# SOLAR VARIABILITY OF POSSIBLE RELEVANCE FOR PLANETARY CLIMATES

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**Abstract.** The global variability of the Sun of relevance for planetary climates has been directly measured for the past few decades. For longer stretches of time models are required. Semi-empirical models can now accurately reproduce the measured records of solar total and spectral irradiance, as well as of the magnetic flux. They can also provide reconstructions of these quantities on longer time scales. Here a summary is given of some of the modelling efforts and of the results achieved so far.

**Keywords:** Sun: activity, Sun: irradiance, Sun: magnetic fields, solar-terrestrial relations, Sun: UV radiation

## 1. Introduction

Solar variability takes on different guises. Many of these correspond to local changes on the Sun (e.g., the appearance of a sunspot group, or the brightening of a system of coronal loops). Planetary atmospheres feel only global changes of the Sun. The global solar variables of possible relevance for planetary climates include the variable solar total radiative flux or total irradiance (i.e., the wavelength integrated radiative flux measured above the Earth's atmosphere), which determines the energy input into planetary atmospheres, the solar spectral irradiance, which affects stratospheric chemistry, the Sun's open and total magnetic flux (the open flux affects cosmic ray flux and planetary magnetospheres) and solar particle flux, including energetic particles (e.g., strength and speed of the solar wind around the ecliptic plane, number and strength of coronal mass ejections). We can safely neglect the direct influence on climate of the Sun's particle flux, since it carries only $2 \times 10^{-6}$ of the energy transported by radiation. However, solar energetic particles may play an indirect role in that they may to a certain extent affect proxies such as cosmogenic isotope concentrations used to reconstruct past solar activity. Note that the Sun's global variability is often driven by local processes and structures (e.g., flares and other eruptive processes, convection cells, sunspots, faculae, chromospheric network, coronal loops, coronal holes and streamers).

The Sun is variable at all time scales on which we can carry out measurements or computations, ranging from seconds to billions of years. The variability at different time scales, however, has different, often quite diverse causes. Thus, convection

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near the solar surface typically affects solar output on time scales shorter than roughly a day, oscillations are known to influence solar irradiance on time scales of minutes, while solar rotation introduces a period of 27–30 days as seen from Earth. At the other extreme, solar evolution, driven by the gradual change in chemical composition in the solar core, produces large, even drastic changes in the Sun's luminosity and radius at time scales of $10^6$–$10^{10}$ years. Finally, the Sun's magnetic field itself changes on a broad range of time scales (the most prominent one being the 11-year cycle) and in addition plays an often dominant role in producing changes in other global quantities. These changes driven by the magnetic field range from seconds (structure seen in radio bursts) to billions of years (evolution of the strength of the Sun's magnetic field and thus of magnetic activity).

In this overview we will concentrate on solar total and spectral irradiance variations. Measurements of these parameters with an accuracy that is sufficient to reliably display their variations are restricted to the last few solar cycles (see Fröhlich, 2006), which, although differing in some important aspects are relatively similar to each other (compared to some earlier cycles that were often much weaker). In order to obtain an estimate of the variation of the Sun on a longer time scale proxies and models are needed, preferably in combination.

There are a number of proxies that have been used to trace solar irradiance or some aspect thereof. These include sunspot number (available since 1610), facular area (available between 1874 and 1976), Mg II core-to-wing ratio (available from 1978), the total magnetic flux (regularly available from 1974), the geomagnetic aa-index (available from 1868), $\Delta^{14}$C and $^{10}$Be concentration (partly available for the whole Holocene). Models and the reconstructions of solar irradiance made therefrom often rely on some such proxy, since it is not yet possible to compute variations of the solar irradiance from first principles.

In the following we first consider reconstructions of irradiance over the last few decades, i.e., the period over which irradiance measurements are available (Sections 2 and 3). Then we discuss longer term reconstructions of irradiance (Section 4) and solar activity (Section 5). Finally, in Section 6 a brief summary and outlook is given.

## 2. Short-Term Total Solar Irradiance Variations

The measured total irradiance record (as put together in a composite (e.g., Willson and Mordvinov, 2003; Fröhlich, 2003, 2004; DeWitte *et al.*, 2004) shows two features that are striking. The first is the dips happening on time scales of a week or two, the second is the solar cycle variation of roughly 0.1% (i.e., roughly 1.3 $\mathrm{Wm}^{-2}$, which converts into 0.24 $\mathrm{Wm}^{-2}$ averaged over the whole Earth).

The dips, some of which can be as deep as 3 $\mathrm{Wm}^{-2}$, are due to the passage of sunspot groups across the solar surface due to solar rotation. A group is visible for a maximum of roughly 14 days, but due to foreshortening and limb darkening (the limb of the Sun is significantly darker than the centre of its disk) the dips typically have a length of 7–10 days. As shown by Spruit (1982) the heat flux blocked by sunspots does not reappear at the solar surface immediately, but is distributed throughout the convection zone, reappearing on a time scale of around $10^5$ years. Therefore, a sunspot at the solar surface leads to a deficit in solar luminosity (i.e., the solar output integrated over all angles) for the period of time that the spot is present. In spite of this, the Sun is brighter at activity maximum, i.e., at a time when there are on average more sunspots on the solar surface. This seemingly inconsistent behaviour is due to the presence of increased amounts of faculae, i.e., bright structures. Sunspots and faculae are both formed together when active regions appear at the solar surface. In the early phases of an active region's development, the sunspots often dominate and lead to a darkening. However, the lifetime of sunspots is shorter than of the surrounding faculae and the sunspots decay into faculae. Hence active regions may be dark early in their life, but turn bright after some time (see Ortiz *et al.*, 2000 for an example).

This qualitative discussion can be tested using quantitative modelling. Different models that aim to reproduce solar total irradiance have been developed (Foukal and Lean, 1990; Chapman *et al.*, 1996; Fröhlich and Lean, 1997; Fontenla *et al.*, 1999, 2004; Fligge *et al.*, 2000; Preminger *et al.*, 2002; Ermolli *et al.*, 2003; Krivova *et al.*, 2003; Jain and Hasan, 2004; Wenzler *et al.*, 2004, 2005). Here we discuss one such set of models in greater detail, the so called SATIRE models (Spectral And Total Irradiance REconstruction). This model is based on the assumption that it is the magnetic field at the solar surface which is responsible for all irradiance variations on time-scales longer than roughly a day. The magnetic field lies at the heart of both the dark (e.g., sunspots) and bright features (e.g., faculae in active regions, and the network distributed over the whole Sun).

SATIRE models are semi-empirical. Spectra computed from model atmospheres are used to describe the radiative influence of different components of the solar atmosphere. These components are sunspot umbrae and penumbrae, faculae (including the network) and the quiet Sun. The model atmospheres are constructed using independent data (i.e., not the irradiance time series). Magnetograms and continuum images measured daily are used to separate the solar atmosphere into its components. Each pixel on the solar surface is then replaced by the corresponding spectrum. After summing over all pixels, the Sun's irradiance spectrum is obtained. After further integration over all wavelengths the total solar irradiance is found. The model has a single free parameter. A more detailed description of the model is given by Fligge *et al.* (2000), while the model atmospheres used are described by Unruh *et al.* (1999).

SATIRE gives a remarkably good correspondence (correlation coefficient of around 0.96) with the irradiance measured by the VIRGO instrument (Fröhlich *et al.*, 1995) flying on SOHO, irrespective of the source of the employed magnetograms (Krivova *et al.*, 2003; Wenzler *et al.*, 2004). On a longer time scale it still shows a good correspondence with the PMOD irradiance composite produced by Fröhlich, see Figures 1 and 2. In particular, there is no trend in the difference between the measured total solar irradiance and that reconstructed by the SATIRE model. This confirms firstly that the dominant part of the observed irradiance variations (on time scales of days to the solar cycle) are due to the surface magnetic field (Krivova *et al.*, 2003; Wenzler *et al.*, 2005, 2006). It also confirms that there is no trend of magnetic origin in the total solar irradiance since 1974 (Wenzler *et al.*, 2006). A putative trend, such as that proposed by Willson and Mordvinov (2003) and DeWitte *et al.* (2004), must therefore be caused by some effect that is independent of the magnetic field.

## 3. Short-Term Solar Spectral Irradiance Variations

Since SATIRE computes the spectrum at each point (pixel) on the solar surface, it is straightforward to reconstruct the Sun's irradiance spectrum. The results are reasonable at wavelengths longwards of 200 nm, since the assumption of LTE underlying the radiative transfer used for computing the model spectra breaks down at shorter wavelengths and more sophisticated techniques have to be used (Fontenla *et al.*, 1999, 2004; Haberreiter *et al.*, 2005). A comparison with SUSIM data in the

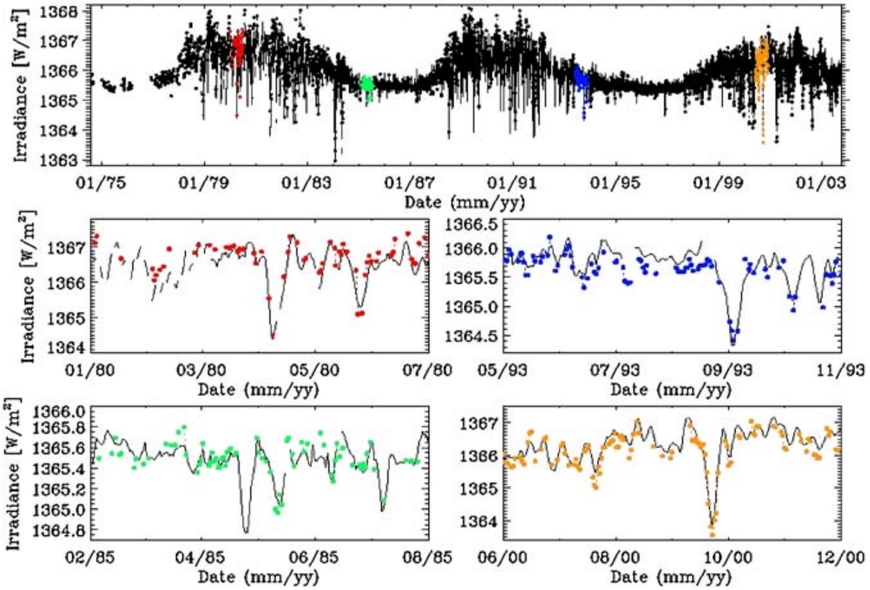

*Figure 1.* Total solar irradiance: composite of measurements of Fröhlich (solid lines) and reconstructed using SATIRE (dots). *Top panel:* Irradiance from 1974 to 2003. *Bottom 4 panels:* Shorter periods chosen at random, displaying more clearly the comparison between measured and modelled irradiance (from Wenzler *et al.*, 2006).

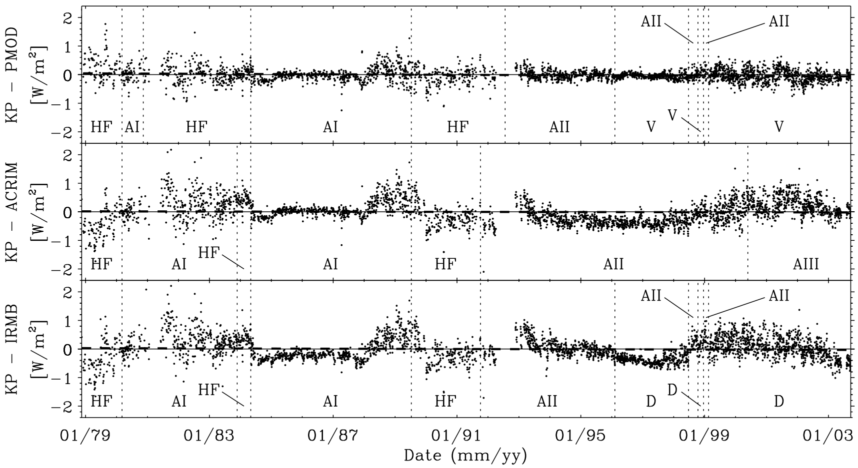

*Figure 2.* Difference between measured and modelled total solar irradiance. The three panels show the difference obtained for the three composites made by Fröhlich (2004) (top panel), by Willson and Mordvinov (2003) (middle panel), and by DeWitte *et al.* (2004) (bottom panel). The modelled irradiance is the output of the SATIRE models (from Wenzler *et al.*, 2006).

220–240 nm band is shown in Figure 3 for the rising phase of solar cycle 23. We stress that the same value of SATIRE's free parameter is used as for the reconstruction of the total irradiance for the same period of time. Although the agreement is not perfect (in particular, the reconstructed spectral irradiance is too low during the winter of 2000/2001), it is nevertheless quite satisfactory, giving a correlation coefficient $R_c = 0.97$. Krivova and Solanki (2005) have found a method to empirically extend the model spectrum to wavelengths as short as Ly-$\alpha$. This allows a more secure estimate of the contribution of the ultraviolet wavelength range ($\lambda < 400$ nm) to total irradiance variations to be made. The main uncertainty results from the wavelength range between 300 and 400 nm, where the SUSIM data are not sufficiently accurate to give reliable estimates of the small irradiance changes. The result is that around 60% of the total irradiance change between solar activity minimum and maximum is produced in the UV part of the spectrum, i.e., shortward of 400 nm, although only 8% of the radiation is emitted at these wavelengths. This result suggests that more attention should be paid to the influence of the Sun's varying UV radiation on the Earth's atmosphere (see Haigh and Blackburn, 2006; Schmidt and Brasseur, 2006).

## 4. Longer-Term Solar Variations

Once it has been shown that the surface magnetic field is responsible for solar irradiance variations via its manifestations such as sunspots and faculae, the reconstruction of solar irradiance on longer time scales requires the computation of the

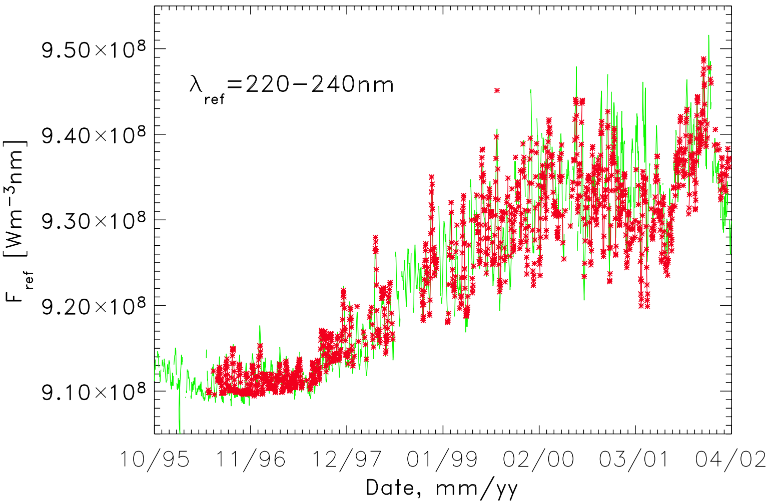

*Figure 3.* Comparison of solar spectral irradiance in the 220–240 nm band measured by the SUSIM instrument on UARS (solid line) with the SATIRE reconstruction (stars).

Sun's magnetic field for the same time scale. When doing this it can be useful to distinguish between cyclic variations, which can often be well described by proxies, and secular variations, which are more tricky to estimate.

The cyclic variations since 1700 have been computed with varying degrees of sophistication by Lean *et al.* (1995); Solanki and Fligge (1999), and others. The quality of the reconstructions is quite reasonable since 1874, but is increasingly lower at earlier times due to the lack of appropriate data (e.g., at earlier times the sunspot number records either are only available in monthly or yearly bins, or have large gaps in them). The change in cycle-averaged irradiance since the Maunder minimum due to the cyclic component is estimated to be 0.6 Wm$^{-2}$.

A potentially much larger effect can be produced by a secular trend in the Sun's irradiance. Evidence for such a trend originally came from Sun-like stars. Baliunas and Jastrow (1990) showed a double-peaked histogram of the number of field stars as a function of calcium emission (a commonly used measure of a star's magnetic activity). The peak at higher stellar activity was interpreted to be produced by cycling stars, while the lower peak was deemed to be populated by stars in a non-cycling, Maunder-minimum-like state. The present-day Sun displays Ca emission at levels corresponding to the higher-activity peak even during solar activity minimum. This was interpreted by Lean *et al.* (1992, 1995) to imply that the Sun was approximately 2.6 Wm$^{-2}$ less bright during the Maunder minimum than averaged over recent solar cycles.

This result has recently been questioned. Newer observations display a single-peaked distribution of activity, with non-cycling stars intermixed with stars exhibiting a cyclic behaviour of their magnetic activity (e.g., Wright, 2004; Giampapa, 2005; Hall and Lockwood, 2004). One clue to the possible cause of the discrepancy between these recent results and the older ones lies in the fact that observations of stars of the same age in the old open cluster M67 support the more recent observations of dwarf field stars. Thus, the older results of Baliunas and Jastrow (1990) may have been a result of an inappropriate inclusion of stars of too broad a range in ages into the diagram. In summary, stellar observations no longer provide any solid evidence for secularly changing solar activity and hence also not of a secular trend in irradiance.

New evidence for secular variations has emerged from another source, however. The interplanetary magnetic field, reconstructed by Lockwood *et al.* (1999) from the geomagnetic aa-index, exhibits a doubling over the last century, besides the normal 11-year cycle similar to that shown by sunspot number. Observations by the Ulysses spacecraft have revealed that the interplanetary field is very closely related to the Sun's open magnetic flux. The open flux is composed of magnetic field lines that are carried out by the solar wind into interplanetary space (closed field lines, by contrast, form loops with heights below a few solar radii). Since 1964 the reconstructed open flux agrees well with direct measurements made by spacecraft. The open magnetic flux of the Sun is responsible for the modulation of cosmic ray flux and hence of the production rate of cosmogenic isotopes. For the reconstruction of solar irradiance, the total magnetic flux is the basic quantity. The open flux directly contributes only a few percent to the total flux. Nonetheless, the open flux reconstruction by Lockwood *et al.* (1999) is an important time series also for irradiance reconstructions, since it runs considerably longer than the time series of total flux (which goes back only to the 1970s).

The mechanism proposed to explain the secular change in the Sun's magnetic field is based on the overlap of the magnetic flux between consecutive activity cycles (Solanki *et al.*, 2000, 2002). An overlap implies that the flux does not drop to zero at activity minimum (as is observed: even at activity minimum, the Sun is still covered by a network of magnetic field). An overlap can be produced either by the emergence of fresh flux belonging to the new cycle, while the old cycle is still in progress, or by the extended lifetime of some of the flux on the solar surface, so that flux that emerged during the old cycle is still present when the new cycle starts.

The basic recipe for computing the Sun's magnetic field over time is to use the sunspot number as a proxy for the emergence of fresh magnetic flux in active regions (since sunspots appear early in the life of an active region and decay relatively fast they are a reasonable proxy of freshly emerged flux). In addition to active regions, emergence of magnetic flux in smaller ephemeral regions is also considered. In a coarse model the overlap between consecutive cycles is achieved in two different ways. Firstly, the open flux is assigned a long lifetime. This applies mainly to the open flux that is built up at the poles of the Sun during solar activity minimum. Since the flux there is mainly unipolar, it decays slowly and is still present when the new cycle is already in full swing. Secondly, the ephemeral regions also introduce an overlap since they start to emerge earlier than the active regions, while the previous cycle is still running strong (ephemeral regions can be assigned to a particular cycle through the latitude of their emergence and, to a lesser extent, by Hale's polarity law). The first form of overlap mainly affects the Sun's open flux, but does not significantly influence the total flux, since the open flux is only a very minor constituent of the total magnetic flux.

Such a model not only reproduces the open magnetic flux reconstructed by Lockwood *et al.* (1999; see Figure 4), but also the measurements of total magnetic flux since 1974 (Harvey, 1994; c.f. Arge *et al.*, 2002; Figure 5), if the result of Krivova and Solanki (2004) is taken into account that in typical synoptic charts (such as those constructed from Kitt Peak magnetograms) around a factor of 2–3 of the magnetic flux in the quiet network is likely to be missed due to cancellation within a typical spatial resolution element.

Once the magnetic flux has been determined, then the time series of measured sunspot areas (or sunspot number) is employed to determine the magnetic flux in sunspots and hence darkening they produce. The remainder of the magnetic field is used to compute the brightening due to faculae. The reconstructed irradiance is compared with the PMOD composite of measurements and found to reproduce them simultaneously with the other data sets shown in Figures 4 and 5 (although the irradiance is reproduced with slightly lower accuracy than the reconstructions based on the magnetograms). The time series of the total solar irradiance reconstructed since the Maunder minimum is plotted in Figure 6. Various things can be seen from that figure. Firstly, the quality of the reconstruction is lower at earlier times. This has to do with the fact that the quality of the data decreases at earlier times (e.g., there are more data gaps). Secondly, a small, but significant secular increase of the irradiance since the Maunder minimum is found. Compared to the Maunder minimum the recent cycle-averaged total irradiance is 1.3 $\mathrm{Wm}^{-2}$ higher in this model (Balmaceda *et al.*, 2006, manuscript in preparation). Other models (Foster, 2004; Lockwood, 2005; Wang *et al.*, 2005) give irradiance rises ranging between 0.9 $\mathrm{Wm}^{-2}$ and 2.2 $\mathrm{Wm}^{-2}$.

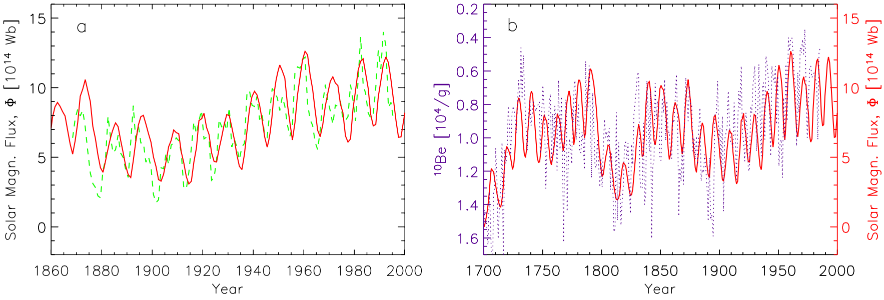

*Figure 4.* The open magnetic flux of the Sun computed by a coarse model (solid curve) compared to (a) the reconstruction by Lockwood *et al.* (1999) (dashed curve), and (b) the $^{10}$Be concentration in Greenland ice (Dye-3; Beer *et al.*, 1990) (dotted curve). Note the inverted scale for $^{10}$Be.

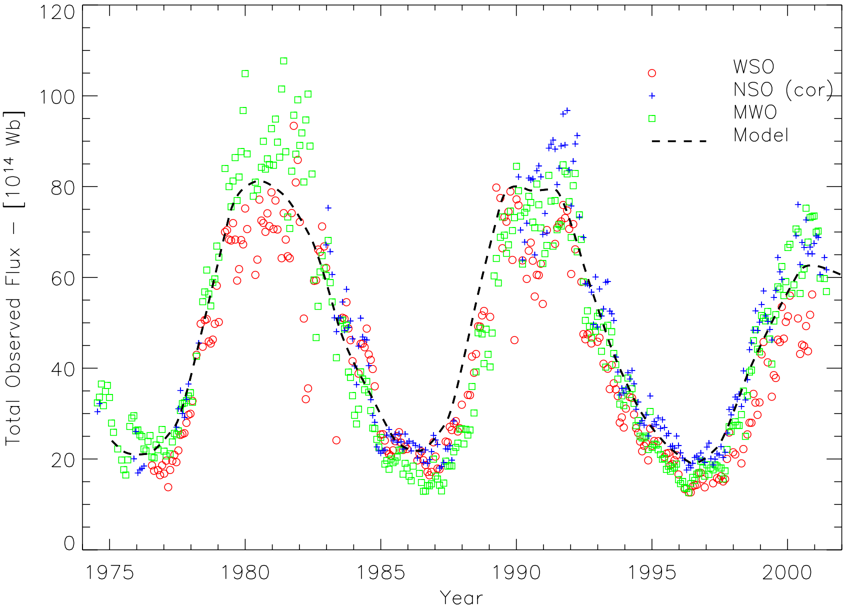

*Figure 5.* Comparison between measured (symbols) and computed (dashed line) total magnetic flux (each symbol is the magnetic flux in a synoptic chart).

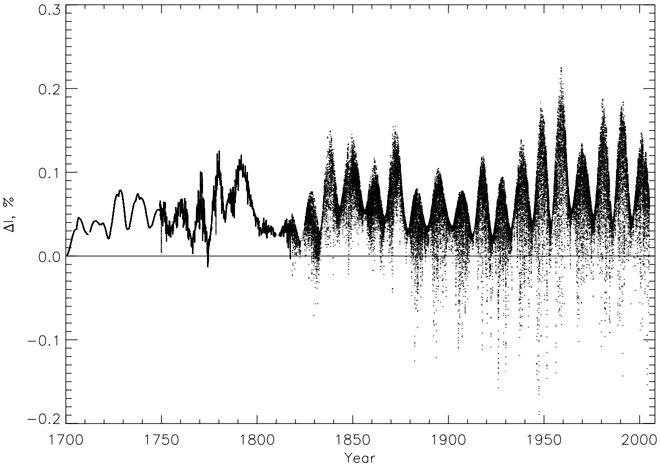

*Figure 6.* The reconstructed total solar irradiance since the Maunder minimum.

In addition to the processes described above, non-magnetic mechanisms are also conceivable for producing a secular change in solar irradiance. However, no concrete mechanism has so far been worked out in any detail and therefore it is not possible to judge how strong a secular change due to putative non-magnetic mechanisms might be.

## 5. Solar Variability Over Millenia

On an even longer time scale no direct measurements of solar variability are available (individual naked-eye observations of sunspots are far too incomplete to give a reliable picture of solar activity). Therefore, indirect proxies must be used, such as the cosmogenic isotopes $^{10}$Be and $^{14}$C, which are produced when high-energy cosmic rays enter the Earth's atmosphere and react with nitrogen and other atoms. Since the intensity of cosmic rays reaching Earth varies with solar activity (more particles make it through to 1 AU from the interstellar medium when the Sun's activity is lower, i.e., when the Sun's open flux is weaker). It is possible, from a measurement of the production rate of cosmogenic isotopes in terrestrial archives to reconstruct the solar modulation parameter, a parameter describing the influence of the Sun's magnetic activity on the cosmic ray flux and from that the strength of the Sun's open magnetic flux. This then allows the sunspot number to be reconstructed (Stuiver and Quay, 1980; Usoskin *et al.*, 2002). Only cycle averaged sunspot numbers can be reconstructed with any accuracy. The reconstructed sunspot numbers agree relatively well with the group sunspot numbers for the period that they overlap (Usoskin *et al.*, 2003, 2004; Solanki *et al.*, 2004).

The most surprising result obtained from these reconstructions is that the Sun is currently in a state of unusually high magnetic activity. The Sun spent only around 3% of the time in the last 11,400 years at a similar level of activity as in the last 60 odd years (see also the error bars; Figure 7). It appears likely that, given the statistics of previous periods of high activity seen in the reconstructed sunspot number, cycle averaged solar activity will decrease significantly within the next 50–100 years. More details on the Sun's behaviour on time scales of centuries to millenia are given by Beer (2006).

## 6. Summary and Outlook

The state of our quantitative knowledge and understanding of solar variability of importance for climate has made significant progress in past years. We can now reproduce observed solar total and spectral irradiance variations with high accuracy, have found a process that can explain a secular change in the solar magnetic field and thus in such quantities as cosmic ray flux and solar irradiance, and have improved methods of reconstructing specific parameters of solar activity throughout the Holocene.

In spite of this progress there is still considerable left work to be done. In the near term, reliable reconstructions of spectral irradiance need to be made for periods extending beyond the time for which direct measurements are available. Fligge and Solanki (2000) carried out a first such reconstruction, but it can be improved upon. A reconstruction of the solar (total and spectral) irradiance over the whole Holocene

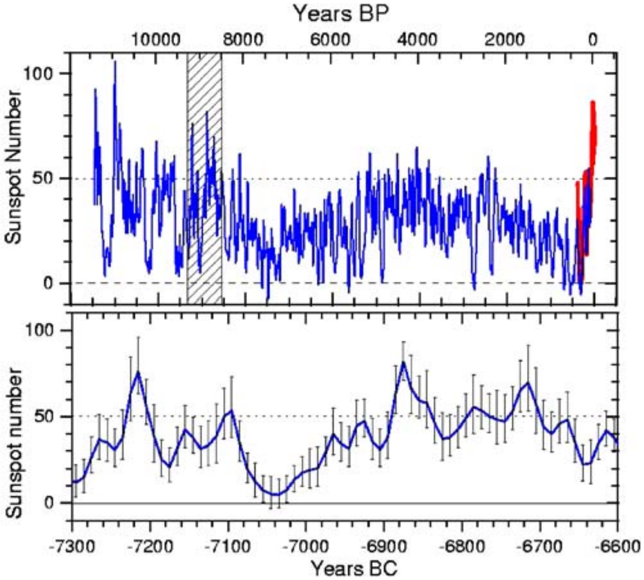

*Figure 7. Upper panel:* Cycle-averaged sunspot number reconstructed from $^{14}$C over the last 11,400 years, combined with the Group Sunspot Number since 1610. *Lower panel:* Blow-up of the hatched region in the upper panel (adapted from Solanki *et al.*, 2004).

should also be possible with the help of the new sunspot number reconstructions. However, given the low temporal resolution of the data, this will be more tricky. The removal of the last remaining free parameter in the reconstructions of the observed irradiance record is needed and will hopefully soon be achievable. Finally, we do not have the capability to reliably predict solar irradiance. Here much work is needed and it is not likely that any quick successes will be achieved.

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