CLIMATE AND WEATHER OF THE SUN - EARTH SYSTEM

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Contents

Summary

The Sun is a variable star whose output, including electromagnetic radiation, magnetic fields and energetic particles varies at different time scales, from seconds to millennia. Solar variability affects the interplanetary medium but also planetary environments,

including that of Earth. The state of the near-Earth environment is collectively called the Space weather, while its long-term changes make the concept of Space Climate. This forms the field of an interdisciplinary research focused on a wide range of topics: from solar physics, solar wind, cosmic rays, to planetary atmospheres and climate. Special emphasis is paid upon the processes that inter-relate solar variability and terrestrial environment – the Sun-Earth system.

In this work, we present an overview on the state of the art in the field of the weather and climate of the Sun-Earth system.

1. Introduction: Space Weather and Space Climate

The momentary state of the near-Earth space is often referred to as the **Space weather**, in analogy with the conventional weather describing the momentary state of the atmosphere. The following definition is given, e.g., by the Encyclopedia of Earth (http://www.eoearth.org/article/ Space_weather_(AMS_statement)?topic=49537) "Space weather refers to the variable conditions on the Sun and in the space environment that can influence the performance and reliability of space-borne and ground-based technological systems, as well as endanger life or health." Studying the Space Weather is very important for the modern technologies, including satellite-based communication and navigation systems. Extreme Space Weather events (viz. disturbances of the near-Earth space, including **magnetosphere**, ionosphere, interplanetary medium) may cause disturbance, aging or even failure of highly technological devices outside the Earth's atmosphere. The concept of Space weather was introduced in the 1990's in aim to summarize the short-term variations in the different forms of **solar activity**, and their effects in the near-Earth environment, including technological and health implications.

Similar to the conventional weather and climate relations in the terrestrial atmosphere, a new concept of the **Space climate** was launched recently to extend the time span to longer-term variations in solar activity, as well as their long-term effects on the **heliosphere**, near-Earth space, climate and other related systems. This concept is not just a formal extension of Space weather towards longer time scale, but rather its natural generalization. It includes different solar, heliospheric and terrestrial processes and mechanisms that are not operational on short-term scale but become dominant at longer scales. The Space climate "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" (Mursula et al., 2007). It is essentially inter-disciplinary research, including solar, heliospheric and geo-physics in their interrelations, that covers time scale from the solar rotation period up to millennia.

Based on available data and mechanisms involved, Space climate studies can roughly be grouped into three different time scales.

The most recent several decades, starting from the 1950-1970's, are characterized by numerous direct data sets available from various ground-based and space-borne observations of the Sun, the heliosphere and the near-Earth space. For this epoch, the data available makes it possible to study in great detail the full variety of effects from the Sun to the Earth.

For the last few centuries there are also some regular scientific data sets covering only a few basic parameters. These data sets include solar observations (solar disc photographs since 1874, and relative **sunspot numbers** since 1610 AD), some geomagnetic indices measured regularly since the second half of 19-th century, and geophysical measurements. However, these data sets are often non-uniform, and their calibration makes a serious problem.

On longer time scales, millennium or longer, information can be obtained only from indirect but still very useful sets of proxy data stored in natural archives. These include data on **cosmogenic isotopes**.

Aims of the Space climate as a scientific discipline are also three-fold:

- to study and ultimately better understand various forms of solar variability, its origins, evolution, and possibly to be able to forecast it, at least in a probabilistic sense;
- to investigate the complex relations between the Sun, the heliosphere and geo-magnetosphere;
- to better comprehend the long-term effect of the variable solar activity on the near-Earth environment, including global climate.

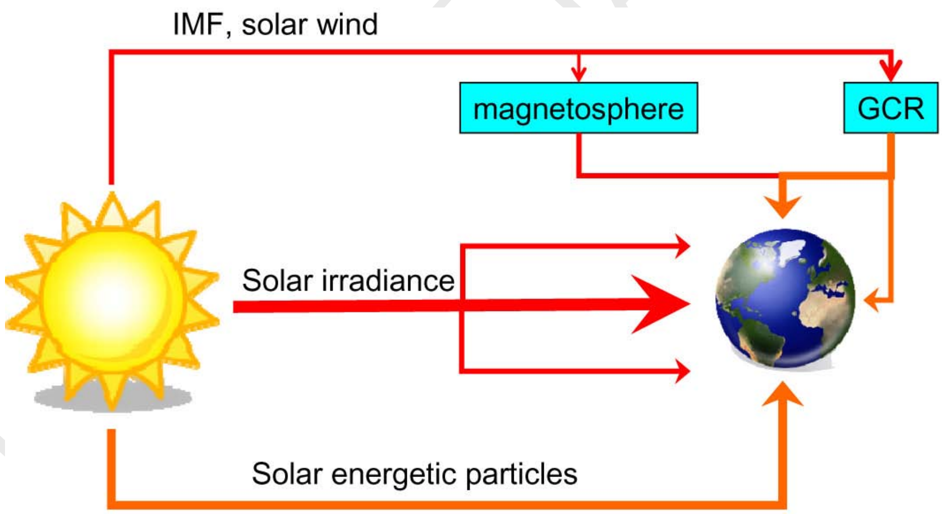

Figure 1. A scheme of the influence of Sun on the near-Earth environment (Space Weather and Climate). Most direct is the solar irradiance (total and spectral in different wave-bands), which has maximum effect in the tropical region getting smaller polewards. Sporadic fluxes of solar energetic particles, produced during eruptive events in the solar atmosphere and corona, affect only polar regions. Interplanetary magnetic field (IMF) and solar wind have a two-fold effect. On one hand, they affect the geomagnetosphere, leading to geomagnetic disturbances and energetic particles precipitation in polar regions. On the other hand, they modulate the flux of galactic cosmic rays (GCR), which form the main source of the radiation effects in the low and middle atmosphere around the globe

A schematic view of the Sun-Earth relation is shown in Figure 1. Variable solar activity, described in Section 2, includes solar irradiance (Section 3) and energetic particle environment (Section 4). Its influence on the Earth's climate is discussed in Section 5.

2. Solar Variability

The Sun is a variable star. The state of its outer layers, including the convection zone, photosphere (or the visible surface) and corona is known to be far from static (often regarded as the "quiet" Sun), as predicted by the standard stellar evolution theory. Essentially non-stationary and non-equilibrium (often eruptive) processes take place on the Sun, making it more dynamic than just a quiet plasma ball. These processes are collectively called solar activity. The concept of solar activity is not unambiguously defined and includes many aspects, such as, e.g., solar surface magnetic variability, eruptive phenomena, coronal activity, and radiation of the sun as a star, or even interplanetary transients and geomagnetic disturbances. The dominant feature of solar activity is the quasi-periodic **Schwabe cycle** with the period of about 11 years.

Many different indices of solar activity have been introduced in order to quantify different observables and effects. Most of them are closely related to each other due to the dominant 11-year cycle, but may differ in some details and/or long-term trends. These indices can be roughly grouped into physical indices, i.e., those representing measurable physical quantities (e.g., radiation flux in some energy bands), and synthetic indices, i.e. calculated using a special algorithm from measured/observed data (a typical example is the sunspot number). In addition, indirect proxy data sets are often used to quantify solar activity via its effect on the magnetosphere or heliosphere.

The most commonly used index of solar activity is the relative **sunspot number,** which is the weighted number of individual sunspots and/or sunspot groups, calculated in a prescribed manner from simple visual solar observations. This is called the Wolf or Zürich sunspot number (WSN) R:

$$R = k\,(10\,G + N)\,, \tag{1}$$

where G is the number of observed sunspot groups, N is the number of individual sunspots in all groups visible on the solar disc and k denotes the individual correction factor, which is needed to normalize different observations to each other. This technique was developed by Rudolf Wolf from Zürich in the middle of the 19-th century. Note that the sunspot number is not the same as the number of observed sunspots, and the minimal non-zero sunspot number, corresponding to a single sunspot is 11, for the standard observer ($k = 1$).

Although synthetic, the sunspot number is a very useful parameter in quantifying the level of solar activity. It was calculated in Zurich before 1982, and after that it is collected at Solar Influence Data Center (SIDC) in Belgium. A great update to the WSN was performed by Hoyt and Schatten (1998) who undertook an extensive archive search and nearly doubled the amount of the original information compared to the Wolf series. Presently, the sunspot number series covers the period since 1610 (see Figure 2) and forms the longest record of directly and regularly observed scientific quantities.

However, newly recovered missing records of past solar instrumental observations continue to be discovered, often outside major observatories (e.g., Vaquero and Vazquez, 2009).

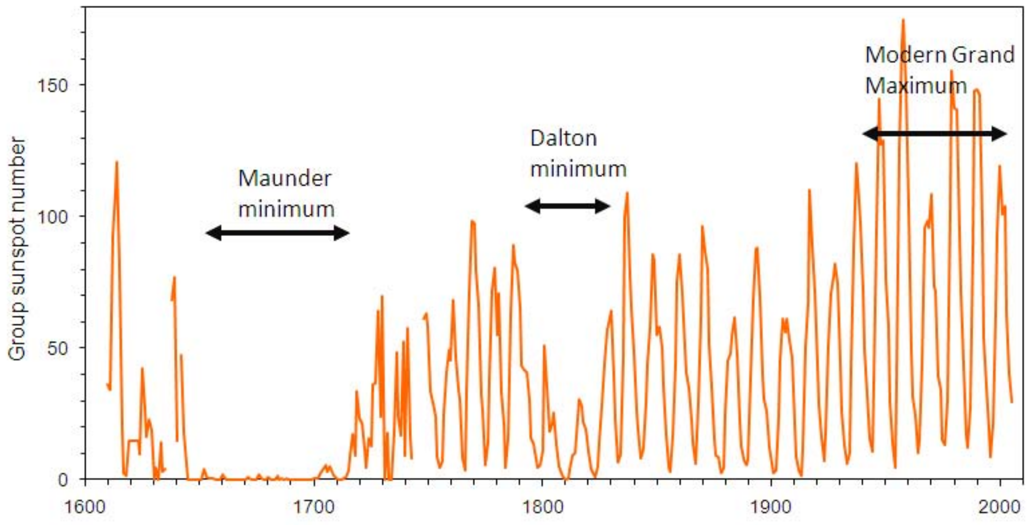

Figure 2. Monthly group sunspot numbers as an index of solar activity since 1610 AD (data available at ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS/). Maunder minimum, Dalton minimum and the Modern Grand maximum of solar activity are indicated.

Other indices of solar activity include (but not limited to):

- The flare index, representing solar flares, is available since 1936 (Özgüç et al., 2003);
- Radioflux of the Sun at the wavelength of 10.7 cm, also known as the F10.7 index, has been continuously measured since 1947 (e.g., Tapping and Charrois, 1994). This emission is produced as a result of the non-radiative heating of coronal plasma over active regions and its wavelength is close to that of the peak of solar radio emission.
- Coronal index (e.g., Rybanský et al., 2005) represents the irradiance of the Sun as a star in the coronal green line (Fe XIV emission line at 530.3 nm wavelength) measured since 1943;
- Sunspot area is often considered as a physical index of solar activity that gives the total area of spots visible on the solar surface in units of millionths of the Sun's hemisphere, corrected for apparent distortion due to the curvature of the solar surface. Sunspot areas are available since 1874.

All these indices are closely correlated to sunspot numbers on the solar-cycle scale, but may depict quite different behaviour on short or long timescales.

Although the Sun is relatively close to us and has been an object of intensive studies since long, we are still far from fully understanding the origin of its variability. Neither can we predict its activity. Many questions remain queuing for being answered by scientists – just to mention a few: Why are solar cycles so different from each other, in both magnitude and length? What causes the long-term activity variations, and in particular Grand minima and maxima? What are the secular changes in the solar irradiance and ensuing effect on climate?

Solar activity depicts a wide spectrum of variability, affecting Space weather and Space climate on different time scales.

2.1. Short-Term Scale (Munutes-Days)

On short time scale, typically minutes to days, the Sun displays a variety of non-stationary phenomena, caused by eruptive events accompanied by strong releases of energy. This includes spectacular flares, prominences, coronal mass ejections, etc. They may significantly disturb the Earth's environment in many different ways.

For example **solar flares** appear in solar active regions, characterized by emerging magnetic flux, leading to magnetic reconnection and energy release. Flares are often accompanied by **coronal mass ejections** (CME), but the relation is not one to one.

During solar flares, **solar energetic particles** (SEP - see Section 4.2) can be accelerated up to high energies in the GeV range. In addition, SEPs can be accelerated in the solar corona and interplanetary medium by a propagating shock wave driven by a CME. Such energetic particles can, when reaching the Earth, greatly affect physico-chemical properties of the Earth's atmosphere. On top of that, CME, including its leading shock and the ejecta (magnetized dense plasma bubble), may lead to a strong disturbance of the Earth's magnetosphere (Section 4.3), initiating energetic particle precipitation and geomagnetic storms. However, not every flare or CME can disturb the Earth. The geoeffectivity (viz. the ability to affect the Earth's environment) of a solar event depends on the mutual Sun-Earth attitude. For example, solar flares are most geoeffective when they occur near the West limb of the Sun, being close to the footpoints of interplanetary magnetic field lines approaching the Earth. On the other hand, the effect of a CME is maximal when it is launched from the central part of the solar disc and is, thus, targeting directly towards the Earth, though large-scale CMEs may hit the Earth by their flanks even if occurring near the solar limb.

Because of the strong effect of solar active phenomena on Space weather, it is important to know how often they occur, and how powerful they can be. Solar eruptive phenomena are related to the Schwabe 11-yr solar cycle, with the maximum occurrence rate around the solar maximum, and a low probability to occur near solar minimum. Around a solar maximum, moderate flares and CMEs may emerge several times a day in different regions on the Sun, while long uninterrupted periods of quiet Sun are typical for a solar minimum. However, strong solar flares can sometimes take place in the very late phase of solar cycle, just before the minimum phase, as, e.g., a burst of activity in mid-December 2006.

Our knowledge of the statistics of the occurrence rate of solar eruptive events is limited to the last few decades of direct scientific data-taking for the Sun. This is probably sufficient for small events, but we do not have a clear idea about how often extreme events may take place. For example, very strong solar events hit the Earth in January 2005, June 2000, October 1989, August 1972, leading to noticeable effects in Space weather. From indirect data we know of extreme solar flares occurred in 1942 and in 1859. The latter is the first scientifically observed optical (so called white flare) flare named after lord Carrington who reported its observation. These events are known to produce strong impact on Earth. For example, radio-emission of solar flares was discovered during the event of 1942 as it disturbed operation of air-defense radars. If such an event had occurred nowadays, consequences for the modern technological society would be serious (Townsend et al., 2003). Therefore, we want to know how often may we expect such or even stronger events to occur. Figure 3 displays an estimate of the probability of occurring of solar events depending on their strength, quantified via fluence (time-integrated flux) of SEP with energy above 10 MeV, as obtained by different methods. One can see that, while moderate events occur roughly every month, strong events happen, on average, once per solar cycle. Extreme events, similar to the Carrington flare in 1859, are expected to take place once in a century. And then probably there is saturation, as it is close to the limit strength of an event the Sun can produce.

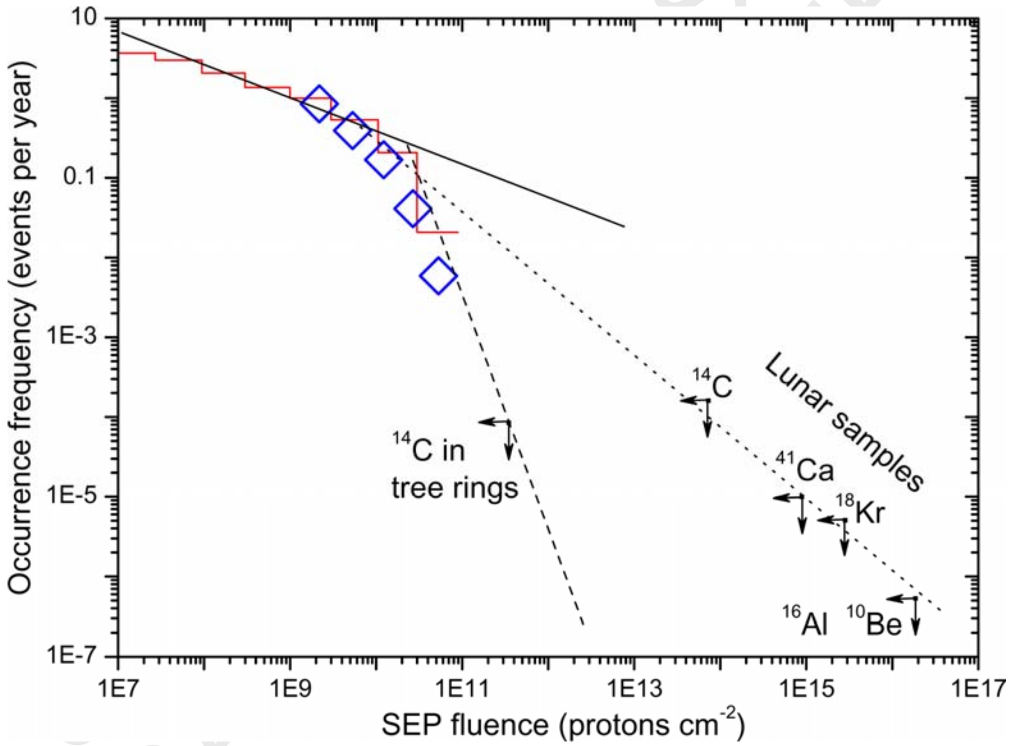

Figure 3. Cumulative probability rate (events per year on average) of occurrence of solar energetic particle events with fluences (>10 MeV) above the given value. Directly observed statistic is represented by the red histogram. Estimates based on different proxies include: nitrates measured in Greenland ice cores (blue diamonds) and radioactive nuclides in tree rings or in the lunar rocks. Adapted by permission from Macmillan Publishers Ltd: *Nature Physics* (Hundson, 2010), copyright 2011.

2.2. Mid-Term Scale (Weeks-Years)

The mid-term solar variability is dominated by the **Schwabe 11-yr solar cycle** (Figure 2). This cycle is a result of the action of solar dynamo in the solar convection zone.

Solar (stellar) dynamo is an interplay between poloidal and toroidal components of the solar magnetic field, which leads, in the solar conditions, to ~11-yr cyclic variations of the surface and coronal magnetic activity. However, the solar cycle is not perfectly regular (Hathaway, 2010). Individual cycles may vary quite a bit in both the length (from 7-8 years to 14 years) and the magnitude (from a dozen up to two hundred in the smoothed sunspot number - see Figure 2). There are some empirical relationships, linking different properties of solar cycles, e.g. the Waldmeier effect (strong solar cycles tend to have shorter rising time), or the Gnevyshev-Ohl rule (every odd-numbered cycle tends to be stronger than the preceding even-numbered cycle). However the robustness of such relationships and their physical origin (if any) are not well understood. Because of the complicated nature of the solar dynamo process and unknown drivers of its long-term variability, reliable predictions of the solar cycles are presently not available (Petrovay, 2010) except for relatively short-term probabilistic forecasts. However, with the advance of remote sensing studies of solar interiors (helioseismology – Christensen-Dalsgaard, 2002) and theoretical developments, we are approaching better understanding of the solar variability.

In fact, the full dynamo cycle takes two Schwabe cycles (the so-called Hale cycle of ~22 years) since the polarity of the solar magnetic field is reversed every Schwabe cycle. However, a 22-year cycle is not expected to be observed in the total (unsigned) solar activity since the dynamo process is essentially symmetric with respect to the changing polarity. A weak (if any) 22-yr variability marginally observed in some solar or geomagnetic indices is related to small north-south asymmetries in the solar-heliospheric properties.

In addition to the main 11-yr cycle, there are a number of other (often intermittent) weak quasi-periodicities (Hathaway 2010). These include, e.g., the 154-day quasi-periodicity in solar flare activity, 1.3-yr periodicity in many different indices (e.g., the solar rotation rate in the bottom of the convection zone, solar wind speed, sunspot areas, etc.), 1.68-yr quasi-periodicity in the heliospheric parameters and quasi-biennial oscillation in solar indices. The latter should not be mixed up with the same term QBO used for climatic mode variability.

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