PERGAMON

Journal of Atmospheric and Solar-Terrestrial Physics 65 (2003) 801–812

Journal of ATMOSPHERIC AND SOLAR-TERRESTRIAL PHYSICS

www.elsevier.com/locate/jastp

Solar activity and terrestrial climate: an analysis of some purported correlations

Peter Laut

Department of Physics, Technical University of Denmark, DK-2800 Lyngby, Denmark

Received 14 February 2002; received in revised form 23 January 2003; accepted 4 February 2003

Abstract

The last decade has seen a revival of various hypotheses claiming a strong correlation between solar activity and a number of terrestrial climate parameters: Links between cosmic rays and cloud cover, first total cloud cover and then only low clouds, and between solar cycle lengths and Northern Hemisphere land temperatures. These hypotheses play an important role in the scientific as well as in the public debate about the possibility or reality of a man-made global climate change. I have analyzed a number of published graphs which have played a major role in these debates and which have been claimed to support solar hypotheses. My analyses show that the apparent strong correlations displayed on these graphs have been obtained by an incorrect handling of the physical data. Since the graphs are still widely referred to in the literature and their misleading character has not yet been generally recognized, I have found it appropriate to deliver the present overview. Especially, I want to caution against drawing any conclusions based upon these graphs concerning the possible wisdom or futility of reducing the emissions of man-made greenhouse gases.

My findings do not by any means rule out the existence of important links between solar activity and terrestrial climate. Such links have over the years been demonstrated by many authors. The sole objective of the present analysis is to draw attention to the fact that some of the widely publicized, apparent correlations do not properly reflect the underlying physical data.

Keywords: Solar activity; Solar cycle lengths; Cloud cover; Galactic cosmic rays; Global warming

1. Introduction

In 1991 Friis-Christensen and Lassen published an article, which seemed to demonstrate a strong correlation between solar cycle lengths and Northern Hemisphere temperatures over the period 1860–1990. In 1995 Lassen and Friis-Christensen presented an extension of this correlation covering the period 1579–1987, and in 2000 Lassen and Friis-Christensen gave an update of the same correlation in response to a critical article by Laut and Gundermann (2000a). At the same time Thejll and Lassen (2000) also published an update containing some of the same results as Lassen and Friis-Christensen (2000). In 1997 Svensmark and Friis-Christensen published satellite cloud data (Svensmark and Friis-Christensen, 1997), which seemed to show that *total cloud cover* was strongly correlated to the *galactic cosmic ray intensity* (GCRI). These results were updated by Svensmark (1998). In 2000 Marsh and Svensmark offered a new hypothesis where '*total cloud cover*' was replaced by '*low cloud cover*' as relevant parameter. In all these articles graphs were presented showing strong correlations between the solar and terrestrial parameters.

I have analyzed these graphs and show that the apparent strong correlations are not supported by the underlying physical observations. Since the articles are frequently referred to in the scientific literature and since their central graphs play an important role in the ongoing public debate concerning global warming and the risk of man-made climate change, I have found it appropriate to draw attention to the misleading character of these articles. Below I will discuss the articles following an order, which roughly reflects their current degree of general interest.

E-mail address: peter.laut@fysik.dtu.dk (P. Laut).

1364-6826/03/$ - see front matter
doi:10.1016/S1364-6826(03)00041-5

When discussing these published graphs I have here chosen to use '*remakes*' of the original figures, i.e., I have first scanned and electronically digitized the curves and then re-plotted the numerical values. This procedure has made it easy to compare numerical values and to introduce different formats and different colors in order to facilitate the structuring and discussion of the graphs. In some cases the layout has been chosen in such a way that the graphs, for all practical reasons, are identical with the originals.

2. Some solar hypotheses

2.1. Total cloud cover and galactic cosmic ray intensity

In 1997 Svensmark and Friis-Christensen published an article claiming a strong correlation of *total cloud cover* with the intensity of *galactic cosmic rays* as measured at Climax, Colorado. The article was updated by Svensmark in 1998. The principal result was presented in Fig. 1 of the latter work. Fig. 1a below is a remake of the original graph obtained as described above. If there are minor uncertainties they are due to the blurred character of the original: Certain areas of the original graph are so blackened by superimposed markers that it is impossible to distinguish whether specific markers contribute or not. This uncertainty is caused by the large size chosen for the markers. It is, e.g., not possible to decide if the data from the *Defense Meteorological Satellite Program* (DMSP)[1]—which are marked by diamonds—follow the 'valley shape' variation of the GCRI curve between 1990–1992 or not, i.e., if they follow the descent exhibited by the ISCCP[2] data in this period. This is, of course, an important question, if one wants to decide if the DMSP data may have any relevance to the present graph, and if they represent the same physical parameter as the ISCCP data, i.e. *total cloud cover*. The diamond markers can be clearly distinguished from 1988 to 1990 and from 1992 to 1995, but the original figure of Svensmark (1998) does not allow to decide if they contribute to the blackened areas between 1990–1992. However, based upon the analyses of Kristjánsson and Kristiansen (2000) it is possible to infer that the DMSP data actually do not contribute to these blackened areas, i.e., that they do not contribute to the cyclic pattern of the GCRI.

A strange feature in Fig. 1a is that, for the major part of the year 1992, it seems to indicate that the total cloud cover has been at a very *high* level (according to the upper, DMSP curve) and, at the same time, also has been at a very *low* level (according to the lower, ISCCP curve).

Fig. 1b is a comparison of DMSP data with ISCCP data for *total cloud cover* as shown by Kristjánsson and Kristiansen (2000). Fig. 1b is a remake of the original, which is re-plotted in the style of Svensmark's figure in order to make comparisons easier. The two data sets are seen to develop quite differently with time. In the overlapping time periods the *total cloud cover* according to the ISCCP data decreases, while the DMSP data increase. The same applies to the overall trends of the ISCCP and the DMSP data, respectively. So, if the ISCCP data are assumed to describe *total cloud cover* correctly, the DMSP data cannot possibly also represent *total cloud cover*.

Fig. 1c is a corrected and updated version of Fig. 1a. The *correction* consists in removing the irrelevant DMSP data, and the *update* consists in adding data for *total cloud cover* presented on http://isccp.giss.nasa.gov/climanal1.html (ISCCP D2 data for the period 1983–1999, smoothed applying a bandwidth similar to Fig. 1a) together with GCRI as observed at station Climax in Colorado. It shows that the two parameters agree fairly well from 1985 to 1989 but disagree strongly thereafter.

The findings of Kristjánsson and Kristiansen (2000) demonstrate, that the period of apparent agreement on Fig. 1a was extended artificially by combining into one curve two incongruous data sets (ISCCP and DMSP), i.e., two data sets representing entirely different physical quantities. Fig. 1a has played an important role in the scientific debate as well as in discussions conducted in the general public on the possible causes of global climate change.

2.2. Low cloud cover and galactic cosmic ray intensity

In Marsh and Svensmark (2000) a new hypothesis was presented claiming that it is '*low cloud cover*', rather than '*total cloud cover*', that exhibits a strong correlation with GCRI, here represented by data from the Peruvian station Huancayo. The central graph in this claim (Fig. 1c in the article) is here shown as Fig. 2a (a remake). Fig. 2b shows an update by Kristjánsson (2002) and Fig. 2c a smoothed version of the same data. A comparison with Fig. 2a gives rise to a number of comments:

(1) The agreement is questionable after 1989. After 1994 there is certainly no agreement.
(2) On first sight the steep rise of *low cloud cover* after 1992 (see Fig. 2c) seems to correlate well with a

[1] The measurements of the Defence Meteorological Satellite Program (DMSP) are performed with the Special Sensor Microwave/Imager (SSM/I) instrument. It measures, among other parameters, frequency of cloud occurrence over ocean. DMSP only detects liquid water clouds. The cloud frequency data have not been validated against, e.g., synoptic observations, as the ISCCP data have been. The DMSP data deviate dramatically from the ISCCP data, even if DMSP data are compared with ISCCP data for water clouds alone. The reason for this is not understood (Kristjánsson and Kristiansen, 2000). Possible explanations are DMSP's inability to distinguish between water clouds and precipitating water and instrument drift due to change of satellites carrying the SSM/I instrument.

[2] ISCCP stands for '*International Satellite Cloud Climatology Project*'. Its data sets are considered the most reliable data sets for cloud cover available. They combine data from geostationary and polar-orbiting satellites, hence giving a global coverage.

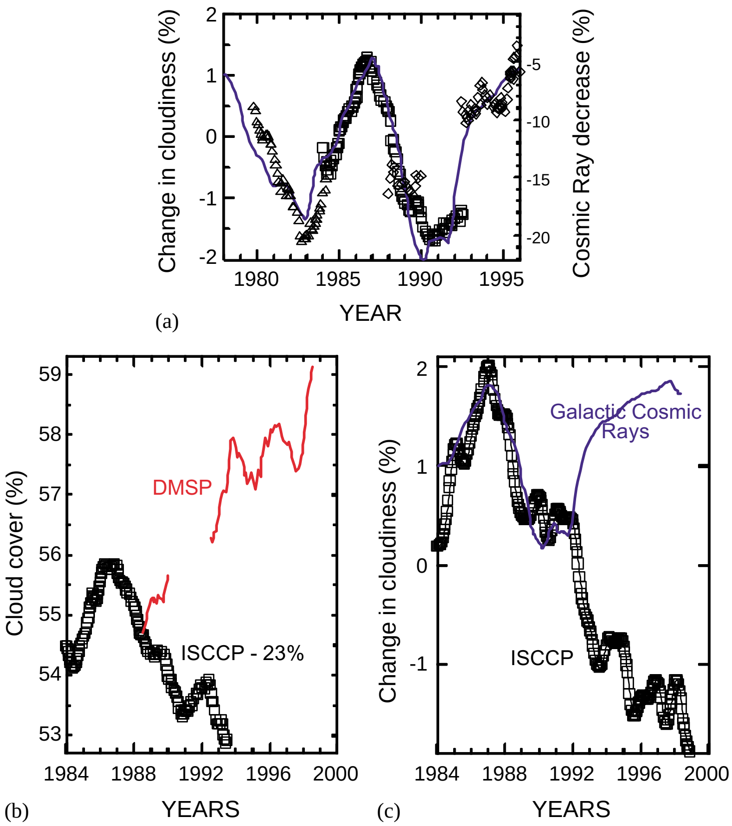

Fig. 1. (a) Earth's '*total cloud cover*' and galactic cosmic ray fluxes as observed at Climax, Colorado (blue solid line, normalized to May 1965). The numerical values are obtained by electronic scanning and digitization from Fig. 1 in Svensmark (1998). The triangles represent cloud data from the NIMBUS-7 CMATRIX project for the southern hemisphere over oceans with the tropics excluded. The squares show ISCCP C2 and ISCCP D2 cloud data derived from geostationary satellites over oceans with the tropics excluded. The diamonds are DMSP data, which—according to Svensmark—represent '*total cloud cover for the southern hemisphere over oceans*'. (b) Comparison of DMSP data with ISCCP data for 'total cloud' cover as shown by Kristjánsson and Kristiansen (2000). The squares show ISCCP data and the solid red curve DMSP data. The relative vertical position of the two curves is rather arbitrary, partly because the intercalibration of the two satellite data series cannot be determined accurately, partly because the two curves represent two different physical parameters as demonstrated by their different time development. In contrast to the ISCCP and DMSP data, which are put together in Fig. 1a, the two data sets on Fig. 1b represent the *same* geographical regions, which allows a proper comparison. In the time periods where the two curves overlap, '*total cloud cover*' represented by the ISCCP data decreases while at the same time the DMSP data increase. The same is true for the overall trends of the ISCCP and DMSP data. So, if it is assumed that the ISCCP data correctly describe '*total cloud cover*' then the DMSP data cannot possibly also represent '*total cloud cover*'. (c) A corrected and updated version of Fig. 1a. Squares denote ISCCP data and the blue solid curve shows galactic cosmic ray intensities as measured at Climax, Colorado, and smoothed as in Kristjánsson and Kristiansen (2000). The *correction* consists in removing the DMSP data, which do not represent '*total cloud cover*' and hence do not belong into this context, and the *update* consists in adding new ISCCP data as available from http://isccp.giss.nasa.gov/climanal1.html (2001).

corresponding steep rise in GCRI. However, the cloud cover is delayed by more than half a year relative to the cosmic rays. According to current theory (e.g. Yu and Turco, 2000) the build-up of cloud condensation nuclei is completed within less than a day after an increase of GCRI. Since the lifetime of these cloud condensation nuclei only amounts to a few days a possible formation of clouds must take place within this span of time and not several months later. Therefore, the cloud response to a change in GCRI should be practically instantaneous when viewed on the time scale of Fig. 2.

(3) Another difficulty is the physical interpretation of low cloud cover data based exclusively on infrared measurements from satellites: most low clouds which are positioned below higher clouds cannot be detected from satellites, and since the range of variation of the different cloud types only amounts to a few percent of the respective cloud cover, an inaccuracy of a few percent

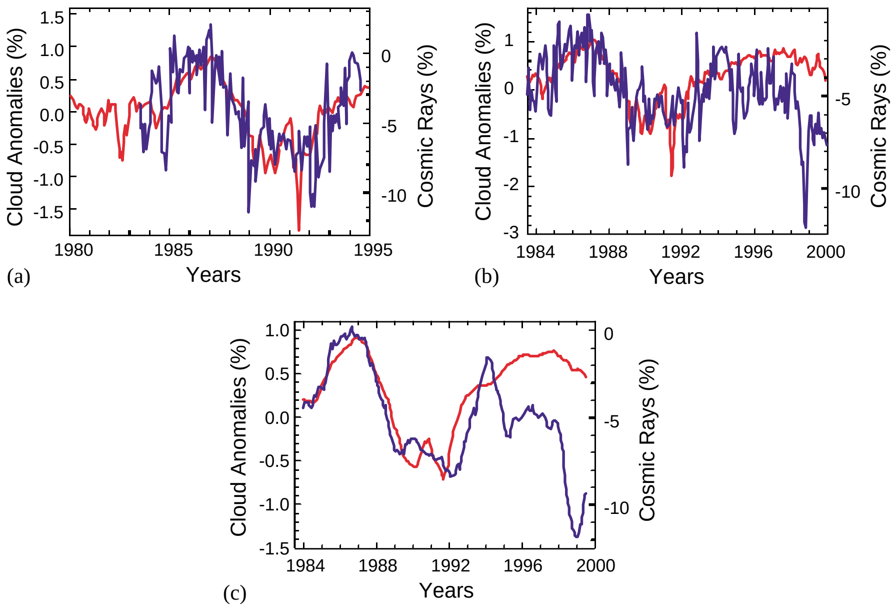

Fig. 2. (a) Low cloud cover (blue solid line) and galactic cosmic ray intensity as observed at the Peruvian station Huancayo (red solid line) according to Marsh and Svensmark (2000). (b) Low cloud cover (blue solid line) and galactic cosmic ray intensity as observed at Huancayo (red solid line) according to Kristjánsson (2002). (c) Same as (b) but smoothed in order to display the trends more clearly.

could entirely spoil the apparent agreement shown in Fig. 2a.

Kernthaler et al. (1999) have studied different cloud types and find no clear relationship between individual cloud types and cosmic ray flux. Wagner et al. (2001) have compared a proxy for cosmic ray flux, the combined flux of ^{10}Be and ^{36}Cl, with proxies for climate, δ^{18}O and CH_4 concentration, over a period from 20 to 60 kyrs BP and found that they are unrelated. Kristjánsson et al. (2002) have compared the correlation of *low cloud cover* with *total solar irradiance* and *GCRI* respectively and found that the correlation coefficient with *total solar irradiance* is by far the highest ($r = 0.80$ vs. $r = 0.47$). This result could indicate that solar activity indeed may influence low cloud cover, but that the physical mechanism may be related to variations in solar irradiance rather than to GCRI. This would be in line with mechanisms discussed in recent years (Bond et al., 2001, Haigh, 1996, 2001; Shindell et al., 1999, 2001; Udelhofen and Cess, 2001) where temperature variations in the stratosphere, caused by variations in solar irradiance at ultraviolet wavelengths (which are considerably larger than the variations in the visible domain), give rise to dynamic responses in the troposphere that can influence surface climate. Here planetary-scale waves seem to play an important role. So the covariance between low cloud cover and GCRI observed by Marsh and Svensmark (2000) may be due to the fact that GCRI and solar irradiance are both parameters connected to solar activity, and that a causal relationship with solar irradiance automatically will imply a certain degree of correlation with GCRI, even if cosmic rays do not play any role whatsoever in the formation of low clouds.

An alternative explanation for the deterioration of the agreement GCRI with low clouds after 1994 (as illustrated on Fig. 2b and c) is offered by Marsh and Svensmark (2002), who claim that the disagreement could be an artifact related to problems experienced with the ISCCP inter-calibration between September 1994 and January 1995. As yet, this claim remains to be further investigated. A discussion of the present, yet quite inadequate state of understanding is given by Carslaw et al. (2002).

Since the variation of the ultraviolet solar irradiation over the last hundred years is not known, and since the mechanisms of its possible influence upon climate are still uncertain, e.g. the degree of non-linearity, it is not possible at this stage to determine if these processes can have contributed significantly to the observed global warming over this period.

2.3. *Solar cycle lengths and Northern Hemisphere land temperatures (1991)*

In 1991 Friis-Christensen and Lassen published an article claiming a '*strikingly good agreement*' between solar cycle lengths (SCLs) and Northern Hemisphere land air temperatures. The article attracted worldwide attention and is still frequently referred to in the scientific literature and still plays an important role in the public debate on

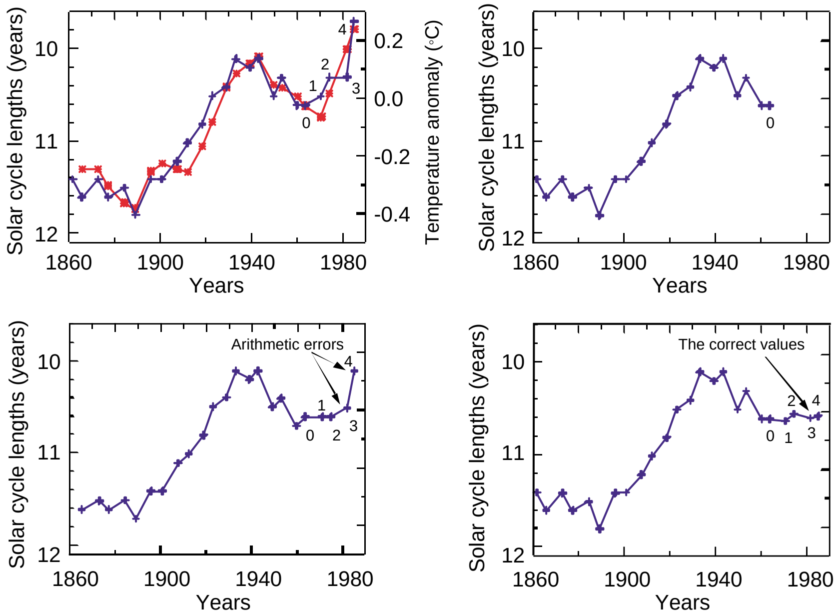

Fig. 3. (a) Solar cycle lengths, SCLs, (blue curve with crosses) and Northern Hemisphere land temperatures (red curve with stars). Here the values of the original Fig. 2 in Friis-Christensen and Lassen (1991) are plotted (a remake). The first 20 points of the 'solar' curve are 1,2,2,2,1-filtered SCLs. The last four points (marked 1–4) denote SCLs, which are only partially filtered (1,2) or not filtered at all (3,4). The steep rise of these last points simply occurs because the non-filtered SCLs (i.e. the raw data) perform violent oscillations around the heavily smoothed curve formed by the 1,2,2,2,1-filtered SCLs. Points 3 and 4 actually constitute a single upward swing of the oscillating raw data. This mixing of different types of data cannot be justified on theoretical grounds, and yet it is this mixing that is solely responsible for the misleading impression created by the graph that recent changes in SCLs correspond to the recent global warming. (b) The way the solar curve should have been published in 1991. Here the solar curve consists exclusively upon 1,2,2,2,1-filtered SCL, which are based upon data, which actually had been observed at that time. The point marked '0' is the last properly filtered value. (c) An update of the solar cycle length curve showing the values published by Lassen and Friis-Christensen (2000) and Thejll and Lassen (2000). The '*steep rise*' of the last two points, 3 and 4 (which Lassen and Friis-Christensen explicitly draw attention to as still reflecting the recent global warming), is simply due to errors in the authors' arithmetic. Their values for all other points (including points 1 and 2) are rounded off but otherwise correct. The rounding off explains the minor deviations from Fig. 3d. (d) An update of the original solar curve in Fig. 3a with points 1–4 calculated applying correct arithmetic to the observed and predicted data used by Thejll and Lassen (2000). Notice, that the recent solar data form a flat curve and do not in any way reflect the recent global warming.

the possible causes of global climate change. The central figure (Fig. 2 in the Science article) is here shown as Fig. 3a, which is a remake with colors and numbers 0–4 added in order to facilitate the structuring and the discussion. Of special interest is the warming of the recent decennia shown by the temperature curve and the corresponding steep rise of the solar curve. The latter seems to exhibit an impressive agreement of solar activity and terrestrial change. However, a careful analysis reveals some problematic details: The solar curve consists of 24 points. The first 20 points are 1,2,2,2,1-filtered SCLs, i.e. running averages over five consecutive maximum–maximum or minimum–minimum cycle lengths with weight factors: 1/8, 2/8, 2/8, 2/8, 1/8. Each of these points therefore represents a time period of about 55 years. Hence, the first 20 points form a curve, which is the result of a strong smoothing (or 'filtering') of the observed data. In contrast to this smoothed curve the non-filtered solar cycle lengths, i.e., the directly observed physical data, perform violent oscillations above and below the smoothed curve. Points 3 and 4 in Fig. 3a represent such non-filtered SCLs, while points 1 and 2 mark data, which are partially filtered. The apparent agreement with the recent global warming is obtained artificially by combining the 20 points of the smoothed curve with the most recent of several 'upward swings' of the oscillating non-filtered data, i.e., by combining two incongruous sets of physical data. Inclusion of one of the 'downward swings' of the observed SCLs would, instead, have produced an agreement with a dramatic global cooling, if such one had occurred. This problem has been discussed in more detail by Laut and Gundermann (2000a, b). To avoid such mixing of incongruous types of physical data, the last four points should have been omitted in the original publication, and the solar data should have been presented as shown in Fig. 3b, ending with point '0', which was the last properly filtered SCL at that time.

Today, utilizing the observations of the intervening years, the properly filtered solar curve can be extended. Lassen and Friis-Christensen (2000) and Thejll and Lassen (2000) offer an update of these four values. Both articles base their updated values upon the two SCLs, which have been observed in the mean time supplemented by two predicted epochs. The two articles employ the same *predicted* values (see Fig. 9 below). Thejll and Lassen (2000) display these updated values both in their Figs. 1 and 2. The solar 1,2,2,2,1-filtered curve employing their updated values is in the present article shown below as Fig. 3c. However, the updated points 3 and 4 on their curve do not correspond to the observed and predicted epochs they employ. This can be checked by a simple calculation of the weighted 1,2,2,2,1 averages of their SCL values as displayed in column 4 of Fig. 9: $1/8\times10.6+2/8\times11.6+2/8\times10.3+2/8\times10.0+1/8\times10.5=10.61$ and $1/8\times11.0+2/8\times11.0+2/8\times9.7+2/8\times10.7+1/8\times10.9=10.59$. Fig. 3d shows the 1,2,2,2,1 filtered solar curve with these 'correct' results included, i.e., values which are based upon precisely the same observed and predicted epochs as cited by the authors, but here derived applying correct arithmetic.

Lassen and Friis-Christensen (2000) present the same erroneous values (=10.6, 10.6, 10.5, 10.1 years) as Thejll and Lassen (2000) for the updated 1,2,2,2,1-filtered SCLs and draw specifically attention to the '*steep rise*' of the solar curve which is created by point 3 and 4 and which still seems to justify their 1991 claim of a '*strikingly good agreement*' and '*a close association between the two curves in the up-going trends from* 1900 *to* 1940 *and since* 1970', i.e., the recent global warming.

But it is by the two erroneous values alone that the author's 1,2,2,2,1-filtered solar curve obtains the upward bend, which creates the false impression that the updated curve shows some agreement with the recent global warming. And the purported '*steep rise*' of the solar curve is in fact neither supported by the recent physical observations nor by the data that were available in 1991 when Friis-Christensen and Lassen (1991) was published.

A graph, which is cited extensively in current climate analyses, is Fig. 3 in Thejll and Lassen (2000). Fig. 4 below displays two curves of this figure (*the observed temperatures and* 1,2,1-*filtered solar cycle lengths of* Fig. 3 *in* Thejll and Lassen, 2000) together with the (corrected) update of the 1,2,2,2,1-filtered solar cycle lengths of Fig. 2 in Friis-Christensen and Lassen (1991). Fig. 4 shows that the authors, by abandoning the original 1,2,2,2,1-filtering and introducing the 1,2,1-filtering instead, obtain a better agreement with the observed temperature development.

When investigating possible correlations it is always a good test to investigate the agreement over as long a time period as possible. In Fig. 5 the 1,2,2,2,1-filtered minimum–minimum SCLs are compared with smoothed Northern Hemisphere land temperatures covering the period 1400–1990. The temperature series is obtained by combining the reconstruction of Mann et al. (1998) with a modern instrumental temperature series issued by the *Hadley Centre* (*Combined land air and sea surface temperature anomalies for the Northern Hemisphere* 1951–1998, *at* http://www.meto.gov.uk/sec5/CR_div/Tempertr/lsst_vals_nh.html). The SCL data in Fig. 5 are the values listed in

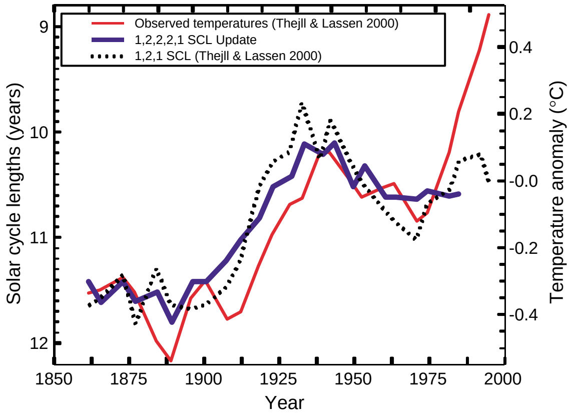

Fig. 4. Observed temperatures (red thin solid line) and 1,2,1-filtered solar cycle lengths (black dotted line) as shown in Fig. 3 in Thejll and Lassen (2000). 1,2,2,2,1-filtered solar cycle lengths as shown in Fig. 2 in Friis-Christensen and Lassen (1991) with four updated points (blue heavy solid line).

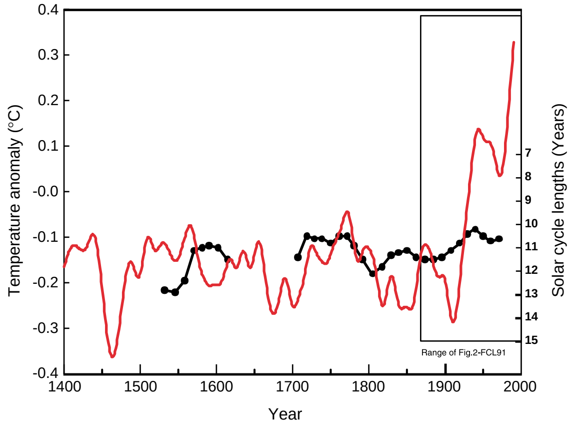

Fig. 5. 1,2,2,2,1-filtered minimum–minimum solar cycle lengths (black curve with solid circles) and Northern Hemisphere land temperatures (red solid line). These are essentially the same physical parameters as in Fig. 3a, but here they are shown over a longer time period. Notice that the method of linear regression in general gives a far less convincing agreement of the solar and terrestrial data when applied to a longer time period where each curve includes a larger number of specific details. The inserted frame indicates the range of Fig. 3a above. It should also be noticed that a scaling that yields a better agreement of the 'S-shapes' of the two curves *within* the range of the frame (a scaling as applied in Fig. 3a) will make the agreement *outside* the range worse. This would, e.g., lead to an increased mismatch between the solar 'top' and the temperature 'valley' around 1600.

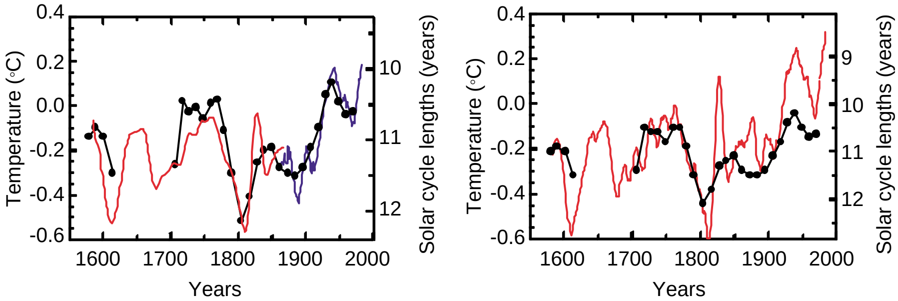

Fig. 6. (a) 1,2,2,2,1-filtered minimum–minimum solar cycle lengths (black line with solid circles) and two different series of Northern Hemisphere temperatures: Grovemann/Landsberg (red solid line) and Jones (blue solid line). The seemingly good agreement of the two temperature curves with the solar curve has been obtained in the following way: (1) The two series are plotted in *different scales*, whereby the right-hand curve is lowered by 0.1°C. This makes about one third of the global warming over the range of the curve disappear. (2) The entire solar curve has been *lifted* so as to achieve a good fit of the curve over the last 150 years, at the expense of the agreement of the older data. As a consequence the solar cycle lengths on the left-hand side are positioned too high. (b) Here the solar data are the same as on Fig. 6a, but the two different temperature series employing different temperature scales are here replaced by a single series (the Groveman/Landsberg/Borzenkova series) with all temperatures measured in the same scale (red solid line). In order to make comparisons easier the Groveman/Landsberg/Borzenkova curve has been extended so that it ends in the same year as the Jones curve. This has been achieved by adding zero-point adjusted Jones data for 1975–1982. The curve fitting is here done by simple linear regression without manual adjustment, but only employing data before 1850 in order to avoid 'contamination' from man-made greenhouse gases.

Table 1 of Lassen and Friis-Christensen (1995). SCL data ranging from 1610 to the present can be obtained from: ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS/maxmin.new. The parameters in Fig. 5 are essentially the same as in Fig. 3a, but cover a longer time period. The fitting of the solar curve to the temperature curve is obtained by linear regression. It is seen that linear regression gives a far less convincing agreement of the solar and terrestrial data when applied to the longer time period where each curve includes a greater number of specific details. Here the likelihood of obtaining a good fit is low unless there exists a causal relationship. The inserted frame indicates the range of Fig. 3a, i.e. the original figure in Friis-Christensen and Lassen (1991). A scaling that would optimize the agreement of the 'S-shapes' of the two curves *within* the frame (as applied in Fig. 3a) would lead to a poor fit *outside* the frame. For example: The mismatch between the solar 'top' and the temperature 'valley' around year 1600 would thereby be increased substantially. If on the other hand the linear regression were based on a time interval around year 1600 the scaling factor would assume opposite sign and thereby convert the 'top' of the solar curve around year 1600 into a 'valley' agreeing well with the temperature valley. This would, however, produce a pronounced mismatch between the two curves *within* the displayed frame.

It should be mentioned that since Fig. 5 only serves to *qualitatively* illustrate a general problem connected with the method of linear regression, it is not important that the temperature curve employed is a composite of two series which have been zero point adjusted by simply adding a constant temperature difference instead of applying the elaborate procedure required to merge the two series into a single internally consistent temperature series fit for use in *quantitative* analyses.

2.4. Solar cycle lengths and Northern Hemisphere land temperatures (1995)

In 1995 Lassen and Friis-Christensen published an updated and extended version of their 1991 Science article. The central figure (Fig. 2 in their article) is here shown as Fig. 6a (a remake). Colors are added in order to distinguish the two different temperature series utilized. In the original figure the two curves can easily convey the impression of being one single curve extending over the whole time interval. But actually the temperature development is represented by two separate series: One series extending over the period 1585–1866, the other extending over the period 1862–1982, with an overlap from 1862 to 1966. A close inspection of the curves (here Fig. 7 with its larger scale is preferable to Fig. 6a) reveals that the two temperature curves, during the period of overlap, are separated by a vertical parallel displacement of about 0.1°C. This occurs because the two series have been plotted directly as raw anomalies, i.e. without taking into account that they are defined relative to two different reference periods. This was discussed in detail by Laut and Gundermann (1998). The older temperatures in Fig. 6a are from Groveman and Landsberg (1979a, b, c) who published a reconstruction for the period 1579–1880. As reference period Groveman and Landsberg chose the interval 1881–1975, utilizing a temperature series established by Borzenkova et al. (1976). Combining their own reconstruction with Borzenkova's data Groveman

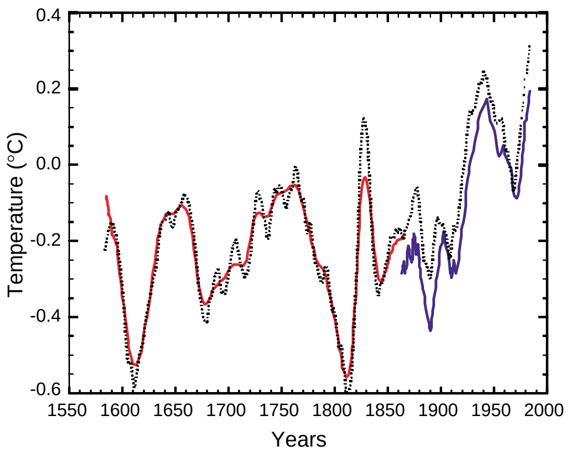

Fig. 7. 11-year running average of the Groveman/Landsberg/Borzenkova temperature series 1579–1975 (dotted line) presented in Groveman and Landsberg (1979a). Simplified version 1585–1866 of the 11-year running average of the Groveman/Landsberg/Borzenkova temperature series (red solid line) as employed by Lassen and Friis-Christensen (1995). The precise definition of curve is unclear since it does not correspond to the authors' description. 11-year running average of temperature series 1862–1982 (blue solid line) from Jones et al. (1986), Jones (1988) and Jones et al. (1998). The Jones curve describes a temperature variation, which is very similar to the corresponding part of the Groveman/Landsberg/Borzenkova curve apart from a downward displacement by 0.1°C because the Jones series employs a different temperature scale. In order to make comparisons easier the Groveman/Landsberg/Borzenkova curve has been extended so that it ends in the same year as the Jones curve. This has been achieved by adding zero-point adjusted Jones data for 1975–1982.

and Landsberg arrived at a series of anomalies spanning from 1579–1975 which is shown as Fig. 1 in Groveman and Landsberg (1979a). Fig. 7 below shows the 11-year running average of this Groveman/Landsberg/Borzenkova temperature series. This series could have been used directly by Lassen and Friis-Christensen in their comparison of SCL data with Northern Hemisphere temperatures since it covers all SCLs employed.

However, instead of using these internally consistent data, Lassen and Friis-Christensen (1995) employed the two separate temperature series with different periods of reference and hence different temperature scales:

(1) The series from 1585 to 1866 on their graph is some *simplified* version of an 11-year running average of the Groveman/Landsberg reconstruction. It is not a proper 11-year running average, as the authors incorrectly state in their article. As can be seen in Fig. 7 it deviates from the proper 11-year running average in that part of the oscillations have been removed. The precise character of this truncation is unclear.
(2) The more recent temperatures in Fig. 6a (which are also displayed as the right-hand curve in Fig. 7) are from Jones et al. (1986), Jones (1988) and Jones et al. (1998) which have the interval 1951–1970 as reference period. This curve is quite similar to the Groveman/Landsberg/Borzenkova series, apart from a vertical displacement downwards of about 0.1°C. The displacement is due to the fact that the reference period of the Jones series (1951–1970) has a mean temperature, which lies about 0.1°C higher than the reference period of the Groveman/Landsberg/Borzenkova series (1881–1975). The numerical values of the Jones series therefore are about 0.1°C smaller than the Borzenkova data. This downward displacement of the Jones-curve causes roughly one third of the global warming over the time period covered by the graph to disappear, and improves the agreement with the solar curve correspondingly. So the procedure conveys the false impression of a good agreement of solar activity and terrestrial temperatures by underestimating the ongoing global warming.

Another contribution to the apparent agreement in Fig. 6a of the solar curve with the recent global warming is obtained by 'lifting' the entire solar curve so as to match the (lowered) modern temperatures on the right-hand side of the graph. This improved fit on the right-hand side, however, has been obtained at the expense of the fit on the left-hand side of the graph. Here most solar points are seen to 'hover' high above the temperature curve. In other words, the curve fitting has not been obtained by an 'impartial' linear regression, but by performing a selective manual adjustment favoring the time period where a man-made contribution to the recent global warming may have played a major role.

Fig. 6b is a revised version of Fig. 6a where some changes in the data treatment have been introduced: (1) Instead of using two temperature series expressed in different temperature scales, the internally consistent Groveman/Landsberg/Borzenkova series has been applied. (2) The curve fitting has been obtained by straightforward linear regression, i.e. without manual adjustment of the right-hand side of the solar curve to the right-hand temperature curve. (3) In order to diminish the risk of 'contaminating' a possible solar/terrestrial correlation by a possible influence from man-made greenhouse gases, only data prior to 1850 have been applied in the linear regression. In case a linear regression based on data prior to 1850 would yield a good agreement of the solar and terrestrial curves, and in case it turned out that this agreement extended beyond 1850 (applying the conversion constants determined by the linear regression of the pre-1850 data), then such an agreement could be seen as an indication that the observed global warming actually might be caused by some solar rather than a human influence. However, as Fig. 6b shows, the temperature curve does not follow the solar curve, but rises clearly above it.

The quality of the Groveman/Landsberg reconstruction as compared to more recent reconstructions shall not be discussed here, since the main focus of the present

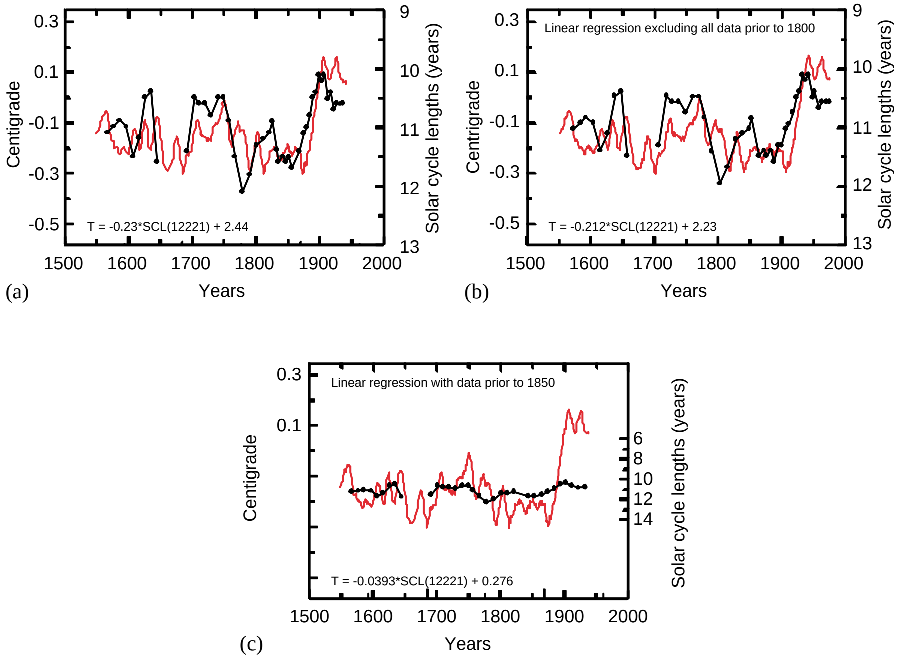

Fig. 8. (a) Solar cycle lengths (black line with solid circles) fitted to Northern Hemisphere land temperatures as presented by Lassen and Friis-Christensen (2000) (red solid line). Here the solar data density after year 1850 (i.e. over the time period where both curves exhibit the above mentioned 'S-shape') has been doubled by adding maximum–maximum cycle lengths to the minimum–minimum cycle lengths previously employed. Thereby a good agreement has been achieved over just the period where man-made greenhouse gases may have caused a global warming trend which is superimposed over the natural temperature fluctuations, whereas the earlier data which are not affected by human influences only show a poor agreement. Hence, the displayed partial agreement may primarily be the consequence of: (1) a certain, spurious similarity in shape of the solar curve and the development of human industrial activity over time and (2) the employment of a (linear regression) scaling factor which does not take into account data outside this specific period. This interpretation is supported by the fact that the agreement of the solar curve and temperature curve is poor before 1870. The problematic utilization of this 'S-shape similarity' is also illustrated in Fig. 5 above where the *flat* S-shape of the solar curve can be scaled up so as to agree with the *steep* S-shape of the temperature curve *inside* the inserted frame. But this special choice of scaling parameter would lead to an unacceptable mismatch of the two curves *outside* the inserted frame. (b) The result of a test calculation, one of a series of test calculations performed in order to determine the numerical weight factors which Lassen and Friis-Christensen (2000) have applied to the older solar data. The numerical values of these factors are not given by the authors. Fig. 8b is obtained by tentatively putting to zero all weight factors of solar data prior to year 1800. It is seen to be practically identical with Fig. 8a. Normally data with a weight factor zero would be omitted, since data, which are deemed too unreliable to be taken into account in a linear regression will not be presented together with valid data, or at least not without warning the reader. The applied reasoning may be described as follows: First the solar and temperature curve are forced to agree over the period 1870 –1960 (where the temperature curve may be strongly influenced by man-made global warming). This is done at the expense of the earlier data. And then the result is presented in a way, which suggests that the temperature rise is caused by solar and not by human activity. (c) Here the same data as in Fig. 8a and b are fitted employing linear regression, leaving out, however, the artificial doubling of the mathematical weight obtained by adding maximum–maximum cycle lengths, but retaining the early solar data and assigning equal weights to all data. However, in order to reduce 'contamination' from possible anthropogenic influences, only data prior to year 1850 have been used in the linear regression.

analysis is on the handling of the physical data in Lassen and Friis-Christensen (1995) and the message conveyed by Fig. 6a.

2.5. Solar cycle lengths and Northern Hemisphere land temperature (2000)

In connection with an article by Laut and Gundermann (2000a) criticizing Friis-Christensen and Lassen (1991) these authors published a 'Reply' article (Lassen and Friis-Christensen, 2000). In this work they present an updated version of their 1995 results (shown as Fig. 6a above). The updated version (Fig. 2 in their new article) is shown below as Fig. 8a (a remake). A control calculation of this figure cannot be performed without some difficulty since the authors do not explain precisely how the curve fit has been obtained. They mention that they have introduced some weight factors taking account of the fact that the older data are somewhat uncertain. They do not, however, give any indication of which numerical values they have chosen for these weight factors. A detailed analysis by Laut and Gundermann (2000b) revealed that in order to obtain their figure the authors must have put all weight factors for data prior to year 1800 to zero or to values very close to zero. Fig. 8b has been obtained by thus putting these weight factors to zero. It is apparent that Fig. 8b is practically identical with Fig. 8a. The choice of zero as weight factor for all solar data covering the first 230 years of the solar record deserves a comment: One may argue that physical data which deserve a weight factor zero should not be displayed on a graph of the present character. They must be too unreliable to be taken into account. In any case one may reason, that the authors should have cautioned the reader about the fact that the first 230 years of the solar record had not been taken into account.

Another interesting change in the authors' up-dated Fig. 8a as compared to their original Fig. 6a is the fact that the number of data covering the period 1850–1980 has been doubled by adding 1,2,2,2,1-filtered maximum–maximum cycle lengths to the minimum–minimum cycle lengths which originally were employed (maximum–maximum cycle lengths are often omitted since they are regarded to be less accurate). Thereby the mathematical weight with which this particular time period enters the linear regression has been doubled. This leads to a scaling which forces the two 'S-shapes' of the solar and temperature curve respectively (mentioned above, in connection with Fig. 5) to agree well over this period, at the expense of the agreement of the other data points. But, since the temperature development over this period may have been influenced significantly by man-made greenhouse gases, any resulting correlation could be the consequence of a spurious covariance of solar activity with human activity rather then being an indication of some solar influence upon terrestrial climate.

Fig. 8c is based upon practically the same data as Fig. 8a, but with some changes in the data handling: (1) The first 230 years of the SCL record have *not* been disregarded. (2) The number of data points between 1850 and 1980 has *not* been doubled. (3) The linear regression has been restricted to data from times where a 'contamination' from man-made greenhouse gases is likely to have been negligible, i.e., data prior to 1850. (4) All data employed have been assigned equal weight factors.

3. Conclusion

Several of the figures which are discussed above have attracted worldwide attention, both in scientific and in public discussions on climate change. Even though they have been obtained by some practices for data handling which do not live up to general scientific standards, there is very little recognition of the fact that they are misleading. Therefore I have found it worthwhile to deliver the present critical analysis.

As to the many publicized studies indicating potential mechanisms for solar-climate interactions through modulation of the atmospheric circulation (Bond et al., 2001; Haigh, 1996, 2001; Shindell et al., 1999, 2001) some of them may indeed have identified important physical mechanisms. However, further work is necessary to confirm their role.

Acknowledgements

I wish to thank Jón Egill Kristjánsson for access to preliminary results of his analyses of cloud and cosmic ray data.

Appendix

Originally, in Friis-Christensen and Lassen (1991), the last four points of the solar curve (on Fig. 3a marked with numbers 1–4) were plotted corresponding to the SCL values: 10.5, 10.3, 10.3 and 9.7 years. Since the ordinate axis has been chosen with downward orientation the *decreasing* values produce a *steep rise* in the solar curve, which corresponds well with the recent global warming. However, points 1–4 do not represent the same type of data as the first 20 points of the curve. The first 20 points are 1,2,2,2,1-filtered, i.e. strongly smoothed data, while points 1 and 2 are only partially filtered and points 3 and 4 are not filtered at all. Therefore, points 1–4 should never have been included into the solar curve. The reason is the following: non-filtered SCL data (i.e. raw data) oscillate violently around the smoothed curve. As shown by Laut and Gundermann (2000a) it is by this mixing of incongruous data alone that the apparent agreement in Fig. 3a of the solar data with the recent global warming is obtained. The actual physical observations do not support this agreement. This applies to the data available today as well as to the data, which were available in 1991 when the figure first was published. In their own recent update (Lassen and Friis-Christensen, 2000) the authors state that "*With the information available today the four values should have been* 10.6, 10.6, 10.5 *and* 10.1" and "*Substitution of the original data by the correct ones, however, does not change the impression of a steep rise in the SCL-curve between* 1970 *and* 1984". Thejll and Lassen (2000) present the same four values (see column 13 in the table above) as a result of their update based on observed as well as two predicted epochs (see column 1 and 2, where the predicted epochs are in italics). The calculation of the weighted 1,2,2,2,1 averages yields the filtered values 10.61 and 10.59 years (see column 12), and not 10.5 and 10.1 (column 13) years respectively as claimed by the authors. The calculation is: $1/8 \times 10.6 + 2/8 \times 11.6 + 2/8 \times 10.3 + 2/8 \times 10.0 + 1/8 \times 10.5 = 10.61$ and $1/8 \times 11.0 + 2/8 \times 11.0 + 2/8 \times 9.7 + 2/8 \times 10.7 + 1/8 \times 10.9 = 10.59$, where the employed SCLs are listed in column 4, successively as

National Geoph. Data Center					Thejll & Lassen 2000				Deviations		1,2,2,2,1 Solar Cycle Lengths		
Year of epoch		Central yrs	SCL	min-min	Central years		SCL [yrs]		Central yrs	SCL	Calculated	Shown	
minimum	MAXIMUM			or MAX-MAX	Shown on	Given on	Shown on	Given on				on Figure 2	Errors
year	year	year	yrs		Figure 2	Table 1	Figure 2	Table 1	yrs	yrs	yrs	yrs	yrs
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1944.2													
	1947.5	1949.25	10.1	m-m	*1949.12*		*10.00*		0.1	0.1	10.50	*10.5*	-
1954.3		1952.70	10.4	**M-M**	*1953.03*		*10.40*		-0.3	-	10.38	*10.4*	-
	1957.9	1959.60	10.6	m-m	*1959.54*		*10.51*		0.1	0.1	10.66	*10.7*	-
1964.9		1963.40	11.0	**M-M**	*1963.58*		***11.81***		-0.2	**-0.81**	10.58	*10.6*	-
	1968.9	1970.70	11.6	m-m	*1970.55*		*11.81*	*11.6*	0.1	-0.2	**10.64**	***10.6***	-
1976.5		1974.40	11.0	**M-M**	*1974.52*		*11.00*	*11.0*	-0.1	-	**10.56**	***10.6***	-
	1979.9	1981.65	10.3	m-m	*1981.86*	*1981.65*	*10.30*	*10.3*	-0.2	-	**10.61**	***10.5***	0.1
1986.8		1984.75	9.7	**M-M**	*1984.90*	*1984.75*	*9.71*	*9.7*	-0.1	-	**10.59**	***10.1***	0.5
	1989.6	1991.80	10.0	m-m	*1991.92*	*1991.80*	*10.01*	*10.0*	-0.1	-			
1996.8		1994.95	10.7	**M-M**	*1995.15*	*1994.95*	*10.70*	*(10.7)*	-0.2	-			
	2000.3	*2002.05*	*10.5*	m-m	*2002.09*	*(2002 ± 1)*	*10.51*	*(10.5)*	-	-			
2007.3		*2005.75*	*10.9*	**M-M**	*2006.24*	*(2006 ± 2)*	*10.91*	*(10.9)*	-0.5	-			
	2011.2												

Fig. 9. Two arithmetic errors in Lassen and Friis-Christensen (2000) and Thejll and Lassen (2000) in the update of points 1–4 in Fig. 3a.

maximum-to-maximum and minimum-to-minimum lengths. Fig. 3d shows the 1,2,2,2,1 filtered solar curve, including points 1–4, obtained by applying correct arithmetic. Here the '*steep rise*' presented in both articles is absent, and so it follows that the '*steep rise*' simply is created by the introduction of two erroneous values for points 3 and 4. These two errors are the only significant arithmetic errors in the articles. All other filtered values are calculated correctly.

In the table form of Fig. 9, the major errors are highlighted (see column 13). For the sake of comparison, the minimum epoch, 1996.8, used by the authors has been retained even though the observed value is 1996.4 (see column 1). For central year 1963.4 Thejll and Lassen (2000) have plotted a SCL of 11.81 years (see column 8) instead of the observed value of 11.0 years (see column 4), but in their calculations they have used the correct value.

The values from the electronic digitization of the graphs (in columns 6, 8 and 13) are given without rounding off in order to avoid introducing a new source of uncertainty.

Columns 7 and 9 only contain the more recent values of central years and SCL, respectively. This is because only these are included in Table 1 in Thejll and Lassen (2000). This limitation means that their table does not contain all SCLs needed to control the values displayed on their Figs. 1 and 2 and, e.g., needed to determine the two arithmetic errors. All other 1,2,1- and 1,2,2,2,1-filtered values on their figures are derived correctly from the NGDC-data, which shows that the two errors do not arise from the application of a different data set.

References

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., Bonani, G., 2001. Persistent solar influence on North Atlantic climate during the Holocene. Science 294, 2130–3136.

Borzenkova, I.I., Vinnikov, K.Ya., Spirina, L.P., Stekhnovskii, D.I., 1976. Variation of Northern Hemisphere air temperature from 1881 to 1975. Meteorologiya i Gidrologiya 7, 27–35.

Carslaw, K.S., Harrison, R.G., Kirkby, J., 2002. Cosmic rays, clouds, and climate. Science 298, 1732–1737.

Friis-Christensen, E., Lassen, K., 1991. Length of the solar cycle: an indicator of solar activity closely associated with climate. Science 254, 698–700.

Groveman, B.S., Landsberg, H.E., 1979a. Simulated northern hemisphere temperature departures 1579–1880. Geophysical Research Letters 6 (10), 767–769.

Groveman, B.S., Landsberg, H.E., 1979b. Reconstruction of northern hemisphere temperature: 1579–1880. Publication No. 79-181, University of Maryland.

Groveman, B.S., Landsberg, H.E., 1979c. Data Appendices to Publication No. 79-181, Publication No. 79-182, University of Maryland.

Haigh, J.D., 1996. The impact of solar variability on climate. Science 272, 981–984.

Haigh, J.D., 2001. Climate variability and the influence of the Sun. Science 294, 2109–2111.

Jones, P.D., 1988. Hemispheric surface air temperature variations: recent trends and an update to 1987. Journal of Climate 1, 654–660.

Jones, P.D., Raper, S.C.B., Bradley, R.S., Diaz, H.F., Kelly, P.M., Wigley, T.M.L., 1986. Northern hemisphere surface air temperature variations: 1851–1984. Journal of Climate and Applied Meteorology 25, 161–179.

Jones, P.D., Briffa, K.R., Tett, S.F.B., 1998. High-resolution palaeoclimatic records for the last millennium: interpretation, integration and comparison with General Circulation Model control-run temperatures. The Holocene 8 (4), 455–471.

Kernthaler, S., Toumi, R., Haigh, J., 1999. Some doubts concerning a link between cosmic ray fluxes and global cloudiness. Geophysical Research Letters 26, 863–865.

Kristjánsson, J.E., 2002. Department of Geophysics, Private communication, University of Oslo, Norway.

Kristjánsson, J.E., Kristiansen, J., 2000. Is there a cosmic ray signal in recent variations in global cloudiness and cloud radiative forcing? Journal of Geophysical Research 105 (D9), 11851–11863.

Kristjánsson, J.E., Staple, A., Kristiansen, J., 2002. A new look at possible connections between solar activity, clouds and climate. Geophysical Research Letters 29 (23), 2107–2110.

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 (8), 835–845.

Lassen, K., Friis-Christensen, E., 2000. Reply to the article "Solar cycle lengths and climate: a reference revisited" by P. Laut and J. Gundermann. Journal of Geophysical Research—Space 105 (A12), 27493–27495.

Laut, P., Gundermann, J., 1998. Solar cycle length hypothesis appears to support the IPCC on global warming. Journal of Atmospheric and Solar-Terrestrial Physics 60, 1719–1728.

Laut, P., Gundermann, J., 2000a. Solar cycle lengths and climate: a reference revisited. Journal of Geophysical Research 105 (A12), 27489–27492.

Laut, P., Gundermann, J., 2000b. Is there a correlation between solar cycle lengths and terrestrial temperatures? Old claims and new results. The First Solar and Space Weather Euroconference: The Solar Cycle and Terrestrial Climate, European Space Agency, pp. 189–191.

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

Marsh, N.D., Svensmark, H., 2000. Low cloud properties influenced by cosmic rays. Physical Review Letters 85 (23), 5004–5007.

Marsh, N.D., Svensmark, H., 2002. GCR and ENSO trends in ISCCP-D2 low cloud properties. Journal of Geophysical Research, in press.

Shindell, D.T., Rind, D., Balachandran, N., Lean, J., Lonergan, P., 1999. Solar cycle variability, ozone, and climate. Science 284, 305–308.

Shindell, D.T., Schmidt, G.A., Mann, M.E., Rind, D., Waple, A., 2001. Solar forcing of regional climate change during the maunder minimum. Science 294, 2149–2152.

Svensmark, H., 1998. Influence of cosmic rays on Earth's climate. Physical Review Letters 22, 5027–5030.

Svensmark, H., Friis-Christensen, E., 1997. Variation of cosmic ray flux and global cloud coverage—a missing link in solar-climate relationships. Journal of Atmospheric and Solar-Terrestrial Physics 59 (11), 1225–1232.

Thejll, P., Lassen, K., 2000. Solar forcing of the Northern hemisphere land air temperature: new data. Journal of Atmospheric and Solar-Terrestrial Physics 62, 1207–1213.

Udelhofen, P.M., Cess, R.D., 2001. Cloud cover variations over the United States: an influence of cosmic rays or solar variability?. Geophysical Research Letters 28 (13), 2617–2620.

Wagner, G., Livingstone, D.M., Masarik, J., Muschler, R., Beer, J., 2001. Some results relevant to the discussion of a possible link between cosmic rays and earth's climate. Journal of Geophysical Research 106, 3381–3387.

Yu, F., Turco, R.P., 2000. Ultrafine aerosol formation via ion-mediated nucleation. Geophysical Research Letters 27 (6), 883–886.