SUPPLEMENTARY MATERIAL

Climate Change Attribution Using Empirical Decomposition of Climatic Data

Craig Loehle[1] and Nicola Scafetta[*,2]

[1]*National Council for Air and Stream Improvement, Inc., 552 S Washington Street, Suite 224, Naperville, Illinois 60540, USA*

[2]*Active Cavity Radiometer Irradiance Monitor (ACRIM) & Duke University, Durham, North Carolina 27708, USA*

A) A STATISTICAL TEST OF THE DETERMINATION OF A ~60-YEAR CYCLE IN A SHORT RECORD

It can be argued that estimation of periodic signals in climate data requires either spectral methods or very long time series, or both. For obtaining a very precise estimate of signal properties this may be true, but for estimating periodicity to within plus or minus a few years, this is not true. To illustrate, we replicate the procedure used in the main manuscript. We take the model from Fig. (**1**) as the target. A sample set is obtained by randomly adding white noise to this model with variance derived from Fig. (**1b**, (sd = 0.13°C). The new model is estimated for the period 1850 to 1950 and then extrapolated to 2009 (see Fig. Suppl **1**). Repeating this 1000 times, the mean estimated period is 64.11 yr *vs* 64.93 for the target, with sd = 2.63 yr. Thus, clearly the proposed estimation method works sufficiently well even on a 100 yr calibration period.

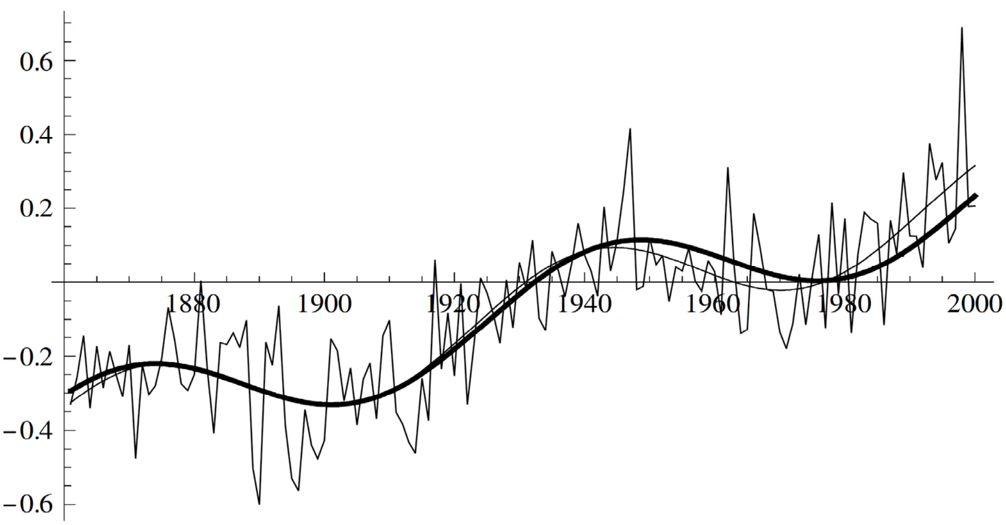

Fig. Suppl (1). Example of model estimation. Thin line is target cycle. Jagged line is target with sample white noise added. Thick line is model fit to randomized data up through 1950 and then extrapolated over the post-1950 period.

B) DISCUSSION OF SOLAR PROXY AND SATELLITE COMPOSITE MODELS

The first direct measurements of TSI were possible in 1978, the year the first satellite experiment measuring TSI started. However, the contiguous 30 year TSI database of satellite observations from late 1978 to the present has to be constructed because no satellite record covers the entire period. Two major groups using TSI satellite measurements have proposed alternative composites. The ACRIM composite (Willson and Mordvinov [1]) shows an upward trend during the period 1980-2002, while the PMOD composite ([Fröhlich and Lean [2]; Fröhlich [3]) shows an almost constant trend during the same period. This paper is not the place for a detailed discussion of the relative merits of the PMOD and ACRIM composites; such comparisons have been made elsewhere (e.g., Scafetta and Willson [4]). Only proxy models can be used for the period prior to 1978. These models adopt ground observables that can reasonably be related to solar activity. Some of the records used are sunspot number, solar rotation, the width of a few spectral lines (10.7 cm radio flux, CaII index, MgII index, HeI index, and a few others), a few magnetic indices, and the radioisotopes ^{14}C and ^{10}Be that are also used as proxies for solar activity (Pap and Fox [5]). All these indexes can give only a very partial representation of the variability of solar activity. In our empirical treatment, we view TSI as just a proxy for all solar components that contribute forcing to the earth system, which include all frequencies of the spectrum (visible light, UV, IR, radio), cosmic ray modulation effects and other possible solar induced effects not well identified yet.

Depending on which proxies one chooses and how one uses them, different TSI proxy models emerge. For example, the TSI proxy models suggested by Lean and colleagues (Lean *et al.* [6]; Lean [7]; Wang *et al.* [8]) are very different from each other and differ significantly from the TSI proxy models proposed by other authors (Hoyt and Schatten [9]; Krivova *et al.* [10]). In addition, a TSI model based on solar cycle length has been also proposed (Friis-Christensen and Lassen [11]; Thejll and Lassen [12]).

Although these proxy models look vaguely similar to each other (e.g., all of them show a minimum during the Maunder (1650-1715) and Dalton (1790-1830) Minima and a maximum during the last decades), the detailed patterns differ considerably. Fig. (**2**) compares three independent TSI reconstructions: Wang *et al.* [8] (red); Hoyt and Schatten [9] (blue); and our revision of a TSI proxy model proposed by Thejll and Lassen [12] (green).

The model proposed by Wang *et al.* [8] (red) shows a slight decrease from 1850 to 1910, an increase from 1910 to 1960, a slight decrease followed by a slight increase from 1960 to 1980, and a constant behavior from 1980 to 2000, which is compatible with PMOD.

The model proposed by Hoyt and Schatten [9] (blue) presents a constant behavior from 1850 to 1880, a decrease from 1880 to 1890, an increase from 1890 to 1940/45, a decrease from 1940/45 to 1970, and an increase from 1970 to 2000, which is compatible with ACRIM. Note that herein we are interested in this pattern structure of increasing and decreasing TSI trends, more than the actual absolute amplitude of the signal, that is an independent issue.

The TSI proxy model (green) is a revision of the proposed model by Thejll and Lassen [12] based on solar cycle length. The physical meaning of this model is that when the solar cycle is longer the sun is quieter because the solar dynamo is running slower, so its irradiance output is lower.

Our revision of the solar cycle length model is made as follows:

1. We used the same solar cycle length published in Thejll and Lassen [12] but correct the last cycle length (originally predicted to cover the period from 1996.8 to 2007.3) to the observed period from 1996.8 to 2009.
2. We applied a type 1-2 smoothing algorithm to extract the trend; that is, we use the algorithm $S_i = (A_{i-1} + 2A_i)/3$ (see Table **1**). This is different from what was suggested by Thejll and Lassen [12], a centered smoothing of the type 1-2-1 and 1-2-2-2-1. There are two reasons for our choice: (a) the algorithm proposed by Thejll and Lassen [12] may not be physical because they assume that the present behavior of the sun may be conditioned by future cycles; and (b) our choice of a smoothing of type 1-2 takes into account that a solar trend may be part of two consecutive 11 year solar cycles that are known to be linked by the 22 year Hale magnetic solar cycle. Moreover, it is assumed that one 11-year solar cycle feels a memory from the previous cycle as all physical complex systems tend to do. Note that this way of doing the calculation avoids the shortcomings of the original records published by Friis-Christensen and Lassen [11] and updated by Thejll and Lassen [12] due to end point issues for which those papers have been criticized.
3. The 1-2 smoothed solar cycle length was transformed into a smooth curve with an annual resolution with an interpolation cspline algorithm.
4. The curve was inverted because short cycles would imply higher TSI. Because the inverted curve presents an increase from 1980 to 2000 that matches the ACRIM record, we calibrate the model to reproduce the ACRIM trend increase from 1980 to 2000.
5. The 11-year modulation extracted from Wang *et al.* [8] was added to the 1-2 smoothed solar cycle length.

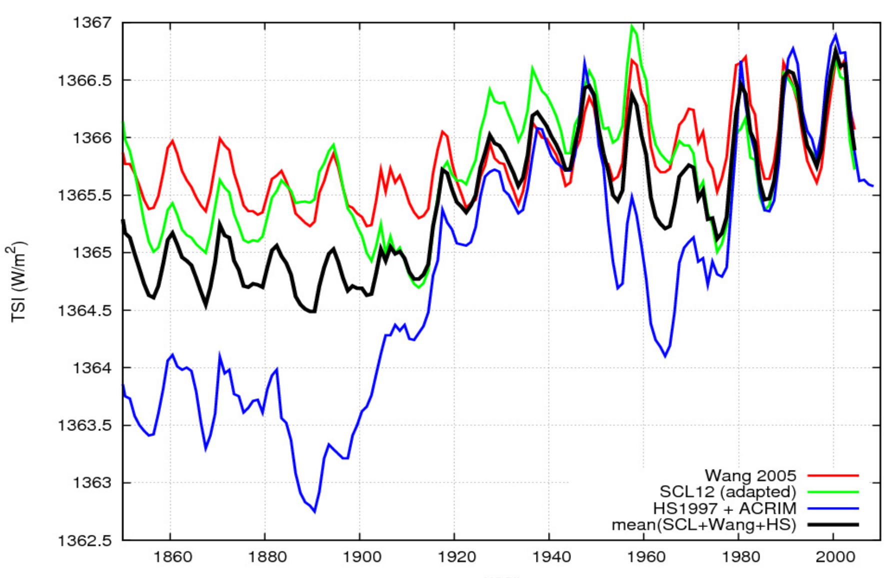

Fig. Suppl (2). Three independently constructed TSI proxy models. Wang *et al.* [8] (red); Hoyt and Schatten [9] (blue) recalibrated at ACRIM level; and a revision of a TSI proxy model proposed by Thejll and Lassen [12] (green) based on a 1-2 smooth solar cycle length. The black curve is the average among the three models.

Table 1. Corrected Smoothed Solar Cycle Data Based on Thejll and Lassen [12]. [a] Cycle Number and Year of Solar Minima at the End of the Cycle from Thejll and Lassen [12]; Last Value Corrected to 2009. [b] Solar Cycle Length; [c] Solar Cycle Trend According to 1-2 Role Smooth

Solar Min Year[a]	SCL[b]	1-2 SCL[c]
00 – 1755.2	11.2	
01 – 1766.5	11.3	11.27
02 – 1775.5	9	9.77
03 – 1784.7	9.2	9.13
04 – 1798.3	13.6	12.13
05 – 1810.6	12.3	12.73
06 – 1823.3	12.7	12.57
07 – 1833.9	10.6	11.3
08 – 1843.5	9.6	9.93
09 – 1856.0	12.5	11.53
10 – 1867.2	11.2	11.63
11 – 1878.9	11.7	11.53
12 – 1889.6	10.7	11.03
13 – 1901.7	12.1	11.63
14 – 1913.6	11.9	11.97
15 – 1923.6	10	10.63
16 – 1933.8	10.2	10.13
17 – 1944.2	10.4	10.33
18 – 1954.2	10	10.13
19 – 1964.9	10.7	10.47
20 – 1976.5	11.6	11.3
21 – 1986.8	10.3	10.73
22 – 1996.8	10	10.1
23 – 2009.0	12.2	11.47

C) AN EMPIRICAL CLIMATE MODEL WITH SHORT AND LONG CHARACTERISTIC TIME RESPONSES

Herein we briefly summarize, for the convenience of the reader, the empirical model used by Scafetta [13] for reconstructing the solar signature on climate, which has been used to produce Fig. (**6**) in the main report. The model assumes that the climate system processes an external input forcing exactly like a traditional climate energy balance model. That is, it is assumed that the thermodynamical properties of climate are characterized by a given sensitivity to the external forcing and by a given heat capacity. The latter determines the time response of the system. The difference between the empirical model and the more traditional energy balance models is that both the climate sensitivity to an external forcing and the time responses of the system are empirically measured on the climate data themselves instead of being theoretically *a priori* deduced.

By using auto-correlation properties of the temperature, Scafetta [14] determined that the climate system is characterized by at least two major characteristic time constants which are about: $\tau_1 = 0.4$ year and $\tau_2 = 12$ year. These two time constants are physically reasonable because they agree well with the idea that the climate system can be approximately assumed to be made of two coupled subsystems such as, for example, the air-land and the ocean. The former subsystem (air+land) is characterized by a relatively small heat capacity; therefore, it responds quickly to an external forcing. The latter subsystem (ocean) is characterized by a relatively large heat capacity; therefore, it responds slowly to an external forcing.

Thus, climate can be approximately considered a superposition of two subsystems each with its own characteristic time response and sensitivity. The two climate sensitivities were deduced in Scafetta [13] by taking into account that the overall climate response to the 11 year solar cycle induces a cycle with a peak-to-trough signature on the global surface temperature of about 0.1^{o}C, as found by several authors (Scafetta [13]; IPCC [15, p 674]).

The measured climate sensitivities to solar variation were k_{1s} = 0.053 K/Wm^{-2} and k_{2s} = 0.41 K/Wm^{-2} for the two subsystems, respectively. Note that these sensitivities are not equivalent to the climate sensitivities to radiative forcing as used by traditional climate models such as those used by the IPCC [15], they are larger. In fact, in the present case, the total solar irradiance is used just as a proxy for the overall climate sensitivity to the overall solar forcing that is not just TSI alone. For example, there may be an additional strong contribution from solar modulated cosmic ray flux that can modulate cloud formation.

By using the above values, the empirical solar signature on climate, which is indicated by ΔT(t), associated to a given TSI record, which is indicated by ΔI(t), can be calculated from the following system of differential equations:

$$\begin{cases} \Delta T = \Delta T_{1S} + \Delta T_{2S} \\ \dfrac{d\Delta T_{1S}(t)}{dt} = \dfrac{k_{1S}\Delta I(t) - \Delta T_{1S}(t)}{\tau_1} \\ \dfrac{d\Delta T_{2S}(t)}{dt} = \dfrac{k_{2S}\Delta I(t) - \Delta T_{2S}(t)}{\tau_2} \end{cases} \qquad (3)$$

These equations were used to derive the curves depicted in Fig. (**6**) in the main report. More details are found in Scafetta [13].

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