DAILY AIR TEMPERATURE AND PRESSURE SERIES FOR STOCKHOLM (1756–1998)

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Abstract. Daily meteorological observations have been made at the old astronomical observatory in Stockholm since 1754. Complete daily mean series of air temperature and sea level pressure are reconstructed from the observational data for 1756–1998. The temperature and pressure series are reconstructed and homogenized with the aid of metadata, statistical tests and comparisons with data from other stations. Comparisons with independently reconstructed daily series for nearby Uppsala (1722–1998) show that the quality of the daily Stockholm data is good, although the reliability is lower before the mid-19th century. The daily temperature data show that the colder winter mean temperatures of the late 18th to early 19th centuries were connected with a particularly high frequency of very cold winter days. The warmer summers of the same period are more connected with a general shift of the temperature distribution towards higher temperatures than in the late 20th century.

1. Introduction

Daily meteorological observations have been made at the old astronomical observatory in Stockholm (59°21′ N, 18°03′ E) since 1754. Monthly mean temperatures for 1756–1905 were calculated by Hamberg (1906). These monthly data have subsequently been updated by the Swedish Meteorological and Hydrological Institute (SMHI). Moberg and Bergström (1997) homogenized the Hamberg/SMHI record from 1861 onwards and discussed the temperature variability back to 1756. A discussion of precipitation data back to 1785 was made by Eriksson (1980a). The air pressure data before 1862 have not been analyzed previously.

Our purpose is to give a rather detailed history for the meteorological station at the old astronomical observatory in Stockholm and to describe the procedures used for reconstruction of complete daily series of air temperatures and sea level pressures for Stockholm back to 1756. The focus is much more on historical and technical details than on climatic analyses, although some aspects of climatic change are analysed in Section 4.5. More comprehensive climatic analyses of the daily records are made elsewhere (Moberg et al., 2000; Jones et al., 2001; Yan et al., 2001, 2002).

Parallel with the work presented here, daily records of air temperature and pressure for Uppsala, situated about 65 km north of Stockholm, were reconstructed

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back to 1722. The work with the two stations was made independently as far as possible. The Uppsala records are presented in a companion paper (Bergström and Moberg, 2002, where some additional aspects of the daily data for Stockholm are discussed.

2. Station History

2.1. GENERAL SITE INFORMATION

The astronomer and statistician Pehr Wargentin (1717–1783), secretary of the Royal Swedish Academy of Sciences, initiated meteorological observations at the astronomical observatory in Stockholm on 1 January 1754. The observatory is located at 44 m a.s.l. on the top of a ≈25 m high esker. In the 1750s, Stockholm had about 60 000 inhabitants and the observatory was then situated in a rural environment about 1 km northwest of the old city border. Strong urban development has taken place since the second half of the 19th century. The population is now about 1.5 million including suburbs. The observatory is today situated in a park (approx. size 200×200 m) in the city center. The urbanization has led to an artificial warming at the observatory by about 0.7 °C on the average (Moberg and Bergström, 1997).

A national Swedish meteorological station network was initiated in 1859. The Stockholm observatory became one of the stations already from the start. The observatory is still an official weather station, although the building is now used partly as a museum for science history.

2.2. OBSERVERS

Wargentin made the meteorological observations from 1 January 1754 until his death on 10 December 1783, except for some short periods of absence. He was followed by Henric Nicander, who made most of the observations until the end of 1803. From 1804 onwards the observers were generally anonymous. Until around 1820 it appears that the scientific staff made the observations, whereas afterwards the task was probably left to the non-scientific staff (e.g., attendants). From 1859 onwards the observers must be expected to have received instructions concerning the Swedish standard procedures for meteorological observations. Station inspection reports from 1915 onwards, which include the observers' names since 1931, are available at the SMHI.

2.3. OBSERVED VARIABLES

During 1754–1755 meteorological observations were made only once a day. Data for these earliest two years have been ignored in this study because they are considered too few for estimation of daily mean values. During 1756–1760 two observations per day of temperature, pressure, wind direction and wind speed were made. Descriptive weather remarks were made and abbreviations for the amount of clouds were also noted. From 1761 onwards the thermometer has been observed three times per day. In 1784, after an invitation from the meteorological society in Mannheim to participate in an international observation programme, the observation routines in Stockholm began to follow standards similar to those recommended by the Mannheim society (Kington, 1974; Moberg, 1998). Three barometer observations per day were made from June 1784. Quantitative precipitation measurements began in January 1785 and indoor temperature (presumably close to the barometer) was reported from February 1785 onwards. From 1859 onwards, the observations followed the Swedish standards, including three daily observations of temperature, air pressure, cloud amount, cloud type, precipitation, humidity etc. Observations of daily temperature maxima and minima were also introduced in 1859.

2.4. OBSERVATION HOURS

Several different time schedules have been used (Table I). Wargentin's temperature observations 1756–1760 were roughly made around sunrise and 13, but no precise documentation was made. A few short periods with only one observation per day also occurred. During 1761–1783, the thermometer readings were made around 6.30–8, 13 and 22–23, still without precise documentation and with a schedule that varied somewhat from year to year. Information about observation hours is often completely missing in this period. For all months when observation hours were not documented, we estimated them[*] by inserting the mean values for all cases during 1761–1783 with documented hours (separately for January, February, etc.). From 1756 to May 1784 the barometer readings were made in the morning and in the evening at varying times and often with no specification of the hours.

In May 1784, observation hours at 06, 14 and 21 were introduced for all variables. Unfortunately, observation hours were not documented at all between June 1784 and December 1822. From January 1823 to the end of 1858 the hours were again reported as 06, 14 and 21. A natural first guess is therefore that the observations were always made at 06, 14 and 21 from May 1784 through December 1858. Hamberg (1906), however, observed a much larger temperature difference noon–morning during 1797–1815 compared with the preceding and following periods. He concluded that a deviation from the schedule must have occurred. Our analyses support Hamberg's conclusion. We follow his suggestion that the observations 1797–1815 were made at sunrise, 14 and 21, although this is an uncertain assumption. During 1859–1940 the three daily observations of all variables were made at 08, 14 and 21. The schedule changed again in 1941 to the hours 08, 14 and 19 and finally in 1947 to 07, 13 and 19.

[*] Observation hours are needed for the reconstruction of daily mean temperatures from a few observations per day.

Table I
Average observation hours (decimal CET) in different time periods

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1756–1760	8.5	7.4	6.0	4.5	3.2	2.6	3.0	4.1	5.3	6.5	7.7	8.6
	12.9	13.0	13.0	12.8	12.7	12.8	12.9	12.9	12.7	12.6	12.5	12.7
1761–1784.04.30	7.7	7.4	6.8	6.3	6.2	6.4	6.3	6.2	6.2	6.5	6.7	7.6
	12.8	12.6	12.8	12.8	12.9	12.9	13.2	13.2	12.8	12.5	12.2	12.6
	22.0	22.1	22.0	21.9	21.9	22.6	22.2	21.8	21.6	21.7	21.4	21.8
1784.05.01–1796	5.9	6.0	6.0	5.8	5.7	5.8	5.9	5.9	5.7	5.6	5.5	5.7
	13.9	14.0	14.0	13.8	13.7	13.8	13.9	13.9	13.7	13.6	13.5	13.7
	20.9	21.0	21.0	20.8	20.7	20.8	20.9	20.9	20.7	20.6	20.5	20.7
1797–1815	8.5	7.4	6.0	4.5	3.2	2.6	3.0	4.1	5.3	6.5	7.7	8.6
	13.9	14.0	14.0	13.8	13.7	13.8	13.9	13.9	13.7	13.6	13.5	13.7
	20.9	21.0	21.0	20.8	20.7	20.8	20.9	20.9	20.7	20.6	20.5	20.7
1816–1858	5.9	5.9	5.9	5.8	5.8	5.8	5.9	5.8	5.7	5.7	5.7	5.8
	13.9	13.9	13.9	13.8	13.8	13.8	13.9	13.8	13.7	13.7	13.7	13.8
	20.9	20.9	20.9	20.8	20.8	20.8	20.9	20.8	20.7	20.7	20.7	20.8
1859–1878	7.9	7.9	7.9	7.8	7.8	7.8	7.9	7.8	7.7	7.7	7.7	7.8
	13.9	13.9	13.9	13.8	13.8	13.8	13.9	13.8	13.7	13.7	13.7	13.8
	20.9	20.9	20.9	20.8	20.8	20.8	20.9	20.8	20.7	20.7	20.7	20.8
1879–1940	8.0											
	14.0	Same hours all months										
	21.0											
1941–1946	8.0											
	14.0	Same hours all months										
	19.0											
1947–present	7.0											
	13.0	Same hours all months										
	19.0											

In Sweden, Local Solar Time (LST) was used before 1841, Local Mean Time (LMT) 1841–1878, and a common civil Swedish time, which differed just 14 seconds from Central European Time (CET), was introduced in 1879 (Lodén, 1968). CET has been used since 1900. All observation hours given in LST or

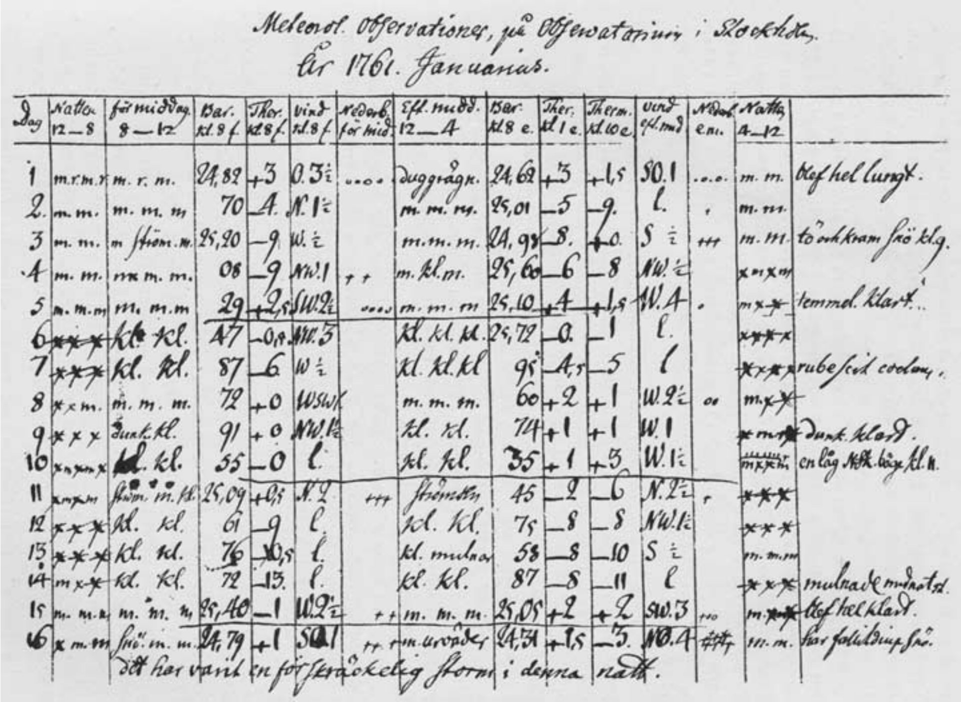

Figure 1. Wargentin’s observation register for January 1761.

LMT were converted here to equivalent CET values before they were used for the reconstruction of daily mean temperatures.

3. Data

3.1. DATA SOURCES

For the period 1756–1861 we used photo-copies of the original hand-written observation journals (Figure 1) as data source. Data for 1862–1960 were taken from printed tables in the meteorological year-books *Meteorologiska Iakttagelser i Sverige*, published by the SMHI or its predecessors. Daily maximum and minimum temperatures were not published in the year-books 1870–1899, therefore we used the original hand-written journal as source for these data. Data from 1961 onwards were supplied as computer files by the SMHI. The original observation journals for 1754–1858 are available at the Academy of Sciences and those from 1859 onwards at the SMHI.

3.2. DETECTION AND CORRECTION OF RANDOM DATA ERRORS

Random data errors occur both in the original hand-written documents and the printed year-books. Further errors were introduced by mistakes during the digitizing. A number of plotting techniques were used to identify errors in both the temperature and pressure data. The overall idea was that with a suitable plot of data, most random errors will be revealed as outliers or 'suspect' values in some sense. Examples of the data plots we used are: time series plots of all data, time series plots of all observations in one month (one plot for all data in January 1756, one plot for February 1756, and so on throughout the entire series), time series plots of temperature differences T_{noon}–T_{morning} and T_{noon}–T_{evening} (one plot for all January data 1756–1998, one for all February data, etc.).

In all cases when evident outliers or more subtle 'suspect' values were found, the source was inspected. If mistakes made during the digitizing were detected, it was straightforward to correct the files. If the outliers turned out to indicate 'suspect' values in the original source, it was more problematic to find a proper value. To deduce reasonably true temperature or pressure values we used the simultaneous information about other weather parameters (e.g., cloudiness, snow or rain, wind direction and speed, general weather comments) in conjunction with meteorological common-sense. Sometimes it was easy to correct a wrong value, for example when a temperature value was 'obviously' wrong by 10 degrees, or when an air pressure value was wrong by one inch (old unit). Other cases were more difficult, for example when the observers had not been consistent in their use of plus and minus signs for temperatures and when the temperatures on such occasions were near zero. In a few cases, when it was impossible to deduce a reasonable value, the observation was considered as missing.

In addition to the plotting techniques, some logical computational tests were performed on the data taken from the meteorological year-books 1862–1960. Monthly mean values were printed in the books. We checked all cases when the printed mean values differed from the those calculated from the digitized values. We also tested if the daily T_{max} (T_{min}) in the data sources were higher or equal (lower or equal) than the warmest (coldest) of the three instantaneous temperature observations each corresponding day. Corrections were applied whenever necessary in order to obtain logically consistent computer files.

The result of all corrections is that the computer files used as input to the reconstructions of daily mean temperatures and air pressures contain no 'obviously wrong' or 'very strange' individual values. We strived at being as conservative as possible, i.e., corrections were made only when we were convinced that the values in the original sources could impossibly be correct.

4. The Temperature Series

In this chapter we describe how a complete series of daily mean temperatures for Stockholm was reconstructed back to 1756. We begin with information and a discussion about thermometers and thermometer positions. Thereafter we describe the actual computations used for estimation of daily mean temperatures and how the data were homogenized. The quality of the data is also discussed. Finally, some statistical analyses of the reconstructed daily temperature series is presented and discussed in a context of climatic changes.

4.1. THERMOMETERS

There is no direct information about the quality of the thermometers before the mid-1820s. Wargentin, however, discussed the various thermometer types used in Europe at his time (Wargentin, 1749). He concluded that the Celsius type was both reliable and easy to calibrate properly. Consequently, he always used the Celsius thermometer. In fact, the Celsius thermometer scale has always been used for the observations in Stockholm, with the readings given in whole and half degrees 1754–1821, thirds and fourths 1821–1838, and in tenths after 1838.

The first note about a thermometer calibration is found in the observation diary of 1826, which states that: “The true zero point on ... the thermometer is at +0.75 on its scale. This has been taken into account in the diary”. There is unfortunately no information about the time point when the incorrectly calibrated thermometer began to be used, or when the correction began to be applied. Therefore, we made a direct comparison with temperatures for Uppsala to estimate the duration of the actual time period. We observed that the temperature difference* Stockholm-Uppsala was systematically about 0.7 °C too large from 1 August 1819 to 13 January 1825. Consequently, we applied a correction of –0.7 °C to all observed tempertures for this period.

There is a second note about a thermometer calibration in the diary of 1858. This time the zero point was found to be correct. The third occasion with similar information is 1915. This is the first year for which a regular station inspection report is available. Station inspection reports from 1915 onwards (available at SMHI), reveal that thermometers were calibrated at each inspection.

4.2. THERMOMETER POSITIONS

The thermometers have been placed at three different positions. Initially, the thermometer was “hung in the free air, outside a window, on the north side of the observatory, and well protected against the morning sun” (Wargentin, 1778). This statement is essentially all available information about the earliest thermometer

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* This difference was calculated from estimated daily mean temperatures obtained later in the work.

Figure 2. The astronomical observatory in Stockholm 1784. The arrow marks the probable thermometer position, outside a window on the north-facing wall, which was used from 1754 to 1875.

position. This position, at 5.8 m above ground (Figure 2) was used until the end of August 1875, when the building underwent major changes and a new section was built on its north side (Hamberg, 1906). From September 1875 through 1960 the thermometer was placed on the new north-facing wall at 1.5–1.9 m above ground. A metal screen, placed in front of a window, (Figure 3) was introduced in January 1878 for protection against radiation. Modén (1963) reported that the screen was painted white, although it is not known if it was painted already when it was new.

In 1947, when the observation hours changed, the window screen became exposed to sunlight at the time of observations in summer mornings. Therefore, a psychrometer-thermometer was placed in a small free standing screen, about 10 metres northeast of the building. The morning observation was made on this thermometer during May–September from 1947 to 1960, whereas all other observations were made in the window screen (Modén 1963). In August 1960 a standard SMHI screen (Stevenson type, thermometer height 1.5–1.7 m) (Figure 3) was introduced. Since 1961, all temperature readings are made there. Inspection reports from 1970 onwards reveal that the screen repeatedly has become dirty because of air pollution. This may have caused temperatures to be positively biased. Furthermore, the position of the screen, between a tall and dense hedge and the building, is not optimal for temperature measurements as the ventilation is poor.

Figure 3. The window screen (at the right arrow) where temperature was measured from 1878 to 1960 and the SMHI screen (at the left arrow) which has been used since 1961. The photograph was taken in October 1984. (Photo: SMHI).

Parallel temperature readings were made for one year (1961) in the window screen and the SMHI screen (Modén, 1963). Differences between instantaneous readings were negligible in the winter but they differed by up to several degrees in the summer. The largest differences were observed at clear-sky conditions, with the window screen being warmer in the mornings and the SMHI screen being warmer at noon. Despite the large differences between individual temperature readings, the difference between monthly averages was within ±0.1 °C. This implies that the change of screen in 1960 is not a serious source of inhomogeneity as far as monthly averages are concerned.

We made an effort to estimate also the effect of the changed thermometer position in 1875. A resistance thermometer was placed in the SMHI screen and another one was placed behind a simple shield outside a north-facing window at about 6 m above ground, corresponding approximately to the oldest thermometer position. Data were collected every tenth minute from June 1995 to May 1997. Results from these parallell measurements (Ekström, 1995; Linde, 1998) are in line with those of Modén (1963). Istantaneous temperatures differed by several degrees at clear-sky conditions in summer, with the 'old' position being warmer in the mornings and the SMHI screen being warmer at noon. The differences in winter were generally negligible and differences in monthly mean values were small in all months.

Certainly, the changed thermometer position in 1875 introduced an inhomogeneity of some kind, but it is difficult to quantify its importance and character in detail.

4.3. ESTIMATION OF DAILY MEAN TEMPERATURES

To estimate daily mean temperatures from a few instantaneous observations per day, it is necessary to use a method that takes into acount the observational hours. For the period 1859–1998 we used the same equation as used for all official Swedish stations since the 1860s. For the earlier period, 1756–1858, no standard equations have been developed so we had to use another method.

The following equation was used for 1756–1858:

$$T_d = \frac{1}{n}(T_1 + f_{cl} \cdot \Delta_1 + T_2 + f_{cl} \cdot \Delta_2 + \cdots + T_n + f_{cl} \cdot \Delta_n)\,, \tag{1}$$

where T_d is the estimated daily mean temperature, $T_1, T_2, \ldots, T_n$ are the recorded instantaneous temperatures in a particular day, and $\Delta_1, \Delta_2, \ldots, \Delta_n$ are the mean deviations from the daily mean temperature at the actual observation hour in a particular day of the year. The scaling factor, f_{cl}, is included to take into account the effect of cloud amount on the amplitude of the daily temperature cycle. Scaling factors were determined for three cloud cover classes ('cloudy', 'clear', 'half-clear') for each day of the year. The number of terms, n, is the number of observations in a particular day. In the overwhelming majority of cases, $n = 3$. Details of how the Δ-values and f_{cl} factors were determined are given in an Appendix.

To study the effect of the inclusion of the f_{cl} factors in Equation (1), daily mean temperatures were calculated also without using the factors. In the overwhelming majority (99.8%) of the days 1756–1858, the absolute difference between daily temperatures calculated with and without the scaling factors was found to be <0.1 °C. The largest absolute difference found was 0.9 °C. The majority (62%) of the few days with differences >0.1 relate to days with only one temperature observation. The scaling factor thus seems to be quite unimportant, in particular when temperature readings are available both in the morning and at noon (i.e. near the time of $T_{\min}$ and $T_{\max}$). One may also conclude that, as long as temperatures are observed near both $T_{\min}$ and $T_{\max}$, the risk of any artificial trends in observed temperatures due to trends in cloud amounts is negligible. A further discussion of the properties of Equation (1) is made by Bergström and Moberg (2002).

For the period 1859–1998, T_d was estimated as:

$$T_d = p \cdot T_1 + q \cdot T_2 + r \cdot T_3 + x \cdot T_{\max} + s \cdot T_{\min}\,, \tag{2a}$$

with the constraint that

$$p + q + r + x + s = 1\,. \tag{2b}$$

Different sets of coefficients (p, q, r, x, s), for various combinations of hours, have been developed for different longitudes by the SMHI or its predecessors. The

Table II

Coefficients ($\times 0.01$) in Equation (2) for calculation of daily mean temperatures in Stockholm in three sub-periods 1859–1998. Observation hours in the sub-periods are given within parentheses. Data from Ekholm (1916), Modén (1939), Sveriges Meteorologiska och Hydrologiska Institut (1966) and Eriksson (1980b)

	1859–1940 (08, 14, 21)					1941–1946 (08, 14, 19)					1947–1998 (07, 13, 19)				
	p	*q*	*r*	*x*	*s*	*p*	*q*	*r*	*x*	*s*	*p*	*q*	*r*	*x*	*s*
Jan	38	23	39			45	20	35			33	15	32	10	10
Feb	34	25	41			41	18	41			31	18	31	10	10
Mar	35	21	44			45	14	41			31	21	28	10	10
Apr	35	18	48			34	09	44		13	23	18	30	10	19
May	31	16	49		4	25	15	38		22	22	20	23	10	25
Jun	25	18	51		6	25	14	39		22	21	19	24	10	26
Jul	25	21	45		9	23	15	39		23	19	18	26	10	27
Aug	32	16	52			26	18	35		21	18	22	23	10	27
Sep	36	19	45			34	22	30		14	25	23	24	10	18
Oct	31	22	47			40	16	44			29	19	32	10	10
Nov	36	25	39			40	18	42			30	16	34	10	10
Dec	37	23	40			40	17	43			34	15	31	10	10

coeffiecents for Stockholm are given in Table II. In cases when at least one of the temperature observations during a certain day was missing, we estimated daily mean temperatures using Equation (1), as Equation (2) requires that no observation is missing.

A drawback of using Equation (2) is that coefficients have been developed only on a monthly basis. The estimated daily mean temperature series can therefore contain small artificial steps at the shift of months. This is probably not a serious problem as such artificial steps can hardly be larger than a few tenths of degrees, whereas real temperature changes from day-to-day can be at least one order of magnitude larger. One reason why we rejected to use Equation (1) for the modern data is the that $T_{\max}$ and $T_{\min}$ cannot be included. Equation (1) is particularly unsuitable for estimation of daily mean temperatures in the summer season after 1859 as the morning readings since then have been made at 08 or 07, i.e., at hours when the temperature generally is far from the daily minimum.

4.4. CORRECTION AND HOMOGENIZATION OF THE DAILY MEAN TEMPERATURE SERIES

When a series of daily mean temperatures for Stockholm had been established using Equations (1) and (2), it was compared with data from nearby stations to search for random errors and systematic inhomogeneities and to find suitable corrections for the data homogenization.

4.4.1. *The Period 1861–1998*

It was shown by Moberg and Bergström (1997) that the Stockholm temperature record is affected by an urban warming trend from the 1860s to 1970s. There is also an abrupt shift to lower temperatures in relation to surrounding stations around 1900. These inhomogeneities were detected with the standard normal homogeneity test for abrupt changes and linear trends (Alexandersson, 1986; Alexandersson and Moberg, 1997), with ten homogenized neighbouring temperature series 1861–1994 used as reference data.

Using the same reference series again, homogeneity tests of the Stockholm temperatures for 1861–1994 were also performed here. Monthly mean temperatures were first calculated from the daily temperatures established in Section 4.3. The approach of combining the tests for abrupt change and linear trend was essentially the same as described by Moberg and Bergström (1997). A difference between the two investigations, however, is that here we estimated the inhomogeneities on a monthy basis, whereas the previous investigation was made on a seasonal basis.

The variability in the time series to be tested (difference: candidate–reference) is larger for monthly data than for seasonal data, whereas the size of inhomogeneities is about the same in both. The determination of exact time points of abrupt shifts, and particularly start and end points of trends, is therefore more uncertain for monthly data. To obtain statistically stable dates, these were always determined from tests on annual mean series. The actual size of inhomogeneities (in °C) were then determined from monthly series (separately for January, February, etc.).

We found a trend section 1868–1888 with increasing bias, an abrupt negative jump after 1903 and a second positive trend section 1914–1966. The two positive trend sections are attributed to an increasing urban warming, whereas the jump after 1903 is not easily explained. A possible explanation is that the window screen, introduced in 1878, was not painted white before 1904 but was painted at that time and thus started to reflect radiation more effectively. This explanation, however, has not been either verified, nor falsified, by any metadata.

The total effect of all inhomogeneities is an average bias of recent annual mean temperatures by +0.77 °C. There is an annual cycle in this bias, with a maximum (+1.37 °C) in May and a minimum (+0.24 °C) in October. We tested if this annual cycle is sensitive to the choice of stations, by repeating the calculations using independent subsets of the reference stations. The results were virtually identical to those for the full set.

The results of the homogeneity tests are listed in Table III. We used these results to construct a time series of daily temperature corrections. Daily correction values were obtained by linear interpolation between the monthly values. The daily correction time series thus starts with zeros in 1868 and reaches its largest values in 1966. For the period 1967–1998 the corrections are constant for each day of

Table III

Estimated biases (°C) in the temperature series after 1861. After interpolation to daily values, these data were used as a basis for homogenizing the temperature series

	Linear change 1868–1888	Constant level 1889–1903	Constant level 1904–1913	Linear change 1914–1966	Constant level 1967–1998
Jan	0.00 to +0.53	+0.53	+0.37	+0.37 to +0.78	+0.78
Feb	0.00 to +0.47	+0.47	+0.23	+0.23 to +0.85	+0.85
Mar	0.00 to +0.47	+0.47	+0.33	+0.33 to +0.96	+0.96
Apr	0.00 to +0.47	+0.47	+0.18	+0.18 to +0.80	+0.80
May	0.00 to +0.78	+0.78	+0.49	+0.49 to +1.37	+1.37
Jun	0.00 to +0.52	+0.52	+0.36	+0.36 to +1.09	+1.09
Jul	0.00 to +0.55	+0.55	+0.35	+0.35 to +1.01	+1.01
Aug	0.00 to +0.52	+0.52	+0.11	+0.11 to +0.78	+0.78
Sep	0.00 to +0.29	+0.29	–0.13	–0.13 to +0.30	+0.30
Oct	0.00 to +0.18	+0.18	–0.11	–0.11 to +0.24	+0.24
Nov	0.00 to +0.31	+0.31	+0.07	+0.07 to +0.47	+0.47
Dec	0.00 to +0.30	+0.30	+0.07	+0.07 to +0.59	+0.59
Annual average	0.00 to +0.45	+0.45	+0.19	+0.19 to +0.77	+0.77

the year, but there is an annual cycle superimposed. The daily corrections were subtracted from the observed daily mean temperatures to create a homogenized series.

In the homogenized series all temperature data after 1868 are adjusted to the conditions corresponding of the 1860s. Note that no weather-dependent day-to-day changes of the urban warming is taken into account. The homogenization is valid only on an average monthly basis. It is beyond the scope of this paper, however, to investigate the nature of errors that certainly still remain because of this.

4.4.2. *Direct Comparison with Uppsala 1756–1998*

After homogenization of the period 1861–1998, the daily Stockholm temperatures were compared with the Uppsala temperatures obtained by Bergström and Moberg (2002). A study of daily differences Stockholm–Uppsala revealed a number of random errors and a few systematic biases in both series. The data sources were inspected and we used all information about other weather variables to judge when ‘suspect’ values should be considered as true or false. Corrections were applied whenever appropriate.

Large systematic differences (several degrees) were observed for several months in 1756. Therefore, we made comparisons with independent temperature observations for Stockholm[⋆] 1756–1758, and concluded that temperatures reported at the astronomical observatory were biased high 1756.04.03–1756.10.31. The observed daily temperatures for Stockholm were therefore substituted with data estimated from the Uppsala temperatures. These estimated temperatures were obtained using a linear regression relation established between the two series 1757–1783. The same regression relation was also used to fill a data gap in the Stockholm series 25–28 February 1763.

Although the direct comparisons Stockholm–Uppsala show that there certainly exist further periods with biased data, in particular before the 1860s (see Bergström and Moberg, 2002), it was not possible to identify any further corrections to apply to the Stockholm series. The corrections mentioned in this section thus complete the description of our efforts to obtain a daily mean temperature reconstruction for Stockholm.

4.5. SELECTED STATISTICAL ANALYSES OF THE DAILY TEMPERATURE SERIES

In this section, the daily temperature series is analysed briefly in terms of some statistical properties. An internal homogeneity test of summer temperatures is followed by some analyses that reveal temporal changes in the statistical distribution of daily temperatures.

4.5.1. *Internal Test of Summer Temperatures*

There is a potential risk for positively biased summer temperatures during much of the period before 1859. The thermometer was then placed on the north-facing wall, and was therefore certainly affected to some extent by heating from sun-rays hitting the wall at the time of the morning observation (at 06) in summer.

Any such bias is expected to be largest at clear-sky conditions. An internal test for the presence of a weather-dependent temperature bias is therefore to compare separate series of temperatures for clear, half-clear and cloudy days. We constructed independent summer average temperatures for each of the three classes (T_{clear}, $T_{\text{half clear}}$, T_{cloudy}), and studied time series of the differences T_{clear}–T_{cloudy} and $T_{\text{half clear}}$–T_{cloudy}. Such plots, presented as anomalies with respect to 1961–1990, are shown in Figure 4. The difference series do not support any sunlight-related bias before 1859, as T_{clear} is generally not relatively warmer than T_{cloudy} and $T_{\text{half clear}}$ in this period (rather the opposite). We conclude that the problem with direct sunlight on the old thermometers is not an important one.

[⋆] Daily meteorological observational data from an unkown site in Stockholm were published in the newspaper *Stockholms Weckoblad* 1748–1770.

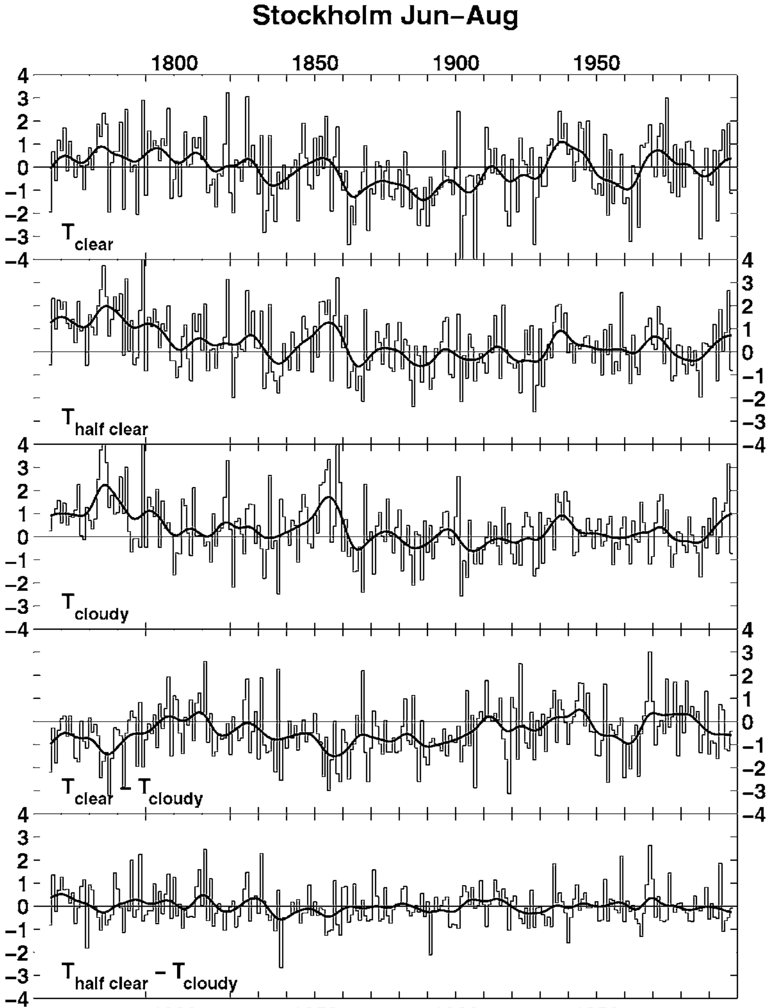

Figure 4. Separate JJA average temperatures 1756–1998, expressed as anomalies from the 1961–1990 mean, calculated using daily mean temperatures for clear days, half clear days and cloudy days separately. The differences T_{clear}–T_{cloudy} and $T_{\text{half clear}}$–T_{cloudy} are also shown.

4.5.2. *Seasonal and Annual Temperature Series*

Time series of annual and seasonal average temperatures, as calculated from the daily reconstruction, are shown in Figure 5. Variability on time scales longer than a decade are highlighted with a gaussian filter (thick curves). For comparison, the corresponding low-pass filtered series of Moberg and Bergström (1997) are also shown (thin curves). The systematic difference between the two records is due to different choices for homogenization. Moberg and Bergström (1997) corrected all data to a level corresponding to the present situtation, whereas the new

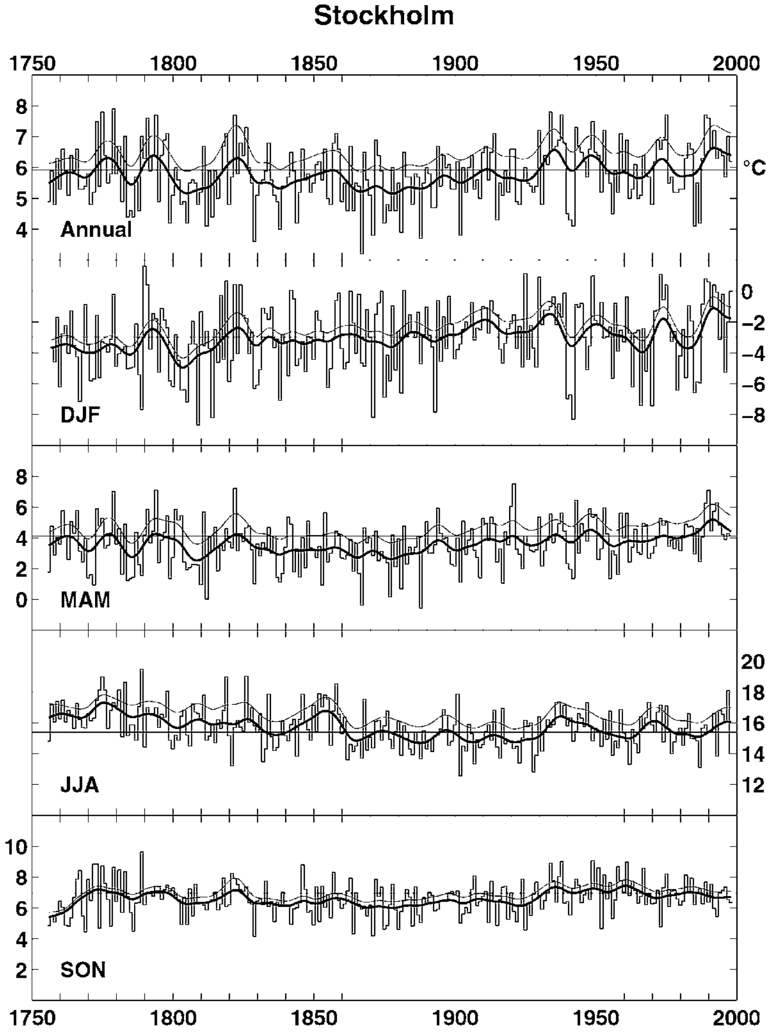

Figure 5. Annual and seasonal mean temperatures in Stockholm 1756–1998, according to the homogenized version reconstructed in this paper. Smoothed time series (Gaussian filter with $\sigma = 3$) for this reconstruction are shown with thick curves. Thin curves represent smoothed temperature series from the reconstruction by Moberg and Bergström (1997).

reconstruction is adjusted to the conditions around 1860. Apart from the systematic difference the low-pass filtered curves are very similar. There do, of course, exist some differences between the two temperature reconstructions, but these differences do not show up easily in low-pass filtered curves. We emphasize that all general conclusions about climatic changes and trends discussed by Moberg and Bergström (1997) are valid also for the new reconstruction.

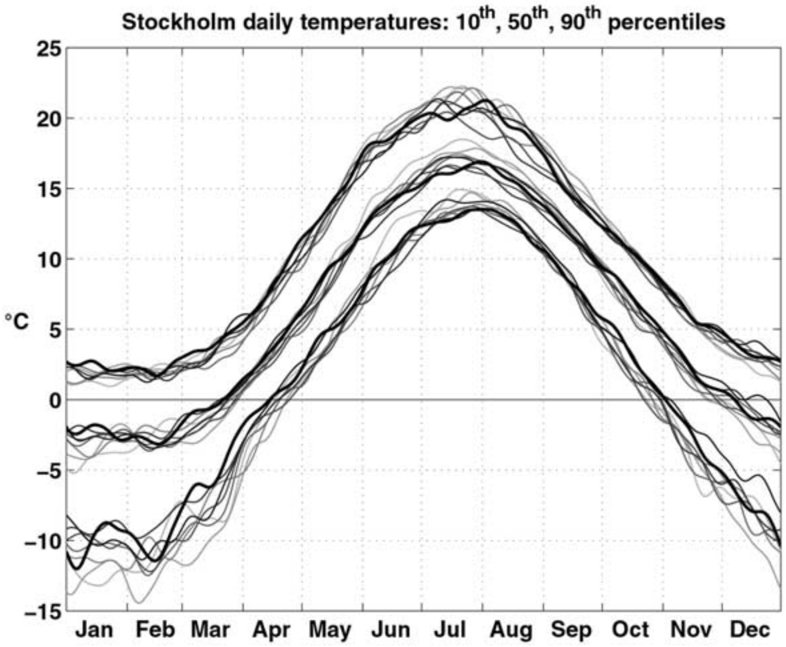

Figure 6. Annual temperature cycle in Stockholm, represented by smoothed sequences of the 10th, 50th and 90th percentiles of the daily mean temperatures in eight time periods. The thick black curves represent the recent period 1961–1998. The thin curves, having different grey tones, represent the periods 1756–1780, 1781–1810, 1811–1840, 1841–1870, 1871–1900, 1901–1930 and 1931–1960. The grey tone indicate the age of the period. The earliest period has the lightest tone. The most recent period has the darkest tone. The smoothing reduces variability on time scales shorter than about two weeks (Gaussian filter with $\sigma = 4.2$).

4.5.3. *Percentiles of Daily Temperatures*

In Figure 6, smoothed 10th, 50th and 90th percentiles of daily temperatures are shown for the earliest 25-year period, six non-overlapping 30-year periods and the most recent 38-year period 1961–1998. The graphs indicate that an overall change has taken place from more continental conditions, with more frequent cold winter days and warm summer days in the late 18th to early 19th centuries, to more maritime conditions in the late 20th century.

In Figure 7, the differences between the smoothed percentile sequences for 1961–1998 and 1756–1840 are plotted. These plots highlight the changes in temperature distributions between the late-18th to early-19th centuries and the late-20th century. A general warming can be observed in autumn, winter and spring whereas a cooling is observed in summer. The 10th percentile for mid-January to early February and the whole of March has increased by as much as 3 °C, which is much more than the corresponding increase for the 50th and 90th percentiles. Thus, winters in Stockholm during 1756–1840 were not only colder on the average than 1961–1998, but the frequency of very cold days was particularly high. The cooling

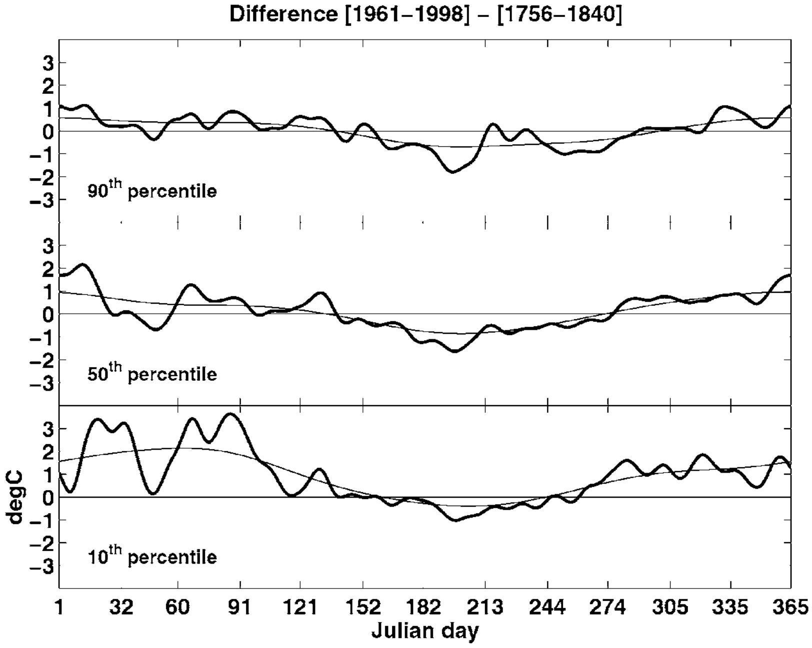

Figure 7. Differences of smoothed 10th, 50th and 90th percentile sequences for the periods 1961–1998 and 1756–1840. Positive values indicate that 1961–1998 has the warmer temperatures. The thick curves highligt variability on time scales longer than about two weeks (Gaussian filter with $\sigma = 4.2$). The thin curves highligt variability on time scales longer than about three months (Gaussian filter with $\sigma = 30$).

of summer temperatures is, on the contrary, almost equal for all three percentiles. There is only a slightly smaller change of the 10th percentile than of the 50th and 90th percentiles. The summer cooling has thus been connected with a general shift of the entire temperature distribution, with a small tendency towards fewer hot days dominating an increase in number of chilly summer days.

4.5.4. *Frequency of Hot Summer Days and Cold Winter Days*

A time-series plot of the changes in frequency of hot summer days and cold winter days is shown in Figure 8. We define a hot summer day as a day with its mean temperature exceeding the 95th percentile for all July days 1961–90 (+21.1 °C). Accordingly, we define a cold winter day as a day with mean temperature below the 5th percentile for all January days 1961–90 (–13.4 °C).

Many years with a high frequency of cold winter days occurred around the 1770s, 1780s and 1800s. From the 1810s to the 1890s cold winter days became less frequent. The frequency of cold winter days declined abruptly around 1900 and they were very rare 1900–1939. After the extremely cold 3-year period 1940–42, the frequency of cold days has varied from decade to decade. Notably, 1985 was one of four years with the highest frequency (23) of cold days in the whole

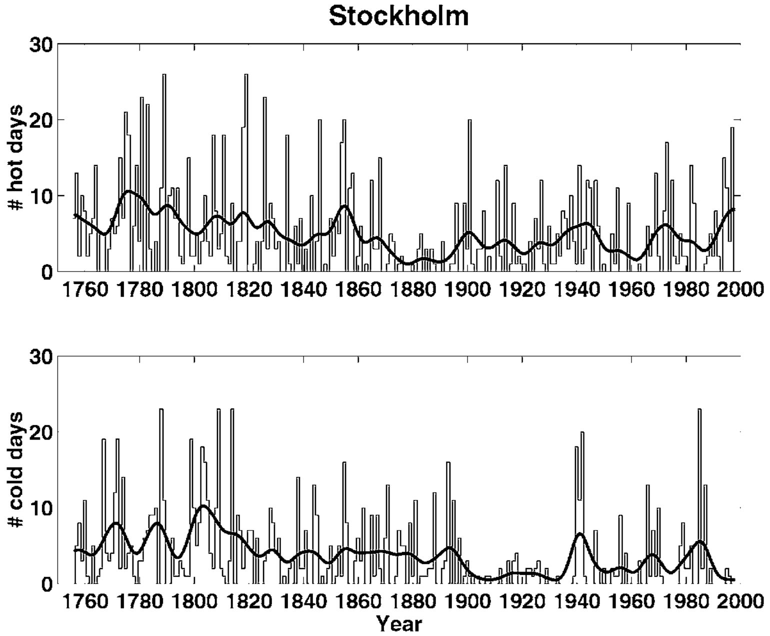

Figure 8. The number of hot days (daily mean > +21.1 °C) and cold days (daily mean < –13.4 °C) in Stockholm each year 1756–1998. A smoothed curve (Gaussian low-pass filter with $\sigma = 3$) is also shown.

record (the others were 1788, 1809 and 1814), whereas the entire 1990s had only three cold winter days. The general tendency for hot summer days is a decline from a high frequency in the 1770s and 1780s to a minimum in the 1870s and 1880s, and thereafter a partial recovery to more frequent hot days in the 20th century.

4.6. DISCUSSION OF THE TEMPERATURE SERIES

We have reconstructed a series of daily mean temperatures for Stockholm 1756–1998, using the original observational data as source. Daily mean temperatures as calculated directly from the observations were subjected to homogeneity tests based on comparisons with data for several surrounding stations after 1861 and homogenized according to the test results. Further corrections were made after comparisons with the simultaneously, but independently, reconstructed temperature series (Bergström and Moberg, 2002) for Uppsala.

With this daily temperature reconstruction it is possible to make more detailed analyses of climatic changes than with the commonly available monthly average data. Some selected analyses that can only be made with daily data were presented in Section 4.5. There is, however, not space for more extensive analyses here. Nevertheless, the results from our few analyses show some details behind the previously observed (Moberg and Bergström, 1997) general cooling of summer mean temperatures and warming of winter mean temperatures since the late 18th century. An example of this is that the colder winter mean temperatures of the late 18th to early 19th centuries is connected with a particularly high frequency of very cold winter days. The warmer summers of the same period seems to be more connected with a general shift of the temperature distribution towards higher temperatures than in the late 20th century.

It can be questioned if these observed changes reflect real climatic changes or if they are seriously affected by data deficiencies that still remain. If the observations reflect real climatic changes, they should be supported by independent observations in other climatic variables and in observations from other stations. A few analyses have already been undertaken (Moberg et al., 2000; Jones et al., 2001; Yan et al., 2001, 2002), but there is a clear need both for further long daily data series to be developed and for more extensive analyses to be made.

5. The Air Pressure Series

Here we describe the reconstruction of a daily air pressure series for Stockholm 1756–1998. Information about the instruments and their locations is followed by a description of our methods. Reductions to sea level pressure of data after 1859 involved only routine calculations, whereas this was a difficult task for the older data because barometers with partly unkown properties were used. Therefore, a detailed description of our approach to perform these reductions is given. To homogenize the series, we applied adjustments derived from comparisons with data from surrounding stations. The essential parts of our methods are similar to those used by Bärring et al. (1999) in reconstruction of air pressures for Lund back to 1780.

5.1. BAROMETERS AND BAROMETER UNITS

We assume that one single barometer was used most of the period 1754–1858, although there is no unequivocal evidence for this. We base this assumption mainly on the following arguments: The barometer unit in the observation journal was always Swedish inches (1 sw.inch = 29.69 mm) 1754–1858. In all contemporary inventories* (dated 1775, 1789, 1807, 1821, 1834) of the instruments at the observatory, there was only one barometer with a Swedish scale mentioned – constructed by the academy's instrument maker Daniel Ekström (1711–1755). There is also a note in the observation journal of 1844 that Ekström's barometer was actually used at that time. This instrument still exists and can be seen at the museum of science history at the old astronomical observatory in Stockholm. It can easily be seen that the Ekström barometer was used for a very long time as the brass scale is heavily worn, probably because of innumerable touches by the observers' thumbs.

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* Available at the museum of science history at the old astronomical observatory in Stockholm.

Figure 9. Barometer constructed by Daniel Ekström around 1750. This barometer was probably used for the daily meteorological observations at the old astronomical observatory in Stockholm most of the time from 1754–1858. (Photo: A. Moberg).

We conclude that it is very likely that the Ekström barometer was used almost the entire period 1754–1858, only with exception for some short periods of restoration of the instrument.

A photograph of the barometer is shown in Figure 9. An X-ray image of its bottom part is shown in Figure 10. The instrument has a mercury container and a glass tube attached to a frame of walnut wood. Its scale is made of brass and covers the range 23–28 sw.inch (≈910–1108 hPa). A mark for what was regarded as a normal pressure at the time (Celsius, 1742) is found at 25.3 on the scale (≈1001.5 hPa). The mercury height was observed with an accuracy of 0.01 sw.inch (≈0.4 hPa). Most of the mercury has been lost and the instrument cannot be used today.

It is likely that another barometer was introduced in 1859, as the unit changed to sw. inch × 10^{-1} and pressure values reduced to 0 °C began to be reported. This coincides with the start time for the Swedish meteorological station net. During 1862–1937 the air pressure was reported in mmHg, and from 1938 onwards in

Figure 10. X-ray image of the lower part of Ekström's barometer. (Image: Stiftelsen Observatoriekullen).

hPa. It can be expected that the barometers used in Stockholm from 1862 onwards were standard instruments, first supplied by the academy of sciences and later by SMHI or its predecessors.

The barometer temperature has been observed since February 1785, but before 1859 reductions to 0 °C were not reported in the journals. Pressure values in the data sources for 1859–1920 were reduced to 0 °C. Data for 1921–1960 were reduced both to 0 °C and normal gravity in the sources. Data for 1961–1998, supplied electronically by the SMHI, were reduced to sea level before delivery.

5.2. BAROMETER POSITIONS

The barometer altitudes in various sub-periods are listed in Table IV. The altitude, and hence the exact position, of the barometer is not precisely known before 1862. From 1862 onwards the barometer has been placed at either 44.4, 48.1, or 51.8 m a.s.l., which correspond to the three floors of the observatory building. Barometer readings were not made at the observatory from July 1939 through February 1950. Air pressure data for this period have instead been taken from Bromma airport, about 10 km from the observatory.

Table IV
Barometer altitude in different sub-periods

Period	Barometer altitude (m a.s.l.)	Comment
1756–1861	44.4 (?)	Assumption
1862–1876	48.1	
1877–1939.06.30	44.4	
1939.07.01–1950.02.28	10.5	Bromma airport
1950.03.01–1959.03.17	44.4	
1959.03.18–	51.8	

For the period before 1862, we assume that the barometer was always placed on the ground floor. We base this assumption mainly on the fact that the observed barometer temperature 1785–1839 rather closely followed the observed outdoor temperatures. The barometer must therefore have been placed in an unheated and rather well-ventilated room, i.e. at conditions desired for a room where astronomical instruments were placed. In this early period, the astronomical instruments were in fact placed on the ground floor.

In 1840 the annual cycle of the barometer temperature switched abruptly from an ‘outdoor’ type to an ‘indoor’ type. The barometer may have been moved to another floor at this occasion, but it is equally possible that it remained in the same room as before and that this room began to be heated in the cold season. This is quite likely to have happened. In fact, a new so-called ‘meridian room’ was built in the 1820s (Alm, 1934), and the old ‘meridian room’ began to be used for other purposes. We assume that the barometer was placed in the old ‘meridian room’ already in 1754, that this room was unheated all the time until 1840, and that the barometer remained in the same room until the end of 1861.

5.3. REDUCTIONS TO SEA LEVEL PRESSURE

Most of this section is devoted to a description and discussion of how we performed the reductions to sea level perssures for data before 1859. We also briefly mention the reductions applied by us to the younger data when reductions were not already applied in the data sources.

5.3.1. *Effect of Changing Air Humidity*

The distance between the lower mercury surface and the brass scale on the Ekström barometer certainly varied somewhat with changing air humidity. Hence, we found it necessary to estimate how large this length change could have been.

Our approach was to calculate the expected maximum average annual range of the length change using known properties of walnut wood (Boutelje and Rydell, 1995) combined with the average annual range of relative humidity (RH) in Stockholm 1961–1990 (obtained from the SMHI). We reasoned as follows:

The total length change from completely dry to completely moist walnut wood is between 0.4 to 0.5%. We use the average value of 0.45%. The equilibrium moisture content (EMC) for walnut is 18.5% at RH 90% and 11.5% at RH 60%. The monthly average RH in Stockholm varies between 65% (in May) and 88% (in November). In this interval we assume that a linear relation between EMC and RH can be used; i.e. an RH of 65% (88%) gives an EMC of 12.7% (18%), which in turn means that the actual maximum range of the EMC is 5.3%. We also assume a linear relation between length change and EMC. The EMC for completely moist wood for typical deciduous wood is 26%. We assume that this value is relevant for walnut. Given these values and assumptions, we estimate that the maximum length change of walnut wood is $5.3 \times 0.45/26 = 0.09\%$ in the actual RH-interval.

With a maximum length change of the barometer frame of about 0.09%, the annual range of the change of the actual distance (25.3 sw.inch) is about 0.02 sw.inch ($\approx$0.8 hPa), wherefore the maximum error in neglecting the moisture effect is $\pm$0.01 sw.inch ($\approx\pm$0.4 hPa). As this is the smallest observable unit on the Ekström barometer, we consider the effect of changing humidity to be negligible. Consequently, no corrections had to be applied.

It should be mentioned that our assumptions of linear relations do not hold for all purposes. For example, the linear relation between EMC and RH is very good for RH $< 80\%$, but the EMC increases more rapidly for larger RH-values (cf. Camuffo, 1998; Cocheo and Camuffo, 2002). However, for an estimation of the maximum average effect on the Ekström barometer, we consider the linear approximations to be relevant.

5.3.2. *Correction for the Ratio between the Mercury Surface Areas*

On a barometer such as Ekström's, with a short fixed scale placed at the upper mercury surface and a non-adjustable lower mercury surface, an observed change of the mercury height does not correspond exactly to the true length change of the mercury column. The reason is that when the level of the upper mercury surface changes, the lower surface also changes slightly, but in the opposite direction. An observed change of one length unit thus corresponds to a slightly larger real change. We measured the scale on the Ekström barometer and found that its unit is exactly the Swedish inch. This means that Ekström himself did not adjust the scale to compensate for the effect. Hence, it was necessary for us to apply a correction to the observed data. Our main problem was to find proper values of the areas of the two mercury surfaces.

It is reasonable to assume that the barometer showed the mercury height correctly at 25.3 on the scale, as this value was specifically marked. Therefore, the following equation was used to convert the observed height (H_{obs}) of the mercury column (in sw.inch) to the true height in sw.inch ($H_{\mathrm{sw.\ inch}}$):

$$H_{\mathrm{sw.\ inch}} = f \cdot (H_{\mathrm{obs}} - 25.3) + 25.3\,, \tag{3a}$$

where

$$f = \left(1 + \frac{a}{A}\right) = \left(1 + \frac{\pi \cdot r_i^2}{\pi \cdot (R_i^2 - r_o^2)}\right)\,. \tag{3b}$$

In Equation (3b), a = area of upper mercury surface, A = area of lower mercury surface, r_i = inner radius of glass tube, r_o = outer radius of glass tube and R_i = inner radius of mercury container. The inner and outer radii of the glass tube were measured in the X-ray image (Figure 10), and were found to be 3 mm and 4 mm respectively. The entire mercury container can unfortunately not be seen in the image because it is covered by a brass shield which cannot be removed. R_i can therefore not be determined from the X-ray image. One can only say that R_i can take any value between about 13 and 28 mm. This corresponds to values of the factor f in Equation (3) between 1.06 and 1.01. We decided to use $R_i = 28$ mm, i.e. the maximum possible radius, giving $f = 1.01$, because it is likely that Ekström wanted to minimize the influence of level changes of the lower mercury surface.

We applied Equation (3a) with $f = 1.01$ to all observed barometer values 1756–1858 and then we converted these values to mm. This seems to be relevant for all cases when the Ekström barometer was used. If another barometer was used some short periods (which certainly happened, see Section 5.5.), another correction might have been more appropriate for these periods. With no explicit information available about any possibly different barometers, however, we found no reason to make other choices of correction.

5.3.3. *Reduction to 0 °C and Conversion to hPa*

Reduction to 0 °C, for the period 1756–1858, and at the same time conversion to pressure in hPa was made using the standard equation:

$$p_0 = g_{45} \cdot \rho_0 \cdot H_{T,\mathrm{mm}} \cdot (1 - \gamma \cdot T) \cdot 10^{-5}, \tag{4}$$

where p_0 = air pressure reduced to 0 °C in hPa, $g_{45} = 9.80665\ \mathrm{m \cdot s^{-2}}$ (normal gravity acceleration), $\rho_0 = 13.5951 \cdot 10^3\ \mathrm{kg \cdot m^{-3}}$ (density of mercury at 0 °C), $H_{T,\mathrm{mm}}$ = corrected length of the mercury column (in mm) at temperature T (in °C), $\gamma = 1.82 \cdot 10^{-4}\ \mathrm{K^{-1}}$ (thermal expansion coefficient of mercury)[⋆] and T = barometer temperature (in °C).

We assumed that the Ekström barometer was correct at 0 °C. This assumption is arbitrary, but it is the common case for modern barometers. If we introduced a

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[⋆] The thermal expansion coefficient of brass ($1.9 \cdot 10^{-5}\ \mathrm{K^{-1}}$) was omitted because the maximum error of omitting this coefficient for the short brass scale on the Ekström barometer is about ±0.03 hPa, which is negligible in this context.

systematic error by making an incorrect assumption here, this error is likely to have been detected, and also corrected for, in the homogenization based on comparisons with pressure series from surrounding stations desribed in Section 5.4.

As no barometer temperatures were observed before February 1785, we had to estimate them from the outdoor temperatures before Equation (4) could be used. As already mentioned, the barometer temperature 1785–1839 roughly followed the outdoor temperature, but with a certain delay. We assume that the conditions were the same 1756–1784, i.e. that the barometer was kept in an un-heated and well ventilated room.

For the estimation of barometer temperatures (T), we used low-pass filtered outdoor temperatures ($T_{\text{out, filtered}}$) as predictor in a simple linear regression model:

$$T = a_1 \cdot T_{\text{out, filtered}} + a_0 \,. \qquad (5)$$

This is essentially the same technique as used by Bärring et al. (1999). The model was used for estimating all barometer temperatures from 1756 to January 1785, and also in case of missing values from February 1785 to 1839.

Before the regression coefficients and filter parameters in Equation (5) could be determined, the series of outdoor temperatures had to be made complete with three values per day. Each missing outdoor temperature was therefore estimated from the actual daily mean temperature by solving Equation (1) for the missing temperature.

The model parameters were determined for the calibration period 1810–1839 and tested on the 24-year validation period 1786–1809. We studied the bias and root-mean-square error for various choices of filters and time lags between outdoor and barometer temperatures (all data were arranged sequentially; T_{morning}, T_{noon}, T_{evening}, $T_{\text{next morning}}$, etc.). The final choice of filter was a one-tailed gaussian low-pass filter with standard deviation of 10 (i.e., 50% of the variability is suppressed for periods <10 days, 80% for periods <5 days). Bärring et al. (1999) used an exponential filter with lag 21 observations (7 days) to mimic the thermal inertia of the walls of the unheated part of the building. With our filter choice, we found that a zero time lag gave the best results. The regression parameters are $a_1 = 0.9350$ and $a_0 = 3.4544$. (For the period 1756–1760, with only two outdoor temperature observations per day, a separate regression model was developed).

The validation period gave a temperature bias of +0.005 °C and a root-mean-square error of 1.82 °C. Hence, about 95% of the estimates are accurate within ±3.6 °C, which corresponds to pressure errors of about ±0.7 hPa. Certainly, the model is very good for catching the changes of barometer temperatures on weekly-to-monthly time scales and longer, but individual values can be rather uncertain.

5.3.4. *Reduction to Normal Gravity and Sea Level*

The reduction to normal gravity for all data 1756–1920 was made using the standard equation:

$$p_{0g} = \frac{g_\varphi}{g_{45}} \cdot p_0 \,, \qquad (6)$$

where p_{0g} = pressure at station altitude reduced to 0 °C and normal gravity, and $g_\varphi = 9.81907\ \mathrm{m \cdot s^{-2}}$ (gravity at station latitude 59°21′ N). Data from 1921 onwards had already been reduced to normal gravity by SMHI or its predecessor.

Reduction to sea level pressure 1756–1960 was made using the relation:

$$p_{0g0} = p_{0g} \cdot e^{\left(\frac{g_\varphi \cdot z}{R_d \cdot T_m}\right)}, \tag{7}$$

where p_{0g0} = air pressue reduced to 0 °C, normal gravity and sea level, z = barometer altitude in m, $R_d = 287.04\ \mathrm{J \cdot K^{-1} \cdot kg^{-1}}$ (gas constant for dry air) and T_m = mean temperature in K in the fictitious air column between station level and sea level. T_m was estimated from the observed outdoor temperature, assuming a lapse rate of 0.6 °C per 100 m.

During 1756–1760, outdoor temperatures were observed only at sunrise and noon, whereas the barometer was observed in the morning and evening. Evening outdoor temperatures for this early period were estimated simply by taking the average between the noon and following morning temperature. The barometer altitude in different sub-periods was set according to the values in Table IV. Data from 1961 onwards had already been reduced to sea level by the SMHI, although with a different method (see Bärring et al., 1999). The difference between the methods is negligible here as the station is situated quite near sea level.

5.4. HOMOGENIZATION OF THE SEA LEVEL PRESSURE SERIES

The procedures described in Section 5.3 were used to create a raw daily sea level air pressure series. From these daily values, monthly and annual mean pressure series were calcultated. The annual series (Figure 11a) exhibits an irregular behaviour with a number of multi-decade long periods with mean values differing by several hPa. Such large pressure differences between various sub-periods can hardly be expected to occur for natural reasons. It is thus evident that the raw series is not homogeneous.

In order to test the homogeneity of the raw Stockholm pressure series and to find the size of the necessary adjustments, we applied the standard normal homogeneity test for single shifts (Alexandersson, 1986). Pressure series from a number of surrounding stations were used as reference data (see Table V). For the most recent period, 1966–1998, data from two nearby Swedish coastal stations were used as reference. Both records are considered as homogeneous (Hans Alexandersson, SMHI, personal comm.). For the period 1890–1990 we used seven Scandinavian series selected from the homogeneity tested North Atlantic Climatic Data Set (Frich et al., 1996). For 1822–1995 we used six European series from the data set obtained within ADVICE (Jones et al., 1999). The longest period for which a reasonably reliable reference series can be found is 1780–1995. For this period we used data for the gridpoint 60° N 20° E in the ADVICE data set (Jones et al., 1999). To search for abrupt changes in the period before 1780, when no

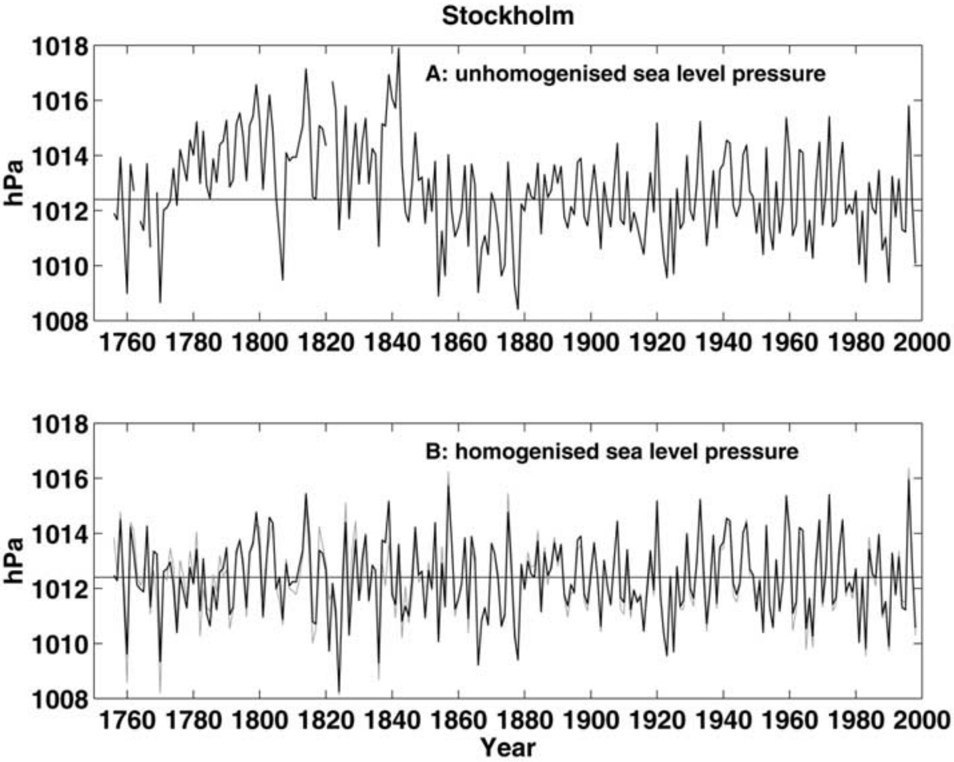

Figure 11. Annual mean sea level pressure in Stockholm 1756–1998. (a) Before homogenization. (b) After homogenization. The homogenized sea level pressures for Uppsala are shown with grey lines in B for comparison. The horizontal line in each plot represent the mean pressure for the homogenized series (1012.4 hPa).

relevant reference series is available, we applied the homogeneity test directly to the Stockholm pressure series itself.

The homogeneity test was applied for several sub-periods to identify all time points of abrupt changes. For each statistically significant break, the observation journal and/or the station reports were inspected to look for a relevant explanation and to find, if possible, the exact date for changed conditions. If the exact date of a change was not explicitly given by the metadata, the most likely date for a change was instead determined from a direct comparison with the simultaneously developed daily Uppsala pressure series (Bergström and Moberg, 2002). The Uppsala series was, however, never used for determination of the size of any corrections, as we strived at homogenizing the two series independently as far as possible.

The results of the homogeneity tests showed that after 22 August 1879 the data was homogeneous except for a few short periods, whereas all older data had to be corrected. For the period when reference series were available, i.e., back to 1780, corrections were applied so as to keep the pressure difference between Stockholm

Table V

Reference series used for homogeneity tests of the Stockholm air pressure series. The abbreviations (NACD7, ADVICE6) defined here are used in Table VI

Period	Reference stations	Comments
1780–1995	Gridpoint 60° N 20° E	Gridpoint data from the ADVICE data set (Jones et al. 1999).
1822–1995	ADVICE6: Trondheim, Lund, Gdansk Bergen, Oslo, St. Petersburg	Six European stations from the ADVICE data set (Jones et al., 1999).
1890–1990	NACD7: Visby, Kalmar, Göteborg Oslo-Blindern, Vaernes/Trondheim Härnösand, Helsinki	Seven Scandinavian stations from the North Atlantic Climatic Data set (NACD) (Frich et al., 1996).
1966–1998	Svenska Högarna Landsort	Swedish coastal stations situated on islands ≈70–80 km east of Stockholm. Data considered homogeneous (Hans Alexandersson, SMHI, personal comm.).

and the respective reference data being the same as for the homogeneous part after September 1879. To find corrections for the data before 1780, we added the criterion that the mean value of the Stockholm pressures before 1780 should be the same as that for 1780–1998.

A graphical view of the character of inhomogeneities in the raw Stockholm pressure series is presented in Figure 12a, which shows an annual time series of the difference in pressure between Stockholm and the gridpoint 60° N 20° E. The estimated biases, i.e., the corrections applied to homogenize the series, are also shown. Details of the corrections (their numerical values, the exact periods to which they were applied, and probable explanations for the inhomogeneities) are given in Table VI. A discussion of the results is presented in Section 5.5. The effect of the corrections can be seen by comparing the b-parts of Figures 11 and 12 with their a-parts. Figure 11b also shows the annual record for the homogenized Uppsala pressures. The interannual variability is obviously very similar in the two final reconstructions.

From the corrected data, daily mean pressures were calculated simply by taking the arithmetic mean value of the instantaneous values each day. To make the daily series complete, it was necessary to fill in missing data for 131 days, of which most occur before 1770. A majority of these values (105) were estimated from Uppsala

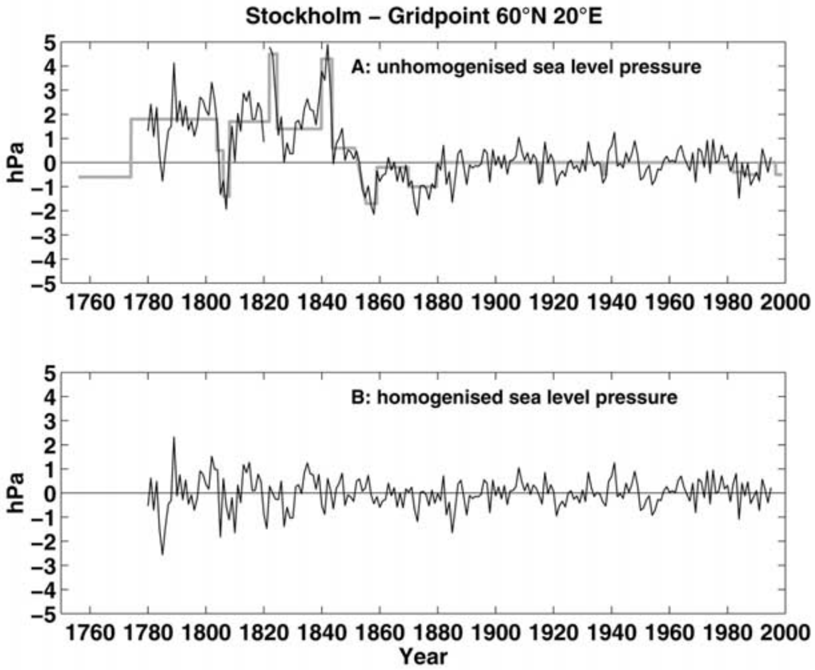

Figure 12. Difference in annual mean sea level pressure between Stockholm and the gridpoint 60° N 20° E (Jones et al. 1999b). (a) Before homogenization. (b) After homogenization. The grey curve in (a) shows the correction constants given in Table VI as a time series (but with opposite signs).

using a linear regression relation. The remainder (26) was filled in through linear interpolation between the pressure for neighbouring days.

5.5. COMMENTS TO THE HOMOGENEITY TEST RESULTS

Concerning the period 1756–1858, the assumed period for the Ekström barometer, there are several sub-periods with different biases. The results suggest that the bias originally was only –0.6 hPa, indicating that the instrument was well made and that our assumptions concerning reductions (Section 5.3) were essentially relevant. An abrupt change to a bias of +1.8 hPa occurred in March 1774. The reason for this is entirely unknown. The bias was thereafter between +1.8 and +1.4 hPa until November 1839, except for two sub-periods (1803–1808, 1821–1824) with markedly different biases. The latter sub-period began with two weeks of missing data in October 1821 and ended with two days in July 1824 having double observations. This suggests that the Ekström barometer (still assuming this one was used) went out of order in October 1821 and was sent for restoration. Another barometer (with bias +4.5 hPa) was probably used until July 1824. The situation may have been similar 1803–1808, although a different barometer (with bias +0.5 to –1.4 hPa) could have been used. From November 1839 to August 1843 the bias was +4.3 hPa (nearly

Table VI

Estimated biases in the observed Stockholm pressure series. These data were used as a basis for homogenizing the series. Comments are given concerning the basis for determining biases and exact dates for start/end of each period. The abbreviations NACD7 and ADVICE6 refer to groups of reference stations as defined in Table V. The letters (m, n, e) indicate if a period starts/ends with the morning, noon or evening observation. An absence of such a label indicates that a period starts with morning and ends with evening observation

Time period	Bias (hPa)	Comment
1756.01.01–1774.02.28	–0.6	Significant abrupt shift of internal mean pressure in the Stockholm series. Correction applied to adjust the earliest data to the average pressure of the rest of the homogenized series (1012.4 hPa).
1774.03.01–1803.11.08	+1.8	Bias: obtained from comparison with gridpoint 60° N 20° E. End of period: obtained from comparison with Uppsala.
1803.11.09–1806.01.07	+0.5	Bias: comparison with gridpoint 60° N 20° E. End of period: comparison with Uppsala.
1806.01.08–1808.02.29	–1.4	Bias: comparison with gridpoint 60° N 20° E. End of period: comparison with Uppsala.
1808.03.01–1821.11.29	+1.7	Bias: comparison with gridpoint 60° N 20° E. End of period: comparison with Uppsala.
1821.11.30–1824.07.15n	+4.5	Bias: comparison with gridpoint 60° N 20° E. End of period: comparison with Uppsala. No barometer data 1821.10.14–1821.10.31 suggest problems with barometer and a possible barometer change. Double observations 1824.06.24–25 suggest that two different barometers were used. Maybe the observers started to use the same barometer as in the previous period, and made double observations for comparison.
1824.07.15e–1839.11.15	+1.4	Bias: comparison with ADVICE6. End of period: comparison with Uppsala.
1839.11.16–1843.08.12	+4.3	Bias: comparison with ADVICE6. End of period: comparison with Uppsala. Start of period is close in time to abrupt change from ‘outdoor’ to ‘indoor’ type of barometer temperature in 1840.01.09. End of period coincides with temporary change from ‘indoor’ to ‘outdoor’ behaviour of barometer temperature.
1843.08.13–1851.05.31	+0.6	Bias: comparison with ADVICE6. End of period: comparison with Uppsala.

Table VI
(Continued)

Time period	Bias (hPa)	Comment
		Notes in observation register reveal that Ekström's barometer was used from April 1844, when a barometer by Littman had been used for about one month.
1851.06.01–1855.05.31	Trend from +0.6 to –1.7	Bias: comparison with ADVICE6. Start and end of period: comparison with Uppsala. The trend-like behaviour of bias suggested by comparison with Uppsala.
1855.06.01–1858.12.31	–1.7	Bias: comparison with ADVICE6. End of period: New barometer probably installed 1859.01.01 as barometer unit changed that day.
1859.01.01–1869.11.30	–0.2	Bias: comparison with ADVICE6. End of period: comparison with Uppsala.
1869.12.01–1879.08.21	–1.0	Bias: comparison with ADVICE6. End of period: comparison with Uppsala.
1879.08.22*m*–1914.12.09	0	
1914.12.10–1916.01.15	–0.8	Bias: comparison with NACD7. Start and end of period: comparison with Uppsala.
1916.01.16*m*–1937.01.20*n*	0	
1937.01.20*e*–1938.03.07*n*	–0.5	Bias: from inspection report 1938.03.07. Start of period: comparison with Uppsala. End of period: from inspection report 1938.03.07. Remarks in inspection report 1938.03.07 that the barometer probably became biased after having been moved from one room to another early in 1937.
1938.03.07*e*–1981.12.31	0	
1982.01.01–1985.10.08*m*	–0.4	Bias: from inspection report 1985.10.08. Start of period: comparison with Uppsala. End of period: from inspection report 1985.10.08. New barometer was installed 1980-05-22; instrument was biased when controlled 1985.10.08.

Table VI
(Continued)

Time period	Bias (hPa)	Comment
1985.10.08*n*–1991.02.01*m*	–0.5	Bias: from inspection report 1991.02.01. End of period: from inspection report 1991.02.01. New barometer installed 1985.10.08; instrument was biased when controlled 1991.02.01.
1991.02.01*n*–1996.09.09*m*	0	New barometer installed 1991-02-01.
1996.09.09*n*–1998.12.31	–0.5	Bias: from comparison with Svenska Högarna and Landsort. Start of period: New barometer 1996-09-09. Homogeneity tests strongly indicate that the instrument is biased. The bias is uncertain, being based on only two years.

the same as 1821–1824), suggesting another period when the Ekström barometer might have been substituted. The start of this anomalous period coincides closely in time with a change of the barometer temperature from an ‘outdoor’ type to an ‘indoor’ type. The end of the same period coincides with a temporary return back to ‘outdoor’ temperatures, so clearly some kind of change took place within this period. Furthermore, some very interesting remarks are found in the journals of March and April 1844. On 12 March there is a statement that observations were made on ‘Littman’s barometer’, whereas it is stated on 9 April: “began to observe Ekström’s barometer”. This note is the only real proof that Ekström’s barometer was actually used. These few remarks in the observation journal, together with the results from the homogeneity tests, are considered as support for the assumption that Ekström’s barometer was actually used most of the time from 1754 to 1858, and that it was replaced with other barometers during a few short time periods. From August 1843 to May 1851 the bias was +0.6 hPa. The homogeneity tests then suggest a gradual, rather than abrupt, change to a bias of –1.7 hPa in June 1855. The bias was thereafter –1.7 hPa to the end of 1858. There is no hint in the journals of any reason for this behaviour near the end of the supposed period of Ekström’s barometer.

The homogeneity tests confirm that 1859 was the beginning of a new period. According to the results the bias was only –0.2 hPa from January 1859 to December 1869. Thereafter, the bias was –1.0 hPa until 22 August 1879. Since this date, the bias is zero nearly all the time until January 1982. After 1982, there is generally a bias of around –0.5 hPa. The station inspection reports confirm problems with the barometers in this most recent period.

5.6. DISCUSSION OF THE SEA LEVEL PRESSURE SERIES

We have reconstructed a series of daily mean sea level air pressures for Stockholm from the original observational data. Performing the reductions to sea level before 1859 was the most difficult part of the work, because little is known about the properties of the used barometers and their positions. Furthermore, no barometer temperatures were observed before 1785, so these values had to be estimated from outdoor temperatures. Comparisons with data from other European stations reveal that the air pressure values for Stockholm, as calculated directly from the observations, exhibit several sub-periods with various systematic biases. A homogenization was therefore done by adding certain corrections obtained from homogeneity tests. The homogenization is expected to correct for most of the systematic errors in the original data, and also for possible systematic errors introduced by us whenever we made wrong assumptions concering the properties of the early barometers and conditions around the observations.

A plot (Figure 11b) of the homogenized annual mean pressures back to 1756 for both Stockholm and Uppsala (Bergström and Moberg, 2002) shows that the year-to-year variability is very similar in these two series. The similarity is even more striking in plots of daily air pressures. Two examples of time-series plots of daily pressures in selected years (1788 and 1819) are shown in Figure 13. The plots illustrate that the day-to-day pressure changes is almost identical in the two series. This is to be expected for two such nearby stations. Other selections of years (not shown) reveal the same high degree of similarity. This is a very good indicator that both records are very reliable reconstructions of daily air pressures. In particular, the data can be used with a high degree of credibility as input for drawing pressure charts over Europe for any particular day.

Regarding long-term trends (multi-decadal scales), the reliability of the data must be considered as lower than for the conditions in individual days. This is rather obvious because the pressure difference between various multi-decade long periods is small in comparison with many of the errors in the observed data. Furthermore, the homogenization of the long-term trends was largely based on comparison with data for surrounding stations, which means that the reliability of trends is dependent on the quality of the reference data.

The reliability of trends is regarded as very high back to 1890, where the homogenization was based on comparisons with the NACD data set of Frich et al. (1996). This data set consists of a large number of series which have been homogeneity tested and maintained by the national meteorological services in several countries. Although we used homogenized reference data back to 1780, the reliability of pressure trends before 1890 must be expected to decrease further back in time. This is because the reference data we used (from Jones et al., 1999) had, in their turn, been homogenized based on comparisons with fewer and fewer surrounding stations further and further back in time. Finally, the Stockholm pressure series can not be used at all for studies of changes in pressure trends before 1780, as the

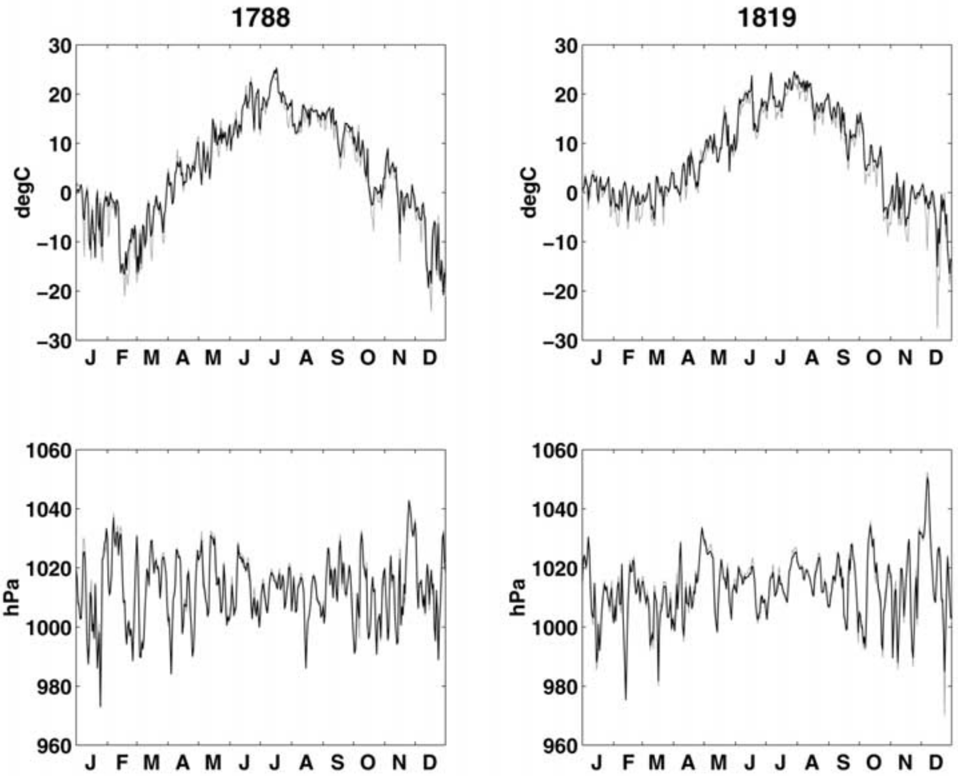

Figure 13. Daily mean air temperatures and sea level pressures for Stockholm (black) and Uppsala (grey) for two selected years, 1788 and 1819.

oldest part was homogenized by assuming that the mean value before 1780 should be the same as that afterwards. Nevertheless, these earliest data still seem to be reliable for reconstructions of weather patterns, drawing of synoptic charts, etc. for individual days.

6. Concluding Remarks

Reconstruction of a 250-year-long daily meteorological record is a time-consuming work. In our case, it included not only the pure calculations leading to the final daily values, but also digitizing of the original data, detective work for identification and correction of various kinds of errors and making reasonable assumptions when basic information about important conditions was missing. We found it extremely valuable to have access to parallell data for the neighbouring station in Uppsala (65 km north of Stockholm), described by Bergström and Moberg (2002). Because of the possibility to compare the two series, many errors in individual temperature or pressure values as well as systematic biases could rather easily be identified and then corrected.

The similarity between the two series can be illustrated by plots of both the daily temperature and pressure data for any selected year. We show two such examples for 1788 and 1819 in Figure 13. These specific years were selected to show examples of years with extreme temperatures. 1788 (1819) was one of the years with most frequent cold winter days (hot summer days) in the Stockholm series. The similarity between the series is striking, and there is no doubt that data for both stations show very well how the temperature and pressure changed from day to day. The overall impression is that both stations have data which, in their homogenized form, should be very reliable for many types of analyses of weather patterns in Europe for individual days back to the 1750s. Therefore, they are of great value for both pure climatological and meteorological research and for scientists who need to know the particular weather conditions in periods of particular historical interest, such as wars or periods of famine.

We emphasise, however, that the series are not perfect. There is a general lower reliability of the data older than the mid-19th century compared with the younger data. The reason is a combination of factors such as less strict routines for observational procedures, a general lack of information about these procedures and about the instruments and instrument positions, lower instrument quality, poorer instrument positions, etc. Furthermore, there are problems also with the most recent data. For example, the corrections for the urban warming trend in the late part of the temperature series were determined only on a monthly basis. It may be possible to refine this correction by separation of the data into classes according to weather type, such as cloudiness, wind direction, humidity etc. Such an analysis would require the availability of long daily series for several surrounding stations too. At present, however, such data do not exist in computer readable form.

Finally, we stress the need for further long daily meteorological time series to be reconstructed from the original observational data at as many sites as possible. The larger the available data set, the better the possibilities to distinguish imperfections in the data from true weather and climate variability. This in turn would lead to improved conditions for all climatic research aimed at understanding the nature of natural climate behaviour on the daily time scale and at distinguishing natural climate changes from man-made changes.

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Appendix

This appendix gives a description of how the Δ-values and f_{cl} factors in Equation (1) were obtained.

MODEL FOR THE DIURNAL TEMPERATURE CYCLE

To determine the Δ-values to be used in Equation (1) we used ninety years (1869–1958) of hourly temperature observations from Uppsala as a basis, as we consider the diurnal temperature cycle in Uppsala to be representative for Stockholm if its amplitude is scaled with respect to the climatic difference and its phase is adjusted for the small time difference between the longitudes (1 min 44 s).

Here we are interested only in the deviations of instantaneous temperatures from the average daily mean temperatures, and not of absolute temperatures. The diurnal cycle of these deviations is abbreviated DC. In order to avoid small irregularities in the DC curves, which may be due to micro-climatic conditions specifically related to conditions at Uppsala, they were smoothed using Fourier series with four harmonics.

For each month, m ($1 \leq m \leq 12$), the DC for Stockholm can be expressed as

$$\mathrm{DC}_m(h) = \sum_{n=1}^{4} A_{m,n}^{(\mathrm{S})} \cdot \cos\left(2\pi \cdot h \cdot \frac{n}{24} + \omega_{m,n}\right) , \tag{A.1a}$$

where

$$A_{m,n}^{(\mathrm{S})} = f_m \cdot A_{m,n}^{(\mathrm{U})} . \tag{A.1b}$$

In these equations, h is the hour (CET decimal hour, $0 \leq h \leq 24$), A is the amplitude of each harmonic (with the superscripts $^{(\mathrm{S})}$ and $^{(\mathrm{U})}$ denoting Stockholm and Uppsala). The amplitudes $A_{m,n}^{(\mathrm{U})}$ and phase angles $\omega_{m,n}$ (the latter with the appropriate phase shift) were determined from the Uppsala data. The scaling factor, f_m,

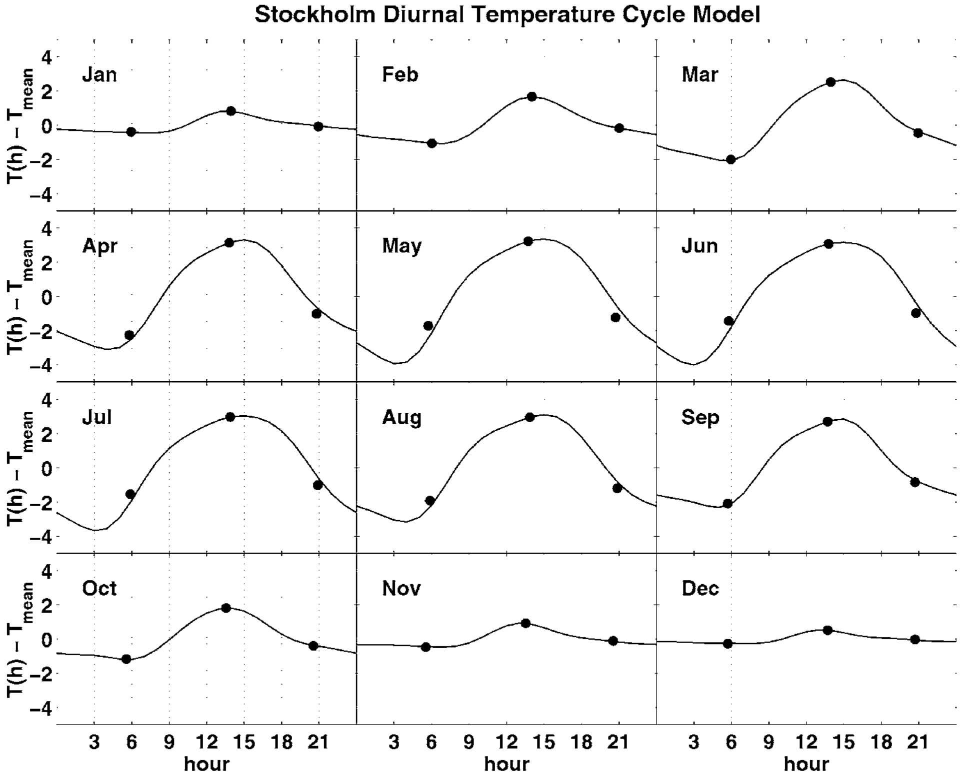

Figure A.1. Model of the diurnal temperature cycle (with the mean value subtracted) for the old astronomical observatory in Stockholm. The dots represent the averages for the three daily observations in the periods 1785–1796 and 1816–1858.

is determined by Equation (A.2). The twelve monthly average DCs for Stockholm are illustrated in Figure A.1. The amplitudes $A^{(S)}_{m,n}$ and phase angles $\omega_{m,n}$ are listed in Table A.I.

The scaling factors, f_m, were determined for each month, m, by calculating the ratio

$$f_m = \frac{\overline{(T_{14} - T_{21})}^{(S)}_m + \overline{(T_{14} - T_{06})}^{(S)}_m}{\overline{(T_{14} - T_{21})}^{(U)}_m + \overline{(T_{14} - T_{06})}^{(U)}_m}, \tag{A.2}$$

where $\overline{(T_{14} - T_{21})}^{(S)}_m$ is the average difference between temperature readings at 14 and 21 in Stockholm during the combined periods 1785–1796 and 1816–1858. $\overline{(T_{14} - T_{06})}^{(S)}_m$ is the corresponding difference for observations at 14 and 06. These periods were selected to ensure that the largest possible amount of data for Stockholm with constant observation hours was used. The entries in the denominator are the corresponding differences for Uppsala 1869–1958.

A monthly average Δ-value can be obtained for an arbitrary hour, h, in a given month, m, simply as $\Delta = -\mathrm{DC}_m(h)$. From monthly average Δ-values for each

Table A.I
Amplitudes and phase angles for the diurnal temperature cycle model in Equation (A.1a)

m	$A_{m,1}$	$A_{m,2}$	$A_{m,3}$	$A_{m,4}$	$\omega_{m,1}$	$\omega_{m,2}$	$\omega_{m,3}$	$\omega_{m,4}$
1	0.5093	0.2307	0.1133	0.0448	2.2737	–0.8933	2.2683	–1.0848
2	1.1681	0.4701	0.1264	0.0111	2.2879	–0.9305	2.1689	1.5211
3	2.1912	0.5599	0.0712	0.1267	2.3480	–0.8125	–0.9984	2.1086
4	3.1591	0.3262	0.2976	0.0598	2.4842	–0.4343	–0.8210	–3.6163
5	3.6186	0.2704	0.3266	0.0898	2.5459	1.6497	–0.5030	–1.3586
6	3.5582	0.4232	0.2317	0.1142	2.5555	2.1085	–0.3625	–1.0308
7	3.3622	0.3024	0.2668	0.1104	2.5467	1.9162	–0.5663	–1.2631
8	3.1367	0.1490	0.3601	0.0487	2.5495	0.0708	–0.7681	–2.5181
9	2.4767	0.5166	0.2108	0.1438	2.5345	–0.6095	–0.7934	–3.7209
10	1.3443	0.4909	0.0629	0.0662	2.5415	–0.6125	–3.4985	–3.7196
11	0.5470	0.2784	0.1161	0.0322	2.5097	–0.6967	–3.6485	–0.8435
12	0.3001	0.1543	0.0741	0.0405	2.4199	–0.7472	–3.7739	–0.9073

integer hour (0, 1, 2, . . . , 23), daily Δ-values were determined by cubic convolution interpolation (Keys, 1981) between the monthly Δ-values. Hence, a 365×24 matrix was obtained, containing Δ-values for all integer hours of the year. Finally, when using Equation (1) for estimation of daily mean temperatures, a linear interpolation between the hourly Δ-values for a particular day was used in cases when observations were not made at exact hours.

SCALING OF DIURNAL TEMPERATURE CYCLE AMPLITUDE WITH RESPECT TO CLOUD AMOUNT

Before the f_{cl} factors in Equation (1) could be determined, each cloud observation was assigned a number corresponding to a cloud cover in tenths. Data for 1873–1960 were given in tenths already in the source. Data for 1961–1998 and 1859–1872 were simply translated from eights and fourths respectively. The conversion to tenths of data from before 1859 involved an interpretation of the various notes and symbols used. In the few cases when no cloud observations had been reported, the gaps were filled in subjectively using information from the other observed weather variables and the cloud amount in the nearest days. Daily average cloud cover values, rounded to integer tenths, were then calculated. Finally, each day was classified as a ‘clear’ (0–3 tenths), ‘half-clear’ (4–7 tenths) or ‘cloudy’ (8–10 tenths) day.

Table A.II

Monthly values of amplification factors for the amplitudes of the diurnal temperature cycle model in Equation (A.3)

m	f_{cl}^{clear}	$f_{cl}^{\text{half clear}}$	f_{cl}^{cloud}
1	1.1482	1.1407	0.9126
2	1.2374	1.1128	0.8787
3	1.2960	1.0951	0.7731
4	1.2485	1.0597	0.7611
5	1.2046	1.0224	0.7711
6	1.2024	1.0107	0.7690
7	1.1988	1.0173	0.7947
8	1.2447	1.0129	0.8018
9	1.2045	1.0275	0.8255
10	1.2547	1.1060	0.8540
11	1.2009	1.1625	0.8899
12	1.2068	1.2045	0.8980

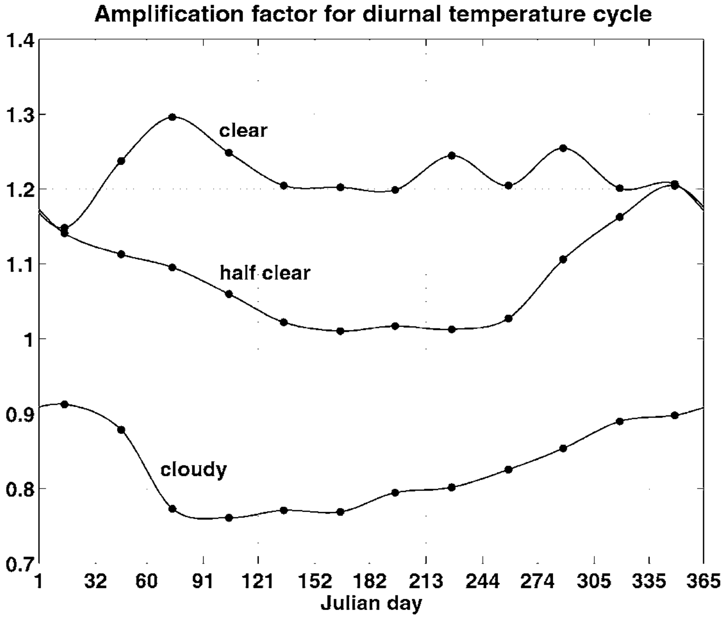

Figure A.2. Amplification factors for the amplitude of the diurnal temperature cycles (in Figure A.1) as a function of Julian day. The dots represent the monthly averages determined from the data for three cloudiness classes. The curves are obtained by cubic interpolation between the monthly averages.

Scaling factors, f_{cl}, were then determined for each class and for each month (all Januaries, all Februaries etc., separately) from the relation

$$f_{cl}^{\text{cloud class}} = \frac{\overline{(t_{\max} - t_{\min})}^{\text{cloud class}}}{\overline{(t_{\max} - t_{\min})}^{\text{all data}}}, \tag{A.3}$$

where ‘cloud class’ refers to one of the classes ‘clear’, ‘half clear’ or ‘cloudy’, using data for 1859–1960; ‘all data’ denotes all data for the same period. This is the longest possible period with $T_{\max}$ and $T_{\min}$ measured at the north-facing wall. The scaling factors are thus thought to be representative also for the conditions before 1859, i.e., the period for which Equation (1) was used and when the thermometer always was placed on a north-facing wall. Monthly averages of the scaling factors are listed in Table A.II. Daily scaling factors (Figure A.2) were obtained by cubic interpolation between the monthly values.

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