Solar activity–climate relations: A different approach

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Abstract

The presentation of solar activity–climate relations is extended with the most recent sunspot and global temperature data series. The extension of data series shows clearly that the changes in terrestrial temperatures are related to sources different from solar activity after ~1985. Based on analyses of data series for the years 1850–1985 it is demonstrated that, apart from a region of positive deviation followed by a similar negative excursion in Earth’s temperatures between ~1923 and 1965, there is a strong correlation between solar activity and terrestrial temperatures delayed by 3 years, which complies with basic causality principles. A regression analysis between solar activity represented by the cycle-average sunspot number, SSN_A, and global temperature anomalies, ΔTA, averaged over the same interval lengths, but delayed by 3 years, provides the relation ΔTA ≈ −0.009 (± 0.002) SSN_A. Since the largest ever observed SSN_A is ~90 (in 1954–1965), the solar activity-related changes in global temperatures could amount to no more than ±0.4°C over the past ~400 years where the sunspots have been recorded. It is demonstrated that the small amplitudes of cyclic variations in the average global temperatures over the ~11 year solar cycle excludes many of the various driver processes suggested in published and frequently quoted solar activity–climate relations. It is suggested that the in-cycle variations and also the longer term variations in global temperatures over the examined 135 years are mainly caused by corresponding changes in the total solar irradiance level representing the energy output from the core, but further modulated by varying energy transmission properties in the active outer regions of the Sun.

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1. Introduction

At this time there are intense ongoing discussions as well as extensive observational and modeling efforts to disclose whether anthropogenic activities have marked influence on Earth’s climate characterized, for instance, by the average global temperature. However, the question of the influence from solar activity remains important and unresolved. Here, the term “solar activity” relates to changes in the state of the Sun and its output of importance to the Earth.

For many solar activity types it is now possible to obtain a long-time record. The magnetic fields embedded in the solar wind influence the level of galactic cosmic radiation (GCR) received by the Earth. Direct measurements of the GCR level have been made with a high degree of reliability by neutron monitor systems around the world for the past 50 years and by less certain measurements for almost a century. The solar wind intensities have been recorded directly by in-situ spacecrafts since the measurements by Pioneer 6–8, launched during 1965–1967, and indirectly by the geomagnetic signatures, e.g., expressed in the aa index, through around 150 years. Similarly, the solar UV- and X-ray levels have been monitored directly by fairly precise measurements from space through around 40 years and indirectly and continuously through monitoring of their proxy, the 10.7 cm solar radio wave emissions, through more than 60 years. For many solar activity parameters it is thus possible to make reliable correlations with the occurrences of sunspots used as the most imminent indicator of the solar activity level. Then, using the varying sunspot number as a proxy, the relations between specific solar activity parameters and the Earth’s climate can be pursued over longer spans of time than possible on the basis of direct measurements.

Consequently, we may examine the causal relationships for climate effects where a specific cause related to solar activity is postulated. This group comprises climate effects related to global electric fields and currents generated by the solar wind and its embedded magnetic field (e.g., Burns et al., 2007; Tinsley et al., 2007); variations in the atmospheric circulation or ozone content related to solar UV- and X-ray levels, solar high-energy protons and radiation belt electrons (e.g., Labitzke and van Loon, 1997; Hood, 1997; Haig, 2001; Erlykin et al., 2010); variations in cloud cover caused by changes in cosmic radiation (e.g., Pudovkin and Veretenenko, 1995; Svensmark and Friis-Christensen, 1997;
Svensmark, 2000; Shea and Smart, 2004); increased atmospheric vorticity at solar wind sector changes (Wilcox et al., 1973).

For the total solar energy output the situation is different. The measurement of spectral solar irradiance (SSI) (Lean, 2000; Harder et al., 2009; Foukal et al., 2006) and total solar irradiance (TSI) (Pap and Fröhlich, 1999), which also includes solar astrometry measurements (Thuillié et al., 2005; Boscardin et al., 2009; Emilio et al., 2010), are very complicated and the precise calibration of the TSI level to the degree required for climate studies is extremely difficult (e.g., Krivova and Solanki, 2008). Thus, presently archived TSI data may provide a fair impression of the relative variation over a short span in time, for instance, a single solar cycle, whereas the trend over a longer span of time is rather uncertain (e.g., Lean et al., 1995; Mendoza, 2005; Lean, 2000; Fröhlich, 2009).

With causality and correlation studies we cannot prove any specific theory correct; however, if a proposed solar activity–climate mechanism fails to comply with causality principles, it can be rejected. For the processes referred to above, the variations in the appointed parameter, for instance, the level of galactic cosmic radiation, corresponds closely to the cyclic variation in sunspot number. It will be argued below that such variable parameters could not possibly be the dominant cause of the observed relation between solar activity and global temperatures. Furthermore, many of the presented processes have a causality problem since it appears that major changes in solar activity follow (not precede) corresponding changes in Earth’s climate. To resolve the causality problem some of the presentations resort to using excessive averaging of the solar activity parameter in order to shift the timing.

The analyses of the relations between solar activity, as monitored through the sunspot numbers, and Earth’s climate represented by the terrestrial temperatures, are divided in two lines. In one line of analyses the sunspot numbers and the terrestrial temperatures are averaged over the length of complete ~11 year solar cycles. The averaging intervals for the temperatures are displaced (by 3 years) to obtain optimum correlation. Otherwise, no further smoothing or shifting is applied to the data. These analyses shall define the long-term relations between the cycle-average parameters and also provide the basis for a discussion of causality problems. In another line of analyses the in-cycle variations in sunspot numbers and terrestrial temperatures are contrasted. This part serves to provide the basis for discussions of the potential interaction mechanisms that might relate global climate to solar activity.

Many investigations have referred to the publications by Eddy (1976), Reid (1987, 1999), and Friis-Christensen and Lassen (1991) (hereafter Eddy’76, Reid’87, Reid’99, and FCL’91, respectively) in support of theories of solar activity as the cause of climate changes. Eddy’76, Reid’87, and Reid’99 use the sunspot numbers to characterize solar energy output while FCL’91 introduced the Solar Cycle Length (SCL) as a relevant parameter to characterize solar activity based on its inverse correlation with the sunspot number (stronger cycles run faster). The SCL is an interesting parameter and no doubt important for studies of solar physics. However, even now, two decades later, it is not resolved whether it relates to any solar energy output parameter of importance for the Earth. Still, the SCL parameter has been used in further publications (e.g., Lassen and Friis-Christensen, 1995; Thejll and Lassen, 2000). These basic reports are first examined more closely in order to underline the differences from the approach taken here.

2. Solar activity and Earth’s climate parameters

A parameter often used to characterize solar activity is the Wolf (1868) Zürich sunspot number \( R = k[10^g+s] \). It has been attempted to deduce sunspot numbers from astronomer’s reports as early as the 16th century. Restorations of a continuous series of sunspot numbers have been made back to around 1600 (e.g., Eddy, 1976). The absolute magnitudes of the early sunspot numbers are rather uncertain. From around 1850 the sunspot numbers are considered observationally reliable.

The official index, the “International Sunspot Number”, is published daily by the Solar Influences Data Center (SIDC) at the Royal Observatory in Belgium. Series of sunspot numbers are published jointly by SIDC (sidc.oma.be) and by the National Geophysical Data Center (NGDC) at NOAA in Boulder, USA, (ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS). Here we focus on the interval from 1850 to present based on the series of monthly average sunspot numbers provided to 1749 (sunspot cycle no. 0) and through 2010 (cycle 24). Furthermore, we use the table of (decimal) years of cycle maxima and minima provided by NGDC back to cycle ~12 starting year 1610 ending with the sunspot minimum in 2008 at the start of cycle 24. In their definition of times of maxima and minima, NGDC notes: "When observations permit, a date selected as either a cycle minimum or maximum is based in part on an average of the times extremes are reached in the monthly mean sunspot number, in the smoothed monthly mean sunspot number, and in the monthly mean number of spot groups alone. Two more measures are used at time of sunspot minimum: the number of spotless days and the frequency of occurrence of "old" and "new" cycle spot groups."

The NOAA definition of solar cycles 9–24 is shown in Table 1, which also presents the min-to-min and the max-to-max cycle-average sunspot numbers based on SIDC monthly sunspot numbers.

The Earth’s climate could be characterized by some average temperature. It is frequently debated whether the atmospheric or the oceanic temperatures provide the proper measure of Earth’s climate. It is also discussed whether northern or southern hemisphere data or global average values are the more representative choice. The present work uses a selection of monthly average temperature anomaly series (base period 1961–1990) provided by the Hadley Centre at the UK Meteorological Office in collaboration with the Climatic Research Unit at the University of East Anglia (Brohan et al., 2006). These data sets are made both on a global basis and for the northern and southern hemisphere separately and further divided into land-surface (CruT3gl/nh/sh), sea-surface (HadSST2gl/nh/sh), and combined land-surface/sea-surface (HadCrut3gl/nh/sh) temperature data sets. Monthly and yearly average temperatures are provided from 1850 up to 2010. The global combined land-surface/sea-surface temperature HadCrut3gl data set is considered the primary data set for the present work, but the northern hemisphere version as well as the global and northern hemisphere versions of the land-surface and sea-surface temperature data sets are considered for consistency. The HadCrut3gl (2010) data series is displayed in Fig. 1 along with the SIDC sunspot number. The min-to-min and max-to-max cycle-average values have been marked by square dots and asterisks, respectively. The thin black lines provide simplified sketches of the variations through segments of the temperature and sunspot data.

When the temperature data displayed in the top panel of Fig. 1 are compared to the sunspot data in the bottom panel of the figure, there appear to be similarities; for instance the slowly decreasing, relatively low level in the last half of the 19th century, the rise in the beginning of the 20th century, and the decline past the middle of the century. For the rise in temperature after ~1985, a different forcing mechanism rather than solar activity has arrived at the end of cycle 22, that is, between 1980 and 1986 (e.g., Lockwood and Fröhlich, 2007). Whether this forcing is caused by anthropogenic activities, and if so, whether it is related to the CO2 concentration in the atmosphere, however intriguing, is not the subject here. In the present analysis the data from cycle
23 are totally discarded and the data from cycle 22 are mostly avoided as well.

Looking into the details of the sunspot and temperature courses discloses considerable differences. The most prominent features in SSN and temperature variations are the rises in the first half of the 20th century. However, the rise in temperature starts in /C241910 and ends in /C241943. The similar-looking rise in sunspot numbers starts around 1930 and ends in /C241960—that is, around 15–20 years later than the rise in temperature. Furthermore, the decline in temperature starts in 1943 to reach a minimum in 1954 while the solar activity appears to maximize in 1959 and only after 1960 declines to reach a minimum in 1970. Again, the temperature changes lead by around 15–20 years over the changes in solar activity characterized by the sunspot number. It is, of course, irrational to conclude that Earth’s temperature affects the solar activity; thus, sophisticated data processing techniques (e.g., smoothing over several cycles) come in play in Reid87, Reid99, and FCL91. Here, we shall avoid smoothing over more than one cycle and suggest a different explanation to restore proper causality.

3. Examination of the solar activity–climate relations reported in Reid (1987, 1999)

The publications by Reid (1987, 1999) are among the referenced key papers (see e.g., Coffey et al., 2010; Viereck, 2001) to support the impression of a close relation between solar activity scaled by the sunspot number and Earth’s climate characterized by global temperatures at land and in the oceans. Hence it is considered worthwhile to examine the analyses made in these papers. A key figure is figure 5 in Reid (1999), which is reproduced here as Fig. 2. The upper part of the left panel displays the 11-years running mean sunspot numbers and departures of sea-surface temperatures from the long-term mean in thin line. Polynomial approximation in heavy line. Temperature data from Bottomley et al. (1990); units: hundredths of a degree Celsius. Composite figures from Reid (1999); figure 5.
By a first view the figure appears very convincing. The oceanic temperatures are very consistent in all three major ocean basins and also consistent with the global sea-surface temperatures (SSTs) shown in the lower left part of Fig. 2. The time series of sunspot numbers appear to have the same shape as the temperature curves. Both time series are subjected to corresponding 11-years running averages. The smoothed curves for sunspot numbers and temperatures are exceptionally alike and the major rise in solar activity starts before the year 1900 well ahead of the rise in temperature starting just after 1900. Hence the physical basis appears to be sound.

However, we shall examine in more detail the processing of the relevant data. The data displayed in the left panel of Fig. 2 (Reid, 1999, figure 5a) have been read off to provide numerical files. The values can now be displayed in diagrams like Fig. 1 above. Fig. 3 displays the most recent (2010) SIDC tables of yearly average sunspot numbers and the UK Met.Office/Hadley sea-surface temperature (SST) anomaly data, HadSST2gl (2009), in blue lines (note: the sea-surface temperatures are used here for consistency with Reid99). The cycle-integrated sunspot numbers are marked by black square dots.

The Reid99 11-year average (in thin red line) and polynomial fit (heavy green) temperature data have been inserted in the upper part of Fig. 3. Note in the polynomial fit that the distinct peak around 1940 and the decline from 1950 to 1960 also seen in Fig. 1 have disappeared. Thus, the temperatures appear now to locally maximize around 1960.

The Reid99 11-year sunspot numbers (thin red line) and polynomial fit (heavy green) have been inserted in the lower part of Fig. 3. Note in the 11-year curve, that the Reid99 running 11-year technique shifts the sunspot curve back. One example is the course through cycles 18 and 19 (1945–1965). One would expect the peak in the curve (thin red line) representing solar activity to be positioned at or near the top of the largest ever recorded solar maximum in 1958 (see Fig. 1). However, the major peak has here been displaced to ~1953 at the trailing edge of cycle 18, i.e., shifted half a cycle back in time. With this shift and the extended smoothing by the polynomial fitting, the solar activity, according to the polynomial fit curve (heavy green line) appears to reach a local maximum level already at 1945 after which the level flattens out until a final rise starting around 1980.

A corresponding effect is seen at the epoch of minimum activity in the beginning of the 20th century. The rise in solar activity starts no earlier than 1915 at the beginning of cycle 15. However, the polynomial fit makes the rise appear to start before 1900. Note the large discrepancy appearing at times between the polynomial fit and the 11-year running averages as well as the differences to the line connecting the cycle-integrated average sunspot numbers.

These “adjustments” serve to change the course of the polynomial fits for the temperature anomaly and sunspot number series such that the solar activity now seems to rise well before the temperature increase in the beginning of the 20th century and to reach maximum amplitude before the middle of the century (~1945) well before the global temperatures represented by the polynomial fit reach their maximum level (~1955). Thus the causality principles are apparently obeyed. However, the data handling procedures used in Reid99 are questionable. The running average and polynomial fitting techniques should be used with extreme caution in order to avoid odd effects on important timing relations by calculating present conditions with additions from past and (in particular) future changes.

4. Relations between solar cycle length and climate

Instead of using the sunspot number as an indicator of solar activity, it was suggested by Friis-Christensen and Lassen in 1991 to use the length of the solar cycle as a parameter to characterize the features of importance for the changes in Earth's climate described by terrestrial temperatures. Their data are displayed in the top fields of Fig. 5 composed of data from Figs. 1 and 2 in FCL91. From top left panel of Fig. 5 it is clear that the rise during 1930–1960 in
solar activity as characterized by the cycle-average sunspot numbers occurs well after the rise in temperature during 1910–1943. There is, as noted above, a delay of 15–20 years between the two otherwise similar-looking characteristic features, which considering causality principles should exclude the temperature rise from being caused by solar activity.

However, they (FCL91) have found a way around this problem by using instead of sunspot numbers the strongly averaged cycle length as a parameter to characterize solar activity. It is still unclear even now, two decades later, what the physical parameter related to the cycle length could be; but the possibility cannot be ruled out that the length of the activity cycle could relate to some solar feature of importance to the Earth's climate, for instance the total solar irradiance power.

Anyway, we shall analyze the effects of the FCL91 data processing scheme. Firstly, it should be noted that the length of the solar cycle is coupled to the sunspot activity. On basis of possible samples since solar cycle 10 starting in 1856, Fig. 4 displays the correlation between cycle length and cycle-average sunspot number calculated as a function of the relative timing between the two parameter sets. Fig. 4 indicates as the general trend that the cycle length is correlated with the sunspot activity (stronger activity during shorter cycles) but displaced on the average by around two cycles.

The second shift is introduced by the averaging method applied using the Gleissberg (1944) “1–2–2–2–1” weighted running averages of the cycle lengths for separate cycle minima and maxima series. The effect of the method is to flatten the strong variability in solar cycle length and substantiate the average two cycles shift obtained by the choice of using the SCL parameter instead of the sunspot number. Thereby, the start and end dates for the change in solar activity source parameter are displaced by up to 2 cycles (~22 years) similar to the effect produced by the polynomial fit averaging in the Reid99 data processing (see the heavy green lines in Fig. 3). The result obtained by FCL91, as seen in their Fig. 2, is reproduced in the top right panel of Fig. 5. Now, the causality between solar activity and terrestrial temperatures appears to be proper but on a questionable basis.

There are further questionable features in the diagram. The final upturn indicated by last points for the running average cycle length is in error. As noted by the authors, for the last three points (at ~1976, 1980, and 1986) the precise lengths of future solar cycles are uncertain.

Fig. 4. Correlation of cycle lengths and cycle-average sunspot numbers vs. relative timing (cycle length values displaced) for cycles 10–23 (~1850–2008). Both min-to-min and max-to-max lengths and averages are used for the statistics.

Fig. 5. Solar activity parameters and terrestrial temperature variations. The top diagrams display re-plots of FCL91 data. Left column of diagrams use sunspot numbers, right diagrams use cycle lengths to represent solar activity. The bottom diagrams display sunspot data and northern hemisphere land-surface temperatures processed as done in FCL91 but based on recent data series.
could not be known at the time of the publication; hence, predicted values have been used. In their update of the figure (Lassen and Friis-Christensen, 2000) the final upturn in cycle length is maintained, but now it is based on trivial arithmetic errors. These inaccuracies have been discussed by Laut and Gundermann (2000), Laut (2003), and Damon and Laut (2004). With proper corrections, instead of the final upturn making the length curve track the recent temperature trend, the cycle length curve flattens after 1960 and then turns downward after 1986, giving now stronger departures than that shown in FCL91 from the upward trend in the important terrestrial temperature development.

Another characteristic feature in the top right field of Fig. 5 is the downward spike seen in both curves at ~1889. The downward peak in temperature is based on the average formed over the max-to-max interval from 1883.9 to 1894.1. For the length of this particular cycle (i.e., 10.2 years, Table 1), the related point would in reality form an upward extreme in the plot. The particular averaging procedure and the occurrence of longer cycle lengths in the adjacent max-to-max intervals form the downward excursion. If instead the running average values were formed, for instance, by mixing min-to-min and max-to-max lengths then the downward peak in cycle length that appears to match so perfectly with temperatures would completely disappear. Hence, it should be considered an artefact.

In summary, the apparent perfect match between the cycle length and the terrestrial temperature is to a large extent due to the questionable data processing techniques, incomplete data coverage, and arithmetic errors.

5. Update of FCL91 data presentations

At present (2010), sunspot data are available for two more cycles compared to the situation for FCL91. Furthermore, the temperature data have been scrutinized and refined. Hence it might be worthwhile to recalculate the relations between sunspot and temperature data using the same procedures as those used in the referenced work. The international (SIDC) sunspot number, the solar cycle max/min data issued by NOAA/NGDC, and the northern hemisphere land-surface temperature data, CruTem3nh, are used since these sources were also used by FCL91.

As noted above, the data in FCL91 Fig. 1 (sunspot number and northern hemisphere temperatures) and Fig. 2 (cycle lengths and temperatures) spanning from around 1865 to 1985 have been re-plotted in the top left and right diagrams, respectively, of Fig. 5. In the bottom part of the figure the corresponding northern hemisphere land-surface data stretching from 1850 to 2010 were plotted using the same procedures and scales as those of the top fields. The solar cycle max and min times are defined from the NOAA values shown in Table 1. The monthly SIDC sunspot numbers and the global temperatures have been averaged over min-to-min cycle times and referred to the sunspot-weighted average cycle time (approx. at the middle of the cycle) while the averages from max-to-max have been referred to the cycle minimum times. Thus, point by point, the sunspot number and temperatures have been integrated over the same interval and referred to the same time. For further compliance with FCL91 the temperature anomaly values have been adjusted to refer to the mean temperature value through the interval from 1951 to 1980.

For the cycle lengths displayed in the top right field of Fig. 5, the FCL91 procedure uses Gleissberg (1944) “1-2-2-2-1” running average smoothing of min-to-min lengths \(L_{\text{min}}\) and max-to-max lengths \(L_{\text{max}}\) separately. Thus the value referring to the middle of cycle \(N\) is constructed as \((L_{\text{min}}(N-2)+2L_{\text{min}}(N-1)+2L_{\text{min}}(N)+2L_{\text{min}}(N+1)+L_{\text{min}}(N+2))/8.\) The corresponding max-to-max value for cycles \(N\) to \(N+1\) is referred to the time for minimum at the start of cycle \(N+1\). It could be argued that the comparison of temperatures averaged over one cycle and cycle lengths averaged over 5 complete cycles is inconsistent. Anyway, since this procedure was used by FCL91, it is repeated here. Furthermore, for the calculation of the second last point of FCL91, the next predicted extreme value was used. Here, correspondingly, for the third and second last points, the NOAA (2010) predicted cycle duration (~11 years) is used to determine the length of cycle 24 (ending mid 2019) and error bars have been plotted between points for the shorter (10 years) and longer (12 years) duration. For the last point, the actual length of the latest available cycle has been used both in FCL91 and here (marked by a circle).

The two top and the two bottom diagrams in Fig. 5 are, in principle, based on the same data up to 1990 (year of preparation of FCL91). The bottom diagrams use in addition the recent data from 1990 to 2010. Before 1980 the FCL91 data and the new temperature and sunspot data displayed in the left figures roughly agree although small differences caused by recent updates of past data are noticed. The max-to-max sunspot numbers at 1986 disagree probably because the FCL91 uses very large predicted sunspot numbers for the remaining part of the (at the time of publication) not yet completed cycle 22. Since 1986 the more recent sunspot and temperature data deviate strongly from their past trends of approximate correspondence. The cycle-average temperatures shoot up while the sunspot numbers continue decreasing.

The divergence of trends is even more pronounced in the new temperature and cycle length data displayed to the right in the bottom diagrams. Here the two curves separate already from 1976. Furthermore, the upturn displayed so pronounced for the last cycle length in FCL91 has been replaced by a steady decrease in cycle lengths for all data points since 1976. The final (erroneous) cycle length upturn feature was an important part of the argumentation presented in FCL91 since it took the alleged close relation between climate and solar activity up to latest epoch (~1990).

In summary, the new data demonstrate a fairly close resemblance between the trends in temperature and the 1-2-2-2-1 smoothed cycle length data up to 1976 and a strong divergence thereafter. For the cycle-average temperature values and sunspot numbers the strong divergence appears only after 1986. However, for these data the major problem is still the delay of around 15–20 years between the rise in temperature during ~1910–1944 followed by the decrease from 1945 to 1960, and the corresponding increase in sunspot numbers from ~1930 to 1959 followed by the decay from 1960 to 1970.

6. Correlation and timing analysis

This far, the analyses of the relations between solar activity parameters and the terrestrial climate have mainly been based on subjective impressions from plots of the relevant data. In order to provide more objective and quantitative substance to the important question, correlation and regression techniques shall be employed. Such techniques face (at least) two major problems. Both temperature and sunspot data are getting more and more uncertain back in time, particularly prior to 1850. This feature calls for a limitation by not using the more distant solar cycles. On the other hand, it is evident that a different temperature control factor enters the relations after around 1985. Thus, the most recent cycles are also invalid for use in solar activity–climate analyses.

Therefore, the correlation analysis interval shall start with cycle 10 beginning in 1856 and include cycle 21 ending in 1886. An interval of particular interest is the span of cycles 16–19 beginning 1924 and ending in 1965 within which the major temperature and solar activity increases take place. First, the relation between solar cycle length and terrestrial temperatures shall be examined. For the cycle lengths, the NOAA/NGDC table
of cycle times is again used (Table 1). For the temperatures the UK-Met Office/Hadley Centre global combined land-surface/sea-surface set, *HadCruT3gl*, is used. The diagram in Fig. 6 displays the temperature anomaly samples vs. solar cycle length using both max-to-max and min-to-min interval lengths (as in FCL91). Cycle numbers have been noted at the points. The temperatures are averaged over the respective min-to-min intervals (displayed by square dots) and max-to-max intervals (displayed by asterisks). The regression slope and the correlation coefficient (-0.3889) calculated on basis of cycles 10–21 only (discarding the recent cycles 22 and 23) are displayed in the left part of the diagram.

Turning now to the corresponding analysis of terrestrial temperature anomalies vs. sunspot numbers, a representative example based on the *HadCruT3gl*-2010 temperature data set is displayed in Fig. 7. In this figure the temperature anomaly data and the sunspot numbers have been averaged over the same length of the min-to-min or max-to-max cycle intervals. However, the temperature intervals have been displaced forward by the amount NDY = 3 years to obtain the highest correlation. The cycle number has been written at each point. The points in the diagram look much more coherent than the corresponding cycle length points in Fig. 6. The calculated regression coefficient (slope), base temperature, and correlation coefficient have been written in the diagram. The derived correlation coefficient is 0.7716.

From Fig. 7 where all data spanning from 1856 to 1986 have been included it is readily seen that the points from cycles 16–19 differ from the remaining points. This interval marks the transition in solar activity from the moderate level held during the 19th century and the beginning of the 20th century to the high level held since the middle of the 20th century. In order to disclose the precise effect of the transitional period, the data from cycles 16–19 have been

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![Fig. 6. Cycle-average temperature anomalies vs. cycle length for cycles 11 through 23. Slope and correlation calculated from min-to-min and max-to-max values for cycles 10–21 only.](image)

![Fig. 7. Cycle-average temperature anomalies vs. sunspot numbers for cycles 10 through 21. Slope, base temperature, and correlation calculated for all cycles 10–21 with temperatures delayed by 3 years.](image)

![Fig. 8. Cycle-average temperature anomalies vs. sunspot number for cycles 10–15 and 20–21. Slope, base temperature, and correlation calculated for cycles 10–21 excl. cycles 16–19. Temperatures delayed by 3 years.](image)

![Fig. 9. Time history of deviation between sunspot-regulated base line based on average regression (0.009 SSN), base temperature (−0.7 °C) and actual cycle-average temperature anomalies. Temperatures delayed by 3 years.](image)

![Fig. 10. In-cycle yearly sunspot numbers (SIDC) and global temperature anomalies (*HadCruT3gl*) during solar cycles 10–23. Thin lines with dots display values for cycle 19. Averages shown by the heavy red lines are calculated for cycles 10–21. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)](image)
exempted from the processing displayed in Fig. 8. Here, the regression, the base temperature, and the correlation coefficient have again been calculated. The data points including those provided from the cycles 20 and 21 after the transition interval during cycles 16–19 are evidently now more closely positioned around the regression line and the correlation is now 0.9746, i.e., very high.

A closer picture of the time history of the temperature data through the studied interval (1856–1986) is provided in Fig. 9. Here, the averages of the regression slopes and base temperatures noted in Figs. 8 and 9 have been used to provide a base line for the temperature development. During cycles 16 and 17 the temperatures display positive deviations of up to around 0.25 °C while during cycles 18 and 19 there are corresponding negative deviations from the general trend. These deviations are further analyzed in the discussion section below.

7. Temperature variations through individual solar cycles

With the varying solar cycle length and the abundance of terrestrial climate cycles with periods around 5–10 years, simple harmonic analyses are inadequate to define the average in-cycle temperature variations. Hence, Fig. 10 has been constructed to examine the yearly average temperature anomaly variations through the 14 solar cycles experienced since 1850 by superposed epoch analyses. The lower part of the diagram displays the SIDC sunspot numbers through the years of the individual solar cycles relative to the central time (t=0) for each cycle derived by weighting the departures by the sunspot number (Table 1). The curve in thin, blue line marked by dots shows the SSN values during solar cycle #19. This cycle peaking in 1957/1958 was the most active cycle within the span of 160 years from 1850 to 2010. The curve in heavy red line displays the average sunspot number for each year relative to the central times of cycles 10–21.

The upper part of Fig. 10 displays the global temperature anomalies averaged year-by-year referred to the same relative solar cycle years within cycles 10–23 as the sunspot numbers displayed in the lower part. The thin blue line with dots displays global temperatures recorded during cycle 19. The heavy red line displays the average values derived for the first 12 of the 14 cycles represented in the plot, excluding (again) cycles 22 and 23.

![Graph showing temperature variations through individual solar cycles](image-url)

Fig. 11. Yearly values of multi-cycle-average yearly temperature anomalies vs. relative cycle time. The top panel uses *HadCruT3gl* combined land–sea temperatures, the middle panel uses *CruTem3gl* land temperatures while the bottom panel uses *HadSST2gl* sea-surface temperatures. The top curve in each panel displays temperatures calculated for 6 cycles with average sunspot number SSN > 50, the bottom curve shows temperatures calculated for SSN < 50, while the middle curve displays average temperatures for all 12 cycles. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)
The average temperature anomalies for all cycles 10–21 are plotted in the three panels of Fig. 11. In the top panel the average temperature anomalies derived from the HadCrut3gl combined land–sea surface data based on the 6 most active cycles (SSN > 50) are plotted in the upper curve in violet line while the corresponding anomalies based on the 6 least active years (SSN < 50) are displayed in the bottom blue curve. The red curve in the middle is a replot from Fig. 10 and displays the averages over all 12 cycles considered here. The average temperature anomalies (relative to 1961–1990 mean) are larger in cycles with higher average sunspot number (SSN > 50) than in years with lower average sunspot activity (SSN < 50).

Noting that the data used for the upper (SSN > 50) and the lower (SSN < 50) curves are from different solar cycles (i.e., independent data), several important and consistent features are seen in the average temperature development within the cycle. The positive trend through the cycle is noted for all three curves. This trend reflects the general increase in temperatures between ~1850 and ~1985 and matches the corresponding trend found in the sunspot numbers. It is important to note that the modulation of temperatures over the solar cycle is fairly small. However, all three temperature curves display a weak maximum shifted 2–3 years forward with respect to the cycle central time. The peak value over the sliding average is around 0.05 °C for all three curves. The temperature curves have consistently a still weaker local maximum at around 1 year before the central time. The peak is barely visible for the weaker cycles (SSN < 50) but quite pronounced for the most active cycles (SSN > 50). For the middle (all cycle) curve the peak value over the sliding average is around 0.025 °C. The peak time corresponds to the time of the peak in sunspot number.

The corresponding calculations have been made for temperature anomalies based on the CruTem3gl global land-surface temperatures and for the temperatures based on the HadSST2gl sea-surface data. The results are displayed in the middle and bottom panels of Fig. 11. The average slopes are about the same for these cases as those reported for the combined land–sea surface case. However, there are some consistent differences among the panels. For the most intense sunspot cycles (SSN > 50), the peak deviation from the average trend at the sunspot peak time (~1 year before central cycle time) is markedly larger for the land-surface temperature anomaly data and considerably smaller for the sea-surface data. The deviation 2–3 years after the central cycle time is shorter in duration for the land-surface temperature cases compared to the combined land–sea surface data while the corresponding deviation for the sea-surface temperatures have a more extended duration. These differences comply well with expectations based on the nature of the temperature data basis (i.e., larger inertia in sea than in land temperatures).

8. Discussions

The data presented above leaves no doubt concerning the most recent climate developments. A different forcing mechanism has arrived at the end of cycle 22 and has been a significant factor since ~1985 (e.g., Lockwood and Fröhlich, 2007). As noted in the introduction (Section 1), the possible cause of this climate development is not the issue here. In the present analyses the data from cycle 23 are totally discarded and the data from cycle 22 are mostly avoided as well.

8.1. Variations within individual cycles

The in-cycle variations in solar activity and terrestrial temperatures displayed in Figs. 10 and 11 demonstrate that the temperature anomaly develops gradually over the solar cycle. There is no indication that the varying solar activity through the individual cycles has effects on the temperature anomalies that anyway nearly matches the variation in sunspot number. This feature speaks against solar activity–climate theories that build on processes where the forcing could be expected to be directly proportional to the actual solar activity level expressed, for instance, in the monthly or yearly average sunspot number. This issue shall be examined more closely in the following.

The possible effects of varying forcing (e.g., characterized by some solar activity-related parameter) could be smoothed out by the inertia (e.g., the Earth’s heat capacity) in the affected system. But increasing the smoothing also increases the effective delay between level changes in the source intensity and the corresponding level changes in the affected system. Fig. 12 is meant to illustrate the problem. The forcing is here described by a sinusoidal function, F, depicted by the strongly varying blue curve, which for a time maintains a constant average level. At some time (at t = 0 in the diagram), the intensity of the source function is stepped up to a higher level, which is then maintained. The affected system, characterized by a state function, T, indicated by the red curve in thin line, has at t = 0 reached steady state conditions with some phase-shifted modulation impressed by the variations in the source function. When the source intensity is stepped up then the affected system could not possibly attain the new steady state at once. Instead, as sketched, it may take several cycles to reach the new level. The sketch in Fig. 12, furthermore, illustrates by the heavy green curve the smoothing of data used, among other, in Reid99 and FCL91. It is seen, that the green curve takes off ~2.5 cycles before the actual change and reaches final level 2.5 cycles after the source level change (corresponding to the Gleisberg “1-2-2-2-1” averaging over 5 cycles, or the Reid99 polynomial smoothing). In addition to giving improper shifts in onset times, the heavy smoothing suppresses possible in-cycle variations.

More specifically, for the construction of Fig. 12 it is assumed that there is a final state, Tf, proportional to F that the affected system would reach with steady (constant) forcing. Thus Tf = aF. Furthermore, for an actual forcing level, F, it is assumed that the rate of change in the system is proportional to the difference between the end state, Tf, corresponding to F and the actual state, T. Thus dT/dt = b(Tf − T) where b is a measure of the inertia in

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Fig. 12. Sketch of sinusoidal source function (e.g., sunspot number for solar activity) in blue line with a sudden step in average intensity at t = 0 (shown by the dashed line), and the derived response function (e.g., global temperature anomaly) in thin red line. The heavy green line displays the result of (improper) heavy averaging of response data used, e.g., in Reid99 and FCL91. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
the affected system. Combining the two relations gives
\[\frac{dT}{dt} = b(T_f - T) = b(aF - T)\] (1)

Taking the principles of the above sketched relations to the solar activity-global climate system, one may note that the level of activity characterized by the cycle-average sunspot number was relatively constant or slightly decaying from 1850 up to around 1925 at values around 30–50 (see Table 1 and Fig. 1). Then, from the start of cycle 16 in 1923 and through the following cycles 17, 18, and 19 ending around 1965 the average sunspot activity has increased to reach a new level around 60–90, that is, an increment by a factor ~2 or by around 30–40 units. During the same time the temperature anomaly level increased from an initial level of ~0.30 to ~0.50 °C to a new level of ~0.20 to 0.00 °C, that is by around 0.30 °C. Thus, the climate "sensitivity", characterized by the parameter \(a\), to level changes in solar activity is around 0.01/(unit SSN level) (as also found earlier by the regression analyses displayed in Figs. 7 and 8). For the inertia characterized by the parameter \(b\), we have no a priori knowledge except that the inertia must be successively larger (\(b\) smaller) for land vs. combined land/sea-surface vs. sea-surface temperatures. The use of the relation in Eq. (1) on the solar activity-terrestrial climate system is illustrated in Fig. 13.

The bottom curves in Fig. 13 display yearly sunspot numbers and the min-to-min (square dots) and max-to-max (asterisks) cycle-average sunspots. The top curves display the yearly average HadCrut3gl-2010 (land/sea-surface) temperature anomalies and their cycle averages. These curves were also shown in Fig. 1. The two middle sets of curves depict the temperature response functions and their cycle averages derived from the monthly sunspot numbers, SSN. The curves are initiated in 1850 assuming that the solar–terrestrial system had attained a steady state at that time corresponding to a SSN level of 52 (average of SSNAL and SSNAU in cycle 10, Table 1). The relation in Eq. (1) has been subjected to numerical integration. For each step from month \(i\) starting at a temperature \(T_i\), the temperature \(T_{i+1}\) for month \(i+1\) is derived using Eq. (1) in the version
\[T_{i+1} = T_i + b(a\text{SSN}_i - T_i)\] (2)

The results obtained for different values of the inertia parameter, \(b\), are displayed in Fig. 13. The treatment of the complicated solar terrestrial system with the simple relation in Eq. (2) is, of course, an extreme over-simplification. However, the displayed curves, which describe the interplay between modulation, effective delay, and flattening, indicate characteristic effects of possible forcing terms that vary over the solar cycle in concordance with the solar activity characterized by the sunspot number. Furthermore, the development of the system parameter (global temperature) with time relative to the forcing parameter (solar activity) also presents the correct causal relations for such cases.

With the inertia (\(b = 0.020\)) used for the upper middle set of response curves the amplitudes of the long-term variations are restored but the cyclic modulation is much greater than that observed in the terrestrial temperatures. Furthermore, the course is delayed by around 20 years with respect to the real temperatures. With the larger inertia (\(b = 0.004\)) used for the lower middle set of response curves the modulation has about the amplitude observed in the global temperatures but the course is further delayed and the excursions are flattened. Hence the result is further away from resembling the shape of the real temperatures shown in the top curves. The main result from the simple modeling in Figs. 12 and 13 is to exclude forcing by drivers that vary over the solar cycle in concordance with solar activity characterized by the sunspot number, from having major effects on the global climate.

The solar UV- and X-ray radiation effects on the atmosphere is an example of forcing that has strong variation over the solar cycle and, consequently, could not be the main cause of the temperature anomalies. The same argument comes into play for the high-energy solar particle radiation, notably the high-energy solar protons related to flare activity, which also have very pronounced variations through the solar cycle. Other suggested processes like Joule heating of the upper atmosphere powered by the solar wind electric field and plasma conditions are further examples of source mechanisms that varies strongly over the solar cycle and thus fail to produce the observed characteristics of the temperature anomaly variations.

The effects of the galactic cosmic radiation (GCR) on the climate through its control of the cloudiness (e.g., Pudovkin and Veretenenko, 1995; Svensmark and Friis-Christensen, 1997; Svensmark, 2000), also fail to comply with gradual temperature
changes. The GCR level is to some extent controlled by the shielding effect of the solar magnetic field extended into the interplanetary space by the solar wind. The alleged temperature effect relies on the assumed net decrease in the energy available near the surface of the Earth as the result of the reflection of solar energy by the additional cloud cover created through nucleation at ions generated by the cosmic radiation. The reflection of solar energy is supposed to dominate over the restraining effects on the energy balance from the excess cloud cover. Neutron monitor data have shown a very close correlation between solar activity characterized by the sunspot number and the depression of GCR through the recent 6 solar cycles. Such data are displayed in Fig. 14 in a format similar to that used for Fig. 13 except for the much shorter span of time. The close correspondence between the GCR depressions and SSN should be noted.

The cloud cover effect on the temperature must be quite prompt since the effect has been reported even for the Forbush decreases lasting only a few days (e.g., Pudovkin and Veretenenko, 1995; Svensmark, 2000). Hence the temperature effect produced by the GCR depression process should follow fairly closely the varying sunspot number through the solar cycle to produce a strong modulation of global temperatures like shown, for instance, by the upper middle curve in Fig. 13. Again, this behavior does not comply with the requirement that the main forcing process should vary smoothly with the average sunspot number; however, the process might contribute to the small variations observed at the peak of the individual cycles.

Variations in the total solar energy output level (total irradiance at all wavelengths), is a potential candidate for the major part of reported effects on the terrestrial climate. Recent satellite-based observations have disclosed variations of around 0.1% through the solar cycle (Fröhlich, 2009), which is adequate to explain the small average modulation of the temperature anomaly over the solar cycle.

8.2. Long-term variations in cycle-average sunspot and temperature data

The comparison of cycle-average values of the sunspot numbers and the global temperatures has displayed a high level of correlation through cycles 10–21. Hence, the cycle-average level of sunspots might be considered to be controlled by and also to indicate the (small) variations in total solar energy output that are responsible for the major part of the longer than decadal terrestrial temperature anomaly variations. This suggestion is in-line with many earlier publications, for instance the above cited Eddy (1976) and Reid (1987, 1999).

However, the essential causality problem remains to be resolved since both the strong rises in sunspot numbers and the temperatures in the first half of the 20th century and the local minima in the second half appear to be shifted in time such that the terrestrial temperatures lead over the sunspot activity by around 15 years. In a large number of publications this problem has been disguised using excessive smoothing in the data handling procedures. Here we shall take a different approach and examine more closely the apparent controversy around the critical solar cycles 16–19.

The deviations of the global temperatures (HadCruT3gl-2010) from the linear relation with the (cycle-average) sunspot number defined by the average linear regression with slope = 0.009 and base temperature = −0.70 °C (see Fig. 9) are taken to be evident. These deviations might be related to some terrestrial climate cycles. However, we shall suggest a different explanation with reference to Fig. 15 that displays the yearly sunspot numbers in
Comparing the equivalent sunspot numbers to the observed sunspot numbers shows the general agreement through cycles 10–21 and discloses also, of course, the deviations through cycles 16–19. It should be noted that the difference areas “a” and “b” in Fig. 15 are about equal in magnitude and opposite in sign. On the basis of the suggestion that (long-term) global temperatures are controlled by the solar energy output, these deviations could be simple propagation effects. Further, we suggest that the average level of solar activity characterized by the cycle-average sunspot number is controlled by the energy flux from the Core to the outer solar regions. This energy must pass from the interior through the outer regions (Interface Layer and Convection Zone) of the Sun to be radiated away mainly from the Photosphere. During gradual changes the cycle-average sunspot numbers may provide a fair and timely proxy for the small variations in the radiated solar energy output level. However, strong magnetic fields and turbulences in the outer solar regions, specifically at the Interface Layer and in the deep Convective Zone, associated with the enhanced activity processes may temporarily impede the energy transmission from the Core (analogous to sunspot darkening) and make the solar energy output level decrease until a new steady state has been established. Consequently, associated with the steep increase in average sunspot level observed through cycles 16–19 (1923 to 1965) we shall expect a relatively stronger increase in the solar energy output in the first rather quiet part of the interval. Hence it is extremely difficult to detect any possible long-term trend for the centennial variations. In coarse terms (Fig. 1), the global land-surface/sea-surface temperature anomaly (HadCruT3gl–2010) has changed from –0.30 (1850) through −0.48 (1910), 0.00 (1943), −0.20 (1953) to 0.00 (1985). Thus, the total changes span from −0.18 to +0.30. In the simple radiation balance calculations used, for instance, by Reid (1999), the change in TSI to produce 1 °C change in global temperature would be ~19 W/m², while in more realistic models (e.g., Hoyt and Schatten, 1993; Rind et al., 1999; Douglass and Clader, 2002; Scafetta and West, 2005) the required change would be within 6–9 W/m². Using the mean (7.5 W/m²) of the latter range of values for the “climate sensitivity”, the required total changes in the average TSI over the span from 1850 to 1985 would be ~1.35 W/m² (1850–1910) to +2.25 W/m² (1850–1985), which compared to measured TSI variations (~1 W/m²) over recent solar cycles (e.g. Fröhlich (2009)) are not excessive figures.

9. Conclusions

The analyses have used the most recent (ultimo 2010) solar activity cycle structure data (cycle min and max) and sunspot numbers provides by NGDC/NOAA and SIDC and the various global and northern hemisphere temperature data sets for land-surface, sea-surface, and combined land-surface/sea-surface temperatures provided by the UK Met.Office/Hadley Centre. The continuation through the most recent solar cycles of formerly published relations between solar activity and terrestrial temperature data series has clearly revealed beyond doubt that starting around 1985 a different forcing mechanism has been added in control of the climate. Since then, the possible forcing by solar activity has decreased while the global temperature has increased strongly. The present analysis does not reveal (or discuss) the cause of the recent temperature changes since 1885.

The quantitative examination of the association between solar activity characterized by the sunspot number and terrestrial climate through the recent ~135 years since 1850 has revealed a linear relation and close correlation between cycle-average values of sunspot numbers and global temperatures. The regression analyses
between solar activity represented by the cycle-average sunspot number, SSN_A, and global temperature anomalies, ΔT_a, averaged over the same interval lengths, but delayed by 3 years, have provided the relation ∆T_a = 0.009 (± 0.002) SSN_A – 0.70 (°C from base 1961–1990). The correlation between the two quantities gave a coefficient of R = 0.772 when extended over all cycles 10–21 and R = 0.975 when the special cycles 16–19 were exempted.

It is suggested that the long-term variations in global temperatures relate to corresponding variations in total radiated solar energy output. Furthermore, it is suggested that the cycle-average level of sunspot numbers is a timely and adequate measure of the (small) variations in solar energy output occurring during quasi-steady conditions. During strong changes in solar magnetic conditions the cycle-average energy output and sunspot levels might, temporarily, get out of phase. For the cycles 16–19 there is a delay between sunspot variations and global temperature changes of around 15–20 years with temperature leading. The sign of this delay apparently violates the causality between solar activity characterized by the sunspot number and terrestrial climate characterized by the global temperature. The delay has been partly disguised in past publications by the use of sophisticated smoothing schemes.

Here, we suggest that the energy output from the core of the Sun is transmitted more easily (faster) through the outer regions of the Sun than through the inner regions. This might, temporarily, get out of phase. For the cycles 16–19 there is a delay between sunspot variations and global temperature changes of around 15–20 years with temperature leading. The sign of this delay apparently violates the causality between solar activity characterized by the sunspot number and terrestrial climate characterized by the global temperature. The delay has been partly disguised in past publications by the use of sophisticated smoothing schemes.

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