Research paper

The earliest daily barometric pressure readings in Italy: Pisa AD 1657–1658 and Modena AD 1694, and the weather over Europe

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Abstract

The earliest daily barometric pressure readings were taken during the Maunder Minimum of Solar activity (1645–1715). In Italy, observations were made at Pisa over the years 1657–1658 by V. Viviani and A. Borelli, and at Modena during the year 1694 by B. Ramazzini. These readings have been recovered, corrected and adjusted to modern units. The early instruments used and their problems have been thoroughly discussed. Barometer observations recorded by John Locke in Essex (UK) during the year 1694 have also been recovered and corrected. Daily observations were recorded during the same period in Paris by L. Morin; these have previously been published by Legrand and Le Goff (1992: Les observations météorologiques de Louis Morin. Monographie No. 6, Direction de la Météorologie Nationale, Ministère de l'Equipement, de Logement et des Transports, 41 pp.). However, cross-comparisons with the Locke and Ramazzini data have shown that the Paris series needed a further correction to take into account instrumental error. Using these three corrected series, it has been possible to reconstruct the atmospheric circulation over Europe for the year 1694. An indication of the state of the atmospheric circulation can also be made by using the earlier observations recorded in Italy. A common feature of the two periods studied (1657–1658 and 1694) is that winters were characterized by higher pressure compared with the reference period 1961–1990, while the summers generally experienced lower pressure. This latter conclusion indicates that the Azores High was late or not well developed, favouring low temperature and frequent rain in the late spring and early summer.

Keywords

Barometer, early instruments, environmental history, circulation indices, Maunder Minimum, climate change

Introduction

Early meteorological observations may initially appear suspect owing to the lack of experience of the observers. Their value, nonetheless, is extremely important. This is principally a result of their uniqueness, and every effort should be made to digitize and correct the data. To modern-day scientists, early observations are difficult to interpret because the presentation is not always complete, the choice of units and the zero point are often omitted or arbitrary, the calibration scale is often unknown, and the readings are affected by a number of observational, instrumental or exposure errors. However, within environmental history early observations merit the highest interest because they are extremely scarce and provide useful information about our past climate, with special reference to the still obscure Maunder Minimum of Solar activity (1645–1715). This period is particularly important because the climate was much less affected by human activity, e.g. less pollution and little land-use change.

The history of modern meteorology was started in Italy thanks to Ferdinand 2nd, Grand Duke of Tuscany. He was a governor and scientist, and in Florence he founded the Cimento Academy (1657–1667) to study the new science based on direct observations of nature. During this period the key meteorological instruments had already been invented, for example the thermometer by Galileo in 1612 and the barometer by Torricelli in 1643. At the Cimento Academy these instruments were improved and the Grand Duke also organized the first meteorological network, called Rete Medicea, which was composed of 11 stations in Europe and was active for the period 1654–1667 (Magalotti, 1761; Targioni Tozzetti, 1780; Antinori, 1841, 1858). Atmospheric pressure was only recorded in Pisa (see map, Figure 1) for the period November 1657–May 1658. Pressure readings were generally

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taken three or four times a day but at hours that varied with the calendar year, according to the so-called Italian Canonic Hours, which started at twilight. In Pisa, the observer was cited by Antinori (1841) as being Vincenzo Viviani, whereas Ramazzini (1695, 1718) cited the observer as being Alfonso Borelli. This is a surprising contradiction, because both sources were well informed: Antinori for having the original documents of the Grand Duke and Ramazzini for being a contemporary. Both of the cited observers are known to have been active in taking meteorological observations. Although Torricelli invented the barometer, Viviani built the first barometric glass tube, set up the experiment and took the very first barometric observation (Magalotti, 1761; Antinori, 1841). Borelli was appointed Professor at Pisa University in the same period and made the earliest barometric observations (Magalotti, 1761; Antinori, 1841). We conclude that Viviani trained Borelli for these kinds of new observations, which were attributed by the Duke's entourage to Viviani, and by Ramazzini to Borelli for the continued readings. Viviani and Borelli worked together in some other experiments, e.g. measuring the speed of sound in wind. However, Viviani was appointed as a superintendent to river hydrology, and this task obliged him to make frequent inspections of rivers, leaving Borelli in charge of continuing the regular observations. A further problem remains: Ramazzini mentioned two years of readings but only three months in winter and one month in spring are available to us. This means that part of the Viviani and Borelli readings have likely been lost.

In Italy, the interest in meteorological observations was maintained not only for climate and agriculture purposes, but also for health. For this reason Bernardino Ramazzini, a leading professor of Medicine at the University of Modena, published the annual Ephemerides barometricae. This periodical contained comments on the weather, as well as information regarding extreme events and their claimed links with crop yields and illnesses. In general, the Ephemerides reported only a few instrumental observations but contained many discussions and hypotheses. In the 1695 publication, Ramazzini (1695, 1718) made a description of the local climate, and published his daily observations of air pressure, wind direction (in quarters), state of the sky and precipitation (only frequency) for the calendar year 1694. This year is of particular interest because in the Central England Temperature (CET) series, which begins in 1659 (Manley, 1974), the year 1694 is ranked as the fifth coldest (Slonosky et al., 2001). Ramazzini's observations provide further information regarding the state of the weather during that year in Europe.

Figure 1. Map of Europe with the locations cited in the text: 1, Florence; 2, Pisa; 3, Modena; 4, Paris; and 5, London

During this period of the late seventeenth century, daily meteorological observations were also recorded in London and Paris. Pressure observations for the years 1697–1706 and 1708 were published by William Derham in 1698, 1699, 1700 and 1709. These observations have been analysed by Slonosky et al. (2001) who calculated atmospheric circulation indices from Paris and London pressure readings. A similar task was attempted by Luterbacher et al. (1999, 2000), but on a monthly basis. In the same period we have a previously unrecovered source of observations made in Oxford and then London by the philosopher John Locke starting from 1666. In Paris daily observations were recorded by Louis Morin during the period 1665–1713 (Legrand and LeGoff, 1992)

The eighteenth century saw the beginning of a number of very long series of daily pressure observations that continue to the present, i.e. Bologna (It), 1716 onwards, that we have just now finished recovering, correcting and adjusting to modern units; Uppsala (Se) (1722–1998) (Bergstrom and Moberg, 2002); Padova (It) (1725–1999) (Camuffo et al., 2006); Stockholm (Se) (1756–1998) (Moberg et al., 2002); Milano (It) (1763–1998) (Maugeri et al., 2002a,b); Cadiz (Sp) (1786–1996) (Barriendos et al., 2002). Together these improve our knowledge of the atmospheric circulation over the last three centuries.

This paper has two aims. The first aim is to correct, study and make available the earliest daily meteorological observations from over 300 years ago, i.e. by Viviani and Borelli in Pisa from 1657 to 1658. The second aim of the paper is to reconstruct the atmospheric circulation for the year 1694 by using the barometer observations recorded by John Locke in London, Louis Morin in Paris and Ramazzini in Modena, and interpret why 1694 was such a cold year. This is achieved by forming a London–Paris–Modena transect from the pressure data. It should be noted that while the Morin data from Paris have previously been analysed by Legrand and LeGoff (1992), the Locke and Ramazzini data are used here for the first time.

Although the Pisa and Modena series cover only two years, they can be regarded as a useful addition to the very few pressure observations existing for the early instrumental period, which includes the Maunder Minimum of Solar Activity in the middle of the 'Little Ice Age'. The recovery of these data is not without problems, however. Following Torricelli's first barometer – made with a simple glass tube – several kinds of barometers were invented, each one with known or unknown problems concerning the scale, the floating zero level, the friction between mercury and glass, the readability of the meniscus and many others. However, the instrument was not the only problem: observers had a number of variables to face, including room temperature, height above mean sea level and gravity. The observers were unable to make the necessary corrections in the early period. Fortunately, these corrections can be done today (provided enough ancillary information was recorded or we can make some assumptions), which improve the quality of the observations.

Early barometers were affected by three key problems: the zero level was incorrect, the section of the tube was large in comparison with that of the cistern and capillarity affected readings, especially in thin tubes. The errors were quite large, making the intercomparison of data and assessments of the required corrections difficult (see Camuffo et al., 2006). The zero level, i.e. the free level of the mercury in the cistern, was established at the level it had when the scale was attached to the tube, and then it was kept unchanged. Barometers calibrated in days with high or low pressure had different zeroes, the difference being considerable. For example, in Padua, Italy, the standard deviation (SD) of the barometric pressure has a SD=10 hPa in winter and half this value in summer. In addition to this problem, the normal pressure variability caused a continual oscillation of the mercury level in the cistern around the fixed zero. This oscillation was proportional to the square of the ratio between the diameters of the tube (D_T) and the cistern (D_C), i.e. $(D_T/D_C)^2$. Another consequence dependent on this ratio was that the pressure changes were attenuated proportionally to $(D_T/D_C)^2$, i.e. in the order of 1% to 5%. Barometers with a thin tube had a lower error, but the thinner the tube, the greater the capillarity forces which cause an underestimate of the reading. The underestimate $U(D_T)$ is given by the equation

$$U(D_T) = 0.0000953\,D_T^{\,4} - 0.006471\,D_T^{\,3} + 0.1625\,D_T^{\,2} - 1.822\,D_T + 7.952 \tag{1}$$

and reaches 6.4 hPa at D_T = 1 mm, 4.9 hPa at D_T = 2 mm, 3.7h Pa at D_T = 3 mm and 2.1 hPa at D_T = 5 mm. The capillarity error was reduced to 1/3 by boiling the glass tube, but this practice was not widely introduced until 1840 (Middleton, 1964).

The observations by Viviani and Borelli (1657–1658) in Pisa, Italy

The instrument used by Viviani and Borelli in 1657–1658 was very simple and consisted of a glass tube, hermetically sealed at the top, filled with mercury and immersed into a vase with mercury (Figure 2). The scale had arbitrary units (AU), attached to an arbitrary level. Readings ranged from 6 to 29 AU, and the average level was 19.42 AU. Briefly, we have an unknown zero level and an unknown ratio between the units 1AU/1 hPa, i.e. two unknowns which require two equations based on two reasonable assumptions that will be discussed in the following section.

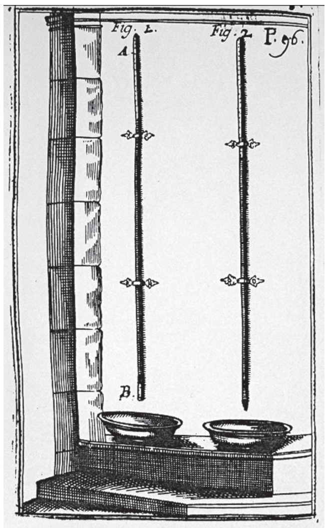

Figure 2. Tubes engraved from the bottom are visible in early barometers (plate between pages 364 and 365 in Ramazzini, 1718)

Correction of the barometric readings in Pisa: adjustment to modern units

In order to adjust the Viviani/Borelli readings from Pisa to a modern scale (hPa) and correct the instrumental errors, we made two assumptions based on a comparison of the early data with modern data. The first concerned the average, and assumed that the average pressure of the early period, i.e. 19.42 AU for hourly readings and 18.27 for daily means, was the same as the modern reference period 1961–1990 for the same days of the calendar year in which we found the early readings, i.e. 1015.5 hPa. This is reasonable because the range of annual pressure at Pisa is very narrow, i.e. in the reference period 1961–1990 the standard deviation (SD) is SD = 1.1 hPa for the 30 yearly averages, but SD = 2.8 hPa for the 30 averages limited to the portion of the calendar year in which the early observations were made (chiefly winter). Under our hypothesis, SD = 2.8 hPa and the likely error is ±1.4 hPa. A similar methodology was followed by Slonosky et al. (2001).

The second assumption concerned the interdiurnal variability, which appears smaller than today. We supposed that the main reason for the attenuation of the high frequency range was not due to an unlikely change in the atmospheric pressure distribution but to an instrumental damping in the Viviani and Borelli glass tube, i.e. a large friction of mercury in a thin tube. Some decades later, friction and capillarity were reduced with the practice of boiling the glass tube. We discarded the idea of comparing the ranges, as the range is strongly influenced by rare, extreme events, which are governed by randomness. We assumed that the bell-shaped frequency distribution of the daily pressure readings is represented by a Gaussian distribution, although this is only true when the sample number approaches infinity (Figure 3). In a Gaussian distribution, the width of the most densely populated and best documented band between -1σ and $+1\sigma$ (where σ is the standard deviation of daily readings) is between 15.87 and 84.14 percentiles. In practice, we assumed that both the 50th percentile (which is also the mean and mode) and the SD of daily readings in 1657–1658 and 1961–1990 for the same days of the calendar year were identical, i.e. 1015.5 hPa and 9.28 hPa, respectively. From these assumptions we deduced that 1 AU = $\sigma_{\mathrm{hPa},1961\text{–}1990}/\sigma_{\mathrm{AU},1657}$ = 1.76 hPa. In addition to this, we know that the lines of the original arbitrary scale were spaced 1.76×(760/1013) = 1.32 mm from each other. The resolution is therefore 1.76 hPa.

This scaling assumption allows us to avoid a further possible problem, typical of very early observations, when the instrument and the care in its construction are not known. The problem is the presence of some small air pockets, entrapped between the mercury and the glass, which eventually enter the upper part of the tube. That area of the tube should be characterized by an absence of air and the presence of mercury vapour only, but if some air is present, the average mercury level is depressed and the range is enlarged. This required special care in the initial filling of the tube, but scientists only become aware of this fact years later. They started to apply remedies, e.g. heating the tube, vibrating it and perturbing the mercury with an iron wire to remove pockets. However, the negative effect of this possible intrusion of air, if any, was substantially removed by the two assumptions described above.

Gravity correction

Pisa is located on the Tyrrhenian coast, 4 m above mean sea level (a.m.s.l.) and latitude 43°43′N. Measurements were possibly recorded from the ground or first floor and as this height probably

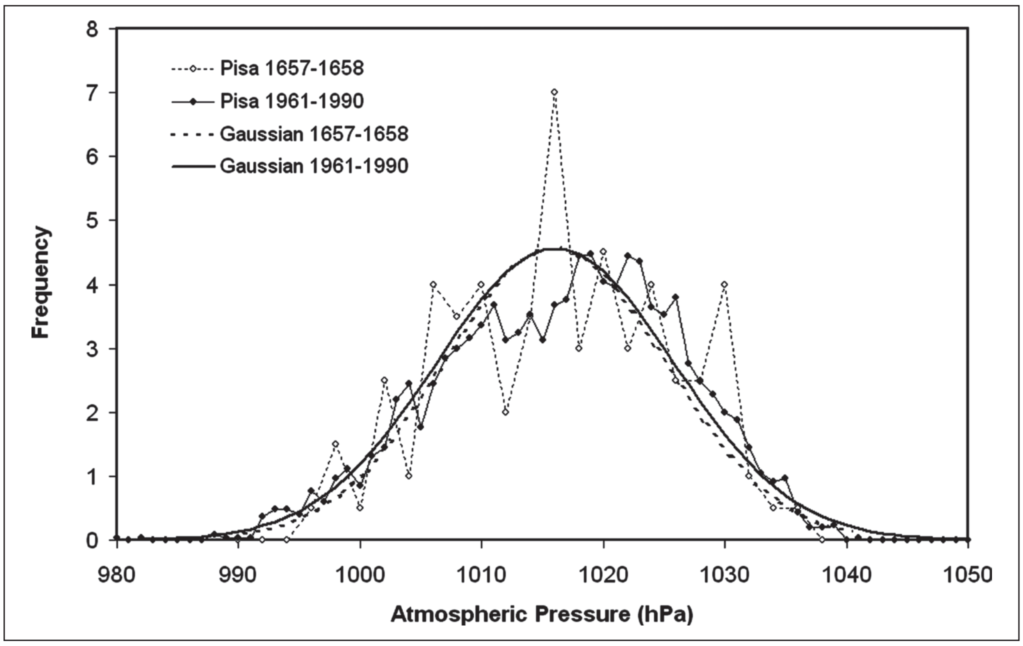

Figure 3. Pressure distribution in Pisa for the four months of observed readings in 1657–1658 (dotted thin line, open circles) and corresponding Gaussian (dotted thick line). As above but for the same months in the reference period 1961–1990 (continuous line, full circles) together with corresponding Gaussian (continuous thick line)

did not exceed 8 m the error from this can safely be ignored. In any case, the corrections to sea level and to standard gravity (approximately 45° latitude), which are both very small, were not necessary as the first assumption of imposing the 1961–1990 average implicitly includes both corrections.

Temperature correction

The density of mercury was corrected following the instructions of the World Meteorological Organisation (WMO) Guide (1983) by using the simultaneous temperature readings, made with a Little Florentine Thermometer (the first spirit-in-glass thermometer). The temperature readings were transformed from the Florentine degrees, also called 'Gonfia', in which the tube was originally divided into 50 parts. The correction of the barometer for mercury density was made using these temperature readings, after they had first been transformed from the original °G scale to °C. This conversion was based on the calibration made by Boffito (1927) and later by Vittori and Mestitz (1981) on 17 Little Florentine Thermometers, which are still preserved in good condition at the Museum of Science in Florence.

The thermometer was hung outdoors, on a northward-facing wall according to the instructions of the Rete Medicea. The barometer was kept inside, at a slightly different temperature. The indoor–outdoor difference has been evaluated from three historical buildings in the same geographic area for which we had simultaneous indoor and outdoor observations from 1716 to 1774. The difference was larger in winter when the indoor temperature was 6°C higher, vanished in the mid seasons and was slightly higher (1°C) in summer. We applied this correction month by month.

Floating of the zero level

The reference zero level in a barometer should be the surface of the mercury in the cistern. However, this level is lowered in the case of high pressure, when some additional mercury is sucked into the tube, and is higher in the case of low pressure when mercury resides in the cistern. However, in early barometers the reference scale was fixed, the zero being in a reasonable position, and was unable to follow the level of the mercury. The difference between the mercury level and the zero mark on the fixed scale was an error that needed to be accounted for. The problem is most relevant when the cistern is small, but becomes irrelevant when the cistern is large. If one considers the volume of the early cisterns, where a vase large enough to be entered with a finger and part of the hand to keep the bottom of the tube closed until it was fixed with an iron wire to a support, this is error is irrelevant. For instance, in Ramazzini's book (Figure 2) the ratio of the tube to the cistern diameter is 1:16, and the corresponding sections to their squares is 1:256. The ratio of the vertical displacements follows the inverse order i.e. $1{:}^{1}/_{256,}$ and with a 20 line range in the atmospheric pressure, the zero level displacement is 0.08 line. This value is negligible.

The weather in Pisa, 1657–1658

The relatively small number of observations available in Pisa imposes limitations to our conclusions. The stronger assertion is that the average winter pressure was much higher than the short period in spring (Figure 4), suggesting that the Azores High was late or not well developed. Also winter values were equally departed from the average, but positive departures were much more frequent than negative ones. Even in the case of doubt about the precision of absolute levels, this consideration, based on the frequency, confirms that high pressures in winter were much more frequent than low pressures. Further definite conclusions regarding the state of the atmospheric circulation cannot be made because only a few months of daily data are available. However, we find it interesting to exploit as far as possible such data, for their uniqueness in this early period, despite an inability to present a detailed examination.

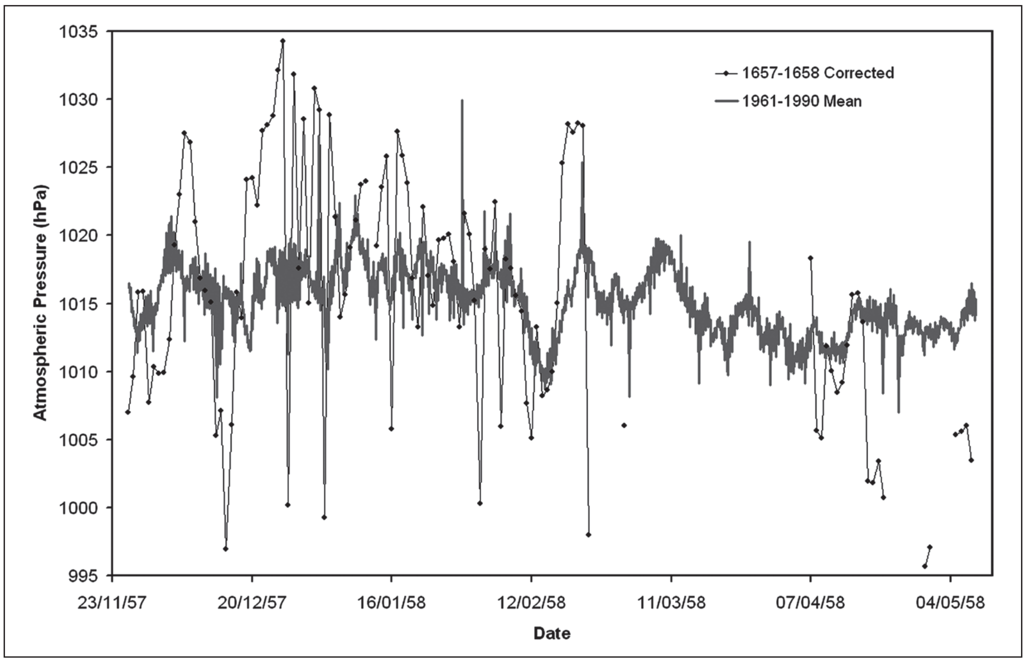

Figure 4. Pisa pressure from November 1657 to May 1658 (black) and the reference period 1961–1990 (thick grey line)

During the winter of 1657–1658, atmospheric pressure was generally higher than in the reference period 1961–1990 (Figure 4), possibly as a result of an anomalous expansion of the African High, or a stronger ridge between the Azores and the Russian High. Some deep depressions crossed the Pisa area causing violent stormy weather and gales (also called Sirocco winds). At the end of the winter, the observations were interrupted but were resumed in April, during which the weather was cold and rainy. Unfortunately the observations were suspended again in May. Ramazzini (1714a) mentions that the year 1658 was famous for severe illness related to the unusual weather. Exceptionally hot and dry conditions were experienced in England, and cold and rainy weather was apparent in Italy, thus confirming the hypothesis of a weak Azores High.

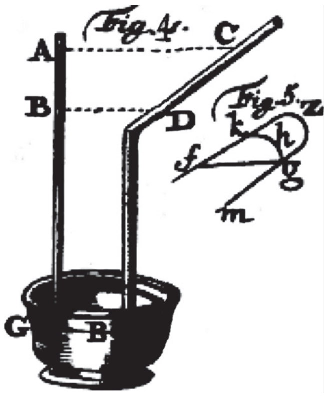

Figure 5. The Morland diagonal barometer, indicating the difficulty difficulty in reading a measurement between points C and D to points A and B on the scale. Also indicated is the problem of establishing the actual position of the inclined meniscus h as commented in the original description by Van Musschenbroeck (1745)

The observations by Ramazzini (1694) in Modena, Italy

The diagonal barometer

In 1694, Bernardino Ramazzini made pressure readings in Modena using a diagonal barometer (Figure 5). The invention of the diagonal barometer is generally attributed to the English diplomat, spy, mathematician and mechanical inventor Sir Samuel Morland, possibly with the contribution of Robert Hooke (Middleton, 1964: 110–14; Bryden, 1975). It has also been hypothesised that it was independently invented in the same period by Ramazzini. The official date attributed by Middleton (1964), and followed by many others, for Ramazzini's invention is 1695, probably because Middleton simply made reference to the date of publication of the Ephemerides barometricae Mutinenses anni MDCXCIV (1695). However, Ramazzini must have built his instrument before the end of 1693, as he started regular daily observations on 1 January 1694.

It is thus not easy to establish who really first invented the diagonal barometer. An interesting comment is provided in a paper by Jean-André de Luc on the history of barometers, published in the Registers of the Royal Academy of Sciences, Paris (1762). He wrote (pp. 28–29) that this style of barometer was very popular at the time and that van Musschenbroeck (1751: Vol. II, 628) attributed its invention to Morland. However, he was unable to find either the date of its invention, or any original paper describing the instrument. He only found a mention by Derham (1699) who supposed that this barometer was invented by one of his friends, without further specification. The Morland diagonal barometer was also mentioned in a previous book by van Musschenbroeck (1745: Vol. II, 143) with the comment that this instrument has the advantage of expanding the scale, although he recognised that there were also certain problems with its design. These problems were as follows: (i) the meniscus is inclined and the observer cannot make reference to the top, but rather to the lower part of the meniscus, where it separates from the glass; (ii) the barometer's scale was separated from the mercury tube and was vertical, which made it difficult to read the height of the mercury (see Figure 5); (iii) the tilted arm was long and this increased friction. The same problems were also mentioned by de Luc (1762).

Ramazzini's diagonal barometer was better than Morland's instrument because the scale was directly engraved onto the inclined arm. This meant that the meniscus was measured as a fraction of the arm, which solved the first two problems of the Morland barometer. However, the problem of friction in the long tilted arm remained unresolved.

Ramazzini's description (in Latin) of the barometer is that: 'The total perpendicular height that the mercury column reached this year in my barometer can be divided into 30 parts, or inches. The tube where mercury moves is laterally bent at the 28th inch and the arm is slightly rising above the horizontal plane in order to observe with a higher resolution its motion. The last two inches in the perpendicular height, which are spread for a longer extent along the bent arm, are subdivided into 90 lines' (Ramazzini, 1695 and 1718: 281).

In Ramazzini's barometer (Figure 5) the total height of the glass tube above the mercury was 30 inches. The tube extended vertically for 28 inches from the level of the mercury and then it was inclined to improve the resolution of the scale. In the inclined arm, the mercury extended diagonally for 90 lines, over 2 inches of vertical rise; this gives an equivalent resolution of 0.75 hPa. Most of the arm was filled with mercury and the level ranged between 76 and 87 lines. There is no specification on the length of the inclined arm. If we hypothesize that all lines had the same width, i.e. the inclined lines were the same as the vertical lines, then according to the definition of 1 line = $^{1}/_{12}$ inch the total length of the inclined arm must have been 90/12= 7.5 inch. The vertical/horizontal side ratio was 2:7.5.

It is interesting to note that a similar barometer was described by Edward Saul (1730: 86–87), who listed similar specifications:

> Since the Mercury will always rise in proportion to the weight of the Air, and remain at the same perpendicular height, however the tube should be inclined. The best and most convenient contrivance for a Barometer seems to be that of a sloping tube rising upright from the stagnant Mercury to the height of 28 inches, and then reclining and running off at an angle, to the length of 12 inches, and to the perpendicular height of 3 inches, according to which the frame, for every inch that the Mercury rises in the perpendicular tube it will rise in the sloping tube 4 inches, and thereby makes any changes in Gravitation of the Air more discernible.

Measurement unit used

No information is available regarding the units used in Ramazzini's diagonal barometer. In international scientific publications at the time (written in Latin) the two most common measurement units used on barometers were either Paris or London inches. In the following paragraph we evaluate the use of both scales, and present a conclusion regarding the scale that was most likely used by Ramazzini.

(1) Paris inches, i.e. 27.07 mm. The total height of the mercury, around 30 inch = 1082.5 hPa is too high for barometric pressure. Alternatively, we can suppose that 30 inches was the total length of the glass tubes, on which the inches and lines were engraved. Tubes engraved from the bottom are visible in early instruments and drawings (see e.g. Figure 2), where the graduation of the tube is clearly seen. We should suppose then that the glass tube was for some $1^{3}/_{4}$ inch immersed into the mercury, the height being evaluated by considering the zero at the beginning of the glass tube and not from the mercury surface. The very early tubes were manually closed with a finger and immersed into the cistern containing the mercury, and we should suppose that an absolute reference level was missed because people were mainly interested in the relative pressure variability. However, the barometer was a mature instrument in 1694, and we should discard this naïve possibility.

(2) London inches, i.e. 25.4 mm. If we assume that all the readings were correctly made and that the glass tube was longer, such that 30 inches is the part of the tube above the cistern, we obtain 1013.5 hPa as the yearly mean pressure. This value is in close agreement with present-day observations. In addition, Ramazzini passed the last years of his life (1700–1714) at Padova University where Giovanni Poleni started to record meteorological observations: at inconsistent intervals initially (1709) and then as a regular series (1725–1761) (Camuffo, 2002). Poleni's barometer was graduated in London inches (Camuffo et al., 2006) as he adhered to the standards of the Royal Society of London, after the James Jurin invitation (1723).

In conclusion, the London inch was the most likely unit of measurement used by Ramazzini, and the data expressed with this unit have the correct order of magnitude.

Correction of the barometric readings

The readings have been corrected for a number of errors (at least from the point of view of a modern observer) and for missed corrections that were not known at the time. Corrections were also applied to account for the viscous friction of the inclined tube. The corrected values and the reference period are presented in Figure 6. The corrections were made in accordance with the instructions of the WMO Guide (1983) and are described in the following six subsections.

The variability in mercury density

This correction requires knowledge of the room temperature where the barometer was kept, which was unfortunately missing. We made reference to the average daily temperature in Modena for each day of the calendar year, using daily observations from 1860 to 1894. In a vertical tube, e.g. Torricelli's barometer, the error in barometric pressure derived from temperature errors is 0.18 hPa/°C, which is negligible for small departures from the correct temperature. In the case of a diagonal barometer, the mercury dilatation is not only in the vertical tube, but also in the inclined arm. However, we are only interested in the vertical projection of the mercury, and this value is irrespective of the length of the inclined arm or the tilting angle. Briefly, the effective height of the mercury column has been corrected for the average temperature of each day of the calendar year. The error is 1 hPa per 5.5°C departure from the average daily temperature.

Height above mean sea level

The correction was made for 40 m a.m.s.l., assuming that Modena is 34 m a.m.s.l. and that the observations were probably made on the first floor. This assumption minimizes the error in the possible range between the ground and the second floor.

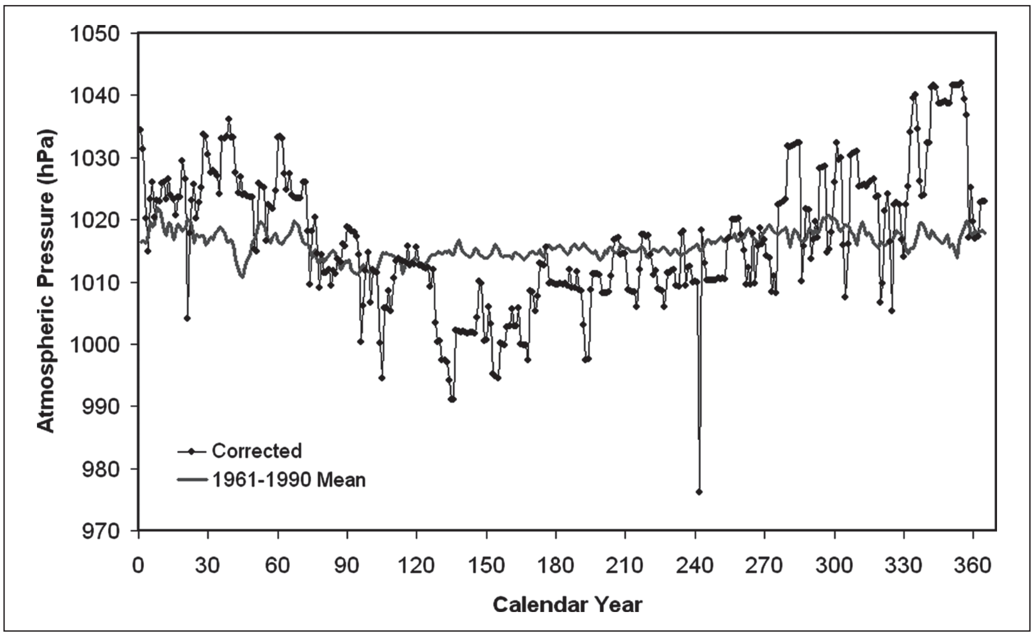

Figure 6. Atmospheric pressure (hPa) observed by Ramazzini in Modena for the calendar year 1694 (black). The data are corrected and adjusted to modern units. The 1961–1990 reference period (thick grey line) is displayed

Gravity for latitude

This correction was extremely small as Modena is 44°39′N and the correction at 45° is zero.

Floating of the zero level

Once again the reference zero level floats with the mercury surface in the cistern (see section 'Correction of the barometric readings in Pisa'), but the use of large cisterns as shown in Figure 2 (after Ramazzini's posthumous paper of 1718) makes this error irrelevant.

Viscous friction inside the tube

The long inclined arm apparently increased the resolution in reading, but in practice it also increased the viscous friction of the mercury in the tube and reduced the sensitivity of the instrument. Although the average pressure level (1013.5 hPa) is correct, friction damped the mercury motions and this is reflected in a reduction of the variance of the data. The yearly range of the atmospheric pressure in 1694 was one-quarter of the present-day yearly range. This effect can be counteracted by expanding the deviations from the average by a factor of four, to reproduce a modern-day atmospheric pressure range. It is assumed therefore that the annual range of pressure has remained unchanged over time. This was the most critical assumption because although it attributes the most probable value it neglects possible year-to-year fluctuations.

Instrumental error

The Ramazzini data have been compared with the average daily pressure in Padua for the period 1725–1998. The two locations are 100 km distant from each other. Ramazzini's readings follow the calendar year distribution on average but with an underestimation of 4.26 hPa, which is assumed to be the instrumental error. The annual pressure range in Modena is 2.1 hPa for the reference period 1961–1990, i.e. the same as in Pisa. The corrected pressure observations in Modena are reported in Figure 6 together with the reference period 1961–1990 mean over the calendar year.

Other European observations in 1694

The observations by Louis Morin (1670–1713) in Paris

The aim of this part of the paper is to get reliable pressure readings for the year 1694, for which it is possible to combine the Paris pressure data with the contemporary observations at Modena and London and obtain the weather over Europe in 1694. Legrand and Le Goff (1992) made the following corrections to the pressure readings in Paris: 9 hPa for instrument error; between 1.3 and 2.7 hPa for temperature, i.e. 1.3 hPa from October to April, 2 hPa from May to June and 2.7 hPa from July to September; and 5.3 hPa for height correction. Morin used two instruments: one barometer until 12 May 1678, and another for the subsequent period. The readings of the first barometer were corrected using values derived by differences in the mean before and after 1678. An additional adjustment factor of 0.3 hPa was then added to adjust the mean of the Morin observations to the long-term mean of the monthly Paris values from 1764 to 1995 (Slonosky et al., 2001). The cross-comparison between the three stations, and particularly the analysis of the frequency distribution of daily values of the difference between the pressure in London, Paris and Modena, show that the Paris data were underestimated, with exceedingly high number of blocking highs over Northern Europe, i.e. high pressure remaining in place for several days or even weeks, as already discussed by Moses et al. (1987) and Wanner et al. (1994, 1995). This demonstrated that the previous corrections needed improvement. To achieve this, Morin's original pressure readings (Figure 7) were corrected once again disregarding the above corrections but using more exact data, i.e. the daily temperature observations at Paris for the same period, also made by Morin. The readings were then

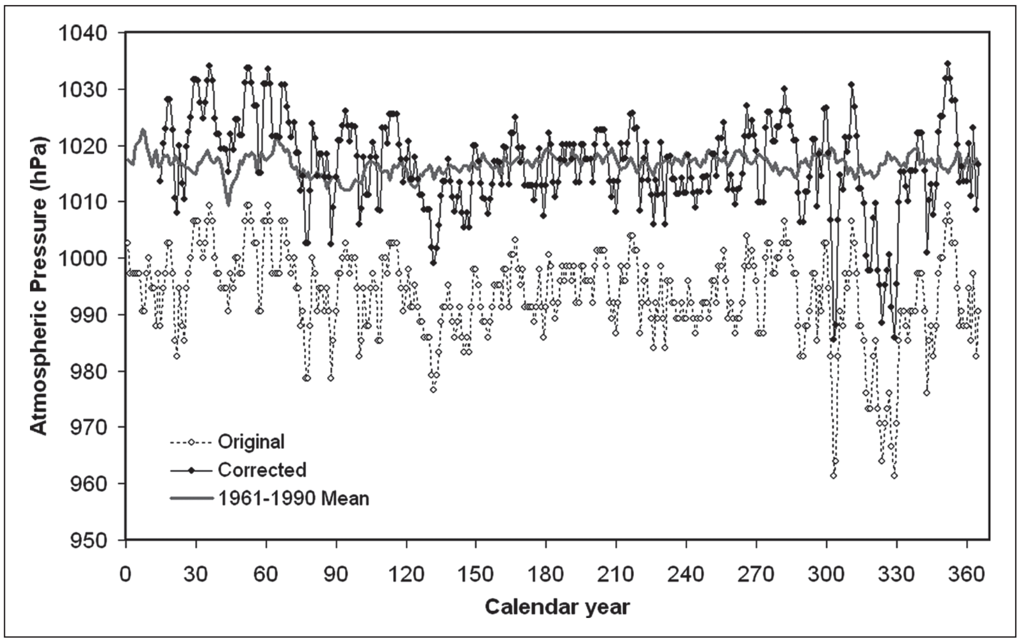

Figure 7. Atmospheric pressure (hPa) observed by Morin in Paris for the calendar year 1694. Raw readings adjusted to modern units (dotted line, open circles) and corrected data (continuous line, full circles). The final correction is the difference between the two lines. The reference 1961–1990 mean over the calendar year is also reported (grey thick line)

corrected for height (40 m a.m.s.l.) and latitude following the well-known formulae and instructions in the WMO Guide (1983). At this point the readings were still far from the local average, being 22.8 hPa below the 1961–1990 mean pressure in Paris for the same days of the calendar year. This difference is most likely attributable to instrumental error and is almost twice the correction deemed necessary by Legrand and LeGoff (1992). A further independent check was made with Paris that has a small average difference, i.e. 1.5 hPa with London. The pressure difference between the two stations in 1694 is reported in Figure 7.

The observations by John Locke (1692–1703) in Essex, UK

John Locke began to keep an intermittent journal of the weather from 1666 whilst living in Oxford (Manley, 1961a). However, when Locke moved to Oates, the home of Sir Francis and Lady Masham in Essex in 1692, his observations of the weather became more systematic until the end of his life (1704). Oates was a small Tudor manor house, situated to the north of Epping Forest in which Locke occupied two first–floor rooms (Cranston, 1959); the barometer and thermometer during 1694 were situated in his bedroom, which faced south. In the weather journal, Locke recorded observations of pressure, temperature, humidity, wind direction/strength and ‘weather’ at least once per day. The format of this diary followed Robert Hooke’s recommendations for maintaining a weather register (see Manley, 1961a). Of particular importance is that the time of the observation, in 24-h format, was also recorded in the journal, with the most common observation being in the morning at between 08:00 and 10:00. Unfortunately observations during the summer months are generally missing from the journal as Locke was often away in London during this time (Manley, 1961a).

The pressure observations were recorded in 1/20ths of an English inch although the type of barometer that Locke used is not recorded. It is noted for earlier readings that Locke read the height of mercury from the top of the convex surface of mercury (Boyle, 1692), which would imply that a wheel barometer was not used. Temperature was recorded, for the year 1694, from a sealed thermometer constructed by Thomas Tompion. The temperature was read as increasing degrees of heat and cold from a zero value marking ‘temperate’ (Locke, 1704). Following later practices, this zero value was probably at 45° according to the Royal Society standard (10°C) and it is assumed that the temperature unit likewise followed this standard, giving 1° equal to 2.4°C (Patterson, 1951, 1953). The conversion of the morning readings using these values yields monthly means of temperature comparable with Manley’s (1961b) corrected values, which are derived for this time from Locke’s readings.

To obtain values of London atmospheric pressure (Figure 8) adjusted to modern standards, three corrections were applied to the barometer readings after they had first been converted to hPa (1 in = 33.86 hPa) and to Gregorian calendar dates. The errors associated with density changes of the mercury due to temperature variation were corrected following the instructions in the WMO Guide (1983) using Locke’s concurrent temperature observations. The pressure readings were reduced to sea level by using the standard equation with the indoor temperature and an altitude of 75 m and to standard gravity. The use of this temperature value is valid given that Locke’s temperature readings are generally indicative of outdoors temperatures, because of the poorly insulated nature of the house (Manley, 1961b). The altitude of the barometer is an estimated value based on the local topography, as the house was demolished in 1802 (Cranston, 1959). The same methodology used for the Morin observations in Paris was applied to Locke’s data to determine the instrumental error. The instrumental error was corrected with the addition of 3 hPa.

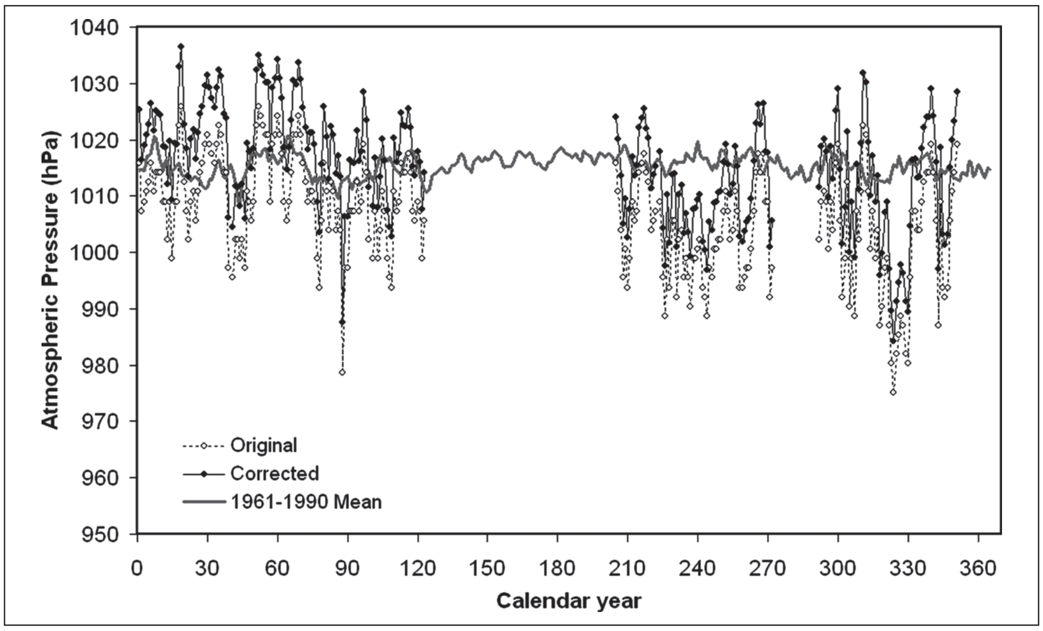

Figure 8. Atmospheric pressure (hPa) observed by Locke in London for the calendar year 1694. Raw readings adjusted to modern units (dotted line, open circles) and corrected data (continuous line, full circles). The final correction is the difference between the two lines. The reference 1961–1990 mean over the calendar year is also reported (grey thick line). A major gap occurs from May to July and a minor one during the first half of October

Atmospheric circulation in Europe in 1694

The winter of 1693–1694 was very cold and dry, as frequently occurred during the late Maunder Minimum (Glaser and Hagedorn, 1991; Pfister, 1992; Camuffo and Enzi, 1992, 1994), and was characterized by higher pressure. Polar or Arctic air masses entered the Mediterranean and probably arrived with a circulation type B1 (Figure 9) (or, A, A1), according to the classification of the UK Meteorological Office (1962). Lamb (1977: 490–91) suggested that in the 1690s a ridge of high pressure extended from the Azores into continental Europe, with a blocking high over Scandinavia. Luterbacher et al. (2000) suggested that in January 1694 a high-pressure system was located west of the British Isles and France, and that a deep trough penetrated from Scandinavia and deepened over the Mediterranean, which was bordered by a Russian high. In February Luterbacher et al. suggested that the high invaded western Europe with the Mediterranean low in attenuation, and the Russian high persisting. The high extending from the Atlantic over western Europe and the blocking high over Scandinavia or Russia seem to be confirmed by Ramazzini's data. From January to March the pressure was generally very high, except for London in mid February, when a deep low passed to the North, establishing a negative gradient from London (lower pressure) to Modena (higher pressure) (Figure 10). The passage was very slow (some ten days) suggesting there was blocking in the eastern North Atlantic European sector with marked retardation of the zonal flow (Moses et al., 1987; Wanner et al., 1994, 1995; Kington, 1995). This resulted in cold continental airsteams being advected westward over the British Isles. This is corroborated by the information in Locke's diary, where high winds and rainfall were recorded in London throughout this period. A similar but more rapidly moving low-pressure system passed through the higher latitudes at the end of March. April had fluctuations around the average, but Modena was lower than usual. From May to July the Mediterranean had a pressure lower than usual and lower compared with northern Europe (in this period London is missing). The implication here is that the Azores anticyclone was not well developed, or it was displaced northward, especially in the late spring (Figure 11): a situation similar to this was discussed above for 1658. The sea-level pressure maps produced by Luterbacher et al. (2000) confirm the situation in 1694, i.e. a late and northward development of the Azores high, which was unable to enter the Mediterranean. Atmospheric pressure in August and September was close to normal, although London had a much lower pressure beginning from mid August, indicating a persistent low. Luterbacher et al. (2000) reported a deep low from Scotland to Scandinavia in August. Once again Locke recorded cloudy conditions in London during this period with frequent rainfall events and generally high winds. October experienced high pressure during the first two weeks, and fluctuations around the average in

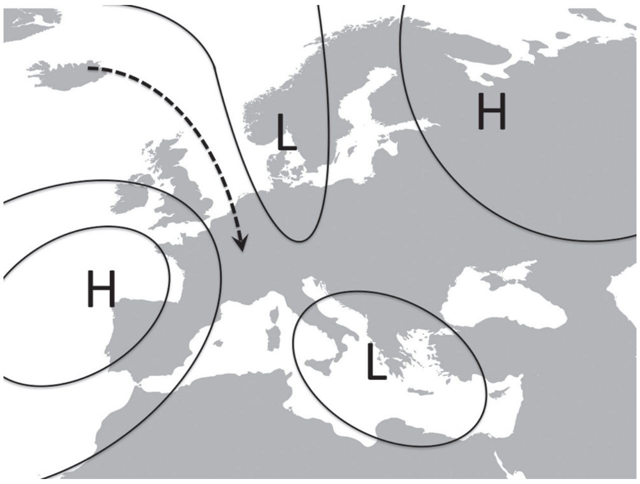

Figure 9. Circulation type B1 of the UK Meteorological Office characterised by a high over Western Europe and a southward trough with cold air advection (dotted line) towards the Mediterranean. This weather possibly characterised the cold and dry winter 1694

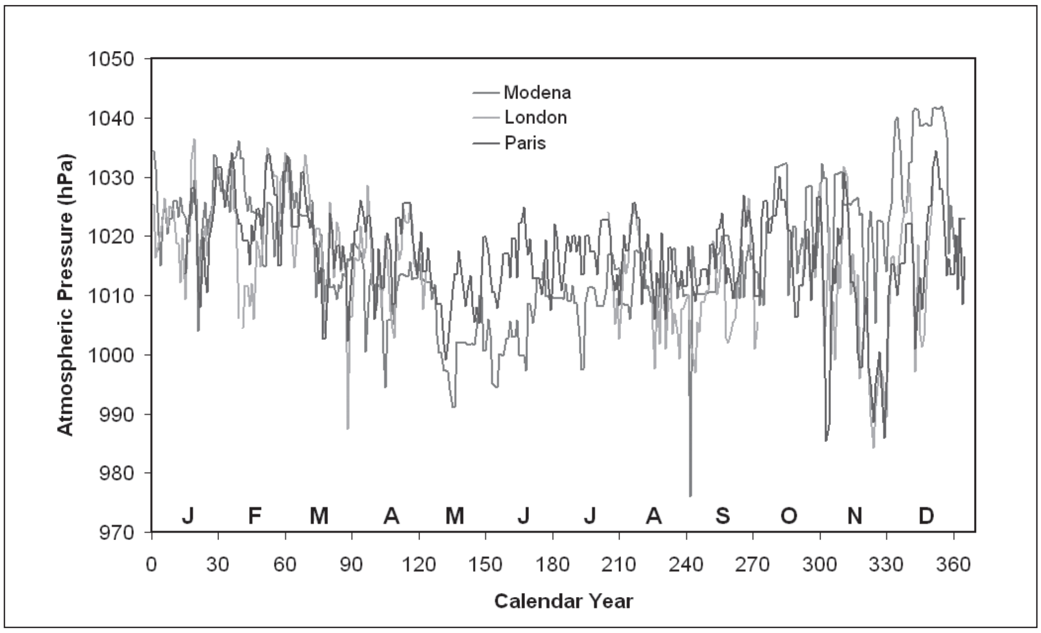

Figure 10. Atmospheric pressure (hPa) observed by Ramazzini in Modena (red), Locke in London (cyan) and Morin in Paris (blue) for the calendar year 1694

the second part of the month. In November and December, a strong pressure gradient was permanently established from southern Europe (higher pressure) toward northern Europe.

The weather map for December 1694 reported by Wanner et al. (1994, 1995) and Kington (1995) does not fit with the data for the first part of the month presented in this paper and only matches during the latter half of the month, when there was snowfall. When Wanner et al. (1994, 1995) drew the maps, pressure data were only partially available for northern Europe. In the absence of detailed information on the pressure in southern Europe, the weather map was drawn on the basis of weather descriptions in Europe and in particular of snowfall in Italy from 23 to 31 December 1694, and in other regions. This is known because one of the authors of this paper had cooperated in drawing the maps. The depiction of the atmospheric circulation using the Modena/Paris/London data is an improvement on the work of Wanner et al. because it takes advantage of actual daily pressure measurements in three key locations. During the first week of November, Paris had the lowest pressure, suggesting a low-pressure system passing across central Europe or a trough penetrating from the north toward the Mediterranean; Luterbacher et al. (2000) suggested that a trough was present. The pressure observations suggest that a sequence of depressions dominated the middle latitudes of Europe, passing northward and southward of London, and westerly winds prevailed over most of the Mediterranean. Modena had a permanent, very high pressure. This brings transitions between maritime polar and occasionally maritime tropical air to the western Mediterranean. Such a situation is characteristic of Weather Type C of the UK Meteorological Office (1962) classification. This is almost exclusively a winter type. Based on this reconstruction, deep cyclones would probably have crossed northern Europe from west to east. On 30 October a depression, the deepest one, passed over Paris and marginally over London. Two other cyclones passed on 20 and 25 November; the former closer to London, and the second closer to Paris. Locke recorded high rainfall in London during all of these three events, but especially for the 30 October storm. This storm was reconstructed by Lamb and Fridendahl (1991) on the basis of the surface winds and other observations and was responsible for the Culbin Sands disaster in northeast Scotland in which dunes of blown sand buried a large area including the buildings with depths up to 30 m of loose sand. We can confirm that the regional reconstruction made by Lamb and Fridendahl on the grounds of wind and ship log data, with a cyclone passing from northern Scotland to Norway, was substantially correct. We can also establish that the date of 30 October proposed by Lamb and Fridendahl for the disaster is very probable for a major drop in pressure; alternatively, other possible dates for this terrible storm were 20 and 25 November.

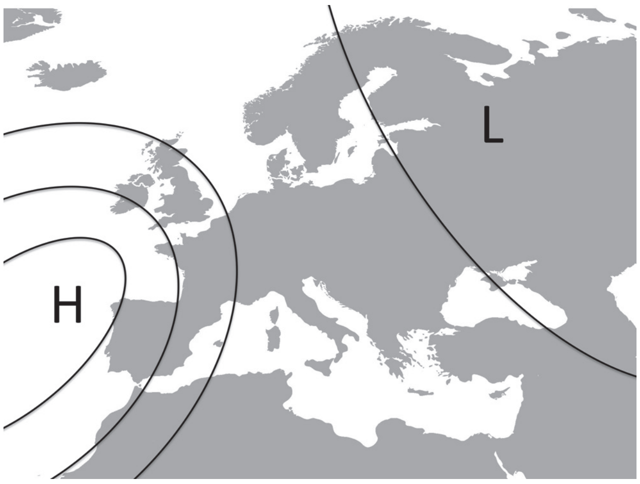

Figure 11. Northern displacement of the Azores High leaving the Mediterranean with lower pressure. This weather possibly characterised the chilly and rainy spring 1694

A short comment on the pressure in relation to the weather descriptions was made by Ramazzini in two papers (1695 and 1714a,b). The winter was exceptionally dry, cold and dusty, as justified by the exceptionally high winter pressure and cold air blowing from the north. After the spring equinox and during the whole of April heavy rains dominated, with two lows bringing

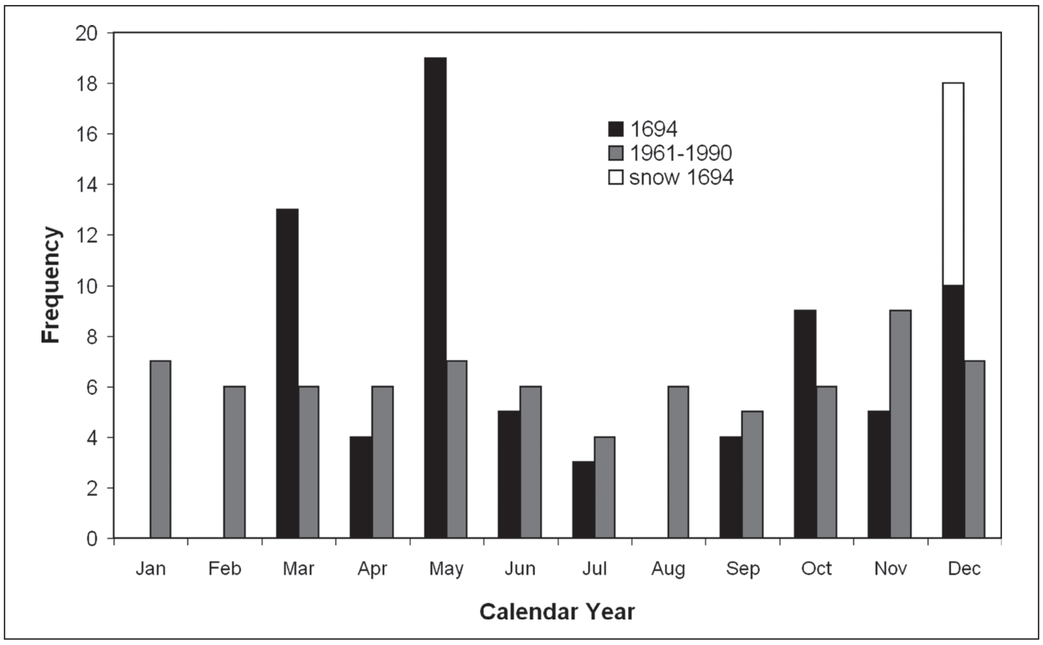

Figure 12. Monthly precipitation frequency in Modena, 1694 (black). White is for snow. The 1961–1990 reference period in grey

Sirocco winds and a severe heat, greater than in June, that reached 70° on his unknown thermometer (we suppose it was a big Florentine Thermometer with 100 subdivisions, which corresponds to about 33.3°C). Ramazzini (1695) reported that May experienced frequent rainfall and that fields were flooded. This is justified by the late arrival of the Azores anticyclone. This is true for the month of August only, or for the typical elevated relative humidity which makes this region uncomfortable. A histogram reporting the monthly frequency is shown in Figure 12. The late summer and the autumn were characterized by high temperature and dryness, broken by rare but stormy rains. The sharp change in pressure observed on 30 August, was explicitly commented upon by Ramazzini (1718: 292) who noted that in the morning the pressure was 72 lines, and at noon was 87 lines (Figure 6). The previous day (29 August) it was 84 lines, so that we may argue that a perturbation might have affected the area during the morning. Such events occur occasionally in the Modena area, especially in the warm season or in early autumn. In recent times, they occurred on the following days: 30 June 1998, 17 August 1998, 29 August 2000, 2 October 2000, 24 July 2001, 16 September 2001, 20 October 2001, 8 August 2002, 26 August 2002, 15 August 2003, 11 August 2005.

The late summer/autumn dryness affected most of northern Italy, so that public rogations were made to save crops and fruits against aridity (Contarini, 1694; Ramazzini, 1695, 1718; Anonymous, 1709; Mantovani, 1886; Camuffo and Enzi, 1994). Starting from 22 December, just at the end of the high pressure period, a unusually large amount of snow fell over northern Italy as is evident from the drop in pressure, with respect to the previous days.

Conclusions

The middle of the 'Little Ice Age' is a relevant but still obscure period not only for the scarcity of known data, but also because early observations are difficult to interpret and need interdisciplinary studies, including the history of science. Early observations suffer from a number of problems and uncertainties concerning both instruments and operational methodologies. However, they constitute the first quantitative and objective information about the climate from centuries ago, and every effort is justified to take advantage of them. The development of meteorology improved the quality of instruments and observations, with scientists learning about the problems and correcting previous errors. However, the idea of 'the oldest the worst' is not justified, because science progressed with attempts in all directions. Under this point of view, the poor technology used by Viviani and Borrelli in 1657–1658 based on a simple glass tube and a separated cistern gave better results than the sophisticated diagonal barometer that became very popular and was widely used for over a century, but which had a large friction that damped the variability and required some work to re-establish the expected variance. The diagonal barometer is attributed to Morland although it is not clear who really invented it. After this study we can conclude that (i) both Ramazzini and Morland worked on the same idea; (ii) Ramazzini's solution with a scale engraved on the inclined arm was better, but remained unknown; (iii) Morland's solution soon became popular, although it would be several decades before an inclined scale was used, as developed by Ramazzini in 1693.

Although there are many problems with early barometer observations, it was possible to correct the Pisa (1657–1658) and the Modena (1694) series, and to adjust them to a modern scale (hPa). In Pisa, the winter 1657–1658 is well documented, with a pressure generally higher than in the reference period 1961–1990, maybe due to an anomalous expansion of the African high, or a stronger ridge connecting the Azores with the Russian High. In contrast, in spring the Azores High was late or not well developed, allowing the penetration of Atlantic disturbances into the Mediterranean basin. Unfortunately, the observations were stopped or lost at this point.

In the second part of the paper, the atmospheric circulation over Europe during 1694 was reconstructed using daily pressure data recorded at Modena, Paris and London.

The winter of 1693/1694 was characterised by high pressure. According to the Central England Temperature record (Manley, 1974), 1695 was the second coldest year in central England since

1659, 1698 was the fourth coldest, and 1692 and 1694 are also both ranked in the five coldest years.

The year 1694 was characterised by a low pressure in the summertime suggesting a late arrival, or northward displacement of the Azores High, similarly to 1658. The hypothesis of a weak Azores high, or its northward deflection, may explain the abundant rain in the late spring. In particular, at the end of the year, a south to north pressure gradient (higher to lower) dominated over Europe possibly establishing a Westerly type circulation over the Mediterranean with the passage of severe storms over northern Europe.

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