract the average values for the meridional circulation on the solar surface and in the deep convection zone, and argue that the solar dynamo operated in a diffusion-dominated regime for the last 12 cycles. On the other hand, during the Maunder minimum, the dynamo would have operated in an advection dominated regime, with the transition from diffusion dominated to an advection dominated regime caused by a sharp drop in surface meridional circulation.

Sunspots and the associated magnetic features play an important role in solar irradiance at time scales of about one month or longer, the appearance of sunspots increases the solar irradiance due to the presence of bright features such as faculae and plages. While the total solar irradiance (TSI) has only been measured over the last three decades or so, longer-term TSI and solar spectral irradiance (SSI) model reconstructions are needed, e.g., for studies of the solar impact on global climate change. Not only the TSI variations but also SSI variations separately have an important role in driving climate dynamics. Krivova, Solanki and Unruh review research efforts to model TSI and SSI. They reconstructed the SSI since 1947 and the TSI since 1610, finding that the cycle-averaged TSI increased by about 1–5 W/m^2 since the Maunder minimum, which is a value significantly lower than that estimated previously. Lukianova and Mursula investigated the mutual relation between sunspots, UV/EUV proxies and TSI reconstructions for the last 35 years. They note a rather abrupt change in 2001–2002 across which UV/EUV proxies remained considerably higher and TSI proxies stayed lower at the same sunspot number level. This is attributed to an unusual reduction in sunspot (or photospheric in general) magnetic fields that occurred at this time, probably due to global solar processes related to the decay of the Grand Modern maximum. This emphasizes the particular interest and need to study the recent solar activity with an accurate reference to corresponding variations in the past.

It would be inappropriate not to mention the important role of modern long-term space- and ground-based observations in the science of Space Climate. While ground-based observations, e.g., of solar and geomagnetic fields are available at the time scale of about one century, a more versatile and complete suite of ground- and

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space-based observations has only come into existence during the last few decades. Damiani et al. review measurements of solar oblateness, noting how historical data, even if in discordance with modern results, can help in constructing new equipment and in developing new theories. They underline the need of accurate space measurements of solar dimensions for a better understanding of the solar core. Turck-Chièze and Lefebvre discuss the SDO and PICARD space missions that were both successfully launched in 2010. They emphasize the crucial information to be obtained from these missions on solar internal circulation and solar asphericity.

It has been known for a long time that solar activity is not uniformly distributed on the solar surface, e.g., there is increasing evidence that various manifestations of solar activity are non-axisymmetric (unevenly distributed over the solar longitude) and mainly occur in two preferred longitudinal ranges, in the so called active longitudes. Zhang et al. conduct an improved analysis of the longitudinal occurrence of all solar X-ray flares between 1975 and 2006 using a dynamic, differentially rotating coordinate system. They find consistent rotation parameters for the three classes of X-ray flares and a higher level of non-axisymmetry than that was obtained earlier. This increases the statistical significance of active longitudes and implies that a significant fraction of X-ray flares is produced by the two active longitudes. They also find a significant difference between the rotation rates in the two solar hemispheres, with active longitudes rotating faster in the northern hemisphere. Zharkov and Zharkova study the statistical properties of flares in solar cycle 23, finding a difference in the latitudinal distribution of flares between the two solar hemispheres. Flares are found to have one maximum at the latitude of 18° in the northern hemisphere but two maxima at 14° and 20° in the southern hemisphere. They also verify the uneven longitudinal distribution of flares in evidence of active longitudes.

2. Solar corona and heliosphere

The heating of solar corona up to millions of degrees is still partly an open issue. However, magnetic reconnection most likely contributes to the heating and structure of solar corona significantly. Priest gives an account of one interesting model of coronal heating called the Flux Tube Tectonics model where a multitude of current sheets continually form and dissipate via magnetic reconnection. The magnetic field of the hot solar corona is carried out into interplanetary space by the solar wind, forming the solar open magnetic field, or the heliospheric magnetic field (HMF) or the interplanetary magnetic field (a dear child has many names—Finnish proverb). Smith reviews the present understanding of the solar cycle evolution of the heliospheric magnetic field and the solar wind, especially keeping in view the essential contributions made by the Ulysses mission. He also discusses the unusual features of the HMF during the exceptionally long declining phase of cycle 23, the connection between the magnetic flux and solar wind mass flux and the north–south asymmetry of the heliospheric current sheet, nicknamed bashful ballerina. The inverse square of the Alfvén speed of solar wind, also called the solar wind quasi-invariant (QI), has been shown to be a good proxy of the sunspot number. Leitner, Farrugia and Vörös determine the yearly probability density functions (PDFs) of QI separately for fast as well as slow solar wind. The PDFs are best described by log-kappa distributions, indicating a non-linear and non-local system with a long-term memory. While the variation in PDFs over the cycle 23 shows a QI maximum in 2002, at the time of dipole reversal, the kappa values maximize in 2005, indicating a more structured solar wind in the mid-declining phase of the cycle.

The heliosphere is penetrated by energetic particles of both solar and galactic origin. The heliospheric magnetic field modulates the flux of galactic cosmic rays (GCR) on Earth. Gil and Alania study the rigidity spectra of the 27-day variability of galactic cosmic rays and its two harmonics using neutron monitor data from 1965 to 2002. They note that the observations can be related to different sizes of corotating interaction regions during the minimum and maximum epochs of solar activity. Ruzmaikin, Feynman and Jun analyze the statistics of extreme solar energetic particle (SEP) events measured by the IMP-8 satellite from 1973 to 1997 and by the GOES satellites from 1987 to 2008, noting that the high intensity tails of probability distributions that determine the rate of extreme SEP events are a critical aspect while evaluating hazards to human and robotic space missions. Using the scaling properties of the maximum particle flux in time intervals of increasing length, they find that both data sets indicate a power-law tail with the exponent close to 0.6. They also note that, since the high fluxes of SEP particles are produced by fast coronal mass ejections (CME) the heavy-tailed distribution also means that the Sun generates faster CMEs than would be expected from a Poisson-type process.

3. Near-Earth space

The interaction of the solar wind and the heliospheric magnetic field with the magnetic field of the Earth leads to a continuously varying level of magnetic disturbance in the near-Earth space, the magnetosphere and the ionosphere. The largest disturbances are the geomagnetic storms that are produced under the specific conditions of the solar wind and HMF that are mainly found during the interplanetary coronal mass ejections (ICME) and high-speed solar wind streams. The geomagnetic storms and other disturbances, and thereby the conditions of the interplanetary space, have been monitored by ground-based observations of the geomagnetic field almost continuously since the 1840s. Since the early observations of the geomagnetic field yield invaluable information on the early solar wind and the HMF, they are an important part of Space Climate. Ribeiro, Vaquero and Trigo use the newly recovered observations of geomagnetic declination made by the Jesuit Antonio Canudas in Guatemala between 1857 and 1859, to enhance the global set of observations during the famous geomagnetic storm in September 1859, also called the Carrington storm. The study shows that the Carrington storm probably included the largest disturbance in magnetic declination ever recorded at the equatorial region.

Geomagnetic storms lead to a large increase in energetic particles in the inner magnetosphere. These particles circulate around the Earth for a couple of days, producing an electric current called the ring current. Magnetic observations at four low-latitude stations are used by Kyoto WDC to construct the Dst index, which monitors the intensity and evolution of the ring current and geomagnetic storms. However, it has been known for some time that the Dst index includes some random and systematic errors. Mursula, Holappa and Karinen note that the four Dst stations contribute to the Dst index systematically by unequal amounts, the largest yearly average contribution being roughly twice as large as the weakest. They show that the contributions are ordered according to the station's geographic longitude, with westernmost stations yielding the largest disturbances. They suggest a correction to the Dst index recipe, after which all stations contribute with equal weights to the Dst index. Gannon and Love aim to circumvent the problems of the Dst index by producing a new 1 min resolution storm index, called Dst(8507-4SM), based on observations made at the four Dst stations in the years 1985–2007. Rather than following the Dst index recipe, they use frequency-domain techniques to excise the solar-quiet variation from the index. They also compare the new index with Sym-H, the 1 min index of Kyoto WDC, which they find to be more disturbed during the storm's main phase than the new index, possibly because of the higher latitude of its contributing observatories.

Energetic particles in the Earth's magnetosphere have been measured by a series of low-altitude polar orbiting NOAA/POES satellites since 1978, covering nearly three solar cycles. The MEPED instruments onboard the NOAA/POES spacecraft measure fluxes of ions and electrons in the energy range of ring current particles. However, the solid-state detectors of the MEPED instruments suffer significant radiation damage, causing the effective energy threshold of the instruments to increase with time. Without correction, this would lead to underestimated particle fluxes in a couple of years after a new satellite's launch. This poses a serious problem when trying to use these data for long-term studies of energetic particles and geomagnetic storms. Asikainen and Mursula calibrate the MEPED ion fluxes by taking the decay of detectors into account and comparing the ion fluxes simultaneously observed by an old and a new satellite at specific locations of satellites orbital conjunction. Calibration greatly increases the mutual agreement in particle fluxes observed by several satellites. The authors present the longest homogeneous series of particle fluxes for the whole NOAA/POES era since 1978. The results emphasize the uniqueness of the minimum of cycle 23, showing that particle fluxes were lower than ever earlier during the last 30 years.

4. Earth's atmosphere and climate

The Sun affects the Earth's atmosphere in a multitude of different mechanisms, some of which are still rather poorly understood. In fact, it is likely that some new mechanisms will be found that are presently being missed. The most obvious effects are due to the various parts of the electromagnetic radiation spectrum, including the visible light, the UV/EUV radiation, the X-rays and the infrared emission. Although the effects of electromagnetic radiation are generally reasonably well known, there are still several topics and open questions to be studied and verified. Shapiro et al. apply a 1D radiative–convective model with interactive neutral and ion chemistry to analyze the responses of hydroxyl, ozone and electron densities in the tropical middle and upper atmosphere to solar spectral variability during the Sun's 27-day rotation. In the stratosphere their sensitivities to SSI changes are largely determined by variability in the Herzberg continuum, while in the mesosphere the changes in the Lyman-α line dominate. The authors compare four different SSI data sets and find that ozone and hydroxyl sensitivities to SSI changes during solar rotation are almost identical for all SSI data sets in the stratosphere. However, in the mesosphere, differences in Herzberg continuum and Lyman-α line between the SSI data sets lead to substantial scatter.

While the effects of electromagnetic radiation are already fairly well known, there are other effects like those caused by charged particles precipitating in the different layers of the atmosphere that are far less well known so far. Three papers in this issue address the topic of energetic particle effects in the atmosphere. Egorova et al. use the SOCOL chemistry–climate model to examine the dramatic effects of a solar proton event that occurred in October 2003 on the composition of the stratosphere and mesosphere. Effects on the composition, in particular the amount of ozone, are thought to be one way in which precipitating particles can change the state of the middle and upper atmosphere. While this effect is now included in several climate models, it is usually parameterized, and the authors show that significant differences are found between these parameterizatons and a more complete representation of the ion chemistry relevant to creation of species that can destroy ozone at high latitudes. The authors note that parameterized ion chemistry underestimates the stratospheric ozone depletion by 10% as late as two weeks after the event, which can be important for the long-term effects of solar energetic protons on the ozone layer.

The tropospheric effects of short-term reductions in the flux of galactic cosmic rays, known as Forbush decreases (FD), are studied by Artamonova and Veretenenko and by Laken and Kniveton. Artamonova and Veretenenko continue earlier similar studies finding further evidence of increasing atmospheric pressure at high latitudes a few days after an FD event. Pressure increases are shown to be caused by the formation of blocking anticyclones and by abrupt slowing down of the motion of North Atlantic cyclones. Laken and Kniveton argue that earlier studies that examined changes in cloud coverage after FD events had not properly weighed the signal. They find indications of cloud cover decrease in the upper troposphere at high southern latitudes. Contrary to earlier studies, the signal is found at the time when the change in GCR flux is largest, not when the flux attains a minimum. Taken together these papers clearly motivate future studies in the area of GCR and other particles' effects on the atmosphere and climate. Exact mechanisms of the direct or indirect effects of GCR on the troposphere have yet to be determined, and the response of the troposphere to the large perturbations in stratospheric composition still needs to be quantified. These tasks are far from trivial considering the complex nature of the troposphere and the need to understand processes across scales from the global to the microphysical.

Three additional papers in this special issue focus on empirical studies of solar–terrestrial relations and solar effects on various climate factors at different, long time scales. Mauas, Buccino and Flamenco study stream flows of major South American rivers, which are excellent climatic indicators since they integrate precipitation over large areas. A positive correlation at multi-decadal time scales between steam flows and sunspot number is found in all cases studied. The correlation with sunspot numbers was found to be higher than that with GCR flux, favoring solar irradiance variations as the probable cause. The results also question the earlier idea that solar activity affects precipitation in South America by controlling the position of the inter-tropical convergence zone.

Ogurtsov et al. have collected a record of stable isotope ratios, $^{13}C/^{12}C$ and $^{18}O/^{16}O$, from pine tree rings of northern Finland from 1600 to 2002. The carbon ratio correlates well with the average temperature during the growth period in northern Finland. The authors find significant periodicities in carbon and oxygen ratios of 100, 11 and 3 years. The 100-year oscillation in the carbon ratio is most evidently connected to the Gleissberg cycle of solar activity. The results support previous evidence from tree ring data for a centennial Sun-climate link in northern Finland. Raspopov et al. analyze several climate proxy data sets, including petrified tree rings and varve sediments that were formed tens to hundreds of millions of years ago. They find persistent, global signatures for a secular and a 200-year periodicity. These can naturally be identified with the Gleissberg cycle and the deVriess–Suess cycle, which are dominant solar periodicities known from present, much more recent, times. The results give evidence for a persistent solar influence on climate over very long time scales. Moreover, they show that solar activity seems to attain roughly the same main periodicities over these long time scales.

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