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Phenomenological reconstructions of the solar signature in the Northern Hemisphere surface temperature records since 1600

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[1] A phenomenological thermodynamic model is adopted to estimate the relative contribution of the solar-induced versus anthropogenic-added climate forcing during the industrial era. We compare different preindustrial temperature and solar data reconstruction scenarios since 1610. We argue that a realistic climate scenario is the one described by a large preindustrial secular variability (as the one shown by the paleoclimate temperature reconstruction by Moberg et al. (2005)) with the total solar irradiance experiencing low secular variability (as the one shown by Wang et al. (2005)). Under this scenario the Sun might have contributed up to approximately 50% (or more if ACRIM total solar irradiance satellite composite (Willson and Mordvinov, 2003) is implemented) of the observed global warming since 1900.

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1. Introduction

[2] In order to identify the causes of climate variability a number of secular reconstructions of global temperature, total solar irradiance (TSI) and climate models have been carried out. These reconstructions serve the purpose of identifying the natural vs. anthropogenic contribution of the observed global surface warming during the last century [*Intergovernmental Panel on Climate Change*, 2001, 2007]. However, although several papers have addressed this issue, the problem remains unsolved and controversial for several reasons.

[3] Global temperature [*North et al.*, 2006] and TSI reconstructions are still debated. For example, global temperature multiproxy secular reconstructions with both lesser [e.g., *Mann and Jones*, 2003] and greater [e.g., *Moberg et al.*, 2005] secular variability have been proposed. Similarly, there are TSI proxy reconstructions with lesser [*Wang et al.*, 2005] and greater [*Lean*, 2000] secular variability. The debate is not limited to proxy reconstructions alone, however. In fact, according to some authors surface warming of the last few decades may be partially due to spurious nonclimatic contamination of the surface observations by heat island and land use effects [*Pielke et al.*, 2002; *Kalnay and Cai*, 2003]. Other authors [*Douglass et al.*, 2004; *Christy and Norris*, 2006] claim the instrumental global surface warming [*Brohan et al.*, 2006] is overestimated because temperature reconstructions for the lower troposphere obtained with MSU satellites since 1978 present a significantly lower warming than the surface record, while others disagree [*Vinnikov et al.*, 2006]. Also the TSI satellite composites since 1978 are debated: the PMOD group [*Fröhlich and Lean*, 1998] claiming that during solar cycles 21–23 TSI did not significantly change on average, while the ACRIM group [*Willson and Mordvinov*, 2003] claiming that the average TSI value during solar cycle 22–23 was higher than during solar cycle 21–22.

[4] Theoretical climate models are also debated. In particular, it has been observed that the exact mechanisms by which solar activity might cause climate changes are not well understood [*Hoyt and Schatten*, 1997; *Pap and Fox*, 2004]. A traditional approach [e.g., *Intergovernmental Panel on Climate Change*, 2001, 2007; *Hansen et al.*, 2002; *Foukal et al.*, 2006; *Hegerl et al.*, 2003, 2006, 2007] makes use of models where a certain number of climate forcing and feedback mechanisms are presumed to operate. Evidently, one difficulty with this approach is that the feedback mechanisms and alternative solar effects on climate, since they are only partially known, might be poorly modeled or not included in the modeling at all [*Pap and Fox*, 2004]. Two examples from this latter category are: UV energy changes which are involved in production and loss of ozone that might in turn amplify stratospheric water vapor changes [*Stuber et al.*, 2001]; variations in the solar wind that might affect the heliosphere and modulate cosmic rays, which may in turn largely affect formation of clouds and influence the Earth's albedo [*Kristjánsson et al.*, 2004; *Svensmark*, 2007].

[5] In addition, because of the extreme difficulty of separately modeling the natural and anthropogenic green house gas (GHG) contributions to climate change, many climate models simplify the procedure by engineering a form of water vapor feedback mechanism and statically adding the measured increase of atmospheric CO_2 and CH_4 concentrations as one of the external climate forcings [*Hansen et al.*, 2002; *Hegerl et al.*, 2003, 2006, 2007]. This simplified approach presents a serious interpretative problem when variation of GHG concentrations are labeled

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anthropogenic forcing with the implicit assumption that they have had only an anthropogenic origin. Note the labeling adopted by the *Intergovernmental Panel on Climate Change* [2007, Figure 2.20 A] that infers that 100% of the observed increase of GHGs concentration since 1750 is anthropogenic.

[6] For example, *Hegerl et al.* [2003, 2007] evaluated amplitudes of scaling factors by which energy balance simulations of volcano, TSI and GHG+aerosol forcings need to be scaled to obtain the best agreement with a set of different paleoclimatic temperature reconstructions. These authors found relatively strong volcano and GHG+aerosol effects and a relatively weak solar contribution. If particular global temperature reconstructions are adopted the scaling factor for the solar signature has even been found to be negative! Evidently, a negative scaling factor for the solar contribution to climate change is unphysical on a large time and spatial scale because it would imply that climate cools when solar activity increases and warms when solar activity decreases. We believe that this unphysical scenario indicates that the errors in the adopted data are indeed too large and/or have peculiar statistical and nonlinear characteristics such that the implemented mathematical methodology, which is based on a multilinear regression analysis, gives unreliable results. Also, this mathematical methodology implicitly assumes that TSI and GHG are independent forcings, but this too is probably an unphysical assumption.

[7] In fact, 420,000 a of Antarctic ice core data [*Petit et al.*, 1999] have unmistakably established the existence of natural GHG (CO_2, CH_4, etc.) feedback mechanisms. These records show that interglacial epochs are characterized by very large oscillations in CO_2 and CH_4 concentrations with peak-to-peak amplitude of up to 30% of their average value. These (evidently non-anthropogenic-induced) GHG oscillations seem to be associated with the Milankovitch cycles [*Muller and MacDonald*, 1997] which are related to the changes in the Earth's orbit that slightly shape the solar input on the planet. A natural variability of GHG concentration is evident also in the ice core record during the last millennium where the CO_2 data show a 10 ppm decrease from the medieval solar maximum (1100–1200) to the Maunder solar minimum (1600–1750). The impression is that changes of solar input might trigger several kinds of GHG feedback (mostly atmosphere-ocean gas exchange [*Cox et al.*, 2000], vegetation cover and bacteria formation [*Brandefelt and Holmén*, 2001]) that might naturally alter the atmospheric GHG concentration. Because solar activity has significantly increased since the Maunder minimum (17th century) and in particular since 1900, we have to expect that the Sun might have partially contributed to the observed GHG increase during the last centuries, perhaps as large as 10–20% of the total increase. Evidently, this fraction of the measured GHG increase should be counted among the indirect solar effects on climate, and not among the anthropogenic ones.

[8] In summary, it is reasonable to believe that solar changes might directly and indirectly alter the climate in many different ways, and it should be acknowledged that most of the Sun-climate coupling mechanisms have still not been incorporated into the large-scale computational climate models. Consequently, these models are incapable of handling such a complex of coupled mechanisms and are not able to disentangle the indirect solar contributions to climate change from each of them and might easily underestimate the Sun-induced climate change by misidentifying the primary causes of various mechanisms.

[9] The importance of investigating novel approaches for studying climate change is justified by the results of phenomenological studies [*Eddy*, 1976; *Lassen and Friis-Christensen*, 1995; *Lean et al.*, 1995; *Crowley and Kim*, 1996; *Hoyt and Schatten*, 1997; *White et al.*, 1997, 2003] who have noted an apparent secular correlation between global surface temperature and TSI reconstructions. Solar change effects are found to be greater than what is assumed in several climate models [*Stevens and North*, 1996; *Hansen et al.*, 2002; *Foukal et al.*, 2004]. For example, *White et al.* [1997, 2003], *Douglass and Clader* [2002] and *Scafetta and West* [2005] found that the amplitude of the 11-a solar signature on the surface temperature record seems to be 3 times larger than some theoretical predictions [*Foukal et al.*, 2004, Figure 1b], and similar or larger factors are likely to persist at lower frequencies as well. The peak-to-trough amplitude of the response to the 11-a solar cycle globally is phenomenologically estimated to be approximately 0.1 K near the surface [see also *Intergovernmental Panel on Climate Change*, 2007, p. 674].

[10] We adopt a phenomenological thermodynamic model (PTM) for reconstructing the solar signature in 400 a of global surface temperature records. This approach attempts to evaluate the total direct plus indirect effect of solar changes on climate by comparing patterns in the temperature to those in TSI reconstructions, such as comparing the 0.1 K 11-a solar signature with the surface temperature. We stress that we do not use a TSI reconstruction as radiative forcing, but as a proxy for the entire solar dynamics. This 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 feedback to TSI variation and/or a stronger climate sensitivity to other solar changes (UV, cosmic rays, magnetic fields, etc.) in such a way as to reproduce the same observed temperature patterns.

[11] PTM recovers the frequency-amplitude-dependent effect of the climate sensitivity to solar changes [*Scafetta and West*, 2005, 2006a, 2006b, 2006c]. For example, according to an energy balance model simulation [*Wigley*, 1988, Table 1], the climate sensitivity to a 160-a period TSI oscillation might be 3–4 times stronger than the climate sensitivity to a 10-a period TSI oscillation, and that by reducing the amplitude of the forcing by one half the climate sensitivity might increase by from 40% (160-a) to 77% (10-a); compare also *Foukal et al.* [2004, Figures 1a and 1b], from which it can be deduced that the climate sensitivity to the smooth component of the secular TSI change might be 3 times the climate sensitivity to the 11-a solar cycle. The frequency dependence of climate sensitivity to solar changes has been confirmed by the analysis of empirical measurements [*White et al.*, 1997; *Scafetta and West*, 2005, 2006a] where 11-a and 22-a solar and temperature cycles were studied. PTM automatically recovers the frequency-amplitude-dependent time lags and better characterizes relaxation patterns whose nonlinear nature would be obscured by a adoption of the linear methodology

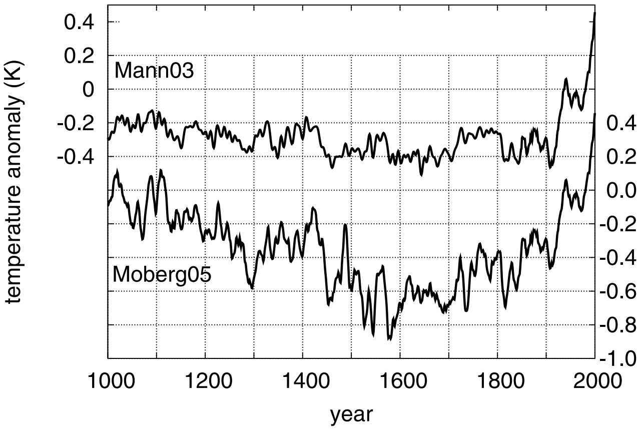

Figure 1. NH temperatures from 1000 to 2000 AD. Proxy reconstructions by *Mann and Jones* [2003] and by *Moberg et al.* [2005] from 1000 to 1849, and the NH instrumental surface temperature data since 1850 [*Brohan et al.*, 2006]. The proxy reconstructions are slightly adjusted in such a way that their 1850–1899 mean temperature values coincide with the instrumental mean.

underling the scale-by-scale transfer climate sensitivity model. The effect is mostly due to the thermal inertia of the ocean that makes the climate more responsive to slower than to faster solar variations such that thermodynamic equilibrium with forcing can be reached only after a few decades [*Meehl et al.*, 2005] with a time constant τ of several years [*Schwartz*, 2006, 2007].

[12] We proceed by briefly describing the Northern Hemisphere (NH) global temperature multiproxy climate and solar reconstructions and adopt a simple PTM. Finally, we discuss the results obtained. Our calculations also assume that the observed secular preindustrial warming before 1900 is induced by the contemporary solar activity increase. This approach assumes that forcing other than TSI during the preindustrial era play a minor role in climate change. We emphasize this point and discuss the possible limitations of our approach in the conclusion section, limitations whose severity, we argue, would depend on the particular temperature reconstruction adopted in the analysis.

2. Climate and Solar Data

[13] The temperature reconstruction by *Mann and Jones* [2003] is an update of a similar reconstruction [*Mann et al.*, 1998, 1999] and has been widely used in many studies. This reconstruction shows the so-called Hockey Stick pattern according to which the global warming occurring during the last century is unprecedentedly high compared to the temperature profile of the preceding centuries. The temperature anomaly (relative to the 1961–1990 mean) remains almost flat and constant within the interval $-0.4K \lessapprox T \lessapprox -0.2K$ from 1000 to 1900 AD (the "shaft"), and since 1900 it abruptly increases up to a value of $T \approx 0.5K$ during recent years (the "blade"). This pattern suggests that climate is relatively insensitive to variation of climate forcing during the preindustrial era, while almost all warming observed during the last century would be anomalous. This interpretation implies that the "blade" has been induced by anthropogenic added forcing produced as consequence of the industrialization since the middle of the 19th century.

[14] The reconstruction by *Moberg et al.* [2005] is obtained from low- and high-resolution multiproxy data. The methodological advantage of Moberg et al.'s wavelet-based approach over that of *Mann et al.* [1998, 1999] is that it uses each proxy type only at those timescales where it is most reliable. This temperature reconstruction presents a larger multicentennial variability and agrees well with temperatures reconstructed from borehole measurements [*Pollack and Smerdon*, 2004]. In particular, this temperature reconstruction presents a wide cyclical pattern with a medieval warm period (≈1000–1200 AD) at $T \approx 0K$ (compared to the 1961–1990 average temperature), a minimum of $T \approx -0.7K$ during the 16th century, a minimum of $T \approx -0.6K$ during the solar Maunder Minimum (1645–1715) and a minimum of $T \approx -0.5K$ during the solar Dalton Minimum (1795–1825). In recent years NH temperature reached a maximum of $T \approx 0.5K$. The wide pattern of this reconstruction might suggest that climate is very sensitive to variation of natural forcing and to solar forcing in particular because, as proven by cosmogenic nuclides record, the solar activity presented a similar pattern with maxima in the medieval and modern periods and minima in the 16–17th centuries and the first decades of the 19th century [*Eddy*, 1976; *Bard and Frank*, 2006].

[15] Figure 1 shows a 10-a moving average smoothing of the above two temperature proxy reconstructions covering the period from 1000 to 1849, and the NH instrumental surface temperature data since 1850 [*Brohan et al.*, 2006]. The temperature proxy reconstructions are slightly adjusted in such a way that their 1850–1900 mean temperature values coincide with that of the instrumental surface temperature data. We adopt these two combined temperature sequences in our following calculations and refer to them as MANN03 and MOBERG05.

[16] We adopt two alternative TSI proxy reconstructions since 1610 AD [*Lean*, 2000; *Wang et al.*, 2005], herein referred to as LEAN2000 and WANG2005, respectively;

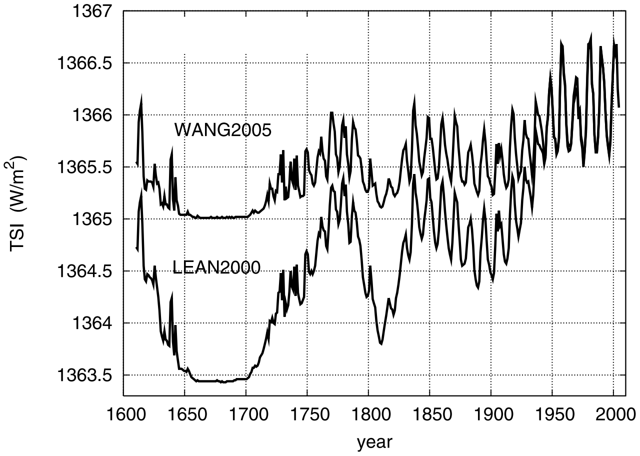

Figure 2. TSI proxy reconstructions that herein we adopt [*Lean*, 2000; *Wang et al.*, 2005]. Note that their patterns are quite similar but with significant differences in the amplitude of the secular trend. Note the lower solar activity periods occurring during the Maunder Minimum (1645–1715) and during the Dalton Minimum (1795–1825).

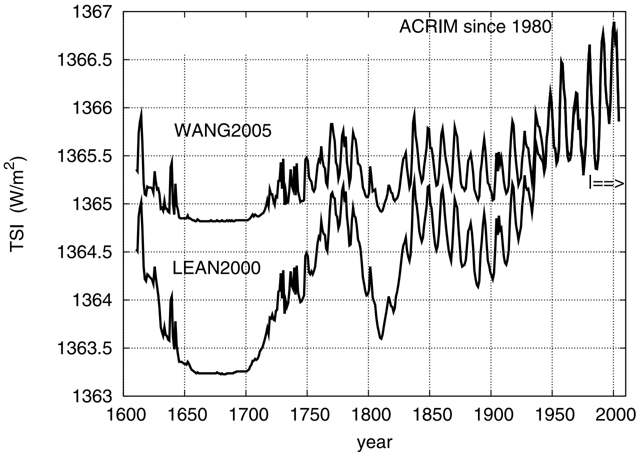

Figure 3. Two secular TSI reconstructions obtained by merging ACRIM composite (since 1980) with LEAN2000 and WANG2005, respectively. The merging has been done by adjusting LEAN2000 and WANG2005 in such a way that their average TSI value during solar cycle 21–22 (1980–1991) coincides with the ACRIM average during the same period. According to ACRIM the average TSI value during solar cycle 22–23 (1991–2002) was higher than during solar cycle 21–22 (1980–1991) by $\Delta I \approx 0.45$ *W*/*m*^{2} [*Scafetta and West*, 2005].

see Figure 2. These TSI reconstructions look similar in the trends but present different secular amplitudes due to some differences in the theoretical solar models adopted in those studies. Since 1950 the two sequences are equivalent. Both reconstructions show that TSI has increased since the 17th century (perhaps, solar activity during the past 70 a has been exceptionally high [*Solanki et al.*, 2004]) suggesting that the Sun might have contributed to the warming since the 17th century minimum.

[17] Since 1978 TSI data from satellites are available. However, there are two composites: the PMOD [*Fröhlich and Lean*, 1998] and the ACRIM [*Willson and Mordvinov*, 2003]. Herein, we do not discuss the controversy between ACRIM and PMOD, but simply recall that ACRIM is obtained by simply composing the published satellite data while PMOD assumes that Nimbus7/ERB satellite data covering the ACRIM gap (1989–1992) are still significantly corrupted and require additional severe adjustments that, once made, induce a step-like difference pattern between PMOD and ACRIM composites. The PMOD pattern, which is recovered by the above two TSI proxy reconstructions, shows that the average TSI value during solar cycle 21–22 (1980–1991) is approximately equal to the average TSI value during solar cycle 22–23 (1991–2002). Instead, ACRIM composite shows that the average TSI value during solar cycle 22–23 was higher than during solar cycle 21–22 in average by step increase of $\Delta I \approx 0.45$ W/m^2 [*Scafetta and West*, 2005]. The ACRIM specific pattern suggests that TSI is sensitive to a 22-a modulation associated with the Hale magnetic solar cycle [*Lee et al.*, 1995; *Scafetta and West*, 2005]. Figure 3 shows two secular TSI reconstructions obtained by merging ACRIM composite with LEAN2000 and WANG2005, respectively, since 1980. The merging has been done by adjusting LEAN2000 and WANG2005 in such a way that their average TSI value during solar cycle 21–22 (1980–1991) coincides with the ACRIM average during the same period.

3. Phenomenological Thermodynamic Model

[18] PTM assumes that the climate system, to the lowest-order approximation, responds to an external radiative forcing as a simple thermodynamical system, which is characterized by a given relaxation time response τ. This should be a valid approximation for small variation of the input forcing. The model depends on only two parameters: the relaxation time τ and a factor α that has the purpose of phenomenologically transforming the irradiance units, *W*/*m*^{2}, into temperature units, *K*. The physical meaning is that a small anomaly (with respect to the TSI average value) of the solar input, measured by ΔI, forces the climate to reach a new thermodynamic equilibrium at the asymptotic temperature value $\alpha\Delta I$ (with respect to a given temperature average value). Thus, if $\Delta I(t)$ is a small variation (with respect to a fixed average) of an external forcing and $\Delta T_s(t)$ is the Earth's average temperature anomaly induced by $\Delta I(t)$, $\Delta T_s(t)$ evolves in time as:

$$\frac{d\Delta T_s(t)}{dt} = \frac{\alpha\Delta I(t) - \Delta T_s(t)}{\tau}. \tag{1}$$

A model equivalent to (1) has been used as a basic energy balance model [*North et al.*, 1981; *Douglass and Knox*, 2005], but herein we use TSI records as a proxy forcing, not as a true radiative forcing as we have explained in the Introduction.

[19] Figure 4 highlights the phenomenological properties of the model. For simplicity, in these examples we assume $\alpha = 1$ and $\tau = 10$. Figure 4a shows the response function $\Delta T(t)$ (thick lines) to two oscillating forcing functions $\Delta I(t)$ (thin lines) with equal amplitudes and different periods. Figure 4a clearly shows that for the signal with larger period (1) the relative response of the system is stronger, that is, $\Delta T(t)$ presents larger amplitudes, and (2) the response is more delayed with respect to the forcing, that is, the time lag is larger. We observe that both properties are expected for the climate system where it has been found that the climate sensitivity and the time lags to a forcing decrease with the frequency of the forcing because of the damping effect of the ocean and atmosphere thermal inertia [*Wigley*, 1988; *Scafetta and West*, 2005, 2006a, 2006b, 2006c].

[20] Figure 4b shows another property of the model. In this case the forcing $\Delta I(t)$ (upper curve) is constituted by a oscillating signal (thin lines) plus a trend (thick lines) which is upward from $t = 0$ to $t = 50$, and after $t = 50$ the trend is rigorously zero. The response $\Delta T(t)$ (bottom curve) shows a more complex shape. In fact, $\Delta T(t)$ increases not only during the period from $t = 0$ to $t = 50$, but continues to increase also for $t > 50$ despite the fact that $F(t)$ oscillates around a constant value during such a period. In this simulation, approximately 20% of the overall increase of $\Delta T(t)$ occurs during the period $t > 50$. (In Figure 4b the thin line is the response to the thin line shown in the upper curve and the thick line is the response to the thick line shown in the upper curve.)

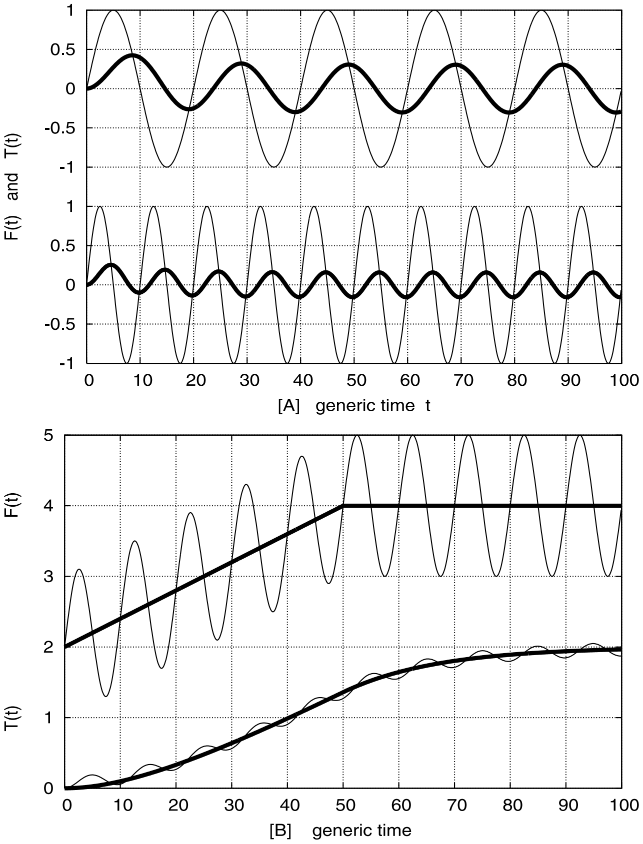

Figure 4. General properties of the phenomenological radiative relaxation model. (a) Both amplitude and time lag of the response are frequency-dependent, and are larger for larger period; the relaxation time in this simulation is $\tau = 10$. (Thin lines are the forcing and the thick lines the response.) (b) Delayed response. If the forcing (top curves) increases from $t = 0$ to $t = 50$ and remains constant after that, the response (bottom lines) shows that approximately 20% of the overall warming of the system occurs during the period $t > 50$ despite the fact that the forcing $F(t)$ is constant during such a period.

[21] This latter property of the model is important because the forcing in Figure 4b schematically simulates the TSI shape since 1900 AD, as Figure 2 shows. *Hansen et al.* [2002] have observed that since 1950 the solar activity has been almost constant according to LEAN2000, therefore the forcing from the Sun during this period was set $\Delta F_{1950-2000} = 0$ [*Hansen et al.*, 2002, Figure 18b]. The implication was that the Sun did not contributed to global warming since 1950. Figure 4b shows that such a claim would be not justified because, as Figure 2 shows, TSI during the second half of the century has been higher than during the first half, as schematically reproduced in Figure 4b. Climate is expected to respond to a forcing as equation (1) describes with a relaxation time τ of the order of several years. Thus the specific TSI shape throughout the 20th century would imply that the Sun might have induced a significant warming not only during the first half of the century, but also during the second half because of the response time of the Earth, as already suggested by *Scafetta and West* [2006a] and implicit in the simulations of *Meehl et al.* [2005]. This delayed response would happen despite the fact that since 1950 TSI has been approximately constant according to LEAN2000 or WANG2005. Figure 4b suggests that the exact solar contribution to the 1950–2000 surface warming increases monotonically with the magnitude of the climate relaxation time response τ.

4. Climate Models and Data Analysis

[22] The two parameters of equation (1) are phenomenologically estimated using two independent constraints. The first constraint is based on the fact that several authors, by using alternative methods of analysis, have identified significant atmospheric climate changes associated with the 11-a solar cycle [*White et al.*, 1997, 2003; *van Loon and Shea*, 2000; *Douglass and Clader*, 2002; *Gleisner and Thejll*, 2003; *Haigh*, 2003; *Coughlin and Tung*, 2004; *Labitzke*, 2004; *Crooks and Gray*, 2005; *Scafetta and West*, 2005]. The peak-to-trough amplitude of the response to the solar cycle globally is estimated, at least since 1980, to be

$$A_{11y} \approx 0.1 \pm 0.01K \tag{2}$$

near the surface. Thus we evaluate the 11-a cycle amplitudes of the curve $T(t)$ by using an algorithm similar to that adopted by *Scafetta and West* [2005]. We use the same wavelet filter to isolate the detail curve with the 11-a cycles $D_{11y}(t)$, and calculate the amplitude as $A_{11y} = 2\sqrt{2}\sigma$, where

$$\sigma^2 = \frac{1}{22}\int_{1980}^{2002} \left[D_{11y}(t)\right]^2 dt, \tag{3}$$

and, finally, impose that this value of A_{11y} is given by (2).

[23] The second independent constraint reflects the hypothesis that the secular TSI increase during the preindustrial era is responsible for the contemporary observed increase of global surface temperature. (In the Conclusion we discuss the limitation of this assumption.) For this purpose, first we estimate the average values of the temperature that occurred during the 17th, 18th and 19th centuries (more precisely we evaluate the averages during the periods 1610–1710, 1710–1810, 1810–1910 because the solar data starts in 1610) and then the preindustrial warming is estimated as the average between the differences of the 18th–17th and the 19th–17th century averages. Using MANN03, we calculate $T_{17} = -0.404 \pm 0.003\ K$, $T_{18} = -0.274 \pm 0.004\ K$ and $T_{19} = -0.352 \pm 0.012\ K$, thus we find the preindustrial temperature change to be:

$$T_{MANN03} = \frac{(T_{18} - T_{17}) + (T_{19} - T_{17})}{2} = 0.09 \pm 0.013\,K; \tag{4}$$

and using MOBERG05, we calculate $T_{17} = -0.628 \pm 0.013\ K$, $T_{18} = -0.468 \pm 0.015\ K$ and $T_{19} = -0.415 \pm 0.019\ K$, thus we find the preindustrial temperature change to be:

$$T_{MOBERG05} = \frac{(T_{18} - T_{17}) + (T_{19} - T_{17})}{2} = 0.186 \pm 0.02\,K. \tag{5}$$

[24] By using the two TSI proxy reconstructions shown in Figure 2 in the PTM and imposing the above two constraints

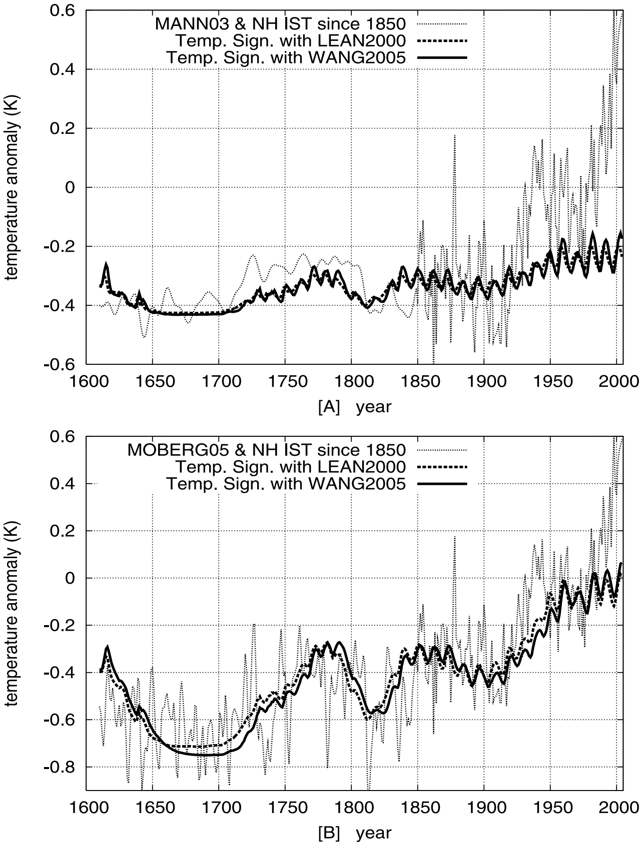

Figure 5. Solar induced temperature signatures obtained with the TSI proxy reconstructions shown in Figure 2 against the NH temperature records. (a) Signatures phenomenologically estimated with MANN03 temperature reconstruction and (b) signatures phenomenologically estimated with MOBERG05 temperature reconstruction. In both cases, we plot the NH instrumental surface temperature since 1850, as done in Figure 1. Note the good correspondence obtained with MOBERG05.

to the evaluated $\Delta T_s(t)$ signal, we numerically determine the parameters α and τ and plot the corresponding temperature signatures associated with the two TSI proxy reconstructions in Figure 5 against MANN03 and MOBERG05. Using MANN03 and the following reconstructions, we found the following parameter values:

LEAN2000 $\alpha = 0.10 \pm 0.04\ \mathrm{K/Wm^{-2}}$,
LEAN2000 $\tau \overset{<}{\approx} 0 \pm 0.9$ a;

WANG2005 $\alpha = 0.28 \pm 0.12\ \mathrm{K/Wm^{-2}}$,
WANG2005 $\tau = 3.5 \pm 1.4$ a.

Using MOBERG05 and the following reconstructions, we found the following parameter values:

LEAN2000 $\alpha = 0.23 \pm 0.11\ \mathrm{K/Wm^{-2}}$,
LEAN2000 $\tau = 2.7 \pm 1.6$ a;

WANG2005 $\alpha = 0.65 \pm 0.28\ \mathrm{K/Wm^{-2}}$,
WANG2005 $\tau = 9 \pm 3.25$ a.

[25] Similarly, Figure 6 shows the temperature signatures obtained with the two TSI reconstructions corrected with ACRIM (Figure 3) against MANN03 and MOBERG05.

5. Discussion

[26] As Figure 5a shows that climate is relatively insensitive to solar variation if we adopt MANN03, which shows a minimal secular variability during the preindustrial era. From the 17th century minimum to the beginning of the 20th century the NH climate warmed by about 0.1*K*, while from 1900 to 2005 the NH climate warmed by about $\Delta T = 0.8K$ and by about $\Delta T = 0.6K$ since 1950. In this calculation the increased solar activity contributed approximately 0.1*K* during the preindustrial (1600–1900) era and 0.17*K* during the postindustrial (1900–2005) era. Thus the Sun could have contributed approximately 1.7/8 = 21% of the global

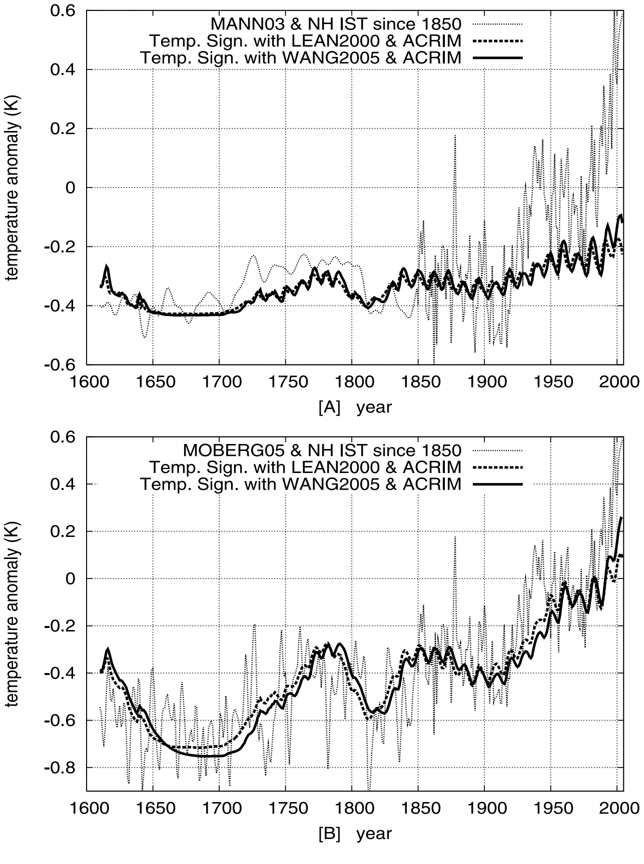

Figure 6. Solar induced temperature signatures obtained with the TSI proxy reconstructions with the ACRIM correction since 1980, as shown in Figure 3. (a) Signatures phenomenologically estimated with MANN03 temperature reconstruction and (b) signatures phenomenologically estimated with MOBERG05 temperature reconstruction. In both cases, we plot the NH instrumental surface temperature since 1850, as done in Figure 1. Note the good correspondence obtained with MOBERG05.

NH surface warming that occurred from 1900 to 2005 (this estimate might present a 20% error). These data would support the conclusion that since 1950 the Sun does not seem to have contributed significantly to the global warming (approximately $0.03K$). This result is essentially consistent with the findings reported by *Intergovernmental Panel on Climate Change* [2001] and *Hansen et al.* [2002] suggesting that almost all warming since 1950 had an anthropogenic origin.

[27] On the other hand, as Figure 5b shows, if we adopt MOBERG05, which shows a larger secular variability during the preindustrial era, the climate is found to be quite sensitive to solar variation. As deduced from Figure 5b, MOBERG05 shows that from the 17th century minimum to 1900 AD the NH warmed by about $0.4K$. The Sun might have contributed at most $\approx 0.35K$ during the preindustrial era (1600–1900) and ≈ 0.4 K from 1900 to 2005. Thus the Sun could have contributed roughly 4/8 = 50% of the global NH surface warming that occurred from 1900 to 2005. Since 1950 the Sun might have contributed $\approx 0.05K$ (0.5/6 = 8% of the warming) using LEAN2000, or $\approx 0.15K$ (1.5/6 = 25% of the warming) using WANG2005. Again these estimates might present an 20% error.

[28] Using MOBERG05 the climate is seen to be very sensitive to solar variation and the relaxation time response of the climate to solar variation τ is of the order of approximately 10 a with WANG05. Although TSI reconstructions shown in Figure 2 do not present a significant increase since 1950, the climate nevertheless has a solar induced warming because of the thermodynamic equilibrium delayed effect with the TSI increase that occurred from 1900 to 1950. This property, which is shown also in the simulation of Figure 4b, stresses the importance of adopting a simple PTM that takes into account the relaxation time response of the system and long time series of data.

[29] The thermal inertia of the ocean with a time response of the order of several years is an expected physical phenomenon [*Manabe et al.*, 1990; *Meehl et al.*, 2005; *Schwartz*, 2006, 2007]. However, by adopting MANN03 and LEAN2000 we find an almost zero relaxation time response. Such a small response time is not physically reasonable and suggests that the amplitude of the 11-a solar signature on climate is significantly smaller than the phenomenological measured value $A_{11y} \approx 0.1 \pm 0.01K$, or at least that one of the two reconstructions, MANN03 or LEAN2000, is erroneously estimated. On the contrary, if the latest, and perhaps more accurate temperature and TSI reconstructions MOBERG05 and WANG2005 are correct, our PTM suggests that climate presents a strong ocean thermal inertia, which drives the global surface climate as well, with a relaxation time response of approximately 6–12 a which seems to be more physical: with an independent methodology, *Schwartz* [2006, 2007] estimated that τ should be no less than 5 ± 1 a and as great as 16 ± 1 a.

[30] The parameter α is a measure of the phenomenological climate sensitivity to solar changes herein indicated by the TSI records used as a proxy of the solar activity. As expected, climate is more sensitive to solar changes by adopting a TSI reconstruction with lesser secular variability such as WANG2005 than a TSI reconstruction with larger secular variability such as LEAN2000. This finding highlights a fundamental difference between our phenomenological approach and the more traditional large-scale computer climate model approach. According to the latter [*Foukal et al.*, 2004] the adoption of WANG2005 TSI reconstruction would yield a lower solar contribution to climate change compared to what would be obtained with the LEAN2000 TSI reconstruction. Instead, our phenomenological approach assumes that the TSI reconstructions are used as a proxy for the overall direct plus indirect solar effects on climate. The phenomenological sensitivity is estimated by comparing the patterns in solar temperature signature and temperature data with the latter patterns remaining unaltered despite the former ones. Thus, if it happens that a TSI proxy reconstruction with small secular variability such as WANG2005 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, and the parameter α would be larger, than what would occur if other TSI reconstructions with larger secular variability would more faithfully represent the real TSI evolution.

[31] Figure 6 shows the comparison between the two NH temperature reconstructions shown in Figure 1 and the phenomenological solar temperature signatures obtained with the TSI proxy reconstructions corrected with the ACRIM TSI satellite composite since 1980, as shown in Figure 3. By assuming ACRIM, the solar activity has an increasing trend during the second half of the 20th century. By assuming MANN03, the Sun is responsible for approximately 0.18 K (or 22%) with LEAN2000 and $\approx 0.23K$ (or 29%) with WANG2005 of the warming occurring from 1900 to 2005, and $\approx 0.05K$ (or 8%) with LEAN2000 and $\approx 0.15K$ (or $\approx 25\%$) with WANG2005 of the warming occurring since 1950. By assuming MOBERG05, the Sun is responsible for $\approx 0.45K$ (or 56%) with LEAN2000 and $\approx 0.55K$ (or $\approx 69\%$) with WANG2005 of the warming that occurred from 1900 to 2005, and $\approx 0.15K$ (or 20%) with LEAN2000 and $\Delta T \approx 0.25K$ (or 42%) with WANG2005 of the warming that occurred since 1950. (The estimates might present an error of about 20%.)

[32] The large solar contribution to the warming found by adopting MOBERG05 and WANG2005 with ACRIM since 1980 is due to both the large climate sensitivity to solar variation found in this case and to the slow system response to solar changes, as indicated by the large relaxation time in this case.

[33] Finally, we calculate the cross correlation between MANN03 and MOBERG05 and the solar temperature signals shown in Figures 5 and 6 gives: for the period 1610–2005 $r \approx 0.76$ for MANN03, and $r \approx 0.87$ for MOBERG05; for the preindustrial period 1610–1900 $r \approx 0.45$ for MANN03, and $r \approx 0.70$ for MOBERG05. Thus the solar-induced temperature signals are consistently better correlated with MOBERG05 than with MANN03. Note that the above conclusion is evidently suggested by the good pattern correspondence observed in Figures 5b and 6b between MOBERG05 and the PTM solar signatures covering all four centuries. The pattern correspondence include those during the Maunder (1645–1715) and Dalton (1795–1825) minima, the cooling between 1860 to 1910, the warming from 1910 to 1950–1960, the cooling afterward until 1975 and the warming since 1975. If ACRIM is

adopted the pattern correspondence since 1980 is further stressed.

6. Conclusion

[34] Climate is relatively insensitive to solar changes if a temperature reconstruction showing little preindustrial variability is adopted. In this scenario most of the global warming since 1900 has to be interpreted as anthropogenically induced. On the other hand, if a secular temperature showing large preindustrial variability is adopted, such as MOBERG05, the climate is found to be very sensitive to solar changes and a significant fraction of the global warming that occurred during last century should be solar induced. If ACRIM satellite composite is adopted the Sun might have further contributed to the recent global warming.

[35] We have argued that MANN03 and LEAN2000 cannot both be correct because they would imply that climate responds almost instantaneously to solar changes. This almost instantaneous response would be unphysical because of the expected existence of a significant thermal inertia induced by the oceans, which would imply a relaxation time τ of the order of several years. We observe that *Mann et al.*'s [1998, 1999] methodology to obtain secular proxy temperature reconstruction [1998, 1999] has been recently criticized by *McIntyre and McKitrick* [2005], see also *von Storch et al.* [2004] and *Wegman et al.* [2006] who have found larger preindustrial temperature variability. Alternatively, MOBERG05 and WANG2005 seems to be more thermodynamically compatible and using these data better pattern correspondence is found during the four centuries since 1600.

[36] Note that minor disagreements between the patterns can be due to possible imprecision in the proxy reconstructions of temperature and/or solar irradiance records. 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, for example *Hoyt and Schatten* [1997], the two peaks would almost coincide.

[37] Our thermodynamic approach assumes that the solar forcing plays the major role in the secular climate change during the preindustrial era. This might be a severe limitation because other effects might be present as well.

[38] Our argument assumes that during the preindustrial era the anthropogenic forcing is negligible compared to natural ones. We believe this is an important topic of discussion because our assumption does not exclude, in principle, the existence of a direct human contribution to past climate change, as *Ruddiman* [2003] suggests. In fact, it should be considered that humans too are part of the climate system and their activity might indeed be effected by climate changes. Thus there might exist a kind of anthropogenic positive feedback to climate change. For example, periods of warmer Sun might favor the rise of large civilizations that once organized might produce more CO_2 via deforestation and agricultural activity, and this would make the climate even warmer (the Roman empire, for example, reached its maximum during the solar maximum of the first century and Vikings inhabited Greenland during the solar medieval maximum). On the contrary, a decrease of solar activity might induce a climate cooling causing periods of severe drought that might cause a civilization to suffer famine and plague and ultimately to collapse with the abandonment of agricultural activity. This collapse would favor a reforestation that would yield to the absorbtion of CO_2 from the atmosphere and a further cooling of the climate (for example, the Maya empire collapsed because of a sequence of droughts occurred probably because of a solar change during the 8th and 9 centuries [*Hodell et al.*, 2001]). These effects, although anthropogenic in nature, may be interpreted indeed as a special kind of climate feedback to solar change. Authentic anthropogenic forcing should be the one that results from human activity that occurs despite the change of natural climate forcing, not the one that occurs because of it. Thus anthropogenic forcing might be significant during the modern age when technology overcomes nature. The issue is in any case debatable [*Ruddiman*, 2003]; *Myhre et al.*, 2005]. In any case, we suggest that variation of GHG concentrations that occured before the Industrialization should be considered as produced by natural and anthropogenic feedback mechanisms and, therefore, excluded from the set of climate forcings.

[39] In addition to solar forcing only volcano activity might have played a significant role in climate change on a global scale during the preindustrial era. However, volcano forcing is very uncertain [*Hegerl et al.*, 2006, 2007] and might be overestimated [*Douglass and Knox*, 2005]. *Fischer et al.* [2007] suggest that volcano forcing might have a significant impact on climate (cooler summers and warmer winters) but only on a time scale of a few years. Some climate model studies [*Shindell et al.*, 2003] have reported that on a secular scale the volcano forcing had the same order of magnitude as solar forcing, other studies would present a wide range of relative contributions.

[40] Therefore our estimates about the solar effect on climate might be overestimated and should be considered as an upper limit. However, the relative error should be much larger with MANN03 than with MOBERG05. In fact, it is very unlikely that current models are significantly underestimating the volcano effect on climate by a factor of two or three because the peculiar spike-like shape of the volcano forcings would make it easy to discover a significant model underestimation of the volcano effects. Thus, if a larger secular temperature variations is found, such as in MOBERG05, the wider pattern has to be explained by assuming a stronger solar effect on climate and our assumption that the Sun is the major cause of the preindustrial secular climate change would be less imprecise (for example an error of 50% with MANN03 would be equivalent to an error of less than 25% with MOBERG05).

[41] Also, a reduced solar activity on climate would imply, according to our PTM, a reduction of the relaxation time constant τ. This time constant τ cannot be too smaller than what we estimated because the ocean requires several decades for reaching a thermodynamic equilibrium with a change in the forcing. We also observe that a recent independent study [*Schwartz*, 2006, 2007] confirms the existence of a climate time constant of $4 < \tau < 17$ a that is consistent with our estimate using MOBERG05 and WANG2005 ($6 < \tau < 12$).

[42] In conclusion, if we assume that the latest temperature and TSI secular reconstructions, WANG2005 and

MOBERG05, are accurate, we are forced to conclude that solar changes significantly alter climate, and that the climate system responds relatively slowly to such changes with a time constant between 6 and 12 a. This would suggest that the large-scale computer models of climate could be significantly improved by adding additional Sun-climate coupling mechanisms.

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