Irradiance models

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Abstract

Measurements of solar irradiance have revealed variations at all the sampled time scales (ranging from minutes to the length of the solar cycle). One important task of models is to identify the causes of the observed (total and spectral) irradiance variations. Another major aim is to reconstruct irradiance over time scales longer than sampled by direct measurements in order to consider if and to what extent solar irradiance variations may be responsible for global climate change. Here we describe recent efforts to model solar irradiance over the current and the previous two solar cycles. These irradiance models are remarkably successful in reproducing the observed total and spectral irradiance, although further improvements are still possible.

Key words: solar activity, solar irradiance, solar magnetic field, solar-terrestrial relations

1 Introduction

Regular space-borne measurements of the total solar irradiance (TSI) started in 1978. The time series of the solar spectral irradiance is even shorter. E.g., daily UV ($\approx 120 - 400$ nm) irradiance has been measured by SUSIM and SOLSTICE on UARS since 1991 (e.g. Floyd et al., 2003). VIRGO on SoHO records irradiance in three spectral channels (red, green and blue centred at 862 nm, 500 nm and 402 nm, respectively) since 1996 (Fröhlich et al., 1997). The SORCE SOLSTICE and SIM instruments provide, since 2003, 6-hourly and daily measurements of solar irradiance between 115 and 2000 nm (Woods et al., 2000). The quantity previously called the solar constant was found to vary on all observable time scales, from minutes up to the length of the solar cycle (Willson and Hudson, 1988, 1991; Fröhlich, 1994). Variations at longer time scales, over decades and centuries, are indirectly revealed by proxy records, such as the sunspot number or the production rate of cosmogenic isotopes (e.g., Eddy, 1976; Beer et al., 1990; Ribes and Nesme-Ribes, 1993; Peristykh and Damon, 2003; Muscheler et al., 2003), and by the evolution of the solar total and open magnetic flux (Cliver et al., 1998; Cliver and Ling, 2002; Lockwood et al., 1999; Solanki et al., 2000, 2002).

The source of irradiance variability on time scales of minutes to days remains less well understood, aside from the well-known *p*-mode oscillations with periods of around 5 minutes that are excited by the turbulent motions in the solar convection zone (see e.g., Gough and Toomre, 1991; Brown and Gilliland, 1994). It has commonly been attributed to granulation, mesogranulation and supergranulation (e.g., Andersen et al., 1994; Fröhlich et al., 1997; Rabello-Soares et al., 1997). More recent studies (e.g., Seleznyov et al., 2003; Solanki et al., 2003) have been aimed at separating magnetic and convective effects. This model implies that at time scales shorter than a few hours convection in the form of granulation seems to dominate. On time scales of hours to days both convective and magnetic signatures appear important. No additional component, like meso- or supergranulation, is required to reproduce observed slopes of the irradiance power spectra. An interest to these time scales has recently been stimulated by the importance of stellar variability for the search for extrasolar planets through detection of transits.

Irradiance variations on longer time scales are of particular interest in the context of Sun-climate studies. A better understanding has been gained of the variability at time scales of days up to the solar cycle, which provides the subject matter for the present review. At these, directly observed time scales the primary goal of models is to elucidate the causes of the irradiance variations. This gives physical insight into which proxies could be utilised in which way in order to reconstruct solar total and spectral irradiance at earlier times, which is necessary for a better understanding of the Sun-climate connection. Most successful have been models attributing variations in solar total and spectral irradiance to the evolution of the solar surface magnetic field (Foukal and Lean, 1986, 1988; Chapman et al., 1996; Fligge et al., 1998, 2000a; Krivova et al., 2003; Ermolli et al., 2003). Here we describe one set of models of this type. Reconstructions of irradiance at even longer time scales are not covered here due to a lack of space. Such models have been recently reviewed by Lockwood (2004) and by Solanki and Krivova (2004).

2 Irradiance models on time scales of days to decades

2.1 Irradiance variations and their origin

Several instruments measuring TSI have been in operation since 1978. Although their relative accuracy is high enough to monitor short-term changes in the irradiance, the absolute accuracy is around 0.1–0.2% and is inadequate to assess long-

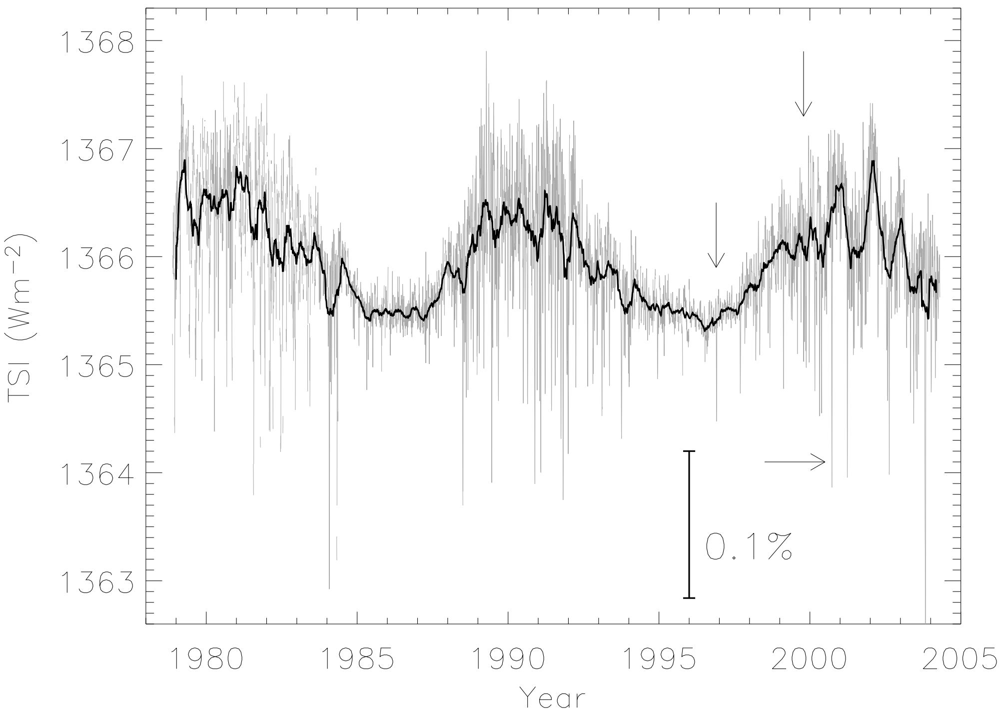

Fig. 1. Composite of total solar irradiance (Fröhlich and Lean, 1998; Fröhlich, 2003) measured by different space-based radiometers. The grey line shows daily averaged values and the black line is a 3-month running mean. The horizontal arrow points to the sunspot seen on the solar disc at the end of September 2000 and shown in Fig. 2, whereas the two vertical arrows refer to the dates when images presented in Fig. 3 have been taken.

term changes. A thorough cross-calibration of the instruments is thus needed in order to create a composite record covering the whole period when measurements are available. This is a real challenge and, as a consequence, three different composites now exist (Fröhlich, 2003; Willson and Mordvinov, 2003; Dewitte et al., 2004). A moot point is whether there has been a secular (minimum to minimum) change in the TSI during the period of observations.

The most prominent feature of the solar total and spectral irradiance record is, as in the case of many other proxies of solar activity, its 11-year cyclicity (Fig. 1). The mean level of the TSI grows from activity minimum to maximum by about 0.1% (e.g. Fröhlich, 2003). Superimposed are more rapid variations, of which deep dips up to several tenths of a per cent lasting a few days are most pronounced. Their close association with sunspots moving across the solar disc (e.g., Fig. 2) was quickly realised (Willson et al., 1981; Hudson et al., 1982). Strong magnetic fields in sunspots suppress convection and impede energy transport to the solar surface. The cooler regions appear dark and the brightness of the Sun decreases (Spruit, 1982). Given the area of a sunspot, its location on the solar disc and a contrast, the shape and the duration of each such dip are nicely reproduced (as in

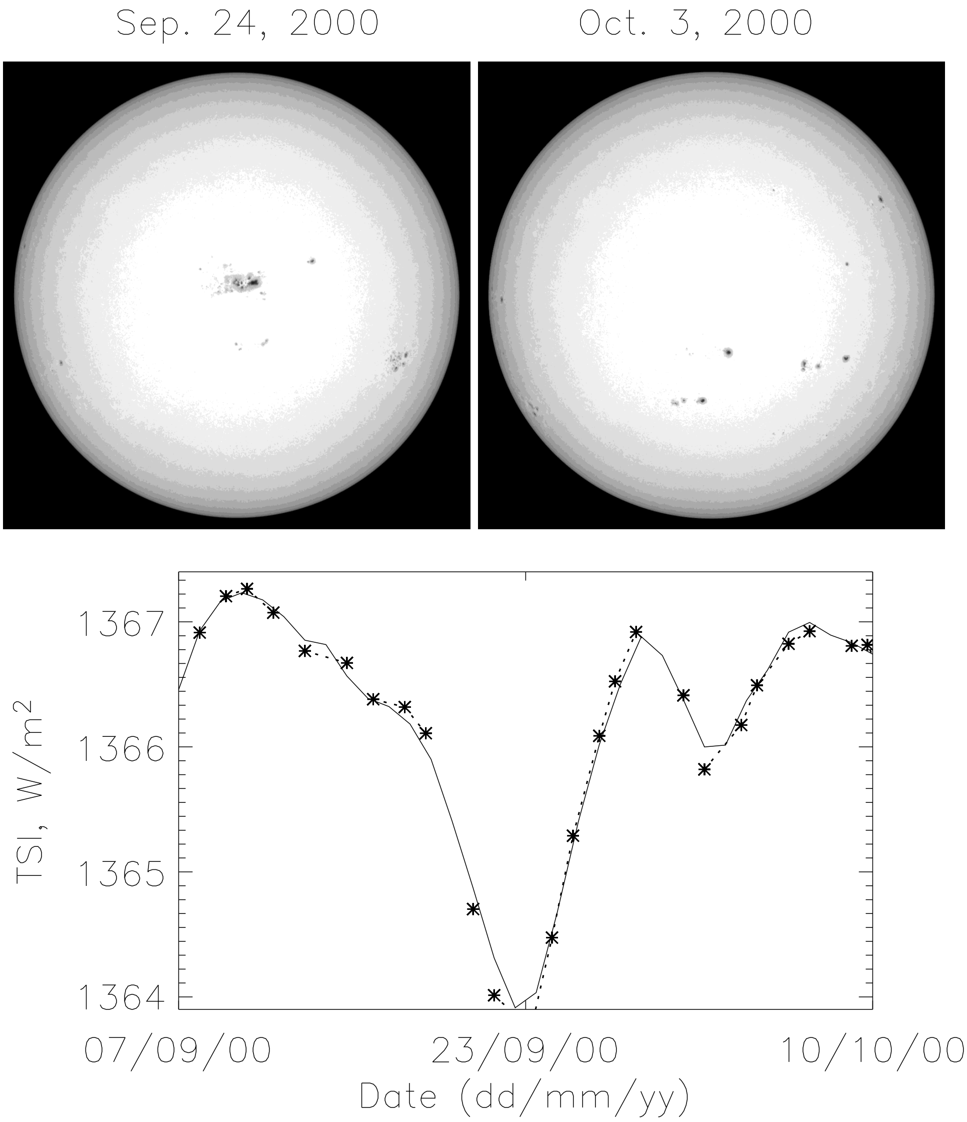

Fig. 2. Top: MDI continuum images recorded on September 24 and October 3, 2000 portray sunspots on the solar disc. Bottom: Dips in the TSI caused by these spots. The larger dip is also marked in Fig. 1 by the horizontal arrow. Spots close to disc centre contribute most. Solid line shows measurements by VIRGO on board SoHO (Fr¨ohlich and Finsterle, 2001) and asterisks connected by the dashed line represent our model (Sect. 2.2).

Fig. 2). Sunspots are thus the most prominent (but not the only) source of irradiance variations on time scales of days to the solar rotation period.

The brightening of the Sun over the solar cycle was an open question for a considerable time. Although bright magnetic elements, faculae and the network, were proposed as possible sources (e.g., Hirayama and Okamoto, 1981; Oster et al., 1982; Chapman et al., 1984; Chapman, 1987), first models, mostly based on chromospheric or other proxies of the magnetic activity and their regressions (e.g., Foukal and Lean, 1986, 1988; Chapman et al., 1996; Fligge et al., 1998; Jones et al., 2003), could not fully reproduce observed changes in the irradiance. The main difficulty was how to properly account for the network. Faculae and the network are manifestations of concentrations of magnetic flux into flux tubes. In that respect they are similar to sunspots, which may be considered to be very large flux tubes. Such small-scale concentrations appear bright in continuum images or in spectral lines (see, e.g., Schüssler et al., 2003). The small size and the relatively small amount of flux in individual elements mean that they are not always well traced by standard proxies and are sometimes even missed by magnetograms (cf. Krivova and Solanki, 2004a). In addition, the distribution of the network over the entire solar disc requires a relatively accurate description of the center-to-limb variation of the brightness of its elements (cf. Fligge et al., 1998, 2000b). As a result, different alternative mechanisms have been proposed, such as r-mode oscillations, changes in the convection properties or the heat flux by the magnetic field in the solar interior, or a change in solar surface temperature (e.g., Wolff and Hickey, 1987; Parker, 1987, 1995; Kuhn et al., 1988).

Employment of detailed maps of the solar surface (e.g., magnetograms, Ca II K or continuum images) lent impetus to the further development of models (Fontenla et al., 1999, 2004; Fligge et al., 2000a; Krivova et al., 2003; Ermolli et al., 2003; Wenzler et al., 2004a,b). The latest models account for more than 90% of all changes in the TSI on time scales of days up to the solar cycle and imply that no additional component is needed to reproduce the long-term increase of solar irradiance between activity minimum and maximum besides faculae and the network. Large concentrations of the magnetic field, such as sunspots, are comparatively rare. Most magnetic flux on the solar surface resides in small-scale elements (see Fig. 3). The number of sunspots and the area covered by them increase with the Sun's magnetic activity. At the same time the total area covered by faculae and the network undergoes a vastly bigger rise (Fig. 3). This leads on average to a brightening of the Sun due to the faculae and network at the maximum of solar activity. At the same time the amplitude of the irradiance variations increases due to the rotational modulation produced by the inhomogeneous longitude distribution of active regions.

2.2 SATIRE

SATIRE is an acronym for a set of models aimed at *Spectral And Total Irradiance REconstructions* (Unruh et al., 1999; Fligge et al., 2000a,b; Krivova et al., 2003) and is based on the assumption that all irradiance changes (on time scales of days up to the solar cycle) are entirely due to the evolution of the magnetic field on the solar surface. In order to calculate solar total and spectral irradiance, we consider a 4-component model of the solar photosphere involving quiet Sun, sunspot umbrae and penumbrae, and faculae including the network (henceforward denoted by subscripts q, u, p, f, respectively).

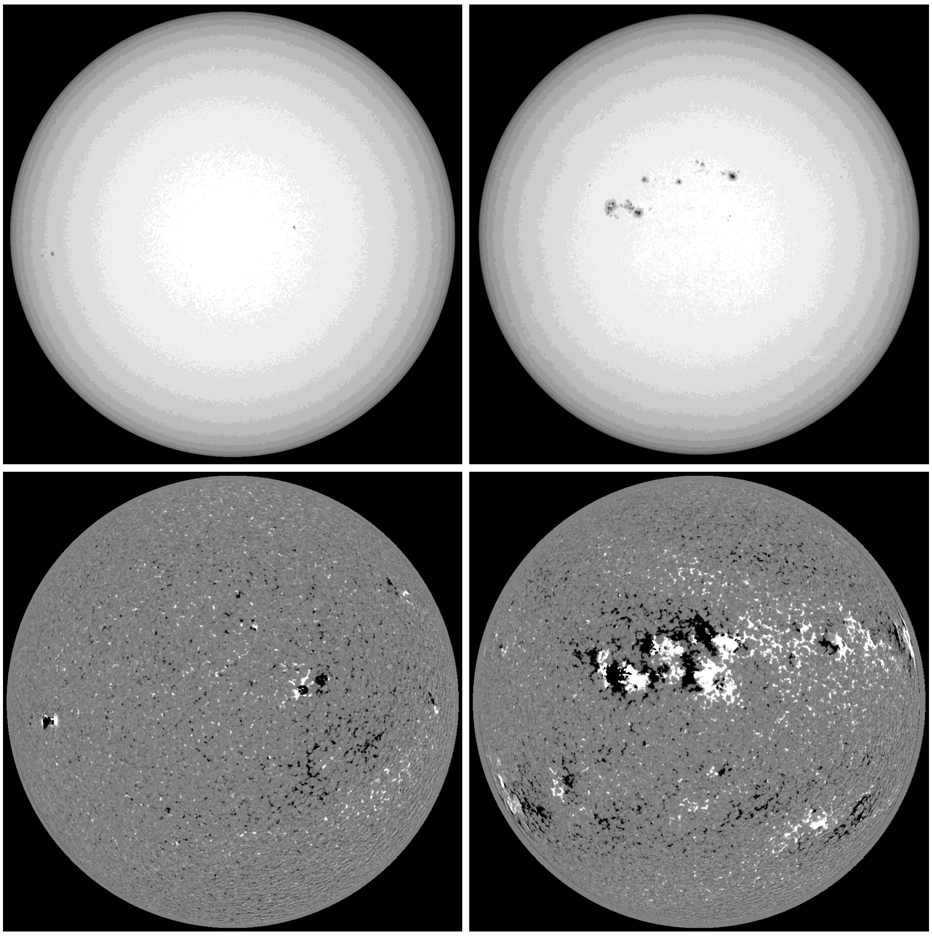

Fig. 3. MDI continuum images (top) and magnetograms (59-minute averages, bottom) recorded on November 22, 1996 (left) and October 15, 1999 (right). The two dates are marked in Fig. 1 by vertical arrows.

The temporal evolution of the surface magnetic field is followed with the help of daily MDI (Michelson Doppler Interferometer on SoHO; Scherrer et al., 1995) magnetograms and continuum images similar to those shown in Fig. 3 and is described by the number of pixels attributed to that component and filling factors $\alpha_{q,u,p,f}$. The physical meaning of the filling factors is the fraction of the solar surface within the pixel in question covered by each photospheric component. They depend on time, t, and the heliocentric angle, θ (or $\mu = \cos(\theta)$). Continuum images are employed for the identification of sunspots. Sunspot boundaries are determined by setting thresholds on umbra and penumbra intensities. Since sunspots are much bigger than the size of an individual pixel (i, j) of the employed images, a pixel within a sunspot is considered to be entirely filled by it: $\alpha_{u,p}(i, j; t) = 1$ within sunspot umbrae or penumbrae and $\alpha_{u,p}(i, j; t) = 0$ outside. All sunspot pixels are then removed from the corresponding magnetograms and the remaining magnetogram signal $B(i, j; t)$ is ascribed to faculae and the network. The corresponding filling factors, $\alpha_f(i, j; t)$ are calculated proportionally to $B(i, j; t)$ until a certain

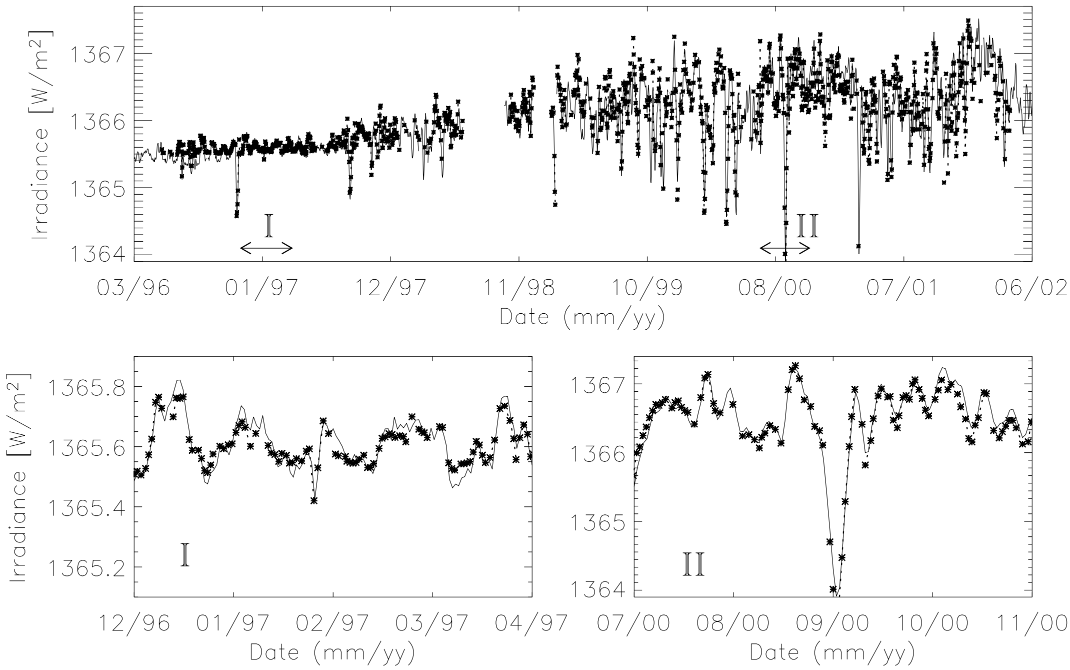

Fig. 4. Reconstruction (asterisks connected by dotted curve when there are no data gaps) and VIRGO measurements (solid line) of total solar irradiance between 1996 and 2002, i.e. from the minimum of cycle 23 to its maximum (top panel). The bottom panels show enlargements of two shorter intervals at different activity levels. The times corresponding to these enlargements are marked in the top panel by roman numerals (from Krivova and Solanki, 2003).

saturation limit $B_{\rm sat}$ is reached. Above this limit the filling factor remains constant. $B_{\rm sat}$ is a free parameter of this model, which takes into account saturation of brightness in regions with higher concentration of magnetic elements (e.g., Solanki and Stenflo, 1984; Solanki and Brigljević, 1992; Ortiz et al., 2002). The space not covered by sunspots or faculae is treated as the quiet Sun: $\alpha_q = 1 - \alpha_u - \alpha_p - \alpha_f$.

MDI data are only used to describe the distribution of the magnetic field on the solar surface and its change with time. The brightness of each photosphere component, $I_{q,u,p,f}$, is calculated using the ATLAS9 code of Kurucz from plane-parallel model atmospheres (for details, see Unruh et al., 1999). The intensities do not change with time but are functions of the wavelength, λ, and $\mu(i,j)$. The sum of the brightnesses of all components weighted by their filling factors and integrated over all μ (or (i,j)) gives the solar irradiance at a given wavelength:

$$
\begin{aligned}
F(\lambda,t) = \textstyle\sum_{i,j}[\ & \alpha_u(i,j;t) I_u(i,j;\lambda) \\
& + \alpha_p(i,j;t) I_p(i,j;\lambda) \\
& + \alpha_f(i,j;t) I_f(i,j;\lambda) \\
& + \alpha_q(i,j;t) I_q(i,j;\lambda)].
\end{aligned}
$$

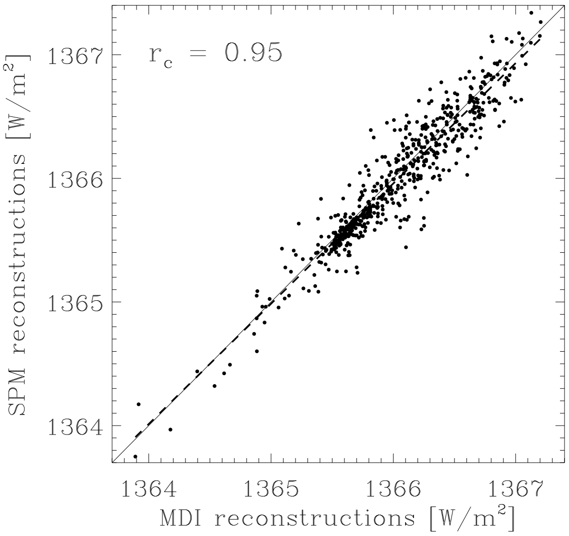

Fig. 5. Modelled total solar irradiance between 1996 and 2001 based on KP SPM data vs. MDI-based reconstructions. The correlation coefficient is 0.95. The diagonal solid line represents the expectation values for perfect models, the dashed line is a regression (from Wenzler et al., 2004a).

The integration over all wavelengths yields the TSI. The method thus automatically provides both the total and spectral irradiance.

The modelled TSI for the period 1996–2002, i.e. between the minimum and maximum of cycle 23, is shown in Fig. 4 together with the VIRGO measurements (Fröhlich and Finsterle, 2001). The close agreement between the model and observations on both the rotational and solar cycle time scales, with a correlation coefficient $r_c = 0.96$, implies that the principal assumption behind the model is valid and it is the surface magnetic field which causes the irradiance variations on time scales of days up to the solar cycle.

However, it has been argued (de Toma et al., 2001) that cycles 22 and 23 might have different or at least not identical sources of radiative variability. In the traditional solar activity indices, cycle 23 looks weaker than cycle 22. The current cycle also has a lower total amount of unsigned magnetic flux, whereas the irradiance levels are about the same. Therefore an extension of the model to earlier cycles is of crucial importance for understanding the mechanisms of the irradiance variability. This appears feasible owing to the set of full-disc magnetograms and continuum images regularly recorded at the Kitt Peak National Solar Observatory since 1974. The ground-based observations are unfortunately not as homogeneous as those recorded by MDI. In addition, the instrument has been improved a few times, with the newest, the Spectromagnetograph (SPM; Jones et al., 1992), being in work since 1992. Therefore, Wenzler et al. (2004a) started from a comparison of the performance of the SPM and the MDI and showed that SPM data can be employed to reconstruct TSI variations with almost the same accuracy as MDI (Fig. 5).

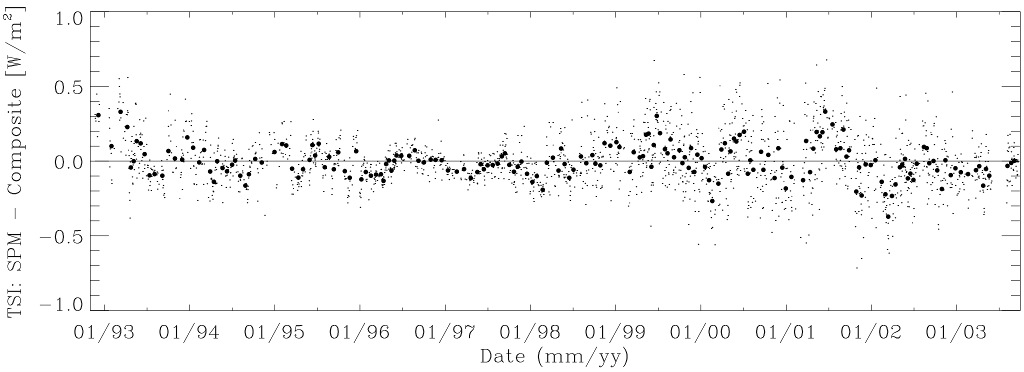

Fig. 6. Differences between the reconstructed TSI based on KP SPM data and the composite measurements. Every dot represents a daily value, the bigger filled circles 10 day averages. The solid line marks a perfect model (following Wenzler et al., 2004b).

In the next step, Wenzler et al. (2004b) have extended the reconstruction over the whole operational period of SPM, i.e. from the declining phase of cycle 22 in 1992 to the declining phase of cycle 23. The correlation coefficient between the model and the TSI composite (Fröhlich, 2003) for the whole period is 0.94 and no bias between cycles 22 and 23 is seen. This is demonstrated by Fig. 6 which shows the 10-day averaged difference between reconstructions and measurements and does not exhibit any asymmetry between the two cycles.

Finally, the SATIRE model can be extended to cover the whole period over which NSO/KP data are available. Before 1992 the older NSO/KP solar magnetograph (Livingston et al., 1976) was in operation, with a noticeably lower quality of the data. In particular, the continuum images are not good enough to distinguish between umbrae and penumbrae. Therefore only entire sunspots could be identified and the umbra/penumbra ratio had to be kept constant. This ratio was taken from the results for the SPM period. The work has not yet been completed but preliminary results look encouraging (Wenzler et al., in preparation). Such a preliminary reconstruction is shown in Fig. 7 together with the composite TSI record of Fröhlich (2003) since 1978. The correlation coefficient between the model and the measurements is 0.9. Despite the obvious decrease of quality of the reconstructions in the earlier period, no bias between the 3 activity cycles has been found. Irradiance changes on all the considered time scales, days to decades, are well reproduced. Our main conclusion that solar surface magnetism is the key source of irradiance changes is thus not confined to cycle 23 but is also valid for earlier cycles.

3 Conclusions

The invaluable record of total solar irradiance measurements now covers about 2.5 cycles. However, it remains too short to allow definite conclusions regarding the Sun’s influence on climate. Also, the question about the presence of a secular

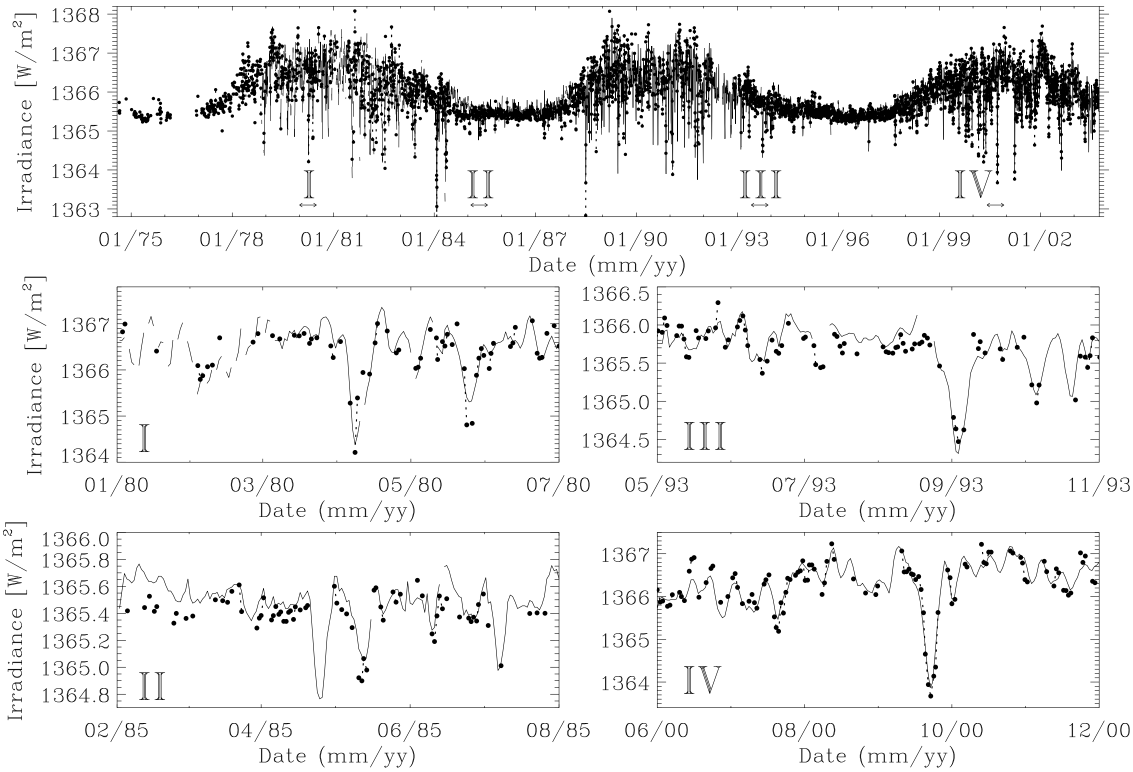

Fig. 7. Top panel: The reconstructed TSI (filled circles, connected by dotted curve when there are no data gaps) based on NSO/KP data between 1974 and 2003. The solid line represents the measured total solar irradiance (composite of Fröhlich) between 1978 and 2003. The bottom panels are enlargements of four shorter intervals at different activity levels from different cycles.

change during the period of observations is still open (Fröhlich, 2003; Willson and Mordvinov, 2003; Dewitte et al., 2004). This calls for models of solar irradiance on both short, days to decades, and long, decades to millenia, time scales. Direct observations cover the shorter time scales allowing the models to be tested against measurements and thus the mechanisms of the variations to be understood. Recent models reproduce observed irradiance variations with high accuracy suggesting that a good understanding of these mechanisms has been gained.

One of the lines of further development of the SATIRE models includes the removal of the remaining free parameter. Another direction is improvement of models in the UV or IR. As mentioned above, SATIRE is applicable to reconstructions of solar spectral irradiance as well. Variations of the spectral irradiance longward of 300 nm are well reproduced by the model (Unruh et al., 2000; Krivova et al., 2003), although a comparison on time scales longer than a few months is hampered by the uncertain long-term trends in the data. However, at wavelengths shorter than 300 nm the LTE approximation used to calculate model atmospheres fails and non-LTE modelling must be called for. An alternative, more empirical approach could be a proper extrapolation of the existing models to shorter wavelengths based on the available measurements in the UV (Krivova and Solanki, 2004b). A disagreement has also been found by Fontenla et al. (2004) between their model and observations in the near-IR. This suggests that long wavelengths are also sensitive tests of irradiance models. The SATIRE models should also undergo such a test.

The aim of the models on longer time scales is to reconstruct the behaviour of the solar irradiance at earlier times. Obviously they cannot be of the same quality as the shorter term reconstructions due to the available proxies, whose number and quality decreases as we go further back in time. Nonetheless, a number of quite detailed reconstructions is now available for the cyclic component of the variations, some going back to the end or even beginning of the Maunder minimum (e.g. Lean et al., 1995; Solanki and Fligge, 1999; Fligge and Solanki, 2000; Foster and Lockwood, 2004). The magnitude of the secular trend remains highly uncertain, however, and strongly calls for further investigation (see, e.g., reviews by Lockwood, 2004; Solanki and Krivova, 2004).

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