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The role of the Sun on the Earth's environment,
Some main open questions

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Studies of the Sun-Earth relationships during the past years have dramatically changed our view on Solar Terrestrial Physics. Neither is the interplanetary medium unstructured or quasi-static, nor is it a simple magnetic stratified object. Thus, the interaction of the solar electromagnetic radiation (photons), hot plasma (electrons, protons and other ions), cosmic rays, microscopic dust particles, and magnetic fields (primarily from the Sun) with the upper environment of our Earth leads to a complex physics which is far to be understandable. This new science is in full effervescence as well as for the physical problems which arise as for its growing impact on our societies. This last case is well illustrated by the emergence of the so-called Space Weather. In spite of a great number of papers and books written on this subject and on a broader one devoted to Solar-Terrestrial links, the different terms deserve to be clarified. In this lecture we will first establish a clear distinction between Space Weather, Space Climate, Space Physics, Sun-Earth connections, and Helioclimatology, this last word being introduced by the author to describe the role of the Sun in the Earth's climate forcing. In a second step, we will emphasize the key role of the ranging time on which the effects may act. We will then underline the necessity to better predict solar activity showing the physical difficulties for such an exercise, yielding the extreme complexity for forecasting specific events of high energy. We will conclude by giving some imprints for the future.

INTRODUCTION.

If it was obvious, since the highest Antiquity up to around the middle of the 70's, that the Sun was the primary source for driving the Earth's climate system, it was not so evident since then. Two major arguments were developed to thwart the assertion that the Sun's output variability may play a key role. The first one concerns the anthropogenic effects and is today widely debated. The second is linked with the so-called total solar irradiance (TSI). Let us try to clarify this last point, the most objectively as possible, as new results are appearing.

The Earth receives at the top of the atmosphere a solar energy that was recognized as constant, and fixed at about 1366 W/m^2 up to the satellites era. Radiometers on board dedicated satellites record a fluctuation of ± 1.3 W/m^2 during a solar cycle, a value considered as too low to significantly affect the climate of the Earth. Furthermore it was claimed that such a "solar constant" is unable to perturb the Earth's atmosphere differently at equatorial, tropical or polar latitudes, whereas it is well-known that the climate varies with all the latitudes. The last argument is that, even by admitting a modulation of the climatic signal on the stratosphere, one cannot understand how such changes can be reverberated on the lower layers, seat of our climate.

Recent works has significantly improved our knowledge on the TSI, mainly on the UV part of the spectrum (Fig. 1, left). The most remarkable issue concerns its variability, reaching a factor 2 peak-to-peak, that was addressed to cause a significant impact on the stratosphere. This finding was followed by a profusion of new studies, which are just beginning to appear (see for instance the proceedings of the 2005 Rome's conference). This may reinforce what Hansen wrote in 2000: "*Even if the solar forcing has been*

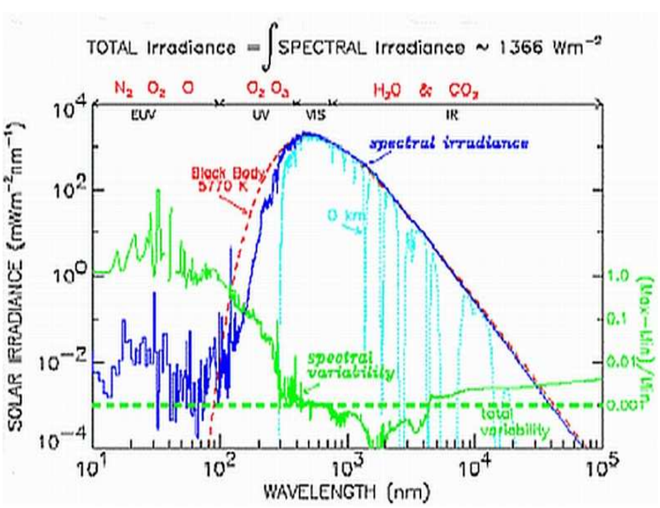

Fig. 1. Left. Wavelength dependence of the solar irradiance. The UV part of the spectrum clearly show a strong variability, ranging a factor of 2 (After, P. Brekke, 2005).

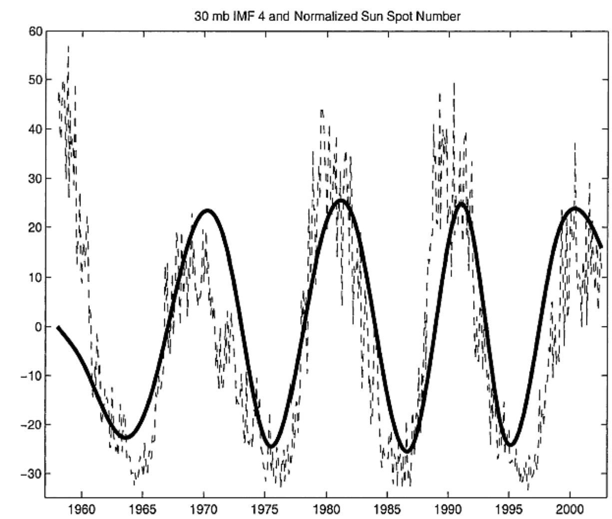

Fig. 1. Right: The dashed line is the normalized sunspot number. The thick solid line is decomposition 4 in the EMD method of the 30 mb geopotential height. The two time series are significantly correlated at 0.70 (after K. Coughlin, 2004).

smaller than the anthropogenic forcing it is incorrect to assume that the Sun necessarily will be an insignificant player in climate change in the 21st century." As the interplanetary medium is neither unstructured or quasi-static, nor is a simple magnetic stratified object, thus, the interaction of the solar electromagnetic radiation (photons), hot plasma (electrons, protons and other ions), cosmic rays, microscopic dust particles, and magnetic fields (primarily from the Sun) with the upper environment of our Earth leads to a complex physics which is far to be understandable; their characterization deserves to be clarified.

SOME MAIN BASIC DEFINITIONS

The study of the Sun-Earth connections is a science in full effervescence, as well as for the physical problems that are raised as for its growing impact on our societies. This last case is illustrated by the emergence of a new field of research called ``Space Weather". The launch of this new concept[1], deserves to be clarified in spite of a great number of papers and books devoted to this question. Weather first induces a brief temporal idea: *weather* is the state of the environment at a given time and place; it may be quiet or violent. Weather is currently associated with local parameters such as temperature, pressure, hygrometry or wind speed. On Earth, prior to the satellite era, such data have been widely recorded and were used, and still are, in meteorological reports. They have been used as time series for correlative studies with solar phenomena, and accompanied by a lot of skepticism among scientists due to a lack of physical mechanisms to account for these correlations. By contrast, *climate* refers to the long term, using data spanning more than one century and even more. Nowadays, climatic studies use a large variety of data other than ``pure meteorological" parameters, such as cloud covering, albedo, extension of polar caps, tree leaves abundance, etc. Using the word ``weather" must not be minimized. It must refer to specific conditions occurring in space, locally, and for which time-scales are of the order of minutes to hours, up to no more than some days (or a few months). Beyond is another field of research.

Sun-Earth connections (in French ``Relations Soleil-Terre") refer on one hand to the structure of the solar plasma by the magnetic field, and on the other hand to the structure of the magnetospheric plasma by the interplanetary medium. It is important here to stress the Sun's fundamental role in shaping the interplanetary space within the solar system, the region known as the ``heliosphere". The physics of the heliosphere and its interactions with the Earth magnetosphere and ionosphere is the domain of Sun-Earth connections, that can be extended to the interactions of the heliosphere with the magnetosphere and ionosphere of other planets, such as Jupiter (space physics). To conclude, we can say that

- ``Sun-Earth connections" deal with the ``physics of the transport and energy conversion in the heliosphere",

whereas, ``Space Weather" may be described as ``Conditions on the Sun and in the Solar Wind, magnetosphere, ionosphere and thermosphere that can influence the performance and reliability of space-born and ground-based technological systems and can endanger human life or health", following the definition made by US National Space Weather.

Some comments on this last definition can be made at this step. First, man-made pollution of space, such as debris or radio-pollution is not taken into account. Second, the life of a human has never been affected by plasma bursts arriving from the Sun on the Earth (at least during the last century where official recorded data are available). There is no direct reference to unspecified dangers but to impacts on the human activity and the living conditions on ground. At last, the word ``meteorology" refers also to an operational system of forecasts. It results that ``Space Weather" can be defined as

- *the science aiming at studying the composition and the dynamic of the upper layers of the atmosphere of the Earth (magnetosphere, ionosphere and thermosphere), the perturbations of which are due to solar events or man-made pollution (such as space debris or radio waves). Effects can endanger human life in space, may have impacts on the performance and reliability of space-borne and ground-based technological systems, yielding economic upshots on our society.*

A new definition is under consideration by COST 724 ``Developing the Scientific Basis for Monitoring, Modeling and Predicting Space Weather" (see http://cost724.obs.ujf-grenoble.fr).

THE KEY ROLE OF TIME RANGING

From the core of the Sun up to the Earth, four main mechanisms generate a variability on the Earth global insolation (J. Beer et al., 2000): (i) nuclear fusion in the core of the Sun (ii) transport through the radiative and convective zone of the Sun (iii) the emission of radiation from the photosphere towards the Earth and (iv) changes in the celestial mechanical parameters (eccentricity, nutation, inclination of orbits). These sources of variability act on different time scales, ranging from billion of years to seasons, sometimes to minutes or days.

The first case (0 to 0.3 R) is studied through different models leading to high luminosity changes through very long periods of time (a doubling of the luminosity over the first 8 billions years, known as ``the early faint Sun paradox"). The second case can be divided into two sub-groups: the first one concerns the energy transport through the radiative zone (0.3 to 0.7R), likely to be stable, and the second one (0.7 to 1R) concerns the convective zone. Although the ultimate source of solar energy is the nuclear reactions taking place in the core, the immediate source of energy is the surface. Nuclear reactions are certainly steady on short time scale, but mechanisms which carry the energy in the convective zone may not be. If the central energy source remains constant while the rate of energy emission from the surface varies, there must be an intermediate reservoir, where the energy can be stored or

[1] Translated in French by ``météorologie de l'espace". It is not exactly the same, but meteorology is better appropriate than climatology, as it is written sometimes abusively. Space Climate is another new field of research, devoted to the study of impacts of solar outflows material in the environment of the Earth over long periods of time. The study of Space Climate thus involves both long-term average behavior and variations about those long-term averages (Cliver, 2005).

released depending on the variable rate of energy transport (Kuhn et al., 1998). The gravitational field is one such energy reservoir. If energy is stored in this reservoir, it will result a change in the Sun's radius, at least in the uppermost layers of the Sun (the leptocline). Recent works show the compatibility of this theory with irradiance variations (Lefebvre and Kosovichev, 2005, Fazel et al., 2005). These mechanisms act the level of days to several years (cyclic solar activity).

The third case is linked with the transport of the radiation from the photosphere up to the Earth. Changes in the global insolation are due on one hand to anistropic transport, and to the other hand, on changes in the UV part of the spectrum, for which certain spectral bands of the atmosphere are very sensitive (ozone layers for instance). The effects are also of the order of days and years. Finally, the variability due to movement of the Earth on its orbit and over its axis of rotation, leads to climatic changes that were first studied by Milankovich in 1930. The time scales involved here are of the order of thousands years.

The three last processes show cyclicities, and the question, which remains an *open question* is: does exist resonant phenomena able to amplify changes in the global warming or cooling of our climate? In the same way, we are still ignorant of how feedbacks may act, but we know that such mechanisms may amplify a weak solar signal.

EMPHAZING FORECASTING SOLAR ACTIVITY

Pseudo-cyclicity of the solar activity is one of the most intriguing puzzle in solar physics. Why the Sun seems to beat regularly, at *around* 11-years, but also at *around* other specific periods, 80 yrs, 400 yrs, etc? This ``around" is the core of the problem. We do not know why the lengths of the solar cycles vary from one cycle to the other, the differences being tiny (≈ 0.5 yr) but significant. This render the prediction difficult. However, planning for satellite orbits and space missions (*especially* for man-lived missions), often require knowledge of solar activity levels years in advance. The study of the Lyapunov exponent, for which the determination is between 3 to 4 years, shows that the solar cycle is not deterministic: it is thus impossible, in the solar case, to accurately determine the date and the level of intensity of the activity signal more than 3 or 4 years ahead. In other words, the *forecast* is good: the behaviour of a sunspot cycle is fairly reliable once the cycle is well underway, about 3 years after the minimum. For instance, in 2004 it is possible to forecast that the next solar maximum will take place around 2011. However the *prediction* is poor: inaccuracy on the date, inaccuracy on the estimate of the level of the signal. The *``observed"* is not enough to deduce the *``observable"*.

There is a great lot of techniques (including neuronal networks), each of them showing advantages and drawbacks. A comprehensive review can be found for instance in http://science.nasa.gov/ssl/pad/solar/default.htm. But we need to improve the scientific way of predicting solar activity, both for a better understanding of the heliosphere and dynamo physics, as well as its usefulness to all space agencies interested in solar activity related phenomena, ranging from power grid spikes, to communication blackouts, to satellite orbital dynamics.

UNDERSTANDING DYNAMICAL SOLAR INTERNAL PROCESSES

A priori, it seems that understanding how the core of the Sun rotates is very far from the climatic research. It is not so sure, as one the key is the magnetism: the interplanetary medium is shaped by the solar magnetism. The solar magnetism is no more considered as a purely superficial phenomenon. If it has been shown that the length of the solar cycle depends on the transition region between radiation and convection, the internal solar magnetism is still poorly known. Three main space missions will increase our knowledge on this difficult problem: one is SDO (Solar Dynamics Observatory), which will focus on the convective zone; the other is GOLF-NG, which aims to investigate the deepest layers of the Sun, and the third one is PICARD. This will help us to get, at the horizon of 2008-2010, a 3-D vision of the Sun. The heart of the complete project is, during the next solar cycle 2008-2017, (i) to follow the luminosity and radius variabilities, (ii) to measure constraints on the core dynamics, and (iii) to obtain a detailed analysis of the convective zone, both for the tachocline and the leptocline. An other mission, launched in 2018 near the solar poles or around the L1 Lagrangian point will allow to obtain all the necessary constraints to build a ``predictable magnetic model" of the Sun and its relationship with our planet (and such a vision will be extended to other stars and planets). The road-map can be found in Turck-Chieze et al. (2005).

All these fascinating experiments are particularly attractive to justify the study of the influence of the Sun on our climate, a new science called "Helioclimatology".

Fig. 2. From left to right, are shown designs of the three space missions aiming at understanding the magnetism of the solar interior for a complete MHD solar vision: GOLF-NG (precise determination of the rotation of the core where half of the mass is concentrated), the European microsatellite PICARD (solar-climate relationship investigation) and the American instrument HMI/SDO (First Space Weather Research Network mission in the Living With a Star –LWS- Program of NASA. SDO is being designed to help us understand the Sun's influence on Earth and Near-Earth space). Starting in 2008, they will enrich our view of the Sun-Earth relationship

CONCLUSION

Understanding the complete chain that links the solar variability output to the complex physical state of the Earth's atmosphere is still a challenge to physicists. We still must carry our efforts towards:

- A better understanding of how irradiance acts on our atmosphere; better reconstruction of past irradiance is needed to be confronted with ancient records; this goes beyond better irradiance models likely including global properties of the Sun, magnetism and shape (fractional changes in radius is determined by f-modes);
- A better understanding of the solar variability output; dynamics of the core is needed, as the observed solar activity is not a purely superficial phenomenon. Internal processes must be included to (i) better estimate the real energetic balance and (ii) to constraint models or the irradiance with the magnetic field (which is not yet the case).

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