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Physics and Chemistry of the Earth 31 (2006) 41–45

PHYSICS and CHEMISTRY of the EARTH
www.elsevier.com/locate/pce

Is it possible to find a solar signature in the current climatic warming?

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Received 5 November 2004; accepted 3 January 2005
Available online 29 March 2006

Abstract

This paper investigates whether it is possible to find a solar signature in the current Earth's climatic warming. The attempt seems audacious as, on one hand, solar output variability on the atmosphere is far to be understood, and on the other hand, there is evidence that most of the warming observed over the last 50 years can be attributed to human activities. However, series of the annual global average temperature, from 1861 up to now are available, showing periods of warming and cooling that are statistically significant. From recent findings, it is also known that solar irradiance shows a variability and can be modeled today with a good accuracy over the last century. The idea was to compare the likelihood linear trends shown in the climatic data with those of the irradiance, during same well defined time ranges. Changes from 1861 to 1975 show an unexpected remarkable correlation, whereas the period 1976–2000 completely deviates from the previous analysis. The 1861–1975 set of data supports the suggestion of an influence of solar irradiance on global climate, which was checked as a natural forcing: the response is found to be $\lambda = 0.46$ °C/W m^{-2}, a quite reasonable value, bearing in mind the imprecision in the irradiance modeling. This analysis is also discussed in the scope of other forcings and uncertainties in the data.

Keywords: Climatology; Earth temperature; Sun; Solar activity; Solar irradiance; Space weather

1. Introduction

Sun and Earth form a complex dynamic system which are linked through radiation, particles and magnetic fields. In principle, a refined study of each component would lead to a better understanding of the complete dynamics of climatic changes. Things are unfortunately not so simple, and the climate that we experience reflects the influence of different forcings, both natural and resulting from human activities, as well as the couplings (and feedbacks) between all terrestrial elements, oceans, stratosphere, polar caps, etc.

If the ultimate goal is to predict climate variations, the question today is to try to reduce uncertainties in the functioning of critical processes. Among them, and the only one which will be discussed here is to try to retrieve a response of the solar irradiance signal in the Earth climate variability.

The Sun is one of the main dominant energy for source for maintaining our climate. The Earth's envelope absorbs all radiations, from far UV to IR and the energy is redistributed through the atmospheric and oceanic circulations, then radiated back to space. To first order, and taking the Earth as a whole, the annual incoming mean solar radiation energy is balanced by the outgoing terrestrial one. Any factor that alters the radiation received from the Sun or lost back to space, alters the redistribution of energy within the atmosphere, land and ocean, and thus can affect the climate. That the solar irradiance, namely at UV wavelengths, exhibits significant variations may help in the future to tackle the puzzle.

This paper deals mainly with this solar forcing, and the main question which is addressed is the following: is it possible (or not) to find again a solar signature in the recent

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1474-7065/$ - see front matter
doi:10.1016/j.pce.2005.01.005

climatic warming? This question seems rather audacious as it is known that the solar contribution is lower than others, such as aerosols or volcanic effects. However, even if the analysis is still rather crude, results obtained are sufficiently remarkable to constitute a basis for future discussions.

The present analysis is focused only on the "instrumental period", since 1860, for which more reliable climate data are available (temperature records for our purpose). As far as the solar irradiance is concerned, changes are continuously monitored for now more than two solar cycles: modeling is still in its infancy, but the total irradiance variability can be reproduced at a ≈90% degree of confidence, a value sufficient for our purpose.

In the first part of the paper we will indicate the choice of our data; then we will identify co-temporal measurements in order to deduce trends over independent periods. The validity of the method will be checked and discussed in the scope of other forcings and uncertainties.

2. Data description and analysis

2.1. Global temperature data

There are now long records of direct measurements of various variables of the climate system. For example, measurements of the surface temperature began around the middle of the 19th century. Series have been compiled and discussed in many papers (see for instance Jones et al., 2001; Jones and Moberg, 2003; Folland et al., 2001). We will use here only one, available since 1860, which is a combination of land surface temperature data and sea surface data coming from the CRU (Climatic Research Unit of the University of East Anglia, UK) and compiled by the Hadley center. These global near-surface temperatures consist of annual differences from 1961 to 1990 normals and are based on regular measurements of air temperature at land stations together with sea surface temperatures measured from ships and buoys.[1]

The results can be briefly summarized as follows:

The global average surface temperature has increased by approximatively 0.6 °C (±0.2 °C) over the last 150 years (exactly 1856–2001). This account for a general trend of 0.042 °C per decade. Most of the increase has occurred in two periods, one from about 1910 to 1945, and the other since 1976. The global warming rate of 0.47 °C of amplitude from 1910 up to 1945 (+0.13 °C per decade), is followed by a "cooler" period from 1946 to 1975, of amplitude of 0.05 °C only (−0.01 °C per decade). If this period appears with a negative trend, the uncertainties show that this decline remains faint. Then, a new warming (not uniformly distributed over all the latitudes) occurred from 1976 to 2001, of about 0.53 °C (+0.21 °C per decade). Confidence in the order of magnitude of these global warming-cooling changes, since the last century, has recently increased due to many new analyses.

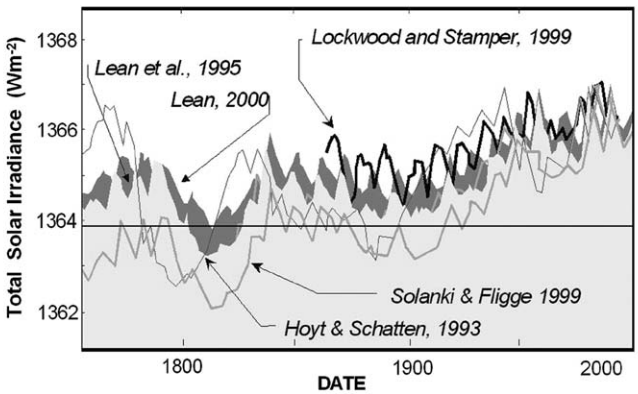
2.2. Irradiance data

Regular space-borne measurements of solar irradiance with sufficient accuracy started in 1978. A number of instruments have been involved and the major fact was the detection of a temporal variability which was not suspected before. Even if the absolute values obtained by different means may differ, changes exhibit very similar features. Critical reviews are made repeatedly (see for instance Pap, 2003; Floyd, 2003 and numerous references herein), in order to inspect the variability put in evidence on different time scales, ranging from minutes to days and years. The major fact is the intrinsic variability of the total solar irradiance, in phase with the solar cycle, at a level of around 3 per thousand (from higher to lower points of the envelope) and around 0.1% from the maximum to the minimum of an averaged mean curve. A composite of all available data was constructed by Fröhlich (2004), covering a full solar cycle (number 22) and one half each of solar cycles 21 and 23.

Unfortunately, this period is not sufficiently long to search for signs of solar influence on climate. In this scope, there is thus a need for an irradiance modeling and many attempts have been made. The majority of the proposed models are based on the changes of the surface magnetic structures, mainly spots and faculae. Such proxies being available since a long time, the models are able to reproduce irradiance back in time. Recently, other models have been proposed, which lie upon the various components that constitute the solar atmosphere (Fontenla et al., 1999; Krivova et al., 2003; Willson and Mordinov, 2003). Such models may well reproduce the observed irradiance covering the present solar cycle 23, as we dispose of the appropriate indicators, but cannot be used for reconstructing irradiance in the past for which such indicators are unfortunately missing. Finally, other mechanisms have been proposed to explain the irradiance variability, based upon a non-magnetic origin or based on indirect connections, such as radius variations (Sofia and Li, 2001; Rozelot et al., 2004). Global parameters can be used to calibrate a solar model in which the 11-year solar irradiance modulation is due to structural adjustments that modify the energy flow from the interior to the surface and affect the entire luminosity of the Sun. This proposal can be used to reconstruct longer lived irradiance changes, for example over several centuries.

Fig. 1 (after Lockwood, 2005) shows several types of reconstruction, which are currently still debating. But in spite of differences, they show over relatively long periods of time, some similarities in the various trends. Our purpose is not to discuss the validity of each proposed model (although it is an interesting topic), but to use these highlighted trends. We used here the model proposed by Solanki and Fligge (2001), which has the merit to

[1] See http://www.metoffice.com/research/hadleycentre/obsdata/globaltemperature.html or http://cdiac.esd.ornl.gov/trends/temp/jones.html



Courtesy, M. Lockwood, Rutherford Appleton Laboratory and Southampton University, UK

Fig. 1. Several solar irradiance models. In spite of differences (mainly in the absolute values), the different reconstructions show similarities in the trends over well defined periods of time, such as (1860–1910), (1910–1945), (1945–1975) and (1976–2000); this last sequence forms the original "kernel" for the reconstruction (Hoyt and Schatten, 1993; Lean et al., 1995; Lean, 2000; Solanki and Fligge, 1999).

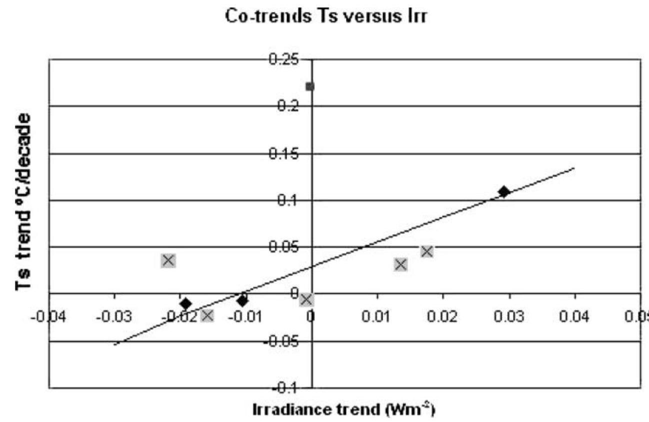


Fig. 3. Combined Land and Marine Temperatures trends versus the Solar Irradiance trends. Diamonds: three independent periods of time: 1856–1910, 1910–1945 and 1946–1975. The crossed squares represents (i) an other independent set of data (1885–1940; 1941–1975) and (ii) two longer (non-independent) segments (1856–1887; 1856–1975). The linear fit obtained leads to a climatic sensitivity parameter of $\lambda = 0.46$ °C/W m^{-2}. The square point is the estimate obtained for the 1976–2000 period of time.

reproduces the reconstructed interplanetary field with high accuracy (Lockwood and Stamper, 1999).

3. Results and discussion

The analysis was first conducted over the following three independent periods of time: 1856–1910, 1910–1945 and 1946–1975. An example is given in Fig. 2. The trends obtained are given in Table 1 where the first line shows the values obtained for the temperature data and the second for the irradiance. A linear fit, as depicts in Fig. 3 (points represented by diamonds), gives a rather unexpected high correlation value of $r = 0.98$. It can be obviously objected that this may be fortuitous. The process was thus repeated for an other set of independent period of time, chosen in such a way that the trends in the temperatures are still significant: 1885–1940 and 1941–1975. At last we added two other sets, 1856–1887, 1856–1975. The linearity is still obtained.

The correlation found between the global temperature trend and the solar irradiance trend (0.98) may appears as very high as based only on three independent points. The two other data sets yields respectively $r = 0.77$ and $r = 0.46$. In order to check the cogency, we performed a classical χ^2 test. The R.A. Fisher transformed correlations (z) are respectively 2.559, 1.021 and 0.498 leading to $\chi^2 = 4.35$. This value having a probability $P = 0.1$ to be exceeded by the simple effect of sampling fluctuations, one can conclude that the correlations do not present

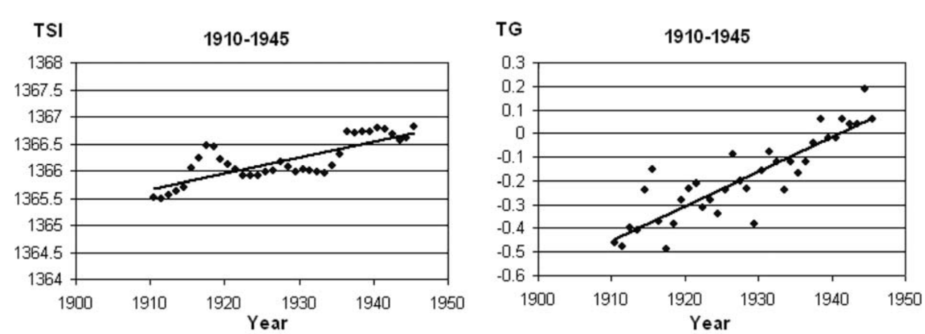


Fig. 2. An example of trends obtained for the ranging time 1910–1945. Left, within the irradiance modeling (TSI in W m^{-2}), and (right), within the temperature records (TG in °C).

Table 1
Trends obtained for the temperature (first line, in °C/year) and irradiance data (second line, in W m^{-2}), for different periods of time

1856–1910	1910–1945	1945–1975	1885–1940	1941–1975	1856–1887	1856–1975
−0.008	0.0145	−0.006	0.045	−0.023	0.035	0.031
−0.0106	0.0292	−0.0193	0.0176	−0.016	−0.0218	0.0136

Table 2
Computed trends obtained from the combined temperature data in °C/decade (second line), compared with those computed by the CRU (Climatic Research Unit of University of East Anglia, UK) from the LSAT data (first line)

1856–2000	1901–2000	1910–1945	1946–1975	1975–2000
0.05 ± 0.02	0.06 ± 0.02	0.11 ± 0.03	-0.01 ± 0.05	0.22 ± 0.08
0.042 ± 0.01	0.064 ± 0.01	0.145 ± 0.02	-0.006 ± 0.04	0.209 ± 0.01

between them significant differences. The mean z value is 1.359, so that the mean correlation coefficient r can be estimated as 0.88, still particularly noteworthy.

In order to check the validity of our results (second line of Table 2), they were also compared with these obtained by the CRU Global Land Surface Air Temperature (LSAT) shown in the first line of this Table.

Comparing the trends, the 1861–1975 set of data supports the suggestion of an influence of solar irradiance on global climate. The slope of the linear fit (2.625), converted into a climatic sensitivity parameter (λ) as defined by Cess and Potter (1988) is

$$\lambda = \Delta T_s/\Delta \mathrm{Irr} = 0.46\ ^\circ\mathrm{C/W\ m^{-2}}$$

assuming a factor correction of 0.7 to take into account the Earth's average albedo and 0.25 to take into account its sphericity. In one-dimensional models, λ is a nearly invariant parameter and is used as a powerful tool for obtaining first order estimates of the relative climate impacts of different perturbations. In three-dimensional models theory, the effect of this parameter has been recently explored and the results obtained so far show that this concept continues to serve as a good estimator (Le Treut et al., 1998). Finally it has been shown that response to individual forcings can be linearly added to obtain the total response to the sum of the forcings (Cox et al., 1995; Roeckner et al., 1994; Taylor and Penner, 1994). Therefore, our value of λ can be compared with the value obtained by other means, which is typically 0.5 °C/W m^{-2} (Ramanathan et al., 1989).

Inspection of Fig. 3 seems to suggests that at zero solar irradiance trend, the temperature will respond by 0.03 °C, which is just above the standard error as indicate in Table 2. This indicates that before the industrial era, other anthropogenic forcings (implicitly contained in the temperature data) such as sulfate aerosol or volcanic effects are present and are significant. By contrast, the computed values obtained for the trends within the period of time 1976–2000 fully deviates from the previous analysis: (irradiance trend: -0.002 W m^{-2}; temperature trend: +0.22 °C), indicating a complete change in the forcing. If we normalize the temperature trend to 100%, our analysis leads to a solar forcing contribution during the last 25 years of no more than 12% (as can be seen from the ratio 0.025/0.21 of Fig. 3).

In a similar way, Solanki and Krivova (2003) estimated the magnitude of the Sun's influence on climate employing an empirical approach and using three data sets: the total and UV irradiance between 1856 and 1999 and the cosmic rays flux between 1868 and 1999. These time series were constructed by the authors, using direct measurements wherever possible and reconstructions based on models and proxies at earlier times; then, they were compared with the climate record for the period 1856–1970. The solar records were scaled such that statistically the solar contribution to climate was as large as possible in the considered period. Under this assumption the comparison was repeated, but including the modern period 1970–1999. Results show that since roughly 1970 the solar influence on climate cannot have been dominant and cannot have contributed more than 30% to the steep temperature increase that has taken place since then. This value is obviously an upper bound, and thus, a bit higher than our own estimate. Finally, it must be pointed out that a statistically significant correlation between the annual surface air-temperature and the geomagnetic activity indices has been also reported by Valev (2001).

4. Conclusion

We have presented here observations that support the suggestion that long-term changes in the solar irradiance may influence the terrestrial climate. Using the one-dimensional climate sensitivity parameter, we were able to find a relatively good fitting between trends of the solar irradiance and combined land-marine temperatures. The value obtained of $\lambda = 0.46$ °C/W m^{-2}, is a quite reasonable value, bearing in mind the imprecision in the irradiance modeling. Results indicate also that since 1976, the influence of other forcings has almost certainly dominated over direct influence of solar variability.

It can be debate whether increased cloudiness could have an impact on the climate, a similar effect due to volcano eruptions, and also, as recently shown by Marsh and Svensmark (2000) how cosmic rays may influence this cloudiness (Kristjansson et al., 2002). An other argument against the suggestion of solar irradiance variabilities as causes of climate changes is the question of the lack of accuracy in the absolute values and the large uncertainties which still occur in the reconstruction methods.

However, one point which deserves to be underlined because it just becomes today to be understood is the large UV variations in solar irradiance, more than twice in amplitude than in other spectral ranges. We are aware of the crudeness of the method presented here (but noteworthy), and we wonder if the response of the upper atmosphere to the large UV variability could not be one possible explanation. While visual and near IR radiation is only moderately attenuated by the Earth's atmosphere, solar UV radiation below 300 nm is almost completely absorbed in the upper atmosphere and stratosphere where it significantly alters the chemical composition and dynamical evolution of those layers, thus controlling the amount of variability of the ozone concentration (Haigh, 1996). This would have to be explored, on a more precise way in a next future, when longer UV wavelength components in the irradiance would become available through satellite data.

References

Cess, R.D., Potter, G.L., 1988. A methodology for understanding and intercomparing atmospheric climate feedback processes in GCM. J. Geophys. Res. 93, 8305–8314.

Cox, S.J., Wang, W.C., Schwartz, S.E., 1995. Climate response to forcing by sulfate aereosols and greenhouse gases. J. Geophys. Res. Lett. 187, 2509.

Floyd, L., 2003. Solar ultraviolet irradiance: origins, measurements and models. In: The Sun's Surface and Subsurface. In: Rozelot, J.P. (Ed.), Lecture Notes in Physics, vol. 599. Springer, pp. 109–128.

Fröhlich, K, 2004. Solar irradiance variability. In: Solar Variability and its Effect on Climate, Solar Energy Flux Variations in American Geophysical Union. Geophysical Monograph Series No. 141 (Chapter 2).

Folland, C.K., Rayner, N.A., Brown, S.J., Smith, T.M., Shen, S.S.P., Parker, D.E., Macadam, I., Jones, P.D., Jones, R.N., Nicholls, N., Sexton, D.M.H., 2001. Global temperature change and its uncertainties since 1861. Geophys. Res. Lett. 28, 2621–2624.

Fontenla, J.M., Avrett, E.H., Loeser, R., 1999. Energy balance in the solar transition region. III—Helium emission in hydrostatic, constant-abundance models with diffusion. ApJ 406, 319–345.

Haigh, J.D., 1996. The impact of solar variability on climate. Science 272, 981–984.

Hoyt, D.V., Schatten, K.H., 1993. A discussion of plausible solar irradiance variations, 1700–1992. Sol. Phys. 76, 211–219.

Jones, P.D., Moberg, A., 2003. Hemispheric and large-scale surface air temperature variations: an extensive revision and an update to 2001. J. Climate 16, 206–223.

Jones, P.D., Osborn, T.J., Briffa, K.R., Folland, C.K., Horton, B., Alexander, L.V., Parker, D.E., Rayner, N.A., 2001. Adjusting for sampling density in grid-box land and ocean surface temperature time series. J. Geophys. Res. 106, 3371–3380.

Kristjansson, J.E., Staple, A., Kristiansen, J., Kaas, E., 2002. A new look at possible connections between solar activity, clouds and climate. Geophy. Res. Lett. 29 (23), 2107.

Krivova, N.A., Solanki, S.K., Fligge, M., Unruh, Y.C., 2003. Reconstruction of solar irradiance variations in cycle 23. Is solar surface magnetism the cause? Astron. Astrophys. 399, L1–L4.

Le Treut, H., Forichon, M., Boucher, O., Li, Z.-X., 1998. Indirect effect and CO_2 greenhouse forcing. Equilibrium response. J. Climate 11, 1673.

Lean, J., 2000. Evolution of the Sun's spectral irradiance since the maunder minimum. Geophys. Res. Lett. 27 (16), 2425–2428.

Lean, J., Beer, J., Bradley, R., 1995. Reconstruction of solar irradiance since 1910: implications for climate change. Geophys. Res. Lett. 22, 3195–3198.

Lockwood, M., 2005. Variability on century timescales. In: Rüedi, I., Güdel, M., Schmutz, W. (Eds.), The Sun, solar analogs and the climate. Swiss Society for Astrophysics and Astronomy Advanced Course, March 15–20, 2004, Davos, Switzerland. Springer, Berlin, pp. 109–306.

Lockwood, M., Stamper, R., 1999. Long term drift of the coronal source magnetic flux and the total solar irradiance. Geophys. Res. Lett. 26, 2461.

Marsh, N.D., Svensmark, H., 2000. Low cloud properties influenced by cosmic rays. Phys. Rev. Lett. 85, 5004–5007.

Pap, J., 2003. Total solar and spectral irradiance: variations from near UV to IR. In: The Sun's Surface and Subsurface. In: Rozelot, J.P. (Ed.), Lecture Notes in Physics, vol. 599. Springer, pp. 129–155.

Ramanathan, V., Cess, R.D., et al., 1989. Cloud radiative forcing and climate. Results from the Earth radiation budget experiment. Science 243, 57–63.

Roeckner, E., Siebert, T., Feichter, J., 1994. Climatic response to anthropogenic sulfate forcing simulated with a GCM. In: Aerosol Forcing of Climate. John Wiley and Sons, p. 349.

Rozelot, J.P., Lefebvre, S., Pireaux, S., Ajabshirizadeh, A., 2004. Are non-magnetic mechanisms such as temporal solar diameter variations conceivable for an irradiance variability? Solar Phys. 224, 229–235.

Sofia, S., Li, L., 2001. Solar variability and climate. J. Geophys. Res. 106, 12969.

Solanki, S., Fligge, M., 1999. A reconstruction of total solar irradiance since 1700. Geophys. Res. Lett. 26, 2465–2468.

Solanki, S., Fligge, M., 2001. Long-term changes in solar irradiance. ESA-SP-463.

Solanki, S., Krivova, N.A., 2003. Can solar variability explain global warming since 1970? J. Geophys. Res. 108 (A5), 1200.

Taylor, K.E., Penner, J.E., 1994. Response of the climate system to atmospheric aerosols and greenhouse gases. Nature 369, 734.

Valev, D., 2001. Statistical analysis of the relations between the global surface air temperature and the solar and geomagnetic activity from the middle of the XIX until the end of the XX century. In: Proceedings of National Conference on 40-years Union of the Scientists, Staru Zagora, Bulgaria, pp. 121–125.

Willson, R.C., Mordinov, A.V., 2003. Secular total solar irradiance trend during solar cycles 21 and 22. Geophys. Res. Lett. 30, 1199–1202.