Estimated solar contribution to the global surface warming using the ACRIM TSI satellite composite

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[1] We study, by using a wavelet decomposition methodology, the solar signature on global surface temperature data using the ACRIM total solar irradiance satellite composite by Willson and Mordvinov. These data present a +0.047%/decade trend between minima during solar cycles 21–23 (1980–2002). We estimate that the ACRIM upward trend might have minimally contributed ∼10–30% of the global surface temperature warming over the period 1980–2002. **Citation:** Scafetta, N., and B. J. West (2005), Estimated solar contribution to the global surface warming using the ACRIM TSI satellite composite, *Geophys. Res. Lett.*, *32*, L18713, doi:10.1029/2005GL023849.

1. Introduction

[2] Among the potential contributors to climate change, solar forcing is by far the most controversial. The Sun can influence climate through mechanisms that are not fully understood but which can be linked to solar variations of luminosity, magnetic field, UV radiation, solar flares and modulation of the cosmic ray intensity [*Pap and Fox*, 2004; *Lean*, 2005]. In addition, there is also controversy about solar data. Figure 1 shows two similar but not identical satellite composites of total solar irradiance (TSI) that cover solar cycles 21–23 (1980–2002): the PMOD due to *Fröhlich and Lean* [1998] and the ACRIM due to *Willson and Mordvinov* [2003], respectively.

[3] PMOD has been widely used in geophysical research. According to this composite, TSI has been almost stationary (−0.009%/decade trend of the 21–23 solar minima [*Willson and Mordvinov*, 2003]) and by adopting it, or the equivalent TSI proxy reconstruction by *Lean et al.* [1995], some researchers and the IPCC [*Intergovernmental Panel on Climate Change* (*IPCC*), 2001; *Hansen et al.*, 2002] deduced that the Sun has not contributed to the observed global surface warming of the past decades. Consequently, the global surface warming of $\Delta T_{1980-2002} = 0.40 \pm 0.04K$ from 1980 to 2002 shown in Figure 2 could only be induced, directly or indirectly, by anthropogenic added green house gas (GHG) climate forcing.

[4] Contrariwise, ACRIM presents a significant upward trend (+0.047%/decade trend of the minima) during solar cycles 21–23 (1980–2002) [*Willson and Mordvinov*, 2003]. The purpose of this letter is to estimate the contribution of this upward trend to the global surface warming from 1980 to 2002, which covers one Hale solar cycle.

2. Climate Models and Data Analysis

[5] The ACRIM upward trend is evaluated by calculating the difference between the TSI average during solar cycle 21–22 (1980–1991) (1365.95 ± 0.08 W/m^2) and the TSI average during solar cycle 22–23 (1991–2002) (1366.40 ± 0.03 W/m^2). We find this difference to be

$$\Delta I_{sun} = 0.45 \pm 0.10 \ \mathrm{W/m^2}. \quad (1)$$

The errors bars are calculated using multiple TSI averages by considering that the period of a solar cycle spans between 10 and 12 years and by keeping fixed the extremum at 1991. Note also that the upward ACRIM modulation during solar cycles 21–23 can be minimally interpreted as a 22-year square waveform modulation, which recalls a Hale solar cycle, with amplitude ΔI_{sun}.

[6] There exist at least two ways to estimate the Sun's influence on climate. The first method relies on climate models, such as energy balance models [*Wigley*, 1988; *Stevens and North*, 1996; *Foukal et al.*, 2004] or general circulation models [*IPCC*, 2001; *Hansen et al.* 2002]. The climate model approach is problematic because the sun-climate coupling mechanisms are not fully understood and, therefore, cannot be confidently included in the computational models [*Hoyt and Schatten*, 1997; *Hansen et al.*, 2002; *Pap and Fox*, 2004].

[7] A second approach, adopted, for example, by *Douglass and Clader* [2002], attempts to estimate the climate sensitivity to solar variation by directly studying the signature of the solar cycles within the temperature data. This is a phenomenological approach but it has the advantage of evaluating the total effect of the Sun-Climate coupling without requiring a detailed knowledge of the underlying physical and chemical mechanisms. Herein we adopt this philosophy using a methodology that differs from the linear regression analysis implemented by *Douglass and Clader* [2002], for reasons explained later.

[8] The climate sensitivity λ to a generic radiative forcing ΔF is defined as $\Delta T = \lambda \Delta F$, where ΔT is the average temperature change induced by ΔF. The radiative forcing associated with a change of TSI, ΔI, is traditionally obtained by averaging ΔI over the entire surface of the Earth and allowing for a fraction (albedo $a \approx 0.3$) of ΔI to be reflected

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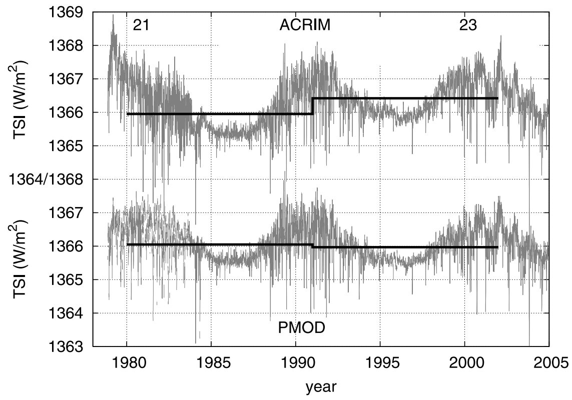

Figure 1. ACRIM TSI composite by *Willson and Mordvinov* [2003] and an update of the PMOD TSI composite by *Fröhlich and Lean* [1998]. The black lines are the TSI averages in the periods 1980–1991 and 1991–2002.

away: $\Delta F_{sun} = \frac{1-a}{4}\Delta I$. However, the above definition is not optimal if, as is commonly believed, the Sun affects climate by means of direct or indirect mechanisms over and above that of the direct TSI forcing. Because solar phenomena present cycles and general patterns that *mimic* TSI patterns, we hypothesize that, to a first-order approximation, TSI can be used as a geometrical proxy for the overall solar activity and its effects on climate. Moreover, there might be a dependence of this response on frequency [*Wigley*, 1988]. Thus, we introduce the following model for the total climate sensitivity to the total solar activity:

$$\Delta T_{sun} = \int_0^\infty Z(\omega)\frac{d\Delta I}{d\omega}d\omega. \quad (2)$$

The frequency-dependent function $Z(\omega)$ is herein defined as the total climate sensitivity to solar variations. Note that *Douglass and Clader* [2002] adopted a model in which the function $Z(\omega)$ is a constant k at all frequencies such that: $\Delta T_{sun} = k\Delta I$.

[9] *Douglass and Clader* [2002] evaluated the climate sensitivity to solar variation, $k = 0.11 \pm 0.02K/(\mathrm{Wm}^{-2})$, by using the PMOD TSI composite and by means of a multiple linear regression analysis based on a predictor for the temperature $T(t)$ of the form $C(t) = f(t) + k_1 I(t - \tau_1) + k_2 S(t - \tau_2) + k_3 V(t - \tau_3)$, where t is the time, $f(t)$ is a linear function, $I(t - \tau_1)$ is the solar irradiance, $S(t - \tau_2)$ is a measure of the El Niño Southern Oscillation (ENSO) indexed by the SST anomalies, $V(t - \tau_3)$ is a measure of the volcano-aerosol signal, τ_i are fixed lag-times that give the highest correlation between each signal and the data, and the k_i are the corresponding forcing constants. However, the multiple linear regression analysis is not optimal because the parameters k_i and τ_i might be time-dependent and, in such a case, keeping them constant would yield serious systematic errors in the evaluation of the parameters k_i. Moreover, climate models predict that the climate sensitivity to cyclical forcing increases at lower frequencies because of the strong frequency-dependent damping effect of ocean thermal inertia [*Wigley*, 1988; *Foukal et al.*, 2004]. Thus, *Douglass and Clader* [2002] evaluated the climate sensitivity to the 11-year solar cycle, but as we have discussed above, the upward ACRIM modulation during solar cycles 21–23 can be minimally interpreted as a 22-year cycle modulation with amplitude given by equation (1). Therefore, we have to evaluate the climate sensitivity to a 22-year cycle and then we can approximate equation (2) as

$$\Delta T_{sun} \gtrapprox Z_{22years}\Delta I_{sun}. \quad (3)$$

[10] We proceed by decomposing the solar and temperature signals with proper band-pass filters for isolating the frequency bands of interest. The purpose is to estimate a linear transfer coefficient $Z(\omega) = A_{out}(\omega)/A_{in}(\omega)$ by comparing the amplitude $A_{in}(\omega)$ of an oscillating input signal at a given frequency ω, with the amplitude $A_{out}(\omega)$ of the oscillating output signal at the same frequency and then to apply equation (3). Linear transfer analysis is the usual method adopted to estimate the sensitivity of a complex but unknown system to external stimulation.

[11] The band pass filter we adopt is based on the maximal overlap discrete wavelet transform (MODWT) multiresolution analysis (MRA) by means of the 8-tap Daubechies least asymmetric (LA8) filter [*Percival and Walden*, 2000]. MRA makes use of scaled waveforms that measure signal variations by simultaneously analyzing the signal's time and scaling properties and, therefore, can powerfully identify local non-periodic patterns and signal singularities, and characterize signal structures [*Percival and Walden*, 2000]. Thus, the wavelet filtering is more efficient than the traditional linear transport frequency filters for extracting patterns from the data.

[12] MODWT MRA decomposes a time series $X(t)$ into a hierarchical sequence of zero-centered band-pass filter curves called *detail curves* $D_j(t)$, and a hierarchical sequence of smooth low-pass filter curves, called $S_j(t)$. High-pass filter curves are referred to as residual curves and indicated with $R_j(t)$. The index j indicates the order of scaling. So, at the J^{th} order MODWT MRA decomposes a signal $X(t)$ as $X(t) = S_J(t) + \sum_{j=1}^{J} D_j(t) = S_J(t) + R_J(t)$. The smooth curve $S_J(t)$ captures the smooth modulation of the data with a time scale larger than 2^{J+1} units of the time interval Δt at which the data are sampled. The detail curve $D_j(t)$ captures local variations with period approximately ranging from $2^j\Delta t$ to $2^{j+1}\Delta t$. Finally, the residual curve $R_J(t) = X(t) - S_J(t) =$

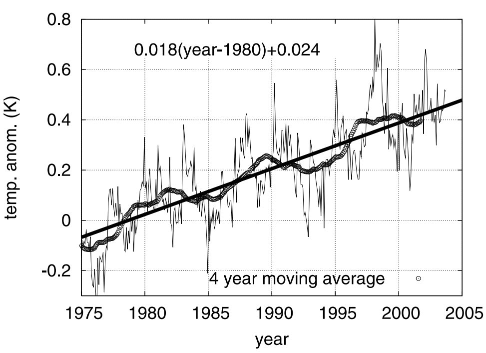

Figure 2. Global mean surface temperature anomalies. The global surface warming from 1980 to 2002, estimated with a linear fit, is $\Delta T_{1980-2002} = 0.40 \pm 0.04K$. Data are from Climatic Research Unit (2005, http://www.cru.uea.ac.uk).

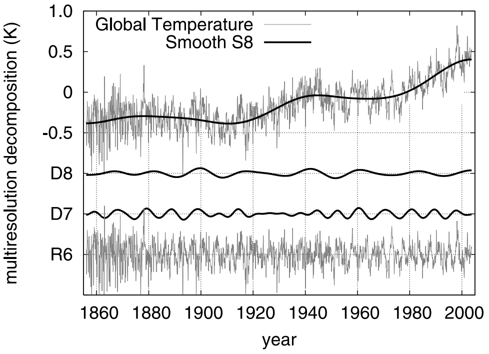

Figure 3. Global surface temperature (1856–2002) (CRU, 2005, http://www.cru.uea.ac.uk) and its MODWT MRA according to equation (4). The residual curve $R_6(t)$ becomes progressively less noisy probably because of improved observations during the last 150 years.

$\sum_{j=1}^{J} D_j(t)$ captures local variations of the data at time scales shorter than $2^{J+1}\Delta t$.

[13] The global surface temperature data are sampled monthly. The 11-year cycle (132 months) would be captured by the wavelet detail $D_7(t)$ that corresponds to the band between $2^7 = 128$ and $2^8 = 256$ months. However, the solar cycles are pseudo-periodic and to avoid an excessive random split of the cycles between adjacent wavelet detail curves, the wavelet filter should be optimized by choosing a time interval Δt such that the 11-year periodicity falls in the middle of the band captured by the curve $D_7(t)$. The average between 128 and 256 is 192, and the correct time interval is $\Delta t = 132/192 = 0.6875$ months. By using a linear interpolation we transform the monthly temperature data into a new time series sampled at $\Delta t = 0.6875$ months, and then apply the MRA to it. Thus, the detail curve $D_7(t)$ captures the scaling band between 88–176 months (or 7.3–14.7 years) centered in the 11-year solar cycle, while the detail curve $D_8(t)$ captures the band between 176–352 months (or 14.7–29.3 years) centered in the 22-year solar cycle. Figure 3 shows the MODWT MRA of the global mean surface temperature since 1856 defined by the decomposition

$$T(t) = S_8(t) + D_8(t) + D_7(t) + R_6(t). \tag{4}$$

The smooth curve $S_8(t)$ captures the secular variation of the temperature at time scale larger than 29.3 years that is reasonably produced by the slow modulation of the GHG and aerosol forcings plus the slow secular variation of the solar forcing. The detail curves $D_8(t)$ and $D_7(t)$ correspond, according to our hypothesis, to the climate signature imprinted by the 22-year and 11-year solar cycles respectively. The residual curve $R_6(t)$ collects all climate fluctuations at a time scale shorter than 7.3 years, which is mostly affected by SST oscillations, volcano eruptions and undetermined noise.

[14] Figure 4 compares the band-pass curves $D_7(t)$ and $D_8(t)$ for the TSI data and global temperature anomalies. For the period 1856–1980 we apply the MRA to the TSI proxy reconstruction by *Lean et al.* [1995], while for the period 1980–2002 the MRA is applied to the ACRIM TSI. Several 11-year solar cycles are easily recognizable in the corresponding $D_7(t)$ temperature cycles, in particular after 1960. The slow 22-year solar cycles are clearly recognizable in the temperature detail curve $D_8(t)$ and the temperature response lags the Hale solar cycles since 1900 by approximately 2.2 ± 2 years.

[15] We evaluate the linear transfer coefficient Z_7 and Z_8 by estimating the amplitude of the solar and temperature oscillations associated with the band-pass curves $D_7(t)$ and $D_8(t)$ during the period 1980–2002. The amplitude A of an oscillating signal, $f(t) = \frac{1}{2}A\sin(2\pi\, t)$, is related to the signal variance $\sigma^2 = \frac{1}{T}\int_0^T [f(t) - \overline{f(t)}]^2 dt$, where T is the time period and $\overline{f(t)}$ is the average of the signal, via the relation $A = 2\sqrt{2}\sigma$.

[16] For the ACRIM data we find $A_{7,sun} = 0.92 \pm 0.05$ W/m^2 and $A_{8,sun} = 0.35 \pm 0.10$ W/m^2. For the temperature data we find (11-year signature) $A_{7,temp} = 0.10 \pm 0.01K$ and (22-year signature) $A_{8,temp} = 0.06 \pm 0.01K$. Thus, we obtain:

$$Z_7 = A_{7,temp}/A_{7,sun} = 0.11 \pm 0.02K/\left(\mathrm{Wm}^{-2}\right), \tag{5}$$

$$Z_8 = A_{8,temp}/A_{8,sun} = 0.17 \pm 0.06K/\left(\mathrm{Wm}^{-2}\right). \tag{6}$$

Equations (5) and (6) refer to the climate sensitivity to the 11-year and 22-year solar cycles from 1980 to 2002 using the ACRIM TSI composite, respectively.

3. Discussion and Conclusion

[17] Our methodology filtered off volcano-aerosol and ENSO-SST signals from the temperature data because these

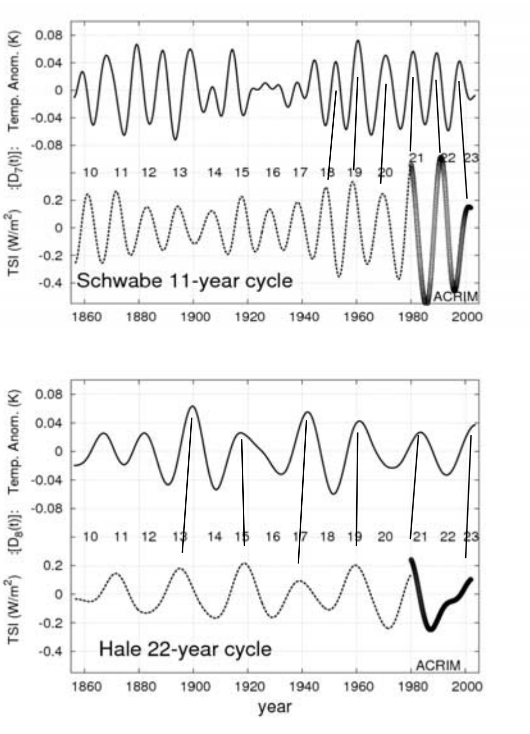

Figure 4. MODWT MRA band-pass curves $D_7(t)$ and $D_8(t)$ of global temperature (solid line) and TSI proxy reconstruction (1856–1980) by *Lean et al.* [1995] (dash line). The '*circle*' curve refers to the MODWT MRA band-pass curves applied to the ACRIM TSI (1980–2002).

estimates are partially consistent with already published independent empirical findings. In fact, the 11-year climate sensitivity $Z_7 = 0.11 \pm 0.02K/(Wm^{-2})$ is equal to the 11-year climate sensitivity k estimated by *Douglass and Clader* [2002]. Douglass and Clader also estimated that the 11-year solar cycle is associated with a $0.10K$ temperature cycle and this value is equal to our estimate $A_{7,temp}$, see also *Lean* [2005]. Because Douglass and Clader used a multiple linear regression analysis to separate the 11-year solar signature from the volcano-aerosol and ENSO-SST signals we can conclude that our wavelet band-pass filter has efficiently filtered off from the temperature data both volcano-aerosol and ENSO-SST signals. Evidently, from 1980 to 2002 volcano-aerosol and ENSO-SST signals affected climate on time scales shorter than 7.3 years which are captured by the residual curve $R_6(t)$.

[18] Our climate sensitivities Z_7 and Z_8 were also approximately anticipated by *White et al.* [1997]. These authors, by adopting Fourier band-pass filters centered at 11 and 22 year periodicities respectively, studied the response of global upper ocean temperature to changing solar irradiance using the TSI proxy reconstruction by *Lean et al.* [1995] from 1900 to 1991. Their regression coefficients between solar and temperature cycles are $k_{11\text{-}years} = 0.10 \pm 0.02K/(Wm^{-2})$ and $k_{22\text{-}years} = 0.14 \pm 0.02K/(Wm^{-2})$. These estimates are slightly smaller than Z_7 and Z_8, respectively, probably because these authors analyzed a different temporal period, and adopted a hypothetical TSI sequence and ocean surface temperature while we used global surface temperature, and over land the climate response to solar variation is stronger than over ocean.

[19] The climate sensitivity to the 22-year cycle, Z_8, is approximately 1.5 times stronger than the climate sensitivity to the 11-year cycle, Z_7, and, on average, the 22-year climate response lags Hale solar cycles by approximately 2.2 ± 2 years. These effects are predicted by theoretical energy balance models. In fact, the actual climate response to cyclical forcing is stronger at lower frequencies because the damping effect of the ocean inertia is weaker at lower frequencies [*Wigley*, 1988, Table 1]. This frequency dependence arises because the system is typically not in thermodynamic equilibrium. The ratio $Z_8/Z_7 = 1.55 \pm 0.55$ is consistent with that between the damping factors for 20 and 10 year periodicities $\eta_{20}/\eta_{10} \approx 1.45$ indicated by *Wigley* [1988, Table 1]. Wigley's model also predicts a response-lag of 2.5–2.8 years for a 20 year periodicity.

[20] In conclusion, we believe our estimates Z_7 and Z_8 of the climate sensitivity to solar variations from 1980 to 2002 are realistic. By using the ACRIM TSI increase estimate ΔI_{sun} (1) and the climate sensitivity Z_8 (6) in equation (3), the warming caused by ΔI_{sun} is $\Delta T_{sun} \gtrapprox 0.08 \pm 0.03$. Thus, because the global surface warming during the period 1980–2002 was $\Delta T_{1980-2002} = 0.40 \pm 0.04K$, we conclude that according to the ACRIM TSI composite the Sun may have minimally contributed $\sim$10–30% of the 1980–2002 global surface warming.

[21] Lastly, we compare the observed 11-year temperature cycle amplitude, $A_{7,temp} = 0.10 \pm 0.01K$, with that estimated by some theoretical climate models. By adopting three energy balance models, *Stevens and North* [1996, Figure 15] show 11-year TSI cycle forcing since 1980 would imprint 11-year global surface temperature cycles with an amplitude $A_{temp} \approx 0.06 \pm 0.01K$; the MAGICC climate model by Wigley gives $A_{temp} \approx 0.035K$ [*Foukal et al.*, 2004]. Consequently, our estimate of the 11-year temperature cycle $A_{7,temp}$ is approximately 1.5–3 times larger than what these models predict. *Douglass and Clader* [2002] arrived at a similar conclusion about the Wigley model. Thus, while the theoretical models approximately predict the relative climate sensitivity ratio Z_8/Z_7 and the response time-lag, they seem to disagree from each other about the actual climate sensitivity to solar variation and significantly underestimate the phenomenological climate sensitivities to solar cycles as we have estimated. Evidently, either the empirical evidence deriving from the deconstruction of the surface temperature is deceptive, or the models are inadequate because of the difficulty of modeling climate in general and a lack of knowledge of climate sensitivity to solar variations in particular. As *Lean* [2005] noted, the models might be inadequate: (1) in their parameterizations of climate feedbacks and atmosphere-ocean coupling; (2) in their neglect of indirect response by the stratosphere and of possible additional climate effects linked to solar magnetic field, UV radiation, solar flares and cosmic ray intensity modulations; (3) there might be other possible natural amplification mechanisms deriving from internal modes of climate variability which are not included in the models. All the above mechanisms would be automatically considered and indirectly included in our phenomenological approach.

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