DAILY MILAN TEMPERATURE AND PRESSURE SERIES (1763–1998): COMPLETING AND HOMOGENISING THE DATA

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Abstract. Daily meteorological observations have been made at the Brera astronomical observatory in Milan since 1763. Even if the data have always been collected at this observatory, the Milan series are far from being homogeneous as several changes were made to instruments, station location and observation methods. Within this context, the purpose of the paper is to discuss data homogenisation. Homogenisation is based both on objective information extracted from the station history (direct methodology) and on some statistical estimates (indirect methodology). Homogenisation by indirect methodology is mainly performed by comparison with other series whereas, if no other homogeneous series are available, it is based on the hypothesis that some statistics, such as the daily temperature range or the day to day variability, have no significant trends within some selected periods. Besides homogenisation also the completion of the series is discussed. The resulting series are complete and homogenised daily minimum, mean and maximum temperatures and complete and homogenised daily mean pressures. They all cover the period 1763–1998.

1. Introduction

The reconstruction of the history of Milan temperature and pressure observations shows that, even if the data always have been collected at the Brera observatory, the series are far from being homogeneous as several changes were made to instruments, station location and observation methods. A summary of the principal events that could cause inhomogeneities in Milan data is reported in Table I where the years in which they happened are shown as well. For a complete discussion of the history of Milan observations see Maugeri et al. (2002).

Therefore a great effort has been made in order to identify non-climate inhomogeneities and adjust the series to compensate for the biases these inhomogeneities produce.

Meteorological series can be tested for homogeneity both by direct and by indirect methodologies. The first approach is based on objective information that can be extracted from the station history or from some other sources, the latter uses statistical methods, generally based on comparison with other series (Peterson et al., 1998).

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Within this context, the purpose of this paper is (i) to discuss how the information on the history of Milan temperature and pressure observations (metadata) presented in Maugeri et al. (2002) can be used to give quantitative estimates of some of the inhomogeneities caused by the events reported in Table I, (ii) discuss data completion and homogenisation by indirect methodology. Homogenisation is performed using a step-by-step procedure and therefore series with different levels of homogeneity are produced. All these series are available as a result of EC-project '*Improved understanding of past climate variability from early daily European instrumental sources*' (IMPROVE).

Some climate analysis on the homogenised series and comparison with other homogenised series is presented in Moberg et al. (2000) and in Yan et al. (2002).

2. Metadata and Temperature Series Homogeneity Evaluation

Milan metadata give evidence of a number of events that could cause inhomogeneities in the temperature series. Unfortunately it is often very difficult to estimate the effect of these events by direct methodologies as metadata rarely contain information that allows quantitative estimations. Such information is available only in a few cases and generally it is not sufficient to perform homogenisation without comparison with other series.

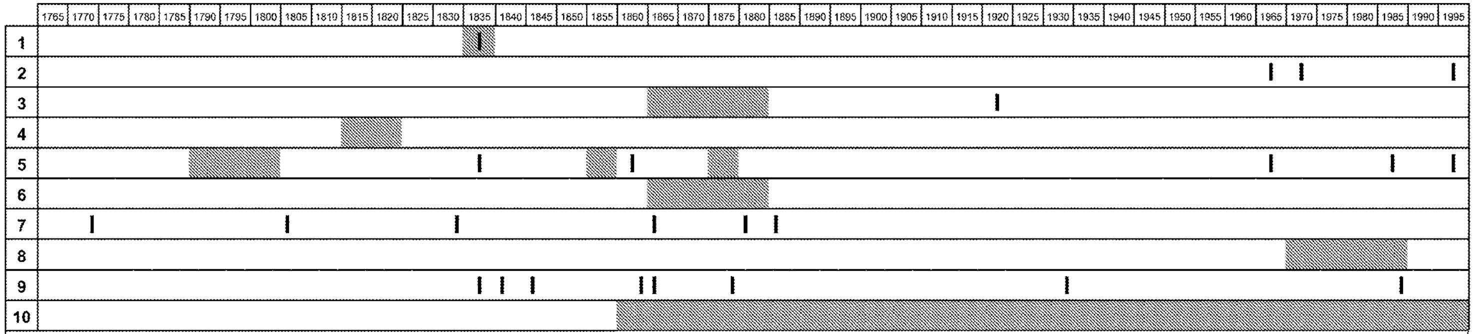
2.1. THE EFFECT OF CARLINI'S REORGANIZATION

Milan metadata contain some quantitative notes for the evaluation of the homogeneity of Carlini's, temperature data with the ones collected before the great reorganisation of the Milan observations he performed in 1835 (Maugeri et al., 2002). Checks of the old thermometer (Carlini, 1855) revealed that the earliest data had to be corrected because of a 0.88 °C error of the thermometer zero-point. Carlini also discussed the reason of this error supposing that it could be due to the shift of the zero-point that usually affected thermometers some time after their construction (Bellani, 1841; Carlini, 1855). Beside the zero-point check, Carlini performed also some comparisons between 'mane' temperatures (i.e., temperatures measured around sunrise (Maugeri et al., 2002)) measured with the old thermometer in the old site and minimum ones in the new site, evidencing a mean difference of 1.26 °C (Carlini, 1855). Unfortunately contemporaneous measures were taken only for some short periods and refer only to winter as Carlini made them in the pursuit of a study on the very cold event of the 24th of January, 1855 that was characterised by temperatures (minimum value: -17.3 °C) that had never been measured in Milan (Carlini, 1855).

Buffoni el al. (1996) tried to estimate the effect of Carlini's reorganisation on yearly mean temperatures too. They assumed the differences were caused only by the zero-point error and by changes in observation methodologies (Maugeri et

Table I

Events that could influence the Milan temperature and pressure series homogeneity (For a more complete discussion of the history of the Milan observations see Maugeri et al., 2002). If the dates are well known the events are identified by a bold line, otherwise they are associated to a grey band.



1: Carlini's 1835 reorganisation; **2**: Other displacements of the instruments; **3**: Changes in the meteorological screen and in its management; **4**: Improvements introduced by Cesaris; **5**: Substitutions of the barometer and changes in instrumental correction; **6**: Effects of standardisation due to development of national and international meteorological networks; **7**: Changes in the observer; they are included only until 1880 as later on standardisation causes the measurements to be less dependent from the observer; **8**: Interruption of Brera observatory series; **9**: Changes in observation hours; **10**: Urban heat island development.

al., 2002) and found a mean error of the old observations of about 0.45 °C. The same method could be used to evaluate monthly and daily errors but it is greatly hampered by the assumption that temperature does not depend on the site.

2.2. THE EFFECT OF THE MICROCLIMATE IN THE METEOROLOGICAL SCREEN

The microclimate in the meteorological screen is a very critical item. Problems are not only connected with its management (Maugeri et al., 2002) and with major changes in its structure (number, position and aspect of the grids), but also with minor changes that cannot be checked on the basis of metadata. In spring 1993 an experiment was performed in the partially restored old screen: it demonstrated that small changes in the position of the thermometer can produce meaningful discrepancies in the measurements. Differences between data taken in the inner side of the screen (where Santomauro located the thermometers in the 1950s) and those taken in the central and more exposed side can reach significant values as high as 0.5 °C. In this case the thermometer placed closer to the wall may have been affected both by the heating of the building and by the heat stored during the day by the wall. It is however very difficult to generalise the result as in 1987 an air quality station had been set up in the Brera tower and therefore in 1993 the old meteorological window and the communicating room could not exactly be restored to the past conditions. The impossibility to restore the conditions of the past causes all the data collected in the screen in the last years (1993–1996) to be only partially representative of the ones collected before 1987. The comparison of these data with the ones in the present site shows that, independently of the season, both maximum and minimum screen temperatures seem to be higher and, furthermore, discrepancies turn out to be greater for the minimum values. As far as the seasonal trend is concerned, the differences seem to be highest in summer.

2.3. THE EFFECT OF THE DEVELOPMENT OF THE MILAN URBAN HEAT ISLAND

Changes in the screen and in the communicating room were not the only relevant ones in the environment around the thermometers. Other changes concern the Brera building and the areas around it. The most important change in these areas took place after Italian political unity (1860), when Milan began to grow fast causing the Astronomical Observatory to be progressively surrounded by other buildings (Figure 1). As a consequence the urban heat island began to increase. At the present, comparison with Milan Linate data allows to quantify its contribution on yearly mean temperature around 1.4 °C (Bacci and Maugeri, 1992).

3. Metadata and Pressure Series Homogenisation

As for temperature, also for pressure Milan metadata give evidence of a number of events that could cause inhomogeneities in the series. In this case, however, much

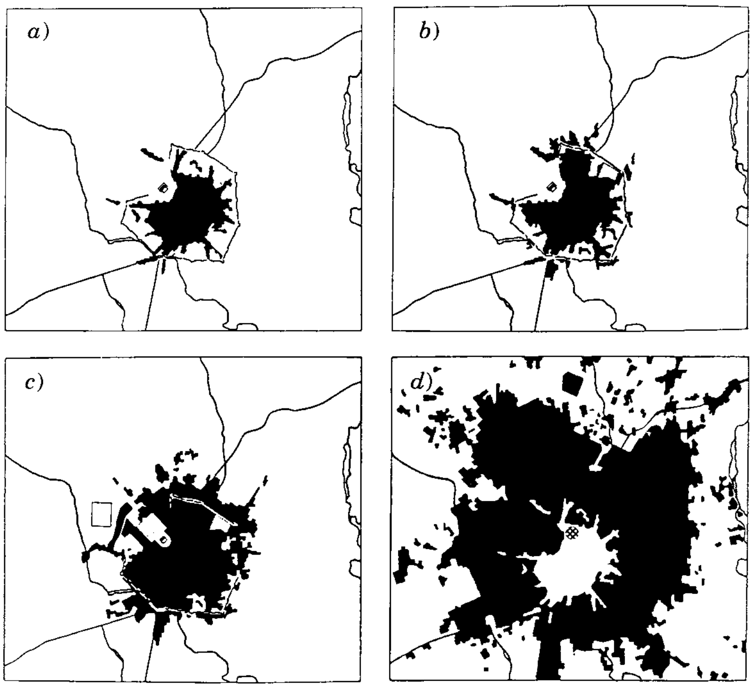


Figure 1. Milan, as well as almost all other Italian and European cities, grew rapidly over the past 150 years. The picture shows the size of Milan in: (a) 1800 (110.000 inhabitants), (b) 1860 (185.000 inhabitants), (c) 1900 (490.000 inhabitants) and (d) 1940 (1.327.000 inhabitants). The white area in (d) reproduces the black one in (a). The black dot in (d) shows the Brera Observatory location.

more quantitative information is available as some of it is connected with problems (temperature of the barometer, observation times and height of the barometer) that are very well documented in the metadata (Maugeri et al., 2002). So an initial homogenisation of air pressure series was performed by direct methods in order to:

- reduce all the data to 0 °C;
- adjust all the daily means to real daily means, i.e., to values that are representative of averages obtained by continuous monitoring;
- reduce all the data to sea level pressures.

3.1. REDUCTION OF AIR PRESSURE DATA TO 0 °C

Barometer temperatures began to be measured only in November 1817, when a small thermometer was annexed to the barometer (Maugeri et al., 2002). They were measured at the same time as air pressure and reported in the observatory registers until 1830, when they stopped being reported. After Carlini's reorganisation they began again to be reported and observed and reduced pressures were reported as well. At the beginning the observations were reduced to 10 °R, then in 1844 the most used value of 0 °C was adopted.

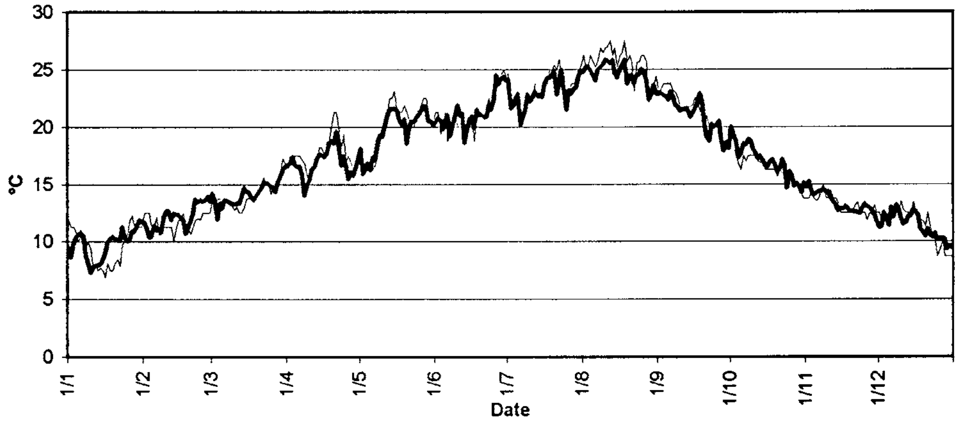


Figure 2. Internal 'vespere' temperatures for the year 1820. Thin line: measured values; bold line: calculated ones.

In order to construct a model for the estimation of the internal temperatures of the periods 1763–1817 and 1831–1834, we analysed the correlation between internal and external temperatures in the period 1818–1830. The analysis showed that internal temperature can be estimated by a multi-linear regression on the basis of the external temperature observed at the same time and on the one relative to the previous observation. The coefficients of the regression depend on the day of the year. Figure 2 shows an example of the results of the model reporting measured and reconstructed internal '*vespere*' temperatures (i.e., temperatures measured around 3 p.m. (Maugeri et al., 2002)) for the year 1820. Considering all the data of the 1818–1830 period the correlation between the observed and the estimated internal temperatures is 0.97 both for '*mane*' (i.e., around sunrise (Maugeri et al., 2002)) and '*vespere*' observations. For both observation times the differences between observed and estimated internal temperatures have a normal distribution function with standard deviation around 1.2 °C. Therefore the error connected to the model estimation of the barometer temperature seems to be around 0.2 hPa. Naturally this estimate does not take into account changes in the barometer room management (e.g., heating) that could have influenced the internal temperature giving larger errors.

Once missing internal temperatures had been estimated, the data of the period 1763–1843 were reduced to 0 °C, using the method recommended by WMO (1983). Actually this method is not completely correct for the Milan data as the old barometer's brass scale was fixed to a wooden case and therefore its position depended both on brass thermal expansion and on wood dilatation, the latter one being mainly influenced by relative humidity. However, as metadata do not contain sufficient details to give a quantitative estimation, this effect was not considered.

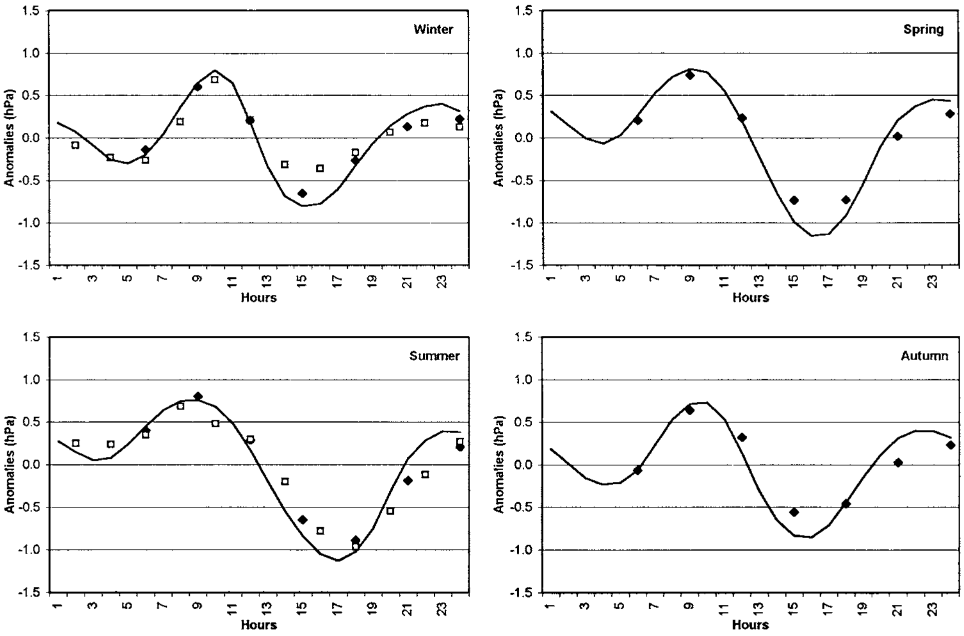


Figure 3. Milan seasonal mean diurnal pressure cycles calculated with data of the period 1988–1998 (bold line). The figure also displays the mean cycles calculated by Schiaparelli and Celoria (1867) on the basis of the 25 years period 1835–1859 (black rhombi) and by Carlini (1828) on the basis of high resolved observation taken around winter and summer solstices in the period 1826-1830 (squares). All the data are expressed in anomalies (hPa) with respect to the cycle means.

3.2. REDUCTION OF AIR PRESSURE MEANS TO REAL DAILY MEANS

Daily pressure means obtained by simply averaging some daily observations cannot be considered representative of the real daily pressure mean values. In order to solve this problem we studied the Milan diurnal pressure cycle in the last 11 years of the series. The results were in good agreement with those of the literature (Chapman and Lindzen, 1969), clearly showing two maxima (9–11 a.m. and 9–11 p.m.) and two minima (3–5 a.m. and 3–5 p.m.). It is worth noticing that at the Milan Observatory studies on the diurnal pressure cycle already began to be performed in the first decades of the 19th century. The first relevant results are due to Carlini who in 1826 performed measures with a 2 hour time resolution (Carlini, 1828). Later on the problem has been studied more in detail by a number of authors mainly interested in highlighting periodicity connected with astronomical cycles (Schiaparelli and Celoria, 1867). Some of the results are shown in Figure 3, together with the data of the last 11 years of the series.

In order to estimate the errors due to calculating the daily average pressure using only a few observations, the diurnal pressure cycles can be expressed in terms of anomalies from the cycle means (Figure 3). This allows an easy estimate of the errors of daily means due to changes in observation hours: They are simply

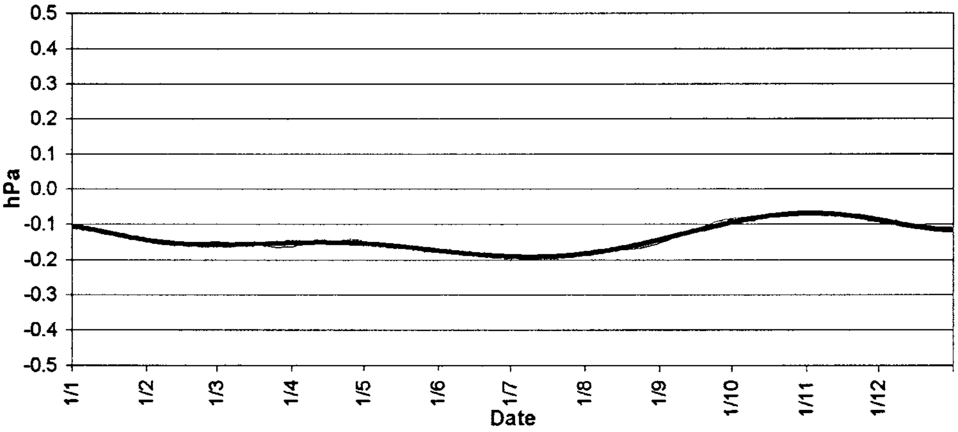


Figure 4. Corrections of air pressure daily means to eliminate the bias introduced by calculating daily means using observations taken at 8 a.m., 2 p.m. and 7 p.m. The corrections apply to the period December 1st, 1932 – December 31st, 1987.

given by the average of the values of the cycles corresponding to the observation hours. This method has been applied to all the sets of observation hours adopted in Milan from 1763 to the present time (for a complete list of Milan observation times see Table I in Maugeri et al. (2002)). For each set of observation hours the error corresponding to each day of the year has been calculated using its typical cycle. Then the errors have been smoothed using an 8th degree polynomial fitting, as continuos monitoring is available only for the last 11 years of the series causing each of the 365 diurnal pressure cycles to be an average over only 11 days. An example of the resulting corrections for the case of observations taken at 8 a.m., 2 p.m. and 7 p.m. is reported in Figure 4. The errors are generally rather low and after 1835 they never exceed 0.2 hPa. The only relevant errors are the ones of the early period (Figure 5) when only two observations were made.

3.3. REDUCTION TO SEA-LEVEL PRESSURE

Reduction to sea-level pressure was performed using the methods currently recommended by WMO (1983) and considering a temperature of 12.8 °C that corresponds to Milan mean air temperature in the period 1763–1998. Gravity was not reduced to 45 degrees as Brera Observatory latitude (45°27′ 59″.2) is very near to this value.

3.4. OTHER INFORMATION CONCERNING AIR PRESSURE

Milan metadata contain some very interesting notes on barometer calibrations (Maugeri et al., 2002). The first documented tests are the ones performed by Carlini in the frame of the 1835 observatory reorganisation (Carlini, 1835); others are discussed in Carlini (1855), Capelli (1864), Denza (1876) and Grassi (1879). It

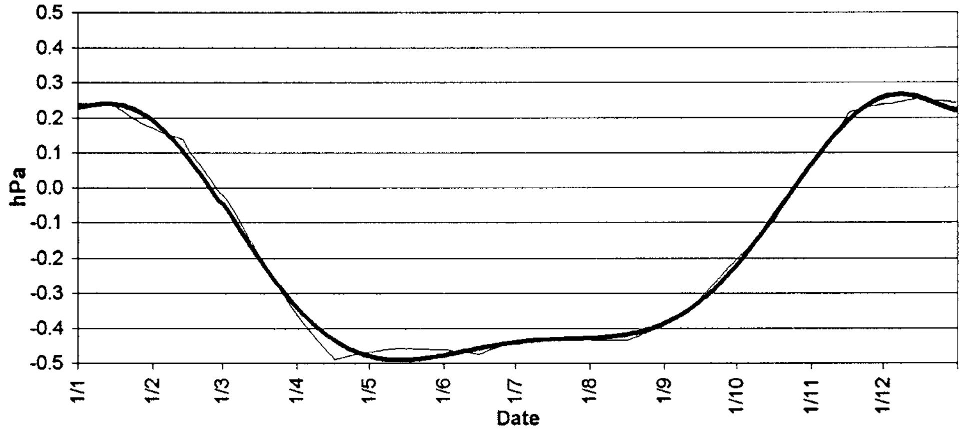


Figure 5. As in Figure 4, but for period 1763–1834. In this case the observation hours change during the year depending on the time of sunrise.

is however very difficult to use this information for correcting the data as the notes are sometimes ambiguous (Maugeri et al., 1998) and, even when they are clear, they generally give insufficient details to understand if and exactly when new barometer instrumental errors began to be adopted.

4. Completing the Data

4.1. TESTING AND CORRECTING ANOMALOUS DAILY VALUES

After Milan data digitisation had been concluded (Maugeri et al., 2002) some tests to check possible errors in temperature and pressure series were performed.

According to some thresholds both for absolute values and for differences between consecutive observations, a number of 'suspicious' data was identified and all the values were individually controlled. Then the ones that were considered errors were either invalidated or corrected.

As far as temperature is concerned this activity causes the current Milan series to have a few values that are different from the ones published in Buffoni et al. (1996). The most relevant differences regard May, 1778 when for 6 consecutive days (26th to 31st) '*mane*' and '*vespere*' temperatures were inverted. Other corrections were made assuming errors to depend on the omission of the sign before the data or from incorrect interpretation of the manuscripts due to unclear handwriting.

Globally the corrected or invalidated values were 48. The effect on monthly means is generally negligible.

Table II

Coefficients that allow the best $c_i \cdot P$ polynomial fittings of the daily temperature range seasonal patterns (1778–1816) to be obtained for the four different state of the sky conditions.

Sunny	Variable	Cloudy	Rainy
1.19	0.97	0.80	0.55

4.2. ESTIMATING '*MANE*' AND '*VESPERE*' TEMPERATURES FOR THE PERIOD 1763–1777

The introduction of a maximum and minimum thermometer in 1838 and the observation times adopted in the previous years (Maugeri et al., 2002) gave daily extreme temperatures or, at least, estimates of them over almost all the Brera series, with the only exception being the initial 15 years (1763–1777) for which only mean temperatures are available (for details on data availability see Table II in Maugeri et al. (2002)).

In order to reconstruct the '*mane*' and '*vespere*' values of this period we constructed a model trying to estimate them on the basis of mean temperatures and sky conditions. The sky conditions were extracted from Milan Observatory Ephemeridis (for details on the sources of Milan data see Maugeri et al. (2002)). The basic idea was first to divide all days from 1763 to 1834 into four different classes in relation to the state of the sky (sunny, cloudy, rainy or variable); secondly to use '*mane*' and '*vespere*' data from 1778 in order to approximately estimate for each day of the year the diurnal temperature range relative to the sky conditions and then, finally, to associate a daily range according both to the cloud cover and the date to each day before 1778. In fact, once the daily range, defined by the difference between temperature recorded in the afternoon and temperature collected at dawn is given, the two observations at '*mane*' and '*vespere*' can easily be calculated from their mean.

In Figure 6, independently of the sky conditions, the mean daily temperature range over the whole year is represented. The curve has been traced averaging the data of the period 1778–1816 that, according to metadata (Maugeri et al., 2002), is homogeneous with the initial one. The 8 degree polynomial curve P (solid line) that best fits the data is also shown in the figure. Once the coefficients of the polynomial curve have been detected by means of least squares method, four further coefficients c_i, which multiply P and which depend on the states of the sky, have been calculated in the same way in order to find the $c_i \cdot P$ curves which best approximate the daily temperature range patterns (figures not shown) according to

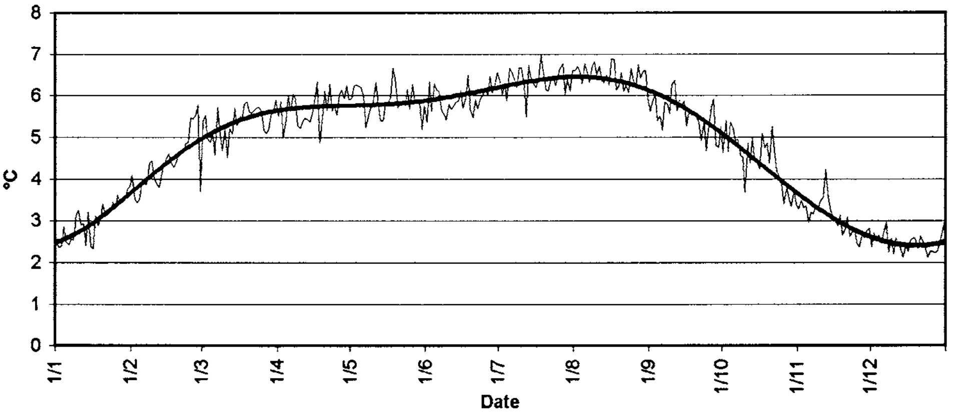


Figure 6. Mean daily temperature range in the period 1778-1816 (thin line) and best fitting 8th degree polynomial curve (thick line).

the four sky conditions (Table II). Then the four $c_i \cdot P$ curves have been used to estimate the daily range of each day of the period 1763–1777.

The reconstruction method has been tested on the decade 1778–1787: the difference between the true daily ranges and the reconstructed ones showed that for only 5% of the data the error was larger than 3 °C.

4.3. FILLING SOME MINOR DATA GAPS IN TEMPERATURE AND PRESSURE SERIES

The Milan series have only a few gaps: Missing data are around 0.3% of the available observations. They are mainly concentrated in the early period and in the last one, whereas no gaps are present from 1849 to 1986. A detailed list of the gaps in minimum and maximum temperature series is reported in Buffoni et al. (1996). The gaps in the pressure series are more or less the same.

In order to fill the gaps we employed a procedure based on the assumption of constant differences between the series to be completed and a highly correlated reference series. This method is widely applied for monthly data (Böhm, 1992) and we extended it to daily ones. As reference series we used an average between Padua and Turin for the early period, whereas for the most recent years data collected by Milan University in another point of the Brera building were adopted.

5. Homogenising the Temperature Series

5.1. HOMOGENISATION OF THE PERIOD 1763–1837

The most important task in homogenising the Milan temperature series was the transformation of the data collected before Carlini's reorganisation (Maugeri et al.,

2002) to values comparable with the ones collected after this major change. The corrections were estimated by the following steps:

- Construction of a monthly mean temperatures reference series for the period 1763–1864 from an average of several other early temperature series. The period was selected both to have sufficient data after 1837 and to minimise the effect of some events that probably influence the homogeneity of the Milan series from 1865 onwards (Table I).
- Use of this series to estimate the effect of Carlini's reorganisation and of some other minor events on monthly mean temperatures.
- Estimation of daily corrections from monthly ones by interpolation between monthly values.
- Estimation of '*mane*' and '*vespere*' corrections from mean temperature ones.

5.1.1. *The Monthly Mean Temperatures Reference Series*

The first step in data homogenisation was the construction of a reference series for the Milan mean temperatures, since Milan daily mean temperatures were calculated using maximum and minimum thermometer data or '*mane*' and '*vespere*' observations according to the considered period (Maugeri et al., 2002).

A great number of mean temperature series going back to the 18th century is now available in Italy and in the neighbouring countries. It is however not possible to use any individual one of them as the only basis for a reference series for Milan in the period 1763–1864, as they generally were not studied for homogeneity and the few ones that have been corrected (e.g., the Austrian one (Böhm and Auer, 1994)) come from stations too far away. Therefore, in order to minimise errors, we constructed the reference series averaging 16 station series (Table III). They were selected both on the basis of distance from Milan and correlation with Milan series. After having transformed the data to anomalies from the means over the 1838–1864 period, the average was performed on a monthly basis weighing each monthly series by the square of its correlation coefficient with Milan one (Alexandersson, 1986; Alexandersson and Moberg, 1997). The mean value of all the monthly correlation coefficients between the station series and Milan was 0.80. The station with the highest correlation was Vigevano ($R = 0.94$), the ones with the lowest were Kremsmünster and Vienna ($R = 0.70$) that are the farthest from Milan as well. After constructing the reference series, its sensitivity to the 16 individual station series was studied by calculating new reference series omitting one of them at the time and comparing the resulting series with the old reference one. These tests verified that the properties of the reference series are not particularly influenced by any of the station series.

5.1.2. *Monthly Mean Temperature Corrections*

Once the mean temperatures reference series was constructed it was compared with the Milan one. Comparison was performed on monthly, seasonal and yearly

Table III

Stations used to construct the reference series for the homogenisation of the monthly mean temperatures of the period 1763–1864

City	Position		Data availability in the period 1763–1834 (%)
	Latitude	Longitude	
Genève	46.20	6.15	100.0
Torino	45.11	7.65	100.0
Basel	47.60	7.60	97.1
Kremsmünster	48.05	14.13	95.9
Wien	48.22	16.35	88.2
München	48.13	11.55	82.4
Hohenpeissenberg	47.80	11.02	82.4
Karlsruhe	49.03	8.37	72.5
Padova	45.40	11.85	69.5
Strasbourg	48.55	7.63	59.8
Bologna	44.48	11.30	49.9
Udine	46.00	13.10	39.2
Genova	44.40	8.92	31.4
Vigevano	45.30	8.87	30.6
Brescia	45.42	10.28	23.4
Mantova	45.13	10.78	19.6

basis and the Craddock homogeneity test (Craddock, 1979) was used to better give evidence of the differences. An example is shown in Figure 7 where the differences between the Milan and the reference yearly mean anomalies are reported. The results of the comparison allowed the following homogeneous main sub-periods to be identified:

- 1763–1804: is the period from the beginning of the series to the beginning of Cesaris's observations;
- 1805–1830: is the period of Cesaris's observations;
- 1838–1864: is the period for which daily extreme temperatures are available.

Moreover Cesaris's observations seem to be characterised by two slightly different periods: 1805–1816 and 1817–1830. They are the periods before and after the improvements in the observations he introduced around 1817 (Maugeri et al., 2002). The different behaviour of this two periods is confirmed by the Milan daily temperature range as well (Figure 8). As far as the very troublesome years between 1831 and 1837 are concerned (Maugeri et al., 2002), four periods could

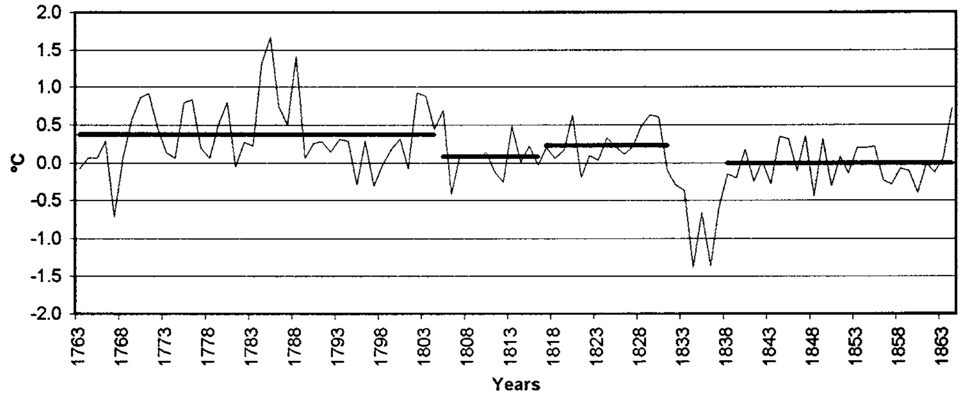


Figure 7. Differences between the Milan and the reference yearly mean temperature anomalies (1763–1864). Both for Milan and the reference series the anomalies are calculated on the basis of the means over the period 1838–1864.

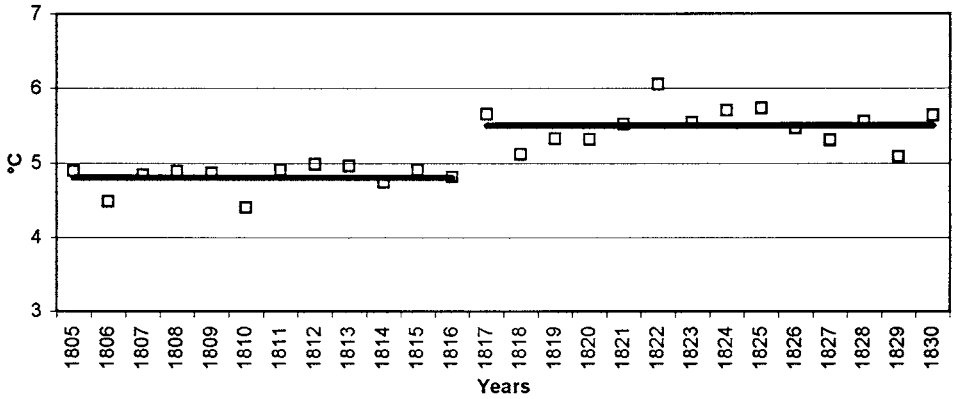


Figure 8. Daily temperature range yearly means in Cesaris's period.

be identified. Therefore the period 1763–1864 was divided into eight internally homogeneous sub-periods.

As the comparisons between Milan and the reference series have been performed using anomalies from the means over the period 1838–1864, the corrections to apply in order to homogenise the data to the ones of this period are simply given by the differences between the average values of the reference and the Milan series over each sub-period. The values for the main sub-periods are reported in Table IV. The corrections are globally slightly lower than the estimation of Carlini's inhomogeneity (−0.45 °C) reported in Buffoni et al. (1996).

5.1.3. *Daily Mean Temperature Corrections*

Once corrections had been calculated for the Milan monthly mean temperatures, daily ones were estimated by interpolation between the monthly values with

Table IV

Corrections (°C) we applied to the monthly mean temperatures of 1763–1830 period in order to homogenise them to the ones of 1838–1864 period.

	1763–1804	1805–1816	1817–1830
January	−0.57	−0.04	+0.33
February	−0.22	+0.38	+0.03
March	−0.16	+0.26	+0.08
April	−0.07	+0.29	+0.19
May	−0.04	−0.03	−0.11
June	−0.07	−0.24	−0.05
July	−0.11	+0.20	−0.22
August	−0.27	+0.02	−0.44
September	−0.65	−0.52	−0.75
October	−0.83	−0.68	−0.64
November	−0.92	−0.55	−0.32
December	−0.56	−0.10	−0.20

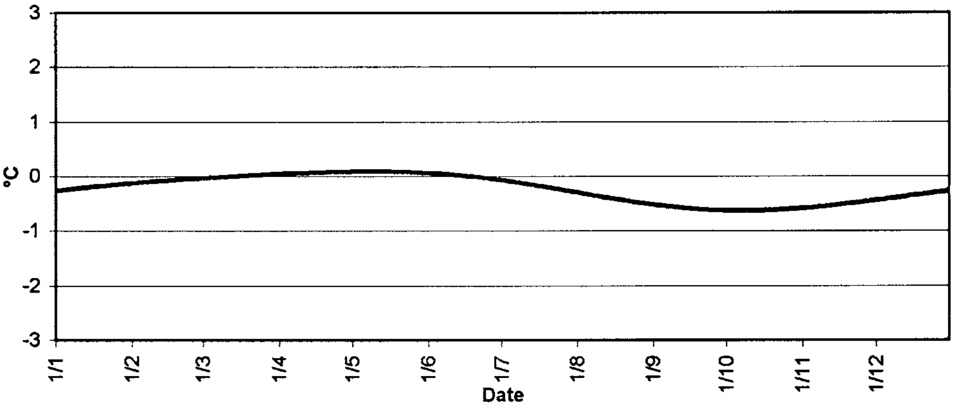


Figure 9. Corrections we applied to the daily mean temperatures of the period 1817–1830 in order to homogenise them to the ones of the period 1838–1864.

trigonometric functions. Figure 9 shows, as an example, the resulting corrections for daily mean temperatures of the period 1817–1830.

5.1.4. *Daily 'Mane' and 'Vespere' Temperature Corrections (1763–1837)*

The corrections for '*mane*' and '*vespere*' data were calculated on the basis of the corrections for their mean values (i.e., mean temperatures) and assuming that all the sub-periods had the same average real daily temperature range of 1838–

1864. The latter hypothesis was based on the evidence that the state of the sky data have no significant trends in the period 1763–1864, since the variations in the observed frequency of clear, overcast and rainy days were less significant than the confidence of the state of the sky data. It was unfortunately not possible to verify it by comparison with other series as homogeneous maximum and minimum Po Valley (Northern Italy) series are at present time available only starting from 1865 (Brunetti et al., 2000a). The assumption of a constant mean daily temperature range allowed us to estimate the corrections to apply in order to homogenise the differences between '*vespere*' and '*mane*' observations of each sub-period in relation to the differences between maximum and minimum temperatures of the period 1838–1864. Homogenisation was first performed on a monthly basis, then daily corrections were estimated fitting the monthly values with trigonometric functions.

Once these corrections had been estimated it was very easy to calculate the corrected '*mane*' and '*vespere*' observations. In fact, assuming that a is the correction to apply to homogenise the difference between '*vespere*' and '*mane*' values of day j in sub-period k to the real daily temperature range of this day and that b is the one to homogenise the '*mane*' and '*vespere*' mean to the real daily mean temperature (i.e., the mean between daily extreme temperatures), the corrected '*mane*' and '*vespere*' observations ($t_{\mathrm{mane,corrected}}$ and $t_{\mathrm{vespere,corrected}}$) are given by the linear system:

$$(t_{\mathrm{vespere,corrected}} - t_{\mathrm{mane,corrected}}) - (t_{\mathrm{vespere,observed}} - t_{\mathrm{mane,observed}}) = a$$

$$\frac{(t_{\mathrm{vespere,corrected}} + t_{\mathrm{mane,corrected}})}{2} - \frac{(t_{\mathrm{vespere,observed}} + t_{\mathrm{mane,observed}})}{2} = b$$

These values are estimates of the daily minimum and maximum temperatures.

Figure 10 shows, as an example, the resulting corrections for daily '*mane*' and '*vespere*' temperatures of the period 1817–1830. It is very interesting to observe that the estimated corrections for Cesaris's '*mane*' observations in the winter season are very close to the value (−1.26 °C) reported by Carlini (Carlini, 1855).

5.2. HOMOGENISATION OF THE WHOLE TEMPERATURE SERIES

After the data collected before 1838 had been homogenised almost all the corrected Milan temperatures were representative of minimum and maximum values measured at Carlini's meteorological window, the only exception concerning some recent periods. Therefore, excluding these periods, the series was homogeneous in relation to thermometer location and to measurement methodologies. However there were at least three other problems:

- microclimate in the meteorological screen and changes in its management;
- increases and modification of the Brera building;
- development of the Milan urban heat island.

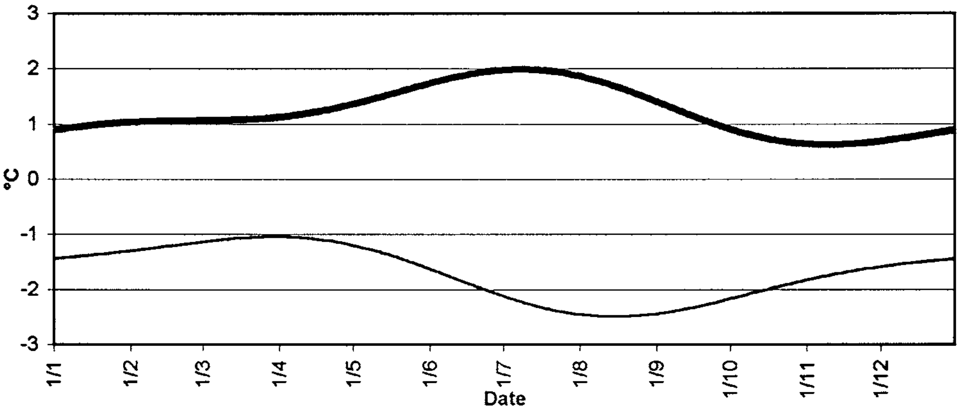


Figure 10. Corrections we applied to the daily 'mane' (thin line) and 'vespere' (thick line) observations of the period 1817–1830 in order to homogenise them to the minimum and the maximum temperatures of the period 1838–1864.

In order to estimate the effect due to all the changes in the environment (screen, communicating room, Brera building, Milan city) around the thermometers we used again comparison with other series. In this case minimum and maximum temperature series were available as they have been recently reconstructed within the Italian National Research Council project '*Reconstruction of the past climate in the Mediterranean area*'. The project allowed us to update, complete and homogenise 15 Northern Italy minimum and maximum temperature series (Maugeri and Nanni, 1998; Brunetti et al., 2000a), among which 11 are for Po Valley stations. The comparison was performed by calculating minimum and maximum anomalies reference series with the same methods used for the period 1763–1864. The results of the period 1951-1996 were also tested by comparison with an Italian Air Force data-set which includes almost only rural stations (Brunetti et al., 2000b).

The results of the comparison showed that the Milan series has some significant inhomogeneities after 1865. As metadata indicated that the most relevant changes should be caused by the microclimate in the screen and by the environment around it (Brera building and Milan city), we fitted the differences between the reference and the Milan series anomalies with a sum of a continuous and a step function, where the former was obtained attributing the mean temperature heat island evolution reported in Bacci and Maugeri (1992) only to minimum temperatures (Landsberg, 1981). This was done first subtracting the heat island contribution from the data, then using the same method adopted for the period 1763–1837, with the reference series extracted from the data described in Maugeri and Nanni (1998) and in Brunetti et al. (2000a,b).

The resulting corrections for yearly mean temperatures are shown in Figure 11 where the ones of the period 1763–1837 are displayed as well. Excluding some very difficult periods, they generally are dominated by heat island contribution. Going from yearly to seasonal values and from mean to minimum and maximum

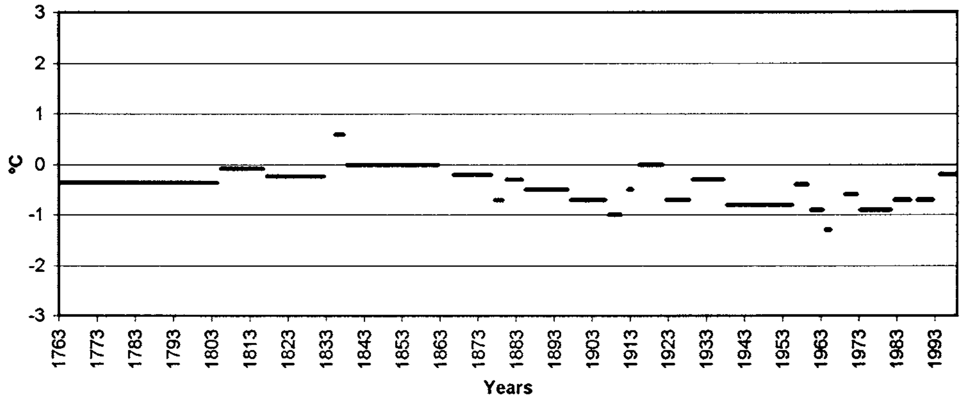


Figure 11. Corrections we applied to Milan yearly mean temperatures in order to homogenise them to the ones of the period 1838–1864.

temperatures, the pattern becomes more complex and sometimes the corrections are near to 2 °C. Globally the most problematic period is the one between 1880 and 1920: It has high negative corrections for maximum temperatures, whereas for minimum ones the corrections are less strong than the ones due to urban effects. Probably in that period the thermometers were located in the more exposed part of the box causing less efficient screening of direct and reflected solar radiation and lower nocturnal heating by the wall. Important corrections are also present after 1963. They generally are well justified by the complex history of Milan series in the last 45 years (Maugeri et al., 2002).

Once the corrections were estimated, Milan minimum and maximum temperature series were homogenised with the same method used for mean temperatures in the period 1763–1837. Homogenisation was performed in order to homogenise all the data to the ones collected before 1865. As a consequence all the data were transformed in minimum and maximum values measured at Carlini's window assuming that it has always been managed as in Carlini's period and that the heat island has kept constant. This constant value is the one of Carlini's period when the Observatory was outside Milan and the urban effect was mainly due to the Brera building.

The homogenised seasonal and yearly Milan minimum, mean and maximum temperature series are shown in Figures 12–14, whereas daily temperature range series are displayed in Figure 15.

5.3. PROBLEMS OF THE HOMOGENISED TEMPERATURE SERIES

The transformation of the original data into homogeneous ones was performed with the aim of giving the best estimate of daily minimum and maximum temperatures, whereas no attempts were made to get homogeneous data distributions. Therefore, even if the data were homogenised, they may be not homogeneous in

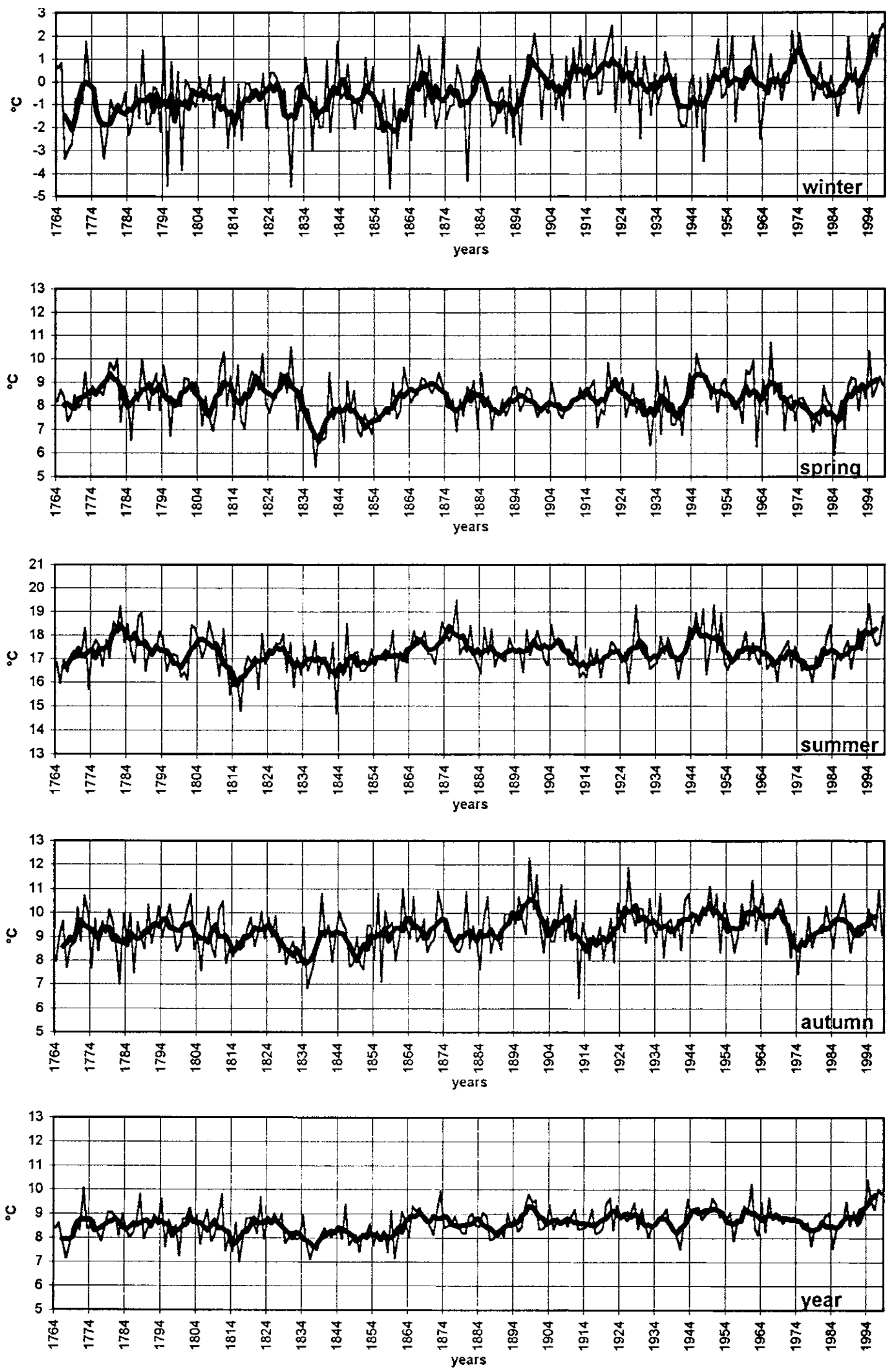


Figure 12. Seasonal and yearly homogenised Milan minimum temperature series (thin lines) and 5-years moving averages.

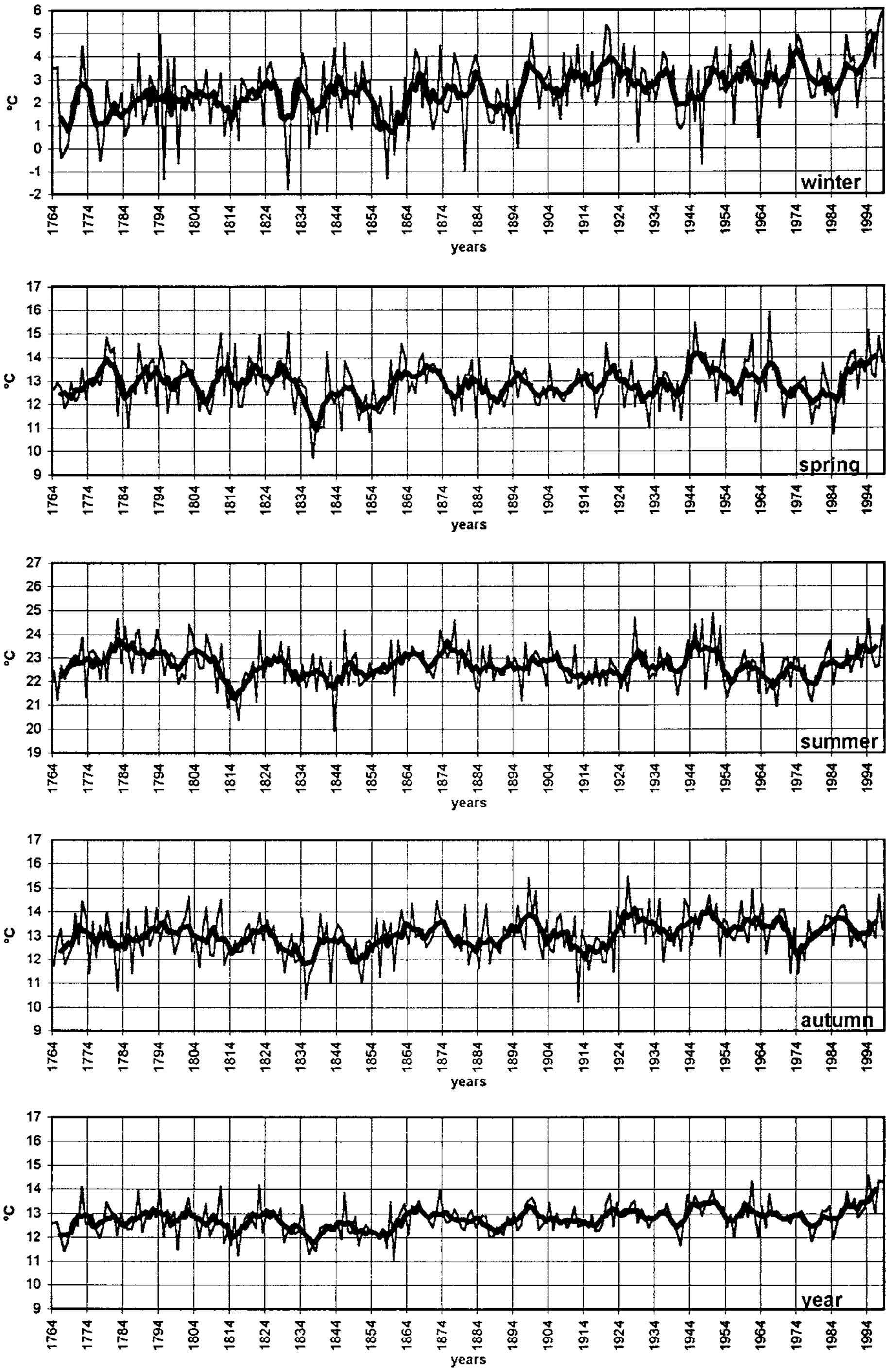


Figure 13. As in Figure 12, but for average temperature.

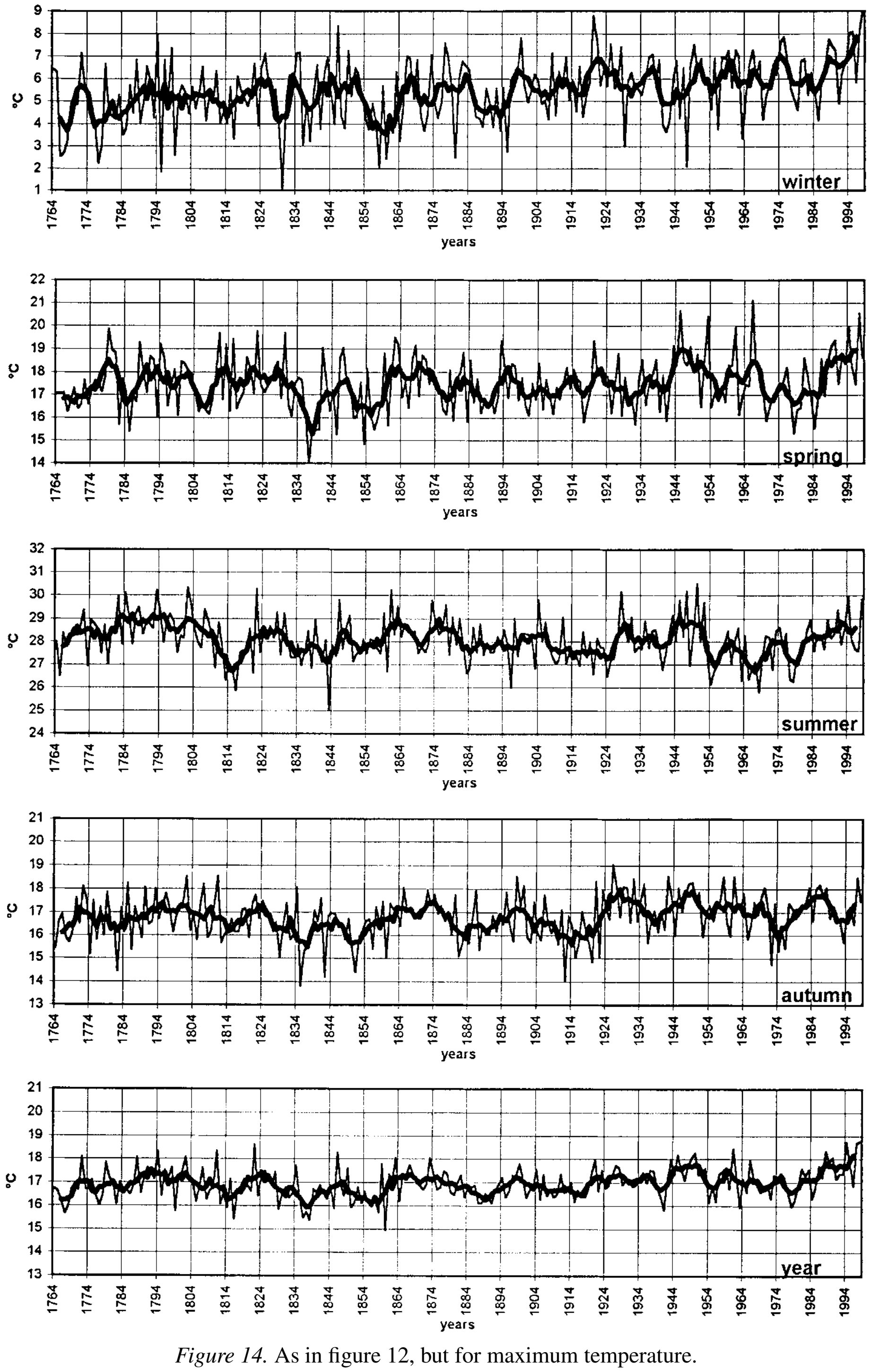


Figure 14. As in figure 12, but for maximum temperature.

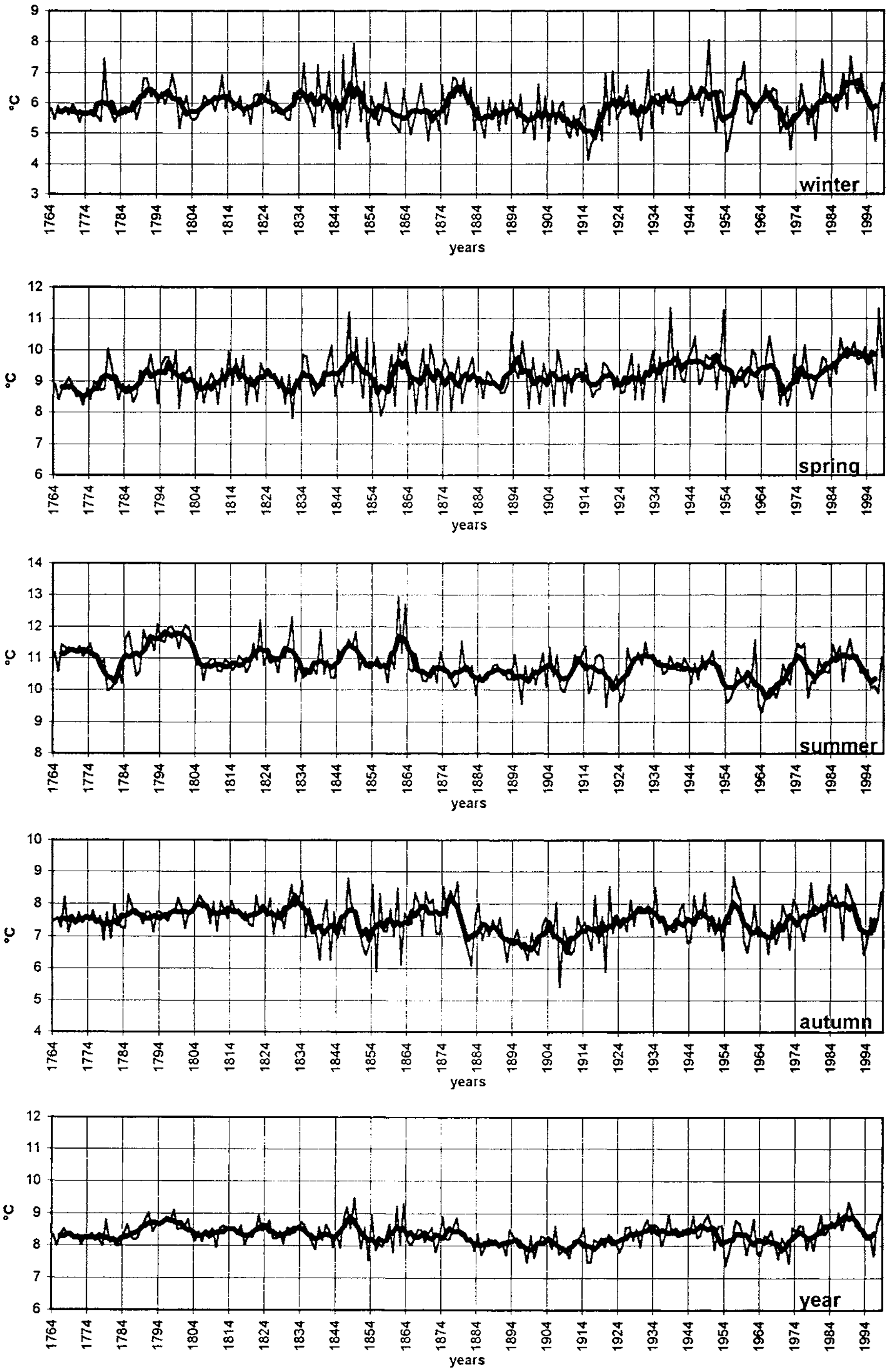


Figure 15. As in Figure 12, but for daily temperature range.

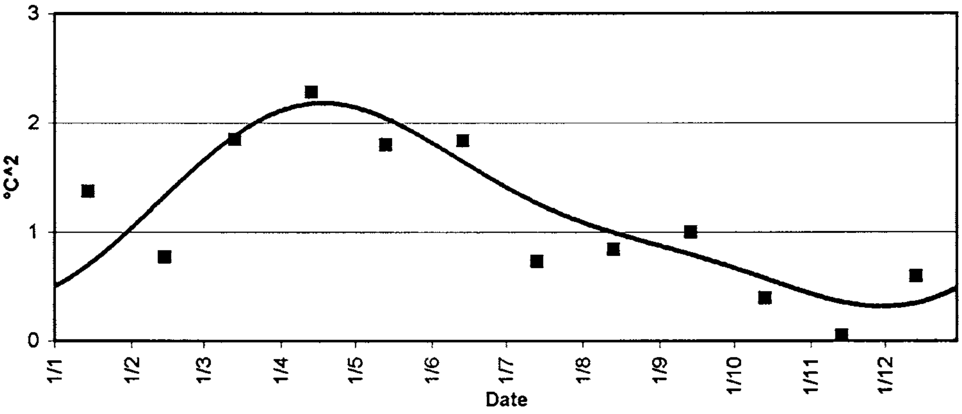


Figure 16. Differences between the monthly variances of the high pass filtered temperature series in the periods 1838–1864 and 1763–1830 (black squares) and trigonometric interpolating curve.

relation to some statistics. An example is day-to-day variability: These statistics show an inhomogeneity corresponding to Carlini's reorganisation (Moberg et al, 2000), as the data collected before 1835, even if corrected, have the same variability of '*mane*' and '*vespere*' observations, whereas after 1838 the variability is the one of maximum and minimum temperatures. It is very important taking account of this kind of problems as they have a significant influence on the results of a number of statistics on daily series.

Theoretically the data could be homogenised in relation to variability applying again comparison with other series, but in this case the method cannot be applied as no other northern Italy homogeneous daily temperature series are available. Therefore a complete variability homogenisation is at present not possible. We made however an attempt to produce a variability homogenised version of the series, adjusting at least the early data (when the daily mean temperatures where calculated averaging '*mane*' and '*vespere*' observations) by assuming that daily mean temperatures had the same real variability in the periods 1763–1834 and 1838–1864. Homogenisation was performed by the following steps:

- filtering the daily series with a high pass filter (i.e., calculating for each day the difference between the measured temperature and the average over a 31 day period centred over it);
- calculating monthly variance series from the high-pass filtered daily data;
- analysing the monthly variance series for evaluating the inhomogeneities in day-to-day variability due to Carlini's reorganisation (Figure 16);
- fitting a trigonometric function to the estimated inhomogeneities in day-to-day variability (monthly resolution) in order to estimate inhomogeneities for each day of the year (Figure 16);
- generating for each day of each year of 1763–1834 period a disturbance (white noise). The disturbance data are random numbers generated according to a

normal distribution function with 0 mean and with the variance given by the values in Figure 16;
- modifying the disturbances introducing a linear relation between the disturbance of day i and the one of day $i - 1$ in order to avoid the disturbances to reduce the autocorrelation of the series;
- adding the disturbances to the data.

The internal homogeneity in terms of day-to-day variability of the series produced using this technique is discussed in Moberg et al. (2000). Naturally the method is very rough as the hypothesis of constant variability cannot be verified without comparison with other series. Moreover it must be stressed that although the homogenisation is valid in a statistical sense for a long period, the temperature value at a particular day may be distorted several degrees from its true value. However, as the variability inhomogeneity connected with Carlini's reorganisation is very strong, it is absolutely necessary to use variability homogenised data if statistics that involve day-to-day variability (e.g., numbers of days with temperatures above/below selected thresholds) are considered.

6. Homogenising the Pressure Series

For the pressure series an initial homogenisation was performed using metadata. After these corrections, comparison with other series was performed with the same methods used for temperatures. The reference series was constructed using 12 selected monthly series (Table V) from the ADVICE pressure data-set (Jones et al., 1999) both on the basis of distance from Milan and the correlation with Milan series. Moreover the length of the series was considered in order to have averages on a sufficient number of data also in the early period. The monthly correlation coefficients between Milan and the other series were calculated for the period 1879–1962 that, according to metadata, seems to be the most homogeneous for Milan. The mean value of all the monthly correlation coefficients between the station series and Milan was 0.89. The stations with the highest correlation (0.97) were Trieste and Zagreb, the one with the lowest correlation (0.78) was Paris. As for temperature the sensitivity of the reference series to the 12 station series was studied and the results showed that the properties of the reference series are not particularly influenced by any of the station series. As far as the very difficult years after 1963 are concerned, a daily reference series of North Italian stations has also been constructed. It is based on seven stations of the Italian Air Force: Milan Linate, Milan Malpensa, Bergamo, Novara, Piacenza, Brescia and Torino. The homogeneity of the series in the recent period was also tested by comparison with the 45° N – 10° W grid point series of the UK Meteorological Office pressure data set (Bassnett and Parker, 1997).

Table V

Stations used to construct the reference series for the homogenisation of monthly mean pressures.

City	Position		Data availability in the period 1763–1995 (%)
	Latitude	Longitude	
Basel	47.60	7.60	100.0
Paris	48.83	2.32	99.6
Genève	46.20	6.15	97.9
Wien	48.22	16.35	94.8
Barcelona	41.42	2.17	92.7
Prague	50.10	14.42	88.8
Budapest	47.50	19.07	80.2
Firenze	43.77	11.25	78.1
Trieste	45.65	13.77	66.5
Marseille	43.30	5.35	62.2
Sibiu	45.77	24.15	62.2
Zagreb	45.80	15.97	57.5

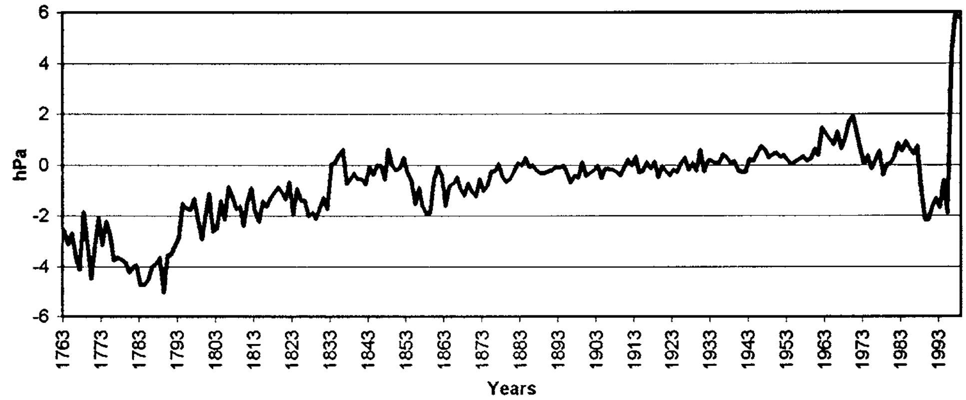


Figure 17. Differences between the Milan and the reference yearly mean pressure anomalies. Both for Milan and the reference series the anomalies are calculated on the basis of the means over the period 1879–1962.

The result of the comparisons is shown in Figure 17 where the yearly means of the differences of the anomalies of the Milan and of the reference series are reported. They give evidence of the following periods:

- 1763–1832: it is the initial period. It can be divided into two main sub-periods (1763–1793 and 1794–1832). Probably the 1793 inhomogeneity is due to the introduction of the Adams barometer (Maugeri et al., 2002). In the initial part of the first sub-period the differences between Milan and the reference series seem to be rather constant. Then, starting from 1775, they show a more complex pattern with a minimum around 1784 and an increasing trend in the following years. According to Behrens (1965) this pattern can be explained by the contemporaneous effect of two error sources: air evaporation from the mercury that, starting from 1775, progressively caused an apparent reduction of the recorded air pressures and deposition of impurities on the glass tube that, starting in the following years, began to influence capillarity introducing an apparent increase of the measures. After 1794 the differences become again rather constant;

- 1833–1836: the first two years of this period correspond to the not-so-well documented period between Cesaris's death and Carlini's reorganisation (Maugeri et al., 2002), whereas the inclusion of 1835 and 1836 in the same period confirms that Carlini's reorganisation did not only coincide with a sharp inhomogeneity on January $1st$, 1835 but also was associated with other important changes in the following 2-3 years;
- 1837–1853: it is the period from the conclusion of Carlini's reorganisation to the construction of his reference barometer (Maugeri et al., 2002);
- 1854–1874: it is the period from the construction of Carlini's reference barometer to Denza's intercomparison campaigns (Denza, 1876). These measures displayed that in 1874 the Milan barometer had an instrumental error of -0.67 mm. More detailed comparisons performed in the following years (Grassi, 1879) showed that Denza's barometer had a significant instrumental error too (+0.21 mm) and therefore the 1874 Milan barometer instrumental error has to be corrected to -0.46 mm (0.61 hPa). The comparison with the reference series shows that the negative error of the Milan barometer detected by Denza in 1874 was probably introduced by the new instrumental correction adopted after the construction of Carlini's reference barometer, as no significant errors seem to be present in the years between 1837 and 1853. That means that after Carlini's 1835 improvements the Adams barometer was probably more exact than Carlini's reference instrument;
- 1875–1962: is the period from Denza's intercomparison campaigns to the introduction of the aneroid barometer (Maugeri et al., 2002);
- 1963–1998: is the recent period. It can be divided into 4 sub-periods: 1963–1970; 1971–1987; 1988–1996 and 1996–1998, corresponding the inhomogeneities between them, respectively, to the end of the Astronomical Observatory series (1970), to its restart (1988) and to a calibration of the barometer (1996). As far as the last sub-period is concerned, the comparison with the reference series shows that the calibration of the barometer performed on February 15th, 1996 was probably not correct.

Table VI shows the corrections we applied in order to homogenise the data, whereas Figure 18 displays the seasonal and the yearly series. It is worth noticing

Table VI

Corrections (hPa) we applied in order to homogenise the pressure series.

1763–1775	+2.9
1776–1793	+2.4 / +4.3[a]
1794–1832	+1.4
1833–1836	−0.5
1837–1853	0
1854–1874	+0.6
1875–1962	0
1962–1971	−1.0[b]
1972–1987	0
1988–1996	+1.7
1996–1998	−5.8[c]

[a] Corrections depend on the year (Behrens, 1965).

[b] Starting from March 1st.

[c] Starting from February 16th.

that corrections based on comparison with other series have been applied only for periods 1763–1836 and 1963–1998, whereas the other data were corrected only on the basis of metadata.

7. Conclusions

The completion and homogenisation of Milan temperature and pressure series has been discussed. The principal results are as follows:

- metadata hardly give quantitative estimates of the inhomogeneities in Milan temperature series;
- for pressure data the situation is quite different: an initial homogenisation could be performed and all the data were reduced to 0 °C, corrected for the bias introduced by calculating daily means using different sets of observation hours and reduced to sea-level. However, also for air pressure, a number of questions remain open;
- The possible inhomogeneities identified by applying indirect methodologies are generally well explained on the light of the history of the observations. Therefore, even if the corrections were estimated by statistical methods, homogenisation was strongly supported by metadata;
- The most important inhomogeneities in the temperature series are connected to Carlini’s reorganisation (1835), to changes in the management of the screen (especially from 1880 to 1920), to the development of Milan urban heat island (especially from 1865 onwards), and to the very troublesome history of

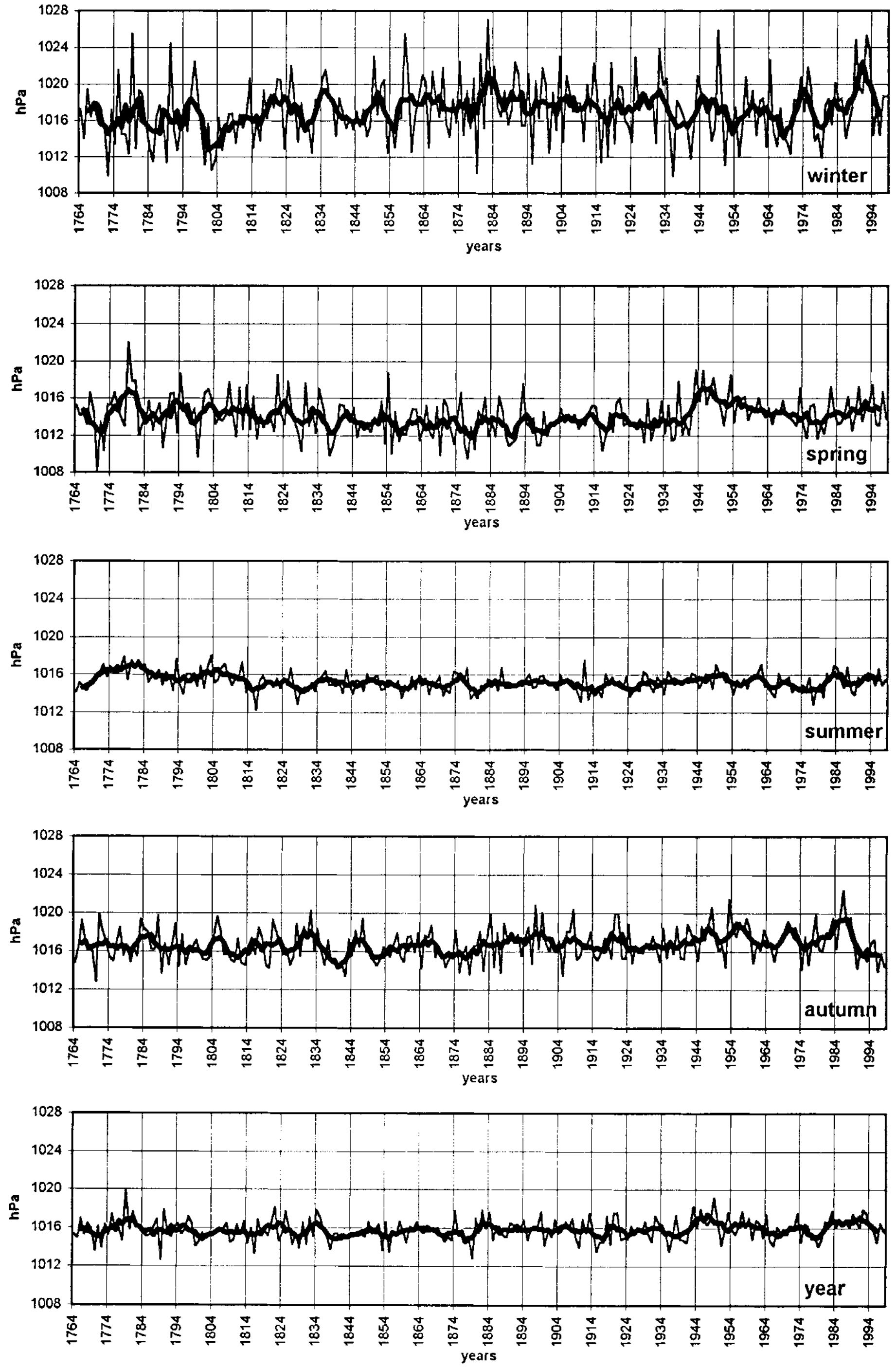


Figure 18. Seasonal and yearly homogenised Milan pressure series (thin lines) and 5-years moving averages.

the observations in the last 40 years, where also pressure data show strong inhomogeneities. Other relevant inhomogeneities in the pressure series are connected to a change of the barometer (around 1800), to Carlini's reorganisation (1833–1837) and to changes in the instrumental corrections (1853 and 1875);

- The application of a step by step procedure to homogenise the data allowed more series to be produced with different levels of homogeneity. All these series are available as a result of EC-project '*Improved understanding of past climate variability from early daily European instrumental sources*' (IMPROVE). The series with lower level of homogenization are closer to the original data, whereas the ones with higher level of homogenization are more useful to investigate long term regional features.

In our opinion the conclusions on the homogenisation of Milan series by direct methodologies can be extended to the most meteorological series as it is very difficult to have more complete metadata than in Milan. That does not mean that metadata are not important. They are essential in analysing and understanding the results of comparisons with other stations, but generally they cannot give sufficient information to homogenise the data.

Globally the corrections we applied cause the resulting temperature data to be significantly influenced by homogenisation based on comparison with other series. For pressure data the situation is completely different as a very important part of the series (1837–1962) has been corrected only on the basis of Milan metadata.

Acknowledgements

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