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# Solar Irradiance since 1874 Revisited

S.K. Solanki and M. Fligge

Institute of Astronomy, ETH-Zentrum, CH-8092 Zürich, Switzerland

**Abstract.** We reconstruct the solar irradiance since 1874 employing an evolved version of previously published models and improved sunspot and facular data. A good correlation between reconstructed irradiance and Earth's global air temperature on time scales longer than the solar cycle is obtained and, in contrast to many earlier models, solar irradiance does not on average lag behind global temperature prior to 1975, although the exact time lag between the two quantities depends somewhat on details of the reconstruction. Since that epoch, however, air temperatures have increased by 0.2 K, whereas solar irradiance has risen a disproportionately smaller amount. Therefore, unless the influence of solar variability on Earth is very strongly non-linear, at least this most recent temperature increase reflects the influence of man-made greenhouse gases or non-solar sources of natural variability.

## Introduction

Based on correlations between solar activity and climate [*Eddy*, 1977; *Reid*, 1987; *Friis-Christensen and Lassen*, 1991; *Lean et al.*, 1995b] it has been proposed that solar irradiance variations have influenced terrestrial climate in historical times. Since solar irradiance has been observed with sufficient accuracy to detect its variations only since 1978 [*Willson and Hudson,* 1988; 1991; *Kyle et al.,* 1994], for earlier epochs it has to be reconstructed from data having a longer time base.

Various recent developments provide a strong impetus for revisiting reconstructions of solar irradiance since 1874 [*Foukal and Lean*, 1990; *Hoyt and Schatten*, 1993; *Zhang et al.*, 1994; *Lean et al.*, 1995b]. Firstly, much of the data needed for such a reconstruction have been improved [*Foukal,* 1996; *Fligge and Solanki,* 1997a; 1997b]. Secondly, we introduce simple but significant modifications into the most detailed current models of solar irradiance variations. Finally, the excellent correlation between solar cycle length and terrestrial temperature found in recent years [*Friis-Christensen and Lassen*, 1991; 1994] makes a careful re-examination of irradiance reconstructions more pressing, since many previous reconstructions [*Foukal and Lean*, 1990; *Zhang et al.*, 1994; *Lean et al.*, 1995a], as well as solar activity indicators in general, show a significant lag relative to climate.

Cyclic variations $\Delta S$ of the solar total irradiance $S$ are to a large extent caused by magnetic activity [*Chapman*, 1996; *Solanki and Unruh*, 1997] (but see *Kuhn et al.,* [1988] for a deviating point of view). Reductions in solar irradiance result from the passage of dark sunspots across the solar disk [*Willson et al.*, 1981; *Eddy et al.*, 1982], while brightenings are due to faculae. In addition, there is evidence for a longer term variation, probably due to changes in the quiet Sun [*Zhang et al.*, 1994; *Baliunas and Soon*, 1995; *Lean et al.*, 1995b; *Willson*, 1997]. We model $\Delta S_{\rm act}$, the contribution of active regions and related features — such as enhanced network — directly from solar data using a model partly based on that of *Foukal and Lean* [1986; 1988; 1990]. The quiet-sun contribution to irradiance variations, $\Delta S_{\rm qs}$, is derived indirectly via stellar observations. We first outline the modelling of the active-region contribution, $\Delta S_{\rm act}$.



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## Modelling the Active-Region Contribution

The influence of sunspots is described by the photometric sunspot index $\Psi$[*Foukal*, 1981; *Hudson et al.*, 1982]. As input to $\Psi$ we employ daily sunspot areas, $A_{\rm s}$, and positions measured at the Royal Greenwich Observatory between 1874 and 1976, and at other observatories since then. The data from the various observatories have been selected and scaled according to recent findings [*Fligge and Solanki*, 1997a], resulting in a time series that differs significantly from the ones previously employed. An important feature of this revised data set is that the sunspot areas of the most recent solar cycles 21 and 22 are no longer anomalous. Following *Foukal and Lean* [1990] faculae are represented by the Zürich relative sunspot number $R_{\rm Z}$, which is now, however, modulated by our new combined facular index [*Fligge and Solanki*, 1997b], a robust combination of five different proxies, including Ca II plage areas, which have only recently become available [*Foukal*, 1996]. The new proxy differs from $R_{\rm Z}$ mainly in that it implies a higher solar irradiance during cycles 16 and 17.

In order to reconstruct the facular contribution to irradiance variations since 1874 we first remove the daily $\Psi$ from $S_{\rm ACRIM}$, the total solar irradiance measurements made between 1980 and 1989 by the ACRIM (Active Cavity Radiometer Irradiance Measurements) instrument on board the Solar Maximum Mission[1]. The residual, $S_{\rm ACRIM} - S_{\rm qs} - \Psi$, which is a measure of the facular contribution, is plotted vs. $R_{\rm Z}$ in Fig. 1 ($S_{\rm qs}$ is the contribution of the quiet Sun to total irradiance, as judged from $S_{\rm ACRIM}$ extrapolated to $R_{\rm Z} = 0$). The plotted relationship during the period 1980–1989 is then used to reconstruct a first estimate of

[1] Reconstructions using data obtained by the ERB (Earth Radiation Budget) instrument on the NIMBUS 7 satellite [*Kyle et al.*, 1994], lead to an almost indistinguishable reconstructed irradiance, except that the amplitudes of the variations are approximately a factor of 1.7 times larger if the original ERB data are used. If, however, the findings of *Lee et al.* [1995] and *Chapman* [1996] are take into account and the early ERB data (1978-1979) are excluded from the analysis, then the reconstructions differ only by a factor of roughly 1.1–1.2

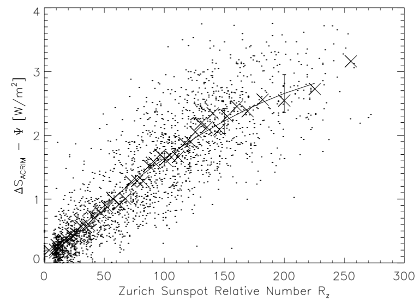


**Figure 1.** Difference between the solar total irradiance measured by the ACRIM radiometer, $S_{\mathrm{ACRIM}}$, and the photometric sunspot index $\Psi$, after removal of $S_{\mathrm{qs}}$, the quiet-Sun contribution, $S_{\mathrm{ACRIM}} - S_{\mathrm{qs}} - \Psi = \Delta S_{\mathrm{ACRIM}} - \Psi$, vs. Zürich relative sunspot number, $R_{\mathrm{Z}}$. Dots are daily values, crosses represent values binned over 50 $\Delta S_{\mathrm{ACRIM}} - \Psi$ points with neighbouring $R_{\mathrm{Z}}$ values. The solid curve is a quadratic fit to the crosses.

$S - S_{\mathrm{qs}} - \Psi = \Delta S - \Psi$ at earlier times. In order to quantify this relationship we bin together 50 neighbouring points and obtain the crosses in Fig. 1. The curve is a quadratic least-squares fit to the crosses (it is almost identical to a similar fit to the dots) that satisfies:

$$\Delta S_{\mathrm{ACRIM}} - \Psi = (1.889 \pm 0.098)10^{-2} R_{\mathrm{Z}} - (3.27 \pm 0.54)10^{-5} R_{\mathrm{Z}}^2. \quad (1)$$

The indicated error bars include statistical errors, as well as any uncertainty introduced by the particular choice of the number of points per bin. The quadratic term is significant at the 6-$\sigma$ level. For $S_{\mathrm{qs}} = S_{\mathrm{ACRIM}}(R_{\mathrm{Z}} = 0)$ a quadratic fit to the ACRIM measurements gives $1366.873 \pm 0.031$.

The saturation of $\Delta S_{\mathrm{ACRIM}} - \Psi$ at large $R_{\mathrm{Z}}$ is mirrored in the behaviour of the Mt. Wilson Ca plage [*Foukal*, 1996] and Greenwich facular areas [*Foukal*, 1993]. We now use sunspot areas and locations to construct $\Psi$, and the curve in Fig. 1 together with $R_{\mathrm{Z}}$ to determine the model value of $\Delta S - \Psi$. Adding these two quantities together one obtains a first estimate of the irradiance variations $\Delta S_{\mathrm{act}}$ since 1874. The reconstruction described so far is similar to the original model of *Foukal and Lean* [1990] and over the interval covered by ACRIM reproduces the observed irradiance equally well.

$\Delta S_{\mathrm{act}}(t)$ turns out to be largely insensitive to systematic changes or uncertainties in $\Psi$. These may be produced by, e.g., the larger sunspot blocking caused by revised sunspot areas [*Fligge and Solanki*, 1997a], or by the uncertainty in the sunspot blocking factor $\alpha$, i.e. the relative intensity contrast of sunspots integrated over all wavelengths.

At this point we wish to highlight a major implicit assumption that has always been made when reconstructing $\Delta S_{\mathrm{act}}$ for periods before 1978. It is assumed that the relationship between $\Delta S - \Psi$ and $R_{\mathrm{Z}}$ (or whichever proxy of facular brightness is used) has remained unchanged over the past 120 years and can be represented by, e.g., the curve in Fig. 1. In the next step we allow the relationship between $\Delta S - \Psi$ and $R_{\mathrm{Z}}$ to vary in the sense that it scales with the ratio of the new combined facular index of *Fligge and Solanki* [1997b] to $R_{\mathrm{Z}}$.

The final $\Delta S_{\mathrm{act}}$ curve we obtain between 1874 and 1992 is plotted in Fig. 2. It differs significantly from the reconstruction of *Foukal and Lean* [1990]. An important part of the difference is due to the new $A_{\mathrm{s}}$ time series we employ, for which $A_{\mathrm{s}}$ of cycles 21 and 22 is no longer unusually small relative to earlier cycles. Consequently, during these cycles $\Psi$ is larger, while $\Delta S_{\mathrm{act}}$ and $\Delta S_{\mathrm{act}} - \Psi$ are smaller than in their model, so that the brightness of cycles 21 and 22 now contrasts less to earlier cycles. The use of the new long-term facular index also has a marked influence on the reconstruction, in particular during cycles 16 and 17. These show much stronger variations in our reconstruction. Additional deviations are introduced by the fact that we find and employ a quadratic relationship between $\Delta S_{\mathrm{ACRIM}} - \Psi$ and $R_{\mathrm{Z}}$ (Fig. 1), instead of the linear relationship previously assumed.

According to the reconstructions described so far the solar irradiance averaged over 11 years has varied by roughly 0.4–0.7 $Wm^{-2}$ in the course of the last century (the lower value results from ACRIM data, the higher value from data obtained by the Earth Radiation Budget Experiment [*Kyle et al.*, 1994]). This is, for ACRIM, approximately half the value found by *Foukal and Lean* [1990] and *Lean et al.* [1995a], mainly due to the uncorrected sunspot areas used by them. It is also smaller than the variation over the last solar cycle and is unlikely, if used as the sole direct forcing agent, to be responsible for the increase in global temperature during the last century [*Foukal and Lean*, 1990; *Kelly and Wigley*, 1990; 1992; *Schlesinger et al.*, 1992]. Consequently, either (1) solar forcing has played only a minor role over the past century, (2) the influence of solar variability on terrestrial climate is strongly non-linear or indirect in nature [*Haigh*, 1994; *Svensmark and Friis-Christensen*, 1997], or (3) there are other mechanisms acting to change solar irradiance on time scales longer than the solar cycle (possibly coupled with a non-linear influence on climate).

## Modelling the Variations of the Quiet Sun

Evidence for a change in the solar irradiance between the last two solar minima, which indicates a change in quiet Sun brightness, has recently been published [*Willson*, 1997]. In addition, the comparison of solar activity data with those of Sun-like stars [*Baliunas and Jastrow*, 1990] suggests that since the Maunder minimum in the 17th century the Sun has increased in brightness by 2–8 $Wm^{-2}$ [*Lean et al.*, 1992; *White et al.*, 1992; *Zhang et al.*, 1994; *Lean et al.*, 1995b]. Since long-term solar records only provide information on active regions, subtle changes in the quiet Sun which would induce irradiance variations of the magnitude deduced from stars could go undetected in such records. We shall now incorporate long-term trends of solar irradiance $\Delta S_{\mathrm{qs}}$ due to hypothetical changes in the quiet Sun into our model. We stress, however, that modelling such trends in $\Delta S_{\mathrm{qs}}$ is less reliable than modelling $\Delta S_{\mathrm{act}}$, since it depends on the exact analogy between the Sun and late-type stars.

Two different relationships between solar activity and long-term irradiance trends have been found via stellar activity measurements. One is a linear relationship between chromospheric emission in the core of the Ca H and K lines and photospheric brightness over a solar or stellar cycle (relationship A), which is generally also taken to hold for the long-term trend from one cycle to the next [*Lean et al.*, 1992;

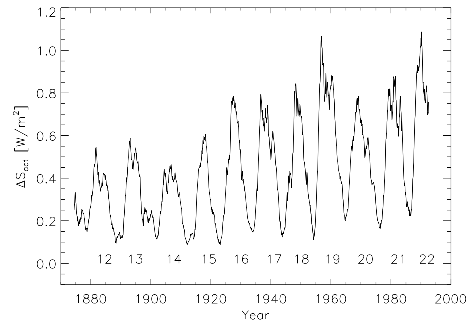


**Figure 2.** Time-dependence of reconstructed solar irradiance variations due to solar active regions, $\Delta S_{\rm act}$, vs. time. The irradiance has been smoothed by a 1-year running mean. Data gaps have been accounted for in two different ways, by interpolating across them and by binning the data points. Both techniques give almost indistinguishable results. Solar cycle numbers are indicated

*Zhang et al.*, 1994; *Lean et al.*, 1995a]. The other is a linear correlation between the length of a cycle and brightness [*Baliunas and Soon*, 1995] (relationship B). This relationship is also based on the assumption that short- and long-term Ca emission changes are related to irradiance in the same manner.

We now use relationships A and B to create two separate reconstructions of $\Delta S_{\rm qs}$ as a function of time. Since the Ca index measured on other stars is a proxy of faculae we employ the strength of the combined facular index as a measure of $\Delta S_{\rm qs}$ using relationship A (we call this reconstruction A). The $R_{\rm Z}$ cycle length (which is identical to the cycle length of the combined facular index) is used as a measure of $\Delta S_{\rm qs}$ in connection with relationship B (reconstruction B). To the $\Delta S_{\rm qs}$ obtained thus we add $S_{\rm qs}$ and $\Delta S_{\rm act}$ to obtain the total irradiance, $S_{\rm rec}= S_{\rm qs}+ \Delta S_{\rm qs}+ \Delta S_{\rm act}$, which is plotted in Fig. 3 for both reconstructions. At present it is not possible to judge which of these two reconstructions is superior. The $\Delta S_{\rm qs}$ underlying the plotted curves increases by about 2.5 $Wm^{-2}$ between 1874 and 1996, which corresponds to $\Delta S_{\rm Mm}$

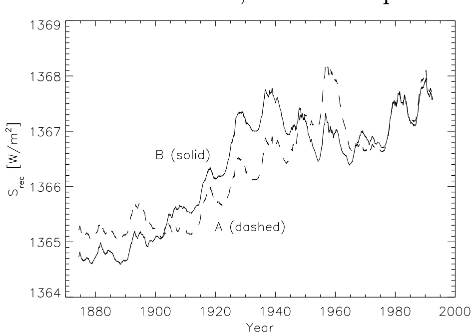


**Figure 3.** Reconstructions of total solar irradiance since 1874, $S_{\rm rec}$, including contributions to the irradiance variations due to active regions, $\Delta S_{\rm act}$, and the quiet Sun, $\Delta S_{\rm qs}$: $S_{\rm rec}= \Delta S_{\rm act}+ \Delta S_{\rm qs}+ S_{\rm qs}$. The dashed curve results when $\Delta S_{\rm qs}$ follows a facular index (reconstruction A), whereas a $\Delta S_{\rm qs}$ proportional to solar cycle length (after a 1-2-2-2-1 smoothing following *Friis-Christensens and Lassen* [1991]) underlies the solid curve (reconstruction B). Both $S_{\rm rec}$ curves have been smoothed by a 1-year running mean and both are for a total increase of 4 $Wm^{-2}$ of irradiance since the Maunder minimum.

$= 4\ Wm^{-2}$ between the Maunder minimum in the 17th century and today, i.e. close to the average value suggested by the stellar observations. The two reconstructions give an indication of the range of irradiance allowed by the currently available data for a given $\Delta S_{\rm Mm}$. To first order the choice of another $\Delta S_{\rm Mm}$ within the allowed range simply stretches the irradiance scale, although the shapes of the curves also react somewhat.

## Discussion

In order to emphasize secular trends we now smooth the $S_{\rm rec}$ curves with an 11-year running mean that averages out most of the variations over individual solar cycles. These smoothed curves are plotted in Fig. 4. Also shown are the global land and sea temperature anomaly, as well as the northern hemisphere land and sea temperature anomaly, both subjected to an 11-year running mean.

We obtain a correlation coefficient $C$ between global land and sea temperature and $S_{\rm rec}$ (after carrying out 11-year running means) of 0.93 for reconstruction A and 0.85 for reconstruction B. Note that $\Delta S_{\rm act}$ and $\Delta S_{\rm qs}$ each individually correlates well with the Earth's climate. In the case of $\Delta S_{\rm act}$ we obtain $C = 0.88$. Just as important as the high correlation is that irradiance no longer lags behind climate in our reconstructions.

Reconstruction B clearly anticipates the rise in temperatures between 1910 and 1940 by approximately 10 years, whereas the increase in irradiance in reconstruction A occurs roughly concurrently with the Earth's temperature increase. In this sense our reconstruction of solar irradiance is compatible with a causal relationship between solar irradiance and climate, at least prior to 1975[2]. Since the irradiance from model A lags behind global temperature between 1930 and 1945, the case for a causal relationship between these two quantities is more marginal in this case.

Since approximately 1975 the situation is clearly different, however, with solar irradiance showing a comparatively much more modest rise than air temperature. Since 1978 direct measurements of solar irradiance are available and can be used to test the reconstructions.

For a change in total irradiance since the Maunder minimum, $\Delta S_{\rm Mm}$, less than 5 $Wm^{-2}$ our $S_{\rm rec}$ reproduces the ACRIM data reasonably well. For $\Delta S_{\rm Mm}$ larger than 5 $Wm^{-2}$, however, the model diverges quite significantly from $S_{\rm ACRIM}$. This sets an upper limit of roughly 5 $Wm^{-2}$ on $\Delta S_{\rm Mm}$. If $\Delta S_{\rm Mm}$ is 2 $Wm^{-2}$ (the lower limit suggested by stellar data) the modelled solar irradiance after 1980 reproduces both $S_{\rm ACRIM}$ and the shape of the climate curves after 1975 better, although the latter quantity still only imperfectly. For any value of $\Delta S_{\rm Mm}$ within the range suggested by combining the solar and stellar observations (2–5 $Wm^{-2}$) $S_{\rm rec}$ and air temperature diverge since roughly 1975. We speculate that this divergence is a signature of warming produced by the increasing concentration of man-made greenhouse gases in the Earth's atmosphere, although the natural variability of the Earth's climate cannot be ruled out as a source.

[2] A longer time series would strengthen such a conclusion, as pointed out by *Crowley and Kim* [1996]. Due to the absence of relevant data prior to 1874 a longer $S_{\rm rec}$ series can currently only be constructed with lower accuracy, however.

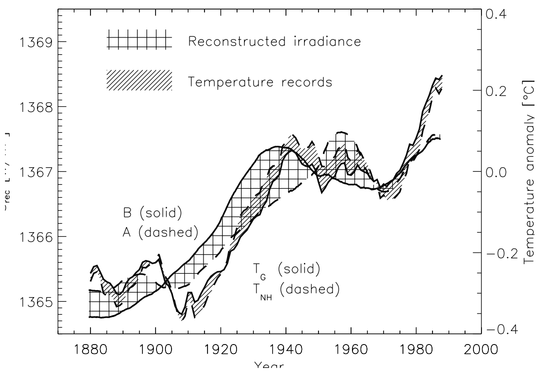


**Figure 4.** Left-hand scale: irradiance reconstructions, $S_{\rm rec}$, between 1880 and 1989. The dashed curve is based on model A while the solid curve results from model B. The hatched area indicates the range within which $S_{\rm rec}$ may lie. Right-hand scale: temperature records. Plotted are the global land and sea temperature (solid curve, $\rm T_G$) and the northern hemisphere land and sea temperature (dashed curve, $\rm T_{NH}$) relative to epoch 1950 as provided by the World Data Center (WDC), Boulder, CO. Global temperatures are as in the report of the International Panel on Climate Change (IPCC, 1992). All curves have been subjected to an 11-year running mean.

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S.K Solanki and M. Fligge, Institute of Astronomy, ETH-Zentrum, CH-8092 Zürich, Switzerland. (e-mail: solanki@astro.phys.ethz.ch; fligge@astro.phys.ethz.ch)

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