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# Introduction to Space Climate

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**Abstract**

"Space Climate" is a relatively new scientific concept, which combines a number of disciplines in space and atmospheric sciences under the common aim to better understand the long-term changes in the Sun, heliosphere and in the near-Earth environment. In this brief summary we define the contents and aims of Space Climate. We also review some recent findings that are discussed in the papers included in this issue of *Advances in Space Research*, noting on some problems that should be solved, as well as some new lines of research that could lead to a better understanding of some of the main questions of Space Climate.


*Keywords:* Space Climate; Space science; Long term changes; Solar activity; Heliospheric magnetic field; Solar wind

## 1. What is Space Climate?

Space Climate was introduced some 10 years ago to denote the long-term variations in solar activity, as well as the related long-term changes in the heliosphere, the solar wind and the heliospheric magnetic field (HMF), and their effects in the near-Earth environment, including the magnetosphere and ionosphere, the upper and lower atmosphere, climate and other related systems. On the other hand, the concept of Space Weather describes short-term variations in the different forms of solar activity, their prediction and effects on the near-Earth environment and technology. Accordingly, Space Climate is the long-term average of Space Weather, in analogy with the relation between the conventional weather and climate of the Earth's atmosphere.

The time scale dividing between Space Weather and Space Climate can fairly naturally be set to a few solar rotations, the time for which reasonable day-to-day forecasts of Space Weather can be made. Thus, Space Climate would encompass time scales longer than a few solar rotations. These long time scales can roughly be divided in three groups based on the available data and observations. First, for the last few decades we have several uniform data sets of extensive ground-based and space-based observations of the Sun, the heliosphere and the near-Earth space that allow us to obtain a better understanding of the full chain of effects from the Sun to the Earth. Second, for the last few centuries we have more limited and less uniform data sets of direct observations of the Sun, as well as of some reliable proxies like geomagnetic activity. Third, for millennium and longer time scales we have some more sporadic or less direct but still very useful proxy data sets like cosmogenic isotopes.

Long-term variations forming Space Climate are a direct consequence of the fact that the Sun contains a magnetic dynamo whose strength varies in time. Actually, the magnetic activity of the Sun is amazingly variable and versatile, taking into account that the Sun is a boringly stable, middle-aged main-sequence star. For example, the strong increase in solar activity during the last 100 years dramatically emphasizes that rapid and essential changes can take place in those physical processes that produce the solar magnetic field. However, we are still quite far from fully understanding how the solar dynamo works, or what causes the long-term variability in its strength.

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The main mode of operation of the solar dynamo is the 22-year solar magnetic cycle, the Hale cycle, which consists of two 11-year activity cycles, also called Schwabe cycles or simply solar cycles. It has long been known that the height and length of solar cycles vary greatly in time. Some periodicities have been claimed in this variation but the evidence is still quite inconclusive and the interval of direct, homogeneous observations is rather short in relation to claimed periods. However, there is no doubt that the Sun occasionally depicts lengthy periods of very low sunspot activity called great minima. The most recent great minimum was the so called Maunder minimum in 1645–1715.

In addition to the dramatic variations in overall magnetic activity, there are also other interesting features in solar magnetism that so far remain partly unexplained. One such feature, known for long, is that the two halves (solar cycles) of the Hale cycle are systematically different so that the odd cycle is more active in total sunspot activity than the previous even cycle. Rephrasing this Gnevyshev-Ohl rule, there is a systematic 22-year variation in solar cycle strength which seems to persist for centuries. As an explanation, it has been proposed that, in addition to the dynamo fields, there is a relic magnetic field in the Sun from the times of solar system formation that could be still sufficiently significant to cause some observable effects. Other interesting and, possibly, related observations are the hemispheric and longitudinal asymmetries in various forms of solar activity. Such asymmetries have been studied extensively over many years, but recent results have yielded new strong evidence for their persistence and systematic nature, leading to new concepts of solar/heliospheric physics like the bashful ballerina and active longitudes.

One of the main aims of Space Climate is to better understand the long-term solar variability and, in particular, the observed extremes and possible repeatable patterns of this variability. Several contributions included in this publication discuss this topic and present interesting new results, e.g., on early sunspot activity, on systematic patterns in solar and heliospheric magnetic fields and their hemispheric and longitudinal asymmetries.

Another important aim of Space Climate is to better understand the complicated relationships between the Sun, the heliosphere and the various proxies of long-term solar activity, e.g., geomagnetic activity, cosmic rays and cosmogenic isotopes, so that these long-term proxy data can be fully exploited for a better understanding of solar changes on the longest possible time scales. It is interesting to note that quite different results are documented even in this publication, e.g., on how the solar wind and the HMF have changed only during the last 100 years. Both based on geomagnetic indices but using different methods, it has been proposed, on one hand, that the HMF has more than doubled its strength and, on the other hand, that it has remained rather constant during the last century. Clearly, this indicates that the long-term relationships between solar, heliospheric and solar–terrestrial parameters are not yet satisfactorily understood. A number of contributions included in this publication discuss the methods and recent results obtained from various proxies of solar activity, e.g., different cosmogenic isotopes and geomagnetic activity.

A third important aim of Space Climate is to better understand the long-term effect of the changing Sun on the near-Earth environment, in particular on the different atmospheric layers and on global climate. Although this wide research area is not fully covered in the papers included in this publication, there are several papers that present interesting new ideas and observations demonstrating that long-term solar variability is an essential factor in the observed variability of global and local climate and its various elements (cloud patterns, ocean streams, winds, etc.).

## 2. Recent advances in Space Climate

A few years ago, helioseismic studies found fluctuations at the period of about 1.3 years in solar rotation speed at the bottom of the solar convection layer, the so called tachocline. Such fluctuations are interesting since the tachocline is a likely source of highly intense magnetic fields, and fluctuations therein may lead to field fluctuations at the surface and even beyond. In fact, it is known that fluctuations in this period range have intermittently existed, e.g., in geomagnetic activity, for centuries. Now, the most recent helioseismic results show that the 1.3-year period no longer exists after 2001. Rather, there are hints of fluctuations at a slightly different (longer) period during the declining phase of the current cycle 23. This is highly interesting since similar period changes have been observed earlier, e.g., in geomagnetic activity, solar wind and HMF. Accordingly, the fluctuations at the tachocline, although seemingly sporadic, may in fact be part of a more systematic phenomenon related to solar magnetism. Helioseismic (as well as heliospheric) observations in the coming years will, therefore, be highly valuable and interesting.

Recent studies have verified the existence of persistent active longitudes in the heliospheric magnetic field, sunspots and solar flares. While sunspots and other active regions are rotating differentially, the structure producing active longitudes is rotating rigidly but may be stretched longitudinally. Such a structure may lead to the observed seemingly migrating active longitudes in sunspots and other active regions. Rigid rotation of the underlying, longitudinally asymmetric structure agrees with heliospheric field observations and emphasizes the role of global solar magnetic fields in the long-term occurrence of active regions. It is also very satisfying to note that the alternation of activity between the two active regions, the so called flip–flop phenomenon, is found in all studied parameters. Moreover, the flip–flop period in the Sun, found in the heliospheric field, sunspots and solar flares, follows the same 3:1 ratio between the main activity period and the flip–flop period as found for starspots. Accordingly, the Sun indeed behaves like a sun-like star. However, there are still several open issues related to longitudinal (an other spatial) and temporal inhomogeneties of solar and heliospheric phenomena that need considerable study in the future.

Long-term observations of the heliospheric magnetic field also depict interesting systematic hemispheric asymmetries that have far-reaching implications for the understanding of solar magnetism. It has been found that the HMF sector that is prevalent in the northern solar hemisphere dominates the observed sector occurrence for about 3 years in the late declining to minimum phase of the solar cycle. This leads to a persistent southward shift or coning of the heliospheric current sheet (HCS) at these times, which has been described by the concept of the bashful ballerina. Direct measurements of the solar magnetic field verified this result and showed that during the years when the HCS was shifted southwards, there was a persistently non-zero solar quadrupole moment which was oppositely oriented with respect to the dipole moment. There are papers in this publication that discuss these hemispheric asymmetries, extending the study to pre-satellite era using information on the HMF sector structure extracted from the geomagnetic field. Also, preliminary considerations and calculations are presented on the cross-hemispheric coupling in Babcock-Leighton-type solar models which seem to suggest that additional effects, such as transequatorial flows may be required to achieve sufficient cross-hemispheric coupling.

New information on long-term (multi-centennial to millennial) occurrence of sunspots and auroras has been found in old archives of mainly naked-eye observations that give interesting possibilities to study the past occurrence of great minima. The new information can be compared with cosmogenic isotope data, giving more accurate information on the length and depth of various great minima. The data indicate that the Spörer minimum in 1410–1510 was the longest period of inactive Sun during the last 1000 years. Also, early camera obscura and telescope observations were re-examined and several mistakes and inconsistencies have been noted, leading to a more correct record of early sunspot activity.

The long-term change in the HMF strength and its implications to cosmic rays are discussed by a few authors in this publication. Using cosmogenic isotope data, it was found that the magnitude of the HMF has increased by a factor of 4.5 during the last 600 years, in agreement with a rough doubling of the field during the last century from about 2.5 nT at the beginning to more than 5 nT at the end of the century. This increase was proposed to be part of a 2300-year solar variability cycle observed in cosmogenic isotopes during the Holocene. However, another author, using geomagnetic activity indices, found a minimum of about 4.6 nT for the HMF at the beginning of the last century, with only a small increase due to the overall increasing solar activity. Alas, the centennial evolution of the HMF still remains unclear, the results being dependent on the proxy used. Thus, more work is needed in order to understand the differences between these conflicting results. In order to facilitate this future work, a new index of geomagnetic activity, the $A_{\mathrm{h}}$ index, was introduced which correlates better with the standard $K_{\mathrm{p}}$ index than those indices used earlier when estimating the centennial change in HMF. Moreover, an interesting speculation was presented in an effort to explain the differences in solar activity in three selected periods 1844–1905, 1906–1956 and 1957–2005. It was noted that the solar inertial motion due to the giant planets had different characteristics in these intervals. The Sun makes the fastest and most ordered circular motions during the second interval while during the two other intervals the solar inertial motion more disordered and slower. If the inertial motion affects solar activity, these differences could explain the different activity levels.

Some interesting considerations and results related to climate are presented in several papers included in this issue of *Advances in Space Research*. The nonlinear nature of solar (or other external) effects on climate is discussed with an application to the dynamics of the Northern Annular Mode (NAM), a wintertime climate anomaly in the northern hemisphere. It was emphasized that rather small solar induced changes could greatly prolong the persistence of one NAM state with respect to the other. Similar situations may exist in other climate systems as well, since most of these are inherently nonlinear. In another study, the short-term reaction of NAM and NAO (Northern Atlantic Oscillation) to different types of solar drivers, such as intense solar flares, high speed solar wind streams, and magnetic clouds was investigated Also, the role of the global electric circuit (GEC) was discussed as an agent in mediating the solar effect on clouds and climate. The mechanisms responding to GEC were proposed to explain sun-climate correlations on multidecadal to millennial time scales, as well as sun-weather effects on day-to-day time scales. An interesting study raised the idea that solar variability may also have dramatically affected – via climate change – various human cultures, and may even have started, after the climatic conditions sufficiently stabilized, the development of stable civilization based on agriculture, leading later to present cultural life.

## 3. Conclusions

The contributions to this issue of *Advances of Space Research* demonstrate that Space Climate is a vibrant, versatile and important branch of space science which is at the very core of solar–terrestrial physics. There are a number of important open questions about the solar magnetism, the long-term behavior of solar activity, the implied changes in the heliosphere and, in particular, the long-term effects at the Earth. These will keep us busy for several decades to come. We would also like to note, with slight speculation but based on the best set of present information, that we will experience, in a not-too-distant future, a dramatic change in our view of the causes and effects of long-term solar activity and, in particular its influence on the Earth's atmosphere and climate. Space Climate will have a lot to give to humanity.