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Phenomenological solar contribution to the 1900–2000 global surface warming

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[1] We study the role of solar forcing on global surface temperature during four periods of the industrial era (1900–2000, 1900–1950, 1950–2000 and 1980–2000) by using a sun-climate coupling model based on four scale-dependent empirical climate sensitive parameters to solar variations. We use two alternative total solar irradiance satellite composites, ACRIM and PMOD, and a total solar irradiance proxy reconstruction. We estimate that the sun contributed as much as 45–50% of the 1900–2000 global warming, and 25–35% of the 1980–2000 global warming. These results, while confirming that anthropogenic-added climate forcing might have progressively played a dominant role in climate change during the last century, also suggest that the solar impact on climate change during the same period is significantly stronger than what some theoretical models have predicted. **Citation:** Scafetta, N., and B. J. West (2006), Phenomenological solar contribution to the 1900–2000 global surface warming, *Geophys. Res. Lett.*, *33*, L05708, doi:10.1029/2005GL025539.

1. Introduction

[2] Figure 1 shows that from 1900 to 2000 the global surface temperature progressively increased: $\Delta T_{1900-2000}$ = 0.74 K, $\Delta T_{1950-2000}$ = 0.45 K and $\Delta T_{1980-2000}$ = 0.38 K; the phenomenon of global warming. This secular variation of the surface temperature is produced by the slow modulation of the greenhouse gas and aerosol forcing plus the slow secular variation of the solar forcing. But in the scientific literature there exist debate and controversy about what actually caused this change, in particular about the relative importance of anthropogenic versus natural causes.

[3] Among the natural causes affecting climate, solar forcing is by far the most controversial. There are ongoing controversies concerning total solar irradiance (TSI) secular records because satellite composites, which are available only since late 1978, are not unique [*Willson and Mordvinov*, 2003; *Fröhlich and Lean*, 1998], and before 1978 only disputed TSI proxy reconstructions, and not direct measurements of TSI, are available (*Lean et al.* [1995], *Stevens and North* [1996], *Hoyt and Schatten* [1997], *Solanki and Fligge* [1998], and others). These TSI proxy reconstructions present significant differences in the amplitudes of their secular trends. Herein, we adopt the original TSI proxy reconstruction by *Lean et al.* [1995] that seems to be a compromise among those TSI proxy reconstructions showing small [*Stevens and North*, 1996] and large [*Hoyt and Schatten*, 1997] amplitudes of the secular trend. In addition, climate sensitivity to solar changes have been estimated using theoretical climate models [*Intergovernmental Panel on Climate Change*, 2001; *Hansen et al.*, 2002]. For example, *Hansen et al.* [2002, Figures 18a and 18b] deduced that while the solar forcing might have played an important role during the past, it did not contributed to the observed 1950–2000 global surface warming. Consequently, the climate warming of the last half century could only be induced, directly or indirectly, by means of anthropogenically added greenhouse gas climate forcing. Nevertheless, several authors have observed that the sun-climate coupling mechanisms are not fully understood and, therefore, not implemented in the models [*Hoyt and Schatten*, 1997; *Pap and Fox*, 2004; *Lean*, 2005]. In addition, there are empirical studies claiming that the solar contribution to climate change has been miscalculated using present theoretical climate models [*White et al.*, 1997; *Douglass and Clader*, 2002; *Scafetta and West*, 2005].

[4] Further controversies about the correctness of the theoretical model predictions rely on the apparent correlation that is observed between secular solar reconstructed activity and global climate change; a correlation that lasts for several centuries according to some authors [*Eddy*, 1976; *Lassen and Friis-Christensen*, 1995; *Crowley and Kim*, 1996; *Hoyt and Schatten*, 1997]. Figures 2a and 2b show two distinct TSI reconstructions made by merging in 1980 the annual mean TSI proxy reconstruction of *Lean et al.* [1995] for the period 1900–1980 and two alternative TSI satellite composites, ACRIM [*Willson and Mordvinov*, 2003], and PMOD [*Fröhlich and Lean*, 1998], for the period 1980–2000, which approximately cover solar cycles 21–23. (Note that according to ACRIM the average TSI increased during solar cycles 21–23, while according to PMOD it did not.) A simple visual comparison between Figures 1 and 2 suggests that global surface temperature approximately parallels the corresponding TSI smooth curves. Both temperature and TSI increased during 1900–1945, were approximately stable during 1945–1970, and again increased during 1970–2000. This apparent secular correlation between TSI and global surface temperature does not prove that the sun had a significant impact on climate change during the last century but, nevertheless, it does suggest the possibility.

[5] Finally, we observe that the climate sensitivity to solar changes is a multiscale phenomenon because the frequency-amplitude-dependent damping effect of the ocean and atmosphere thermal inertia should make the climate more sensitive to slower solar variations [*Wigley*, 1988; *Foukal et al.*, 2004; *Scafetta and West*, 2005]. In fact, the lower the frequency or the amplitude of an external energetic forcing, the stronger will be the response of a thermal

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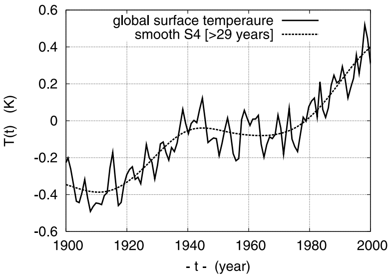

Figure 1. Global annual mean surface temperature anomalies. Data are from Climatic Research Unit (2005, http://www.cru.uea.ac.uk).

system. Herein, we adopt a multiscale model of the climate sensitivity to solar forcing based on four scale-dependent empirical climate sensitive transfer parameters to solar variations to estimate the empirical solar contribution to the global surface warming during the industrial era of the 20th century. We study four periods (1900–2000, 1900–1950, 1950–2000 and 1980–2000) and use the two alternative TSI reconstructions shown in Figures 2a and 2b.

2. Climate Models and Data Analysis

[6] *Scafetta and West* [2005] assumed that TSI is a reasonable proxy for the entire solar activity and estimated the climate sensitivity to 11-year and 22-year solar cycles by means of a transfer function methodology that compares the amplitude of the TSI cycles with the amplitude of the corresponding temperature cycles. This approach has the advantage of determining the total (direct plus indirect) effect of the sun-climate coupling without requiring a detailed knowledge of the underlying physical and chemical mechanisms; a major advantage compared to the theoretical climate model approach that would require a perfect knowledge of such mechanisms to disentangle and then collect all direct and indirect solar effects on climate, which can be embedded in several climate forcings.

[7] By using ACRIM, the climate transfer sensitivities to 11-year (Schwabe) and 22-year (Hale) solar cycles during the period 1980–2002, estimated in terms of a transfer function Z_{period}, are Z_{11y} = 0.11 ± 0.02 K/(Wm^{-2}) and Z_{22y} = 0.17 ± 0.06 K/(Wm^{-2}), respectively [*Scafetta and West*, 2005]. Additional support for the value Z_{11y} has been found by *Douglass and Clader* [2002] by means of a multiple linear regression analysis which separates the PMOD TSI induced temperature 11-year cycle signal from the volcano-aerosol and ENSO-SST temperature signals. Moreover, approximate phenomenological values of the climate transfer sensitivities Z_{11y} and Z_{22y} were anticipated by *White et al.* [1997] who studied the response of global upper ocean temperature to solar cycles from 1900 to 1991 by using appropriate band-pass filters of the TSI proxy reconstruction by *Lean et al.* [1995], and showed that these temperature data present cycles which correspond to the 11 and 22-year solar cycles. Finally, the relation $Z_{22y} \approx 1.5\ Z_{11y}$ has been predicted by theoretical energy balance models because of the frequency-amplitude-dependent damping effect of the ocean and atmosphere thermal inertia [*Wigley*, 1988, Table 1].

[8] The empirical solar contribution to global warming for the periods 1900–2000, 1900–1950, 1950–2000 and 1980–2000 can be estimated by assuming that the climate sensitivity parameters Z_{11y} and Z_{22y} can be applied with equal reliability to the data for the period 1900–2000, and by estimating climate sensitivity parameters to slower secular solar trends. We adopt the following model for the *total* climate sensitivity to the *total* solar activity:

$$\Delta T_{sun} = \int_0^\infty Z(\omega)\frac{dI}{d\omega}d\omega, \qquad (1)$$

where the frequency-dependent function $Z(\omega)$ is herein defined as the *total climate sensitivity transfer function* to solar variations. Equation (1) can be more easily used by decomposing the TSI sequence with a scale-by-scale opportune filter. We use the maximal overlap discrete wavelet transform multiresolution analysis (MRA) by means of the 8-tap Daubechies least asymmetric (LA8) filter [*Percival and Walden*, 2000]. Figures 2a and 2b show the two TSI sequences, $I(t)$, and their MRA decomposition according to

$$I(t) = S_4(t) + D_4(t) + D_3(t) + R_2(t), \qquad (2)$$

where the indexes j = 2, 3 and 4 refer to the time-scale of the filter. By sampling the data with a linear interpolation algorithm at a time interval of Δt = 11/12 = 0.92 years, the smooth curve $S_4(t)$ captures the TSI secular variation at time scale larger than $2^5\ \Delta t$ = 29.3 years. The band-pass curve $D_4(t)$ captures the variation at a time scale from $2^4\ \Delta t$ = 14.7 to $2^5\ \Delta t$ = 29.3 year periodicities, which are centered on the 22-year cycle. The band-pass curve $D_3(t)$ captures the fluctuations at a time scale from $2^3\ \Delta t$ = 7.3 to $2^4 \Delta t$ = 14.7

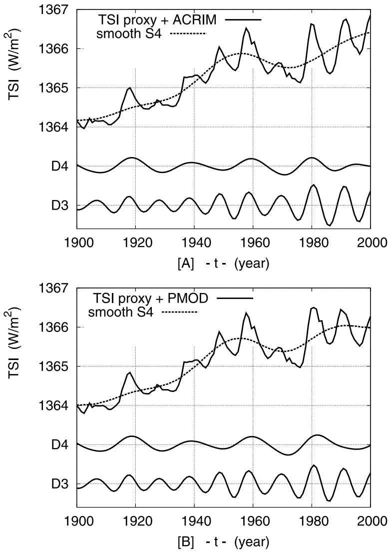

Figure 2. Total solar irradiance sequences and their maximal overlap MRA decomposition according to equation (2). The data for the period 1980–2000 are given by TSI satellite composites: (a) ACRIM [*Willson and Mordvinov*, 2003], and (b) PMOD [*Fröhlich and Lean*, 1998]. The period 1900–1980 is covered by the TSI proxy reconstruction by *Lean et al.* [1995] that has been adjusted by means of a vertical shift to match the two TSI satellite composites in the year 1980.

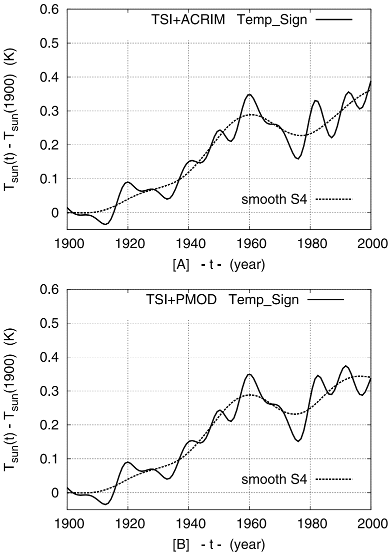

Figure 3. (a and b) Estimate global surface temperature signature induced by the two TSI sequences shown in Figures 2a and 2b, respectively, in term of the anomaly $T_{sun}(t) - T_{sun}(1900)$, according to equation (3).

year periodicities, which are centered in the 11-year cycle. The residual curve $R_2(t)$ (not shown in the figures) collects all fluctuations at a time scale shorter than 7.3 years.

[9] Using equation (2), equation (1) can be rewritten by using four scale-dependent phenomenological climate sensitive transfer parameters. Thus, the solar signature on the global surface temperature on time scales larger than 7.3 years is given by

$$T_{sun}(t) = Z_{eq}\langle S_4(t)\rangle + Z_{S4}[S_4(t-\tau_{S4}) - \langle S_4(t)\rangle] + Z_{22y}D_4(t-\tau_4) + Z_{11y}D_3(t-\tau_3). \quad (3)$$

The value $\langle S_4(t)\rangle$ is the average TSI during the century commonly known as the *solar constant*; the parameters Z_{22y} and Z_{11y} are the transfer climate sensitivities to the 22-year and 11-year solar cycles [*Scafetta and West*, 2005]; Z_{S4} is the transfer climate sensitivity to slower secular solar variation at time scales larger than 29.3 years; finally, Z_{eq} is the equilibrium transfer climate sensitivity. The values of τ_{S4}, τ_4 and τ_3 are the correspondent time-lags: we adopt the same time-lags as predicted by *Wigley*'s [1988, Table 1] model: $\tau_{S4} \approx 4.3$ years, $\tau_4 = 2.5$ years and $\tau_3 = 1.3$ years.

[10] The equilibrium climate sensitivity transfer parameter Z_{eq} can be approximately estimated by dividing the average global surface temperature, which is $\langle T\rangle \approx 15°C = 288$ K, by the average TSI, which is $\langle S_4(t)\rangle \approx 1365$ W/m^2:

$$Z_{eq} = \frac{\langle T\rangle}{\langle S_4(t)\rangle} \approx 0.21\mathrm{K}/\left(\mathrm{Wm}^{-2}\right). \quad (4)$$

The rationale of the above simple expression is that it is the solar energetic input that, being absorbed by the atmosphere, the land surface and the ocean, keeps the surface of the earth warm at $\langle T\rangle \approx 288$ K. Note that the overall strength of the equilibrium sun-climate coupling can be estimated via equation (4) without the need of taking into account the albedo and the sphericity of the earth, and knowing all solar-climate coupling mechanisms with all their feedback and amplification mechanisms, many of which are probably unknown [*Lean*, 2005].

[11] The climate sensitivity transfer parameter to the slow secular solar variation, Z_{S4}, cannot be empirically measured. In fact, it refers to climate changes with a time scale larger than 29.3 years which are shaped by the change of multiple climate forcings that might not be, directly or indirectly, linked to solar variations, such as anthropogenic-added greenhouse climate forcing. But, according to theoretical energy balance climate model predictions [*Wigley*, 1988, Table 1], the following relation reasonably holds:

$$Z_{11y} < Z_{22y} \approx Z_{S4} < Z_{eq}. \quad (5)$$

We observe that the above estimated values of Z_{11y}, Z_{22y} and Z_{eq} already fulfill equation (5). Moreover, because Z_{eq} would give the upper limit and because the transfer sensitivity $Z_{22y} = 0.17$ K/(Wm^{-2}) has a 30% error, we may assume that the transfer sensitivity Z_{S4} has the same value as Z_{22y} with a similar uncertainty, that is, we assume that Z_{S4} realistically falls between Z_{11y} and Z_{eq}.

[12] Note that it is preferable to assume $Z_{11y} < Z_{S4} < Z_{eq}$ with $Z_{22y} \approx Z_{S4}$, rather than $Z_{22y} < Z_{S4}$, because climate sensitivity to solar variations should decrease with both frequency and amplitude of the input irradiance signal [*Wigley*, 1988, Table 1]. Figure 2 shows that the amplitude of the slow secular variation of the curve $S_4(t)$ is significantly larger than the amplitude of the curve $D_4(t)$. Nevertheless, although the amplitude of $S_4(t)$ is two to four times larger than the amplitude of $D_3(t)$, which is centered on the 11-year periodicity, $Z_{11y} < Z_{S4}$ is reasonable because the theoretical estimates [*Wigley*, 1988, Table 1; *Foukal et al.*, 2004] suggest that given a signal A with an amplitude two to four times larger than a signal B, a periodicity of the former signal four to eight times larger than of the latter is already sufficient to yield a climate sensitivity $Z_A > Z_B$.

[13] Figures 3a and 3b show the theoretical TSI climate signature during 1900–2000 in term of $T_{sun}(t) - T_{sun}(1900)$, according to equation (3). Table 1 records the average global surface warming, the estimated average warming induced by the sun according to the two alternative TSI

Table 1. Solar Contribution to the Global Warming[a]

	ΔT	ΔT_{sun}	P_{sun}
TSI+ACRIM			
1900–2000	0.74 K	0.36 K	49%
1900–1950	0.29 K	0.22 K	76%
1950–2000	0.45 K	0.14 K	31%
1980–2000	0.38 K	0.13 K	34%
TSI+PMOD			
1900–2000	0.74 K	0.34 K	46%
1900–1950	0.29 K	0.22 K	76%
1950–2000	0.45 K	0.12 K	27%
1980–2000	0.38 K	0.09 K	24%

[a] ΔT represents the global surface warming during the four periods by using the smooth curve in Figure 1; ΔT_{sun} represents the estimated warming induced by the sun according to the two TSI reconstructions as deduced from the smooth curves of the two hypothetical TSI climate signature shown in Figures 3a and 3b; P_{sun} is the percent solar contribution to the global warming during the four periods.

reconstructions, and the percent solar contribution to the warming.

3. Discussion and Conclusion

[14] A sun-climate coupling model should take into account that the climate sensitivity to solar changes is frequency-amplitude-dependent and a correct estimate of the solar impact on climate can be done by using a minimum set of four scale-dependent empirical climate sensitivities to solar variation. Note that the amplitude-dependence of the climate sensitivity will also reduce the dissimilarity among the results about the secular solar contribution to climate change obtained by using different TSI proxy reconstructions.

[15] According to the findings summarized in Table 1 the increase of solar activity during the last century, according to the original *Lean et al.*'s [1995] TSI proxy reconstruction, could have, on average, contributed approximately 45–50% of the 1900–2000 global warming: the low and high estimates depend on whether PMOD or ACRIM satellite composite TSI is used for the period 1980–2000, respectively. This contribution is not constant during the century because the increase of solar activity could have, on average, contributed approximately 75% of the 1900–1950 global warming but only 25–35% of the 1980–2000 global warming. By considering a 20–30% uncertainty of the sensitivity parameters, the sun could have roughly contributed 35–60% and 20–40% of the 1900–2000 and 1980–2000 global warming, respectively. These findings would confirm that anthropogenic-added climate forcing might have progressively played a dominant role in climate change during the last century and, in particular, during the last decades. The sun played a dominant role in climate change in the early past, as several empirical studies would suggest [*Hoyt and Schatten*, 1997; *Eddy*, 1976; *Crowley and Kim*, 1996; *Lassen and Friis-Christensen*, 1995], and is still playing a significant, even if not a predominant role, during the last decades.

[16] The impact of solar variation on climate seems significantly stronger than predicted by some energy balance models. For example, by using different TSI proxy reconstructions, *Stevens and North* [1996, Figure 15], *Crowley and Kim* [1996, Figure 3] and *Foukal et al.* [2004, Figure 1] estimated that solar forcing might have approximately contributed $0.035\ \mathrm{K} < \Delta T_{1900-2000,sun} < 0.2\ \mathrm{K}$ of the global warming. This is approximately from two to ten times lower than what we have found. Moreover, *Scafetta and West* [2005] found that the amplitude of the 11-year solar signature on the temperature record seems to be from 1.5 to 3 times larger than the theoretical predictions.

[17] The significant discrepancy between empirical and theoretical model estimates might arise because the secular TSI proxy reconstructions are disputed and/or because the empirical evidence deriving from the deconstruction of the surface temperature is deceptive for reasons unknown to us. Alternatively, the models might be inadequate because of the difficulty of modeling climate in general and a lack of knowledge of climate sensitivity to solar variations in particular. In fact, theoretical models usually acknowledge as solar forcing only the direct TSI forcing while empirical estimates would include all direct and indirect climate effects induced by solar variation. These solar effects might be embedded in several climate forcings because, for example, a TSI increase might indirectly induce a change in the chemistry of the atmosphere by increasing and modulating its greenhouse gas (H_2O, CO_2, CH_4, etc.) concentration because of the warmer ocean, reduce the earth albedo by melting the glaciers and change the cloud cover patterns. In particular, the models might be inadequate [*Lean*, 2005]: (a) in their parameterizations of climate feedbacks and atmosphere-ocean coupling; (b) 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; (c) 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 the phenomenological approach presented herein.

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