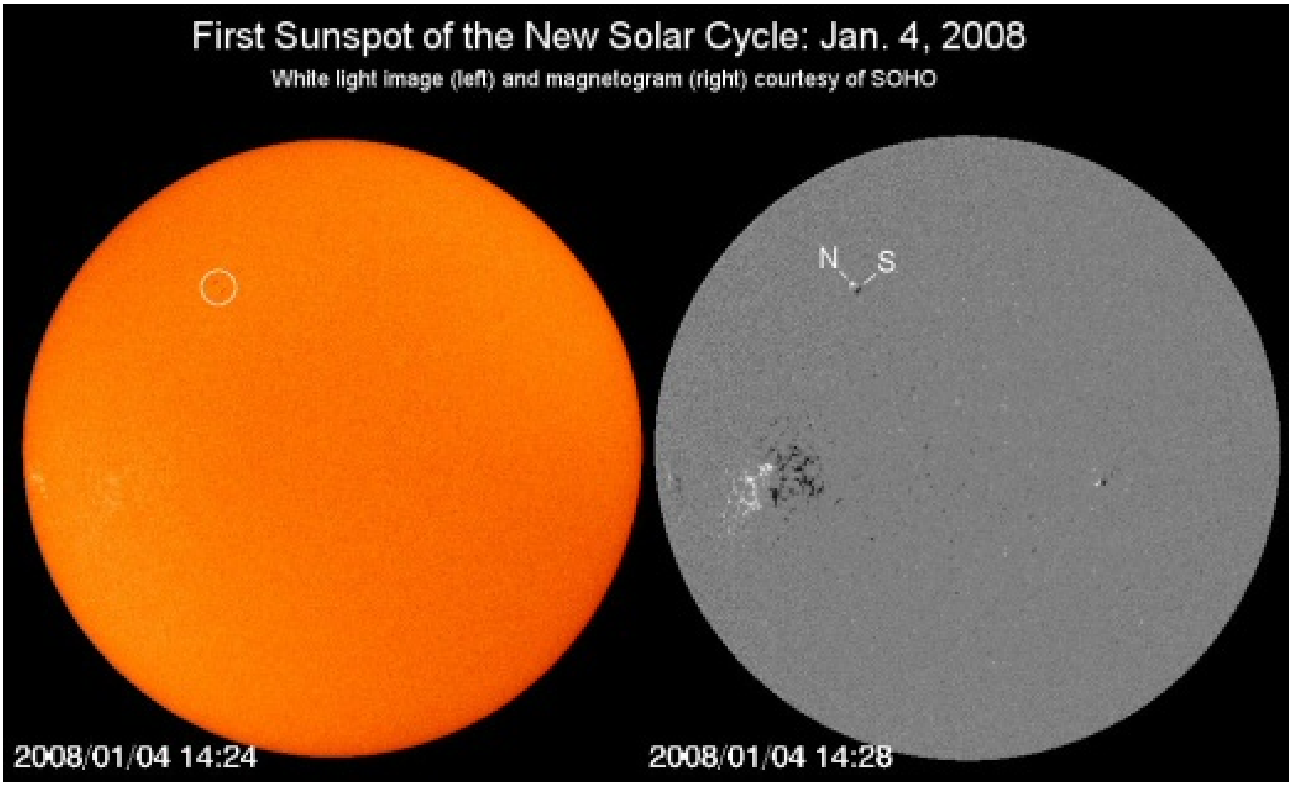
Danish Meteorological Institute
Ministry for Climate and Energy

Danish Climate Centre Report 09-01

Update of the Solar Cycle Length curve, and the relationship to the global mean temperature

Peter Thejll



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Contents

1. Dansk resumé

Kurven for solpletperiodens længde opdateres og sammenlignes med Jordens middeltemperatur. Det vises at de statistiske betingelser for anvendelse af mindste kvadraters metode er tilstede hvis de oprindelige data, der blev brugt i 1991 af Friis-Christensen og Lassen, bruges, men at disse betingelser ikke opfyldes når nyere data, fra samme kilde (CRU i England), anvendes. En tilpasning med høj kvalitet til T kurven, ved brug af data for SCL og forcering fra drivhusgasser samt vulkaner, er mulig hvis forceringerne forskydes i overenstemmelse med den forventede kausalitet imellem forceringer og klima. De sneste data for temperaturen på den nordligehalvkugles landområder viser et tydeligt ’hop’ i de sidste 10 år hvilketmedfører en yderligere afvigelseimellem kurven for T og den skalerede SCL kurve.

2. Abstract

The curve for the solar cycle length is updated and compared to the mean (NH) land temperature curve. It is shown thah the statistical requirements for using ordinary leats squares to find a match exists for the data originally used by Friis-Christensen and Lassen in 1991, but that more recent data from the same soruce as used before no longer allows the use of such a method. A fit of high quality between the forcings represented by SCL, volcanoes, and greenhouse gasses and T is found if the forcings are shifted in accordance with the expected causality between forcings and climate. The latest data for the northern hemisphere land temperatures shows a distinct ’jump’ for the last 10 years, which accounts for the enhancement of the gap bteween T and the scaled SCL curve.

3. Introduction

The relationship between NH land mean temperature and solar cycle length was discussed in EFCKL91 and rose to be a frequently cited paper in the sun-climate field (see Figure 3.1). The use of the solar cycle length as a proxy for the solar influence on the climate is based on the observation that cycle length and height are somewhat inversely proportional, so that short cycles tend to be intense and long ones less intense, in terms of attained sunspot numbers at maximum. Sunspot extrema (dates of maxima and minima) are better known back in time than are the actual sunspot numbers, so the use of solar cycle lengths as a proxy for solar activity is attractive.

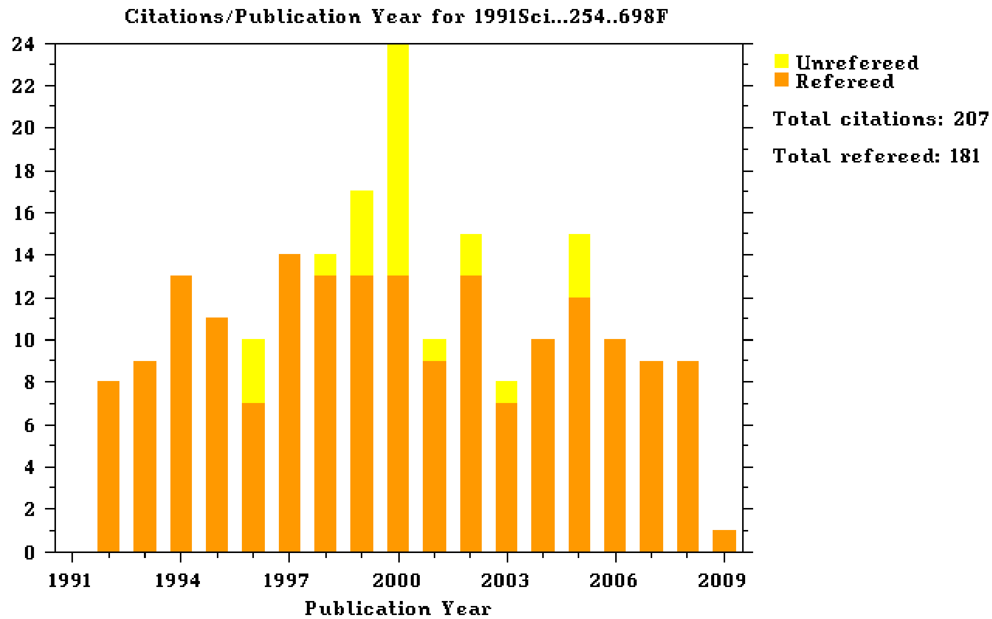

Figure 3.1: The number of annual citations of the paper EFCKL91, according to the ADS, which is not a complete source of citation data.

Several factors under solar control vary with the solar cycle: Solar irradiance seems to be governed on decadal and shorter timescales by the activity level in the photosphere - periods with many sunspots and faculae correspond to periods with higher irradiance in the visual range of the spectrum. In the ultraviolet the flux increases much more than in the visual range during high solar activity. The flow of ionising galactic cosmic rays also appears to be governed by the level of solar activity since turbulence in the heliosphere acts as a scattering opacity on the flow of GCR towards Earth with active periods corresponding to lower GC flux at Earth. Likewise, relativistic electron flux enhancements occur during periods of strong geo-magnetic activity which is governed by solar activity, and these ionising electrons may play a role in the global electric circuit, as do protons injected from solar storms and the galactic cosmic rays.

Thus, the level of solar activity may be influencing the climate system in several ways - through direct variations in irradiance; through variations in ionising UV light which plays a role in the formation of ozone and therefore might be influencing stratospheric dynamics and the stratosphere-troposphere coupling; through variations in the flux of penetrating ionising galactic cosmic rays which have been suggested to modify the processes of cloud nucleation nuclei formation and the global electric circuit, and through higher-level modifications of the conductivity of the high atmosphere and thus the global electric circuit.

If these factors are proportional to the level of solar activity, then the solar cycle length may be an excellent although probably composite and complex proxy for these factors. Eddy (1976) was one of the first to note the relationship between solar cycle length and levels of solar activity in a framework related to climatic influences. EFCKL91 used smoothed values of the SCL curve, using three- and 5-point filters variously called 121 and 12221 after the weights employed and applied to cycle lengths. The fit shown by EFCKL91 between NH land temperatures (binned according to solar cycle extrema) and the SCL121 curve was very good and suggestive of a physical relationship between smoothed solar activity levels and mean temperatures.

In 2000 there were more data available for both the solar cycle and temperatures and the SCL121-T relationship was revisited (TL00). It was shown that temperatures appeared to have outrun the SCL121 curve - a good fit was no longer possible using the latest data, and it was suggested that this was a sign of the increasing influence of greenhouse gasses on global mean temperatures, but the GHG forcing was not included as a regressor.

A quite apparent lag seems to exist between the SCL121 curve and the temperature curve with SCL1212 rising before the T rise in the 1920-50s, implying that solar forcing rose first and then temperatures followed. This is not an unreasonable interpretation since the climate system has some sort of inertia due to the coupling of the atmosphere to the huge heat capacity of the ocean. Other factors influencing the climate should have similar lags and this is an idea we will investigate in the present work, when we include GHG forcing as a regressor.

There is a particular problem with imposing lags on very smooth slowly rising factors - shifting the curve may be equivalent to applying a multiplicative factor to the un-shifted curve. This problem has bearing on the quality of the fit as well as the value of the regression constant found. It is therefore necessary to consider whether the new regressors are added in order to gain new insight (by using the value of the coefficients found - e.g. for climate sensitivity studies) or just to compensate for otherwise unexplained variance.

The issue of unexplained variance is raised in the present work to an extent not done in EFCKL91 or TL00: In the first work regression as such was not performed - a fit by eye was performed by shifting and scaling the SCL121 curve until it fitted the T curve well. In TL00 the issue of unexplained variance as seen in residual structure was discussed but no formal steps were taken to address the issues that follow from such a problem, other than limiting the range of abscissae for use in the regression and discussing the residuals outside this range. Unexplained variance can be due to many things, as we shall discuss here. Some of the reasons can be addressed by allowing lags on the regressors, if such a lag is sensible in terms of physics and causality. Other reasons - such as variance due to internal climate system dynamics, which cannot be modelled historically - can be dealt with with so called econometric regression methods, and we shall discuss these.

4. The solar cycle

The solar cycle length curve is based on extrema dates of the sunspot cycle - maxima and minima. The dates for observed extrema used in the present work are taken from the NGDC list "MINIMA AND MAXIMA OF SUNSPOT NUMBER CYCLES" presently available at ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS/maxmin.new. This list is updated as new 'official' sunspot minima and maxima dates become available. The extrema dates are determined by a panel of solar science experts. The version downloaded in December 2008 is shown in figure 4.1

The last official extremum is thus the maximum in 2000.3. Since then the Sun has reached a minimum in 2007 - but the actual minimum date has not yet been agreed upon since the next cycle, cycle 24, at the time of writing (December 2008), had not yet started. The start of a solar cycle is usually heralded by the appearance of high-latitude sunspots of reversed polarity. In January 4 2008 a reverse-polarity sunspot was observed. However, there has not been many more so the onset of cycle 24 seems to be waiting.

We will sidestep this question for now, and merely make 'best estimates' of the date for the minimum in 2007/8, based on what experts say, and then estimate future extrema entirely on the basis of the mean observed solar cycle length - simply generating future expected extremum dates from previous ones by addition of the mean solar cycle length (11.0 years - see Table 4.1).

We will adopt the date for the minimum between cycles 23 and 24 as occurring on 2008.0.

The adopted and estimated extrema used in this work are shown in table 9.1 while the observed extrema of table 4.1 are used as given there.

5. The SCL curve

The SCL values, as used in the works of EFCKL91 and KLEFC95 and TL00, are a composite of weighted values from the dates of the maxima and minima. Briefly, the procedure is the following:

- Lists of cycle lengths and central years are generated separately for the maxima and minima. Cycle lengths are the differences between adjacent extrema of same kind. The central year is the average of the epochs of these extrema.
- the separate lists of cycle lengths are smoothed with a three-point sliding window (weights are 1/4,1/2, and 1/4 - for brevity called the 1-2-1 filter). The central year of the middle value is retained as the time index.
- the lists for central years and 121-weighted solar cycle lengths (called SCL121 from now on) are joined and sorted by ascending central year.

Figure 5.1 shows the resulting curve, along with uncertainty estimates. Over-plotted are previously published SCL121 values.

Figure 4.1: The NGDC list of solar cycle extrema, downloaded December 2008

MINIMA AND MAXIMA OF SUNSPOT NUMBER CYCLES

Sunspot Cycle Number	Year of Min*	Smallest Smoothed Monthly Mean**	Year of Max*	Largest Smoothed Monthly Mean**	Rise to Max (Yrs)	Fall to Min (Yrs)	Cycle Length (Yrs)
-	1610.8	--	1615.5	--	4.7	3.5	8.2
-	1619.0	--	1626.0	--	7.0	8.0	15.0
-	1634.0	--	1639.5	--	5.5	5.5	11.0
-	1645.0	--	1649.0	--	4.0	6.0	10.0
-	1655.0	--	1660.0	--	5.0	6.0	11.0
-	1666.0	--	1675.0	--	9.0	4.5	13.5
-	1679.5	--	1685.0	--	5.5	4.5	10.0
-	1689.5	--	1693.0	--	3.5	5.0	8.5
-	1698.0	--	1705.5	--	7.5	6.5	14.0
-	1712.0	--	1718.2	--	6.2	5.3	11.5
-	1723.5	--	1727.5	--	4.0	6.5	10.5
-	1734.0	--	1738.7	--	4.7	6.3	11.0
-	1745.0	--	1750.3	92.6	5.3	4.9	10.2
1	1755.2	8.4	1761.5	86.5	6.3	5.0	11.3
2	1766.5	11.2	1769.7	115.8	3.2	5.8	9.0
3	1775.5	7.2	1778.4	158.5	2.9	6.3	9.2
4	1784.7	9.5	1788.1	141.2	3.4	10.2	13.6
5	1798.3	3.2	1805.2	49.2	6.9	5.4	12.3
6	1810.6	0.0	1816.4	48.7	5.8	6.9	12.7
7	1823.3	0.1	1829.9	71.7	6.6	4.0	10.6
8	1833.9	7.3	1837.2	146.9	3.3	6.3	9.6
9	1843.5	10.5	1848.1	131.6	4.6	7.9	12.5
10	1856.0	3.2	1860.1	97.9	4.1	7.1	11.2
11	1867.2	5.2	1870.6	140.5	3.4	8.3	11.7
12	1878.9	2.2	1883.9	74.6	5.0	5.7	10.7
13	1889.6	5.0	1894.1	87.9	4.5	7.6	12.1
14	1901.7	2.6	1907.0	64.2	5.3	6.6	11.9
15	1913.6	1.5	1917.6	105.4	4.0	6.0	10.0
16	1923.6	5.6	1928.4	78.1	4.8	5.4	10.2
17	1933.8	3.4	1937.4	119.2	3.6	6.8	10.4
18	1944.2	7.7	1947.5	151.8	3.3	6.8	10.1
19	1954.3	3.4	1957.9	201.3	3.6	7.0	10.6
20	1964.9	9.6	1968.9	110.6	4.0	7.6	11.6
21	1976.5	12.2	1979.9	164.5	3.4	6.9	10.3
22	1986.8	12.3	1989.6	158.5	2.8	6.8	9.7
23	1996.4***	8.0	2000.3***	120.8	4.0		
Mean Cycle Values:		6.1		113.2	4.7	6.3	11.0

*When observations permit, a date selected as either a cycle minimum or maximum is based in part on an average of the times extremes are reached in the monthly mean sunspot number, in the smoothed monthly mean sunspot number, and in the monthly mean number of spot groups alone. Two more measures are used at time of sunspot minimum: the number of spotless days and the frequency of occurrence of "old" and "new" cycle spot groups.

**The smoothed monthly mean sunspot number is defined here as the arithmetic average of two sequential 12-month running means of monthly mean numbers.

***May 1996 marks the mathematical minimum of Cycle 23. October 1996 marks the consensus minimum determined by an international group of solar physicists. April 2000 marks the mathematical maximum of Cycle 23. However, several other solar indices (e.g., 10.7 cm solar radio flux) recorded a higher secondary maximum in late 2001.

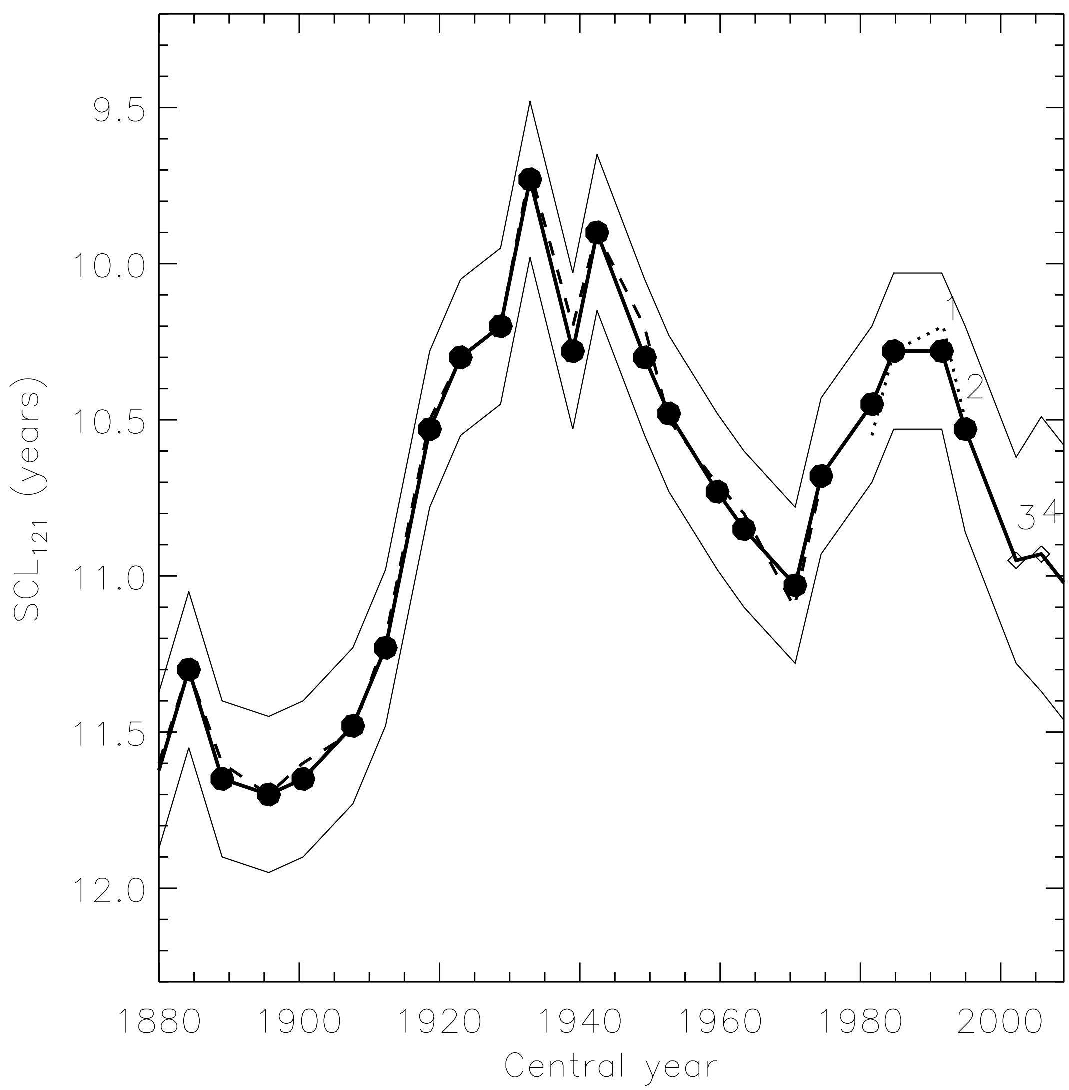

Figure 5.1: The solar cycle length (SCL) curve. Previously published curves are plotted (dotted (Thejll and Lassen, 2000) and dashed (Friis-Christensen and Lassen, 1991) lines) and the 2009 updated curve (solid line with filled dots) are shown. The 1-2-1 weighting scheme has been used - see text for details. The annotations can be used to identify data points: 1 is based on observed solar cycle minima, except for the 2007/8 minimum estimated to occur in 2008.0, 2 is based on observed solar cycle maxima, except for the maximum estimated to occur in 2011.3, points 3 and 4 are based on two estimated extrema and are thus less reliable than 1 and 2. Uncertainties are shows as the thin curves and are based on estimated uncertainties of 0.5 years for observed extrema and 1, 1.25 and 1.5 years for extrema 1,2 and 3 steps into the future.

Table 6.1: Temperature series used in this work. They all give NH land temperatures. The plots of binned T values are shown in Figure 6.2

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- 0 - The NH land temperature dataset - called CRUTEM3 - downloaded in December 2008 from : http://www.cru.uea.ac.uk/cru/data/temperature/ The provisional annual mean value is used even if the December measurement is not included.
- 1 - The series used in EFCKL91
- 2 - A series complete to end of 1998 (Jones, private communication 1998)
- 3 - Another series complete to end of 1999 (Jones, pc, 2000)

6. The NH mean land temperature curve

NH mean land temperatures are generated in order to make a comparison to the SCL121 curve. This can be done in several ways. For reasons of continuity we choose the method of averaging first used in EFCKL91, and further investigated, as "method C", in Thejll and Lassen (2000). It consists of forming bin averages.

We have four sources of mean NH temperature anomalies. These are all NH land temperatures, as originally used in EFCKL91. The new data for temperature used in this report were acquired from the Climate Research Unit at University of Norwich (CRU) home page for such data (http://www.cru.uea.ac.uk/cru/data/temperature/). Earlier versions of the data - as used in EFCKL91 and TL00, are no longer distributed from this homepage, but are available from the author[1]. The four temperature series, plotted in Figure 6.1, are listed in Table 6.1.

The binning is performed on bins defined by the extrema of the solar cycle curve, as explained under "method C" in Thejll and Lassen (2000). That is, adjacent same-type extrema (max-max or min-min) are used to delimit a period in time one solar cycle in length (variable in time) and the mean temperature values falling in that interval are averaged to form the bin mean.

The four thus binned mean temperature series are shown in Figure 6.2. One notices how high the most recent series is for the last few points: several tenths of degrees higher than the three other series. We also note that the last points on the two other curves that lie just beyond year 2000 have jumped in the new data. This indicates a significant change in the data provided from CRU for the last decade or so, and the cause of the changes remain unclear at this point in time. We note that all curves have altered their appearance at almost all dates, and yet the describe the same thing - the NH land temperature. How is this possible?

The database used to calculate large-area means are continually updated as more historic data are found and submitted to the database. This is an ongoing job and therefore values for temperature in the past will continue to change. This suggests one explanation that is possible for the jump in the curve in the last decade: Perhaps a backlog of data became available sometime recently and were added to the database.

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[1]Conceivably, past versions of the CRU data are available through internet archive services: http://www.archive.org/index.php

Figure 6.3 shows the difference between the NH land temperature in the CRUTEM3 dataset and the SH land temperature. A large difference is observed near the end of the time sequence. It is entirely consistent with our qualitative understanding of global warming to see this pattern of differences: The NH land areas warm up much faster, given external forcing, than the SH areas which are more influenced by the damping effect of the oceans that dominate the SH. Whether the magnitude of the difference is realistic can be estimated from a coupled land-ocean model with realistic forcings and description of land and ocean. We use the GLIMPSE model output [Stendel et al., 2006], and show the difference in temperature between the NH land areas and SH land areas since model year 1900 in Figure 6.4. Why there is a mean difference of about 2 degrees is not understood. The variability, however, is of the same order as seen in reality.

Upon being asked, Phil Jones at the CRU, replied that ’back data can be up to 3 years old’. We plot annual values of the data series in Figure 6.5. It would appear that the strong el Nino of 1998 was not fully expressed in the data series we collected near year 2000. In the recent data the ENSO is expressed fully. This is probably as Jones explains due to a backlog of data. Nevertheless, the level of the years 2000 and onwards seems to be elevated by 0.2 degrees C over the trend estimated for the years before. It is this ’lift’ that is seen in the plots of binned data in Figure 6.2 - the binning we emply has straddled the end of the old data and the new data and has had an effect on the last two bin values of the new curve.

7. The relationship between SCL121 and binned mean temperature

In EFCKL91 the temperature curve and the SCL121 curves were compared and plotted together. In TL00 the relationship between the two curves was determined from a least squares fitting procedure using a date-restricted range of data. We will here follow this method and see what the 'best looking' relationship between the two curves is like, and explore formal statistical aspects of the relationship.

The regression between SCL121 and the binned mean land temperature is performed using the ordinary least squares (OLS) method. The data between AD 1885 and AD 1970 were used. The results for the conversion factor between SCL121 and temperature are shown in Table 9.6, along with other statistical quantities describing the quality of the regression fit.

The OLS method is based on the assumption that the regression residuals are "i.i.d" - that is, independent and identically distributed. These two assumptions may not be met by the residuals in which case the results may be biased or have biased uncertainty estimates. We can use the auto-regression of the residuals, as well as the so-called Durbin-Watson statistic (e.g. Draper and Smith, 1981, section 3.11), to evaluate the level of autocorrelation in the residuals.

In Table 9.6 we see that the autocorrelation is not near zero, and the decorrelation time can be estimated to be from 10 to 30 years for the four temperature series - i.e. more than the average point spacing, which is an indicator that there is dependence between points in the residual series.

The DW statistic d indicates whether residuals are autocorrelated or not - if they are autocorrelated they cannot be assumed to be independent and then basic conditions for OLS are not met. d is calculated as

$$d = \frac{\sum(r_i - r_{i-1})^2}{\sum r_i^2}, \tag{7.1}$$

where r is the time series of the residuals. d can lie between 0 and 4. Positive autocorrelation in a series r tends to generate d's below 2 while negative autocorrelation (rare) gives d's above 2.

The "i.i.d" requirement also contains a requirement that the residuals are identically distributed, i.e. that they are stationary in terms of mean value and standard deviation. We will not test for this property here, although such tests have been described by Benestad (2008). We will only inspect the DW statistic here.

7.0.1 1885 - 1970

The DW statistic d will asymptotically attain the value 2 for a long un-correlated series, but we have a limited sample of 15 data points. We fit two parameters (an intercept and the factor converting SCL121 into degrees C) and must therefore use the DW tables with n=15 and k=2 and *a priori* choose a significance level α. We choose the 5% level. Draper and Smith (1981) gives values of the significance levels d_L and d_U which are functions of the number of points in the series and the number of parameters determined in the regression. Table 3.2 in DS81 is inspected and we find that d_L and d_U are 1.08 and 1.36, respectively. Similar tables can be found at `http://www.stanford.edu/~clint/bench/dwcrit.htm`.

The value for d, from Table 9.6 must be compared to these values in order to test the null hypothesis. The test proceeds as follows: For $d < d_l$ we can reject the null hypothesis that there is no positive autocorrelation, for $d > d_U$ we can reject the hypothesis that there is no negative autocorrelation, and for $d_L < d < d_U$ the DW test is unfortunately indeterminate.

The result is that positive autocorrelation in the residuals can be ruled out in two cases; that there is positive autocorrelation in one case; and one case is indeterminate. In all four cases negative autocorrelation in the residuals can be ruled out. We note here that the data originally used in EFCKL91 passes the DW test - i.e. the application of OLS in this case is valid as the residuals do not test positive (or inconclusive) for positive autocorrelation, nor for negative. This also applies for the data used in TL00 but for recent data the test for positive autocorrelation is inconclusive, and a warning flag must be raised.

7.0.2 1850 - 1970

The interval used to perform the regression above was not the full interval available. This was done for reasons of continuity with methods and choices applied in TL00. We can use other intervals - for instance, we can expand the lower limit to AD 1850. The results are shown in Table 9.7.

Here, k=2, n=21 and d_L and d_U are 1.22 and 1.42 respectively. For three of the T series we find $d_L < d < d_U$ in which case the DW test is inconclusive. For the fourth series we can reject (at the 5% level) the null hypothesis. In all four cases we can rule out negative autocorrelation in the residuals. In summary, we have signs of positive autocorrelation in the residuals for one case, and cannot say whether there is positive autocorrelation or not in the other three. Use of OLS in all cases is therefore controversial from a statistical point of view.

We conclude that a regression method is needed for those cases where positive autocorrelation in the residuals is indicated or cannot be ruled out.

7.1 Why are the residuals not "i.i.d"?

Understanding why the residuals may not be "i.i.d" can give insight into relationship between the regressor and the regressand. A list of possible reasons for non-iidness include:

- the regressor and regressand may not be physically related
- regressors may be missing
- there may be a physical link between the regressor and the regressand that is not expressible by contemporaneous values of the two series - i.e. a time lag may be in order

The first possibility is discussed in the published sun-climate literature. The second possibility will be investigated next by including more, physically probable, regressors, such as a term for the influence due to greenhouse gasses and a term for the impact of volcanic aerosols. The third possibility will be investigated at the end.

7.2 Missing regressors: including greenhouse gasses and volcanoes

This is done using [Myhre et al., 2001] GHG forcing data. The results are shown in Table 9.8, and the actual regression fits are shown in Figures 7.1-7.2.

Evidently, the DW test for positive serial correlation in residuals still tests positive (one case) or is indeterminate (three cases), while negative serial correlation in the residuals can be ruled out in all cases. The hope that adding regressors to the regression model would eliminate residual structure has not worked out. Looking at the fits and the residuals it would seem that the SCL curve leads the T curve, indicating that some sort of lag structure should be considered.

7.2.1 Missing regressors: What if you do not know them?

When it is know or suspected that a regressor has been omitted from the regression model it is possible to deal with the residual structure directly and thus avoid the need to know the missing regressors.

The field of econometrics has developed methods to handle these situations, see Ramanathan (2002). One simple method is the so-called Cochrane-Orcutt (CO) method which has been explored for geophysical applications in Thejll and Schmith (2005). The CO method is a modified OLS method which includes an extra regressor, namely the weighted residuals. The weight must have that value which causes the residuals of the CO regression to become "i.i.d", and can be found iteratively or by determining it in an overall minimisation approach.

When the residual structure is present but is suspected to be due to a physically based lagging relationship between the regressor and the regressand - such as an external forcing causing a climate response that appears with a lag due to the climate systems thermal inertia - then one cannot hope to retrieve a meaningful regression relationship by using the CO method; instead, the lag structure of the series should be explored for insight on the causality relationship.

7.3 Lagged regressors: Causality testing

We repeat the fit of T against GHG forcing and SCL121 allowing for lags in the SCL121 curve. We could of course also consider lags in the GHG curve but due to its almost monotonic rise there will be little effect of doing this. We report the result of allowing a shift on the GHG curve below.

We use data from 1850 to 1990 this time, which gives n=26. In the DW test we have to set k=4 since one more parameter - the shifts - is being determined. For different lags on the SCL121 curve the results are shown in Table 9.9. We test lags on the SCL121 curve from -3 to +3 steps - where positive shifts move the SCL121 curve into the future. We see that for three out of four T series a positive shift of 1 step explains the most variance - for the fourth series the most variance is explained for a lag of 2 steps. We also see that the decorrelation time is at a minimum for these same lags. The DW test indicates indeterminacy for three of four cases in terms of positive serial autocorrelation, while one series allows a rejection of the null hypothesis of positive residual correlation. By allowing shifted regressors we have thus removed the one positive DW test which indicated presence of positive serial correlation, without lags, and we have turned one indeterminate test into a null rejection.

Figure 7.3 shows the fits.

7.3.1 Shifting also the GHG curve

To some degree the climate system should respond to changes in external forcing in similar ways. Therefore we expect that if a shift is required in the SCL121 curve then a shift is also needed in the GHG curve - and in any other curves representing external forcing.

Shifting the GHG curve by the same amount as the SCL121 curve gave results shown in Table 9.10.

We used GHG data from [Myhre et al., 2001] and since these tables end in 2000 we have to extrapolate to avid problems with end-effects when we shift the data. We extend the forcing due to the combined GHGs in Myhre by to 2015 using a 1.2% increase in the forcing from year to year - this gives a rather linear extension of the Myhre data. See Figure 7.4.

From Table 9.10 we see that only one series - the series originally used in EFCKL91 passes the DW test. The most recent series for temperature fails in the sense that the DW test indicates the presence of positive serial correlation in the residuals and the tests for the other two series are indeterminate.

In Table 9.11 we repeat what we did for Table 9.10 but using only the same set of years. This limits the longer newer series to the same years that were available for the work in EFCKL91. We see that the results are slightly different - the original series from EFCKL91 still is the only one to pass the DW test, but now the other series at least do not fail the test - the test is merely indeterminate. The 'winning lags' are also slightly different now. It would appear that adding the data for the years since EFCKL91 has one effect on the matter, but that the choice of series also is relevant: That is, there may be some property of the T series assembled since the first data series was produced by the CRU. Perhaps it is the rapid rise in the later years or it is the subtle changes in shape before those years - due to small changes in available data and perhaps treatment methods at the CRU.

7.3.2 Granger causality

The use of lagged regressors implies that we should look at the so-called 'Granger Causality' (GC) which is a concept from econometrics. The presence of GC implies that a physical causal relationship from regressor(s) to regressand could be present, but does not prove it. The GC test is based on a set of regressions with variously lagged regressor(s). If past values of a regressor correlate well with the regressand while future values of the same regressor(s) do not, then GC is indicated by the test. We have such a relationship here - as seen in Tables 9.9 and 9.10, negative shifts on the regressor does not correlate well with the regressand, while positive shifts of 1 (and 2) does: This is the basis for the presence of a GC relationship from the regressors and the regressand.

The GC test is more than showing that past values of the regressors give the regressand; the issue of serially correlated residuals also enters the picture. We shall go no further into this topic here, but it is covered in [Reichel et al., 2001]. At the moment we note that only the original EFCKL91 series gives no serially correlated residuals, and that OLS therefore is an acceptable technique for relating GHG and SCL121 to mean T for that series.

7.3.3 Cochrane-Orcutt

We now investigate whether the CO method can be used to perform a regression in the cases where the residuals are either serially correlated or may be so. Rather than experimenting with adding more regressors (volcanic forcing, or ENSO, for instance) we shall assume that there may be inherently autocorrelated internal dynamics not related to the ENSO in the climate system: We cannot hope to model this and therefore must expect it to appear in the residuals to some extent. We need the CO method which offers a way to remove the problem with the autocorrelated residuals.

However, it turns out (not shown) that the CO method does not solve the problem satisfactorily for the cases which fail the DW test for OLS. Applying 'pre-whitening' by regressing first differenced series (regressors and regressand) against each other also does not solve the problem. These methods are related to each other.

7.4 Influential data points

It is of interest to inspect the regression in each case and see which data points are influential. This can help us understand which parts of the data drive the fit. Some points may turn out to have a positive influence on the fit quality while others may actually have the opposite effect: Such observations can for instance help us understand whether we have missing regressors.

For each regression performed with OLS we withhold one data point at the time and make a new regression and calculate the variance explained before and after. We then plot the change in variance explained and look at the plot (Figure 7.5). In this example the data point near 1890 clearly has a harmful influence on the overall variance explained since exclusion of the point causes variance explained to increase. The last data points in the 20'th century have the opposite effect - omitting them causes variance explained to decrease.

We summarise in Table 9.12 the information about the influence of single data points for each of the four T series and for the two choices of extent of data series - namely 'all data possible for each series', and 'same years for all series'. It would appear that there is a systematic effect of points at 1870 and 1890 and the several last points. The point at 1890 (or 1870, depending on the data series and shifts involved) has a value that is not explained by the regressors - this could be a hint that a regressor is missing or that the data point is erroneous. Only physical factors that are short lived in time could explain that this point alone has the value it has - perhaps there is a strong volcanic effect in 1890 (or 1870)? The data range near the end of the series seem to be important to include as the regressors are able to explain the variance - these data 'drive' the fit.

7.4.1 Including volcanic forcing

We next test the influence of volcanic forcing on the fit. We take volcanic forcing data from [Myhre et al., 2001], as used in the GLIMPSE model run, and bin it as we did for GHG. We test the effect of shifting volcanic forcing, and also without shifts when GHG and SCL1212 are shifted. This is done because the effect of volcano eruptions on the climate is know to be almost prompt, but extends over a few years after the eruption.

We find that only in the case of the original time series used in EFCKL91 is there an improvement in the fit when volcanic forcing is included. The improvement occurs only when there is no shift on the volcanic forcing. The effect of including volcanic forcing is mainly one of reducing the influence of the point near 1890 - it halves in size. This implies that the model has improved there. There is also some effect near 1970 of opposite sign - the influence of that point has grown somewhat, implying that inclusion of volcanic forcing highlights the gap between model and observations in that 'dip' near 1970. It is the 1990's volcanism that has had an effect on the late-20th century temperature and thus highlights the difficulties there are with explaining the 1970's minimum in temperature. The overall effect of including volcanic forcing is one of improving the fit and reducing the tendency for individual points to have a large influence on the overall fit.

8. Summary and Discussion

8.1 Summary

We have tried to relate data series for NH land temperatures, solar cycle lengths and greenhouse gas forcing to each other with regression methods in order to provide an update of the work originally presented in EFCKL91 and later updated in TL00.

We have extended the T and SCL121 curves because new data have become available since TL00 - in essence one more data point can be added to the SCL121 curve, which is defined by the solar cycle minima and maxima. We have projected the solar cycle curve into the future using reasonable epochs for future extrema in order to avoid edge-effects, as was done in TL00. This is done mainly to enable use of the latest T data, which otherwise would have to be discarded. We have also extended the expected forcing due to greenhouse gases using almost linear extrapolation from the level and trends in 2000 and before. This also enables the use of all data in recent decades. We have used data-management techniques (averaging and binning) that ensures continuity with previous method choices.

We have applied ordinary least squares methods, focusing on the need to test whether the conditions for the use of OLS are met. This is done by inspecting the residuals for serial correlation. We have seen that without an imposed shift on the SCL121 curve of 1 or 2 steps (about 6 or 12 years) we could not attain zero serial correlation in residuals. This lead-lag structure was previously used to investigate the concept of Granger Causality between the T and SCL series. Such considerations of lags were not exploited in the original work in EFCKL91.

We imposed a similar lag on the GHG curve from the point of view that forcings with a slowly varying nature, whether solar or radiative, should have about the same effects on the climate system and should thus have the same lags.

We finally found that only the original T mean curve could be modelled with OLS using SCL121 and GHG as regressors - newer updates of the curve did not allow an OLS regression to be formed without serial correlation in the residuals. Methods that try to solve serial correlation in residuals with concepts related to differencing (pre-whitening) failed.

8.2 Discussion

What do we make of these results?

It is apparently possible to find a good fit using OLS between the original T series for NH land temperature and SCL121 and GHG, if you allow shifts in the regressors. It is apparently not possible to find a good relationship using newer updates of that T series, even if we additionally throw in tricks that try to solve the problem of the serially correlated residuals.

We showed that curtailing all data series to the length of the original series used in EFCKL91 improved the situation slightly, but, probably due to small changes in the CRU data prior to the 1990’s, the DW test did not pass in all cases - it still is only indeterminate for the three new series. When the data for the 90’s and up to now are added the OLS approach fails for one series (the newest update from CRU) while it is still indeterminate for the other two (used in TL00). No amount of fancy statistics could remove the serial correlation in the residuals for the newest update.

The above situation can be resolved in various ways:

- Perhaps the regressors are not physically linked to T, and any previous successes were due to a statistical fluke
- Perhaps the regressors are physically linked to T, and the presently observed failures are flukes
- Perhaps the regressors and T are related, even for the latest T data, but in a way (nonlinearly, for instance) that cannot be adressed with linear methods.

Finally, we note that the temperature data from CRU show signs of a ’lift’ in their level, for the last 10 years or so. Not only have all the historical values of CRUTEM3 changed subtly, but the ENSO in 1998 is now fully expressed in the new data, and the level of the rising data for the years since 1998 appears to have ’jumped’. This jump accounts for the substantial rise in binned T values observed in this work, and has caused the previous missmatch between SCL121 and T for recent decades to take on an even extremer appearance.

9. Tables and Figures

Table 9.1: List of adopted and estimated solar cycle extrema used in this work, and estimated uncertainties, in years. 'm' and 'M' indicate minima and maxima respectively. The minimum in 2008.0 is based on the absence of observed reverse-polarity high-latitude sunspots at that time: At the time of writing (Dec 2008) there were however still no clear signs that Cycle 24 had started. Other extrema are estimated by adding 11 years to the previous extremum of that kind - 11 years being the average of solar cycle lengths since 1610 AD according to the NGDC list of minima and maxima shown in table 4.1.

Epoch	Δ	m/M
2008.0	0.5	m
2011.3	1.0	M
2019.0	1.0	m
2022.3	1.25	M
2030.0	1.25	m
2033.3	1.5	M
2041.0	1.5	m

Table 9.2: SCL values for solar cycle maxima.

Epoch	m/M	Δ	L	Ctr.	SCL121	Δ
1639.5	M	0.5				
			9.5	1644.3	10.88	0.25
1649.0	M	0.5				
			11.0	1654.5	11.63	0.25
1660.0	M	0.5				
			15.0	1667.5	12.75	0.25
1675.0	M	0.5				
			10.0	1680.0	10.75	0.25
1685.0	M	0.5				
			8.0	1689.0	9.63	0.25
1693.0	M	0.5				
			12.5	1699.3	11.42	0.25
1705.5	M	0.5				
			12.7	1711.9	11.80	0.25
1718.2	M	0.5				
			9.3	1722.9	10.63	0.25
1727.5	M	0.5				
			11.2	1733.1	10.83	0.25
1738.7	M	0.5				
			11.6	1744.5	11.40	0.25
1750.3	M	0.5				
			11.2	1755.9	10.55	0.25
1761.5	M	0.5				
			8.2	1765.6	9.07	0.25
1769.7	M	0.5				
			8.7	1774.1	8.83	0.25
1778.4	M	0.5				
			9.7	1783.3	11.30	0.25
1788.1	M	0.5				
			17.1	1796.7	13.77	0.25
1805.2	M	0.5				
			11.2	1810.8	13.25	0.25
1816.4	M	0.5				
			13.5	1823.2	11.38	0.25
1829.9	M	0.5				
			7.3	1833.6	9.75	0.25
1837.2	M	0.5				
			10.9	1842.7	10.27	0.25
1848.1	M	0.5				
			12.0	1854.1	11.35	0.25
1860.1	M	0.5				
			10.5	1865.4	11.58	0.25
1870.6	M	0.5				
			13.3	1877.3	11.83	0.25
1883.9	M	0.5				

Table 9.3: Table 9.2 continued. Values in cursive are based on estimates of maxima epochs.

Epoch	m/M	Δ	L	Ctr.	SCL121	Δ
1883.9	M	0.5				
			10.2	1889.0	11.65	0.25
1894.1	M	0.5				
			12.9	1900.6	11.65	0.25
1907.0	M	0.5				
			10.6	1912.3	11.23	0.25
1917.6	M	0.5				
			10.8	1923.0	10.30	0.25
1928.4	M	0.5				
			9.0	1932.9	9.73	0.25
1937.4	M	0.5				
			10.1	1942.5	9.90	0.25
1947.5	M	0.5				
			10.4	1952.7	10.48	0.25
1957.9	M	0.5				
			11.0	1963.4	10.85	0.25
1968.9	M	0.5				
			11.0	1974.4	10.68	0.25
1979.9	M	0.5				
			9.7	1984.8	10.28	0.25
1989.6	M	0.5				
			10.7	1995.0	*10.53*	*0.33*
2000.3	M	0.5				
			11.0	*2005.8*		
2011.3	*M*	*1.0*				

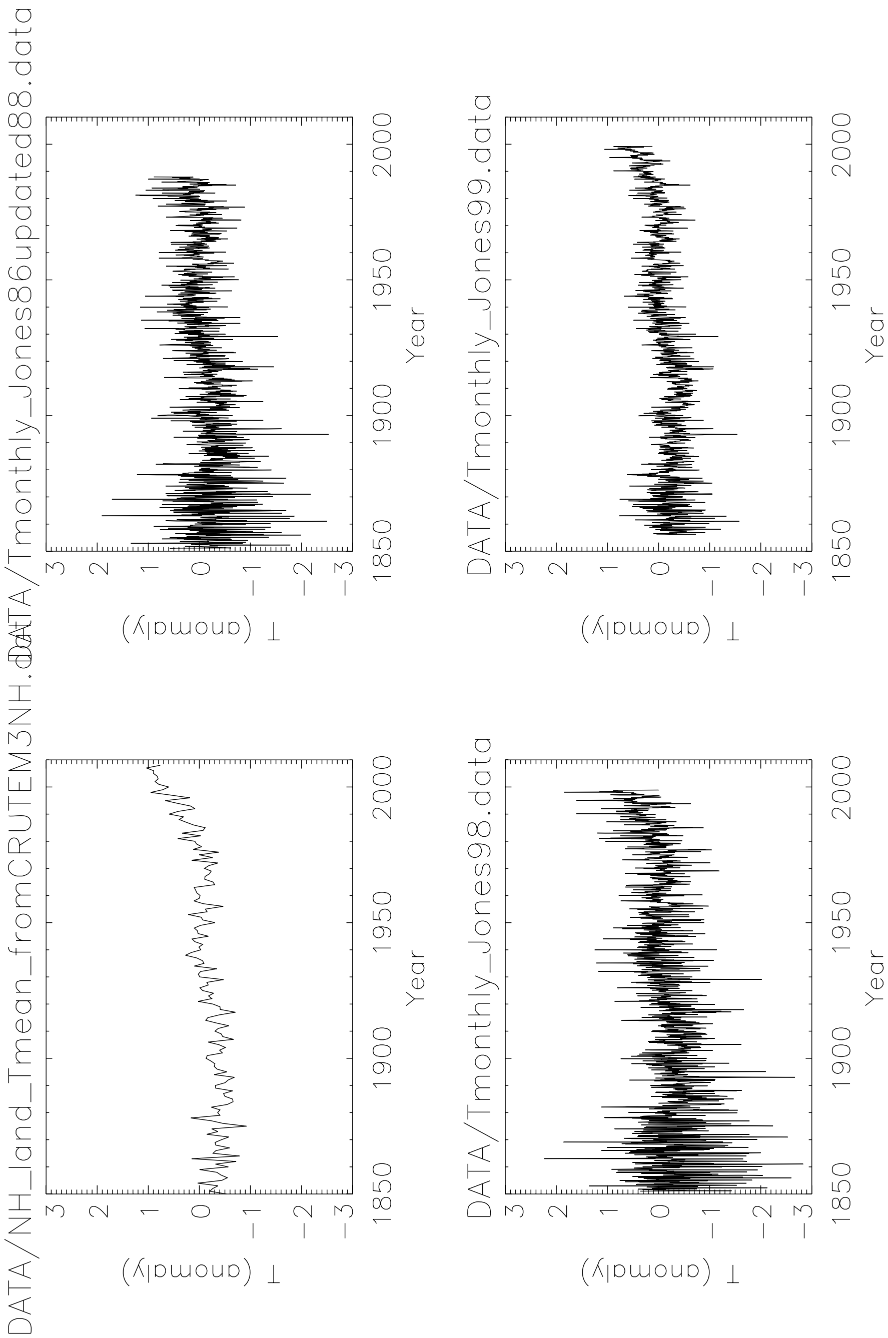

Figure 6.1: NH land mean temperatures used in this work.

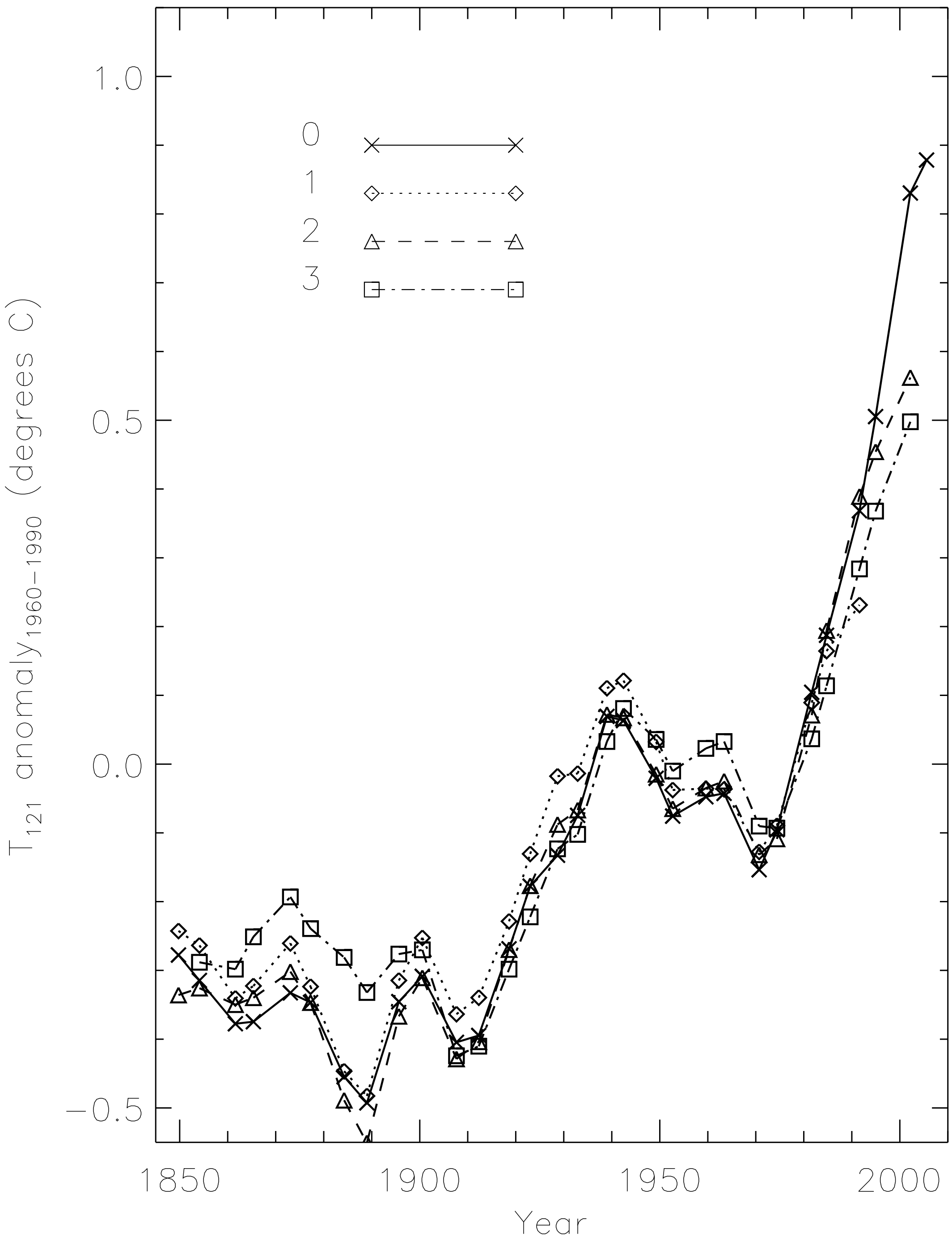

Figure 6.2: Four mean temperature curves, from CRU, are shown binned into bins defined by the extrema of the solar cycle (see text for details). Each curve is shown as the anomaly with respect to that curves mean in the period from 1960 to 1990. The annotations are defined in Table 6.1.

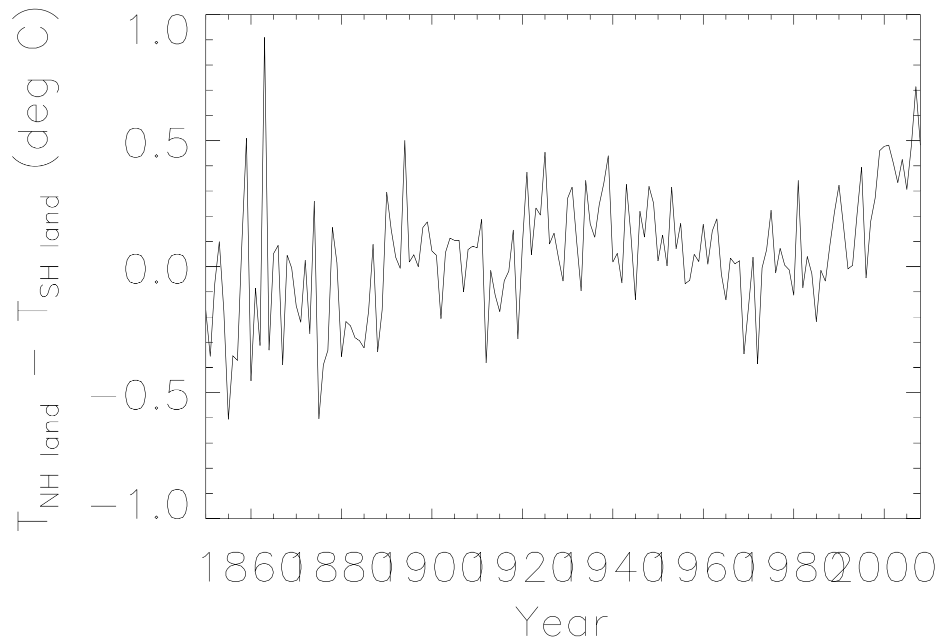

Figure 6.3: Difference in the CRUTEM3 NH land and SH land temperatures.

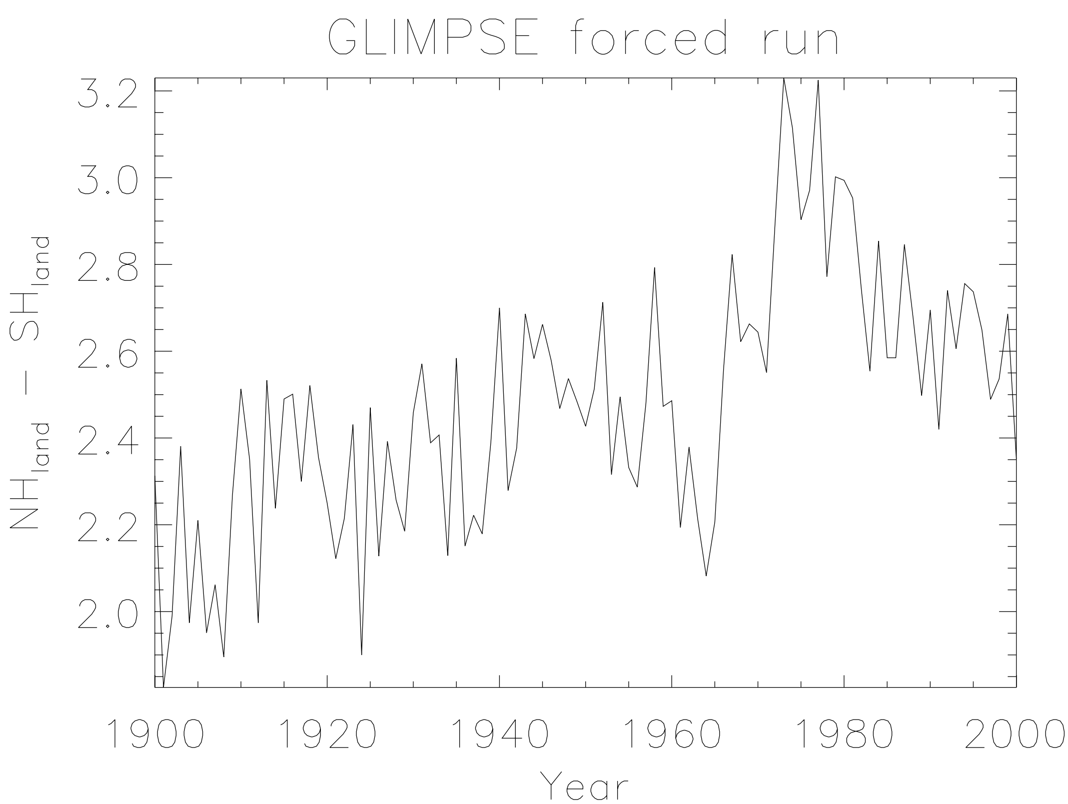

Figure 6.4: Difference in the GLIMPSE AOGCM model run for NH land and SH land temperatures.

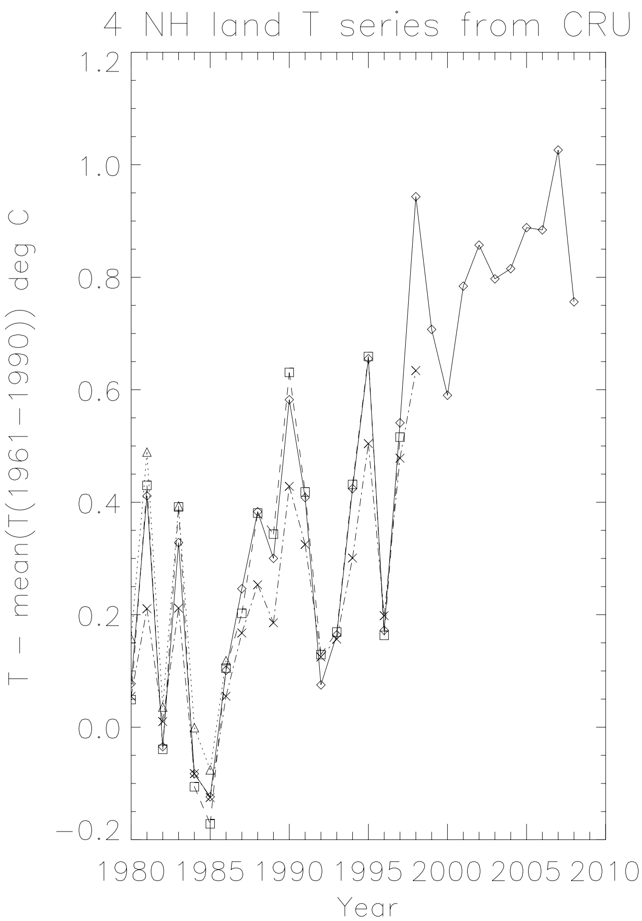

Figure 6.5: Four annual-mean NH land temperature curves, from CRU.

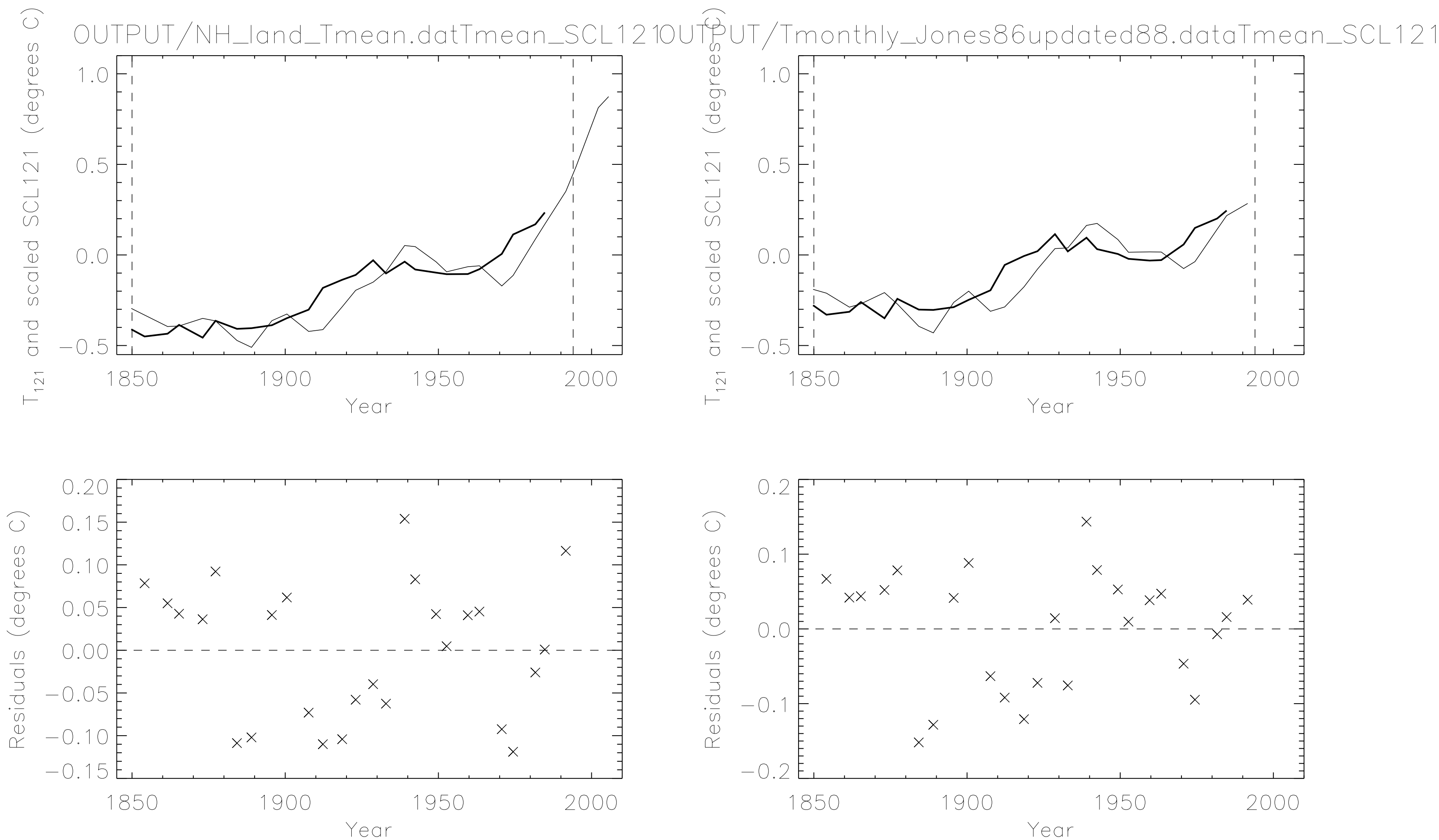

Figure 7.1: Multivariate regressions using GHG and SCL121 without lags.

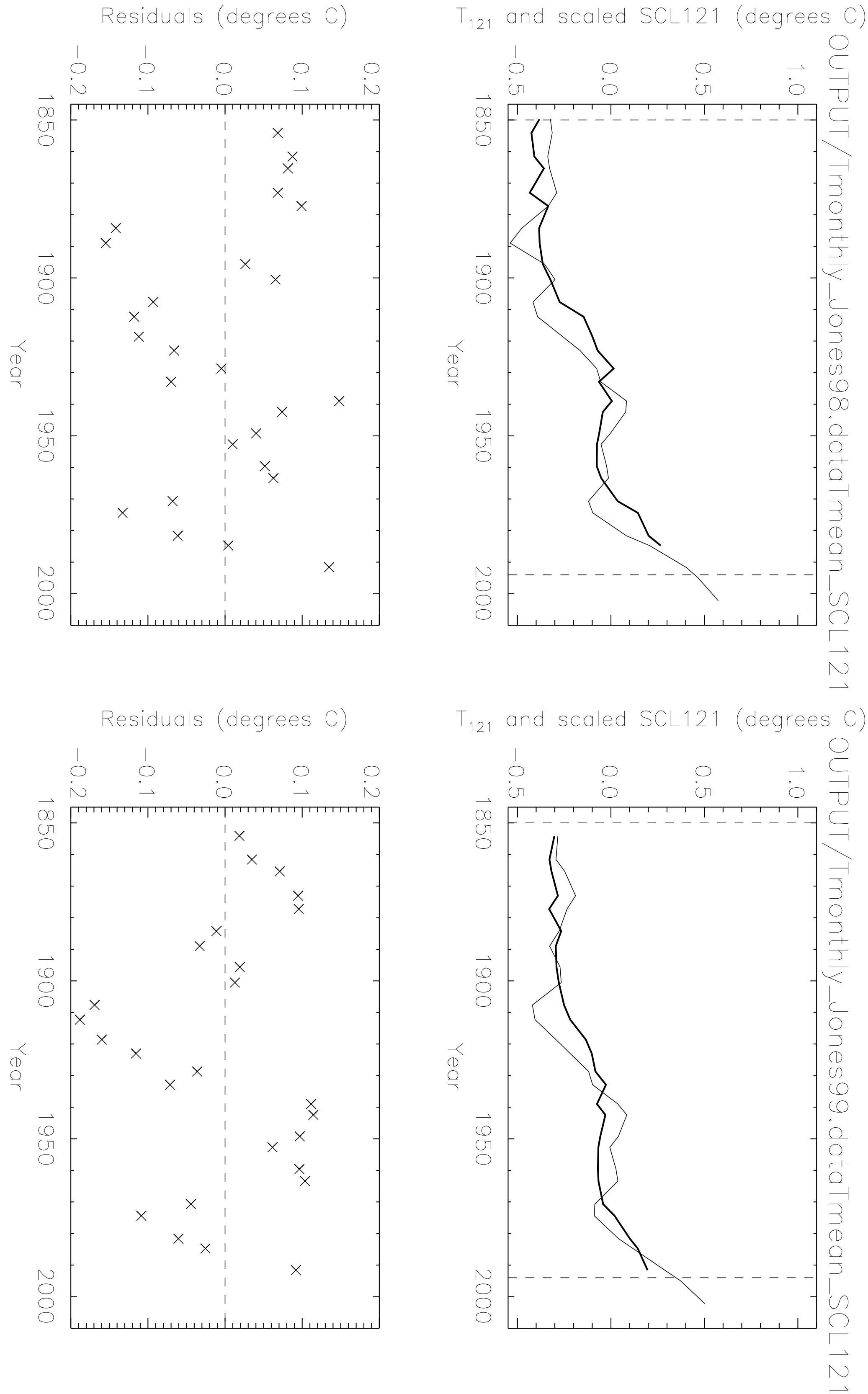

Figure 7.2: Multivariate regressions using GHG and SCL121 without lags.

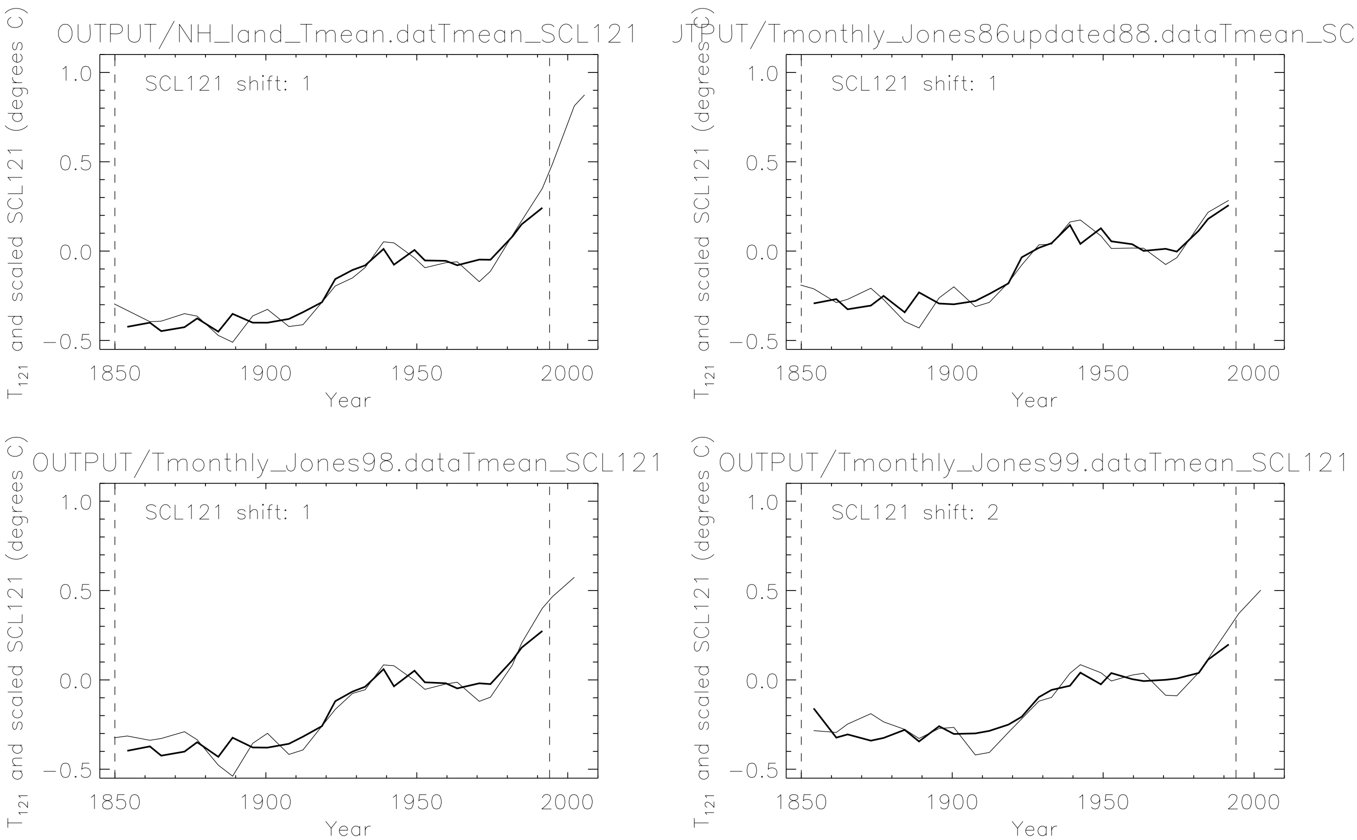

Figure 7.3: Fits with optimal lags, here 1 time step in the upper an lower left panels, 2 in the lower right panel.

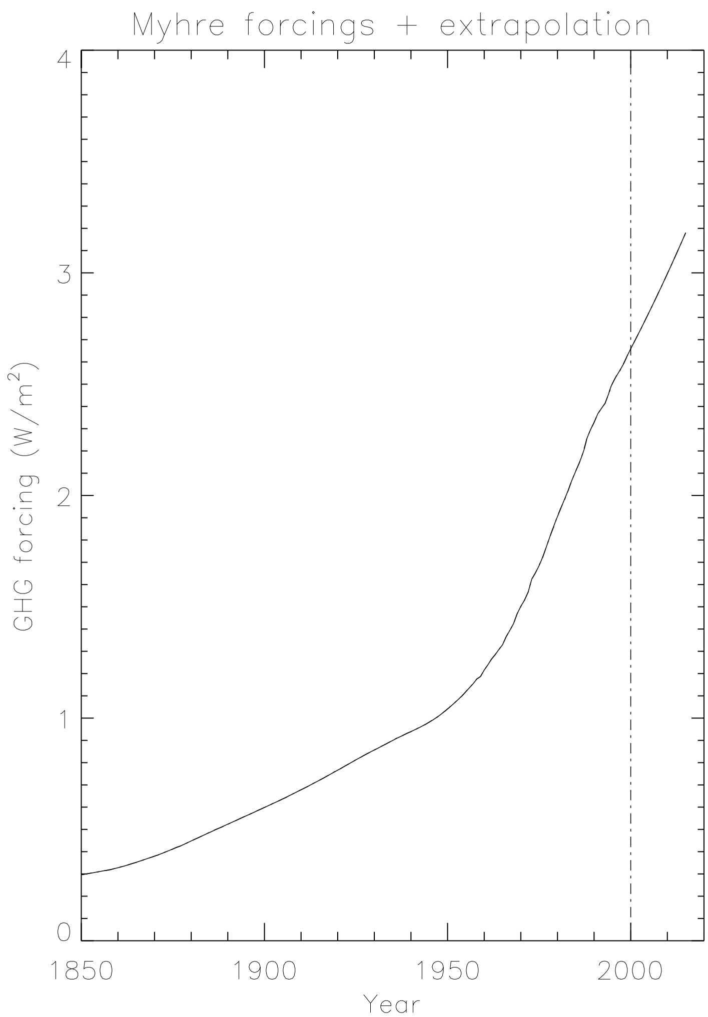

Figure 7.4: GHG forcings due to GHG concentrations due to [Myhre et al., 2001]. The data beyond 2000 are extrapolated using a 1.2% annual increase.

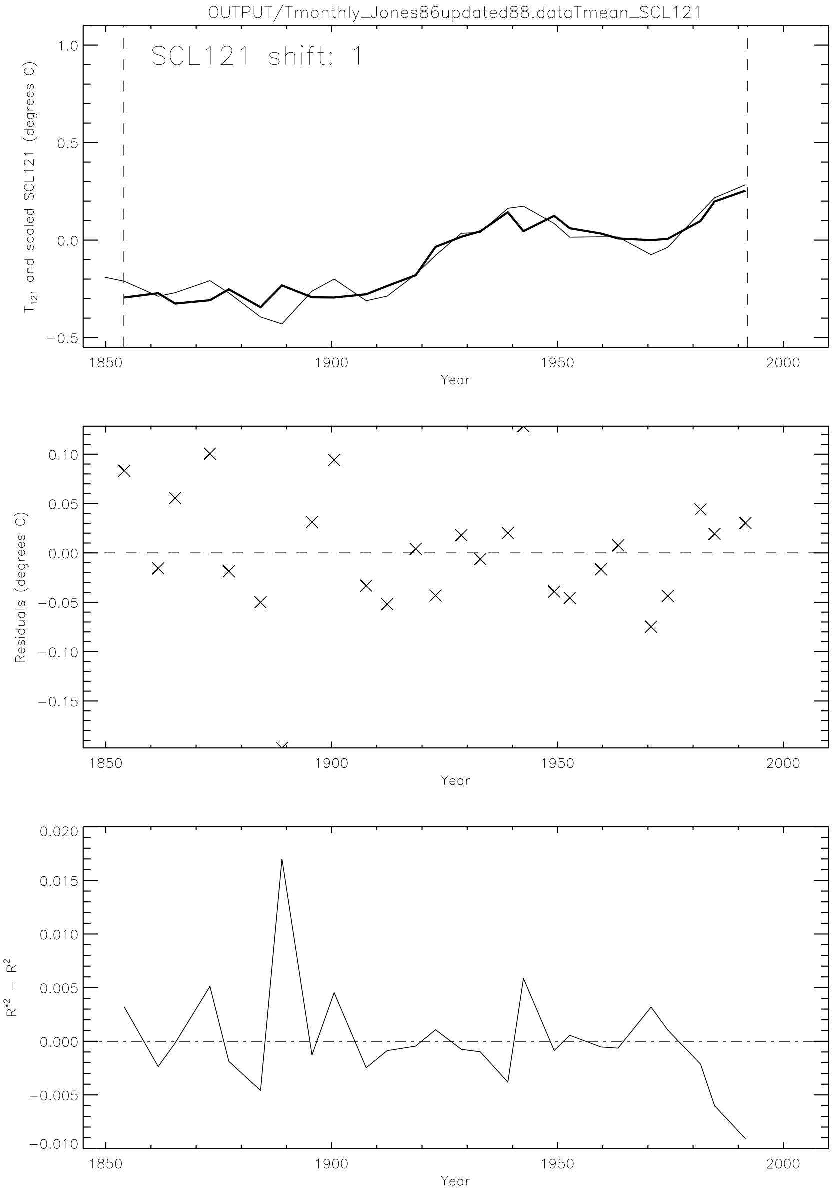

Figure 7.5: Fit and residuals (upper and middle panels). Lower panel: Change in amount of variance explained as one point in turn is omitted from the regression. The year of the data removed is on the x-axis.

Table 9.4: SCL values for solar cycle minima.

Epoch	m/M	Δ	L	Ctr.	SCL121	Δ
1634.0	m	0.5				
			11.0	1639.5	11.75	0.25
1645.0	m	0.5				
			10.0	1650.0	10.50	0.25
1655.0	m	0.5				
			11.0	1660.5	11.38	0.25
1666.0	m	0.5				
			13.5	1672.8	12.00	0.25
1679.5	m	0.5				
			10.0	1684.5	10.50	0.25
1689.5	m	0.5				
			8.5	1693.8	10.25	0.25
1698.0	m	0.5				
			14.0	1705.0	12.00	0.25
1712.0	m	0.5				
			11.5	1717.8	11.88	0.25
1723.5	m	0.5				
			10.5	1728.8	10.88	0.25
1734.0	m	0.5				
			11.0	1739.5	10.67	0.25
1745.0	m	0.5				
			10.2	1750.1	10.67	0.25
1755.2	m	0.5				
			11.3	1760.9	10.45	0.25
1766.5	m	0.5				
			9.0	1771.0	9.63	0.25
1775.5	m	0.5				
			9.2	1780.1	10.25	0.25
1784.7	m	0.5				
			13.6	1791.5	12.18	0.25
1798.3	m	0.5				
			12.3	1804.5	12.73	0.25
1810.6	m	0.5				
			12.7	1817.0	12.08	0.25
1823.3	m	0.5				
			10.6	1828.6	10.88	0.25
1833.9	m	0.5				
			9.6	1838.7	10.57	0.25
1843.5	m	0.5				
			12.5	1849.8	11.45	0.25
1856.0	m	0.5				
			11.2	1861.6	11.65	0.25
1867.2	m	0.5				
			11.7	1873.1	11.33	0.25
1878.9	m	0.5				

Table 9.5: Table 9.4 continued. Values in cursive are based on estimates of minima epochs.

Epoch	m/M	Δ	L	Ctr.	SCL121	Δ
1878.9	m	0.5				
			10.7	1884.3	11.30	0.25
1889.6	m	0.5				
			12.1	1895.7	11.70	0.25
1901.7	m	0.5				
			11.9	1907.7	11.48	0.25
1913.6	m	0.5				
			10.0	1918.6	10.53	0.25
1923.6	m	0.5				
			10.2	1928.7	10.20	0.25
1933.8	m	0.5				
			10.4	1939.0	10.27	0.25
1944.2	m	0.5				
			10.1	1949.3	10.30	0.25
1954.3	m	0.5				
			10.6	1959.6	10.73	0.25
1964.9	m	0.5				
			11.6	1970.7	11.02	0.25
1976.5	m	0.5				
			10.3	1981.7	10.45	0.25
1986.8	m	0.5				
			9.6	1991.6	*10.28*	*0.25*
1996.4	m	0.5				
			11.6	*2002.2*	*10.95*	*0.33*
2008.0	*m*	*0.5*				
			11.0	*2013.5*		
2019.0	*m*	*1.0*				

Table 9.6: Results for OLS between AD 1885 and 1970. Columns are: 1=OLS slope, 2=standard deviation of slope, 3=lag one autocorrelation of residuals, 4=(1+ac1)/(1-ac1), the decorrelation time in units of point spacing, 5=4 expressed in years given an average distance between points of 5.7 years; this is an estimate of the decorrelation time in years for the residuals, 6=the Durbin-Watson test statistic d of the residuals, 6=DW test outcome (P: indicates the result of the test for positive autocorrelation and N: the results of the test for negative autocorrelation), and 7=the name of the temperature series. There are 15 data points in the residual series.

slope	σ_{slope}	ac1	tau	tau*5.7	DW	DW test	T series name
-0.221	0.044	0.435	2.537	14.463	1.364	P:?,N:no	OUTPUT/NH_land_Tmean.datTmean_SCL121
-0.238	0.041	0.294	1.834	10.453	1.651	P:no,N:no	OUTPUT/Tmonthly_Jones86updated88.dataTmean_SCL121
-0.244	0.048	0.352	2.088	11.902	1.599	P:no,N:no	OUTPUT/Tmonthly_Jones98.dataTmean_SCL121
-0.181	0.055	0.674	5.136	29.278	0.678	P:yes,N:no	OUTPUT/Tmonthly_Jones99.dataTmean_SCL121

Table 9.7: As for Table 9.6 but using the data interval from 1850 to 1970. There are 21 data points in the residuals.

slope	σ_{slope}	ac1	tau	tau*5.7	d	DW test	T series name
-0.221	0.033	0.383	2.243	12.784	1.226	P:?,N:no	OUTPUT/NH_land_Tmean.datTmean_SCL121
-0.235	0.032	0.307	1.886	10.749	1.361	P:?,N:no	OUTPUT/Tmonthly_Jones86updated88.dataTmean_SCL121
-0.233	0.036	0.369	2.169	12.365	1.269	P:?,N:no	OUTPUT/Tmonthly_Jones98.dataTmean_SCL121
-0.164	0.039	0.672	5.089	29.005	0.721	P:yes,N:no	OUTPUT/Tmonthly_Jones99.dataTmean_SCL121

Table 9.8: Multivariate regression based on SCL121 and GHG - both without shifts. There are 21 data points in the residuals.

c	k_{SCL}	k_{GHG}	σ_c	σ_{SCL}	σ_{GHG}	ac1	tau	tau*5.7	d	d test	T series name
1.250	-0.153	0.233	-	0.032	0.036	0.351	2.080	11.855	1.184	P:?,N:no	NH_land_Tmean.datTmean_SCL121
1.797	-0.187	0.156	-	0.031	0.035	0.303	1.868	10.646	1.360	P:?,N:no	Tmonthly_Jones86updated88.dataTmean_SCL121
1.411	-0.164	0.229	-	0.037	0.041	0.377	2.212	12.608	1.156	P:?,N:no	Tmonthly_Jones98.dataTmean_SCL121
0.820	-0.104	0.188	-	0.038	0.042	0.663	4.935	28.127	0.659	P:yes,N:no	Tmonthly_Jones99.dataTmean_SCL121

Table 9.9: Results of a multivariate regression using SCL121 and GHG forcing as regressors, and allowing for lags or shifts on SCL121. Columns are as before, but column 1 now indicates the lag applied to SCL121. 'P' and 'N' give the results of the DW test for Positive and Negative serial autocorrelation respectively: - a '+1' indicates 'no', '1' indicates 'yes' and '0' indicates an indeterminate test. R^2 gives the variance explained by the regression.

lag	c	k_{SCL}	k_{GHG}	σ_c	σ_{SCL}	σ_{GHG}	ac1	tau	tau*5.7	d	P	N	R^2	T series name
-3	-0.400	-0.009	0.328	-	0.044	0.046	0.720	6.145	35.027	0.527	1	-1	0.739	0
-3	0.138	-0.044	0.257	-	0.048	0.050	0.758	7.281	41.503	0.483	1	-1	0.631	1
-3	-0.331	-0.013	0.329	-	0.049	0.051	0.728	6.344	36.164	0.516	1	-1	0.701	2
-3	-1.027	0.058	0.282	-	0.041	0.043	0.732	6.469	36.876	0.536	1	-1	0.670	3
-2	0.026	-0.047	0.307	-	0.043	0.046	0.666	4.990	28.442	0.605	1	-1	0.752	0
-2	0.619	-0.086	0.232	-	0.045	0.048	0.675	5.147	29.337	0.625	1	-1	0.669	1
-2	0.105	-0.051	0.308	-	0.048	0.051	0.672	5.099	29.062	0.602	1	-1	0.715	2
-2	-0.696	0.028	0.270	-	0.042	0.045	0.776	7.911	45.090	0.449	1	-1	0.647	3
-1	0.713	-0.106	0.264	-	0.040	0.044	0.561	3.560	20.293	0.766	1	-1	0.801	0
-1	1.320	-0.146	0.183	-	0.040	0.044	0.572	3.678	20.963	0.808	1	-1	0.759	1
-1	0.877	-0.118	0.259	-	0.044	0.049	0.586	3.829	21.824	0.728	1	-1	0.772	2
-1	0.056	-0.038	0.231	-	0.043	0.048	0.736	6.578	37.495	0.513	1	-1	0.652	3
0	1.250	-0.153	0.233	-	0.032	0.036	0.351	2.080	11.855	1.184	0	-1	0.867	0
0	1.797	-0.187	0.156	-	0.031	0.035	0.303	1.868	10.646	1.360	0	-1	0.849	1
0	1.411	-0.164	0.229	-	0.037	0.041	0.377	2.212	12.608	1.156	0	-1	0.839	2
0	0.820	-0.104	0.188	-	0.038	0.042	0.663	4.935	28.127	0.659	1	-1	0.728	3
1	1.473	-0.172	0.225	-	0.027	0.030	0.146	1.343	7.655	1.530	0	-1	0.906	0
1	1.943	-0.199	0.153	-	0.027	0.030	0.067	1.144	6.520	1.826	-1	-1	0.888	1
1	1.669	-0.186	0.219	-	0.031	0.034	0.211	1.534	8.743	1.438	0	-1	0.884	2
1	1.301	-0.146	0.164	-	0.031	0.034	0.463	2.723	15.519	1.035	1	-1	0.818	3
2	1.197	-0.149	0.260	-	0.027	0.030	0.329	1.982	11.295	1.450	0	-1	0.888	0
2	1.580	-0.170	0.195	-	0.029	0.032	0.386	2.257	12.865	1.250	0	-1	0.849	1
2	1.379	-0.163	0.256	-	0.031	0.034	0.351	2.083	11.872	1.429	0	-1	0.866	2
2	1.265	-0.144	0.185	-	0.026	0.029	0.334	2.003	11.416	1.509	0	-1	0.845	3
3	0.710	-0.107	0.288	-	0.033	0.037	0.522	3.181	18.134	0.953	1	-1	0.820	0
3	0.998	-0.119	0.229	-	0.037	0.041	0.571	3.658	20.853	0.861	1	-1	0.738	1
3	0.878	-0.120	0.286	-	0.037	0.041	0.516	3.136	17.875	0.980	1	-1	0.795	2
3	1.031	-0.124	0.204	-	0.029	0.032	0.434	2.534	14.441	1.210	0	-1	0.801	3

Table 9.10: Best results when both SCL121 and GHG are shifted. Tests were performed for shifts from -3 to 3 points, but only the 'best' in the sense that explained variance is highest, are shown here. Note that the lags are not the same. For each series the maximum number of data-points were used, based on the availability of T data (this is not the same in each series). The number of available points is given in the column labelled 'n'.

lag	c	k_{SCL}	k_{GHG}	σ_c	σ_{SCL}	σ_{GHG}	ac1	tau	tau*5.7	d	P	N	R^2	n	T series name
2	0.565	-0.103	0.477	-	0.035	0.035	0.593	3.918	22.331	0.795	1	-1	0.928	29	0
1	1.863	-0.193	0.179	-	0.027	0.034	0.077	1.168	6.656	1.799	-1	-1	0.890	26	1
2	1.051	-0.138	0.375	-	0.030	0.032	0.443	2.590	14.765	1.152	0	-1	0.923	28	2
2	0.984	-0.123	0.292	-	0.027	0.030	0.491	2.928	16.687	1.135	0	-1	0.900	28	3

Table 9.11: Like Table 9.10 but using only the data between 1854 and 1992 so that all series have the same extent.

lag	c	k_{SCL}	k_{GHG}	σ_c	σ_{SCL}	σ_{GHG}	ac1	tau	tau*5.7	d	P	N	R^2	n	T series name
1	1.366	-0.163	0.261	911	0.027	0.034	0.138	1.319	7.518	1.527	0	-1	0.907	26	0
1	1.863	-0.193	0.179	911	0.027	0.034	0.077	1.168	6.656	1.774	-1	-1	0.890	26	1
2	1.124	-0.143	0.344	911	0.030	0.043	0.370	2.175	12.398	1.167	0	-1	0.878	26	2
2	1.094	-0.131	0.247	911	0.027	0.038	0.391	2.286	13.027	1.070	0	-1	0.849	26	3

Table 9.12:

Series	years	best lag	Positive influence on R^2	Negative influence on R^2
0	all	+2	last several points	near 1890 and 1870
1	all	+1	last several points	near 1890
2	all	+2	last several points	near 1890 and 1870
3	all	+2	last several points	near 1890 and 1870
0	same	+1	last several points	near 1890
1	same	+1	last several points	near 1890
2	same	+2	last several points	near 1870
3	same	+2	last several points	near 1870

10. References

[Benestad, 2008] Benestad, R. E. (2008). A Simple Test for Changes in Statistical Distributions. *EOS Transactions*, 89:389–390.

[Draper and Smith, 1981] Draper, N. and Smith, H. (1981). *Applied Regression Analysis*. John Wiley&Sons, Inc., 2 edition, New York.

[Eddy, 1976] Eddy, J. A. (1976). The Maunder Minimum. *Science*, 192:1189–1202.

[Friis-Christensen and Lassen, 1991] Friis-Christensen, E. and Lassen, K. (1991). Length of the Solar Cycle: An indicator of Solar Activity Closely Associated with Climate. *Science*, 254:698–700.

[Houghton et al., 2001b] Houghton, J., Ding, Y., Griggs, D., Nouger, M., van der Linden, P., Dai, X., Maskell, K., and Johnson, C. (2001b). Climate Change 2001: The scientific basis. Contribution of Working Group 1 to the third Assessment Report of the Intergovernmental Panel on Climate Change. Technical report, Cambridge University Press.

[Lassen and Friis-Christensen, 1995] Lassen, K. and 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 Terrestrial Physics*, 57:835–845.

[Myhre et al., 2001] Myhre, G., Myhre, A., and Stordal, F. (2001). Historical evolution of radiative forcing of climate. *Atmospheric Environment*, 35:2361–2373.

[Reichel et al., 2001] Reichel, R., Thejll, P., and Lassen, K. (2001). The cause-and-effect relationship of solar cycle length and the northern hemisphere air surface temperature. *Journal of Geophysical Research*, 106:15635–15461.

[Stendel et al., 2006] Stendel, M., Mogensen, I. A., and Christensen, J. H. (2006). Influence of various forcings on global climate in historical times using a coupled atmosphere ocean general circulation model. *Climate Dynamics*, 26:1–15.

[Thejll and Lassen, 2002a] Thejll, P. and Lassen, K. (2002a). Erratum to “Solar forcing of the Northern hemisphere land air temperature: new data”JASTP 62 (2000) 1207-1213. *Journal of Atmospheric and Terrestrial Physics*, 64:105–105

[Thejll and Schmith, 2005] Thejll, P. and Schmith, T. (2005). Limitations on regression analysis due to serially correlated residuals: Application to climate reconstruction from proxies. *Journal of Geophysical Research D (Atmospheres)*, 110(9):18103–+.