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A reconstruction of total solar irradiance since 1700

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Abstract. The irradiance of the Sun is reconstructed from 1700 to the present, whereby the contributions of active regions and the quiet Sun are modelled separately. A method is proposed which allows the contribution of active-region faculae and sunspots to irradiance changes to be isolated even when only a single proxy of solar activity, such as sunspot relative number, R_Z, is available. The resulting reconstruction explicitly takes the non-linear relationship between R_Z and irradiance variations into account. Nevertheless, due to the decreasing accuracy of the solar proxy data the accuracy of the reconstruction decreases at earlier epochs. The main uncertainty, however, lies in the reconstruction of the quiet-sun irradiance variations.

Introduction

The total irradiance of the Sun has been observed to change by 0.1–0.2% between solar activity maximum and minimum [*Willson and Hudson*, 1991; *Fröhlich and Lean*, 1998]. Although this variation is relatively small it has nevertheless been proposed as a possible driver of climate change [*Eddy*, 1977; *Reid*, 1987; *Friis-Christensen and Lassen*, 1991; *Lean et al.*, 1995; *Lawrence and Ruzmaikin*, 1998]. Precise measurements of the irradiance have only been made since 1978, whereas longer time series are required in order to establish a possible relationship with climate. It is therefore necessary to reconstruct solar irradiance over as long a time as possible using historical records of solar activity indicators and a model of how these are related to the irradiance.

Most such reconstructions are based on the assumption that the irradiance variations, ΔS, are caused by changes in the magnetic field at the solar surface. That changes in the magnetic flux at the solar surface affect the irradiance almost instantaneously has been demonstrated by *Spruit* [1982]. Typically the contributions from three components of surface magnetism are included: Sunspots lead to a darkening of the Sun, while faculae and the network result in a brightening. Sunspots and faculae are both concentrated in active regions. Their combined contributions to the irradiance variations is denoted by $\Delta S_{\rm act}$ and is responsible for much of the irradiance variations over time scales of the solar cycle and less [*Foukal and Lean*, 1988; *Chapman et al.*, 1996; *Solanki and Unruh*, 1998; *Fligge et al.*, 1998; but see *Kuhn et al.*, 1988 for a deviating viewpoint].

The network (and possible changes in solar convection) provides the main contribution to irradiance variations on time scales longer than the solar cycle, as has been argued by *Lean et al.* [1992] and *White et al.* [1992]. We term this contribution to the solar irradiance variations the quiet- Sun contribution, or $\Delta S_{\rm qs}$.

Long-term reconstructions depend on the availability of proxies for the 3 components over the time interval in which the irradiance is to be reconstructed. Since 1874 time series of a number of such proxies exist (including sunspot and facular areas), so that solar irradiance can be reconstructed relatively accurately. The only records reaching back to earlier epochs are the Zürich Sunspot Relative Number, R_Z and the closely related Group Sunspot Number, R_g [*Hoyt and Schatten*, 1997]. This paucity necessitates a simplification of the modelling process. Thus, *Lean et al.* [1995] assumed that $\Delta S_{\rm act}$ is simply proportional to the 1-year average of R_g and $\Delta S_{\rm qs}$ to the cycle-averaged R_g. *Hoyt and Schatten* [1993], on the other hand, assumed irradiance variations to be proportional to various parameters including the solar cycle length and the decay rate of sunspots.

Separating spot and facular contributions

Chapman et al. [1997] pointed out that the ratio of facular to sunspot area decreases roughly linearly with increasing R_Z (or R_g). Also, the total facular brightness shows signs of saturating at large R_Z [*Foukal, 1993*; *Solanki and Fligge*, 1998a, henceforth referred to as SF-I]. These two observations suggest that there should be both, a quadratic and a linear term in the relationship between $\Delta S_{\rm act}$ and R_Z. As we shall see the data support this expectation.

In Fig. 1 we plot daily values of $S_{\rm obs}$ vs. R_Z (dots), where $S_{\rm obs}$ is the observed total irradiance taken from the composite published by *Fröhlich and Lean* [1998]. The scatter in the points is very large and no obvious relationship is visible. We have therefore binned 50 $S_{\rm obs}$ points with neighboring R_Z values together. The binned values are represented by the plus signs. The initial increase of $S_{\rm obs}$ with R_Z is due to the increased density of faculae on the solar surface. At low levels of solar activity most of the surface magnetic field is concentrated into the network and faculae. At larger R_Z, however, sunspots become increasingly prominent, causing $S_{\rm obs}$ to saturate and eventually to decrease again.

The binned values obviously outline a clear relation between $S_{\rm obs}$ and R_Z. The solid curve is a quadratic polynomial fit through them:

$$\begin{aligned} S_{\rm obs} \quad = \quad & (1365.43 \pm 0.02) + (1.61 \pm 0.04) 10^{-2} \cdot R_Z \\ & -(5.5 \pm 0.2) 10^{-5} \cdot {R_Z}^2 \end{aligned} \qquad (1)$$

Using Eq. (1) the daily measured R_Z values can be replaced by $S_{\rm act}$ and hence in principle a record of $\Delta S_{\rm act}$ ($= S_{\rm act} - 1365.43$) can be created. However, during the period covered by the $S_{\rm obs}$ composite $\Delta S_{\rm act}$ gives a reasonable reconstruction only on time scales longer than the solar

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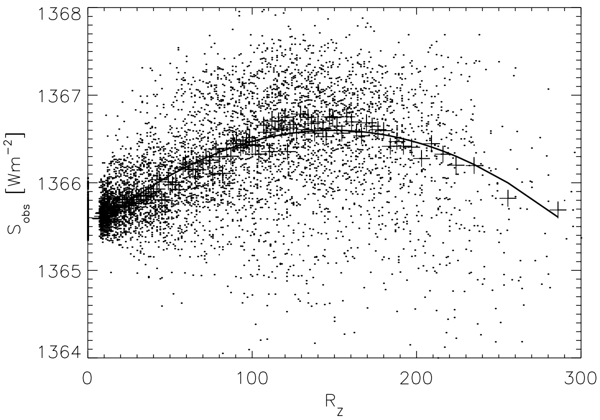

Figure 1. Observed solar irradiance, $S_{\rm obs}$, vs. the Zürich Sunspot Relative Number, $R_{\rm Z}$. Dots are daily values, crosses are binned values and the solid curve is a quadratic fit to them.

cycle, because the total integral $\int \Delta S_{\rm act} dt$ over the solar cycle equals $\int \Delta S_{\rm obs} dt$ to a very high degree (with less than 2% relative deviation). Even though we expect that this integral is the primary quantity of interest for climate studies a better fit to the data would be of advantage.

An important reason why the $S_{\rm obs}$ data are relatively poorly reproduced on short time scales is that the contributions of spots and faculae vary on different time scales, although in Fig. 1 their combined influence produces a smooth curve when binning over $R_{\rm Z}$. Most sunspots are visible over only a single rotation, whereas facular areas often survive multiple rotations (finally contributing to $S_{\rm obs}$ as so-called enhanced or active network). To take this better into account in the model we first smooth $S_{\rm obs}(t)$ and $R_{\rm Z}$ with two-month running means using autoregressive fore- and backcasting [Chatfield, 1992], obtaining $\langle S_{\rm obs}\rangle$ ($\langle\ \rangle$ means temporal averaging), which represents the slowly varying faculae. We also construct $S_{\rm obs} - \langle S_{\rm obs}\rangle$, which describes rapid variations in $S_{\rm obs}$ and is thus representative of the contribution of sunspots. Similarly, $\langle R_{\rm Z}\rangle$ and $R_{\rm Z} - \langle R_{\rm Z}\rangle$ provide us with proxies for these two magnetic components.

In Fig. 2a $\langle S_{\rm obs}\rangle$ is plotted vs. $\langle R_{\rm Z}\rangle$, while $S_{\rm obs} - \langle S_{\rm obs}\rangle$ is plotted vs. $R_{\rm Z} - \langle R_{\rm Z}\rangle$ in Fig. 2b. The dots once more represent daily values. Due to the running mean not all daily $\langle S_{\rm obs}\rangle$ and $\langle R_{\rm Z}\rangle$ are independent, which produces the patterns visible in Fig. 2a. Crosses are obtained after binning over 50 points with neighboring $\langle R_{\rm Z}\rangle$ (Fig. 2a), respectively $R_{\rm Z} - \langle R_{\rm Z}\rangle$ (Fig. 2b) and the solid curves are quadratic fits to the crosses. The qualitative behavior of $\langle S_{\rm obs}\rangle$ and $S_{\rm obs} - \langle S_{\rm obs}\rangle$ in these figures corresponds to that expected for faculae and sunspots.

In a next step we reconstruct $\Delta S_{\rm act}(t)$ by using $\langle R_{\rm Z}\rangle$ and $R_{\rm Z} - \langle R_{\rm Z}\rangle$ corresponding to the values for the day in question and the solid curves in Fig. 2 to obtain $\langle S_{\rm obs}\rangle(t)$ and $(S_{\rm obs} - \langle S_{\rm obs}\rangle)(t)$. These are then combined to obtain

$$\Delta S_{\rm act}(t) = \langle S_{\rm obs}\rangle(t) + (S_{\rm obs} - \langle S_{\rm obs}\rangle)(t). \qquad (2)$$

Following SF-I we also modulate the slowly varying part (i.e. $\langle S_{\rm obs}\rangle(t)$) by the long-term trend of the combined facular index as proposed by *Fligge and Solanki* [1998]. The resulting $\Delta S_{\rm act}$ reproduces $S_{\rm obs}$ with significantly higher accuracy than a reconstruction based on Fig. 1. Just as importantly $\Delta S_{\rm act}$ reconstructed as described above for the period 1874–1990 is very similar to the $\Delta S_{\rm act}$ reconstructed using separate facular and sunspot proxies by SF-I.

Much of the difference between the reconstruction of SF-I and the present one is due to the fact that the photometric sunspot index (PSI; *Foukal*, 1981), which was used by the former, predicts much larger, short term excursions of ΔS due to spots. Apparently, only a partial separation between spot and facular contribution is obtained by only separating different time scales in a single proxy.

A similar reconstruction can also be made using $R_{\rm g}$ instead of $R_{\rm Z}$. Although the quadratic term in the $S_{\rm obs}(R_{\rm g})$ relationship is less pronounced than in Eq. (1), it is nevertheless significant and the final $R_{\rm g}$-based reconstruction is rather similar to those based on $R_{\rm Z}$.

Going back in time

Older historical records are incomplete and often of reduced quality. Between 1749 and 1818 only monthly averages of $R_{\rm Z}$ are available and prior to 1749 only yearly values. In order to recreate $\Delta S_{\rm act}$ back to 1700 using $R_{\rm Z}$ we can only employ the relationship between $R_{\rm Z}$ and $S_{\rm obs}$ obtained from Fig. 1 between 1700 and 1818. This reconstruction, although somewhat further removed from the more accurate one of SF-I, still shows the correct long-term trend.

As a further test we have also reconstructed $\Delta S_{\rm act}$ using data from cycles 21 and 22 individually. We find that the differences between $\Delta S_{\rm act}$ reconstructed using the two cycles are on the whole far smaller than the $\Delta S_{\rm act}$ values themselves (≤ 3 % of $\Delta S_{\rm act}$). In spite of its success this test cannot, however, rule out that the relationship between $\Delta S_{\rm act}$ and $R_{\rm Z}$ does indeed change from cycle-to-cycle, particularly since cycles 21 and 22 were rather similar in strength.

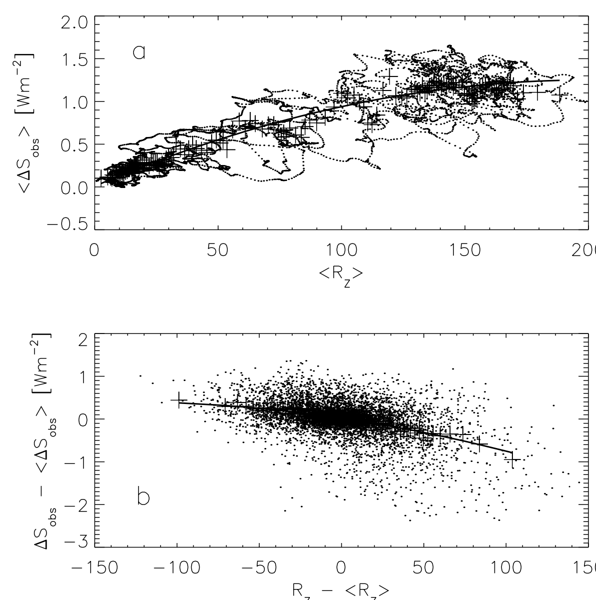

Figure 2. a: $\langle S_{\rm obs}\rangle$, i.e. temporally smoothed $S_{\rm obs}$, vs. $\langle R_{\rm Z}\rangle$, i.e. temporally smoothed $R_{\rm Z}$. **b:** $S_{\rm obs} - \langle S_{\rm obs}\rangle$ vs. $R_{\rm Z} - \langle R_{\rm Z}\rangle$. Dots, crosses and solid curves have the same meanings as in Fig. 1.

We have also reconstructed $\Delta S_{\rm act}$ using just ACRIM I data [*Willson and Hudson*, 1991]. This provides a test whether any uncertainty in the composite of $S_{\rm obs}$, introduced e.g. by the combination of data from different instruments [*Fröhlich and Lean*, 1998], seriously affects our results. $\Delta S_{\rm act}$ obtained in this manner differs from that obtained from the full composite by approximately the same amount as $\Delta S_{\rm act}$ obtained from the individual solar cycles does. Given this relatively small difference we use only the full composite of $S_{\rm obs}$ for the further analysis.

A composite of irradiance reconstructions

Due to the availability of increasingly diverse and accurate data with time the best possible reconstruction of $\Delta S_{\rm act}$ is a composite of individual reconstructions covering different periods, each of which is based on the best data available for that period and the appropriate method of reconstruction. For the period since 1874 we expect that the reconstruction of SF-I, which makes use of all available data, is superior to the present ones based only on $R_{\rm Z}$ or $R_{\rm g}$. Between 1818 and 1874 $\Delta S_{\rm act}$ is obtained from daily values of $R_{\rm Z}$ using the separation into $\langle R_{\rm Z}\rangle$ and $R_{\rm Z} - \langle R_{\rm Z}\rangle$, between 1749 and 1818 from monthly values of $R_{\rm Z}$ using the relationship plotted in Fig. 1. Finally, yearly values are employed between 1700 and 1749.

A second record of reconstructed irradiance can be created using $R_{\rm g}$. Daily values of $R_{\rm g}$ are available back to 1610, although with large data gaps during earlier times. We linearly interpolate $R_{\rm g}$ across such gaps before decomposing it into $\langle R_{\rm g}\rangle$ and $R_{\rm g} - \langle R_{\rm g}\rangle$, and reconstructing $\Delta S_{\rm act}$. After 1874, we also employ the PSI to account for the influence of the spots and follow SF-I to reconstruct $\Delta S_{\rm act}$ based on $R_{\rm g}$.

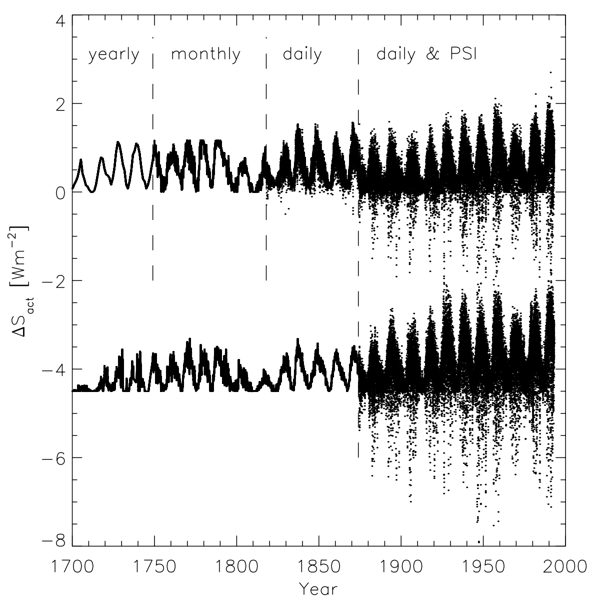

Figure 3. The upper curve corresponds to the composite irradiance record based on $R_{\rm Z}$ using different reconstruction methods while the lower curve (shifted by -4.5W/m^2) is based on $R_{\rm g}$.

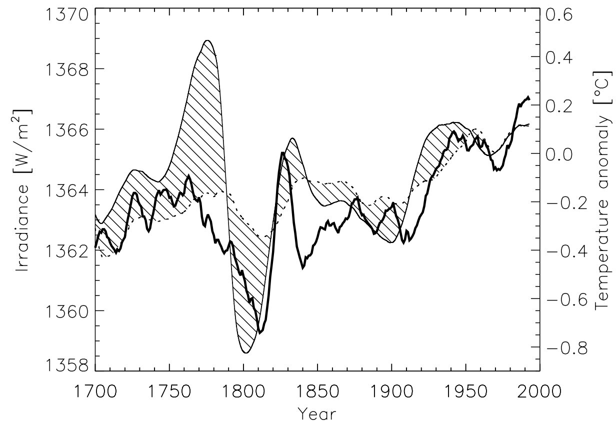

Figure 4. 11-year running mean of the two reconstructed $S_{\rm rec}$. Thin solid curve: $\Delta S_{\rm qs}$ is represented by the solar cycle length; thin dashed curve: The amplitude of $R_{\rm g}$ is used as a proxy of $\Delta S_{\rm qs}$. The hatched area gives a rough indication of the uncertainty in the reconstructions. Also plotted is the northern hemisphere land temperature (thick solid curve) according to Groveman and Landsberg (1700 – 1880) and the IPCC (1880 – 1990).

The two $\Delta S_{\rm act}$ records are plotted in Fig. 3. The upper curve shows the composite based on $R_{\rm Z}$, the lower a similar composite based on $R_{\rm g}$. The final $\Delta S_{\rm act}$ record is an average of the two.

Long-term trend in solar irradiance

The next step in the reconstruction is to determine the long-term quiet-Sun irradiance variation $\Delta S_{\rm qs}$ since the Maunder minimum. We stress, however, that determining the quantitative long-term variations of the quiet Sun is highly speculative and subject to large uncertainties. Again, we follow SF-I and reconstruct two such time series, one based on the amplitude of $R_{\rm g}$, the other on the length of the solar cycle. Evidence for both these approaches is given by the comparison of the Sun with Sun-like stars [*Lean et al.*, 1992; *White et al.*, 1992; *Baliunas and Soon*, 1995]. We employ the composite cycle length record constructed by *Fligge et al.* [1999]. Since it is based on a wavelet analysis and on a more comprehensive data set we expect it to be more objective and more robust than earlier analyses. It is, however, similar in appearance to the cycle-length record of *Lassen and Friis-Christensen* [1995]. We scale $\Delta S_{\rm qs}$ (and extrapolate it into the present) in such a way that $S_{\rm obs}$ is reproduced as well as possible by $S_{\rm rec} = S_0 + \Delta S_{\rm qs} + \Delta S_{\rm act}$, where S_0 is just a constant which is added in order to produce the correct absolute value of the observed irradiance (i.e. according to Eq. (1), $S_0 = 1365.43 W/m^2$). The procedure followed to reconstruct $\Delta S_{\rm qs}$ and to combine it with $\Delta S_{\rm act}$ in order to form $S_{\rm rec}$ is the same as that used by SF-I and we refer to that paper for details.

Finally, in Fig. 4 the reconstructed irradiance time series (thin curves) are compared with records of northern hemisphere land temperature according to *Groveman and Landsberg* [1979] for 1700–1880 and following the IPCC record for years 1880–1990 (thick solid curve).

The $\Delta S_{\rm act}$ underlying both plotted curves is the final composite based on both $R_{\rm Z}$ and $R_{\rm g}$. The two curves are, however, based on different $\Delta S_{\rm qs}$. In the case of the solar cycle length as proxy of $\Delta S_{\rm qs}$ (thin solid curve) the irradiance variation since the Maunder minimum is not unique and depends on which proxy is given more weight for the determination of the cycle length. For example, ^{10}Be gives a relatively short cycle in the Maunder Minimum (cf. *Beer et al.*, 1998), while other proxies (such as $R_{\rm Z}$ or $R_{\rm g}$) do not allow a cycle length to be determined accurately in that period, suggesting a large length.

All curves in this plot have been smoothed by an 11-year running mean to stress their general trend. The quiet Sun model following the cycle length shows good agreement during the last century but fails at earlier times due mainly to the strong cycle length variation seen between 1750 and 1800. The amplitude model (thin dashed curve) shows better agreement for much of the time series since 1750 although the irradiance increase in the 20th century does lag somewhat behind the well documented temperature rise.

Conclusions

We have presented a new reconstruction of solar irradiance since 1700. Two sources of solar irradiance variations are thereby treated separately: variations on time scales of the solar cycle and less due to active regions on the solar surface and long-term variations due to the evolution of the solar network or other processes.

New techniques to reconstruct the active-region contribution from a single proxy of solar activity are determined and applied. The amplitude and strength of the solar activity cycle are used to describe the long-term contribution, in agreement with previous reconstructions [*Hoyt and Schatten*, 1993; *Lean et al.*, 1995; SF-I].

The modelling of irradiance variations due to active regions has steadily improved in recent years (e.g., *Chapman et al.*, 1996; *Lean et al.*, 1995, 1998; SF-I; *Fligge et al.*, 1998) and reproduces the data increasingly well. The modelling of the variability of the quiet-Sun contribution, on the other hand, is far from satisfactory. The difference between the two reconstructions are practically as large as $\Delta S_{\rm qs}$ itself, e.g. between 1750 and 1850. Increased efforts to improve this situation are necessary.

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