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New findings increasing solar trend that can change Earth climate

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Abstract. Early attempts to find how solar activity can influence the Earth's climate involved comparison of many physical processes, such as dynamo mechanism, magnetic reconnection and eruptive activity, irradiance, open flux and particles variations, global atmospheric chemistry and dynamics.... However, such direct links seem to be weak even if the solar effects has been found to be stronger during extended maxima or minima of solar activity. Thus, temporal scales ranging from days to thousand of years must be investigated. A description of the most recent results on solar variability and its possible influence on the Earth's climate and atmosphere will be here addressed, with a particular emphasize on modulations of about 120 years (and harmonics). The extrapolation indicates a significant negative decrease of the solar signal, and consequently a decrease of the global Earth's temperature in the forthcoming years. Such a modulation is also testifying by other means, such as spectral observations of temperature sensitive lines indicating a decline of solar activity around 2015 (up to a new prolonged minimum). Prediction of global effects from the Sun's influence over the climate is thus planted in a new way.

Keywords. Sun: general, activity, sunspots, solar-terrestrial relations; Earth

1. Introduction

If it is obvious, since the highest Antiquity, that the Sun is the primary source for driving the Earth's climate system, it is not so evident since the middle of the 70's, that the solar changes may have a corresponding response on the climate system. 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. If a general consensus is reached concerning the increase of global Earth's temperature due to human activities (see reports from the IPCC†), it seems that this increase tends to slow down since a few months: does this break in the positive temperature trend since the years 1970 corresponds today with the low solar activity as seen from the year 2008?

The second argument is linked with the so-called Total Solar Irradiance (TSI). 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 (Foukal *et al.*, 2006).

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† IPCC: Intergouvernental Panel on Climatic Change, Fifth Assessment Report.

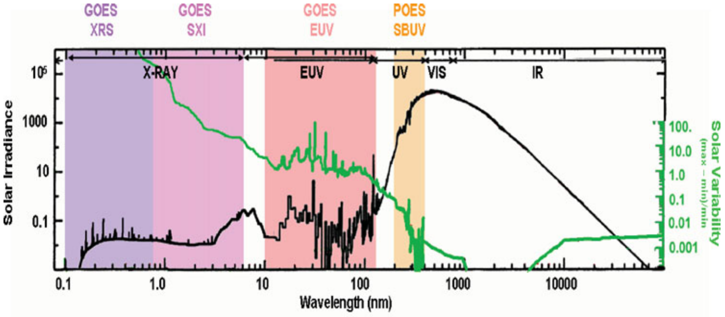

Figure 1. The solar spectrum (black curve) is highly variable (green curve: the spectral variability is the ratio (max-min)/min). The UV and EUV portions of the spectrum have the greatest variability. After NOAA forecast center.

Furthermore, if such an estimate of the “solar constant” may produce a climatic forcing, do its variations are of enough sensitivity to explain the differently equatorial, tropical or polar latitudes perturbations of the Earth’s atmosphere? Even by admitting a modulation of the climatic signal on the top of the stratosphere, how changes can be reverberated on the lower layers, seat of our climate? An embryo of answer is suggested for example by Haigh (1994) who emphazised the role of the ozone destructive cycle, or more likely, through an amplification of the solar signal within the UTLS (Upper-Troposphere-Lower-Stratosphere) zone (Kodera and Kuroda, 2002; Kilifarska, 2006)‡.

Recent works has significantly improved our knowledge on the TSI, mainly on the UV part of the spectrum as seen in Fig. 1. 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 be discussed in many symposia. This may reinforce what Hansen wrote in 2000: *“Even if the solar forcing has been 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 understood; their characterization deserves to be clarified.

The solar output variability which may influence our Earth’s environment and more specially our climate is called helioclimatology (Rozelot, 1990, Lefebvre *et al.*, 2007).

2. 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 (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) 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

‡ Let us quote here Kodera: “it is suggested that the solar influence produced in the upper stratosphere and stratopause region is transmitted to the lower stratosphere through (1) modulation of the internal mode of variation in the polar night jet and (2) a change in the Brewer-Dobson circulation; see also Lefebvre *et al.*, these proceedings.

variability act on different time scales, ranging from billion of years to seasons, sometimes to days or minutes.

The first case (in the range of 0 to 0.3 solar radius 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 0.7 R), 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 released depending on the variable rate of energy transport (Pap *et al.*, 1998). The gravitational field (the virial theorem indicates that there is a connection between magnetic energy and gravitational energy), 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; Stothers, 2006; Fazel *et al.*, 2008). These mechanisms act at the level of days to several years (cyclic solar activity). This radius variability will be addressed later on.

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 to 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 the 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: do 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. In this scope, the UTLS region is a key-layer in the understanding of climatic phenomena. Changing chemistry in this region has lead us to better unravelling the dynamical feedback that can occur here. Undoubtedly, this effect in conjunction with the solar irradiance changes, can influence the interannual variability of temperature in this zone (Kilifarska, 2006, Damiani-Badache *et al,* 2007).

3. 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, 211-yrs, 400-yrs, even 2115-yrs (Damon and Jirikowic, 1992). 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 significant, of the order of 2 to 3-yr for the Schwabbe 11-yr cycle for instance, more for other cycles. This renders 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 (Benest *et al.*, 2007), 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 what will be the "observable".

There is a great lot of techniques (including neuronal networks), each of them showing advantages and drawbacks. Predictions for solar cycle 24 has been made by several authors, leading to a large range of amplitude of the signal (15 papers are available on the subject for the single year 2008). In spite of the fact that some methods predict a relatively high cycle 24, three different analysis lead to about the same conclusion:

- Kilcik *et al.* (2009) reported that the maximum intensity of cycle 24, will be of 87.4 in December 2012; according to this forecast, the current solar cycle will have a magnitude far lower than any other since 1890–1910.
- Kitiashvili & Kosovichev (2008 and this proceedings) using a nonlinear dynamo model as described by Kleeorin & Ruzmaikin (1982), which takes into account dynamics of the turbulent magnetic helicity, predict that the next sunspot cycle will be significantly weaker (by $\approx 30\%$) than the previous cycle, continuing the trend of low solar activity.
- Using direct polar field measurements, now available for four solar cycles, Svalgaard *et al.* (2005) predict that solar cycle 24 (2011 maximum) will have a peak of 75 ± 8 in the smoothed monthly sunspot number, making it potentially the smallest cycle in the last 100 years.

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 and to satellite orbital dynamics.

4. 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. Some main space missions will give us a 3-D vision of the Sun at the horizon of about 2012, which will increase our knowledge on this difficult problem (for instance DynaMICCS, Turck-Chièze *et al.*, 2008).

5. Are we entering a new "blank" area?

Space-based measurements reveal the existence of 11-year cycles in solar radiation upon which are superimposed larger and shorter term changes. Indirect proxies of solar activity† exhibit 11-year solar cycles as well as longer-term changes or cycles that exceed the amplitudes of their 11-yrs cycles. Comparisons of these proxy records with direct

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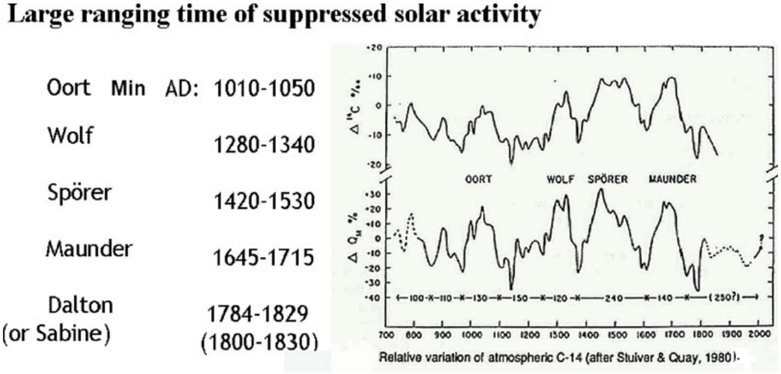
† Such proxies can be listed as: dendochronology, palynology, isotopic variations of marine sediments (foraminifers), ice analyzes (trapping of CO_2, Be^{10}), criticized study of old documents (parochial registers, ship's books, dates of harvests and vintages, wheat prizes, plum blossoming in Japan), glaciers advance and retreats, comets and auroras registers, C^{14} analysis, etc).



Large ranging time of suppressed solar activity

Oort Min AD:	1010-1050
Wolf	1280-1340
Spörer	1420-1530
Maunder	1645-1715
Dalton (or Sabine)	1784-1829 (1800-1830)

Relative variation of atmospheric C-14 (after Stuiver & Quay, 1980).

Figure 2. The different past solar minima (inverted from the C^{14} analysis due to the Forbusch effect) show a pseudo long oscillation. An extrapolation shows that the next prolonged minima will occur by around 2020. (After Suiver and Quay, 1980, Sol. Phys., 74, 2, pp. 479–481). See also Hiroko Miyahara, these proceedings.

observations suggest that anomalously low solar activity have existed in the past. These periods are commonly known as the “Dalton”, “Maunder”, “Spörer”, “Wolf” and “Ort” Minima (which occurred from 1784 to 1829, from 1645 to 1715, from 1420 to 1530-1535, from 1280 to 1340 and 1010-1050 respectively: see Fig. 2).

By contrast, since about 1950, solar activity increased steadily, to an amplitude never reached during the first half of the twentieth century. A crude analysis of the frequency at which appeared the above-mentioned minima together with this last remark, lead us to conclude that we are entering a new long solar minima, which will occurred around next cycle 25. If solar activity continues as low as it has been since 2007, 2008 would have racked up a whopping 290 spotless days by the end of December, making it a century-level year in terms of spotlessness (Hataway, 2008). At the end of the year 2009, even if newly emerged Cycle 24 regions were recorded, plages were still of low probability of producing any activity, even if some have been seen (such as on 2009, November, 1st).

Penn and Livingston (2006) observed spectroscopic changes in temperature sensitive molecular lines, mainly in the magnetic splitting of a Fe I line, and in the continuum brightness of over 1000 sunspot umbrae from 1990–2005. There measurements show consistent trends in which the darkest parts of the sunspot umbra have become warmer (45K per year) and their magnetic field strengths have decreased (77 Gauss per year), independently of the normal 11-year sunspot cycle.

Left panel of Figure 3 shows the decrease in field strength now found with respect to time (1992–2009), which shows a linear trend independent of the solar cycle: a linear extrapolation of this trend may suggest that few sunspots will be visible after 2015. Because of the nature of the observing program, the earliest measurements in this plot are probably skewed toward higher magnetic field values (larger sunspots); nonetheless, the linear trend in the magnetic field value is clear, even excluding all pre-1995 data. Is this an omen of long-term sunspot decline, analogous to the Maunder Minimum?

Climatic parameters of many types often exhibit cycles that are also common in solar activity proxies, such as near 11–, 22–, 80– and 210– years. It is well known that times of cooler climate in past millennia usually coincide with reduced levels of solar activity. For instance, during the Little Ice Age, which occurred from about 1450 to 1850, surface temperatures were from 0.6°C to 1°C colder than at present (depending on geographic location, as changes in solar radiation can often result in regional or local responses). Solar activity was lower than at present because of the occurrence of the above-mentioned

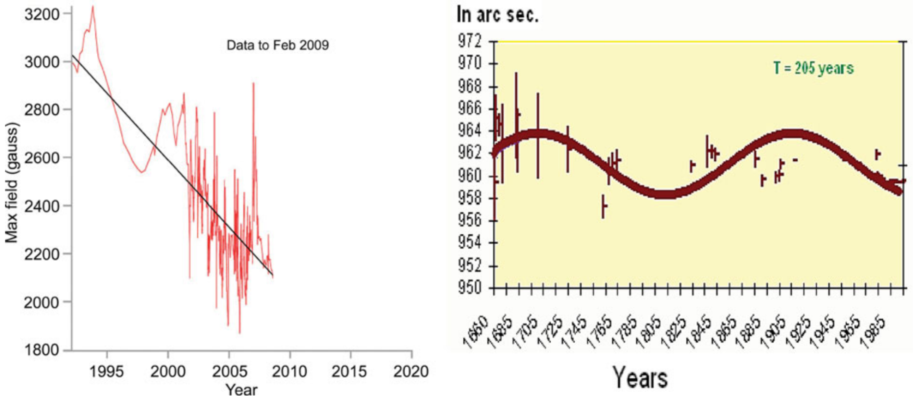


Figure 3. Left: The maximum sunspot field strength is plotted versus time, during the period from 1992 to February 2009; a 12- point running mean is shown, and a linear fit to the data is plotted. Apart from a few measurements, the linear trend has been seen to continue throughout this solar minimum. By courtesy of W. Livingston and M. Penn, 2009. Right: Solar radius variations as observed since the pioneer's work of Picard and La Hire, two french astronomers at the time of the reign of Louis XIV named "Roi-Soleil". In spite of the fact that the error bars were large at that time, a general sinusoidal fit can be adjusted, leading to a next minimum in around 2015–2018.

Minima. Low-frequency signals in long tree-ring chronologies have been used to reconstruct past temperature variability since the year 631 (Esper *et al.*, 2002; see also Fig. 2 in Feynman, 2007). Yearly data has been plotted in Fig. 4 and a sinusoidal fit has been adjusted. In spite of the global warming which occurred these last few years, a general behaviour appears that would lead to a next minimum around the years 2018. The period found, of roughly 425-years, is twice the powerful harmonic (212-yrs) considered as fundamental by Damon and Jirikowic (1992).

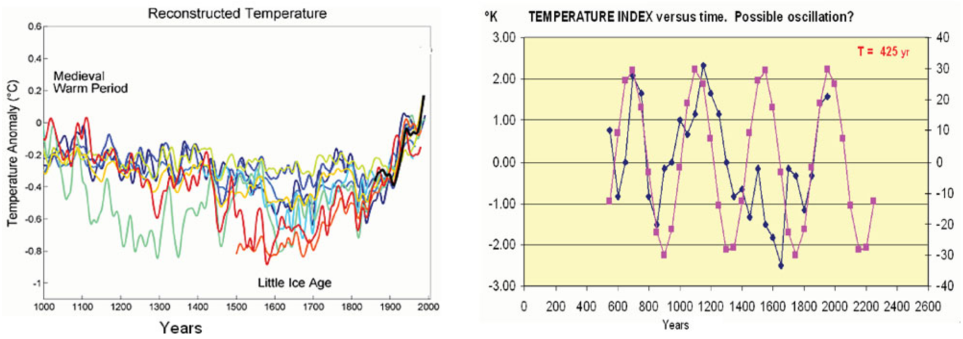
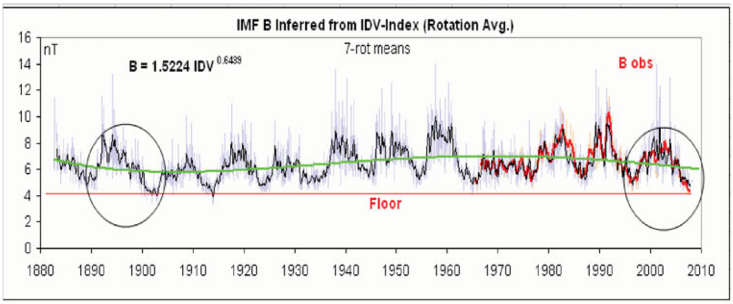


Figure 4. Left: Comparison of 10 different published reconstructions of mean temperature changes during the last 2000 years. More recent reconstructions are plotted towards the front and in redder colors, older reconstructions appear towards the back and in bluer colors. For instance: Red (1-1979): A. Moberg, D.M. Sonechkin, K. Holmgren, N.M. Datsenko and W. Karln (2005). *"Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data"*, Nature, 443: 613–617. Light green (831–1992): J. Esper, E.R. Cook, and F.H. Schweingruber (2002). *"Low-Frequency Signals in Long Tree-Ring Chronologies for Reconstructing Past Temperature Variability"*, Science, 295(5563): 2250–2253. Right: Adjusting a sinusoidal fit which smoothes the data during the ascending phase of the temperature due to men's effects -and bearing in mind the possible pause of Earth's temperature since 2008–, it can be seen that we may enter a new era of low temperature.



Heliospheric Magnetic Field. Cycles 13 and 23 are circled.
L. Svalgaard, E. Cliver, and P. LeSager, Determination of interplanetary magnetic field strength, solar wind speed, and EUV irradiance 1890-2003, in International Solar Cycle Studies Symposium, June 23-28, 2003, Tatranska Lomnica, Slovak Republic, Proceedings (ESA SP-535), 15, ed. A. Wilson. 2003

Figure 5. The Interplanetary Magnetic Field strength shows a modulation that may reach a minimum in 2015.

An analysis of the solar radius variability, as it appeared for instance in Thuillier *et al.* (2005) or Kilcik *et al.* (2009) indicates that a modulation of amplitude can be seen of about 205-years will lead to a next "bigger" Sun by 2018 (Fig. 3-right). Even if this variability must be taken with cautious, and as the data are certainly not all of the same quality, it can be noticed nevertheless that this periodicity is about 205-yrs, i.e. the fundamental, as above stated.

Finally, the analysis of the interplanetary magnetic field strength as described by Svalgaard *et al.* (2003 -see caption of Fig. 5) shows a similarity of cycles 13 and 23, which will leads again to a minimum after 2013 as seen in Fig. 5.

The authors are perfectly aware of the empirical character of the predictions made here. But it is rather striking, that the four parameters described, temperature index, solar radius variability, umbral-sunspots magnetic fields and interplanetary magnetic field strength, lead to a new great Minima which might occur between 2015 and 2018.

6. Conclusion

Comparison of cycles 4 and 23, then 13 and 23 lead to the conclusion that solar activity will be less intense in the future. This is reinforced by a long-term oscillation in the temperature reconstruction, in the photospheric radius variations, in the decreasing of the solar magnetic field in the quiet solar disc and in the interplanetary magnetic field strength.

It is extremely likely that we are just entering a new Minima. The level of solar activity remained very low during several months in 2008. During that time, high-latitudes region of activity yielded frequently no flares, despite developing mixed-polarity areas indicating a new cycle difficult to start. A lot of predictions based of the past dataset point out that even if the maximum of solar activity has been increasing since the late 19th century, the next maximum will begin to decrease. By looking at all the past Minima deduced from historical records, it can be set forth that solar activity is certainly modulated over long periods of time. This modulation of amplitude is undoubtedly driven through dynamo processes, but the gravitational energy in the most outer layers certainly plays a key role (the "leptocline" shallow layer may be the cradle of turbulent pressure –Lefebvre *et al.*, 2007; Lefebvre *et al.*, 2008–). This gravitational energy expands or shrinks the solar envelope on an antiphasing process with the activity. Lastly, a magnetic field analysis conducted at Kitt Peak on spectral observations of temperature sensitive lines, show a possible long negative trend indicating a decline of solar activity, which could lead also to a suppressed activity in the forthcoming years.

The analysis over a long period of time of the deviation to the mean of the Earth's temperature, also shows a probable declining, the anthropogenic effect not taken into account. This can be done precisely because the study is conducted over several centuries, which smooth the recent ascending trend. We do not claim that this last effect does not exist, and we do not claim neither that the Earth's temperature follows the solar cycle. We merely said that a sinusoidal fitting of the data would yield a next temperature minima in a few years. This would happen without strong effects on our climate, due to man's activity.

Cautiously, we can argue that the next Grand Minima will occur by 2015-2018. Prediction of long-term global effects from the Sun's influence over the climate is thus impinged in a new way.

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