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Climate
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On misleading solar-climate relationship

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Abstract

A key issue of climate change is to identify the forcings and their relative contributions. Solar-climate relationship is currently the matter of a fierce debate. We address here the need for high quality observations and adequate statistical approach. A recent work by Le Mouël et al. (2010) and its companion paper by Kossobokov et al. (2010) show spectacular correlations between solar activity and meteorological parameters. We question both the data and the method used in these works. We stress 1) that correlation with solar forcing alone is meaningless unless other forcings are properly accounted and that sunspot counting is a poor indicator of solar irradiance, 2) that long series of temperature require homogenization to remove historical artefacts that affect long term variability, 3) that incorrect application of statistical tests leads to interpret as significant a signal which arises from pure random fluctuations. As a consequence, we reject the results and the conclusions of Le Mouël et al. (2010) and Kossobokov et al. (2010). We believe that our contribution bears some general interest in removing confusion from the scientific debate.

1 Introduction

Exploring relations between the solar decadal variations and climate has been a matter of interest over several decades (e.g. Siscoe, 1978; Gray et al., 2005; Cahalan et al., 2010). One of the main motivation of such studies is to assess the role of solar variations in the observed climate variations, compared to internal variability and changes induced by anthropogenic effects. The simplest view is to consider that, either in trend or decadal variations, the variations of total solar irradiance have an order of magnitude of 0.1%, at least five times smaller than the present increase of radiative forcing due to greenhouse gases (Solomon et al., 2007). The modulation is larger in the UV range of the radiative spectrum by about a factor three. The stratosphere is affected with consequences onto the troposphere (Gray et al., 2005). There is no trend, however, in the UV part of the solar spectrum over the last decades (Fröhlich, 2009).

An other approach is to hypothesize that the impact of solar variations should leave a signature in data and to analyse empirically the link between solar forcing and climate records (White, 2006; Camp and Tung, 2007; Lean and Rind, 2008)

Correlations are a basis of knowledge in areas, like medicine, sociology and finance, where the theory is qualitative and does not provide mathematical tools for prediction. In such fields, the application of rigorous procedures is mandatory to establish that correlations are not spurious. This depends on the ability to formulate and test null hypothesis versus alternative. Unfortunately such recipe is not always applied and a number of studies interpret as significant correlations which are in fact obtained by chance due to the lack of tests or the application of inappropriate statistical tests (e.g., White, 2000). Another important source of spurious results is data artefacts that have not been corrected. This case is encountered for long historical series collected using methods, instruments and protocols which varied with time and for which information about such changes is not necessarily available. Long solar series where various proxies are used to estimate the solar radiation are also prone to bias. Last, when multiple factors have to be taken into account, as in climate studies, it is important to assess the important of all of these factors together.

A recent series of three articles (Le Mouël et al., 2009, 2010; Kossobokov et al., 2010) published by the same group of authors has studied long series of ground temperatures collected by the European Climate Assessment and Dataset project (Klein Tank et al., 2002) (hereafter ECA&D) and found a number of correlations with several indexes of the solar activity.

We focus here on the last two papers of this series, which are based on very long temperature records, starting in the late 18th century. Part of our study, particularly regarding homogeneity, applies also to Le Mouël et al. (2009) which has already been commented by Yiou et al. (2010), concluding that displayed solar-climate correlations are not significant.

Le Mouël et al. (2010) (hereafter LMKC) and Kossobokov et al. (2010) (hereafter KLMC) use the number of sunspots to separate the years belonging to the interval 1775–2005 into two ensembles of High versus Low solar activity and produce daily composites of the temperature difference between these two ensembles for three European stations, Praha, Bologna and Uccle which have recorded temperatures over the last two centuries. They claim to find highly significant results that demonstrate the prominent role of solar variations in local climate.

Here we demonstrate that the approach of LMKC and KLMC is pervaded by a combined effect of data series artefact and inadequate error analysis which impairs their results. In Sect. 2, we discuss the multiple forcing of climate variability and the appropriateness of sunspot counting as solar proxy. In Sects. 3 and 4 we discuss issues related to inhomogeneities in temperature series and in particular in the public dataset used by LMKC and KLMC. In Sects. 5 and 6, we show that inadequate account of the number of degrees of freedom leads to a large underestimate of the confidence interval found in LMKC, and that the remaining significance is only due to coincidence of high solar activity with anthropogenic forcing over the last 50 years. The calculations related to these two sections are also provided as a Mathematica notebook along with source data in the Supplementary Material (http://www.clim-past-discuss.net/6/767/2010/cpd-6-767-2010-supplement.zip). Section 7 offers further discussion. Although this study is focused on the discussion of a single work, we believe that it is useful to enlighten a fairly large field of current research on solar-climate relations.

2 Solar variations and other climate forcings

Both papers (LMKC and KLMC) are based on the comparison of three time series of surface temperature with a record of sunspot numbers, taken as a proxy of solar variations. We point out that a proper attribution study should also take into account other sources of natural variability, such as major volcanic eruptions or internal oscillations of the climate system (e.g. the El Niño-Southern Oscillation (ENSO)), and of the anthropogenic forcing over the last century (greenhouse gases (GHG), aerosols). It has been demonstrated that a correlation analysis that takes only one cause into account can lead to a spurious attribution (e.g., Scafetta and West, 2006a,b, 2007 criticized by Benestad and Schmidt, 2009).

As an obvious example, it is useful to consider the global temperature record since 1950. Interannual changes on the order of 0.1–0.2 °C are superimposed on the long-term trend of 0.2°C/decade usually attributed to anthropogenic forcing (Meehl et al., 2004; Easterling and Wehner, 2009). These fluctuations in the global temperature record are partly linked to the 11-yr sunspot cycle, whose irradiance influence has been evaluated to ≈0.1 °C (Hansen et al., 2005). However, a statistical attribution should also take into account the last three major eruptions Agung (1963), El Chichon (1982) and Pinatubo (1991): their influences lasted a couple of years after the events, falling roughly during the descending phases of solar cycles #19, 21 and 22, respectively. Similarly, the ENSO variability is directly responsible for some apparent correlations with the 11-yr sunspot cycle over the century, the most recent La Niña phase being a relevant example as it occurred during the descending phase of solar cycle #23.

Multiple causes should also be considered when studying other individual forcings. Indeed, several authors showed that a correct evaluation of the climatic impact of the 1991 Pinatubo eruption should account for the global temperature modulation by ENSO (Soden et al., 2002; Robock, 2003; Hansen et al., 2005).

Besides the global temperature record, it is also possible to further constrain the attribution by considering the spatial patterns, which are very distinct for volcanism, ENSO, GHG and solar forcing (e.g., Lean and Rind, 2008, who calculated spatial correlations to identify these signatures over the last century).

The studies of LMKC and KLMC focus on the past two centuries. Over this period, the sunspot record is characterized by a long-term modulation of the 11-yr sunspot cycle. This is expressed as two prolonged solar minima, broadly equivalent to the famous Maunder Minimum between 1645 and 1715 (Eddy, 1976). These minima occurred during the intervals 1795–1830 (Dalton Minimum) and 1880–1920 (Modern Minimum) as evidenced with various solar indicators: sunspots (Hoyt and Schatten, 1998), aurorae (Silverman, 1992), *aa* geomagnetic index (Lockwood and Stamper, 1999; Lockwood et al., 1999), cosmogenic nuclides (Delaygue and Bard, 2010). However, these two time periods also include some of the largest volcanic eruptions ever recorded in history. The first period comprises the cold decade linked to the Tambora (1815) and the 1809 stratospheric eruption (Cole-Dai et al., 2009), while the second phase includes a series of major eruptions starting with the Krakatoa in 1883 and ending with Mt Katmai in 1912 (Robock, 2000).

Climate modelling allows quantifying the collective impact of these forcings in order to explain the temperature history of the past few centuries (e.g., see the model-data compilation in IPCC AR4 Sect. 6.6.3.4 with Figs. 6.13 and 6.14 in Solomon et al. (2007), [http://www.ipcc.ch/publications_and_data/ar4/wg1/en/figure-6-14.html], or the more recent paper by Gao et al., 2008). The Northern Hemisphere temperature drops corresponding to the Dalton (0.2–0.3 °C) and Modern solar minima (0.1–0.2 °C) are partly linked to an enhanced volcanic forcing. This implies that the attempt by LMKC and KLMC at studying the Sun-climate relationship cannot be performed with a simple approach that omits the influence of volcanic eruptions.

A further oversimplified aspect of this approach is the use of the raw sunspot record to distinguish two types of periods referred to as High and Low phases. Indeed, recent studies on solar parameters indicate that the sunspot number is not linearly coupled to solar forcing (Wang et al., 2005). This is illustrated by the last two solar cycles #22 and 23 for which the sunspot maxima yield very different values, whereas the total solar irradiance (TSI) values are indistinguishable. By contrast, the last two sunspot minima are similar in spot numbers, but the TSI record shows a decreasing trend (Fröhlich, 2009). This complexity led several authors to reconstruct the TSI by using empirical models taking into account different types of solar features such as sunspots and faculae (from the seminal paper by Foukal and Lean, 1990, to the recent review by Lean, 2010, who wrote “terrestrial studies are no longer relegated to using geophysically meaningless sunspot numbers a proxy for solar irradiance”).

3 Reliability of climate series

To study the evolution of temperatures since 19th century, many long instrumental climate records are available and can provide useful information in climate research. These datasets are essential to describe the recent past climate, the detection and the attribution of climate change at a regional scale, and the validation of climate models.

The homogeneity of these long instrumental data series (up to 300 years in some cases) has been studied because of the interest in describing long-term variations in climate. A homogeneous climate time series is defined as one where variations are caused only by variations in weather and climate (Conrad and Pollack, 1950). But in most cases, these series are altered by changes in the measurement conditions, such as evolution of the instrumentation, relocation of the measurement site, modification of the surroundings, instrumental inaccuracies, poor installation, and changes in observational or calculation rules. In many cases, such changes are not recorded in the archives, which are often incomplete. These modifications, thereafter called inhomogeneities, manifest themselves as a shift in the mean that can be sudden (break point or change point), or gradual. Moreover spurious observations are frequent. As the artificial shifts often have the same magnitude as the climate signal, such as long-term variations, trends or cycles, a direct analysis of the raw data series might lead to wrong conclusions about climate evolution. It is important, therefore, to remove the inhomogeneities or at least to determine the error they may cause as clearly stated in Aguilar et al. (2003).

These problems are not anecdotal. During the construction of the HISTALP precipitation dataset (Auer et al., 2005), one break could be detected on average every 23rd year in a series of 136 years. A total of 192 precipitation series were processed, and none of them could be considered free of inhomogeneities. For other elements, e.g. sunshine duration, the average homogeneous subinterval is even shorter (Auer et al., 2007). Della-Marta et al. (2004) showed that each of the 99 annual temperature records in Australia high quality dataset required 5 to 6 adjustments throughout the

100 year record. Analysing long French temperature series, Caussinus and Mestre (2004) found no reliable series within a set of 70 maximum and minimum temperature series covering the 20th century, each series being affected on average by 4 to 5 significant changes. As a result, non corrected series were strongly contaminated by inhomogeneities, and exhibited trends ranging from −3 to +3 °C per century. Thus the detection and correction of these inhomogeneities are absolutely necessary before any reliable climate study can be based on the instrumental series.

4 ECA&D dataset

The ECA&D dataset and metadata are freely available through ECA&D web interface [http://eca.knmi.nl]. The temperatures used by LMKC are three daily series of maximum (TX) and minimum (TN) temperatures collected in Praha since 1775, Bologna since 1814 and Uccle since 1833. Owing to policy changes, the Uccle data were not available during the writing of this paper. Since the density of available series is poor, ECA&D team has chosen to test the quality of the series through “absolute” testing described by Wijngaard et al. (2003), without using the *relative homogeneity principle* described below. Although, this procedure leads to poorer detection capabilities, more than 94% of the stations are flagged as “doubtful” or “suspect” over the period 1900–1999 (Wijngaard et al., 2003). This is not surprising, given the generally observed frequency of inhomogeneities in climate series.

As an example, a simple plot of the difference between two nearby temperature series in the Netherlands, from Maastricht and DeBilt, distant of 145 km, (see Fig. 1) shows a jump of about −1 °C between 1945 and 1950. Checking metadata available on ECA&D site ([http://ecad.knmi.nl/utils/stationdetail.php?stationid=168], [http://ecad.knmi.nl/utils/stationdetail.php?stationid=162]) reveals that the location of Maastricht shelter moved on 30 November 1945, from 20.10 m to 2.20 m above ground, and that DeBilt station was relocated twice on 16 September 1950 and 27 August 1951 and that the shelter was changed on 16 May 1950. Other discontinuities are documented and can be identified in these series. Both have been considered as homogeneous and used by Le Mouël et al. (2009) and they contribute to their Netherlands sub-ensemble.

Praha, Uccle and Bologna are among the "suspect" stations (see Table 1) extracted from ECA&D website and this contradicts LMKC who mention those series as having the *highest quality code in ECA&D*, for both TN and TX temperatures. Notice that the test is based on "blended" series where gaps are filled with synoptic observations or data interpolated from nearby stations but this is not affecting Praha, Bologna and Uccle which exhibit complete series over the 20th century. The lack of homogeneity over the 20th century is, of course, a serious warning about the quality of data over the 18th and 19th centuries.

Bologna temperature series exhibits a clear artefact, larger than 2 degrees between 1865 and 1880, as shown in Fig. 2. This strange feature is acknowledged in LMKC:

> On the other hand, the two TN and TX curves at the other two stations differ significantly, for instance from 1865 to 1880 in Bologna, when a large positive anomaly of 2.1 °C lasting 15 years is seen in TX and not in TN; we have no evidence of human-induced changes that would lead us to consider this feature as an artefact.

After checking Bologna metadata, we found that in 1867 the "Grindel" thermometer, in Réaumur scale, read four times a day at 9 a.m., 12 p.m., 3 p.m. and 9 p.m., was changed to a "Milano" min-max thermometer in Celsius scale. In 1881, the thermometers were relocated to a different place (Michele Brunetti, CNR-ISAC, personal communication, quoting Capra, 1939). The 1867 change is listed in the ECA&D metadata [http://ecad.knmi.nl/utils/stationdetail.php?stationid=169]. LMKC state that:

> It is a general observation that one must trust the way ancient observers did the maximum they thought possible to obtain the best data

Of course, observers did the best they could, but this does not ensure that data are reliable.

To check homogeneity of Bologna series, we use the *relative homogeneity principle* (Conrad and Pollack, 1950): since a climate signal is mostly undetermined and non-stationary, it has, as far as possible, to be removed to reveal outliers or changes in measurement conditions. Comparing Bologna series with neighbouring series by calculating annual differences, we put into evidence artificial changes, since comparisons series are much less affected by climate variations. It is often assumed that noise within those differences is normal, independent, and that most of the shifts are step-like changes which typically alter the average value only (Caussinus and Mestre, 2004). These differences are then tested for discontinuities, using a dynamic programming algorithm (Hawkins, 2001) and an adapted penalized likelihood criteria (Caussinus and Lyazrhi, 1997). If a detected change-point is preserved throughout the set of comparisons of a candidate station with its neighbours, it can be attributed to this candidate station and the corresponding series can be corrected, estimating break amplitude by standard least-squares techniques.

When Bologna maximum temperature series is compared to its ECA&D neighbours (see Fig. 3), artefacts clearly occur around 1919, 1996–1997, 2001 (around 1 °C in amplitude), and maybe more, but due to insufficient station density, the noise is high (standard deviation around 0.35 °C), resulting into poorer detection.

According to Michele Brunetti, quoting Osservatorio della Regia Università di Bologna (1915), the 1915 bulletin mentions a change in thermometers position (also mentioned by ECA&D). For the most recent part (from 1979 to about 2000) the data come from the former National Hydrographic Service. This service has been dismantled after 2000 and the network has been scattered among the different regional environmental agencies. Many station were relocated, explaining the break in 2001. The change-point around 1997 is not supported by metadata, but it is large enough to be considered as an artefact.

An homogenized version of Bologna monthly series of mean temperature is available. It is an update of that described in Brunetti et al. (2006). This series is used in Sect. 6.

Praha-Klementinum is an historical station located on the top of the Czech National Library in the center of Praha, for which there are no metadata available on the ECA&D site. There are also not enough nearby stations in the ECA&D datasets, hence the signal to noise ratio is low when applying relative homogeneity procedures and this cannot be taken as a test of quality – Praha temperature series are flagged ”suspect” anyway. No homogenized series is presently available for Praha up to our knowledge and establishing one is beyond the scope of this study. Uccle data could not be tested due to their removal from the ECA&D site.

As a conclusion, Le Mouël et al. (2008, 2009) and LMKC results are all based on raw inhomogeneous data, contrary to their claims. This is a bit striking, since information about data quality is easily available in ECA&D website.

5 Praha temperature

Here we use the raw Praha series of minimum and maximum temperature like LMKC, i.e. without concerns of homogenization and we focus on the statistical significance of the results of LMKC. The Praha series of TX and TN, shown in fig.4, was the longest available in the ECA&D dataset until recently.

Let us first briefly recall the method used by LMKC. LMKC classifies the 21 solar cycles between 1775 and 2005 in two ensembles, of High versus Low activity according to the number of spots relative to the median. The High activity ensemble (*H*) includes the following periods (1775–1798, 1834–1856, 1868–1878, 1945–2005) and the Low activity ensemble (*L*) includes the following periods (1799–1833, 1857–1867, 1879–1944).

It is important to notice that the last 50 years are entirely contained within the *H* ensemble. Over this period an indisputable forcing by the increase of GHG has become prominent. The fact that this forcing is of anthropogenic nature is not even important in the attribution study. The crucial point is that it must be taken into account in any attempt to extract the solar component

The first step in LMKC is to calculate a 21-day moving average of the temperatures over the whole dataset $\tilde{T}_{i,j}$ where i is the calendar day of the year and j is the year. Based on the clustering of N^H and N^L years, respectively, into the H and L ensembles, LMKC calculate the daily difference $\bar{T}_i^S$ between the average low-pass filtered temperatures over the H and L ensembles, that we denote as *solar shift* in the sequel:

$$\bar{T}_i^S = \frac{1}{N^H}\sum_{j\in H}\tilde{T}_{i,j} - \frac{1}{N^L}\sum_{j\in L}\tilde{T}_{i,j}. \tag{1}$$

The two panels of Fig. 5 show the solar shift for the TX and TN series of Praha. The two curves are identical, up to irrelevant details, to the two curves shown in Fig. 4a of LMKC. Since the 21-day average commutes with the composite operation of the solar shift, the average could be performed with identical result on the solar shift calculated for unfiltered daily data.

The unbiased estimate of the variance of 21-day averages over ensemble H is given by

$$(\bar{\sigma}_i^H)^2 = \frac{1}{N^H-1}\sum_{j\in H}(\tilde{T}_{i,j}-\bar{T}_i^H)^2, \tag{2}$$

where $\bar{T}_i^H$ is the average of $\tilde{T}_{i,j}$ over the H ensemble. Similar expression holds for the L ensemble. Since the successive years can be considered as independent realisations for 21-day averaged temperatures, we can consider that the unbiased estimate of the variance of the solar shift is a weighted sum of variances:

$$(\bar{\sigma}_i^S)^2 = \frac{(N^H-1)(\bar{\sigma}_i^H)^2+(N^L-1)(\bar{\sigma}_i^L)^2}{N^H+N^L-2}\left(\frac{1}{N^H}+\frac{1}{N^L}\right). \tag{3}$$

Under the null hypothesis that the true mean value of the solar shift is zero, the variable $t=\bar{T}_i^S/\bar{\sigma}_i^S$ obeys a Student law $A(t,\nu)$ with $\nu = N^H+N^L-2$ degrees of freedom (Weatherburn, 1961). The two-sided 90% confidence is delimited by the interval $[-a\bar{\sigma}_i^S, a\bar{\sigma}_i^S]$

where a is the quantile 0.95 of the Student law, that is $a = 1.65\cdots$. This interval is plotted in Fig. 5 for TX and TN. With the number of degrees of freedom used in this study, the Student law is hardly distinguished from the limit normal law.

The definition of the confidence interval shown by LMKC in their Fig. 4a was not explained. After trials and an exchange with the leading author of LMKC we deduced that the error estimate is based on a biased estimate of the variance of the daily fluctuations within all the days contributing to an average value $\bar{T}_i^H$, that is, for the ensemble H

$$(\sigma_i^H)^2 = \frac{1}{21 \times N^H} \sum_{j \in H} \sum_{l=i-10}^{i+10} \left(T_{l,j} - \bar{T}_i^H\right)^2,$$

where $T_{l,j}$ is the daily temperature at day l and year j. This expression can also be written as

$$(\sigma_i^H)^2 = \frac{1}{N^H} \sum_{j \in H} \frac{1}{21} \sum_{l=i-10}^{i+10} \left(T_{l,j} - \tilde{T}_{i,j}\right)^2 + \frac{N^H - 1}{N^H} (\bar{\sigma}_i^H)^2,$$

that is as the sum of the daily squared fluctuations within the 21-day intervals and, up to statistical bias, the squared fluctuation of the average. The statistical error is then calculated in LKMC as

$$\sigma_i^{\mathrm{LKMC}} = \left(\frac{(\sigma_i^H)^2}{21 \times N^H} + \frac{(\sigma_i^L)^2}{21 \times N^L} \right)^{1/2}.$$

The region enclosed by $\pm\sigma_i^{\mathrm{LKMC}}$ is shown in gray in Fig. 5 and is visually identical to the region bounded by thin lines in Fig. 4a of LMKC. It is obviously much smaller than our estimate of the confidence interval.

There are two main reasons for this discrepancy.

1. The first one is that LMKC assume that the daily temperature fluctuations are independent. Would it be the case, the mean variance of the 21-day averages

would be much smaller and the two estimates σ_i^{LKMC} and $\bar{\sigma}_i^S$ would coincide, up to statistical bias. In fact, we would have $\bar{\sigma}_i^H \approx \frac{1}{\sqrt{21}} \sigma_i^H$. This assumption, however, is incorrect as it is well known that daily temperatures are correlated over several days. In Le Mouël et al. (2009), the daily fluctuations are represented by an AR(1) process with a correlation of the order of 0.85 over two successive days. Our estimate of the integral scale of the auto-correlation of the TN or TX daily temperature in Praha, after removal of the mean annual cycle, is about 9 days as shown in the Supplementary Material (http://www.clim-past-discuss.net/6/767/2010/cpd-6-767-2010-supplement.zip). Hence the number of effective degrees of freedom is about 9 times smaller than estimated by LKMC and consequently the estimated variance of the ensemble average is about three times larger. See below for a more accurate estimate.

2. The ±σ interval shown in LMKC is a 68% confidence interval, which means that under a Gaussian condition, 32% of the data can be outside this interval without being meaningful. The standard width for a two-sided confidence interval is 90% which leaves two sides of 5% each and which is about 1.65 times larger.

Hence, considering these two factors together, LMKC underestimates the confidence interval by about a factor 5. This is what is seen on Fig. 5.

In order to check further the correctness of our result, we also calculate the confidence interval by bootstrapping (Davison and Hinkley, 2006), a totally independent method which is non-parametric. In a first step, we perform random permutations of full years within the 21-day filtered temperature series and, for each permutation, we calculate the difference of H and L averages, keeping these ensembles unchanged. After doing this over 10 000 drawings, the distribution of $\bar{T}_i^S$ is ordered for each day and the 5% and 95% quantiles of this distribution are shown on Fig. 5. It is visible that this estimate of the two-sided confidence interval falls almost exactly over our previous estimate of the confidence interval based on the estimated variance. In a second step, we perform an independent random permutation of the years for each day of the unfiltered temperature series within each ensemble H and L. In this way, we build a *decorrelated dataset* which has the same solar shift as the true temperature series but has lost daily temperature correlation. We then proceed to calculate 21-day filtered data and the variance of the solar shift using Eq. (3). This new variance, which is on the average 2.7 times smaller than the one obtained from the true series (for both TN and TX), is plotted as dashed lines in Fig. 5, missing the factor a like LMKC. It is visible that it fits perfectly the error interval claimed by LMKC. This fully corroborates the above discussion. It validates our hypothesis that the 21-day averages can be considered as independent variables over successive years and that the oversampling of daily fluctuations by LMKC leads to underestimate the solar shift variance by a factor 2.7. In other words, the estimate of the solar shift variance by LMKC would be valid on a hypothetical planet with temperatures following the decorrelated series that we have calculated but not on the Earth.

Comparing now the TN and TX solar shift with the confidence interval, we see that the high level of significance claimed by LMKC is not supported by the data. It appears that the TN curve almost entirely lays within the boundaries and hence that the null hypothesis of zero solar shift is not rejected for the minimum temperature. The TX curve, on the contrary, lays above the upper 95% boundary much more than 5% of the time, although it also lays mostly within the boundaries. Hence we can say that it rejects the null hypothesis and that the solar shift of maximum temperature is significantly positive, at least over some part of the year.

It is necessary to recall that the last period of the H ensemble, that accounts for about half of this ensemble, coincides with a period associated with anthropogenic forcing (Solomon et al., 2007). It is thus expected that the anthropogenic forcing contributes to the positive signal of the solar shift and cannot be separated. The pure effect of solar variation can only be estimated by removing this period to eliminate the alternative hypothesis that the solar shift is only due to the anthropogenic forcing. LMKC recognize this problem and define several truncated datasets in this purpose, but they fail again to draw a conclusion due to the underestimation of the confidence interval. Here we will consider only the P-IV dataset in LMKC terminology, in which the last 5 solar cycles, that is the period after 1954, are removed. The remaining dataset preserves 6 cycles of high solar activity in the *H* ensemble and the 10 cycles of low solar activity are left unchanged in the *L* ensemble. The upper row of Fig. 6 shows the solar shift for the TN and TX temperatures and the 90% two-sided confidence interval calculated by bootstrapping like in Fig. 5. It is visible that most of both curves lay within the confidence interval and that the proportion of points outside is hardly meaningful. The significance can be further estimated by calculating the p-value of the Student t-test for the solar shift. The lower panel of Fig. 6 shows this quantity for both TN and TX series. The solar shift does not differ significantly from the difference between two random samples in both cases.

In the Supplementary Material (http://www.clim-past-discuss.net/6/767/2010/cpd-6-767-2010-supplement.zip), we have performed similar calculations on daily data without filtering and replacing the 21-day filter by 11-day and 41-day filters. We have also applied an independent Kolmogorov-Smirnov test. All these calculations are consistent with the finding that the solar shift is not statistically different from zero.

6 Bologna temperature

The temperature series for Bologna are shown in Fig. 7. The large bump seen in Fig. 2 is only visible on the TX series. It is intriguing that, although the daily fluctuations (not shown) of TX and TN series are well correlated, the decadal variations are badly correlated over the record, unlike Praha (see Fig. 4). This is a fairly strong indication of inhomogeneities. The red curve in the middle of Fig. 7 is the average of TX and TN temperature and the black curve is the homogenized series of mean temperature after Brunetti et al. (2006).

The analyses for the Bologna series can be conducted in the same way as for Praha and are fully shown in the Supplementary Material (http://www.clim-past-discuss.net/6/767/2010/cpd-6-767-2010-supplement.zip). We summarize here the main results.

The confidence interval is again much larger than the error interval shown in Fig. 4b of LMKC. The difference between TN and TX solar shifts is more pronounced than for Praha. When the whole dataset is used, the solar shift for TX remains above the 90% confidence interval for most of the year while the curves for TN or the average temperature lay almost entirely within the confidence interval. When the reduced P-IV dataset is used, removing all years after 1954, the TX solar shift still offset the confidence interval, but only for half of the year, while the TN solar shift still does not. This correlation is, however, highly questionable because of the spurious features in the Bologna series. In particular the positive bump of about two degrees between 1867 and 1881 which occurs only in the TX series coincides with an isolated high solar cycle and contributes strongly to the solar shift. Removal of the cycle 11 reduces the portion of the TX solar shift that offsets the confidence interval to 11% and thus it is not meaningful.

Since an homogenized series of mean monthly temperatures is available for Bologna, we analyse this series here. The procedure remains essentially the same except that the daily 21-day moving averages are replaced by 12 monthly averages. The composite calculations of the solar shift are performed for each monthly mean in the same way as previously for the daily data.

The results exhibit very clear difference according to whether the anthropogenic forcing period is taken into account or not. Figure 8 shows that the solar shift is almost always above the confidence interval for the homogenized series when all the years are used and the p-value of the student t-test is under 0.05 for 7 months, thus demonstrating a very significant signal. However, Fig. 8 also shows that this features fully disappears when the five last solar cycles are discarded and the P-IV dataset is used. The solar shift is now entirely within the confidence interval and the p-value stays above 0.05 for the whole year.

7 Conclusions

We have shown that the error estimate in LMKC is strongly under-evaluated and that when it is corrected the significance in the solar shift is only due to the second half of the 20th century, coinciding with anthropogenic forcing, or spurious features of the raw data.

KMLC discuss other tests of the results of LMKC. They perform essentially bootstrapping using the Kolmogorov-Smirnov distance and find that the significance is high in most cases. This work deserves a more detailed analysis that will be provided elsewhere but it can be said safely that it does not contradict our results for two main reasons.

1. The tests are only applied to the whole dataset except in the supplement of KLMC where the P-IV dataset is considered. We have also found that anthropogenic forcing produces a significant solar shift difference for the whole dataset. When P-IV dataset is considered, KLMC is in qualitative agreement with our results, namely weak or no significance for Praha temperatures and significance for the Bologna non homogenized temperatures.
2. The high significance values found in KLMC, in particular for the P-IV datasets, are often based on a flawed usage of significance tests for bootstrapped data. The univariate tests meant to reject the null hypothesis is repeated several times, up to six, with several variables which are to some extent independent (table SM3). The success of one of the test is wrongly interpreted as a rejection of the null hypothesis. This error produces considerable overestimation of the significance. For instance, if the observed variables are all at the 40% confidence value, that is not significant, the combined null hypothesis is expected to be rejected with 99.5% confidence. Such values are indeeed found in table SM3 of KLMC but are obviously meaningless.

Our unequivocal conclusion is that the results in LMKC and KLMC which are not due to spurious features of the raw datasets are due to the coincidence of anthropogenic forcing during the second half of the 20th century with a sequence of high solar activity. This coincidence does not carry any causality in itself.

Many efforts have been devoted recently to attribute climate variations to the various forcings acting on the climate system, either from the empirical point of view (White, 2006; Lean and Rind, 2008; Lean, 2010) or from the modelling point of view (Shindell et al., 1999; Meehl et al., 2009; Cahalan et al., 2010). All concur to find that the response to solar decadal variations accounts for variations of the order of 0.10±0.05 °C of the mean surface temperature with complex, but so far badly characterized, regional signature. These variations have modulated the anthropogenically induced global warming, along with volcanic eruptions and internal modes like ENSO, and will certainly continue to do so in the future (Lean and Rind, 2009). There are many uncertainties on how the various part of the solar spectrum are modulated (Harder et al., 2009) and how to reconstruct the past history of the solar irradiance (Fröhlich, 2009; Lean, 2010). There is also a need to improve our modelling ability to reproduce solar induced processes, e.g. in the multiband approximation of the short wave spectrum and in the representation of stratospheric processes and stratosphere-troposphere coupling.

Other processes like the role of cosmic rays have been proposed to establish a strong link between solar variations and climate (Svensmark et al., 2009). Although, this suggestion should not be discarded at first, and is worth further study, the underlying physics is still highly speculative (Bondo et al., 2010) and the observed empirical evidence (Svensmark et al., 2009) is seriously challenged by other studies (Laken et al., 2009; Calogovic et al., 2010; Kulmala et al., 2010) who conclude the absence of relation between cosmic rays, aerosols and clouds. This is, anyway, not offering a way to compensate anthropogenic forcing since no trend has been observed for cosmic rays over the last decades (Bard and Delaygue, 2008)

Progresses in deciphering the relationship between solar variations and climate will arise from confronting the best available data with the best models of the climate systems that represent our state of understanding. Careful data mining and processing is required to enlighten this matter.

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Interactive Discussion

Table 1. Excerpt of table TEMP_19012007__homogeneity.txt from ECA&D on homogeneity checking results for 1901–2007 period.

Country	Staname	Staid	Class
Belgium	Uccle	17	Suspect
Czech Republic	Praha-Klementinum	27	Suspect
The Netherlands	De Bilt	162	Suspect
The Netherlands	Maastricht	168	Suspect
Italy	Bologna	169	Suspect

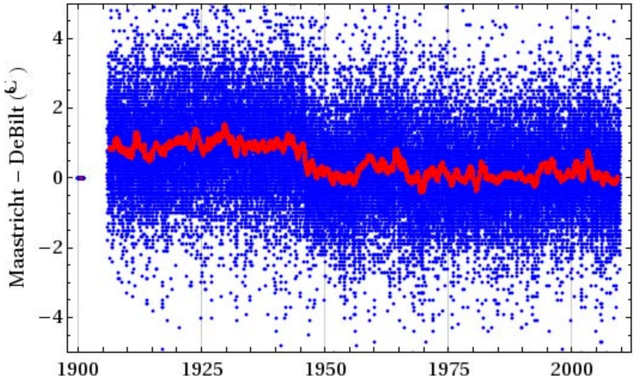


Fig. 1. Blue: Difference of mean daily temperature between the weather stations of Maastricht and DeBilt in the Netherlands. Red: Same data with a one-year moving average.

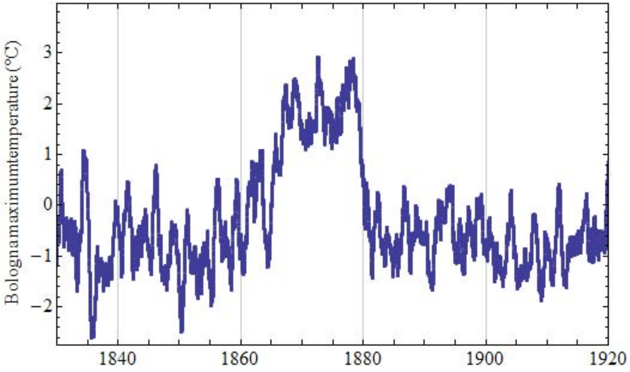
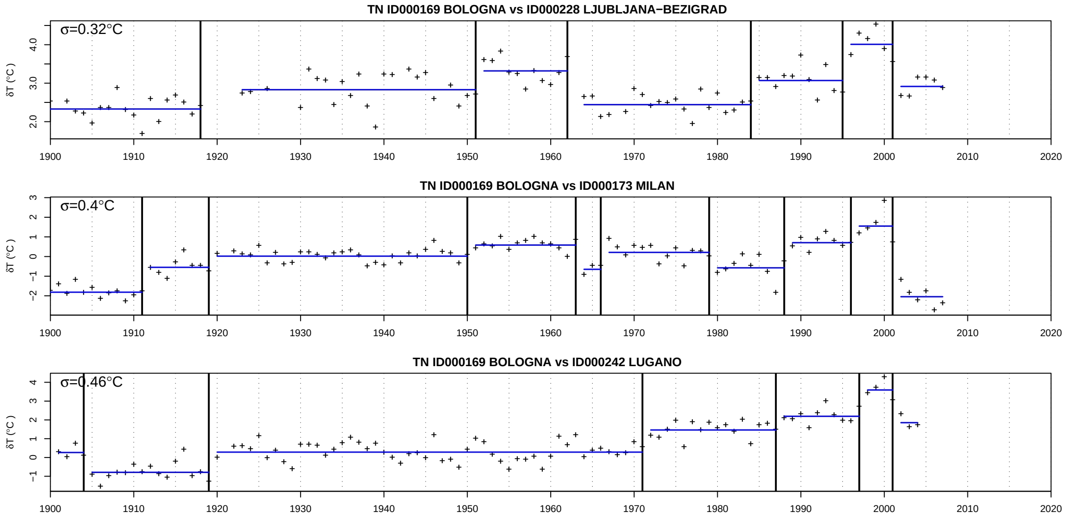


Fig. 2. One-year moving average of the maximum temperature in Bologna after removal of the mean annual cycle.


TN ID000169 BOLOGNA vs ID000228 LJUBLJANA−BEZIGRAD

TN ID000169 BOLOGNA vs ID000173 MILAN

TN ID000169 BOLOGNA vs ID000242 LUGANO

Fig. 3. Discontinuities detected on annual difference of Bologna versus neighbouring ECA&D minimum temperature series.

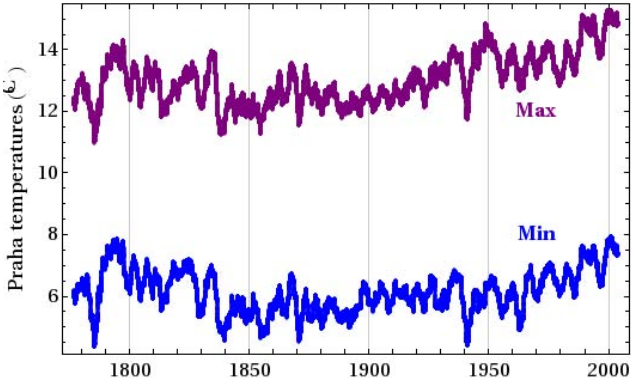


Fig. 4. Three-year moving average of maximum (purple) and minimum (blue) temperatures for Praha.

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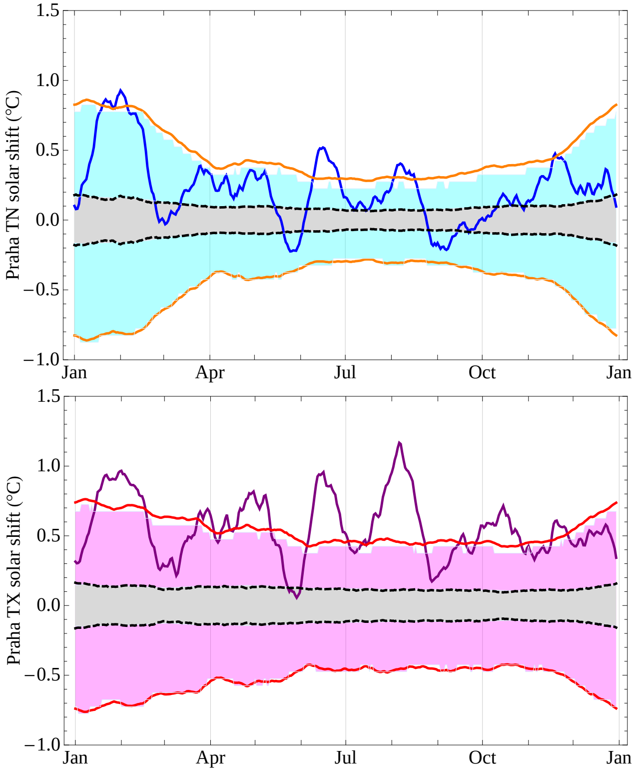

Fig. 5. Upper panel: Blue: Solar shift for the minimum (TN) temperature in Praha. Orange: bounds of the 90% confidence interval $\pm a\bar{\sigma}_i^S$. Dashed black: ± variance of the solar shift for the decorrelated dataset. Grey area: confidence interval according to LMKC. Cyan area: 90% confidence interval according to boostrapping. Lower panel: Purple: Solar shift for the maximum (TX) temperature in Praha. Red: bounds of the 90% confidence interval $\pm a\bar{\sigma}_i^S$. Dashed black: ± variance of the solar shift for the decorrelated dataset. Grey area: confidence interval according to LMKC. Magenta area: 90% confidence interval according to boostrapping.

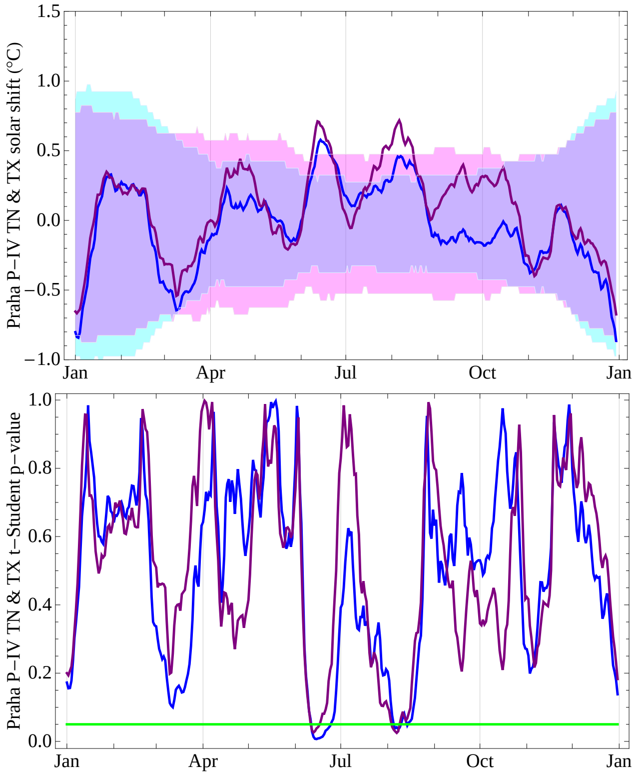

Fig. 6. Upper panel: Solar shift for TN (blue) and TX (purple) temperatures in Praha after removal of the 5 last solar cycles. Cyan area: 90% confidence interval for TN solar shift. Red area: 90% confidence interval for TX solar shift. Lower panel: p-value of the Student t-test for the TN (blue) and TX (purple) solar shifts. The green line marks the 95% confidence level.

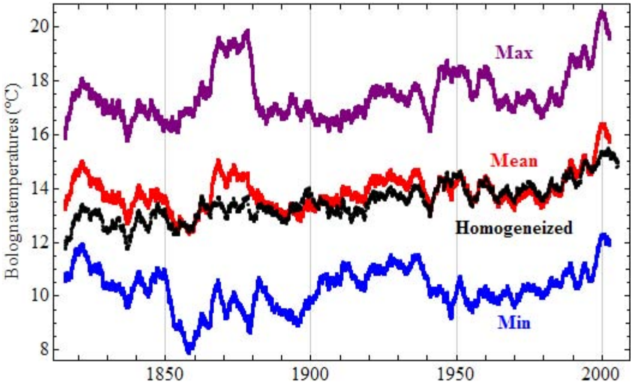

Fig. 7. Three-year moving average of Bologna minimum (blue), mean (red) and maximum (purple) temperatures and homogenized mean temperature (black).

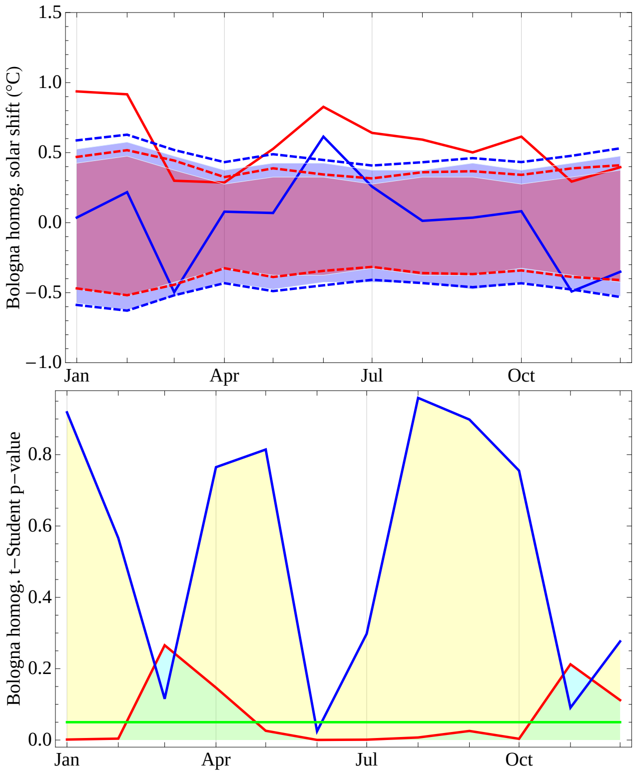

Fig. 8. Upper panel: Bologna solar shift for homogenized mean monthly temperature for the whole dataset (solid red) and P-IV dataset (solid blue). Boundary of the 90% confidence interval from the variance, for the whole dataset (dashed red) and the P-IV dataset (dashed blue). Confidence interval according to bootstrapping for the whole dataset (red area) and the P-IV dataset (blue area). Lower panel: p-value of the Student t-test for the whole dataset (red) and the P-IV dataset (blue).