CORRECTIONS OF SYSTEMATIC ERRORS, DATA HOMOGENISATION AND CLIMATIC ANALYSIS OF THE PADOVA PRESSURE SERIES (1725–1999)

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Abstract. A short history of the series with daily observations of barometric pressure in Padova (since 1725) is made, with special reference to the types of barometers used, their locations, the types of corrections (which were only partial in the early period), the calibrations and the comparison with primary instruments. The paper also describes the homogenisation of the series and the procedures used to fill the small gaps. The Padova series was compared with previously well investigated series from the ADVICE and IMPROVE projects and especially with the nearby Milan series in order to check its reliability. Trend analysis shows an increase in pressure (some 1 hPa) during the last a hundred year. This trend is a common feature for Northern Italy. An effect of the increased air pressure is a local lowering of the Northern Mediterranean Sea level by 1 cm. The part of the year mostly affected by this increase is from late spring to August and corresponds to an extension of the hot season, characterised by an earlier start, and longer duration of the Azores Anticyclone. This reduces the penetration of the Atlantic disturbances in the Northern Mediterranean and the precipitation associated with the passage of fronts. This change is associated with an increase in thermoconvective activity with thunderstorms and heavy precipitation. This explains why, in the last decades, the annual total amount of precipitation is slightly decreased and at the same time the frequency of intense rainfall is increased. Moreover, a comparison of the day-to-day pressure variability with the Western Mediterranean Oscillation (WeMO) indicates a significant positive correlation during the late autumn-early winter period. An increase of the WeMO index means a strengthening of the baric dipole from Azores to Northern Italy, that could be explained by a deepening of the cyclonic circulation over northern Italy from November to January.

1. Introduction

In the recent past, monthly series of air pressure were produced and used within the EU project ADVICE to deduce atmospheric circulation indices. This analysis included 20 European pressure series starting before around 1820, of which ten start before 1780. A North Atlantic Oscillation (NAO) index was derived using Gibraltar and Reykjavik (1821–1995), a western European zonal index using Madrid, Barcelona, Trondheim and Lund (1786–1995), and an index constructed using Paris and London (1774–1995) (Jones et al., 1999a; Slonosky et al., 2000, 2001).

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It is clear that even more interesting results can be obtained using the data mentioned above at a daily resolution. For this reason tremendous efforts have been made to recovering, correcting and homogenising the long daily series of barometric pressure in Padova (Italy, 1725–1997), Milan (Italy, 1763–1998), Uppsala (Sweden, 1722–1998), Stockholm (Sweden, 1756–1996) and San Fernando/Cadiz (Spain, 1786–2000). These series have been produced within the EU project IMPROVE and published together with the long daily temperature series from the same stations plus Central Belgium (1767–1998) and St Petersburg (Russia, 1743–1996) (Camuffo and Jones, 2002). All of these series have been made available in a CD-ROM associated with the book which reports, in addition to the metadata, all the histories of these series, the corrections and the homogenisation procedures.

In the IMPROVE book, mainly devoted to the temperature series, the history concerning the atmospheric pressure in Padova, at that time not yet concluded, was not provided. The observations, however, were included in the CD-ROM, although a new version of the homogenised pressure series is now available for further analysis. The original readings were transformed into modern units (hPa) and corrected following the standard recommendations to sea level and 0 °C. Corrections for the errors found by the observers by comparison of their instruments with 'primary' barometers, or recognised from metadata in recent analyses, were applied. A gravity correction was not necessary because Padova is at 45° latitude. Gaps in the series were also filled with the aid of data from nearby sites. However, further corrections for instrumental drift, calibration errors and homogenisation for instrumental or observational changes needed a more extended research.

The study has now been completed and the fully corrected and homogenised pressure series is here presented for the first time together with its history.

2. Short History of the Series

The history of the long series of meteorological observations in Padova (1725–1997) includes air temperature (Camuffo, 2002a,b,c; Cocheo and Camuffo, 2002), air pressure, precipitation (Camuffo, 1984), wind, and other visual observations (e.g. fog, cloudiness, thunderstorms, hailstorms).

For the earliest period, the observations include measurements by Giovanni Poleni and his son Francesco (measurements 1725–1764) and the parallel observations by Giovanbattista Morgagni (measurements 1740–1768).

Giuseppe Toaldo and his nephew and assistant Vincenzo Chiminello continued the measurements (1766–1811). Toaldo measured first in S. Lorenzo Street (1766–1767), then in the mediaeval Castle that was transformed into an astronomic and meteorological observatory, called *the Specola*. During the transformation works, Toaldo lived and made his observations in different places of the Castle, i.e. first in the Munitioner House (1768–1775) then in the Astronomer House (1775–1777) and finally in the Meridian Room of the main tower (the *Specola*). In the period

1794–1811 the observations were undertaken also for the *Societas Meteorological Palatina*, Mannheim, and followed (with some departures) the protocol established by Hemmer (1783). The instrument remained in the same location, i.e. the Meridian room, from 1775 to 1959.

In recent times, measurements have been made by the *Water Magistrate* (1920–today) and at the local airport by the Air Force (1951–1990), following the standard procedures for barometric readings and corrections.

3. Location of the Barometer and Height Above Mean Sea Level

The Poleni's observations were made with the barometer being hung in the library at the first floor, 8.5 m above the level of the river, as confirmed by Toaldo (1770). The river is 13.65 m above m.s.l. Nothing can be said about the exact location of Morgagni's barometer, except that it was located in his home, at ground level or at the first floor, i.e. at the same level or somewhat lower than Poleni's.

Toaldo (1778) indicated the location of the barometer in the Astronomer House in a paper describing a thunderstorm on 11 May 1777, when he was inspecting a barometer in a corridor. The mentioned barometer was not the instrument used for the daily observations, but we can reasonably suppose that the same corridor was also the site for the regular observations.

The first precise information about the position of the barometer in the *Specola* is found in the *Giornale Astro-Meteorologico* (Toaldo, 1777) for the year 1776. In the explanatory notes to the list of the main meteorological events that occurred in the previous year 1776, he specified that the barometer was at the height of 4 perches, i.e. 24 feet (1 Paris foot = 32.48 cm), above the level of the river.

A note is found in the register of the astronomical observations which begun on 2 May 1779, the day in which Toaldo left Padova for a travel. On the first page, Chiminello made a short description of the astronomical and meteorological instruments and their exposure. The same description can be found in a lecture given by Chiminello in 1780 and that appeared in 1786 in the *Saggi Scientifici e Letterari* of the Padova Academy. It was clearly stated that the barometer and the thermometer were at the same height; the thermometer was hung in a window exposed to north, at the height of about 70 Paris feet, i.e. 22.7 m above the river. He also described the room of the barometer: a room facing south, next to the Astronomic Observatory, i.e. the so-called *Lower Observatory* or *Room of the Meridian* (where the local meridian has been traced to follow the culmination). In the original register, in a note written at the end of the observations for June 1780, it is clearly stated that the thermometer was hung in the window of the *Room of the Meridian*.

Zantedeschi (1869), who worked in the Specola, certified that in 1806 the barometer was at 40 Paris feet above river level; in 1817 it was 56 feet above river level; in 1834, 94 feet (unspecified whether Paris or Padova foot) above mean sea level and since 1850 in the *Room of the Meridian* of the Specola, which is at 30.65 m a.s.l. However, a short report composed of a few pages that were included into the register, gives another description. This report was written after a control of the Padova weather station and the calibration of instruments had been made between 1864 and 1865 under the supervision of Father A. Secchi. A number of different heights of the barometer are found mentioned; however, these should be interpreted as different estimations of the same height, that Toaldo, Santini and others evaluated using different units and zero reference levels. The conclusion is that the barometer was always at the same level in the period from 1776 to 1937, and that this was assumed to be at 30.65 m a.s.l., which is the average of the previous estimates. The homogeneity test applied to the series confirms that no discontinuity for relocation occurs.

In 1865 the first reduction to the sea level was made, but this practice was interrupted in 1869. It became a routine only after 1914.

No corrections were needed for the measurements performed by the *Water Magistrate* (1920–today) at the first floor and by the Air Force (1951–1990).

4. Correction due to the Temperature

Poleni was aware that the barometric reading should be corrected for the temperature (Poleni, 1709), but he did not apply such correction. Morgagni, who was a close and good friend of Poleni, strictly followed the same observational procedure.

Toaldo and Chiminello did not mention any corrections to the barometer readings. In the Mannheim period (1794–1811), the barometer was kept inside, in an unheated room, with a thermometer on the same walnut support to correct the readings, as suggested by Hemmer (1783). However, no temperature corrections were applied.

In 1827 the register reports for the first time the note: "barometer reduced to zero" and in the following this correction was apparently always made. However, the comparison with a reference series composed using a number of nearby European stations, produced within ADVICE and direct comparison with the Milan series (Maugeri et al., 2002a,b) has shown the presence of a discontinuity in 1828. The discontinuity was of the order of 1 hPa, which is of the same order of the 0 °C correction.

We can conclude that the reduction to zero was made only for the day or for a few days after the note, and that reduction became systematic only from the following year, as this was possible to verify with statistical tests.

5. Correction of Systematic Errors

After the data had been recovered, a number of typing errors have been identified after comparison with neighbouring reference series.

In the early period, the reference level of the scale was always affected by an error. The zero level was established at the free level of the mercury on the cistern in the moment when the scale was attached, but this level was dependent on the height of the mercury in the column, i.e. on the actual atmospheric pressure. A calibration made in a day with high pressure resulted in a depression of the zero, and vice versa for a low pressure day. This introduced a shift of the zero level, making the comparability between instruments difficult. In addition, the normal pressure variability caused a continual oscillation of the level around the zero, which resulted in an apparent oscillation of the zero. The latter can be easily calculated from the volume of mercury displaced from the tube to the cistern. If H_T is the change of height of the mercury in the tube, H_C the corresponding change in the cistern, D_T is the diameter of the tube and D_C the diameter of the cistern, then $H_C = H_T(D_T/D_C)^2$. Briefly, the amplitude of the oscillation of the mercury in the cistern was proportional to the square of the ratio between the diameters, and the proportionality coefficient $(D_T/D_C)^2$ characterised the uncertainty of each barometer. The size of this uncertainty can be decreased by decreasing D_T and increasing the capacity of the cistern. However, the thinner the tube, the greater the effect of capillarity which caused an underestimate of the reading. This error has been reported in Figure 1, extrapolating experimental values by Negretti and Zambra (1864). The error is much greater for unboiled tubes, but the practice of boiling tubes was introduced more later, by Daniell in 1840 (Middleton, 1968). For unboiled tubes the error was negligible, i.e. < 0.1 hPa, for diameters $D_C > 15$ mm and substantial, i.e. > 1 hPa, for $D_C < 8$ mm.

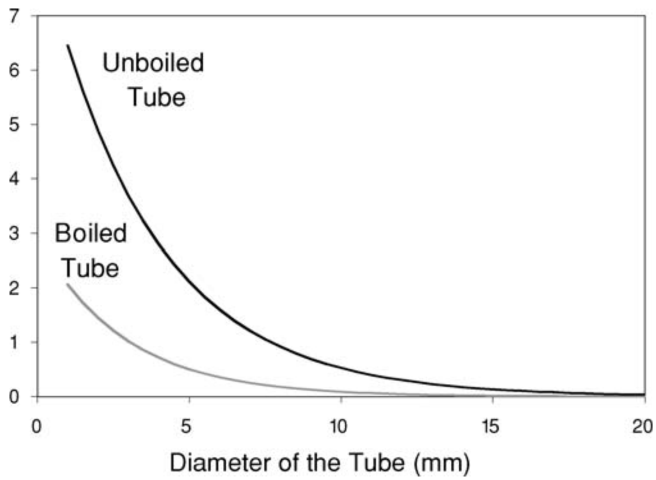

Figure 1. Capillarity error for boiled and unboiled glass tubes in contact with mercury (barometers and thermometers). The effect is always negative: a depression of the mercury column. Curve extrapolated after the experimental data by Negretti and Zambra (1864).

By measuring the diameters in the two drawing representing a Torricelli's barometer in the Poleni's publication (Poleni, 1709), the two proportionality coefficients are found to be respectively 0.015 and 0.030. This means not only that the zero was shifted, but also that the pressure changes were attenuated respectively by 1.5 and 3%, respectively. The problem was partially solved later applying the correction for the capacity of the cistern, although this correction was considered necessary only for scientific purposes, not for predicting the weather (Negretti and Zambra, 1864). The problem was definitely solved more later, by introducing an adjustment for the zero of the scale, e.g. the Fortin's barometer invented in the early 1800s, or passing to the aneroid sensors, produced in 1843 by Lucien Vidie (Middleton, 1968).

A second problem is the sliding of the scale. The Florentine instruments had the scale directly marked on the glass tube, but this good practice became popular only one century later. In general, the scale on early barometers was fixed to the support or to the capillary (or vice-versa) with an iron wire (Camuffo, 2002b). The result was a drift which lasted for years or decades. Drift-free observations began in 1766 with Toaldo, who used higher quality instruments with the scale firmly attached to the support.

The observations in the Poleni period (12.1.1725 to 31.12.1764) have been corrected for a displacement of the scale, which included a nearly linear drift and an incorrect position of the reference level. In 1725, the zero level was shifted by 10.33 hPa and in 1764 by 6.07 hPa. In this case, the drift of the slipping scale reduced progressively the error of the incorrect position of the reference level. The drift was characterised by a trend equal to 0.278 hPa yr^{-1} and had a very small deviation from the linearity, with second order coefficient -0.0040 hPa yr^{-2}.

Other corrections derived from the metadata were applied, as reported in Table I.

TABLE I
List of the corrections performed to the series

Period	Correction (hPa)	Note
12.1.1725 to 31.12.1764	from 10.33 to 6.07	Displacement of the zero and drift of the scale. After comparison with the subsequent period
1.5.1766 to 23.7.1770	+18	From the metadata
24.7.1770 to 31.12.1780	+9	From the metadata
1.1.1812 to 19.7.1826	−0.6	From the metadata
9.6.1828 to 16.12.1868	+1	Error not precisely defined from metadata: estimated after comparison with the reference series
16.12.1868 to 31.12.1913	0.5	From the metadata

6. Reading Errors

On 23 July 1770, Toaldo wrote in the register that the scale, made with a cardboard strip and stuck on the frame, was 3 lines of Paris inch (1 Paris inch = 2.707 cm; 1 line = 2.707/12 cm = 2.2558 mm = 9.0 hPa) “higher than the due”. He added this correction since that day, but the previous period remained uncorrected and we do not know when the deformation started.

In November 1775 Toaldo wrote that the cardboard was not fixed, but mobile; for this reason he regulated and fixed it again.

In December 1780 he wrote that the new barometer (built by Rodella) overestimated the pressure by 3 lines in comparison with the old one.

In 1828 the wood scale of the siphon barometer was shortened by 1/2 line for a deformation of the frame. This error is corrected for in the following.

Unclear readings occur before 31 December 1864 because the glass was obscured by mercury oxide.

7. Comparison with ‘Primary’ Instruments

On 3 August 1827 the barometer was compared with a ‘primary’ instrument by Carlini, astronomer-meteorologist in Milano.

On 20 and 23 July 1830 it was compared with another ‘primary’ barometer by Schow, active in Copenhagen.

On 31 December 1864 Father A. Secchi went to Padova to calibrate the barometer and other instruments.

The departures between the instruments are known (they generally lie between 0.2 and 0.5 lines of the Paris inches; i.e. between 0.6 and 1.5 hPa) and they have been used here for the correction of data.

On 27 March 1872 Father F. Denza went to Padova with a ‘primary’ barometer from the Moncalieri Observatory. The difference was -0.41 mmHg when reduced to $0\,^{\circ}$C and $+0.41$ was herein added to correct the Padova readings till 1885. The end date is supported from both the metadata (instrument change) and homogeneity test.

8. Barometers Used

Poleni built his instruments himself. We know that he built a traditional Torricelli’s barometer (Figure 2a) in 1709, when he was in Venice and this instrument is accurately described in a paper (Poleni, 1709). In 1711, when he was in Padova, he built also a Descartes’ two liquid barometer (Cossali, 1813). The Descartes’ barometer (Figure 2b) was composed of a glass tube with a cylindrical reservoir in the middle. This tube was then filled with a first liquid and inserted into a cistern filled of

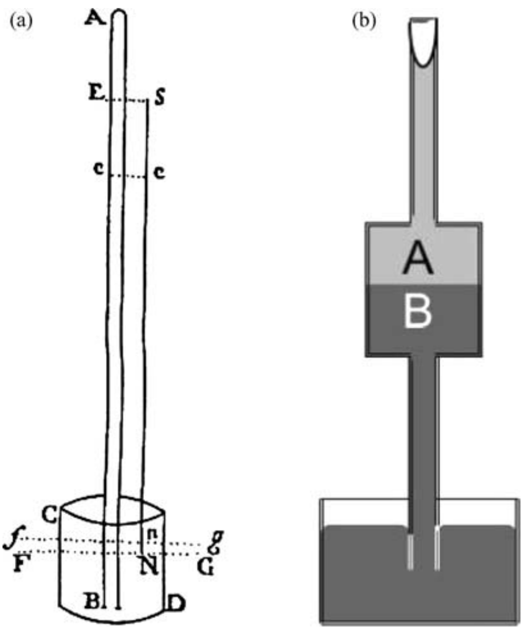

Figure 2. (a) Torricelli's barometer (after Poleni, 1709); (b) Descartes' two-liquid barometer. The tube and the upper half of the intermediate cistern were filled with a first liquid (A), and then inserted into a lower open cistern filled with mercury (B), as usual.

mercury, as usual. The bulb was 4 Paris inches high, and the lower and upper tubes more than 24 inches each one. The lower tube and half of the bulb were filled with mercury (in total 26 inches above the free surface of the mercury in the cistern). The upper tube was partially filled (i.e. 18 inches) with a mixture of water (7/8) and alcohol (1/8) to avoid freezing. The problem was the expansion of the alcohol and water vapour when the temperature rose, and vice-versa. The drawbacks connected with this instrument became soon evident. Poleni studied the problem and found analytical solutions to compute the actual value, but it is very probable that he used a traditional Torricelli's barometer in his observations, at least to avoid the complex correction of the reading. This is confirmed by the fact that the register has the readings in good order, without corrections, which is possible only with simple readings if we assume that when Poleni was off, the readings were made by his son Francesco, or by a trained servant.

The first precise information about barometer type concerns an old siphon instrument that was used by Toaldo after 1780 and was very probably built by Rodella. The latter was a very good technician and instrument maker working in the *Specola*, engaged by Toaldo in 1780 and active until 1834. It is possible that Toaldo received a similar instrument from Mannheim, but we could not find any confirmation of this. The atmospheric pressure was measured from 1780 until 1868 with the same type of siphon barometer, mentioned "Gay Lussac type" in the register in connection

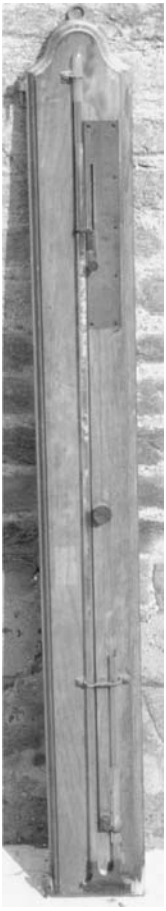

Figure 3. Siphon barometer with shape similar to the Gay Lussac type, still preserved at the Specola.

with a re-calibration made the 31 December 1864. At this date the instrument was disassembled and the glass tube was cleaned to remove the mercury oxide that had made the earlier readings uncertain. This instrument, with two movable scales in Paris inches and vernier in brass is still preserved at the *Specola* (Figure 3). We suppose that this is the instrument used for the recalibration in 1864 and not the one built by Rodella in 1780 for the following reasons. (i) The wooden frame is not manufactured with a craftsman style, but with automatic machinery typical for the 19th century. (ii) The frame shows the sign of a small rectangular label, now lost, very probably with the name of the manufacturing company. The Rodella style was to sign the frame with oil colour. (iii) The wood species is not "a thin board of fir wood, a wood that is the least likely of all to alter, light, and very common" as Toaldo (1775) preferred. (iv) The scale with the vernier in brass is at most about one and half a century old. Toaldo used first a cardboard scale, whereas Rodella painted the wood frame with oil colour and then painted the scale directly on it. In reality, the instrument supposedly made by Rodella has the same shape of the Gay Lussac model, but not the well known device with the capillary and the air trap for transport. This old type of instrument, without cistern, had the advantage of having a tube with constant diameter, so that the error for capillarity was absent. The observed column height was the difference between the two free levels of the mercury, read separately.

From 1868 (as we found reported in the register and not from 1871 as Favaro (1906) suggests) to 1884 observations were made with the Siphon Belli type barometer built by the Tecnomasio Factory, Milan. This siphon barometer had two large chambers, whose diameter was 28 mm in bore. It had a movable scale ranging from 715 to 830 mm, with an index at the lower end by which the zero was adjustable to the level of mercury. The upper index and the scale were both moved by micrometer screws and had a vernier to 0.1 mm. The instrument was supplied in 1868 by the newly established Observatory of the Royal Ministry of Agriculture and Commerce in Rome, charged of the responsibility for controlling the data quality of the Italian stations.

The analysis of the homogeneity of the series shows an anomalous period 1814–1815. This could confirm some doubts that we have about a statement by Zantedeschi (1869) that the same instrument was always used. One possibility is that the instrument was re-calibrated in 1814–1815 and that a cistern barometer with floating index built by Angelo Bellani in 1812, which was hung in the room of the anemometer, was temporarily used. This barometer is still preserved.

In January 1875, a Hipp aneroid barograph was purchased. From 1885 measurements were made with an aneroid barometer built by Jean Adrien Deleuil. This instrument was supplied in 1883 by the Central Office for Meteorology, Rome, which since 1876 was established as responsible for controlling the data quality of Italian stations. Since 1913, barographs were regularly used in parallel to the barometer readings. In the last period, when high quality observations were dismissed, readings were probably limited to automatic monitoring.

The Water Magistrate (1920 onwards) and the Air Force (1951–1990) used the standard Fortin barometer.

9. Data Homogenisation

Comparison was made with the Milan series (Maugeri et al., 2002a,b). After correction for all the individual and systematic errors, the standard normal homogeneity test for single shift and for trend (Alexandersson, 1984, 1986; Alexandersson and Moberg, 1997) was applied to all the discontinuity portions of the entire series. The following intervals with inhomogeneities were identified:

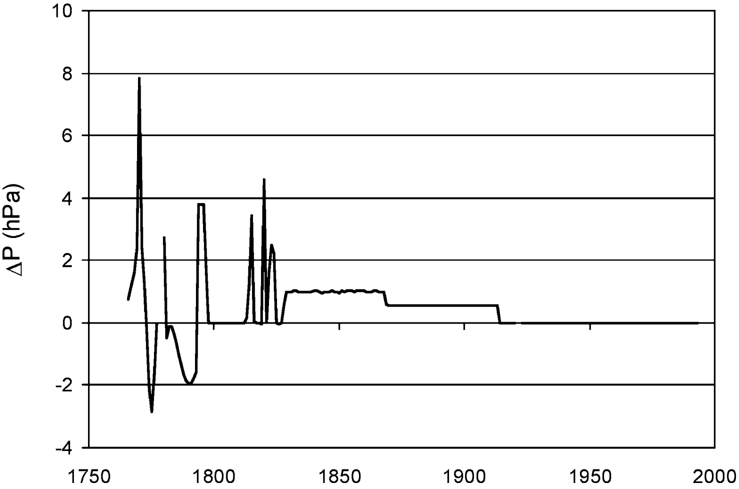

Figure 4. Algebraic sum of the annual values used for correction and homogenisation of the air pressure in Padova.

1.5.1766 to 28.2.1777; 1.1.1780 to 31.12.1793; 1.1.1794 to 17.6.1797; 11.8.1814 to 9.9.1814; 10.9.1814 to 19.2.1815; 20.2.1815 to 22.9.1815; 27.1.1820 to 31.1.1821; 3.5.1822 to 22.11.1824; 9.6.1828 to 16.12.1868. The corrections applied to homogenise the series are illustrated in Figure 4.

10. Filling Gaps

A large number of missing data prevents both to complete the series of monthly mean pressures and to analyse the interdiurnal variability on a long time scale. A way to overcome this problem is to fill in missing data by means of interpolation from a homogeneous reference series. In this study, the Milan series has been used as neighbouring reference site for the common period from 1763 to 1997.

For each month, the average difference between the two sites was calculated for the entire period, which represent the local seasonal effect illustrated in Figure 5. Missing data for Padova were then obtained by adding to the corresponding daily Milan data the average monthly difference.

Figure 5 shows that in summer Milan has a pressure higher than Padova and this can be interpreted as an effect of the lowering of the Azores High for the greater distance from the High centre (Milan is 230 km west of Padova). In winter Padova has a slightly higher pressure than Milan reflecting an easterly influence linked to the Russian High and moderate outbreaks of air from north east.

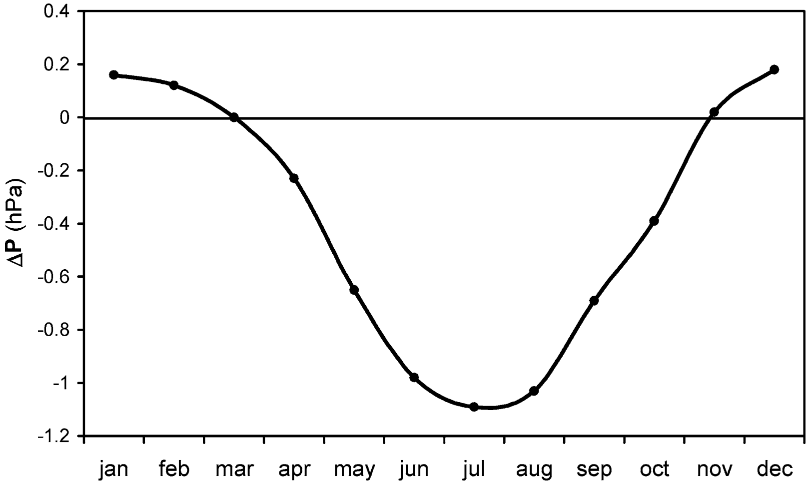

Figure 5. Monthly difference between the Padova and Milan pressure series averaged over the entire period.

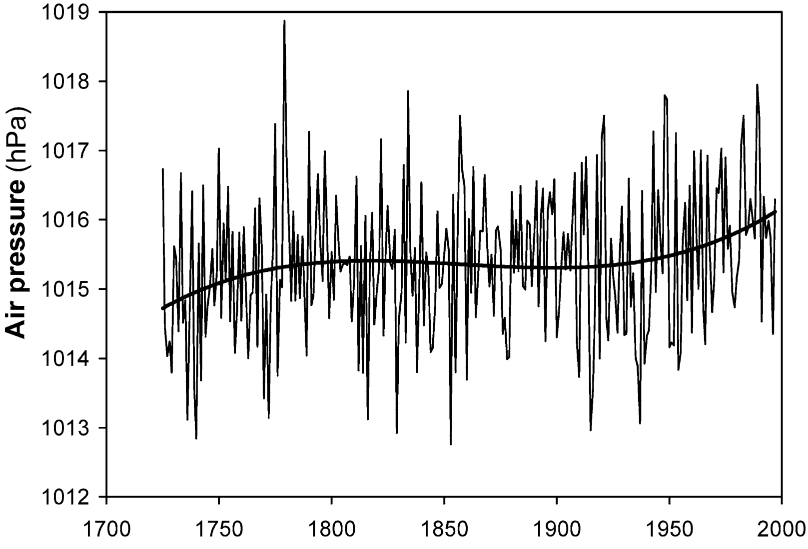

Figure 6. The series of annual mean values of atmospheric sea level pressure in Padova, 1725–1997 and its third order polynomial regression (all the model parameters are statistically significant at the 0.05 level).

11. Yearly and Seasonal Trends

The annual mean series of atmospheric sea level pressure observed in Padova after correction and homogenisation is reported in Figure 6. The low values before 1760s should be interpreted cautiously, because of the possible errors made at the beginning of this observational practice in combination with the fact that no reference series is available prior to 1763. The rise at the modern times, however, is well marked, it persists over a long period (some 60 years) with reliable data and is present also in all the other neighbouring series, including Milan. This increase in pressure, of the order of 1 hPa, can be interpreted in terms of a real change in the climate of the northern Adriatic region, which is associated to less frequent invasions of air masses from north east, and especially of the Bora wind (Pirazzoli and Tomasin, 1999). In Trieste, some 150 km East of Padova, Crisciani et al. (1994) found for the recent period a marked increase of the air pressure and solar irradiance and also a lowering of the sea level caused by the increased air pressure. These circulation changes are reflected in the frequency of the temperature extremes. The analysis of the frequency of the daily highest and lowest temperatures, found a reduction of the cold extremes evident in the Mediterranean sites due to weaker winter outbreaks from higher latitudinal continental areas (Yan et al., 2000). The analysis of atmospheric circulation changes based on daily sea level pressure data shows coincident results with those of the temperature changes (Yan et al., 2000).

The calendar day distribution was estimated for each decade starting from 1720–1729 and ending in 1990–1999. Figure 7 shows calendar day distributions averaged on fifty year periods from 1750 to 1999. Calendar day pressure values show significant rising trends, at the 95% level, in the seasonal intervals 8th July–28th July and 18th September–9th October. The increase in annual mean pressure seems to be related to a strengthening of the Azores High influence, which starts earlier and ends later in the last decades. This has been influential on the autumn rainfall which

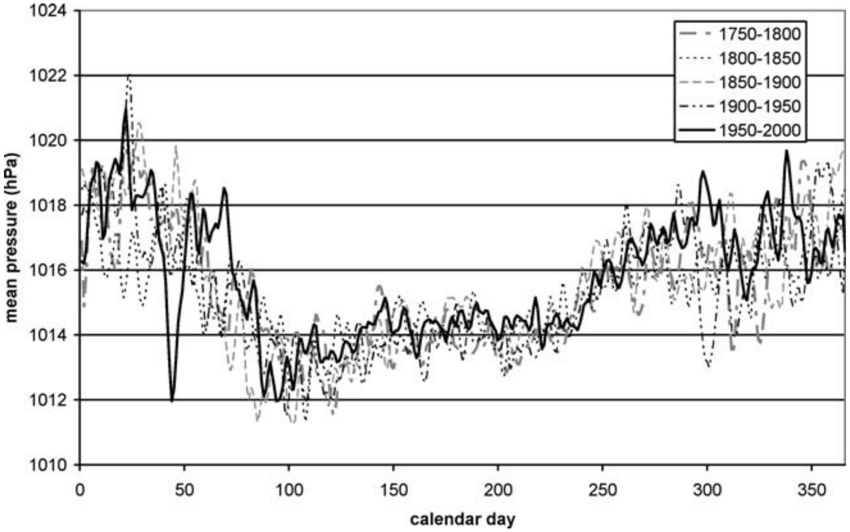

Figure 7. Time evolution of the calendar day distributions from 1750 to 1999, averaged every fifty years.

is related to the attenuation of the Azores anticyclone and the arrival of Atlantic perturbations.

12. Daily Values and Day-to-Day Pressure Variability

The highest daily pressure, i.e. 1047 hPa, was measured on January 24th 1907 and the minimum, 972.3 hPa, on December 2nd 1976. Such extreme values are confirmed by the Milan series where 1045.6 and 976.6 were measured, respectively. The 1976 depression is one of the fastest on record, with a -26.9 hPa decrease in one day and -49.1 hPa in two days. The percentile distribution of the entire series has its 1-percentile at 995.5 hPa and its 99-percentile at 1033.4 hPa. The average for the period 1725–1997 is 1015.4 hPa. Least squares linear trends (in hPa) from 1778 to 1997 in the series of 5th and 95th percentile of the annual distributions of daily pressure measurements shows statistically significant (at 0.05 level) increase of $+0.8$ hPa and $+1.1$ hPa respectively.

Day-to-day variability was investigated for the Padova and Milan sea level pressure series following the method suggested by Moberg et al. (2000). A cross comparison was performed for the overlapping period 1763 to 1997. Trends in the day-to-day pressure anomaly variability in Padova were also calculated for each month in order to recognize seasonal climatic changes over long time span.

Pressure variability is based on daily pressure anomalies with respect to the average annual pressure cycle in the reference period 1961–1990. The annual pressure cycle was obtained by calculating the average values for each calendar day in the period 1961–1990 (Jones et al., 1999b) and then smoothing the sequence using a tenth order polynomial regression. The annual cycle of the sea level pressure in Padova for the reference period and its smoothing curve are indicated in Figure 8. The lowest values (1012–1013 hPa) fall in April and the maximum ones in January (1018–1019 hPa). In the cold season October-February the mean pressure remains above 1016 hPa under the influence of the high pressure ridge extending from the Siberian High to the Azores High. Lower values are generally measured in the warm season.

The pressure anomalies have been calculated as the deviations from the tenth order polynomial regression average annual cycle. Pressure variability is then given by the mean absolute value of differences in anomalies between two adjacent periods of time, like two consecutive 1-day or 5-day periods. Folland et al. (1999) suggested to use inter-period differences for 1-, 5- and 10-day periods. From each of the series of the daily N-day changes ($N = 1, 2, 5, 10, 20$) we calculated monthly averages. Time series of monthly average values for 1-day variability for Padova is indicated in Figure 9. In order to compare the changes in daily variability at the two sites of Padova and Milan, each monthly series was normalized with respect to the reference period (1961–1990). Normalization was accomplished by subtracting from each monthly value the 30-year average in the reference period for the actual

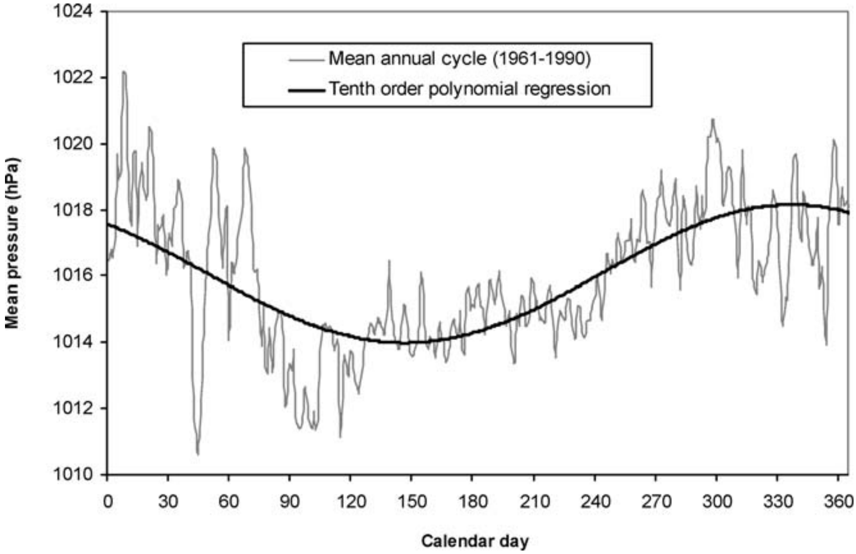

Figure 8. Average annual pressure cycle. The arithmetic average within the period 1961–1990 for each day of the year is shown with thin grey line. The tenth order polynomial regression (thick black line) represents the smoothed annual cycle.

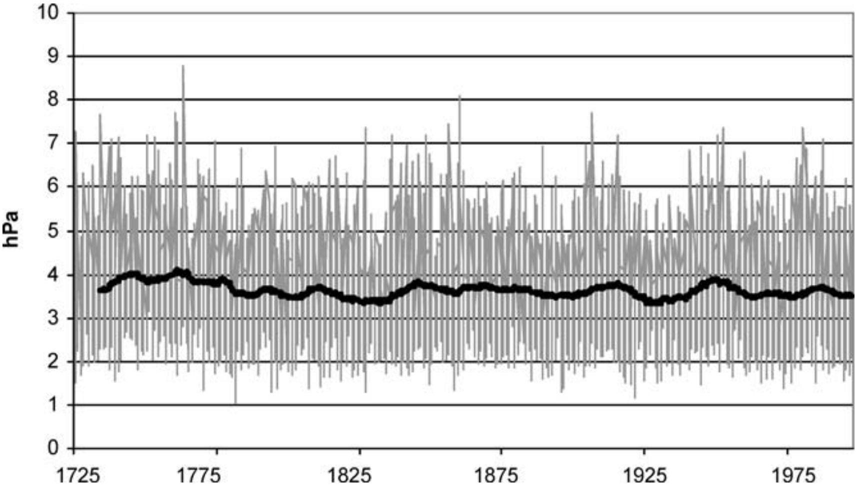

Figure 9. Time series of monthly average values for 1-day variability for Padova pressure series. Low frequency changes are highlighted by a 20-year moving average.

month of the year and dividing by the corresponding standard deviation for the reference period.

A direct comparison of the daily variability at the Padova and Milan stations was made by plotting the pressure differences Padova–Milan in the normalized series of absolute 1-day changes (Figure 10). As the two stations are quite close to

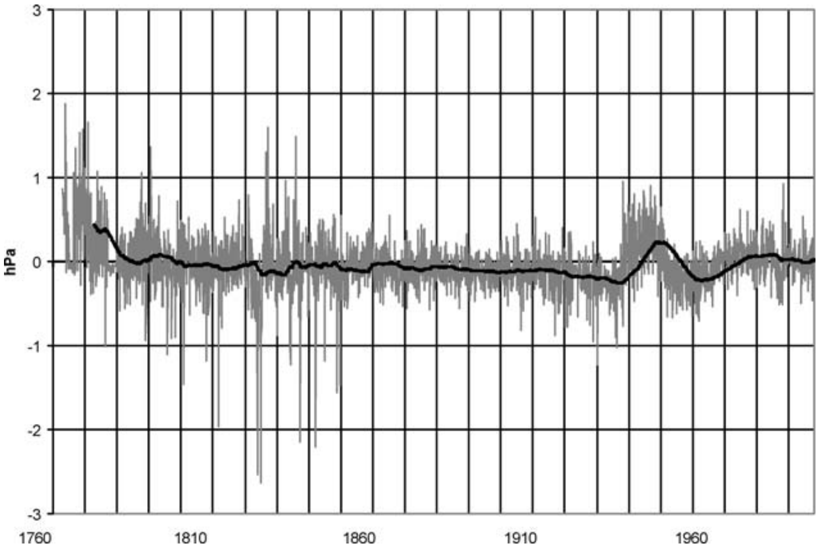

Figure 10. Time series of differences between normalized monthly values of daily pressure variability (1-day) in Padova and Milan. Low-frequency changes are high-lighted by a 20-year moving average.

one another (some 230 km) in a quite homogeneous region, no large departures are expected in the two pressure variability series. Thus, the comparison between the two series of daily variability stands as an useful diagnostic tool for the identification of inhomogeneities still persisting even tough a cross homogenisation process was already performed on these series. The graph (Figure 10) of the series of the inter-station differences shows that long-term average is always close to zero except for the period prior to 1780 and from 1938 to 1950. The larger differences between the two series prior to 1780 can be explained in terms of the lower inertia of the early siphon barometer used by Toaldo in the period 1766–1780. The differences found in the recent period, from 1938 to 1950, are explained by the use of the Water Magistrate observations (with reduced daily sampling) to continue the *Specola* series, whose measurements ended on 1937.

Evaluation of long term trend of daily pressure variability was, therefore, carried out starting from 1778. Linear trends (in hPa) were calculated from 1778 to 1997 in the seasonal averages of the monthly series of sea level pressure, absolute N-day differences and standard deviations. Seasons are defined as 3-months periods, i.e. December, January and February (DJF); March, April and May (MAM); June, July and August (JJA); September, October and November (SON).

No statistically significant changes (at 0.05 level) were found neither in the linear trends of the N-day variability series nor in the standard deviations. The only significant trend ($\alpha = 0.03$) was in the average autumn (SON) values, which show an increase of about 0.4 hPa/100 yrs and a total increase of 0.9 hPa from 1778 to 1997. On a shorter term, in the last century (1898–1997), a significant increase of the average pressure in spring (MAM), with 1.7 hPa total increase (at 0.02 level), and in summer (JJA), with a 0.8 hPa total increase (at 0.05 level) were found. Consequently, the annual average pressure series shows a significant increase (at 0.05 level) of 0.8 hPa.

The standard deviation is larger during winter, when the weather is more variable, due to more frequent cyclone passages, and is lower during the warm months, as a result of the more persistent anticyclonic situations.

13. Day-to-Day Pressure Variability Index for Northern Italy and its Relation with WeMO

The principal component analysis and cluster analysis applied to mean meteorological records distributed all over the Mediterranean countries identified some homogeneous climatic regions (Goossens, 1986; Douguédroit and Norrant, 2003). One of them covers the Western Mediterranean including the Mediterranean coast of Spain, the southern coast of France, the north and the centre of Italy, the Balearic Islands, Corsica and Sardinia. This region is characterised in terms of the pressure oscillation across the Western Mediterranean, i.e. the Western Mediterranean Oscillation (WeMO). The WeMO index is defined as the normalized pressure difference between Cadiz/San Fernando (Spain) and Padova (Italy). The index is positive when the pressure decreases from the Iberian Peninsula towards Northern Italy, as it happens when the Azores High is growing or when a cyclonic depression is forming over the Ligurian Sea or on the lee of the Italian Alps and in this case bad weather affects northern and central Italy. It is null when a high pressure dominates the Mediterranean with sunny weather. It is negative when an Atlantic depression approaches the Iberian Peninsula, causing heavy rains.

The monthly WeMo index was calculated from 1821 to 1987, using the normalized monthly pressure series of Padova and San Fernando (reference period: 1958–1987). To investigate the possible influence from the WeMO on the day-to-day pressure variability on northern Italy an average variability index was constructed using Padova and Milan pressure series. Northern Italy Index (NII) was calculated as the average of the normalized monthly 1-day pressure variability for Padova and Milan, from 1778 to 1997. The annual average day-to-day variability (Figure 11) does not exhibit a significant long term linear trend. The 20-year periods with the highest variability with respect to the period 1961–1990 are 1835–1854 (+16%) and 1900–1919 (+16%), while the period from 1813 to 1832 has the lowest variability (−12%). The correlation coefficients between the monthly NII series and the monthly WeMO Index were also calculated for various combinations of months. Seasonal relationships were investigated by correlating both the indices for each successive combination of 3-month averages. Figure 12 shows the correlation coefficients, where the abscissa is the central month of each 3-month period. A seasonal cycle is evident, with the weakest correlation (+0.20) during the period

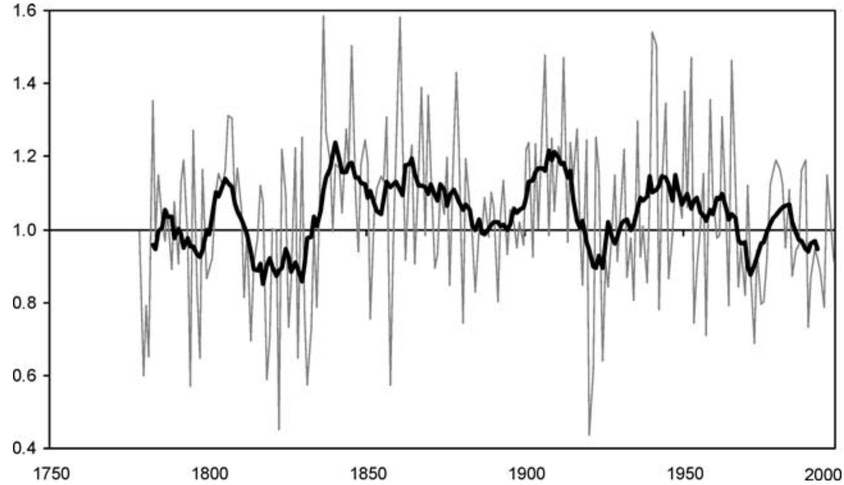

Figure 11. Northern Italy Index (NII) of annual averages of normalized day-to-day pressure variability. The index is constructed using pressure values of Padova and Milan stations. Low-frequency changes are high-lighted by a 20-year moving average.

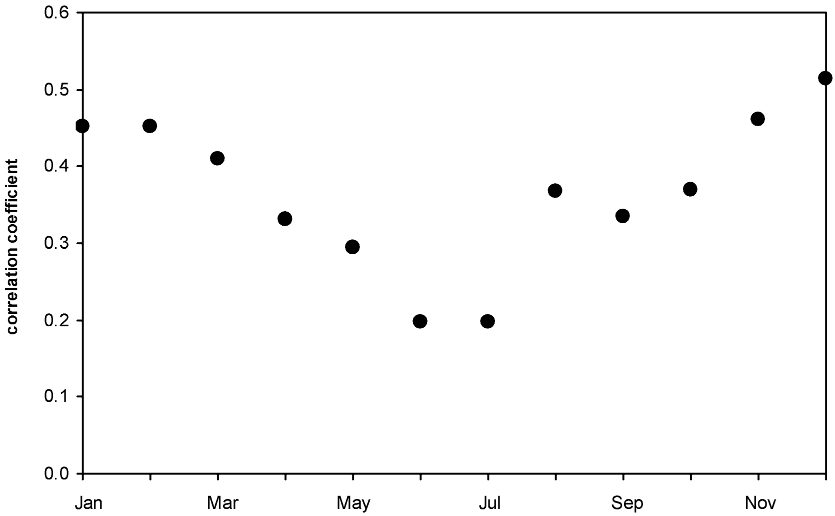

Figure 12. Correlation coefficients between the 3-month average NII and WeMO Indices. Abscissa is the central month of each trimester.

June–August and the strongest one (+0.51) during the quarter November–January. All the correlation coefficients are statistically significant at least at the 0.01 level, with the exception of that for May–July, who is significant at the 0.05 level. A scatter plot of the WeMo index and the averages of normalized day-to-day northern Italy pressure variability for the quarter November–January (Figure 13) shows that an increase of the WeMo index of 1 unit corresponds to an increase in day-to-day

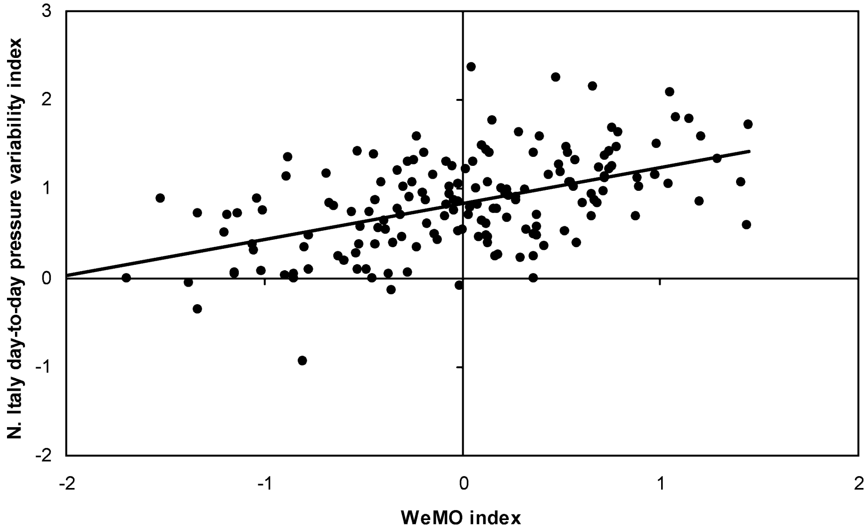

Figure 13. Scatterplot of the WeMO index and November–January averages of the normalized day-to-day pressure variability averaged for the northern Italy station of Padova and Milan. Data for the period 1821–1997.

variability of 0.41 units. Thus, during late autumn-early winter period, day-to-day pressure variability in northern Italy is most sensitive to changes of the WeMo index.

An increase of the WeMO index means a strengthening of the baric dipole from Azores to Liguria, that could be explained by a deepening of the cyclonic circulation over northern Italy. This circulation pattern is typical of the passage of successive cyclones with continuous fluctuations of the sea level pressure values, frequent instability phenomena and strong winds and can be interpreted as an index of climatic risk. A preliminary analysis of the frequency of meteorological bombs, i.e. an extra-tropical cyclone deepening at a rate $\geq$1 hPa/h at least for 24 h (Sanders and Gyakum, 1980), seems to confirm that, in northern Italy, the peak of the frequency falls exactly during the winter months.

14. Conclusions

The Padova pressure series (including both data and metadata) has been recovered, carefully corrected and homogenized and is now available since 1725 at daily resolution. This has been accomplished by a thorough study of the series, the instruments, their construction, calibration and location. The type of early corrections, how and when they were made, is another essential feature.

The analysis of the day-to-day pressure variability and the cross-comparison with the long Milan series (some 230 km West of Padova), has shown that the

Padova series is reliable, at least since 1780. In terms of trends, long pressure series are more reliable than the temperature ones as the temperature is highly affected by apparent warming due to growing urbanisation and increased heat island effect.

The data clearly show an increase in pressure (some 1 hPa) that has characterised the last a hundred years. This trend is a common feature in Northern Italy. The effect of the increased air pressure is a local lowering of the Northern Mediterranean Sea level by 1 cm.

The time of the year that is mostly affected by this increase ranges from the late spring to the end of the summer. This means an extension of the main period influenced by the Azores anticyclone, characterised by an earlier start and longer duration of the influence. This reduces the penetration of the Atlantic disturbances in the Northern Mediterranean and the precipitation associated with the passage of fronts. On the other hand, this increases the thermoconvective activity and this favours thunderstorms and heavy precipitation. This could explain why, in the last decades, the total amount of precipitation has slightly decreased while at the same time the frequency of intense rainfall has increased (Piervitali et al., 1998).

Finally, the day-to-day pressure variability shows a significant positive correlation with the Western Mediterranean Oscillation (WeMO) during the late autumn-early winter period. As the increase of the WeMO index means a strengthening of the baric dipole from Azores to Liguria, this correlation could be explained by the deepening of the cyclonic circulation over northern Italy from November to January.

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