DAILY AIR TEMPERATURE AND PRESSURE SERIES FOR UPPSALA (1722–1998)

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Abstract. Daily meteorological observations have been made in Uppsala, Sweden, since 1722, and complete series of air temperature and sea level air pressure have been reconstructed and homogenised for the period 1722–1998. The reconstruction work was based on the hand written registers and printed monthly bulletins before 1985, after which data was directly stored on computers. Methods to determine daily average temperatures from the typically available 2–3 observations per day were developed. These methods take into account observation times and cloud amount. Pressure reductions back to 1840 involved only routine calculations, while earlier pressure data needed major homogenisations. All data were searched for errors by comparisons with previously determined monthly averages and by different plotting techniques, mainly comparing with independently reconstructed data from Stockholm, 65 km south of Uppsala. This comparison also shows that the quality of the data is generally good, although the reliability is lower before the mid-19th century. Results are given illustrating changes in the daily average temperature and pressure climate on a 200–250 year time scale.

1. Introduction

Instrumental records of the climate in Europe are available since the time of the invention of the meteorological instruments in the middle of the 17th century (Lamb, 1977). These records are detailed indicators of the past climate with a temporal resolution down to the daily values, although commonly only the monthly averages are considered in old data. Very few records, however, are complete for the whole time period since before the 1750s.

Swedish archives are rich in meteorological observation journals from the time before the ‘modern’ instrumental epoch started around 1860. The most well known Swedish meteorological record is that of monthly air temperatures for Stockholm, beginning in 1756, but the longest record is that from Uppsala beginning in 1722. As early as in 1778, the temperature series from Stockholm and Uppsala were used in a study of climatic changes (Wargentin, 1778). These two long temperature series provide important documentary evidence for the variations of the air temperature that have occurred in southern Sweden during the past ∼250–280 years. In view of the increasing interest in climate change due to the increasing amounts of

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greenhouse gases in the atmosphere, it is important to obtain as much information as possible about past climate variations. One source of knowledge in this context is the long records of instrumental observations.

This paper describes the Uppsala climate data series. The daily average temperature and pressure data have been reconstructed, and information on how this has been done is given in detail. Some aspects of climate change over the observational period as regards temperature and pressure is also presented. Focus is then given to results only possible to obtain by having access to data with a daily resolution. Some comparisons with the daily data for Stockholm (Moberg et al., 2002) will also be presented, aiming primarily at acquiring knowledge on the accuracy of the data.

2. Station History

2.1. GENERAL HISTORY

The Society of Science in Uppsala initiated the earliest organised meteorological observations in Sweden around 1720. Other observational sites were also initiated during the 1720s and 1730s, among them were Risinge and Linköping in Östergötland and Bettna in Södermanland (Figure 1). The oldest still available observations from Uppsala are from January 1722. The registers are, however, not complete before July 1773. Major periods with missing data are: June 1732–December 1738, June 1742, April 1745, May 1750–August 1751, April 1766–June 1767, August 1767–December 1767, April–May 1770, August 1770–December 1771, February 1772–June 1773. During the 1760s there are several other shorter periods with missing data. It is, however, possible to construct a complete daily temperature series for Uppsala by extrapolation from data for Risinge, Bettna, Linköping, and Stockholm.

Until August 1853 the observations were made at the Old Astronomical Observatory (59°51.63′ N, 17°38.44′ E, 15 m a.s.l) in the centre of Uppsala, which was then a small town (8 000 inh. in 1860). From September 1853 the observations were taken at the New Astronomical Observatory. This site was then located in open fields just outside the town, about 900 m west of the old site. A few minor relocations were made at the New Observatory, in the Observatory Park, in October 1865, June 1952, and in August 1959. All these sites were however within a couple of hundred metres distance from each other in the vicinity of the observatory. But the area eventually became more and more surrounded by buildings, as Uppsala increased its population to around 120 000 inhabitants in the 1990s. From August 1959 the measurements were made at the Department of Meteorology at Uppsala University (59°51.56′ N, 17°37.52′ E, 13 m a.s.l.), and in January 1998 the measurement site was moved about 1.4 km further south to 'the Geocentre' (59°50.85′ N, 17°38.10′ E, 25 m a.s.l.) as the old Department of Meteorology joined

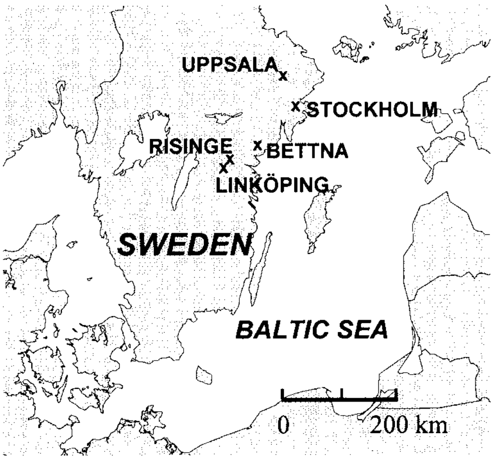

Figure 1. Map of Southern Sweden showing the sites where the 18th century climate observations used here were taken.

the new Department of Earth Sciences. Temperature measurements were, however, taken in parallel at this new site and at the old site in the Observatory Park during almost 3 years.

2.2. OBSERVERS

Erik Burman, professor of astronomy, initiated the observations in the 1720s. A young student, Anders Celsius – who later became professor of astronomy at the university and who invented the ‘Celsius’ or ‘Centigrade’ thermometer scale, was actually carrying out the observations, and was responsible for them after Burman’s death in 1728. A period with missing data from June 1732–December 1738 was related to Celsius’ journeys to other European universities and to his participation in the expeditions to the polar circle in northern Sweden. Back in Uppsala, Celsius arranged that meteorological observations were again brought onto the agenda in 1739. Celsius, now the professor of astronomy, most of the time did not make the observations himself, but they were commonly the responsibility of the astronomical observer (‘observator’), a procedure which seems to have continued for over 100 years.

After the initiation of a Swedish national weather observation net around 1860, the scientific interest in climate observations further increased during the 1860s. From June 1865 hourly observations were made, in the beginning with the help of a large number of students. However from 1868 recording instruments were used (Theorell, 1868), and manual observations were only made on 8 occasions during daytime, from 0600 in the morning to 2100 in the evening. This type of observation schedule was kept until 1958, and students and attendants at the Department of Meteorology, which in 1878 was formed by the scientific branch of the Astronomical Observatory dealing with weather and climate, made the manual observations. From 1959–1984, standard recording instruments were used. These data were checked using manual observations made by students three times per day (0600, 1200, and 1800 UTC). Since 1985 an automatic weather station has been used, only occasionally checked with manual observations.

2.3. OBSERVED VARIABLES

Already from 1722 all the most important meteorological parameters were observed. Temperature and air pressure were measured with instruments. Wind direction and wind strength, judged on a scale from 0 to 4, were noted, together with some short notes regarding clouds, rain, snow, fog, thunder, and other weather conditions. From 1723 also the amount of precipitation was measured. During the 18th century, temperature measurements were commonly made simultaneously on two or more thermometers, especially so before 1750, indicating that it must have been obvious to observers of that time that the use of many different thermometer scales could potentially be a problem when making temperature climate analyses. Two barometers were also often used in parallel during the 18th century.

2.4. OBSERVATION TIMES

It was not until 1832 that the observations in Uppsala began to be taken at fixed hours. During the first 110 years, observations were commonly made 1–4 times per day, often in the morning, in the afternoon, and in the evening. It is obvious from notes and 18th century publications that the climatologists of that time were aware of the need to make the temperature observations at about the time of the daily minimum and maximum temperatures in order to be able to accurately determine the daily average temperature (e.g., Wargentin, 1778). Thus one observation was usually made around sunrise and one in the afternoon. The exact times of the observations were always noted in the registers until about 1790, after which it became more and more common to just note the time as ‘morning’ and ‘afternoon’. It does, however, seem likely that the same routines were followed until 1831, as the observation times, which were now and then, although seldom, noted in the journals, are in agreement with earlier observational routines. From 1832 to 1862, observations were made at 0700, 1400 and 2100. In 1863 the time of the morning observation was changed to 0800. Since June 1865, the observations have been made every hour, 24 times per day, and the mean temperatures are based on arithmetic averages of the hourly observations.

3. The Data

3.1. DATA SOURCES

Data from 1722 to 1854 have been digitised from the original hand written registers, while data from 1855–1862 have been taken from the first printed weather diary from Uppsala, '*Résultat des observations météorologiques faites au novel observatoire d'Upsal'*. For the period 1863 to May 1865 the original hand written journals were used. Data from June 1865 to 1868 were taken from '*Observations météorologiques horaires, exécutées par une Société d'étudiants à l'Observatoire de l'Université d'Uppsala*, and from 1869 to 1958 data have been digitised using the printed Uppsala Bulletin, '*Bulletin mensuel de l'Observatoire météorologique de l'Université d'Uppsala'*. The printing of this bulletin ceased with the 1958 issue, and once again the original weather registers were used. With the introduction of an automatic weather station in 1985, data were directly stored on a computer.

3.2. ERROR CONTROL

The data have been checked for errors in several steps. Already in the original registers monthly averages were commonly determined and weather summaries were made each month. In the early 1980's the monthly average temperatures were recalculated for the period 1722–1854 and compared with the old estimates. It was discovered that a rather large percentage of the original averages were erroneous, and a new series of corrected monthly average temperatures was constructed (Bergström, 1990). After having digitised the daily temperature observations in this study, monthly averages were again computed and compared with the series from the 1980s. When differences were discovered, the digitised data were checked and corrected if errors were found. Due to differences in how the monthly averages have been determined (cf. Section 4.3), the monthly temperature sums have also been compared with the sums from the recalculation in the 1980s in search of errors. No earlier estimates of monthly air pressure were made, that is why similar error controls of pressure could not be made for the period before the first printed bulletin in 1855.

For the period 1855–1958, monthly averages of both temperature and pressure as determined from the digitised daily data have been compared with the estimates given in the printed bulletins (1863–May 1865 in the original registers) and data was checked when differences were found. During the years 1959–1980 no printed diaries exist, and comparisons were again made with earlier recalculated estimates of the monthly averages made in the 1980s. From 1981 to August 1992 data have been digitised monthly on a continuous basis, and from September 1992 stored directly on a PC. Monthly averages have, since 1981, been compared with nearby weather stations.

Finally the daily average data of both temperature and pressure (after homogenisation of the data) have been compared with data from Stockholm. Simply by plotting on a monthly basis the daily differences between the observations in Uppsala and Stockholm, it was found rather easy to detect the majority of printing errors. When larger than expected differences were found, data was checked and corrected if errors were confirmed.

4. Temperature

Before constructing a daily average temperature series, several problems with the original data have to be overcome. For the oldest data, before the Celsius thermometer came into use, knowledge about the thermometers and the thermometer scales that were used, is necessary. There are also problems with how the thermometers were placed, at least before 1739 (cf. Section 4.2). Also the method that was used to calculate daily averages from the individual observations, must be investigated.

4.1. THERMOMETERS

Before 1751 a variety of thermometer scales were used, among them of course Celsius' own thermometer (Figure 2; Celsius, 1742). The observers were, however, already during the period 1720 to 1750 aware of the uncertainties caused by the various thermometer scales, whose fixed points were sometimes poorly determined. As a consequence of this, observations were often made with several thermometers at the same time (e.g., Celsius, de l'Isle, Hawksbee, Réaumur, and Fahrenheit). This makes it possible today to 'calibrate' the poorly determined, or sometimes even unknown, thermometer scales against the thoroughly calibrated Celsius thermometer. Fortunately there are always some overlapping periods with all types of thermometers that were used, making a 'calibration' to degrees Celsius rather straightforward to do back to 1739. An example of such a 'calibration' is shown in Figure 3, giving the relation between the de l'Isle thermometer and the old Celsius thermometer used simultaneously in Uppsala from June 1743 to June 1746.

To calibrate the thermometers used in Uppsala between 1722–1732, the major gap in the Uppsala observations from May 1732 to December 1738 has to be overcome. This was done using the observations made at Risinge during this period. But the thermometer used at Risinge is of unknown origin and with an unknown calibration. Fortunately the observations at Risinge continued until January 1741, and as the observations in Uppsala began again in January 1739 there are two years of simultaneous temperature readings. This enables us to 'calibrate' the Risinge thermometer against the Uppsala data, and the result is shown in Figure 4. As the distance between Uppsala and Risinge is about 200 km, the scatter is of course rather large, but as a mean the result should give temperature data representative of Uppsala from the readings at Risinge. This calibration procedure also automatically

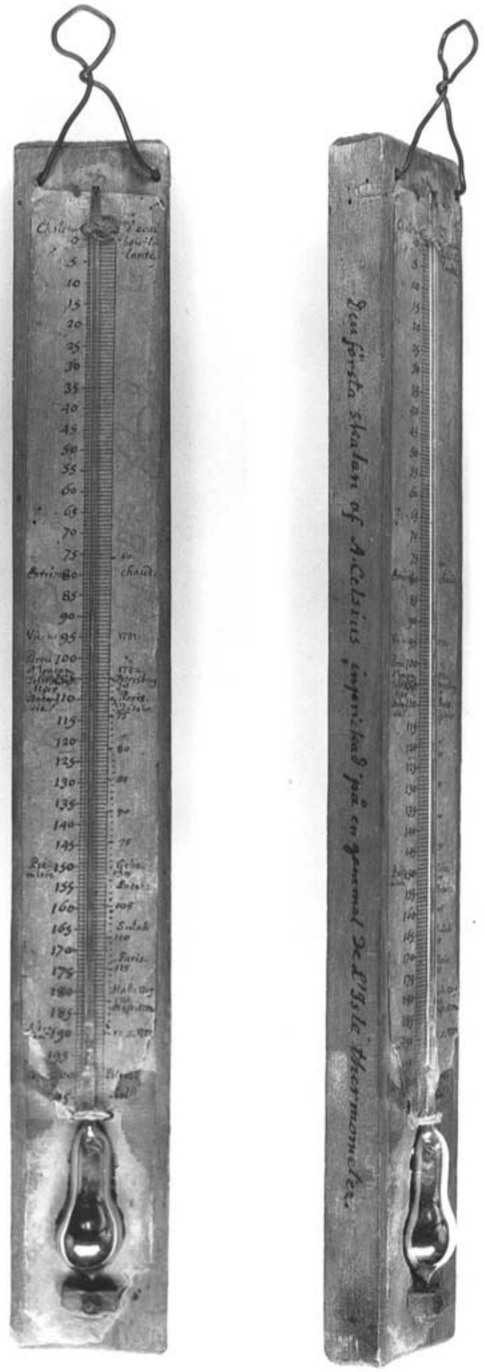

Figure 2. Celsius experimental thermometer with his 100° scale (100° at the freezing point and 0° at the boiling point of water) marked on an old de l'Isle thermometer. (Photo: Gösta H. Liljequist).

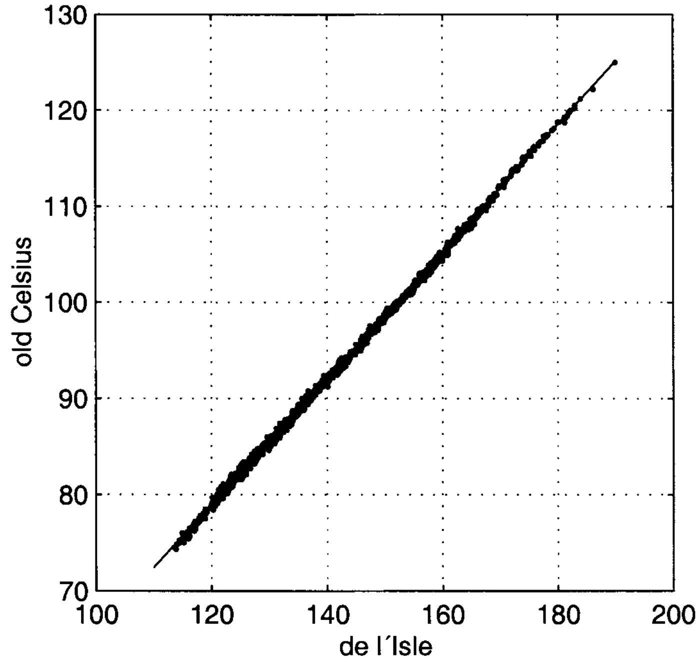

Figure 3. Relation between the de l'Isle thermometer and the old Celsius thermometer with inverted scale used in Uppsala 1743–1746.

takes account of possible differences between the temperature climates at the two sites, although they can be expected to be rather small as judged from modern data.

It then remains to calibrate the oldest thermometers, which were used in Uppsala 1722–1732. Once again this was accomplished by comparing simultaneous readings in Uppsala and at Risinge, this time for the period Jan. 1730 to May 1732. One could argue that it might have been better to use the calibrations of the Hawksbee thermometer used from 1739–1748 also for the earlier Hawksbee thermometers used from 1725–1732. But they were definitely not the same as the one used in 1740. Comparing the calibrations we get using the Risinge data with the calibration from the 1740s, we find that they disagree and that we will get unrealistically high temperatures if we use the calibration for the 1740s in association with the older Hawksbee thermometer. It was also mentioned in the 1740s that several thermometers of the Hawksbee type existed in Uppsala, and that at least two of them disagreed by as much as 12 degrees (Wargentin, 1749), which is in good agreement with the results we get here.

4.2. THERMOMETER POSITIONS

A difficulty with the oldest observations in Uppsala from 1722–1732 is that they followed the recommendations of James Jurin, at the Royal Society in London, about the thermometer position. According to Jurin the thermometer should be

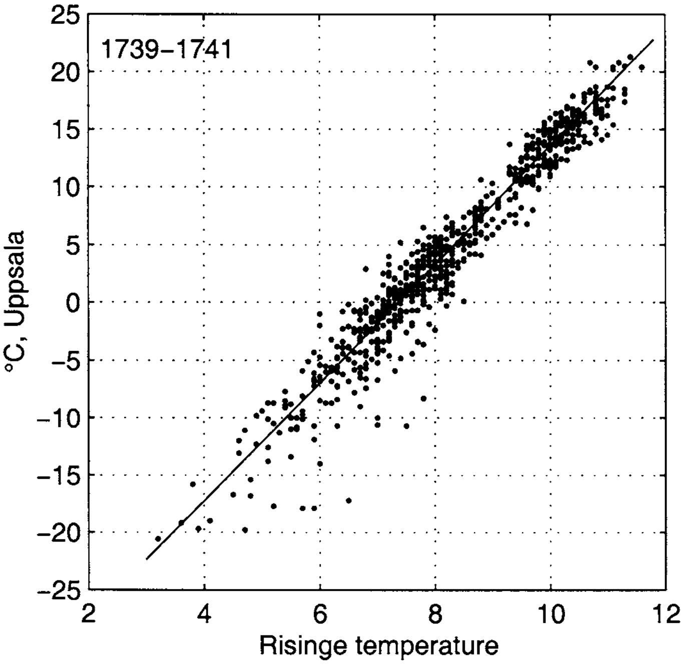

Figure 4. Relation between the thermometer used at Risinge and the temperature readings in Uppsala converted to °C. Data from 1739–1741.

placed in a north facing and well-ventilated room with no fire. This did at least have the consequence that the measured diurnal temperature cycle was much reduced compared to the true outdoor temperature cycle, which is obvious from Figure 5 showing the diurnal cycle for present data (full line) together with the mean of the morning, noon, and evening observations in Uppsala 1722–1732 (×). However, by simply comparing the daily amplitude for the old data with that of the present day, we get a ratio between the two, which can be applied to approximately correct the old data ('o' in Figure 5). As it turns out when comparing monthly averages with and without correction for the reduced diurnal cycle, the difference between the two is small, seldom more than 0.1–0.2 °C. Thus the resulting daily averages should, as a mean, also be rather insensitive to the reduced diurnal cycle, but to individual days the correction could give quite a difference in the daily average temperature as there is probably also a time lag between the measured temperature and the true outdoor temperature, together with a low pass filtering of the data so that the number of hot and cold days will be underestimated (cf. Jones et al., 2002; Moberg et al., 2000). The data for Risinge also show a reduction of the diurnal cycle, but not as pronounced as that for the Uppsala data.

As notes about type of precipitation are given in the records, it is possible to make a rough check on the accuracy of the indoor temperatures and also on the 'calibration' of the thermometer scales by comparing the percentage of liquid

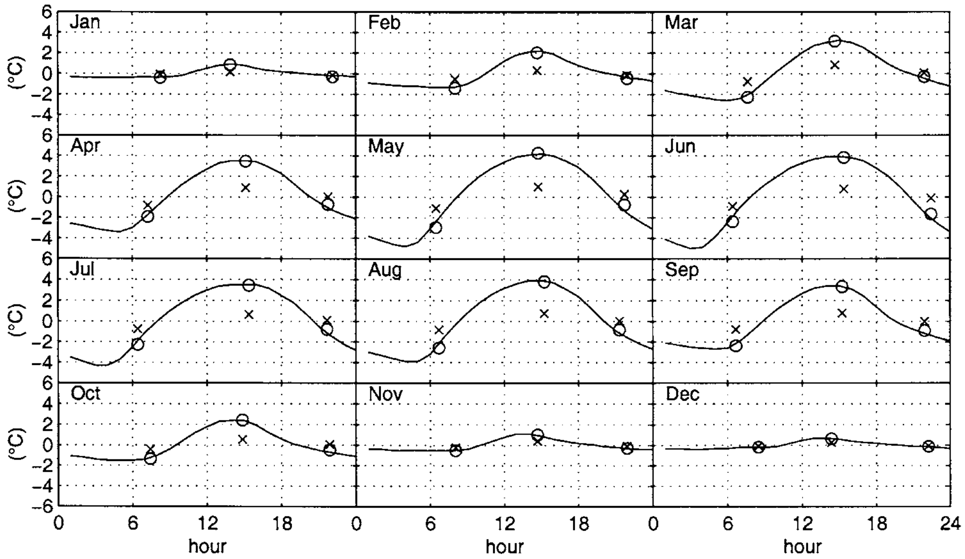

Figure 5. Diurnal temperature cycles with reference to the monthly averages in Uppsala 1961–1990 (full line), and compared to the mean temperature readings 1722–1732 in the morning, in the afternoon, and in the evening. ×: measured values, ○: corrected with a factor in order to take account of the reduced cycle amplitude.

precipitation with temperature. This is shown in Figure 6 for the Uppsala data 1722–1732 and 1739–1750, together with Risinge data and modern data from Uppsala. It is obvious once again that the earliest temperature readings are filtered as a consequence of the thermometer positions, while data from 1739–1750 are much more in agreement with present day data. It is also clear that the temperature readings before 1739 as a mean are about correct around 0 °C, as all curves cross the 50% level at about the same temperature. In spite of this, it is still possible that the indoor measurements may filter off the high and low temperatures such that for example the number of extreme cold days in winter will be underestimated, which could also have the consequence that the winter average temperature could be slightly too high in spite of the good agreement around 0 °C. In view of this, all temperatures before January 12 1739 should be regarded as less accurate, especially on a daily basis.

According to what has been documented in the weather diaries (which is not much), from January 1739 the temperature observations were made outdoors in the free air in the shadow. Nothing more specific is said, however, about the thermometer positions, just some words on a few occasions mentioning the thermometer outside a window or in a shelter/screen, without any details. But comparing the diurnal cycles from 1739 onwards with present day data, show that they are of the same order.

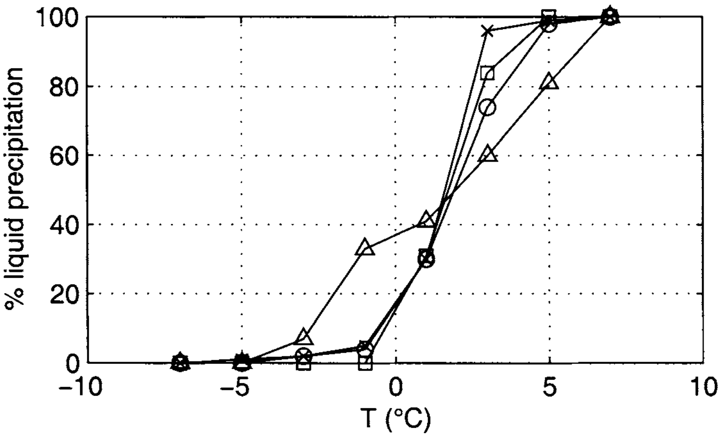

Figure 6. Relation between temperature and percentage of the precipitation falling in liquid form. Data from Uppsala 1962–1982 (×), Uppsala 1739–1750 (o), Uppsala 1722–1732 (△), Risinge 1730–1741 (□).

In 1840 temperature readings began to be noted both outside a window and in the garden, again without any description of shelter. As a mean the differences between these two readings are very small, only some hundredths of a degree on the annual averages 1840–1845. During the same period individual months seldom have differences larger than 0.1 °C, and there seems to be no bias over the year.

From September 1853, when the observational site was moved from the Old to the New Astronomical Observatory in the Observatory Park, then just outside the city limits (cf. Andersson, 1969), the thermometers were placed in a Lawson shelter (cf. Middleton, 1966). From June 1865 to November 1868 126 students of the University made hourly observations, and on October 1, 1865, the shelter was moved about 100 m to a newly built small observation house. An ingenious meteorograph, the ‘Theorell’ (Theorell, 1868), was installed on August 9, 1868. It recorded readings of dry and wet bulb temperatures, and of the mercury barometer every tenth minute. The thermometers were unventilated and placed in a screen located outside a west-facing wall of the observation house.

A new version of the ‘Theorell’, printing figures every quarter of an hour (Theorell, 1872), was installed in 1874 and began to work on August 8. The thermometers were unventilated and placed in a wooden screen about 2 m from the north-facing wall of the observation house, and with the bulb 1.3 m above ground. This instrument worked until June 1, 1952, when the site was moved 200 m to Rackarberget (a small hill). From then a Stevenson screen was used, and the thermometers were ventilated with the bulbs at 1.8 m above ground. On August 17, 1959, the site had to be moved again about 300 m, back to the Observatory Park. The use of a Stevenson screen continued, and Assmann psychrometer readings were made three times per day to adjust the hourly readings made with a thermograph and a hygrograph. From 1982 the height above ground was reduced to 1.5 m, and from January 1, 1985, a

Pt-100 resistance thermometer placed in the screen has been used. After the latest site removal on January 1, 1998, the Pt-100 thermometer placed in a screen has been complemented with a Pt-100 thermometer in a white-painted and ventilated radiation shield mounted in the free air.

4.3. DAILY MEAN TEMPERATURE

To determine daily temperature averages as accurately as possible, it is necessary to take into account the observational hours. Especially during days with just one observation or when the observations were not made close to the time of minimum and maximum temperatures, the estimated daily average could otherwise be quite erroneous. Account must consequently be taken of the observed diurnal temperature cycle. For the period 1722–1839 this was done by estimating the daily mean temperatures according to

$$t_d = \frac{1}{n}(t_1 + f_{cl} \cdot \Delta_1 + t_2 + f_{cl} \cdot \Delta_2 + \cdots + t_n + f_{cl} \cdot \Delta_n)\,, \tag{1}$$

where t_d is the daily mean temperature, $t_1, t_2, \ldots, t_n$ denote the recorded temperatures, $\Delta_1, \Delta_2, \ldots, \Delta_n$ denote the mean deviation from the daily mean temperature at the actual observation hour, and f_{cl} is a scaling factor depending on cloud cover. The number of observations made each day determines the number of terms, n, in the sum. A simplified version of Equation (1) (with $f_{cl} = 1$) was used by Bergström (1990).

The Δ-values at each hour of the day for each month of the year were estimated, making use of the mean diurnal cycles determined from hourly observations from 1869–1958 as illustrated in Figure 7, where the different curves correspond to different 30-year periods illustrating very similar conditions during this 90-year period. It is preferable to use daily Δ-values rather than monthly averages in order to avoid artificial jumps in the daily average temperatures as months are shifted. Therefore daily Δ-values were determined by interpolation between the monthly Δ-values by fitting a step-by-step cubic polynomial to the monthly data for each hour of the day (cf. Moberg et al., 2002), after which a matrix with hourly temperature differences was obtained with one value for each hour of the year. Linear interpolations have been used in case the observations were not made at exact hours.

The cloud scaling factors, f_{cl}, were used to weight the Δ-values according to cloud cover. The amount of clouds was divided into three classes: (1) clear or almost clear skies with a cloud cover of less than or equal to 3/10, (2) half clear with a cloud cover between 4/10 and 7/10, and (3) cloudy with a cloud cover of more than or equal to 8/10. Since 1855, the cloud cover amounts have been given in the registers and bulletins, either in tenths or in eighths, and could consequently be used directly. To classify cloud cover before 1855, somewhat subjective assumptions had to be made in order to translate the cloud observations given in the registers

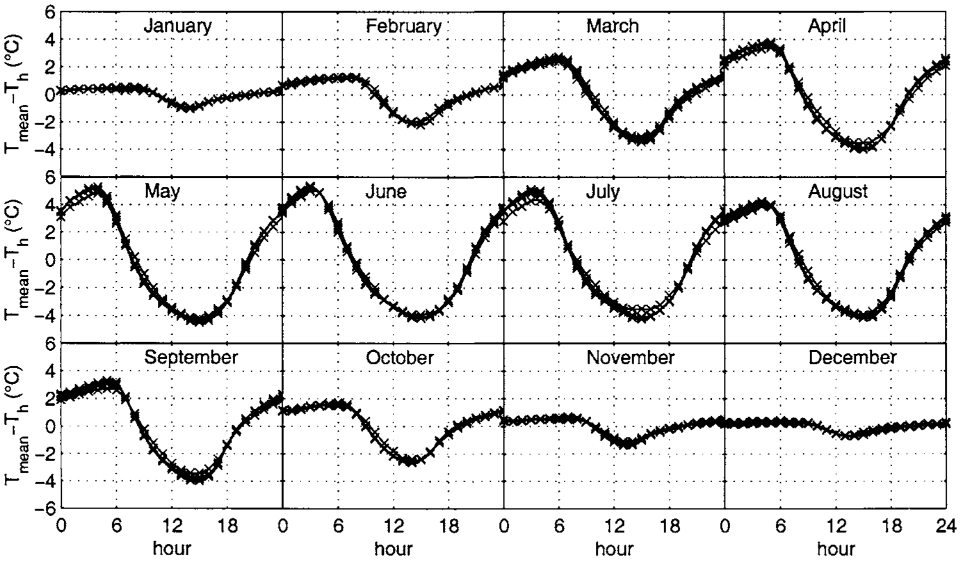

Figure 7. Mean monthly diurnal temperature cycles in Uppsala 1869–1958. The different curves correspond to different periods of about 30 years.

to cloud cover amounts. In the few cases when no cloud observations were noted, half-clear conditions were assumed.

The scaling factor, f_{cl}, was determined for each of the three cloud cover classes and each month of the year according to

$$f_{cl}^{\text{cloud class}} = \frac{\overline{(t_{\max} - t_{\min})}^{\text{cloud class}}}{\overline{(t_{\max} - t_{\min})}^{\text{all data}}}, \tag{2}$$

i.e., the ratio between average daily temperature ranges for each cloud class and for all data. The daily temperature ranges were taken as the difference between the maximum and minimum temperatures. As the daily Δ-values for each hour of the day originally were determined for all data, irrespective of cloud cover, the scaling factor may thus be used directly as a weight when calculating the daily averages. The scaling factors are based on hourly temperature data from 1869–1958. A graph of the daily scaling factors is shown in Figure 8. Again a step-by-step cubic polynomial has been fitted to the monthly data in order to obtain daily values. Temperature amplitudes for clear days are amplified by 1.3 to 1.46 compared to the average amplitude for all data, with the largest values in spring and autumn. Amplitudes for half-clear days are amplified by 1.01 to 1.33, while amplitudes for cloudy days are diminished by 0.66 to 0.82.

On average the differences between the daily mean temperatures estimated by Equation (1) and mean temperatures determined by simply taking the average of the observations are rather small. As can be seen in Figure 9 the average difference over the year varies between about –0.4 °C and +0.2 °C. Taking account of cloud

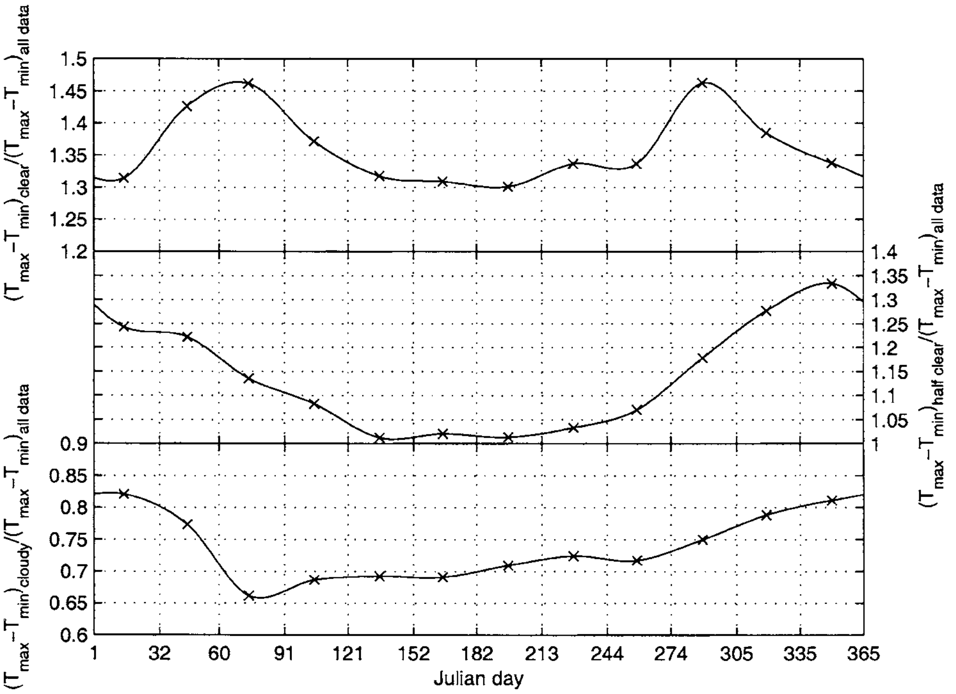

Figure 8. Yearly variation of the ratio between the mean daily temperature amplitude with three different classes of cloudiness and the mean temperature amplitude for all data.

cover can be quite important for individual days, especially if there is only one observation, but, as a mean, including cloud cover into the estimation does not affect the daily averages all that much, as can be seen in Figure 10. The daily mean differences between the averages estimated taking account of cloud cover, and the averages ignoring cloud cover (i.e., using $f_{cl} \equiv 1$) varies between –0.1 and +0.2 °C, being as a mean largest during spring and early summer, amounting to +0.1 °C. The mean difference over the entire period from 1722–1839 is 0.03 °C. The largest observed absolute difference in an individual day is 2.2 °C, and 0.6% of the days have differences larger than 1 °C.

The daily mean temperatures were determined using Equation (1) for the period 1722–May 1865, including the amplitude scaling for cloud amounts. Since June 1865, the observations have been made every hour, 24 times per day, and the mean temperatures are based on arithmetic averages of the hourly observations.

4.4. HOMOGENISATION OF DAILY MEAN TEMPERATURE

Having determined the daily mean temperatures, the series was compared with nearby stations in order to search for errors and inhomogeneities. As the urban area of Uppsala has grown considerably during the last century, a false warming trend is expected in the temperature series. Moberg and Bergström (1997) estimated

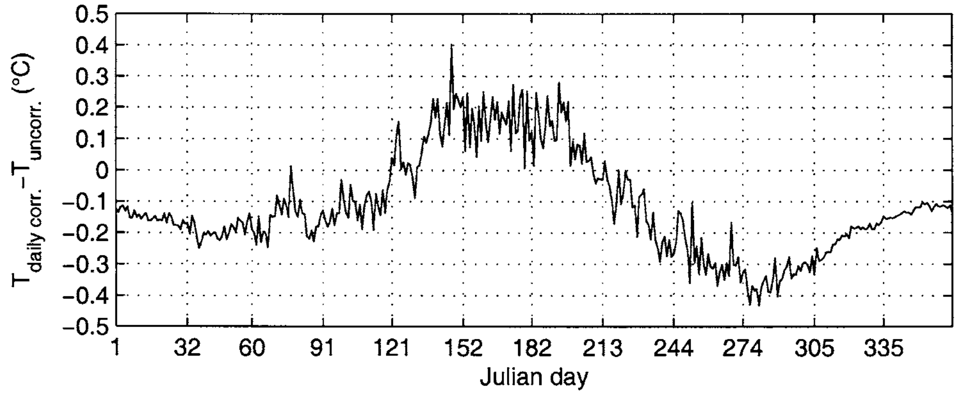

Figure 9. Average difference between daily temperature averages estimated using daily corrections to take into account the observational hours and averages just determined as arithmetic averages of the given observations. Date for Uppsala 1722–1839.

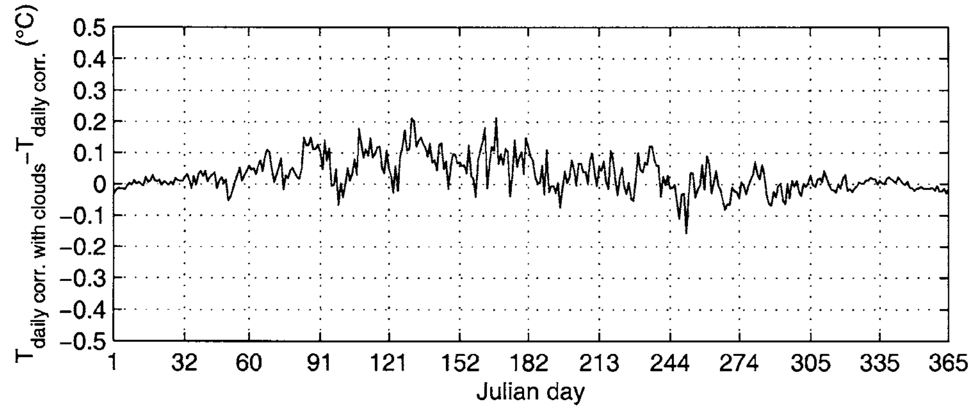

Figure 10. Mean difference between daily temperature averages estimated using daily corrections to take into account the observational hours, with and without taking account of the amount of clouds. Data from Uppsala 1722–1839.

this urban heat island effect on a seasonal basis using a set of 10 homogenised temperature series and found that the annual mean temperature had increased by 0.47 °C since 1861 due to the urbanisation effect.

The homogenisation was repeated here using the same set of 10 stations, but now on a monthly basis, using monthly mean temperatures calculated from the new set of daily mean temperatures. The analysis was made using the Standard Normal Homogeneity Tests (SNHT) for trends and single shift (Alexandersson, 1986; Alexandersson and Moberg, 1997). The exact dates for breakpoints of shifts and for starting and ending points of trend sections as estimated by the SNHT, were observed to vary somewhat between individual months, although the overall appearance was qualitatively the same for neighbouring months. As there were no true reasons to vary the dates of inhomogeneities between months with similar

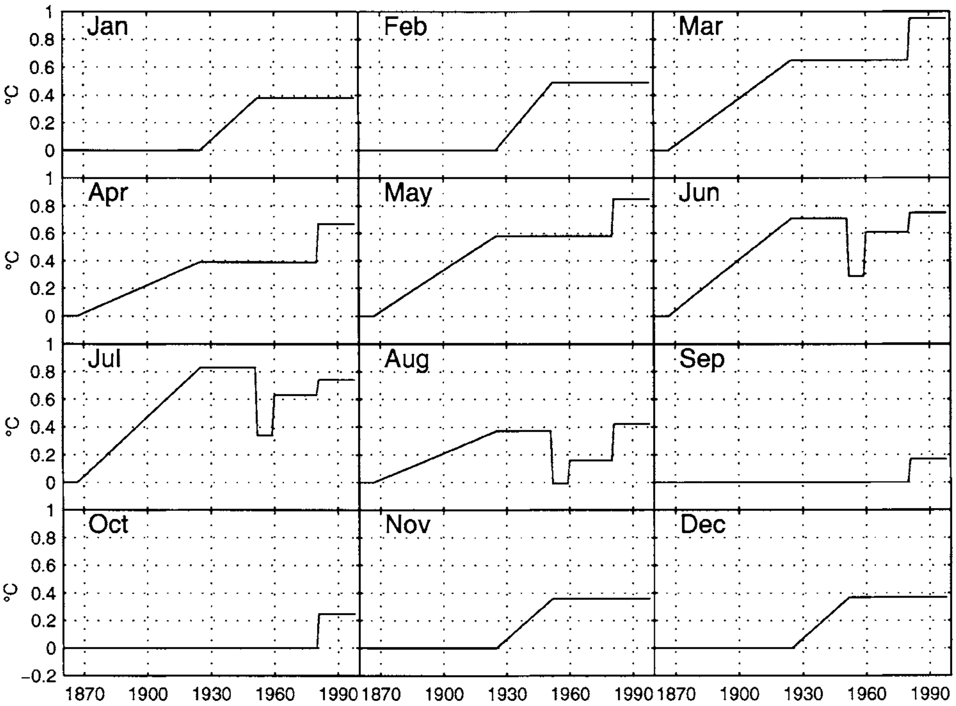

Figure 11. Monthly values of the corrections for the urban heat island according to the homogeneity tests for Uppsala 1861–1998.

behaviour, the same time points were used for groups of months with a similar character of inhomogeneities. These dates were determined from tests on average temperatures for selected groups of months, and were, whenever possible, also chosen to coincide with relocations of the site.

The results of the homogeneity tests are presented in Figures 11 and 12. A significant positive trend for the months March to August started in 1868 and ended in 1925, while the positive trend did not start until 1926 and ended in 1952 for the months November to February, and was completely absent for the months September and October. An abrupt negative jump occurred for the summer months June to August in 1952 and seems to be connected to the relocation of the observation site from the old observation house to Rackarberget, cf. Section 4.2. Possibly the reason for this jump was that the old screen was changed to a freshly white painted Stevenson screen, but this could not be the whole truth as the next site movement in the middle of August 1959 back to the Observatory Park was followed by an almost as large positive jump in 1960. Finally another positive jump occurred in the months March to October in 1981, which may have been caused by the building of new houses west and southwest of the observation site.

Except for the jumps in 1952 and 1960, other jumps and trends may be related to the growth of the urban area, although the effects were not the same during all

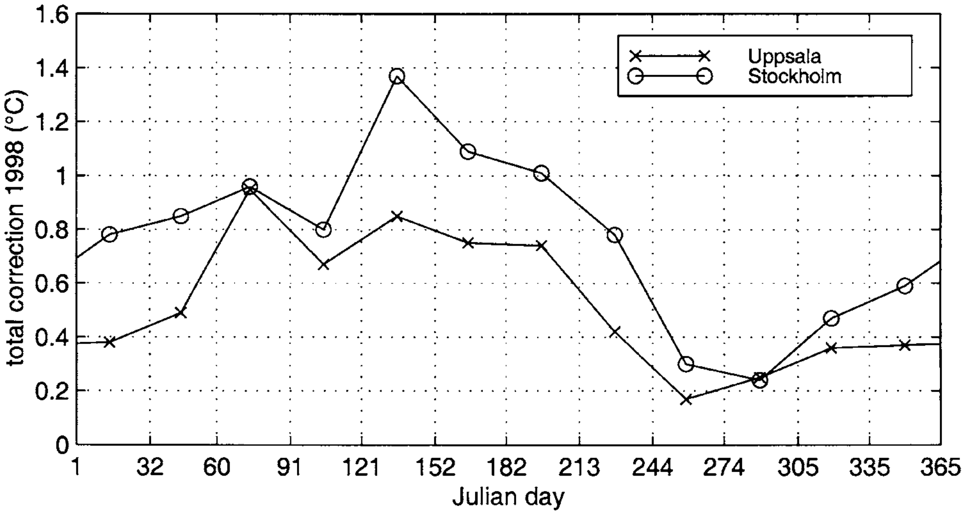

Figure 12. Total effect of corrections for urban heat island and other inhomogeneities in Uppsala and Stockholm 1998 in relation to the conditions in 1861.

parts of the year. The urban warming seems to have affected the spring and summer months first, then the winter months, and last the autumn months September and October which were not affected until 1981 in connection with the building of new blocks on the western outskirts of Uppsala. The total effect of the urbanisation and also other inhomogeneities has caused the annual mean temperature to be 0.53 °C too high after 1981. As can be seen from Figure 12, there is also an annual variation, with a maximum in spring and summer and the highest value, 0.95 °C, in March, while a minimum is found in the autumn with the lowest value, 0.17 °C, in September. A comparison with the corresponding corrections for Stockholm used in Moberg et al., (2002) is included in Figure 12, and shows a similar annual cycle but with the highest value, 1.37 °C, in May and the lowest value, 0.24 °C, in October. The total correction on the annual mean temperature is 0.77 °C for Stockholm.

Homogeneity tests with SNHT on the difference of monthly mean temperature series for Stockholm (Moberg et al., 2002) and Uppsala, also suggest a shift in the Uppsala temperature around 1854, close to September 1853 when the site was moved from the Old Astronomical Observatory in the city centre to the new one just outside the city limits. An early urban heat island effect can thus be assumed to have affected the Uppsala temperatures before that date, and we have chosen to correct the early part of the series to correspond to the conditions that prevailed in the Observatory Park during the 1850s and 1860s. In that way the homogenised Uppsala temperature series should be as representative as possible of the rural conditions around Uppsala. Monthly mean values of the different corrections used to homogenise the Uppsala temperatures are given in Table I. The corrections were applied with specific daily values, which were obtained through interpolation between the monthly values.

Table I

Monthly values used to correct the Uppsala temperature series for inhomogeneities. For columns giving one year in the heading, the numbers given are the corrections used from that year onwards. For columns with trend sections, the first and last values of the linearly changing corrections are given. A dash (–) indicates the use of the same corrections as an earlier period. The corrections, after having been interpolated to daily values, are subtracted from the daily mean temperatures to obtain the homogenised series

	1722	1853	1854	Trend section 1868–1925	Trend section 1926–1952	1952	1960	1981
J	0.11	–	0.00	–	0.00–0.38	–	–	–
F	0.47	–	0.00	–	0.00–0.49	–	–	–
M	0.66	–	0.00	0.00–0.65	–	–	–	0.95
A	0.55	–	0.00	0.00–0.39	–	–	–	0.67
M	0.27	–	0.00	0.00–0.58	–	–	–	0.85
J	0.15	–	0.00	0.00–0.71	–	0.29	0.61	0.75
J	0.11	–	0.00	0.00–0.83	–	0.34	0.63	0.74
A	0.03	–	0.00	0.00–0.37	–	–0.01	0.16	0.42
S	0.08	0.00	–	–	–	–	–	0.17
O	0.19	0.00	–	–	–	–	–	0.25
N	0.24	0.00	–	–	0.00–0.36	–	–	–
D	0.22	0.00	–	–	0.00–0.37	–	–	–

4.5. COMPARISONS WITH STOCKHOLM

Except for the shift in 1853, the daily Uppsala temperatures have up to this point been homogenised independently of the reconstructed Stockholm series (Moberg et al., 2002). A comparison on a daily basis revealed a number of occasions with obviously erroneous daily mean temperatures. In each case we tried to identify which of the stations it was that had the incorrect data and corrections were applied. Except for some scattered days with printing errors from the data digitising, the only period identified for which the Uppsala temperature data was incorrect was 6 May to 30 June 1833. Comparisons were made not only with data for Stockholm, but also with data for Strängnäs, about 65 km south of Uppsala and Tolvfors, about 100 km to the north. As the other three stations show very similar temperatures, we decided not to use the Uppsala data from this period, but instead used Stockholm temperatures and extrapolated the temperatures for the erroneous period on the basis of a linear regression relation obtained for the period 1756–1835. It is worth noting that in a remark in the original registers it is said that '*the observations for the years 1833, 1834, 1835, are unreliable as I was abroad. GS*'. (The initials *GS* stands for Gustav Svanberg, later professor of astronomy at the university). This

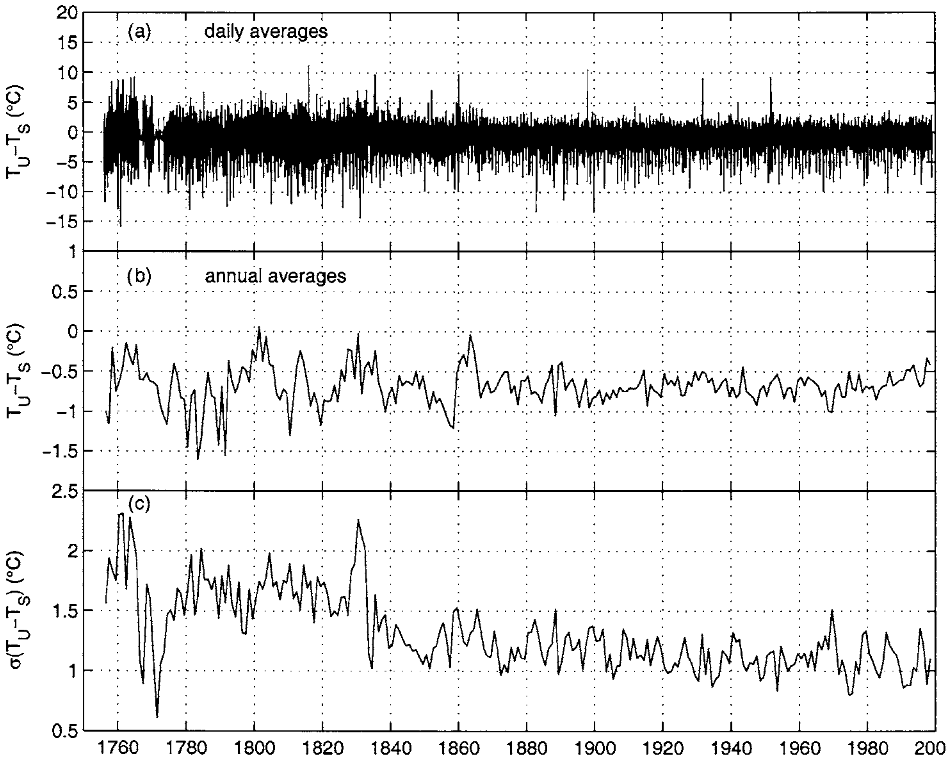

Figure 13. Comparison between temperature observations in Uppsala and Stockholm: (a) difference between the daily average temperatures in Uppsala and Stockholm; (b) difference between the annual average temperatures in Uppsala and Stockholm; (c) annual values of standard deviation of the daily average temperature difference between Uppsala and Stockholm.

period with less reliable observations is also obvious as regards the air pressure data, (cf. Section 5.4).

The temperature difference between Uppsala and Stockholm, using the final version of both series, is plotted in Figure 13. In subplot (a) the difference is plotted on a daily basis, showing that for individual days the temperature may differ by as much as 10–15 °C, although as a mean the difference is commonly 0 to 1 °C. This can be seen in Figure 13b, showing the annual mean temperature differences. In Figure 13c, the annual standard deviation of the difference is plotted. It is obvious that the data series before the middle of the 19th century shows a larger scatter, indicating that the earlier data from one or both stations are less reliable. The standard deviation series, plotted in Figure 13c, shows smaller values after about 1835.

Following Moberg and Bergström (1997), we assumed that the variance after about 1835 is due to natural variability, while the variance for the earlier data may be regarded as the sum of natural variability and some random error caused by imperfections in the data and the procedures used to determine the daily averages.

Using this assumption on the daily temperature series, a rough estimate of the accuracy of the early daily temperatures shows that 95% of the individual daily mean temperatures for both series are correct to within ±1.1 °C.

4.6. TEST OF SUMMER TEMPERATURES

In view of the rather poor knowledge about thermometer positions for the early part of the temperature series, it is relevant to ask if direct sunshine hitting the thermometers might have given rise to radiation errors. Especially this could be the case regarding the morning observations during summer if the thermometers were located outside a north-facing wall. As any bias associated with direct sunlight clearly must be larger for clear sky conditions than for cloudy conditions, one way of testing for radiation errors is to calculate separately summer average temperatures for three cloud conditions: clear, half clear, and cloudy. The resulting annual summer averages are plotted in Figure 14. If the radiation errors were larger for the early period, before the middle of the 19th century, the early summer temperatures would be expected to be larger than temperatures after the mid-19th century for clear sky conditions. There is, however, no evidence of such an increase of early clear sky temperatures. Rather, increased temperatures seem to be more evident for cloudy and half clear skies than for clear skies. The reason for this behaviour is not clear, but we may conclude that any problem with direct sunlight on the early thermometers is not significant.

4.7. SOME DAILY TEMPERATURE CLIMATE STATISTICS

The mean annual temperature cycle based on the daily average data from 1722–1998 is shown in Figure 15 (thick black line), together with the limits (thick grey lines) given by adding $\pm\sigma_{Td}$ to the mean value, and the observed highest and lowest daily mean temperatures for each day of the year. In the lower part of the figure the annual variation of the standard deviation of the daily mean temperature is shown in more detail.

As could be expected, the annual cycle estimated from direct observations of daily averages have a rather smooth appearance when based on a 277-year long record. One feature, hard to verify from monthly averages, is the plateau like behaviour with almost constant average temperatures through the winter, from the end of December to the end of February. In view of the large standard deviations, being about 6 °C in winter, falling to 2.5–3.0 °C in summer and early autumn, the smaller irregularities in the mean annual cycle curve may be expected to be insignificant, although the accuracy of single daily mean temperatures is given by $\pm\sigma_{Td}/\sqrt{n}$, where $n = 277$, and not by the standard deviation itself. This decreases the uncertainty of the temperature average for individual days to about ±0.7 °C in winter and to ±0.3 °C in summer on a 95% confidence limit. In view of this, the tendency for two minima in the annual cycle, one just after new-year, and another in the middle of February, may not be totally insignificant. As can be seen

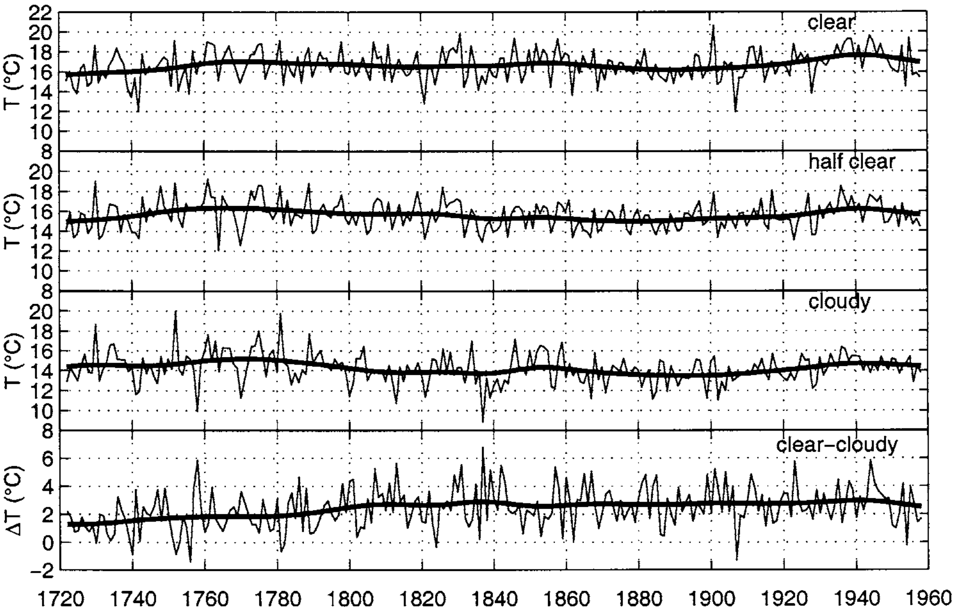

Figure 14. Summer average temperatures in Uppsala 1722–1958 divided into three classes of cloud cover, and temperature difference between clear and cloudy skies. The smooth curves are made using a Gaussian filter with standard deviation of 9 years.

in Figure 16, showing the annual cycle for eight 30-year periods (the earliest period is 29 years long) given by the thin black lines, compared to the 1961–1998 average given by the thick grey line, this behaviour can more or less be observed in most of the 30-year periods.

The annual cycle of the standard deviation is also similar for the different 30-year periods, and most periods show the rather sudden decrease in variability from the end of March to the beginning of April, followed by a slight increase in variability again with a maximum at the end of May, before the summer minimum. It is expected to have maximum variability in winter and minimum in summer, as the north-south temperature gradients are largest in winter. This is also due to the development of strong ground-based inversions, which is more favourable in winter at the high latitudes of Uppsala. The minimum in variability at the beginning of April, followed by an increase in the variability during two months before the summer minimum, is probably connected to the snow melting, which occurs during this part of the year. As the temperature of melting snow always is at 0 °C, this has a stabilising effect on the air temperature and reduces the variance. This effect can be observed for most of the 30-year periods as we can see in Figure 16.

The distribution of the daily average temperature is plotted in Figure 17, showing the expected negative skewness with a tail towards low temperatures, together with a double peak where one maximum is found for temperatures between 0 and 1 °C, the other peak at temperatures around 14 °C, and a minimum around 7–8 °C.

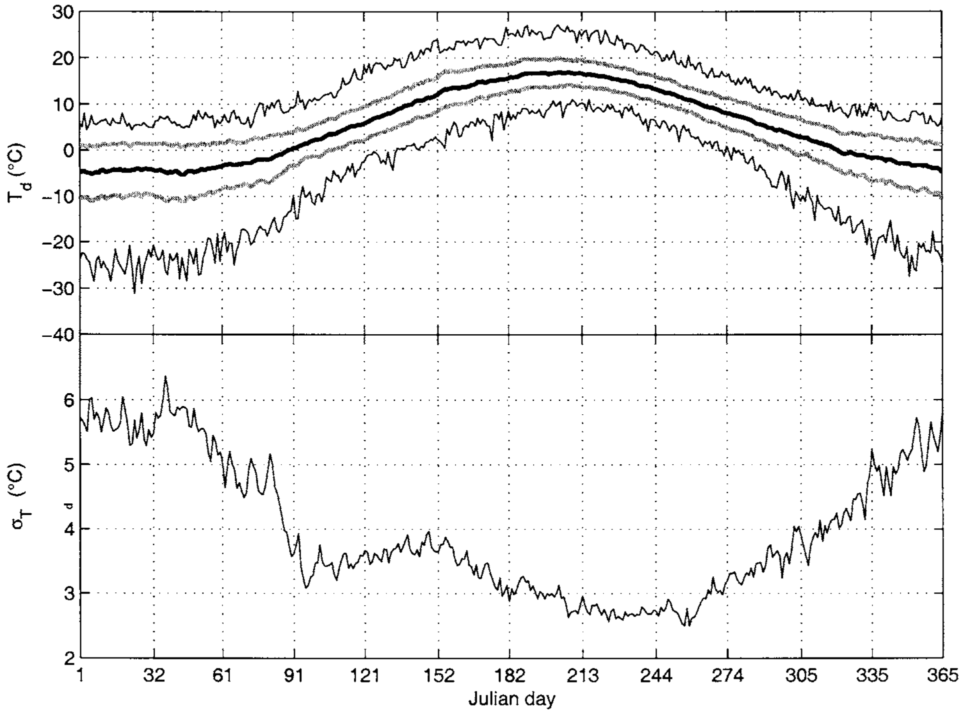

Figure 15. The top figure shows the mean annual temperature cycle based on daily temperature averages 1722–1998 (thick black line), together with limits (thick grey line) given by adding $\pm\sigma_{Td}$ to the mean value. Also shown are the extreme highest and lowest daily averages. The bottom figure shows the mean annual cycle of $\pm\sigma_{Td}$, the standard deviation of the daily averages as determined for each day of the year.

The peak at 0–1 °C is probably mainly a consequence of snow cover during the winter season, giving temperatures close to 0 °C during melting conditions. The secondary peak at 14 °C indicates a dominant occurrence of temperatures close to that originating both from the summer season and from warm late spring and early autumn days. The minimum shows a relatively less importance of typical spring and autumn days in the annual distribution.

Comparing the temperature distribution from three centuries, (bottom part of Figure 17), we see that the dominant peak at 0–1 °C is very pronounced for all centuries, while the secondary peak is more variable. During the 18th century this peak was more flat and at higher temperatures, 14–16 °C. In the 19th century it was closer to 15 °C, while for the 20th century the secondary peak has been located at an even lower temperature of around 13–14 °C. It may also be noted that the highest probabilities for warmer days are found in the 18th century, in agreement with the somewhat warmer summers then, and that this increased probability for warm days is mainly compensated by smaller probabilities for days with an average temperature between 5 and 14 °C, while the distribution for wintertime tempera-

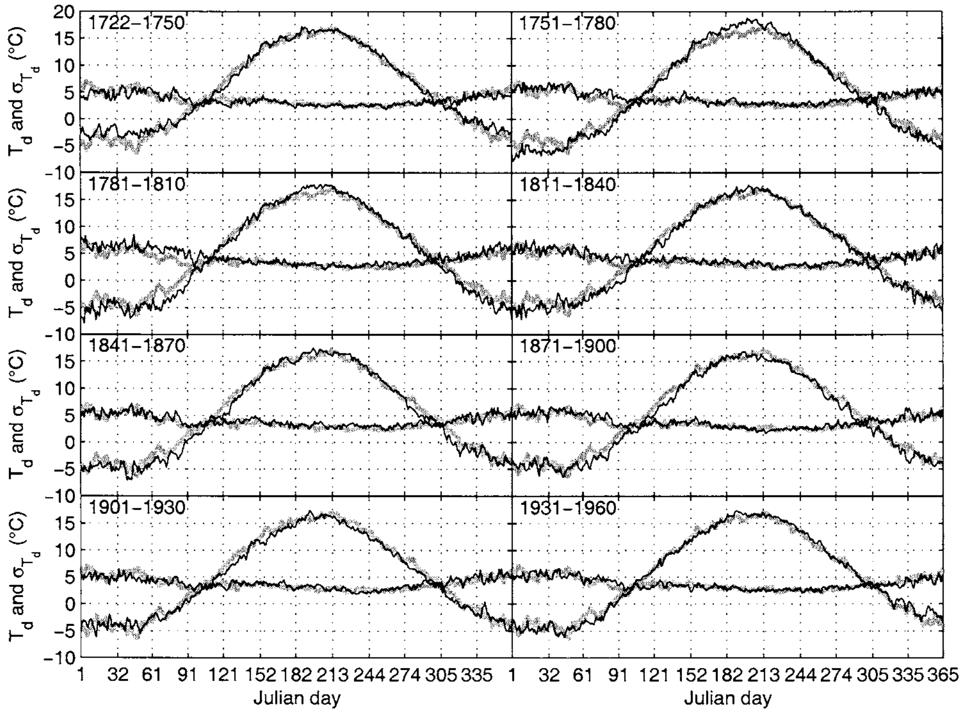

Figure 16. Mean annual cycles of daily average temperature and of the standard deviation of the daily average temperature, given for eight 30-year periods (the earliest period is 29 years) as thin black lines, and compared to the corresponding averages for the period 1961–1998, given as thick grey lines in all subplots.

tures looks much like the 20th century distribution except for somewhat smaller probabilities in the temperature range –3 to 1 °C and a small increase in probabilities for days with temperatures around 4 °C. During the colder 19th century, we observe an increased probability for daily average temperatures below –4 °C, with a corresponding decreased probability for days with temperatures between 4 and 14 °C. The warm end of the distribution during the 19th century appears to be much like that in the 20th century.

To conclude this section on daily temperature climate statistics, we will look for trends in annual daily average temperature extremes, in annual variability of the daily means as measured by the annual standard deviation of the daily mean temperatures, and in asymmetry of the annual distribution using the skewness as a measure. The results are plotted in Figure 18. The years 1722–1738 (delimited by the thick vertical line in Figure 18) are excluded in the following discussion as the 'indoor' measurements during these years (cf. Section 4.2) caused the temperature data on a daily scale to be unrepresentative for true outdoor conditions.

Looking at the warmest day of each year as represented by the highest daily average temperature, we see a falling trend of about 2 °C, as given by the Gaussian

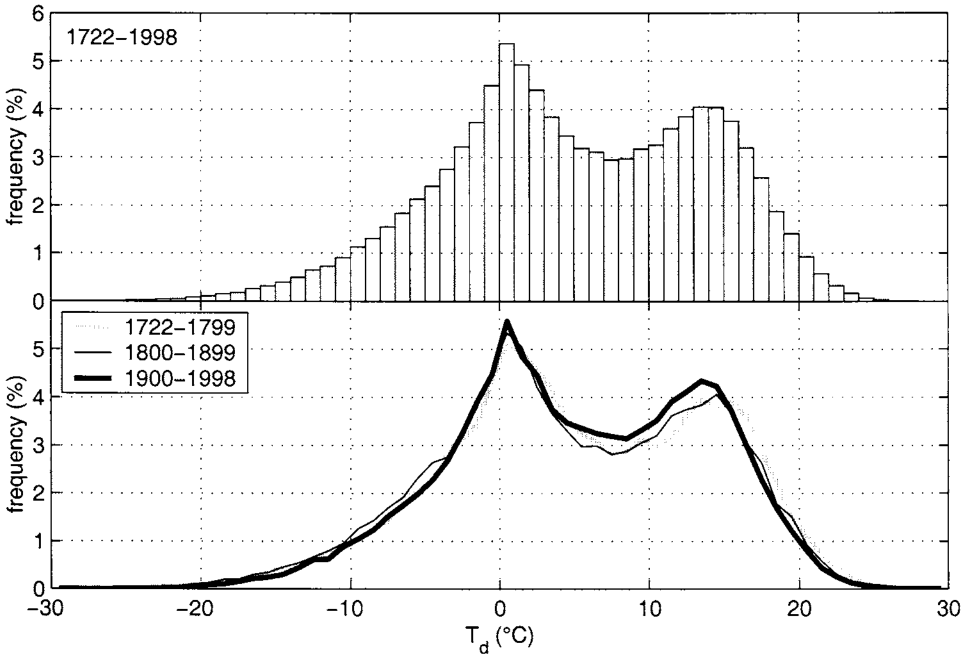

Figure 17. Frequency distribution of daily mean temperature for the whole period 1722–1998 (top subplot). In the bottom subplot the distributions for the 18th, 19th, and 20th century data are compared.

filtered curve, from the middle of the 18th century towards the end of the 19th century. During the 20th century there was some smaller variability with a warmer period in the 1930s and also high values after 1980, but the mean of the highest daily averages are still about 1 °C colder than in the 18th century.

The coldest days of the year on the other hand, show an increasing trend from around 1800, when the filtered value indicates that the annual minimum of the daily temperature average was about –22 °C, while the corresponding number has increased to around –15 °C in recent times. During the 18th century, the coldest day of the year decreased from about –19 °C in the 1740s.

The combined effect of the trends in the warmest and in the coldest days of the year on the mean annual daily average temperature range, is that from a more or less constant mean value of 43–44 °C during the latter part of the 18th century, it decreased during the whole of the 19th century to about 38 °C in 1900. During the 20th century the rate of decrease of the extreme temperature range was small, but since 1980 was again decreased, and is now about 37 °C as a mean.

Thus the temperature climate has, in terms of the difference between the warmest and the coldest days of the year, become less continental since the 18th century. This tendency towards a temperature climate with smaller extreme values as regards the daily means, can also be observed in terms of the annual values of

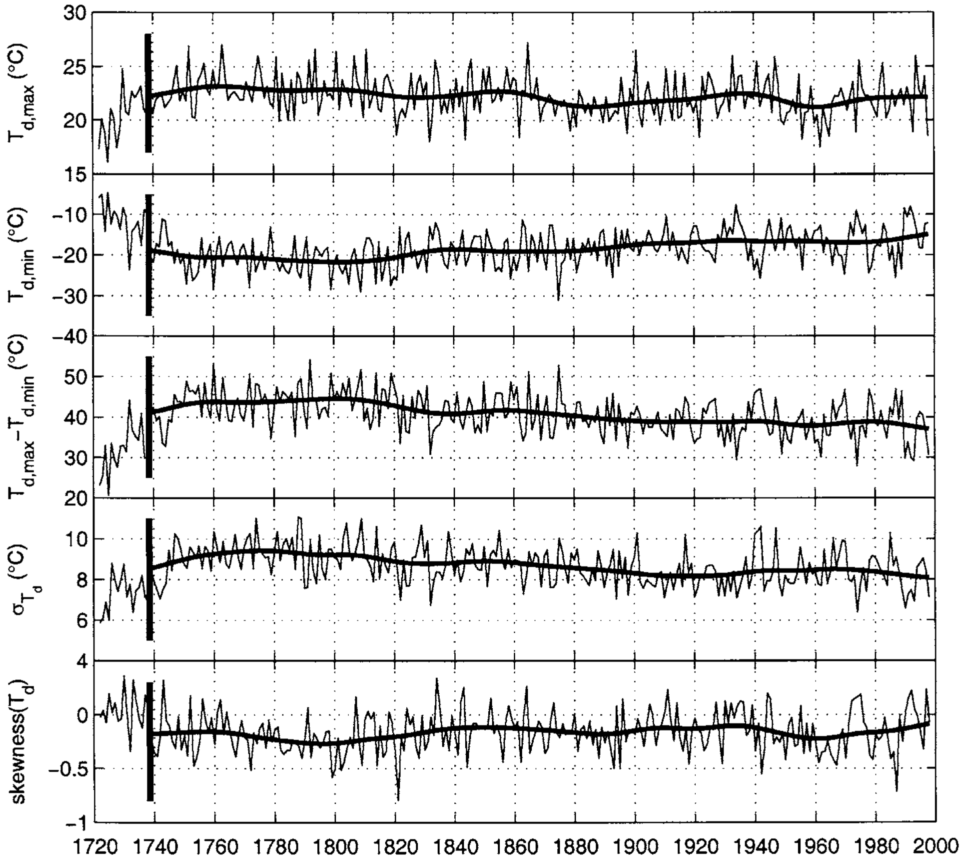

Figure 18. Daily average temperature statistics for Uppsala 1722–1998 giving from the top down: highest annual daily temperature mean, lowest annual daily temperature mean, difference between the warmest and coldest day each year, annual standard deviation of daily temperature means, and annual skewness of daily temperature means. The smooth curves are made using a Gaussian filter with standard deviation of 9 years. The vertical lines at 1739 delimit the old 'indoor' data, which are not accurate on a daily basis.

the standard deviations of the daily temperature averages, also shown in Figure 18. From its highest level at about 9.5 °C as a mean during the 1770s and 1780s, the standard deviation values have decreased to 8 °C in the 1990s, indicating a less variable daily average temperature climate.

The bottom subplot in Figure 18 shows the annual skewness of the daily average temperature. The tendency is that the predominantly negative skewness has become smaller since the 18th century. From average values around –0.3 in the 1790s, the skewness increased to almost –0.1 in the 19th century, and has, after a period with smaller values, gone down to –0.25 around 1960, again increased to –0.1 on the average during the 1990s. This supports the trend in the annual minimum daily average temperatures. The major changes in the temperature climate are found in less extreme cold spells, while changes as regards the warmest days are smaller.

5. Pressure

To reconstruct and homogenise the air pressure data was a rather difficult task for the period before 1840. The barometers used then are poorly known, no indoor temperatures were noted, and the exact height above sea level is unknown. From 1840 onwards it was, however, straightforward to construct the pressure series reduced to 0 °C, normal gravity, and sea level height. But in order to obtain a homogeneous series it was necessary to make a number of corrections to the early part of the series. In this section we will describe how the homogenisations were made, and a homogeneous air pressure series back to 1722 will be presented.

5.1. BAROMETERS

Information about the barometers used in Uppsala is given in Table II. The only sources of information on the types of barometers used before 1840 were the original registers where sometimes the column headers give the name of the barometer. As this information is far from complete, it is quite possible that changes of barometers might have occurred on more occasions than are indicated in Table II.

During the earliest period, 1722–1732, the barometer readings were always in English inches. Several barometers were used, sometimes in parallel. The barometer observations made at Risinge, Bettna, and Linköping, used during periods with missing data for Uppsala 1732–1751, were also given in English inches. The Hawksbee barometer was used during the 1740s until August 1749, from 1745 in parallel with a barometer constructed by Celsius in Uppsala. Observations on the Celsius barometer (in Swedish inches) continued until July 1754. In June 1753 two other barometers constructed in Sweden began to be used. They were both constructed by Professor Strömer at Uppsala University, and were named ‘large tube’ and ‘small tube’. Both Strömer barometers were used during the rest of the 18th century, except for about four years in the 1770s when it appears that another barometer was used.

The barometer observations continued to be given in Swedish inches until September 1839, but from 1801 no information is given in the registers as regards the barometer type. Only one barometer was used during this time, and it was possibly one of the Strömer barometers. In May 1833 readings of the indoor temperature at the barometer began to be noted.

In September 1839 another barometer came into use in Uppsala. Its units were in French inches and according to later notes given in the first printed monthly bulletin in 1855, it was probably a Pistor barometer. From 1840 reductions to 0 °C were done directly in the journals. The French barometer was used until 1862, and

Table II

Barometers used in Uppsala, 1722–1998

Barometer type	Period	Unit	Height	Reductions	Indoor-temp.
Hawksbee?	1722–1749.08.28	English inch	∼15	No	No
Celsius	1745.01.01–1754.07.16	Swedish inch	∼15	No	No
Strömers large and small	1753.06.01–1774.10.31	Swedish inch	∼15	No	No
‘My barometer’ (Erik Prosperin?)	1773.08.01–1777.10.06	Swedish inch	∼15	No	No
Strömer’s large and small	1777.10.04–1800.04.06	Swedish inch	∼15	No	No
Strömer’s large	1800.04.06–1800.12.31	Swedish inch	∼15	No	No
Strömer’s large?	1801.01.01–1833.05.28	Swedish inch	∼15	No	No
Strömer’s large?	1833.05.29–1839.09.30	Swedish inch	∼15	No	Yes
Pistor	1839.09.21–1853.08.31	French inch	∼15	0 °C from 1840	Yes
Pistor	1853.09.01–1862.12.31	French inch	∼19	0 °C	Yes
Åderman	1863.01.01–1865.05.31	mm Hg	∼19	0 °C	Yes
Åderman	1865.06.01–1951	mm Hg	24	0 °C	Yes
Fuess	1952–1965.10.31	hPa	15	0 °C and normal gravity	Yes
Fuess	1965.11.01–1998.01.31	hPa	13.5	0 °C and normal gravity	Yes
Fuess	1998.02.01–	hPa	31	0 °C and normal gravity	Yes

in 1863 a new barometer whose units were mmHg began to be used. In the bulletin of 1865 it was noted that a barometer made by Åderman in Sweden was used, and probably this barometer was already taken into use in 1863. The Åderman barometer seems to have been used together with the Theorell meteorograph (cf. Section 4.2) in order to correct the readings of this early type of automatic weather station.

From 1952 the barometer observations were printed in hPa (mbar) in the bulletins, and in addition to the correction to 0 °C, a correction to normal gravity was made from this year. This change was made in connection with the relocation of the barometer site from the small Observation House to the new building where the Department of Meteorology had been relocated. From November 1965 a Fuess Normal Barometer has been used as the standard instrument to correct the automatically registering instruments.

5.2. BAROMETER LOCATION

The exact barometer location during the early part of the pressure series is unknown. The Old Astronomical Observatory in the centre of Uppsala, where the observations were made until August 1853, is a three-storey building. The astronomical instruments were placed in a small wooden building on the roof of the observatory. The barometer was also possibly located there as, at least according to the indoor temperature readings that were noted from 1833, the temperature at the barometer varied over the year from typically 2–3 °C in winter to 18–19 °C in summer. Thus the barometer must have been located in an unheated room, which is to be expected for the room where the astronomical instruments were kept. A comparison between the uncorrected Uppsala series and the corrected Stockholm pressure series (Moberg et al., 2002) was made, and showed that, before 1840, there was definitely an annual cycle in the pressure difference between Uppsala and Stockholm, although the amplitude of this annual cycle varied over time. As Stockholm has indoor temperature readings as early as 1785, this variation was most likely caused by different temperature conditions at the location of the barometer in Uppsala.

We conclude therefore that the barometer in Uppsala may have been moved between different rooms in the Old Observatory, or at least the room with the barometer was heated during some periods and not heated during other periods. The barometer locations at Risinge, Bettna, and Linköping are also unknown, and we do not have any information about barometer temperatures at these sites either. In view of the uncertainties of the reduced pressure values, which follow from not knowing the barometer temperatures, it is less important to know the exact altitude of the barometer, and we have simply assumed a mean altitude of 15 m during the period until August 1853.

In September 1853, when the observation site moved to the New Observatory, the barometer was located in the observatory at an altitude of about 19 m. A few years later, in June 1865, the barometer was moved to the small meteorological Observation House with an altitude of 24 m. The barometer altitude changed to 15 m in 1952, when it was moved to the new house of the Department of Meteorology, and again in November 1965, due to moving it to another room in this building, the altitude decreased to 13.5 m. From February 1998, when the observation site was removed to the new Geocentre, the barometer height has been 31 m.

5.3. REDUCTION TO 0 °C, NORMAL GRAVITY, AND SEA LEVEL

To be able to compare and analyse measurements of air pressure at different sites, it is necessary to correct for differences in temperature, as the barometer readings will depend not only on the pressure itself but also on the temperature of the mercury and on the scale upon which the readings are made. By an international agreement it has been decided to make a reduction to the common temperature 0 °C. It is also necessary to correct for differences in the acceleration of gravity between different sites, and the barometer readings should therefore be reduced to a value $g_0 = 9.80665\ \mathrm{ms}^{-2}$. Finally the barometer reductions include transforming the observations to mean sea level. All these reductions were accounted for before further homogeneity tests were made, and they will be briefly described in this section. Corrections for expansion and contraction of the wooden frame to which the barometer is fastened, due to air humidity changes, has been disregarded as they are very small in comparison with other errors, cf. Moberg et al., 2002.

After first having transformed the pressure observations to mmHg from English inches (= 25.4 mm), Swedish decimal inches (= 29.69 mm) and French inches (= 27.08 mm), using the equation

$$p_{sg} = g_0 \cdot \rho_0 \cdot H_t \cdot (1 - \gamma \cdot t) \cdot 10^{-5} , \tag{3}$$

where p_{sg} = air pressure at station level reduced to 0 °C (hPa), $g_0 = 9.80665\ \mathrm{ms}^{-2}$ (normal acceleration of gravity), $\rho_0 = 13.5951 \cdot 10^3\ \mathrm{kg} \cdot \mathrm{m}^{-3}$ (density of mercury at 0 °C), H_t = height in mm of the mercury column at temperature t in °C, $\gamma = (\gamma_{Hg} - \gamma_{\mathrm{brass}}) = 1.63 \cdot 10^{-3}\ \mathrm{K}^{-1}$ where γ_{Hg} and γ_{brass} are the thermal expansion coefficients for mercury and brass respectively, and t = barometer temperature (°C).

As the barometer temperature, t, was not recorded until May 29, 1833, it was not possible to use Equation (3) directly. First, a model for the annual variation of the indoor temperature had to be made. In view of a rather strong variation over time of the annual cycle in pressure difference between Uppsala and Stockholm (not shown here, cf. Section 5.2), it was judged sufficient to use the indoor temperature data from the period 1836–1839, see Figure 19, (data from 1833–1835 show a different behaviour and were not used) to make an estimate of the average annual cycle of the barometer temperature, and not, as in Moberg et al. (2002), develop a model for the indoor temperature using a filtered value of the outdoor temperature. A reduced annual cycle, given by the dashed line in Figure 19, was used for some

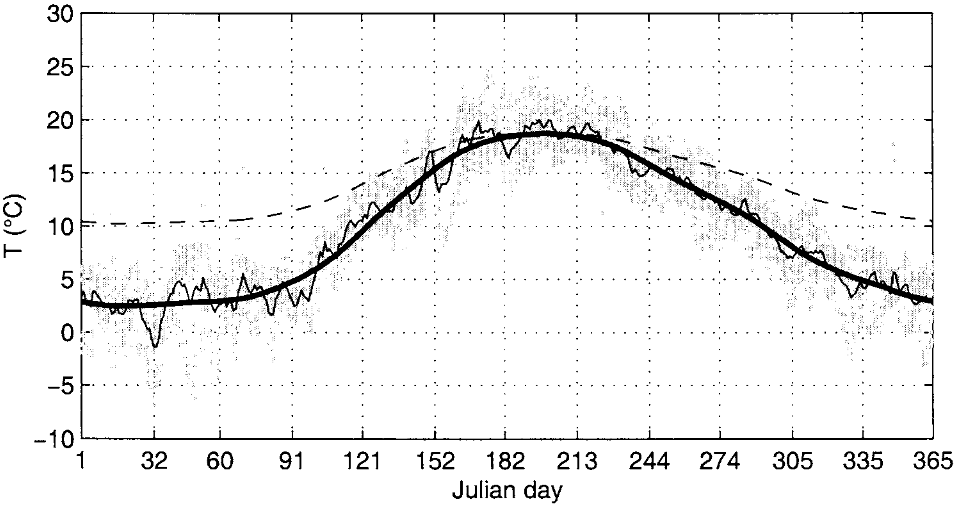

Figure 19. Annual cycle of the indoor temperatures at the barometer, 1836–1839. The scattered data points are the individual observations, the thin line show the averages for each day of the year, the thick line is a smoothed average curve determined by step-by-step cubic interpolation of the daily averages, and the dashed line with a reduced amplitude is used during periods when the barometer room seems to have been heated during the winter.

periods when comparisons with the Stockholm pressure data indicated that the room where the barometer was located must have been heated in the winter.

Having estimated the air pressure values at 0 °C for the period 1722–1839, we proceeded by reducing to normal gravity using the equation

$$p_s = \frac{g_\varphi}{g_0} \cdot p_{sg} , \tag{4}$$

where p_s = pressure at station level reduced to 0 °C and normal gravity and $g_\varphi = 9.8192\ \mathrm{ms}^{-2}$ (acceleration of gravity at station latitude 59°51′ N). This was done for the period 1722–1951, as data from 1952 onwards had already been reduced to normal gravity.

Finally the reduction to mean sea level pressure was made for the whole pressure series using the relation

$$p = p_s \cdot e^{\left(\frac{g_\varphi \cdot z}{R_d \cdot T_m}\right)} , \tag{5}$$

where p = air pressure reduced to 0 °C, normal gravity, and mean sea level ($z = 0$), z = barometer altitude (m), $R_d = 287.04\ \mathrm{J \cdot K^{-1} \cdot kg^{-1}}$ (gas constant for dry air), and T_m = mean temperature of a fictitious column of air between station level and sea level (K). For stations close to sea level, as in the case of Uppsala, it is sufficient to use the station screen height temperature.

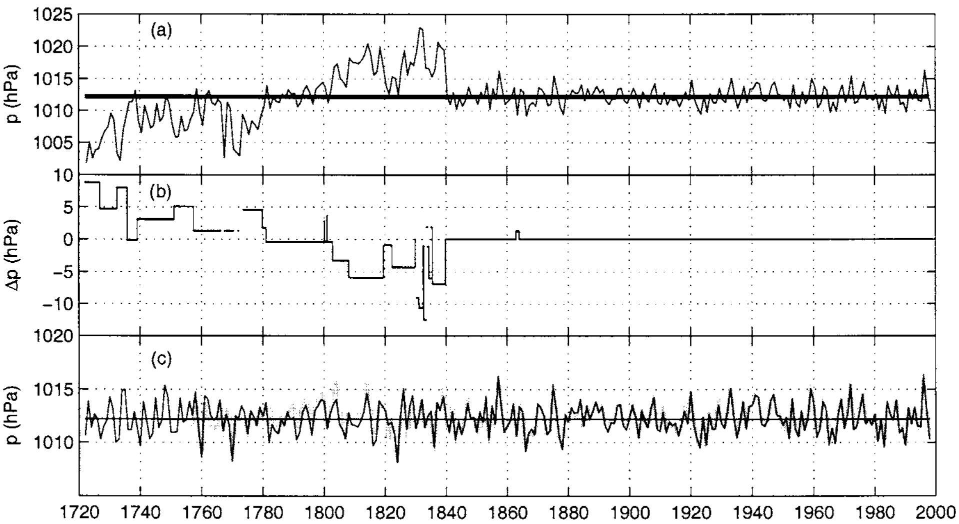

Figure 20. Annual mean sea level pressure at 0 °C and normal gravity for Uppsala 1722–1998. (a) Time series before homogenisation of the data. (b) Corrections applied to homogenise the data. (c) Time series after homogenisation, together with the corresponding annual averages for Stockholm (grey line). The lines correspond to the mean value 1840–1998, 1012.2 hPa.

5.4. HOMOGENISATION OF SEA LEVEL PRESSURE

Up to this point the pressure observations have been reduced to a common temperature of 0 °C, to normal gravity, and to sea level. Annual averages of this pressure series are shown in Figure 20a. It is obvious that the data are quite homogeneous back to 1840, while before that year large inhomogeneities exist, except possibly for a couple of decades at the end of the 18th century.

The entire pressure series was internally homogeneity tested on a monthly basis. The SNHT for single shifts and linear trends (Alexandersson and Moberg, 1997) was used to search for abrupt and gradual changes. We started by testing the earliest part of the series, and the length of each test period was chosen so that it did not include more than one inhomogeneity, as the SNHT does not allow more than one abrupt change. When possible, the test periods were chosen according to known breaks in the data, such as the early Uppsala period 1722–May 1732, the Risinge period from June 1732–December 1738, or when notes on change of barometer were made in the registers. If it was not possible to relate a break to the station metadata, the precise date of change was located by a comparison with the pressure data from Stockholm, looking for discontinuities in the pressure difference on a daily basis. When this scanning had been completed, we decided to treat all identified inhomogeneities as shifts rather than allowing for periods with trends.

The pressure data between 1722 and 1839 were then corrected using two methods. With method 1 the mean value within each sub-period, regarded by SNHT as homogeneous, was set equal to the long-term average for 1840–1998, which is 1012.2 hPa. This was the only way to homogenise the data before 1780. With method 2, which could be used from 1780 to 1839, reference series from the North Atlantic Climate Data Set (Frich et al., 1996) and from ADVICE (Jones et al., 1999) was used, cf. Moberg et al. (2002).

As we have seen in Figure 20, the pressure series seems to be homogeneous back to 1840, and no corrections have been made to this part of the data except for the year 1863. This year a new barometer came into use (cf. Section 5.1 and Table II), and by comparing with the reference series and with data from Stockholm it was noted that a correction of +1.4 hPa was needed for that year.

All data before October 1839 had to be corrected, as several earlier sub-periods were identified by the SNHT as having different systematic errors. Due to the uncertainty in the temperature corrections, a check for the existence of any annual cycle in the difference between the pressure in Uppsala and Stockholm was made. This led to the identification of one period, 1808–1829, when a reduced annual cycle (cf. Figure 19) was used to model the indoor temperature. For all other periods the observed average for the period 1836–1839 was used. When this special treatment of the period 1808–1829 had been applied, no obvious systematic annual variation in the pressure difference between Uppsala and Stockholm remained, and the corrections determined in the homogeneity test were simply added to the observed pressure after reduction to 0 °C, normal gravity, and mean sea level. Comparisons were also made with pressure data for Stockholm for identification of the exact dates of the breaks. Some problematic periods still remained after the first homogenisation. These periods were 1779–1781, 1800–1801, and the first half of the 1830s. For these periods a direct comparison with data for Stockholm was used to obtain the corrections.

Details on the corrections are given in Table III, and the corrections are also plotted in Figure 20. Some of the dates for identified breaks coincide with documented changes of barometers or broken instruments, but most dates remain unexplained by metadata. It is obvious that the early half of the 1830s was a period with less accurate data. The magnitude of the corrections jumps up and down, sometimes with only about a week's interval. The reason for this is uncertain. It could be either a malfunctioning barometer or observers unable to handle the barometer. However, the breaks before 1840 typically occur on a decadal time scale.

In Figure 21 a comparison is made between the homogenised annual average air pressure for Uppsala and the corresponding data for Stockholm and for the grid point 60° N 20° E series. The pressure difference fluctuates around zero for the whole period, but the difference between Uppsala and Stockholm indicates that before about 1860 the quality of the data from one or both sites is less good. Comparing with grid point 60° N20° E, the differences seem to be larger before about 1840. We can also see from Figure 21c that the difference between the almost completely internal homogenisation (method 1), and the homogenisation using the reference series, is very small except for the latter half of the 1830s. This lends

Table III

Corrections applied to homogenise the sea level pressure series for Uppsala using method 1, keeping the average at the same level as 1840–1998 (1012.2 hPa)

Period	Correction (hPa)	Remarks
1722.01.12–1726.10.31	+8.8	
1726.11.01–1732.05.30	+4.7	
1732.05.31–1735.09.30	+8.0	Data from Risinge this period
1735.10.01–1739.01.11	–0.2	Data from Risinge this period
1739.01.12–1750.12.31	+3.1	Data from Linköping May 1750–Aug. 1751
1751.01.01–1757.05.31	+5.1	
1757.06.01–1772.12.31	+1.3	
1773.01.01–1779.10.31	+4.6	New barometer 1773
1779.11.01–1781.01.31	+1.8	
1781.02.01–1800.02.08	–0.4	
1800.02.09–1800.04.05	+2.8	
1800.04.06–1800.12.30	–0.4	
1800.12.31–1801.02.14	+3.7	
1801.02.15–1802.10.29	–0.4	
1802.10.30–1808.02.29	–3.3	
1808.03.01–1819.07.17	–5.9	
1819.07.18–1822.03.31	–0.9	Barometer error noted 1819.07.17
1822.04.01–1829.11.16	–4.3	
1829.11.17–1829.12.31	0.0	Barometer out of order, no data 1829.12.01–1830.03.31
1830.01.01–1831.01.31	–9.0	
1831.02.01–1832.06.15	–10.6	
1832.06.16–1832.06.25	–1.0	
1832.06.26–1832.06.30	–10.6	
1832.07.01–1732.07.14	–1.0	
1832.07.15–1832.07.21	–10.6	
1832.07.22–1832.09.30	–1.0	
1832.10.01–1833.06.30	–12.5	
1833.07.01–1833.12.31	+1.9	
1834.01.01–1834.05.31	–1.1	
1834.06.01–1834.12.31	–6.0	
1835.01.01–1835.07.08	+1.9	
1835.07.09–1839.09.30	–6.9	
1839.10.01–1862.12.31	0.0	New barometer 1839.10.01
1863.01.01–1863.12.31	+1.4	New barometer 1863.01.01
1864.01.01–1998.12.31	0.0	

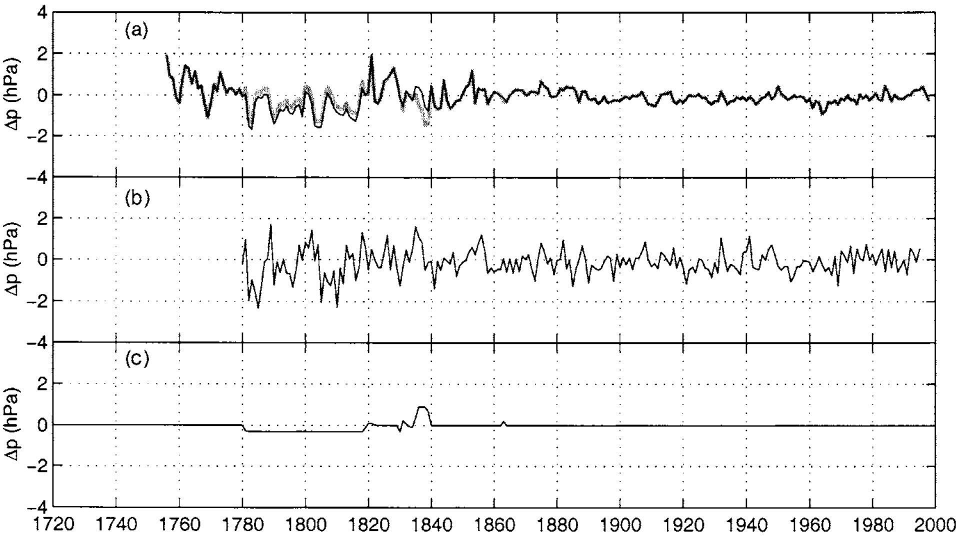

Figure 21. Annual averages of homogenised air pressure differences between: (a) Uppsala and Stockolm – the black curve represents Uppsala data homogenised so that the mean value 1840–1998 (1012.2 hPa) was kept (method 1), while for the grey curve reference data from the grid point 60° N 20° E was used (method 2); (b) Uppsala (method 1) and grid point 60° N 20° E; (c) method 1 and method 2, used to homogenise the Uppsala series.

some support to method 1, which had to be used prior to 1780 if Stockholm data were not to be used as reference. We avoided this as far as possible in order to keep the two series essentially independent of each other, whereby a comparison between the two will give some indications on the accuracy of the early data. Forcing the average to 1012.2 hPa, however, obviously prohibits the discovery of any long-term trend in air pressure, at least for the period before 1780.

5.5. SOME DAILY AIR PRESSURE CLIMATE STATISTICS

The daily averages of the reduced and homogenised sea level pressure data were determined simply by taking the arithmetic means of all observations during each day. The homogenised (according to method 1 throughout this section) annual average pressure series for Uppsala is plotted in Figure 20c, together with the corresponding series for Stockholm, and, as can be seen, the two pressure series are very similar as expected, given the short distance between the stations.

The average annual cycle of the air pressure is shown in Figure 22a. A maximum of about 1015 hPa is found in May, and a minimum of 1010–1011 hPa occurs in July. Winter shows the highest variability, connected to the more intense cyclonic activity. This can also be seen in the annual cycle of the standard deviation of all 277 years for each date (Figure 22b) which has a minimum in summer and a maximum in winter. The higher variability in winter is also obvious from Figure 22c,

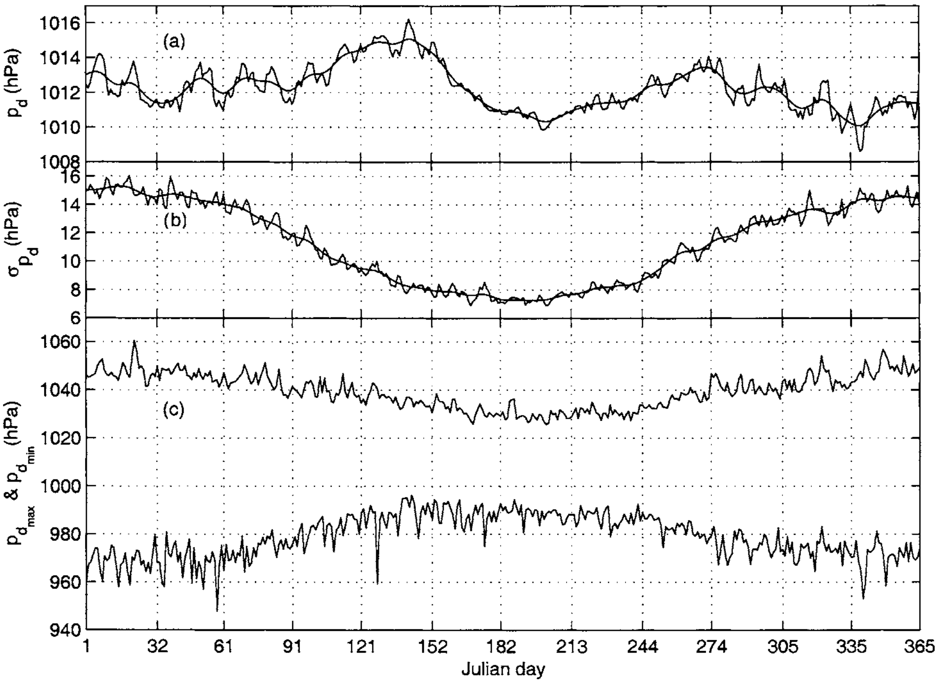

Figure 22. Mean annual cycles, 1722–1998 of: (a) daily mean sea level pressure; (b) standard deviation of daily averages; (c) maximum and minimum of daily average pressure. The smooth curves give Gaussian filtered averages using a standard deviation of 4.2 days.

which shows the annual cycles of the extreme highest and lowest daily averages. Typically the highest maxima and the lowest minima are found in winter.

The 30-year mean annual cycles are illustrated in Figure 23, where the averages for the periods before 1960, given by the black lines, are compared to the average cycle from 1961–1998, given by the grey line. The typical spring maximum and summer minimum are found for all periods although differences in details occur. For example the summer minima of 1722–1750 and 1901–1930 are found later in the summer compared to other periods, and the spring maximum is seldom the maximum of the year. Instead this maximum is often related to some winter or autumn peak, but due to the high variability in winter, these peaks are not found at the same dates when comparing the 30-year periods and consequently the annual maximum is found in May when looking at the whole period from 1722–1998, cf. Figure 22. Most periods depict a very high variability in winter on a time scale of a few weeks, but some periods clearly show less variation than others, e.g. comparing 1811–1840 and 1931–1960.

The distribution of the daily average air pressure (Figure 24) shows a peak at about 1013 hPa, i.e., at a somewhat higher value then the mean value, 1012.2 hPa. This is due to the negatively skewed distribution (cf. Figure 25) with a tail towards lower pressure and a median value at 1012.7 hPa. Comparing the distribution from

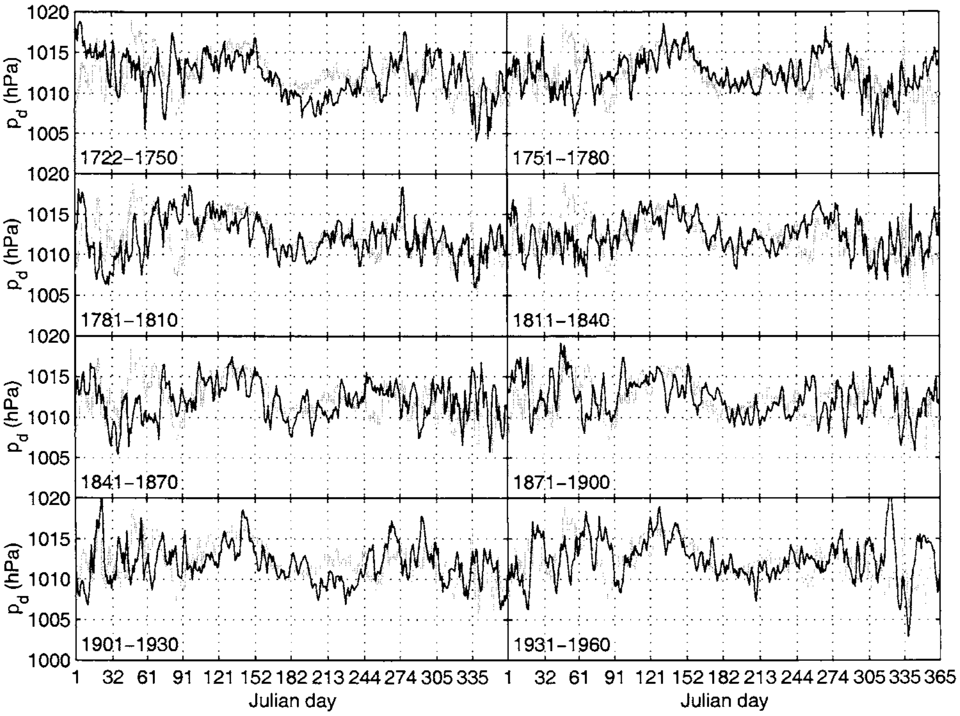

Figure 23. Mean annual cycles of daily average sea level pressure, given for eight 30-year periods (the earliest period is 29 years) as thin black lines, and compared to the corresponding average for the period 1961–1998, given as thick grey lines in all subplots.

three centuries (Figure 24) we see that they resemble each other much more than the corresponding distributions of the daily average temperature (Figure 17). The only more marked difference is the wider maximum for the 18th century, for which period the maximum is also located at a lower pressure than for the other periods. This is related to a skewness closer to zero for the 18th century, giving the median 1012.5 hPa as compared to 1012.8 hPa for the 19th century and 1012.6 hPa for the 20th century.

The variation over time of some annual air pressure statistics is given in Figure 25. The annual maxima of the daily average pressure do not show any clear trend over the centuries, but by looking at the filtered curve, two periods with lower maximum values may be seen, one around 1820 and another around 1970. Regarding the annual minima, a weak trend may be seen, with highest minimum values in the 1720s and around 1800, with a lower level in between. After about 1820 the mean level remained rather constant until about 1970, after which the minimum values decreased to the lowest level throughout the series.

As the annual maxima have remained at a more or less constant level, the annual range of the daily average pressure shows an increasing trend from about 64 hPa in the 1720s to about 72 hPa in the 1990s. This indicates that the climate has become

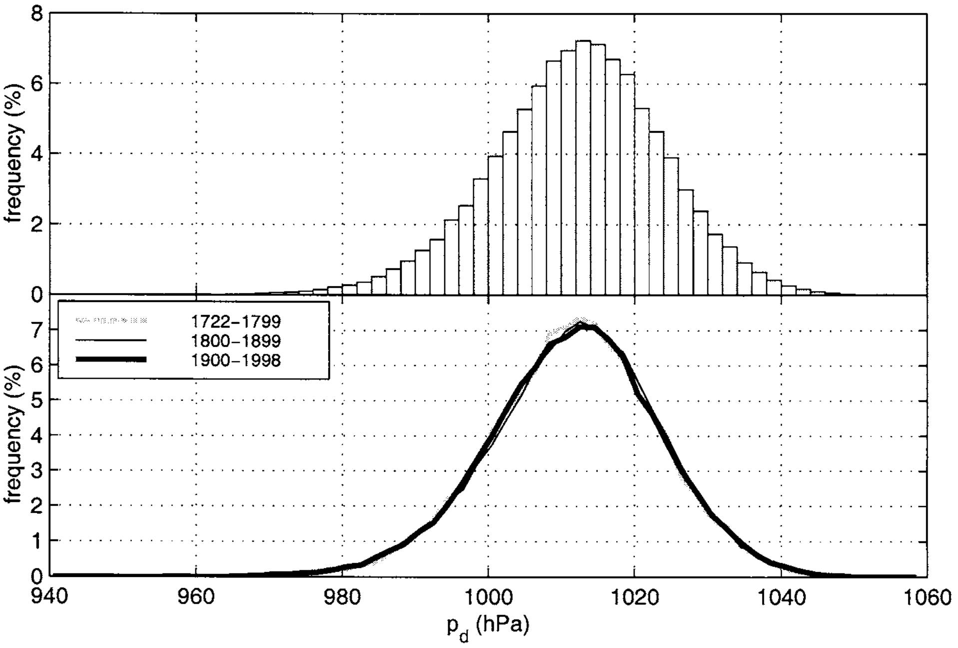

Figure 24. Frequency distribution of daily average sea level pressure, in the top subplot for the whole period 1722–1998, while in the bottom subplot the distributions for the 18th, 19th, and 20th century data are compared.

somewhat more extreme in view of a larger difference between the highest and lowest daily average pressure each year, seemingly due to deeper low-pressure systems. The same may be noted when looking at the annual standard deviation of the daily average pressure, which also shows an increasing trend from a minimum level at about 11.2 hPa in the 1720s to values around 12 hPa in the 1990s. The skewness of the annual distribution of daily average pressure also shows larger negative values in the 1990s, about –0.3, than was observed in the 1720s when the value was about –0.1, although no single trend over the whole period can be observed.

6. Concluding Remarks

Temperature and air pressure observations for Uppsala from 1722–1998 were digitised and series of daily averages of homogenised temperature and sea level pressure were reconstructed. The work was based on hand written registers and printed monthly bulletins. All data had to be digitised except for the period from 1985 onwards, when automatic weather stations came into use. The unknown or poorly calibrated early thermometers were 'recalibrated' numerically against the thermometer scale invented by Celsius at the beginning of the 1740s. Methods

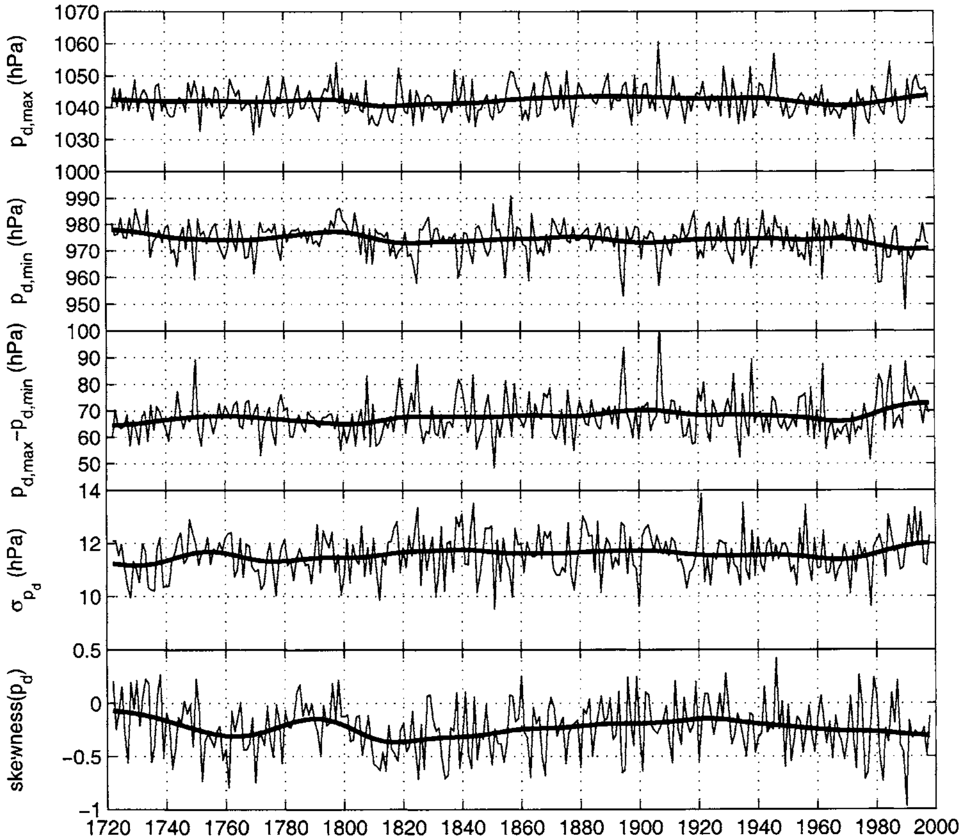

Figure 25. Daily average sea level pressure statistics from Uppsala 1722–1998 giving from the top down: highest daily pressure average each year, lowest daily pressure average each year, difference between the highest and lowest daily pressure average each year, annual standard deviation of daily pressure average, and annual skewness of daily pressure average. The smooth curves are made using a Gaussian filter with a standard deviation of 9 years.

were developed to estimate the daily average temperature from the available 1–4 observations per day. These methods include taking account of observation time and cloud cover.

The daily data were searched for errors by comparing with previously determined monthly temperature averages. By plotting the data, outliers originating from printing errors could easily be detected. In order to be sure that the series are homogeneous, it is necessary to have access to reference series for stations that are not too far away, which is often difficult or impossible regarding 18th century or early 19th century data. The existence of data for Stockholm, 65 km south of Uppsala, made the search for errors much easier. The correlation between the two series is 0.995 for the period after 1850 and 0.975 for the early data as regards air pressure. The corresponding correlations for temperature are 0.991 and 0.984

respectively. In spite of all efforts to homogenise the data series, they could still be inhomogeneous in some aspects with which it has not been possible for us to deal, cf. Moberg et al. (2002).

With access to daily data for temperature and sea level pressure, it is possible to make much more detailed climate analyses than is possible using only monthly data. For example as regards the day-to-day temperature variability (Moberg et al., 2000), and the growing season or frost season degree-days (Jones et al., 2002). We have demonstrated here that the annual variability in daily average temperature, as measured by the annual standard deviation of the daily average temperatures, has decreased over the last 200–250 years, and that this is mainly a consequence of the decreased number of extremely cold days. This is also evident from the trend as regards the coldest day of the year, which as a mean has increased by about 7 °C since around 1800. On the other hand, the air pressure climate seems to have become somewhat increasingly variable when measured in the same way. Especially during the last 30 years the annual extremes as regards daily average pressure have shown a tendency to become on average more extreme, and the difference between the annual maximum and minimum daily average pressure has shown an increasing trend from a mean level of 65 hPa around 1800 to about 72 hPa in the 1990s, although there was a secondary minimum at about 67 hPa in the 1960s, mainly caused by a decrease in the annual maximum.

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