SOLAR TOTAL AND SPECTRAL IRRADIANCE: MODELLING AND A POSSIBLE IMPACT ON CLIMATE

N. A. Krivova and S. K. Solanki

Max-Planck-Institut für Aeronomie, 37191 Katlenburg-Lindau, Germany

ABSTRACT

There is growing evidence that solar variability influences the Earth's climate, although the underlying mechanism is not yet understood. Variations in the solar total and spectral irradiance often play a central role within various processes that have been suggested. Whereas changes in the total irradiance can affect the overall energy balance of the Earth's atmosphere, variations in its spectral distribution, in particular in the UV, have a pronounced effect on the chemistry of the Earth's upper atmosphere. Measurements of the solar total irradiance are only available since 1978 and the spectral irradiance record is even shorter. This calls for a reconstruction of irradiance variations at earlier times with the help of models. We first outline our current understanding of the main mechanism responsible for irradiance variations and describe the efforts to reconstruct them. The reconstructed total and UV irradiance is then employed to estimate the solar contribution to global warming, with particular emphasis to the period since 1970.

1. INTRODUCTION

Global climate change has become a key scientific topic. Climate can vary for many reasons. In particular, human activity leads to radiative forcing by changing the atmospheric concentrations of greenhouse gases and aerosols. The amount of carbon dioxide in the atmosphere has increased by more than 25% in the past century (Houghton et al., 1996). Concentrations of other greenhouse gases have also increased. Things are complicated by the fact that anthropogenic changes lie on top of natural climate variability, whose nature remains uncertain.

Since solar radiation is the principal driving force for the Earth's environment, we have reasons to believe that it can also play a part in determining the Earth's climate. But how crucial is the Sun's role? In actual practice, this is difficult to assess. Related terrestrial changes take place on long time scales, decades to centuries, and cannot be measured directly. On the other hand, there is growing evidence that a connection exists.

The coincidence of the Spörer and Maunder minima with two temperature dips of the Little Ice Age in the 16th and 17th centuries and of the Grand Maximum with the Medieval Warm Period during the 9th to 13th centuries (e.g., Eddy, 1976) argues for this interrelation. Also, the Dalton minimum at the beginning of 19th century agrees with a cold and severe period. The decade 1810–1820 was the coldest in England since the end of the Maunder minimum and the Thames froze over to a sufficient depth to allow the Christmas Fair to be hold there. Good correlations have been found between different proxies of solar activity and climate records, e.g., between the sunspot number and global sea surface temperatures (Reid, 1987), the length of the solar cycle and Northern hemisphere air temperature (Friis-Christensen & Lassen, 1991), solar irradiance and the global and Northern hemisphere temperatures (Solanki & Fligge, 1999; Solanki & Krivova, 2003) or cosmic ray flux and the cloud coverage (Marsh & Svensmark, 2000). On yet longer, centennial to millennial time-scales solar activity can be traced by the production rates of cosmogenic isotopes, such as ^{10}Be, ^{14}C or ^{36}Cl (Stuiver & Quay, 1980; Beer et al., 1990; Baumgartner et al., 1998). Comparison with different climate records gave significant correlations (e.g., Eddy, 1976; Bond et al., 2001; Neff et al., 2001; Hodell et al., 2001; Ogurtsov et al., 2002). For more about long-term correlations see the review by Muscheler and Beer (these proceedings).

However, the correlations on their own do not yet provide information on the mechanisms of this influence. The Sun can affect the Earth's climate in different ways, but neither sunspots nor the length of the solar cycle can directly influence the climate. Being the principal source of energy for the Earth, solar net radiative output can influence the energy balance of the Earth's surface and atmosphere. In addition, variations of solar UV irradiance affect stratospheric chemistry, in particular the balance between ozone production and destruction (e.g., Haigh, 1994, 1996, cf. Schmidt & Brasseur, these proceedings). Finally, the cosmic ray flux modulated by variations in the Sun's open magnetic flux has been proposed to trigger changes in the global coverage by low-lying clouds (Svensmark & Friis-Christensen, 1997; Marsh & Svensmark, 2000).

Nonetheless, it remains unclear how strong the Sun's influence is and which process is playing the main role. This is not least due to the relevant time scales. Here we describe some recent efforts to improve this situation.

Proc. ISCS 2003 Symposium, 'Solar Variability as an Input to the Earth's Environment', Tatranská Lomnica, Slovakia, 23-28 June 2003 (ESA SP-535, September 2003)

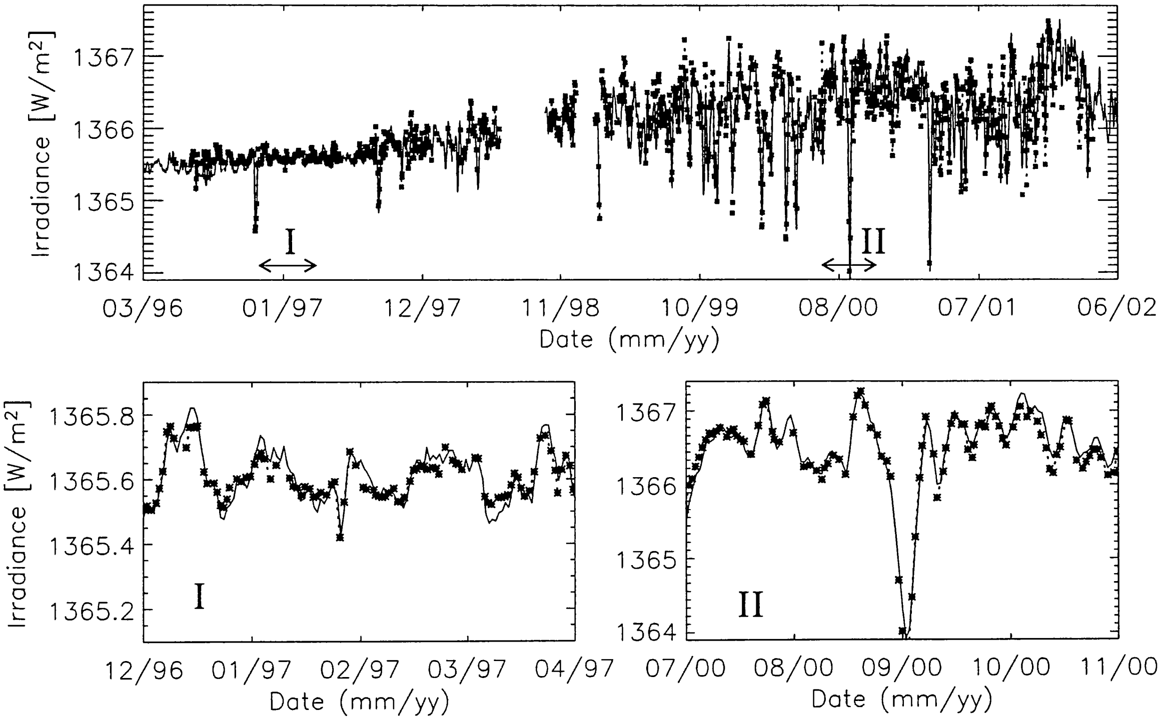

Figure 1. Reconstruction (asterisks connected by dotted curve when there are no data gaps) and VIRGO measurements (solid line) of total solar irradiance between 1996 and 2002, i.e. from the onset of cycle 23 to its maximum (top panel). The bottom panels show a zoom-in to two shorter intervals at different activity levels. The times corresponding to these zoom-ins are marked in the top panel by roman numerals.

2. IRRADIANCE CHANGES ON TIME SCALES OF THE SOLAR CYCLE AND SHORTER

Measurements of the solar total irradiance with sufficient accuracy have been carried out only since 1978 and the record of well calibrated spectral irradiance is even shorter (see reviews by Fröhlich and Floyd et al., these proceedings). Obviously, the length of the time series is much too short to allow any conclusions about climate effects. Due to the coupling of the Earth's atmosphere with the oceans, and due to the strong short term fluctuations (El Niño, seasonal effects) trends in climate due to external forcing only become visible in longer time series. This calls for a reconstruction of irradiance variations at earlier times, which in turn requires a certain understanding of the mechanisms underlying this variability.

The models that have been worked out in greatest detail assume that the variations of the total solar irradiance are due to the evolution of the solar surface magnetic field, subdivided into dark sunspots and bright faculae (including the network) (Foukal, 1992; Chapman et al., 1996; Fligge et al., 2000a,b; Krivova et al., 2003). Sunspots are the largest concentrations of magnetic flux tubes on the solar surface and appear dark. Their passage across the solar disc leads to decreases of solar brightness and dominates irradiance changes on the time scale of a solar rotation. The smaller flux tubes forming faculae and the network cause a brightening of the Sun. Both sunspots and the bright magnetic features are modulated with the solar activity cycle, although in absolute terms the total area covered by sunspots increases not nearly so much as that of the bright elements. As a result, the Sun brightens at activity maximum.

To model irradiance variations on time scales of a solar cycle and less, Fligge et al. (2000a) and Krivova et al. (2003) adopted a four-component model of the solar photosphere including quiet Sun (i.e. the part of the solar surface free of magnetic fields), umbrae and penumbrae of sunspots as well as faculae. The total solar brightness is then given by the time independent brightness of the quiet Sun and the brightness of the flux tubes whose number and distribution on the Sun is steadily evolving. The fluxes are calculated using the ATLAS9 code of Kurucz (1992) from plane-parallel model atmospheres of the quiet Sun, umbra, penumbra and faculae (see Unruh et al., 1999, for details). The filling factors of each component are extracted from daily full-disc magnetograms and continuum images recorded by the Michelson Doppler Interferometer (MDI, Scherrer et al., 1995). The model contains a single free parameter, which takes into account saturation of brightness in faculae. To put it differently, the magnetic elements in regions with

2003ESASP.535..275K

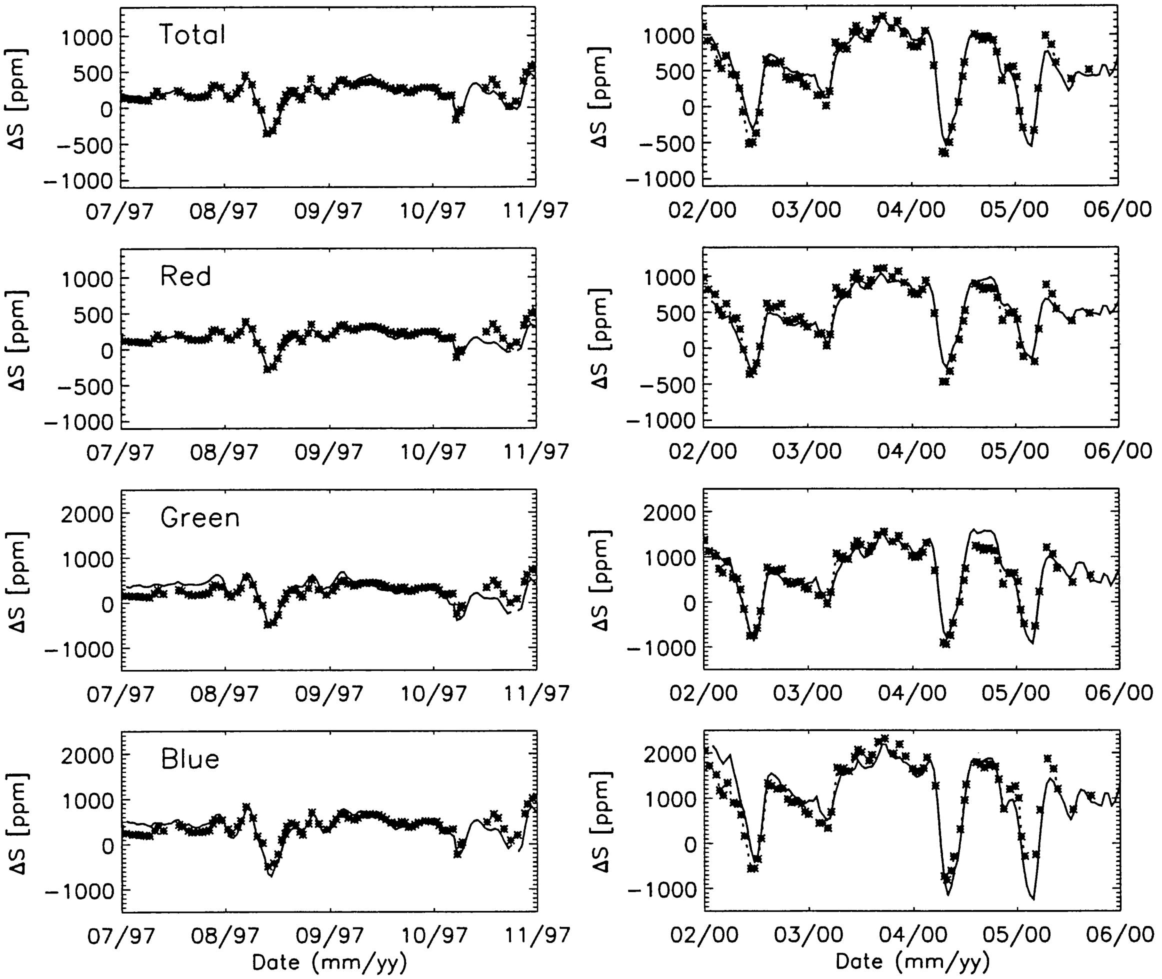

Figure 2. From top to bottom: reconstructed irradiance variations (asterisks connected by dotted lines) for the total solar irradiance as well as for the three VIRGO spectral channels centred at 862 nm, 500 nm and 402 nm for two periods of 4 months each around activity minimum (left panels) and maximum (right panels). The VIRGO measurements are represented by the solid line (from Krivova et al. 2003).

higher flux are less bright (e.g., Solanki, 1986; Solanki & Brigljević, 1992; Ortiz et al., 2002), whereas a single atmosphere is used in the model to describe faculae and the network. The free parameter is taken such that the model reproduces short-term irradiance variations caused by solar active regions passing across the solar disc as the Sun rotates. Simultaneously, however, this model reproduces very well the slow variation over the solar cycle.

Figure 1 shows the whole period of the reconstruction (1996–2002, top panel) as well as two extracts on an enlarged scale (bottom panels). Also shown are the level 2 VIRGO measurements (Fröhlich & Finsterle, 2001). The figure is an updated version of Fig. 1 from Krivova et al. (2003). At the time of submission of that paper, VIRGO data were only available till September 2001 and showed a first maximum in the irradiance in the year 2000. The reconstructions predicted a second maximum, at least as strong as the first one, around the turn of 2001. The second maximum is now seen in the more up to date VIRGO data too and observations are in excellent agreement with the reconstructions.

The model, still with the same value of the free parameter, also reproduces spectral irradiance variations. Figure 2 compares the model with the measurements of the total irradiance as well as irradiance in the three VIRGO spectral channels: red, green and blue centred at 862 nm, 500 nm and 402 nm. Unfortunately, the quick degradation of VIRGO's spectral photometers does not allow a complete elimination from the long-term instrumental trends (see Fröhlich, these proceedings) and makes a comparison on time scales longer than several months impossible.

The MDI came into operation in 1996, so that it is not possible to reconstruct irradiance further back in time. However, magnetograms with a nearly daily cadence have also been recorded at NSO/Kitt Peak (KP). Like all ground-based observations they suffer from less stable seeing than the MDI data. A big advantage, however, is that they are available back to 1974, i.e. for two more solar cycles (although at reduced quality prior to 1992). The analysis by Wenzler et al. (in preparation) shows that the quality of the data is good enough to be used for reconstructions of solar irradiance. Wenzler et al. have completed a reconstruction based on the KP data for the MDI period and compared it with that of Krivova et al. (2003). Although showing a slightly higher scatter, the model is in accordance with the VIRGO data and MDI reconstructions. Whereas the correlation coefficient is $r_c = 0.96$ for the MDI reconstruction, it is only slightly lower, $r_c = 0.94$, for the KP data-based model (Fig. 3).

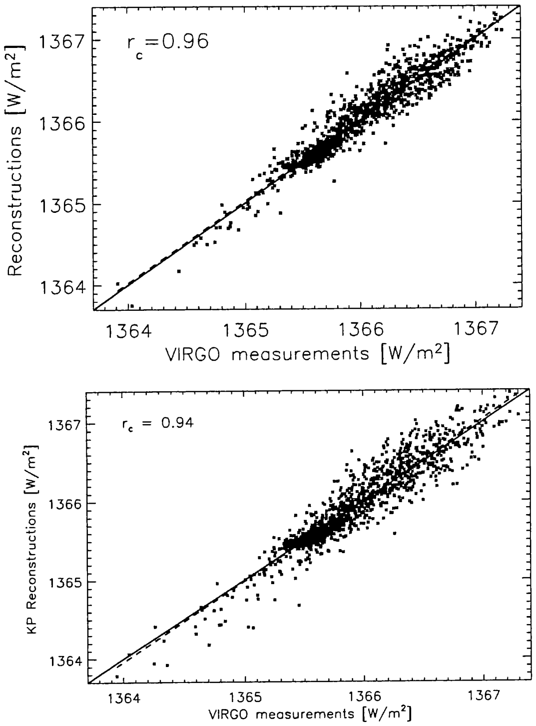

Figure 3. Modelled total solar irradiance vs. VIRGO measurements. The top panel shows the model based on MDI data (correlation coefficient $r_c = 0.96$). The bottom panel was obtained using KP data ($r_c = 0.94$). (The bottom plot has kindly been provided by Th. Wenzler).

The excellent agreement between models and data provides strong support for the conclusion that the magnetic field at the solar surface is the main driver of the solar irradiance variability at time scales of the solar rotation and the solar cycle. No additional component is required to reproduce the long-term increase of solar irradiance between activity minimum and maximum apart from sunspots and small magnetic elements forming faculae and the network.

3. LONGER-TERM VARIATIONS OF SOLAR IRRADIANCE

3.1. Cyclic component

Such detailed models cannot be extended to earlier times, before regular magnetograms started being recorded. They imply, however, that if the evolution of the solar surface magnetic flux is known (either from direct measurements or by proxy), it is possible to reconstruct the cyclic component of the past irradiance changes, although in less detail. A number of reconstructions based on different proxies of the magnetic field distribution and their combinations have been performed in the last decade (Foukal & Lean, 1990; Hoyt & Schatten, 1993; Lean et al., 1995, 2001; Solanki & Fligge, 1998, 1999; Fligge & Solanki, 2000; Lockwood & Stamper, 1999; Foster & Lockwood, 2003). The most frequently used proxy record is the Zürich Relative Sunspot Number, R_z, available as yearly means since 1700, monthly means since 1750 and daily data from 1818 onwards. Back to 1610 goes the record of the Group Sunspot Number, R_g, including daily measurements since 1874 and monthly averages before that. Since 1874 daily sunspot and facular areas have also been recorded.

Figure 4 shows the reconstruction by Solanki & Fligge (1999) of the cyclic component of total solar irradiance back to 1700 based on R_z (upper curve) and R_g (lower curve). The quality of reconstructions progresses with time following that of the proxies and is best after 1874 when the sunspot and facular areas started being recorded individually. Averaged over 11 years, the increase in the total irradiance due to the cyclic component is about 0.4–0.7 $\mathrm{W\,m^{-2}}$ (Solanki & Fligge, 1998, 1999). This seems rather little to cause significant changes in global climate.

3.2. Secular change

There is some evidence, however, that the solar irradiance might have changed more in the last centuries. The first, circumstantial piece of evidence comes from the comparison of the Sun with other sun-like stars. Emission in the cores of the Ca II H and K lines of other stars can be used to estimate their magnetic activity. It has been argued that stars with the lowest Ca II brightness do not show any cyclic modulations (Baliunas & Jastrow, 1990). On the other hand, White et al. (1992) found that during the last few cycles the Sun's Ca II level always remained considerably higher than that of most other late-type field stars. This leads to an estimate of about 2 to 6 $\mathrm{Wm^{-2}}$ in the Sun's total irradiance change since the Maunder minimum, provided the relationship between solar Ca II brightness and irradiance did not change. Other indicators also support an increase between 2 and 8 $\mathrm{Wm^{-2}}$ (Nesme-Ribes & Manganey, 1992; Hoyt & Schatten, 1993; Zhang et al., 1994; Lean et al., 2001).

Based on such evidence a number of models including a secular irradiance trend have been constructed (Hoyt & Schatten, 1993; Lean et al., 1995; Solanki & Fligge,

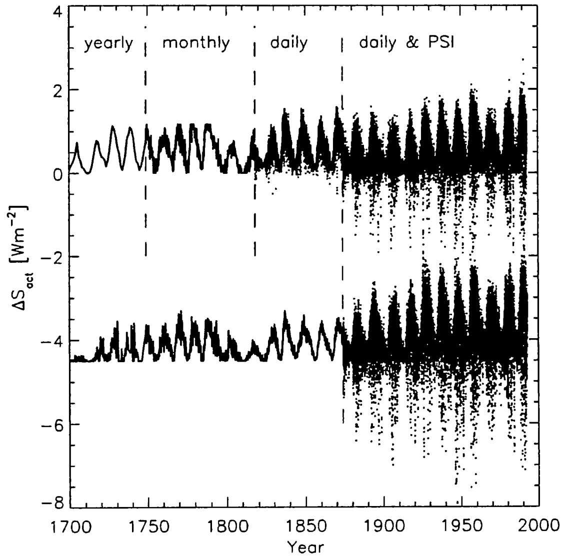

Figure 4. Cyclic component of the reconstructed total irradiance. The upper curve is based on the R_z record, the lower on R_g (from Solanki & Fligge 1999).

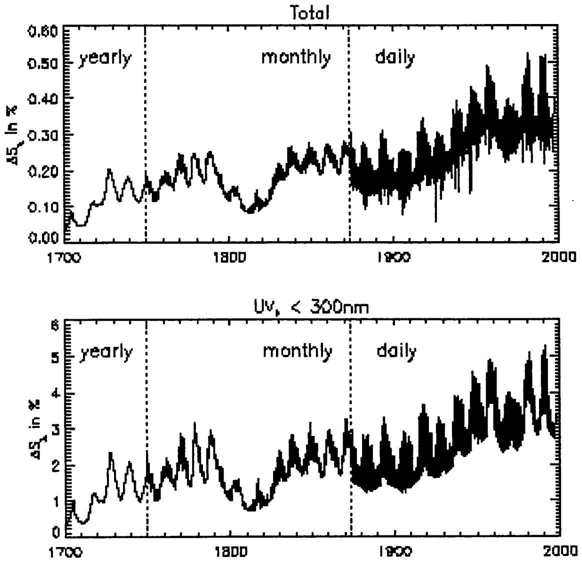

Figure 5. Reconstruction of the total (top) and UV (<300 nm, bottom) irradiance since the Maunder minimum (from Fligge & Solanki 2000).

1998, 1999; Fligge & Solanki, 2000). Figure 5 shows the reconstruction by Fligge & Solanki (2000) of the total and UV (below 300 nm) irradiance since the end of the Maunder minimum. It includes both the cyclic component shown in Fig. 4 and the secular trend of 4 Wm^{-2}. Both the total and UV irradiance evolved very similarly, at least during the recent centuries. Results for the other spectral regions can also be found in the paper.

3.3. Solar variability and global warming

Solanki & Krivova (2003) have used the reconstructed irradiance shown in Fig. 5 to tackle the question, whether the Sun can be responsible for the climate change of the last few decades. The mean global surface temperature has increased by about 0.3° to 0.6°C since the late 19th century, and by about 0.2° to 0.3° over the last 40 years (Houghton et al., 1996). An estimate of the magnitude of the solar influence on climate normally requires some assumptions of the radiative forcing due to solar contribution (and other sources). We are still, however, quite far from a comprehensive understanding of the forcing in such a complex system as the Earth's atmosphere, which imbues all estimates of this kind with a measure of uncertainty.

Therefore, the work by Solanki & Krivova (2003) is based on a different assumption, namely that the Sun has been entirely responsible for the change of terrestrial temperature prior to 1970. Assuming also that the interplay between the two systems remained the same after 1970, it is possible to estimate which fraction of the temperature rise after that date could be due to the influence of the Sun. Other sources might have contributed (and previously did) to the climate change at earlier times, so that the Sun actually played a smaller role. But in this way one cannot overestimate the contribution of the Sun after 1970 and the approach gives an upper limit on the possible magnitude of this influence.

In order to construct an irradiance record of sufficient length to allow its comparison to the Earth's climate, the reconstructions of the total solar irradiance by Fligge & Solanki (2000) have been merged together with measurements since 1978. These measurements have been obtained by different instruments, whose intercalibration is a rather intricate challenge. One composite has been put together by Fröhlich & Lean (1998, see also the review by Fröhlich), which indicates that the irradiance was about the same during the two recent solar activity minima. In contrast, Willson (1997) believes that the total solar irradiance increased by 0.036% from the solar minimum in 1985 to that in 1996. A contentious point is how to interface the ERB/NIMBUS-7 data with measurements by other instruments. Poor overlap with other instruments does not allow a reliable estimate of its degradation. Chapman et al. (1996) proposed to introduce a correction amounting to a total of 0.63 Wm^{-2} to the ERB/NIMBUS-7 observations, which was accepted by Fröhlich & Lean (1998) but not by Willson (1997).

Figure 6 shows the reconstruction by Fligge & Solanki (2000, black dots) overplotted on two composites, that of Fröhlich and Lean in the top panel and Willson's at the bottom (grey curves). The reconstruction is in good agreement with the record of Fröhlich & Lean (1998), but diverges after 1990 from that of Willson (1997). Since the secular trend of the reconstruction was obtained completely independently, this provides strong support for the

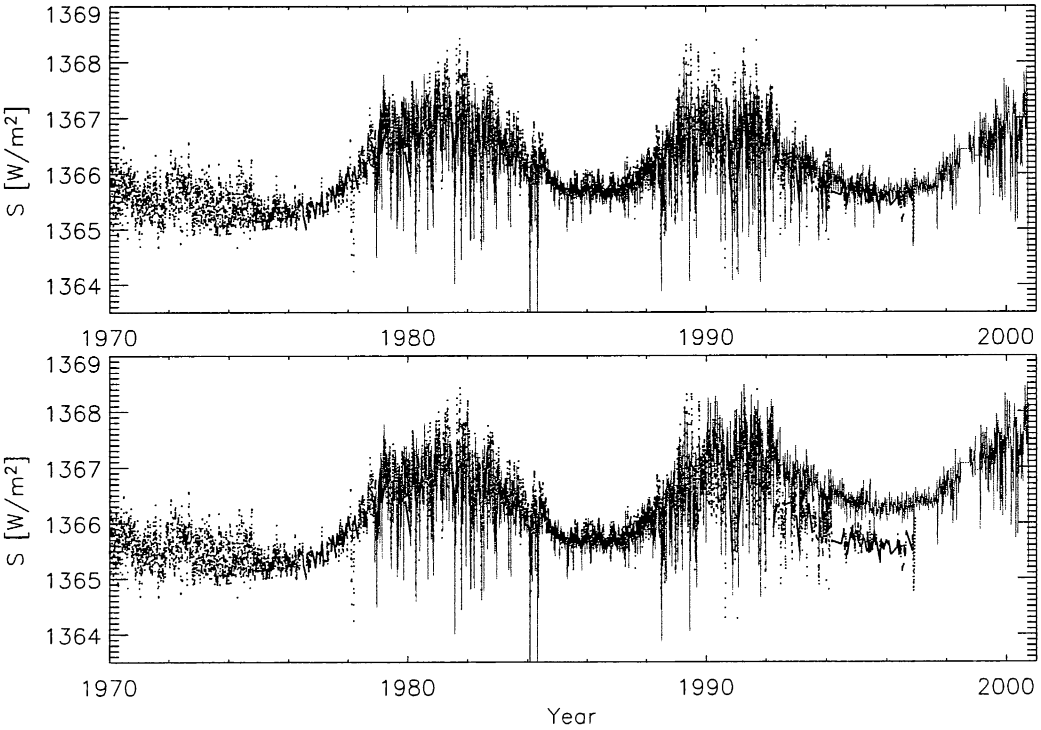

Figure 6. Reconstructed total solar irradiance (black dots, following Fligge & Solanki 2000, the complete record is shown in the top panel of Fig. 5) and measurements (grey solid curve): the latter corresponds to the composites by Fröhlich & Lean (1998, top panel) and by Willson (1997, bottom).

composite of Fröhlich & Lean (1998). An additional argument against the secular increase of the total irradiance is provided by the evolution of the UV irradiance. Neither the Mg II core-to-wing ratio, which is the standard proxy of UV irradiance, nor the UV-irradiance reconstruction show the increase from one minimum to another (Cebula et al., 1992; Viereck & Puga, 1999; Fligge & Solanki, 2000).

Figure 7a shows the resulting total solar irradiance for the period 1856–2000. 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 amplitude (thin solid curve), the other the cycle length (thick, see Solanki & Fligge, 1999). Also plotted are two temperature records compiled by the Climatic Research Unit of the University of East Anglia, one exhibiting global (thick dashed line), the other northern hemisphere (thin) surface temperatures (Jones, 1994; Parker et al., 1995; Jones et al., 2001). Considering the period prior to 1970 results in excellent correlation between either of the irradiance and temperature records, with low χ^2 values ($\chi^2/N = 0.001 - 0.005$, where N is the number of observations). If the period after 1970 is included the χ^2/N increases to 0.012–0.020.

The irradiance curves in Fig. 7a are based on an increase in the 11-year averaged total irradiance since the Maunder minimum of 4 Wm^{-2}. This quantity is subject to large uncertainties, with values between 2 Wm^{-2} and 8 Wm^{-2} being usually quoted (see Sect. 3.2). Since the change in irradiance after 1978 is fixed by the measurements, a larger increase between 1700 and 1978 would thus lead to a stretching of the scale for the irradiance change prior to 1978. 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 change since 1700 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. Figure 7b shows again the quantities already presented in Fig. 7a, but for the secular change in the reconstructed irradiance of 2 Wm^{-2}. From the figures we conclude that, if variability of the solar total irradiance is the main channel of the solar influence on the Earth's climate, then less than 30% (50% for the Willson's composite) of the dramatic temperature rise since 1970 can be attributed to the Sun.

The situation does not change if the UV irradiance is considered as the main driver of the Earth's climate. The Mg II core-to-wing ratio measured since 1978 (Cebula et al., 1992; Viereck & Puga, 1999) can be combined with the UV irradiance reconstructions of Fligge & Solanki (2000) to provide a complete record for the period 1856-2000. The 11-year average of the UV irradiance has a form very similar to the total irradiance

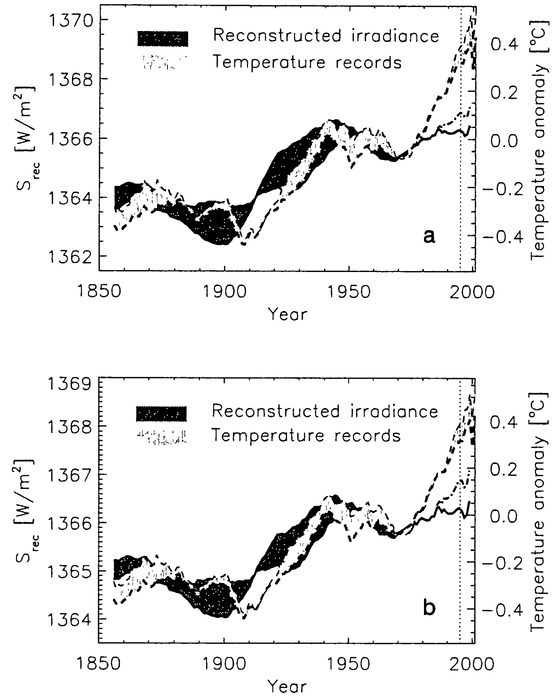

Figure 7. Total solar irradiance and terrestrial temperature vs. time: **a)** *for an irradiance reconstruction with an increase in the 11-year averaged irradiance between 1700 and 1980 of 4 Wm*$^{-2}$*;* **b)** *for an irradiance reconstruction with an increase in the 11-year averaged irradiance between 1700 and 1980 of 2 Wm*$^{-2}$*. 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 & 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 (from Krivova & Solanki 2003).*

for the same period, except that the relative change is larger for the UV irradiance. For the period prior to 1970, $\chi^2/N = 0.001 - 0.004$, but it increases to 0.011–0.017 if the period after 1970 is included. If UV irradiance is the main mechanism by which the Sun affects climate, then the Sun has also contributed less than 30% to the temperature rise since 1970.

Another major channel through which the Sun can affect climate is the cosmic ray flux. The cosmic ray flux has been proposed to modulate the cloud cover and thus influence tropospheric temperatures (Svensmark & Friis-Christensen, 1997; Marsh & Svensmark, 2000). Direct measurements by the Climax Neutron Monitor since 1953 can be combined with modelled flux based on the reconstruction of the evolution of the Sun's open magnetic flux since 1868 by Lockwood et al. (1999) and Solanki et al. (2000). The combined, 11-year averaged record is plotted in Fig. 8. Also shown are the same two temperature records as in Fig. 7. The two records follow each other up to 1970. Note that between 1970 and 1985 the cosmic ray flux, although still behaving similarly to the temperature, in fact lags it and cannot be the cause of its rise. Thus changes in the cosmic ray flux cannot be responsible for more that 15% of the temperature increase.

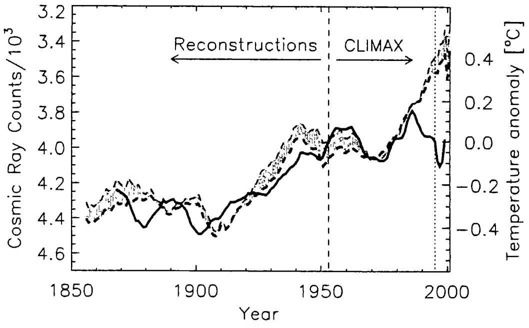

Figure 8. The same as Fig. 7, but for cosmic ray flux (solid) instead of irradiance (from Krivova & Solanki 2003).

3.4. Secular change: new evidence and outlook

The most uncertain and speculative question remains the one regarding the magnitude of the secular change in the solar irradiance. The stellar evidence mentioned in Sect. 3.2 is indirect, based on a number of assumptions and has been criticized (see e.g., Patten & Simon, 1996; Mendoza, 1997; Schmitt, 1997). Alternative evidence for the long-term change in solar activity and irradiance comes from the reconstruction of the evolution of the solar magnetic field.

Lockwood et al. (1999) used the geomagnetic *aa* index to reconstruct the solar open magnetic flux back to the end of the 19th century (dashed line in Fig. 9a). They found that the open flux has doubled during the last century, which points to the presence of a slowly changing component.

A model (solid line in Fig. 9) has then been constructed by Solanki et al. (2000) that explains the secular change and reproduces the Lockwood et al. reconstructions (Fig. 9a) and the ^{10}Be concentration in ice cores (Fig. 9b; Beer et al., 1990) very well. The secular change is built into the model by taking into account the long decay time of the open flux. Whereas magnetic flux emerging in active regions disappears within several days or weeks, the open flux can live on the solar surface for years (e.g., Wang et al., 2000). As a result, when fresh magnetic flux from a new cycle starts emerging, there is still a substantial amount of the old decaying fields, so that subsequent cycles overlap. Therefore, even at activity minimum when the flux in active regions almost disappears,

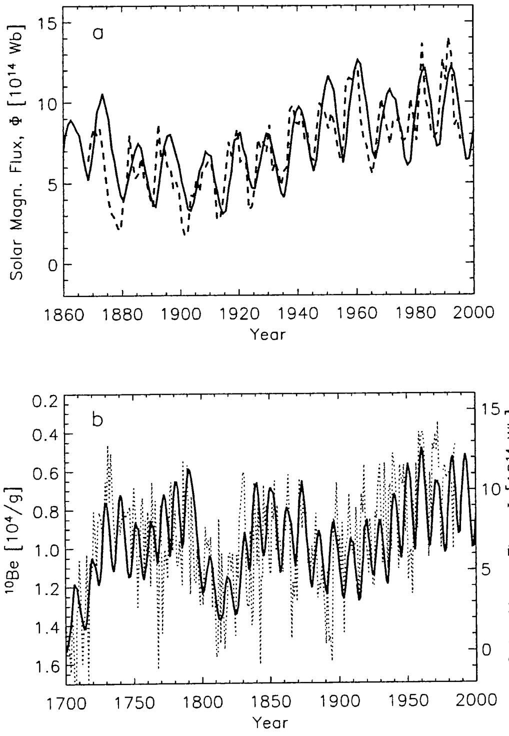

Figure 9. Evolution of the open magnetic flux at the solar surface since 1700. The model by Solanki et al. (2000) is represented by the thick solid curve and compared to **(a)** *reconstructions by Lockwood et al. (1999, dashed) and* **(b)** *the ^{10}Be concentration in ice cores (left y-axis) by Beer et al. (1990, dotted).*

a considerable background flux is still present on the surface. If the cycles are long and weak (like during the Maunder minimum) the overlap periods shrink and flux from a previous cycle can wane completely, which finally causes a depletion of the background.

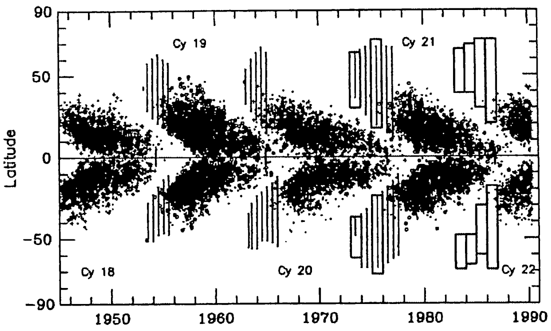

Figure 10. Butterfly diagram for sunspots (symbols), Ca^+ plage regions (vertical lines) and ephemeral regions (boxes). Vertical lines on the zero x-axis mark sunspot cycle minima (from Harvey 1992).

The open flux comprises only a few percent of the Sun's total magnetic flux and cannot be responsible for significant irradiance changes. For these the total flux is the appropriate quantity. Activity cycles in their standard representation, outlined by the evolution of active regions and in particular by the sunspot number have well-defined boundaries. The reason is the short life time of active regions and the fact that active regions of a new cycle only start appearing when the old activity cycle has almost died. A different situation exists for ephemeral active regions. Harvey (1992) has shown that a significant amount of fresh flux in ephemeral regions appears at the surface already during the previous decaying cycle, well before the new sunspot cycle starts (see Fig. 10). Significant background flux is thus present on the solar surface even at activity minima. This flux is actually comparable to the flux in active regions at activity maximum (Harvey, 1994; Krivova et al., 2002a,b). Therefore, a secular change in the background field caused by the varying length and strength of the solar cycle can be appreciable.

Using this idea, Solanki et al. (2002) have reconstructed the evolution of the solar total magnetic flux back to the end of the Maunder minimum. The modelled flux in active and ephemeral regions as well as the total flux are plotted in Fig. 11. The open flux component is shown in Fig. 9 and it agrees well with the empirical reconstruction by Lockwood et al. (1999) and the concentration of the ^{10}Be isotope in ice cores (Beer et al., 1990). The total flux can also be compared with observations for the last two cycles and both records have been found to be in good correspondence (Solanki et al., 2002).

Since we now know how to convert solar surface magnetic flux into irradiance (Sect. 2), it is becoming possible to use the long-term model of the total flux by Solanki et al. (2002) to reconstruct also the irradiance back to the end of the Maunder minimum. This work is currently in progress.

4. OUTLOOK

Reconstructions based on modelling of the solar atmosphere and magnetic fields have now reached a state that it is possible to reproduce the irradiance variations over a solar cycle with high precision using just a single free parameter. The conclusion reached from such modelling that at the solar cycle time scale it is the magnetic field at the Sun's surface which causes irradiance variations (Fligge et al., 2000a; Krivova et al., 2003) has been confirmed by other investigations (Woodard & Libbrecht, 2003; Livingston & Wallace, 2003). So far the question whether the irradiance variations over multiple cycles can be reproduced by exactly the same model (i.e. also with the same value of the free parameter) has not been addressed. Given that simpler models have difficulty reproducing the results of cycles 22 and 23 consistently (e.g., Fröhlich, these proceedings; Pap et al., these proceedings) the results of such an investigation are of considerable interest.

On longer time scales there are two major points that require further work. The first is the secular variation of

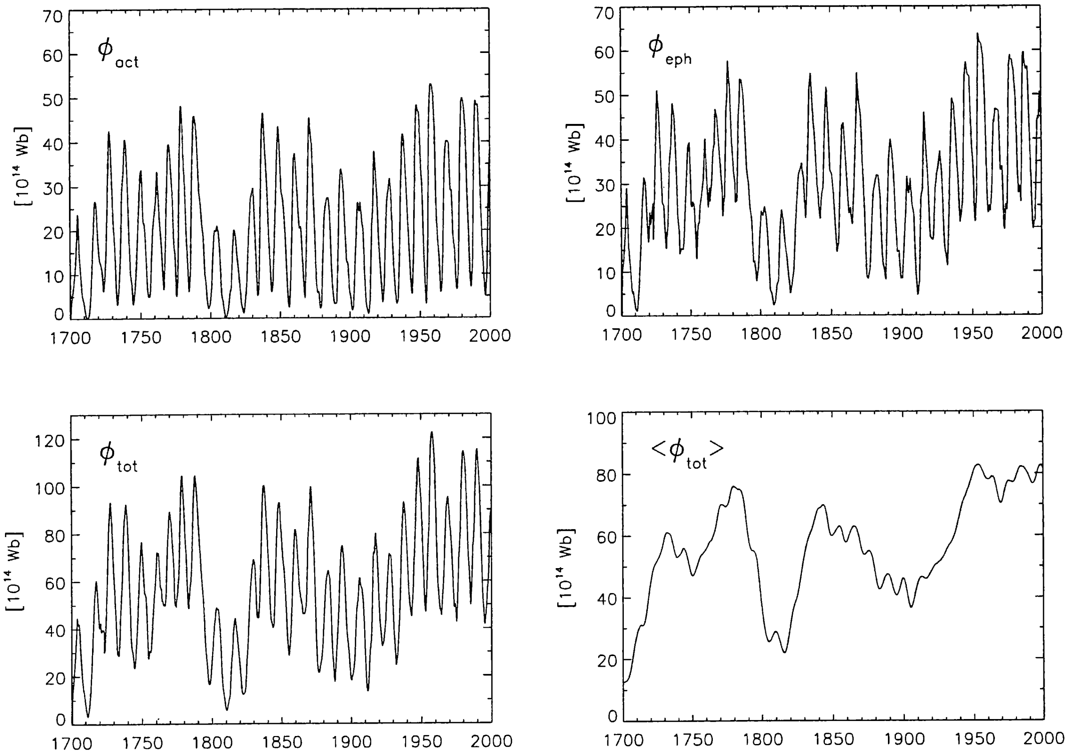

Figure 11. Reconstructed magnetic flux since 1700: active regions (upper left), ephemeral regions (upper right), total flux (lower left), and 20-year running mean of total flux (lower right). From Solanki et al. (2002).

irradiance. Any solid means to increase the reliability in such a secular variation or in its absence would be extremely useful. Further work in this direction is required and planned, in particular the use of the modelled secular variation of the magnetic flux to deduce a physics-based secular variation of the irradiance.

The second point that needs to be addressed, in particular if we wish to compare solar irradiance variations with climate is the need for longer time series. This requires the use of cosmogenic isotopes as proxies of the magnetic flux since direct solar observations during pre-telescopic times are rather unreliable.

ACKNOWLEDGMENTS

We thank Thomas Wenzler for providing Fig. 3 (bottom panel). This work was supported by INTAS grant No. 01-0432.

REFERENCES

Baliunas S., Jastrow R., 1990, Nature, 348, 520

Baumgartner S., Beer J., Masarik J., et al., 1998, Science, 279, 1330

Beer J., Blinov A., Bonani G., et al., 1990, Nature, 347, 164

Bond G., Kromer B., Beer J., et al., 2001, Science, 294, 2130

Cebula R.P., Deland M.T., Schlesinger B.M., 1992, J. Geophys. Res., 97, 11613

Chapman G.A., Cookson A.M., Dobias J.J., 1996, J. Geophys. Res., 101, 13541

Eddy J.A., 1976, Science, 192, 1189

Fligge M., Solanki S.K., 2000, Geophys. Res. Lett., 27, 2157

Fligge M., Solanki S.K., Meunier N., Unruh Y.C., 2000a, ESA-SP, 463, 117

Fligge M., Solanki S.K., Unruh Y.C., 2000b, Astron. Astrophys., 353, 380

Foster S., Lockwood M., 2003, Astron. Astrophys., in press

Foukal P., 1992, In: ASP Conf. Ser. 27: The Solar Cycle, 439–449

Foukal P., Lean J., 1990, Science, 247, 556

Friis-Christensen E., Lassen K., 1991, Science, 254, 698

Fröhlich C., Finsterle W., 2001, In: ASP Conf. Ser. 203: Recent Insights Into the Physics of the Sun and Heliosphere — Highlights from SOHO and Other Space Missions, 105–110

Fröhlich C., Lean J., 1998, In: Deubner F.L. (ed.) IAU Symp. 185: New Eyes to See Inside the Sun and Stars, 89–102, Dortrecht: Kluwer

Haigh J.D., 1994, Nature, 370, 544

Haigh J.D., 1996, Science, 272, 981

Harvey K.L., 1992, In: ASP Conf. Ser. 27: The Solar Cycle, 335–367

Harvey K.L., 1994, In: Pap J.M., Fröhlich C., Hudson H.S., Solanki S.K. (eds.) IAU Coll. 143: The Sun as a Variable Star: Solar and Stellar Irradiance Variations, 217–225, Cambridge: Cambridge Univ. Press

Hodell D.A., Brenner M., Curtis J.H., Guilderson T., 2001, Science, 292, 1367

Houghton J.T., Meira Filho L.G., Callander B.A., et al. (eds.) 1996, Intergovernmental Panel on Climate Change (IPCC). Climate Change 1995. The Science of Climate Change, Cambridge Univ. Press

Hoyt D.V., Schatten K.H., 1993, J. Geophys. Res., 98, 18895

Jones P.D., 1994, J. Climate, 7, 1794

Jones P.D., Osborn T.J., Briffa K.R., et al., 2001, J. Geophys. Res., 106, 3371

Krivova N.A., Solanki S.K., 2003, Adv. Sp. Res., in press

Krivova N.A., Solanki S.K., Fligge M., 2002a, ESA-SP, 505, 461

Krivova N.A., Solanki S.K., Fligge M., 2002b, ESA-SP, 508, 155

Krivova N.A., Solanki S.K., Fligge M., Unruh Y.C., 2003, Astron. Astrophys., 399, L1

Kurucz R.L., 1992, Revista Mexicana de Astronomia y Astrofisica, 23, 187

Lean J., Beer J., Bradley R., 1995, Geophys. Res. Lett., 22, 3195

Lean J.L., White O.R., Livingston W.C., Picone J.M., 2001, J. Geophys. Res., 106, 10645

Livingston W., Wallace L., 2003, Solar Physics, 212, 227

Lockwood M., Stamper R., 1999, Geophys. Res. Lett., 26, 2461

Lockwood M., Stamper R., Wild M.N., 1999, Nature, 399, 437

Marsh N.D., Svensmark H., 2000, Phys. Rev. Lett., 85, 5004

Mendoza B., 1997, Astrophys. J., 483, 523

Neff U., Burns S.J., Mangini A., et al., 2001, Nature, 411, 290

Nesme-Ribes E., Manganey A., 1992, Radiocarbon, 34, 263

Ogurtsov M.G., Nagovitsyn Y.A., Kocharov G.E., Jungner H., 2002, Solar Physics, 211, 371

Ortiz A., Solanki S.K., Domingo V., Fligge M., Sanahuja B., 2002, Astron. Astrophys., 388, 1036

Parker D.E., Folland C.K., Jackson M., 1995, Climatic Change, 31, 559

Patten B.M., Simon T., 1996, ApJ Suppl. Ser., 106, 489

Reid G.C., 1987, Nature, 329, 142

Scherrer P.H., Bogart R.S., Bush R.I., et al., 1995, Solar Physics, 162, 129

Schmitt J.H.M.M., 1997, Astron. Astrophys., 318, 215

Solanki S.K., 1986, Astron. Astrophys., 168, 311

Solanki S.K., Brigljević V., 1992, Astron. Astrophys., 262, L29

Solanki S.K., Fligge M., 1998, Geophys. Res. Lett., 25, 341

Solanki S.K., Fligge M., 1999, Geophys. Res. Lett., 26, 2465

Solanki S.K., Krivova N.A., 2003, J. Geophys. Res., 108(A5), 1200, doi:10.1029/2002JA009753

Solanki S.K., Schüssler M., Fligge M., 2000, Nature, 408, 445

Solanki S.K., Schüssler M., Fligge M., 2002, Astron. Astrophys., 383, 706

Stuiver M., Quay P.D., 1980, Science, 207, 11

Svensmark H., Friis-Christensen E., 1997, Journal of Atmospheric and Terrestrial Physics, 59, 1225

Unruh Y.C., Solanki S.K., Fligge M., 1999, Astron. Astrophys., 345, 635

Viereck R.A., Puga L.C., 1999, J. Geophys. Res., 104, 9995

Wang Y.M., Sheeley N.R., Lean J., 2000, Geophys. Res. Lett., 27, 621

White O.R., Skumanich A., Lean J., Livingston W.C., Keil S.L., 1992, Publ. Astron. Soc. Pac., 104, 1139

Willson R.C., 1997, Science, 277, 1963

Woodard M.F., Libbrecht K.G., 2003, Solar Physics, 212, 51

Zhang Q., Soon W.H., Baliunas S.L., et al., 1994, Astrophys. J. Lett., 427, L111