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Phenomenological solar signature in 400 years of reconstructed Northern Hemisphere temperature record

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[1] We study the solar impact on 400 years of a global surface temperature record since 1600. This period includes the pre-industrial era (roughly 1600–1800 or 1600–1900), when negligible amount of anthropogenic-added climate forcing was present and the sun realistically was the only climate force affecting climate on a secular scale, and the industrial era (roughly since 1800–1900), when anthropogenic-added climate forcing has been present in some degree. We use a recent secular Northern Hemisphere temperature reconstruction (Moberg et al., 2005), three alternative total solar irradiance (TSI) proxy reconstructions (Lean et al., 1995; Lean, 2000; Wang et al., 2005) and a scale-by-scale transfer climate sensitivity model to solar changes (Scafetta and West, 2005, 2006). The phenomenological approach we propose is an alternative to the more traditional computer-based climate model approach, and yields results proven to be almost independent on the secular TSI proxy reconstruction used. We find good correspondence between global temperature and solar induced temperature curves during the pre-industrial period such as the cooling periods occurring during the Maunder Minimum (1645–1715) and the Dalton Minimum (1795–1825). The sun might have contributed approximately 50% of the observed global warming since 1900 (Scafetta and West, 2006). We briefly discuss the global cooling that occurred from the medieval maximum (≈1000–1100 AD) to the 17th century minimum. **Citation:** Scafetta, N., and B. J. West (2006), Phenomenological solar signature in 400 years of reconstructed Northern Hemisphere temperature record, *Geophys. Res. Lett.*, *33*, L17718, doi:10.1029/2006GL027142.

1. Introduction

[2] A number of secular reconstructions of global temperature and TSI have been carried out in order to understand the causes of climate variability, and in particular to identify the relative natural vs. anthropogenic contribution of the observed variations. However, the mechanisms by which solar activity might cause climate changes are not well understood [*Hoyt and Schatten*, 1997; *Pap and Fox*, 2004].

[3] A traditional approach relies on theoretical climate models [*Intergovernmental Panel on Climate Change*, 2001; *Hansen et al.*, 2002] where a certain number of climate forcing and feedback mechanisms are pre-determined in the model. By adopting this philosophy the solar impact on climate would significantly depend on the amplitudes of secular trends of the adopted TSI forcing, (compare Figure 1A and 1B of *Foukal et al.* [2004]). In fact, by keeping the model unaltered in its mechanisms, weaker TSI forcing would yield to weaker climate feedback to TSI variation, and the total effect of solar change on climate would be weaker. One difficulty with this approach is that the feedback mechanisms and alternative solar effects on climate (for example, UV energy changes are involved in production and loss of ozone, variations in the solar wind affect the size and intensity of the heliosphere and modulate the cosmic rays that may affect formation of clouds affecting Earth's albedo [*Pap and Fox*, 2004]), since they are only partially known, might be poorly or not modeled at all.

[4] To circumvent the lack of knowledge in climate physics, we adopt an alternative approach that attempts to evaluate the total *direct plus indirect* effect of solar changes on climate by comparing patterns in the secular temperature and TSI reconstructions. Herein, a TSI reconstruction is not used as a radiative forcing, but as a proxy of the entire solar dynamics. We find that this phenomenological approach yields a result that is less sensitive to the particular TSI reconstruction adopted in the analysis because a weaker TSI forcing would simply imply the presence of stronger climate feedbacks to TSI variation and/or a stronger climate sensitivity to other solar changes (UV and cosmic rays) in such a way as to reproduce the same observed temperature patterns. This phenomenological approach is justified by the findings of several authors [*Eddy*, 1976; *Lassen and Friis-Christensen*, 1995; *Lean et al.*, 1995; *Crowley and Kim*, 1996; *Hoyt and Schatten*, 1997; *White et al.*, 1997] who have noted an apparent secular correlation between global surface temperature and TSI reconstructions. We use a novel scale-by-scale transfer climate sensitivity model (SbS-TCSM) [*Scafetta and West*, 2005, 2006] to solar changes for this purpose.

[5] We assume that the secular climate sensitivity to solar change can be phenomenologically estimated by comparing the secular warming between the solar and temperature records during the pre-industrial era (roughly 1600–1800 or 1600–1900 AD), when, reasonably, only a negligible amount of anthropogenic-added climate forcing was present. During this period the sun was the only realistic force affecting climate on a secular scale. Any secular change of the albedo and of greenhouse gases (GHGs) (H_2O, CO_2, CH_4, etc.) occurring during this pre-industrial era should be considered natural climate feedback to solar change, and therefore, counted as an indirect solar effect on climate. In fact, for example, it may be misleading to assume that all changes of CO_2 concentration must have an anthropogenic

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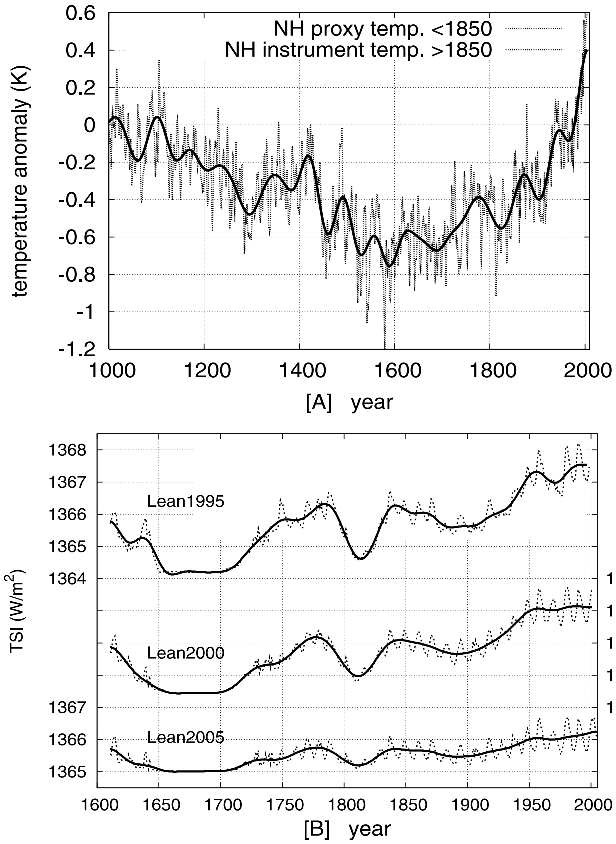

Figure 1. (a) NH temperatures since 1000 AD. Proxy reconstruction by *Moberg et al.* [2005] from 1000 to 1850, and the NH instrumental surface temperature data since 1850 [*Brohan et al.*, 2006]. The Moberg's data are slightly adjusted in such a way that the two 1850–1900 mean temperature values coincide. (b) Three different TSI proxy reconstructions that herein we adopt [*Lean et al.* 1995; *Lean*, 2000; *Wang et al.*, 2005]. Note that their patterns are quite similar but with significant differences in the amplitude of the secular trend. Note the low solar activity periods occurring during the Maunder Minimum (1645–1715) and during the Dalton Minimum (1795–1825).

origin because the existence of CO_2 natural feedbacks are indeed known and involve ocean-atmosphere gas exchange interaction [*Cox et al.*, 2000] and respiration rates of bacteria in the soil [*Brandefelt and Holmén*, 2001].

2. Climate Models and Data

[6] We adopt a recent Northern Hemisphere (NH) temperature reconstruction obtained from low- and high-resolution proxy data [*Moberg et al.*, 2005]; see Figure 1a. The methodological advantage of *Moberg et al.'s* [2005] wavelet-based approach is that it uses each proxy type only at those timescales where it is most reliable. This temperature reconstruction presents larger multi-centennial variability than most previous multi-proxy reconstructions, but agrees well with temperatures reconstructed from borehole measurements and with some theoretical temperature prediction obtained with certain general circulation models; see references given by *Moberg et al.* [2005]. In particular, this temperature reconstruction presents a medieval maximum ($\approx$1000–1100 AD) at $T \approx 0$ K (compared to the 1961–1990 average temperature), a minimum of $T \approx -0.7$ K during the solar Maunder Minimum (1645–1715) and a minimum of $T \approx -0.6$ K during the solar Dalton Minimum (1795–1825). In recent years NH temperature reached a maximum of $T \approx 0.5$ K.

[7] We adopt three different TSI proxy reconstructions [*Lean et al.*, 1995; *Lean*, 2000; Wang et al., 2005]; see Figure 1b. They look similar but present different secular trend amplitudes due to some differences in the adopted solar theoretical models. TSI has increased since the 17th century. Note that a decrease in solar activity, as proven by the ^{14}C record, likely induced the cooling of $\Delta T \approx 0.7$ K from the medieval maximum to the 17th century minimum [*Eddy*, 1976], suggesting that an equivalent or larger increase in solar activity could induce a climate warming of comparable or greater size. And, perhaps, solar activity during the past 70 years has been exceptionally high [*Solanki et al.*, 2004].

[8] Finally, we adopt SbS-TCSM. This empirical methodology relies on the fact that climate sensitivity to solar changes is a multiscale phenomenon because the frequency-amplitude-dependent damping effect of the ocean and atmosphere thermal inertia makes the climate more sensitive to slower solar variations. For example, according to an energy balance model simulation [*Wigley*, 1988, Table 1], the climate sensitivity to a 160-year TSI cycle might be 3–4 times stronger than the climate sensitivity to a 10-year TSI cycle, and that by reducing the amplitude of the forcing by one-half the climate sensitivity might increase by from 40% (160-year cycle) to 77% (10-year cycle); compare also Figures 1A and 1B of *Foukal et al.* [2004], where the climate sensitivity to the smooth component of the secular TSI change is approximately 3 times the climate sensitivity to the 11-year solar cycle. The frequency dependency of climate sensitivity to solar changes has been confirmed by the analysis of empirical measurements [*White et al.*, 1997; *Scafetta and West*, 2005, 2006] where 11-year and 22-year solar and temperature cycles were studied.

[9] Solar effects on climate has to be modeled as

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

where the frequency-dependent function $Z(\omega)$ is herein defined as the total climate sensitivity transfer function to solar variations [*Scafetta and West*, 2005, 2006]. Equation (1) can be more easily used by decomposing the TSI sequence with a scale-by-scale wavelet opportune wavelet filter as

$$I(t) = S(t) + D_{22y}(t) + D_{11y}(t) + R(t). \quad (2)$$

The smooth curve $S(t)$ captures the secular variation at time scale larger than 29.3 years. The band-pass curve $D_{22y}(t)$ captures the variation at a time scale from 14.7 to 29.3 year periodicities, which are centered in the 22-year cycle. The band-pass curve $D_{11y}(t)$ captures the fluctuations at a time scale from 7.3 to 14.7 year periodicities, which are centered in the 11-year cycle. The residual curve $R(t)$ collects all fluctuations at a time scale shorter than 7.3 years.

Table 1. Numerical Results[a]

	NHtemp	Lean1995	Lean2000	Lean2005
$\mu_{17\text{th}}$	−0.63	1364.65	1363.78	1365.16
$\mu_{18\text{th}}$	−0.49	1365.48	1364.44	1365.43
$\mu_{19\text{th}}$	−0.41	1365.64	1364.68	1365.52
$\Delta\mu_1$	0.14 ± 0.01	0.83 ± 0.08	0.66 ± 0.07	0.27 ± 0.03
$\Delta\mu_2$	0.22 ± 0.01	0.99 ± 0.07	0.90 ± 0.06	0.36 ± 0.03
$Z_{S,1}$		0.17 ± 0.02	0.21 ± 0.03	0.52 ± 0.07
$Z_{S,2}$		0.22 ± 0.02	0.24 ± 0.02	0.61 ± 0.06
Z_S		0.20 ± 0.03	0.23 ± 0.03	0.57 ± 0.07

[a]Rows 1, 2 and 3: average values during the corresponding centuries: unit for the temperature is K (error ±0.01K) and for the TSI is W/m^2 (error ±0.05K). Rows 4 and 5: $\Delta\mu_1 = \mu_{18\text{th}} - \mu_{17\text{th}}$ and $\Delta\mu_2 = \mu_{19\text{th}} - \mu_{17\text{th}}$. Rows 6, 7 and 8: the climate secular sensitivities to solar changes $Z_{S,1}$, $Z_{S,2}$ and Z_S are defined in equations (5, 6, 7), in units K/(Wm^{-2}).

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

$$T_{sun}(t) - \langle T_{sun}\rangle \approx Z_S S(t-\tau_S) + Z_{22y} D_{22y}(\tau - \tau_{22y}) + Z_{11y} D_{11y}(\tau - \tau_{11y}) + const, \tag{3}$$

where *const* is an opportune constant, $\langle T_{sun}\rangle$ is a temperature average during a certain period and each scale is characterized by an opportune time-lag. The TCSM sensitivities to the Hale (22-year solar) cycle and to the Schwabe (11-year solar) cycle are Z_{22y} = 0.17 ± 0.06 K/Wm^{-2} and Z_{11y} = 0.11 ± 0.02 K/Wm^{-2} [*Scafetta and West*, 2005].

[11] Herein, we need to estimate the transfer climate sensitivity to smooth secular solar change, Z_S, and use only the secular component of the above equation:

$$T_{sun,secular}(t) - \langle T_{sun}\rangle = Z_S S(t-\tau_S) + const. \tag{4}$$

Z_S is estimated by assuming that the secular warming during the pre-industrial era was caused by the contemporary TSI increase. We calculate: a) the TSI and temperature averages for the 17th, 18th and 19th century; b) the TSI and temperature average increases occurred between the 17th and 18th centuries and between the 17th and 19th centuries; c) the secular transfer climate sensitivity to solar changes

$$Z_{S,1} = \frac{\Delta\mu(T)_1}{\Delta\mu(I)_1} = \frac{\langle T_{18\text{th}}\rangle - \langle T_{17\text{th}}\rangle}{\langle I_{18\text{th}}\rangle - \langle I_{17\text{th}}\rangle} \tag{5}$$

$$Z_{S,2} = \frac{\Delta\mu(T)_2}{\Delta\mu(I)_2} = \frac{\langle T_{19\text{th}}\rangle - \langle T_{17\text{th}}\rangle}{\langle I_{19\text{th}}\rangle - \langle I_{17\text{th}}\rangle}; \tag{6}$$

d) finally, we can use any of the two above estimates, or their average that would cover three centuries but lightly overweighting the 1600–1800 pre-industrial period,

$$Z_S \approx \frac{Z_{S,1} + Z_{S,2}}{2}. \tag{7}$$

The above numerical results are reported in Table 1. Note that $Z(\omega)$ is a *transfer climate sensitivity* function to solar changes where TSI is used as a proxy of the overall solar activity. Thus, $Z(\omega)$ does not have the same meaning of a *climate radiative sensitivity* to TSI as used in the climate models.

3. Discussion and Conclusion

[12] Our findings, summarized in Figure 2, show the comparison between NH temperature reconstruction for the past 400 years and the phenomenological solar temperature signature obtained with the smooth curves of the TSI proxy reconstructions (shown in Figure 1) and equations (4, 7).

[13] Since the 17th century minimum the sun has induced a warming of $\Delta T \approx 0.7$ K. This warming is of the same magnitude of the cooling of $\Delta T \approx 0.7$ K from the medieval maximum to the 17th century minimum. Because anthropogenic contributions to climate change are unlikely before 1800–1900 AD, this finding suggests the presence of a millenarian solar cycle, with two medieval and contemporary maxima, driving the climate of the last millennium [*Eddy*, 1976].

[14] There is good agreement between the patterns at least for the three pre-industrial era centuries, 1600–1900 AD: the cooling of $T \approx -0.7$ K during the Maunder Minimum (1645–1715), the cooling of $T \approx -0.6$ K during the Dalton Minimum (1795–1825), the relative warming between these two cooling periods and from 1850 to 1875 and another local minimum around 1900 are well recovered. During the 20th century one continues to observe a significant correlation between the solar and temperature patterns: both records show an increase from 1900 to 1950, a decrease from 1950 to 1970, and again an increase from 1970 to 2000. However, a divergence in the upward trend of the two records is also evident. A comparison between the

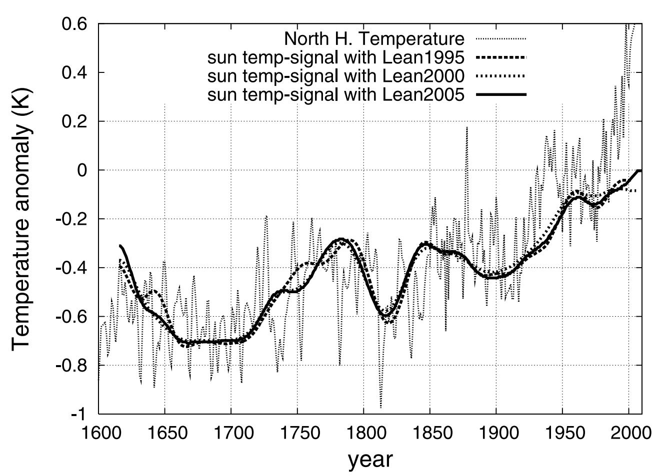

Figure 2. NH temperature for the past 400 years vs. the three smooth curves representing the solar temperature signature of the three smooth TSI reconstruction shown in Figure 1B, by adopting equations (4, 7). An hypothetical time-lag $\tau_s = 5y$ is used [*Wigley*, 1988, Table 1]. The curves are plotted in such a way that their 1600–1900 average values coincide. Note the good correspondence of the patterns in particular during the pre-industrial era (1600–1900) and the significant discrepancy occurring in the 20th century with a clear surplus warming.

curves indicates that the sun might have contributed approximately 50% of the total global surface warming since 1900 [*Scafetta and West*, 2006]. Since 1975 global warming has occurred much faster than could be reasonably expected from the sun alone.

[15] Minor disagreements between the patterns can be due to possible imprecision in the proxy reconstructions of temperature and/or solar irradiance records and to indetermination of the time-lag, which is also frequency/amplitude dependent. For example, the temperature record peaks around 1950 while the solar temperature signature shown in Figure 2 peaks around 1960, however, by adopting a different TSI proxy reconstruction [e.g., *Hoyt and Schatten*, 1997], the two peaks would almost coincide. If the ACRIM TSI satellite composite [*Willson and Mordvinov*, 2003] better describes the historical TSI evolution since 1979, the solar contribution to the recent global warming would be further stressed if climate responds to smooth solar changes with a sensitivity as strong as $Z_S \approx 0.57$ K/Wm^{-2}, as deduced with Lean2005 TSI. The difference since 1975 might also decrease if part of the observed NH warming comes from spurious non-climatic contamination of the surface observations such as heat-island and land-use effects [*Pielke et al.*, 2002; *Kalnay and Cai*, 2003]. Some authors [*Christy and Norris*, 2006; *Douglass et al.*, 2004] suggest that the recent surface warming is overestimated because temperature reconstructions for the lower troposphere obtained with MSU satellites since 1978 present a significant lower warming than the surface record, but other authors would disagree [*Vinnikov et al.*, 2006]. In any case, it has been recently observed an anomalous warming behavior of the global average land temperature vs. the marine temperature since 1975 [*Brohan et al.*, 2006, Figure 12] that, perhaps, is partially due to contaminations of the land temperature record.

[16] The three TSI proxy reconstructions yield similar results. This highlights the fundamental difference between our phenomenological approach and a more traditional theoretical climate model approach. According to the latter the adoption of Lean2005 TSI reconstruction would yield a lower solar contribution to climate change compared to what would be obtained with the other two TSI reconstructions. Instead, our phenomenological approach assumes that the overall strength of the *direct plus indirect* solar effect on climate should be estimated by comparing the patterns in TSI (interpreted as a proxy of the total solar activity) and temperature data. In fact, independently of the TSI reconstructions, the alternating cooling and warming secular periods observed in the climate during the pre-industrial era should be considered induced by a solar variation (simply mimicked by the TSI variation) by means of climate mechanisms that might be still unknown and, therefore, not properly modeled yet. This is suggested by the sufficiently good pattern correspondence as observed in Figure 2 such as during the Maunder (1645–1715) and Dalton (1795–1825) minima. Thus, if it happens that a TSI proxy reconstruction with small secular variability such as Lean2005 better represents the historical TSI evolution, the logical conclusion would be that the climate secular feedback to TSI change and/or alternative solar effects on climate (such as UV and cosmic ray change effects) are much stronger than what would occur if other TSI reconstructions with larger secular variability would more faithfully represent the real TSI evolution.

[17] We also observe that the measured secular transfer climate sensitivities to solar change, Z_S, estimated with Lean1995 and Lean2000 TSI proxy reconstructions ($Z_S \approx 0.20$ K/Wm^{-2} and $Z_S \approx 0.23$ K/Wm^{-2}, respectively) are in agreement with the value $Z_{eq} \approx 0.21$ K/Wm^{-2} that we have predicted [*Scafetta and West*, 2006] as a possible upper limit for the secular global climate sensitivity to solar changes. Instead, the value $Z_S \approx 0.57$ K/Wm^{-2} obtained with Lean2005 suggests that climate is very sensitive to solar changes. However, although Lean2005 is the latest TSI reconstruction, it cannot be a-priori excluded that future development of solar physics would yield to new TSI proxy reconstructions that might present secular trends similar to those shown in the previous proposed reconstructions.

[18] In any case, as some authors have already noted [*Douglass and Clader*, 2002; *Scafetta and West*, 2005, 2006], solar change effects are greater than what can be explained by several climate models [*Stevens and North*, 1996; *Intergovernmental Panel on Climate Change*, 2001; *Hansen et al.*, 2002; *Foukal et al.*, 2004]. For example, *Douglass and Clader* [2002] and *Scafetta and West* [2005] found that the amplitude of the 11-year solar signature on the temperature record seems to be 3 times larger than the theoretical predictions, and similar or larger factors are likely to persist at lower frequencies as well.

[19] In conclusion, a solar change might significantly alter climate. It might trigger several climate feedbacks and alter the GHG (H_2O, CO_2, CH_4, etc.) concentration, as 420,000 years of Antarctic ice core data would also suggest [*Petit et al.*, 1999]. Most of the sun-climate coupling mechanisms are probably still unknown. However, they should be incorporated into the climate models to better understand the real impact of the sun on climate because they might strongly amplify the effects of small solar activity increases.

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