Long-term Variations in Solar Activity

and their Apparent Effect on the Earth's Climate

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Abstract

The varying length of the 11-year cycle has been found to be strongly correlated with longterm variations of the northern hemisphere land surface air temperature since the beginning of systematic temperature variations from a global network, i. e. during the past 130 years. Although direct temperature observations before this interval are scarce, it has been possible to extend the correlation back to the 16th century due to the existence of a series of proxy temperature data published by Groveman and Landsberg in 1979. Reliable sunspot data do not exist before 1750, but we have been able to derive epochs of minimum sunspot activity from auroral observations back to 1500 and combine them with the direct observations to a homogeneous series.

Comparison of the extended solar activity record with the temperature series confirms the high correlation between solar activity and northern hemisphere land surface air temperature and shows that the relationship has existed through the whole 500-year interval for which reliable data exist.

A corresponding influence of solar activity has been demonstrated in other climatic parameters. Thus, both the date of arrival of spring in the Yangtze River Valley as deduced from phenological data and the extent of the sea-ice in the Atlantic sector of the Arctic sea have been shown to be correlated with the length of the sunspot cycle during the last 450 years.

Conclusion

70-90 years oscillations in global mean temperature are correlated with corresponding oscillations in solar activity. Whereas the solar influence is obvious in the data from the last four centuries, signatures of human activity are not yet distinguishable in the observations.

Introduction

Variations in the activity of the Sun greatly influence the physics of the upper atmosphere. Thus, magnetic disturbances, occurrence of auroras at low latitudes, sporadic ionization above -80 km altitude, and - as a consequence of the latter - reduced quality of shortwave radio transmissions all appear to follow the approximately 11-year soler activity cycle. This cycle is most distinctly seen in two observed parameters: the sun- spot number and the 10,7 cm radiation. For analytical purposes the intensity of the 10,7 cm radiation may be the best suited, but it has the drawback that observations were first initiated in the 1950s. For studies involving longer data series the only usable directly observed signature of solar activity is the varying number of sunspots. This has been subject of observation through several hundred years and may be regarded as reliable since 1750 (Eddy, 1976). The sunspot number, generally denoted R, is highly correlated with the 10,7 cm flux.

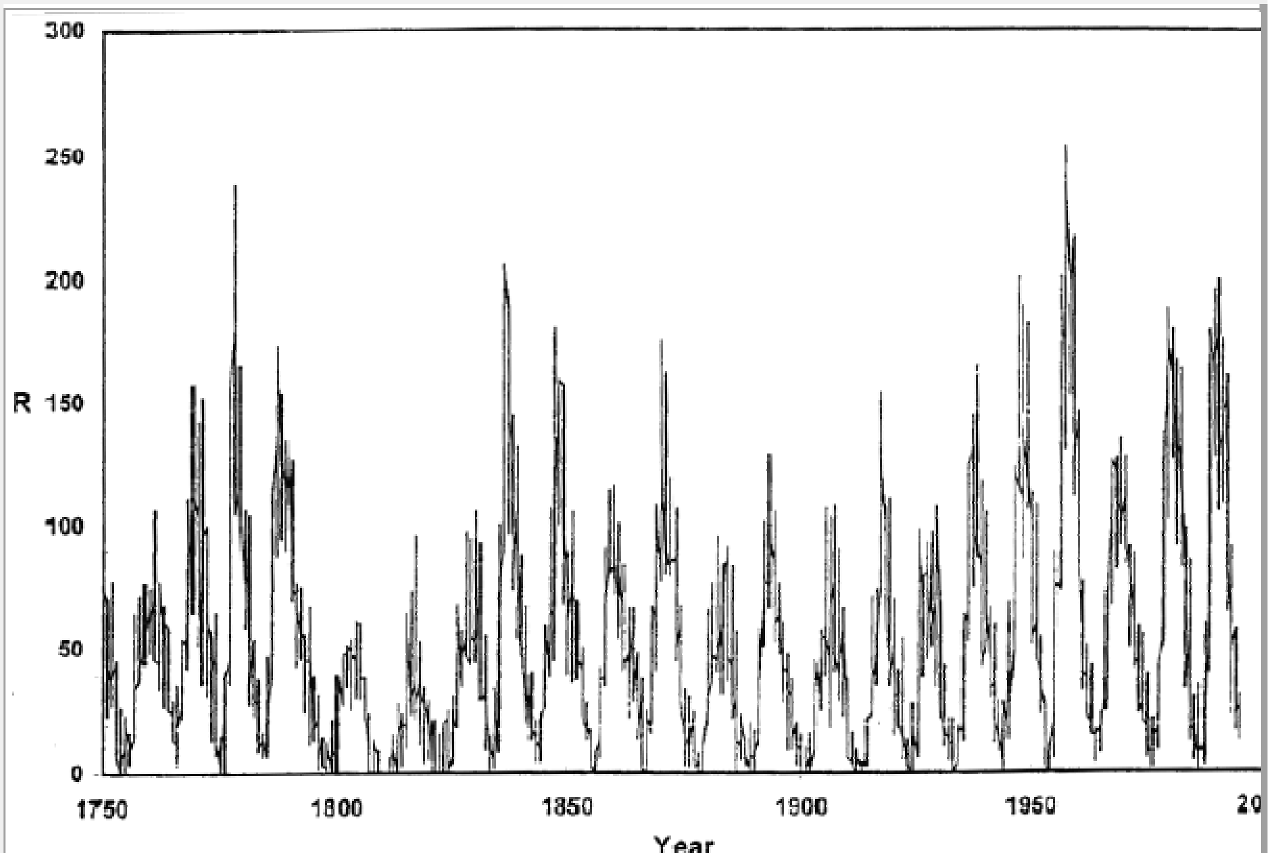

Fig. 1 Average monthly sunspot number R 1750-1992

In Fig. 1 is shown the average monthly sunspot number from 1750 to 1992. It is evident that the monthly mean sunspot number is affected by noise that is superposed on an assumed and apparent quasi-regular 11-year period. In applications of the sunspot number a method of weighted 13-months running mean has traditionally been used in order to avoid the month-to-month variations. In addition to the very clear approximately 11 year period in the monthly sunspot number, it is observed that the magnitude of the maximum sunspot number in each 11-year cycle changes in an apparently oscillatory way. This oscillation with a period of about 70 to 90 years has been named the Gleissberg period.

Given all the evidence of a solar influence on the upper atmosphere it has been natural to expect a similar relation in the variability of weather and climate. Numerous reports about this item have been published, but often they have suffered from poor statistical significance and from being restricted to a too short span of years. One exception of particular interest is the study by Labitzke and Van Loon (1997), who reported on statistically convincing correlations between the 11-year solar activity and selected parameters in the stratosphere and upper troposphere. A distinct 10-12 year period in height and temperature of certain isobar sheets was shown to be phaselocked to the solar activity cycle during the last three cycles. Although many meteorologists rejected the association, careful statistical tests demonstrated that the probability of the effect being just a coincidence is less than 1%.

Global temperature and sunspot number

Reid (1987) noticed a certain amount of similarity of the secular variation in globally averaged sea-surface temperature (SST) over the past 130 years to the corresponding variation of solar activity as revealed by the envelope of the 11-year running mean sunspot number. He pointed out that 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, and a brief drop during the 1960s followed by a final rise. Based on this comparison Reid suggested that the solar irradiance may have varied by approximately 0.6 % from 1910 to 1960 in phase with the 70-90 year cycle (the Gleissberg period) of solar activity. He found that the necessary range of variation in the solar constant during the total 130 year period is less than 1%. 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. However, no measurements yet exist that do exclude the possibility of larger variations in total irradiance over a longer period of time.

Friis-Christensen and Lassen (1991) pointed out a major difficulty with Reid's interpretation. They examined the northern hemisphere land air temperature and noted that this record was leading both the SST record and the sunspot record by as much as 20 years. From this discrepancy they concluded that if a cause and effect relation between solar activity and terrestrial climate is to be maintained, it is unlikely that long-term variations of solar activity can be sufficiently well represented by some average value of the sunspot number itself.

But as they pointed out there are other parameters 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 (Fig.2).

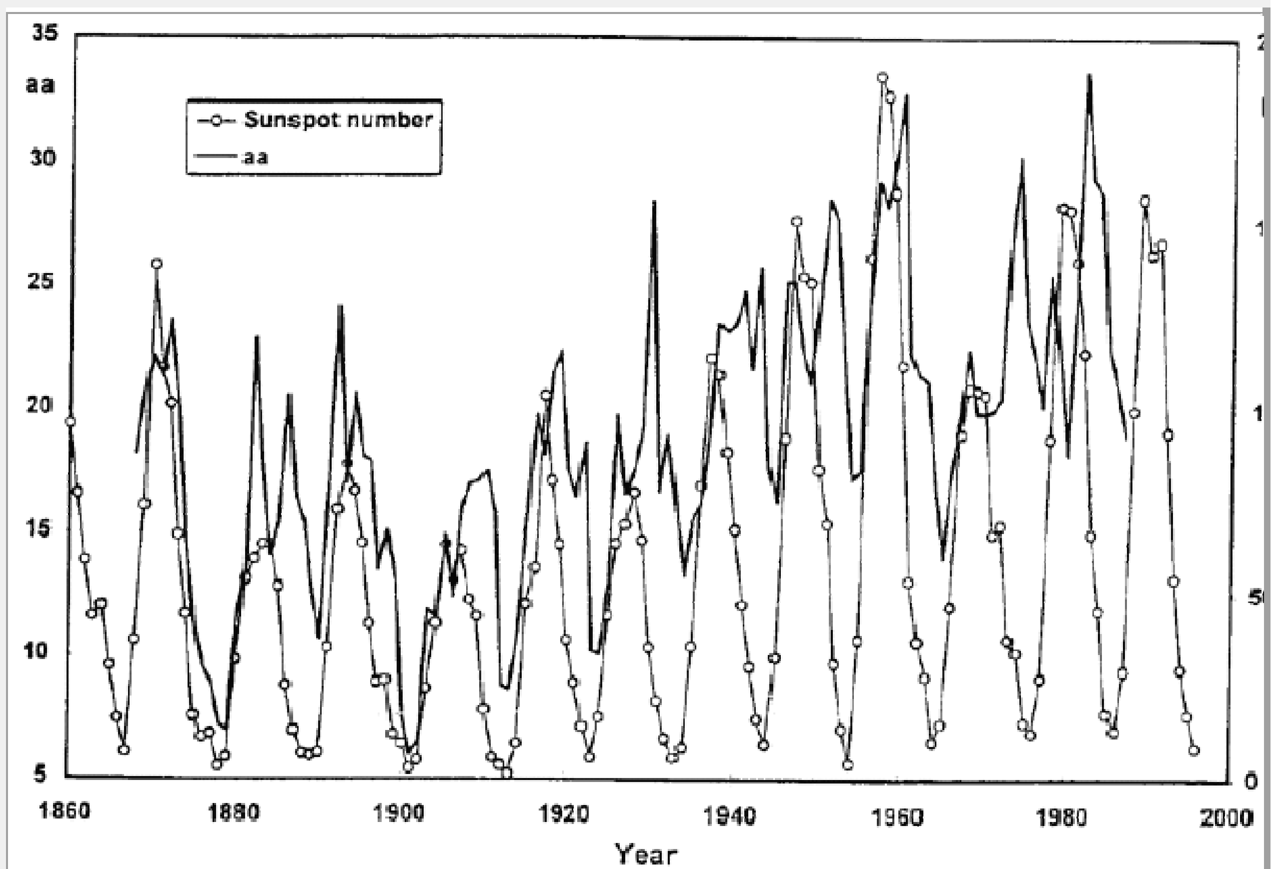

Fig. 2 Annual sunspot number R and geomagnetic index aa 1860-1992

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 includinging a nearly monatomic increase from 1900 to 1950. This has been interpreted as a signature of an increase in the solar wind velocity through the century. 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.

Instrumental temperature and solar cycle length

A different solar parameter showing long-term changes is the length of the approximately 11-year sunspot cycle. This quantity is far from being constant. It 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 (1944) demonstrated that the variation occurred in a systematic manner with a periodicity of 70-90 years similar to, but not exactly in phase with the variation of the magnitude of the sunspot number.

The sunspot cycle length record is subject to "noise", due to the fact that the time of the start of a cycle cannot be easily defined because of the presence of short-term variatiations in solar activity that obscure this (Fig.l). This is the case when the minimum activity in the "11-year" cycle is regarded as the start of the cycle, but it is even more difficult to define the start of a cycle by means of the time of maximum solar activity. Therefore, the cycle length record must be filtered (Fig.3).

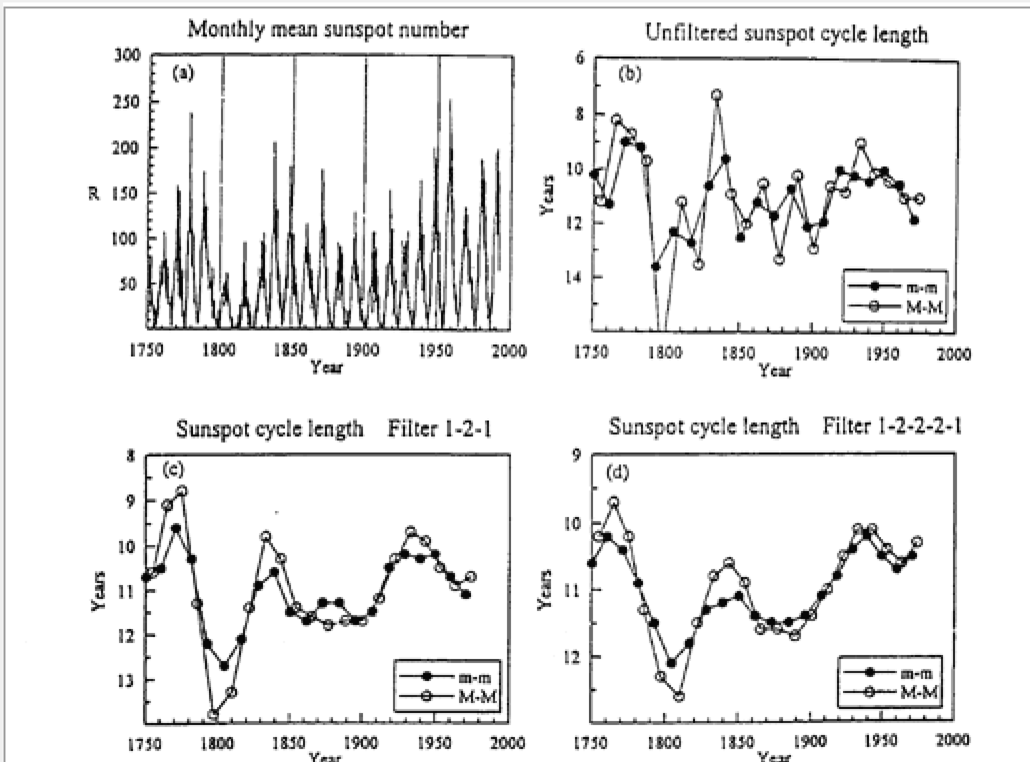

Fig. 3 (a) Monthly mean of the sunspot number 1750-1991. (b) Sunspot cycle length 1750-1990, unfiltered. Open circles: derived from epochs of sunspot maxima. Filled circles: from epochs of minima. (c) As (b) but with an applied smoothing filter with the coefficients 1-2-1. (d) As (c) but with the coefficients 1-2-2-2-1. All values have been plotted at the centre of each cycle

In order to reveal the essential behavior of the sunspot cycle, Gleissberg applied a low-pass filter with coefficients 1-2-2-2-1 to the series of individual sunspot maximum and minimum epochs, respectively. This filter has been used traditionally. Occasionally, it may, however, be preferable to use a binomial filter with coefficients 1-2-1 to avoid too strong smoothing that might mask important details in the time series.

Friis-Christensen and Lassen (1991) demonstrated that the correlation between the northern hemisphere land surface air temperature and solar activity was markedly improved when the sunspot number was replaced by the length of the solar cycle as an index of the long-term variability of the Sun, and it was concluded that this parameter appears to be a possible indicator of long-term changes in the total energy output of the Sun (Fig.4).

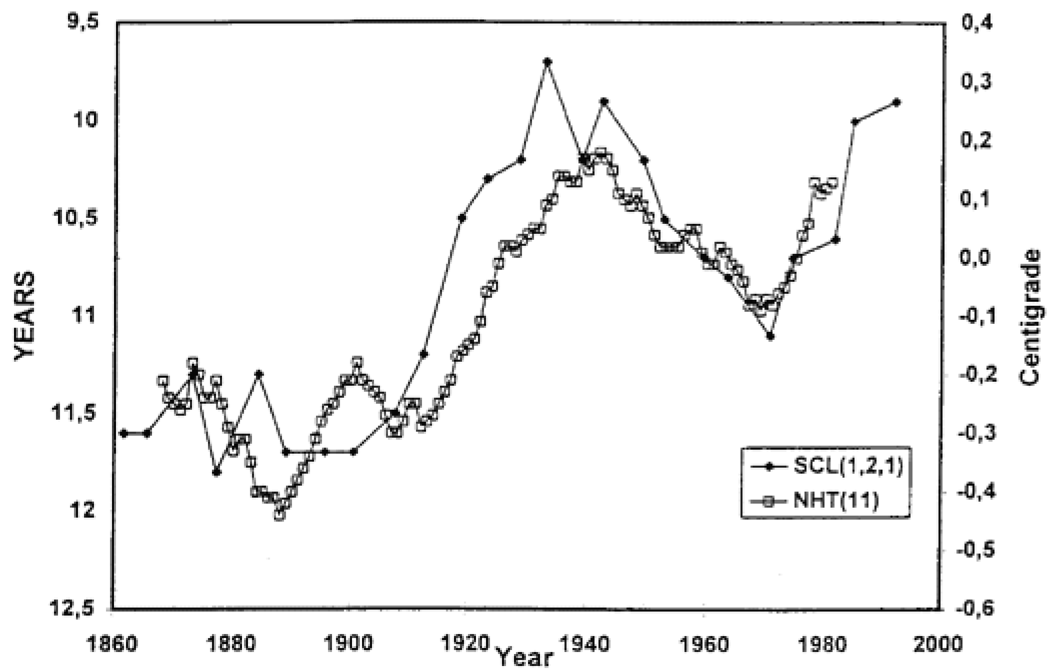

Fig. 4 Eleven-year running mean of the annual average northern hemisphere land air temperature relative to the average temperature 1951-1980, and the (1-2-1)-filtered length of the sunspot cycle

The high correlation between an indicator of long-term solar activity and global mean temperature through a little more than a century is, however, not a proof of the existence of a physical relationship between solar activity and global temperature. In principle, it can not be excluded that the temperature by mere chance has varied in concert with the solar activity just in the present period.

Accordingly, it is necessary to try to expand the interval to a longer span of years as well as to other, independent data series to check the result.

Solar cycle length 1500-1990

Several attempts have been made to extend the sunspot record back in time. Since the occurrence of low-latitude auroral displays is known to be controlled by solar activity it has been generally accepted that they may be used as proxy data in the study of the 11-year sunspot variation. Sunspot numbers prior to 1750 as well as epochs of maxima and minima have been computed from catalogues of auroral sightings from Central Europe and East Asia, but the reliability of this data set has Seen questioned (Eddy 1976). However, an improved record of the number of auroral nights for the past 500 years was published by Silverman (1992). In his presentation of the secular variation of low-latitude aurora 1500-1948 there is a clear indication of a decadal variation of the number of auroras also prior to 1750.

Silverman's figures have been used to estimate the epochs of minimum occurrence of low-latitude auroral displays and sunspots during the interval 1500-1948 (Lassen and Friis-Christensen, 1995). It was not found justified to try to make a similar estimate for sunspot maxima, since it is known that maximum auroral frequency may be delayed several years relative to the sunspot maximum, depending on the character of the actual solar cycle.

The overlap in time between 1750 and 1948 of the auroral cycle curve derived from Silverman's auroral frequencies with the solar cycle curve makes a direct comparison of the two curves possible. From Fig.5, in which the two time series have been plotted together (after smoothing with the Gleissman filter), it is seen that they are nearly identical within the uncertainty of the determination.

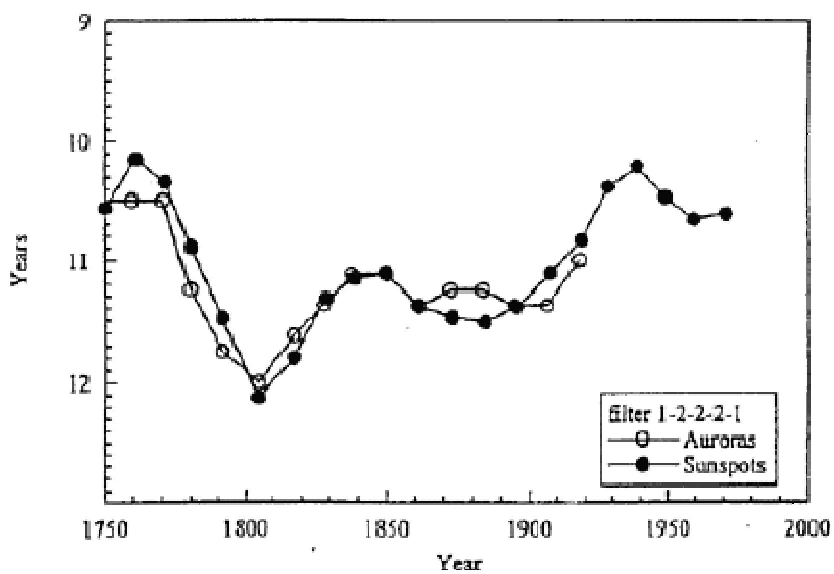

Fig. 5 Variation of the sunspot cycle length 1750-1990 determined by means of sunspot minimum epochs (filled circles) and auroral minimum epochs (open circles), respectively, with an applied smoothing filter with the coefficients 1-2-2-2-1. All values have been plotted at the centre of each cycle

In the following we have therefore represented the complete long-term variation of the solar cycle length from 1500 to 1990 by cycle lengths derived from minimum epochs inferred from Silverman's auroral data during the interval 1500-1749 followed by the cycle lengths derived from the already existing list of sunspot minimum epochs based on direct solar observations (Lassen and Friis-Christensen, 1995). The smoothed series of solar cycle lengths are shown graphically in Fig.6.

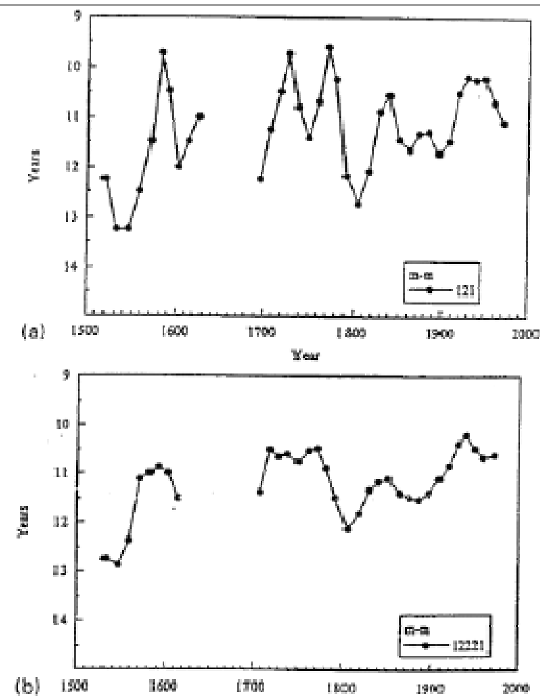

Fig. 6 Variation of the sunspot cycle length 1500-1990 determined by means of sunspot minimum epochs: (a) with an applied smoothing filter with the coefficients 1-2-1; and (b) using the coefficients 1-2-2-2-1. All values have been plotted at the centre of each cycle

Temperature and solar cycle 1500-1990

The completed list of solar cycle lengths has been compared with time series of climate data in order to extend the examination of the assumed association between climate and solar variability as far back in time as the climate data allow.

A comprehensive reconstruction of the northern hemisphere temperature since 1579 was achieved by Groveman and 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.

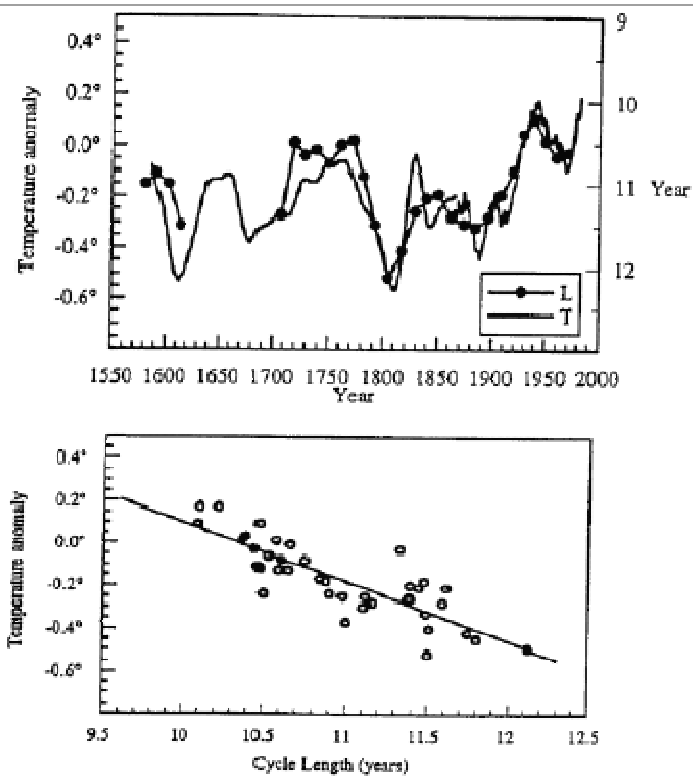

Fig. 7 Upper frame. Eleven-year running average of annual mean values of the northern hemisphere land air temperature 1579-1860 relative to the average temperature 1881-1975, reconstructed by Groveman and Landsberg (1979) together with corresponding values for 1851-1987 relative to 1951-1980 from Jones et al. (1986) and Jones (1988). Also plotted is the (1-2-2-2-1)-filtered value of the sunspot cycle length. Lower frame: Temperature deviations vs. filtered value of the solar cycle length

In Fig.7, upper frame, is plotted an 11-year running average of the annual mean values of their reconstructed temperatures from 1579 to 1860, together with corresponding values for 1851 to 1987 from Jones et al. (1986) and Jones (1988). The reconstructed temperature values are given as departures from the average northern hemisphere temperature 1881-1975, those of the instrumental series from the average northern hemisphere land air temperature 1951-1980. Also plotted in the figure are the smoothed values of the solar cycle length from 1564 to 1989, with the exception of the interval 1641-1674, for which reliable data are missing.

Naturally, the reconstruction of the northern hemisphere temperature must be less confident than the modern record. Groveman and Landsberg give a standard error of 0,2-0,30 C for the single annual averages. Besides this, there exist, of course, year-to-year variations due to internal oscillations in the climate, El Nino effects, volcanic eruptions, etc. Taking these variations into consideration, the comparison between the temperature record and the solar activity indicates a good association between the long-term variations

in the temperature and in the solar cycle length record, although the coincidence may be less obvious during the pre-instrumental period than for the modern instrumental record. The relation is illustrated in Fig.7, lower frame, in which the temperature deviations from the two data series are presented together as a function of the solar cycle length. The graph illustrates how the northern hemisphere land air temperature has varied with solar cycle length since the last decades of the sixteenth century (the second half of the seventeenth century excluded). The temperature decreases monotonically with increasing solar cycle length. The relationship is approximately linear with regression coefficient (-0.28+0.03)0 C/yr. The correlation coefficient is 0.83.

Chinese climate data 1580-1990

A comparison of solar cycle length with phenological data has been presented by Hameed and Gong (1993). These authors combined the data of blossoming of plants noted in personal diaries and other documents originating from the area of the Middle and Lower Yangtze River Valley with records of the last day of snow event in the spring season of each year between 1720 and 1800 kept in the Palace Museum in the Forbidden City. The combined data sets made it possible to estimate the long-term variation of spring temperature in the region from 1580 to 1920. Their figure demonstrates a strong co-variation between the spring temperature in Central China and the length of the solar cycle since 1750.

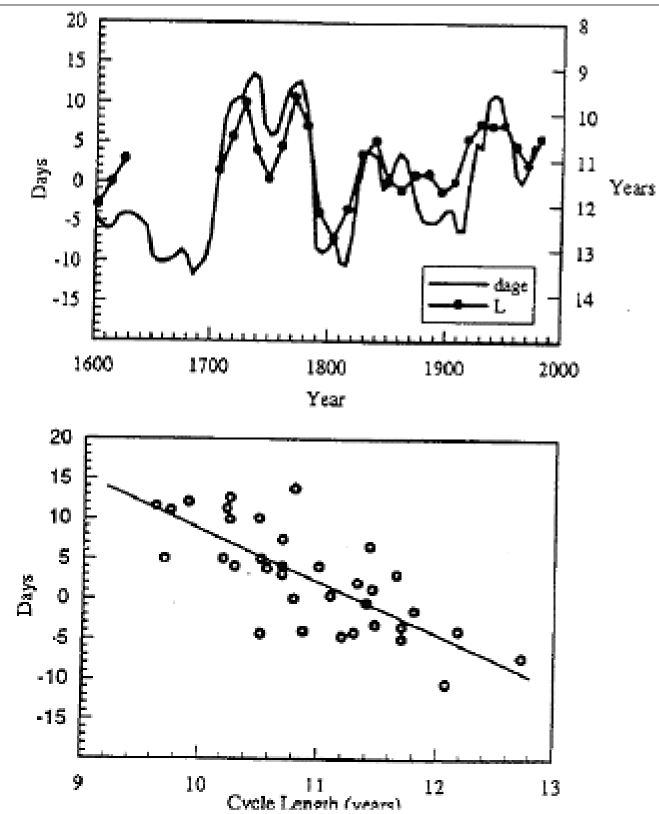

Fig. 8 Upper frame: Five-year running average of spring temperature in the Middle and Lower Yangtze River Valley deduced from phenological data. The curve is redrawn after Hameed and Gong (1993). The ordinate indicates "days before or after an average date". Also plotted is the (1-2-1)- filtered value of the solar cycle length. Lower frame: Deviations vs. (1-2-1)-filtered value of the solar cycle length

In Fig.8, upper frame, their smoothed temperature curve has been redrawn and shown together with the time series of the solar cycle length back to 1600. The figure demonstrates that the spring temperature in this region of Asia has oscillated in concert with solar activity during the past 300 years.

Prior to 1690 the "temperature" curve is situated at a lower level than the remaining par of the curve. If real, this fact may be related to the occurrence of the Maunder minimum in solar activity and/or the Little Ice Age. It is notable, however, that the early part of the curve has been computed from a series of diaries ending in 1689 without overlap with the following series based on the dates of the last snowfall and beginning in 1720 For this reason, and since solar cycle lengths for the interval 1630-1690 are lacking, the graph in Fig.8, lower frame, has been constructed solely from data after 1720.

The figure shows how during nearly three centuries, an increase of the average solar cycle (smoothed) of 1 year has resulted in an average delay of the spring time as represented by blossoming of selected plants and data of last snowfall of nearly 7 days [(6.6Y.0) day/yr; correlation coefficient 0.76].

Iceland ice 1550-1990

An important parameter in the modeling of climate variations is the extent of the Arctic sea-ice. Fig. 9 gives an impression of the extent of sea-ice in the North-Atlantic sector in the early summer.

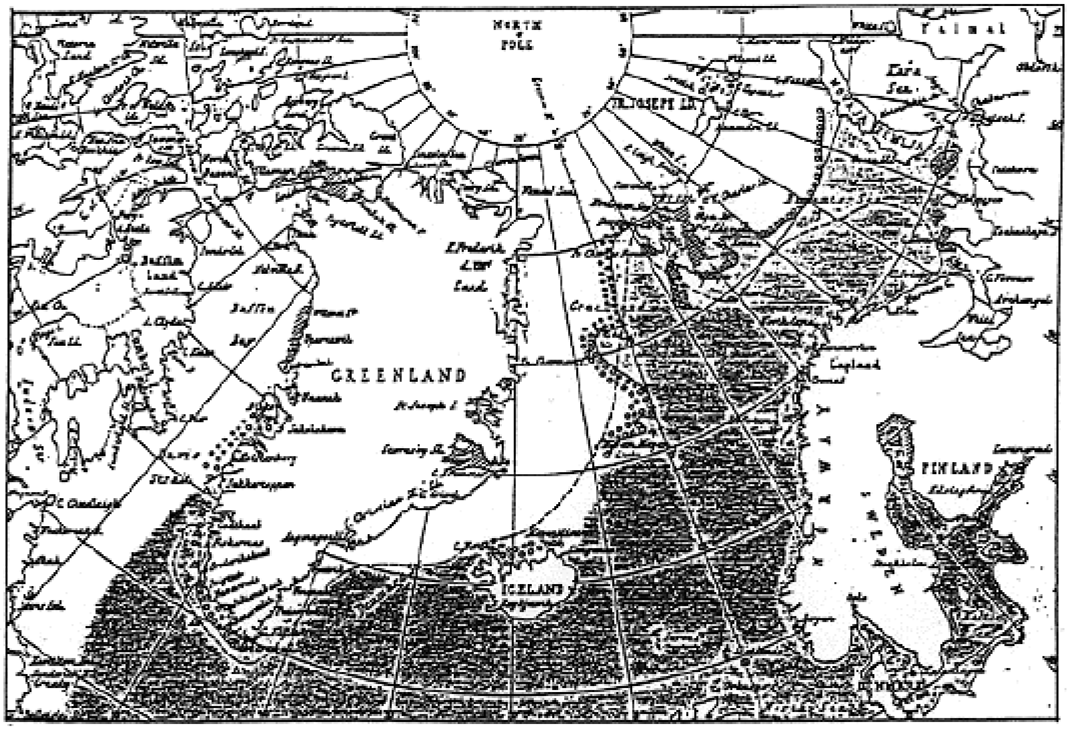

Fig. 9 DMI-ice chart showing the ice situation in May 1938

In this particular month the ice occupied a large part of the Greenland Sea, from Spitzbergen via Jan Mayen to Iceland and Greenland. Ice-charts of this type covering the summer months have been published since the last decades of the nineteenth century from reports of observations from ships, later supplemented by airplane reconnaissance (DMI Yearbooks, see ref). The drift ice in the Greenland Sea (the East-Greenland ice) sometimes approaches the coast of Iceland. Reports of the occurrence of this Iceland ice have been collected by several authors, most comprehensively by Koch (1945). His record consists of an index based on a combination of duration (in weeks) and extent along the coast of Iceland of the drifting ice from the Greenland Sea on an annual basis during the last millennium. In Fig.1O is shown the smoothed year-to-year variation of Koch's index from 1550 AD to present.

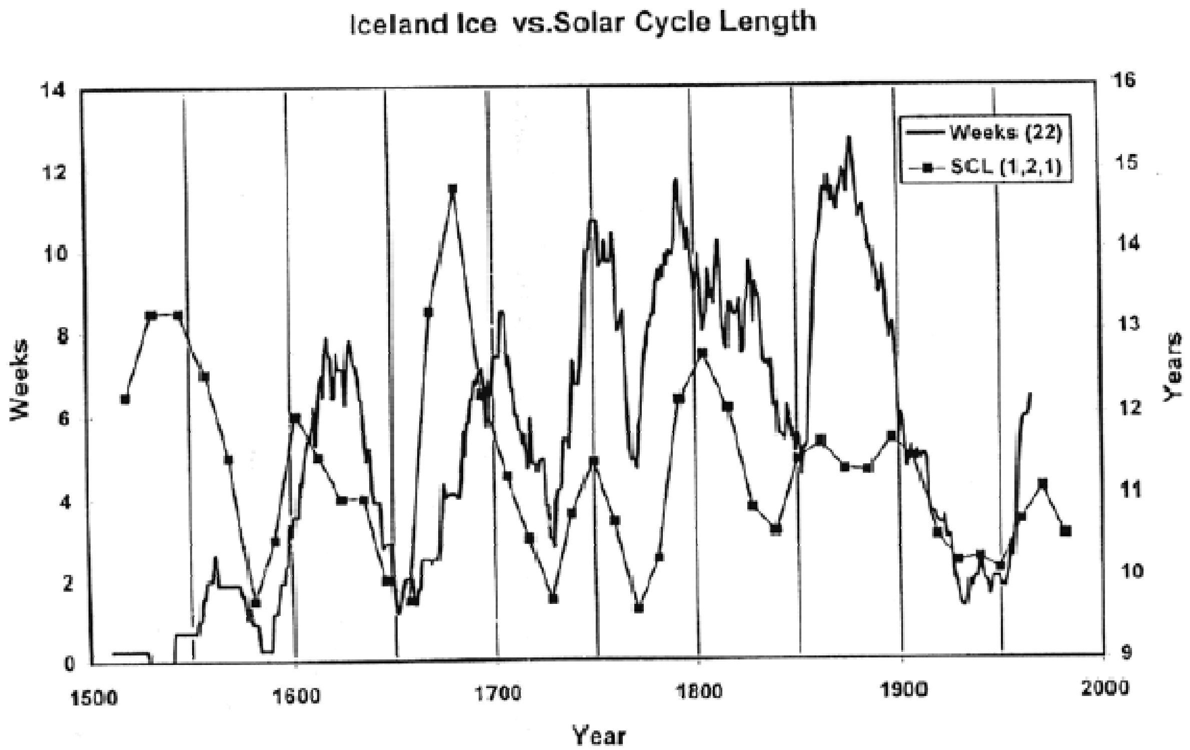

Fig. 10 Variation of Iceland ice-index (21-year running mean) and solar cycle length (1-2-1)-filter 1550-2000 A.D.

A relatively ice-free period in the 15th century was followed by a period of increasing amounts of ice culminating in the 19th century ("The Little Ice Age" ?) and ending with an abrupt fall in the present century. Overlapping this variation are a number of fairly uniformly distributed "bays' with less icecover. Also shown in Fig.1O is the slightly smoothed solar cycle length (reversed scale). There is a clear tendency for the two curves to vary similarly, in agreement with the hypothesis that short solar cycles correspond to higher global temï perature and reduced amount of sea-ice.

Greenland ice core 1550-1974

Dansgaard et al. (1975) compared temperature variations derived from the 18-O concerntration in snow fallen in Central Greenland with temperatures in Iceland through the interval 900-1970. They concluded that most of the pronounced medium frequency (60ï 200 yr periods) oscillations back to 900 are essentially in phase, so that the 18-O curve is representative of climatic changes far beyond the Greenland area. In accordance with their conclusion we show in Fig.11 that the temperature data derived from the ice-core in Central Greenland like the variation of sea-ice extent at Iceland have varied in concert with the medium length solar activity during most of a 500 year period.

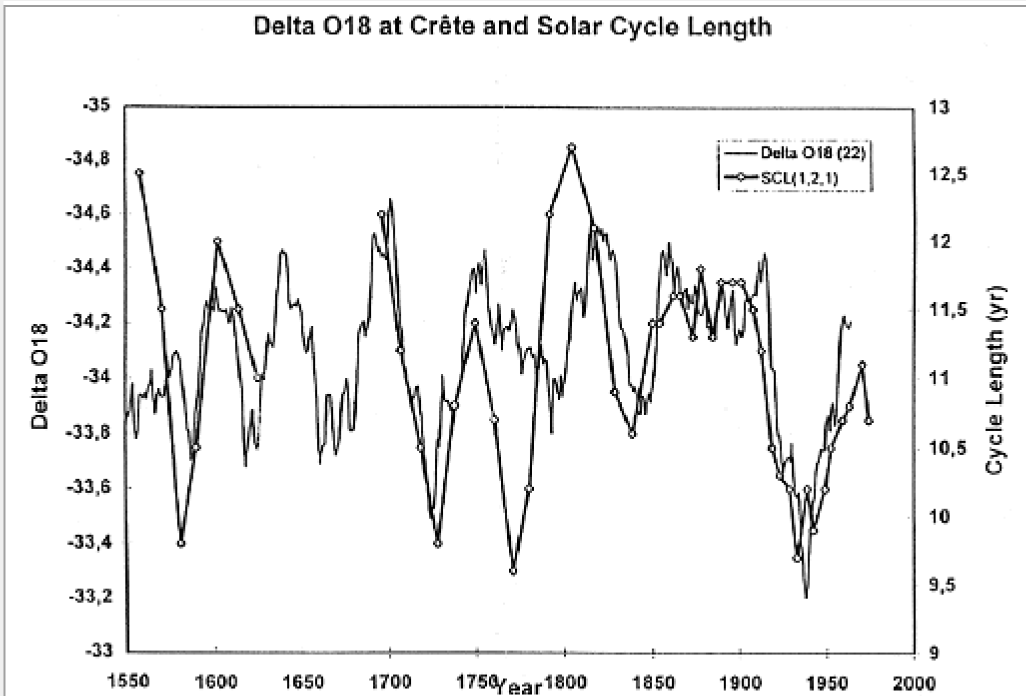

Fig. 11 Variation of delta ^{18}O at Crête on the icecap of Central Greenland 1550-1974 (22-year running mean) and (1-2-1)-filtered solar cycle length

Conclusion

70-90 years oscillations in global mean temperature are correlated with corresponding oscillations in solar activity. Whereas the solar influence is obvious in the data from the last four centuries, signatures of human activity are not yet distinguishable in the observations.

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