Solar Activity and Global Temperature

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A major problem in the determination of the magnitude of a possible solar effect on climate is that no physical parameter of solar energy output exists that has been observed long enough to be used for long-term analyses. Therefore, a number of indirect parameters have been proposed, with the sunspot number as the most commonly used parameter. Recently it has been suggested that climatic effects may be more directly associated with the length of the solar cycle. Whereas the magnitude of the sunspot number is only believed to be reliable back to 1750, determination of solar activity minima may be based on other types of data. A recent reconstructed series of solar cycle lengths back to 1500 gives new information about solar activity in particular before and during the Maunder Minimum. A comparison with reconstructed temperature records has revealed that the good agreement between the solar cycle length and the global temperature found for the modern instrumental temperature record is also characteristic for the total series of reconstructed temperature data. A further result is that the response of the temperature during the pre-instrumental era is the same as for the modern temperature record. This finding confirms the close association beween terrestrial temperature and solar activity measured in terms of the solar cycle length.

1. Introduction

An observed rise in the global average temperature of about 0.5° C since 1890 has caused concern in the public because it could indicate the climatic response to a changing composition of the atmosphere due to an increase of greenhouse gases caused by anthropogenic activity. Therefore an Intergovernmental Panel on Climate Change (IPCC) was established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environmental Programme (UNEP). In the report published by this panel it is concluded that it is presently not possible to ascribe unequivocally the found changes in climate to the enhanced greenhouse effect since the size of the global warming is of the same magnitude as natural climate variability.

One of the reasons for the uncertainty regarding the cause of the observed increase in temperature is that the temperature has not followed the monotonic rise that observations of greenhouse gases and theoretical calculations predict. On the contrary, there have been intervals, in particular from around 1940 to around 1970, where the global temperature was decreasing during a period of rapid build-up of CO_2 in the atmosphere. These apparently contradictory observations are usually ascribed to a high degree of internal variability in the climate system, which may be reproduced in the results of climate models. A different explanation of the long-term variations of the temperature could, however, be a possible connection between observed climate changes and changes in solar activity. Thus, in a detailed study of long-term solar variations Eddy (1976) drew attention to the coincidence of the so-called Maunder Mimimum in solar activity with the coldest excursion of the "Little Ice Age", already noted by many who had looked at the possible relationships between the Sun and terrestrial climate.

Reid (1987, 1991) noticed a striking similarity between the globally averaged sea surface temperature (SST) and the long-term variation of solar activity represented by the 11-

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year running mean Zürich sunspot number. In accordance with Eddy (1976) he suggested that the solar irradiance may have varied by approximately 0.6% from 1910 to 1960 in phase with the 80-90 year cycle (the Gleissberg period) of solar activity represented by the envelope of the 11-year solar activity cycle. Friis-Christensen & Lassen (1991) pointed out a major difficulty with this interpretation. They examined the Northern Hemisphere land air temperature and noted that this record was leading both the SST record and the sunspot record, in fact by as much as 20 years. From this discrepancy they concluded that it is unlikely that long-term variations of solar activity can be sufficiently well represented by some average value of the sunspot number itself. They further pointed out that the long-term variation of the variable length of the '11-year' sunspot cycle was well correlated with the Northern Hemisphere land surface temperature during the entire interval of systematic temperature measurements and suggested that the solar cycle length could provide an indicator of long-term variations in solar luminosity.

Thus, there appears to be an increasing approval to the view that the long-term variation of the solar activity contributes appreciably to the long-term variations of the mean global temperature. An elucidation of the magnitude of a possible solar contribution to the temperature increase of the present century crucially influences the estimate of the magnitude of the anthropogenic greenhouse forcing and consequently the predictions of the climate models.

2. Solar activity

It is well-known that solar activity varies with an approximately 11-year cycle. This cycle is a well documented feature first found by analyzing the observational record of the number of sunspots on the solar disk. Later the existence of the cycle was noticed in a number of different observations of the Sun as well as of the upper atmosphere, which is influenced by the varying flux of solar energetic particles and ultraviolet radiation. The amplitude of the 11-year cycle appears to be modulated by a 70-90 years undulation, the so-called Gleissberg period.

This is illustrated in Figure 1 which shows the monthly mean sunspot number from 1750 to 1991. It is evident that the monthly mean sunspot number is affected by noise that is superposed on an assumed quasi-regular 11-year period. Apparently the sunspot number returns to a rather low minimum value during each cycle but this does not necessarily mean that this activity level is close to a possible lower threshold of solar activity as such. The solar activity at different sunspot minima may be rather different, even if it does not manifest itself in the observed sunspot number directly. This fact may be clearly demonstrated by looking at a quite different parameter of solar activity. During more than 120 years systematic observations of the geomagnetic field on the surface of the Earth have been performed. The geomagnetic activity shows a dominating approximately 11-year cycle, although not as evident as the annual sunspot number. Contrary to the sunspot variation, however, the geomagnetic cyclic variations are superimposed on a long-term variation of similar amplitude including a nearly monotonic increase from 1900 to 1960. From the statistical relation between geomagnetic activity and satellite measurements of the solar wind, Feynman & Crooker (1978) conclude that solar activity as represented by the solar wind velocity or that the southward component of the interplanetary magnetic field has been increasing since the beginning of the century. The long-term variation in solar output through the solar wind measured by means of the geomagnetic aa-index suggests that similar longterm changes in other manifestations of solar energy output may also have occurred.

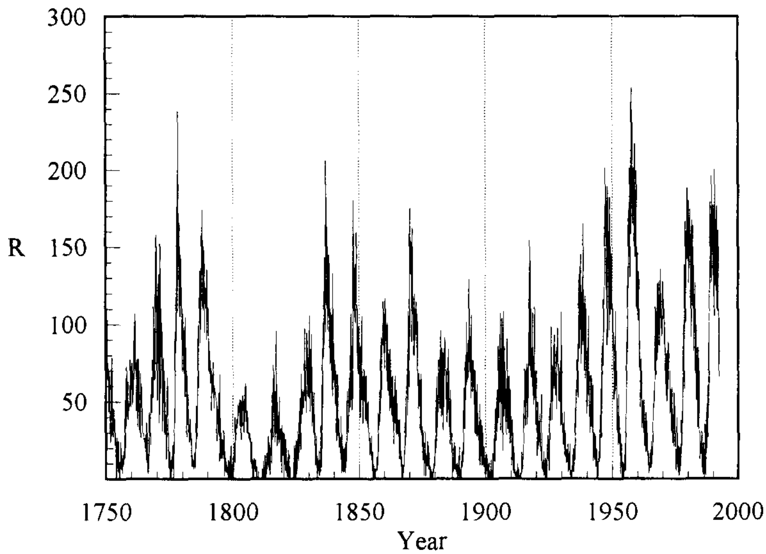

FIGURE 1. The monthly mean of the sunspot number 1750 to 1991.

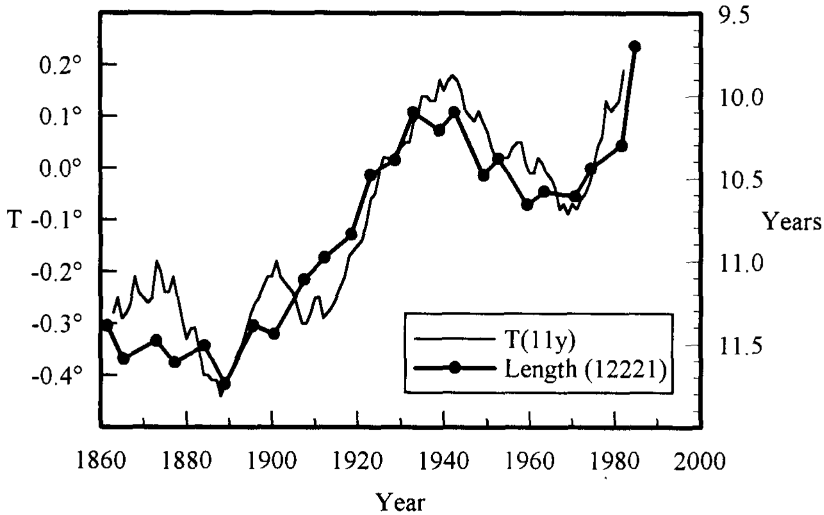

FIGURE 2. 11-year running mean of the annual average Northern Hemisphere land air temperature by Jones *et al.* (1986) and Jones (1988) relative to the average temperature 1951-1980, and the filtered length of the sunspot cycle.

3. Solar cycle length versus temperature

The most acknowledged virtue of the sunspot number is that this parameter has been observed over a very long time period. However, as discussed by Friis-Christensen & Lassen (1991) the long-term behaviour of solar activity may be better represented by the varying length of the solar cycle. Support for this suggestion was found in a very high correlation between this parameter and the long term variation of the Northern Hemisphere land air temperature as given by Jones *et al.* (1986) and Jones (1988).

Figure 2 shows the variation of the sunspot cycle length together with the 11-year

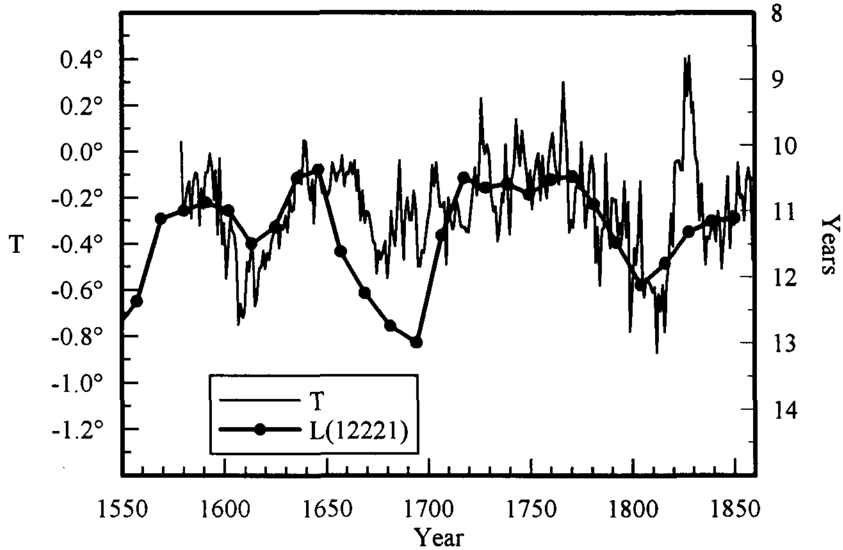

FIGURE 3. Annual mean values of the Northern Hemisphere land air temperature 1579-1860 relative to the average temperature 1881-1975, reconstructed by Groveman & Landsberg (1979). Also plotted is the filtered value (1,2,2,2,1 filter) of the sunspot cycle length.

running mean of the Northern Hemisphere land air temperature from 1860. The 11-year running mean filter was chosen in order to suppress the temperature variations within a solar cycle which obviously cannot be ascribed to the possible long-term external forcing.

The limited extent of instrumental temperature records and the possible complex behaviour of a Sun-climate relationship that makes a filtering of the time series necessary, also means that the statistical significance of the correlation is not sufficiently large to prove that the correlation is not just a coincidence. Since the shorter term variations in solar activity and temperature may have quite different relationships the only possible way to obtain an increased significance is to try to use a longer time series of temperature data.

Although reconstructed temperature series are available back to the second half of the 16th century, solar activity has not been regularly monitored prior to 1750. However, several efforts have been made to reconstruct the sunspot variation during the preceding centuries by means of sporadic observations in combination with proxy data. Lassen & Friis-Christensen (1993) have recently made a critical assessment of such published solar data covering the period 1500-1750. Based on this they presented a revised series of epochs of minimum solar activity and compared this with reconstructed temperature time series.

A comprehensive reconstruction of the Northern Hemisphere temperature covering a 400 year period was performed by Groveman & Landsberg (1979). They used several local temperature measurements together with proxy data from many places in the Northern Hemisphere and performed a multiregressional analysis of the data that resulted in a set of empirical formulas relating each proxy data series to the measured Northern Hemisphere temperature. Using this set of empirical relations they then calculated the temperature for the Northern Hemisphere for the last 400 years.

In Figure 3 is plotted annual mean values of their reconstructed temperatures from 1579 to 1860 on the same graph as the variation of the sunspot cycle length. The reconstructed temperature values are given as departures from the average Northern Hemisphere temperature 1881-1975.

Naturally, the reconstruction of the Northern Hemisphere temperature must be less confident than the modern record. Apart from this there exist, of course, year-to-year variations due to internal oscillations in the climate, El Niño effects, volcanic eruptions etc. Taking these variations into consideration, the comparison between the temperature record and the solar activity during the pre-instrumental period reveals that there is a good association between the trends in the temperature and in the solar cycle length record.

An obvious disagreement between the two time series in Figure 3 is noticed in the second half of the seventeenth century. Whereas the solar activity here reaches its lowest level of the five centuries the reconstructed temperature remains at a level remarkably higher than during the two surrounding minima near 1610 and 1805. This is the more surprising because this period of low solar activity - the so-called Maunder Minimum - is often regarded as being associated with the culmination of the Little Ice Age (Eddy 1976). However, it is possible that the restricted number of localities used in the reconstruction of the temperature may have resulted in an average temperature variation that is biased by a local effect at a single station.

In addition to the Groveman-Landsberg series there exist a few independent series of proxy temperature data representing more restricted regions of the Northern Hemisphere.

Thus, it has been demonstrated earlier (Friis-Christensen & Lassen 1991) that an index of the North-Atlantic sea ice in the waters around Iceland oscillated in concert with the longterm variation of the solar activity during the years 1750-1970. 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 hemispheric average temperatures. Lassen & Friis-Christensen (1993) show a comparison between the smoothed sunspot cycle lengths and a 22-year running mean of the extent of sea ice around Iceland from 1600 to 1780. The comparison supports and improves their earlier result that maxima in the long-term solar activity have been accompanied by minima in the 22-year running mean of the extent of sea-ice around Iceland, i.e. by increased average temperatures at high northern latitudes.

A similar conclusion was reached by Hameed & Gong (1993). These authors combined data of blossoming of plants noted in personal diaries and other documents originating from the area of the Middle and Lower Yangtse River Valley with records of the last day of snow event in the spring season of each year between 1720-1800 kept in the Palace Museum in the Forbidden City. The combined data sets made it possible to estimate the long-term variations of spring temperature in the region from 1580 to 1920. Their results show a strong co-variation between the spring temperature in Central China and the length of the solar cycle since 1750. In Figure 4 we have redrawn their smoothed temperature curve and show it together with the revised (extended) time series of the solar cycle length. Note that the proxy temperature values are given in the unit "days before or after an average date of the event". It is clearly demonstrated that the climate in this region of Asia has oscillated in concert with solar activity at least during the past 300 years. Elsewhere it has been argued that regional Chinese time series of climate data represent large-scale temperature changes rather well (Bradley & Jones 1993).

In common the above-mentioned three examples reveal that the good agreement between the solar cycle length and the global temperature found for the modern instrumental temperature record is also characteristic for the total series of reconstructed temperature data. The only essential exception is the disagreement between the two

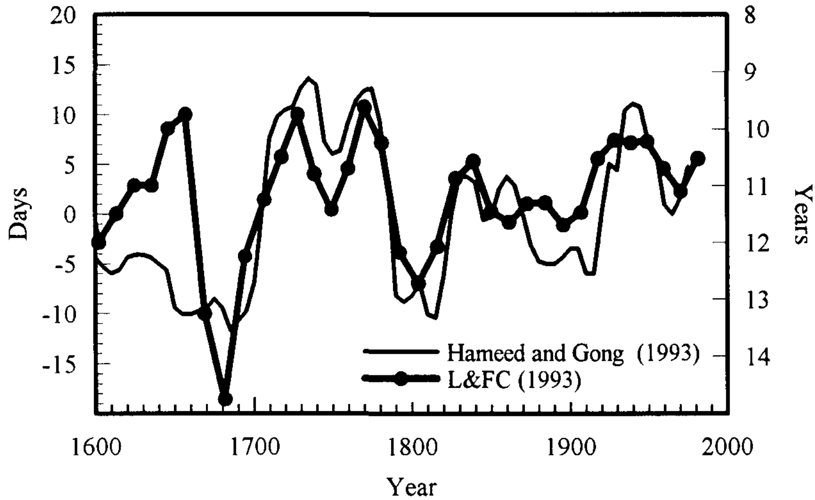

FIGURE 4. Variation of spring temperature in the Middle and Lower Yangtse River Valley deduced from phenological data. The curve is redrawn after Hameed & Gong (1993). The ordinate indicates "days before or after an average date". Also plotted is the filtered value (1,2,2,2,1 filter) of the solar cycle length (Lassen & Friis-Christensen 1993).

time series in the second part of the seventeenth century (Figure 3). However, no counterpart to this is apparent in the series from Iceland and China. This seems to confirm our assumption that the reconstructed temperatures of Groveman and Landsberg are unreliable (too high) during the interval 1650-1700. The remaining part of the figure shows a strong association between the trend of the reconstructed temperature curve and the long-term variation of the length of the solar cycle. There appears to be a linear relation between the two quantities. This is illustrated in Figure 5 which also shows the regression line with a regression coefficient ($\pm\sigma$) of $(0.23 \pm 0.04)^{\circ}$C/y.

Essentially, the reconstructed temperature series 1579-1880 covers a period that is situated prior to the rapid increase of industrial production and resulting air pollution. It is therefore of interest to compare the magnitude of the regression coefficient for this period with a similar coefficient for the latest 130 years as shown in Figure 6. Since the solar cycle length in Figure 2 is essentially decreasing with time it might be expected that the effect of an increasing greenhouse warming through the 130 years would show up as a curvature of the function combining temperature and solar cycle length, or in an increase in the slope of the regression line. Neither of these possibilities is apparent in the figure. Actually, the regression coefficient has been found to be $(0.30 \pm 0.03)^{\circ}$C/y. The difference between the regression coefficients is barely significant. Thus we must conclude that the data used in our study do not indicate any change in the relationship between Northern Hemisphere temperature and long-term solar activity through the last 400 years. In consequence, influence of anthropologic activities cannot be traced with certainty in our data up to the 1980's.

4. Discussion

Research in possible Sun-climate relationships has been dominated by the unsuccessful attempts to identify a physical mechanism that could account for the hypothesized effects on climate based on a large number of correlations between various solar and climate

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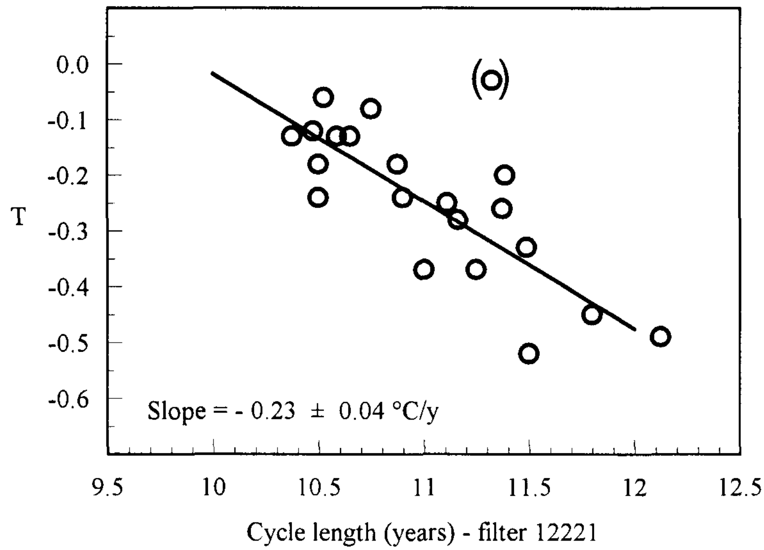

FIGURE 5. Annual mean values of the Northern Hemisphere land air temperature from Figure 3 (1656-1696 not included, see text) versus filtered value (1,2,2,2,1 filter) of the solar cycle length. The value labelled () is not included in the calculation of the regression coefficient.

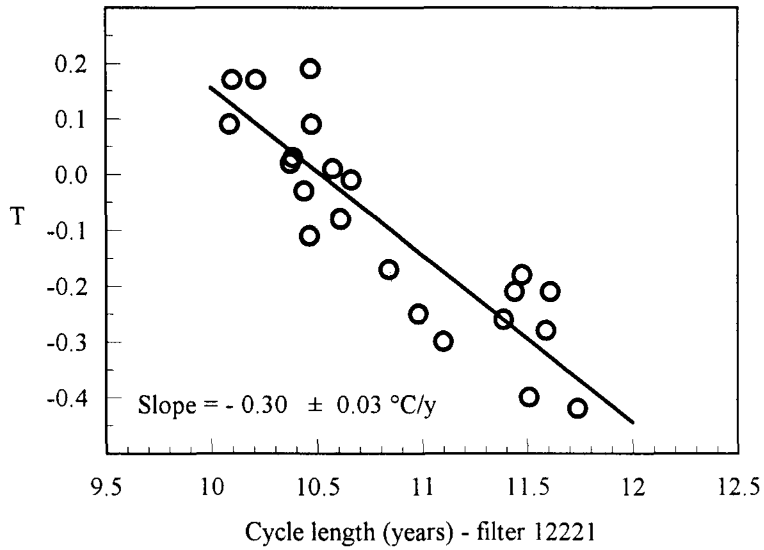

FIGURE 6. Annual mean values of the Northern Hemisphere land air temperature from Figure 2 versus filtered value (1,2,2,2,1 filter) of the solar cycle length.

parameters. The simplest conceivable physical mechanism would be a long-term variation of total solar irradiation that is sufficiently large to have an observed temperature effect on climate. Satellite measurements over approximately one solar cycle have shown that the irradiance is not constant, but model calculations show that it varies too little (less than 0.1%) during a solar cycle to be of major importance for climate (Wigley & Raper 1990). However, no measurements yet exist that do exclude the possibility of larger variations in total irradiance over a longer period of time. On the contrary, Lean *et al.*

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(1992) from correlations between total solar irradiance measurements and Ca II solar emissions estimate that in the absence of surface solar magnetism (which may have been the case during the Maunder sunspot minimum period around 1700) the total solar irradiance may have been reduced by about a quarter per cent.

The hypothesis of a solar forcing through total irradiance variations may be tested using simple energy-balance climate models. Schlesinger & Ramankutty (1992) find strong circumstantial evidence that there have been intercycle variations in solar irradiance which have contributed to the observed temperature changes since 1856, but they also, in agreement with Kelly & Wigley (1992), find that greenhouse gases have been since the nineteenth century the dominant contributor to the observed temperature changes. Kelly & Wigley (1992) conclude that the combination of greenhouse forcing and solar cycle length forcing can explain many features of the observed temperature record. They do call for caution, however, regarding the interpretation of this result because the cycle-length history is not uniquely defined and because they regard the implied irradiance changes prior to 1900 as unrealistically large. Schlesinger & Ramankutty (1992) simulate the temperature anomalies from 1638 to 1985 for different values of the various forcing parameters. Their simulated temperatures may be compared with the temperature record shown in Figure 2 and Figure 3. Such a comparison shows the best agreement when greenhouse gases as well as solar forcing and anthropogenic sulphate aerosol radiative forcing are taken into account. In all cases, however, the inclusion of solar influence in the simple climate model does imply a large reduction, at least 48%, of the estimated sensitivity of the climate to an increased CO_2 content of the atmosphere.

The energy-balance models are simple and inexpensive in terms of computer resources. The problem with these models is that it is assumed that the global climate can be calculated solely by means of global averages of radiative forcings. The different radiative forcings that exist, including solar irradiance, greenhouse gases, and anthropogenic sulphate aerosols, all have different spatial distributions and, in case of the latter, a particularly inhomogeneous distribution that makes it rather dubious if a one-dimensional climate model is at all appropriate in a quantitative distinction of the effects of these different forcings. Whether the cause of a temperature trend is *solar*, through changes in the Sun's luminosity or *human*, through an increase in greenhouse gases, the effect is unlikely to be through direct radiation, but more likely through changes in the general circulation. It is conceivable that a comparatively small rise in the Sun's irradiation can effect a steeper tropical to polar temperature gradient, because of the different solar zenith angle at low and high latitudes (Labitzke & van Loon 1993). If so, an increased Hadley circulation may create regional temperature trends. In particular the fact that most of the rise in global temperature during the present century had its origin in a very fast increase in the temperature in the Northern polar regions during 20 years from 1920 to 1940, simultaneous with a similarly fast rise in the solar activity expressed in the variation of the length of the sunspot cycle, suggests a more direct solar effect than the climate models indicate.

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