

## A solar pattern in the longest temperature series from three stations in Europe

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### ABSTRACT

We analyze the longest temperature series from Prague, Bologna and Uccle. We partition daily minimum and maximum temperatures and their differences in two subsets as a function of high vs low solar activity, using the superimposed epochs method. Differences display patterns with significant amplitudes and time constants  $\sim 3$  months. These are recognized in all stations and are stable against a change in the analyzed period. Amplitude of variations is  $\sim 1^\circ\text{C}$ . Differences between average annual values corresponding to high vs low activity periods are also  $\sim 1^\circ\text{C}$ . Solar activity may account for these long-term temperature variations. These variations also present local characteristics, which may render identification of a global correlation delicate. We discuss possible physical mechanisms by which solar variation could force climate changes (e.g. through solar activity itself, the EUV part of the solar flux, cosmic rays, the downward ionosphere-earth current density, etc.).

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### Introduction

There is a strong interest in the recent evolution of climate on Earth, at both the global and more regional scales. The 2007 IPCC report illustrates mean global temperature anomalies since 1850 for each main continent, for the overall continental set, for oceans and for the entire globe (Figure SPM-4 of the Working Group 1 part of the IPCC Fourth Assessment Report, 2007). All these curves display significant warming, which is mainly attributed to the recent increase in anthropogenic greenhouse gases (GHGs) release. Indeed, current physical understanding argues for a much larger contribution of  $\text{CO}_2$  to the general heat budget than variations for instance of total solar irradiance (but see Lindzen and Choi, 2009). We recently re-analyzed temperature data from Europe and North America (Le Mouél et al., 2008), with particular focus on temperature variability. We provided evidence that temperature variability is modulated by solar activity, estimated using the classical sunspot numbers or other classical (aa index) or less classical (range of daily variations of geomagnetic field components; Le Mouél et al., 2005) proxies.

This has led us to analyze in more detail series of daily temperature data in another way, in order to search for statistically significant changes in evolution of these temperatures. This is feasible only if one can obtain very long time series

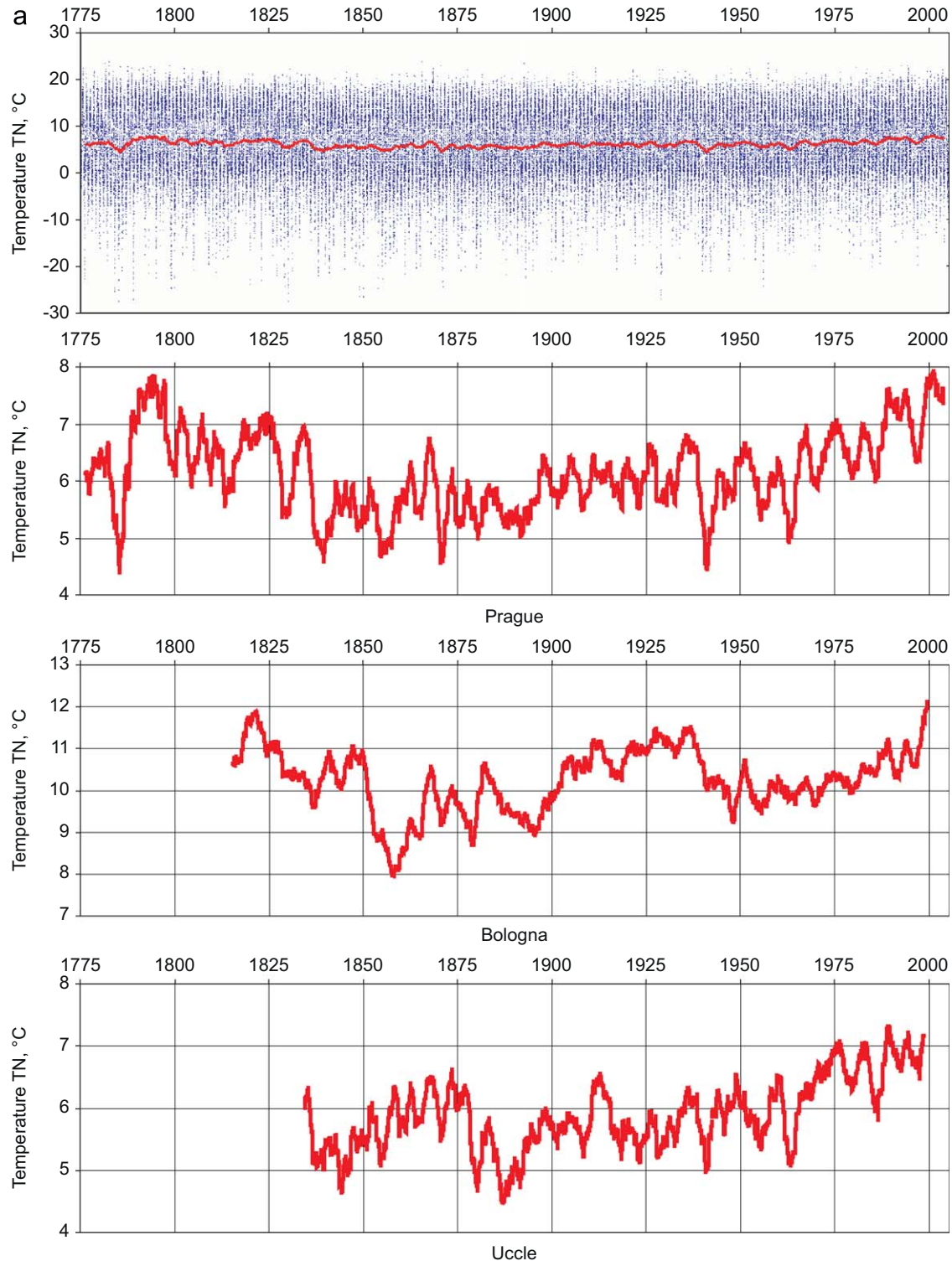
of high quality data. We are fortunate that the European Climate Assessment dataset (Klein Tank et al., 2002), available at <http://eca.knmi.nl/>, contains three long, high-quality series: non-blended data on temperatures recorded at Praha-Klementinum (Prague), Czech Republic, from 1775/01/01 to 2005/04/30 (source id 100079 for daily minimum temperature TN and 100081 for daily maximum temperature TX), Bologna, Italy, from 1814/01/01 to 2000/12/31 (source id 100548 for TN and 100549 for TX), and Uccle, Belgium, from 1833/01/01 to 1999/12/31 (source id 100044 for TN and 100045 for TX). These are the three longest series of the ECA database with no missing data for durations (respectively) of 230, 187, and 167 years. TN and TX values are all of the highest quality code in ECA at each of the three locations. We have used non-blended daily data, that is raw data taken at face value, without making further tests of data quality. But we have not used data resulting from some form of model prediction calculated from fragmentary observations. It is a general observation that one must trust the way ancient observers did the maximum they thought possible to obtain the best data, since many of the details of instrument and baseline control are only rarely reported. This is true with meteorological or magnetic observatories, and may remain partly true up to fairly recent times. The longest series of non-blended data in the data bases is indeed from Praha-Klementinum (<http://www.chmi.cz/meteo/ok/klemhiste.html>). Although regular measurements there began in 1752, they were not the first instrument-based records. But earlier observations were not systematic, often not published and their records preserved in private letters or parish

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chronicles. Measurements remained fragmentary until 1774, and the beginning of the series we use is on January 1, 1775. From then on, air temperature was measured twice a day: in the morning, either at sunrise or in summer 2 h after sunrise, and in the afternoon around 3 pm. The two ECA series are continuous and free of gaps as viewed against modern criteria, and start a few years before the invention of the maximum–minimum thermometer: James Six introduced his U-tube thermometer in

1782. Meteorological observations have continued at the Klementinum to this day and although they have naturally been influenced by a number of factors (exact location of measurement, urban growth effect, changes in instruments), they represent a quite unique and valuable source of information on weather and climate over two and a half centuries. One may wonder why we have not analyzed here the very long series of central England temperatures (Parker et al., 1992): the reason is that the non-



**Fig. 1.** (a) The 3-year centered average of the daily minimum (a) and maximum (b) temperature series TN and TX at Prague, Bologna, and Uccle. The top row shows for Prague both the original daily data and the 3-year averages on a different scale.

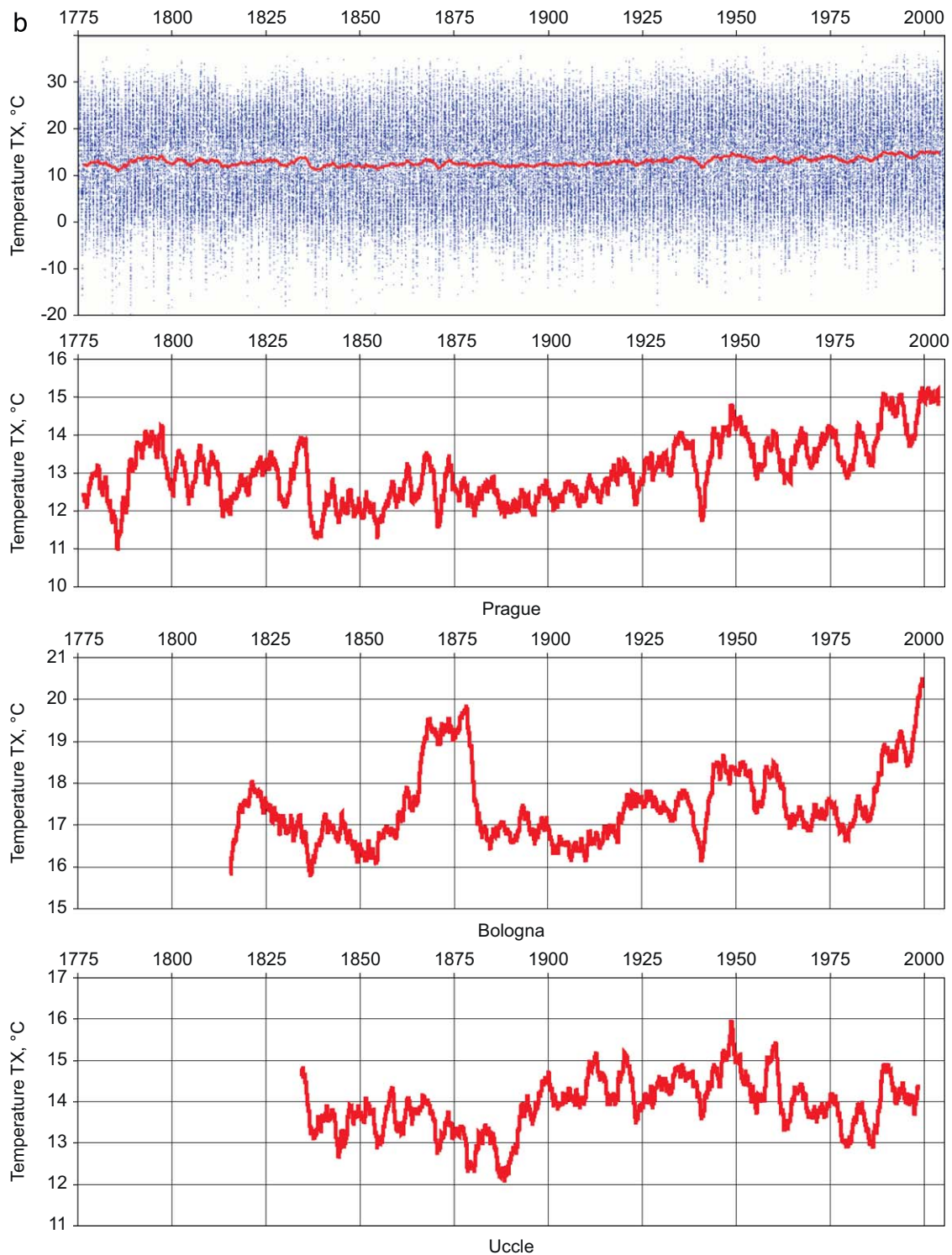
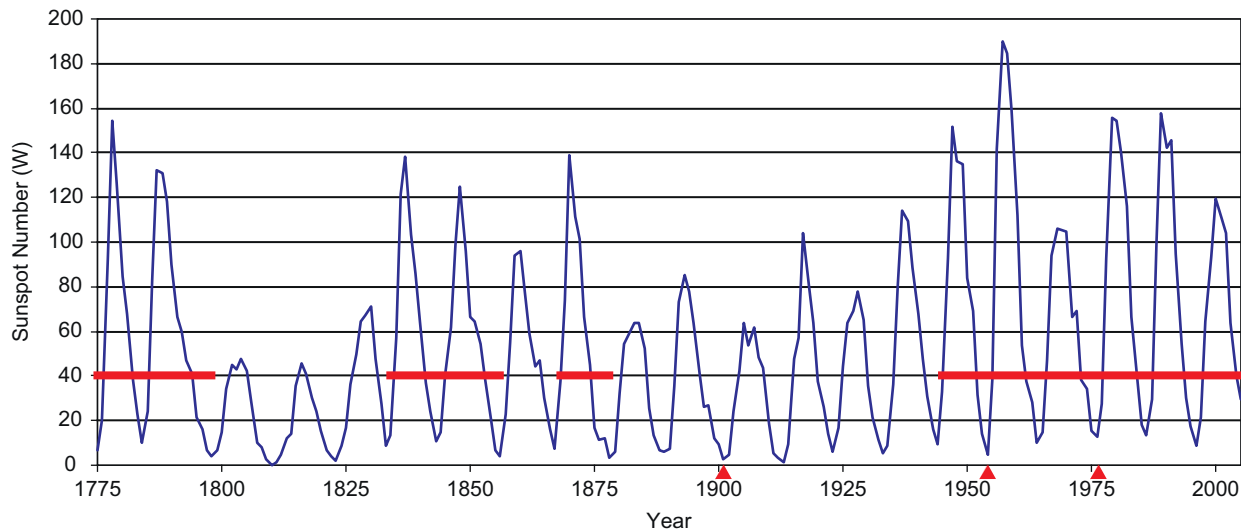


Fig. 1. (Continued)

blended data in that series start only in 1881 (see also Klein Tank et al., 2002).

The top line of Fig. 1a shows daily minimum temperature data in Prague (in blue) and a centered 3-year average (in red) at the same scale, illustrating the large amplitude of short-term and annual variations compared to longer-term variations. Respective amplitudes range from 40 °C for raw data to 3 °C for the smoothed data and underline the need for careful statistical treatment to

extract meaningful long-term properties of the data sets. The second to fourth rows of Fig. 1a display at a larger scale the 3-year centered moving averages of the minimum daily temperature series from (from top to bottom) Prague, Bologna and Uccle. Fig. 1b displays a similar set of frames for the maximum temperatures. A feature that is common to all plots and the subject of much ongoing research is the warming (or positive trend) in the last half to quarter of the 20th century. But there are



**Fig. 2.** Annual mean sunspot numbers from 1775 to 2005. The median value of total number of sunspots in a given cycle is 618.4 (see text). Cycles with larger total numbers are considered as showing high (H) solar activity and are indicated by red bars; cycles with lower values are considered as showing low (L) solar activity. Triangles on the abscissae axis mark the ends of cycles 13, 18, and 20 and are used for various partitions of the total data sets (see text and figures).

also significant differences between stations. The respective behaviors of the TN and TX curves in Prague are rather similar, in terms of both decadal to centennial (or secular) trends and shorter-term features, such as the sharp 1940 temperature minimum or step-like increase around 1987, both found to be a general signature of 20th century European climate (Le Mouél et al., 2008). 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 flat positive anomaly of 2 °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. Another observation is that from 1950 to 1980 in Uccle the decadal trend is positive for TN but negative for TX. It is well-recognized that climate evolution, and notably temperature evolution, is a mix of more smoothly varying regional features (responses) with more local ones, with high spatial variability (e.g. Hartmann, 1994; De Jager, 2005).

In order to analyze whether we can detect any significant contributions to temperatures that could be linked to variations in solar activity, we use the sunspot (Wolf) number as a proxy. The longest time series of values is available at the world data center for the sunspot index at the Royal observatory in Brussels ([http://sidc.be/sunspot\\_data/](http://sidc.be/sunspot_data/)). Fig. 2 shows the annual average of the sunspot series from 1775 (that is the onset of the longest temperature series in Prague) to 2005. Sunspot cycles are actually longer than the interval between successive minima and sunspots of two successive cycles overlap. For instance, we are currently in a deep solar minimum and the few spots and flares observed could be attributed to either cycle 23 or 24. We chose to avoid the fuzzy classification of time that would result from taking this into account. It is a very minor effect, since in the case of Prague only 6 out of 230 years could be affected (see Table 1 and Fig. 1).

We first introduce a number of partitions of the Prague data set as a function of the amount of solar activity indicated by solar cycles. We then analyze the annual signature of maximum and minimum temperatures (along with their difference and the first time differences of the three) belonging to partitioned sets (that is 5 different time series for each station) as a function of calendar date. We next perform the same analyses on the Bologna and Uccle stations and describe common results and differences. The paper ends with a discussion section.

**Table 1**

Dates of onset and end of solar cycles 3–23 used in this paper. High-activity cycles in plain font, low-activity cycles in italics. See text and Fig. 2.

Solar cycle number	Onset	End	Total number of sunspots
3	1775	1784	624.0
4	1785	1798	840.2
5	1799	1810	281.9
6	1811	1823	236.8
7	1824	1833	396.9
8	1834	1843	655.0
9	1844	1856	691.9
10	1857	1867	548.5
11	1868	1878	618.4
12	1879	1889	383.3
13	1890	1901	461.8
14	1902	1913	372.4
15	1914	1923	445.9
16	1924	1933	410.3
17	1934	1944	609.1
18	1945	1954	751.5
19	1955	1964	955.6
20	1965	1976	707.9
21	1977	1986	830.1
22	1987	1996	780.4
23	1997	2005+	647.6+

### 1. Splitting temperatures and temperature variations into high- and low-solar activity subsets (the case of Prague)

We split the solar cycles themselves into cycles of low and high activity. The generally accepted dates of onsets (and terminations) of solar cycles 3–23 are from [http://sidc.be/sunspot\\_data/](http://sidc.be/sunspot_data/) (see also Table 1). We use the number of sunspots for each year  $n(i)$ , then sum up the total number of sunspots in each one of the 21 cycles under consideration ( $N_j = \sum n(i)$  for all years  $i_j$  belonging to cycle  $j$ ). The median  $M$  of the 21  $N_j$  values is equal to 618.4. High-activity cycles are defined as those for which  $N_j > M$ , and low-activity cycles are those for which  $N_j < M$ . High-activity cycles are numbers 3 and 4, 8 and 9, 11, and 18–23 (Fig. 2, color bars). Low activity cycles are numbers 5–7, 10, and 12–17. We note from the very beginning that the sequence ends with a succession of six cycles with high activity, preceded by six cycles



with rather low activity. Such a long-term (more than ten cycles long) solar signature has not previously been seen in historical records, though it may be reminiscent of the period of the Maunder minimum and that immediately following it. We distribute the daily temperature values  $T(t)$  into two subsets,  $E_H$  and  $E_L$ , in the following way: the temperature  $T(t)$  of any day belonging to a high- (resp. low-) activity cycle is assigned to ensemble  $E_H$  (resp.  $E_L$ ). For the Prague series, there are 40906 daily values in  $E_H$  and 43320 in  $E_L$ . In the following, we compare mean data in subsets  $E_H$  vs  $E_L$  and their reunion, and also in other subsets defined in a similar way.

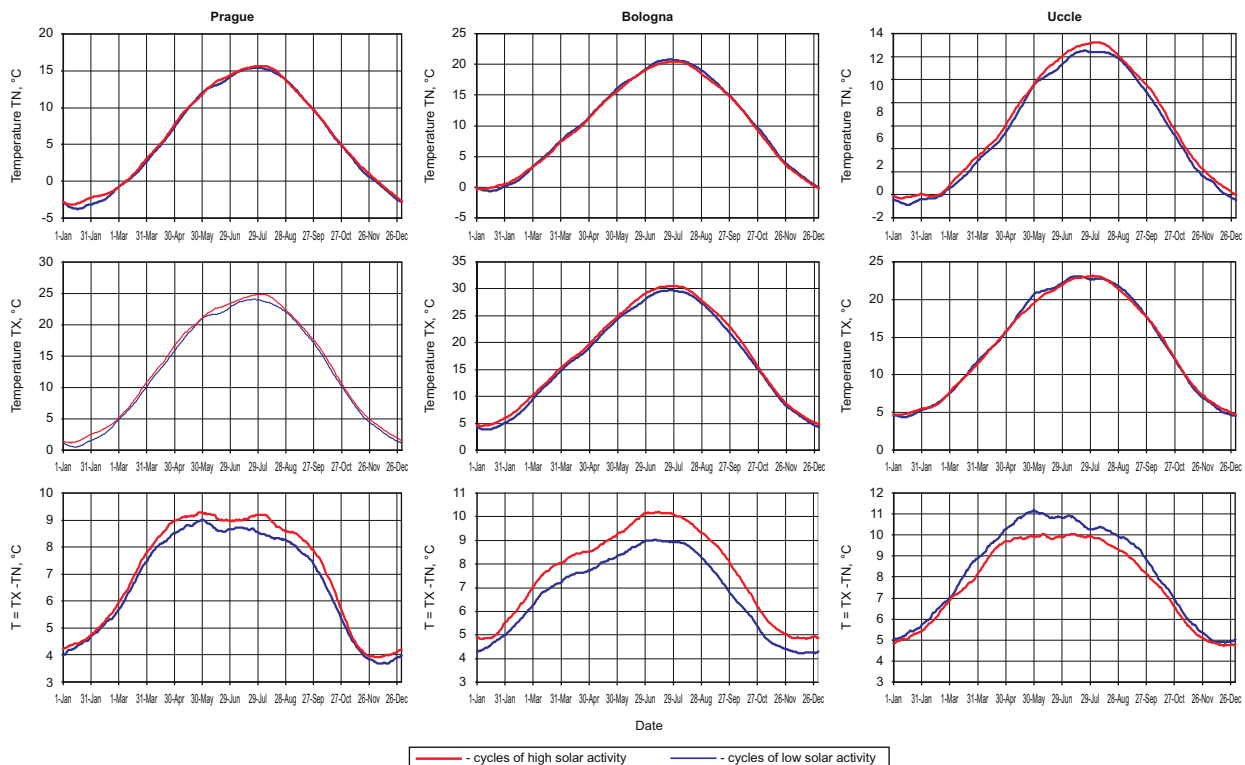
### 1.1. Seasonal variations

Our method of analysis is first illustrated with the data from Prague. We split each of the temperature data sets TN and TX, and their range  $\Delta T = TX - TN$ , into the two  $E_H$  and  $E_L$  ensembles, and average them according to their calendar date, using the classical technique of “superimposed epochs”. Results are shown in Fig. 3 (left column; each subset of three frames representing minimum, maximum and range). A 21-day (i.e. 3-week) centered moving average is applied: indeed, this is both long enough to stabilize the still noisy averaged calendar values and yet short enough that features with monthly and longer time constants are well preserved. The annual temperature cycle is of course the dominant feature of all these figures, with annual amplitude variations of 19 °C for TN, 25 °C for TX and 5 °C for  $\Delta T$ . Fig. 4 (top row) illustrates the differences between temperature curves corresponding to high ( $T_H$ ) and low ( $T_L$ ) solar activity shown in Fig. 3: the red curve is for TX, the blue for TN and the green for  $\Delta T$ . The set of thin curves (symmetrical with respect to the abscissa axis) represents the statistical errors  $\sigma$  of the differences, at each day, between the high activity and the low activity curves.

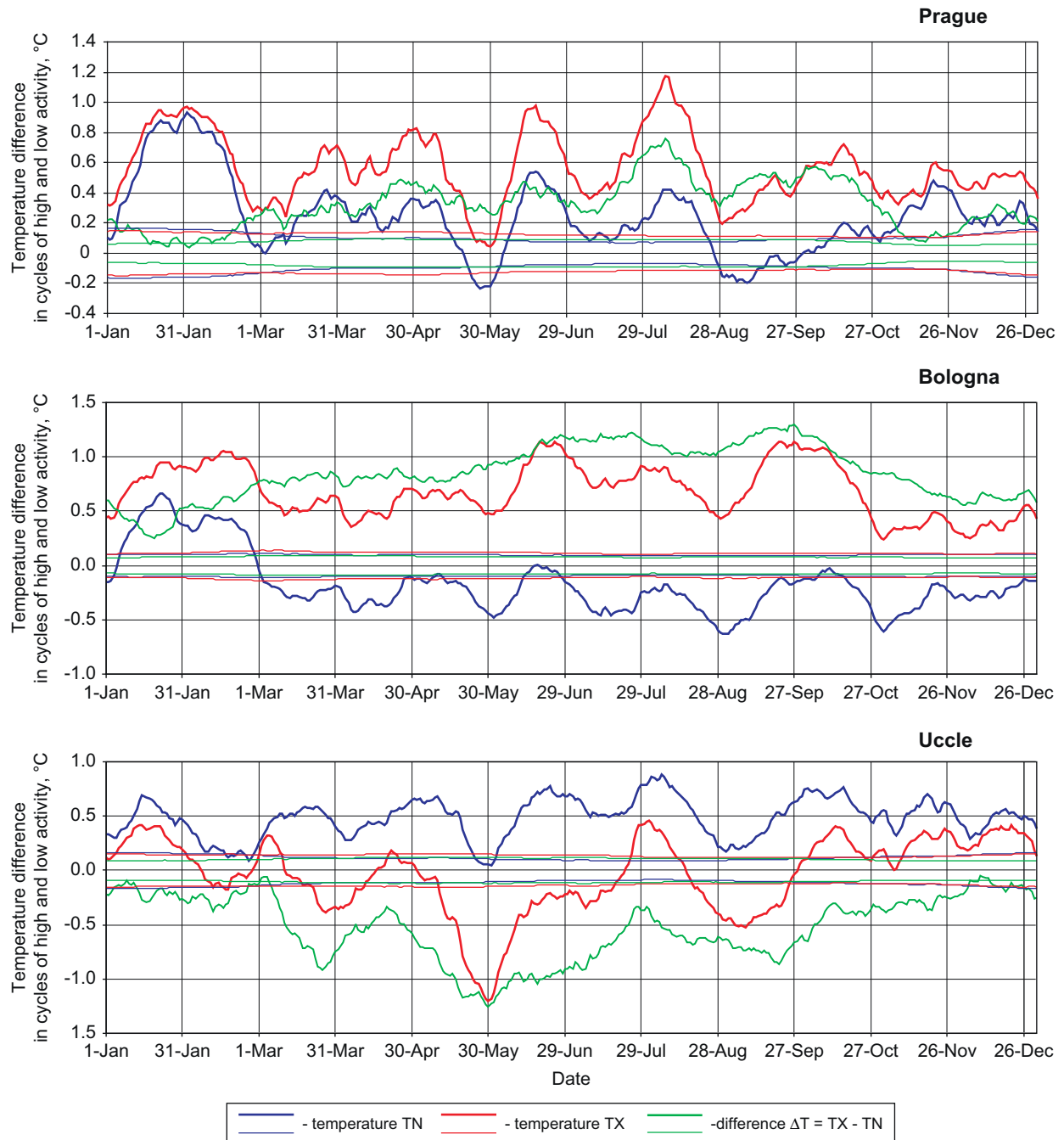
We see that all curves are outside the range of error all or most of the time; hence, the differences between high and low activity periods are significant for all temperature curves. And their values are not small: the differential effect between periods of high and low solar activity on TX in Prague reaches 1 °C. The average over the whole year is about 0.6 °C. This is a significant effect, which is on the order of long-term changes in global temperature over the past. The curves for TX and TN present very similar fluctuations (the difference between the two being a more slowly varying function of calendar date).

### 1.2. Changing the time span under study

The Prague series is sufficiently long so that it can be partitioned in different ways to generate a number of subsets for which meaningful statistical analyses are still possible, i.e. with a large enough number of data points in each resulting subset. The aim of such exercises is to further check the stability and robustness of the results above, in particular the intriguing seasonal variations that retain a signature over 200 years, as will be seen shortly. This is illustrated by the set of 5 frames in Fig. 5a. The frames (rows) show results for successively (from top to bottom) the last 10 cycles (P-I; 1900–2005), all 21 cycles (P-II; 1775–2005 considered so far), and then removing the most recent 3 (P-III), 5 (P-IV), then 10 (P-V) cycles, thus ending with only cycles 3–13 (i.e. 1775–1901) to see whether the more recent cycles affect the results (the 6 most recent ones since 1950 all have high activity as defined above). Note that the colored triangles in Fig. 2 correspond to the different times of onset and end of subsets P-I to P-V. The last half of the 20th century is the one in which global warming attributed to the significant increase in anthropogenic GHGs release was thought to have started (IPCC report, 2007), although this is now often reduced to the last quarter of the 20th century. We therefore check whether the



**Fig. 3.** Average annual variation of temperatures in the three stations. The first column of three frames is for TN, TX, and  $\Delta T$  in Prague. The red curve is for 21-day moving averages of the samples in H (high solar activity) times, and the blue one in L (low solar activity) times. The second and third columns are the same for Bologna and Uccle, respectively.



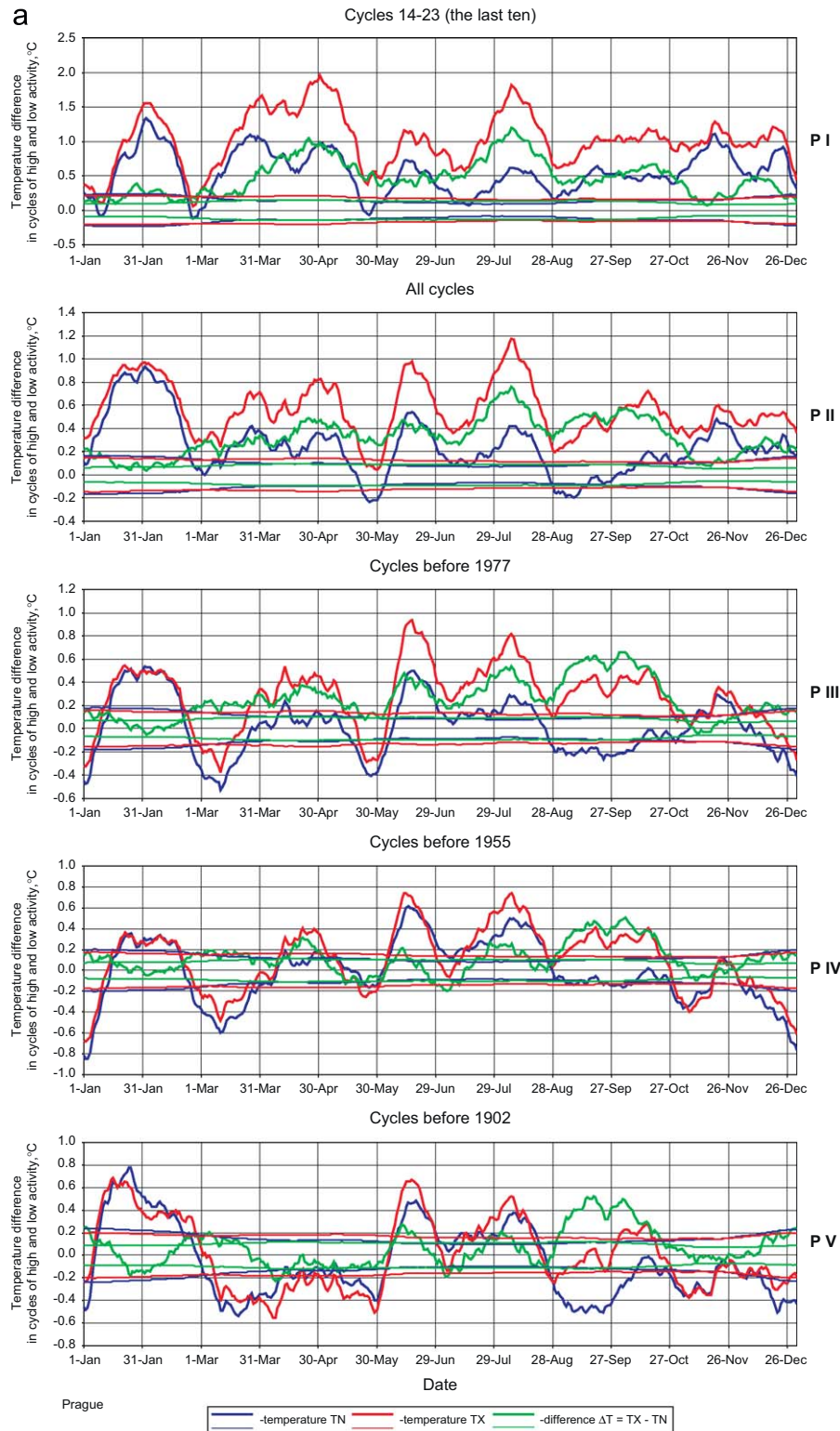
**Fig. 4.** Differences of sample 21-day moving averages between H (high solar activity) and L (low solar activity) times as a function of calendar date, for (from top to bottom) Prague, Bologna and Uccle. Blue curves are for TN, red curves for TX and green curves for  $\Delta T$ . Uncertainties are given as a pair of thin lines about the 0 ordinate with the relevant color (see text).

splitting of high versus low sunspot cycles has not in fact isolated the recent period in which sources of temperature change might actually be independent of the Sun (and be for instance the rise in GHGs). This is the reason for our progressive removal of recent cycles in the last 3 frames of each set in Fig. 5 (P-III to P-V). We have performed for all these subset series the same analyses described above in Figs. 3 and 4. We find again that for all subsets the differences corresponding to maximum (TX) and minimum (TN) temperatures, respectively, at times of high (red,  $T_H$ ) and low (blue,  $T_L$ ) solar activity are similar and parallel to each other, with the same characteristic wavy signature dominated by (pseudo-) periods of about 2–3 months. Also these curves are fairly similar from one subset to the next. There are in fact progressive changes

in the patterns from P-I to P-V but the pattern remains recognizable. The differences (particularly in March and April) are largest for P-I and P-V, which have no time intersection. We conclude that, within the limitations of this analysis, the signature expressed in the seasonal variation of the differences  $T_H - T_L$  (for TX, TN and  $\Delta T$ ) takes the form of a characteristic pattern. We come back to the significance of this pattern in the discussion. There are no significant changes in this presumably solar signature when the last large cycles are removed (curves P-II vs P-IV in Fig. 5a). This would argue against the emergence of a major independent source of temperature change in either the second half (P-IV) or last quarter (P-III) of the 20th century.

For comparison, we can perform the same operation for various splittings ( $E_1, E_2$ ) of the data. We show several examples in Fig. 6, which is for the difference ( $T_2 - T_1$ ) between the respective  $T_1$  and  $T_2$  curves, for splitting ( $E_1, E_2$ ) given in the

figure caption. They are from top to bottom: (a) our original  $H$  vs  $L$  splitting (the same as in Fig. 5a). (b) Odd vs even years. (c) Data are split in 2-year intervals, which are then renumbered—the new intervals are assembled in two ensembles, one with the odd



**Fig. 5.** Differences of sample 21-day moving averages between  $H$  (high solar activity) and  $L$  (low solar activity) times as a function of calendar date. Three sets of five frames are shown: (set a) Prague; (set b) Bologna; (set c) Uccle. In each set the frames correspond to different time spans: from top to bottom, cycles 14–23 (P I, B I, U I), 3–23 (P II, B II, U II), 3–20 (P III, B III, U III), 3–18 (P IV, B IV, U IV), and 3–13 (P V, B V, U V). Blue curves are for  $T_N$ , red curves for  $T_X$  and green curves for  $\Delta T$ . Uncertainties are given as a pair of thin lines about the 0 ordinate with the relevant color (see text).

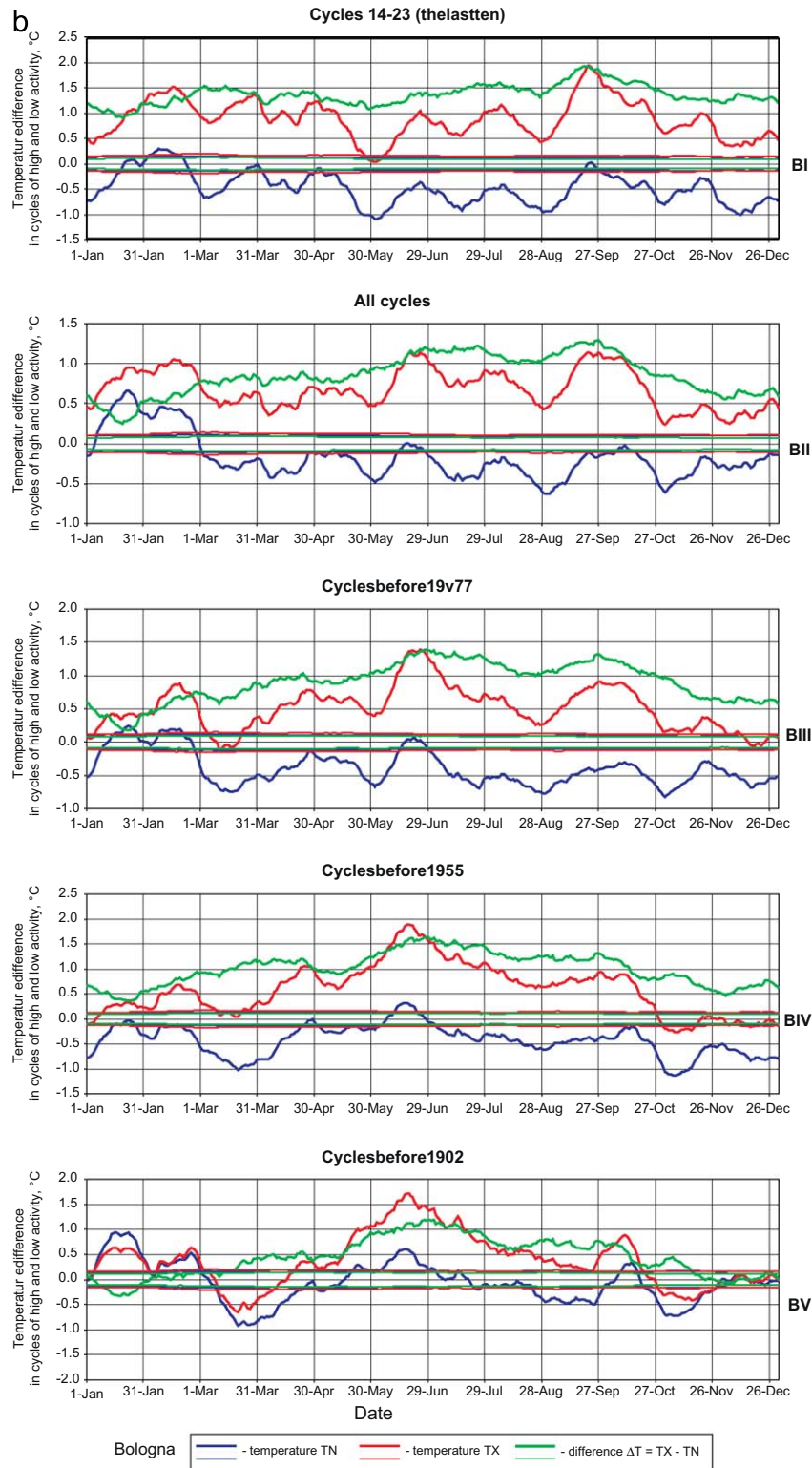


Fig. 5. (Continued)

and the other with the even numbers, called for short “2-odd” and “2-even” years. (d–f) The same is done with 4-year, 8-year and 13-year intervals. The TN and TX curves remain generally similar, as could be expected from the natural correlation of all temperatures within a given day. A correlation between them should therefore appear in any splitting of the data. But all curves in Figs. 6b–e are different from 6a and from one another, and the yearly average of the daily range  $\Delta T$  is significantly different from

zero for all calendar dates around the year only for the physically motivated splitting of Fig. 6a.

### 1.3. From temperatures to temperature variations (first differences)

The influence of solar activity on short-term variations of temperature (i.e. temperature perturbations, or temperature



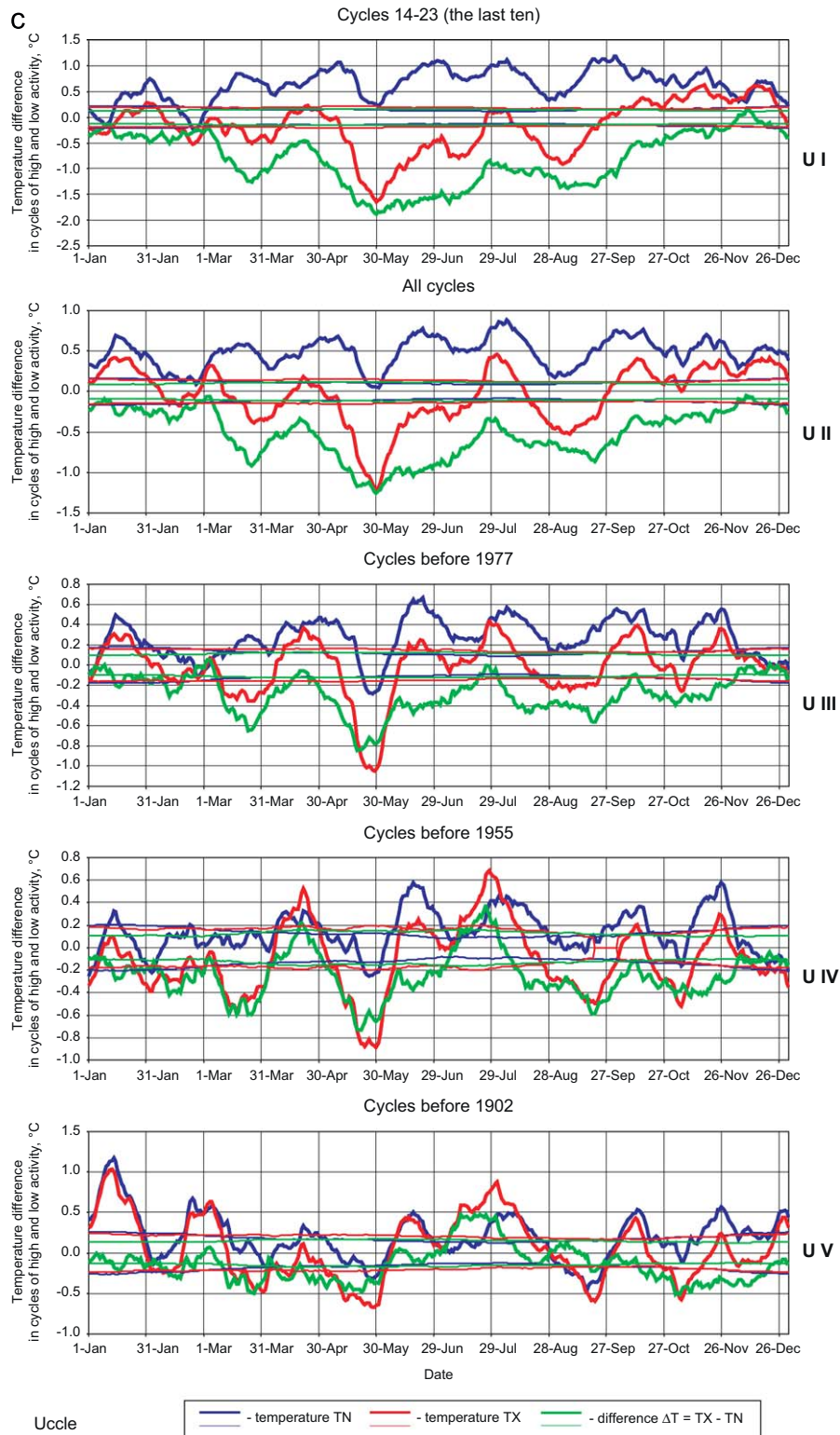
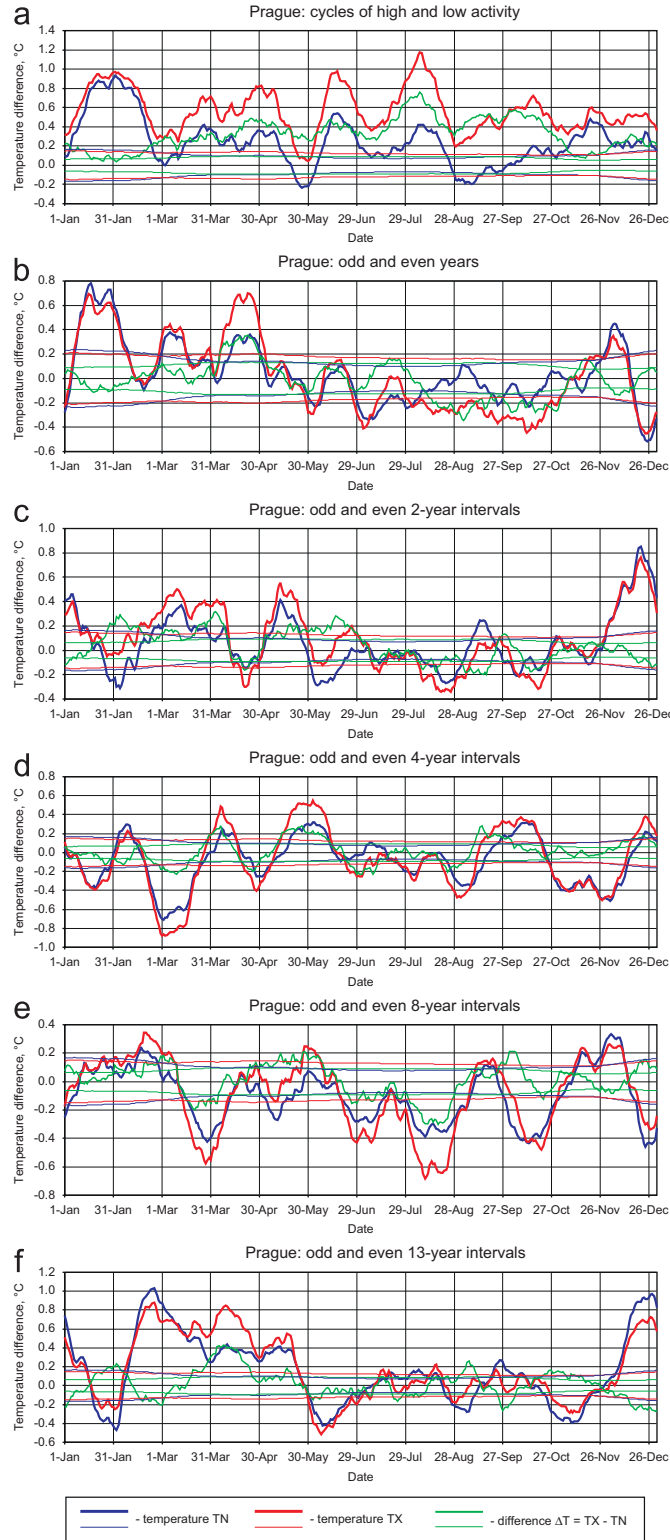


Fig. 5. (Continued)

“activity”) has apparently received less attention than its influence on absolute temperatures themselves. Yet this influence can be evidenced and is not a minor effect (e.g. Le Mouél et al., 2008). In order to further characterize this activity, we consider the absolute value of the first derivative of temperature ( $|dT(t)/dt| = |T(t+1) - T(t)|$ ,  $t$  being the sequential number of the day in a series) as a measure of their short

time scale variation. We apply the splitting ( $E_H, E_L$ ) to all temperature data from Prague since 1775 and represent the seasonal variation after 21-day smoothing as above: a large effect is again apparent. The amplitude of the seasonal variation, due to the Earth’s annual revolution around the Sun, ranges from 0.7 °C/day for  $dTN/dt$  and  $dTX/dt$  to 1.0 °C/day for  $d\Delta T/dt$  (Fig. 7a, left column). The difference in seasonal temperature

variation between high and low activity times ( $|dT_H/dt| - |dT_L/dt|$ ) reaches  $0.15^\circ\text{C/day}$  for TN, oscillates from  $-0.07$  to  $0.15^\circ\text{C/day}$  for TX and reaches  $0.25^\circ\text{C/day}$  for  $\Delta T$  (Fig. 8a, top row).



**Fig. 6.** Same presentation as in Figs. 4 and 5 for Prague only with different splittings of the data. From top to bottom: (a) the H vs L separation as in Fig. 4a (first row) and 5a (second row; P II distribution); (b) a separation into odd and even years; (c) for “2-odd” and “2-even” years; (d) for “4-odd” and “4-even” years; (e) for “8-odd” and “8-even” years; (f) for “13-odd” and “13-even” years (i.e. data are regrouped in intervals of 2, 4, 8, and 13 years; the intervals are renumbered and odd and even numbers are associated separately—see text).

## 2. Analysis for Bologna and Uccle

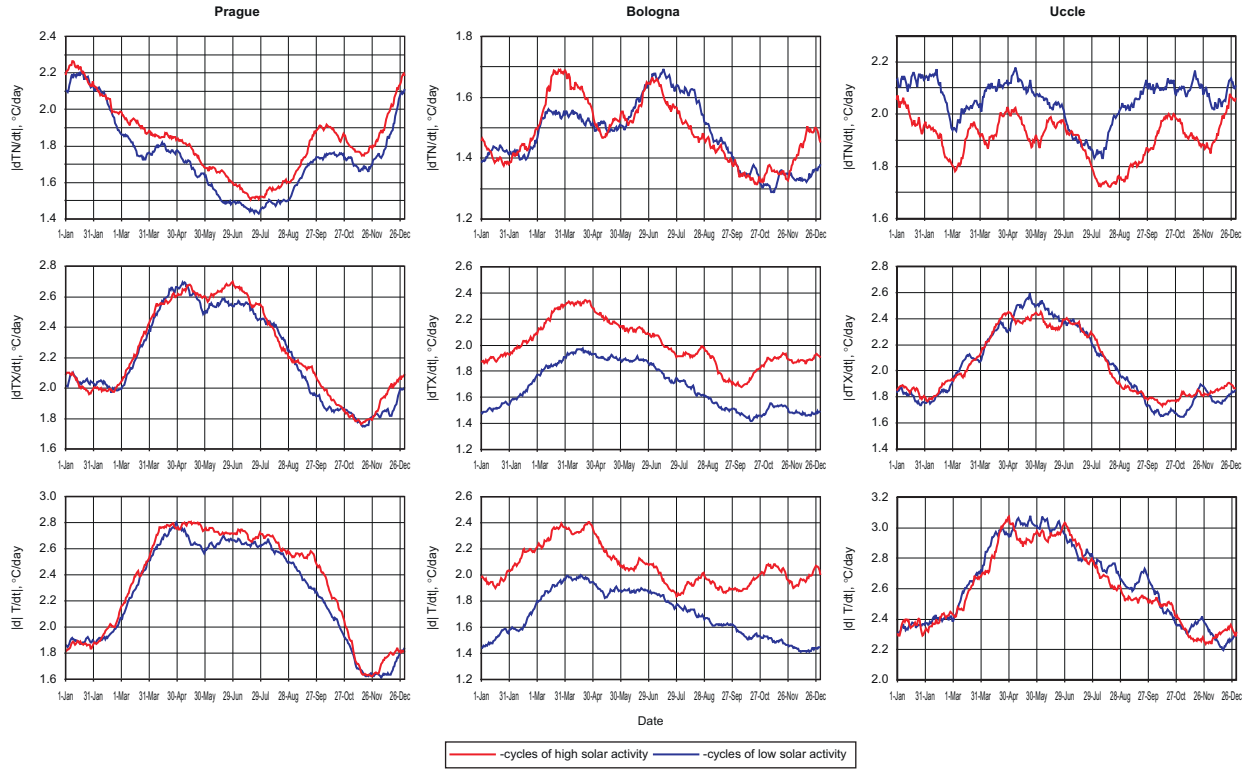
After having tested our method on the longest available series, that from Prague, it is important to see whether it carries to other locations. For this, we present in this section the results obtained with the other two stations with the next longest series of observed temperatures, i.e. Bologna and Uccle. The three stations may in a way represent the European oceanic (Uccle), central European (Prague) and Mediterranean (Bologna) climatic regions of Europe. Both common and different features emerge from a comparison of the three stations in terms of the expression of solar activity in each one of them. We return to those parts of the previous figures that have not been discussed so far.

We stress again that decadal to centennial changes in the 3-year running means for minimum temperature in Prague, Bologna, and Uccle are not always similar (Fig. 1). High frequency changes are more subdued in Bologna, where the decadal to centennial trend of TN (Fig. 1a) is amplified and more readily apparent, particularly the decelerating rise from 1900 to 1930, the decrease to 1950 and the accelerating rise since. That rise has been shown to average to a quasi step-like change in Europe around 1987 (Le Mouél et al., 2008), and is readily seen in the Prague curve where it accounts for almost half of the warming since 1900. It seems to occur a bit earlier in Uccle and later in Bologna. When maximum temperature curves are considered (Fig. 1b), the similarity between Prague and Bologna after 1900 is rather strong. Also, for maximum temperatures, the trend in Uccle has been flat on average throughout the 20th century (even decreasing since 1950). The 1987 step is apparent in all TX curves.

Figs. 3b and c displays seasonal variations of TN, TX, and  $\Delta T$  at Bologna and Uccle. Fig. 4 gives an enlarged view of the differences ( $T_H - T_L$ ) between the high and low solar activity curves. Deviations from the error limits are systematically large for TX and  $\Delta T$  at Bologna, and for TN and  $\Delta T$  at Uccle. The difference ( $\Delta T_H - \Delta T_L$ ) is positive most of the time in Prague and Bologna, but negative at Uccle. Despite some deviations between the temperature differences at the three stations, we cannot fail to notice significant common features between the 9 curves of Fig. 4: for instance a series of three rather sharp alternations of maxima and minima from the end of April to the end of August. This common signature, with distinct changes between periods with high vs low solar activity, could be attributed to a common response of the European climate to solar variations.

In Figs. 5b and c, which display the seasonal variations of the differences at Bologna and Uccle (as was done for Prague in Fig. 5a) for 5 different cases of partitioning of solar cycles, we find that the patterns can be followed with some deformation from one frame to the next both in Uccle and in Bologna, and more clearly in Uccle than in Bologna, despite the fact that in the former case the last series (U-V) extends over only 68 years (which is about the minimum time span required by our analysis).

Seasonal variations in the time derivatives of the various temperature distributions are illustrated in Figs. 7b and c. The separation of high vs low solar activity curves is particularly pronounced for  $|dT_X/dt|$  and  $|d\Delta T/dt|$  in Bologna and for  $|dT_N/dt|$  in Uccle. For  $|dT_N/dt|$ , there is an inverted annual cycle at Bologna and a more complex signal at Uccle. Where the annual cycle is clear, it is in phase (e.g. for  $|dT_X/dt|$  at the three observatories). The differences between periods of low and high solar activity are enlarged in Figs. 8b and c. These differences are highly significant for  $|dT_X/dt|$  and  $|d\Delta T/dt|$  at Bologna (reaching  $0.4$  and  $0.6^\circ\text{C/day}$ , respectively), and for  $|dT_N/dt|$  at Uccle (reaching  $0.3^\circ\text{C/day}$ ).



**Fig. 7.** Temperature variations  $|dT_N/dt|$ ,  $|dT_X/dt|$  and  $|dT/dt|$  at times of high (H) and low (L) solar activity. Same as Fig. 3 but for the absolute value of the day-to-day temperature differences (d/dt) of TN, TX, and  $\Delta T$ .

### 3. A connection between temperature, temperature variation, and solar forcing

Splitting long series of daily temperature data according to the level of solar activity as defined in this paper reveals statistically significant patterns, which it is reasonable to interpret as the signature of a solar effect on these temperatures. Should this signature be attributed to another cause, this cause would have to still be present in the rather complex time distribution of high versus low solar cycles (Fig. 2). Two consequences should be emphasized at this point.

(a) The average annual values of the  $T_H - T_L$  differences shown in Fig. 5 have been calculated in Table 2, together with their errors  $\sigma = (\sigma_L^2 + \sigma_H^2)^{1/2}$ . These errors are quite small, less than  $0.03^\circ\text{C}$  in all cases. Whereas the mean value of each difference slowly changes with time, the patterns seen in Fig. 5 remain quite stable. For instance the curves for Prague for sets III and IV (which do not contain the last 30 and 50 years, respectively) do not show any significant difference with respect to set I, which does contain all these years. Therefore, there is no sign that some different external forcing factor emerged in the past 50 or 30 years. The differences are larger when the completely separate sets I and V are compared (although much of the 3-month-long patterns remain comparable). But one does not expect climate to be stationary over two successive disjoint centuries. Much the same can be said of Bologna and Uccle.

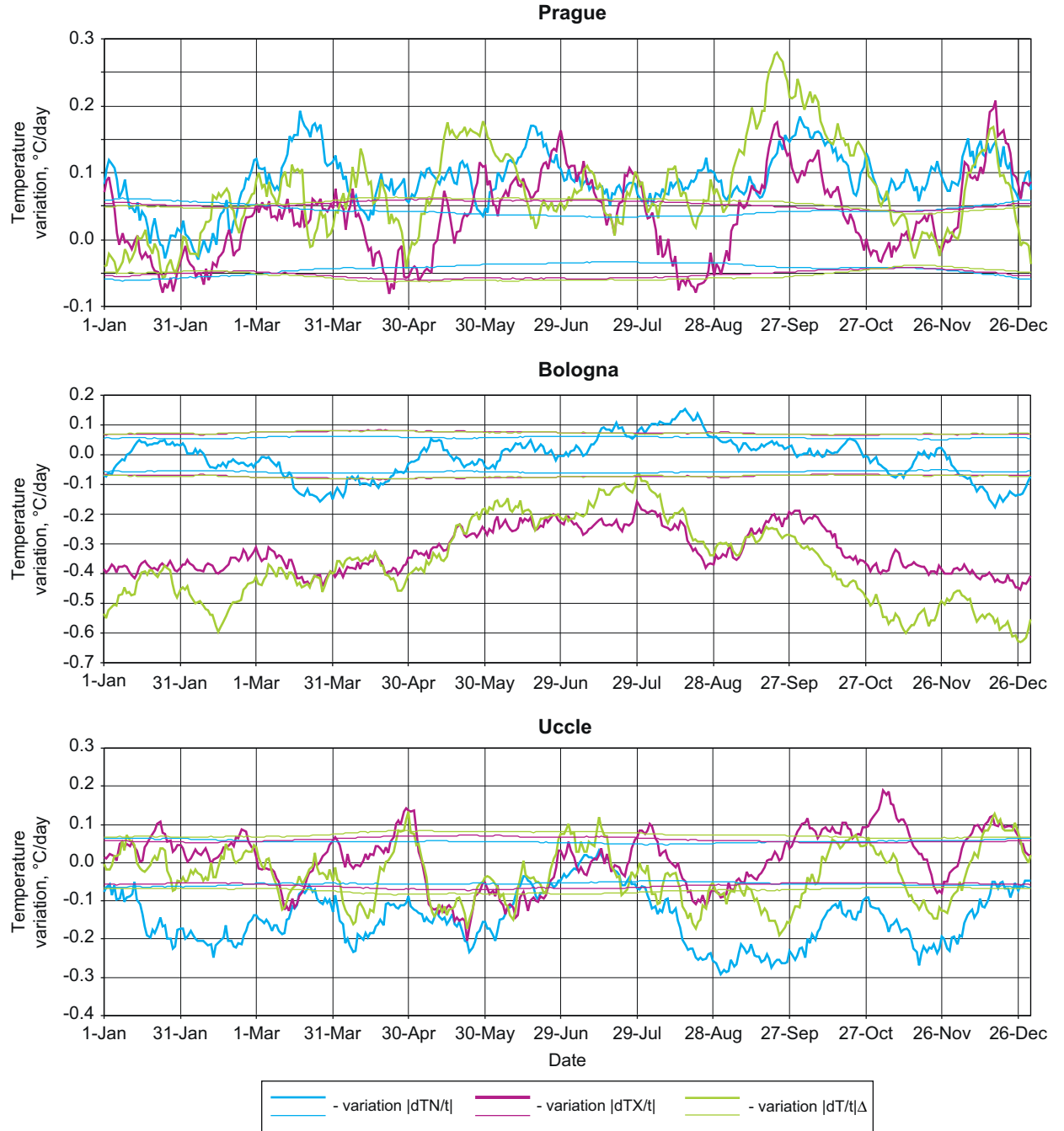
Given the errors, the largest, most significant differences are for TX in Prague, TX and  $\Delta T$  in Bologna, and TN and  $\Delta T$  in Uccle (Table 2). In Prague, the average annual values of TX differences as a function of solar cycle activity ( $TX_H - TX_L$ ) increase in time from  $0.01^\circ\text{C}$  for set V (cycles 3–13) to  $1.03^\circ\text{C}$  for set I (cycles 14–23) (see Fig. 5a). In Bologna, the corresponding change for TX is also an increase from  $0.38$  to  $0.89^\circ\text{C}$  (Fig. 5b), and that for  $\Delta T$  from  $0.44$  to  $1.37^\circ\text{C}$ . In the case of Uccle, we find an increase from  $0.20$  to  $0.64^\circ\text{C}$  for TN and from  $0.15$  to  $0.82^\circ\text{C}$  for  $\Delta T$  (Fig. 5c).

We note that in stations and for temperatures (TN and TX) for which  $T_H - T_L > 0$ , the current temperature is expected to rise when solar activity rises, and to decrease when  $T_H - T_L < 0$ . Thus, the increases observed in the 20th century (in TX and TN at Prague, TX at Bologna, and TN at Uccle; Fig. 1) are compatible with our analysis. Variability in solar activity over the period of about two centuries might be sufficient to account for local climatic variability in temperatures at the three stations we have analyzed.

(b) We have noted that the amplitudes of the differences in temperature indices  $\Delta T$  and  $|d\Delta T/dt|$  between times of high ( $E_H$ ) and low ( $E_L$ ) activity, which we propose above are linked with solar activity, may be quite large—as large as the amplitudes of the annual variation of these indices themselves. The differences in the temperature first derivatives are likely to be as significant as differences in temperatures themselves. The larger these temperature perturbations (or activity, as defined in Section 1.1), the more numerous extreme events are expected to be. It is sometimes reported that the frequency of extreme meteorological events has increased in the last decades. Detailed, quantitative analysis of individual meteorological phenomena has not yet established this conclusively (Landsea, 2007). Usoskin et al. (2003); see also Solanki et al., 2004; Duhau and de Jager, 2008) have argued that the period of high solar activity in the second half of the 20th century has been unique in the past 1150 years. Solar activity could therefore be considered as a potential cause of this increase in extreme events. However, Muscheler et al. (2005, 2007) have argued on the opposite that solar activity has been high but not exceptional with respect to the past millennium.

### 4. Discussion and conclusion

In recent papers, we have focused on temperature perturbations (which can also be called activity, or variability), which we have measured using inter-annual squared variations or lifetimes



**Fig. 8.** Differences of sample 21-day moving averages between temperature variations  $|dT_N/dt|$ ,  $|dT_X/dt|$ , and  $|dT/dt|\Delta$  at times of high (H) and low (L) solar activity. Same as Fig. 4 but for the absolute value of the day-to-day temperature differences ( $d/dt$ ) of TN, TX, and  $\Delta T$ .

(e.g. Le Mouél et al., 2008). Using these tools, we have shown the existence of solar effect contributions to temperature perturbations (at least in Europe and in the USA—Le Mouél et al., 2009; Courtillot et al., 2009): a rather clear correlation with a number of solar proxies (sunspot numbers, aa index, inter-daily squared variations of magnetic components in almost any geomagnetic observatory, etc.) occurs throughout the 20th century for some 200 climatological stations in the two continents.

In the present paper, we have analyzed the longest time series of daily temperatures that are available, implying a more restricted geographical subset of three European stations. We found rather large variations with characteristic patterns that could presumably be linked to solar activity: when the data are

split into the  $E_H$  and  $E_L$  subsets (corresponding to high and low solar activity cycles as illustrated in Fig. 2), and differences  $T_H - T_L$  are computed and stacked according to their calendar date, the curves indeed present many stable features, namely 2–3-month-period high-amplitude variations (Fig. 4). When one changes the total time period under consideration (Fig. 5), the amplitudes of these differences are found to range up to  $2^\circ\text{C}$  (e.g. for TX at Bologna in 1814–1954, i.e. Fig. 5b—B IV). We have seen that the overall local patterns of the  $T_H - T_L$  curves retain similar features, even when cycles from the second half of the 20th century are removed. For instance, the curves for the period before 1902 (V in Figs. 5a–c) and those from 1902 onwards (I in Figs. 5a–c), which have no overlap, retain a similarity, mainly in Prague and Uccle



**Table 2**

Annual mean values and errors  $\sigma$  of temperature differences  $T_H - T_L$  between times of high vs low activity cycles (see text).

Set		TN (°C)		TX (°C)		$\Delta T$ (°C)	
		Mean	$\sigma$	Mean	$\sigma$	Mean	$\sigma$
<b>Prague</b>	I	0.55	0.02	1.03	0.02	0.48	0.01
	II	0.24	0.01	0.57	0.01	0.32	0.01
	III	0.03	0.01	0.28	0.01	0.26	0.01
	IV	−0.01	0.02	0.10	0.02	0.11	0.01
	V	−0.06	0.02	0.01	0.02	0.07	0.01
<b>Bologna</b>	I	−0.48	0.02	0.89	0.02	1.37	0.01
	II	−0.17	0.01	0.69	0.01	0.85	0.01
	III	−0.38	0.01	0.52	0.02	0.90	0.02
	IV	−0.42	0.02	0.59	0.03	1.01	0.02
	V	−0.06	0.02	0.38	0.03	0.44	0.02
<b>Uccle</b>	I	0.64	0.02	−0.19	0.03	−0.82	0.03
	II	0.49	0.01	−0.04	0.02	−0.52	0.02
	III	0.28	0.01	−0.02	0.01	−0.29	0.01
	IV	0.14	0.01	−0.11	0.02	−0.25	0.01
	V	0.20	0.02	0.05	0.02	−0.15	0.01

(the change from one set to the next is mostly seen in the longer term, i.e. annual, evolution, but many shorter-term features, notably in the 2–3-month range, remain). Possibly the main and clearest message is seen in Figs. 3 and 7, notably their bottom rows with the annual pattern of variations in the differences between daily maximum and minimum temperatures and their first time derivative: the corresponding data sets, which contain temperature measurements only, “know” whether measurements are being made during a time of high versus low solar cycle. We will further elaborate on the statistical significance and robustness of these differences in a forthcoming paper.

There is no clear indication in the observations we report that a new source of warming would have appeared either near the middle or near the last quarter of the 20th century. The fact that the pattern remains recognizable in the three separate stations and in different time intervals (Fig. 5) argues that (most of) the signal we extract is not an artifact of the analysis, nor of measurement errors occurring during the long measurement period in these stations. These  $T_H - T_L$  patterns indicate a regional signature (at the scale of Western Europe), modulated by a more local response function.

We do keep in mind that the present study has only a regional character. And, even at this regional scale, variability is significant. This leads us to conclude that the most promising approach to continue this type of work is to start from regional studies, progressively attempting to enlarge the domain under study. As De Jager (2005) points out: “*Therefore, studies based on a supposed unique global variation of temperature or pressure variations, to be characterized by one unique  $\Delta T(\text{time})$ -curve, valid for the whole Earth’s surface, are likely to fail*”. With this proviso in mind, we can however conclude with some more general, yet tentative remarks. One consequence of our study is that numerical values of sensitivities or any parameter linking solar activity (energy input as a function of wavelength) to climate response (notably temperatures) might need to be revisited (see below and also Miura et al., 2005; Chylek et al., 2007).

Reports on a solar impact on climate have come and gone in the literature in the past decades. Among the better known and more generally accepted observations are the connection between low solar activity (including the Maunder sunspot minimum) and cooling (the Little Ice Age, increasingly considered as a global feature) spanning several centuries in the middle of the past millennium, and the extension of this millennial scale correlation backward through the Holocene based on analysis of deep-sea

sediments from the North Atlantic (Bond et al., 2001). The present paper and our other recent work (Le Mouél et al., 2008, 2009; Courtillot et al., 2009) provide increasing evidence of a solar influence on climate, whose forcing mechanism remains to be demonstrated. Forcings by variations in total solar irradiance, UV flux, solar modulation of cosmic rays, downward ionosphere-earth current density, and influence of these on the water cycle and notably cloud cover have been recently argued for by a number of authors. We briefly review some of these.

Satellite measurements have provided an ever more accurate view of the solar radiative output, its variability and its absorption by the atmosphere (e.g. Fröhlich and Lean, 2004). The respective long-term mean values (over 3 solar cycles when we have satellite data) of total solar irradiance (TSI, the integral of spectral irradiance) and mean incident solar radiation (a quarter of TSI) are about 1366 and 341 W m<sup>−2</sup>. The 11-year cycle amplitude in TSI and mean incident solar radiation is on the order of 0.1% (or respectively, 0.3 and 1.3 W m<sup>−2</sup>). Larger variations of order 0.2% are associated with the Sun’s 27-day rotation period. Even larger variations occur at shorter periods. Longer periods were considered as rather negligible (less than 0.1 W m<sup>−2</sup>), but have recently been revised by Scafetta and Willson (2009) to about 1 W m<sup>−2</sup> (the so-called problem of the ACRIM satellite gap), that is a correction by a factor in excess of one order of magnitude. On the other hand, Lindzen and Choi (2009) have recently estimated climate feedbacks from fluctuations in the outgoing radiation budget from the latest version of Earth Radiation Budget Experiment nonscanner data. They find that, for the entire tropics, the observed outgoing radiation fluxes increase with the increase in sea surface temperatures. The observed behavior of radiation fluxes would imply negative feedback processes, associated with relatively low climate sensitivity. This is the opposite of the behavior of 11 atmospheric models forced by the same SSTs. Taken together, the recent papers by Scafetta and Willson (2009) and Lindzen and Choi (2009) could lead to a revision of either sensitivities of climate to atmospheric CO<sub>2</sub> concentration and solar forcing or their respective contributions to global temperature change: taken at face value, they imply a reduction by a factor  $\sim 6$  of the former and an increase of a factor  $\sim 10$  of the latter with respect to generally accepted previous estimates (all these figures with considerable uncertainties).

Moreover, variations in solar irradiance depend strongly on wavelength. In the visible spectral range, solar irradiance reaches maximum values on the order of 10<sup>3</sup> mW m<sup>−2</sup> nm<sup>−1</sup>. In the EUV spectral range, which is largely absorbed by the lower atmosphere but most severely affects space weather and the thermosphere (e.g. Chanin, 2006), solar irradiance is limited to values on the order of 10<sup>−2</sup> mW m<sup>−2</sup> nm<sup>−1</sup> (that is, five orders of magnitude below the visible range) but its variability in a solar cycle exceeds 100% (three orders of magnitude above the visible range). A number of climate models, most of them amounting to a linear response to TSI dominated by the visible spectral range, find the effects of solar activity on temperatures in the lower atmosphere to range from negligible to at most a few tens of percent of total change (e.g. Foukal et al., 2006; IPCC report, 2007). However, there is increasing evidence that a significant part of the influence of solar activity on climate is not fully captured in model predictions (Scafetta and West, 2007; Camp and Tung, 2007; Tinsley et al., 2007; De Jager, 2008). The effect may be far larger than would be predicted from the very small changes observed over the past three solar cycles by satellites (Foukal et al., 2006; Fröhlich, 2006). Based on phenomenological thermodynamic models, Scafetta and West (2007) estimate that “*the Sun might have contributed up to approximately 50% or more*” of the observed global warming since 1900. De Jager and Usoskin (2006) use different sets of global/hemispheric temperature reconstructions

for the last 400 years and find that “in so far as the Sun-climate connection is concerned tropospheric temperatures are more likely affected by variations in UV radiation flux”. The importance of variations in the XUV-EUV solar flux for space weather purposes has been recently reviewed by Lilensten et al. (2008) and the potential importance of connections between large temperature variations in the thermosphere and temperature variations in the lower atmosphere through the downward ionosphere-earth current density  $J_z$  by Tinsley et al. (2007). We briefly recall these two important items.

In a short review, Dudok de Wit (2008) emphasizes again also that relative contributions in all UV emissions amount to only 7% of total solar power, but that relative variations exceed 100% for EUV below a wavelength of 100 nm. These have a significant effect on daily atmospheric variations. The problem is that most models cannot explain how such variations in UV radiations could have noticeable effects down to ground level. Actually, most models do not include the UV flux as such but proxies, such as the decimetric index  $f_{10.7}$ , which represents the solar power emitted at the radio wavelength of 10.7 cm. Yet, this is only a rough approximation. Moreover, models do not correctly account for atmospheric layers above 20 km and do not feature interactions between the various layers. Some recent models, which take into account ozone reactions and chemical reactions linked to UV solar emissions, clearly reveal an impact on climate, but they cannot as yet provide quantitative estimates of temperature changes at the ground. For instance, Haigh (1996) has simulated changes in solar irradiance and ozone with a general circulation model and found that the response of the atmosphere (temperatures, zonal winds and storm tracks) to the 11-year solar activity at solar maximum is similar, though smaller in magnitudes than actually observed ones. The combined effects of ozone and irradiance, and the shortwave radiation scheme used (UV and its high variability distinguished from visible) are essential for the model's success. Haigh advocates a solar-climate link via a chain starting with the UV effect on the middle atmosphere and coupling between the atmospheric layers leading to climate change. The effect is expected to be particularly strong at mid-latitudes and in the North Atlantic, i.e. close to Europe. However, Foukal et al. (2009) have recently found that solar UV flux variations in the ozone-determining wavelength required by this mechanism are only poorly correlated with global temperature variation during the 20th century. They conclude that “although solar UV irradiance variation may affect climate through influence on precipitation and storm tracks, its significance in global temperature remains elusive”. Actually, the poor correlation (computed in the traditional way) could be a result of the complex response of climate to solar activity. This regional and temporal variability has been stressed by many authors (e.g. de Jager, 2005; see also Le Mouél et al., 2008, 2009).

The large variability of the UV solar spectrum remains a good candidate for action of the Sun on climate (Dudok de Wit, 2008), but this requires much additional theoretical and modeling work and stronger evidence in the observations for such an influence. Moreover, short-term meteorological features such as changes in cloud cover or atmospheric temperatures respond to the downward current density  $J_z$  that flows from the ionosphere to the surface. This current generates space charges that can affect microphysical interactions between droplets and ice-forming and condensation nuclei, and therefore affect cloud cover and climate. Tinsley et al. (2007) propose that mechanisms responding to  $J_z$  could explain sun-weather-climate correlations on multi-decadal to millennial timescales.

Another much studied possible link that could connect solar activity and climate variations is the effect of cosmic rays on cloud formation in the atmosphere (e.g. Svensmark, 1998). This has been recently reviewed by Usoskin and Kovaltsov (2008). A small

change in cloud cover will affect the amount of solar radiation absorbed and reflected by the atmosphere (all other terms being equal), and the flux of cosmic rays is modulated by solar activity, providing yet another possible mechanism by which solar and climate variations could be connected. Usoskin and Kovaltsov (2008) summarize the debate generated by the original proposal of Svensmark and Friis-Christensen (1997) between pros and cons of the links between Sun and climate through cosmic rays. The key observation was the persistent and highly significant correlation between low cloud cover and cosmic rays in some geographical regions, which has been confirmed by Voiculescu et al. (2006) and agrees with model results (Kazil et al., 2006). Again, as clearly stated by Usoskin and Kovaltsov (2008), “A use of global or even zonally averaged data may be misleading”. The gradual improvement in building a physical model of the cascade in the atmosphere that leads to the ionizing effects of cosmic rays is described by Usoskin and Kovaltsov (2008): one mechanism involves ionization, which affects production of cloud condensation nuclei, in the presence of aerosols; another mechanism assumes that cloud formation is affected by the atmospheric electric field, with cosmic rays influencing atmospheric conductivity. Recent progress in modeling lower atmosphere chemistry in the laboratory has been obtained by Svensmark (2007). Most recently, Svensmark et al. (2009) have shown that following close passages of coronal mass ejections from the Sun, corresponding to so-called Forbush decreases, low clouds contain less liquid water and water content of the oceanic atmosphere can diminish by as much as 7%. This provides a link between sun, cosmic rays, aerosols, and liquid water clouds. Further studies are clearly needed and some are already in progress (e.g. in Carslaw et al., 2002).

A better picture of the solar effect on temperature of the lower atmosphere may be in sight, despite the complexities, non-linearities and multi-scale character of the processes and responses involved. De Jager and Duhau (2009) use their model of the phase transitions of the solar dynamo to forecast the parameters of the next sunspot cycle (24) and beyond to the next Gleissberg cycle. They predict several decades of continued decrease of peak solar activity, after a transition from a Grand Maximum state back to one of less energetic Regular Oscillations. The most recent satellite observations of TSI reveal a previously unsuspected and quite significant long-term (decadal to secular) decrease as measured from times of solar minima (see also Scafetta and Willson, 2009). After two decades of observed decrease of solar (Fig. 2) activity, and a decade with a slight but real decrease of global mean temperature (e.g. Hadley Research Center website), the coming decade(s) of detailed satellite and surface observations should indicate whether these predictions will pass the test of time.

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