J. Space Weather Space Clim. **3** (2013) A21
DOI: 10.1051/swsc/2013043

EDITORIAL OPEN ACCESS

Long-term solar activity and its implications to the heliosphere, geomagnetic activity, and the Earth's climate

Preface to the Special Issue on Space Climate

Kalevi Mursula[1,*], Periasamy Manoharan[2], Dibyendu Nandy[3], Eija Tanskanen[4], and Pekka Verronen[4]

[1] Leading Guest Editor, Department of Physics, University of Oulu, 90014 Oulu, Finland
*Corresponding author: e-mail: Kalevi.Mursula@oulu.fi
[2] Guest Editor, Radio Astronomy Centre, Tata Institute of Fundamental Research, Ooty 643001, India
[3] Guest Editor, Department of Physical Sciences and CESSI, Indian Institute of Science Education and Research, Kolkata, Mohanpur 741252, India
[4] Guest Editor, Earth Observation, Finnish Meteorological Institute, 00101 Helsinki, Finland

Received 1 April 2013 / Accepted 24 April 2013

ABSTRACT

The Sun's long-term magnetic variability is the primary driver of space climate. This variability is manifested not only in the long-observed and dramatic change of magnetic fields on the solar surface, but also in the changing solar radiative output across all wavelengths. The Sun's magnetic variability also modulates the particulate and magnetic fluxes in the heliosphere, which determine the interplanetary conditions and impose significant electromagnetic forces and effects upon planetary atmospheres. All these effects due to the changing solar magnetic fields are also relevant for planetary climates, including the climate of the Earth. The ultimate cause of solar variability, at time scales much shorter than stellar evolutionary time scales, i.e., at decadal to centennial and, maybe, even millennial or longer scales, has its origin in the solar dynamo mechanism. Therefore, in order to better understand the origin of space climate, one must analyze different proxies of solar magnetic variability and develop models of the solar dynamo mechanism that correctly produce the observed properties of the magnetic fields. This Preface summarizes the most important findings of the papers of this Special Issue, most of which were presented in the Space Climate-4 Symposium organized in 2011 in Goa, India.

Key words. Space Climate – solar activity – heliosphere – space weather – climate

1. Studies on solar activity

Sunspots, the regions of the most intense magnetic fields on the Sun's surface, are the only magnetic structures on the Sun visible to naked eye and, therefore, the most traditional and the most important long-term proxy of long-term solar magnetic variability. Thus, sunspots still remain as an essential topic of space climate research. Several parameters and indices have been reconstructed from the observed sunspots and used as proxies of solar activity and tracers of the underlying dynamo mechanism, including sunspots areas, the international (earlier, Zurich) sunspot numbers (ISN) and the group sunspot numbers (GSN). Several thousand scientific studies have already been published on various aspects of solar activity using one of these parameters or proxies. Most of them assume either tacitly or explicitly that these proxies are correct and homogeneous over the whole time interval covered by the respective index or proxy. However, this may not necessarily be the case, since, e.g., observatory instruments, practices and seeing conditions have varied in time. Accordingly, increased activity has recently been raised in order to study the homogeneity of ISN and GSN, the two most important sunspot indices.

As part of the program to study the homogeneity of solar activity indices, Pérez Aparicio et al. (2012) in their paper "The proposed "Waldmeier discontinuity": How does it affect to sunspot cycle characteristics?" reanalyze several consequences of a recent claim that there is a significant inhomogeneity in the ISN series over 1945 when Max Waldmeier started producing the ISN. According to this claim the ISN before 1945 should be raised by 20% in order to balance this inhomogeneity. Naturally, if such a step really existed in the ISN, it would have serious consequences to many inferences about long-term solar variability. Aparicio et al. study the question of whether the well-known relationships characteristic for solar cycle evolution are changed (improved, as expected) if the ISN series is modified in the suggested way. The four studied relationships include, e.g., (quite aptly) the Waldmeier effect, i.e., the anticorrelation between cycle amplitude and the length of cycle ascending phase, and the correlation between cycle amplitude and the activity level at the previous minimum ("amplitude-minimum effect"). For a comparison, they make the same analysis not only for the original and modified ISN series but also for the GSN series (which need not be modified according to the claim). The authors verify the earlier known relationships and differences of results between the original ISN and GSN, but find no evidence for statistically significant improvement for any of the studied relationships when using the modified ISN. In fact, in one case (amplitude-minimum effect for cycles 10–22) the opposite is seen in that a relationship, which is significant for the original ISN, is not significant for the modified ISN. Interestingly, this is the relationship where the effect of the modification is expected to be most clearly visible. So, the obvious conclusion of this study is that cycle characteristics do not require or support the need for the modification of the ISN series, as they are not improved by the claimed 20% rise in the ISN. Despite its slightly slim conclusions, this study is important in order to evaluate the consequences of such a suggested inconsistency to the established relationships relating to the solar cycle. Of course, more work is still needed in order to really conclude if such a step did occur and if the ISN series really has to be rescaled and by how much. Moreover, in addition to the Waldmeier step discussed in this paper, there may be other times when artificial discontinuities are introduced in the ISN series.

Another issue of possible concern about the reliability and homogeneity of sunspot observations was raised recently, as the behavior of the Sun in the last 10–15 years has turned out to be quite unusual. The latest minimum between the solar cycles (SC) 23 and 24 became to be surprisingly long and low in sunspot numbers. One has to go almost a century back in time in order to find a minimum with such unusual sunspot characteristics. Not only sunspots show strange fatigue recently, related weakening has been observed in solar polar fields, heliospheric magnetic field, solar wind density, solar irradiance, and geomagnetic activity and storminess. Moreover, the ongoing cycle 24 has started very slowly and is going to remain very weak. This unusual solar behavior has motivated detailed investigations of the causes of the weakening activity trend and raised the possibility of an impending grand minimum. The last grand minimum was the Maunder minimum between 1645 and 1715 AD, when the regular sunspot cyclicity disappeared for a few decennia; the latter phase also coincides with the deepest part of the little ice age. Clette & Lefèvre (2012) in their paper "Are the sunspots really vanishing? Anomalies in solar cycle 23 and implications for long-term models and proxies" provide an extensive overview of sunspot observations related to this recent unusual trend in solar activity. The exceptional nature of the previous cycle 23 was first noted in the change of the long-term relationship between sunspot numbers and several UV proxies, which occurred around the maximum of cycle 23. Since about 2,000 there were less sunspots producing the same amount of UV flux, the relative reduction being by some 15%. This raised the acute concern about the homogeneity of sunspots in cycle 23. The authors show that the same change occurs in two completely independent sunspot series (ISN and AAVSO), thus excluding, e.g., possible problems in the main ISN observatory in Locarno. By comparing the distribution of sunspots and sunspot groups of different morphology, they find that the number of small spots without penumbra and of groups without large spots dropped by a factor of more than 2 in cycle 23, causing the observed lower values of the ISN relative to other, more global indices of solar activity like the UV proxies. So, the answer to the question posed in the title is affirmative "yes" but applies only to the smallest spots. The authors relate their observations to those on the recent weakening of maximum sunspot magnetic fields by noting that if small spots indeed disappear due to weakening of their magnetic fields (below the 1,500 G threshold of sunspot formation), the vanishing spots would become intermediate magnetic flux elements (plages and faculae with 100–1,500 G), enhancing chromospheric emissions and contributing to the observed discrepancy between sunspots and UV proxies. Finally, they note that the observed scale-dependent change and the implied decoupling between small- and large-scale elements are difficult to explain with a single source mechanism for all sunspots, and raise the question of two separate mechanisms for spot formation and decay, where different mechanisms may be dominant at different depths and have different effects on small and large magnetic elements. Thus, the odd behavior of cycle 23 may, e.g., give additional evidence for the existence of a superficial dynamo, and calls for new modeling efforts to explain how this could be coupled with the deep dynamo to produce the observed properties of the solar cycle.

The paper by De Jager & Duhau (2012) "Sudden transitions and grand variations in the solar dynamo, past and future" adds to the already fairly extended list of predictions on the height and timing of the maximum of the solar cycle 24. They use the geomagnetic aa index (actually two versions of it, the original and modified) in order to extract a long-term proxy for the solar poloidal magnetic field. Then, together with the ISN series, they study the development of the mutual relationship between the solar toroidal and poloidal phases since 1840s. Based on this analysis, they predict that SC 24 maximum will occur in 2013.5 with maximum sunspot number of 62 ± 12. Dividing the solar activity during the ISN time interval into three types of different levels, called "grand episodes" (grand minima, grand maxima, and regular oscillation), the authors argue that the relationship between the solar toroidal and poloidal phases suggests that a new grand episode in solar activity has started in 2008, and that this grand episode will be of the regular oscillation type, similar as the long period between 1724 and 1924. Thus they bravely argue that the fairly common expectation of an imminent grand minimum of solar activity is not supported by solar magnetic evolution. Even more so, there should be no grand minima during the starting millennium, mainly because of the present, rising phase of the suggested 2,300-year Hallstatt periodicity of solar activity. However, the current theoretical understanding of the solar dynamo mechanism does not permit so long forecasts of solar activity. Moreover, the results are dependent on the need and method of revising the aa index for which, however, no community approval exists. Therefore, the results presented in this paper are interesting, but conditional to the correctness of a number of assumptions that remain to be verified.

In her paper "Statistics of sunspot group clusters" Getko (2013) analyzes the Greenwich sunspot group database with group areas and locations in order to study the clustering of sunspot groups in 1874–2008. She uses the Zubrzycki method of clustering, where the size of the clustering region is determined by calculating distance-dependent correlation functions, weighted by cluster area. Clusters are searched for the descending, ascending, and maximum phases of each solar cycle separately. Overall, about 30% of all sunspot groups in the ascending and descending phase create clusters, around maxima this fraction is slightly larger, about 35%. The sunspot clusters contribute to activity "nests" and which may significantly enhance solar activity during their lifetime. The author calculates the number distribution of sunspot groups within a cluster for all above cases separately. These results offer a new possibility to explore long-lived structures such as complexes of solar activity, fragmentation of flux tube, periodicities in solar activity, magnetic flux emergences, active longitudes, and solar hemispheric asymmetries. These results can further be used to guide solar dynamo model output. Obviously, studies like this rely on the quality and homogeneity of sunspot group observations.

The paper by Kretzschmar et al. (2012) "Extreme Ultraviolet Solar Irradiance during the rising phase of solar cycle 24 observed by PROBA2/LYRA" deals with the calibration and validation of EUV data from the LYRA (Large-Yield RAdiometer) instrument on board the PROBA2 satellite. The authors aim to provide a reliable long-term EUV irradiance series at daily resolution for two of the four LYRA channels over two years (from February 2010 until February 2012) from the start of PROBA2 science phase. The LYRA channels 3 and 4 use aluminum and zirconium filters, respectively, and have a pass band both in the EUV part as well as in the soft X-ray (SXR) part of the spectrum, but at different wavelengths. The authors first note that the higher-sampling data even up to the 1-min level-3 data still suffer from various artifacts, including effects due to spacecraft rotation by 90 degrees every 25 min, instrument cover opening/closing, instrument switch-on/reload, moon eclipses, and occultation of the Earth's atmosphere, and exclude these effects from the data. Then they make a detailed analysis of the degradation of these two LYRA channels, making use of the modeled LYRA response to EUV spectra observed by corresponding instruments on board the TIMED and SDO satellites. While channel 4 shows excellent agreement with modeled irradiance both in absolute level and variation, channel 3 shows roughly correct level but significantly reduced variation. After careful detective work, the authors track this to the enhanced degradation of the EUV band of channel 3, whereby this band has almost completely disappeared from channel 3 by the end of the observation period. By using a new, multiplicative calibration and channel 4 data, the authors can revive this lost information to finally conclude with a very good agreement with modeled irradiance even for channel 3. As a result of this study, the authors produce a reliable series of EUV/SXR irradiance from these two LYRA channels at daily resolution over the whole PROBA2 lifetime. The LYRA observations verify the duplication of EUV irradiance from the low levels before February 2010 until the higher activity times in November 2011 with the start of the active phase of solar cycle 24. The calibrated series of LYRA EUV/SXR channels will also be useful, e.g., for space weather, thermospheric and ionospheric studies.

2. Solar dynamo, solar space, and its coupling to Earth

Returning to the genesis of solar activity, the magnetic fields produced by the dynamo mechanism in the interior of the Sun – which eventually find their way to the surface and are dispersed into the heliosphere with the solar wind – couple the solar interior to our space environment. Thus, studying properties of magnetic fields in the heliosphere and inside the Sun allow one to set constraints on physical processes across the whole solar-dominated system. Magnetic helicity (twist) is one such magnetic property, which is important because it is an invariant in ideal magnetohydrodynamic systems. Warnecke et al. (2012) in their paper "Magnetic twist: a source and property of space weather" use numerical simulations to study the evolution of magnetic twist from the solar interior through the solar atmosphere into the heliosphere. Magnetic twist plays an important role in solar dynamo, which produces negative magnetic helicity at small scales and positive at large scales (in the northern hemisphere). However, in the heliosphere this is reversed and the magnetic helicity is positive at small scales and negative at large scales. The mechanism that sustains negative small-scale helicity is turned off in the solar wind, and only turbulent magnetic diffusion remains, which contributes with opposite sign. Helicity is also important in producing eruptions like CMEs. The authors show that the hemispheric sign rule of magnetic helicity does not extend unchanged into the interplanetary space, but must flip sign somewhere above the solar surface. This is against the long-held finding that the magnetic clouds follow Hales polarity and that the sign of the magnetic helicity is the same as in the interior. The authors also present evidence for finite magnetic helicity density in the heliosphere, and relate it to the magnetic field properties of the dynamo in the solar convection zone. As the authors admit, the models are still rather unrealistic, but have already given new insight into the interplay between dynamo models and solar wind turbulence.

Sharma & Srivastava (2012) study in their paper "Presence of solar filament plasma detected in interplanetary coronal mass ejections by in-situ spacecraft" two different interplanetary coronal mass ejection (ICME) events on 20–21 November 2003 and 3–5 August 2010, with the main aim to identify the presence of filament material within or annexed to the ICME plasma. Although nearly all ICMEs (and their source CMEs) are connected with the eruption of filaments, filament material has been identified at 1 AU only in a few of ICMEs. The authors have collected an impressive suite of data about the source CMEs and the properties of the ICME plasma measured by several instruments aboard a number of spacecraft. They use this database to identify the magnetic cloud (i.e., flux rope configuration) and the different plasma regions within the ICME and, in particular to study the question which parameters are most appropriate to distinguish the filament plasma. While the filament is expected to show up as high density, cool temperature plasma region within ICME, the identification based on these bulk properties is often not straightforward. They are better seen as depletions in thermal velocities of heavy ions (He, C, O), in increased He^{++}/proton and He^{+}/He^{++} ratios and in decreased heavy ion charge state ratios (O7/O6 and C6/C5). This emphasizes the need to continuously monitor a wide range of solar wind and IMF properties, including heavy ions and their different charge states. The magnetic, plasma, and compositional parameters were found to be in the same range for the two ICMEs despite the fact that they originated from different types of CMEs (flare-associated vs. quiescent eruption) and different phases of solar cycle. Interestingly, in both cases the authors find filament material both within the magnetic cloud and in the solar wind trailing the cloud. The extensive suite of parameters and detailed analysis make this an important paper in studying the structure of ICMEs observed at 1 AU, which will have future application to space weather studies.

In this Special issue, Richardson and Cane contributed with two papers. These papers report the analysis of the properties of solar wind and interplanetary magnetic field at 1 AU, and their effect in the near-Earth environment causing geomagnetic activity and storminess. In the paper "Near-Earth solar wind flows and related geomagnetic activity", Richardson & Cane (2012a) extend their earlier classification of the near-Earth solar wind into three basic flow types to include the earliest years of the OMNI database since November 1963, as well as the more recent times until the end of 2011. This extension allows one more solar cycle (SC 20) and the time period around the latest solar minimum between cycles 23 and 24 to be studied in detail. The included times are interesting since both cycle 20 and cycle 23 were lower in sunspot activity than the so far classified cycles 21 and 22. In particular, the late declining phase of cycle 23 depicts exceptional weakness in many solar and solar-terrestrial parameters. As in their earlier studies, the authors classified the solar wind into three basic flow types, the high-speed streams associated with coronal holes and co-rotating interaction regions, the slow wind originating from streamer belts, and the transient flows related to interplanetary coronal mass ejections (ICMEs), including their associated upstream shocks and post-shock regions. Despite the rather meager data coverage of the main data source (the OMNI database of satellite observed solar wind properties) in several years, the authors have come up with a surprisingly complete time coverage for their classification by cleverly employing additional information from auxiliary proxy parameters like geomagnetic activity indices and fluxes of solar energetic particle and galactic cosmic rays. After reviewing the classification criteria and giving some samples of the different solar wind flows, the authors discuss the fraction of time covered by the three flow types. The temporal extension reveals the interesting fact that the occurrence of CME-associated flows at solar maximum remains roughly at the same level (about 50–60%) even during the weaker sunspot cycles 20 and 23 as during the two higher cycles 21 and 22. The fraction of slow solar wind in cycle 20 is also the same as in cycles 21 and 22 but is significantly enhanced during the exceptionally weak minimum between cycles 23 and 24. The authors calculate the contribution of the three flow types to the *aa* index of geomagnetic activity and the intensity of the interplanetary magnetic field (IMF), finding that both the recent minimum and cycle 20 follow the same pattern as other, more active cycles, in that the IMF intensity closely tracks the mean fields found in high-speed streams and slow solar wind. The authors suggest that the solar cycle variation of IMF intensity at 1 AU is, contrary to Owens & Crooker (OC) model, not mainly caused by the magnetic fields of transients like ICMEs but due to the background magnetic field contributing to the slow solar wind and high-speed stream intervals. This suggestion is further supported by the fact that there is no correlation during cycle 20 between IMF intensity and ICME flow fraction. The authors also discuss other factors that could possibly make cycle 20 conform to the OC model, but exclude all of them. Accordingly, the temporal extension of solar wind flow types to cycle 20 presented in this paper, was crucial in order to reach this new, alternative view on the solar cycle evolution of the solar open magnetic field.

In their other paper "Solar wind drivers of geomagnetic storms", Richardson & Cane (2012b) use the solar wind flow-type classification to determine the drivers of geomagnetic storms of various size ranges in 1964–2011. They use two storm size classification methods (by Gosling and by NOAA), which are rather similar and both based on the *Kp* index of global geomagnetic activity. Since the *Kp* index is available from 1932 onwards, the authors also study the storms in the whole *Kp* index time interval without separating them to their drivers. Extending the solar wind flow-type classification to cycle 20 verifies that the number of ICME-associated (but not HSS-associated) storms follows the sunspot activity level, the number of ICME storms being higher in cycles 21 and 22 than in cycles 20 and 23. Continuation to recent years shows that, while the stream-associated storms are typically dominating for about 3–4 years during the declining phase of the cycle, they were only prominent for one year (2003) in cycle 23. Instead, during cycle 23, the ICME-associated storms continued to be observed past the stream-associated peak in 2003 and exceptionally late into the declining phase. These results show that there are large variations in the relative contributions from ICME and stream-associated storms from one cycle to another. Dividing solar cycles roughly in two intervals of "minimum" and "maximum" activity, the authors determine the number of storm days of different size and the fraction to which the ICME and HSS drivers cause them. While there are only some 10–15% more of weak storm days in maximum than minimum time (1,128 vs. 991), there are three times more of major storms (115 vs. 38). At solar minimum, streams are responsible for three-quarters of weak and medium storms, a half of large storms, and 13% of major storms, while at solar maximum, streams are responsible for a half of small storms, only a third of medium storms and 9% of large or major storms. These results show the different contribution of streams and ICME flows at solar minimum and maximum, and the fact that ICME flows are responsible for the most severe storms throughout the solar cycle. Using the whole 80-year time interval of *Kp* index, the authors emphasize the uniqueness of the low activity around the recent solar minimum in 2008–2011, when the four consecutive years depicted the smallest annual numbers of small storms. The previous record low number of small storms was in 1966, soon after the all-time record sunspot activity. This indicates that the solar wind conditions, geomagnetic activity and storminess in the recent minimum were unusually quiet since at least 1932. The 80-year long study also reveals that, although the number of weak and moderate storms per cycle follows the cycle-to-cycle variations in cycle size (according to sunspot activity), this is less aptly (or practically not at all) the case for large storms. The authors note that advance prediction of the height of sunspot cycle is a weak indicator of the number of intense geomagnetic storms. The same study also shows that the typical numbers of storm days/cycle quoted in the standard NOAA G storm table for G1–G4 storms appear to be significantly higher than obtained here, suggesting that they should be revised considerably downward. These results are very useful for understanding the long-term variation of the causes and correct occurrence rates of the most dramatic events in the near-Earth space.

3. Near-Earth space and climate

The geomagnetic field is an important element of the solar-terrestrial research, which, together with the solar wind and IMF, determines the size and location of the disturbances following from their mutual interaction. While the geomagnetic field can be considered practically constant (despite variations related to its orientation) over short time scales of space weather, the longer time intervals related to space climate need to take into account the consequences due to the changing geomagnetic field. Korte & Muscheler (2012) in their paper "Centennial to millennial geomagnetic field variations" summarize the present knowledge of the magnetic field evolution during the Holocene. The authors first briefly present the properties of the archeo- and paleomagnetic data, and discuss how the database has extended since the previous model versions. Then they review their two new spherical harmonic models CALS3k.4 and CALS10k.1b, which cover the last 3ky and 10ky (so, almost the whole Holocene), respectively, and compare them to their earlier spherical harmonic models and to various dipole field reconstructions based on virtual axial dipole moments (VADM) and virtual geomagnetic poles (VGP). The authors wisely note of the remaining subjectivity of model construction (e.g., related to choice of model regularization factors), which may somewhat affect model results. For example the CALS10k.1b model was obtained as an average of 2,000 models (obtained by varying data within limits), which necessarily damps higher harmonics and reduces temporal resolution. Comparing the CALS10k.1b model to the standard VADM model, the authors find considerably better agreement than for their earlier 7ky CALS7k.2 model, which is thus now outdated. Still, there are notable differences in the evolution of the dipole moment between the two methods, especially at about 500 BC and 500 AD, where the VADM model depicts a larger moment. The authors note that in order to resolve this discrepancy, one needs more archeomagnetic data from the southern hemisphere. Because of the method used, the tilt of the dipole in CALS10k.1b is damped and depicts overall smaller values than the VADM model. CALS10k.1b model does not show the rather strong 1,150y oscillation of the VADM model tilt angle, but the two models do roughly agree during the last 2,500 years. Also, estimates of the dipole axis longitude differ considerably in the two models. It seems that the method used in CALS10k.1b is less appropriate for long-term studies in dipole tilt orientation than the VADM model. The authors also use the (low-pass filtered) 10Be and 14C cosmogenic isotope data to extract independent proxies on the dipole moment evolution. The solar influence dominates the cosmogenic isotope production at short time scales, while the geomagnetic field plays a dominant role at long time scales beyond 500y. While the authors find a reasonable agreement between the different dipole moment estimates at multi-millennial time scales, they maintain that a notable solar variation remains in cosmogenic isotope estimate even at time scales up to a few millennia. Overall, this paper is a useful and balanced presentation of the multi-millennial models of geomagnetic field evolution. Although models seem, after sophisticated methods, to slowly converge to a common view, there are still significant differences, mainly due to insufficient and unevenly distributed data. Therefore, the authors carefully recommend to test if any interpretation depends on the choice of geomagnetic field model.

Bruce Tsurutani et al. (2012) discuss in their paper "Extreme changes in the dayside ionosphere during a Carrington-type magnetic storm" the consequences in the dayside ionosphere during very intense geomagnetic storms. The authors note that during the main phase of 30 October 2003 super-storm (peak $Dst = -390$ nT), dayside O^+ ions were uplifted to DMSP satellite altitudes of about 850 km, and O^+ ion peak densities were multiplied by a factor of 6 compared to the quiet level. In addition to normal dual peak structure, the DMSP satellite observed sharp density enhancements and depletions on either side of the equator at about 12–15 of absolute latitude. The authors suggest the interpretation that these are spatial rather than (only) temporal structures and could be the analogs of earlier observed plasma bubbles. It is still unclear how such structures are borne but they may be due to Rayleigh-Taylor instability caused by the rapid plasma uplift process. The authors then continue to simulate the ionospheric uplift in terms of the electric field $E \times B$ drift, using the modified NRL SAMI2 code and the estimated value of about 4 mV/m for the prompt penetration electric field (PPEF). Obtaining a very good agreement with the total electron densities (TEC) above 400 km measured by the CHAMP satellite, the authors note that the anomalies can be explained by the PPEF alone, with no need for disturbance winds, and that most, if not all of the peak TEC intensities are caused by the PPEFs during the first 2 h of an intense magnetic storm. Encouraged by this success, the authors continue to model the dayside uplift during one of the strongest (if not the very strongest) geomagnetic storms, the famous Carrington storm in 1859, whose extreme conditions (peak $Dst = -1{,}760$ nT, E(PPEF) = 20 mV/m) have earlier been estimated by the lead author. In the simulation run the equatorial region was swept clean of plasma, and the high-density plasma was moved to higher altitudes (about 500–900 km) and latitudes (15–35) within 15–30 min after the prompt penetration electric field started affecting. Subsequent evolution depicted the further latitudinal widening of the high-density region to about 15–45 LAT and, soon after the electric field disappeared, the lowering and further enhancement of the peak density region as the results of photoionization were no longer uplifted to higher altitudes. The authors emphasize that, especially during intense magnetic storms, the ionosphere is highly dynamic and far from an equilibrium state. They also note of the possible harmful effects to, e.g., vanishing GPS connections due to plasma bubbles and enhanced satellite drag due to uplifted material. If a Carrington-type super-storm would occur nowadays, it would cause a lot of trouble to the high-tech systems, naturally much more than in 1850s. Event studies like this are not only useful for space weather, but also for space climate, since the long-term evolution is not only a collection or average of typical cases, but greatly affected by individual extreme events like the one studied here.

The paper "The effects of changing solar activity on climate: contributions from paleoclimatological studies" by Engels & van Geel (2012) is a concise review, in which they discuss mainly paleoclimatological evidence for the past influence of solar variability on the Earths climate, highlighting the effects of solar forcing on a range of time scales. The paper first presents the known natural forcing factors of climate, e.g., the orbital forcing, solar forcing, and volcanic activity. Then the solar forcing factors due to total solar irradiance (TSI), UV forcing, and galactic cosmic rays are presented, and the so-called bottom-up and top-down feedback amplification of the direct effects are discussed. In the bottom-up mechanism, increasing solar absorption in fairly cloud-free subtropical oceans during solar maxima leads to increased evaporation, increased moisture in the precipitation zones, intensified upward vertical motions and stronger Hadley circulation. Strengthened atmospheric circulation enhances subtropical subsidence, resulting in a positive feedback mechanism of further reduced cloud formation and increased solar absorption in subtropics. On the other hand, in the top-down mechanism, enhanced UV radiation increases stratospheric temperatures and winds, which can influence the underlying troposphere, e.g., by disturbing the stratospheric polar vortex and, possibly, the tropospheric jets. Historical and paleoclimatological evidence for the influence of TSI on the Earth's climate is presented at different time scales from decadal to millennial time scales, the related data including radioisotopes from marine and lake sediments, tree rings, and ice cores. As a topic closest to their own work, the authors discuss in detail the period of low solar activity starting at 2,800 BP, which is evidenced by a sharp rise in the dendrochronology calibrated 14C curve. The authors present ample evidence that this period coincides with a transition to colder and wetter climate conditions in large parts of Europe. Even more dramatically, large areas in the Netherlands experienced simultaneously a decrease in population densities, as many locations became uninhabitable due to increased precipitation. In Siberia, accelerated cultural development can be seen following a change from semi-desert environments to steppe landscapes. Moreover, dryness crisis in West Africa provides evidence for a large-scale climate change at this time. The combined evidence points toward a large-scale reorganization of atmospheric circulation patterns around 2,800 BP. The authors note that the observed spatial pattern of climate change is in line with the pattern obtained from climate model simulations during low solar activity where reduced solar activity reduces the latitudinal extent of the Hadley circulation, relocates mid-latitudinal storm tracks equatorward, leading to cooling at mid-latitudes and drier conditions in the tropics. The authors also note that the cold temperatures during the Maunder Minimum/ Little Ice Age are mainly a winter/early spring phenomenon, with model simulations showing that low solar activity results in a pressure and temperature pattern at the Earth's surface that resembles the negative phase of the NAO index with reduced winter temperatures. The authors conclude that although there is a wealth of paleoclimatological evidence of solar activity-climate relation, which suggest that the Earth's climate is sensitive even to rather small changes in direct solar forcing factors, we are still far from completely understanding the underlying mechanisms. This paper is very useful as a quick overview of the basic principles and major paleoclimatological evidences for solar-related changes in the Earth's climate.

Acknowledgements. K.M. and E.T. acknowledge financial support by the Academy of Finland to the Projects Nos. 128189 and 131350, and to the Projects Nos. 128189 and 128632, respectively. P. M. is partially supported by the CAWSES-India Program sponsored by ISRO. D.N. acknowledges financial support by the Ramanujan Fellowship program of the Department of Science and Technology and the Ministry of Human Resource Development of the Government of India. The Guest Editors of the Special issue on Space Climate would like to thank the following organizations for their sponsorship of Space Climate-4 Symposium: Indian Institute of Science Education and Research, Kolkata, Asian Office of Aerospace Research and Development, CAWSES/SCOSTEP, Indian Institute of Astrophysics, Bangalore, Indian Institute of Geomagnetism, Navi Mumbai, Montana State University, Bozeman, NASA Living With a Star Program, National Center for Antarctic and Ocean Research, Goa, and the University of Oulu, Finland.

References

Clette, F., and L. Lefèvre, Are the sunspots really vanishing? Anomalies in solar cycle 23 and implications for long-term models and proxies, *J. Space Weather Space Clim.*, **2**, A06, 2012.

De Jager, C., and S. Duhau, Sudden transitions and grand variations in the solar dynamo, past and future, *J. Space Weather Space Clim.*, **2**, A07, 2012.

Engels, S., and B. van Geel, The effects of changing solar activity on climate: contributions from palaeoclimatological studies, *J. Space Weather Space Clim.*, **2**, A09, 2012.

Getko, R., Statistics of sunspot group clusters, *J. Space Weather Space Clim.*, **3**, A09, 2013.

Korte, M., and R. Muscheler, Centennial to millennial geomagnetic field variations, *J. Space Weather Space Clim.*, **2**, A08, 2012.

Kretzschmar, M., I.E. Dammasch, M. Dominique, J. Zender, G. Cessateur, and E. D'Huys, Extreme ultraviolet solar irradiance during the rising phase of solar cycle 24 observed by PROBA2/ LYRA, *J. Space Weather Space Clim.*, **2**, A14, 2012.

Pérez Aparicio, A.J., J.M. Vaquero, and M.C. Gallego, The proposed "Waldmeier discontinuity": How does it affect to sunspot cycle characteristics?, *J. Space Weather Space Clim.*, **2**, A12, 2012.

Richardson, I., and H. Cane, Near-earth solar wind flows and related geomagnetic activity during more than four solar cycles (1963–2011), *J. Space Weather Space Clim.*, **2**, A02, 2012a.

Richardson, I., and H. Cane, Solar wind drivers of geomagnetic storms during more than four solar cycles, *J. Space Weather Space Clim.*, **2**, A01, 2012b.

Sharma, R., and N. Srivastava, Presence of solar filament plasma detected in interplanetary coronal mass ejections by in situ spacecraft, *J. Space Weather Space Clim.*, **2**, A10, 2012.

Tsurutani, B., O.P. Verkhoglyadova, A.J. Mannucci, G.S. Lakhina, and J.D. Huba, Extreme changes in the dayside ionosphere during a Carrington-type magnetic storm, *J. Space Weather Space Clim.*, **2**, A05, 2012.

Warnecke, J., A. Brandenburg, and D. Mitra, Magnetic twist: a source and property of space weather, *J. Space Weather Space Clim.*, **2**, A11, 2012.

Cite this article as: Mursula K, Manoharan P, Nandy D, Tanskanen E & Verronen P: Long-term solar activity and its implications to the heliosphere, geomagnetic activity, and the Earth's climate. J. Space Weather Space Clim., 2013, **3**, A21.