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Advances in Space Research 34 (2004) 361–364
ADVANCES IN SPACE RESEARCH
(a COSPAR publication)
www.elsevier.com/locate/asr

Solar variability and global warming: a statistical comparison since 1850

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Received 19 October 2002; received in revised form 26 February 2003; accepted 26 February 2003

Abstract

The magnitude of the Sun's influence on climate has been a subject of intense debate. Estimates of this magnitude are generally based on assumptions regarding the forcing due to solar irradiance variations entering climate modelling. Given the complexity of the climate system, however, such modelling is perforce based on simplifying assumptions, which leaves it open to criticism. We take a complementary approach. We assume that the Sun has been responsible for climate change prior to 1970 and that their interrelation remained unchanged afterwards. Then, employing reconstructions and measured records of relevant solar quantities as well as of the cosmic-ray flux, we estimate statistically which fraction of the dramatic temperature rise after that date could be due to the influence of the Sun. We show that at least in the most recent past (since about 1970) the solar influence on climate cannot have been significant.

Keywords: Solar activity; Solar variability; Global warming; Global climate

1. Introduction

Good correlations between solar magnetic activity and the temperature of the Earth's atmosphere have been found by, e.g., Eddy (1976), Reid (1987), Friis-Christensen and Lassen (1991), Lean et al. (1995), Solanki and Fligge (1998, 1999) on a time-scale of decades to centuries. Recently, Marsh and Svensmark (2000) presented also a correlation over a solar cycle between the cosmic-ray intensity, which is modulated by the strength of the Sun's interplanetary magnetic field, and the coverage of low-lying clouds. In spite of this there have been indications that in recent years the correlation between the secular variation of solar quantities and the evolution of global temperature has waned (Solanki and Fligge, 1998; Thejll and Lassen, 2000; Lean et al., 2001). Here we consider this point in greater detail.

Estimates of the magnitude of the solar influence on climate are generally based on assumptions regarding the forcing due to solar irradiance variation and climate modelling. However, the Earth's atmosphere is a complex system and the forcing from all sources is not understood, which makes such estimates very uncertain. We therefore, consider an alternative, empirical approach. We *assume* that the Sun has been responsible for the change of terrestrial temperature prior to 1970 and that this interplay remained the same after 1970. Then, using reconstructions and measured records of relevant solar quantities, we estimate which fraction of the dramatic temperature rise after that date could be due to the influence of the Sun. Since, by dint of our original assumption, we cannot underestimate the solar contribution to global warming prior to 1970, through the present analysis we should obtain an upper limit on the fraction of the warming due to the Sun also after 1970.

2. Solar activity and terrestrial temperature

Various processes have been invoked by which the inconstant Sun can influence the troposphere: (i) changes in the energy input into the Earth's atmosphere

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doi:10.1016/j.asr.2003.02.051

through variations in the total solar irradiance; (ii) changes in stratospheric chemistry through variations of solar UV irradiance; (iii) changes in cloud cover induced by modulations in the cosmic ray flux produced by variations in the Sun's open magnetic flux. We now consider the solar data and reconstructions relevant for each of these mechanisms and compare them with climate records.

3. Total solar irradiance

Measurements of the total solar irradiance exist since 1978. Unfortunately, no single instrument managed to survive over the whole period, so that the irradiance record for this period is a patchwork made from the measurements of a number of individual instruments, each of which has its own calibration and exhibits a slightly different absolute total solar irradiance. It is therefore, not surprising that Willson (1997) and Fröhlich and Lean (1998) reached different conclusions regarding the secular trend of the composite record. Willson (1997) claimed that the total solar irradiance increased by 0.036% from the solar activity minimum in 1985 to that in 1996, while Fröhlich and Lean (1998) see no evidence for such an increase. We therefore, use both composites here.

To extend the total solar irradiance record to earlier times we use recent reconstructions of Solanki and Fligge (1999) and Fligge and Solanki (2000). The resulting curves for the total solar irradiance are plotted in Fig. 1(a). Prior to 1979 the irradiance is described by two curves based on different assumptions regarding the secular evolution of the irradiance. One follows the cycle length (thick solid curve), the other the cycle amplitude (thin; see Solanki and Fligge, 1999 for details). The true evolution of the irradiance is expected to lie roughly between these curves. Note that the two reconstructions both agree very well with the composite of Fröhlich and Lean (1998) for the period 1978–1997 (Fligge and Solanki, 2000).

Also plotted in Fig. 1(a) are two temperature records compiled by the Climatic Research Unit of the University of East Anglia, one exhibiting global (thick dashed curve), the other northern hemisphere surface (thin) temperatures (Jones, 1994; Parker et al., 1995). If one considers the period prior to 1970, there is an excellent correlation between either of the irradiance and the temperature records, with low χ^2 values ($\chi^2/N =$ 0.001–0.006, where N is the number of data points). If the period after 1970 is included the χ^2/N increases to 0.011–0.020.

The irradiance curves plotted in Fig. 1(a) are based on an increase in the 11 year averaged total irradiance since the Maunder minimum of 4 W/m^2 following Solanki and Fligge (1999). This quantity is relatively uncertain, with values between 2 and 8 W/m^2 being quoted in the literature on the basis of stellar observations and their comparison with the Sun. Since the change in irradiance since 1978 is known (within the uncertainty given by the two composites), the amplitude of the secular irradiance changes since that time is fixed, irrespective of the amplitude before that epoch. A larger increase between 1700 and 1978 would thus lead to a stretching of the scale for the irradiance change prior to 1978 in Fig. 1(a). In this case solar total irradiance variations can be responsible for an even smaller part of the temperature rise after 1970.

If, however, the secular irradiance change between 1700 and 1978 was smaller, the scaling would change in the opposite direction and it is conceivable that the Sun has provided a bigger contribution to global warming since then. Different arguments suggest a lower limit to the secular change in irradiance since 1700 of at least 2

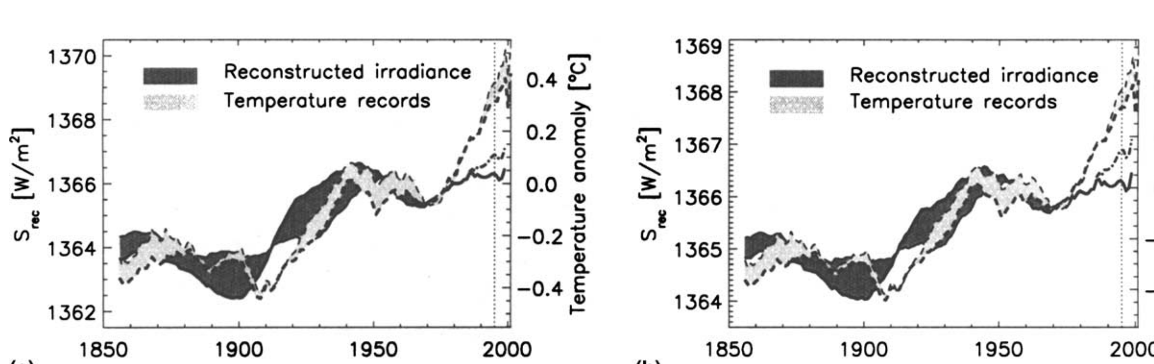

Fig. 1. Total solar irradiance and terrestrial temperature anomaly vs. time: (a) for irradiance reconstructions with an increase in the 11 year averaged irradiance between 1700 and 1980 of 4 W/m^2; (b) for irradiance reconstructions with an increase in the 11 year averaged irradiance between 1700 and 1980 of 2 W/m^2 (see the left-hand scale). The solid curves prior to 1985 represent irradiance reconstructions (thick curve: cycle-length based, thin: cycle-amplitude based). From 1985 onwards they represent total irradiance measurements (solid: composite of Fröhlich and Lean, 1998; dot-dashed: composite following Willson, 1997). The dashed curves represent global (thick) and northern hemisphere (thin) temperatures. All curves have been smoothed by an 11 year running mean. After the epoch marked by the vertical dotted line the averaging period has been successively reduced.

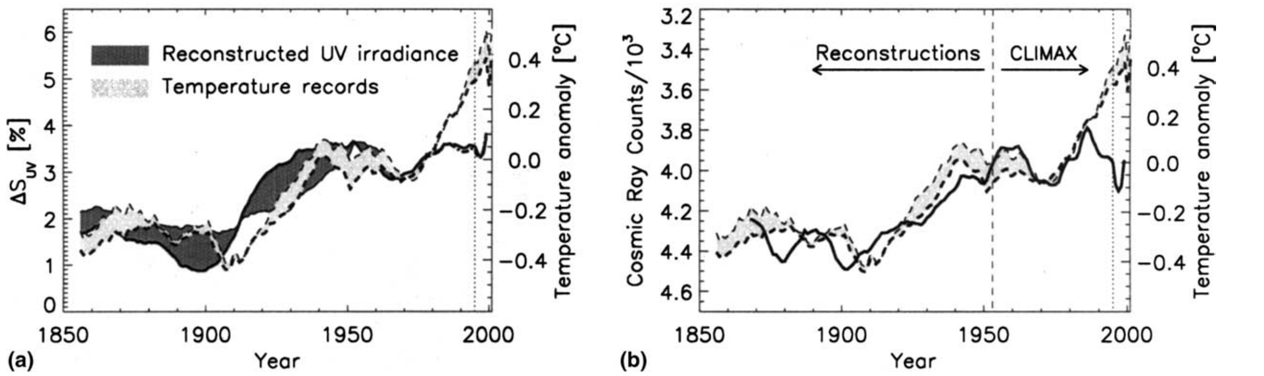

Fig. 2. (a) The same as Fig 1(a), but for UV irradiance (solid curves). From 1986 onwards Mg II measurements are shown (solid and dot-dashed lines represent compilations by Viereck and Puga, 1999 and Cebula et al., 1992, respectively). (b) The same as Fig. 1, but now exhibiting a composite of cosmic ray flux (solid) instead of irradiance.

W/m^2 (see Solanki and Fligge, 1998, 1999). In Fig. 1(b) we replot the quantities already shown in Fig. 1(a), but with the secular part of the irradiance reconstruction now scaled to give 2 W/m^2 change in the 11 year average of the total irradiance since the Maunder minimum. Because the enhancement since 1970 remains fixed, in particular the reconstruction incorporating Willson's composite now lies closer to the temperature curve. Nevertheless, even in this most optimistic case the solar total irradiance variations cannot be responsible for more than roughly half of the steep temperature increase since 1970.

3.1. Solar UV irradiance

Consider now UV irradiance variations. We use the Mg II core-to-wing ratio obtained on-board several spacecraft (Cebula et al., 1992; Viereck and Puga, 1999) as a proxy of UV irradiance since 1990 and combine it with the reconstruction ($\lambda < 3000$ Å) of Fligge and Solanki (2000) for the period 1856–1990. The 11 year average of the UV irradiance has a form very similar to the total irradiance between 1856 and 1999, except that the relative change is larger for the UV irradiance (Fig. 2(a)). In particular the 11 year mean is flat since 1975, in agreement with the composite of Fröhlich and Lean (1998) for the total irradiance. If we accept that total and UV irradiance have the same cause, namely changes in the amount and distribution of the magnetic flux at the solar surface (e.g., Solanki and Fligge, 2002), then this fact provides strong independent support for the composite of Fröhlich and Lean (1998) compared with that constructed following Willson (1997).

For the period prior to 1970, $\chi^2/N = 0.001$–0.005, but it increases to 0.011–0.017 if the period after 1970 is included. We estimate that if UV irradiance is the main channel by which the Sun influences climate, then the Sun has contributed less than 30% to the temperature increase since 1970.

3.2. Cosmic ray flux

The third major mechanism proposed to affect tropospheric temperature is cloud-cover variations induced by modulations in cosmic-ray flux caused by changes in the Sun's open magnetic field (Svensmark and Friis-Christensen, 1997; Marsh and Svensmark, 2000). In this case we are in the fortunate situation that there is a relatively reliable estimate of the evolution of the Sun's open magnetic flux since 1868 (Lockwood et al., 1999; Solanki et al., 2000), which modulates the cosmic ray flux. Direct measurements of sufficient quality by the Climax Neutron Monitor (cut-off 3 GV) are available from the University of Chicago since 1953. An overlap of more than 40 years between the open magnetic flux and neutron monitor data has been used to convert the indirect record into cosmic-ray flux for the earlier period.

The combined cosmic-ray record is plotted in Fig. 2(b) after applying an 11 year smoothing. Also plotted is the global temperature record repeated from Fig. 1. In this case the two quantities follow each other closely up to 1985, after which they strongly diverge.

4. Conclusions

We have compared records of three solar quantities considered to be candidates for influencing the Earth's climate. We have extended the observed records of these quantities to earlier times by combining them with reconstructions taken from the literature. In all but one case, namely the measured total irradiance record following the intercalibration due to Willson (1997), the reconstruction and the data agree relatively well with each other during the period over which they overlap. These combined records of the solar total and UV irradiance as well as the cosmic-ray flux are then compared with climate records. We have shown that even in the extreme case that solar variability caused *all* the global climate change prior to 1970 it cannot have been responsible for more than 30% (50% for the intercalibration by Willson, 1997) of the strong global temperature rise since 1970.

Acknowledgements

We thank M. Fligge for his kind help with the irradiance reconstruction and M. Lockwood for providing the coronal source flux. The temperature record has been compiled by the Climatic Research Unit (University of East Anglia), Mg II data by GSFC for 1978–1993, NRL for 1991–2001 and, alternatively, by NOAA for the whole period. Total solar irradiance measurements have been provided by PMOD/WRC, Davos, Switzerland and the Climax Neutron Monitor data by the University of Chicago.

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