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Long-term reconstruction of the total solar irradiance based on neutron monitor and sunspot data

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Abstract

A new approach for the reconstruction of the past total solar irradiance (TSI) based on neutron monitor (NM) data and sunspot number (SSN) is presented. Our assumption is that the long-term trend of the TSI can be reconstructed by using radionuclide data while the reconstruction of the short-term trend can be achieved by using SSN. The reconstructed TSI correlates well, $r^2 = 0.84$, with space-based TSI measurements. This work will serve as the basis for the reconstruction of the TSI back to the Maunder minimum and beyond by replacing NM with radionuclide data, for which longer time series exist.

Keywords: Solar irradiance; Reconstruction; Maunder minimum

1. Introduction

From space-based total solar irradiance (TSI) (Fröhlich, 2006) since the mid 1970s, and Spectral Solar Irradiance (Floyd et al., 2002) measurements since the 1990s we know with high accuracy that the solar energy output varies on timescales from days to months and years to decades. Evidence for the Sun to vary on long time scales (century to millennia) can be seen in radionuclide proxy data from ice cores. Radionuclides are produced in the Earth's atmosphere by cosmic ray particles. Their flux is controlled by the heliospheric magnetic field and the geomagnetic field. Reconstructions of the heliospheric magnetic field by Caballero-Lopez et al. (2004) and the solar activity by Vonmoos et al. (2006) show clearly that solar activity fluctuates between states of grand solar minima (e.g., Maunder and Spörer minima) and high activity (as at present).

Paleoclimatic studies by Van Geel et al. (1996) and Neff et al. (2001) reveal clear correlations between solar activity and climate records. Model calculations by Haigh (1994, 1999), Shindell et al. (2001) and Egorova et al. (2004) point to a strong influence of the total and spectral irradiance on the Earth's climate.

To quantify the influence of the variable solar energy output on the Earth's climate long-term records of solar irradiance are needed. But continuous space based observational records of solar irradiance exist only since 1978, a period of high and relatively constant solar activity. Direct data for a grand solar minimum are lacking and therefore they have to be deduced from proxy data covering much longer periods of time.

Several authors have already reconstructed the TSI using various proxies of solar activity. For example, Hoyt and Schatten (1993) built a composite using sunspot data to obtain an irradiance reconstruction beginning in 1700. Lean et al. (1995) and Lean (2000) use information of solar type stars for estimating the level of TSI during the Maunder minimum, and sunspots for short-term variations. Solanki and Fligge (1998) also

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employ information of solar type stars to estimate the level of the quiet Sun. To get the contribution of active regions to the TSI sunspot and facular data is utilised. Foster (2004) worked out a reconstruction which is not based on solar type stars but on sunspot data and the surface magnetic field measured by the MDI instrument on SoHO. Wenzler (2005) showed that both short-term (daily) and long-term (annual) variations of TSI can be reconstructed using only magnetic solar phenomena, i.e., sunspot umbra and penumbra, network and faculae. The mentioned reconstructions have in common that it is assumed that the irradiance variations are driven by a varying solar magnetic activity. Having verified the reconstruction approach using NM and SSN, employing radionuclides instead of NM data will allow us to extend the reconstruction back to the Maunder minimum.

In the approach presented in this paper, we differentiate between short-term (monthly to decadal) activity, represented by SSN data and long-term (above decadal) activity, described through the NM data.

Since the TSI measurement of the last three minima do not show a significant trend it is difficult to derive a long-term trend. However there is a secular trend in the observed radionuclide and neutron data. Therefore our working hypothesis is that the long-term trend indicated by the latter can be deduced from the amplitude of the Schwabe cycle.

2. The data

Radionuclides, e.g., ^{10}Be, are produced by the interaction of cosmic ray particles, entering the Earth's atmosphere, with the atoms in the atmosphere (Beer, 2000). Their production rate is anti-correlated with the extent of heliospheric magnetic field, as a strong field shields the Earth's atmosphere and reduces the amount of incoming cosmic rays. During the same process, neutrons are generated as by-product. Thus, the production rate of neutron and ^{10}Be are very closely linked. Beer (2000) discusses in detail the similarity of the physical processes and shows that one can be substituted by the other.

The goal of this paper is to test wether the observed TSI can be reconstructed by a combination of SSN (SIDC, 1610–2006) and NM observed with the climax neutron monitor.

Both proxies, SSN and NM data, that are used to reconstruct the TSI are given in Table 1, together with the time span they cover. Also shown are the TSI itself and available radionuclide data.

As radionuclide data is not available for the last 50 years and we use NM-Ion composite based on the ionisation chamber data from McCracken and Heikkila (1933–1965) to obtain a continuous record starting in 1933.

Fig. 1 shows the time series of observed TSI by Fröhlich (2006) and the two proxies SSN and NM. The 11-year solar cycle is clearly visible in TSI and in both proxies: SSN and NM. The latter showing features which cannot be found in

Table 1
TSI and proxies of it that are used to reconstruct the TSI

	Start
Data	
TSI–space-based	1978
Proxy	
SSN	1610
NM	1951
NM + ionisation chamber data (NM_{Ion})	1933
^{10}Be	10.000 BC

TSI data such as Forbush decreases (Lockwood, 1971) and ground-level enhancements (Duldig, 2001). Both are characterised by distinct count rate changes. For an example see Fig. 1, dashed vertical line close to 1990. We suppress these NM features by removing all data points above 3σ of the 2-year running mean.

The short- and long-term behaviour of SSN show different correlations with the TSI. If we apply a monthly running mean to SSN we find a strong positive correlation of $r^2 = 0.9$. On the other hand, on short time scales the SSN is anti-correlated with the TSI which is a direct consequence of sunspot darkening (Wenzler, 2005). NM does not exhibit TSI like short-term behaviour due to the inertia of the heliosphere. Therefore we only consider the long-term (>2 month) behaviour of the TSI, thereby excluding the short-term behaviour of all the data. Hence the three time series we use are

$$\mathrm{TSI}^* = \mathrm{TSI} * f_n \quad (1)$$

$$\mathrm{SSN}^* = \mathrm{SSN} * f_n \quad (2)$$

$$\mathrm{NM}^* = \mathrm{cut}_{3\sigma}(\mathrm{NM}_{\mathrm{Ion}}) * f_n \quad (3)$$

with $(\cdot * f_n)$ the running mean over $n = 2$ months.

3. Methods

The neutron monitor data show a time lag relative to the TSI (Fröhlich et al., 2005) of 111 days which was determined by a best fit algorithm.

For the reconstruction a spectral analysis is applied to determine the long-term and short-term trends of the data sets yielding the following equation.

$$\mathrm{TSI}^* \approx \alpha\ \text{long-term}(\mathrm{NM}^*) + \beta\ \text{short-term}(\mathrm{SSN}^*) + (\gamma_1 + \gamma_2). \quad (4)$$

In a first step, the long-term NM is fitted to the TSI, that is α and γ_1 are calculated. Then the short-term SSN is fitted to the residual $(\mathrm{TSI}^* - (\alpha \mathrm{NM}^* + \gamma_1))$ by calculating β and γ_2.

The result is shown in Fig. 2 for two different averaging intervals, 2 month and yearly. Note that the time interval used to calculate the coefficients does not significantly change the residual, if the interval is longer than 14 years [see Fig. 3(a)]. Second, the error decreases with increasingly smoothed data. When the data is smoothed by applying a running mean, dips from e.g., sunspots are removed. This

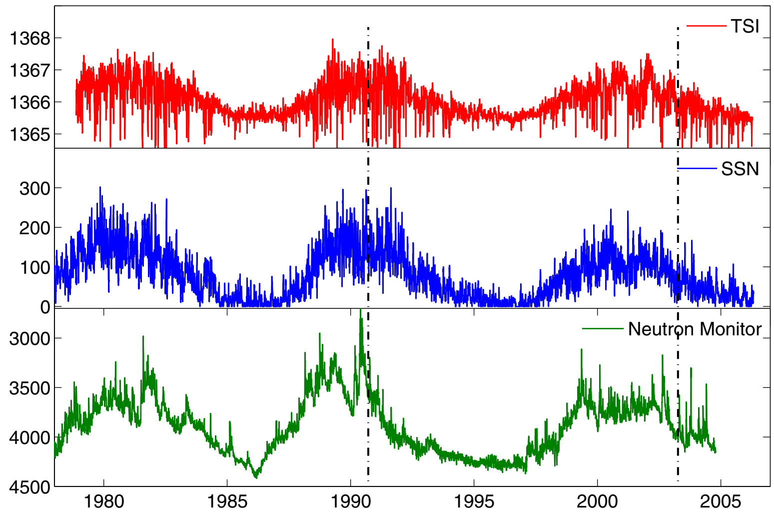

Fig. 1. Total solar irradiance from Fröhlich (2006) and proxies sunspot number from SIDC, 1610–2006 and the climax neutron monitor data.

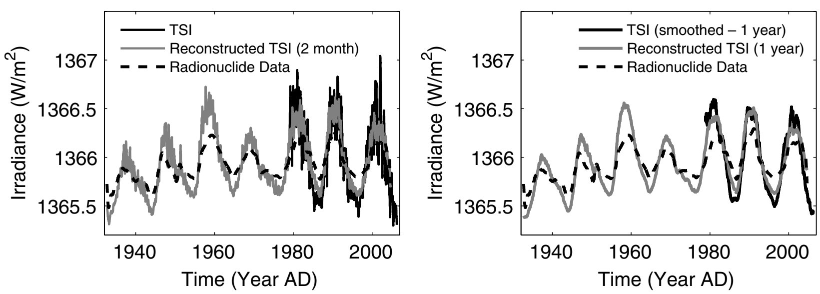

Fig. 2. Reconstruction of the TSI from sunspot numbers and radionuclides. Shown is the TSI, reconstructed TSI and fitted radionuclide data. The best results are achieved using long-term intervals.

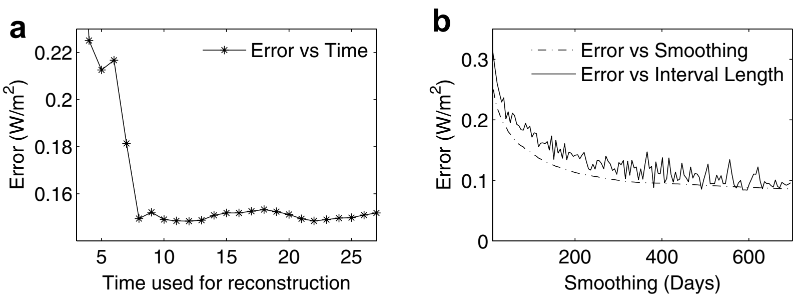

Fig. 3. (a) The mean error of the reconstruction versus the length of the time interval used to calculate the coefficients using a 2 smoothing. (b) the mean error of the reconstruction for the last 27 years, overlapping with space-based TSI observations, versus the interval length (solid line) and smoothness of the data (dashed line).

eliminates a large fraction of the error yielding a monotone function. Thus, the error of the reconstruction using short time intervals is dominated by short-term derivations. With a smoothing interval of 6 month the mean error ($\int_T |\mathrm{TSI}^*_{\mathrm{rec}} - \mathrm{TSI}^*| \mathrm{d}T/|T|$; T, the time domain) is 0.16 W/m^2.

4. Discussion and conclusion

In Fig. 4 our is reconstruction is compared with the work by Lean et al. (1995), Solanki and Fligge (1998), Lean (2000), Lockwood (2003). Our reconstruction shows similar trends and levels as the one by Foster (2004). Theirs and our secular trend are not that distinct than the other ones shown in Fig. 4.

The quality of reconstruction depends on the averaging interval and smoothing. The best results are achieved using a high-resolution data series with high smoothing factors. Hence, we cannot reconstruct short-term variation from sunspots, however, most importantly, the long-term trend can be reconstructed.

The largest discrepancy between our reconstruction and the TSI is in the last 4 years. The sharp decrease of the

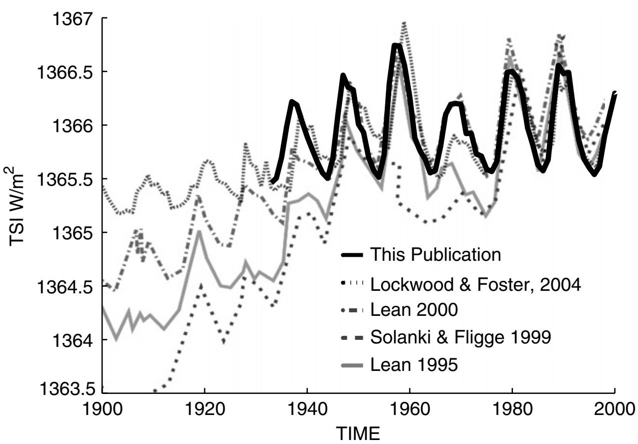

Fig. 4. Our Reconstruction in comparison with others work. As can be seen our reconstruction shows a similar behaviour as Foster (2004).

observed TSI is not yet confirmed and may be corrected once the observational data is re-evaluated with a more elaborated data reduction model.

Generally the time lag is not constant but depends on the size of the heliosphere. For a larger heliosphere the time-lag increases and the NM count decreases (Beer et al., 2003). Hence the time-lag of the NM data can be approximated using the NM count rate (Fröhlich et al., 2005). This might lead to a stronger weighting of the NM data in the reconstruction of the TSI and hence a stronger long-term trend.

Non-linear models did not result in a significant increase in accuracy. We therefore use a linear model. Since our ultimate aim is to reconstruct the TSI for the past 10,000 years we will have to rely solely on radionuclide data, namely ^{10}Be. This will probably require non-linear models of larger complexity.

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