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It has recently been suggested that the solar irradiance has varied in phase with the 80- to 90-year period represented by the envelope of the 11-year sunspot cycle and that this variation is causing a significant part of the changes in the global temperature. This interpretation has been criticized for statistical reasons and because there are no observations that indicate significant changes in the solar irradiance. A set of data that supports the suggestion of a direct influence of solar activity on global climate is the variation of the solar cycle length. This record closely matches the long-term variations of the Northern Hemisphere land air temperature during the past 130 years.

Much scientific effort has been exercised in order to understand the effects on climate of the release of increased quantities of CO_2 into the atmosphere. Because realistic experiments on a global scale are not possible, verification of physical theories have relied on model simulations or observations. Model simulations are limited by the necessary assumptions, and observations suffer from the lack of sufficiently long time series of fundamental quantities.

One of the most fundamental quantities in relation to the terrestrial climate is the sun's radiation. This is one of the parameters of which we have the least exact knowledge. Eddy (*1*) pointed out that apparent long-term relations between solar activity and certain indicators of the global climate might be caused by changes in the solar irradiance. Only recently, however, during the satellite era, have reliable measurements of the variability of the sun's irradiance been obtained (*2*), but these measurements are for a time scale shorter than a solar cycle.

Reid (*3*) discussed a striking similarity between the globally averaged sea-surface temperature (SST) and the long-term record of solar activity, as represented by the 11-year running mean Zürich sunspot number. He pointed out that although not identical, the two time series had several features in common. Most noteworthy was the prominent minimum in the early decades of this century, the steep rise to a maximum in the 1950s, a brief drop during the 1960s and early 1970s followed by a final rise, which apparently has not stopped.

Reid used these observations to show that the solar irradiance may have varied by approximately 0.6% from 1910 to 1960 in phase with the 80- to 90-year cycle (the Gleissberg period) represented by the envelope of the 11-year solar activity cycle. To estimate the response of the upper ocean to changes in the solar constant, Reid used a simple one-dimensional ocean thermal model of Hoffert *et al.* (*4*). He found that the necessary range of variation in the solar constant required to account for the temperature increase during the 130-year period is less than 1%, which is consistent with the magnitude of the long-term trend that could be derived from the measurements of the solar irradiance.

Correlations regarding sun-weather relations have traditionally been attacked for two main reasons. The first, and perhaps most serious one, is the lack of a physical mechanism that could lead to the claimed relations. The second has been the poor statistical significance of the correlations.

Kelly and Wigley (*5*) argued that the required change in the sun's energy output largely exceeds the changes that are suggested by direct measurements. On the basis of directly measured irradiance data from the short time period of satellite measurements, Foukal and Lean (*6*) constructed a model of the total solar irradiance variation between 1874 and 1988. Variations of less than 1.1 W/m^2, which is less than 0.1% of the total output, were predicted. However, they explicitly noted that additional low-frequency changes in the irradiance might be present that could not be deduced from the limited series of irradiance data.

Even for a change in the solar energy output compatible with the value estimated by Reid, model calculations by Kelly and Wigley (*5*) indicated that solar forcing is unlikely to have accounted for more than a small part of the observed temperature variation. An important reason for this conclusion was the limited statistical correlation between the two time series used by Reid.

There is, however, no a priori reason to believe that the long-term changes of solar irradiance are perfectly represented by the number of sunspots. In this paper we pre-

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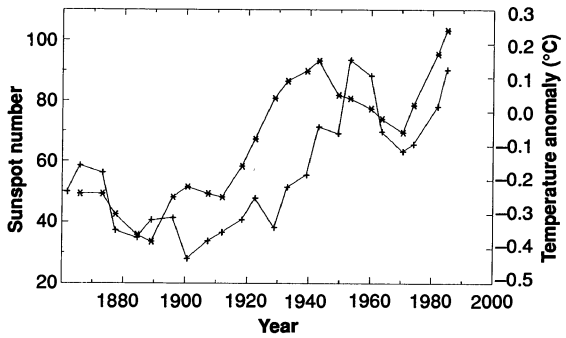


Fig. 1. Northern Hemisphere temperature anomalies from 1861 to 1989 (right-hand scale). The symbols (*) represent average values of the temperature record corresponding to individual solar cycles from solar maximum to solar maximum and from solar minimum to solar minimum, respectively. The second curve (+) shows the corresponding 11-year running mean values of the Zürich sunspot number (left-hand scale). For both curves, the abscissas of the plotted points correspond to the central time of the individual solar cycles.

sent a set of data that supports the idea that a change in solar activity could be related to global temperature.

Both solar activity and temperature records are subject to serious deficiencies. The land and sea-surface temperature records show similar behavior, but the SST record as well as the air temperatures over the ocean show a lag of several years relative to the land temperature. Reid (7) concluded that the lack of the long-term consistency between the two curves suggests that there was some slowly varying systematic error in one or the other, or in both, time series. A lag of the SST could, however, be explained by a significant response time of the ocean to possible changes in solar forcing. The Northern Hemisphere land temperature record presented by Hansen and Lebedeff (8) and Jones *et al.* (9) is probably the most reliable indicator of the global temperature because it is based on the largest systematic set of temperature measurements. Therefore, we have used the land air temperature for the Northern Hemisphere, expressed as anomalies relative to the interval 1951 to 1980, smoothed by Jones [see (*10*)].

From the plotted time series (Fig. 1), it is apparent that the variation of the Northern Hemisphere land air temperature has some similarity with the 11-year smoothed sunspot number, as was also the case for the SST record shown by Reid. But the data show that the land air temperature record leads the sunspot record. Therefore, if a relation between solar activity changes and surface temperature is to be maintained, the smoothed sunspot number cannot be a usable index of solar forcing.

There are independent measures of solar activity that indicate that the sunspot number is probably not necessarily also a good indicator of long-term changes. An example is the geomagnetic activity that is caused by the interaction between the solar wind and the geomagnetic field. There is a fundamental difference in the long-term behavior of the sunspot number and the geomagnetic activity (*11*). Whereas the sunspot number returns to near zero at each 11-year minimum, the 11-year geomagnetic activity variations are superposed on a long-term variation of similar amplitude including a nearly monotonic increase from 1900 to 1950. From the statistical relation between geomagnetic activity and satellite measurements of the solar wind velocity, Feynman and Crooker (*11*) estimated that solar wind velocities were low at the beginning of the century. A plausible physical mechanism for a direct effect on climate of a varying solar wind has not yet been demonstrated, however. But the observed long-term variation in solar energy output by means of the solar wind suggests that similar long-term changes in other manifestations of solar energy output may have occurred.

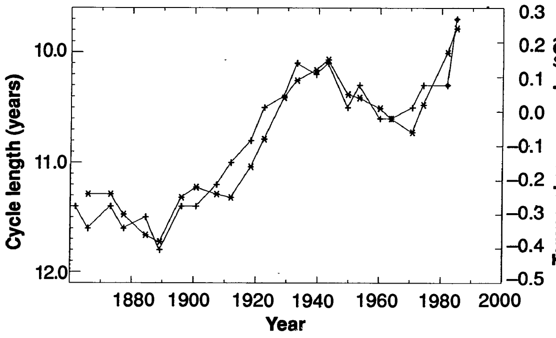
A different solar parameter showing long-term changes is the length of the sunspot cycle. This parameter is known to vary with solar activity so that high activity implies short solar cycles whereas long solar cycles are characteristic for low activity levels of the sun. Gleissberg (*12*) demonstrated that the variation occurred in a systematic manner with a long-term periodicity of 80 to 90 years, now known as the Gleissberg period.

We determined the length of the sunspot cycle using epochs of maxima and minima found by the secular smoothing procedure introduced by Gleissberg (*12*) (Fig. 2). This procedure corresponds to the application of a low-pass filter with coefficients 1, 2, 2, 2, 1 to the series of individual sunspot maximum and minimum epochs. This particular filter was selected because it has been generally used in the determination of long-term trends in solar activity, but the use of a different filter would not change the results significantly, as long as the short-term variations related to the 11-year cycle and shorter periods are removed. For the last two extrema, the available data do not allow full smoothing. Therefore, we filtered the second to last extrema by estimating the next extremum (because this is included in the filtering with a weight of one-eighth only); the last extrema express the unfiltered epochs. The consistency between the independent determinations of the cycle length based on the epochs of maximum and minimum of the sunspot number, respectively, indicates that the sunspot cycle length may be associated with a physically meaningful index of solar activity.

The introduction of this parameter of solar activity instead of the smoothed sunspot number removes the apparent lag of the solar activity curve relative to the surface temperature (Fig. 2). Furthermore, a strikingly good agreement between these two curves is revealed. There is a close association between the two curves in the up-going trends from 1900 to 1940 and since 1970, as well as in the important decrease from 1945 to 1970. For the total data, this approach gives a much closer fit to the temperature data than that for the smoothed sunspot number obtained by Reid (7). We therefore find that this agreement supports (although it does not prove) the suggestion of a direct solar activity influence on global temperature.

The temperature record is only available for the last 130 years, which is about 1.5 cycles of a possible 80- to 90 year oscillation. The official Zürich sunspot number, however, extends back to 1715, and it is therefore possible to calculate the smoothed sunspot cycle length from 1740. This in principle allows a comparison between the length of the solar cycle and a parameter that could be regarded as a reasonable estimate of the

Fig. 2. Variation of the sunspot cycle length (left-hand scale) determined as the difference between the actual smoothed sunspot extremum and the previous one. The cycle length is plotted at the central time of the actual cycle (+). The unsmoothed last values of the time series have been indicated with a different symbol (*) which represents, as in Fig. 1, the Northern Hemisphere temperature anomalies.



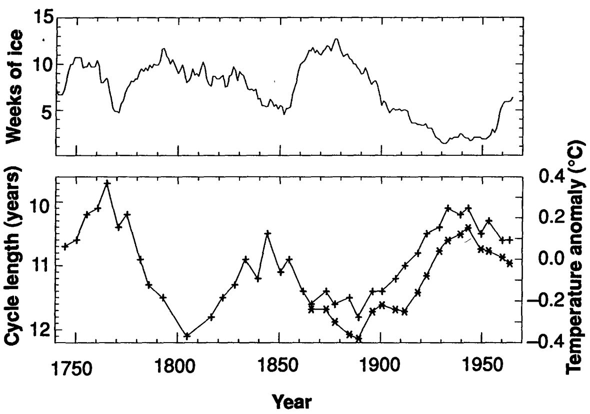


Fig. 3. (**Top**) 22-year running mean of the amount of sea ice around Iceland from 1740 to 1970 during summer months (represented by the number of weeks when ice was observed). (**Bottom**) Smoothed sunspot cycle lengths from 1740 to 1970 (left-hand scale) and Northern Hemisphere mean temperature (right-hand scale).

global temperature. One parameter covering this long time period is an index of the North Atlantic sea ice, which is known to show similar long-term variations. Although the individually measured extensions of sea ice suffer from a number of different influences and probably cannot be used directly as a temperature index, it seems reasonable that the absence of considerable amounts of ice would be associated with relatively high global, or at least hemispheric, average temperatures. We therefore compared (Fig. 3) the smoothed sunspot cycle lengths and a 22-year running mean of the extent of sea ice around Iceland (*13, 14*). The comparison clearly shows that each maximum in the long-term solar activity around 1770, 1850, and 1940 has been accompanied by a corresponding minimum in the 22-year running mean value of the extent of sea ice around Iceland.

We have presented observations that support the suggestion by Eddy (*1*) and Reid (*3*) that long-term changes in the solar activity influence the terrestrial climate. Using a perhaps more suitable parameter of the terrestrial climate than the one used by Reid, namely the Northern Hemisphere land air temperature difference and a possibly more direct indicator of long-term solar activity, namely the solar cycle length, we were able to improve the goodness of fit relative to that obtained by Reid.

Kelly and Wigley (*5*) argued that a change in the solar constant is unlikely to have accounted for more than a small fraction of the observed warming in global mean surface temperature since the mid-19th century. They used data compatible with the data used by Reid (*3*) to investigate temperature changes simulated in a model of the climate system, and they extended their analysis over a range of different climate sensitivities and solar-forcing scaling factors. They examined the departure of the observed temperature from the modeled one for the various processes. Their results indicated that since the mid-19th century, the influence of the enhanced greenhouse effect on global mean temperature has almost certainly dominated over direct influence of solar variability.

A major contribution to the enhanced greenhouse effect is due to a nearly exponential increase in the concentration of CO_2 in the atmosphere. Although the Northern Hemisphere temperature record includes a significant net increase during the last 130 years, which could partly be caused by the increased greenhouse effect, the temperature record does show a considerable departure from this long-term trend from 1940 to 1970. During these years the temperature decreased, simultaneously with a decrease in solar activity as indicated by the variation of solar cycle length (Fig. 2).

The use of the solar cycle length as a measure of solar activity instead of the 11-year running mean of the sunspot number would significantly affect the analysis by Kelly and Wigley (*5*). The high correlation between the two series, based on intervals of increasing as well as decreasing temperatures, could reduce the importance of measured greenhouse gases relative to the direct influence of solar variability. This result would not necessarily indicate that an increased greenhouse effect does not exist —it could just mean that other effects may be counteracting the greenhouse effect. In particular it has been debated whether increased cloudiness due to increased global pollution could have a cooling influence on the climate, similar to the effects due to volcano eruptions, as discussed by Lamb (*15*).

A different argument against the suggestion of solar irradiance changes as causes of climate changes is the question of whether the available satellite observations of the solar irradiance could be used as an indication of long-term changes. There are several indications that there are low-frequency changes in the solar constant that are not yet distinguishable in the satellite data. Reid (7) referred to data published by Fröhlich (*16*) based on pre-satellite era measurements from rockets and balloons. From these data he concluded that there was a real change in the solar output from 1968 to 1978 of 4 W/m^2 which is about 0.3% of the total output. Comparing this value with the data shown in Fig. 2, it is seen that the corresponding change in solar cycle length from 1968 to 1978 was about half of a year. From this change we can expect that the corresponding change in the solar constant from 1890 to 1984 was about 1%, which is consistent with the number estimated by Reid (*3*).

The observations we have presented suggest that long-term variations in Earth's temperature are closely associated with variations in the solar cycle length, which therefore appears to be a possible indicator of long-term changes in the total energy output of the sun. If this result can be related to a real physical mechanism there is a possibility to determine the greenhouse warming signal and predict long-term climate changes by appropriate modeling of the sun's dynamics. Estimation of the natural variability of the Earth's climate and its causes are needed before any firm conclusion regarding anthropogenic changes be made.

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