Solar forcing of the Northern hemisphere land air temperature: New data

P. Thejll*and K. Lassen
Solar-Terrestrial Physics Division
Danish Meteorological Institute,
Lyngbyvej 100, DK-2100 Copenhagen Ø, Denmark

7 December 1999

Abstract

It has previously been demonstrated that the mean land air temperature of the Northern hemisphere could adequately be associated with a long-term variation of solar activity as given by the length of the approximately 11-year solar cycle. Adding new temperature data for the 1990's and expected values for the next sunspot extrema we test whether the solar cycle length model is still adequate. We find that the residuals are now inconsistent with the pure solar model. We conclude that since around 1990 the type of Solar forcing that is described by the solar cycle length model no longer dominates the long-term variation of the Northern hemisphere land air temperature.

1 Introduction

The long-term (above decadal) variation of the Northern hemisphere land (NHL) air temperature has been found to be negatively correlated with the long-term variation of solar activity during the interval of systematic instrumental temperature measurements from 1861 to 1989 (Friis-Christensen and Lassen 1991 - FCL91 from now on). The close correlation was obvious to see once the smoothed solar cycle length (SCL) was chosen as an index of long-term variability of the Sun, and it was concluded that this parameter appears to be an indicator of long-term changes in the total energy output of the Sun, which in turn was mainly responsible for the long-term variations of the temperature through the period studied. Subsequently it has been demonstrated (Friis-Christensen and Lassen 1992, Hoyt and Schatten 1993, Hameed and Gong 1994, Lassen and Friis-Christensen 1995

*corresponding author: email=thejll@dmi.dk, fax=(+45) 39 15 74 60

- LFC95 from now on, Butler and Johnston 1996, and Zhou and Butler 1998) that this correlation has probably been present for centuries. Wilson (1998) presented a similar result, but found that the solar activity could more correctly be represented by the length of the double solar cycle (the Hale cycle). The findings can be regarded as an extension and confirmation of the finding by Johnsen et al. (1970), who studied the variation of the air temperature since 1200 A.D. as deduced from the ratio of oxygen isotopes in an ice-core from Camp Century in Greenland. Spectral analysis of their data showed two dominant peaks that corresponded to 78 years and 181 years, which they interpreted as originating from changing conditions on the Sun. In particular they noted that the 78 year period was almost identical with the so-called Gleissberg period in the length of the sunspot cycle (Gleissberg 1944). However, there have also been several papers criticizing the solar cycle hypothesis (see for example Kelly and Wigley, 1992, and Schlesinger and Ramankutty, 1992 and 1994, and the discussion in LFC95).

FCL91 concluded that if their result can be related to a real physical mechanism there is a possibility to determine the greenhouse warming signal better 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 were needed before any firm conclusion regarding anthropogenic changes could be made. The corresponding statement in IPCC (1995): '*the balance of evidence suggests a discernible human influence on global climate. Any human-induced effect on climate will be superimposed on the background "noise" of natural climate variability, which results from internal fluctuations and from external causes such as solar activity or volcanic eruptions*' appears to be generally accepted.

With the aim of bringing the study of the association between the solar activity and the NHL air temperature as far up to date as possible FCL91 included in their Figure 2, in which time series of the two quantities were presented, the unsmoothed last values of the solar cycle length-series. It has now become possible to substitute these values by the filtered values (Figure 1). The smoothed values are lower than the unfiltered ones originally presented, and the revised figure may now suggest a deficit of the solar activity in relation to the average temperature.

Since the first presentation in 1991 of the correlation with solar activity there has been a continued increase in the average annual temperature of the Northern hemisphere, so that in the most recent years the temperature level is in fact the highest measured since the beginning of systematic measurements. The rapid temperature rise recently seems to call for a quantitative revisit of the solar activity-air temperature association to see to which degree the solar cycle length model is able to explain the observed ongoing temperature increase.

The smoothed data series in Figure 1 end with the data-points situated in 1985. The width of the data-filter does not allow for a reliable extension of the curves beyond this epoch and extended temperature values can only be obtained by substitution of the complete series by a new revised one (Jones 1999, private communication). Accordingly, we have repeated and extended the study by FCL91 using the revised temperature series and a different and narrower filter on the solar cycle lengths.

We assume the Null hypothesis that the solar cycle lengths provide a good fit to observed NHL mean air temperatures. We test that hypothesis, for various intervals, data sets and methods of temperature averaging, by comparing the correlation coefficient (R), between the best fitting linear solar model ($T_m = a + b * SCL$) and observed temperatures, to the distribution of R's generated in Monte Carlo simulations of the analysis process and randomly generated SCL curves. Generating the suitable SCL curves is performed under the assumption that series with the same lag-one autocorrelation, and same mean and standard deviation as the real SCL curve, are suitable choices for Null hypothesis testing.

The assumed model is linear, partly for reasons of continuity with previous work, and partly because there are probably not enough data to accommodate more than two free parameters in any model-fit to the instrumental era temperatures. There is a trend in these data, but we are not free to remove it, as the very nature of the temperature evolution is similar to a linear trend – as are the predictions from, e.g., greenhouse gas forced models.

In section 2 we discuss the formalism of the solar cycle length model - how the SCL's and the attached uncertainties are calculated. We also describe the procedure for our calculation of NHL air temperature cycle means. In section 3 we perform a least squares fit between the temperature data and the SCL's and perform the Monte Carlo simulations to get the significance levels of the correlation coefficient. We discuss the results of this test in section 4, where we also look at the problem of using predictions about future solar cycles and the likelihood of future cycles being so short that they invalidate our predictions and results therefrom.

2 Data, and the methods of calculating means

2.1 Solar Cycle Length calculation

From a list of Zurich relative sunspot (R_z) cycle minimum and maximum dates (NGDC 1999) two lists of solar cycle lengths were prepared - one defined by the durations from minimum to subsequent minimum and another defined by the durations between maximum and subsequent maximum (LFC95 and Table 1). Associated dates are taken at mid-cycle. Following the procedure introduced by Gleissberg (1944) in his study of the underlying regular variation of the length of the solar cycle FCL91 applied a 5-point filter with the consecutive weights (1/8, 2/8, 2/8, 2/8 and 1/8) (from now on referred to as the 12221 filter) to each list of cycle lengths. Finally, the two lists of weighted cycle lengths were merged such that the abscissae increase in time. In the present study we shall apply a similar procedure, but with the narrower 3-point filter with weights (1/4, 2/4 and 1/4) (referred to from now on as the 121 filter). For a detailed discussion of the filters the reader is referred to LFC95. Here we show in Figure 2 that application of the two filters results in almost identical shapes of the smoothed solar cycle curve.

In order to update the study we use the 1990's temperatures and predictions and estimates for the next three cycle extrema. The next maximum is predicted (Joselyn et al. 1997) in early 2000. Wilson et al. (1998) predict 'before May 2000' (we adopt 2000.3 $\pm$ 1.0; the notation 2000.3 refers to fractions of the year – i.e. about day 109 in a 365 day year, or a date near the middle of April). We then assume that the maximum after that will follow 10.9 years later - i.e. in about 2011.2 $\pm$ 1.6 years, based on the mean and standard deviation of the cycle length since 1851 and the uncertainty on the estimated date for the minimum in 2000.3. Using the average cycle length the next minimum should appear sometime in 2007 – Wilson et al. (1998) predict 'before May 2007' (we pick 2007.3 $\pm$ 1). We use an uncertainty of half a year on the date for any observed minimum or maximum and have then propagated the errors for the cases relying on predictions. The SCL uncertainty for any set of dates that are all observed is then 0.25 years if the errors on the defining dates are independent. The uncertainties on all the weighted SCL's are shown in Table 1.

2.2 Cycle mean temperatures

The longest available series of mean instrumental NHL air temperature anomaly data, covering the period 1851 to now, was prepared by Jones (1994) and updated through 1998 by Jones (1999, private communication). The data are given as monthly mean anomalies referred to the interval 1961-1990.

Cycle means of the temperatures are calculated from the list of solar cycle extremum dates using three methods, in order to allow comparisons of method-dependencies. The first two methods use the list of R_z sunspot maxima and minima to define time intervals that are near 11 years long, and near half that amount respectively, while the third method applies the method originally used in FCL91. The differences between the choices are subtle, but have some importance for the results and therefore need to be carefully described. The reader uninterested in these details can safely skip to the last paragraph of this section.

Method 'A' uses the central years, defined as described above, which therefore are alternately for minima and maxima. With a given choice of central year the adjacent central years are used to define a roughly 11 year long interval over which the temperatures are averaged. Thus, if the central year chosen is 1984.75 (i.e. a central year defined as being at the midpoint between the dates for the sunspot maxima in 1979.9 and 1989.6) then the interval boundaries used for the temperature averaging for that point are at 1981.65 and 1991.80 (both central years from *minima*).

Method 'B' uses the half-way points to these boundaries. Thus, the temperature averaging for the same central year as above is done from 1983.2 (the midpoint between 1981.65 and 1984.75) to 1988.35 (the midpoint between 1984.75 and 1991.8).

Method 'C' is the method originally chosen in FCL91 and consists of using same-type cycle extrema dates (i.e. not central years) to define the interval boundaries. 'Same-type' refers to using minima dates if the central year is a minimum one and maxima dates if the central year is a maximum one. Thus, the intervals used to get the temperature average when the central year is 1984.75, is in method 'C' from 1979.9 to 1989.6 (both maxima). Similarly, for the next central year (1991.8 - a minimum central year) the intervals used are thus from 1986.8 to 1996.8.

Method 'C' is the method that gives 'symmetric intervals' as far as the interval endpoint dates are concerned. Methods 'A' and 'B' use intervals that are somewhat shifted in time with respect to 'C'. Methods A and C give roughly 11 year long intervals that thus overlap since there is a central year on the average every $\frac{11}{2}$ years, or so.

The use of intervals that overlap, and the use of intervals that are arbitrarily defined with respect to the solar activity gives rise to concerns about biases and the dangers of erroneously optimistic results. Both these concerns are dealt with by our choice of a Monte Carlo method for estimating statistical significances. The temperature averaging method is necessarily arbitrary since there is little hint of how the Sun might influence the temperature so that the physically most meaningful method of temperature averaging cannot be chosen. The choices made here have to do with ease of implementation and continuity of previous methods.

3 Fitting, and Monte Carlo simulations

The solar cycle length values, with 1-2-1 weighting (SCL121 from now on) - calculated as described in section 2.1, are regressed against interval-averaged temperatures calculated as described in section 2.2.

After the best linear regression is found (see Figure 3), the correlation coefficient R is calculated. Significance levels for R are then calculated using a Monte Carlo simulation of the regression above, using simulated SCL121 series instead of the real one. A similar approach is described in Wilks (1995) and has been recently used by Mann et al. (1998). The method basically generates a universe of statistically similar simulated SCL121 series that are not generated by natural processes. Applying this method we ensure that any steps taken during the analysis that may be causing bias towards unnaturally good (or bad) regressions will also act during the simulations and thus bias the results of these in the *same way*, giving a sound basis for determining robust significance levels.

The simulated series were generated auto-regressively using the lag-one autocorrelation of the real SCL121 series. The series generated thus were scaled to the same mean and standard deviation as the original temperature series. From 1000 simulations the distribution of R was formed and the probability of a given value of $|R| < |R_{obs}|$ calculated simply as the ratio of the number of R values between $-|R_{obs}|$ and $|R_{obs}|$, divided by the total number of values.

For three different temperature series and the three above choices of averaging method the Monte Carlo simulations were run and the values of R and their probabilities found. A conventional 95% significance level was used. The results are shown in Table 2.

The results are that using all three methods of averaging on the original data used in FCL91 we find significant correlations from -0.79 to -0.87. Switching to monthly data restricted to the same range of years as in FCL91 does not reproduce the results of that case in absolute terms, but in relative terms - i.e., method A has the highest correlation, followed by methods C and B. This failure to reproduce the results from the data set used in FCL91 is probably linked to the changes in the data sets - these temperature averages are the results of choices of data (about 10% more historical data in the newer set), and the use of different reference intervals the choice of which has non-linear consequences for the resulting temperature anomaly. However, the choice of dataset is, as we shall see next, not as important as whether the set includes the temperatures of the 1990's.

When the temperature data for the 1990's are included the correlations drop in all cases by a larger amount. This shows that the inclusion of the 1990's has caused a marked divergence between the solar model and the observed temperatures during that time. We see that the method of temperature averaging that does the least amount of smoothing (method 'B') also has the smallest and least significant correlation to the solar model, underlining the earlier findings of FCL91 and LFC95 that only the long-term (more than decadal) behavior of the temperature can be well fitted to the solar model. As not only the correlation is greater when methods A and C are employed, but also their significances, we know we are not just seeing the expected effects of greater smoothing leading to a larger correlation. Smoothing at the decadal level is uncovering an underlying physical relationship between the Solar influence and temperatures.

4 Discussion

Let us review the uncertainties, in data and methods, that the above results are affected by.

The arbitrariness in observed sunspot minima and maxima times is typically a few months. In Table 1 we have adopted 0.5 years, leading to an uncertainty of about 0.3 years on the smoothed value. A new, median based definition of the solar cycle length proposed by Mursula and Ulich (1998) was shown to reduce the inaccuracy in cycle length to a few days, which is a factor of 30-50 smaller than in the case of the conventional method. The resulting median cycle lengths agree well with the official (min-min) cycle lengths during the instrumental temperature interval, and the median cycle lengths were demonstrated to verify the correlation suggested by FCL91 between the solar cycle length and the NHL air temperature. Accordingly, the uncertainty in the estimated cycle lengths used in the present study has not influenced our results perceptibly.

Fligge et al. (1999) presented a more objective and general cycle length determination, based on wavelet analysis and several solar activity indicators. All records were found to exhibit cycle length variations which are, within the error bars, in accordance with the record originally proposed by FCL91.

As our result is based on predictions of the next 3 extrema (2 maxima and one minimum) it is possible that unusual evolution in the solar activity will invalidate our results. We will now consider which changes in solar activity are required for this to happen, and how likely they are.

For the SCL curve to match the recent increase in cycle mean temperatures it is required that the current and the next cycle be very short. Since 1750, when reliable Wolf sunspot numbers are available, the lengths of all observed cycles have lain between 9 years and 13.6 years. The 9 year cycles occur twice out of about 38 values considered - only minima to minima cycles have been considered from 1750 to 1850 due to the data quality while both min-min and max-max cycles have been considered since 1850. If aurora are used to estimate the activity in the solar cycle back to 1500 one finds (in Table 1 of LFC95) two cycles of length 8 years in the central years 1581 and 1728, out of 19 values considered. It would therefore seem that cycles as short as 8 years have occurred only twice out of 57 cycles or about 3.5% of the time.

Using these extremely short cycle lengths we re-estimate the 121-weighted SCL values for the next few cycles, as an experiment. The maximum of cycle 23 (the current cycle) is predicted to fall near May or April 2000, but the behavior of the cycle is very anomalous and plots of the observed preliminary sunspot numbers indicate a cycle that is lower in numbers than predicted. If the numbers decline from now on, the maximum will have occurred near 1999.0, it seems. Using this to get the shortest possible length of cycle 23 (9.4 years), and adopting 8 years for unobserved cycle lengths we can calculate the new 121-weighted SCL values, and thereafter, using the new central years, new cycle mean temperatures.

The results are that for the 121-weighted min-min cycle with unchanged central year in 1991.8 the length is reduced to 9.6 years, that the weighted max-max cycle with central year in 1984.75 changes to a length of 10.0 years, and that the weighted max-max cycle with central year previously in 1994.95 changes to central year 1994.3 with a length of 9.1 years.

These changes are such that the 121-weighted SCL curve now follows the cycle mean temperatures very well in the last points of the curve, instead of diverging. See Figure 4.

We have therefore shown that, given the occurrence of short, but not unprecedentedly short, solar cycle lengths in the next few decades, the SCL curve may match the cycle mean temperatures as well as before - but that this has a probability of occurring of only about 3 - 4%. As the probability of two consecutive 8 year cycles is even lower we consider that there is an upper limit of a few percent on the chance that the SCL model will fit the temperatures during the next decades.

4.1 Residual structure

Having rejected the hypothesis that the Solar model fits present data for temperature means, we consider the alternatives. As Table 2 shows, it was not simple to reject, on statistical grounds, the original hypothesis with data up to the end of the 1980's. The residuals of the fit, using the regression equation for the data to the end of the 1980's, should therefore be examined for insight into the factors that cause the failure of the model when data through the 1990's are added. Figure 5 shows the result in a format similar to previous figures, but with a lower panel that displays the residuals. These appear to have two structures that look systematic – the trough from 1900 to about 1930, and the rise after 1970. The trough is a signature of the delay of the temperature rise seen in the upper panel of the figure. The magnitude of the delay is to some extent dependent on the data interval used in the regression as well as on the choice of reference level for the temperature anomaly. A corresponding study (not shown here) of the Northern hemisphere temperature variation during 1881-1975 computed by Borzenkova et al. (1976) does not show a similar delay. The residuals from this time series have been included in the lower panel of Figure 5 as filled triangles. The distribution of the combined residuals in the lower panel seems to indicate a random residual scatter before 1970. The interesting upturn in the residuals from about 1970, which is much larger than any of the variations in the residuals before 1970, is similar to predictions from greenhouse gas driven climate models. It is unlikely that a statistically strong statement could be made about the resemblance of this upturn to quantitative predictions by greenhouse-gas forced general circulation models as the reduction in degrees of freedom due to the small amount of data available and the use of models with additional free parameters would make the statistical significance very low. It seems possible that the upturn is a result of human activity, but we cannot on the basis of the existing data say that we have proven the emergence of the effects of greenhouse gases – we can however say that we have shown that the Solar model fails to fit the temperature data convincingly through the 1990's.

5 Summary

In this paper we have investigated the effects of adding the newest temperature and solar cycle data on the hypothesis that the Sun, somehow, is controlling the evolution of the NHL air temperature in terms of the decadal-scale averages. About 10 years ago, FCL91 found that a good fit existed between the solar cycle length curve and the cycle mean temperatures. Today we conclude that the addition of data for the 1990's has changed that picture – a solar model with decadal smoothing can now only explain about half the variance in the mean temperatures whereas it was able to explain about 2/3's before 1988, admittedly with some dependence on the decadal smoothing method used. Since about 1970 the residuals have risen monotonically.

This conclusion is based on assumptions about as-yet unobserved solar cycles, and we estimate the chance that these unobserved cycles will be short enough to alter our new perception. We find that there is only a small chance (less than 3 - 4 %) that the next few cycles will be short enough to do that, which is so little that we do not see it as a threat to our findings.

Acknowledgments: This work was supported by the Danish Climate Centre at DMI. We thank Phil Jones for so kindly providing us with updated monthly temperature data. Our discussions with Bo Christiansen are warmly acknowledged.

References

[1] Borzenkova, I.I., Vinnikov, K. Ya., Spirina, L.P., and Stekhnovskii, D.I., 1976, Variation of Northern Hemisphere Air Temperature from 1881 to 1975, Meteorologiya i Gidrologiya **7**, 27-35

[2] Butler, C.J. & Johnston, D.J. 1996. A provisional long mean air temperature series for Armagh Observatory. Journal of Atmospheric and Solar-Terrestrial Physics 58, 1657-1672

[3] Fligge, M., Solanki, S.K., and Beer, J., 1999, Determination of solar cycle length variations using the continuous wavelet transform, Astronomy and Astrophysics **346**, pp. 313-321

[4] Friis-Christensen, E. & Lassen, K. 1991. Length of the Solar cycle: An indicator of Solar activity closely associated with climate. Science **254**, 698-700

[5] Friis-Christensen, E. & Lassen, K. 1992. Global temperature variations and a possible association with Solar activity variations. Danish Meteorological Institute Science Report 92-3.

[6] Gleissberg, W. 1944. A table of secular variations of the Solar cycle. Terrestrial Magnetism and Atmospheric Electricity **49**, 243-244

[7] Hameed, S. & Gong, G. 1994. Variation of spring climate in lower-middle Yangtse river valley and its relation with Solar-cycle length. Geophysical Research Letters **21**, 2693-2696

[8] Hoyt, D.V. & Schatten, H.K. 1993. A discussion of plausible Solar irradiance variations 1700-1992. Journal of Geophysical Research **98**, 18.895-18.906

[9] (IPCC) Intergovernmental Panel on Climate Change 1996, Climate Change 1995, page 4

[10] Johnsen, S.J., Dansgaard, W., Clausen, H.B. & Langway, C.C. 1970. Climatic oscillations 1200-2000 AD. Nature **227**, 482-483

[11] Jones, P.D., 1988. Hemispheric Surface Air Temperature Variations: Recent Trends and an Update to 1987, Journal of Climate **1**, pp.654-660

[12] Jones, P.D. 1994. Hemispheric surface air temperature variations: A reanalysis and an update. Journal of Climate **7**, 1794-1802

[13] Jones, P.D., Raper, S.C.B., Bradley, R.S., Diaz, H.F., Kelly, P.M., and Wigley, T.M.L., 1986. Northern Hemisphere Surface Air Temperature variations: 1851-1984, Journal of Climate and Applied Meteorology **25**, pp.161-179

[14] Joselyn, J.A. et al., 1997. Panel achieves consensus prediction of Solar cycle 23. EOS **78**, 205

[15] Kelly, P.M., and Wigley, T.M.L., 1992, Solar cycle length, greenhouse forcing and global climate, Nature **360**, 328-330

[16] Lassen, K. & Friis-Christensen, E. 1995. Variability of the Solar cycle length during the past five centuries and the apparent association with terrestrial climate. Journal of Atmospheric and Solar-Terrestrial Physics **57**, 835-845

[17] Mann, M.E., R.S. Bradley, M.K. Hughes, 1998, Global-scale temperature patterns and climate forcing over the past six centuries, Nature **392**, pp. 779-787

[18] Mursula, K., and Ulich T., 1998, A new method to determine the solar cycle length, Geophysical Research Letters **25**, pp.1837-1840

[19] (NGDC) National Geophysical Data Center, Boulder, Colorado, USA, 1999. List of cycle minima and maxima (file 'maxmin') published by the NGDC on the Internet at
`ftp://ftp.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS/`

[20] Schlesinger, M.E., and Ramankutty, N., 1992, Implications of global warming of inter cycle solar irradiance variations, Nature **360**, 330-333

[21] Schlesinger, M.E., and Ramankutty, N., 1994, An oscillation in the global climate system of period 65-70 years, Nature **367**, 723-726

[22] Wilks, D.S., 1995, Statistical Methods in the Atmospheric Sciences, Academic Press, section 5.3.2

[23] Wilson, R.M. 1998. Evidence for Solar-cycle forcing and secular variation in the Armagh Observatory temperature record (1844-1992). Journal of Geophysical Research **103**, (D10), pp. 11.159-11.171.

[24] Wilson, R.M., D.H. Hathaway and E.J. Reichmann, 1998, An estimate for the size of cycle 23 based on near minimum conditions, Journal of Geophysical Research **103**, (A4), pp. 6595-6603

[25] Zhou, K., and Butler, C.J. 1998. A statistical study of the relationship between the solar cycle length and tree-ring index values. Journal of Atmospheric and Solar-Terrestrial Physics **60**, 1711-1718

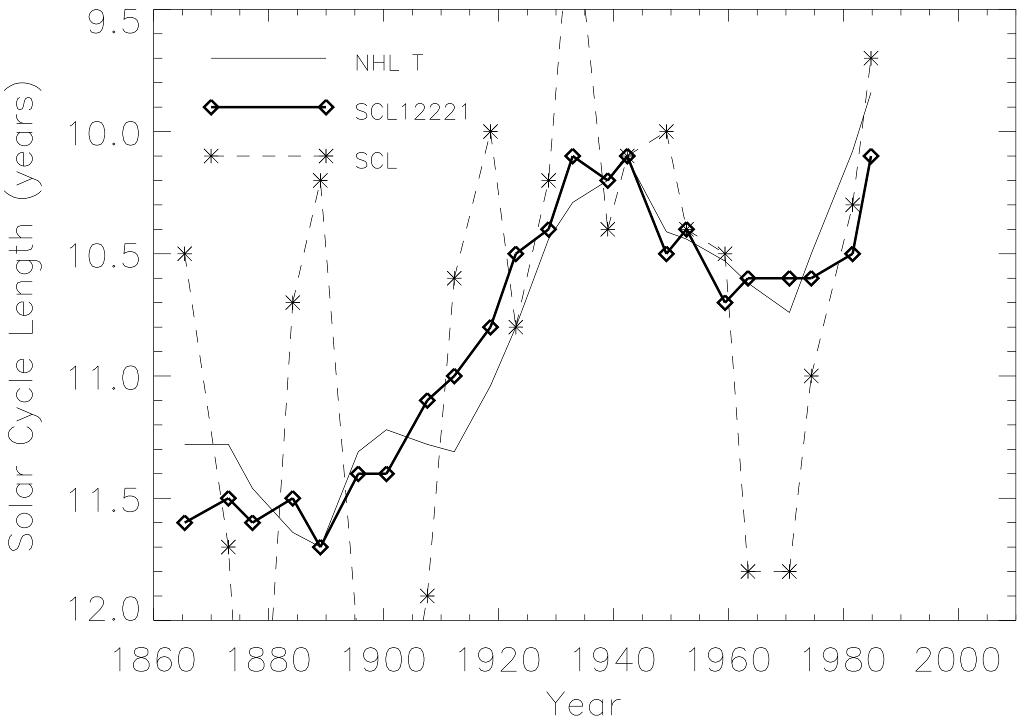

Figure 1: Observed cycle mean temperatures (thin solid line) and best fitting (1-2-2-2-1) SCL model (thick solid line with diamonds). This is a reconstruction of Figure 2 in FCL91 with update of the last values of the SCL12221, now calculated as the rest of the points on the curve but in 1991 represented by unsmoothed cycle length values. Also shown in the figure is the unsmoothed time series of the unfiltered SCL (dashed line with asterisks) to illustrate that the association found is between the long-term variation of the cycle length and the temperature, not the instantaneous values. Notice how the two properly calculated values of SCL12221 in the 1980s lie lower than the two preliminary values used in FCL91. The use of preliminary SCL values in FCL91 suggested a better fit between temperatures and the SCL model than is the case with the actual weighted values.

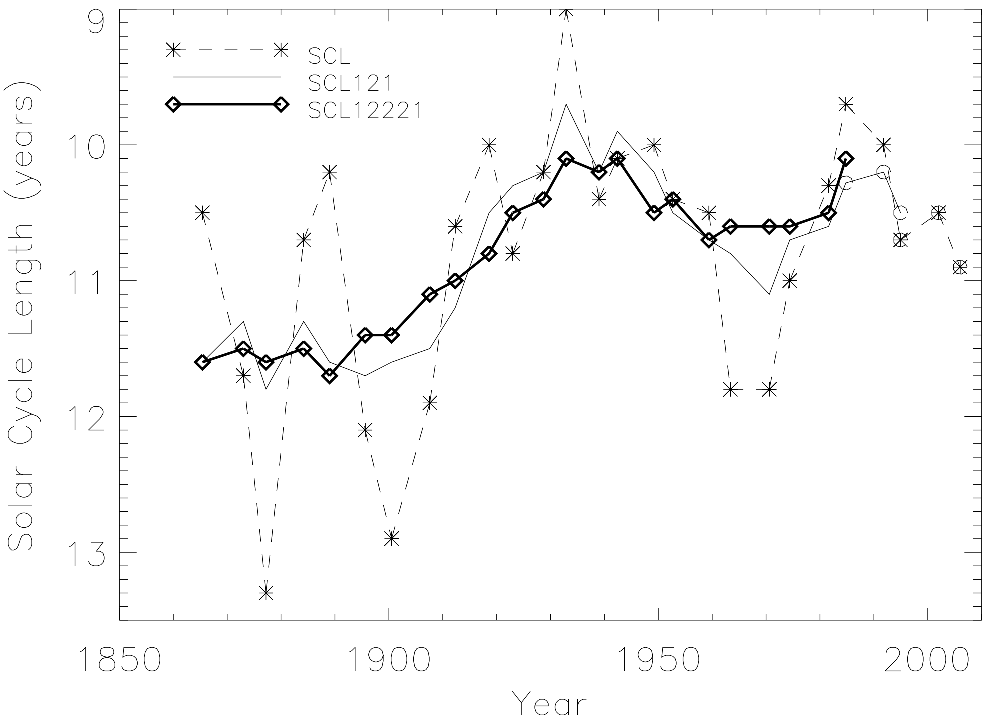

Figure 2: Variation of solar cycle length (SCL) 1865-1985. The figure shows time series of the observed SCL (dashed curve with asterisks, predictions encircled), the (1-2-1) filtered SCL (thin solid line, predicted points encircled), and the (1-2-2-2-1) filtered SCL (heavy solid line with diamonds). The filtered curves are nearly similar, except for a few points (especially 1970.6) where the difference amounts to 0.5 years. Note that the predicted values are based on different amounts of predictions: the raw SCL value in 1994.95 depends on 1 predicted maximum date, the one in 2002 on one predicted minimum date and the one in 2006 on 2 predicted maximum dates. The SCL121 value in 1984.75 depends on one predicted maximum date, the one in 1991.8 depends on 1 predicted minimum date, and the one in 1994.95 depends on 2 predicted maxima.

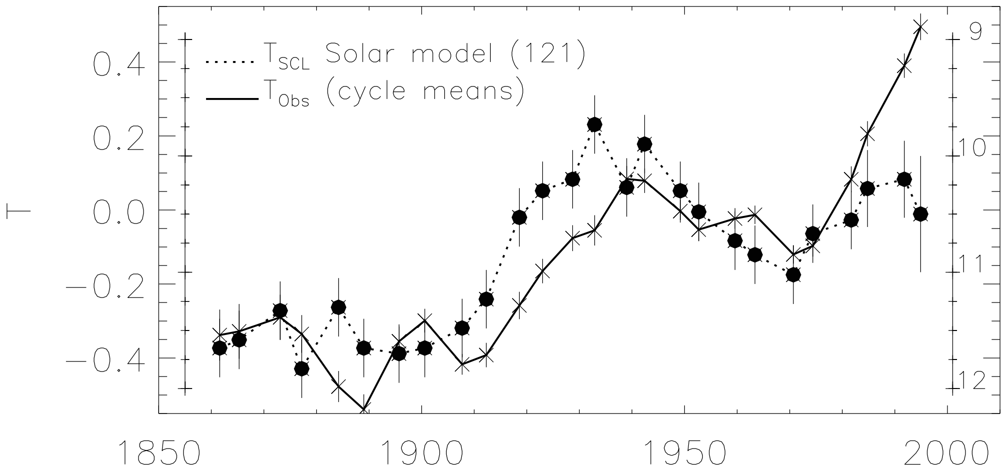

Figure 3: Observed temperatures and best-fitting SCL121 model. A regression of SCL121 values onto temperature cycle means (method 'C', see section 2.2) has been performed. To the right and left inside the figure panel are axes showing the solar cycle lengths corresponding to the best fitting regression, in years. The equation for the best-fitting SCL121 model is: $T_m = 3.3(\pm 0.1) - 0.31(\pm 0.01) \times$ *SCL121*, where the quantities in parentheses are the formal uncertainties on the fitted parameters. All points on the SCL curve have error bars reflecting estimates of uncertainties in observed and predicted cycle extrema. Bars on the cycle means of T are standard deviations of the mean.

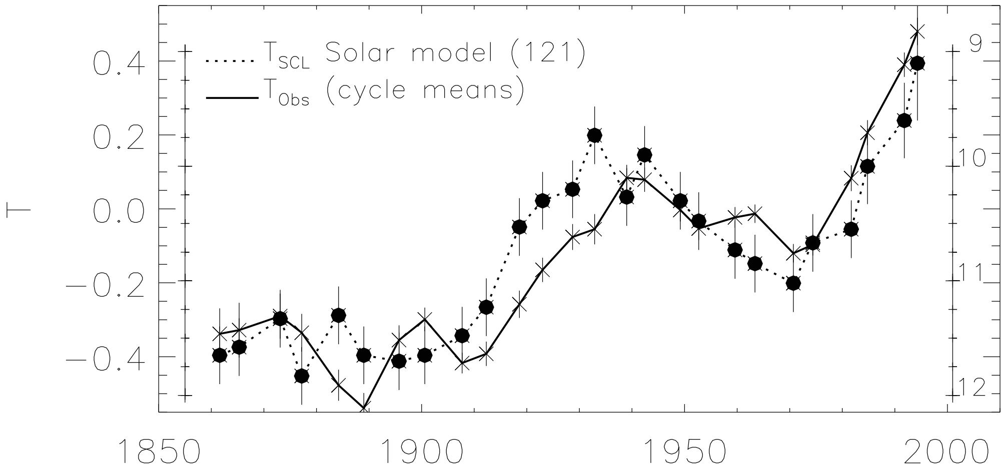

Figure 4: As Figure 3, but with the data at the end points altered under the assumption of very short (8 year) solar cycles. The fit is in this case so good that one would not be able to reject the hypothesis that the SCL model fitted the observed temperatures well. The probability of consequtive very short solar cycles occurring now, however, is estimated to be less than a few percent.

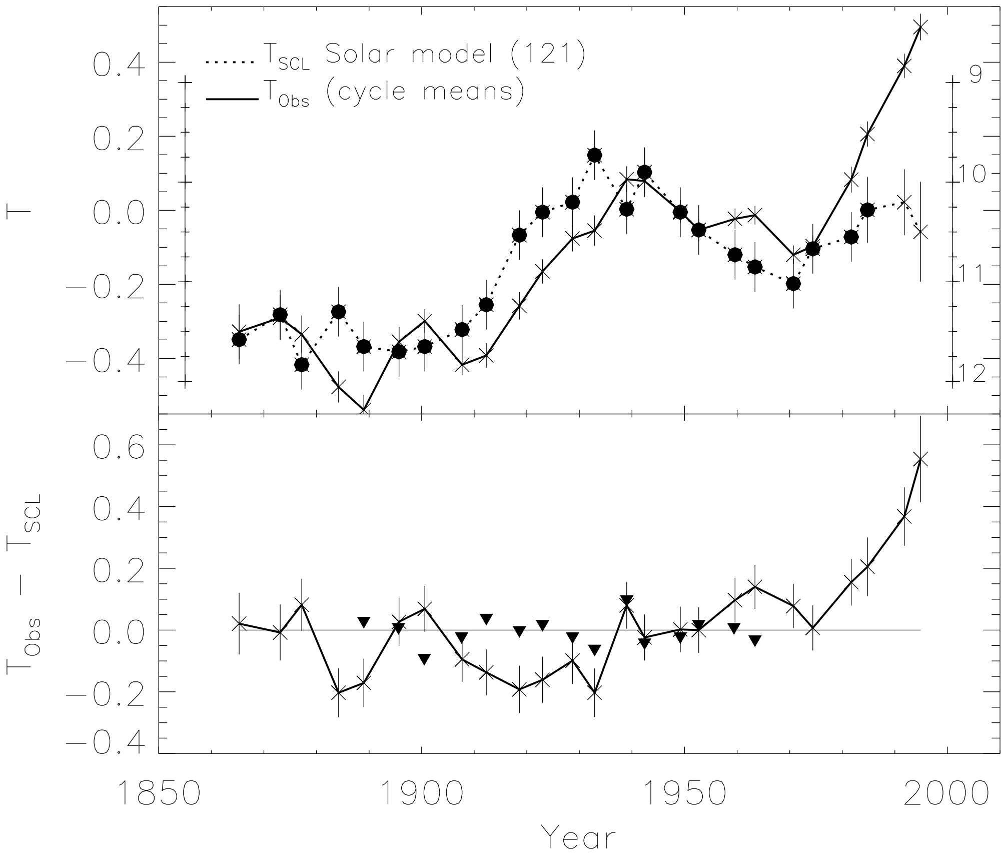

Figure 5: Fitting the 1-2-1 weighted SCL to cycle mean temperature data up to 1985. The heavy dots indicate the data points used in the regression. The best-fitting regression equation is: $T_m = 2.8(\pm 0.1) - 0.26(\pm 0.01)\times$ *SCL121*. In the lower panel the residue between the model and the temperature is shown. The filled triangles between 1890 and 1970 are the residuals formed when the appropriate best-fitting SCL121 model is subtracted from the Northern hemisphere temperature reconstruction by Borzenkova et al. (1976).

Table 1: Solar cycle extrema and SCL's - for minima (upper half of table) and maxima (lower half). All data based on predictions are marked in parentheses. Column 1 gives the date for the extremum - in decimal years, 2 gives the type of extremum (m for minima and M for maxima), 3 gives the uncertainty of the extremum date in years, 4 gives the unweighted SCL, 5 gives the date, or Central year, of the weighted SCL, 6 gives the weighted SCL and 7 gives the calculated uncertainty on the weighted SCL in years assuming independent errors on the extremum dates. Refer to LFC95 for earlier values of SCL's.

Extremum date	m or M	Δ	SCL	Central year	SCL121	Δ
1964.9	m	0.5				
			11.6			
1976.5	m	0.5				
			10.3	1981.65	10.55	0.25
1986.8	m	0.5				
			10.0	1991.80	(10.2)	0.33
1996.8	m	0.5				
			(10.5)	(2002$\pm$1)		
(2007.3)	m	1.0				
1968.9	M	0.5				
			11.0			
1979.9	M	0.5				
			9.7	1984.75	(10.28)	0.33
1989.6	M	0.5				
			(10.7)	(1994.95)	(10.5)	0.50
(2000.3)	M	1.0				
			(10.9)	(2006$\pm$2)		
(2011.2)	M	1.6				

Table 2: Observed correlation coefficients (R) and their significance levels. Results of 1000 Monte Carlo simulations for each of 3 temperature series and three choices of temperature averaging. 'A' refers to averaging over roughly 11 year long intervals. 'B' refers to averaging over intervals half that length. 'C' refers to the original method used in FCL91. Original temperature data are (1) annual values up to 1988 from Jones et al. (1986) + update Jones (1988), and monthly values (series 2 and 3) into 1999 (Jones 1994 + 1999 update (Jones 1999, private communication)) – either complete through 1988 (series 2) or to end of 1998 (series 3). The percentages give the fraction of simulations of $|R|$ that were smaller than the observed $|R|$, where vertical bars denote absolute value. Entries in bold face are significant at the 95% level or better.

	Series	Method A	Method B	Method C
1	Jones (1986)+87&88 update	**-.87 (98%)**	**-.79 (95%)**	**-.83 (97%)**
2	Jones (1999) - 1989 incl.	**-.82 (97%)**	-.77 (90%)	-.80 (93%)
3	Jones (1999) - 1998 incl.	-.76 (88%)	-.71 (85%)	-.73 (88%)