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CLIMATE AND WEATHER OF THE SUN - EARTH SYSTEM

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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, and planetary atmospheres to 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 Earths atmosphere. The concept of Space weather was introduced in the 1990s 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 1950-1970s, 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.

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

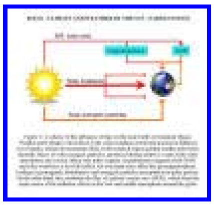

Figure 1: A scheme of the influence of Sun on the near-Earth environment (Space Weather and Climate). Most direct is the solar irradiance (total and spectral in different wave-bands), which has maximum effect in the tropical region getting smaller polewards. Sporadic fluxes of solar energetic particles, 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 gerions. 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

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 Zrich sunspot number (WSN) *R:*

$$R = k\,(10\,G + N)\,, \qquad (1)$$

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 Zurich 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).

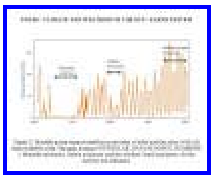

Figure 2: Monthly group sunspot numbers as an index of solar activity since 1610 AD (data available at ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA /SUNSPOT_NUMBERS/). Maunder minimum, Dalton minimum and the Modern Grand maximum of solar activity are indicated.

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

- The flare index, representing solar flares, is available since 1936 (zg 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., Rybansk ý 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

Suns 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 (Hours-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 examples 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 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 quite 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-defence 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 of 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.

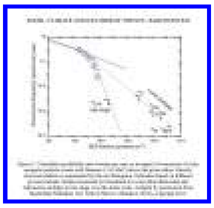

Figure 3. Cumulative probability rate (events per year on average) of occurrence of solar energetic particle events with fluences (>10 MeV) above the given value. Directly observed statistic is represented by the red histogram. Estimates based on different proxies include: nitrates measured in Greenland 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.

2.3. Long-Term Scale (Decades-Millennia)

The quasi-periodic Schwabe cycle, described in Section 2.2, is subject to longer-term (called centennial) modulation, whose nature is not well-understood. This is shown in Figure 2 as the average curve. One can observe that the overall level of solar activity (quantified in sunspot numbers) varies by more than an order of magnitude between the Maunder minimum and the contemporary period. In particular, the sunspot activity has doubled during the first half of the 20-th century. A special attention should be paid to the period of the Maunder minimum of activity (Eddy, 1976), when practically no spots appeared on the sun during ~70 years (1645-1715). It was indeed a period of low sunspot activity, not just lack of observations (Usoskin, 2008). That period corresponds to a special state of the solar dynamo with greatly suppressed activity, called a Grand minimum, although the Schwabe cycle was still in operation but at a very low level. The Maunder minimum is not unique, and several similar periods of suppressed activity have been identified in the recent Sun's history (see Figure 4), including Sprer (ca. 1500 AD), Wolf (ca. 1300 AD) and Oort (ca. 1040 AD) minima.

The recent activity, during the second half of the 20-th century, was very high and corresponds to a Grand maximum, which is the maximum rarely reachable state of the activity of solar dynamo (see Figure 4). Thus, the period of the last 400 years, covered by the sunspot number series, is characterized by the full span of solar activity variability - from a Grand minimum in the second half of 17-th century up to a Grand maximum in the second half of 20-th century.

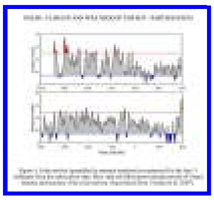

Figure 4. Solar activity (quantified in sunspot numbers) reconstructed for the last 11 millennia from the radiocarbon data. Blue- and red-filled areas indicate periods of Grand minima and maxima of the solar activity. Reproduced from Usoskin et al. (2007).

In order to study the solar variability and its consequences for the Earths environment one needs to use indirect proxy data, i.e., cosmogenic isotopes, which are produced in the atmosphere by cosmic rays, modulated by solar magnetic activity in the heliosphere. Upon production, the cosmogenic isotopes are stored, after terrestrial transport/deposition process, in independently dateable (by dendrochronology or glaciology) natural archives. Most useful here are ^{14}C (radiocarbon), recorded in tree rings around the globe (Stuiver & Braziunas, 1989) and ^{10}Be, recorded in polar ice cores (Beer et al., 1990). By means of studying their concentration in such archives and knowing independently geomagnetic field changes in the past, one can evaluate the cosmic ray flux and then, applying reasonable assumptions, solar activity in the past (Solanki et al., 2004). Such reconstructions cover the last 11 millennia of the Holocene period with its relatively stable climate. Unfortunately, the reconstructions of solar activity presently cannot be extended further back in time, to the last glacial period, because unknown changes in the Earth's climate and large scale ocean/atmosphere circulation patterns (and thus in the cosmogenic isotope transport/deposition) may greatly disturb the reconstruction.

Figure 4 displays a long-term reconstruction of solar activity for the Holocene. One can see that the solar activity is subject to great variability within the normal regime (grey-filled areas) sometimes intervened by fast transitions to Grand minima (blue-filled areas) or Grand maxima (red-filled areas). According to this statistics, the Sun spends about 3/4 of its time in the normal mode of solar dynamo operation and 1/6 (1/10) of time in special states of Grand minima (maxima). The recent solar activity (1940-2009) corresponds to a special state of Grand maximum.

3. Solar Irradiance

The total flux of solar electromagnetic energy received at the top of the Earths atmosphere is called the total solar irradiance (i.e. integrated over the entire spectrum), TSI, or the solar constant. Since the distance between the Earth and the Sun varies over a year and also on longer time scales as Earths orbital parameters change (see Sect. 3.3), solar irradiance is formally defined as the solar flux at distance of one astronomical unit (AU), which is the mean distance between the Sun to the Earth. Solar electromagnetic energy is emitted over essentially the entire spectrum. Almost half of this energy originates in the range visible to the human eye (roughly 400 to 800 nm wavelength range), more than 40% come from the infrared, IR, range (wavelengths above 800 nm), and only less than 10% are contributed by the ultraviolet, UV, radiation (wavelengths below 400 nm).

3.1 Measurements of Solar Irradiance

Direct regular measurements of the solar irradiance from space started in 1978 and thus cover more than three decades. About a dozen of different radiometers placed on various spacecraft monitored TSI over this period. The radiometric accuracy of these measurements is of the order of 0.1 − 0.2%, or even 0.035% in case of TIM on SORCE. The long-term stability is also high enough to trace the 11-year solar cycle changes of the TSI of only about 0.1% (see Fig. 5), although some differences in the trends measured by different instruments are also evident. Figure 5 also shows that there are significant differences in the absolute levels of the TSI measured by different radiometers. Prior to the launch of TIM on SORCE in 2003, the values for the TSI during activity minima converged towards the value of 1365.41.3 W/m^{-2}. Measurements by TIM on SORCE suggest a lower value of 1360.80.5 W/m^{-2} (Kopp & Lean, 2011). The higher value hinted by the older radiometers is probably due to uncorrected scattering and diffraction.

In contrast to the absolute calibration of the radiometers, the relative changes in the TSI measured by different instruments agree well with each other. In particular, it is obvious that solar irradiance is not constant. Most evident is the variation in phase with the solar cycle with an amplitude of roughly 0.1% and the short-term fluctuations reaching up to about 0.3%. There could also be a longer-term (secular change) in the irradiance, but it is difficult to assess based on the available data.

Construction of a homogeneous composite TSI time series is not a trivial task. Fortunately, operations of different radiometers partly overlap in time. Still, because of individual problems and sensitivity changes of each instrument, it is not always possible to evaluate corrections to individual data sets in an unambiguous way, especially if only two instruments were in simultaneous operation. Examples of such uncertainties are the early period of TSI monitoring, when only the Nimbus-7/HF instrument was at work, the so-called ACRIM-gap between the operations of SMM/ACRIM I and UARS/ACRIM II instruments in 1989-1992; and a correction to the early sensitivity change of the two VIRGO radiometers, DIARAD and PMO6V. As a result, three different composite TSI records currently exist, called the PMOD (Frhlich, 2006), ACRIM (Willson & Mordvinov, 2003) and IRMB (also RMIB; Dewitte et al., 2004) composites, shown in panels b), c) and d) of Fig. 5, respectively. Each of these has its own absolute scale (although the differences between the composites are much smaller than their difference to the SORCE/TIM absolute level), uses a distinct combination of data from different instruments, which are also adjusted to each other in somewhat different ways.

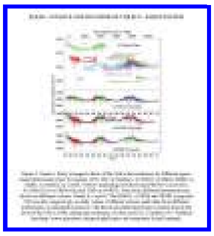

Figure 5: Panel a: Daily averaged values of the total solar irradiance by different space-based radiometers since November 1978: HF on Nimbus7, ACRIM I on SMM, ERBE on ERBS, ACRIM II on UARS, VIRGO (including DIARAD and PMO6V) on SOHO, ACRIM III on ACRIM-Sat, and TIM on SORCE. Data from different instruments are shown in different colours. Panels b, c and d: The PMOD, ACRIM and IRMB composite TSI records, respectively, as daily values. Different colours mark data from different instruments, as indicated in panel a. The thin horizontal black lines in panels denote the level of the TSI in 1986, during the minimum of solar cycle 22. Courtesy of C. Frhlich (see http://www.pmodwrc.ch/pmod.php?topic=tsi /composite/ SolarConstant).

The three composites show considerable differences in the TSI level during consequent solar minima, i.e. in the secular change. Most of the differences come from the uncertainty in the cross-calibration of the ACRIM I and ACRIM II data. A model that reconstructs TSI from the observed distribution of dark (sunspots) and bright (faculae and the network) features on the solar surface agrees significantly better with the PMOD trend as compared to the other two composites (Krivova et al. 2009). This suggests that, overall, the TSI has slightly decreased over the last three activity minima, although the value of the decrease lies within the measurement uncertainty.

Solar irradiance has also been measured in some specific spectral ranges. Irradiance variability in the ultraviolet range, UV, between approximately 115 and 420 nm wavelengths, was monitored by two instruments, SUSIM and SOLSTICE, onboard UARS satellite launched in 1991. These observations showed that changes of the solar irradiance are strongly wavelength-dependent, with the amplitude of variations increasing rapidly towards shorter wavelengths (see Fig. 6). The variability in the vicinity of Lyman-α, the strongest line in the solar spectrum at 121.6 nm, reaches up to 100%.

Regular irradiance observations in the visible and infrared IR ranges started in 2002/2003 with the launch of ENVISAT/SCHIMACHY and SORCE/SIM instruments, respectively. The IR irradiance (1000 - 2500 nm wavelength range) shows a weak variation of the order of 0.1% in anti-phase with the solar activity cycle (Harder et al. 2009). This is because of the low or even negative contrast of faculae (i.e. faculae do not appear bright compared to the surrounding solar surface; see Sect. 3.2) at these wavelengths and is in agreement with model predictions (Krivova et al. 2011).

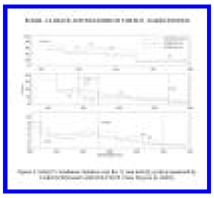

Figure 6: Solar UV irradiance variation over the 11 year activity cycle as measured by UARS/SUSIM and UARS/SOLSTICE. From Floyd et al. (2003).

3.2 Mechanisms and Reconstructions of Solar Irradiance Variation

Solar irradiance varies also on time scales shorter than a day. Solar *p*-mode oscillations (Christensen-Dalsgaard, 2002) excited by the turbulent motions in the solar convection zone have periods of around 5 minutes and are responsible for the irradiance variation on this time scale.

Other measured fluctuations in solar irradiance are attributed to the effect of various bright and dark structures on the solar surface. Figures 7 and 8 show a full-disc solar image and a small part of the solar surface with higher spatial resolution, respectively. One can see that the solar surface is not homogeneous but exhibits brightness fluctuations on various spatial scales. The smallest well distinguishable structures (Fig. 8), which make the surface appearing grainy, are called granules. They have the average size of roughly 1000 km, live on average for 5 to 10 minutes and are responsible for irradiance variation on time scales of minutes to hours. Because of the short time scales involved, irradiance fluctuations caused by solar granulation and p-mode oscillations are not important for the Sun-Earth connection.

Irradiance changes on time scales longer than approximately a day are caused by changes in the distribution of the solar surface magnetic field. The magnetic flux emergent on the solar surface forms sunspots, faculae and the network. With temperatures of 4500-5000 K, sunspots are cooler than the surrounding photosphere (5700 K) and appear dark (Figs. 7 and 8). The bright structures are the faculae and the network. Faculae are found in active regions and are mainly seen near the limb of the Sun. Weaker brightenings are observed in the quiet Sun conditions and form the network. By identifying different components on the solar surface in full-disc solar images and quantifying their contributions to changes in the solar brightness, modern models are able to reproduce the measured changes in solar irradiance in great detail (e.g., Domingo et al. 2009, Krivova et al. 2011).

Figure 7: Continuum image of the Sun taken by the SoHO/MDI instrument on 30 March 2001. Courtesy of SoHO/MDI consortium. SOHO is a project of international cooperation between ESA and NASA (http://sohowww.nascom.nasa.gov/gallery/bestofsoho.html).

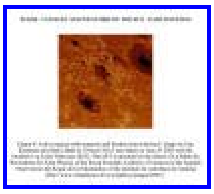

Figure 8: Active regions with sunspots and faculae near solar limb. Image by Dan Kiselman and Mats Lfdahl in G-band (430.5 nm) taken on June 29 2003 with the Swedish 1-m Solar Telescope (SST). The SST is operated on the island of La Palma by the Institute for Solar Physics of the Royal Swedish Academy of Sciences in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofsica de Canarias (http://www.solarphysics.kva.se/gallery/images/2003/).

Full disc solar images with sufficient cadence and quality are only available for less than four decades, whereas reliable estimates of solar influence on Earths climate require much longer time series. Most irradiance reconstructions over the last few centuries employ sunspot numbers. This is the only direct proxy of solar magnetic activity going back to 1610, when Galileo started his telescope observations of the Sun. Records of concentrations of cosmogenic isotopes in natural terrestrial archives allow reconstructions of solar activity (Sect.2.3) and hence brightness over longer periods, up to the whole duration of the Holocene (e.g., Vieira et al., 2011).

3.3. Earth Orbital Variability (Milanković Cycles)

The Earth's orbit around the Sun is not perfectly planar and circular - it experiences some slow changes in precession, obliquity and eccentricity with periods ranging from 20,000 to 100,000 years. Although having nothing to do with the solar activity per se, it modulates (as first noticed by Milutin Milankovi ć in the first half of 20-th century) the amount of solar radiation received by Earth, and thus affects the climate. This Milankovi ć cycle is fully understood and can be predicted well ahead. Its influence on climate, including the ocean dynamics, is straightforward and is considered to be a major cause for ice ages and intergalciations (Hays et al., 1976).

4. Energetic Particle Environment

Energetic particles are always present in the vicinity of Earth and play an important role in the Space weather and Space climate effects (Vainio et al., 2009). The most important effects of energetic particles are related to the chemical and physical changes of the atmosphere via ionization of the air, technological effects related to the malfunctioning/degradation of electronics due to radiation damage, or to distorted radiowave propagation, and biological effects particularly at space mission and aircraft cruising altitude. The radiation environment is very dynamic, varying by many orders of magnitude at time scales from seconds to decades. Three main sources of energetic particles in near-Earth space are considered below: Galactic cosmic rays, Solar energetic particles and Precipitating particles of magnetospheric origin. They are all different in the origin, characteristics and the caused effects.

4.1. Galactic Cosmic Rays

Galactic Cosmic Rays (GCRs) are very energetic particles (energy from 10^5 up to 10^{20} eV, or from 10^{-14} to 20 Joules per particle), consisting mostly of protons and about 10% (in particle number) of α-particles and <1% heavier species. GCRs are produced mostly in our Galaxy by shocks around numerous supernova remnants, but most energetic cosmic rays may be born in more exotic extra-galactic sources. After production they diffuse in the galaxy for millions of years, that makes their flux in the local interstellar medium fairly homogeneous. However inside the heliosphere, GCRs become affected by the solar wind and frozen-in heliospheric magnetic field, leading to the solar modulation of GCR flux near Earth. The modulation of GCRs is largely defined by the 11-year solar cycle in inverse relation with the overall solar activity. On shorter time scales the GCR flux responds to interplanetary transients, such as interplanetary shocks driven by coronal mass ejections, magnetic clouds or fast solar wind streams. These transient events lead to suppressions of the GCR flux near Earth for hours-days. On longer time scales (centennia to millennia), solar activity and slow changes of the geomagnetic field drive the GCR variability.

GCRs are always present in the Earths environment and, thanks to their high energy, may affect the entire atmosphere and even underground. In particular, GCR forms the primary source of the atmospheres ionization in the troposphere and stratosphere. GCRs are routinely measured, via the nucleonic component of the cosmic-ray induced cascade in the atmosphere, by ground-based neutron monitors since 1950s. Direct in-situ space-borne measurements of cosmic rays for the last decade were limited to lower energies, below 500 MeV, but for the last few years full energy range instruments are orbiting the Earth, such as PAMELA or AMS.

4.2. Solar Energetic Particles

CLIMATE AND WEATHER OF THE SUN - EARTH SYSTEM

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4.2. Solar Energetic Particles

During eruptive processes originated at the Sun, such as strong solar flares and Coronal Mass Ejections (CME), acceleration of charged particles up to high energy (MeV to GeV for protons) may occasionally take place. These particles, observed near Earth, are called Solar Energetic Particles (SEPs). While SEPs are not present during quiet Sun periods, their flux during a SEP event can exceed the GCR background by many orders of magnitude during several hours up to a week. According to their characteristics and origin, SEP events can be roughly grouped into two main classes, impulsive and gradual. Impulsive event, often related to impulsive solar flares, are fast (lasting for hours-days) and characterized by enrichment in electrons, ^3He and heavy ions. On the contrary, gradual events have typical abundances and charge states of the solar corona and may last from a few days to a week. They are typically related to CMEs. Because of their larger proton fluences and longer duration, gradual SEP events are usually more important for the Space weather. SEP events occur more often and stronger around solar activity maximum and in the declining phase of the solar cycle. Therefore, in contrast to GCR, SEPs exhibit the variability that co-varies with the solar activity. Thus, the terrestrial effects of these two sources of energetic particles are competing SEP flux tends to be higher when GCR is lower and vice-versa. Energy spectrum of SEP is much softer than that of GCR, with the maximum intensity being below several tens of MeV. Accordingly, terrestrial effects of SEPs are most important in the polar region, where the shielding by the geomagnetic field is not present. Because of the relatively low energy of SEP, the effect is limited to the upper and middle atmosphere.

4.3. Energetic Particles of Magnetospheric Origin

In addition to extra-terrestrial sources (GCR and SEP) there are energetic particles with near-Earth origin. These include particles, mainly electrons and protons, (quasi)trapped by the geomagnetic field in the so-called radiation belts. These particles are accelerated in the Earths magnetosphere, or can be a population of SEP trapped in the closed magnetic field configuration during enhanced geomagnetic activity or produced locally as a result of decay of secondary neutrons produced by high-energy cosmic rays in the Earths atmosphere, that decay into protons and electrons which may become trapped inside the geomagnetic field. Protons trapped in the radiation belt can be quite energetic (up to hundred MeV), i.e. comparable with SEP and form a hazard for low orbiting satellites. A specific region is located in the South Atlantic Anomaly where the geomagnetic field is weaker leading to precipitation of these particles into the upper atmosphere. These radiation belt particles can precipitate into the atmosphere during geomagnetic disturbances leading to the effects similar to those caused by SEP. The proton density in the radiation belts is inversely related to the solar activity cycle.

In addition to the relatively energetic particles trapped in the radiation belts, there is another, less energetic, population of precipitating particles of magnetospheric origin particles accelerated in the magnetospheric tail during geomagnetic disturbances. These particles after acceleration follow the configuration of the geomagnetic field lines and precipitate in the auroral oval leading to the effects in the upper atmosphere, including spectacular aurorae.

4.4. Solar Wind and Magnetospheric Disturbances

An important source of changing the Earth's environment is related to the magnetospheric disturbances, caused by interaction between the Earth's magnetosphere and interplanetary medium, which includes solar wind and heliospheric magnetic field "frozen" into it. The magnetosphere (spatial region controlled by the geomagnetic field) has a bullet shape with the nose always headed sunwards and the prolonged tail in the opposite direction. This shape is caused by dynamical flowing of the solar wind around the magnetosphere. In normal conditions, the heliospheric magnetic field has only radial and tangential components, without latitudinal one (i.e., B_Z=0). However, during interplanetary transient events, originated from the solar surface and coronal activity, B_Z may be essential nonzero. If B_Z becomes negative, i.e., magnetic lines of the heliospheric magnetic field are directed towards the geographical south, it can interact with the geomagnetic field whose magnetic lines are directed northwards. This can lead to reconnection of the oppositely directed magnetic lines and further to distortion of the magnetosphere. Another source of magnetospheric disturbances is related to faster and/or denser than usual solar wind streams or interplanetary shocks, which compress the magnetosphere, leading to shrinking of the magnetospheric tail and to magnetic reconnections there.

Magnetic reconnection leads to particle acceleration and changes in the radiation environment. On the other hand, magnetospheric disturbances can produce essential currents in the terrestrial environment and distort magnetic field. Radiation environment and currents can pose a danger for satellite hardware, including induced charging and radiation aging of electronics, malfunctioning of onboard computers, etc. In addition, enhanced fluxes of x-ray, UV and precipitating particles may lead to heating and expansion of the upper atmosphere decelerating and lowering low-orbiting satellites. Disturbed ionosphere may affect radio-wave propagation and reflection and thus disrupt space-based communication and navigation systems. Varying geomagnetic field can induce dangerous spurious currents in the long-ranged ground systems such as electrical grids or pipe-lines. The most famous examples are the electrical blackout in the Quebec province of Canada induced by a strong geomagnetic storm in March 1989 or disruption of the telegraph connection during the storm in 1859.

The pace and severity of geomagnetic storms also vary within the 11-year solar cycle. Usually there are two peaks of geomagnetic activity caused by different mechanisms. The first one near the maximum of solar activity is caused by high rate of solar eruptive phenomena, in particular solar flares and CMEs. Another peak usually happens in the declining phase of solar activity, when the rate of CME occurrence decreased but large solar coronal holes migrate to the solar equator. Such coronal holes are the main source of fast solar wind, which also causes geomagnetic disturbances, often in quite regular recurrent manner.

5. Sun-Earth Relations and Implications For The Earth Climate

The question on whether the Earths climate is a closed system or can be affected by extra-terrestrial factors is very important, especially in relation to the separation of natural and anthropogenic factors. It is particularly related to the possible solar influence on climate (see, e.g., a review by Gray et al., 2010). A possible influence of Sun on the climate was proposed more than 200 years ago by Sir W. Herschel and has since then been intensively studied. Since the Sun provides, in the form of electromagnetic radiation, the main source of energy for Earth, any changes of the total solar irradiance would directly affect the Earths climate. However, the estimated variations of TSI are too low to explain the recently observed climate trends (Solomon et al. 2007). The level of scientific understanding of this influence is low and does not include indirect effects (Table 1). On the other hand, in addition to direct mechanisms of solar influence on climate via the changing flux of incoming radiation, indirect mechanisms (discussed below) may be essential. For example, if the Earth was a black body (absorbed solar radiation = emitted infrared radiation), its mean temperature would be ~255 K, while the actual present day temperature is about 33 K higher. This excess is due to non-black body effects and leaves a possibility for indirect mechanisms to affect climate without invoking notable changes in the solar irradiance.

Table 1. Radiative forcings (W/m^2) from different external sources discussed here along with the net anthropogenic forcing for the last centuries (from Solomon et al. 2007).

5.1. Does Solar Variability Affect The Climate (Empirical Evidence)?

Although a direct unequivocal compelling evidence of notable influence of the Space climate on Earth climate is not available, there are numerous indirect arguments suggesting that such a relation does take place, particularly on the long-term scale in the pre-industrial epoch. One of the most famous examples is related to the cold period known as the Little Ice Age in the European weather (its global nature is still debated) associated with Sprer and Maunder grand minima of solar activity (Eddy, 1976).

Below we consider, in some detail, different time scales.

5.1.1. Solar Cycle Time Scale

Since solar activity is dominated by the 11-year solar cycle, the primary effect to look for in the solar-climate relations is related to this time scale. Many relationships with solar activity have been claimed including near surface temperature, precipitation, cloud cover, wind patterns, ozone concentration, and even global climate modes, as based on statistical studies. While solar signal is well documented in the stratosphere (e.g., temperature or zonal wind patterns), where the solar influence is most direct, its tropospheric counterpart is much less clear. Moreover, because of the system's complexity, the results are not straightforward to interpret. For instance, some solar-climate relations can be influenced by the climate internal variability modes, such as quasi-biennial oscillations QBO (Labitzke and van Loon, 1988). Moreover, since some modes of the climate variability have time scales close to the solar cycle, it is difficult to disentangle a solar signal in climatic parameters from intrinsic climate variability.

5.1.2. Long-term Scale

Even though solar influence on climate may be masked by other factors on the inter-annual scale, it can become dominant on longer terms, in particular during the pre-industrial epoch, when anthropogenic effects were small. This seems difficult as reliable records of meteorological observations are limited both temporarily and spatially. Fortunately, there are numerous "proxy" records, stored in natural archives and measured nowadays, that represent different aspects of the local or global climate parameters in the past. These are, e.g., ice cores, marine or lake sediments, tree rings, corals, speleothems, etc. Although such proxies provide only indirect information leaving room for some uncertainties, they can tell us about climate variability in the past on different time scales.

Many pieces of evidence have been found on the relation between regional or global climate changes and solar activity. These include striking correlation between $\delta^{18}O$ in cave stalagmites (Neff et al., 2001), ice-rafted debris in Northern Atlantic (Bond et al., 2001), glacier advances (Wiles et al., 2004), ocean circulation (Oppo et al., 2003), cold/wet climate shifts (Versteegh, 2005) on one hand, and solar activity, on the other hand. Although the proof power of each individual example can be disputed, in the aggregate they support the idea that solar forcing is an important player in the long-term climate changes. However, it is apparently not the only player in the field of climate change and cannot be responsible for the entire climate variability.

On the other hand, climate variations may have a strong regional pattern (cooling/precipitation in one region may be accompanied by warming/draught in another), leading sometimes to seemingly contradictory proxy records. Because of the limited set of proxy data, many details of the global picture still remain unclear.

5.1.3. Short-term Scale (Instant Effects)

There are numerous attempts to observe direct response of the Earths climate to solar influence on the short-term scale (days-weeks). This is related to the Space Weather events, such as sudden enhancements (GLE) or suppressions (Forbush decreases) of galactic cosmic rays, SEP events (see Chapter 4.2), geomagnetic storms, etc. While stratospheric responses related, e.g., to ozone, are unambiguously identified, tropospheric effects are not clearly resolved.

5.2. Possible Mechanisms

Despite many empirical studies of solar influence upon climate, that cannot provide a causal mechanism, a theoretical approach is still under development with some mechanisms better elaborated and others being yet generic. Physically, mechanisms potentially transferring and amplifying the solar signal in the geosphere can be roughly divided into those related to variations in solar irradiance (total or spectral - see Chapter 3) and those related to energetic particles (cosmic rays and energetic precipitating particles - see Chapter 4).

5.2.1. Solar Irradiance

The impact of solar irradiance (or any other factor) on Earths surface temperature and climate is often described in terms of its radiative forcing (Solomon et al. 2007), which quantifies the way the energy balance of the Earth-atmosphere system is influenced when factors that affect climate are altered. In equilibrium, the global average temperature of the Earth is determined by a balance between the incoming solar energy absorbed in the atmosphere and by the surface on one hand, and the energy of the thermal infrared radiation emitted back into space on the other hand. Thus, in equilibrium, the net radiative flux at the top of the atmosphere is zero (globally and annually averaged). If the amount of the absorbed solar or emitted infrared radiation changes (e.g., through changes in solar irradiance, Earths reflective properties or atmosphere composition) then, before a new equilibrium is established, the net flux at the top of the atmosphere is not zero. Radiative forcing is defined as the instantaneous change in the value of the net downward radiative flux. Positive radiative flux means an increase in the amount of energy retained by the Earth-atmosphere system. This could be due to an increase in the incoming or a decrease in the outcoming energy and leads to an increase in the Earths temperature.

In addition to direct heating by TSI, changes in spectral irradiance may lead to indirect amplification effects (see Chapter 5.2.4). Changes in the total solar irradiance affect Earths climate and temperatures directly. Changes in the spectral distribution of the irradiance (see Fig. 6) heat the upper and middle atmosphere and affect the composition and chemical processes in the middle and lower atmosphere. The latter leads to changes in the composition and temperature structure of the atmosphere and thus in the amount of the infrared radiation emitted into space. Therefore the relationship between changes in the solar irradiance and Earths temperature is complex and non-linear and is not yet fully understood.

An important role is played by the ocean which directly absorbs solar radiation. Because of its large heat capacity and slow mixture between deeper layers, this leads to the long-term (centennial) integration of effects.

5.2.2. Energetic Particles and Ozone

Energetic precipitation particles include SEPs (see Chapter 4.2) and less energetic magnetospheric particles (Chapter 4.3). They can penetrate atmosphere in (sub)polar regions down to the mesosphere or upper stratosphere, where they cause ionization, dissociation, and production of important chemicals such as odd hydrogen and odd nitrogen and, finally, ozone (Jackman et al., 2008). In addition, stratospheric ozone is affected by the solar UV irradiance. Changes in the ozone concentration affect the radiative balance in the stratosphere and, indirectly, air mass circulation pattern. It can potentially affect climate via indirect mechanisms (Chapter 5.2.4) but the full details of the tropospheric influence of this process are still missing.

5.2.3. Cosmic Rays and Clouds

Cosmic rays form the main source of ionization in the low and middle atmosphere. Although the level of ionization is very low (the lower atmosphere is essentially neutral), it may lead to some physical-chemical consequences. As proposed by Ney (1959), cosmic rays induced ionization may directly affect cloud formation via the ion-induced/mediated nucleation leading to facilitated formation of cloud condensation nuclei (Svensmark 1998). However, as suggested by both theoretical models (Pierce and Adams, 2009) and dedicated laboratory experiments (Kirkby et al. 2011; Enghof et al., 2011), this direct effect is not sufficiently strong.

Another potential mechanism affecting cloud cover is via the global Earths electric current circuit, which can be modulated by cosmic rays and geomagnetic activity. Vertical current may lead to charge separation near the edges of existing clouds and affect their microphysical parameters (see details in, e.g., Tinsley, 2008). However, a full model describing this process is missing along with a realistic estimate of the size of the effect.

5.2.4. Indirect Effects

In addition to various direct effects described above, several indirect feed-back mechanisms have been proposed that can amplify the solar variability signal in climate. Those include the possible solar influence on large scale circulation patterns, such as Hadley cells (meridianal circulation) or Walker (longitudinal tropical) circulation. Also discussed is a potential solar effect on natural climate variability modes, such as quasi-biennial oscillations (QBO) or annular modes.

Amplifying mechanisms can be roughly divided into "top-down" (propagation of the stratospheric solar response downwards to the troposphere) and "bottom-up" (dynamic coupling of the directly heated ocean with air circulation) groups. Both mechanisms include dynamic coupling inside the climate system and may be missing in a static climate model (see an extensive review in Gray et al., 2010).

5.3. Anthropogenic Influence

Assessment of the anthropogenic effect in climate change is a very difficult task, complicated by concurrent natural factors (solar, volcanic, aerosol) operating on the same time scale. Since a clear direct separation of the man-made changes is hardly possible in such conditions, the role of anthropogenic factors is evaluated on the basis of extensive and sophisticated modelling. Because of the essential chaotic component of the climate system, any such assessments are possible in the statistical or probabilistic sense, as based on an ensemble of model simulation runs. Such an assessment is a major task of the Intergovernmental Panel of Climate Change (IPCC). According to detailed model simulations (Solomon et al. 2007) the major part of the climate change (warming) in the first half of the 20-th century was caused by natural (solar and volcanoes) forcing. However, anthropogenic factors became a major player since the last quarter of the 20-th century, mostly related to enhanced emission of greenhouse gases but also man-made aerosol loading and ozone destruction.

6. Conclusion

The Weather and Climate of the Sun Earth system is dynamically variable on different time scales, from minutes to millennia, as discussed in Chapter 2. While the 11-year Schwabe cycle dominates the variability during the last decades of direct observations, there exists an essential longer term (centennial) variability which is crucially important for the terrestrial effects. Most important for the geosphere (see Figure 1) are variations of the solar electromagnetic radiation (Chapter 3), corpuscular radiation (Chapter 3) and changes in the interplanetary magnetic field and solar wind. Influence of these factors upon the Earths climate is discussed in Chapter 5. While direct influence via the total solar irradiance is estimated to be relatively small, an indirect mechanism of the influence may be important. Although there are numerous pieces of evidence that it plays a role, many details, including exact physical mechanisms and corresponding quantitative models, are yet unresolved.

Related Chapters

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Glossary

Astronomical Unit (AU)	**:** 49597870.7 km - the mean distance from the Sun to the Earth.
Coronal Mass Ejection (CME)	**:** Explosive supersonic ejection of solar coronal plasma into the interplanetary space. CME often drives an interplanetary shock and, if hitting the Earth, may cause geomagnetic disturbances.
Cosmogenic isotopes (nuclidess)	**:** Rare isotopes (radioactive or stable) whose main source in the terrestrial system is in situ production by high energy cosmic rays. By measuring the concentration of cosmogenic isotopes in natural archives, it is possible to obtain information on cosmic ray variability in the past. Most useful (within the scope covered by this article) cosmogenic isotopes are ^{14}C (radiocarbon), used also for dating of archeological samples, and ^{10}Be.
Facula	**:** Brightening on the solar surface, mainly visible near the limb, often found in the vicinity of sunspots.
Heliosphere	**:** The region, of about 200 AU across, around the Sun which is controlled by the solar wind and magnetic field, bounded by the termination shock and heliosheath as an interface between the heliosphere and interstellar medium.
Holocene	**:** The present interglacial period of fairly stable warm climate started about 11-12 millennia ago, after the last ice age and deglaciation.
Magnetosphere	**:** A bullet-shaped region (15-25 Earth radii across and hundred Earth radii along) around the Earth formed by dynamical interaction between the Earths magnetic field, solar wind and interplanetary magnetic field.
Schwabe cycle	**:** A dominant quasi-periodic cyclic variability in various aspects of solar activity. Its mean period is about 11 years but the individual cycle length varies from 8 to 15 years. The Schwabe cycle is caused by the solar dynamo mechanism operating in the convection zone of the Sun.
Radiative forcing	**:** Radiative forcing is a measure of how the energy balance of the Earth-atmosphere system is influenced when factors that affect climate are altered. It is the rate of energy change per unit area of the globe as measured at the top of the atmosphere.
Solar activity	**:** A variety of nonstationary, nonequilibrium (often eruptive) processes on the Sun and in the solar corona is broadly regarded as solar activity. It includes solar-surface magnetic variability, eruptive phenomena, coronal activity, radiation of the sun as a star or even interplanetary transients and geomagnetic disturbances.
Solar Energetic Particles (SEP)	**:** Particles (mostly protons) with energy from 10^4 to 10^8 eV originated from the solar corona or the interplanetary space. They are sporadic and exist during eruptive solar phenomena. Because of the geomagnetic shielding, they

can impinge the atmosphere only in the (sub)polar regions.

Solar flare : Explosive energy release on the Sun, observed as sudden local brightening. SF may lead to enhanced emission of hard and soft radiation as well as particle fluxes. It can be accompanied by a CME.

Solar spectral irradiance : Solar irradiance at a particular wavelength or in a given spectral interval. Solar spectral irradiance integrated over all wavelengths gives Total Solar Irradiance (TSI).

Space weather : 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.

Space climate : An interdisciplinary concept combining 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.

Sunspot : Dark area on the solar disc (size up to 10^5 km, lifetime weeks-months), characterized by a strong magnetic field, which leads to a lower temperature and observed darkening.

Total Solar Irradiance (TSI) : Total solar electromagnetic energy flux at a distance of one Astronomical Unit (AU).

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1. Introduction: Space Weather and Space Climate