Climate Change Attribution Using Empirical Decomposition of Climatic Data

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Abstract: The climate change attribution problem is addressed using empirical decomposition. Cycles in solar motion and activity of 60 and 20 years were used to develop an empirical model of Earth temperature variations. The model was fit to the Hadley global temperature data up to 1950 (time period before anthropogenic emissions became the dominant forcing mechanism), and then extrapolated from 1951 to 2010. The residuals showed an approximate linear upward trend of about 0.66°C/century from 1942 to 2010. Herein we assume that this residual upward warming has been mostly induced by anthropogenic emissions, urbanization and land use change. The warming observed before 1942 is relatively small and is assumed to have been mostly naturally induced. The resulting full natural plus anthropogenic model fits the entire 160 year record very well. Residual analysis does not provide any evidence for a substantial cooling effect due to sulfate aerosols from 1940 to 1970. The cooling observed during that period may be due to a natural 60-year cycle, which is visible in the global temperature since 1850 and has been observed also in numerous multisecular climatic records. New solar activity proxy models are developed that suggest a mechanism for both the 60-year climate cycle and a portion of the long-term warming trend. Our results suggest that because current models underestimate the strength of natural multidecadal cycles in the temperature records, the anthropogenic contribution to climate change since 1850 should be less than half of that previously claimed by the IPCC. About 60% of the warming observed from 1970 to 2000 was very likely caused by the above natural 60-year climatic cycle during its warming phase. A 21st Century forecast suggests that climate may remain approximately steady until 2030-2040, and may at most warm 0.5-1.0°C by 2100 at the estimated 0.66°C/century anthropogenic warming rate, which is about 3.5 times smaller than the average 2.3°C/century anthropogenic warming rate projected by the IPCC up to the first decades of the 21st century. However, additional multisecular natural cycles may cool the climate further.

Keywords: Attribution, climate change, ENSO, LULC change, solar activity, UHI effect.

1. INTRODUCTION

There is little doubt that the Earth has warmed since 1850, the time when global instrumental temperature estimates are first available (Brohan *et al.* [1]). A significant increase in the warming has been observed since 1970 relative to the period from 1940 to 1970: see Fig. (**1A**). This sudden change in the warming trend has suggested an alarming anthropogenic effect on climate (IPCC [2]). However, partitioning causation has proven to be problematic. It is important to establish the relative importance of forcing factors in order to properly calibrate climate models used to project future climate scenarios and, in particular, it is necessary to determine whether multidecadal climatic patterns may be induced by natural multidecadal cycles.

Attribution studies are based on either statistical or simulation approaches, or a combination of these. Several studies (e.g., Andronova and Schlesinger [3]; Crowley [4]; Damon and Jirikowic [5]; Hoyt and Schatten [6]; Lean *et al.* [7]; Scafetta [8]; Serreze *et al.* [9]; Stott *et al.* [10]; Tett *et al.* [11]) have arrived at divergent estimates of anthropogenic forcing. One reason for these divergent results is that the computations are poorly constrained. Each factor considered is uncertain both in terms of forcing and in terms of data, as documented by Scafetta [8]. For example, while greenhouse gases such as CO_2 and CH_4 no doubt have a warming effect and sulfate aerosols produced by volcanoes or industrial emissions no doubt have a cooling effect, the IPCC [2] itself acknowledges that there are large uncertainties as to the magnitude of their effects on climate. The same can be said of brown clouds (warming), black soot (warming), solar activity, and other factors. In none of these cases is a precise global dataset for the past 160 years available to provide input to an attribution study (Kiehl [12]), nor is the precise forcing known independently of attribution studies (e.g., Visser *et al.* [13]). For example, the IPCC's best estimate of the climate sensitivity to CO_2 doubling is 3 +/- 1.5 °C, although the distribution is skewed and has a tail to 10 °C (see figure 9.20 of IPCC [2]). Other climate mechanisms in climate models are also either poorly modeled (cloud cover, water vapor, ocean oscillations) or highly uncertain (land cover). More spatially resolved climate simulations (e.g., Wyant *et al.* [14]) produce cloud and water vapor patterns that differ from those in operational climate models. These differences are difficult to resolve within the traditional attribution study framework.

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To overcome this problem we apply an empirical decomposition method that does not depend on assumptions about forcing magnitudes, on detailed historical inputs of the various factors, nor on climate models. Our approach is to empirically characterize the pattern of global temperature change and to relate this pattern to the historical timing of anthropogenic greenhouse gas forcing.

2. DECOMPOSITION ANALYSIS

Long-term climate trends and cycles have been detected in many geologic datasets. The most regular of these are the repeated cycles of glaciations evident in ice core data (e.g., Rasmussen *et al.* [15]), though the precise factors governing this cycle are not fully worked out. A number of studies claim to have found decadal to centennial periodic behaviors in climate records that can be associated to solar cycles (discussed later). As well, the 11 and 22 year sunspot cycles appear to result from the effect of planetary tidal forces on the sun (e.g., Bendandi [16]; Hung [17]). These findings offer the possibility that decadal to centennial scale climate could have some structure in the absence of human activity, rather than being featureless. This possibility is not ruled out by the IPCC [2] because no scientific consensus exists on the importance of solar forcing and the current level of understanding associated with it is stated by IPCC to be low.

Using the pattern of perturbations of the sun's location from the center of mass of the solar system as a measure of the oscillations of the sun-planets system due to gravitational and magnetic interactions, which can be back-calculated by orbital calculations to any desired length of time, Scafetta [18] showed *via* spectral analysis and other means that two particularly strong periodic signals occur with the periods of about 60 and 20 years. These oscillations are synchronous in both astronomical records and numerous global surface temperature and climate records. Spectral decomposition of the Hadley climate data showed spectra similar to the astronomical record, with a spectral coherence test being highly significant with a 96% confidence level. A model based on these astronomical cycles fit the global temperature data well and fit the ocean temperature data even better. On the contrary, the spectral patterns of climate model simulations did not match those found in the climate at all (just a 16% confidence level), suggesting that current general circulation models adopted by the IPCC do not reproduce the climate oscillations at the decadal and multidecadal scales (Scafetta [18]).

The physical mechanisms responsible for the cycles are not understood yet and, therefore, are not included in the current climate models. However, it is reasonable to speculate that planetary tides and solar angular motion affect solar activity (Scafetta [18]; Wolff and Patrone [19]). Changes of solar activity then influence the Earth's climate through changes of direct total solar irradiance, the sun's magnetic field and the solar wind. Very likely, solar activity changes influence also the intensity of cosmic rays reaching the Earth, the electrical physical properties of the terrestrial magnetosphere and of the ionosphere. The latter influences the generation of clouds which modulate terrestrial albedo and, consequently, the climate (Kirkby [20]; Tinsley [21]; Svensmark *et al.* [22]). The above empirical relationship, even if the exact mechanisms are not understood yet, offers

an opportunity to detect the anthropogenic signal as a residual component not explained by natural cycles.

In what follows, we empirically estimate the structure of the temperature history data over a 160 year interval and evaluate the components of the empirical model as well as the residuals to assess natural *vs* anthropogenic forcings. A key to the analysis is the assumption that anthropogenic forcings become dominant only during the second half of the 20th century with a net forcing of about 1.6 W/m² since 1950 (e.g., Hegerl *et al.* [23]; Thompson *et al.* [24]). This assumption is based on figure 1A in Hansen *et al.* [25] which shows that before 1970 the effective positive forcing due to a natural plus anthropogenic increase of greenhouse gases is mostly compensated by the aerosol indirect and tropospheric cooling effects. Before about 1950 (although we estimate a more precise date) the climate effect of elevated greenhouse gases was no doubt small (IPCC [2]).

The approach we take is illustrated by the work of Klyashtorin and Lyubushin [26] who identified a periodicity of about 60 years in long-term climate data and fit a model to the global anomaly data, with good results. A problem with their model is that it is fit to the period in which we wish to detect a difference from any natural cycles of climate. A better approach would be to fit the model to the period prior to elevated greenhouse gases and then extrapolate it forward and determine whether the forecast climate pattern corresponds to the observed one. In fact, in the latter case the model would be tested on its forecasting capability.

As explained above, we follow Thompson *et al.* [24] and IPCC [2] in identifying 1950 as the approximate year after which an anthropogenic signal appears to dominate climate forcings. Hegerl *et al.* [23] identified 1960 as the cutoff year, but their analysis might have found an earlier year if sulfate aerosols were not included in it. Given the strong periodicity in the solar signal detected by Scafetta [18], we used this model, with two cycles of lengths 60 and 20 years, plus a linear term. A free fit of the Hadley HadCRUT3 global surface temperature data found cycles quite close to this, but we use the Scafetta solar periodicities plus a linear trend. The linear trend would approximately extrapolate a natural warming trend due to solar and volcano effects that is known to have occurred since the Little Ice Age, a period that encompassed the Maunder and Dalton solar minima of the 17-19th centuries (Eddy [27]; Scafetta [8]).

As explained in Scafetta and West [28] and in Scafetta [8] most of this warming is likely due to the increased solar activity with the volcano effect playing only a minor effect if recent paleoclimatic reconstructions of the global climate, which show a large pre-industrial variability (e.g. Moberg *et al.* [29]), are adopted. On the contrary, analysis using only *Hockey Stick* temperature graphs, which do not show a significant pre-industrial variability (e.g. Mann *et al.* [30]), suggest that volcanic and solar effects are equally important in explaining the Little Ice Age (Crowley [4]; Scafetta and West [28]).

The model was fit by nonlinear least squares estimation using *Mathematica* functions, with phase and amplitude free but period fixed as above. The validity of this approach for estimating parameters for a time series model with data of
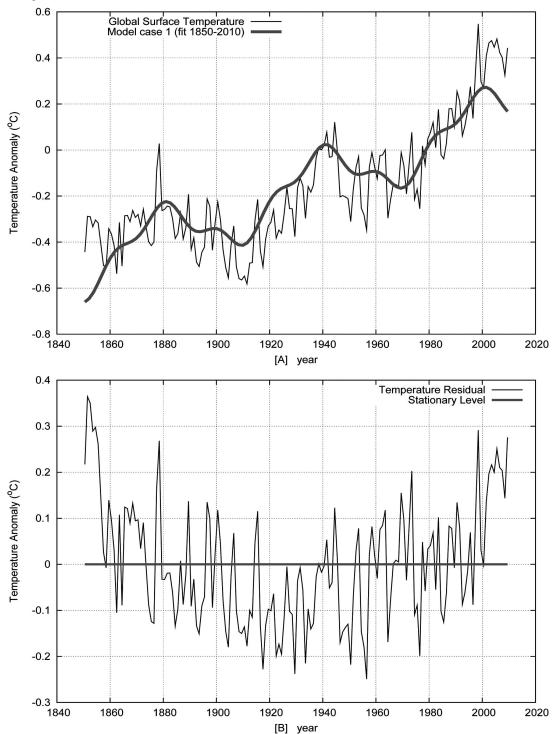
Fig. (1). A) Model for entire period utilizing HadleyCRUT3 global surface temperature April 8, 2010 dataset. **B**) Residuals showing clear model mis-specification.
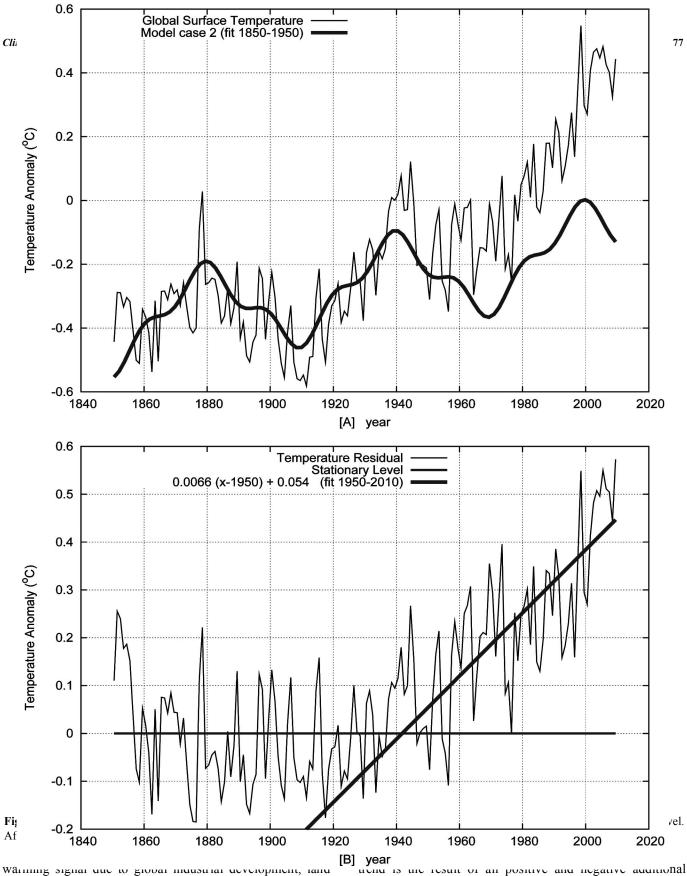
this length is demonstrated in Supplemental Information a. When fit to the entire 160 year period, the model

$$y(t) = A \cos[2\pi(t-T_1)/60] + B \cos[2\pi(t-T_2)/20] + C(t-1900) + D \quad (1)$$

performs only decently (Fig. **1A**), as the nonrandom residual signal over the entire period (Fig. **1B**) reveals that the model is deficient. Since this mis-specification could result from not including anthropogenic effects that could have accelerated the warming since 1950, the model was refit

using the data only up to 1950 (Fig. **2A**). See Table **1** for the evaluated regression coefficients in the two cases.

Just as in the solar data, the 60-year cycle has about three times the peak-to-trough amplitude (~0.24ºC) of the 20 year cycle (~0.08 ºC). The model fit is $R^2 = 0.53$. Comparing the residuals over the entire period depicted in Fig. (**2B**), they appear stationary up to 1950, but there is a visible positive trend from 1950 to 2010. The residual warming observed since 1950 is mostly induced by an increasing anthropogenic

[A]   year

[B]   year

warming signal due to global industrial development, land usage change and urban heat island (UHI) effects since 1950.

A linear fit to the residuals since 1950 (Fig. **2B**) has a slope of 0.66 +/- 0.08°C/century (R^2 = 0.59) and begins (>0) in 1942. Note that given a roughly exponential rate of CO_2 increase (Loehle [31]) and a logarithmic saturation effect of GHG concentration on forcing, a quasi-linear climatic effect of rising GHG could be expected. In any case, this upward

trend is the result of all positive and negative additional climatic forcings (e.g., the anthropogenic ones) and other possible contributions (e.g., poor adjustment of the temperature data) that are not implicit in our model beginning in 1942.

Fig. (**2A**) shows that the model fit from 1850 to 1950 reproduces the modulation of the temperature up to 1942 and has random residuals over this period (Fig. **2B**). It is very

unlikely that the 60 and 20-year cycles would match the pattern of temperature over this period by chance; thus, the empirical model calibrated on the temperature data before 1950 has the capability of *forecasting* the multidecadal oscillations of the temperature after 1942, which we do next.

Table 1.   Regression Coefficients of the Harmonic Model Plus Linear Trend Depicted in Eq. (1) Used in Fig. (1, fit 1850-2010) and in Fig. (2, 1850-1950), Respectively

	Case 1	Case 2
A	0.121 +/- 0.015 ºC	0.121 +/- 0.016 ºC
B	0.034 +/- 0.016 ºC	0.041 +/- 0.016 ºC
C	0.0042 +/- 0.0002 ºC/year	0.0016 +/- 0.0004 ºC/year
D	-0.297 +/- 0.013 ºC	-0.317 +/- 0.011 ºC
T_1	1998.62 +/- 1.2 year	1998.58 +/- 1.3 year
T_2	2000.98 +/- 1.5 year	1999.65 +/- 1.3 year

Note that the harmonic coefficients A, B, T_1 and T_2 are compatible within the error of measure. Parameter A is the 60-year cycle amplitude and B the 20-year cycle amplitude.

The above finding is also confirmed by two recent studies that show a similar linear anthropogenic warming trend after about 1950 (Thompson *et al.* [24]) and about 1960 (Hegerl *et al.* [23]. Both studies also find a small residual warming in the pre-1950 or 1960 period but do not attribute this trend to human influences. The magnitude of the Thompson *et al.* [24] residual post-1950 trend (i.e., the anthropogenic component) is similar to our result. These studies attempt to filter out sources of extraneous noise, such as ENSO events and volcanoes. They make many assumptions, which are not needed in the present study in which short-term perturbations are simply noise relative to the 60 year cycle and the long-term natural trend.

To verify the combined effect of natural plus anthropogenic forcings, a full model was constructed, with the anthropogenic linear trend obtained by fitting the residual from 1950 to 2010 assumed to be in effect since 1942. This model (Fig. **3A**) fits the entire 160-year record better than any model we have seen. Fig (**3B**) depicts the two harmonics at 60 and 20-year period and the linear natural trend (fit 1850-1950) added to the anthropogenic linear trend (fit of the residual in 1950-2010) since 1942.

It would thus appear that the modeling approach used here has captured the essential features of the climate from 1850 to 2010. A model based on 100 years of data (from 1850 to 1950) shows stationary fluctuating residuals (Fig. **2B**). The extrapolation period 1950 to 2010 shows an upward linear pattern of residuals, which we interpret as a signal of anthropogenic warming. The slope of this anthropogenic warming trend is 0.66°C/century since 1942. Fig. (**3A**, **B**) show that about 50 +/- 10% of the 0.8ºC global surface warming observed from 1850 to 2010 is likely the result of a natural warming trend recovery since the LIA plus the combined effects of 20- and 60-year natural cycles. In particular, the sudden and alarming warming increase observed from 1970 to 2000 is mostly a consequence of the combination of the 20- and 60-year natural cycles. Both cycles were at their minima in about 1970 and at their

maxima around 2000, as Fig. (**3B**) shows. These cycles would imply a combined warming of about 0.32ºC on the total observed warming of about 0.5ºC since 1970. Thus, about 60% of the warming observed since 1970 can be associated with natural 20- and 60-year multidecadal cycles.

3. MULTI-SECULAR EVIDENCE OF A QUASI 60-YEAR CLIMATIC CYCLE

Here we list empirical studies supporting the existence of a quasi 60-year cycle in the climate system. A 20-year cycle with smaller amplitude will necessarily be harder to detect in geologic records, and is not evaluated here. Also, note that climate may be characterized by other cycles with periods longer than 60-year (e.g., Loehle and Singer [32]). Because complex interference patterns may emerge through the superposition of all cycles and volcano eruptions can further disrupt the signal, perfect 60-year harmonics may not be easily visible in the records. Noisy geologic data may not show a signal even if one is present.

While spectral coherence of the Hadley historical data and solar data has been established (Scafetta [18]), does this effect extend before 1850? Before 1850 global instrumental temperature records are not available. Thus, it is possible to use only a few historical European temperature records dating back since the 17th century and several paleoclimatic records. These records may present several problems and may be a poor proxy for the real global climate.

It has been recently noted that a 500 year temperature reconstruction in the Mediterranean basin (Spain, France, Italy) by means of documentary data and instrumental observations suggests a dominant ~60 year oscillation (Camuffo *et al.* [33]). Moreover, there are multidecadal periods of high and low ENSO-type activity evident in historical records going back several hundred years (e.g., Biondi *et al.* [34]; Mantua and Hare [35]; Mantua *et al.* [36]; Minobe [37-39]; Patterson *et al.* [40]; Shabalova and Weber [41]; Wiles *et al.* [42]; figure 5 in Gergis and Fowler [43]). The long-term ENSO-type signal has been shown to be quasi-periodic, with period of 50 to 70 years, in records such as the Greenland ice core, bristlecone pine ring widths, and sea sediment records of fish abundance going back thousands of years (Klyashtorin and Lyubushin [26, 44]; Klyashtorin *et al.* [45]). Over these long periods, cycles of 50 to 70 years were shown, using moving window spectral decomposition, to increase in strength over the last 600 to 1000 years, reaching a peak strength in the 20th century. Klyashtorin and Lyubushin [26] and Klyashtorin *et al.* [45] also showed that over the past 100+ years an average 60 year global temperature cycle is strongly coherent with the Pacific Decadal Oscillation (PDO), the zonal mode of the Northern Hemisphere Atmospheric Circulation Index, the Aleutian Low Pressure Index, flood levels in the Neva River (Russia), and precipitation in Oregon, among others. In addition, the ups and downs of major ocean fish stocks are almost completely explained by this ~60 year climate cycle (e.g., Klyashtorin and Lyubushin [26]; Mantua *et al.*, [36]). The Atlantic Multidecadal Oscillation also closely tracks this approximately 60-year cycle (figure 2 in Levitus *et al.* [46]). Wiles *et al.* [42] found evidence for the persistent effect of the PDO on climate in Alaska over the past 1000 years. A quasi-60 year periodicity is found in secular monsoon
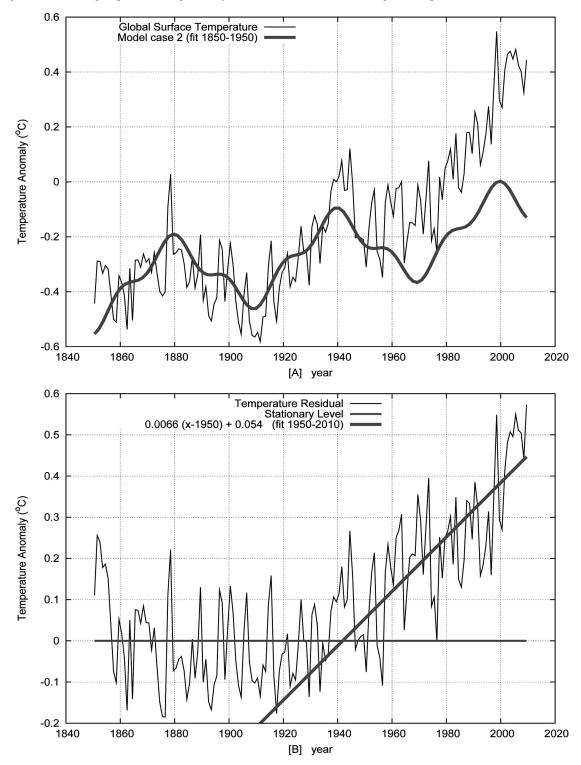
Fig. (3). A) Full reconstruction model, which uses Eq. 1 (= natural modulation) fit from 1850 to 1950 plus the additional residual upward linear trend (=anthropogenic modulation) since 1942. **B)** Components of the model.

rainfall records from India (Agnihotri and Dutta [47]). Yousef [48] showed a good anti-correlation between ENSO events and the Wolf-Gleissberg cycle over 300 years. A clear quasi 60-year cycle is observed in the global sea level rise record since 1700 (Jevrejeva *et al.* [49]). A 50 to 80 year cycle over hundreds of years has also been found in sedimentary records in the northeast Pacific and their cause has been related to solar and cosmic ray activity cycles

(Patterson *et al.* [40]). Ogurtsov *et al.* [50] found strong evidence for the cycle, such as a 60 to 64 year period in [10]Be, ^{14}C and Wolf number over the past 1000 years, which may indicate a solar origin. The solar system oscillates with a 60-year cycle due to the Jupiter/Saturn three-synodic cycle and to a Jupiter/Saturn beat tidal cycle (Scafetta [18]).

Fig. (**4**) depicts two multi-secular climate records showing multiple quasi-60 year large oscillations since 1650.
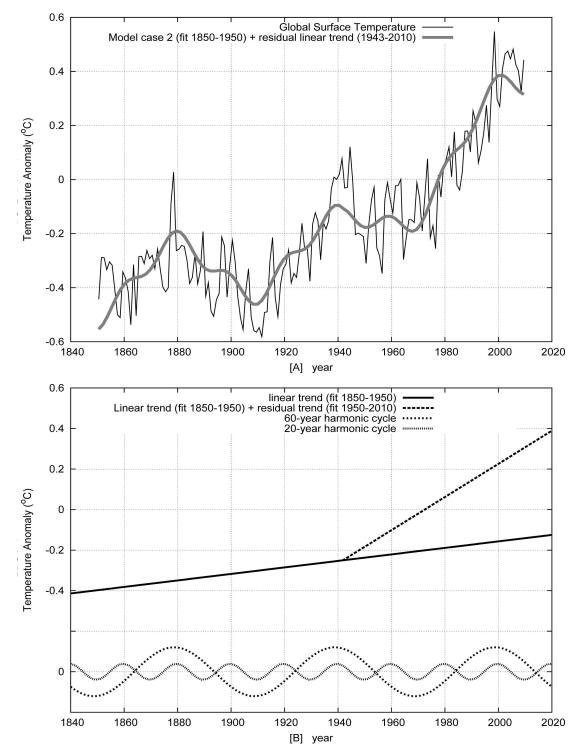
Fig. (4). A) *G. Bulloides* abundance variation record found in the Cariaco Basis sediments in the Caribbean sea since 1650 [Black *et al.*, 1999]. **B)** tree-ring chronologies from Pinus Flexilis [MacDonald and Case, 2005] as an index to the PDO. Both records show five large quasi 60-year cycles since 1650.

Fig. (**4A**) depicts the abundance of *G. Bulloides* (an indicator of surface temperatures) found in the Cariaco Basin sediments in the Caribbean sea since 1650 (Black *et al.* [51]): the best sinusoidal fit gives a period of about 61.5 +/- 4 years. This record, which correlates well with time series of solar output, is an indicator of the trade wind strength in the tropical Atlantic Ocean and of the North Atlantic Ocean atmosphere variability. Fig. (**4B**) depicts the reconstructed

PDO based on tree-ring chronologies from *Pinus flexilis* in the United States West Coast (MacDonald and Case [52]): the best sinusoidal fit gives a period of about 59.5 +/- 4 years. Thus, both records show a clear 60-year cycle. These cases negatively related to temperature due to the type of proxy.

A potential source of data for evaluating this cycle can be found in multiproxy temperature reconstructions (e.g., Moberg *et al.*, [29]). Unfortunately, most of these reconstructions must be rejected as accurate data sources: in fact, paleoclimatic temperature reconstructions appear quite different from each other (North *et al.* [53]). Many rely on tree ring data, but it has been shown (e.g., Loehle [54]) that tree ring data, as well as other proxy records have issues that need to be resolved before they can be used to develop reliable climate histories.. In other cases, multiple proxies either are dated at wide intervals such as 100+ years, precluding detection of a multi-decadal signal, or suffer from large dating error, which in combined series will lead to a smearing of multi-decadal peaks (Loehle [55]).

Given that this ~60 year periodic climate pattern has such a long empirical history with some evidence for links to solar activity and solar system oscillations, it cannot be attributed to human activity and cannot be simply random noise. Therefore, we are justified in factoring it out of the historical record in order to discern the human influence on climate. We next evaluate additional components that can be potentially factored out and, then, develop a final model that is extrapolated to 2100.

4. TROPOSPHERIC AEROSOLS

A major factor often considered crucial for proper climate modeling is the influence of tropospheric aerosols that result from industrial activity, which are often assumed to have been a major cooling influence in the 1950s through the 1970s due to their reflective properties (although Schiermeier [56] argues that the aerosol extent and forcing data are shaky at best). However, because the climate appears to contain a ~60 year cycle for several centuries, much of the cooling may have been induced by this cycle, which was in its descending trend during this period. In fact, the residuals from the pre-1950 model (Fig. **2B**) over the decades of the 1950s through 1970s show not a decline but a constant linear rise for the anthropogenic component, which is inconsistent with a strong cooling effect over this period. Our full model (including the linear anthropogenic effect since 1940) shows a cooling in the 1950s through 1970s without any forcing from tropospheric aerosols (Fig. **3A**). Note that the amplitude of this 60-year cycle has been determined fitting the data before 1950. Moreover, the periods 1880-1910 (slight cooling) and 1910-1940 (significant warming) are statistically equivalent to the periods 1940-1970 (slight cooling) and 1970-2000 (strong warming), respectively. Thus, while tropospheric aerosols might have contributed to the cooling between 1940 and 1970, most of the observed cooling is likely associated with the 60-year cycle, which was in the declining phase during that period.

5. LAND USE EFFECTS ON TRENDS

The final factor considered is the urban heat island (UHI) effect, including other land use/land cover (LULC) changes (e.g., Klotzbach *et al.* [57]). The UHI effect has long been known (e.g., Klysik and Fortuniak [58]). It results because urban structures have lower albedo, which raises temperatures, and retain heat, which raises nighttime minima. In addition, there is less evaporative cooling in a city. Herein, we discuss the current uncertainty relative to

this phenomenon. It is not known how well the land surface temperature records are corrected for the UHI effect.

The UHI effect arises not from the mere fact that a city is warmer than a rural site (e.g., Klysik and Fortuniak [58]), which is of no consequence for calculating trends, but from the effect at a given weather station location as the city grows around it, causing a gradual warming bias over time ([e.g., Böhm [59]; Magee *et al.* [60]).

While many studies have documented UHI effects at the city level, few have done so at larger scales. The contribution of UHI effects at larger scales arises from the fact that a large proportion of weather stations have been established to serve cities and airports, with few in remote locations. Thus, UHI effects contaminate the instrumental temperature record. In a landmark study, Jones *et al.* [61] evaluated the UHI effect for China and found that 39.6% of the instrumental warming from 1951 to 2004 was contributed by UHI and related effects. In another set of studies, McKitrick and Michaels [62, 63] and McKitrick [64] showed that local warming (deviations from global trends) was proportional to national economic activity, a surrogate for urbanization, and that this effect is real and not caused by, for example, atmospheric circulation patterns. They estimated that about half of the land warming claimed by the IPCC to be UHI and land use related. In an analysis of trend differences between satellite and surface data, Klotzbach *et al.* [57] suggested that from 30 to 50% (based on UAH satellite data) of the instrumental land surface warming trend from 1979 to 2008 was spurious. Kalnay and Cai [65] found 0.27°C per century of the warming trend over the continental United States to be due to land use change effects. Other studies (e.g., Christy *et al.* [66]; Fall *et al.* [67]) support these results.

The above studies suggest that the contribution of UHI warming to land warming is difficult to determine accurately and to filter from the global surface temperature record. The warming since 1950 might be lower than what is currently believed and the climate effects of the anthropogenic forcings may be overestimated also for this reason. Thus, the modeled upward warming trend attributions depicted in Fig. (**3A**) should be interpreted as an upper limit for an anthropogenic (GHG plus aerosol) contribution to climate change.

6. 21ST CENTURY FORECAST OF CLIMATE CHANGE

Based on the analysis in this study, it is possible to make a preliminary forecast of future trends that may be reliable for the coming few decades. We believe this is possible because the natural variability may be assumed in first approximation to be a sum of a possible upward linear trend started since the Little Ice Age, which may still continue during the next decades although it is likely part of a millennial long natural cycle which includes the Medieval Warm Period and the Little Ice Age (see Loehle and Singer [32]), plus the periodic multidecadal component we have detected.

That a natural trend may not exceed the above estimated upward linear trend from 1850 to 1950 may be indirectly suggested by the fact that since 1930 the rate of sea-level is slowing slightly (Houston and Dean [68]), which may suggest that a millenarian natural climate cycle is turning
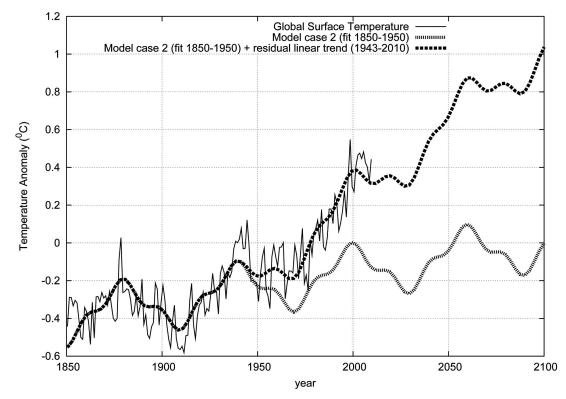
Fig. (5). Forecast models. Thick line is the global surface temperature. Dashed thick line is the total (natural plus anthropogenic) model reconstruction. Dashed light line is the continuation of the modeled natural component alone.

down. Interestingly, the measured deceleration of the sea-level rise from 1930 to 2010 occurred despite the strong positive acceleration of anthropogenic GHG emissions during the same period. Moreover, the anthropogenic component of the warming (GHG and aerosol forcings and/or LULC and UHI effects) seems to have resulted in a linear additional warming trend from 1942 through 2010, which matches the long-term climate model outputs (IPCC [2]). The combined (20 and 60-year cycle plus two linear trends) model depicted in Fig. (**3A**) matches the 160-year historical record exceptionally well. Thus, extrapolating the model another 90 years may be useful.

The result (Fig. **5**) is a continued warming with oscillations to a high in 2100 of about 0.6 °C above 2000 values. However, if part of the linear warming trend is due to UHI and LULC changes, the anthropogenic effect due to GHG and aerosol would be smaller. Moreover, the full anthropogenic effect of 0.66 ºC/century would be masked by the natural multidecadal 20 and 60-year cycles until 2040. Note that for the full model the downturn in temperature evident in the satellite observations after 2000 (Loehle [69]) is present. This downturn in the temperature since 2000 was not reproduced by any projection of the climate models adopted by the IPCC [2] although it is predicted by the celestial empirical model of climate recently proposed by Scafetta [18]. The above estimate of a possible warming of only 0.6 °C above 2000 should be compared against the IPCC projections that claim a monotonic anthropogenic warming with an average global value in 2100 of about 3°C above 2000 values for the likely scenarios and even more for the upper bound scenarios.

7. CAN SOLAR ACTIVITY EXPLAIN THE TEMPE-RATURE MODULATION?

If anthropogenic forcing has been overestimated by the models adopted by the IPCC, it is necessary that other natural forcings such as the solar forcing have been underestimated by the same models to balance the secular warming trend observed in the temperature record.

Herein we investigate whether solar activity can explain a quasi 60-year modulation of temperature and at least part of the upward trend by expanding the discussion presented in Scafetta [8]. The task is not simple, because past total solar irradiance (TSI) variation is not known with certainty (Supplemental Information b). We develop an enhanced version of the Scafetta [8] model in Supplemental Information c, which uses the TSI record as a proxy for determining a phenomenological signature of the total solar effect on climate. This model empirically evaluates the climate sensitivity to solar changes and, therefore, it automatically takes into account natural amplification mechanisms such as those due to cloud and GHG feedbacks.

Figure Suppl. (**2**) in Supplemental Information c shows that the proxy model (green) presents a slight increase between 1850 and 1880/90, a decrease from 1880/1890 to 1910, an increase from 1910 to 1940/50, a decrease from 1940/50 to 1970/80, and an increase from 1970/1980 to 2000, and a decrease after 2000. Thus, it shows a quasi 60-year cycle, which is clearly present in the gravitational oscillations of the solar system (Scafetta [18]). The latter 30-year pattern since 1980 is perfectly compatible with the ACRIM total solar irradiance satellite measurements that show an increase from 1980 to 2000 and a decrease from 2000 to 2010 (Scafetta and Willson [70]). This is an

important result because some solar scientists currently believe that the ACRIM trend is instrumental and not of solar origin (Fröhlich [71]; Lockwood and Frohlich [72]).

From the above, it appears that these TSI proxy models can approximately reproduce the quasi 60-year modulation of the temperature. In addition, they contain an upward trend that is part of a multisecular solar cycle responsible for much of the cooling from the Medieval Warm Period to the Little Ice Age and the warming from the Little Ice Age to the current warm period. To better show this we applied the empirical temperature model of Scafetta [8] to the novel green TSI proxy curve and to the average of the three TSI curves represented by the black curve in the Supplemental figure to obtain values for forcing. We plotted the two solar phenomenological signatures in Fig. (**6**) against the global surface temperature record.

Fig. (**6**) confirms that there is good agreement, especially after 1900, between the empirical ~60 year modulation of temperature (Fig. **3A**, thick line) and the climate signature that would be imprinted by solar multidecadal variation. If the correspondence is not rigorous it is because the available TSI proxy models can only approximately reproduce the real multidecadal TSI variation and more research is needed on this topic. It also appears that a modest upward trend over the period since 1850 of 0.11°C/century is reproduced by the TSI reconstructions. This is a critical point because the rising temperatures from 1850 to 1950 (or 1942) could be due to the secular increase of solar activity observed since the 18th century (Scafetta [8]). Thus, the cause of both the 60-year cycle modulation plus an upward trend since 1850 is likely to be linked to the multidecadal and multisecular oscillatory nature of the solar variation. This is evident over long

timescales and is apparent in cosmogenic isotopes. For example, Ogurtsov *et al.* [50] found strong evidence for solar cycles with 60 to 64, 80 to 90, 128, 205, and 1020 year periods in ^{10}Be, ^{14}C, and Wolf number over the past 1000 years. Mazzarella [73] also found a clear link between the 60-year solar cycle and climate oscillations during the last 150 years.

8. DISCUSSION AND CONCLUSION

Herein we have argued that the global surface instrumental temperature record, as well as longer term records, contain a quasi 60-year natural cycle. This cycle may be associated with a low frequency modulation of the ocean oscillations such as the ENSO signal. It appears to be present in solar and astronomical records as well, although a perfect match is difficult to obtain because of the uncertainties about the current total solar irradiance proxy models. Better solar irradiance models or alternative solar system direct forcings (Scafetta, [18]) may be required to find a perfect match.

Thus, this quasi 60-year cycle observed in the temperature record likely has an astronomical/solar and, therefore, natural origin. The weaker quasi 20-year cycle is not as easily detected in geologic records but it is clearly detected in the global surface instrumental records (Scafetta, [18]). The projected rate of temperature increase due to human influences in our analysis suggests a value for climate sensitivity. Using an estimate of doubling time of greenhouse gases based on historical doubling times for carbon dioxide (Loehle [13]) as a proxy, the anthropogenic warming resulting from doubled forcing would be at least two to three times less than previously thought, that is on average about 1-1.5°C or less from our linear model, which
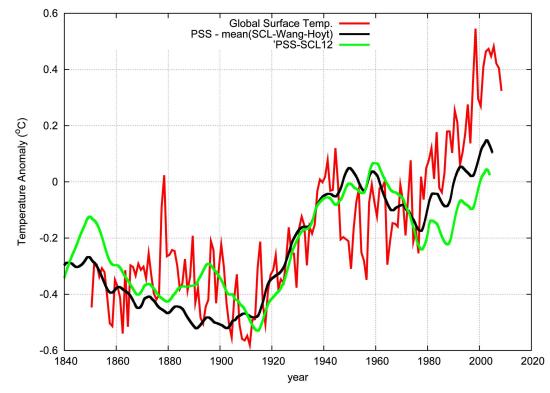

Fig. (6). Global surface temperature against the phenomenological solar signature obtained with the model by *Scafetta* [2009] applied to the green and black TSI proxy model curves depicted in Supplemental Information c.

may also suggest the presence of a slight negative feedback to CO_2 in the climate system.

The models adopted by the IPCC [2] assume that more than 90% of the warming observed since 1850 to 2000 and about 100% of the warming observed since 1970 has been caused by anthropogenic forcing. This information can be deduced from a direct analysis of the figures published there, such as Fig. (**9.5a**, **9.5b**), which claim that natural forcing alone (solar plus volcano) would have induced a cooling since 1970. However, these climate models are not able to reproduce decadal and multi-decadal natural cycles (Scafetta, [18]). We showed that the Hadley global anomaly data from 1850 to 1950 are matched closely by a periodic model with periods 60 and 20 years plus a linear trend. The residuals from this model after 1950 are strictly linear, matching other attribution studies (e.g., Hegerl *et al.* [23]; Thompson *et al.* [24]). Based on this result, our full model (natural plus anthropogenic effects after 1942) closely matched the full 160-year record. It had far higher pattern accuracy than any traditional analytical computer general circulation climate model output. We further found no clear evidence for a significant cooling effect due to troposphere aerosols, since our model shows cooling in the 1950s through 1970s without invoking this mechanism, and there are no unexplained residuals corresponding to the period of assumed influence of this factor. Comparing the temperature rise from the 1970s to 2010 (~0.5°C) due to the 60 and 20-year cycles (~0.3°C) with that evident in the model residuals (Fig. **2B**, ~0.2 °C), we can see that more than half of the warming since the 1970s is the result of the timing of the upturn of the 20 and 60 year cycles. Our empirical model further predicts a lack of warming since about 2000, in contrast to IPCC model projections of steady linear warming due to anthropogenic forcing alone of about +2.3°C/century from 2000 to 2010 (see IPCC 2007 figure SPM.5), which is a 3.5 time larger rate than the +0.66°C/century warming that we have estimated above.

In conclusion, we have shown that the effect of natural oscillations is critical for proper assessment of anthropogenic impacts on the climate system. Since the rapid increase in temperature in the 1980s and 1990s is due partially to natural cycles, then any model-based estimate of climate sensitivity based on elevated greenhouse gases will be too high, a point also made by Scafetta and West [74], Scafetta [8, 18], and Klyashtorin and Lyubushin [44]. The same applies to attribution studies that focus on these decades. Proper consideration of these cycles and of longer natural cycles is also critical for detecting underlying trends. For example, a millenarian or longer period cycles might explain the pattern of the Medieval Warm Period and Little Ice Age (Loehle and Singer [32]) as well as warming since about 1800.

It is also worth noting that by starting in a cycle trough in 1900 and ending on a cycle peak in 2000, graphical depictions of warming in IPCC and other reports give an exaggerated depiction of the rate of warming, a point noted by Karlén [75] and Soon *et al.* [76]. By further failing to mention solar effects and warm bias in the instrumental record, it is implied that almost all the warming of about 0.8°C over this period is human caused, when really no more than 0.4°C is likely to be. Reporting such a lower number would probably cause much less alarm than what was

recently claimed by Rockström *et al.* [77]. Moreover, because the 60-year natural cycle will be in its cooling phase for the next 20 years, global temperatures will probably not increase for the next few decades in spite of the important role of human emissions (see Fig. **5A**), as predicted by multiple studies (reviewed in Loehle [69]; Scafetta [18]).

CONFLICT OF INTEREST

No outside funding was used to conduct this work. No financial interests of conflicts of interest are involved.

SUPPLEMENTARY MATERIAL

This article contains supplementary material and it can be viewed at publisher's website.

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