The solar spectral irradiance since 1700

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Abstract. The change in the irradiance spectrum of the Sun from 1700 to the last solar minimum is determined and compared to the change in the spectrum between activity minimum and maximum. For this purpose we have used detailed model flux spectra of solar magnetic features. Also, time-series of the solar spectral irradiance since 1700 in different wavelength bands are reconstructed. We expect that these reconstructions are more accurate than previously published ones, although they suffer (like all reconstructions of solar irradiance on such time-scales) from uncertainties in our knowledge of the evolution of the solar network with time.

Introduction

Solar irradiance variations are known to exhibit a strong wavelength dependence, with the amount of variability increasing towards shorter wavelengths (Lean 1991, Solanki & Unruh 1998). The integrated spectrum (total solar irradiance) changes by roughly 0.1% over the solar cycle. The same amount of variability is found for the visible wavelengths where most of the solar radiative output occurs.

Variations at UV and shorter wavelengths, however, exceed those at visible by orders of magnitude. Since solar UV radiation controls the amount of stratospheric ozone these variations have been proposed as a significant driver of changes of the terrestrial climate system (Haigh 1996). Therefore, reconstructions of the past evolution of the solar spectrum, particularly at shorter wavelengths, is of fundamental importance for investigations addressing the influence of the Sun on atmospheric chemistry and eventually climate.

The change in the solar spectrum (from extreme UV to far IR wavelengths) between the minimum and maximum of solar activity was first modeled by Solanki & Unruh (1998), and found to reproduce the observed spectral trend in the UV (Lean et al. 1993, London et al. 1993). Using the same technique Fligge et al. (1998; henceforth referred to as PAP-I) reconstructed solar total and spectral irradiance variations over the last two cycles and compared them to spectral irradiance measurements recorded by VIRGO as well as the composite of irradiance measurements proposed by Fröhlich and Lean (1998). The basic assumption of this model is that solar irradiance variations (on time-scales of days to centuries) are due to the changing distribution of solar surface magnetic features only.

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The model presented in this paper is an extension of the model of PAP-I back to the Maunder minimum using a third variability component to account for secular changes of solar irradiance on time-scales of decades to centuries. This third component is identified as the slowly varying solar surface magnetic network (e.g. White et al. 1992).

Model

The model employs three separate contributors to irradiance changes. These are: Sunspots, active region faculae and the network. Sunspots and active region faculae dominate irradiance changes on short time-scales, which includes their cyclic part. The network, which is responsible for the secular changes of solar irradiance, is expected to vary on time-scales significantly longer than the solar cycle.

Following PAP-I, the flux-spectrum of each of the three components is taken to be time-independent. The temporal evolution of the solar irradiance then originates from the changing surface coverage of the Sun by the individual components. The solar irradiance $S(\lambda;t)$ at wavelength λ and time t is thus given by

$$\begin{aligned} S(\lambda;t) &= \alpha_s(t)\cdot S_s(\lambda) \\ &+ \alpha_f(t)\cdot S_f(\lambda) \\ &+ \alpha_n(t)\cdot S_n(\lambda) \\ &+ (1-\alpha_s(t)-\alpha_f(t)-\alpha_n(t))\cdot S_{Mm}(\lambda), \end{aligned} \tag{1}$$

where $S_s(\lambda)$, $S_f(\lambda)$, $S_n(\lambda)$ and $S_{Mm}(\lambda)$ are the flux-spectra of sunspots, active region faculae, network and the Sun in its Maunder minimum state, respectively. $\alpha_x(t)$ is the fractional coverage of the Sun by component x, i.e. the filling factor of component x. Therefore, $\alpha_x(t)\cdot S_x(\lambda)$ is the contribution of component x to solar irradiance at time t and wavelength λ.

Flux spectra

The flux-spectra of sunspots and active region faculae, i.e. $S_s(\lambda)$ and $S_f(\lambda)$, have been taken from Unruh et al. (1999; henceforth referred to as PAP-II), where they have already been successfully applied to reconstructions of solar total and spectral irradiance variations over the solar cycle. The quality of such a reconstruction of the cyclic component of irradiance changes is shown in Fig. 1 which is similar to Fig. 8 of PAP-I, but has been carried out using the new models constructed in PAP-II. The agreement between data and model is high, with a correlation coefficient of 0.75 - 0.8.

From detailed empirical modeling of flux-tubes and their surroundings there is increasing evidence (e.g. Solanki & Brigljevic 1992) that the small-scale magnetic features

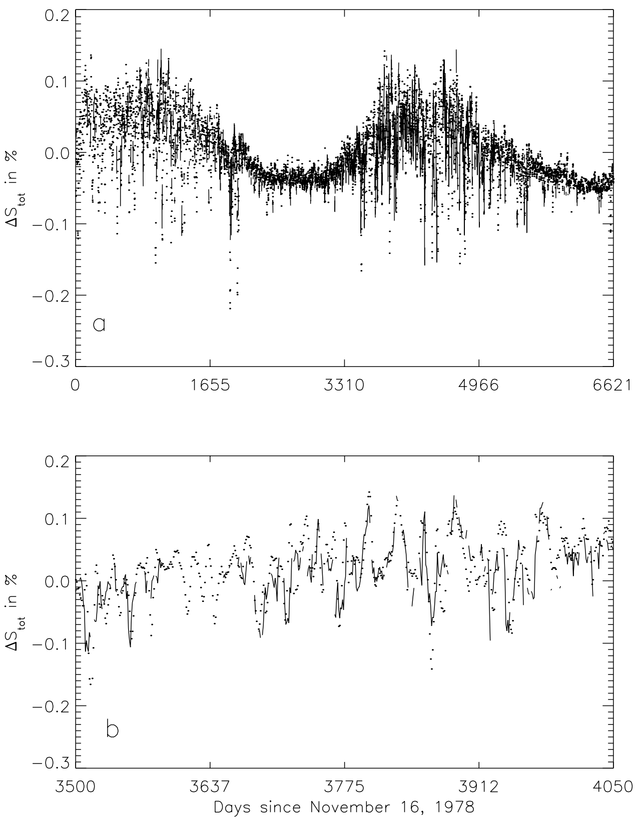

Figure 1. Measured (dotted; Fröhlich & Lean 1998) and reconstructed (solid) total solar irradiance variations, (a) over the last two solar cycles, (b) over a shorter period around the maximum of cycle 22. The figure is adapted from Fligge et al. (1998) using the improved flux-spectra described by Unruh et al. (1999).

within faculae and network regions show different brightness signatures. Within the level of accuracy achievable by long-term irradiance reconstructions, however, we can set

$$S_n(\lambda) = S_f(\lambda), \tag{2}$$

as has been implicitly done in all previous reconstructions. Finally, the solar flux spectrum during the Maunder minimum, $S_{Mm}(\lambda)$, is estimated from the comparison of the Sun with Sun-like stars (Baliunas & Jastrow 1990, White et al. 1992). Following Solanki & Fligge (1999) we assume that the Sun's *total* radiative output was roughly $0.3\pm0.1\%$ lower during the Maunder minimum than during the two most recent activity minima. This allows us to estimate $S_{Mm}(\lambda)$ by

$$\begin{aligned} \int S_{qs}^{1996} d\lambda &= \int \left[S_{Mm}\cdot(1-\alpha_n^{1996}) + S_n\cdot\alpha_n^{1996}\right] d\lambda \\ &= 1.003\cdot\int S_{Mm} d\lambda, \end{aligned} \tag{3}$$

where S_{qs}^{1996} is the solar flux spectrum during the magnetic activity minima in 1996 and α_n^{1996} the corresponding filling factor of the network. This implies $\alpha_n^{1996} = 0.043$ (i.e. 4.3%). Note that this filling factor describes the area coverage by a brightness structure corresponding to S_n and cannot be equated with the magnetic filling factor.

The relative change in the flux spectrum of the present-day Sun between activity maximum and minimum resulting from our model, i.e. $(S_{act} - S_{qs})/S_{qs}$, is plotted in Fig. 2 (dotted line). Also shown is the modeled difference between S_{qs} and the Sun during the Maunder minimum, i.e. $(S_{qs} - S_{Mm})/S_{Mm}$ (solid line). Both curves show a similar amount of variability for wavelengths shorter than 400 nm but differ significantly at visible and IR wavelengths, with weaker variations within an activity cycle than between the present-day activity minima and the Maunder minimum. The difference between the two curves partly stems from the fact that whereas the number of sunspots changes over the solar cycle, they affect the spectra neither at solar activity minimum nor during the Maunder minimum.

Filling factors

To reconstruct the evolution of solar irradiance variations back to the Maunder minimum we need to know the time-dependence of the filling factors for all three components, i.e. $\alpha_s(t)$, $\alpha_f(t)$ and $\alpha_n(t)$, respectively. Following PAP-I, $\alpha_s(t)$ is directly proportional to the observed total sunspot area, A_s, i.e. $\alpha_s(t) = a\cdot A_s(t)$, with $a \approx 1$. Sunspot areas are recorded regularly by several solar observatories, with records between 1874 and 1976 being maintained by the Royal Greenwich Observatory. We use the corrected composite record of sunspot areas proposed by Fligge & Solanki (1997). For the period before 1874, $\alpha_s(t)$ is extrapolated further back in time, using the Zürich sunspot relative numbers, $R_z(t)$. To this end we derive a linear relation between $\alpha_s(t)$ and $R_z(t)$ for the period since 1874, i.e. when $\alpha_s(t)$ can be independently determined. We assume this relationship applies unchanged also to earlier times.

The temporal evolution of the facular filling factor is derived from PAP-I, where $\alpha_f(t)$ has been determined from time-series of Mg II core-to-wing ratios for cycles 22 and 23. $\alpha_f(t)$ is extrapolated back to 1700 following the method of Solanki & Fligge (1998), i.e. $\alpha_f(R_z(t))$ is derived from binned values of $\alpha_f(t)$ plotted versus binned values of $R_z(t)$. The resulting quadratic relation is $\alpha_f(t) = (1.5\pm0.2)\cdot10^{-3} + (2.35\pm0.04)\cdot10^{-4}R_z(t) - (3.4\pm0.2)\cdot10^{-7}R_z(t)^2$. Again, this is assumed to apply back to 1700.

Finally, to complete the model input, the temporal evolution of the secular variations must be encoded into the time dependence of the network filling factor, $\alpha_n(t)$. In Sect. we

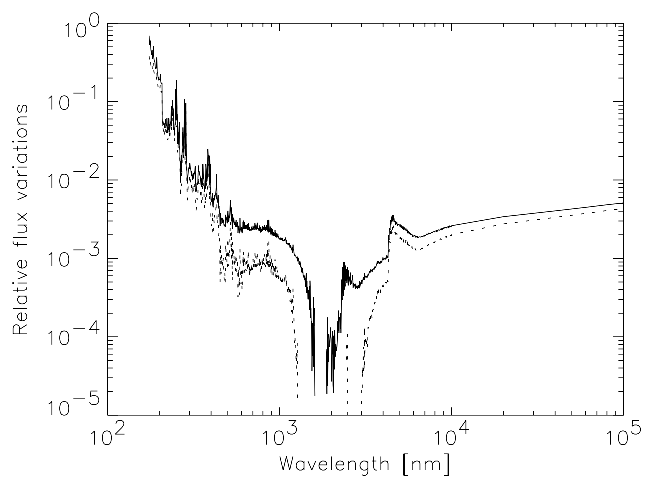

Figure 2. Relative solar irradiance changes between (present-day) activity maximum and minimum (dotted line) as well as between (present-day) activity minimum and the Sun in a Maunder minimum state (solid line).

Table 1. Increase of solar spectral irradiance at solar activity cycle minimum since the Maunder minimum for five wavelength bands.

	wavelength [nm]	[%]	irradiance [W/m^2]
Total	all	0.31	4.3
UV	< 300	3.0	0.4
NUV	300–400	1.3	1.2
Visible	400–700	0.32	1.7
IR	> 700	0.15	1.0

showed that in order to have a 0.3% increase of the total solar irradiance between the Maunder minimum and today, the fractional coverage of the Sun by the network component must have increased by around 4.3% since the Maunder minimum. We follow Solanki & Fligge (1999) and employ two different scenarios for the temporal evolution of $\alpha_n(t)$ between the Maunder minimum and today: either $\alpha_n(t)$ follows the amplitude of the activity cycle (Zhang et al. 1994, Lean et al. 1995) or $\alpha_n(t)$ follows the inverse of the cycle length (Baliunas & Soon 1995). For the solar cycle length we use the record proposed by Fligge et al. (1999) based on a continuous wavelet analysis of several proxies of solar magnetic activity.

Results

The spectral range and resolution of the reconstructed irradiance changes are dictated by factors such as the tabulated ODFs entering the spectral synthesis code (ATLAS, Kurucz 1992) used to calculate the flux spectra, so that the spectra are calculated from 160 nm to 160000 nm with a resolution of better than 200 in the visible. It is possible to reconstruct the irradiance at each wavelength point at which we have tabulated the individual flux spectra S_s, S_f and S_{qs}.

In the following analysis, however, we focus on five selected wavelength bands. These are: the total irradiance (i.e., all wavelengths), UV (< 300 nm), near UV (300 nm–400 nm), Visible (400 nm–700 nm) and IR (> 700 nm) wavelength bands. The evolution of the solar irradiance in the selected spectral bands between the Maunder minimum and the activity minimum in 1996 is shown in Fig. 3 and summarized in Table 1.

Although the total (and visible) irradiance has only increased by roughly 0.3% since the Maunder minimum the enhancement of UV and NUV radiation during the last 3 centuries is ten and four times larger, respectively. The variability of the IR was only moderate, i.e. at the 0.15% level. Nevertheless, as indicated by Fig. 2, the secular increase in brightness since 1700 at longer wavelengths would be even smaller if the secular change in the spectrum would have the same form as over the solar cycle. Note that in Fig. 3 for clarity only a secular variation inversely proportional to the cycle amplitude is considered. Between 1700 and 1749 yearly means are plotted, between 1750 and 1874 monthly means and daily values are used for the period after 1874. Plotted are from top to bottom the total, UV, near UV, visible and IR wavelength bands, respectively. As can be seen for the period since 1874 the UV and NUV are dominated by the contribution from active region faculae and the network, while the influence of sunspots is perceptible mostly at visible and longer wavelengths.

Table 1 reveals that as far as the absolute change in energy output is concerned the NUV, visible and IR wavelength bands give similar contributions.

Fig. 4 shows the 11-year average of the reconstructed irradiance for both secular irradiance trends considered here, namely, following the cycle length and the cycle amplitude. The result is plotted for two wavelength bands, the near UV band between 300 nm and 400 nm and, for comparison, the visible spectral range. Clearly, the variation in the two wavelengths bands differs almost only in amplitude. This is also true for the other wavelengths.

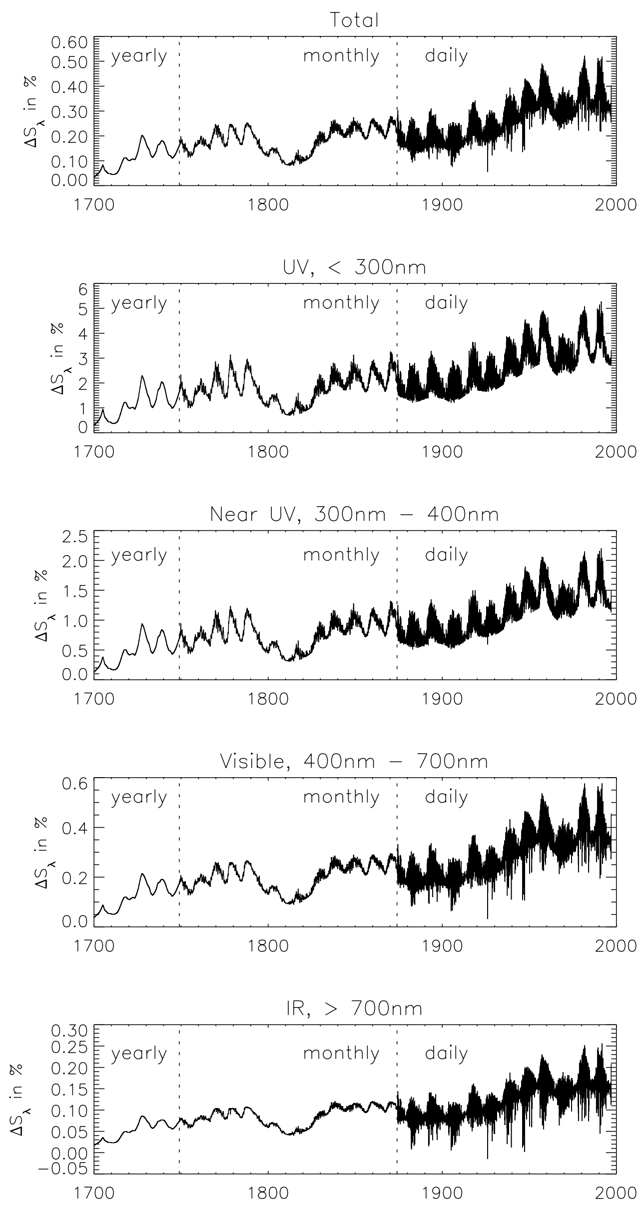

Figure 3. Reconstruction of the increase (in percent) of spectral solar irradiance since the Maunder minimum. From top to bottom, the following wavelength bands are plotted: Total irradiance, UV (< 300 nm), Near UV (300 nm – 400 nm), Visible (400 nm – 700 nm) and IR (> 700 nm), respectively.

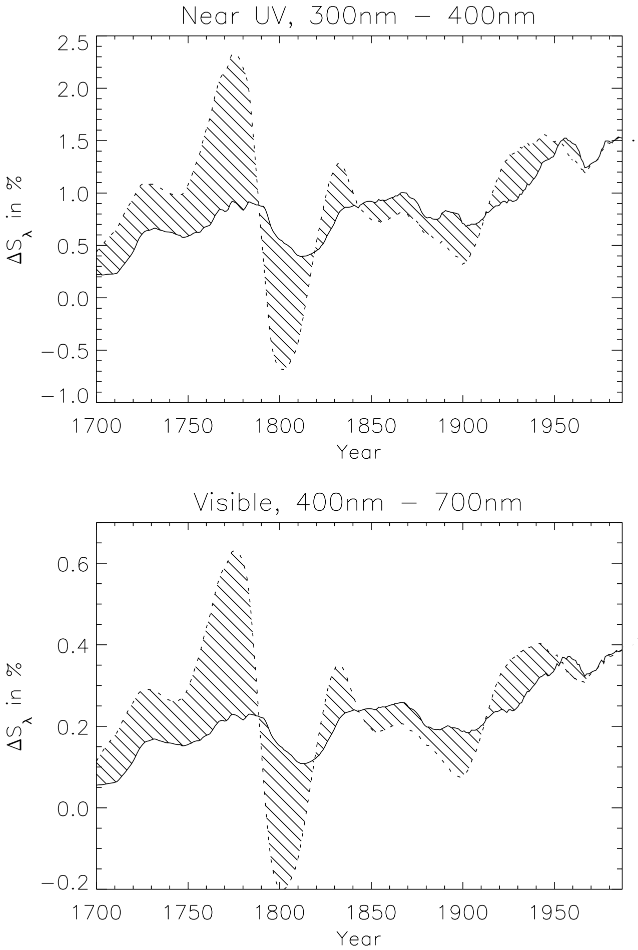

Figure 4. 11-y running mean of reconstructed solar spectral irradiance for (a) near UV wavelengths and (b) the visible using the amplitude (solid) and length (dotted) of the solar cycle to derive the long-term trend of α_n.

Conclusions

The ozone abundance in the Earth's atmosphere is influenced strongly by the level of solar UV radiation (e.g., Haigh 1994). Knowledge of the evolution of the solar spectral irradiance is therefore important for obtaining an idea of long-term changes in stratospheric chemistry and possible associated climate changes.

We have used the models of Unruh et al (1999) and a combination of the techniques of Fligge et al. (1998) and Solanki & Fligge (1999) to reconstruct the solar spectral irradiance from 1700 to the present. For the cyclic component of spectral irradiance changes the approach has been shown to be very successful in reproducing the observations. The cyclic part of the spectral irradiance should therefore be reconstructed relatively accurately. The secular variations are based mainly on stellar observations and both their amplitude and time dependence are the major source of uncertainty in the present reconstruction. This is to a certain extent demonstrated by Fig. 4. If we assume that the magnitude of the total irradiance increase since the Maunder minimum is correct, however, then we expect the change in the spectral irradiance since the Maunder minimum depicted in Fig. 2 to be roughly correct.

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