LONG-TERM CHANGES IN SOLAR IRRADIANCE

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ABSTRACT

Measurements of solar irradiance with the necessary precision to reveal the sun's intrinsic variability started in 1978. These measurements have revealed dips in solar brightness due to the passage of sunspots across the solar disc on a solar rotation time scale and a remarkable increase of the solar irradiance at solar activity maximum. In order to uncover a possible connection between solar irradiance variations and climate, however, it is necessary to extend the irradiance record to earlier times with the help of models.

A brief introduction is given to the results of irradiance measurements and to our current understanding of the underlying physical causes, followed by an overview of the efforts to reconstruct irradiance or the underlying magnetic field at earlier times. The secular variation of solar irradiance, in particular the magnitude of the irradiance increase since the Maunder minimum, is critically discussed.

1. INTRODUCTION

There is considerable circumstantial evidence that solar variability influences the Earth's climate. For example, indicators of solar activity (^{14}C concentration) and of climate (glaciers) show a clear correlation over the last 7000 years (Eddy 1977). Also, the solar cycle length shows an excellent correlation with northern hemisphere land temperatures since approximately 1860 (Friis-Christensen and Lassen 1991), although more recently the two records have diverged (see Sect. 5).

In order to determine whether there really is a significant solar contribution to global climate change or whether these are just chance correlations we need to first determine the variation of solar quantities that actually could affect the Earth's climate, since parameters such as the solar cycle length are at best proxies of the relevant physical variables. In a second step it is then necessary to study the reaction of the Earth's atmosphere with the variability of the solar parameters. The present review concentrates on the first step.

Three main routes by which the Sun could influence climate have been identified:

1. Variations of the total solar irradiance, i.e. the brightness of the Sun as measured above the Earth's atmosphere, integrated over all wavelengths. This quantity represents to very high accuracy the total radiative input to Earth.
2. Variations of the Sun's spectral irradiance, i.e. changes in the Sun's brightness at a certain wavelength or within a given wavelength range. The UV radiation influences atmospheric chemistry, in particular the production and destruction of ozone (e.g. Haigh 1994, 1996). A different rate of change of UV relative to total irradiance can have a significantly different effect on the radiative heating of the Earth's atmosphere (Larkin et al., 2000).
3. Variations in the heliospheric magnetic field (which is anchored in the Sun's interior). Such variations, coupled with corresponding changes in the solar wind, influence the number and the energy spectrum of the cosmic rays reaching the Earth (Potgieter 1998, Simpson 1998) These in turn have been linked to global cloud cover by Svensmark and Friis-Christensen (1997), Svensmark (1998), Marsch and Svensmark (2000).

This review concentrates on the long-term variations of total and spectral irradiance, where long-term implies a time scale of centuries. Thus, changes on the solar evolution time scale (10^9 years) and the thermal time scale of the convection zone (10^5 years) will not be touched upon. Also, variations on the time scale of solar rotation up to that of the solar cycle are dealt with relatively briefly. More details on these shorter term variations are presented by Fligge et al. (2000a, these proceedings). In addition to the irradiance we also briefly touch upon changes in the underlying magnetic field, which has an influence on the cosmic ray flux.

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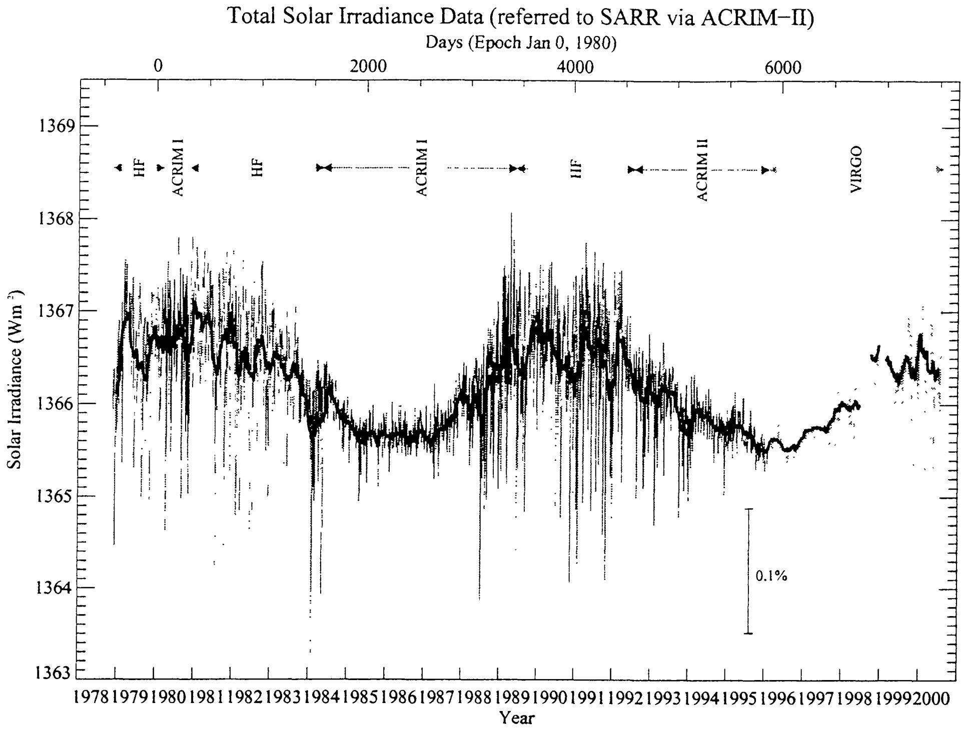

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Figure 1. The total solar irradiance vs. time. Plotted is a composite of measurements made between 1978 and 2000 by various instruments. Figure kindly provided by C. Fröhlich.

2. PHYSICAL CAUSES OF SOLAR IRRADIANCE VARIATIONS

Measurements with sufficient accuracy to reveal total solar irradiance (TSI) variations at a level of 0.1% have been regularly carried out since 1978 (see Fröhlich 2000 for a review). A number of instruments have been involved, each with its own absolute irradiance calibration. The absolute values obtained by the various instruments may differ somewhat, but they exhibit very similar relative changes. A consistent time series combining the outputs of the various instruments (i.e. a composite) was constructed by Fröhlich and Lean (1998, cf. Fröhlich 2000, 2001). This composite is plotted in Fig. 1 and now covers a full solar cycle and one half each of two others.

Unfortunately, this period is not sufficiently long to search for signs of solar influence on climate due partly to the large intrinsic short-term variability of the climate system. Also, the cycles covered so far (Nos. 21, 22, 23) are too similar to directly allow us to extrapolate to earlier times, when the Sun was either more active (cycle 19) or, as was usually the case, less active.

In the case of solar spectral irradiance the observational evidence is even less complete. Almost all the measurements are restricted to the UV. Knowledge of the variability in the visible is limited to the results of VIRGO on SOHO (and is only reliable on short time scales) and no direct measurements exist of irradiance variability at wavelengths greater than 1 micron.

In order to learn how total or spectral irradiance varied in the past we need to obtain a physical understanding of the causes of irradiance variability. To help reconstruct past irradiance we also need to uncover proxies of irradiance that have been measured for as long a time as possible (a quantitative reconstruction from first principles is not currently possible). In addition, the variability and activity level of Sun-like stars needs to be studied. The investigation of a sufficiently large sample of Sun-like stars may help to determine the full range of solar variability within a short period compared to that required to gain the same knowledge from the study of the Sun alone. All these (complementary) approaches have been taken by various investigators.

On time scales of the solar cycle and less the major source of both spectral and total irradiance variability is the magnetic field at the solar surface. For sunspots this was already clear in the early 1980's (e.g. Hudson et al. 1982, Foukal 1981). A theoretical explanation for why the Sun darkened globally due to (local) spots at its surface had also been provided (Spruit 1982). The dip in TSI due to the passage of a sunspot group across the solar surface is illustrated in the upper panel of Fig. 2, while the lower panel exhibits the brightening due to the passage of a region composed mainly of faculae.

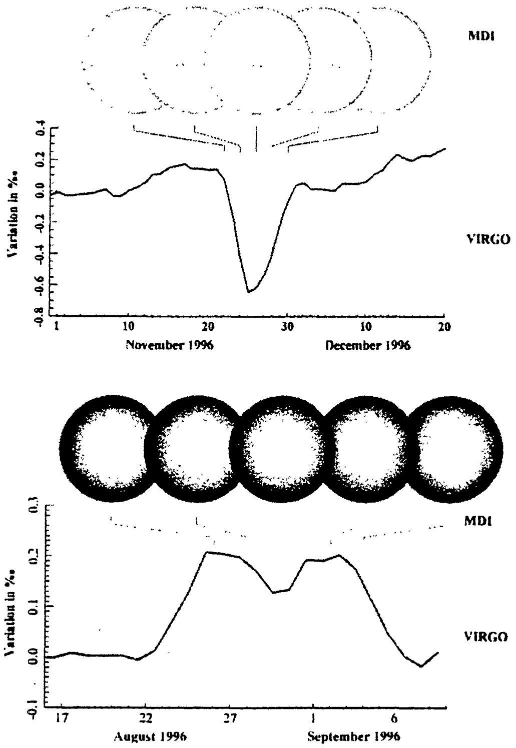

Figure 2. Traces of the total solar irradiance recorded by the VIRGO instrument on SOHO (thick solid curves) in November and December 1996 (upper panel) and in August and September 1996 (lower panel). Above each trace MDI full disc continuum images for five days within these periods are marked. Note the passage of two small spots (upper panel) and of the faculae (lower panel).

The role of bright faculae and the network has taken a considerably longer time to work out. Due to the network's distribution over the whole solar disc, the small size of individual elements and the weakness of an individual element's signature in almost every proxy, it was particularly difficult to include in the analysis, and even today poses the largest problem. Early work (e.g. Foukal and Lean 1986, 1988) employed chromospheric proxies of faculae and the network. More recently, Fligge et al. (2000b, 2001, cf. Solanki and Fligge 2001) have directly determined the fraction of the irradiance variations caused by the magnetic field using a combination of magnetograms and atmospheric models of the various types of magnetic features. They have shown that over 95% of the measured irradiance variability is caused by magnetic fields at the solar surface (see Fligge et al. 2000a, these proceedings, for details).

This work, together with that of Fröhlich and Lean (1998), suggests that also the irradiance variations over past solar cycles can be determined from the surface distribution of the magnetic field, if appropriate records of the field distribution or of proxies thereof are available.

Since the spectra of sunspots and faculae can be calculated over a broad range of wavelengths (covering over 99% of the contribution to the TSI and its variation) with sufficient accuracy to reproduce the best observations (Unruh et al. 1999) it is straightforward to model also changes in the spectral irradiance on time scales of a solar cycle or less, once the total irradiance has been reconstructed (Solanki and Unruh 1998, Unruh et al. 1999, Fligge et al. 2000b). the results of the models are in surprisingly good agreement with the available data.

3. RECONSTRUCTIONS OF PAST CYCLIC IRRADIANCE VARIATIONS

Proxies of the magnetic flux distribution are indeed available in the form of the Zürich Sunspot Relative Number (R_z, since 1700), the Group Sunspot Number (R_g, since 1610), sunspot and facular areas (A_s, A_f, since 1874), Ca II plage areas (A_p, since 1915), etc. None of these is a perfect proxy for either the sunspot or facular contribution to the TSI, whereby the sunspot contribution is more reliably represented than that of the faculae. This has to do with the clearer signal produced by sunspots.

Nevertheless, these data can be employed to reconstruct the cyclic component of the irradiance back to the Maunder minimum. It should be noted that in this Section we do not discuss any possible secular trend, so that the irradiance curves shown here indicate only a part of the total change of the irradiance. The various reconstructions of this type differ in the length of time that they cover, the data they are based on and the underlying assumptions regarding the details of the reconstruction (Foukal and Lean 1990, Lean et al. 1995, Solanki and Fligge 1998, 1999, Lockwood and Stamper 1999). In Fig. 3 we plot the reconstruction due to Solanki and Fligge (1999) from 1700 to 1998. As more and increasingly better data are available, the quality of the reconstruction improves. Thus between 1700 and 1749 only yearly values of the sunspot number are reliably available, between 1750 and 1817 only monthly and between 1818 and 1874 daily values are available, while from 1874 onwards other proxies in addition to daily sunspot number can also be used. The increasing quality of the reconstruction is clearly visible in the figure; whereas in the early part of the reconstruction only the outline of the cycle is reproduced, from 1818 onwards the reconstruction can separate, even if only partially, between the contributions of faculae and sunspots.

It is possible to separate between these distinct contributions on the basis of a single data record by taking into account the fact that the sunspot and facular contributions have different time scales. Finally, from 1874 onwards the contributions from these two sources can be clearly separated due to the availability of separate data records (note that for the faculae a set of five proxies are used in order to obtain

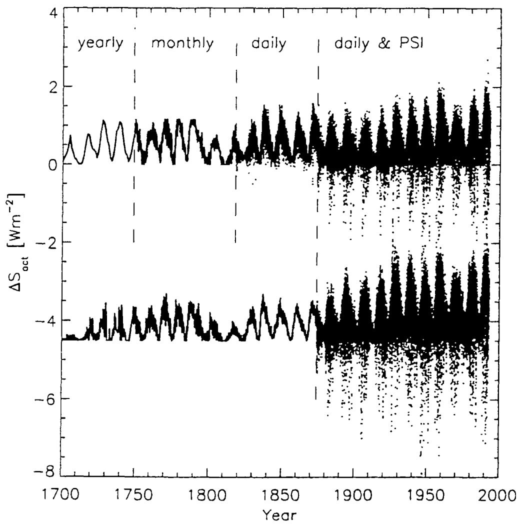

Figure 3. Reconstructed cyclic component of solar total irradiance since 1700. See text for details. (From Solanki and Fligge 1999).

results that are as robust as possible, Solanki and Fligge 1999).

A number of assumptions need to be made for such a reconstruction. For example, the properties of sunspots and faculae are assumed to be independent of time. Thus there is little room in such models for the factor of 2-3 enhanced cyclic brightness variability seen in Sun-like stars by Lockwood et al. (1992). Earlier modelling (Schatten 1993) appeared to support the possibility of such strong cycles within the context of our understanding of solar surface features. However, more recent and more careful modelling (Radick et al. 1998, Knaack et al. 2001) has shown that the behaviour of these stars cannot be reconciled with that of the Sun unless their surface features differ significantly from those on the Sun. Could this imply that the Sun is currently in an atypical state, so that we may not use measurements of current irradiance variations to reconstruct the past? However, there is new evidence for a bias among the observations of Lockwood et al. (1992) in the selection of stars (Radick 2001), which suggests that the behaviour of the Sun in the last 2–3 cycles is not atypical and may be used as a guide for the reconstruction of TSI at earlier times.

The magnitude and source of the cyclic component of irradiance variations is thus well known. Further improvements of the reconstructions of this component of the complete irradiance variation are needed, and indeed possible, but these are expected to improve things quantitatively (e.g. improve the separation between sunspots and faculae prior to 1874) but not qualitatively.

Once the spectral irradiance changes over a given cycle can be reproduced by a model (see Sect. 2) it is possible to determine them all the way back to the Maunder minimum. The remarks made above regarding the TSI reconstructions apply equally to the spectral irradiance. Here the uncertainty is larger due to the weaker constraints set by observations during the space era.

4. SECULAR IRRADIANCE VARIATIONS: INCREASE IN THE IRRADIANCE LEVEL SINCE THE MAUNDER MINIMUM

Let us now turn to the possible secular change in irradiance. There is some evidence that the cyclic irradiance variations discussed above lie on top of a slowly changing irradiance background. Such a secularly changing background is important for a possible influence of solar irradiance variations on climate since, if we average over 11 years, the net increase in TSI due to the cyclic component alone corresponds to only 0.6 W m^{-2} (i.e. roughly 0.04%) since the Maunder minimum.

There are basically two lines of evidence for secular changes in solar irradiance, both of them somewhat indirect.

4.1. Stellar evidence

As the Sun's magnetic activity waxes and wanes not only does its irradiance vary but also the brightness in the cores of prominent spectral lines such as Ca II H and K in the violet part of the solar spectrum. White et al. (1992) found from a comparison of the Ca II emission of 102 field stars (measured by Baliunas and Jastrow 1990) with the Sun that the range of the Ca II emission from the Sun lies considerably higher than for most of the stars in this sample.

Thus the Sun is more active than these stars even during the minima of its last few activity cycles. Baliunas and Jastrow (1990) concluded that the stars with the lowest Ca flux levels are in a Maunder minimum state. Since the Ca II core emission is produced mainly in faculae and the network and there are no faculae at activity minimum, the lower emission seen in these stars must be due to a reduced network. White et al. (1992) actually found that the emission must be reduced to below the level achieved by simply removing all the network emission (although there is considerable uncertainty about this). If correct, this would imply that other mechanisms than purely magnetic ones are responsible for the reduced Ca II flux at Maunder minimum.

Lean et al. (1992) and Zhang et al. (1994) used the correlation between variations of Ca II and of irradiance (respectively irradiance due to faculae) over the solar cycle to extrapolate the irradiance back to the Maunder minimum level. They obtained that the Sun was less bright by 0.24% (Lean et al. 1992),

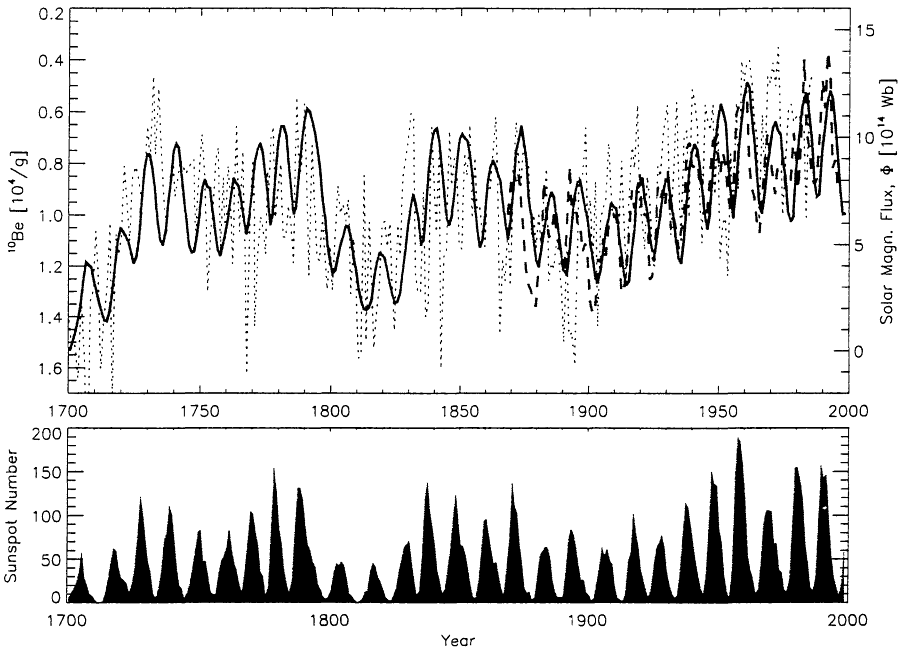

Figure 4. Evolution of the open magnetic flux at the solar surface since the end of the Maunder Minimum in 1700 as predicted by a model of the surface evolution of the Sun's magnetic field (upper panel, solid curve). For comparison, the flux of the interplanetary magnetic field (Lockwood et al., 1999) reconstructed from the geomagnetic aa-index (dashed curve) and the ^{10}*Be concentration in ice cores (Beer et al., 1990) (dotted curve and left-hand, inverted scale) are also plotted. The interplanetary flux values have been multiplied by a factor of 2 in order to obtain the total unsigned flux. The* ^{10}*Be record has been plotted without any smoothing or filtering. For comparison, the lower panel shows the corresponding time sequence of the sunspot number, R (see Solanki et al., 2000 for details).*

respectively by 0.2-0.6% compared to the present (Zhang et al. 1995).

One problem with the Baliunas and Jastrow (1990) result is that for the stars in their sample there is no good way to distinguish between stars of solar age in a Maunder minimum state and older, less rapidly rotating stars with generally lower activity levels. Newer observations of the old open cluster M67 show that there are indeed some stars with an activity level below that of the Sun (Radick 2001).

From the stellar side there is thus some (although not quite definite) evidence for the decrease in network magnetic flux and hence of the irradiance. Also, there is considerable uncertainty regarding the magnitude of the irradiance change between the Maunder minimum and a present day activity minimum. This is partly seen in the large range of possible values given by Zhang et al. (1995) in their admittedly simple analysis. Additional uncertainty is caused by the fact that it is now unclear which stars in the sample of Baliunas and Jastrow (1990) represent true Maunder minimum stars.

Schmitt (1997) has argued on the basis of a complete volume sample of stars observed in X-rays that there is no evidence for stars exhibiting much smaller magnetic activity than parts of the Sun (vis. coronal holes). According to him therefore the Sun would still have considerable magnetic flux during the Maunder minimum and would thus not be much less bright at than during a current minimum. This suggests that either the network fields do not weaken significantly in the Maunder minimum relative to the present-day minimum, or another source of X-rays opens up there, or that stars in a Maunder minimum state are extremely rare (and the lower Ca II emission in many Sun-like stars has other, unknown, causes). It should be noted, however, that X-ray flux depends at least as strongly on magnetic field topology (open or closed flux) as on the total amount of magnetic flux.

4.2. Heliospheric evidence

Evidence for secular trends in solar activity comes from the interplanetary magnetic field reconstructed from the aa-index of geomagnetic activity (Lockwood et al. 1999). They find that the interplanetary magnetic flux at the minimum of solar activity has roughly doubled since 1900. The reconstructed interplanetary field is plotted in the upper frame of Fig. 4 (dashed curve). The secular trend is even stronger than the cyclic signal in the interplanetary field. This behaviour is mirrored by the ^{10}Be concentration in Greenland ice (Beer 2000), which is represented by the dotted curve in Fig. 4. ^{10}Be is produced by the interaction of cosmic rays with constituents of the upper atmosphere. Since the cosmic ray flux is modulated by the heliospheric magnetic field and by the solar wind, the ^{10}Be concentration (like that of ^{14}C) is a measure of the heliospheric effect of solar activity.

Lockwood and Stamper (1999) have argued that since the irradiance over a solar cycle correlates rather well with the interplanetary flux that therefore the secular trend in the latter must also be reflected in the TSI. This is an interesting approach, although one needs to keep in mind the following. The heliospheric magnetic field is the extension of the open magnetic flux on the solar surface. The open flux is only a small fraction (a few percent at solar maximum) of the total magnetic flux. A model has been proposed by Solanki et al. (2000), which reproduces both the reconstructed interplanetary field (Lockwood et al. 1999) and the ^{10}Be record with high accuracy. The model is represented by the solid curve in Fig. 4. The model produces a secularly varying open flux by requiring that this flux has a lifetime of years (in contrast to the major part of the magnetic flux emerging at the solar surface, which disappears again within days or, at the most, months). Such a long lifetime of a small fraction of the total flux has been confirmed by Wang et al. (2000). Unfortunately, due to the much shorter lifetime of most of the magnetic flux we cannot use the same or a similar model to explain a secular trend in the total magnetic flux. This implies that another cause must be found for any significant secular trend in the irradiance.

4.3. Other approaches

An alternative approach regarding the magnitude of a possible secular trend since the Maunder minimum is to try to set limits on it. A lower limit is obviously close to zero (there is as yet no definitive evidence that a trend exists). Setting an upper limit is far less straightforward and is never quite free of assumptions. Besides stars and the interplanetary field there are basically two ways in which such limits can be set.

4.3.1. Comparison of reconstructed irradiance with measurements

By requiring that part of the reconstructed irradiance record since 1978 should match the observed irradiance, an upper limit can be set on the irradiance change since the Maunder minimum. It is an upper limit, since cycles 21, 22 and 23 are relatively similar. The composite record of measured irradiance plotted in Fig. 1 is consistent with no secular trend (excepting the controversial analysis of Willson 1997), and cannot be reconciled with large secular trends. Solanki and Fligge (1998) used this technique to set an upper limit of 5 W m^{-2} since the Maunder minimum (Solanki and Fligge 1998, 1999).

4.3.2. Limit derived from magnetograms

One can in principle set an upper limit on any secular change in irradiance due to changes in the magnetic flux by considering a magnetogram at solar activity minimum. If we know the irradiance enhancement due to each magnetic feature and obtain the flux in the magnetic features at activity minimum (i.e. in the network), then we can estimate the brightness of the Sun in the absence of the network. This technique, which assumes that the secular variations are entirely magnetic in origin, has never been applied. It requires extremely deep magnetograms (tests have shown that the resulting increase in irradiance since the Maunder minimum increases linearly with decreasing noise level) and a very good knowledge of the brightness of network elements.

In summary, there is circumstantial evidence for a secular trend in solar irradiance. However, none of this evidence is clear-cut or straightforward, so that the absence of such a trend cannot be ruled out. Even more difficult than determining the magnitude of the secular irradiance variations is to discover their detailed time dependence.

5. FUNCTIONAL FORM OF THE SECULAR IRRADIANCE CHANGE

For studies of the influence of solar variability on climate it is not sufficient to know by how much the irradiance has changed since the Maunder minimum, one also requires the exact time dependence of its variation. So far three approaches have been taken.

Lean et al. (1995) have assumed that the background irradiance is proportional to the amplitude of the solar cycle (specifically the amplitude of the group sunspot number) and have reconstructed the irradiance accordingly.

Hoyt and Schatten (1993) on the other hand propose a trend corresponding closely to cycle length, although a number of other indicators also enter into it. Baliunas and Soon (1995) have presented evidence that the amplitudes of stellar cycles (seen in Ca II H + K) scale with the length of the stellar cycle. Such a relation is also known for the Sun (although with a relatively low correlation coefficient of 0.4 or less).

In the absence of a clear-cut preference for one or the other of these possible trends Solanki and Fligge (1998, 1999), cf. Fligge and Solanki (2000), have

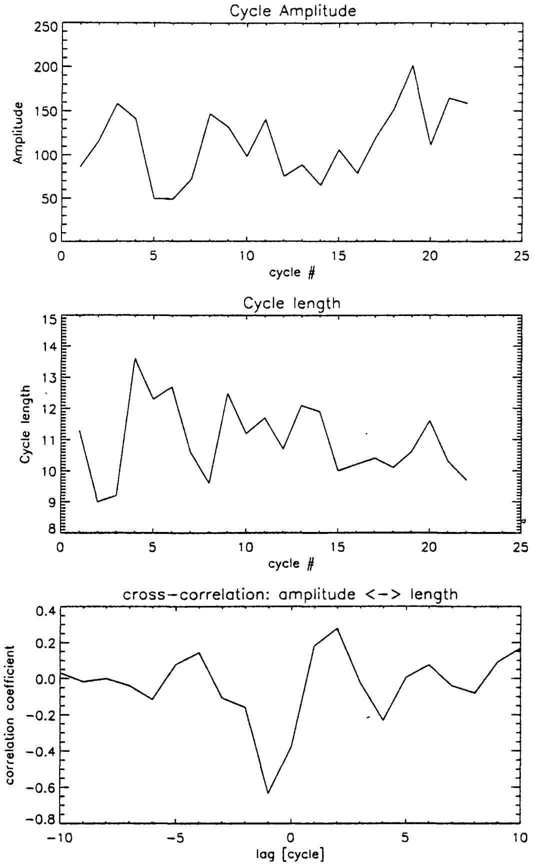

Figure 5. (a) Record of cycle amplitude derived from the sunspot relative number record. (b) Cycle length (obtained following the procedure given by Friis-Christensen and Lassen 1991). (c) Cross-correlation function of the two quantities.

presented two reconstructions, one based on a secular trend following the cycle amplitude, the other following cycle length.

Finally, Lockwood and Stamper (1999) have employed the secular trend of the interplanetary magnetic field to determine the secular behaviour of the irradiance. Specifically, they correlate the measured irradiance with the measured interplanetary fields (over cycles 21 and 22) and apply the same correlation to the interplanetary magnetic field at earlier epochs to obtain the irradiance. As shown by Solanki et al. (2000) the trend in the interplanetary field is determined by both the cycle amplitude and length (with the amplitude playing a somewhat bigger role). As pointed out in Sect. 4.2, so far no a priori physical reason for the irradiance to follow the interplanetary magnetic field has been found, although a connection should not be ruled out.

The cycle length and amplitude records are more closely related than suggested by the correlation coefficient, which typically is on the order of 0.3–0.4. The cross-correlation *function* between the two

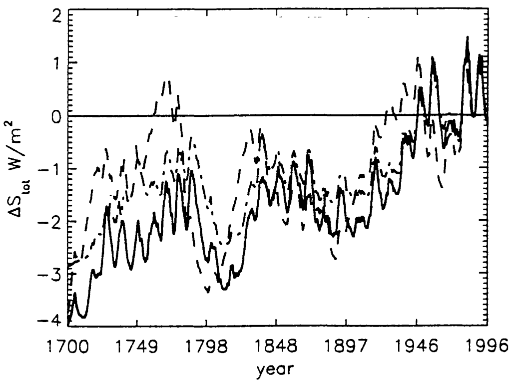

Figure 6. Reconstructed total solar irradiance vs. time. Plotted are the reconstructions due to Hoyt and Schatten (1993; dashed), Lean et al. (1995; dash-dotted), Solanki and Fligge (1998; solid). The plotted curves include both a cyclic and an estimated secular component.

quantities has a maximum amplitude when the two records are out of phase by roughly one cycle, with the cycle length leading the cycle amplitude. This is illustrated in Fig. 5. This explains why Friis-Christensen and Lassen (1991) found a good correlation with air temperature over land masses, while Reid (1987) noted that sea surface temperatures had risen faster than solar activity.

The complete change in irradiance is given by the combination of the cyclic variability (described in Sect. 3) and the secular variation (note that in the model of Lockwood and Stamper 1999 these two contributions are not modelled separately).

The total solar irradiance as reconstructed by Hoyt and Schatten (1993; dashed), Lean et al. (1995; dash-dotted) and Solanki and Fligge (1998, 1999; solid) is plotted in Fig. 6. Note that the reconstruction following cycle length and amplitude are not too different since approximately 1850, but deviate considerably prior to that.

In Fig.7 the irradiance curves since 1978 resulting from the various models are compared with the measurements (as presented by Fröhlich 2000). Considerable differences between the curves are seen, and not all models exhibit a satisfactory agreement with the data. The models of Solanki and Fligge (1998, 1999) turn out to reproduce this set of data very well.

If we make the assumption that the secular irradiance change is due to changes in the magnetic network alone, then it it possible to not only estimate the evolution of the TSI but also that of the spectral irradiance. Fligge and Solanki (2000) and Lean (2000) have both used the models of Unruh, Solanki and Fligge (1999) to reconstruct the spectral irradiance since the Maunder minimum (Lean et al. 1995 previously carried out a simpler reconstruction of in-

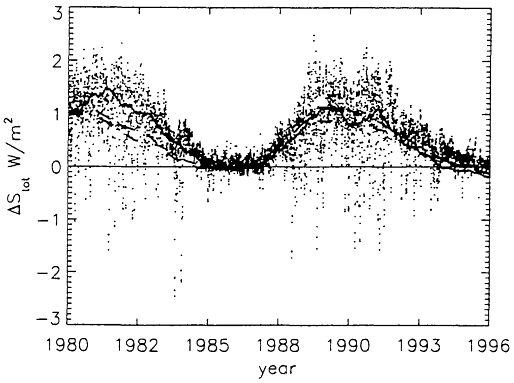

Figure 7. Measured (dotted curve) and reconstructed total solar irradiance vs. time. The plotted models are due to Hoyt and Schatten (1993, dashed curve), Lean et al. (1995, dash-dotted curve) and Solanki and Fligge (1999, solid curve).

tegrated UV irradiance). Fligge and Solanki (2000) employed the TSI changes modelled by Solanki and Fligge (1999), while Lean (2000) chose those of Lean et al. (1995). Accordingly Fligge and Solanki (2000) obtain two different secular trends, one following the cycle amplitudes, one the cycle length. The reconstructed irradiance at wavelengths shortward of 300 nm is plotted in the upper part of Fig. 8, while the irradiance longward of 700 nm is displayed in the lower part of Fig. 8. Note the order of magnitude larger variation in the UV, where however the influence of sunspots is far weaker compared to the IR.

In addition to the assumption underlying the TSI reconstruction the spectral irradiance models have the additional uncertainty that they assume the spectrum of the network elements to be the same as of active region faculae. The results of Topka et al. (1997) and Ortiz et al. (2000) suggest, however, that this is not the case. Hence, there are grounds for improving and extending the models of long-term spectral irradiance measurements.

6. CONCLUSIONS

An overview has been given of our present knowledge of solar irradiance variations since the Maunder minimum. The results as well as the assumptions underlying them and the uncertainties are discussed. In spite of the significant progress of the last years considerable uncertainties remain, some of which become visible in the difference between the various reconstructed records of past irradiance. Before these are sorted out the exact role played by solar irradiance in determining climate will remain unclear.

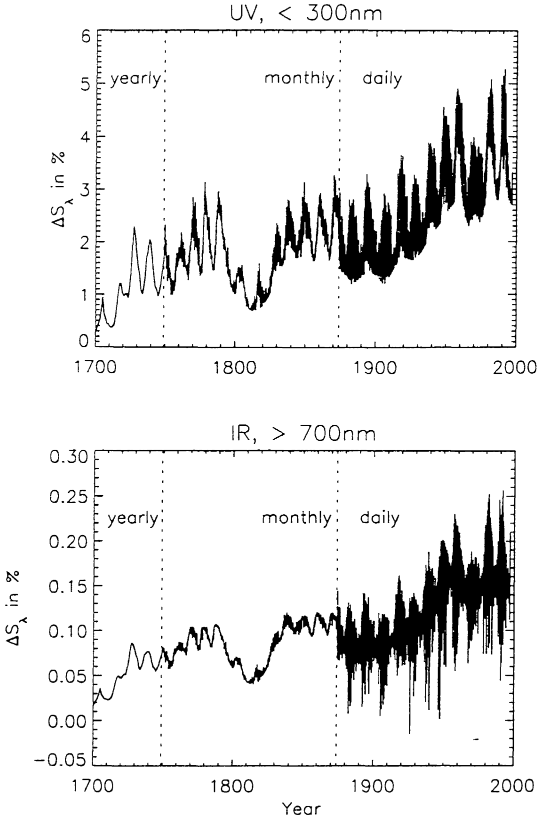

Figure 8. Reconstruction of the increase (in percent) of spectral solar irradiance since the Maunder minimum. Top: for the ultraviolet at $\lambda < 300$ nm, Bottom: for the infrared at $\lambda > 700$ nm. (From Fligge and Solanki 2000).

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