HISTORY OF THE LONG SERIES OF DAILY AIR TEMPERATURE IN PADOVA (1725–1998)

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Abstract. The history of the origin of the study of meteorology in Padova and its connection to the major developments of this science in Italy and the international context are presented. Special topics are: the scientific legacy of Galileo Galilei and the *Accademia del Cimento*, the birth of the first meteorological networks, i.e., Ferdinand II and Leopold de' Medici who created the *Rete Medicea*, J. Jurin and the network of the *Royal Society*, London, L. Cotte and the *Société Royale de Médicine*, Paris, J. J. Hemmer and the *Societas Meteorologica Palatina*, Mannheim. After outlining the cultural background that favoured the development of meteorology, emphasis is given to the plurisecular time series of meteorological observations, taken in Padova since 1725, in its national and international context. This long series includes barometric pressure, air temperature, wind direction and speed; state of the sky and occurrence of meteorological events and precipitation. Special reference is made to indoor and outdoor temperature observations. Solar radiation falling on each exposure has been modelled in order to know when data were fully reliable and when they were less so. A vertical profile of air temperature has allowed corrections of the change of instrument level, when necessary. In terms of homogeneity, the series can be divided into several periods, during which instruments and operational methods, position, general criteria were unchanged: origins in homes of the first observers (1725–1767); the First Period at the *Specola* (1768–1812); the Second Period at the *Specola* (1813–1864); the Third and Fourth Periods at the *Specola* (1865–1937); the Last Measurements at the *Specola* (1938–1962); the *Giovanni Magrini* Observatory of the Water Magistrate (1920–today); the *Gino Allegri* Airport (1926–1990), the Botanical Gardens (1980–today), the CNR (1984–1986; 1993–today). The latest period, with the birth of new weather stations, is the most affected by anthropic effect. The simultaneous presence of an urban and a rural weather station pointed out local effects which dominate the urban heat island.

1. Introduction

The Padova series of meteorological observations, although affected by errors, minor gaps and non-homogeneity as all long series are, is among the most interesting ones, not only for the exceptional length of nearly three centuries. However, different ways of taking measurements have been met: the number of daily observations and the times of thermometer readings were changed; the thermometer was displaced changing height, exposure and shielding; external influences were no longer the same.

Every series is composed of data sets collected with some minor or major changes in the course of centuries. These may reflect in spurious climate changes and lead to erroneous interpretations. For this reason it is vital to know exactly

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the detailed history of each series, to correct and homogenise all the data, and to assess the reliability of each period. Data without metadata may lead to uncertain conclusions.

In every series three kinds of errors should be distinguished: (i) random errors that on average tend to compensate each other and have a minor impact; (ii) individual systematic changes that have a local impact; (iii) changes determined by national or international recommendations which can be found in every station, and for this reason can be misinterpreted as climate changes. All apparent discontinuities that occurred in periods in which operational methodologies were being changed, are suspect and should be critically revised. An accurate analysis of the history of every series is always necessary to distinguish real climatic signals from changes in average or extreme levels determined by operational methodology.

All the Padova data and the metadata have been gathered for two purposes: to perform careful correction, validation and homogenisation of the series before analysing it; to establish general principles, based on this case study, to apply to other long series.

However, not only history helps: also mathematical tests and the analysis of interdiurnal variability of the data allowed us to establish the influence of the building on observations or other discontinuities in the data. The findings of historical research, the analysis of metadata, the use of statistical tests and a cross comparison with other nearby series have been applied first to correct and homogenise the series (Cocheo and Camuffo, 2002) and then to interpret the results in order to distinguish climatic interpretation from spurious signal misinterpretation. A further advantage of a long and accurate work like this one (i.e., >20 years) is that missing data considered lost forever were found.

This case study constitutes a useful example of general interest for the documentation and solution of a number of typical problems that are found in the long life of a secular series.

2. Links between Padova and the Development of Meteorology

The thermometer was invented and applied to environmental and medical research at Padova University. In 1593, Galileo Galilei (1564–1642) invented the thermo-baro-scope and he and his pupils started observing temperature differences between sites and seasons. His pupil Francesco Sagredo wrote to Galileo on 9 May 1613: ‘I have made the instrument you invented to measure heat in a number of styles, so that we can measure differences in the *degree of heat* (= temperature) between one site and another.’ Since 1612 this instrument has been studied, improved, transformed into a thermometer and currently used for medical purposes by Santoro Santorio (1561–1636). Unfortunately, Galileo’s Inquisition trial (1633) dampened the enthusiasm for meteorological observations as a politically dangerous practice and the period after his condemnation (1633) and death (1642) was particularly dark. For instance, Giovan Francesco Sagredo (1571–1620), a close disciple of Galileo's, one of the protagonists in Galileo's *Dialogues*, built thermometers and performed regular observations at Venice. But after he died, when times became dangerous, his brother Zaccaria destroyed his instruments and records to avoid any risk with the Inquisition.

Fortunately, two good friends and supporters of Galileo's, i.e. the Grand Duke of Tuscany Ferdinand II (1610–1670) and his brother Leopold de' Medici (1617–1675), with Galileo's pupils, continued along the first steps of meteorology and invented the key instruments for observations. Benedetto Castelli invented the rain gauge and the evaporimeter (1639). Ferdinand II and Evangelista Torricelli improved the thermometer (1641): they rotated the graduated air thermoscope upwards, built the first liquid-in-glass thermometer using spirit and made it independent from air pressure by sealing the capillary. Torricelli also invented the barometer (1643) and finally, Ferdinand II a condensation hygrometer (1655).

In addition, Ferdinand II and Leopold, with the assistance of Father Luigi Antinori S.J. (Court Chaplain, director of the Physics Laboratory, and later Secretary of the meteorological network), had the political ability, and courage to establish the first international meteorological network, called *Rete Medicea*. This network began between 1653–54 with stations in Florence, Vallombrosa, Cutigliano, Bologna, Parma, Milan, Paris, Innsbruck, Osnabrük and Warsaw. The Grand Duke supplied observers with identical instruments made in Florence by the same instrument maker, called '*il Gonfia*', and recommended (following the suggestion by Luigi Antinori) to expose thermometers in an elevated position, on a north-facing wall, in order to obtain absolutely comparable data. The *Rete Medicea* ended its activity in 1667, after the closure of the *Accademia del Cimento*, but some stations (e.g., Paris, Vallombrosa) continued observations.

In Florence, Ferdinand II and Leopold also incorporated the famous *Accademia del Cimento* (i.e., Experiment Academy), active from 1657 to 1667. This Academy reunited Galileo's pupils for the preservation and continuation of his ideas, i.e. the pre-eminent role of experimental observations in contrast with the passive acceptance of Aristotle's statements crystallised by theological interpretation. The *Accademia* performed many field observations and Laboratory experiments. The activities of the *Accademia* and the *Rete Medicea* were documented by the secretary Lorenzo Malagotti (1667), the local historians Targioni-Tozzetti (1780) and Antinori (1841) and, recently, by Cantù (1985), Maracchi (1991) and Colacino and Valensise (1992).

The second part of the century was a flourishing period in which a number of scientific activities, mainly academies and journals on an international scale, were created, i.e.: in 1662 the *Royal Society*, London; in 1665 the *Philosophical Transactions*, London, and the *Journal des Savants*, Paris; in 1666 the *Académie Royale des Sciences*, Paris; in 1667 the *Giornale de' Letterati*, Rome; in 1682 the *Acta Eruditorum*, Leipzig.

Within this spirit of scientific renovation that followed the dark times of the Inquisition, in 1678 Padova University appointed Geminiano Montanari (1633-1687), to teach '*Astronomy and Meteors*'. He was strictly connected with the *Accademia del Cimento*, and came up from Bologna University. The decision of giving to a follower of Galileo's this delicate chair, connected with Aristotle's heritage and theological interpretation, was courageous and open. After Montanari, Michelangelo Fardella (chair from 1694 to 1700) and Giovanni Graziani (1703–1709) were awarded this chair. In 1700, the University appointed a medical doctor from the University of Modena, Bernardino Ramazzini (1633–1714), interested in meteorological phenomena. He carefully documented several unusual climatic events, such as rainy periods and dryness, very cold or hot seasons, acid fog, acid dew and so on. He also took regular daily observations of air pressure and wind direction for the whole year 1694 (Ramazzini, 1718a,b), although his diagonal barometer had a very low sensitivity. The diagonal barometer is known as a Moreland type, but very probably was invented by Ramazzini. He was in touch with all the leading scientists of his time. In Padova he continued his interest in meteorology and climatology publishing descriptions of exceptional events (e.g., the great winter 1709), but there is no memory of active experimental activity in Padova, in the last part of his life, when he was nearly blind. However, although Ramazzini had been appointed to the chair of Medicine, he nevertheless was an important reference for meteorology; in fact, in that period, natural observations were made and taught by two faculties: Philosophy-Mathematics (e.g., Galileo, Poleni) and Medicine-Surgery-Pharmaceutics (e.g., Santorio, Ramazzini, Morgagni). The interest for the relationship between meteorological factors and epidemics explains the key role of medical doctors like Ramazzini and Morgagni.

An important moment in Ramazzini's last years, was when three young scientists and close friends first met in Venice and then reunited in Padova: Poleni, Zendrini and Morgagni. Giovanni Poleni (1683–1761) studied philosophy, theology (1700) and law (1703) but loved and studied physics, mathematics, astronomy and hydraulics. With the co-operation of some friends he carried out experiments with a barometer and thermometer in Venice (Poleni, 1709) prior to his appointment to teach *Astronomy and Meteors* at Padova University in 1709. Bernardino Zendrini (1679–1747) was a good mathematician, astronomer, hydraulic engineer and meteorologist. He took his degree at Padova in 1701; after three years he went to Brescia, and then returned to Venice (1704) where he took meteorological observations from 1727 on (Zendrini, 1741). Giovan Battista Morgagni (1682–1771) was a leading medical doctor, with meteorological interest, formed at Bologna University. After his degree he went to Venice where he met and assisted Poleni in some of his early experiments (Ongaro, 1988). In 1711, Morgagni was appointed to teach Medicine at Padova University and was reunited with Poleni. Later, he will take meteorological measurements in his house, both for his professional interest of combining meteorology with medicine, and to compare his results with those of Poleni for continuous scientific discussion.

The experiences of Ramazzini, Poleni, Morgani and Zendrini were got together in Padova, together with the practice of building and using thermometers. The elder and most expert scientist was Ramazzini and we can suppose that he encouraged his young colleagues in this direction. The year 1709 was exceptional for the extreme severity of the winter described by Ramazzini (1718c); Poleni performed some measurements (Poleni, 1740) and a tornado in the same winter was described by Zendrini (1709). Poleni was young and full of enthusiasm and was inclined to do experiments, but preferably in association with somebody else. He started in Venice with Zendrini and Morgagni. In Padova he measured the air temperature in 1709, probably under the influence of Ramazzini. In 1711, i.e., the year in which Morgagni arrived in Padova, he took irregular measurements (Poleni, 1731), now lost, with gaps due to his absences. In 1716, Poleni began a new series in Padova, working in parallel with Beccari, active in Bologna. Regular indoor observations began in 1725 following Jurin's (1723) invitation. Finally, when Morgagni initiated his observations in 1740, either to establish connections with epidemics or under pressure from Poleni, Poleni began a parallel sub-series with a Fahrenheit thermometer, possibly to obtain regular external observations.

Fortunately, Poleni's daily observations in Padova, i.e., air pressure and temperature, rainfall, cloud cover and hydrometeors for the period 1 January 1716 – 21 May 1717 (with a gap from 10 July to 12 October 1716), as well as yearly rain totals for the years 1713, 1714 and 1724, have been preserved in the *Marciana Library*, Venice (Poleni, 1716/25). Also the observations carried out in Bologna by Jacopo Bartolomeo Beccari (1682–1766) from 1716 to 1737 are preserved in the Astronomic Observatory of the University of Padova, called '*The Specola*'.

A second attempt to form an international meteorological network was made in 1723, when James Jurin, secretary of the *Royal Society*, London, invited some scientists to join a new meteorological network, and to publish their data in *Philosophical Transactions*, London. Jurin (1723) established precise norms for instruments, operational methodology, exposure and reading times. Unfortunately, he suggested measuring temperature indoors, in a north-facing room where fire was never, or hardly ever lit, following the use introduced in 1660 by John Locke in London. This network was active from 1724 to 1735. In Italy, two scientists joined this network: Carlo Taglini in Pisa (but only for a short time) and Giovanni Poleni in Padova. Poleni, who was a member of the *Royal Society*, accepted this invitation with enthusiasm and sent two six-year reports, each of them summarising the results of his observations, which were published in *Philosophical Transactions* in 1731 (n. 421, pp. 201–216) and 1738 (n. 448, pp. 239–248). He also published his results in the *Commentaries* of St Petersburg (*Comm. Accad. Scient. Petropolitanae*, Vol. IX, 1740) and elsewhere. The original records of his regular observations taken since 1725, written in good order, are still preserved in the archives of the *Specola.*

In the years 1776–1786 Luis Cotte, on behalf of the *Societé Royale de Médicine*, Paris, instituted a new meteorological network that started out brilliantly with 22 stations. Cotte and his network were particularly interested in the relationships between weather and health, but this scientific activity was interrupted by the French Revolution. In 1780, Antoine Laurent Lavoisier promoted certain international conferences to build a European network with comparable instruments and calibrations, but he too was stopped by the same political events. In 1778, Johann Lorenz Bockman established a regional weather network composed of 16 stations in Baden (Germany), which also had a short life. Finally, Wolfgang Goethe, in the period in which he was minister of the Grand Duke of Weimar (1775–1832), organised an efficient regional network.

The most important network of this period was organised by the Prince Elector Karl Theodor von Pfalz and his secretary John Jacob Hemmer, who founded the *Societas Meteorologica Palatina*, Mannheim (Hemmer, 1783, Colacino, 2000). This international network, active in the period 1781–1792, was composed of 39 sites spread throughout Europe except England and the Iberian Peninsula; there were three stations in Russia, one in Greenland and two in Massachussetts. In Italy, the stations were in Padova (Toaldo and Chiminello), Chioggia (Vianello), Rome (Calandrelli) and Bologna (Matteucci). The *Societas* established the operational methodology and the observations schedule. It also distributed instruments following the style of the *Accademia del Cimento*, or specified their characteristics, following the style of the *Royal Society*, London. The observations were published in the *Ephemerides Societatis Meteorologicae Palatinae* from 1783 to 1795 (real years from 1781 to 1792). Von Humboldt (1817a,b) and many others based their studies on climate on these data.

In Padova, Giuseppe Toaldo followed the networks of the *Societé Royale de Médicine*, Paris and the *Societas Meteorologica Palatina*, Mannheim. In 1778 he founded the *Giornale Astro-Meteorologico*, a yearly journal that published astronomical ephemerides, the report of the main meteorological events of the previous year, scientific articles with particular application to the influence of weather on medicine and agriculture. The key aim of the journal was to perform meteorological forecasts based on the statistics of the past, and astronomical cycles, especially the 18.6 yr lunar nutation cycle that he called Saros. With this journal, Toaldo encouraged colleagues and amateurs to perform meteorological observations and to correspond with his journal; in this way he formed a national network composed of 32 observers. This network disappeared with Toaldo's death.

The new century (1800s) began without there being any particular initiative for meteorology, and for the long series of Padova this was a period of decline that continued till the discovery of the telegraph in 1842 that was utilised to transmit weather observations. Knowing the weather observations in real time and over the whole synoptic scale once again raised the interest in meteorology to make the dream of weather forecasting come true.

In the 1860s, the formation of national meteorological services renewed interest in meteorology. While wars and political events in Italy were leading to the unification of the Country into one Kingdom (1861), some leading meteorologists, Father Angelo Secchi, Father Francesco Denza, Giovanni Cantoni and others worked to unify local meteorological services into a national one. Angelo Secchi (1818–1878) was a leading astronomer, but also meteorologist. In 1849 he became director of the Meteorological and Astronomical Observatory of the *Collegio Romano*, Rome, and was a founder of the first modern meteorological network in central Italy, in the territory of the Pontifical State prior to the unification of Italy. Francesco Denza (1834–1894) in 1881 was founder and then President of the Italian Meteorological Society. In 1862 Secchi founded a new journal, the *Bullettino Meteorologico*, to spread ideas and methods, and with Denza, Cantoni and others visited all the observatories with primary instruments to check calibrations and homogenise methodologies.

The interest for meteorological observations was reinforced in 1865, when the new Italian government established the first meteorological service for the navy and civil boats, the *Servizio Operativo Marittimo*. After the General Management of Statistics of the Ministry of Agriculture, Industry and Commerce was charged with gathering meteorological observations, the *Ufficio Centrale di Meteorologia* was instituted in 1876 and became active in 1879 with the publication of the *Annali dell'Ufficio Centrale della Meteorologia Italiana*. In 1887 this office became the *Ufficio Centrale di Meteorologia e Geodinamica* (UCMG). It had the aim of co-ordinating, controlling, gathering and publishing observations carried out by astronomical observatories, schools and other authorities that had reliable equipment.

Interest in the weather, and in 'real time' information, performed every day by telegram transmission, continued to grow. In 1872 the Italian Ministry for Agriculture, Industry and Commerce, statistical Division, responsible for meteorology, published a norm about meteorological instruments and observation methodology in the official bulletin *Supplemento alla Meteorologia Italiana* (Direzione Statistica, 1872).

After the unification of Italy, modern units were adopted, i.e., the thermometric scale was changed from Réaumur's to Celsius'; the Paris inch was substituted with the millimetre; air humidity was regularly measured with a psychrometer; wind speed and direction were automatically recorded with a mechanical anemograph. In addition, several mentions of controls and calibrations can be found, some of them taken under Father Denza's direct supervision.

An important international agreement for co-operation was signed in 1860 between George Biddel Airy (Greenwich Observatory) and Urbain Jean-Joseph Le Verrier (Paris Observatory) to collect British and French observations and forecast storms close to these two countries. This was the first step in establishing wide international co-operation after certain conferences in Leipzig (1872), Vienna (1873) and Rome (1879). In Vienna (1873) the foundation of the *International Meteorological Committee* was established, whose first president was Christoph Buys Ballot. From 1875 on, Buys Ballot published daily meteorological observations taken simultaneously in Europe, Algeria, Turkey, Russia (European and Asiatic), U.S.A. and Canada at 7.35 a.m. Washington mean time (i.e., 1.33 p.m. Rome mean time), thus founding the *Bulletin of International Meteorological Observations*, to which Padova regularly sent its observations. The *International Meteorological Committee* was the ancestor of the *World Meteorological Organisation*, i.e., the specialised agency of the United Nations established in 1950 with 160 Members.

3. Padova Series

This long series can be divided into a number of periods, during which instruments, operational methodology, location and general criteria were unchanged. In a general sense, the first division could be made as follows: Homes of the first observers (1725–1767); the First Period at the *Specola* (1768–1812); the Second Period at the *Specola* (1813–1864); the Third and Fourth Periods at the *Specola* (1865–1937); the Last Measurements at the *Specola* (1938–1959); the *G. Magrini* Observatory of the Water Magistrate (1920–today); the *G. Allegri* Airport (1926–1990), the Botanical Gardens (1980–today), the CNR (1984–1986; 1993–today). The location of key sites in this long series is indicated in the city map by G. Valle (1781) in Figure 1.

The original registers and contemporary publications were a primary source for metadata, e.g., which instruments were used and relative scales, how and when instruments were calibrated, their locations and reading schedules. However, such information was often found to be insufficient given that the indication on the instrument and methodology was not always recorded or was ambiguous. Therefore, it was often necessary to consult many works of the time to confirm uncertain information; to trace, where possible, the missing information or, at least, find an indication which would be useful in reconstructing the most probable methodology.

Over the last ten years all the data and metadata available in the registers from the beginning till now have been recovered, corrected, validated and homogenised based on historical documentation, statistical tests and comparison with nearby available series. The examination of the old registers, except Poleni's, has been laborious because figures, columns and comments are not always in good order and the writing of some observers is difficult to decipher, particularly in the case of non-numerical notes.

Serious problems were found chiefly in the early period of the series relating to non-homogeneity of measurements, which were taken at different times, with different methodologies and in different locations. After a first analysis of all the data and the metadata, it was essential to subdivide the series into homogeneous sub-intervals. Once methodologies, approximations used and other causes of errors have been identified, it was necessary to evaluate their effects on measurements and proceed with the work necessary to transform the original set of data into a reliable, homogeneous time series. This research has concluded a very long study, clarifying

Figure 1. Map of Padova by G. Valle (1781) showing site locations: G. and F. Poleni (GFP) in Beato Pellegrino street (1725–1764); F. Poleni (FP) in the Convent of the Philipine Fathers (1764–1767); G. B. Morgagni (GBM) in S. Massimo street (1740–1768); G. Toaldo (TSL) in S. Lorenzo street (1766–1767); the Ezzelino Castle (CA) including the Munitioner's House, the Astronomer's House and the *Specola* (1768–1959) and the Botanical Gardens (BG) (1980–today). The *G. Magrini* Observatory (1920–today) is 700 m W of the *Specola* and the *G. Allegri* Airport (1926–1990) is 1300 m W; the CNR (1984–today) is 4.5 km ESE of the *Specola,* and are all sited outside the area shown in the map.

many obscure points and uncertainties met with in the past (Camuffo and Zardini, 1997) and, in addition, was useful in finding many scattered or lost data.

4. Observations by Giovanni Poleni (1725–1761)

The site

G. Poleni took early spot measurements (January 1716 – May 1717) in his first unknown home where he lived until 1718, slightly more than one mile far from his next house (C.F., 1725) in *Contrada San Giacomo* n. 3959, now Beato Pellegrino Street, number 5. For the period 1725–1764 (April) measurements were personally taken by G. Poleni or his son Francesco, or exceptionally by a trained servant.

The city map by G. Valle (1781) shows that the *Contrada San Giacomo* was in the northern side of the town, oriented NW–SE, near the city walls. The quarter was scarcely inhabited, with several, extended kitchen-gardens and outside the walls corn fields and meadows. The building, at that time property of the counts Capodilista, was surrounded by the street *Contrada San Giacomo* on the NE side, the *Bovetta* channel (now filled in) on the SE side, and the Italian garden on the other two sides. The building was erected in the 16th century, with thick walls, and composed of three floors (Figure 2a,b). The first floor had the main entrance, the kitchen, the Physics Laboratory, some private rooms and a loggia. The second floor was for Poleni's family and probably also for teaching, as Prof. M. Carburi, teacher of Chemistry, did after 1768. The last floor, with small windows, was devoted to the domestic staff. The house has undergone some transformations: the first of them was after Poleni's death, the Physics Laboratory was adapted to the School of Chemistry of the University (Rossetti, 1776; Brandolese, 1795; Moschini, 1817; Giormani, 1984). However, the main structure has remained the same and we had the opportunity to inspect it with the owner's kind permission and assistance.

4.1. INSTRUMENTS AND OBSERVATIONS

The series of regular meteorological observations began on 1 January 1725 Julian Style, i.e., 12 January 1725 according to the Gregorian Style. In the register, the data are grouped within well-ordered columns (Figure 3), as follows: (a) date in the old Julian Style in use in England, as expressly requested by Jurin (1723); the corresponding Gregorian Style (out-of-phase by 11 days); (b) hour of the observation; (c) barometric pressure; (d) air temperature; (e) wind direction and speed; (f) state of the sky and meteorological events at observation time; (g) quantity of rain (or snow). The variables (c), (d) and (g) were measured in London inches and decimals. In addition to the regular observations, the register contains other parallel temperature readings, taken with different thermometers and which, therefore, have been useful in detecting instrumental errors and drifts of the principal series after cross comparison. Poleni made the observations once a day, usually 15 minutes af-

Figure 2a. View of the SW facade of the Poleni House facing the garden. On the right, the Bovetta Channel has now disappeared, covered with earth. On the ground floor, in the middle, the three arches of the loggia, i.e., the Summer Room. On the left, the Physics Laboratory. On the first floor, on the right, the last two windows are of the Library where the Amontons thermometer was located.

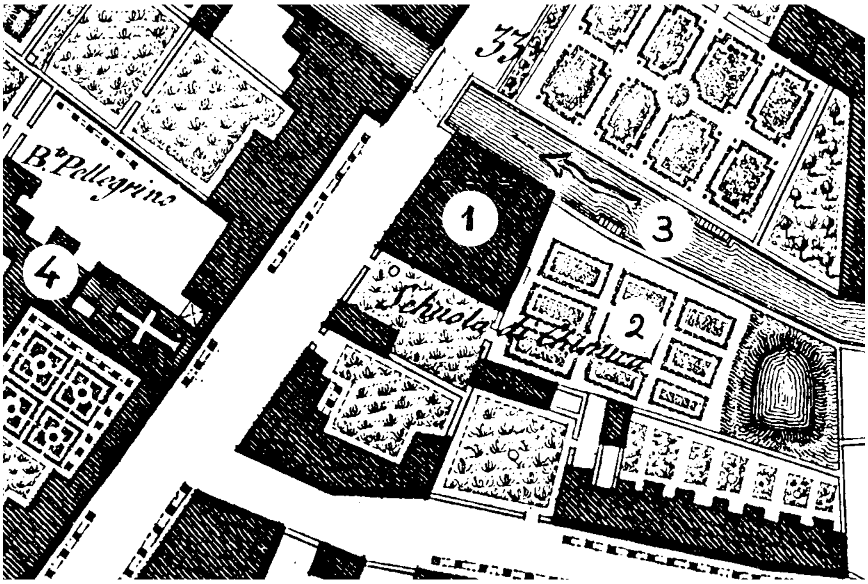

Figure 2b. Detail of the City Map by G. Valle (1781) showing the Poleni House (1) (indicated as '*Schuola di Chimica*', i.e., School of Chemistry) facing *Contrada San Giacomo* (now S. Pellegrino Street, indicated 33 in the map), with the garden (2) contoured by the Bovetta river (3). On the opposite side of the street, the church of B. Pellegrino (4) with the bell tower and the vane observed by Poleni for the wind direction. Buildings are in dark shadow. North is at the left side.

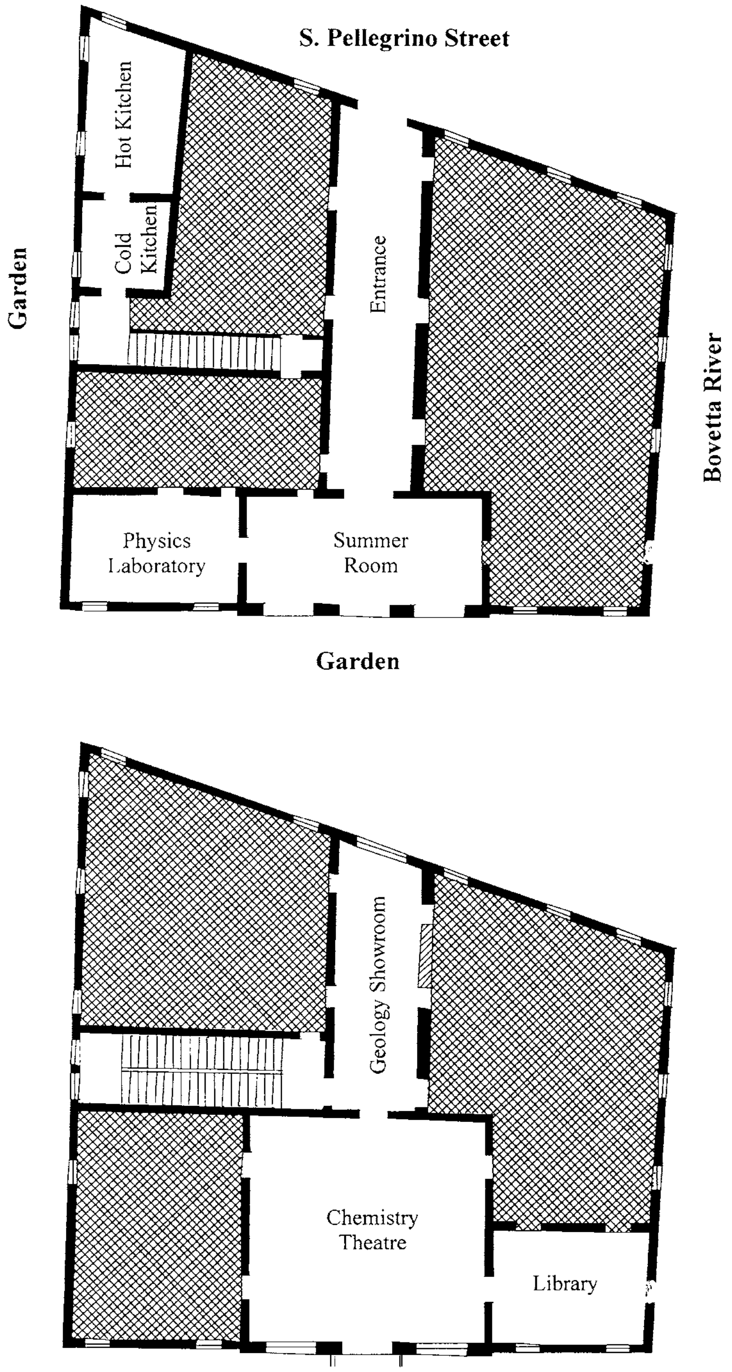

Figure 2c. Top: Cross section of the ground floor of the Poleni House, showing the Physics Laboratory, the kitchen, the summer room. Bottom: The first floor, indicating the Library in the corner room where the Amontons thermometer was hung. The Chemistry Theatre and the Geology Showroom in use at the Carburi' time.

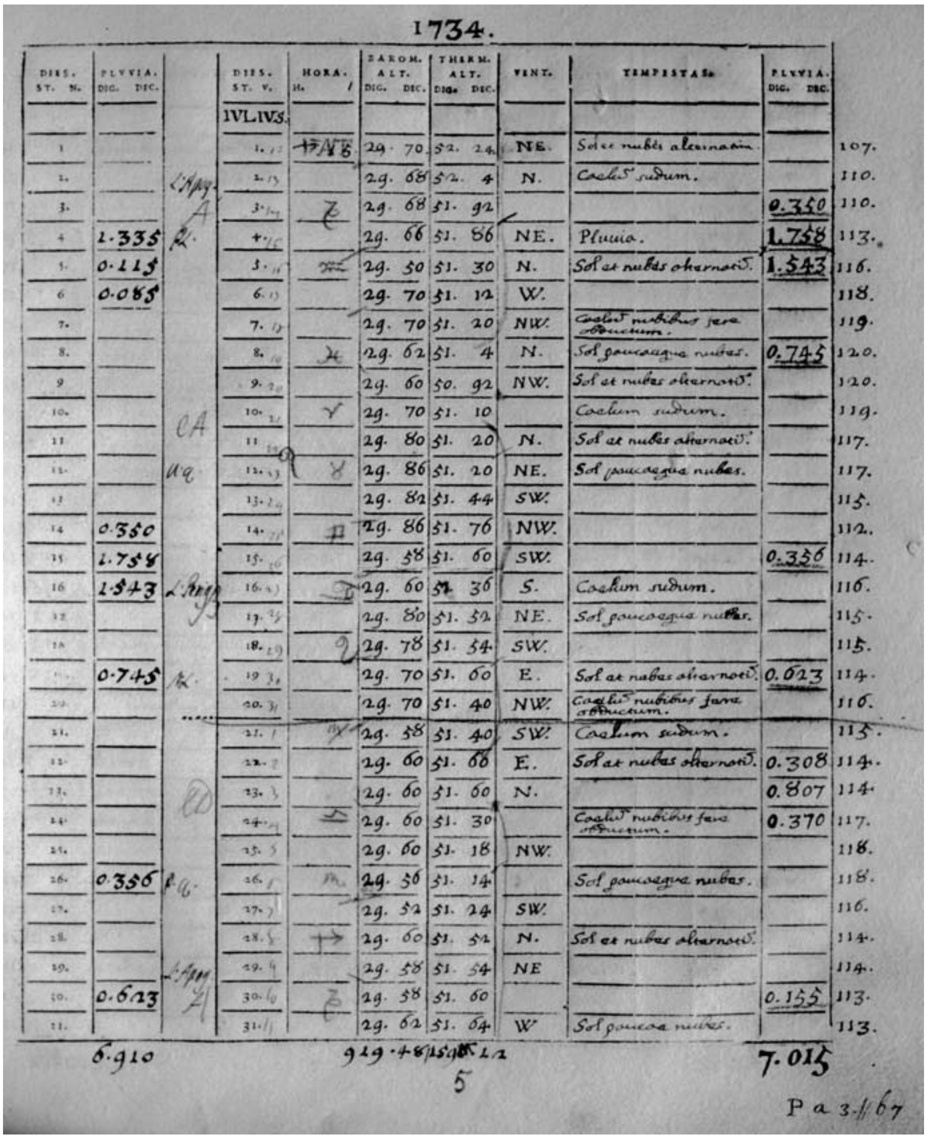

Figure 3. The Poleni register. Ordinate pen writing by Poleni. Pencil marks, symbols of astronomical conjunctions and grouping lines by Toaldo. (By courtesy of the Historical Archives of Astronomical Observatory, Padova.)

ter mid-day, the time he set as the day's beginning following astronomers' practice. Otherwise, he recorded the change in observation time.

The series of precipitation is the only one known. The monthly totals of rainfall amount and frequency have been published in various writings based on two different studies: that undertaken by Eredia (1921) until 1915 and that by Crestani et al. (1935) up to 1934. Crestani's work is more accurate, but still has errors: e.g., a printing error repeats the December 1867 value, then moving the whole column until 1875, with the final value obviously missing. The series, in its monthly totals, was already presented (Crestani et al., 1935; Camuffo, 1984) even though further work is still underway for a critical revision, correction and homogenisation of daily values.

The details of instruments and observing methodologies were reported in the register and in some letters (Poleni, 1731; 1738a). With reference to operational procedures, Poleni followed as far as possible indications given by Jurin (1723) and as a consequence he measured temperature and pressure indoors. Some additional measurements were taken outside.

Amontons' thermometer was derived from the Galileo thermo-baro-scope, with correction for pressure changes (details about the history of the instrument are reported by Middleton, 1966). The instrument is a nearly constant volume gas thermometer acting as an open tube manometer. The temperature is closely proportional to the pressure of the air pocket in the thermoscopic ampulla, which is determined by the height of mercury in the tube, plus the contribution of atmospheric pressure acting on the open tube and therefore transmitted to the ampulla. Therefore, thermoscopic readings must be summed to barometric readings, measured separately. The physical principle and typical errors of this instrument, and early thermometers, are discussed in another paper (Camuffo, 2002a). This instrument was very popular in the cultural environment of Padova, and the choice of this thermometer combined local tradition of improved thermoscopes, with strict international contacts between scientists for the advancement of science, which were demonstrated by continuous exchanges of letters, atmospheric observations and instruments.

Poleni built his own instruments, namely Amontons' (Poleni, 1709) and Fahrenheit's (Cossali, 1813) thermometers, but also used Delisle's thermometer that he received as a gift from Joseph-Nicolas Delisle (1688–1768). We know that also Zendrini took measurements from 1727 to 1738 in Venice (Zendrini, 1741), both indoors and outdoors, using Amontons' thermometer inside and Delisle's outside (Crestani, 1933). Given the strict link between Poleni and Zendrini, who very probably used the same methodologies and the same instruments to compare their observations, the information about Zendrini is a further indirect confirmation of what Poleni did in Padova.

In the register, in addition to the main regular Amontons' readings, other temperature data were recorded, taken with different thermometers, i.e., Delisle's, and Fahrenheit's. Comments about these measurements are noted in the margin of the register on the right of the last column, but without specification that these annotations refer to the secondary thermometers. At the beginning these notes caused some confusion since it was thought that they could refer to the main thermometer. In fact, in 1731 Poleni wrote: 'I always used the same instrument, exposed in the same place and observed in the same manner' (Poleni, 1731). However, starting in 1735 relocations were annotated in the register on several occasions, especially with the season. This contradiction is avoided when you realise that Amontons' thermometer was always carefully kept in the same place, and the register notes refer to relocations of the secondary thermometers.

Briefly, Poleni's main series (1725–1764) is composed of data taken inside with Amontons' thermometer, and is representative of a temperature lying between the daily mean (due to the smoothing influence of walls), and the daily maximum (for the hour not far from the actual maximum and with a good ventilation of the room before each reading, as has been deduced from an analysis of interdiurnal variability). Parallel observations taken outside after 1733 do not add much new light, because they are affected by the thermal inertia of the external wall, to which the thermometer was hung. However, these have been useful in detecting instrumental errors and drifts of the principal series.

Thermometer Location

In the registers, Poleni did not clearly specify all the thermometer locations, and this poses no small problem. The site of the principal instrument, i.e., Amontons' type thermometer, is fortunately known. The thermometer was hung to the inner wall of a room, where the fire was hardly ever lit, and read once per day, following Jurin's instructions (1723) who, unfortunately, limited our knowledge of the actual climate of that time. A possible reason for justifying such instruction is that it was difficult to find scientists with free time to perform more than one observation per day. Only one indoor reading was considered representative of the average daily temperature for the reason, probably unknown, that the daily cycle was smoothed by thermal diffusivity of walls. However, Poleni wrote that he did not have a suitable room facing north, and exposed the thermometer in the corner room with one wall facing the southern sector and one the eastern (Poleni, 1731), respectively in front of the garden and the channel. The walls are not exactly oriented to east and south, but are at 125° and 215°. The room was on the first floor, i.e., 8.5 m above the level of the channel, and was the Library where the barometer was also hung (Toaldo, 1770; Crestani 1926). The position was always the same as Toaldo (1770) explicitly mentioned. The data analysis showed that Poleni used to open windows before each reading to reach equilibrium with the external air, so that his observations were similar to the Morgagni outdoor ones (Cocheo and Camuffo, 2000).

The register reports indications of several relocations, inside and outside, for thermometer readings. The hypothesis that the notes refer to Amontons' thermometer, and in particular that observations with Amontons' thermometer were made outside is not in accordance with early writings by Poleni (1731 and 1738a) and then by Toaldo (1770). Toaldo stated that Poleni observed indoors, and specified that all the observations were made in the same room with a wall facing south and one facing east. We can exclude that Poleni changed style after the above-mentioned writings and that Toaldo was mistaken, because Toaldo had close contact with Francesco Poleni. In addition, this is in contrast with the second paper by Giovanni Poleni (1738a) which is dated three years after the relocation to the kitchen. The only possible interpretation is that Amontons' thermometer was always in the same room, as Poleni specified twice, and the seasonal changes refer to secondary thermometers used for additional measurements, which constitute further sub-series. Poleni was extremely interested in the official Amontons series and considered of secondary importance his experiment made outside the framework of the international network; this explains why the comments on the other sub-series are sometimes incomplete or ambiguous.

From 12 December 1733 to 19 July 1740 Poleni took other measurements forming the first parallel sub-series whose data are reported in the register on the right margin of each page. The values are higher in winter than in summer, indicating a thermometer with reversed scale. In a letter describing the Polaris Aurora on 16 December 1737, Poleni (1738b) reported two temperature values, one measured inside with Amontons' thermometer, and another with Delisle's thermometer (outside) which was some 4.5 °C less. Another comparison between Amontons' and Delisle's readings reported in a letter to A. de Pompeis (Poleni, 1740) on occasion of a Polaris Aurora on 29 March 1739 and a second temperature column in the register, shows that this second thermometer was the one received from Delisle. In fact, measurements were in accordance with those reported in the register, except for minor changes possibly due to a smaller departure between inside and outside temperatures in spring with open windows, or for a short time lag between the two readings with differing locations.

In February 1740, on an outside northern wall, Poleni exposed the Fahrenheit thermometer he had built, in order to record winter minima, taking measurements before sunrise (Poleni, 1740). Toaldo (1781) also suggested that in the summer of 1737 the thermometer was probably outside, as that was found to be the hottest summer in the series, while Poleni stated that the hottest summer was in 1728. The conclusion is that either Poleni was wrong, or he failed to mention the year 1737 as the measurements were not homogeneous, having been taken outside. On 20 July 1740, the register reported a new parallel sub-series with Fahrenheit readings that substituted the Delisle's.

Lastly, on 12 December 1761 Francesco Poleni started to use a Réaumur type thermometer for the last parallel sub-series made in this house.

How and where Giovanni and Francesco Poleni took the parallel sub-series made with the Delisle, Fahrenheit and Réaumur thermometers, is not always clear. Crestani, who carefully studied the problem wrote that he was convinced that the thermometers were hung outside, on a northern wall (Crestani, 1926) and promised to explain why in another paper, never written. This hypothesis could be supported with the following reasons:

(i) In his letter to De Pompeis, G. Poleni (1740) explicitly mentioned that in that winter the thermometer was exposed outside, in that he was interested in measuring the minimum temperature.

(ii) Poleni was always interested in taking measurements outside, especially in the case of severe cold; when he had more than one instrument, he had the possibility of taking one observation inside and one outside.

(iii) Moreover, his close friend Morgagni took his measurements both inside and outside and these two good friends were used to comparing their data. In particular, Morgagni made his readings near sunrise and two hours after noon, i.e., at times similar to those chosen by Poleni.

Starting from 1735 the register reports that the location of the (subsidiary) thermometer seasonally changed, as shown in Table I. However, indications about seasonal relocations were not diligently noted every year, leaving room for some doubt on the exposure, and sometimes also on the exact date of the relocation. The notes show that the thermometer was in one (inside?) location in the cold season, generally from October–November to March–April, and in a different one (outside?) in the remaining months. The thermometer was located 'inside the kitchen' and 'outside the kitchen' from 1735 to 1742; after 1749 in the 'room', in the 'summer room' and in the '<Physics> Laboratory'.

Measurements taken in a kitchen are surprising, especially for the presence of the fire, and Poleni was well aware of the recommendation of observing in a room where the fire was never, or nearly never, lit. A first hypothesis might be that important buildings had two kitchens: one for the cold season and one for the hot, both on the first floor, to make the supply of food and wood easier. However, this is not the case of Poleni. The kitchen was composed of a complex of three rooms facing NW, to prepare food and cook it, and only the last of them had a fireplace and oven. The external wall was hit by solar radiation only in the hot season, in the late afternoon, i.e., after the noon reading. The kitchen floor was of compressed earth and is now separated from the entrance hall by a narrow room that served as a deposit. Once the narrow room was open, ending with an arch on a loggia facing the garden. This ensured the passage for supplies and good ventilation to the deposit room. Winter measurements were taken 'inside the kitchen', the summer ones 'outside', but it is not specified where. Taken literally, it seems outdoors, but the data do not show any sharp discontinuity, as would be expected. However, a comparison with Toaldo's outside measurements, shows that inside-outside temperature difference was much greater in winter than in summer, and in summer the difference was not easily recognisable. In conclusion, it seems that for the period 1735–1742 summer measurements were fairly regularly taken outside (although the difference is very small) and winter ones inside.

Nothing is specified about the period 1743–1748. From 1749 some notes indicate that winter measurements were taken in the 'Laboratory', i.e., the Physics Laboratory for University students because in 1738 Poleni had the chair of 'Mathematics and Experimental Philosophy'. Very probably the room was at ground level, on the western corner of the house, with the longer side facing SW and the shorter with the entrance facing NW, on the side of the kitchen. Students entered directly

Table I
Notes in Poleni's register showing the changes of room

1734 March 17	today I came out of the kitchen
1735 November 2	today I came into the kitchen
1736 March 25	today I came out of the kitchen
1736 November 19	today I came into the kitchen
1737 March 31	today I came out of the kitchen
1737 December 11	today I came into the kitchen
1738 April 5	today I came out of the kitchen
1739 April 7	today I came out of the kitchen
1741 April 24	today I came out of the kitchen
1741 November 27	today I came into the kitchen
1742 April 16	today I came out of the kitchen
1742 December 12	today I came into the kitchen
1749 April 23	today I came out of the <Physics> Laboratory
1751 December 26	today I came into the <Physics> Laboratory
1752 April 20	today I come to study in the room
1752 November 5	today I came into the <Physics> Laboratory
1753 November 1	today I came into the <Physics> Laboratory
1754 April 11	today I came into the summer room
1754 November 24	today I came into the <Physics> Laboratory
1755 April 7	today I came into the summer room
1755 December 28	today I came into the <Physics> Laboratory
1756 April 28	today I came into the summer room, because I was out of Padova
1757 March 28	today I came into the summer room
1757 October 23	today I came into the <Physics> Laboratory
1759 October 25	today I came into the <Physics> Laboratory
1761 October 8	today I came into the <Physics> Laboratory

from the garden through one of the secondary doors, without passing through the house. It is certain that the Physics Laboratory was later used for the Chemistry Laboratory, as Moschini (1817) mentioned. The room was sometimes flooded by the *Bovetta* channel, as was reported in Carburi's letters (Giormani, 1984). The Physics Laboratory and the three kitchen rooms were separated by a corridor, probably open to the garden, for the supply of wood and food. For some years Poleni mentioned the kitchen, and later the Laboratory; it therefore seems reasonable to suppose that in winter the thermometer was always hung in the same site, i.e., the corridor which separated the kitchen from the Physics Laboratory, and was probably open to the garden, or close to the door in the NW wall.

Nothing is said about summer measurements except in 1752, April 9, when Poleni wrote: ‘I came inside the room’ and from 1754 onwards when he specified the ‘summer room’. The first hypothesis is that ‘the room’ was the ’summer room’ and that this room was on the ground floor, which is cooler in the summer. This floor could be divided into three parts: the NW side with the kitchen and the Physics Laboratory; the middle which is a very long entrance ending with a room without the SW wall, forming a loggia facing the garden (Figure 2c); the SE side facing the canal. The summer room might either be the loggia or a room located on the SE side. The loggia seems the most convincing possibility, as it was used in the hot season and coincides with Poleni’s interest in outdoor observations. The ground floor rooms on the SE side should be excluded because they were sometimes flooded by the channel *Bovetta,* and the central room, that has not been restored, is still very humid, with wall dampness and plaster fading, so that a preferential use of this room is not credible. If the ground floor is excluded, another possibility might be the central room facing SE on the first floor, on the side of the library with Amontons’ thermometer. However, this hypothesis should be rejected for two reasons: it is illogical to perform observations in two contiguous rooms; in the summertime this room is less comfortable than the loggia. We should conclude that the loggia is the ‘summer room’.

Solar Disturbance in Poleni’s Library

Poleni’s Library had two walls exposed to direct solar radiation. The instantaneous values of solar radiation I falling on the two walls of the Poleni Library (facing 125° and 215°) has been calculated (Figure 4) as a function of solar height H_o and azimuth A_o, according the equations (Robinson, 1966):

$$H_0 = \arcsin(\sin\delta\sin\phi + \cos\delta\cos\phi\cos\theta$$
$$A_0 = \arcsin[\cos\delta\sin\theta/\sqrt{1-(\sin\delta\cos\theta+\cos\delta\cos\phi\cos\theta)^2}]$$
$$I = I_o\cos A_w[\tan\phi(\sin\phi\sin\delta+\cos\phi\cos\delta\cos\theta)-\sin\delta\sec\phi]+\sin A_w\cos\delta\sin\theta$$

where δ is the solar declination, ϕ the latitude and θ the hour angle defined as $\theta = \pi t/12$, where the time t is computed in hours starting from the culmination of the sun, I_o is the flux of radiation across a surface which is perpendicular to the solar beam, A_w the azimuth of the wall. The quantity of energy supplied to the walls is not marginal: if we neglect variations for atmospheric absorption, the maximum energy is at the equinoxes, the minimum at the winter solstice

Also advective inflows occurred, following the opening of doors and windows. The interdiurnal variability of the internal temperature measured with Amontons’ thermometer closely follows the variance of Morgagni’s external measurements and is some three times greater than the variance of Morgani’s internal measurements. This means that the windows of the Poleni library were open, possibly determining air currents, for a long time before each reading; this both in the cold winter and in the hot summer, when windows tend to remain open to make the indoor microclimate more comfortable.

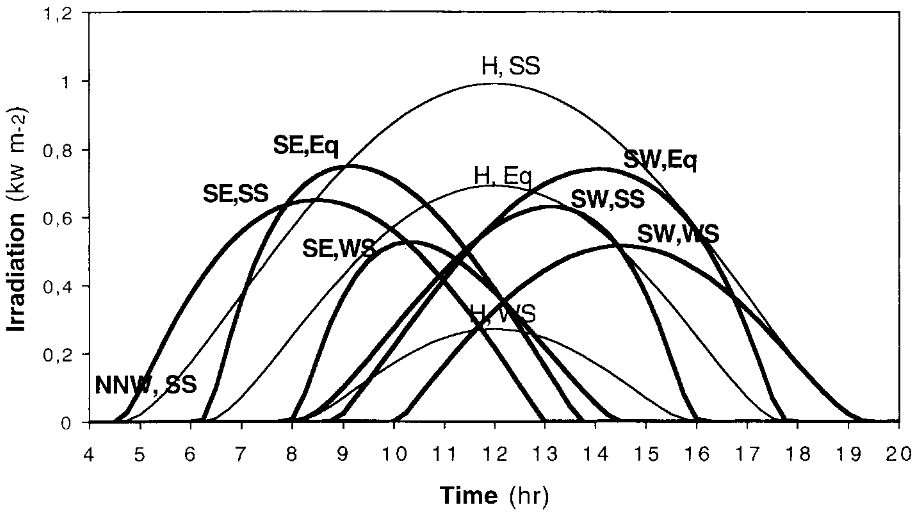

Figure 4. Solar radiation falling on the two external walls SE and SW (facing 125° and 215°) of the Poleni Library which contained the Amontons thermometer and that falling on the horizontal plane (H), computed for the summer and winter solstices (SS, WS) and the equinoxes (Eq).

It is clear that, even if new measurements were taken today inside and outside Poleni's house, it would impossible to evaluate the exact difference between the inside temperature measured by Poleni and the outside one, because domestic heating has changed, as has door and window insulation and tightness of fixtures etc. At that time it was unusual to heat rooms, so that the main source of heat was due to cookers in the kitchen on the lower floor, but nothing is known about Poleni's culinary habits, except for his daily hot chocolate. From Poleni's measurements in December 1737 the departure was 4.5 °C. In an essay written in 1788 (and published in 1794), Toaldo noted that, as a result of the location of the room where Poleni took measurements and the fact that these were taken at noon, the average annual temperature was greater than the effective one 'as heat slowly enters inside and slowly goes outside, and not all the amount that enters goes out' (Toaldo, 1794). Toaldo made some approximate evaluations of the difference between inside and outside temperatures, and he wrote (Toaldo, 1770; 1781): 'If the thermometer had been outside, a larger span would have been measured, with more marked extremes for both hot and cold. However, the <40 year> average would be unchanged'. 'The span of Poleni's observations was 47.5 and 52.5 <inches, i.e., °Po> because the thermometer was inside a room; we can suppose <that the outside values were> 47 and 53 <inches>'. Note that 0.5 °Po = 2.53 °R = 3.16 °C and 2 °R = 2.5 °C, so that Toaldo suggests that the temperature inside was attenuated by 2.5 or 3 °C in summer and was warmer to the same extent in winter. In a note at the beginning of Poleni's register, Toaldo stated that the 'degree of heat indicated [by Poleni] was different from that measured on a thermometer facing north, outside in the free air, by at least two [Réaumur] degrees, as I myself, by various comparisons, have ascertained'.

Conclusive Remarks about G. Poleni's Observations

In conclusion, we have obtained satisfactory knowledge of the situation: the main series was absolutely homogeneous, taken with the same instrument (Amontons') in the same location (the Library) and observed in the same way for the whole period. The other parallel subseries, made with additional thermometers, were made in a number of places, some inside, others outside. The 'summer room' is the open loggia; when the site is not specified in summer after the note 'I came out of the kitchen' or 'out of the Laboratory', the thermometer was very probably outside, hung on the northern wall, on the southern edge of the garden. In this respect, Poleni followed the indication of the *Accademia del Cimento* (1657–1667) formulated by Antinori, i.e., to hang the thermometer up high, on a wall facing north. Unfortunately, the indoor series cannot provide daily maximum and minimum temperatures, but can be used to follow climate variability in that period.

The register and observations were taken with extreme care. When Giovanni Poleni died, on 14 November 1761, his son Francesco regularly reported the observations of the day and annotated 'this evening, the blessed soul of my Father has gone to Heaven'.

The many books and notes in Poleni's library were transported to the Monastery of S. Giustina where other sons of G. Poleni, monks, lived. However, the books were later dispersed by the invasion of Napoleon's troops; some of his writings with early records fortunately survived in the Marciana Library, Venice.

5. Observations by Francesco Poleni (1761–1769)

The Site

After Giovanni Poleni died, the University rented Poleni's house and the Laboratory of Physics was transformed into the School of Chemistry. Francesco continued his observations till 5 April 1764 in Beato Pellegrino Street, and from 26 April 1764 to 31 December 1769 in the Convent of the Philipine Fathers in San Tomaso Street (Figure 5). The latter site is some 1260 m south of the house in Beato Pellegrino Street, on the northern side of the mediaeval Castle where Toaldo will later continue the series. The site was on the outskirts of the city, with a row of buildings along the river, and then kitchen gardens up to the walls. The northern side of the Convent faced the street, the southern the garden. We do not know which room he had, whether on the first or the second floor.

Observations

The register contains observations performed in the new house from 26 April till 31 December 1764. Francesco Poleni further continued observations for another 5 years, but the original register with daily values has been lost. Toaldo (1770, 1781) who was sceptical about their accuracy after the move, reported the monthly averages from January 1765 to December 1769. Toaldo supposed that the mea-

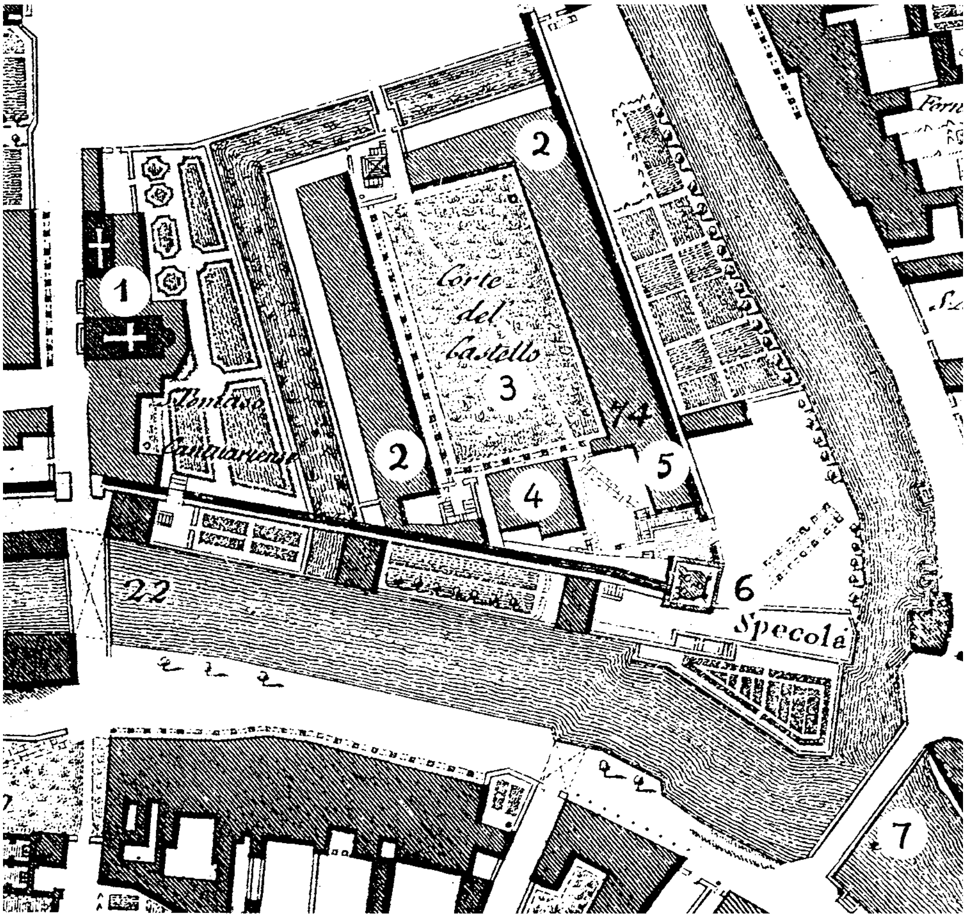

Figure 5. Detail of the City Map by G. Valle (1781) showing the Philipine Convent (1), the Ezzelino's Castle (2), with the internal courtyard (3) where the Munitioner's House (4), the Astronomer's House (5) and the Astronomic Observatory, called *the Specola* or *Torlonga* (6; for details see Figure 11) are located. On the right and the bottom, the river (7).

surements in the Philipine's Convent were too different from the previous ones, and attributed the departure to the leakage of air bubbles which escaped from the ampulla of the Amontons' thermometer during the move. For this reason, the data were considered of bad quality and thrown away. This is possible, but it is difficult to think that Francesco, who noted the observations even on the day of his father's death, took so little care of the instrument during the move. It is more probable that the new room was colder, either because it faced north instead of having SE and SW walls, or because of a poorer insulation, or the Convent was less heated than the house of the Marquis Poleni.

Figure 6a. Morgagni's house.

6. Observations by G. B. Morgagni (1740–1768)

The site

Morgagni's house was (Figure 6a) on the SE side of the town, near the city walls and the surrounding channel. The map by G. Valle (Figure 6b) shows that S. Massimo Street was oriented WSW-ENE, with a few lonely houses with gardens and kitchen gardens and a channel parallel to the street, behind the kitchen gardens. The Morgagni house was the first one, on the right. The interior of the building has been completely transformed; only the facade has been preserved. As Poleni and Morgagni were close friends and were used to compare data, it is logical to suppose that Morgagni adopted an observational methodology similar to Poleni's. The external thermometer was probably situated in a northern exposure because Morgagni was certainly familiar with Antinori's (1653) and Jurin's recommendations (1723) about placing thermometers on a north-facing wall, which Poleni had tried to follow whenever possible. For this reason we suppose that measurements were taken from a window on the facade that faced NNW, probably on the upper floor (about 4.5 m above the ground) in order to avoid vandalism from passers by.

Given the exposure of the facade, i.e., 335°, direct solar radiation reached it rather briefly after sunrise in summer, and for a longer period before sunset (about 5h 30′ at the summer solstice, when solar radiation fell at a tangent after 14.00) as shown in Figure 7. The radiation hitting the wall is practically zero in the morning throughout the whole year, while in the afternoon it is zero at the winter solstice

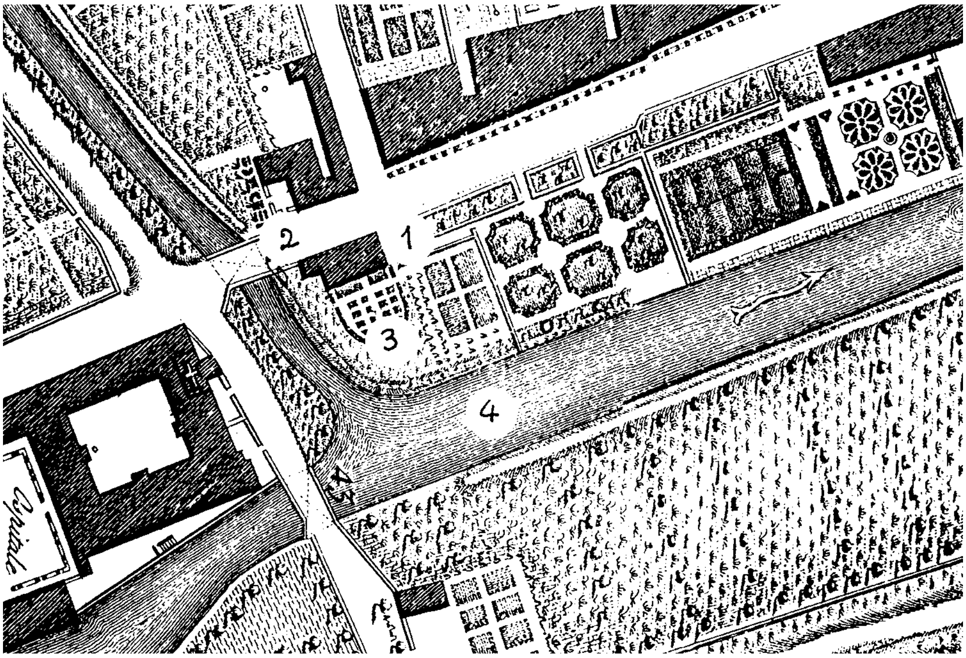

Figure 6b. Detail of the City Map by G. Valle (1781) showing the Morgagni house (1) facing S. Massimo Street (2), with the garden (3) contoured by the river (4). Gardens and crops around. Buildings are in dark shadow.

and rather modest at the equinoxes and reaches a maximum at the summer solstice. It would have been opportune to place a screen to the west of the thermometer for afternoon observations. However, Morgagni generally took measurements one hour after sunrise and two hours after noon (errors and corrections connected with the sampling time are discussed in Camuffo, 2002b) before the sun shone on the wall, the temperature not being affected by direct radiation.

Indoor and Outdoor Observations

Observations began in 1740, the same year in which Poleni initiated the sub-series with Fahrenheit's thermometer. The readings are recorded in a register (Figure 8) preserved in the *Specola*: (a) day and time of observations; (b) barometric reading; (c) two temperature readings, one outside and one inside; (d) state of the sky; (e) wind; (f) main meteorological events. Morgagni used Réaumur's scale, which is confirmed by Toaldo (1784) for the external thermometer when he compared the winters of 1746 and 1782: in fact, Toaldo reported his data in Réaumur's scale, which were identical to the readings in Morgagni's original log. Comparing the external with the room readings, it is evident that both Morgagni's thermometers were of the same kind.

Morgagni made two observations a day, but not at fixed times. However, the first was generally made, on average, one hour after dawn, i.e., near the tempera-

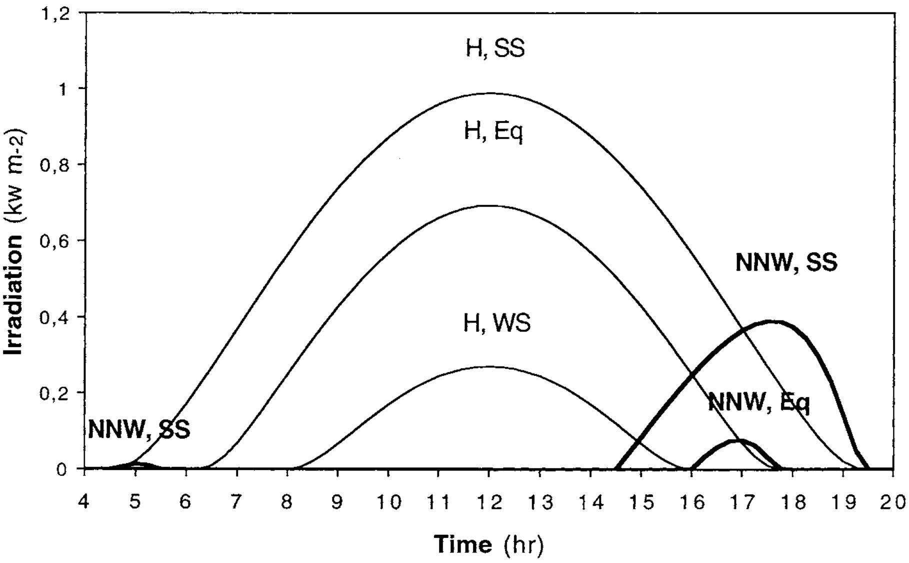

Figure 7. Solar radiation reaching the facade (facing 335°) of the Morgagni house (NNW) and the horizontal plane (H), computed for the summer and winter solstices (SS, WS) and the equinoxes (Eq).

ture minimum, the other usually about two hours after solar culmination (i.e., the passage of the sun across the local meridian) and was close to the temperature maximum. However, the result was quite different from what might have been expected, because the early morning and noon readings were quite similar due to the influence of the building.

The choice of these two times of observations was probably determined by two reasons: to know the daily extremes, and to obtain the average daily temperature with only two readings, i.e., the minimum and maximum daily temperatures, which were supposed to be near sunrise and after midday. This averaging practice was followed by Toaldo and was very popular in the 18th, 19th and early 20th centuries (Flammarion, 1888; Ceconi, 1939).

The data analysis shows that the early morning observations were too similar to the noon readings. This leads to two hypotheses: (i) the thermometer was exposed to the eastern side, and was reached in the morning by solar radiation; this means that the noon observations are good and those in the morning should be rejected; (ii) the thermometer was strongly influenced by the building structure, e.g., thermometer sited in a niche, which smoothed out the daily extremes, with the consequence that both the observations were affected by an error which should be individuated. An analysis of the variance of the interdiurnal variability of the temperature (Cocheo and Camuffo, 2002), which is slightly less than the variance of Poleni's outside observations, rejects the first hypothesis and confirms that the outside thermometer was influenced by the inertia of the building. Toaldo (1784)

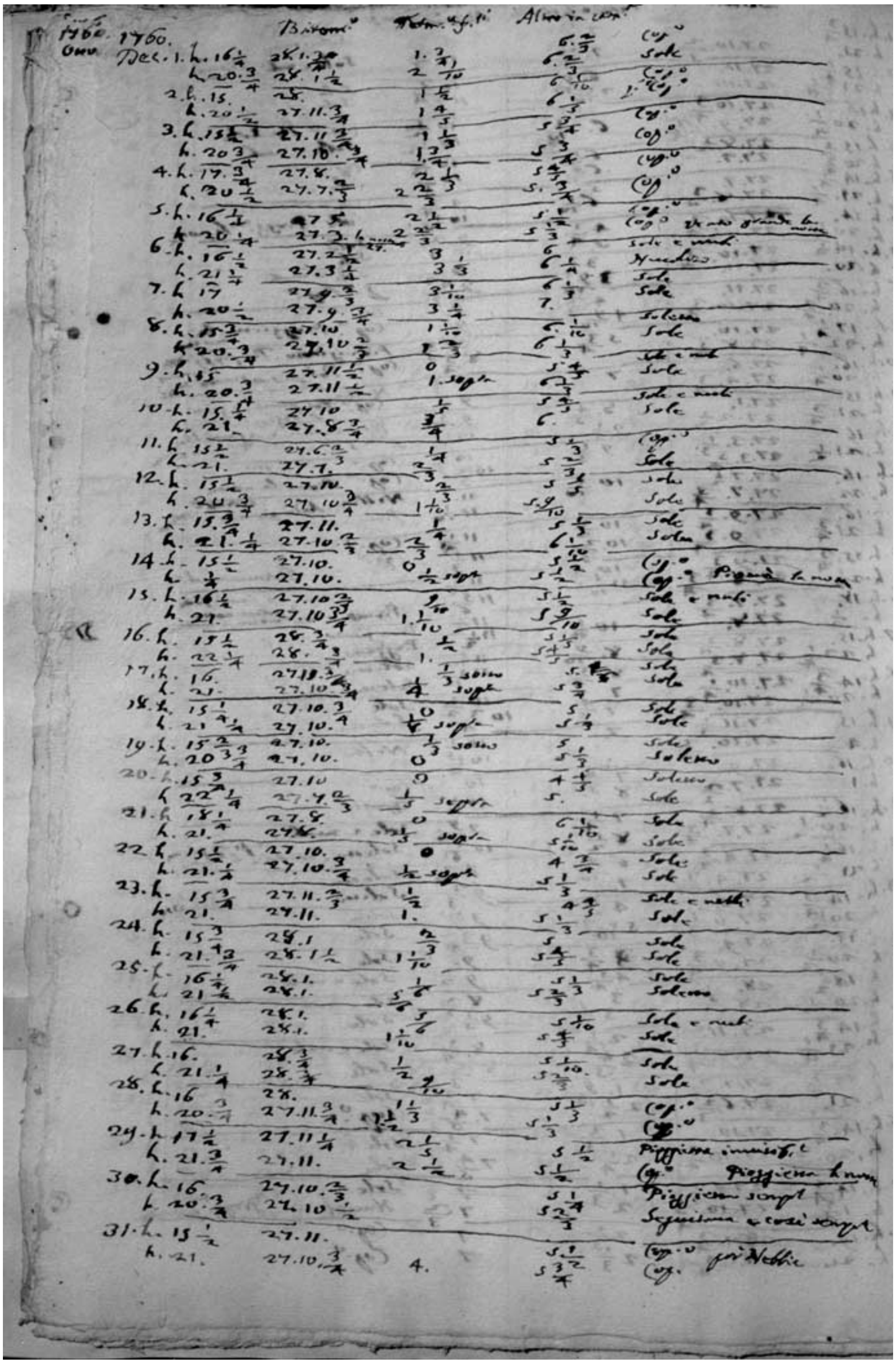

Figure 8. The Morgagni register (by courtesy of the Historical Archives of the Astronomical Observatory, Padova).

also confirmed this finding when he compared outside temperatures of the winters 1746 and 1782. He commented that Morgagni's thermometer was located in a site which was less open and ventilated than his (i.e., outside the main turret of the *Specola*), and less sensitive to external temperature changes. The only helpful mention found in Morgagni's register is for 9 February 1740: two comments are reported beside two observations of external temperature, i.e., '2 degrees with closed window' and, a few hours later: '2 degrees with open window'. This induces us to suppose that the thermometer was hung outside the windowpane, probably adherent to the limestone window jamb and too close to it. The stone influence was even more evident if the wooden frame of the thermometer had, as was customary, a hole in correspondence to the bulb (Camuffo, 2002a) to allow for the volume of the bulb and free air circulation. In this case the bulb was at a close distance from the stone and faced it without any interposed insulation or shield.

7. Observations by Toaldo and Chiminello and the First Period at the *Specola* (1766–1811)

Toaldo and his Co-Workers

Giuseppe Toaldo (1719–1797) was appointed to Padova University on 5 May 1764 to teach Astronomy and Meteorology, and was in charge of visiting the most famous astronomic observatories to be able to build a new one in Padova. He played a key role in planning the works that transformed the architectural complex of the mediaeval castle of the Lords of Padova and the main tower (built 10th–11th century, named *Torlonga*), into an efficient astronomic observatory, *the Specola*, of which he was the first director.

When Toaldo started taking his meteorological observations, he contacted Francesco Poleni, and carefully observed his register of data, instruments and practice. He later marked with a red pencil all the astronomic ephemerides in Poleni's register, searching for a teleconnection between meteorology and solar or lunar influences. He also contacted Morgagni, but with less success, and after Morgagni died he received his original register from a third person, professor Calza (Toaldo, 1781).

Toaldo was in some aspects genial, very interested in performing sound statistical analyses, to find teleconnections between astronomical and meteorological events, and to establish practical connections between meteorology and human health or agriculture (Camuffo, 2000). He was not an enthusiast of routine and order, as it appear from his registers (Figure 9) and probably for this reason he preferred to leave observations to his nephew and assistant Vincenzo Chiminello (1741–1813). Toaldo and Chiminello officially invented a hygrometer (Salmon, 1798; Ferrari, 1815) based on the expansion of a goose quill, which in 1783 won a prize by the *Societas Meteorologica Palatina*, Mannheim (Chiminello, 1785) and was adopted as the most reliable hygrometer. However, a replica of this instrument and its re-calibration shown many limits (Cocheo and Camuffo, 2000). Very probably the actual inventor was Chiminello, as we can deduce from a paper (Chiminello, 1785) in which he discusses the theory and practice of the instrument. Toaldo ceased taking observations three days before his death, 11 November 1797, caused by an apoplectic fit. Chiminello was a good scientist, an accurate instrument maker and a precious co-worker of Toaldo's from 1776 on; in 1779 he was officially nominated associate astronomer; when Toaldo died, he was given his chair at the University and became director of the *Specola*. Giovanni Battista Rodella (active 1780–1834) was a technician and internationally renowned instrument maker.

The site of the observations changed several times before, during and after the construction of the *Specola*. This period can be divided in sub intervals by taking into consideration both the site and the style of the registers.

7.1. OBSERVATIONS IN S. LORENZO STREET (MAY 1766 – TOWARDS THE END OF 1767)

The Building

Little can be said about exact thermometer location in the very first period when Toaldo lived in a mediaeval building with a tower, property of G. Zabarella, built by the Da Carraras, Lords of Padova (1318–1405). Toaldo chose this building when he returned after having visited the astronomic towers in Pisa and Bologna in 1775. It is logical to expect that Toaldo, appointed to the chair of Astronomy and Meteorology, was especially interested in the tower for astronomical and probably also for meteorological observations.

The building is on the corner between the street of the Zabarella Family and S. Lorenzo Street (now called S. Francesco), that starts in the heart of the city, near the University, and proceeds in a WNW–ESE direction (Figure 10). The facade is on the longer side of the building, facing SSW and S. Lorenzo Street and at the back there is a courtyard. The building is a two-storey one with a tower, twice the height of the building in the WNW corner. In the absence of precise information, it might be logical to expect that he kept his instruments in the tower from which he inspected the sky, especially because later he was to hang his instruments in another astronomic tower, the *Specola*.

Observations

The notes in the register show that, following the example of Morgagni and Poleni, at least two thermometers were used, one inside (i.e., according to Jurin's recommendations and as in Poleni's main series) and one outside. However, looking at the written documents, it is not clear which of these two temperatures was recorded in the register. Unfortunately, Toaldo's writings are incomplete and obscure; they do not specify the number and position of thermometers. In the register till 1769 we often find the following ambiguous annotation: 'measurement taken indoors' (Table II). After 1769, the annotation 'freezing outside' was occasionally found. Four

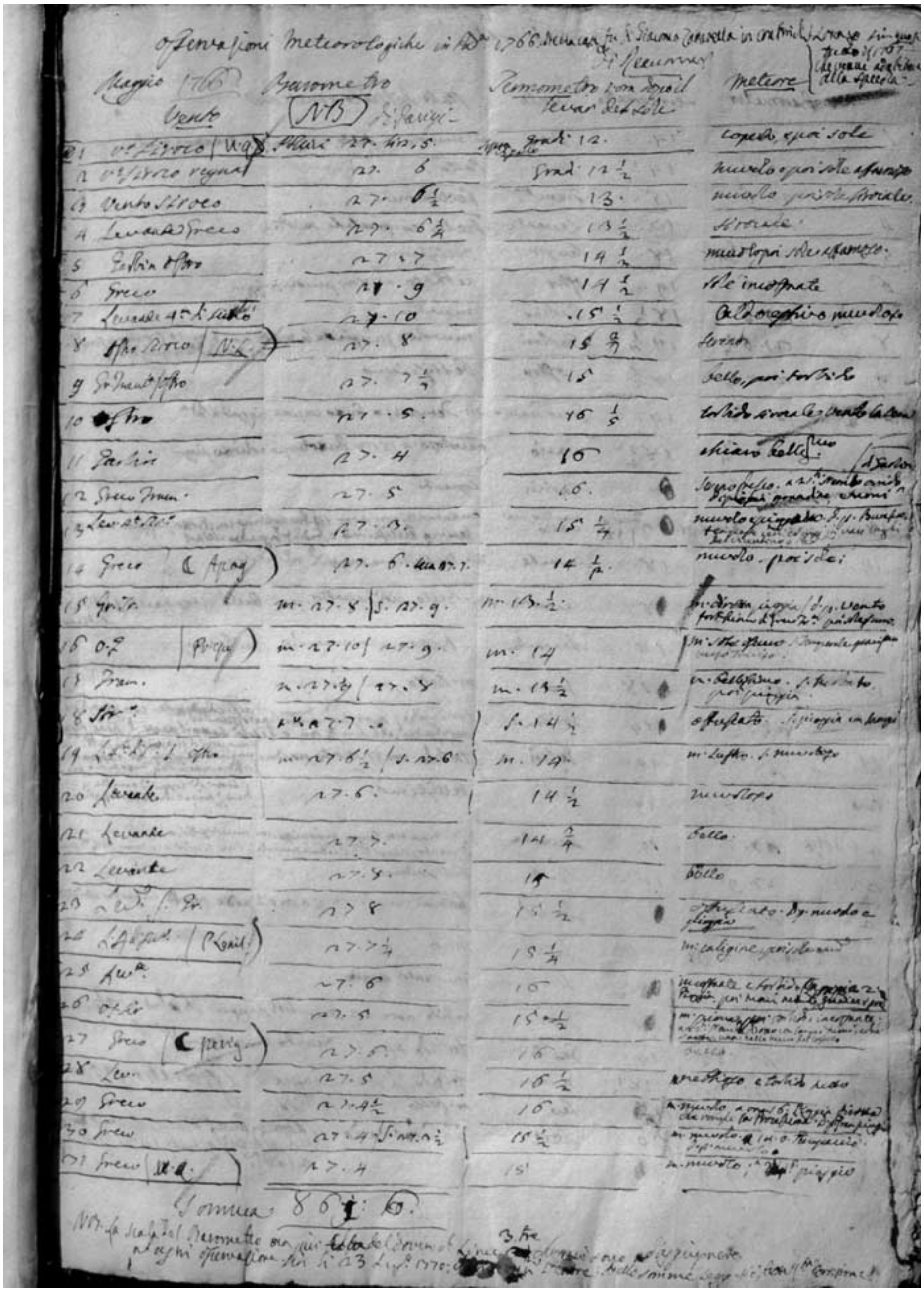

Figure 9. The Toaldo register (by courtesy of the Historical Archives of the Astronomical Observatory, Padova).

Figure 10. Picture of the Zabarella building with the tower where Toaldo made his early observations.

hypotheses can be advanced. (i) Toaldo regularly made two observations a day, one inside and one outside, possibly similar if both the thermometers were hung to, and strongly influenced by, the same wall, as found with Morgagni. He reported the inside readings as representative of both, except for commenting when there was a considerable difference between the two. However, it is unrealistic to expect such

Table II

Notes in Toaldo's register showing the position of the thermometer (inside or outside). The degrees are Réaumur's.

1766 December 12	−2° outside; +2° inside
1767 July 18	outside
1767 November 4	in the room
1767 November 30	6° in the room but outside around <?> deg. with freezing temperature
1767 December 2	5° but freezing outside
1767 December 3	4° but freezing outside
1767 December 4	4° but very cold outside
1767 December 5	3° but severe frost outside
1767 December 6	3° inside; −3° outside
1768 March 4	0° frost
1768 November 11	my thermometer hanging in the room broke
1768 November 26	in the room
1768 November 29	freezing outside
1768 November 30	freezing outside
1768 December 7	freezing outside
1768 December 8	freezing outside
1769 February 26	0° frost
1769 May 28	in the room
1769 December 15	1° <inside but> frost <outside>
1770 December 30	after 0° and 2.8° at two different times, the note: frost <outside>
1771 December 24	1° outside hoarfrost and ice
1773 March 29 after	1° and 6.25° at two different times, the note: freezing outside
1774 January 1	at 22 <Italian Time> frost

good agreement between inside and outside temperatures. (ii) Following a style common at that time, and used also by Morgagni, each annotation was intended to refer to all the subsequent data, until a new annotation was given to update and change the meaning. However, this does not seem to be the key. (iii) Toaldo only measured inside, and noted when the temperature outside was very different, e.g., below zero, given the presence of frost. This seems a reasonable hypothesis. (iv) Toaldo only measured outside, e.g., on the top of the tower in the city centre, and he commented on anomalies or apparent departures as hoarfrost in the gardens or ice on the river, or exceptionally he added observations taken inside.

The last hypothesis is the most convincing and is supported by the following three key reasons. (i) His observations were taken after sunrise and noon and this makes sense only when measuring the extremes of the daily cycle in the free air. (ii) In a paper written in 1774 and printed in 1775, Toaldo wrote (Toaldo, 1775) that for

8 years he had been taking measurements outside, with the thermometer exposed to the free air, but shielded against solar radiation. (iii) Building structures smooth the natural interdiurnal variability of air temperature. Hanging a thermometer directly on an external wall reduces the variance, which is further reduced in the case of indoor observations. An analysis of the interdiurnal variability of temperature readings showed for Toaldo's readings a variance ($\sigma^2 \sim 6$) which was slightly smaller than that of present day measurements in the free air ($\sigma^2 \sim 9$). Toaldo's variance was nearly one order of magnitude greater than that of the Morgagni's external measurements ($\sigma^2 \sim 0.8$) and still greater than that of Morgagni's indoor measurements ($\sigma^2 \sim 0.2$) (Cocheo and Camuffo, 2002). Therefore, we should conclude that all of Toaldo's measurements, including the earliest ones, were taken outside, although in a site whose temperature variability was slightly limited by wall influence. In addition, in his log Toaldo included some internal readings with the specification: 'measurement taken indoors'.

7.2. OBSERVATIONS IN THE MUNITIONER'S HOUSE IN THE MEDIAEVAL CASTLE (1768–SEPTEMBER 1775)

The Site

The mediaeval Ezzelino castle was an edifice built around a rectangular courtyard, but with non-homogeneity and some outbuildings on the W, along the channel around the W and S side. The external perimeter was trapezium; on the SW corner there was the main old tower, named *Torlonga* (Figure 5). The architecture, images and history of the castle and the works are well documented in the Astronomic Observatory, the University and the City Archives as well as in various publications (Lorenzoni, 1885, 1896; 1921; Bozzolato et al., 1986; Bressan, 1986; Zaupa, 1990).

Toaldo moved to the Castle in order to closely follow the works (from March 1767 to May 1777) to transform the *Torlonga* into the Astronomic Observatory. A portion of an outbuilding near the *Torlonga* was transformed into the house of the Astronomer and additional rooms for the Observatory. The courtyard and the surrounding building were transformed into state prisons and are now being transformed yet again.

The Munitioner's house was number 10 in the W part of the court and had a portico with a loggia above it. Over the portico and the loggia there was an uncomfortable third storey, but the floor under the roof was used only as a deposit. The Munitioner's house (Figure 11) was originally obtained by joining two buildings temporarily used by G. Toaldo, D. Cerato, and V. Chiminello. Domenico Cerato (1715–1792) was the architect responsible for transforming the main tower of the Castle into the Astronomic Observatory (1766–1777). The ground floor had a portico, and the first floor had a loggia facing E; there were also walls and windows facing the other three compass directions. The ground floor was mainly used as a

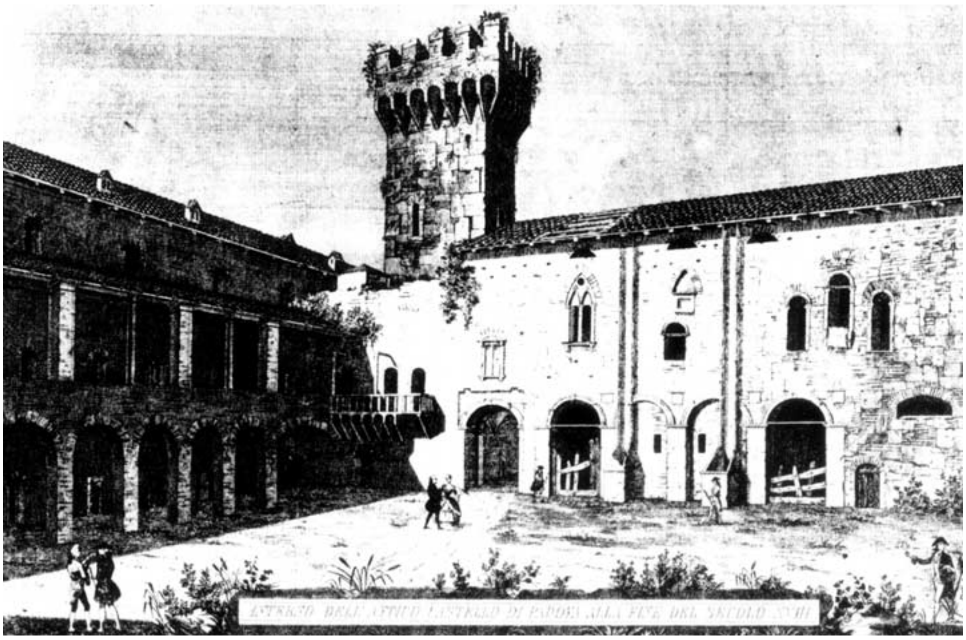

Figure 11. Old lithography of the northern (on the left) and eastern (on the right) side of the courtyard of the Ezzelino Castle. The Munitioner's House had a portico and a loggia with the same structure as the left side building. The tower, now destroyed, is not the *Torlonga*, which is located at the opposite side of the Castle.

deposit as can be deduced from Cerato's plans (1767–1777) and the works done on the staircase to reach the first floor.

Indoor or Outdoor Observations?

The exact location of the thermometer(s) was not specified. A note in the register, taken 11 November 1768, generates some confusion and raises some questions, as he wrote: 'my thermometer hanging in the room broke' and the measurements were not interrupted. Why this interest for the inside thermometer? Were observations reported in the register made inside with this instrument? In this case, why they are unbroken? Was he able to quickly mend the thermometer or to substitute it by using the outside one? This does not seem credible. It is more realistic to conclude that this comment was a spontaneous comment, and that he always measured outside for the reasons discussed above. In addition, in the list of the main meteorological events of the year 1773, Toaldo (1774) reported several data well below zero, especially when he commented on the severity of that winter. These data were certainly measured outside, and the same was found in the yearly issues of the *Giornale Astro Meteorologico* (GAM) for subsequent years. Therefore, the observations were taken outside, and Toaldo explicitly wrote (Toaldo, 1775) that his thermometer was hung in the free air, but in the shade, in the loggia among the other houses of the castle. In the same paper he explicitly admitted that he was interested in knowing the difference between Poleni's indoor measurements and outdoor values, and for this reason he used his data, taken near sunrise and two or three hours after noon, with a thermometer in the shade. An analysis of the variance of interdiurnal variability confirms that the data were taken outside.

7.3. OBSERVATIONS IN THE ASTRONOMER'S HOUSE IN THE EZZELINO CASTLE (SEPTEMBER 1775–1777)

The Site

The Astronomer's house, next to the *Torlonga* on the E side, was obtained after extensive works on the southern side of the castle. The works transformed three high floors into five (Figure 12). The ground floor was for deposit; the first floor was for the assistant Chiminello; the second and the third floors were for the Astronomer; the top floor for the library, the Observatory and for teaching. The rooms faced south with windows in the thick castle walls (thickness: 4 feet i.e., 1.5 m ca.), and a corridor to the north made access to the rooms possible. The second floor had a kitchen and a fireplace, so that it was unsuitable for measurements. It is probable that measurements were taken at one of the third-floor windows where Toaldo lived, at some 10 m above ground level.

Indoor or Outdoor Observations?

The first written information about the position of the thermometer in this building is found in GAM (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, noting monthly averages of temperature, pressure and precipitation, the type of thermometer utilised and its position were mentioned, i.e.: 'Réaumur's thermometer exposed outside in the free air without sun'. This is the first certain information, of a documentary nature, about the external exposition of the thermometer. This leads us to conclude that the thermometer was hung on one of the small corridor windows, along the north wall. In the same note he specified that the barometer was at the height of 4 perches, i.e., 24 feet above the level of the river. However, after Cerato's (1767–1777) cross section of the house, 24 Padova feet above the river correspond to mid-height of the first floor, but to the second floor if reference is made above the ground. As Cerato's vertical cross section was quoted with reference to the ground, it is very probable that Toaldo improperly made reference to the river in this, as well as in several other cases. Some confusion is probable especially because not all the plans and cross sections are exactly in scale, but with altered proportions and only with a few important levels quoted here and there. In conclusion, it is very probable that the thermometer remained in the same position for the whole period.

Toaldo calculated the bulk average of air temperature, using 40 yr of Poleni's observations and then updating with 16 yr of his observations. Then, he calculated day by day the positive and negative deviation from the bulk average relative

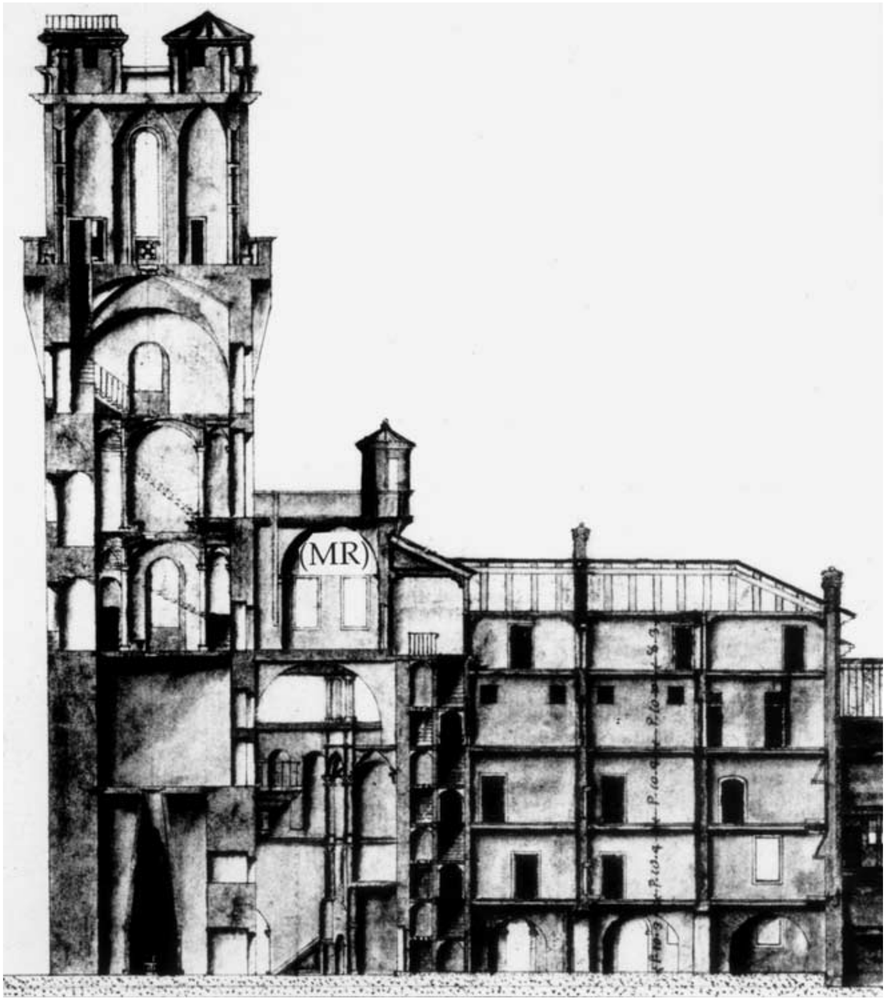

Figure 12. Drawings by Domenico Cerato (dated 1767-1777) showing a section of the *Torlonga* and the Astronomer's House. The *Meridian Room* (MR) is shown.

to the entire series. Per each month he then separately summed the positive and negative deviations and divided by the number of days. These values, respectively called 'Sums of Hot' and 'Sums of Cold', represent something like the positive and negative anomalies expressed in terms of degrees-day above or below bulk average. These 'Sums' expressed in inches of Hg according the Poleni style, have been published for the individual months and years (Toaldo, 1770; 1781). Although more sophisticated methods have been applied to point out discontinuities in this time series and recognise the change in character of observations (Cocheo and Camuffo, 2002), it is nice to see that Toaldo's calculations can be used to point out the passage from Poleni's indoor to Toaldo's outdoor observations. Plotting

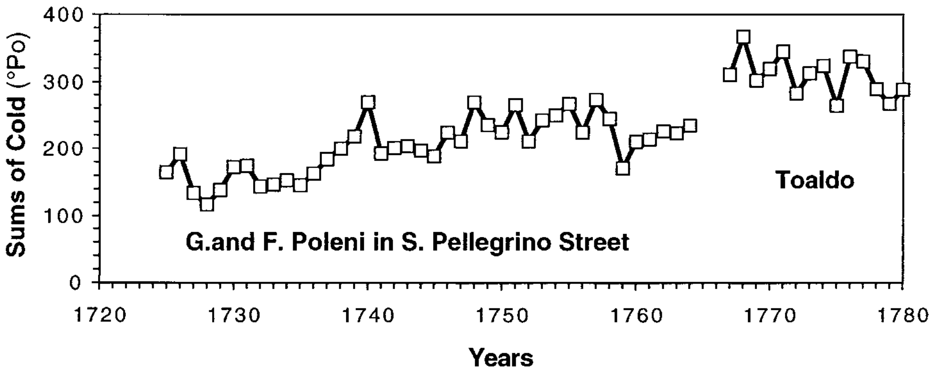

Figure 13. Negative temperature anomalies, called 'Sums of Cold' expressed each year as the normalised sum of all the degree-days below the bulk average computed by Toaldo (1770, 1781) over the whole previous period (since 1725). These 'Sums' are expressed in London inches of Hg, or Poleni degrees (Po), according to Poleni's style.

these 'Sums' in a graph (Figure 13) the discontinuity between Poleni's indoor observations and Toaldo's outdoor observations is evident.

In the Poleni Period the drift of Amontons' thermometer is reflected in a decrease of the sums of positive anomalies and an increase of the sum of negative anomalies. The drift has been distinguished from the climate signal and has been established independently, after comparison with other parallel observations made by Poleni with secondary thermometers, for the period of overlap.

The Sums of Cold for each year as well as for each month of the cold season clearly show that the period till 1764, i.e., indoor Poleni measurements in B. Pellegrino Street, is homogeneous, and the outdoor Toaldo readings, i.e., after 1766 are clearly different. The observations by Francesco Poleni at the Philipine Convent have an intermediate character. The instrument was probably outside, in a loggia, or in another well-ventilated site. For this reason Toaldo (1770) was impressed by the deviation and was sceptical about instrument reliability after the move. No discontinuity was found in the hot months, when the ventilation through open windows reduced the difference between the inside and outside temperature.

8. Toaldo, Chiminello and others at the *Specola*

8.1. OBSERVATIONS FROM THE WINDOW OF THE SPECOLA (1777–1865)

The Site

Measurements taken at the *Specola* are not homogeneous to the previous ones, as the greater distance from the soil smoothed the daily and seasonal waves reducing extreme temperatures, given the diminished influence of the soil. Favaro (1906), who worked for many years in the *Specola*, wrote that temperature measurements taken there were always made in the same place. At first the thermometer was hung at the northern window of the *Meridian Room*, on the *Torlonga*. In order to make observations easier and expose other meteorological instruments, in the same place a small terrace was built in 1865, and enlarged in 1871. The window of the early measurements was then transformed into a door to enter the terrace. Instrument level remained unchanged, i.e., some 17 m above ground. The original drawings by the architect Cerato (1767–1777), cross sections by G. Silva (1911), evidence of the works on the site, past pictures and accurate descriptions by Lorenzoni (1896, 1921) and Zaupa (1990) all help to reconstruct the details of the site as we will see later.

Instrument Location

In addition to the original register of meteorological observations, in Italian, another register for astronomical observations (1779–1780), in Latin, was kept by Toaldo with the cooperation of Chiminello, Dudan and Zendrini. The register of astronomical observations began 2 May 1779, the day on which Toaldo left Padova for a trip to Lombardy, and the beginning was written in Chiminello's hand. On the first page (Chiminello, 1779) he gave a short description of the astronomical and meteorological instruments and their exposure. The same description can be found in a lecture held by Chiminello in 1780 that appeared in 1786 in the *Saggi Scientifici e Letterari* (SSL) of the Padova Academy. He was clearly stated that the barometer and thermometer were at the same height; the thermometer was hung at the window facing 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, i.e., a room facing south, next to the Astronomic Observatory, i.e., the so-called *Lower Observatory* or *Meridian Room* (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, we find that the thermometer was hung at the window of the *Meridian Room*. Favaro (1906) also stated that the thermometer was always attached to the same window, i.e., at 17 m above the ground. The level of the ground with reference to the river was 5.7 m, and this figure will be useful further on.

A Resolved Uncertainty about the Exact Location in the Early Period

A very important, contradictory point is that the height of the window at 17 m above ground level is in disagreement with another lecture given by Toaldo in 1780 and published in 1786 in the same SSL. He wrote that the level of the barometer was 56 Padova feet, with reference to the Medoacus (also called Brenta) River. Padova is crossed by an array of rivers and channels, one of which passing just on the side of the Specola, all having the same level of the main river, i.e., the Medoacus. The thermometer was correctly exposed to free air, to the north, in the shade, at the height of some 70 feet, i.e., 25 m, above the ground. This poses some questions.

(i) It might be objected that the paper by Chiminello (1786) referred to another, new series of hourly observations of air temperature and barometric pressure that continued during 1778 and 1779 although with some gaps (the original hourly temperature data are still unknown). However, it is not reasonable to think that he had a duplicate of the instruments for his new experiment. The hourly values of air temperature grouped and averaged for the winter, spring and summer seasons, have been published by Toaldo (1781). The above hypothesis is unrealistic, as more frequent readings do not need another set of instruments.

(ii) Returning to Toaldo's paper (1786), it is possible to note that the difference between the two heights is 70-56 = 14 feet (i.e., 5 m), close to the difference between the two reference levels, i.e., the ground and the river. If we wish to take Toaldo literally, and assume that both these heights are correct, and that the barometer was placed in the *Lower Observatory* or *Meridian Room*, it is possible to identify where the thermometer was hung. The closest window on the tower is on the same vertical, at a distance of 33 Padova feet. The only possibility for hanging the thermometer 14 feet over the barometer was offered by one of the two turrets in the NE and SE corners of the terrace that constitutes the roof of the *Lower Observatory*. Only the turret (now abated) on the NE corner had a window facing north. Taking observations in the turret, obliged the observers to go outdoors and cross the terrace, which was uncomfortable especially in bad weather. This possibility is corroborated by the fact that a thermometer with a metal screen was put in the same position in the octagonal turret that was built to the side in 1836. However, this interpretation is not a logical one: why observe at another window of the tower, at a different level from that of the barometer, which was next to the *Lower Observatory*, as confirmed by the register note? A possible, but unlikely answer might be that it was too high to read a thermometer without mounting a staircase and, in effect, when observations were made there later, a small, rough set of stairs was built.

(iii) It is much more realistic to assume that Toaldo was inaccurate in quoting the levels, and this in not surprising, when one is familiar with his original documents and papers. One possibility is that the number of feet expressing the levels was correct, but not the reference level, i.e., the greater height was referred to the ground instead of the river, or vice versa, which may justify some 5 m. We can also hypothesise that the first level was given in Padova feet (with the transformation ratio for Paris feet), and the second in Paris feet, quoting the same round figure used by Chiminello. On several occasions Chiminello demonstrated his love for precision, unlike Toaldo who had many official responsibilities and was more interested in finding connections between meteorological and astronomic phenomena than in taking regular observations. Here, both Toaldo and Chiminello seem unclear.

(iv) Toaldo and Chiminello had as a reference Cerato's (1767-1777) cross sections (quoted in Padova feet) and we must refer to these to find a correspondence with their writings, and then measure the distances on the more recent cross section by G. Silva (1911). Looking at Cerato's maps, the window of the

Lower Observatory was 45 Padova feet above ground, and the top of the abated turret was 70 Padova feet. The individuation of the turret is consistent with the 'some 70 feet' declared by Toaldo and becomes exact (i.e., instrument at mid-level) if Paris feet are considered, but the turret as an appropriate site is not convincing. The three most important levels are: the *Lower Observatory* and the window nearby on the main tower, the turret on the terrace, and the next, upper window on the main tower. According to Cerato they are respectively 44, 63, 77 Padova feet, i.e., 15.7, 22.5, 27.5 m from the ground. According to Silva the same levels are 17, 23.7, 29 m, respectively. If we refer to the river, we should add 5 m plus some tens of cm which correspond to the baseline of the drawings, not clearly declared, which does not coincide with the river level. A more precise level was determined by Zantedeschi (1869) who reported that the barometer was 16.7 m above ground, and more recently by Silva (1911) who established it as 17.06 m; the land level is some 14 m above mean sea level.

What are the conclusions to be drawn about all the differences between the previous two descriptions by Toaldo and Chiminello? Although the barometer had its own thermometer (for inside temperature), the outside thermometer was also hung nearby, for practical reasons, and this has undoubtedly been confirmed as we have seen. The hypothesis of the turret has been raised just to interpret the heights reported by Toaldo (1786) literally, and not for a detailed description. On the contrary, the location on the window is clearly supported by other evidence. These heights were on this, and many other occasions, expressed approximately, reported by heart, without specific interest for this kind of information, so that the distinction among Padova, Paris or London feet was considered unimportant, as were the reference to the river or to the ground. Briefly, a contradiction was found between Toaldo and Chiminello. It was not easy to justify a different interpretation of Toaldo's indication. Chiminello was always precise and reliable. The note in the original register and Chiminello's writings clearly individuate the window of the *Meridian Room* at 17 m above the ground.

It could be noted that, in another paper that appeared in the SSL, Toaldo (1789) wrote that there were thermometers at the four windows of the penultimate floor of the main tower, at 80 feet (undeclared Paris or Padova) from the ground. The height (in Padova feet) corresponds exactly to the windows of the penultimate floor on Cerato's maps (1767–1777), actually some 28 m on Silva's map. Fortunately, this is not contradictory information about the series, but the description of another parallel experiment. In fact, in 1785 and 1786 Toaldo set several meteorological instruments and also some indicators of the quality of the air in the four cardinal directions in order to investigate different effects, if any. To do this, he built some wooden screens, containing the instruments, and placed them outside the windows of the penultimate storey. He was obliged to expose the instruments at this elevated

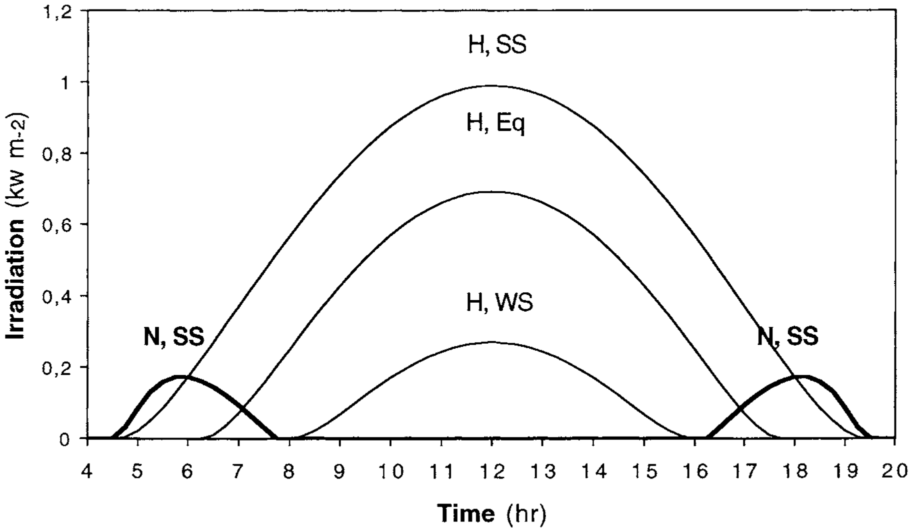

Figure 14. Solar radiation falling on the meteorological window of the *Specola* facing north in the summer solstice (N, SS) and on the horizontal plane (H) at the two solstices (SS, WS) and the equinoxes (Eq).

level, because there were not four windows facing the four cardinal directions at lower levels.

Solar Radiation and Thermometer Screens at the Specola

Solar radiation has been modelled in order to see when the thermometer was heated by direct solar radiation. In the warm season, direct solar radiation falls on the walls facing north in the early morning and late afternoon. The curves representing the solar radiation falling on the meteorological window of the *Specola* and on the horizontal plane at the two solstices and equinoxes is shown in Figure 14. Incident radiation on the window is very modest and is limited to a brief period, when the sun is very low on the horizon, during the summer. The first measurement in the morning needed a screen and Toaldo provided one. Later, Zantedeschi (1869) wrote that during the period 1850–1860 in which he was interested, the thermometer was situated 'outside, to the north of a window near the *Meridian Room*, protected from radiation by a piece of cardboard'. This was the same window (and probably the same kind of shield) used by Toaldo and Chiminello. Zantedeschi was a direct witness (he wrote only 5 years after the period which he refers to) and is very precious because he confirms (as did Favaro in 1906) that the official measurements were always taken from the same window. Therefore, we should exclude observations from the *Meridian Circle* on the terrace that covers the *Meridian Room* as we will discuss later.

Toaldo discovered the disturbance caused by solar radiation. 30 June 1780 he wrote in the original register: 'Till 4 <June> the thermometer at the <northern>

window of the *Meridian Room* was probably overheated by one degree in the morning. It will be necessary to subtract half a degree from the <daily> average, at least beginning from March, because solar radiation arrives in the morning and the evening.' Why till 4 June and not later? Three hypotheses are possible. (i) He arbitrarily corrected the morning observation of the previous days, subtracting 1 degree, but this is unrealistic or imprecise, especially because the correction to be made in the case of mist or partial cloud cover was not clear. (ii) He relocated the thermometer, but this also is unrealistic, as the thermometer was exposed on the best side, i.e., north and we should exclude that he moved the thermometer daily, following the course of the sun. (iii) He invented and applied a screen to shield the thermometer. This is the only realistic hypothesis, and is confirmed by the fact that a few years later he specifically mentions thermometers protected by a wooden box. In fact, in the 1785–86 experiment, the thermometers were placed in 'niches or table drawers' hung outside so that the instruments 'were exposed to the elements and protected against harm from the sky' (Toaldo, 1789). This is the first news of a fixed wooden screen against solar radiation and rainfall; Middleton (1966) dates 1835 as the earliest printed account of screens to his knowledge.

Concerning the bias expected on observed air temperature, Parker (1994) summarises the results of a number of specific studies comparing thermometer readings from a north-facing wall, with and without shelters, with those in screens (e.g., Stevenson screen, Wild shield). Results suggest that both screened and unscreened north-wall exposures enhance heat-retention by the wall at night in summer. Screened north-wall exposures give reduced diurnal cycles because of the influence of the great thermal capacity of the wall. Unscreened exposure gives enhanced diurnal cycle for the uncontrolled contribution of solar radiation. In both cases the results are very site dependent because of the differing influence of the site which interacts with local meteorological factors.

The thermometer was Réaumur's, with mercury, correctly exposed to the north, in the free air in the shade (Toaldo, 1786); then, the thermometer was placed into wooden screens in order to protect it against the weather (Toaldo, 1789). The elevated position smoothed daily and seasonal temperature cycles reducing extreme temperatures, given the lesser influence of the soil. The level remained the same for the rest of the series till 1959.

Observations

The data were reported in a unique register, written in Italian, initiated by Toaldo (1766–October 1797) and concluded by Chiminello (November 1797–1804), with all their observations. Toaldo's register reflects Toaldo's character, not too conditioned by regularity and order. In the earliest times, measurements were taken at different times, with a variable number of daily observations (for errors and corrections connected with sampling time see Camuffo, 2002b). With the regular help of Chiminello (from 1779) the register gained order and observations were more regular, especially for the second reading in the afternoon. From 1780, the measurements were made near sunrise and after noon (Toaldo, 1786) with the aim of recording minimum and maximum temperatures, from which to obtain mean value. In 1780 Toaldo mentioned a comparison with a new siphon barometer. The register reports the following: time of observation, barometer, thermometer next to the barometer, thermometer outside 'in the free air', Chiminello's hygrometer, magnetic declination, wind (direction and strength), rain (Paris inches), state of the sky (represented by symbols), meteorological events (symbols) and special observations. At the end of every month there is a summary of the main meteorological, hydrological and astronomical events and other relevant happenings.

The records from 1780 to 1787 were also published in the *Saggi Scientifici e Letterari* of the *Accademia di Scienze Lettere e Arti* of Padova (Toaldo, 1786; Toaldo and Chiminello, 1789; 1794), but with some changes due to a revision of the data. This publication is in Italian.

8.2. MEASUREMENTS TAKEN AT THE SPECOLA FOR THE SOCIETAS METEOROLOGICA PALATINA (1794–1811)

Sheets with Meteorological Readings

Another set of big registers written in Latin contain the records from 1794 to 1811, with one register every 3 years. The volume that begins on 23 November 1797, i.e., 12 days after Toaldo's death, is signed by Chiminello as author and First Astronomer, which also means Director of the *Specola*. These registers contain some loose sheets with tables from a parallel series of observations for the period 1794–1804. Toaldo (1794) mentioned that in 1782 the *Societas Meteorologica Palatina* published his meteorological observations made during the cold winter of 1782, and this was the beginning of his engagement with the *Societas Meteorologica Palatina*, Mannheim (1794–1811). The word '*Manheim*', written in pencil, is found on the back of loose sheets with tables of meteorological and astronomical observations. The structure and symbols used in the compilation of observations also follow the indications of the *Societas Meteorologica Palatina*. F. Zantedeschi (1869) confirmed that Chiminello took these observations with instruments sent by the *Societas Meteorologica Palatina.*

Observational Procedures

In the first volume of the *Ephemerides*, Hemmer (1783) described instruments, suggested observational methodology, i.e., applying the thermometer to a walnut tablet and hanging it externally at a north-facing window, exposed to the free air, possibly close to the barometer. This recommendation corresponds to the style used by Toaldo and Chiminello, so that a new thermometer was added next the previous one, or the previous was used for both the *Specola* and the Mannheim series. It is reasonable to suppose that all instruments were at the same place because it was considered the best; the screen was the same; it was possible to compare results or supply data if one instrument was broken. Hemmer recommended even three observations a day, at 07.00, 14.00 and 21.00 hr. In practice measurements in Padova were taken between 7.00 and 8.00 hr in the morning, in the early afternoon between 14.00 and 15.00 hr and in the evening between 20.00 and 22.00 hr.

On the basis of these recommendations, the barometer was kept inside, in an unheated room, with a thermometer on the same walnut support to correct the barometric reading for thermal expansion of mercury. It is reasonable to suppose that in this first period the instruments used for, or furnished by Mannheim, were placed at the side of those of the *Specola* both because the location in use was the best and the most appropriate for operational ease. After some time, however, the data in the register became substantially identical to those on the loose sheets, showing that the same instruments and the same observations were used for both Padova logs and *Ephemerides* publications.

Chiminello's Very Last Period

In 1807, Chiminello too suffered an apoplectic fit. He was probably unable to go up and down the stairs and to take observations, for he engaged a new assistant, Francesco Bertirossi-Busata (astronomer, active from 1807 to 1825) who was very probably trained by Chiminello himself. Observations continued in the same way till 1811 when the register was terminated; after Bertirossi-Busata continued with a new register and a slightly different style. Although Chiminello remained in office as director till the last year of his life, in 1813, it can be supposed that Chiminello was able to manage the direction, even though formally and with visible decline, till 1811. Later, Bertirossi-Busata, with the assistance of the technician Rodella, continued observations, but with some personal autonomy. After Bertirossi-Busata died (1825) the quality of the series worsened.

9. Decline after Toaldo and Chiminello at the *Specola* (1813–1864)

Observers

After Chiminello died, the astronomer Giovanni Santini (1787–1877) was appointed director to the *Specola* from 1813 to 1877. His lack of interest in meteorology caused a general decline and some minor gaps in the series. Meteorological observations were performed or supervised by astronomers, i.e., Francesco Bertirossi-Busata and Carlo Conti (active 1827–1842), Gaetano Pietropoli (active 1834–1847), Virgilio Trettenero (active 1848–1863, an early student of Santini's and then teacher at the University), Jacopo Michez (active 1861–1866), Enrico Nestore Legnazzi (active 1855–1862) and finally Giuseppe Lorenzoni (active 1864–1879), an early student of Santini's, but with meteorological interests. He later became professor at the University and director of the *Specola*. His papers (Lorenzoni, 1872; 1921) constitute an important record for this period. The chief technician Rodella died on 19 February 1834 aged 85, and observartions were less regular and accurate after he disappeared. Rodella was assisted by Giuseppe Stefani (active 1807–1842), but in that period the quality of observations was not good, there were several gaps. Paolo Rocchetti (active 1842–1877) was a technician and instrument maker of great worth.

Instruments and Observations
Two registers report the observations of this period: one from January 1812 to April 1838 and one from January 1839 to December 1864. The first register reports: date, barometer (Paris inches), barometric mean, thermometer inside (associated with the barometer for temperature correction), thermometer outside (both thermometers were Réaumur's), hygrometer (Chiminello's and Deluc's, but the record ends in 1830), wind direction and force, rainfall, cloud cover and other observations. The observations were made at times close to Mannheim hours, i.e., at 7.30, 14.30, 20.30; from December 1820 to May 1828 observations are irregular, usually two, in some cases only one or even absent. In the second register the columns for the mean barometric value and humidity were omitted but a new column was included for a new thermograph. In 1827, for the first time the barometer has the note: 'barometer reduced to zero'. The barometer was an old siphon instrument, probably the one used by Toaldo and built in 1780 by Rodella, or the one he received from Mannheim. Toaldo (1789) wrote that Rodella built his thermometers. Rodella devised and built clocks, thermometers, a recording pluviograph, a recording evaporigraph and several other devices (Zaccaria 1932). In one of Toaldo's registers, a note recorded for January 1781 mentions the calibration of a thermometer and a hygrometer in snow, and both gave exactly 0.0° R. There is a specification that measurements were taken between 7.00 and 8.00 in the morning, at 13.00 and between 19.00 and 20.00. This great uncertainty of 1 hr caused a large error in morning measurement, especially in the summertime.

9.1. MEASUREMENTS AT THE SPECOLA IN THE MERIDIAN CIRCLE (OCTAGON TURRET, 1836 ONWARDS)

The Thermometer on the Meridian Circle
In 1836, the director Santini destroyed the two turrets on the NE and SE corners of the big terrace, that topped the *Meridian Room*, on the eastern side of the main tower, and built a new bigger octagonal turret, called *Meridian Circle*, for the telescope (Figure 15). The pyramid dome was mobile, made of two parts to form a slit for the telescope and from 1837 to 1877 it was used as a giant rain gauge (Lorenzoni, 1872; Crestani et al., 1935). The holes and metal connections that can actually be observed on the stone parapet on the northern side of the *Meridian Circle* show where the measuring container was attached.

The problem is whether this new room was also used for meteorological observations and in particular if this thermometer was employed for the main temperature series or only for some additional observations by astronomers.

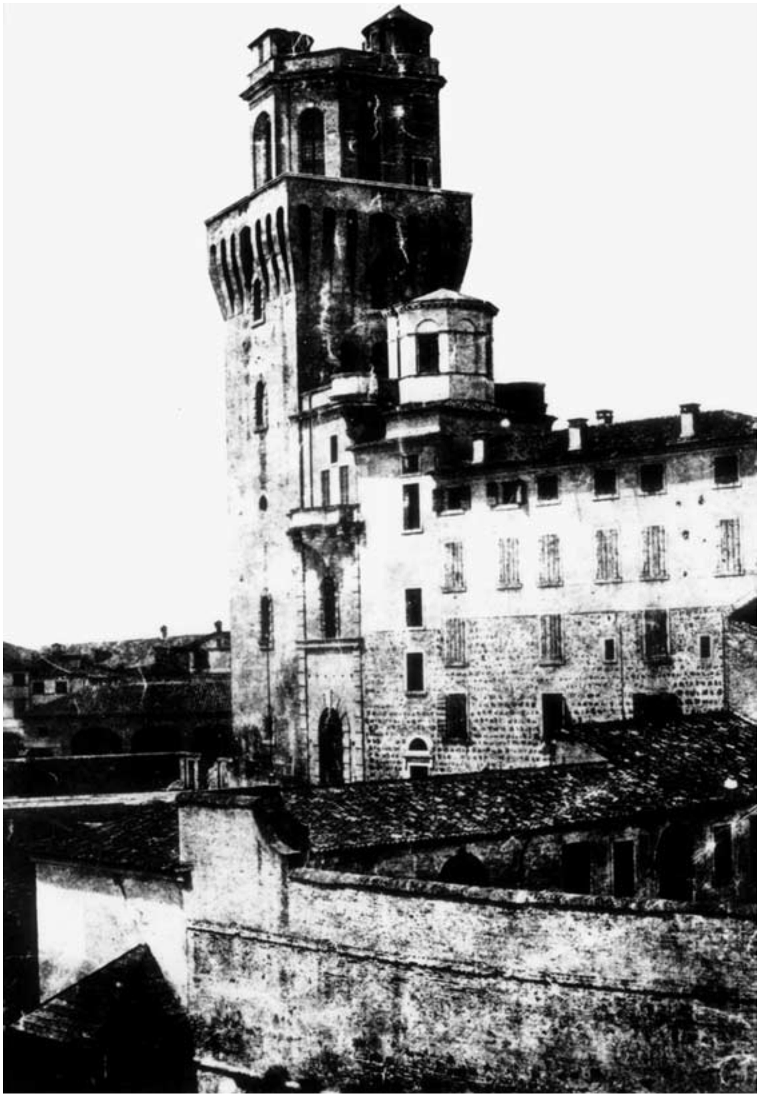

Figure 15. A photograph of the *Specola* (1840) with the new octagonal turret called *Meridian Circle* whose pyramid dome has been used as a raingauge. The picture dates back to 1840 (Bressan, 1986), i.e., two years after the invention of the photograph by Niepce and Daguerre in 1838. (By courtesy of the Historical Archives of Astronomical Observatory, Padova).

On the northern side of this octagonal turret a very rusty and corroded iron screen for thermometers is still visible (Figure 16). The screen is a half cylinder with many regular holes, like a grater, fixed with two hinges to the wall to be opened for instrument readings. The dimensions of the cylinder are: diameter 10 cm; height 58 cm; distance of the cylinder base from the floor of the terrace, 118 cm. This has regular holes (diam. 3 mm and 16 mm from each other, on a square

Figure 16. Iron screen that shielded a thermometer on the northern side of the octagonal turret called *Meridian Circle*.

reference frame), in the lower part (for at least 17 cm), and that can be moved away from the wall by rotating two hinges. Below the screen, two nails are driven into the wall, on the same vertical, spaced 51.7 cm. The thermometer was at some 21.5 m above ground level according to Cerato's maps, 24 according to Silva's ones. This screen can also be seen from an old photograph, with the screen in a very precarious condition, almost identical to its actual condition.

The screen was necessary in that a thermometer was exposed to sunlight for short periods after sunrise and before sunset. Modelling the disturbance caused by the solar radiation falling on this screen (substantially the same as in Figure 14) it appears that the duration of irradiation is longest after sunrise at the summer solstice, with about 3 h 30 m, when the sun disappears at the height of 35°. In the absence of a screen, this causes an error in morning measurements. Before sunset, the thermometer was shielded by the shadow of the *Torlonga*. The screen was hit only when the solar azimuth was greater than 297°. This means that at the summer solstice some direct radiation is possible for the last 45 m before sunset, when the height of the sun is lower than 7° and most of the energy is absorbed by the very large optical thickness of the atmosphere. However, when in summer the sun was facing the terrace, it was very low at the horizon, and most of its energy was intercepted by the terrace parapet 1 m tall, so that the floor was almost never overheated. Some overheating was possible on the Tower wall.

Were all the meteorological instruments relocated on the octagonal turret of the *Meridian Circle*? Or was the new turret used only for regular rainfall observations, and in addition was another thermometer used for unpublished observations made by astronomers working there?

A note in the register, on 10 January 1838, describes the check of the lower calibration point made by Conti after a snowfall. It is explicitly mentioned that he had: a thermometer for the barometer in the *Meridian Circle*, a portable thermometer with a brass scale attached to a wooden tablet and a dipping thermometer. Conti wrote that by immersing the three thermometers into the snow, these showed respectively 0.0°, 0.5° and 0.6°R.

In the register no mention was found of relocations of the main thermometer, and Zantedeschi (1869) and Favaro (1906) clearly excluded any relocation. This means that the main thermometer used for meteorological observations always remained attached to the grating of the window of the lower floor. This is not surprising, as documents exist (Carlini, 1838; Ferretti et al., 1993; Maugeri et al., 2002) that prove that in the same period in the Brera Astronomic Observatory, Milan, official meteorological observations were taken on the floor of the house of the astronomers, and other similar unpublished measurements were taken on the astronomic turret.

It may be possible that these observations were temporarily taken for official use on two occasions, when it was necessary to remove the main thermometer for some works. The first occasion was in 1865, when a small meteorological terrace was built The second was in 1871, when the small terrace was enlarged.

9.2. MEASUREMENTS AT THE SPECOLA ON THE FIRST SMALL TERRACE (1865–1871)

In the framework of the unification of the Italian weather network, after the political unification of Italy, on 31 Dec. 1864, Father Angelo Secchi went to Padova to calibrate the barometer and other instruments. Gay Lussac's siphon barometer was dismounted and the glass tube was cleaned to remove mercury oxides, which made readings uncertain. Calibration with the thermometers immersed in the snow on 31 December 1864 gave 0.2°R for the two Bertelli thermometers, and 0.75°R for the Bellani type; the upper point was respectively 78.8°, 79.65° and 80.3°R.

This visit was an opportunity to decide to build a small terrace for meteorological observations on the northern side of the *Torlonga*, in correspondence to the window where observations were regularly made. The grating of the window was taken down and the window was transformed into a door with steps to reach the terrace. This decision was taken to locate instruments in the free air, with a better thermometric shield and more space. In 1865 the grating was removed and a small terrace was built outside the window, with the floor sited over the roof of a building joined to the tower. G. A. Favaro, who from 1902 was assistant astronomer and responsible for meteorological observations, gave a precise description of what happened in that period: 'Until 1865 the thermometers were still in their old position; they had always been attached to the grating and frame of the north-facing window, whereas now, they have been moved to the meteorological terrace' (Favaro, 1906).

The terrace built by Santini, assisted by Lorenzoni, had an iron framework and a parapet, the base being a continuation of the window ledge. Thermometers were read from the parapet of the small terrace. They were placed about 70 cm from the wall of the tower, inside a sheet iron screen, which was completely open to the north and without a bottom so that bulbs of thermometers were wholly exposed to the air, about one meter from the wall. The screen was well ventilated inside and was protected from the morning and evening solar rays, by a screen of thick cloth, placed some distance away (Favaro, 1906). The magnification of an old photograph (taken from a nearby bell tower in the period 1865–1871) with an aerial view of the *Specola* (Figure 17) has made the whole picture clear showing the sheet iron screen.

This terrace was supported by the roof of underlying buildings, and was not in the free air. However, the terrace was in the shade of the Tower and the Astronomer House for most of the day, except early morning and late afternoon in summer, when solar radiation is not too strong and nearly horizontal. Under these conditions, the terrace floor was shielded by the parapet and never overheated.

Observations after 1865 are distinguished from the preceding ones, in particular because the schedule suggested by A. Secchi was used, that is, four observations a day at 07.00, 12.00, 15.00 and 21.00 hr average local time.

From July to December 1867 observations were at 7.00, 12.00, 15.00, 19.00 hr; from 1868 on, at the times established by the *Ufficio Centrale di Meteorologia*, i.e., 09.00, 15.00 and 21.00 hr. The clock was based on the average local time up to the whole of 1893, and from 1st of January 1894 on, it was based instead on the average Western European Time, so that observations in Padova were earlier by 12 m 30 s (Camuffo, 2002b).

In this period, a Bertelli mercury psychrometer was used; the scale was made with diamond engraving on a glass frame to which the column was attached with

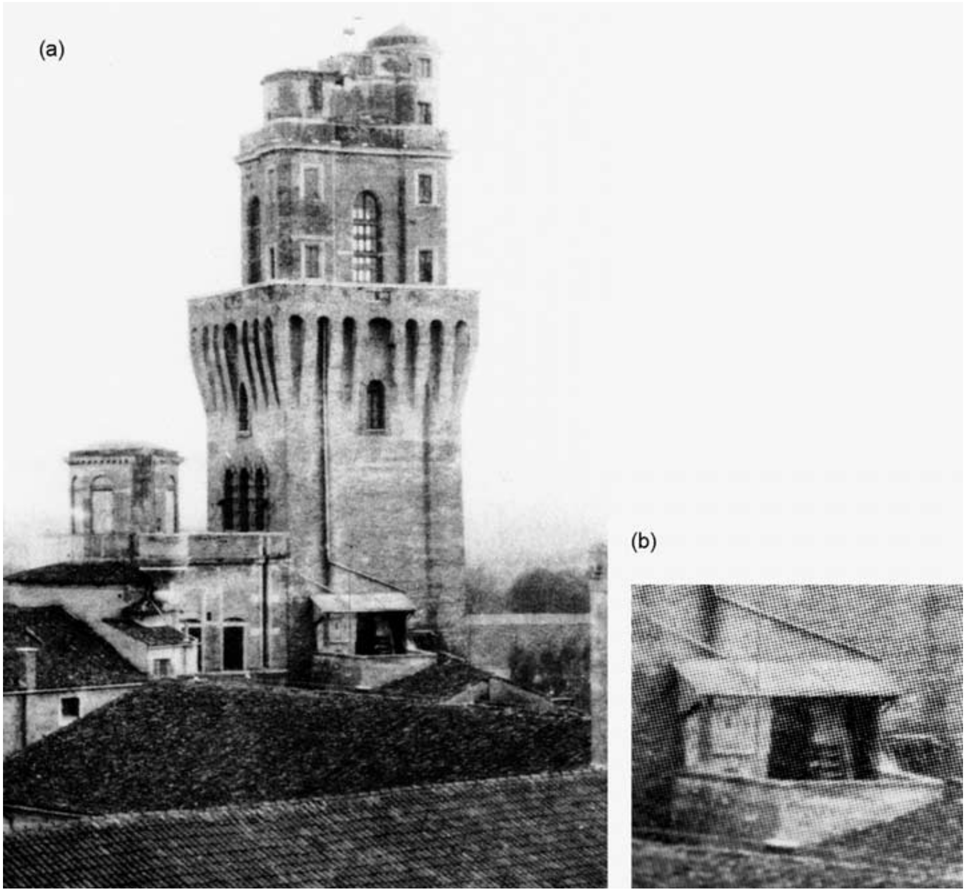

Figure 17. (a) Aerial view of the *Specola* from a photograph taken from the bell tower of the S. Tomaso Philipine's Church in the period 1865–1871. The picture includes the meteorological terrace set on the roofs with a sheet iron screen, completely open to the north and without bottom, the open instrument cage (the rectangle on the left), the door (the black in the centre) and a step-ladder (right) to reach the instruments. (b) Magnification of the terrace with the instruments.

iron wire and had 0.2 °C resolution. From 1866 to 1874, temperature extremes were measured with a Six and Bellani thermograph, also built by Bertelli. The atmospheric pressure was measured till 1871 with a siphon barometer. In 1780, in his register, Toaldo mentioned that he calibrated the new siphon barometer, but that instrument was deteriorated and substituted at an unknown date. Another instrument of the same kind, mentioned as a 'Gay Lussac type' is found in the register on the occasion of a re-calibration made 31 December 1864. In reality, it had the same shape, but was not a device with a capillary and air trap for transport. This old type of instrument, without cistern, had the advantage of having the tube with a constant diameter, so that the error for capillarity was absent. The column

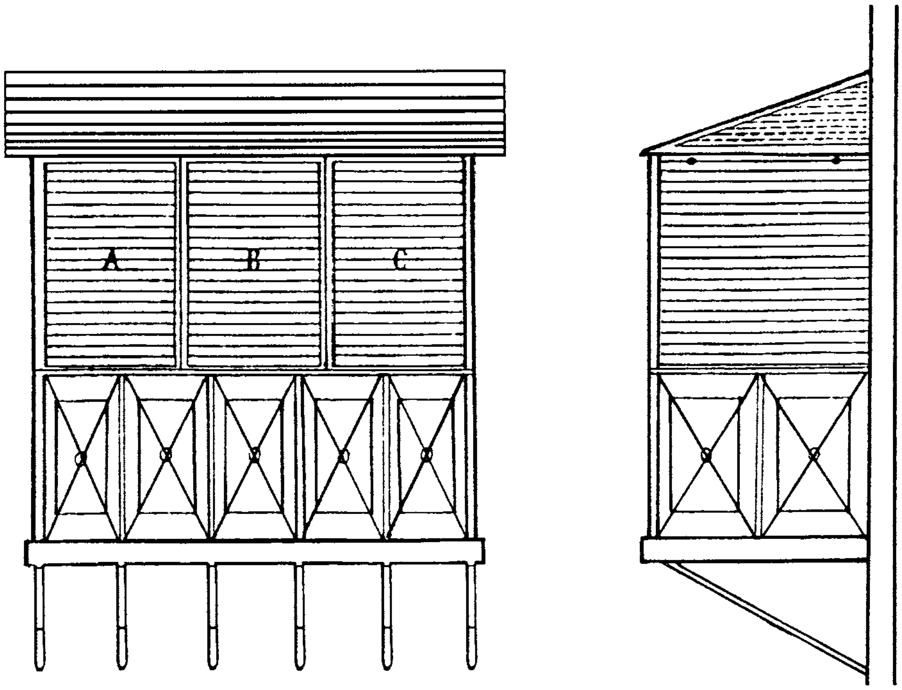

Figure 18. Drawing of the cage style Denza, suggested by the *Ufficio Centrale di Meteorologia e Geodinamica* and installed on the new meteorological terrace.

height was the difference between the two heights of the two free levels of mercury, read separately.

The rough data were first reported without corrections in five registers (periods: 1867–1874, 1875–1887, 1888–1897, 1898–1907, 1907–1913) then corrected and copied into six orderly official registers for the periods: 1865–1867, 1868–1877, 1878–1887, 1888–1897, 1998–1907, 1908–1913.

9.3. MEASUREMENTS AT THE SPECOLA ON THE SECOND METEOROLOGICAL TERRACE (1871–1962)

The Second Meteorological Terrace

The meteorological terrace and iron screen attached to the wall, that was discussed with (but possibly not accepted by) Father Secchi, constituted a completely different solution from that suggested by Father Denza (1882) and reported by Parker (1994) as typical for Italy. The Denza screen was a large louvred cage, made of wood (Figure 18), attached outside the north-facing window, and with the side cage facing the building open and the window kept shut. The side of the cage to the north was left open except during storms when it was manually closed.

Evidently, the authority of Denza won out: 'This small terrace was demolished in 1871 and substituted by the actual terrace, and the iron screen was substituted in

1874 by the actual wooden shelter, with fixed louvers' (Favaro, 1906). The wooden cage is hardly visible in an early aerial picture of Padova (taken 1920 s, ca.), which includes the *Specola*. Ciro Chistoni, who worked at the *Specola* and was a member of the National Commission for Unification, was probably responsible for this change. The presence of a shelter for thermometers is confirmed by the following note which appears in the first-note register for observations in July 1869: 'Somebody forgot to turn the shelter and it was therefore impossible to note the true daily maximum'. The following note in the first-note register, dated January 1875 also confirms the change in the type of shelter: 'Today the two rectangular holes on the floor of the new meteorological shelter were opened'.

Observers

In 1877 Lorenzoni was appointed to the direction of the *Specola*, a position he held until 1913. The observations were performed by: Antonio Abetti (active 1868–1879), Ciro Chistoni (he was an astronomer and was very interested to meteorology; he was in Padova only in 1874, and later played an important role in the national meteorological service after its foundation), Francesco Miari-Fulcis (active 1877; 1881–1886), Giuseppe Naccari (active 1879–1880), Giuseppe Ciscato (active 1886–1894), Antonio Maria Antoniazzi (active 1894–1925), Sabena (active 1899–1902) and Giuseppe Alessandro Favero (active 1902–1911, a meteorologist and accurate historian of the series). Giuseppe Cavignato (active 1868–1909, but had a strong decline in 1897) was chief technician. From 1874, Cavignato was assisted by Sante Mioni aged only 11. Mioni became chief in 1909 and was active till he died in 1928 (Zaccaria, 1932).

Instruments and Observations

According to Favaro, thermometers were placed in a wooden shelter from 1874 onwards, 'with the result that maximum summer temperatures are considerably lower than those obtained earlier, while average temperatures are the same'. On comparing the values calculated by Zantedeschi (1869) for the period 1780 to 1860, there is a difference of 2.8 °C for the maximum values in June, 1.6 °C in July and 2.7 °C in August. In these three months, the departure was always less than 0.3 °C in terms of average values.

The following note was found in the register, in June 1913: 'A small evaporimeter, for meteorological observations and already in use in the Observatory, was placed above the east parapet (about half way down) of the terrace, to the north of the Tower. It was situated 19 m above the ground.' The station remained unchanged for the whole period when meteorological observations were carried out at the *Specola*, as appears from the indication of instruments height in the '*Bollettino Statistico*' of the Padova Municipality that was published yearly till 1937, and this was the last year with complete observations. After, observations were reduced to a few variables monitored once a day (9.00 a.m.).

According to the financial book for the period 1871–75 the following items were purchased: anemometer, meteorological cage, Hipp's thermograph, Hipp's barograph, ventilated psychrometer, device for steam point calibration. From 1868 (as reported in the register and not from 1871 as Favaro (1906) suggested) to 1884 observations were made with Belli's barometer, and since 1885 with Deleuil's cistern barometer. From 1874 onwards (at least till 1906), a psychrometer built by Tecnomasio, with a scale directly engraved on the column and resolution 0.1°R, was used. From 1874 to 1880, minimum and maximum temperatures were recorded with a Ulisse Marchi thermograph and then (at least till 1906) with a Richard thermograph distributed by the *Ufficio Centrale di Meteorologia*, Rome. Temperature corrections ranged between 0.3° and 0.6 °C, i.e., 0.3 °C for the dry bulb, 0.4 °C for the Réaumur thermometer and 0.63 °C for the wet bulb. From April 1880 maxima and minima were recorded with Auvergnat thermographs supplied by the *Ufficio Centrale di Meteorologia* (register note). Instruments and errors were also reported by Favaro (1906), who accurately documented this period and the previous history, as did Lorenzoni (1872; 1921).

10. The Fourth Period at the *Specola* (1914–1937)

Observers

The registers ended in 1913, slightly after A.M. Antoniazzi was appointed director of the *Specola* (1913–1925). Reduced observational activity continued with Luigi Carnera (director 1925-1926) and Giovanni Silva (director 1926-1952). Francesco Zagar (active 1926-1936) carried out meteorological observations during Silva's direction. After Sante Mioni died in 1928, his two sons Arturo and Antonio became technicians.

The Decline

In this period the series declined progressively, although the Meteorological Department of the Supreme Command was established in the *Specola* during the last two years (1917–18) of World War I. New organisations were created outside the University for the collection of meteorological data and weather forecasts. The University reduced its interest in this field and the activity of the *Specola* was only focused on astronomy. Since 1 January 1920, when the new *Magrini* Observatory began its activity, Antoniazzi was reluctant despite the external pressure of Luigi Palazzo, director of the *Ufficio Centrale di Meteorologia e Geodinamica*, Rome, to continue this precious series. Antoniazzi decided to limit the number of observations, and to continue for a short period only. This was just to check recording instruments and to establish a teleconnection between observations at the *Specola* and the *Magrini* Observatory, with a view to completely abandoning the series and to leaving the measurements to the new Observatory. Instrumental readings were made only once a day, in the morning at 9.00 hr. Daily mean, maximum and minimum temperatures were therefore deduced from strip chart records.

Observations

Only some small note-books with irregular observations written in pencil are preserved in boxes in the *Specola* archives. In reality, meteorological observations were recorded in rough note-books from 8 May 1898, and then copied in the regular registers, but after the end of 1913, when the registers ended, the note-books constituted the only original documentation preserved. Observation frequency changed with time. In January 1914 readings were made four times a day, at the hours 8.00, 9.00, 15.00, 21.00 and included: wet and dry bulb temperature, minimum and maximum temperature (after the thermo-hygrograph Richard) atmospheric pressure, wind speed and direction, state of the sky, and once a day precipitation and evaporation. In 1915, with the beginning of the war, the nocturnal observation at 23.00 was added. On 1 January 1920, activity was reduced to only one observation a day, i.e., at 9.00 hr, but on 1 May 1920 observations were made at 9.00, 15.00 and 21.00 hr; on 1 July 1920 activity was again reduced to two readings at 9.00 and 18.00 hr. The number of observations changed again, but always remained limited to a few observations per day. Original note-books are in poor order and do not specify whether or not the readings include corrections.

Meteorological observations till December 1937 were preserved in a more reliable form thanks to another publication: the *Bollettino Statistico* published yearly by the Municipality of Padova. A table is given every month with the daily observations of: atmospheric pressure (mean of readings at 9.00, 15.00, 21.00 hr), mean temperature (obtained from max, min, readings at 9.00, 21.00 hr), maximum and minimum temperatures, relative humidity (psychrometric readings at 9.00, 15.00, 21.00 hr), prevailing wind direction, mean wind speed; cloud direction at 9.00 and 15.00 hr; cloud cover, precipitation, visual observations. The year 1917, when meteorological observations were made by the army for strategic reasons, is badly documented, with many errors made in copying data, especially in signs (i.e., below or above zero). When the absolute value of the minimum temperature (below 0 °C) was greater than the maximum, the value was written in the column of the maximum, and vice versa.

In particular, in the period 1914–1922, the same data were also published by the Water Magistrate. A comparison between the *Bollettino Statistico* and the data published by the Water Magistrate, shows many unjustified differences, between 0.5 and 1 °C. Mean temperature, from 1915 to 1922, was corrected after reduction to sea level with an adiabatic compression, similarly to the practice used for barometric readings. The correction consisted in subtracting an expansion value ranging between 0.15 and 0.21 °C. Another reason was found in a paper by Crestani (1928) in which he specified that the daily average and extremes were corrected using a correction diagram (Crestani, 1927) with strip chart recorder readings in the abscissa, and departures from direct observations in the ordinate. This correction was made until 1933. This is equivalent to assuming that the error was only a function of the instantaneous value of the parameter, without considering instrument and shield inertia i.e., the first and second derivative, which determine the under- or over-displacement of the pen trace, due to gear friction, loose couplings and the friction of pen to paper, and the heat accumulated (or lost) by the structure. However, some other minor unknown corrections were also made, as there are several apparently unjustified departures.

11. The Last Period at the *Specola* (1938–1962)

This is the last period, but it might also be called 'the lost period'. At that time, the director Silva proposed building a new astronomical observatory at 1050 m above mean sea level in Asiago, in the mountains, to get a better atmospheric transparency. From 1947 astronomical observations were transferred to Asiago; the personnel went up and down and research activity in Padova was reduced; meteorological observations were sacrificed. Silva was formally director until 1957, but in practice was substituted by Guglielmo Righini (director 1952–1953) Antonino Gennaro (director 1953–1955) and Leonida Rosino (director 1955–1986).

In the last period interest was focused on astronomy alone and meteorological observations ceased completely. Only some small note-books with irregular observations, mainly once a day (i.e., 9.00 hr) written in pencil are preserved in boxes, and have now been recovered. On 13 July 1956 observations were limited to only one reading per day of: air temperature, barometric pressure, wind direction and speed, sky cover and precipitation. The last observation is dated 16 September 1959 and is signed by the technician Bacchin. Of course, only one observation per day is insufficient for climate research purposes.

The most reliable observations were taken by the technicians Arturo and Antonio Mioni under the responsibility of the astronomer Salvatore Taffara; less accurate readings have the signature of Miro, Alfonso, Bacchin, Miolo, Tiso, all technicians. The last diagram still attached to Richard's thermograph is dated 27 April 1962 and is the very last measurement. Unfortunately, not only were measurements stopped, but also all strip chart records with the previous diagrams were considered of no interest and thrown out to make space.

12. Measurements at the *G. Magrini* Observatory (1920–present)

In 1920 another parallel series was started, when the Water Magistrate (founded 1907) of the Hydrographic Office of the Ministry of Public Works created, in the fields just outside town, a new meteorological observatory, later called after its founder, Giovanni Magrini. The new Observatory is about 900 m west from the *Specola* and after some years was absorbed by the town that was in continuous growth after World War II. Now the station can be reached through a thin street, Nervesa della Battaglia, which joins the Observatory to Sorio Street. Houses have encroached upon the area and most of the green has disappeared, with very few exceptions, one of which is fortunately just at the back of the Observatory.

All measurements were taken according to international recommendations; temperature was recorded with a G.M. Richard thermograph placed in a Stevenson screen on grassy ground (height: 2 m). The records were corrected daily according to three direct observations at synoptic hours 8, 14, 19 local time. The first director was Augusto Levi (period: 1920-1921), then Giuseppe Crestani (1922–1956), a leading climatologist who was also Director of the Meteorological Section of the Hydrographic Office and during his life this Observatory had its golden age as the centre of the meteorological network of the Water Magistrate. After Crestani died in 1956 things changed, especially with a general low interest in meteorological observations in Italy, the poor re-organisation of different meteorological networks that, instead of being unified and enhanced, were progressively abandoned, except for that of the Air Force. The staff of the *Magrini* Observatory was reduced and measurements continued with recording instruments, spot controls and many gaps.

Following international recommendations, thermometers (Six and Bellani's Minima and Maxima; Richard's thermograph) were placed in a Stevenson screen on grassy ground near the building of the Observatory (Figure 19), so that the height of the sensors was 2 m above ground. The error introduced by Stevenson's screen with the local climate has been evaluated $+1.5\,°C$ during daytime with a clear sky and no wind, as typically occurs during summertime in Padova, and $-0.5\,°C$ for radiative loss during clear nights (Cicala, 1970). Stevenson's screen became of wide use, especially after having been recommended at the International Meteorological Conference, Paris, 1896.

Meteorological observations were published yearly in the *Annali Idrologici* of the Water Magistrate. For a certain period, starting from 1938, data were also published in the *Bollettino Statistico* in substitution of the *Specola* series, which had ended. Daily maximum, minimum and average temperatures were reported in addition to atmospheric pressure, relative humidity, wind, precipitation, cloud cover and other observations. Daily averages of air temperature were computed as the mean of 13 readings taken at even hours, where the two midnight values, at the beginning and end of each day, were included with half weight.

In the years 1920, 1921 and 1922 mean daily temperature was published after having been reduced to sea level, i.e., 14,30 m. Actual observations can be obtained by subtracting the correction from published data. At the beginning, this lay between 0.07 and 0.17 °C and then was kept constant, i.e., 0.1 °C. From 1927 on the correction for the error introduced by the graphic recording was made (Crestani, 1927). The *Annali Idrologici* mentions this correction each year until 1933, but Ceconi (1939) stated that this was currently in use in his times. From May 1922, observations were interrupted until the end of 1923. Measurements were quite reg-

Figure 19. The thermometer cage, raingauge and other instruments at the *G. Magrini* Observatory.

ular till 1977, when activity ceased, or was dramatically reduced. In more modern times efforts have been made to continue this activity.

13. Measurements at the *G. Allegri* Airport (1951–1990)

The General Direction of the *Servizio Aerologico* (the early Meteorological Service) was established in Padova during World War I, in the *Specola*. In 1923 the Air Force Meteorological Service was founded, with a forecast department (*Servizio Presagi*) created with the co-operation of the Water Magistrate and the Hydrographic Service of the River Po (founded 1912). In 1926 an airport named after *Gino Allegri* was created (Servizio Meteorologico dell'Aeronautica, 1975; Ferrantini, 1958).

The airport *Gino Allegri* was located in the open country on the left side of the river Bacchiglione, some 750 m west of the *Magrini* Observatory and some 1300 m west of the *Specola*. Currently, this small airport has been completely absorbed by the town and is no longer representative of a rural site.

The meteorological data of the Airport were originally included in the international network for flight assistance, based on measurements taken at 5.00, 7.00, 10.00, 13.00, 15.00, 18.00 WET during wintertime and 7.00, 10.00, 13.00, 15.00, 18.00 WET during summertime, and data were transmitted at 8.50 and 19.50 GMT. However, the importance of this airport was very short lived. It was not named in the subsequent reorganisation of the Meteorological Service; in 1934 Venice was chosen for the Regional Meteorological Office and in 1935 the Venice Airport was designated as Centre of Flight Assistance.

Padova airport was subsequently classified as third class: that means with a limited number of observations, taken only during daytime, i.e., from 6 a.m. to 6 p.m. GMT. Some parameters were measured with recording instruments but it is not easy to recover all these records.

From 1951 to 1960, temperatures were measured twice a day, i.e., at 6 a.m. GMT and 18 GMT; in the period from 1961 to 1978 data consist of 3-hourly synoptic observations from 3 a.m. GMT to 18 GMT with some rare nocturnal observation. Air pressure and other key observations exist on magnetic tape from 1951 to 1990, measured every 3 hours from 3 a.m. GMT to 18 GMT. Measurements were taken according to international airport recommendations. Temperature is recorded with a 0.1 °C resolution, but is affected by typical errors of standard instruments (and especially of the Stevenson Screen in sunny areas with low ventilation) described by Cicala (1970) for the Italian Air Force. After 1990, the station stopped monitoring.

14. The Botanical Gardens (1980–present)

The historical Botanical Gardens are a small green area in the city centre, and in 1979 started taking meteorological observations with instruments at 1.6 m height in a louvered wood cage on grass terrain, some 8 m from the buildings. Measurements started with a SPIGE mechanical thermohygrograph. In the early period data were copied from the strip chart into a log, with some copying errors. From 1984 to 1990 two SPIGE minima and maxima glass thermometers (resolution: 1 °C) were also used. On 24 October 1990 the Botanical Gardens installed modern electronic instruments, with temperature sensors at 3.5 m above ground and 5 m from the buildings. Measurements are under the control of the *Centro Meteorologico di Teolo*, of the *Regione Veneto* in association with the Department of Biology of Padova University. Automatic samplings include maximum and minimum daily temperatures, wind, rainfall and pH of precipitation. Data have been recorded on magnetic support since 1980.

15. The National Research Council (CNR) (1984–present)

Meteorological measurements are automatically taken every 10 minutes with modern instruments in the CNR campus, in the country, just outside the city, 4.5 km ESE of the *Specola*. Temperature is monitored with Platinum resistance sensors on a mast, as follows: soil temperature (−2 cm); air temperature near the soil (+5 cm); at screen level (2 m) and at 10 m. Sensor accuracy is better than 0.1 °C, but overall accuracy is ± 0.2 °C, the limiting factor being the radiation shield, as usual. The radiation shield is composed of a plastic multi disc system.

As the CNR is aimed at research and not at routine service, meteorological records were taken with some gaps from 1984 to 1986; however, since October 1993 observations (air pressure, soil and air temperature at 2 cm, 2 m and 10 m, relative humidity, wind direction and speed, rainfall, sunshine) have been automatically taken every 10 minutes.

A simple comparison between instruments in the *Specola* suspended at 17 m above the soil, and in a standard weather station at some 2 m above the soil, shows a departure which follows the diurnal heating and nocturnal cooling of the soil. The superadiabatic gradient in the heart of the day, and the nocturnal inversion at the end of the night generate a difference, which may reach a few degrees. The CNR records with screened sensors at 2 m and 10 m shows an attenuation of the daily range with height, with a seasonal cycle which increases in the hot season (the maximum is found in August) and decreases in the cold season (Figure 20). Small departures are found in the rainy months. The monthly average of the difference between the two readings shows that the temperature at 2 m was up to 1.1 °C higher by day and up to 1.1 °C lower than that of the identically screened thermometer 10 m above the ground. Soil influence attenuates rapidly with height and decreases with increasing wind speed or overcast sky, and especially in the presence of fog or rainfall.

The vertical profile of air temperature measured at the CNR has been useful in finding the equations to reproduce the daily cycles of temperature and to compute the daily maxima and minima from past measurements made at intermediate times and taken at differing levels. It was also useful to homogenise measurements taken in the past, by the different stations, at different heights. In particular, a transfer function was found to transform data from one level to another and to homogenise all the later series (i.e., Water Magistrate, Air Force, Botanical Gardens) with the *Specola*.

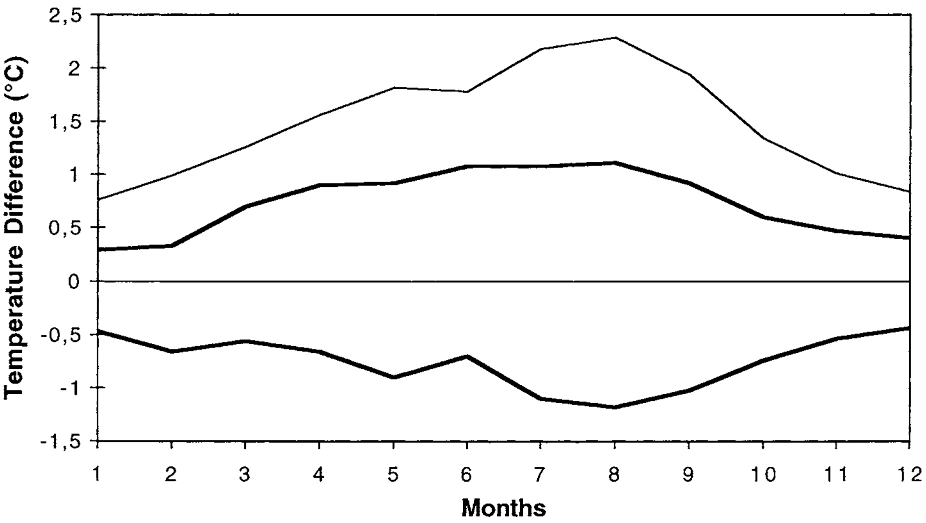

Figure 20. Attenuation of the daily range of air temperature with height. Extreme values of monthly average difference between the temperature observed at 2 m and that at 10 m. Positive thick curve: maximum average difference by day. Negative thick curve: maximum average difference by night. Positive thin curve: maximum average difference in the daily cycle.

16. Expansion of the Town and Urban Heat Island

Not only does the distant past constitute a critical period for the long series, but also the most recent past, with the influence of the urban heat island generated by radiant energy entrapped in streets by buildings and, secondarily, by change in albedo (especially after the wide use of asphalt), domestic heating and traffic.

The longest European series flourished centuries ago within, or at the edges of, small towns when the urban area was extremely small and not densely populated. The historic walls surrounding Padova formed an equilateral triangle of about 3 km per side but much of the land inside was green or cultivated, or even swampy. The population of Padova during the 18th century oscillated around 30,000 inhabitants and had an exponential growth after the middle of the past century. Now it has stabilised at around 250,000 inhabitants. Although Padova is a small town, the last part of the series should be considered separately. The size of the town did not vary much until the turn of the previous century; after World War II it expanded considerably (Figure 21). Gardens and vegetable gardens were taken over by new and taller buildings, which increased urban density, expanded the town entrapping more solar radiation and losing less IR at ground level. In addition, in the decades of the reconstruction after the end of World War II, in many streets the cobble paving was substituted with asphalt, reducing the albedo. The population changed life style and heating habits, with higher indoor temperatures, longer heating times, and increasing traffic. In the previous century and the first decades of this one, winter domestic heating was limited to a few hours and the maximum temperature

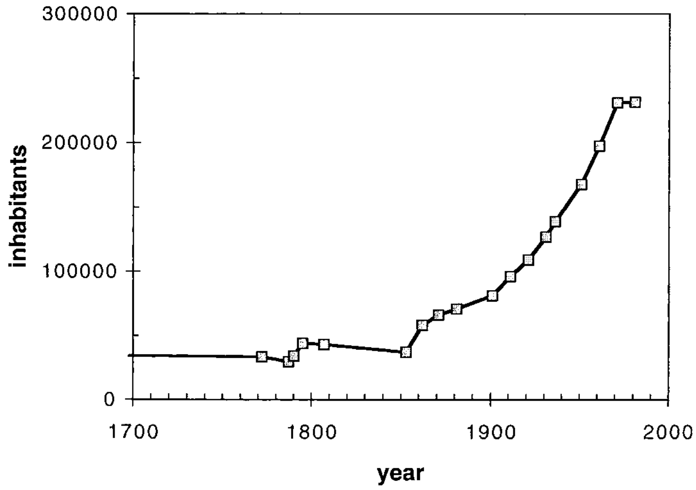

Figure 21. The number of inhabitants of Padova.

was less than 14 °C by day; water froze in sleeping rooms at night. Now room temperature is some 20 °C by day and night.

As cities grow, the increasing temperature difference with respect to the countryside is one of the main problems for the long instrumental series, whether the site has remained unchanged or has been relocated to outlying areas. Although several studies have been carried out to evaluate urban warming (e.g., Mitchell, 1953; Landsberg, 1981; Cayan et al., 1984; Goossens and Berger, 1986; Jones et al., 1986; Kukla et al., 1986; Lee, 1992), a reliable urban warming rate is difficult to establish and Kukla et al. (1986) suggested that on average the urban heating rate 0.12 °C per decade may be considered as indicative. A comparison made with other cities in Italy (Colacino and Rovelli, 1983) and especially in the same climatic area of Padova, the Po Valley (Zanella, 1976; Marseguerra et al., 1979; Bacci and Maugeri, 1992) is more representative.

Modena is 110 km SW of Padova, and has 180,000 inhabitants, with its observatory located in a situation similar to that of Padova. A study for the period 1869–1976 (Marseguerra et al., 1979) has shown no marked seasonal effect. The heating effect is most evident for the daily minima, i.e., 0.14 °C per decade; the daily average increases by 0.08 °C per decade; the daily maximum seems to decrease by 0.04 °C per decade, although this trend seems questionable because it is different from the other cities.

Parma is 130 km SW of Padova and has 170,000 inhabitants. Comparing urban and rural (airport) data for the period 1959–1973 (Zanella, 1976), an average difference of 1.4 °C was found, with the maximum departure found in the daily maximum temperature (1.6 °C); the difference varied seasonally with the maximum in spring and summer. Considering that the distance between the two stations is 2.5 km, this difference is considerably high (gradient of 0.64 °C/km), for a relatively small city, and can be justified by the fact that the city centre is characterised by an uninterrupted sequence of buildings and asphalt roads, unbroken by greenery.

Milan is some 200 km west of Padova and has some 1,600,000 inhabitants and is the largest metropolitan area in the Po Valley. A study of the temperature difference between the city centre and the Linate airport (Bacci and Maugeri, 1992), led to the difference of 1.4 °C, with a heating rate of 0.13 °C per decade, close to that of the above smaller cities.

A comparison between urban measurements, taken at the Botanical Gardens in the city centre, and the rural ones at the CNR, has shown that in January the minimum temperature is higher (+0.8 °C) in the city and the maximum is more or less the same (−0.2 °C). In July the deviation of the minimum temperature is substantially unchanged (+0.7 °C), whereas the deviation of the maximum is the opposite (−0.7 °C). The higher minimum temperature in the city can be explained in terms of a smaller radiative loss from the soil. It was totally unexpected to find that, in summertime, in the hottest hours, the city centre was milder than the rural environment. This result can be explained only by the fact that the Botanical Gardens are an oasis in the urban context, where the temperature is milder because of the shade and the evapo-transpiration of plants and trees. With sunshine, the local effect is dominant over background ambient temperature.

17. Conclusions

Every series is affected by two kinds of systematic errors: those of local nature and those determined by national or international protocols. The latter may be reflected in a change of the signal that is found in every station, and that for this reason can be misinterpreted as a climate change. Only a careful historical research may help distinguish real from spurious climate signals. Therefore, the detailed knowledge of both local metadata and general directives is fundamental for interpreting the results of a series.

Series Homogeneity and Main Problems

From the point of view of homogeneity, the Padova series can be divided in three main parts:

(i) The early period (1725–1768) made with thermometers inside or outside but strongly influenced by building. The observations made inside were intentionally representative of the mean daily temperature, although the approximation was not overly accurate. Toaldo made an evaluation of the average error, i.e., ± 2°R, but this is insufficient to correct all the data and make them homogeneous to the subsequent period of outdoor measurements. However, these observations, being homogeneous, are precious in detecting climate variations and trends over this period.

(ii) Measurements in the *Specola* (1775-1919), homogeneous as for exposure, height from the ground, site location and urban size.

(iii) The recent period (1920–today) is the most affected by urbanisation, with the birth of new parallel weather stations at standard height.

An important problem were observations with changing height from the ground. When the thermometer was near the soil, it was strongly influenced by daytime heating and nocturnal cooling of the ground; when at elevated heights, the daily range was reduced. The level of thermometers in the Poleni period was at the first floor. The measurements at the Specola were taken at 17 m; the observations for the period 1920–today were taken by more than one station at the standard Stevenson's screen height, i.e., between 1.5 and 2 m. All the readings, taken at the first floor, in the elevated *Specola* and at standard meteorological screen height have been transformed to the same level to homogenise the series. Fortunately, the *Specola* and the *Water Magistrate* operated in parallel for 37 years, and this overlapping period enabled a reliable comparison between the two stations. The further comparison between the *Water Magistrate* and the other stations operated in parallel with the *Water Magistrate* enabled the establishment of the teleconnections between all of these stations. The risk of errors is minimised if the transformation for homogenisation is applied to the shortest records. In order to compensate for the change of elevation, the short modern series have been homogenised after a transformation, which corresponded to a virtual raise of the standard stations. The transformation was made computing, for each month, the teleconnections between the pair of series and then applying a transfer function.

Teleconnections connect average characteristics of a first population (a time series) with those of a second population (a parallel series). The homogeneity assessment made by means of teleconnections between two stations is essentially controlled by bulk statistical properties of the two distributions. In the case of long-term daily records, the application of a transfer function based on a teleconnection, operates by applying average properties and losing something of the peculiarity of individual days and interdiurnal variability. Although this is irrelevant for climate analyses based on averages or modes, it does slightly affect the daily variance and the analysis of extreme value frequency, e.g., at the level of 10 and 90%ile, or more extreme percentiles (Moberg et al., 2001, Yan et al, 2001).

Shelters

At the beginning thermometers were placed at windows facing north, then in loggias, until in 1780 Toaldo applied the first known shield. In the early period, thermometers were strongly influenced by the walls to which they were hung. Shields were made in different ways, with different materials. This variety of shield introduced new systematic errors at each change.

In general, the use of free standing louvered screens (e.g., Wild, Stevenson) became world-wide after having been recommended by the International Committee on Meteorology at the Congresses held in Vienna (1873) and Rome (1879). The Congress held in Paris (1896) left the observers free to choose the most appropriate shield, but recommended the Stevenson Screen (which soon became very popular) or a Canopy French Style screen. The old-style Stevenson screen was a louvered cage with an open base; the newer version had a double roof with staggered board across the base to exclude radiation reflected from the ground. The cage is prone to diurnal overheating and nocturnal cooling. Tests made in Italy on the standard model in use by the Air Force or the Water Magistrate show that the error reaches $+1.5\,^{\circ}$C by day in summer and $-0.5\,^{\circ}$C by night (Cicala, 1970). The Canopy French Style consisted of a roof with small lateral shields (except to the north) to prevent rain falling on instruments. There is no bottom and the air moves freely among the instruments that are hung under the roof. The French screen overheats by day because of accumulated heat and radiation reflected from the ground. However, although a louvered shield generates overheating, it may lead to an apparent cooling of thermometers that were previously even more affected by solar heating. This problem is to be especially expected in the sites where solar radiation is not too strong. It was under-evaluated, or shielding was made with inappropriate screens. This explains why, in the Northern Hemisphere before 1880, summer appears to have been systematically warmer, and winter systematically colder (Folland et al., 1990; Parker, 1994). The widespread use of the Stevenson Screen in the late 19th or early 20th century introduced a more or less evident non-homogeneity and a bias in the signal. At each station, the bias was more or less enhanced depending upon solar radiation, ventilation, local effects, and the response of the previous shielding device.

City Growth and Urban Heat Island

A comparison of observations made in the city centre with those effected in a rural site has shown that it is impossible to define an urban temperature for Padova. The reason is that it varies from place to place, and local effects are dominant over the urban-rural difference, especially in response to strong daily radiation in the hot season. Unfortunately, once again, the disturbance is of the same order of magnitude as the average value of the climate signal. For this reason, climate investigations based on statistics of extreme values are more reliable, as extreme values depart much more, and are less affected by the unknown change of the background level.

A final question concerns the interest in continuing a time series, which is disturbed by the urban heat island. We could arrive at the conclusion that the interest in this, and other urban ultrasecular series died tens of years ago, when the environmental homogeneity was lost. Should continuing observations today at the *Specola* be considered a mere love for data collection which is useless in studying the climate, or is it an important way to document an increasing (although local) anthropic impact? Now, the last point of view seems the most stimulating, although very long series are not necessary to this aim. Long series are extremely rare and precious to study the past. In combination with new, younger unaffected (or less affected) series, they form a set of information which is essential to interpret the present and predict future changes.

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CORRECTIONS OF SYSTEMATIC ERRORS AND DATA HOMOGENISATION IN THE DAILY TEMPERATURE PADOVA SERIES (1725–1998)

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Abstract. The correction, validation and homogenisation of the long temperature series of Padova (1725–1998) are discussed. After a careful historical investigation made in order to discover the metadata concerning the series, i.e., instrument features, calibrating methodologies, operational procedures (i.e., exposure, timing and number of daily observations), instrument maintenance, relocations and instrument replacements, the series has been corrected for all the systematic errors derived from any change in the instruments or the operative methodology. Above all, correction focused on instrumental drift, scale expansion, building influence, relationship between indoor-outdoor measurements, minima and maxima evaluation from observations performed at different times, homogenisation for difference of level and change of site. Statistical tests applied to the data and the comparison with other known series has clarified some uncertainties about exposure and operational procedures that the historical analysis of metadata was unable to solve. Moreover, gaps have been filled after the comparison of the series with others of neighbouring sites. The critical work of debugging, correcting, validating and homogenising the series is essential for a correct interpretation of data, as in some cases the errors that have been corrected have been found to be greater than the climate signal. Especially in the early period, the algebraic sum of the corrections of the mean daily temperature exceeds 8 °C, where monthly corrections can reach 6 °C. After correction, validation and homogenisation, the linear trend of the Padova series is positive, +0.31 °C/100 yr over the period 1774–today. Looking at post-industrial warming, the temperature rise is +0.44 °C in the last 130 years, which means +0.34 °C/100 yr, not far from the above bulk average.

1. Introduction

A description of the climate and its variability is essential to advance in the evaluation of the consequences of human activities on the environment. Our ability to quantify the human influence on the global climate is currently limited because there is a limited number of instrumental series exceeding one century and only a few of them going back up to two centuries or more and reaching the period before any anthropogenic effect.

It is first necessary to carry out an accurate historical investigation in order to learn everything about the series, not only in terms of the instruments used and their position, but also the operational habits of the observers and their scientific beliefs. This aspect is very important, especially at the beginning of every long instrumental

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series, when many fundamental concepts had not yet been established, or there were still many false beliefs, so that each single observer applied his own personal criteria in order to overcome the various real or presumed difficulties which were encountered. Hand-written meteorological observations have been copied from the original registers, digitised, corrected, validated and homogenised.

The typical errors of the early measurements (e.g., calibration, exposure, relocation, timing of observation, method of computing the average daily values) have been identified. In terms of homogeneity, the series of Padova can be subdivided in sub-periods: observations in the Homes of the First Observers (1725–1767) mainly indoor, at the first floor; the First Period at the *Specola* complex (Munitioner's House, Astronomer's House) and Tower (1768–1812) outdoor, and on the *Specola* Tower at 17 m above the soil; the Second Period at the *Specola* Tower (1813–1864), same height; the Third and Fourth Periods at the *Specola* Tower (1865–1937), same height; the Last Measurements at the *Specola* Tower (1938–1962), same height; the *Giovanni Magrini* Observatory of the Water Magistrate (1920–today) 2 m above the soil; the *Gino Allegri* Airport (1926–1990) 2 m above the soil, the Botanical Gardens (1980–today) 2 m above the soil, the CNR (1984–1986; 1993–today) 2 m and 10 m above the soil (Camuffo, 2002a). In a number of cases the variation in measuring methodologies or the adoption of new conventions or international recommendations reflected in apparent regional climate changes (Camuffo, 2002b,c). Combining the findings of the various analyses, based on existing documents and instruments, it is possible to estimate appropriate corrections, which vary with season and geographical position, and improve the quality of the long series.

Reconstructing and determining the reliability of time series constitutes a delicate and complex preliminary phase of any mathematical analysis, on which the reliability of the results depends. A key problem regarding the representativity of a series is establishing when changes were due to different criteria in taking data, or to the recent transformation of the territory and human activity.

2. Instrumental Drift

Instrumental drift of early liquid-in-glass thermometers may be due to a number of causes, the most known of them are: deformation of the glass tube and bulb, polymerisation of organic thermometric liquids, e.g., spirit, linseed oil, deposit of pigments colouring the liquid, ageing of the wood support bearing the scale (in the case of 18th century instruments), slipping of the scale or the capillary, when the latter was attached to the scale with an iron wire (Camuffo, 2002b).

In the time series, drifts are made evident by the presence of long-term trends, which can be detected with statistical tests, e.g., Mann-Kendall (Kendall, 1976), cross comparison with other nearby series in association with statistical tests, e.g., Alexandersson (1986).

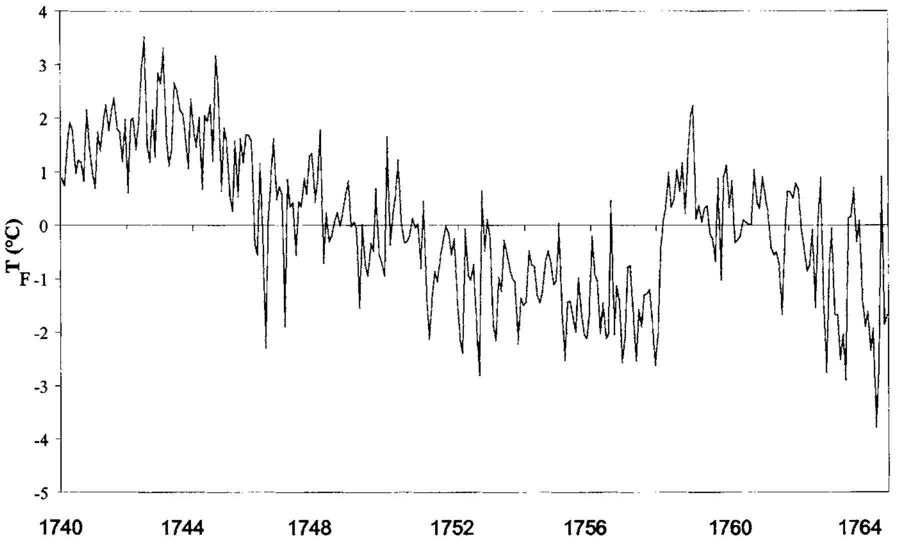


Figure 1. Monthly mean temperature differences between Poleni's Amontons thermometer and Morgani's outdoor thermometer.

In the case study of the main Poleni series, made with an Amontons (Poleni, 1709) thermometer (1725–1764), clear trends have been found for the periods 1744 to 10 February 1758 and 11 February 1758 to 31 December 1764 after cross comparison with the Morgagni outdoor and the indoor series (1740–1768). The departure between the Amontons readings in the Poleni series and the Morgagni outdoor series is reported in Figure 1. This difference is free from a climate signal and depends only upon the different response of the two thermometers. A similar analysis performed with the same Amontons readings compared with the Morgagni indoor series and with the secondary Poleni series made with a Fahrenheit thermometer substantially gives the same result. A cross comparison between the two Morgagni series and the Fahrenheit one showed neither trends nor discontinuities, thus proving that the trends and the abrupt change on 10 February 1758 can be attributed to the Amontons thermometer. A similar analysis performed with the other thermometer, i.e., Delisle's, used by Poleni in the period 1733–1740 once again gives a decreasing trend for the Amontons thermometer.

It is not easy to interpret what happened to this thermometer. It is only clear that the abrupt change on 10 February 1758, which corresponded to 3.4 °C, was due to the shift of the scale. We can suppose that this displacement was made by placing it in the appropriate position, i.e., with zero corresponding to the level of the free surface of the mercury in the ampulla.

We can exclude that the scale was out of place because of an accidental impact, because the opposite abrupt change cannot be found. This means that the anomalous decreasing trend in the temperature is due to an instrumental drift, and that the scale was displaced in an attempt to compensate. A possible interpretation is

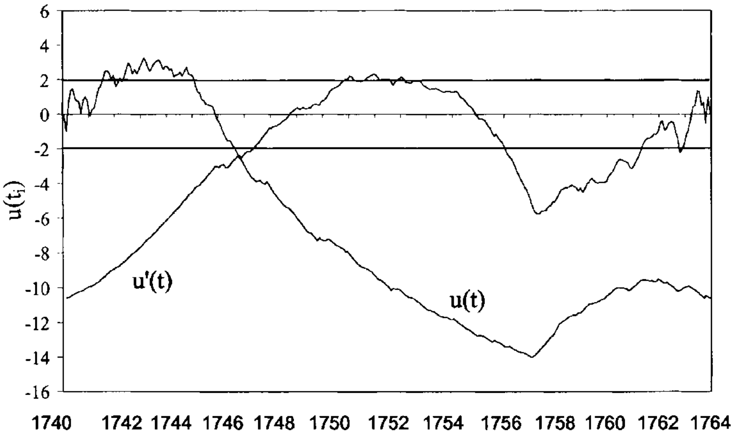


Figure 2. Mann–Kendall test applied to the series of monthly mean temperature differences between Poleni's Amontons thermometer and Morgani's outdoor one, before corrections.

that the capillary, attached to the wooden scale with an iron wire, progressively slipped because of vibrations, favoured by the weight of the mercury in the ampulla. Another possiblity is that the air pocket in the ampulla lost some oxygen because of mercury oxidation. As a consequence, in every Amontons thermometer, the volume of air in the ampulla could be progressively decreased up to 21%, that is the percentage of oxygen in the free air. In the first hypothesis, the trend may start at any time; in the second the trend has an exponential decay, starting from the beginning. Moreover, a combination of the two hypotheses is possible. Whatever the cause, the correction has been carried out after an analysis of the departure between this instrument and the other ones.

The Mann–Kendall test, applied to the series of the differences between the Amontons thermometer and the two Morgagni ones, individuated the point from which to start the correction before 10 February 1758. The mean value of the coefficients of the second order interpolation polynomials for the two series has been used to calculate the progressive correction of the Amontons data. The same has been made for the period 10 February 1758–1764. Figure 2 reports the results of the first application of the Mann–Kendall test to the whole overlapping period of the Poleni and Morgagni series. The starting point of the trend was located on November 1746. After this correction, the test was once again applied to the corrected data to look for an eventual residual trend. This iterated approach displaced the starting point from 1746 to January 1744. A further application of the Mann Kendall test showed no residual trends.

In the hypothesis of mercury oxidation, with a low oxidation rate, a decreasing trend is expected starting from the beginning of the main Poleni series (1725). A comparison between the Amontons data and the secondary Poleni series made with the Delisle thermometer (1733–1740), shows that the trend is still present. Nothing can be said for the previous period, except that it seems logical to expect that this too is affected by drift, especially in view of the decreasing trend of the temperature, although we are unable to distinguish the climatic signal from the error for lack of a certain reference. However, the Delisle thermometer was not always kept in the same place, so that this series is a weak reference which does not give conclusive results.

If mercury oxidation occurred during the time span of these measurements, not only a drift of the scale occurred, but also a displacement of the fixed points. In the impossibility of having the instrument to recalibrate it and to find a sound correction, the actual correction was limited to the compensation of the departure proved by comparison with independent reference thermometers.

3. Temperature and Humidity Expansion of the Scale

In the early period, till the 19th Century, many instruments had the capillary separated from the support frame, to which the capillary was fixed with an iron wire. The scale was in many cases written directly on the wooden support, or written on a strip of chart paper glued to the wood frame. It is well known that wood is sensitive to changes in temperature and, especially in relative humidity (Giordano, 1986, 1993). Hemmer (1783) suggested using walnut and Toaldo (1803) red fir, although other kinds of wood were used. Expansion in the support was reflected in expansions of the scale and in reading errors.

The expansion coefficient is not the same in the three key directions in the timber, i.e.: tangential to the tree rings, radial (or perpendicular to the tree rings), and longitudinal (parallel to the grain). Temperature expansion is very slight compared with relative humidity expansion; for the latter the three expansion coefficients present the approximate ratios $1:0.5:0.3$ or less (Sliker and Summitt, 1980). For practical reasons the capillary and the scale were attached to the wood supports always along the longitudinal direction, that is the direction less influenced by both thermal and hygrometric expansion.

As an example, the thermal longitudinal expansion coefficient for seasoned red fir wood with an equilibrium moisture content (*EMC*) of 15% is $5.4 \cdot 10^{-6}\ °\mathrm{C}^{-1}$, where the *EMC* is the percentage ratio between the mass of water contained in the wood to and the mass of dry wood.

In the case of the Amontons thermometer the maximum error due to thermal expansion can be estimated to be 0.05 °C. In fact, at 30 °C, the sum of the heights of the barometric and the thermometric mercury columns was 52.5 London inches (133 cm). Thermal expansion for this length with reference to 0 °C is:

$$\Delta l = 5.4 \cdot 10^{-6} (°\mathrm{C}^{-1}) \cdot 30\,(°\mathrm{C}) \cdot 133\ (\mathrm{cm}) = 0.02\ \mathrm{cm}$$

that represents an error of 0.05 °C, because of 1 °C corresponded to 0.4 cm. Morgagni's, Toaldo's and Chiminello's instruments had supports shorter than Poleni's and, as a consequence, smaller errors. It is therefore possible to conclude that, in

Table I

Equilibrium moisture content of the wooden support of the indoor and outdoor thermometers as a function of the seasonal average relative humidity

Quarter	Outdoor			Indoor		
(months)	T	RH	EMC	T	RH	EMC
1-2-12	1.4	89	22.0	6.2	63	12.0
3-4-5	11.1	79	16.0	12.9	70	13.5
6-7-8	23.4	74	13.5	23.4	74	13.5
9-10-11	12.4	87	19.5	15.9	69	13.5

any case, the error due to the thermal expansion of the support was negligible. The same is not true for hygrometric expansions that cause larger variations in wood dimensions.

To calculate daily dimensional changes of the support, a seasonal reference value of *EMC* should be established. In turn, the *EMC* depends on the microclimate of the environment in which the instrument is exposed. This task has been carried out by calculating the 50th percentiles of daily average relative humidity (*RH*) for the quarters starting with the months of March, June, September and December and using the data taken in Padova by the Air Force from 1960 to 1990. Finally, knowing both the 50th percentiles of the outdoor *RH* values and the monthly average differences between indoor and outdoor temperatures from Morgagni's data, it has been possible to calculate, day by day, the indoor *RH* levels during the XVIII century. These data are reported in Table I.

The *EMC* changes at a slow rate because of the slow response of wood, and interseasonal changes are in general much more important than interdiurnal ones. For this reason quarter values of *EMC* have been used to represent the yearly cycle. From each value of *EMC* it is possible to calculate the relationship between the RH and the longitudinal expansion of the support (Camuffo, 1998), as reported in Figure 3 in the case of an *EMC* = 13.5% that is representative of the indoor typical value.

To estimate the daily expansions of the supports of the early instruments, the RH value has been computed day by day in the first part of the time series. This estimate was carried out indirectly on the basis of the weather situation reported in the original registers by Poleni, Morgagni, Toaldo and Chiminello. To every day one of the three following meteorological classes was assigned:

'Wet' class:	Foggy, rainy or snowy day
'Normal' class:	Variable or overcast day
'Dry' class:	Clear day

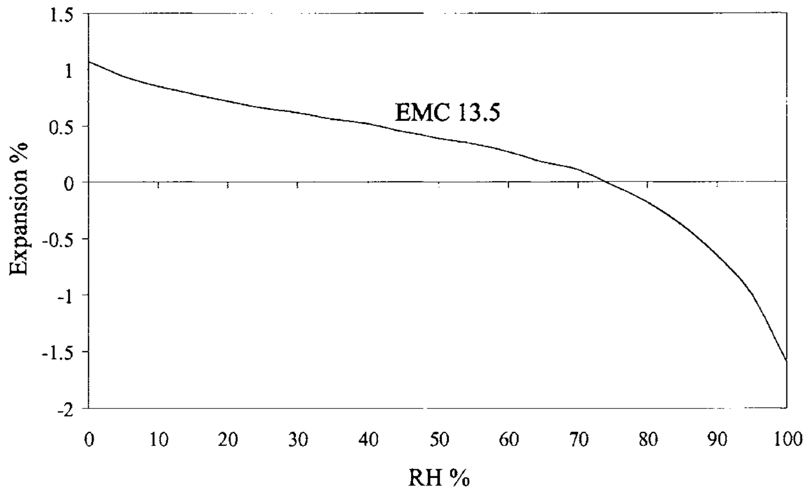


Figure 3. Relationship between RH% and longitudinal expansion of the wood support for an EMC = 13.5%.

An application of the same classification to present day data allowed us to determine the *RH* level typical of each class per month. This statistical analysis was performed using the meteorological observations taken by the Air Force in the period 1960–1990.

Returning to the early period of the time series, after the reading of the external temperature T_e, the estimated value of the external relative humidity RH_e, and the reading of the indoor temperature T_i, the indoor value of the relative humidity RH_i has been calculated with the following equation

$$RH_i = RH_e \cdot 10^{\frac{a \cdot b \cdot (T_e - T_i)}{(b+T_i)\cdot(b+T_e)}}$$

where a and b are the Magnus coefficients, i.e., $a = 7.5$ and $b = 237.3\,°\text{C}$; T is obviously expressed in °C.

Indoor and outdoor *RH* levels are respectively used for computing the expansion of the wood frame and scale. This was necessary to correct scale expansion as reported in Table II and, consequently, the error in temperature readings.

As already seen, in the case of the Amontons thermometer a measure of 30 °C corresponded to a sum of the heights of the barometric and thermometric mercury columns of 52.5 London inches (133 cm). If measurements were taken during a wet summer day, Table II gives an expansion of the support of -0.35% with a resulting $+1$ °C temperature overestimate. During a dry day the expansion was $+0.25\%$ and the temperature underestimated by about –0.9 °C.

The scales of Morgagni's and Toaldo's instruments began at -12 °R, therefore an expansion δx of the support at a temperature T caused a reading error *RE* of:

$$RE = (T + 12) \cdot \delta x\,°\text{R}$$

Table II
Wood frame expansion as a function of relative humidity.

Quarter	Weather class	T °C out	RH % out	T °C in	RH % in	% Expans. out	% Expans. in
12-1-2	Wet	1.4	94	6.2	67	−0.25	−0.05
12-1-2	Normal	1.4	81	6.2	58	+0.40	+0.15
12-1-2	Dry	1.4	73	6.2	52	+0.60	+0.20
3-4-5	Wet	11.1	89	12.9	79	−0.35	−0.20
3-4-5	Normal	11.1	75	12.9	66	+0.15	+0.10
3-4-5	Dry	11.1	67	12.9	60	+0.25	+0.20
6-7-8	Wet	23.4	85	23.4	85	−0.35	−0.35
6-7-8	Normal	23.4	75	23.4	75	−0.05	−0.15
6-7-8	Dry	23.4	68	23.4	68	+0.25	+0.25
9-10-11	Wet	12.4	93	15.9	74	−0.40	−0.05
9-10-11	Normal	12.4	81	15.9	65	+0.25	+0.15
9-10-11	Dry	12.4	74	15.9	59	+0.40	+0.20

As an example, from Table II it is possible to estimate the error at the temperature 25 °R, during a wet summer day:

$$RE = (12 + 25) \cdot (-0.35/100)°\text{R} = 0.13\,°\text{R} = 0.16\,°\text{C}$$

4. Building Influence

The influence of the building implies smoothing the daily cycles, reducing inter-diurnal variability and introducing a time lag in instrument response. Attenuation of cycles can be tested when both daily maximum and minimum temperatures are available. When only one daily measurement is available the analysis of interdiurnal variability is useful. If in addition parallel series exist, it is possible to compare them by looking at the correlation between the less-known and the more well-known series, or looking at the lag introduced by the building structure in comparison with the instrument in the free air.

An analysis of the interdiurnal variance gives important information about the influence of the building structure that tends to smooth daily cycles with its large thermal capacity. This analysis allows us to understand if the instrument was exposed to free air or was conditioned by the building structure. The first step was to calculate, per month, the temperature difference between consecutive days, and then the mean variance over the entire series. The variance of the Air Force measurements, for the period 1951–1990, was considered representative of the

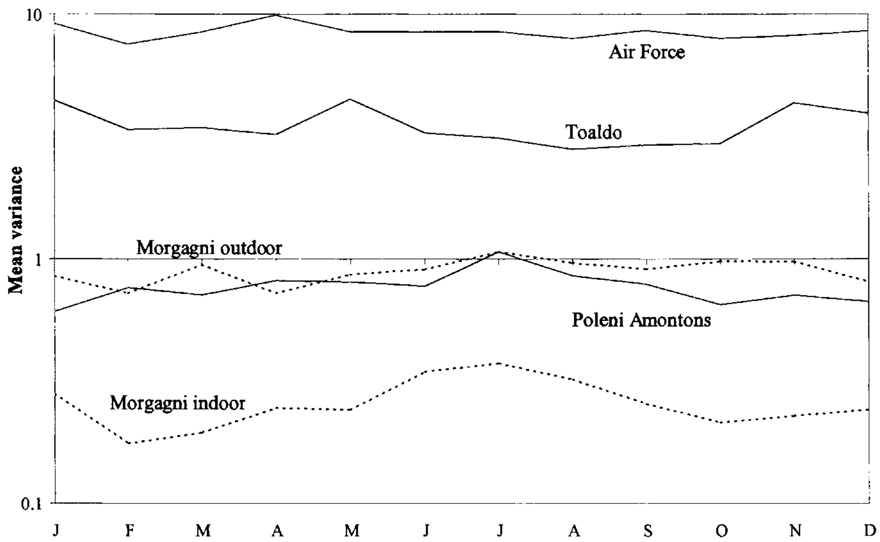


Figure 4. Interdiurnal temperature variability; series of: Poleni, Morgagni outdoor and indoor, Toaldo, Air Force.

completely free air variability. Figure 4 shows, in logarithmic scale, the variance of the Amontons, Morgagni indoor and outdoor, Toaldo and Air Force data.

From the figure it is evident that Toaldo's measurements have an intermediate variability between that of a closed room and the free air. This means that the thermometer was outside, but conditioned by the building structure. In the very first period we do not know the exact location, but in 1768–1775 Toaldo measured in a loggia and in 1776–1793 outside a north-facing window in a well-ventilated location.

Morgagni used two thermometers. The influence of the building structure on the external thermometer was greater than in the Toaldo case, and was so strong that the variability of the outdoor thermometer was midway between Toaldo's and the indoor thermometer.

5. Influence of the Indoor Environment and Management

Surprisingly, Poleni's indoor measurements had a variability which was similar to that of Morgagni's outdoor observations and greater than Morgagni's indoor ones. This can be explained by supposing that Poleni opened the windows of the room for some time before the readings to obtain, with ventilation, a better equilibrium with the outdoor temperature. This analysis helps to interpret data since we know that Poleni's indoor measurements are more representative of the outdoor temperature than might be expected.

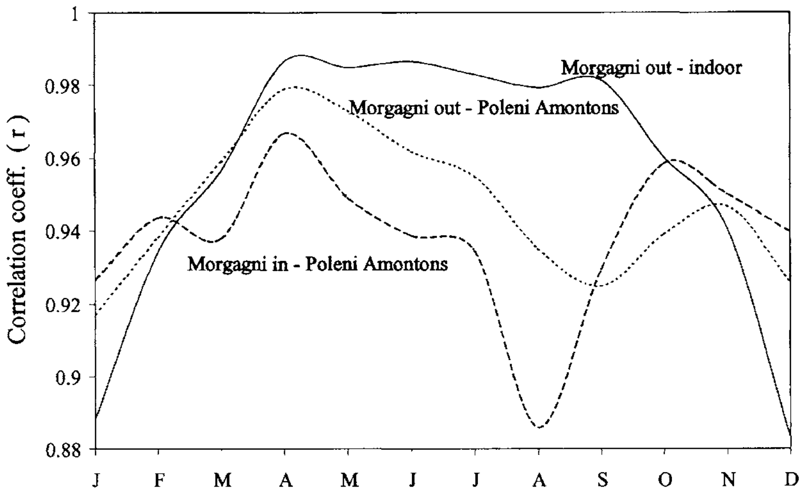


Figure 5. Monthly mean correlation coefficients between Morgagni's and Poleni's measurements.

Another way to extend our knowledge about the actual representativity of the observations is to correlate parallel series to establish an order of correspondence that links each series to the better known ones. To ensure the comparability between the Poleni and the Morgagni series, the data taken before 13 hr or after 17 hr have been excluded from the analysis, because they are not representative of daily maximum temperatures. The monthly mean correlation coefficients, between 1740 and 1760, are reported in Figure 5.

The two Morgagni series (indoor and outdoor) are highly correlated in the warm season, from April to September, but less so in winter because of the greater disturbance caused by the inhabitants e.g., closing windows. Even if Morgagni followed Jurin's (Jurin, 1723) recommendations to take measurements inside, in a non-heated room, it is unavoidable that the human activity inside the building influenced thermometric measurements. Poleni's Amontons thermometer has a higher correlation with Morgagni's outdoor instrument than his indoor one, confirming the hypothesis of the ventilation of the environment in which it was located. A drop in correlation is evident in August (Poleni–Morgagni indoor) and less so in September (Poleni–Morgagni outdoor) probably because Poleni and Morgagni were used to taking summer holidays from the end of July and the person who took the measurements for Poleni took less care in ventilating the room. On the other hand, Morgagni did not use a substitute and his data present many gaps in summer. As a consequence, there is a fall in data quality and less correlation between the series.

Another attempt to evaluate the influence of the building on the indoor microclimate was carried out by calculating correlation coefficients between the pairs obtained with Poleni's and Morgagni's two series, taking one series as a reference and applying an increasing time lag, from zero to 15 days to the other series. The

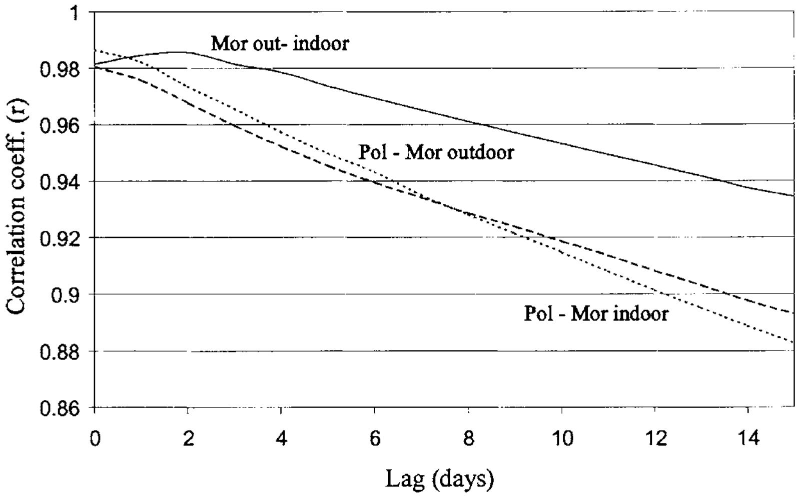


Figure 6. Correlation coefficients between Morgagni's and Poleni's measurements with increasing lag from 0 to 15 days.

correlation between Morgagni's indoor and outdoor series shows a maximum in correspondence of a 36–48 hour lag, as shown in Figure 6. This seems to be the order of magnitude of the delay induced by the thermal inertia of the walls on the penetration of external forcing.

A final analysis concerns the Morgagni outdoor thermometer. The daily thermal span obtained from the daily maxima and minima observed by Morgagni is too small compared with the mean seasonal values for Padova, having 0.2 °C as 10th percentile, 0.8 °C as median and 1.6 °C as 90th percentile. This is not due to a calibration problem, because there is not an analogue flattening in the yearly thermal span. The most convincing explanation is the heavy influence of the building. As the Morgagni measurements are homogeneous, they can be used to look at trends in the period; however, they cannot be used for as analysis of daily cycles or interdiurnal variability.

6. Evaluation of Daily Extremes from Observations Performed at Different Times

In 1774 Toaldo began the first regular observations near the daily maximum and minimum. They were taken at fixed times and, as a consequence, at variable distances from daily thermal extremes, according to the period of the year. Real extremes are, therefore, unknown and they have been extrapolated as specified later. Automatic records of daily extremes started only in 1874, with the introduction of the Six and Bellani maximum and minimum thermometer.

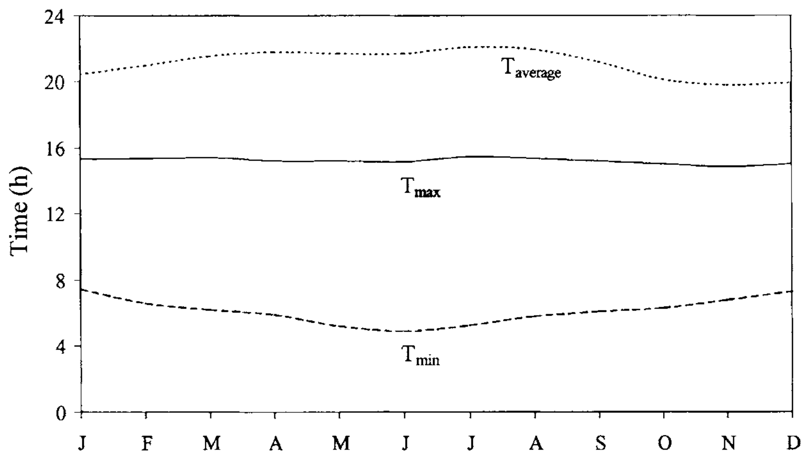


Figure 7. Monthly times of the maximum, minimum and average daily temperatures.

After the heat balance at the ground-atmosphere interface, the daily maximum temperature occurs some three hours after noon, the minimum about half an hour before dawn. In reality, especially during winter, the maximum temperature might be anticipated by more than 30 minutes. In Padova, the shape of the temperature cycle near the maximum is flat and measurements taken within 30 minutes around the time of the maximum differ from the real maximum temperature by less than 0.1 °C in July and 0.2 °C in January. Solar culmination oscillates within 12^h 15m and 12^h 45m with reference to *Western European Time*. The daily maximum, therefore, usually falls between 15^h 15m and 15^h 45m (Figure 7) and all the measurements taken between 14^h 45m and 16^h 15m do not differ from the real maxima by more than 0.2 °C. In the same figure, together with the maximum and minimum temperature, also the evening time (between 20^h and 21^h) in which the air temperature equals the daily average has been reported. This because in certain periods it was customary to take three observations a day, i.e., at sunrise, near the maximum and between 20^h and 21^h, to obtain the daily average (Camuffo, 2002c).

The rapidly increasing intensity of solar radiation immediately after dawn is followed by a similar increase in air temperature. As a consequence, a delay or an advance in taking the observation of the daily minima causes a temperature over- or underestimate, e.g., some 30 minutes delay leads to a 0.4 °C overestimate in January and a 0.8 °C in July, as an average of all possible weather conditions, i.e., clear sky, overcast sky, changeable weather.

Early daily temperature measurements, from 1794 to 1864, were taken at 7^h 30m, from 1865 to 1867 at 7^h 00m and, finally, from 1868 to 1878 at 9^h 00m (mean local time). As the time of dawn changes during the year, observing at 9^h 00m causes departures of up to 3^h 30m from the instant of the true minimum temperature, giving rise to an overestimate that in July might exceed 4 °C.

The estimation of daily temperature extremes was performed on the basis of present daily thermal cycles obtained, month by month, from the measurements taken at the CNR, since 1984, at 2 m and 10 m above the ground. The curves for January, April, July and October are shown in Figure 8a–d.

As observations at the *Specola* were taken at 17 m above the ground, only the 10 m records have been considered in this analysis. Monthly mean values of the daily minima (T_m), maxima (T_M), and temperature span (ΔT_d) have been calculated. The differences between a measurement taken at time h and daily extremes, normalised with respect to the daily temperature span, are performed by means of the coefficients $C_{h,m}$ and $C_{h,M}$ given by the equations:

$$\left|\frac{T_h - T_m}{\Delta T_d}\right| = C_{h,m}$$

$$\left|\frac{T_h - T_M}{\Delta T_d}\right| = C_{h,M}$$

For each month, as the coefficients are extracted from the average daily temperature cycle, they depart depending on the various weather conditions, day by day. The choice of average, and not actual, daily temperature cycles was made because of the uncertainties regarding the observations of the weather conditions at the instant of measurements during 18th and 19th centuries. In that period, the observations of weather conditions were attributed to the whole day or a large part of it, giving rise to doubts about real weather conditions at any moment other than that of the reading. Using an average cycle seems to minimise the risk of introducing errors larger than the corrections themselves.

Assuming, as a first order approximation, that the average temperature cycle in Padova has not changed in the last centuries, the coefficients C are the same for current and past data. Starting from a past observation T'_h (where the label $'$ is for original observation; temperature without this label is calculated as explained above) made at the time h and knowing the maximum temperature T'_M for the same day, the minimum temperature T'_m is given by solving the system:

$$\left|\frac{T'_h - T'_m}{\Delta T'_d}\right| = C_{h,m}$$

$$\left|\frac{T'_h - T'_M}{\Delta T'_d}\right| = C_{h,M}$$

from which:

$$T'_m = T'_h - \frac{C_{h,m}}{C_{h,M}}(T'_M - T'_h) = T'_h - \left|\frac{T_h - T_m}{T_h - T_M}\right|(T'_M - T'_h) ,$$

where $C_{h,m}$ and $C_{h,M}$ are derived from modern data.

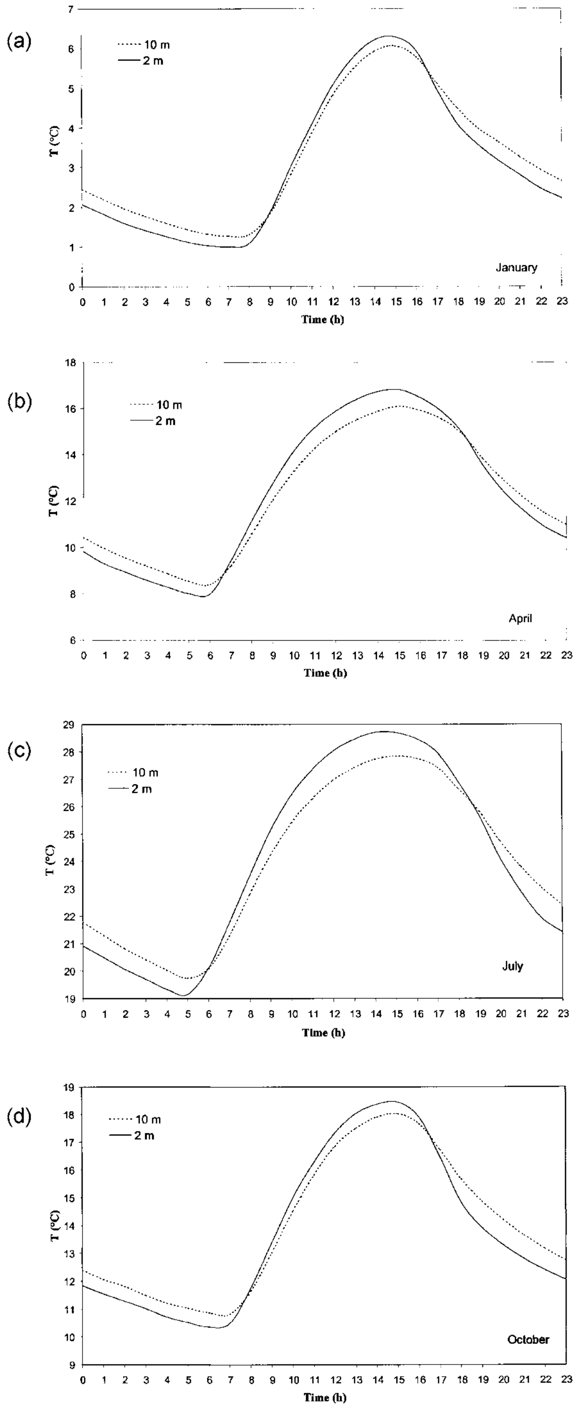


Figure 8. Daily thermal cycles at 2 m and 10 m above the ground from present data (CNR): (a) January, (b) April, (c) July, (d) October.

This method is, in fact, independent of the past daily thermal span ($\Delta T'_d$), but needs the knowledge of at least one of the two daily temperature extremes. This system is easy to use for any time of measurement on condition that the observation falls between the instant of the minimum and maximum temperatures. This procedure is applicable only in the cases (90% of all the data) in which the value of the first measurement is smaller than the second.

7. Homogenisation between Different Series: Correction for Difference in Level and Different Locations

From 1920 to 1977 the Water Magistrate carried out a new series of meteorological observations at a distance of about 750 m from the *Specola*. Temperatures were recorded with a Richard G.M. thermograph, a Six and Bellani and a sling thermometer. There is a long period in which the Water Magistrate data overlap with the *Specola* series, from 1920 to 1956, and again with the Air Force data, from 1951 to 1977. As the main *Specola* series ends in 1956, the series of Padova was continued with the Air Force data, from 1956 to 1990 and with those of the Botanical Gardens from 1990 to today.

The problem in using different sub-series is to find appropriate corrections to obtain a final set of absolutely homogeneous data.

Instead of a direct comparison between the *Specola* and the Air Force series, that have only a five-year overlap, an intermediate use of the Water Magistrate series was preferred, in that it gave better results by virtue of the longer overlap (i.e., 36 yr) between these series. As a first step, the Water Magistrate data were homogenised on the basis of the *Specola* series; then, the homogenised Water Magistrate series were used to homogenise the Air Force data.

The Water Magistrate homogenised data were calculated by means of monthly transfer functions with respect to the *Specola*. The transfer functions are the least square interpolation polynomials obtained comparing, month by month, the first with the second series. The case of minimum temperature transfer function for January is reported in Figure 9.

The influence of anomalous data on the quality of transfer functions was avoided by excluding measurements exceeding 10th and 90th percentiles of the series of daily differences between the two series.

Transfer functions from the *Specola* series to the Water Magistrate series, for minimum and maximum temperatures and for each month are reported in Table III.

Transfer functions from the Air Force series to the homogenised Water Magistrate series, were obtained in a similar way. The results are shown in Table IV.

Finally, transfer functions were calculated in order to homogenise the Botanical Gardens series with respect to the homogenised Air Force series, with a 1980-1990 overlap period. Results are reported in Table V.

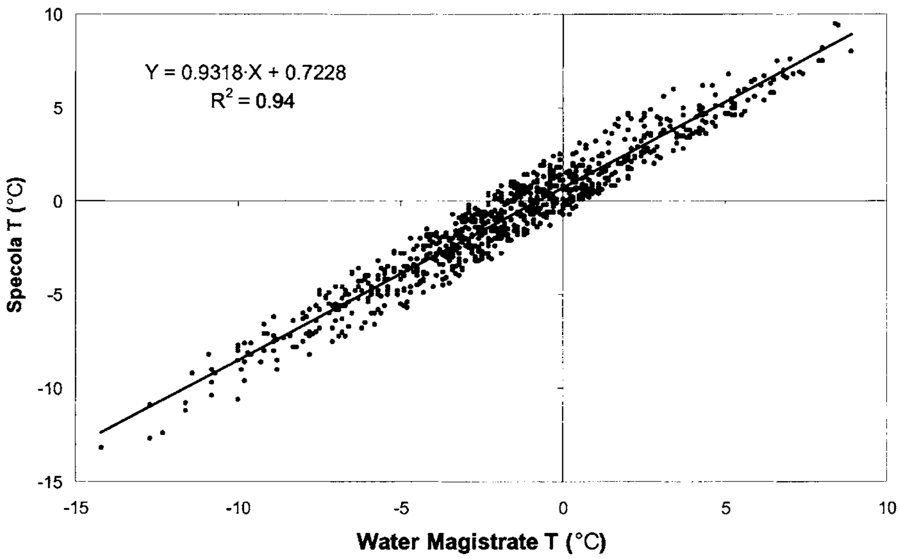


Figure 9. Transfer function from *Specola* to Water Magistrate; January minimum temperatures (1920–1956).

8. Filling Gaps

The presence of gaps in data prevents both completing the series of monthly mean temperatures and analysing interdiurnal variability on a long time scale. Overcoming this problem was obtained with the interpolation of missing data by means of a homogeneous reference series.

The reference series was constructed as correlation coefficients weighted mean of as many neighbouring homogeneous series as possible (Alexandersson and Moberg, 1996). The coefficients were calculated, month by month, correlating, for one common period, the Padova series with other ones. In the case study, the Milan and Mantova series were used as neighbouring reference sites for the common period from 1828 to 1894. The reference series was calculated with the formula:

$$T_{i,j} = \frac{(T_{i,j})_{Mi} \cdot (R_j)_{Mi} + (T_{i,j})_{Mn} \cdot (r_j)_{Mn}}{(r_j)_{Mi} + (r_j)_{Mn}} ,$$

where $T_{i,j}$ is the value for the ith day and jth month, and the Mi or Mn labels indicate the neighbouring series of Milan and Mantova, respectively.

Monthly mean differences between the Padova series and Milan, Mantova and reference series and all the series of daily temperature span were also calculated.

Whenever the Milan or Mantova series presented gaps, it was not possible to calculate a reference series. In this case the only possibility was to use the remaining, neighbouring sites if they were unbroken. If both the series of Milan and Mantova had the same gaps, the procedure changed as explained below. To summarise, there are three possible cases.

Table III

Transfer functions from Specola to Water Magistrate, T_{min} and T_{max}, overlapping period: 1920–1956

Month	T_{min} (°C)	r^2	T_{max} (°C)	r^2
January	$Y = 0.9318 \cdot X + 0.3$	0.94	$Y = 0.9090 \cdot X - 0.1$	0.94
February	$Y = 0.9186 \cdot X + 0.9$	0.95	$Y = 0.9111 \cdot X - 0.4$	0.95
March	$Y = 0.8861 \cdot X + 1.3$	0.94	$Y = 0.9174 \cdot X - 0.1$	0.96
April	$Y = 0.9085 \cdot X + 1.6$	0.94	$Y = 0.9467 \cdot X - 0.3$	0.97
May	$Y = 0.9686 \cdot X + 1.3$	0.95	$Y = 0.9768 \cdot X - 0.5$	0.97
June	$Y = 0.9632 \cdot X + 1.7$	0.94	$Y = 0.9982 \cdot X - 0.7$	0.96
July	$Y = 0.9669 \cdot X + 1.8$	0.93	$Y = 0.9572 \cdot X - 0.4$	0.96
August	$Y = 0.9623 \cdot X + 1.9$	0.93	$Y = 0.9535 \cdot X + 0.2$	0.96
September	$Y = 0.9662 \cdot X + 1.6$	0.95	$Y = 0.9525 \cdot X - 0.1$	0.97
October	$Y = 0.9261 \cdot X + 1.8$	0.94	$Y = 0.9282 \cdot X + 0.1$	0.95
November	$Y = 0.9189 \cdot X + 1.3$	0.95	$Y = 0.9318 \cdot X + 0.0$	0.94
December	$Y = 0.9348 \cdot X + 0.8$	0.95	$Y = 0.9650 \cdot X - 0.2$	0.96

Table IV

Transfer functions from Water Magistrate to Air Force, T_{min} and T_{max}, overlapping period: 1951–1977

Month	T_{min} (°C)	r^2	T_{max} (°C)	r^2
January	$Y = 0.8800 \cdot X + 1.0$	0.92	$Y = 0.8452 \cdot X + 0.4$	0.94
February	$Y = 0.8686 \cdot X + 1.3$	0.95	$Y = 0.8890 \cdot X - 0.0$	0.95
March	$Y = 0.8342 \cdot X + 1.9$	0.94	$Y = 0.8990 \cdot X + 0.3$	0.96
April	$Y = 0.8197 \cdot X + 2.8$	0.90	$Y = 0.9108 \cdot X + 0.7$	0.95
May	$Y = 0.8724 \cdot X + 3.0$	0.90	$Y = 0.9571 \cdot X + 0.4$	0.95
June	$Y = 0.8804 \cdot X + 3.3$	0.90	$Y = 0.9705 \cdot X + 0.4$	0.95
July	$Y = 0.8601 \cdot X + 4.1$	0.86	$Y = 0.8864 \cdot X + 2.2$	0.94
August	$Y = 0.8238 \cdot X + 4.5$	0.85	$Y = 0.8832 \cdot X + 2.5$	0.93
September	$Y = 0.8595 \cdot X + 3.5$	0.90	$Y = 0.8947 \cdot X + 1.5$	0.95
October	$Y = 0.8508 \cdot X + 2.9$	0.93	$Y = 0.8894 \cdot X + 0.8$	0.95
November	$Y = 0.8272 \cdot X + 1.9$	0.91	$Y = 0.8882 \cdot X + 0.6$	0.95
December	$Y = 0.8655 \cdot X + 1.7$	0.94	$Y = 0.9288 \cdot X + 0.3$	0.95

(a) It was possible to reconstruct the reference series.

(b) A reference series does not exist. Gaps can be filled after comparison with the series of Milan, or Mantova.

(c) The same gaps were found in both neighbouring sites.

Table V

Transfer functions from Air Force to Botanical Garden, $T_{\min}$ and $T_{\max}$, overlapping period: 1980–1990

Month	$T_{\min}$ (°C)	r^2	$T_{\max}$ (°C)	r^2
January	$Y = 0.8954 \cdot X - 0.8$	0.79	$Y = 0.8010 \cdot X + 0.5$	0.88
February	$Y = 0.9658 \cdot X - 0.4$	0.91	$Y = 0.9275 \cdot X - 0.4$	0.98
March	$Y = 0.9707 \cdot X + 0.1$	0.91	$Y = 0.9106 \cdot X + 0.3$	0.96
April	$Y = 0.9461 \cdot X + 0.6$	0.91	$Y = 0.9157 \cdot X + 0.6$	0.95
May	$Y = 0.9399 \cdot X + 1.0$	0.95	$Y = 0.9499 \cdot X + 0.3$	0.98
June	$Y = 0.9114 \cdot X + 2.1$	0.94	$Y = 0.9425 \cdot X + 0.7$	0.97
July	$Y = 0.9485 \cdot X + 3.4$	0.93	$Y = 0.8963 \cdot X + 1.6$	0.97
August	$Y = 0.8830 \cdot X + 2.7$	0.92	$Y = 0.9174 \cdot X + 1.2$	0.96
September	$Y = 0.9046 \cdot X + 1.9$	0.92	$Y = 0.9035 \cdot X + 1.1$	0.96
October	$Y = 0.9487 \cdot X + 0.7$	0.94	$Y = 0.8900 \cdot X + 0.8$	0.97
November	$Y = 0.9712 \cdot X - 0.2$	0.93	$Y = 0.8949 \cdot X + 0.5$	0.96
December	$Y = 1.0353 \cdot X - 0.7$	0.91	$Y = 0.9082 \cdot X + 0.6$	0.92

In case (a), the missing data in the Padova series $(T_i)_{Pd}$ were filled using the formula:

$$(T_i)_{Pd} = (T_i)_{ref} - \overline{\Delta(ref - Pd)}$$

where $(T_i)_{ref}$ is the value for the reference series and $\overline{\Delta(ref - Pd)}$ is the monthly mean difference between the reference and Padova series.

In case (b), if at least one of the daily temperature extremes for Padova exists, the other extreme was obtained by:

$$^{\max}_{\min}(T_i)_{Pd} = {}^{\min}_{\max}(T_i)_{Pd} \pm \left(\frac{\overline{(DTS)_{Pd}}}{\overline{(DTS)_{Mi,Mn}}} \right) \cdot (DTS_i)_{Mi,Mn} \ ,$$

where $\overline{DTS}$ (Daily Temperature Span) is the monthly mean of the daily temperature span, is the daily temperature span for the ith day for either the Milan or the Mantova series.

In case (b), again, but lacking both the Padova temperature extremes, the minima and maxima were obtained by the formula:

$$^{\max}_{\min}(T_i)_{Pd} = {}^{\max}_{\min}(T_i)_{Mi,Mn} - {}^{\max}_{\min}\overline{\Delta(Mi, Mn - Pd)}$$

where ${}^{\max}_{\min}\overline{\Delta(Mi, Mn - Pd)}$ is the monthly mean difference between the Padova and either the Milan or Mantova series.

Finally, in the rare case (c), gaps were filled with the monthly mean values of maxima and minima, calculated on the Padova series.

Table VI shows the correlation coefficients and monthly mean differences between series and monthly mean daily temperature span.

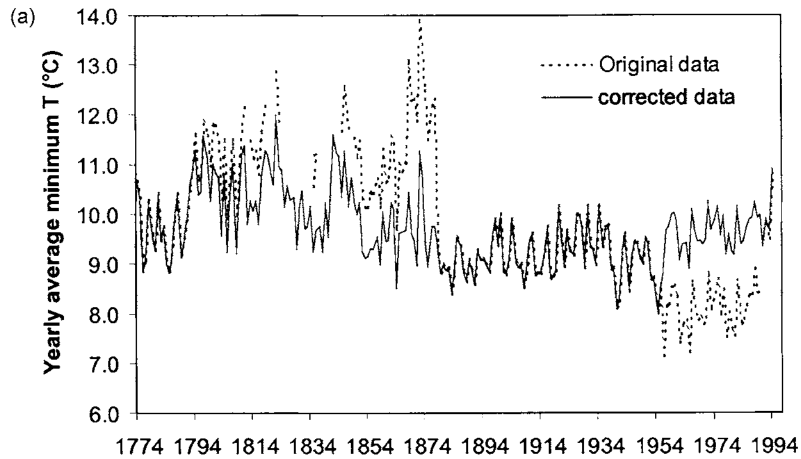
Table VI

Correlation coefficients (r), mean monthly differences Δ(Series-Pd) between a series (ref, Mi, Mn) and Padova (Pd) and monthly mean of the Daily Temperature Span (DTS)

		r_{Mi}	r_{Mn}	$\Delta(ref - Pd)$	$\Delta(Mi - Pd)$	$\Delta(Mn - Pd)$	DTS_{Pd}	DTS_{Mi}	DTS_{Mn}	DTS_{ref}
January	min	0.74	0.68	−1.6	−1.8	−1.5				
	max	0.81	0.77	−0.4	−0.7	−0.2				
	max-min						4.2	5.5	5.5	5.5
February	min	0.69	0.77	−1.1	−1.4	−1.0				
	max	0.72	0.78	0.5	0.2	0.7				
	max-min						4.2	6.9	6.9	6.9
March	min	0.70	0.81	−0.6	−0.7	−0.4				
	max	0.80	0.84	1.7	1.5	1.9				
	max-min						6.2	8.4	8.4	8.4
April	min	0.68	0.72	−0.4	−0.8	−0.2				
	max	0.8	0.83	2.2	1.9	2.5				
	max-min						5.8	9.4	9.3	9.4
May	min	0.70	0.70	−0.3	−0.8	0.1				
	max	0.82	0.84	2.2	1.9	2.5				
	max-min						6.3	10.1	9.6	9.9
June	min	0.64	0.66	−0.3	−1.0	0.4				
	max	0.76	0.76	2.6	2.4	2.9				
	max-min						8.0	11.1	10.0	10.5
July	min	0.56	0.58	−0.1	−0.8	0.5				
	max	0.76	0.77	2.8	2.6	3.2				
	max-min						7.0	11.6	10.5	11.1
August	min	0.57	0.59	0.1	−0.7	0.9				
	max	0.79	0.74	2.5	2.0	2.9				
	max-min						6.9	10.9	9.9	10.4
September	min	0.62	0.71	0.5	−0.6	0.8				
	max	0.81	0.82	1.6	1.2	2.0				
	max-min						6.5	9.3	8.5	8.6
October	min	0.78	0.84	−0.6	−1.4	0.0				
	max	0.84	0.87	0.7	0.1	1.2				
	max-min						6.0	7.5	7.2	7.3
November	min	0.77	0.85	−0.9	−1.5	−0.4				
	max	0.78	0.86	−0.1	−0.6	0.3				
	max-min						4.8	5.6	5.1	5.4
December	min	0.77	0.84	−1.4	−1.7	−1.1				
	max	0.74	0.83	−0.4	−0.7	−0.1				
	max-min						4.2	5.1	5.1	5.0

9. Annual Temperature Series: Corrections and Trends

Results can be summarised with the conclusive drawings (Figure 10a,b; Figure 11a,b; Figure 12a,b) showing the temperature series before and after correction, validation and homogenisation, and then reporting the algebraic sums of the corrections.



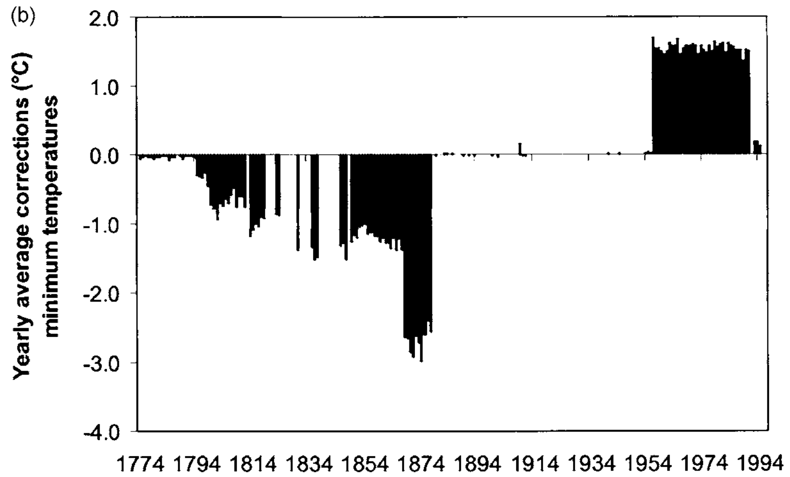


Figure 10. (a) Yearly average of minimum temperatures before and after correction; (b) yearly algebraic sum of the corrections for minima.

The temperature minima, which had to be observed at uncomfortable hours, needed more corrections than the maxima, taken more easily after noon. The corrections for the minima often had the opposite sign than for the maxima. In the mid 1800s, large errors arose due to an inappropriate observing schedule. Until 1878, when automatic measurements of minima and maxima were introduced, it was necessary to apply corrections that lowered the observed minima. On the contrary, the minima of modern observations after 1956 were corrected with an increase of temperature for reasons of homogeneity, recent data were measured at standard meteorological screen height, instead of 17 m above ground as the main body of the series, measured at the *Specola* tower.

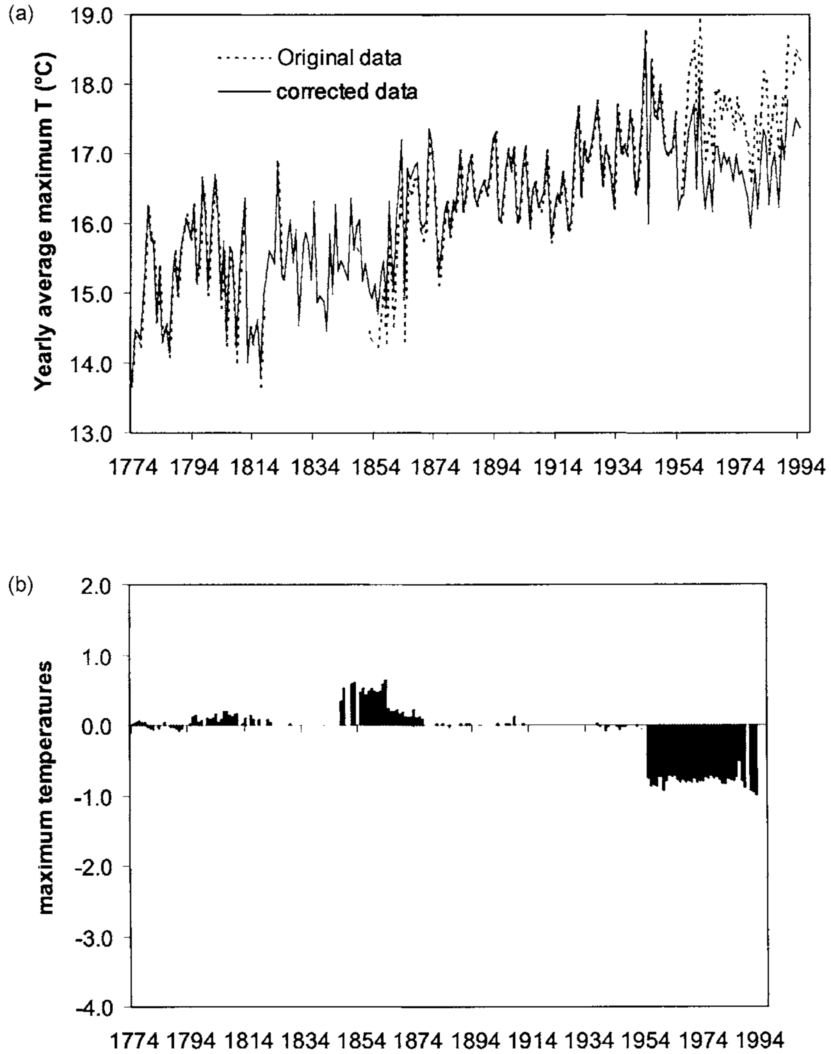


Figure 11. (a) Yearly average of maximum temperatures before and after correction; (b) yearly algebraic sum of the corrections for maxima.

On the other hand, the maxima were corrected by increasing their level in the early period when they were measured not at the appropriate moment but slightly after noon. The error in the mid 19th century is still visible. The maxima of the recent period (after 1956) were attenuated by making them homogeneous with the previous observations performed at a greater height.

As a consequence, the daily temperature span was increased for the early period prior to 1878 and was decreased after 1956.

The linear trend observed for the bulk original, uncorrected and non-homogenised series from 1774 to 1997 is nearly stationary, or slightly positive, +0.07 °C/100 yr,

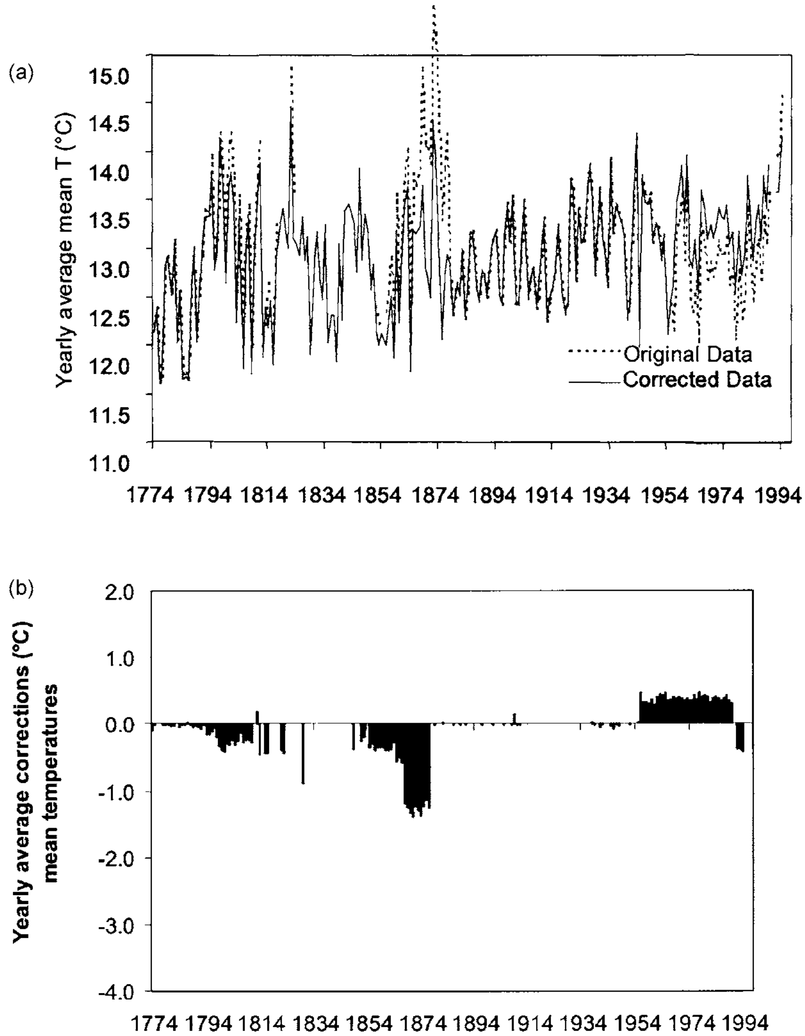


Figure 12. (a) Yearly average of mean temperatures before and after correction; (b) yearly algebraic sum of the corrections for averages.

but with a drop −0.14 °C in the last 130 years. This was especially due to the inclusion, for the modern period, of standard data taken at a lower height. After correction, validation and homogenisation, the trend has a more marked increase of +0.31 °C/100 yr over the entire period, with a +0.44 °C warming in the last 130 years, which can be compared with the +0.6 °C found by Jones.

10. Conclusions

The completeness of the long temperature series of Padova (1725–today) ensures an excellent opportunity to study local climate variability during the last three centuries. Creating a network of long meteorological series is then possible to evaluate climate change on a global scale. In this way, it is possible to extend, back in time, the results by Jones (Jones, 1985), who estimated $+0.6\,^{\circ}$C warming in the last 130 years for the Northern Hemisphere. This result was assumed to be free from errors as the average of some 3000 series of data.

In reality, long time series are affected by many kinds of systematic errors, as demonstrated by this case study. This work has cleared the Padova series from errors, has validated it and has arrived at a homogeneous and reliable long time series, after having clarified uncertainties about the exposure and operational procedures that the historical analysis of existing metadata was unable to solve. The comparison between the parallel sub-series of Padova and the analysis of interdiurnal variability allowed us to: (i) identify instrument relocation, replacement and re-calibration and indoor or outdoor exposure, (ii) recognise changes in observing schedule, (iii) discriminate the climatic signal from noise generated by errors or inhomogeneities.

This research emphasises once again the need for a critical revision of series in view of a more precise interpretation of climate change. This is especially true in the case of systematic errors generated by international directives about observation modalities, which have caused the same kind of inhomogeneity in all the series.

Acknowledgements

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CALIBRATION AND INSTRUMENTAL ERRORS IN EARLY MEASUREMENTS OF AIR TEMPERATURE

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Abstract. Calibration and instrumental errors of early thermometers are analysed. The first concepts, the development of scientific ideas, the main problems linked to the construction of early thermometers and the calibration are considered in order to evaluate errors. The operating principle of the '*constant-volume*' air thermometer is presented and its limits are discussed. The theory shows that for an ideal Amontons' thermometer, only one calibration point is sufficient from which the other can be calculated; it is therefore possible to determine the difference from an ideal instrument. A comparison is made between calibrations and instruments made by G. Amontons (1699), G. Poleni (Venice, 1709; Padova 1725), and J.H. Lambert (1779). Amontons' thermometer needs to be integrated with a barometric reading; an important error arises from the different density of mercury during calibration and usage. The calibration was made in winter and at the upper point the thermometer was at 100 °C, while the barometer remained near 0 °C. However, field observations were made with both instruments at the same temperature and this caused an error that in the cold season is negligible, but in the hot season reaches 1 °C. Problems connected with the calibration and scale linearity are discussed in view of the beliefs of the time and the operative methodologies used in early meteorology. Emphasis is given to comparability of different instruments, thermometric scales and calibration methodologies used in Padova in the 18th century for Amontons', Poleni's, Fahrenheit's, Réaumur's and Delisle's thermometers. The instrument supports and the incision of the scale were subject to expand or contract depending on temperature or humidity changes, and this was a source of error that can be corrected with the help of observed or estimated data. Problems linked to the construction of thermometers have been evaluated, as well as the linearity of displacements of the thermometric liquid, or the drift due to ageing and transformation of the thermometric liquid, the glass or the support. All these errors have been evaluated and some of them have been found negligible, but some are of the order of 0.5 °C. The quantitative results obtained here can also be usefully applied to correct and validate other long series.

1. The Invention of the Air Thermometer and Its Improvements

From December 1592 to 1610, Galileo Galilei (1564–1642) was appointed to the chair of Mathematics at Padova University and invented the early prototype of the air thermometer slightly after his arrival, very probably in 1593 (Giovanfrancesco Sagredo, 1612; 1613; 1615; Benedetto Castelli, 1638; Vincenzio Viviani, 1654; Targioni Tozzetti, 1780; Renou, 1875; Favaro, 1883; Boffito, 1929; Middleton, 1966; Frisinger, 1983). The instrument was a glass vessel filled with air and fitted to a vertical tube with the lower extremity immersed in water, or in red wine, to better show the height of the column of liquid in the tube when the vessel was heated.

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In reality, the instrument was a thermo-baroscope, as it responded to both the air temperature and pressure, and it needed improvement. Santoro Santorio (1561–1636), a medicinal doctor appointed to the same University to teach Medicine one year after Galileo's departure, applied a quantitative scale to the air thermoscope to measure human body temperature during illness. As the thermoscope responded to both temperature and pressure, Santorio eliminated the undesired pressure influence with the help of a compass, by adding or subtracting the variation of the day from the reference value which was established by measuring a healthy body temperature.

The first attempt to transform the thermo-baro-scope into a thermometer was jointly made by Ferdinand II of Tuscany (1610–1670) and Evangelista Torricelli (1608–1647) in 1641. They invented various thermometers, but the key point was that they hermetically sealed the tube by melting the glass tip, allowing heat, but not pressure exchanges across the instrument. Another key step was the use of spirit as a thermometric fluid; the Florentine thermometer used later by the *Accademia del Cimento* was a spirit-in-glass thermometer.

Towards the end of the 1600s, the air thermometer was studied by numerous scientists and the most important work was carried out be Guillaume Amontons (1663–1705). On the basis of his experiments, Amontons (1695; 1702) showed that the pressure of different quantities of air increased by the corresponding rise in temperature and that the relationship between pressure and temperature was independent of initial pressure. He thus postulated a linear relationship between pressure and temperature (Taton, 1961; Middleton, 1966).

Amontons' thermometer was popular at the end of the 17th century and beginning of the 18th. It was essentially derived from the Galileo's thermo-baro-scope, and the measuring apparatus is similar to that of a manometer. It consists of a J-shaped glass tube (a capillary) with an ampulla; the upper end of the tube is open and the other is sealed to a closed ampulla (Figure 1). An air pocket entrapped by mercury in the upper part of the ampulla acts as a thermometric substance; the mercury also fills the capillary up to a certain height, compressing the air pocket.

In practice a rise in the ambient temperature T results in a rise of the mercury column in the capillary. However, the capillary being open, an increase in the atmospheric pressure is reflected in a lowering of the mercury in the capillary, so that this apparent depression must be compensated by adding the barometric variation to the thermoscopic reading. From this point of view, the name 'thermometer' for this instrument is inappropriate, as it gives only one of the two readings necessary to determine the temperature, and only the sum of the two readings, i.e. Amontons' thermometer and the barometer, gives the real temperature. As these pressures were given by the heights of the mercury columns in the thermometer and the barometer, a measure of length represented either the pressure in the ampulla or the air temperature. The disadvantage was the need of two instruments to determine the temperature.

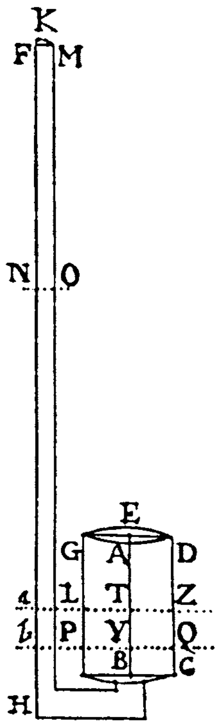

Figure 1. Amontons' thermometer: a J-shaped glass tube with an ampulla. The air pocket entrapped in the cylindrical ampulla expands displacing the level of mercury from the initial level LTZ to the final level PYQ, in the ampulla, and from NO to FM in the tube. The height of the column was from LTZ to NO before warming; and from PYQ to FM after warming (After Poleni; 1709).

Giovanni Poleni (1683–1761) started his early measurements at Venice with Amontons' thermometer (Poleni, 1709), he then moved to Padova where he made measurements in the period 1716–1717 and 1725–1761 with the same type of instrument (Camuffo, 2002), continuing the local tradition of gas thermometers. In his Venice (1709) and first Padova (1716) calibrations, Poleni used Paris inches; in the better-known second Padova calibration (1725), Poleni used London inches and each degree, 1 °Po, corresponded to 1 Hg London inch.

At the beginning of the 18th century the *Accademia delle Scienze e delle Arti*, Bologna, studied the air thermometer to determine the working principle and the possibility of comparing measurements taken with different instruments; the results were published in the *Commentaries* (Baiada, 1986; Lo Vecchio and Nanni, 2000). It was noticed that various Amontons' thermometers did not always give the same results. Some scholars put this down to the different sizes of the bulbs, while others thought it was due to the different ratio between the size of the bulb and the capillary. The most common belief however, was that the variety of results was due to the different kinds of air found in the thermometer bulb. In particular, Philippe de la Hire (1640–1718) in Paris and Vittorio Francesco Stancari (1678–1709) in Bologna demonstrated that thermometers behaved differently when very humid air was used (because of the problem of moisture condensation). They underlined the need to utilise dry air when constructing instruments in order to get comparable readings. Around 1707 Stancari sealed the longer arm of the tube, thus leaving a vacuum between the surface of the mercury and the end of the tube, in order to make the air thermometer independent from the barometric pressure. This instrument was less popular than Amontons' thermometer, probably because Stancari was less renown and had a short life, and also because the need for an additional barometer reading was not a problem for weather observers.

The observations carried out from 1716 to 1737 in Bologna by Jacopo Bartolomeo Beccari (1682–1766), and called '*Meteorological Ephemerides*', were taken with Stancari's thermometer whose original calibration is reported in the register. The register with an original copy of the data (i.e., collected by Beccari) is still preserved in the Astronomic Observatory of the University of Padova. In a previous study of these data (Comani, 1987), the scale passed unobserved and was erroneously considered unknown, so that the instrument was calibrated with the comparison with some series from Tuscany. However, the crucial error was that the instrument was, by mistake, believed to be Amontons' thermometer and, consequently, the barometric heights were summed to the temperature readings. The result was the addition of noise with the same order of magnitude of the observation. The early part of the Bologna series needs complete careful revision, with the recovery, validation, correction and homogenisation of the original data, and this is underway.

In the early period of meteorology, Amontons' air thermometer was a key instrument. In general, the interest for the air thermometer started to decline in mid-17th century, and sealed glass thermometers containing a liquid became more and more popular.

2. The Operating Principle of Amontons' Air Thermometer

In the ampulla, a change in ambient temperature dT determines a change in the pressure dP and volume dV of the air pocket, which is obtained by differentiating the equation of state for perfect gases, i.e.,

$$dT = \frac{P_0\,dV + V_0\,dP}{nR}\,, \tag{1}$$

where n is the number of air moles entrapped in the pocket, and R the gas constant for air. From the instrument features, it is easily seen that

$$dV = S_a dh_a = S_c dh_c \tag{2}$$

$$dP = \rho\, g\, dh_c\,, \tag{3}$$

where S is the section, h the height of the mercury; the labels a and c refer respectively to the ampulla and the capillary; ρ is the density of the mercury and g the acceleration of gravity. After substitution of the formulae for dV and dP in the above equation, one obtains

$$dT = \frac{P_0 S_c + V_0 \rho g}{nR} dh_c , \tag{4}$$

i.e., a change dT results in a change dh_c observable in the capillary, and the sensitivity of the instrument dh_c/dT is directly proportional to the number of moles entrapped in the air pocket, and inversely proportional to the sum $P_0 S_c + V_0 \rho g$ where the second term is the dominant one.

In the capillary, the change dh_c in the height of mercury, determines in the ampulla a change in volume $dV_c = -dV_a = S_c dh_c$ and a change in pressure $dP = \rho g dh_c$. The ratio

$$\frac{dV_a}{dP} = \frac{S_c}{\rho g} \tag{5}$$

is of the order of 2.5×10^{-3} cm^3/hPa for a capillary radius $r = 1$ mm, and 6.1×10^{-2} cm^3/hPa for $r = 5$ mm (1 mm-Hg = 1.333 hPa). The smaller the capillary section S_c, the smaller dV compared to dP and the better the '*constant-volume*' approximation.

When the capillary is very thin and S_c approaches zero, and at the same time the air pocket volume V_a is large enough, then in Equation (4) the term $P_0 S_c$ can be neglected when compared to $V_0 \rho g$. In this case,

$$dT = \frac{V_0 \rho g}{nR} dh_c = \frac{V_0}{nR} dP \tag{6}$$

which is the equation for constant-volume gas thermometers. Under these conditions, P is proportional to T, the coefficient of proportionality being V_0/nR. In Amontons' real themometer, V remains (nearly) constant and P is (nearly) linearly proportional to T. Finally, the change in level of mercury in the ampulla $\Delta h_a = \Delta h_c \times \Delta S_c/S_a$ depends on the ratio of the sections of the capillary S_c and the ampulla S_a. The smaller this ratio, the more stable the level of mercury in the ampulla, to which the 'zero' of the scale refers, and the more reliable the readings on instruments with (necessarily) fixed scale. A good Amontons' thermometer has, therefore, a thin capillary and a wide ampulla.

The thermometer regularly used by Giovanni and Francesco Poleni in Venice (1709) and Padova (1716–1717 and from 1725 to 1764) was built and calibrated by G. Poleni following Amontons' indications, and was described in a paper (Poleni, 1709) and a letter to James Jurin (Poleni, 1731). Unfortunately, the original thermometer did not survive, although four drawings in Poleni's (1709) paper present the same ratio 1:25 between the section of the capillary and the ampulla. As the ratio is always the same, we are induced to suppose that this was not casual. Some

58 years later, when practice and theory were more consolidated, Hemmer (1783) used the ratio 1:81 for his measurements in Mannheim.

In conclusion, every imbalance in T reflects in a well-determined change in P and a very small change in V. If the capillary is thin, and ΔV is negligible, then in a good approximation, ΔP is linearly proportional to ΔT, with two practical consequences: (i) changes in ambient temperature can be measured by observing changes in the height of mercury in the column; (ii) the actual value of the temperature is obtained by measuring the total pressure in the ampulla, i.e., the sum of pressures in the thermometer and the barometer.

Another problem arises with this thermometer. A drift toward lower temperatures has been noted for Amontons' thermometer used by Poleni in Padova. In the period 1740–1758, when comparison with other independent and reliable thermometers was possible, the drift was of the order of 0.2 °C/yr. Another similar drift was found for the Beccari series in Bologna, but for Stancari's air thermometer. The drift occurred because of a progressive displacement of the zero reference level, but a downward slipping of the scale occurring at constant speed for tens of years is not credible. In fact, the scale was stuck on the frame and the capillary was attached to it with an iron wire, so that in the case of slipping we would expect a downward displacement of both the capillary and the ampulla, which would have the opposite effect, i.e., a relative rise of the scale. The other alternative is a constant rise in the free level of mercury in the ampulla, as if the air pocket were being progressively reduced. We should exclude air migrating and escaping across the glass ampulla. Water vapour can interact with the glass and disappear from the gas phase, but the amount is too little and insufficient to have this effect. A tentative explanation might be that some air escaped through an accidental crack in the glass of the ampulla, under the pressure exerted by the mercury column. Another tentative explanation might be that, in the long run, the oxygen entrapped in the ampulla may combine with the mercury and possible impurities, thus diminishing the air pocket. In the literature we find that mercury and oxygen are unstable with respect HgO at room temperature, and that their rate of combination is exceedingly slow; the reaction proceeds at useful rate at 300 to 350 °C, and reverses over 400 °C (Cotton and Wilkinson, 1972). The very slow kinetic might explain why the drift (and the reaction) was still continuing in 1758, i.e., at least 33 years after the calibration in 1725. Another possible explanation might be that the glass ampulla and tube underwent a plastic drift which altered the volume. Angelo Bellani (1808) analysed the drift of the zero in thermometers with accurate laboratory tests. He found two causes: the first due to abrupt changes in temperature, e.g., during calibration; the second due to glass ageing with the shift continuing for about one year. According to César Mansuète Despretz (1837), the drift for glass ageing (of course glass of his century) can continue for four or five years. However, a drift for glass ageing which continued for more than thirty years is hardy believable. None of the above hypotheses is fully convincing.

Returning to the gas thermometer, if the reason for drift is some air escaping from the ampulla, or the subtraction of oxygen through oxidation, we can distinguish two cases. When $P_0 S_c \ll V_0 \rho g$, the air pressure in the ampulla is proportional to the actual temperature through the coefficient n/V_0, and the loss of air or oxygen diminishes in the same proportion both n and V_0, leaving their ratio unchanged. The response of the instrument remains the same, i.e., the same displacement of the column for the same change in temperature, except for a shift in the values. Therefore, a good Amontons' thermometer is unaffected by the reduction of the air pocket, e.g., for oxidation of mercury, except for the zero of the scale that is displaced. When $P_0 S_c$ is not much smaller than $V_0 \rho g$, the thermometer needs to be re-calibrated.

3. The Operating Principle of the '*Constant-Volume*' Air Thermometer

In a '*constant-volume*' thermometer, a change in temperature is reflected in a change in pressure, with the volume remaining constant, and Amontons' and Stancari's thermometers can be thus classified in a first approximation because of certain complicating factors which cause small departures (McGee, 1988). It is possible to demonstrate that this thermometer tends to keep the volume $V =$ constant. In fact, we can suppose that changes in ambient air temperature T induce changes in both P and V in the air pocket entrapped in the ampulla, which passes from the initial state T_0, $P_0 V_0$ to a new state T_1, $P_1 V_1$. The latter is not defined by any of the infinite pairs $P_1 V_1$ lying on the isothermal hyperbola $T_1 =$ constant in the phase diagram, but only by the pair in which $V_1 = V_0$, or with V_1 very close to V_0. In fact, in the air pocket ΔT_1 determines a rise in pressure $\Delta P_1 = P_0 - P_1$ which, in the capillary, generates a rise of mercury Δh_c such that $\Delta P_1 = \rho g \Delta h_c$. Similarly, ΔT_1 may expand the air pocket by $\Delta V_1 = V_0 - V_1$, and in turn ΔV_1 displaces the same volume of mercury $\Delta V_1 = \Delta h_a \times S_a$ and forces it to rise into the capillary by $\Delta h_2 = \Delta h_a \times S_a/S_c$ increasing the hydrostatic pressure, at the base of the column and in the air pocket, by $\Delta P_2 = \rho g \Delta h_2$. Actually, ΔP_2 is overpressure in excess above the equilibrium value P_1, whose effects are: (i) to oppose expansion ΔV_1 which has generated ΔP_2; (ii) to compress the air pocket; and (iii) to return to the initial volume V_0. The opposite occurs if ΔV_1 is negative. Therefore, the equilibrium is displaced toward the pair $P_1 V_0$, although in practice there is a minor departure ΔV due to the volume of mercury transferred from the ampulla to the capillary and the adjustment for the differential expansions of the other materials (i.e., mercury, glass).

Typical causes of error in early gas thermometers were not only the undesired expansion of mercury and glass, but also condensation of moisture in the air pocket, or release of air bubbles which initially adhered to the glass. For this reason, the mercury was inserted gradually, at high temperature, and mixed with an iron wire, when the tube was wide enough. In the case of a thin capillary, the top was provided

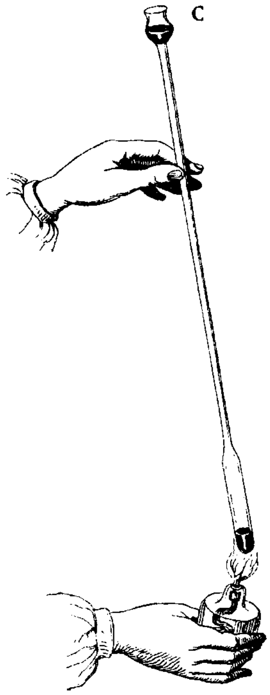

Figure 2. Filling the bulb with mercury. C is a reservoir on the top of the capillary that will be removed after operation (after Ganot, 1860).

with a reservoir-funnel and the bulb was heated over a flame so that some of the bubbles of dilated air escaped from the capillary (Figure 2). The operation was repeated until all the air escaped. Then the mercury was brought to ebullition to completely remove any residual part of air. At this point, the mercury was expanded up to the end of the capillary, the reservoir was removed, and the top of the capillary sealed. At room temperature, the mercury retreated leaving only mercury vapour in the upper part of the capillary. Many early thermometers were not sealed and still preserve the reservoir at the top.

As opposed to the '*constant-volume*' thermometer, the '*constant-pressure*' type has a (nearly) constant pressure, and the volume expansion is the main variable on which measurements are based. Henri Victor Regnault (1847) demonstrated that these two thermometers are very nearly equivalent, although the constant-volume is to be preferred for its better manageability (Middleton, 1966). In modern gas thermometers, the manometer tube is free so has to be displaced vertically, to make the level of the mercury in the ampulla coincide with the zero of the scale, thus keeping the volume of the air pocket constant (Yavorsky and Pinsky, 1979). The same goal can be attained with a fixed apparatus, but by adding or subtracting mercury (Doebelin, 1990).

4. A Comparison between Calibrations and Instruments Made by G. Poleni (Venice, 1709; Padova, 1731), G. Amontons (1699) and J. H. Lambert (1779) and the Equation for an Ideal 'Constant-Volume' Thermometer

G. Poleni built and calibrated Amontons' thermometer when he lived in Venice (Poleni, 1709). After going to Padova, he took measurements in his first house for a short period (1716–1717) with an unknown scale, and then made regular observations in his second Padova house from 1725 to 1761. In these three cases, however, the response of the thermometer was different, and we found it extremely instructive to understand why. Possibly the instrument was the same, and the scale changed after having replaced the mercury (and the air pocket) after the move from Venice to Padova in 1709, and/or after the second move in 1718. When the mercury was again poured into the instrument, a slightly different air pocket was included. Another possibility is that the thermometer was transported first from Venice to Padova, and then from the first house to the second one, without removing the mercury, and that a small bubble of air escaped from the air pocket as a consequence of a shock during the move. The distance from Venice to Padova is some 37 km and the transport needed was first a boat and then a chariot; the distance from the two houses in Padova was slightly more than one mile, and required the use of a chariot. In the Venice calibration (Poleni, 1709), when the ampulla was immersed in boiling water, the difference in the level between the free surface of the mercury in the capillary and the ampulla was 45 Paris inches (one Paris inch being equal to 27.07 mm) when the barometer indicated the 'standard' atmospheric pressure corresponding to 28 Paris inches (i.e., 758 mm Hg). This is equivalent to saying that the air pressure in the ampulla corresponded to $45 + 28 = 73$ Paris inches = 68.5 °Po, which was the upper fixed point. Poleni, and his colleagues, disregarded the atmospheric pressure during the calibration and the error (that at 758 mm was −0.074 °C) will be discussed later. When the thermometer was immersed in water with melting ice, the mercury dropped by 21 inches, i.e., 52 Paris inches = 48.9 °Po. In the second, and the only known Padova calibration, the boiling point was 63.1 °Po and the freezing point was 47.3 °Po.

We can verify the quality of Poleni's instrument. First we will look at the ratio $R_p = P(100\,°\mathrm{C})/P(0\,°\mathrm{C})$ of the pressures in the ampulla at the two calibration points. In the Venice calibration (Poleni, 1709), $R_p = 1.404$; in the Padova calibration (Poleni, 1731), $R_p = 1.33$. These findings can be compared with the similar results by G. Amontons (1699), i.e., $R_p = 1.404$ (identical to Poleni), and Johan Heinrich Lambert (1779), i.e., $R_p = 1.370$ (Schooley, 1986). In theory, this ratio should equal 1.366 as we will see later. It is now possible to pass to calculate the ratio $R_v = V(100\,°\mathrm{C})/V(0\,°\mathrm{C})$ of the volumes of the air pocket at the two fixed points. From the equation of the state for perfect gases, one obtains

$$R_v = \frac{P(0°\mathrm{C}) \times nR\,373}{P(100°\mathrm{C}) \times nR\,273} = \frac{R_T}{R_P} \tag{7}$$

where $R_T = 373/273 = 1.366$ is the ratio of the calibration temperatures, in K. In the case of Poleni, Venice calibration, $R_v = 0.973$; in the Padova calibration, $R_v = 1.024$, i.e., still close to 1, within $\pm 2.7\%$. The same ratio can be calculated for Amontons' and Lambert's instruments, i.e., $R_v = 0.973$ and $R_v = 0.997$, respectively. The closer to 1 this ratio, the more accurate the instrument and its calibration. This comparison shows that the quality of Amontons' and Poleni's original instruments was substantially the same; Lambert's was better, i.e., 3‰. These departures are justifiable in terms of the limits of the instrument, small experimental errors, the approximation used to make a round figure of the readings, and the absence of further corrections for thermal expansions.

Poleni built his instruments and described them in his papers; the hypothesis that Poleni made more than one of Amontons' thermometers is not confirmed by documentary research, and this induces us to think that the instrument in Venice and the two in Padova were the same, although with different fixed points. In Padova, the scale was changed from Paris to London inches following Jurin's (1723) invitation, but this is not overly relevant. It is reasonable to think that the substantial change occurred when the mercury was removed and then poured back into the instrument or with the loss of small air bubbles during one or both of the moves.

The size of the air pocket, the number of moles in the ampulla and the pressure impressed by the mercury in the capillary tube characterise the response of each instrument. Calculating the ratio P_V/P_P between the air pressures in the ampulla in the Venice and the second Padova calibration, one obtains for the freezing point $(P_V/P_P)_0 = 1.032$ and for the boiling point $(P_V/P_P)_{100} = 1.085$. As $P_V/P_P = n_V V_P / n_P V_V$, where the labels V and P refer to Venice and Padova, respectively. This suggests that in Venice and in Padova the instrument was essentially the same although it met with some mishaps during its journeys with the consequent change in calibration. The calculation of the ratio n/V allows one to compute the mass of air per unit of volume of the ampulla and, therefore, the ratio δ between the density of the air in the ampulla and the standard atmosphere in Venice and Padova at the two fixed points, i.e., $\delta_V(100) = 2.77$; $\delta_V(0) = 1.98$; $\delta_P(100) = 1.99$; $\delta_P(0) = 1.63$. The ratio δ_P/δ_V for the two fixed points gives $(\delta_P/\delta_V)_0 = 0.823$ and $(\delta_P/\delta_V)_{100} = 0.718$, which supports the hypothesis of the same instrument, but with a loss of air, or a re-filling with less air.

If the same instrument was used in 1709 and after 1725, it was also used in the early Padova period 1716–1717, prior to the move to the second Padova house, when the mercury was possibly removed again for the move. With a good Amontons' thermometer, it is possible to calculate an unknown scale, i.e., the second fixed point, when the first is known. In fact, the zero can be approximately determined after days of snow and rain, and the unknown boiling point can be calculated with the help of Equation (7), which assumes the form:

$$P(100\,°\mathrm{C}) = P(0\,°\mathrm{C}) \times R_T/R_v = 1.366 \times P(0\,°\mathrm{C})\,, \tag{8}$$

where $P\,(0\,°C)$ is the temperature in °Po (which equals the pressure in London inches) at 0 °C, $R_T = 1.366$ and $R_v = 1$. For an ideal Amontons' thermometer, only one calibration point is sufficient and the other can be calculated, giving the unknown scale. For the above thermometers, the departures Δ of Equation (8) from this thumb rule lay between $\Delta = +2.78\%$ (Amontons and Poleni at Venice) and $\Delta = -2.63\%$ (Poleni at Padova); the best instruments were built by Lambert, with $\Delta = 0.29\%$. The absolute error increases as far as T departs from 0 °C, if the calibration is made with freezing point. Using *constant-pressure* air thermometers, which are regulated by the same Equation (8), but with V instead of P, Joseph-Louis Gay Lussac (1802) found ratios R_v from 1.375 to 1.380 (Schooley, 1986). The departures Δ were 0.66 and 1.02%. In the worst case (i.e., Amontons, or Poleni at Venice), in winter the error is negligible, and in summer the error remains smaller than 1 °C even when the ambient temperature reaches 35 °C.

It is now possible to examine the first, unknown, Padova calibration (observations 1716–1717). The register reports, among others, a column named '*barometric height*' and one named '*thermometric height*'; the unit is Paris inches, for the data of atmospheric pressure range around 27 and 28 inches. Snow occurred on 1, 13, 20, 22, 28 and 29 January 1716 and the previous and the next of each of these days were slightly milder and above zero (e.g., rainfall), so that on these days the temperature was close to 0 °C. Summing the two heights, the freezing point was determined as the average of these days, i.e., 71.93 inches = 67.49 °Po, and the upper point calculated with Equation (8) was 92.19 °Po. These values are too elevated when compared with the other two calibrations, and application is unrealistic, as summer temperature would reach some 15 °C. As a consequence, we should assume that the '*thermometric height*' represents the so-called '*true thermometric height*' i.e., the sum of the two heights in the thermometer and the barometer columns. Under this hypothesis, the freezing point is 44.47 Paris inches and the upper point is calculated at 60.75 inches; a transformation to °Po gives 41.72 and 57.00 °Po, slightly below the previous and the next calibrations. The hypothesis of air bubbles escaped during the moves should be rejected for it requires the fixed points midway between the Venice and the second Padova calibration. We should conclude that the mercury was removed at each move, except in 1761 when the mercury was preserved inside to avoid changes in the calibration.

An application of the above scale to the 1716–1717 series gives realistic results, in agreement with the local seasonal averages and can therefore be accepted.

5. Errors Due to Different Density of Mercury in Amontons' Thermometer

This section is necessary to understand the corrections that have been applied to the series of Padova for the period 1725–1764 (Cocheo and Camuffo, 2002) to correct data for calibration errors and dimensional changes in the wooden support.

Poleni called '*true thermometric height*' h the sum $h = h_c + h_b$ of the height of mercury columns h_c and h_b observed in his Amontons' thermometer and the barometer, and noted h in his register (Poleni, 1731). The sum $h_c + h_b$ represents the actual value of T only when both h_c and h_b are determined at the same ambient temperature T. This can be demonstrated as follows. The pressure P inside the ampulla is given by the sum of the two pressures that can be written according to Stevin's law:

$$P = \rho g h_c + \rho g h_b \,, \tag{9}$$

where ρ is the density of mercury, g the acceleration of gravity. By substituting P from equation of state for perfect gases, one obtains:

$$T = (h_c + h_b)\rho g V/nR \,, \tag{10}$$

where the sum $h_c + h_b$ is proportional to T. This sum was independent of atmospheric pressure, in that in the case of changes of atmospheric pressure Amontons' thermometer was similar to an inverse barometer and its decreasing mercury column compensated exactly for the increase of the barometer, and vice versa, so that $\Delta h_c = -\Delta h_b$. In the case of the Padova series h_c was in the region of 50–60 cm and h_b was 70–80 cm.

The height h_c was not affected by large errors resulting from the variation in the density of mercury induced by temperature changes, in that the calibration included this effect at two fixed points, and each intermediate temperature was correctly evaluated, except for a slight departure from linearity, typical of mercury.

On the other hand, the barometric reading h_b caused an error, which was particularly large in the summer, which is evaluated as follows. If, in the first approximation, ρ is independent of T, Equation (10) is always true. However, with reference to the explicit expression of $\rho(T)$:

$$\rho(T) = \rho_0/(1 + \beta T) \,, \tag{11}$$

where ρ_0 is the density at $T = 0\,°\mathrm{C}$ and $\beta = 0.1818 \times 10^{-3}\,°\mathrm{C}^{-1}$ is the cubic expansion coefficient of mercury, the problem arises when the mercury in the two columns has different temperatures T_c and T_b. Therefore, in Equation (10) each height, h_c and h_b, should be multiplied by the respective density $\rho(T_c)$ and $\rho(T_b)$, while $h_c + h_b$ is no longer proportional to T_c. This problem does not depend on the observational procedure, in that Poleni had the barometer and the thermometer in the same room, therefore, T_c was close to T_b. The error may arise in the case of the barometer at room temperature T_b and the thermometer exposed outdoors at a very different temperature T_c.

In the realistic case that the calibration was made in winter (in order to have snow or ice), the thermometer was immersed in snow or melting ice, and the barometer was at ambient temperature close to 0 °C. At the zero point $T(0)$, T is proportional to $h_c + h_b$ in the resulting calibration, as seen above. At the upper point, the actual problem consists in the method of calibration, because the thermometer was at boiling point, while the barometer remained at ambient temperature, near 0 °C. With regards to the point $T(100)$ corresponding to boiling water, the thermometer was situated at a temperature of 100 °C while the barometer remained at 0 °C so that the situation at the two fixed points was, respectively:

$$T(0) = [h_c(0) + h_b(0)]\rho(0)gV/nR \tag{12}$$

$$T(100) = [h_c(100)\rho(100) + h_b(0)\rho(0)]gV/nR \tag{13}$$

Field observations were made under conditions which were different from the calibration, i.e., with the two instruments at the same temperature. There is no error if the two readings are made separately and multiplied by the appropriate mercury density. For example, in the event of a field observation at 30 °C, the direct reading of the two instruments gives:

$$T_{\text{obs}} = [h_c(30) + h_b(30)]\rho(30)gV/nR \tag{14}$$

while reference to the calibration conditions gives

$$T_{\text{cal}} = [h_c(30)\rho(30) + h_b(0)\rho(0)]gV/nR \tag{15}$$

However, Equations (14) and (15) give the same result because of the difference

$$[h_b(30)\rho(30) - h_b(0)\rho(0)]gV/nR = 0 \tag{16}$$

for the elongation of the mercury column is directly compensated by its diminished density, as can be easily demonstrated with the help of Stevin's law. However, a large error derives from the fact that only the heights h_c and h_b were read, without multiplying them by the due density value or correcting the barometer reading for expansion. In winter, temperatures were close to calibration conditions (cold thermometer and barometer) and therefore reliable, while summer measurements were less accurate. It is possible to evaluate the order of magnitude of the error which derives from an incorrect reading of the barometer with the help of Equation (11). If the average height of the mercury column is $h_b = 760$ mm, then for $T = 30$ °C, the expansion $\Delta h_b = 4.12$ mm which corresponds to an overvaluation $\Delta T = 1.03$ °C. A more exact evaluation of the error could be made by also taking into consideration the real behaviour of a fixed well barometer, that is, the dilatation of the reading scale, the glass capillary and the metal ampulla of the well containing the mercury. A detailed analysis of the problem, found in all writings on meteorology, leads to an evaluation that is only slightly inferior to the above, that is $\Delta h_b = 3.8$ mm, equivalent to $\Delta T = 0.94$ °C. This error has been corrected in the Padova series. If Amontons' thermometer and the barometer are both displaced to a level which is different from that of calibration, the variations in the two mercury columns compensate each other exactly. A problem could arise instead, when only one of the instruments had been moved to a different level, for example the barometer. The variation in pressure can be calculated from the hypsometric formula which gives, for each rise of 10 m, a drop in the column of about $\Delta h_b = -0.9$ mm, which corresponds to a temperature error of $\Delta T = -0.2$ °C. This is not a particularly high value, especially because Poleni's house had a ground floor and first floor, with a margin of error of $\Delta T = \pm 0.1$ °C only.

6. The Problem of Establishing Comparable Scales

The need to compare meteorological observations made in different sites led to the standardisation of instruments and calibrations. In occasion of the first meteorological networks, i.e., the *Rete Medicea* established 1654 by Ferdinand II de' Medici (Targioni Tozzetti, 1780), the *Royal Society*, London (established 1723 by James Jurin (1723) and the *Academia Meteorologica Palatina*, Mannheim (established in 1781 by Karl Theodor von Pfalz (Hemmer, 1783), identical instruments were made by the same craftsman, or following precise recommendations and then sent to the various stations (Camuffo, 2002). Unfortunately, the greater part of early instruments has been destroyed, so that it is not possible to verify, today, their calibration, unlike in the case of the Little Florentine Thermometer (Vittori and Mestitz, 1981) and other rare exceptions. Even though early thermometers and their calibration have been described in a number of historical works (e.g., Amontons, 1695, 1702; Poleni, 1709; Boerhaave, 1749; Deluc, 1772; Toaldo, 1775; Lambert, 1779; Hemmer, 1783; Ganot, 1860; Negretti and Zambra, 1864; Guillaume, 1889) and a few modern papers (Middleton, 1966; Frisinger, 1983; Baiada, 1986; Lo Vecchio and Nanni, 2000), our knowledge is far from being complete.

During the first stages of meteorology, the expansion of different bodies as a response to changing temperature or humidity, could not be expressed in terms of a physical law or a thermodynamic principle. This was only an empirical, repeatable finding that resulted in an apparently different response typical of each material used to detect environmental variations. The "degree" was only one space interval on the scale, generally in the local length unit, or in a unit determined by cultural or political reasons (e.g., the troops of the French Revolution), without being conventionally related to the extent of change in the variable. The quantitative change of the variable was absolutely unknown, and defined only in terms of the effect. The use of different instruments based on different principles soon required a standardisation. The substances used for the sensor of thermometers were air, spirit, linseed oil, or mercury. The problem was even more complex for humidity sensors, made of cotton, seeds, straw, wood, ivory, goose quill, whalebone, hair or parchment. The response of thermometric fluid was either linear (e.g., gas) or non-linear (e.g., spirit); the scale was forward or reverse (e.g., Delisle, early Celsius) and many types of units were used. After people had recognised that all bodies responded in a slightly different way, but following the same physical principle, the law was discovered.

To establish a standardised temperature scale, which could be easily reproduced, it was necessary to define the type of instrument, choose one or more repeatable fixed points and find a way of graduating the scale. When only one fixed point was used, e.g., the gas thermoscope by Santorio, it was logically expected that one degree should correspond to a stated proportion of the increase in the volume, or the pressure, or the length of the thermometric substance, above or below the fixed point. When two or more fixed points were used, the interval between them was linearly subdivided into a number of equal parts, called degrees. Both methods assumed that the change of the thermometric substance, taken as an index, was linearly related to changes in the actual air temperature, so that equal increases in the index would indicate equal increases in temperature. This situation was not verified, except in the case of the gas thermometer (e.g., Amontons) and in general the departures from linearity varied with the substances used. This created many problems given that the various instruments utilised different liquids. The most common liquid used in thermometers was spirit, which was then gradually substituted in the 18th century by mercury, but other liquids were used.

A number of fixed points, or supposed constant and repeatable points, were suggested for the calibration of thermometers, namely: the temperature of the human body, freezing water, melting ice, the temperature of a mixture of ice and salts, the cellars of the Paris Observatory (which repeated measurements had shown to be more or less constant), or that of boiling water. The combination of the water freezing point and human body temperature was an apparently uncertain scale, but appropriate for the seasonal range of air temperature and its application was no worse than the use of freezing and boiling points. In fact, the upper point was too far from a realistic range, with two negative consequences: (i) the introduction of large errors in the case of non-linearly expanding liquids, (ii) a low resolution for having calibrated the whole capillary and practically using only a small portion.

Numerous scales were used in the 18th century. Louis Cotte (1774) published a table that compared the 15 most popular scales of his times, including Poleni's. Landsberg (1985) reported a table comparing the 36 main scales, in use at his times, to centigrade one with some inaccuracies. In fact, in Poleni's scale the freezing point is at 47.5 °Po instead of 47.3 °Po and 1 °C is said to correspond to 0.22 °Po instead of 0.158 °Po. This paper will examine some scales that were particularly common and were used to measure the temperature of the air in the Padova series, i.e., Fahrenheit's, Réaumur's, Delisle's, Amontons' and Poleni's.

6.1. FAHRENHEIT'S SCALE

Daniel Gabriel Fahrenheit (1686–1736) used both spirit and mercury thermometers and described their calibration (Fahrenheit, 1724). He used three fixed points for graduating his thermometer: the first, at the beginning of the scale, was obtained from a mixture of ice, water and 'ammonia salt' or sea salt. This corresponded to 0 °F. The second was obtained by mixing ice and water without any addition of salt and corresponded to 32 °F. The third point was found at 96 °F and represented the temperature of a healthy human body. The scale was practically dimensioned to cover the yearly temperature range of the air in Europe. The boiling point of water was not originally used as a fixed point, in that it was considered too far away from the usual range of meteorological temperatures, but Fahrenheit did actually measure it by extrapolating the scale upwards, whereby he calculated it at 212 °F. Middleton (1966) was of the opinion that there were only two fixed points: the temperature of melting ice and that of the human body, which are more representative of the temperature range of the air in the U.K.

Poleni, in a letter (Poleni, 1740) discussed his methodology to obtain Fahrenheit's scale following the instructions given by Pieter van Musschenbroek (1731–1732). From this description it appears that Poleni adopted only two fixed points: one obtained when the thermometer was immersed in a mixture of snow (or crushed ice) and an equal amount of ammonia salt, whereby the height of the mercury was given as 0 °F. The other fixed point was obtained when the thermometer was immersed in pure ice. The interval between these two points was then divided into 32 parts, called degrees. These degrees were then used as the basis for extending the scale upwards. Successively placing the thermometer in boiling water (but without paying attention to the barometric pressure), it was seen that the mercury rose to 214 °F and not 212 °F as written by Fahrenheit. Poleni used Fahrenheit's thermometer for his meteorological observations, but he did not specify the calibration, i.e., whether it was the original Fahrenheit's thermometer with three fixed points, or as described by Peter Musschenbroek (1731–1732), with two fixed points only. The calibration was in any case not the standard one, as the observations departed too far from the other parallel series. Poleni wrote that the mixture of ice and ammonia salt should not be regarded as a true fixed point, in that the height of the mercury in the thermometer varied with the proportion of ice to salt. He therefore followed the tendency of using pure ice and boiling water as fixed points, graduating the thermometer between these two extremes. In any case, around 1740, it had become quite common to consider that the temperature at which water boiled was 212 °F and this was also taken as a fixed point for calibration, thus excluding the temperature of the human body.

Fahrenheit's thermometer built and used by Poleni departed by some 5 °C to 7 °C with reference to the other thermometers exposed in different parts of his house. This departure can be interpreted in terms of bad calibration of the lower point. Probably for this reason, and for this thermometer, Giuseppe Toaldo commented that 'In the mixture of crushed ice and salts there can be an uncertainty of more than 5 degrees' (Toaldo, 1775).

In reality, Fahrenheit also wrote (1724) that the lowest point, obtained with a mixture of ice, water, and salt-ammoniac or sea-salt succeeds better in winter than in summer. Middleton (1966) interpreted this sentence and method optimistically. Probably, some decades were needed before all instrument makers had the possibility of having sufficiently pure salts to obtain a reliable calibration.

6.2. RÉAUMUR'S SCALE

The scale proposed by René-Antoine Ferchault de Réaumur (1683–1757) became particularly popular in France, Italy and central Europe. In Padova it was used by, among others, Morgagni and Toaldo and was abandoned in the second half of the 19th century. For instance, the description of the calibrations performed 31 Dec. 1864, found in the original registers mentions that the thermometer associated with the barometer had Réaumur's scale and the readings were converted into Centigrade with the help of a table. This French scale was commonly used in mercury thermometers, which were uniformly graduated between two fixed points: the melting point of ice (0 °R) and the boiling point of water (80 °R). This scale differed, however, from Réaumur's (1730, 1731) original one, which was described, not always clearly. The calibration was based on only one fixed point, 'zero' on the scale, i.e., the degree of cold at which water began to freeze. The subdivision in degrees corresponded to a constant increase in the volume occupied by spirit at zero, after having established a standard dilution: Réaumur knew, in fact, that the expansion of spirit varied according to the proportion of water. This method has two weak points, i.e., the imprecise definition of the temperature in which the water 'begins' to freeze, and the non-linear expansion of spirit. These modifications in the method of calibration, which was, however, always indicated as Réaumur's, caused a certain amount of confusion, as Toaldo underlined in a treatise on improving barometers and thermometers (Toaldo, 1775), in which he summarised a famous article by Jean André Deluc (1772). In order to clarify the situation, Toaldo drew up a table whereby three scales were compared: (i) the most widespread scale which Toaldo advised, relating to a mercury thermometer graduated between 0° and 80 °R corresponding to two fixed points, melting ice and boiling water; (ii) the scale referring to a spirit thermometer, also calibrated between the same two fixed points; (iii) Réaumur's original scale, with spirit, but based on only one fixed point, 'Réaumur's Zero' which corresponded to -0.8 degrees on the mercury thermometer scale.

Gradually, mercury became more popular than spirit. Toaldo (1775) advised using it for the following reasons: '(i) because its expansions and contractions are greater and more regular than all the other graduated materials; (ii) because mercury, more than any other material, is more easily cleared of air, because it bears the heat of boiling water better than all other liquids; (iii) because more than any liquid it is suitable for measuring great *heat* <i.e., temperature> differences . . . ; (iv) mercury conforms more readily to variations in the air . . . ; (v) because all mercury follows the same expansion and contraction being a wholly homogeneous metal . . . ' unlike spirit whose variable composition and behaviour created serious comparison problems.

6.3. DELISLE'S SCALE

Another scale invented by Joseph Nicolas Delisle (1688–1768) and utilised by Poleni, was based on only one fixed point. The original scale, established in 1732, took the temperature of boiling water as the fixed point, considered 'zero' on the scale, and the degrees were marked on the basis of the contraction of mercury with respect to the volume occupied at 'zero' (Delisle, 1734). This was an 'inverted' scale that, as Toaldo said, showed 'the degrees, so to say, of cold'. Celsius also presented the original centigrade scale in its inverted form. Some experiments carried out in St. Petersburg by J. Weitbrecht, on Delisle's suggestion, showed that the contraction of mercury between the boiling point and freezing point of water was quite close to 150 parts per 10,000 of the volume at boiling point. A scale with two fixed points was therefore established: the boiling point being represented by 0° and the freezing point at 150°. Delisle sent thermometers which had been calibrated by himself to various scholars, among whom Celsius in Uppsala and Poleni in Padova, who then carried out meteorological observations with them. Fortunately, the thermometer sent to Uppsala survived, and is still preserved at the University (Bergström and Moberg, 2002).

7. Calibration Points and Scale Linearity

In 1665, Christian Huygens (1629–1695) suggested using melting ice and boiling water as fixed points. However, this suggestion was not too popular for these fixed points were not always correctly defined, the corresponding temperature was not always exactly the same and invariable, and the boiling temperature was too high compared with the meteorological span or the body temperature. This, obviously, led to a great deal of confusion and made the comparison of measurements taken with different thermometers difficult. In Italy, the immersion of a thermometer in snow was a fairly reliable method, according to a tradition that began with Sebastiano Bartolo in 1679, Carlo Renaldini in 1681. This practice became widespread with Newton's (1701) authoritative suggestion. Summarising and commenting the treatise by Deluc (1772) on the construction, calibration and use of barometers and thermometers, Toaldo (1775) wrote that the calibration was made according to Renaldini's method.

Outside of Italy, the lower fixed point was obtained with the freezing of water (e.g., Réaumur and Jean Antoine Nollet before the year 1732), or the melting of ice (e.g., Fahrenheit, Réaumur and Nollet after the year 1732) (Middleton, 1966). In theory, the point of equilibrium between the liquid and solid state is well defined, and in very slow dynamic conditions the point of change of state from liquid to solid coincides with the inverse one which, for water, corresponds to 0 °C under normal pressure. Moreover, from a practical point of view, the two processes can lead to departures when there are sufficient differences between ambient temperature, water and ice. In the case of freezing, the water temperature proceeds from an initial higher value to zero towards a final lower one (e.g., the environment or the container). It is unusual to reach superfusion but there are, however, temperature gradients between the two phases, and the temperature might not be homogeneous inside each phase, especially if the dynamics are fairly rapid. It is not advisable to place the thermometer in such a way that it becomes imprisoned in the ice, otherwise it might break on being removed. The bulb was in contact with the liquid phase which, for the greater part, was at a still higher temperature than zero, while the capillary was often exposed to air, where the temperature could well be below zero. Glass was a relatively good heat conductor and the mercury in the capillary may, under such conditions, further complicate the problem.

The problems linked to the choice of the lower fixed point are clearly summarised in the following words by Toaldo (1775): ‘The term freezing is unclear: one time it means the degree of cold that is sufficient to freeze, as Réaumur suggests; later … Fahrenheit took the forced freezing with ammonia salt, which occurs at 32 <degrees> on the Fahrenheit scale below the zero defined by Réaumur. These definitions are different, and both uncertain. It is necessary to take ice that is melting as Newton first did; this degree is fixed. Neither ice, nor snow ever melt at temperatures that are different from this fixed point’.

In the above-mentioned comments on the construction and calibration of barometers and thermometers, Toaldo (1775) wrote that the method suggested by Réaumur of using the freezing point of water was imprecise, leading to an uncertainty of 3°, 4° and sometimes 5 °R.

In the case of melting ice, the inner part of the ice remains below zero, while the liquefied part reaches temperatures above zero because of exchanges with the external environment, of necessity above zero, otherwise the ice would not melt. Melting occurs, in fact, when there is a time variation in the temperature (that is, under dynamic conditions) and the various components of the system are not in equilibrium, creating internal temperature gradients. Even continuous mixing does not completely eliminate this state of affairs. This could be mitigated if a mixture of crushed ice were used, in order to redistribute the existing gradients around each grain of ice, over a very small scale. In order to further reduce any adverse effects during the liquid phase, the melted water was drained off following the suggestion of the Abbé Jean Antoine Nollet (1740/48). However, it is impossible to remix the mixture and there could be small temperature imbalances. Even if the mixture reaches a temperature very close to zero, for thermometers not completely immersed, overlying air is a source of error.

Refrigeration mixtures that were already in use in the *Accademia del Cimento* in the 1600s (Targioni Tozzetti, 1780), were also utilised and became popular in the following period (Boerhaave, 1749). Moreover, this habit was not adopted in Padova because the variable composition of these mixtures made them unacceptable, as Poleni (1740) and Toaldo (1775) pointed out, suggesting that the error was ‘more than 5 degrees’. Poleni described the calibration as follows: ‘The ampulla of my thermometer immersed in ice, the mercury rose to the height of 47 inches and 30 tenths; immersed in boiling water, the mercury rose to the height of 63 inches and 10 tenths' (Poleni, 1731). It was not specified whether a mixture of ice and water was used (as Amontons did). In a letter to A. de Pompeis (Poleni, 1740), referring to Fahrenheit's calibration, Poleni indicated pure ice but as opposed to the mixture of ice and salts. The ice used in Padova was formed naturally and therefore calibrations were possible only in winter. No mention of summer calibrations with crushed hailstones was found, or with old snow preserved in wells insulated and topped with straw.

Another problem with the early period concerns the non-standard pressure in establishing the fixed points. First of all, the boiling point was not so well defined especially because it was observed that the temperature of boiling water was not constant. Toaldo noted that 'from the water that started to boil, up to actual boiling when water swirls in vortexes, there is one degree' of difference in the reading of the thermometer (Toaldo, 1775). Poleni proved that only after the water had reached a certain degree of ebullition, did the mercury level in the thermometer remain constant even if the heat source, i.e., the flame, was increased or continued for longer (Poleni, 1709). Anders Celsius, in 1742, observed that when ebullition was 'complete', i.e., there were large bubbles on the whole surface of the water, the temperature shown by the thermometer was stationary.

The fact that atmospheric pressure could influence the boiling point of water was noted at the beginning of the 18th century, but Poleni refused to accept such observation. It should be noted that Poleni believed in Amontons' affirmation that boiling water had a fixed point, in that 'completely boiling water remains at about the same *degree of heat*'. However, he initially claimed that boiling temperature was independent of atmospheric pressure, and was against the opinion that 'water begins to boil at different temperatures depending on the different weight of the air' (Poleni, 1709).

Fahrenheit (1724), re-examining the question, discovered that the boiling point varied according to pressure and that pressure had to be specified at each calibration. Although a standard pressure was not established, it was, however, possible to determine the differences in temperature between boiling points fixed under different conditions, once the pressure was known. For example, Toaldo, referring to the work by de Luc on this very point, said that 'one inch more or less on the barometer leads to one degree of difference in the heat of boiling water, and it is necessary to regulate the graduation of the scale' (Toaldo, 1775). Further discussion on this point can be found in Boerhaave (1749).

The boiling point of water T_{bp} depends on atmospheric pressure P according to the law:

$$\Delta T_{bp} = 100 + (P - 1013.25)/35.8 \text{ [°C]} \tag{17}$$

from which $\Delta T_{bp} = 1/35.8 = 2.8 \times 10^{-2}$ °C/hPa. With normal atmospheric ranges of $\pm$ 30 hPa, $\Delta T_{bp} = \pm\, 0.84$ °C, which shows that the value given by Toaldo was, substantially, correct. In fact 1 inch [Hg, London] = 0.93 inches [Hg, Paris] = 33.9

hPa, and as a result of the variation of 1 Paris inch in the barometric pressure the variation in the boiling point was $\Delta T_{bp} = (33.9 \times 0.028)/0.93 = 1.02\,°C$. The thermometer readings should therefore be corrected on the basis of the indication about the calibration procedure, when this is specified. In the case of missing indication, the error is proportional to the distance from zero, and is therefore negligible in the winter. In the summer, when $T = 30\,°C$, this error may range from 0 °C (no calibration error) to (30/100) $\Delta T_b = \pm 0.25\,°C$ (maximum calibration error).

Also the temperature of melting ice T_{mi} depends on atmospheric pressure, but such dependence is fortunately negligible, in that the variation is $\Delta T_{mi} = 8 \times 10^{-6}\,°C/hPa$ (Rivosecchi, 1975).

Calibration methodology became correct after 1777, when a Commission charged by the *Royal Society*, London, formed by Cavendish, Heberden, Alex-Aubert, Deluc, Maskelyne, Horsley and Planta published in the *Philosophical Transactions* (Cavendish et al, 1777a) recommendations for finding the reference points and how to operate. The paper become so popular that an Italian translation of it (Cavendish, 1777b) was published at Venice together with other more or less famous papers collected after the *Transactions*. The main suggestions were: (1) find the boiling point at 29.8 London inches air pressure, or correct the data in accordance with the enclosed table; (2) the bulb of the thermometer should be immersed in boiling water for 1 or 2 inches only, and on the side rising convective motions; (3) the capillary with mercury should be immersed in hot steam; details are given on how to build the pot and lid; (4) prefer intense boiling and wait for a few minutes; (5) the pot must be covered to avoid mixture with external air; (6) an alternative method suggested by Deluc was to envelope the thermometer with scraps of cloth and wet them continually with boiling water; (7) when the capillary is at a different temperature, the readings should be corrected in accordance with correction tables; (8) insert bulb and the part of the capillary with mercury into crushed ice; when the capillary is out of the ice, correct on the basis of a given table and linear interpolation.

Calibration was generally made by fastening a silk thread or a woollen yarn on to the capillary in correspondence to the fixed points, and then fixing the capillary on to a support (Toaldo, 1775; Hemmer, 1783). Some slipping was possible, and when the capillary slipped, re-calibration was necessary. The wooden frame of some instruments had a hole in correspondence with the bulb in order to allow better ventilation and check the fixed points without damaging the frame and the scale. It was possible to expose the bulb to hot steam or envelope it with compressed snow or scraps of cloth wetted with boiling water; another method to facilitate this operation was to use folding frames which kept the bulb free during calibration (Figure 3).

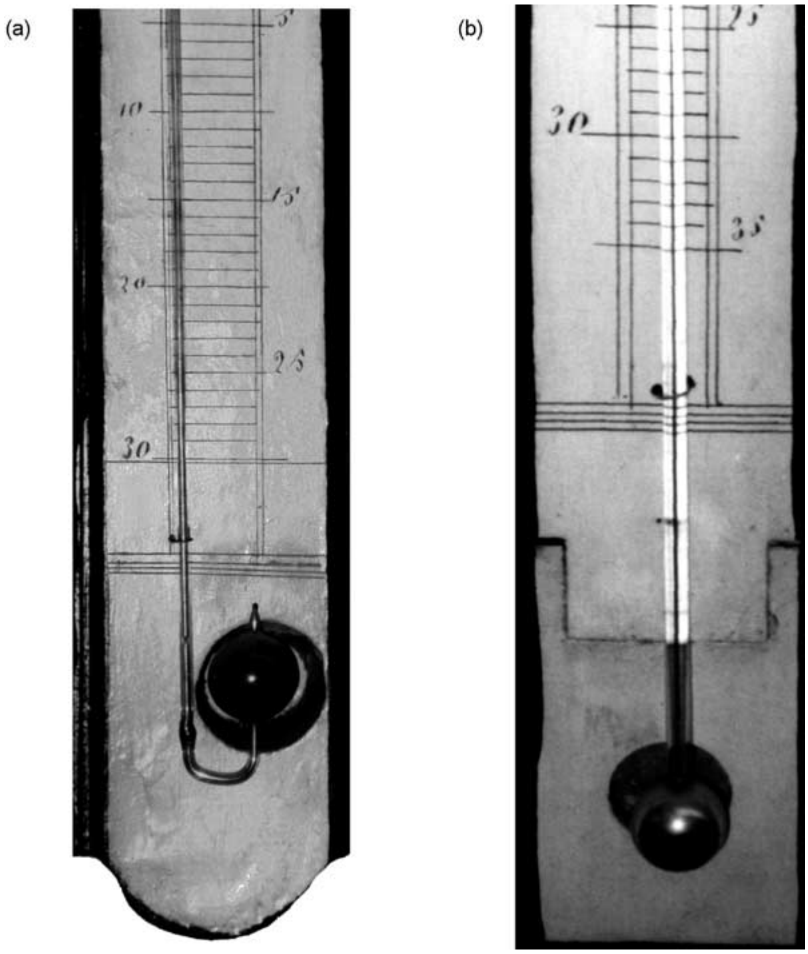

Figure 3. (a) Amontons' thermometer with a hole in the wooden frame around the bulb to host the sensor and allow a better exchange of air (making re-calibration easier). (b) Thermometer with folding panel in order to free the bulb in case of re-calibration. In both cases, the capillary was tied with an iron wire to a wood panel used as a support; the scale was painted on the frame. Museum of Scientific Instruments, Physics Department, Padova University, by courtesy of Prof. G. A. Salandin.

8. Instrument Supports and Scale Incision

In early instruments, the glass thermometer (i.e., bulb and capillary) was generally separate from the scale. Only a few instruments, like the Florentine thermometers of the *Accademia del Cimento* had the scale impressed on the glass tube; more usually, the thermometer was tied with a iron wire to a wood frame used as a support (visible in Figure 3). The scale was directly drawn on the support or over a paper strip glued to the frame. The *Societas Meteorologica Palatina*, Mannheim, suggested aged walnut supports (Hemmer, 1783). Toaldo advised using 'a thin board of fir wood, a wood that is the least likely of all to alter, is light, and very common' and to fix the thermometer in such a way that 'the bulb is as isolated as possible, by boring a hole in the board' (Toaldo, 1775). Seasoned wood has a moisture content outdoors equal to 15–18%; 8–10% indoors in a hot modern building; 15% is a reasonable reference in unheated rooms, especially for Padova which is characterised by relatively high relative humidity (RH). The coefficient of linear expansion for this kind of wood for an average moisture content of 15% is $5.4 \times 10^{-6}\,°\mathrm{C}^{-1}$ in the direction along the grains and $34 \times 10^{-6}\,°\mathrm{C}^{-1}$ perpendicularly to them; more specifically $25 \times 10^{-6}\,°\mathrm{C}^{-1}$ radially and $35 \times 10^{-6}\,°\mathrm{C}^{-1}$ tangentially to the tree rings. Fortunately, for practical reasons capillary and scale were fixed along the grains of the wood, to obtain minimum expansion. Under these conditions, at a rise of temperature $\Delta T = 30\,°\mathrm{C}$, a frame 100 cm long (more or less the size of early instruments), expanded by $\Delta L = 0.16$ mm, corresponding to an error of $\Delta T = 0.04\,°\mathrm{C}$ in Poleni's thermometer. If the error is calculated not on the expansion of the entire support, but only on the part corresponding to the actual temperature range, this error is further reduced by 2/3 in the summer (when it is at its maximum) and tends to vanish in winter, when the temperature is close to calibration conditions. In brief, this error is of the order of $\Delta T = 0.01\,°\mathrm{C}$ in the hot season, and totally negligible in the cold season.

On the other hand, hygrometric expansion is much more relevant, and unfortunately, the data available leave room for greater uncertainty, the RH not being measured in the very early period. In order to have a crude estimate of the RH in this period, the days have been classified into three classes, i.e., humid (e.g., during fog and rainfall), intermediate (e.g., cloud cover) and dry (e.g., clear sky). If for moisture absorption a realistic expansion coefficient (representative of several seasoned wood species) of 0.2% is considered, this could lead to an error $\Delta T = 0.5\,°\mathrm{C}$ for a board 1 m long. However, in Poleni's thermometer, the reading was the sum of the thermometric and barometric columns (the first ranged between 17 and 23 inches, the second was 28 inches in average), which were both affected by the expansion and bulk error which may be of the order of $1\,°\mathrm{C}$ or more. In the case of Toaldo or Vincenzo Chiminello, who used seasoned fir wood, the coefficient is 1‰ (Giordano et al., 1993) and the error is half the previous one. In the Mannheim instrument, the coefficient for walnut is even smaller, i.e., 0.8‰.

Except for Amontons' thermometer, only the portion of the frame corresponding to the height of the mercury column should be considered and the largest error occurs in the hot season. For example, by making reference to a Réaumur thermometer, preserved at the Botanical Gardens of Padova University, made by Paolo Rocchetta (active 1842–1877), who was Chief Technician of the Specola, the scale started from $-14\,°\mathrm{R}$, so that when the temperature was $30\,°\mathrm{C}$ (i.e., 24 R), the error due to changes in RH was 1‰ of $(14° + 24\,°\mathrm{R})$ i.e., $0.047\,°\mathrm{C}$. It is difficult to compute the exact correction as a function of the difference between the actual RH during observation and the original value during calibration, except for the crude classification above and assuming that at boiling point, excess vapour wetted the support.

Things improved when metal supports (mainly brass), with the scale engraved, became popular. Thermal expansion of metals has the same order of magnitude as that of wood, and in addition metals are not expanded by humidity. For example, bronze with tin has a linear expansion coefficient $1.7 \times 10^{-5}\,°\mathrm{C}^{-1}$, about three times that of fir wood, but still negligible in practical terms.

The method of fixing thermometers and marking the scale, also caused other inconveniences. Above all, the fact that the capillary protruded with respect to the plane of the scale meant that parallax errors were introduced, because of the alignment between the meniscus of the liquid and scale graduation. Some made reference to the base of the meniscus, others to the top, as we do today. To eliminate these errors, Deluc suggested that the capillary should be fixed in a groove in the support, so that the plane of the scale passed through the axis of the capillary. In any case, when performing observations, care was taken to avoid such errors in the following way: 'it is necessary to place the eye well at the level of the mercury, which is confirmed when the lines dividing the scale at that site lie in the direction of their images in the capillary' (Toaldo, 1775).

The capillary would also slip accidentally, or continually, on the scale fixed to the support, or the scale became progressively deformed. In such cases, a systematic, or a slowly variable error was introduced. An example of the above was found when examining the original registers of Toaldo's meteorological observations. In the comments at the end of each month, for the 23 July 1770, we read: 'having <controlled> the barometer scale above which I had made a mark, I found the card higher than it should have been by 3 lines, so that all the heights marked must have increased by 3 lines'. And again, in November 1775, 'there was disorder in the barometer card that was mobile ... and this morning the 19 it was regulated and fixed'. In the case of the Padova series a few mentions of such errors were found but, although not always noticed from the metadata, some instrumental drift or discontinuity appear in the data after statistical analysis. In the absence of precise information from metadata, the starting date and the trend have been detected and corrected with the help of the Alexandersson (1984) test.

The problems with slipping scale started to disappear in the second half of the 18th and in the 19th century, when the capillary and paper scale were enclosed and sealed in another glass capillary. This problem was eliminated when the scale was directly engraved on the glass capillary or on a thin, flat glass base to which the capillary was attached, the whole then being enclosed in another glass tube that was soldered at the top of the bulb.

9. Problems Linked to Thermometer Construction

Great care was always devoted in constructing and controlling instruments. The great Academies like the *Accademia del Cimento*, the *Royal Society* and the *Societas Meteorologica Palatina*, which collected data from different observers, underlined the necessity of homogenising instruments and methods. The *Societas Meteorologica Palatina* sent Mannheim thermometers to observers, and very probably also to Toaldo and Chiminello. Comparable thermometers needed a 'perfectly cylindrical' tube for the displacement of thermometric liquid, or at least a tube with a constant internal section along its entire length. The first to dream up a reasonably precise method for determining the regularity of the section was the astronomer Ole Christensen Rømer, around 1702 (Middleton, 1966). The method consisted in checking that the length of the mercury cylinder, that was obtained by introducing a drop of this liquid into the tube, was still the same when it was displaced into the capillary. This same method is, substantially, still used today.

When a thermometer is heated, not only the liquid in the thermometer expands, but also the glass. The height reached by the thermometric column indicates the difference between these two counteracting effects, where the expansion of the liquid is dominant (the cubic expansion coefficient β of glass is about 1/10 of mercury: for 'Jena glass' $\beta = 1.7 \times 10^{-5}\,°C^{-1}$, while for mercury $\beta = 1.818 \times 10^{-4}\,°C^{-1}$ (Rivosecchi, 1975). Scientists from the *Accademia del Cimento* already knew this. It was also observed that different types of glass dilated to different degrees. In 1749, the chemist Hermann Boerhaave, recording the results of some experiments carried out by Fahrenheit, wrote that 'the glass worked in Bohemia, Britain and Batavia, dilated, at the same *heat* <i.e., temperature> more or less easily, more or less at the same speed' (Boerhaave, 1749). He therefore advised that glass of the same type should be used if instruments that could be compared with each other were required. Fahrenheit thought that two thermometers made by him, one with spirit and the other with mercury and which did not agree with each other, could be explained by the different expansion of glass. He was not, obviously, aware that the main cause was due to the fact that the expansion of spirit and mercury are not linear and are different.

9.1. NON-LINEARITY OF THE DILATATION OF THERMOMETRIC LIQUID

The fact that different types of glass have different expansion coefficients does not create problems of comparison when close to reference points, in that there the expansion of glass is automatically taken into consideration. Problems arise from the fact that the expansion coefficient of glass varies with temperature and is different for different types of glass. In the intermediate points on the scale, this can cause different departures from linearity, depending on the type of glass used, and can determine different readings with different thermometers. This happens for the method used in the construction of the scale (subdividing the interval between the two fixed points in equal parts), which assumes that the relationship between temperature and height reached by the liquid in the thermometer is linear.

The fact that the thermal expansion of a substance is linear with the temperature is only valid for perfect gases in accordance with the Charles-Gay Lussac law:

$$V = V_o(1 + \beta T)\ , \tag{18}$$

Table I
Departure (°C) from linearity of mercury and spirit

Temperature	−38	−20	0	+20	+40 °C
Mercury	+0.42	+0.17	0.0	−0.08	−0.11
Spirit	+0.9	+0.8	0.0	−3.0	

where $\beta = 3.66 \times 10^{-3}\,°C^{-1}$ is the cubic expansion coefficient for air; $\beta = 1.58 \times 10^{-4}\,°C^{-1}$ for mercury in normal glass and $\beta = 1.04 \times 10^{-3}\,°C^{-1}$ for ethanol in normal glass (Michalski et al., 1991). However, this is only strictly true with the first approximation, as in the case of the majority of liquids used in thermometers. The non-linear response of thermometers is accentuated moreover, by irregular expansion of the glass container. The overall deviation for some types of thermometers is shown in Table I (Rivosecchi, 1975).

The non-linearity of mercury is, on average, rather limited, generally below 0.1 °C, while spirit departs much more (e.g., –3 °C at T = 20 °C) and the readings should be corrected, especially in the hot season. The large departure found in summer between spirit and mercury thermometers has contributed in justifying, in early meteorology, the choice of the human body as the upper calibration point, e.g., as Fahrenheit did after the example of Santorio who chose this reference for medical purposes. Even though this point may not be precise, nevertheless a summer temperature reading performed with a spirit thermometer calibrated at human temperature is more accurate than with a calibration at boiling point and with linear interpolation.

Toaldo knew that the departure of spirit from linearity was very high and described a method of calibration in use at that time (Toaldo, 1775) in order to reduce the error especially in the hot season. The spirit thermometer was compared with a mercury thermometer: both were attached to a frame and immersed in melting ice in order to mark the zero and then immersed in water at 40 °R in order to mark this upper point. The intermediate degrees were then interpolated. The error was negligible near the calibration points, and was larger in the middle of the span, i.e., around 20 °R (25 °C) which is close to summer temperatures. In a time series of temperature, the change from spirit to mercury thermometer introduces an apparent cooling in winter and heating in summer. Fortunately, most of the Padova series was taken with mercury thermometers and the early measurements were made with a gas thermometer.

9.2. DRIFT

Drift may be due to a permanent deformation of the support due to ageing of the wood (that may be considered within 0.25% along the grains) and therefore of the scale attached to it or engraved on it, as discussed earlier.

Another cause of drift was the alteration in thermometric liquid, especially when organic liquids were used, such as spirit. In the 18th century it was observed that in some thermometers of this type, zero gradually became lower and lower over the years. Various explanations were proposed; however, today it is known that the phenomenon was due to the diminishing volume of organic liquid as a result of polymerisation. Mercury thermometers (as those used in Padova) are of course free from this problem.

Also the glass container (capillary and bulb) is subject to hysteresis: when it undergoes sharp temperature variations, it does not immediately return to its original size. As a consequence, there is a temporary drop in the zero in the thermometer after it has been exposed to high temperatures, for example after the upper fixed point determination. Glass used in modern thermometers has a small hysteresis: the temperature cycle 0 – 100 – 0 °C, produces an error that does not generally exceed −0.2 °C (Rivosecchi, 1975).

Although the cause was not known, this effect had been observed even in the 18th century and for this reason it was suggested that thermometers were calibrated by marking first the point of ebullition and only successively the 'freezing' point, in that this latter 'could again become incorrect if it had been marked first' (Strohmeyer, 1775, in Middleton, 1966). In practice, the problem was linked to calibration, for the determination of each point displaced the calibration of the other. This kind of hysteresis was not increased for meteorological observations, given that temperature variations are generally gradual.

Modifications in the structure of glass are more relevant. These cause, in the long run, a decrease in bulb capacity. As a result, part of the liquid is transferred to the capillary, bringing about a permanent change of calibration. This slow rising of the zero, that often goes on for years, is particularly evident in certain mercury thermometers, and was clearly described for the first time in 1808 by Angelo Bellani who correctly attributed this shift to a gradual contraction of the glass in the first year, or a sudden contraction when calibration was incorrectly made immersing the thermometer first in boiling water and then in melting ice (Bellani, 1808, 1841; Guillaume, 1889).

In the 19th century, also other speculative explanations were suggested, e.g., one which attributed the rise to the fact that there was a small amount of air in the 'pores' of the liquid that, although they did not cause any change in the volume of the liquid itself, could later join up to form small bubbles that then caused an increase in the apparent volume of mercury, thus bringing about a rise in the zero. Although there was no general agreement about the cause of this phenomenon, a partial solution was, however, found. This consisted in calibrating thermometers several months after they had been made and sealed.

Towards the end of the 19th century, it was discovered that the composition of glass could influence upward movement of the zero. Glass containing lead oxide was abandoned, and 'hard glass' was used instead, thanks to which the rise could be reduced to one tenth. The use of more stable glass made it possible to reduce the rise of zero to 0.03 °C over three years. Thermometers used in the 1700s were less accurate, being built with low quality glass and without precautions, like that of waiting for at least one month before calibration. The upward displacement of the zero in mercury thermometers used in the *Specola* in the second half of the 19th century was about 0.3–0.6 °C, as demonstrated by the accurate measurements carried out in the second half of the 19th century, noted in the observation registers.

10. Conclusions

The early period of meteorological observations was extremely fruitful and complex, with new ideas, uncertain beliefs, and different instruments, scales and calibrations. Fortunately, the first steps were well documented although only little information can be found in modern papers in comparison with the huge amount of original documents. The use of different scales is not a problem: the key problem is whether calibration was carefully made and described, with well-defined fixed points.

The operating principle of Amontons' thermometer and the other '*constant-volume*' air thermometers, where the pressure is (nearly) proportional to air temperature, is simple and reliable from the general point of view, but complex in details, especially when a high precision is required. For a rise in ambient temperature, the increase in pressure inside the ampulla is compensated by an equal increase in the pressure of mercury in the capillary, and this is determined by an increase in height of the column. On the other hand, in the capillary, the volume of mercury required for this compensation displaces an equal volume from the ampulla, slightly changing the volume of the air pocket. Therefore, the thinner the capillary the better the *constant-volume* approximation; the smaller the ratio between the capillary and the ampulla sections, the more stable the level of mercury in the ampulla, and the smaller the departure from zero on the reference scale.

The comparison between calibrations of instruments built and used by G. Amontons (1699), G. Poleni (Venice, 1709, and Padova 1731), and J. H. Lambert (1779) has shown that these instruments were of good quality, with departures smaller than 3%. Amontons' thermometer needed to be integrated with a barometric reading, and an important error arose for the different conditions of mercury density during calibration and operation. Calibration was made in winter: at the lower fixed point the thermometer was immersed into snow or melting ice, and the barometer was at ambient temperature close to 0 °C. At the upper point, the thermometer was at boiling temperature, while the barometer remained at ambient temperature, near to 0 °C. On the other hand, field observations were made with both instruments at the same temperature and this was a cause of error. In the cold season this error was negligible, but in the hot season it reached 1 °C.

For an ideal Amontons' thermometer, only one calibration point is sufficient (if unknown, this can be derived from knowledge of its readings during snowy days) and the other can be calculated with a simple equation. In the case of a real thermometer, this approximation is good in winter, and the error may approach 1 °C in the summer. This equation allows us to interpret data taken with an unknown scale and calibration, e.g., the first period in Padova, 1716–1717. In addition, the formula derived for an ideal thermometer allows us to verify how a real thermometer departs from ideal conditions and a test on calibrations of famous thermometers (Amontons', Lambert's, Gay Lussac's, Poleni's at Venice and Padova) gives departures lying between $\pm 2.7\%$.

The above instrument analysis has been useful to know how an Amontons' thermometer works, and the Poleni observations 1725–1764 have been corrected only for working conditions different from the calibration (i.e., thermometer and barometer at the same temperature) and for hygrometric expansion of the wood support with the scale. However, we know too little about the details of the specific instrument used in Padova to undertake a more sophisticated second-order correction concerning the oscillations of the reference level in comparison with the scale or the differential expansion between mercury and glass.

The supports of the instrument, and the incision of the scale, were subject to expand or contract with temperature or humidity changes, and this was a source of errors that have been corrected (Cocheo and Camuffo, 2002) with the knowledge of ambient temperature and humidity, or with estimated data, i.e., by classifying days into the following classes: 'humid' (during fog and rain), 'average' (cloudy days) and 'dry' (sunny days) and attributing to each class the average level of relative humidity found today for the same classification. Problems linked to the construction of thermometers have been analysed, as well as the linearity of displacements of thermometric liquid, or drift due to ageing and transformation of thermometric liquid, glass or the support.

Most of the errors are fairly limited, usually less than 0.5 °C, often near to 0.3 °C. Only in some cases did individual errors reach or exceed 1 °C. One problem is that possible errors are manifold and the sum of absolute values often reaches impressive values. However, sometimes they tend to compensate each other out in the same reading (e.g., expansion of different materials), or in the case of medium (e.g., monthly) or long term (e.g., yearly) averages concerning random errors, as e.g., daily scale expansions when data are used to find monthly averages. The most important problem does not consist in random errors, but in systematic ones, and especially when a change in methodology was applied. Accurate knowledge of a series, its history and its metadata, constitutes the primary step for reliable correction of data. Then, further validation can be performed by comparing the actual series with other highly correlated, reliable series, or with the help of statistical tests.

The excellent results for the early instruments show that the dawn of modern meteorology, and subsequent period, was due to incredibly careful and precise instruments. After such a good start, however, we should not underestimate the problems in the more recent periods. In reality, each series can be subdivided in a number of more or less small portions, each one homogeneous, with measurements performed by different observers, with different instruments and methods. The case study of the Padova series (1725–today), which is one of the longest and best documented, has shown that careful corrections, validations and homogenisation are necessary before drawing any climatic analysis, in order to avoid unreliable conclusions.

The critical analysis of instruments and operative methodologies has shown that daily inadvertent climate changes which affect trends extremely slowly, can be hardly detected because they generally remain below the uncertainty threshold determined by observational accuracy, instrument resolution and errors. On the other hand, a change in frequency of extreme events, which largely exceed the average values as well as the observational uncertainty, is soundly detected. An analysis of the frequency of extreme events seems the most reliable method to detect climate changes.

The complex problem of correcting calibration and instrumental errors must be faced individually for each series, first on the basis of metadata from an accurate historical and critical analysis concerning instruments, operative methodology and then on a statistical analysis of errors, comparing teleconnected series. However, metadata are more relevant: it is not sufficient to hold that an increase or decrease in local or global temperature has been proven simply because it has appeared simultaneously in the trend of a number of series in different locations. In fact, the scientists of the time were in close contact with each other and followed ideas or directives from the most prestigious Academies, or international Conferences. When a number of observers simultaneously applied a change in the method of calibration, construction of instruments, exposition, or time of observation, they, in fact, generated an apparent climatic signal on a wide scale.

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ERRORS IN EARLY TEMPERATURE SERIES ARISING FROM CHANGES IN STYLE OF MEASURING TIME, SAMPLING SCHEDULE AND NUMBER OF OBSERVATIONS

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Abstract. Study of the Padova series (1725–today) is a useful example, of general interest, of a critical revision of long time series. These are composed of a number of inhomogeneous parts, each of them with mean daily values, and extremes, computed in different ways, based on observations taken at different times, or with the time expressed in different styles. Imprecise clocks, little care for the schedule established for meteorological readings, changing style of evaluating time, inappropriate choice of observing schedules, too small a number of readings to compute the daily average, generated errors that caused significant departures in time series, that could be interpreted as a climate signal. In the past, average values were obtained with only a few daily measurements. The first problem is to correct the data and extrapolate the hourly temperatures needed to evaluate the daily minimum, maximum and average values in a homogeneous way. The change of style in temporal reference introduced spurious seasonal changes. Styles (or combinations of styles) used were: *Italian time* in use till 1789, in which the hours were computed starting from twilight; *apparent solar time* based on the actual motion of the sun; *mean solar time* based on the average motion of the sun; *local time* referred to the actual passage of the sun across the local meridian (local culmination); *French time* starting at midnight and regulated on the local culmination; *Western European Time* regulated on the culmination of fictitious average solar motion on a reference meridian 15° East. A test was performed to verify whether the times chosen for readings were appropriate, in particular when observations were performed not close to the daily minimum and maximum. In effect, in the early period with Morgagni and Toaldo, the choice of schedule of observations was good, but afterwards the introduction of new observations, not always established at the most appropriate schedule, reduced the representativity of the data. The error in calculating the daily average temperature after a given number of observations taken at different hours of the day has been analysed. National, and especially international recommendations have been particularly important in the choice of observations times, and in determining averages. These recommendations have been simultaneously applied on a large number of sites, causing an in-homogeneity that may be misinterpreted as a well-documented, widespread climate change.

1. Introduction

Several papers have been devoted to the correction of data deriving from instrumental or calibration errors in long time series. It is less common to find papers that estimate the error resulting from irregular, or inaccurate time, or from changes in sampling time especially in early periods of meteorology, when clocks were not exact and scientists were not used to following a precise temporal sampling. The spirit of the 18th century, dominated by the Enlightenment, focused more on scientific

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curiosity and the aim of gathering new data, and less on regularity of observations for future use. Timing inaccuracy introduced a noise, not necessarily white. At this point two possibilities exist: (i) to suppose that the error is random and that departure is compensated in sets formed by many data; (ii) to eliminate day by day timing errors after careful correction and homogenisation of observations. The former is meaningful only for average values and is the easiest and more common solution. The latter is time consuming but allows precise daily data and the study of interdiurnal variability. In addition, only after having completed the long, critical task of detailed correction indicated at item (ii), can we see whether the assumption (i) is really correct. For this reason, this paper discusses the timing errors which are typical of all long series, deriving from change in the style of determining the hour of the day (e.g. actual solar time, average solar time, reference meridian); imprecise clock; scant respect for the schedule recommended for meteorological readings; inappropriate choice of time in taking measurements; insufficient number of daily observations.

Another problem is homogeneity, for in every long time series the number and the time of daily observations varies following individual, national, or international directives. The first approach to solve this problem is a detailed analysis of all the data and metadata in the context of the styles used centuries ago to compute the hours of the day. In the 18^{th} century, many different styles were used to indicate the time of the day. This depended on when the day officially started, and therefore, establishing the local time, which was always linked to the apparent trajectory of the sun.

All long time series are composed of a number of inhomogeneous parts, each of them with mean daily values computed in different ways, based on observations performed at different times, or with the time expressed in different styles. For instance, the change of measuring style, and the passage from the sun to the clock as a time reference, not only implied a mere transformation of units, but generated a substantial seasonal shift in time, i.e., the same hour corresponding to a different position of the sun. This implies an inhomogeneity in a series that might be misinterpreted as a climate change. The case study of Padova (1725–today) with its history, correction and homogenisation (Camuffo, 2002a,b; Cocheo and Camuffo, 2002) is a useful example, of general interest, of a critical revision of this kind of error in long meteorological series.

2. Styles Used to Compute the Hours of the Day

In Italy, the most popular style used until the arrival of the French Revolution army in 1789, was *Italian Time*, a style derived from the canonical hours which have been in use since the Middle Ages. The same can be said for all the European countries, except for the exact date of the change from the mediaeval to the modern style of computing the time of the day. The end, and the beginning, of the 24-hour day was linked to the sunset or, better, to twilight. This system was deeply rooted in the population with the secular tradition of setting the rhythms of daily life to the striking of the canonical hours, the principle one being the *Ave Maria* and *Compieta* i.e. the Compline, which marked a new day. The main advantage of this style was that it was very traditional and understandable, for the sunset and the following darkening physically represented the end of the old day. In addition, the very familiar canonical hours were announced by the tolling of bells, so that 'the whole population had a concrete sign that pointed to the end or the beginning' (Toaldo, 1789a) of the working day. After, there was only the night for sleeping. This was coherent with the life style of the time. This tradition of beginning a new day at twilight was in use for official as well as for scientific purposes.

In theory, twilight proceeds gradually and is not characterised by a precise instant. From this point of view the disappearance of the upper edge of the sun below the astronomical horizon would have been preferable as a reference. However, as mountains, clouds, or other obstacles, especially in towns often mask the actual instant of the sunset, twilight was preferred, as clearly visible (sooner or later) to everybody. Daylight, due to the light scattered by the atmosphere in addition to direct sunlight, shows a minor dependence on the altitude of the sun. After sunset, the earth's shadow gradually rises upwards. As air density falls off rapidly with height, so do the scattering coefficients. The scattered sunlight becomes weaker and weaker, sky brightness diminishes as does the illuminance on the earth's surface. When the atmosphere is turbid, scattering is greater and twilight may persist longer; when the sky is overcast illuminance is reduced by an order of magnitude, but has almost no effect on the progress of darkness as the sun declines (Rozenberg, 1966). In addition, twilight duration is controlled by the speed with which the sun sinks below the horizon and this varies with the season. At present, civil twilight is defined as the interval between sunset and the time when the true position of the centre of the sun is 6° below the horizon, when the first stars are visible and darkness forces the suspension of normal outdoor activities (List, 1971). The latitude of Padova is 45° 24′ North and the civil twilight varies as follows: 35 min at winter solstice, 30 min spring equinox, 39 min summer solstice, and 31 min autumn equinox. The variability of twilight caused some confusion in the case of precise time measurements, and people referred to a seasonally variable delay after sunset or a fixed delay of 30 min or 40 min, without any precise rule.

For example, Morgagni in his meteorological observations (from 1740 to 1768) used *Italian Time* (IT). The hours indicated in the Padova series followed the standard practice of beginning the new day IT 30 min after sunset, which corresponded to the sun 4° 30′ below the horizon at the solstices and 5° 15′ at the equinoxes. Proof that this was the most commonly used style can be found in tables for astronomical ephemerides written by Toaldo (1789b) in the *Giornale Astro Meteorologico*. Sunrise and sunset were defined as the moments when the upper edge of the sun appeared or disappeared. In the same tables Toaldo also noted that time evaluation might be imprecise because the refraction of the air was not constant. The tables showed, for each day of the year, the time when the sun rose, mid-day, sunset and midnight both in terms of *Italian Time* and *European Time* (ET). The day in *European Time* began at the true midnight of the site (i.e., passage of the sun across the local meridian, on the opposite side), so that each town had an hour which was variable depending on its geographical longitude. On the other hand, in every site, at every ET time, all the celestial coordinates of the sun, moon, planets and stars were the same. Returning to Toaldo's (1789b) tables, and considering 1 January 1799, for example, sunset was at 23.30 IT, i.e., 30 min before the end of the day, when the hour 24.00 IT coincides with the new 0.00 IT. Another column in the same table shows that sunset was at 4.21 [p.m.] ET. Therefore, taking sunset as the official start of the day, midnight should fall, in terms of *Italian Time*, at 7.39, but the time reported in the table is 7.08. The anticipation of 29 min confirms that the time was computed starting from half an hour after sunset, and the approximation of 1 min may be due either to atmospheric refraction or truncation of digits in computations.

Italian Time, however, had – as Toaldo pointed out – some basic defects. The main one was the need to update the clock every day to adjust it to seasonal changes in order to meet sunset at 23.30 IT. This was not, however, a particularly relevant inconvenience given that the clocks of the period were not very precise, and they needed winding up and updating every day anyway.

Some scientists, and in particular astronomers, took the local culmination (i.e., the passage of the sun across the local meridian) as the starting point. The method was not popular. In the Padova series, only Giovanni and Francesco Poleni used this style (observations at noon from 1725 to 1764).

The Enlightenment and the French Revolution established a new lay style in opposition to the canonical hours. The new day began at midnight and counted 24 hours from this point on, dividing them into two cycles, one starting at mid-night and one at noon. This method, called *French Time, Ultamontane Time* or *European Time* was widespread throughout Europe and made compulsory by Napoleon's troops. When this style was imposed, it was not willingly accepted by the people and needed to be presented and explained more than once (Toaldo, 1789c). However, the use of clocks was widespread, so that people were becoming more and more independent from bell tolling and the time was mature for the dissemination of this method, although the official start of this style was controversial and had to be repeated several times. Toaldo, even though with some reservations, endeavoured to have *French Time* also used in Padova, where, starting from November 1788, the University and Public School Clock were regulated according to this style of computing time (Toaldo, 1789c). With the *French Time* system, the clocks of astronomers continued to be regulated according to the sun's culmination (i.e., to the passage of the sun across the local meridian that is the start of the *apparent solar day*). However, people continued to refer to sunset (or sunrise) with the help of daily tables (ephemerides) which reported the instant of sunrise and sunset. In his early meteorological records (1766–1789), Toaldo used *Italian Time*, but in his publications (e.g., *Saggi Scientifici e Letterari* of the *Accademia delle Scienze e Lettere di Padova*) after 1789, he annotated exceptional events in *French Time*.

The *apparent solar day* (i.e., the time interval between two successive culminations of the sun) is variable because of the obliquity of the ecliptic and the eccentricity of the earth's elliptical orbit. However, if time is measured with a clock, it is necessary to eliminate this variability and refer, rather, to an *average solar day*, the duration of which is constant, equal to the exact average of all the durations of the actual days in one year. *Apparent solar time* (AST) is a measure of time based on diurnal motion of the true sun and undergoes seasonal variations. *Mean solar time* (MST) is based conceptually on the diurnal motion of the fictitious mean sun, under the assumption that the earth's rate of rotation is constant (*average solar day*). *French Time* was based on *mean solar time.* The difference between these two solar times (which lies between -14.26 and $+16.33$ min) is given by the *equation of time* which represents the departure between apparent and mean solar time.

In the 18th century, the precise clocks of astronomers were regulated with the local culmination of the (apparent) sun on clear days; however, they ran at a speed calibrated on average solar time. For example, in the above quoted *Giornale Astro Meteorologico* by Toaldo and Chiminello, AST was used. Clock technology was poor and clocks were inaccurate. The following words by Toaldo are significant in this respect '…the main Clock used as a reference for the clocks in the town should never be over an hour off, not even half an hour off within the space of a few days' (Toaldo, 1789c).

Moreover, especially in scientific fields, the tendency to refer to average time became ever more widespread at the end of the century when clocks were improved. In particular, at a meeting of astronomers in Gotha (Germany) in 1798 it was recommended that astronomical ephemerides be expressed in mean solar time (Rajna, 1897). This suggestion was not however immediately taken up.

Mean Local Time (MLT) was MST related to the culmination of the sun across the local meridian. In Italy, the application of MLT to civilian life began in Turin in 1852, followed by Bologna in 1858, then Milan and the other Italian towns in 1860 (Rocca, 1893). In 1866, after Italy was unified into one Kingdom, a Royal Decree signed by King Vittorio Emanuele II established the use of *Mean Rome Time* (MRT), starting from the winter of 1866/67. In fact, the telegraph and railway made synchronisation of all the clocks necessary.

Finally, after the world time zones were established in 1884, King Umberto I decreed that, starting from 31 October 1893, reference would be to *mean Etna time* (MET) for culmination. This because Mount Etna (15° 0′ 14″ longitude East) practically coincided with the first meridian, 15° longitude East of Greenwich, i.e., the *mean time of Central Europe*, also called *Western European Time* (WET). MET = WET is 10 min and 4.5 s earlier than MRT, and the MLT of Padova is 12 min 30 s earlier.

Following a suggestion by A. Secchi, observations were taken from 1865 to 1867 at 7.00, 12.00, 15.00 and 21.00 MLT. According to the following directive in 1868, observations were carried out at 9.00, 15.00 and 21.00 hr, when Padova adopted MRT (Lorenzoni, 1908). In 1894, the WET style was completely established. In fact, P. Tacchini (1893), director of the *Ufficio Centrale di Meteorologia e Geodinamica*, responsible for all meteorological observations, with two circular letters established that all measurements be taken in WET.

In Rome, clocks were synchronised at mid-day, WET style, in three different and simultaneous ways, i.e., with (i) an optical signal, consisting in dropping a 'balloon' at the *Collegio Romano* Observatory; (ii) an acoustic signal, firing a cannon sited at *Castel Sant'Angelo* (the time needed for the sound wave to reach Rome and the surrounding region was calculated and subtracted); (iii) a telegraphic signal sent by the *Collegio Romano* (Tacchini, 1892).

3. Transformation from *Italian Time* to *Western European Time*

In order to transform *Italian Time* into modern conventional units it is necessary to evaluate the time span that occurred two centuries ago, day by day, between twilight and midnight. Toaldo was not only a valuable meteorologist, but also a very accurate astronomer and published (1789b), in addition to the astronomic ephemerides, also the hourly values of the apparent midnight, although in astronomical units that have since been transformed into minutes and tenths of minutes.

In practice, the time corrections have been calculated as follows, starting from the *apparent solar time of midnight* (MAST). The MAST was subtracted from the actual time of the observation read in *Italian Time* (IT) in order to find *the apparent solar time* (AST), i.e.,

$$\text{AST} = \text{IT} - \text{MAST}\ .$$

In order to calculate *mean solar time* (MST) it is necessary to correct the AST by the equation of time (TE). The relationship between AST and MST is given by:

$$\text{MST} = \text{AST} - \text{TE} = \text{IT} - \text{MAST} - \text{TE}\ .$$

For example, if the culmination on 1 January was 12 hr 0 min (AST) then the MST is:

$$12\text{ hr }00\text{ (AST)} - (-3\text{ min }15\text{ s})\text{ (TE)} = 12\text{ hr }3\text{ min }15\text{ s (MST)}\ .$$

The actual WET is calculated with a further correction for the change in longitude (CL). The longitude of Padova is 11° 53′ E of Greenwich, i.e., 3° 8′ W of the first meridian and the CL = +12 min 30 s; therefore, WET = MST + CL = MST + 12.5 min. Finally,

$$\text{WET} = \text{MST} + \text{CL} = \text{IT} - \text{MAST} - \text{TE} + \text{CL}\ .$$

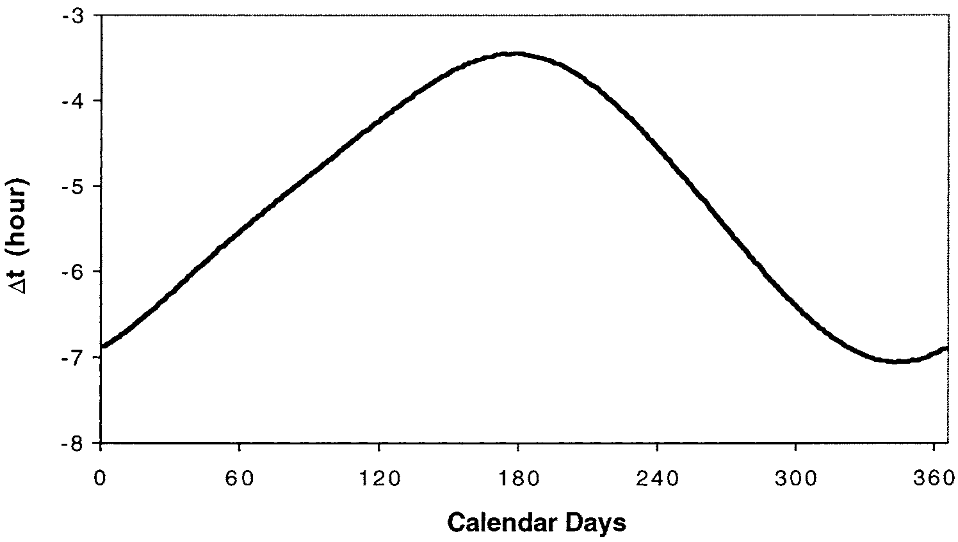

Figure 1. Bulk correction to transform into *Western European Time* (WET) the time of observations made in *Italian Time.*

The correction necessary to transform the time of observations from the original *Italian Time* (computed after the astronomical ephemerides of the sun in the 18th century) to the modern WET is reported in Figure 1.

4. Error Due to the Change from *Apparent Solar Time* to *Average Solar Time*

In 1894, when temporal reference was changed from *apparent* to *average solar time*, two inhomogeneities were introduced. The first, a seasonal double oscillation given by the equation of time and that reaches up to ± 15 min. A note from the Meteorological Service specified that this was practically irrelevant, but we will quantify the effect. Another time shift was introduced by making reference to the First Meridian (15° long. East) which departs more or less from the local meridian. In Italy, the country extends from −9 min on the eastern longitude to +34 min on the western one. Padova is displaced +13 min from the reference meridian.

The effect of the equation of time can be shown by the difference between temperatures observed at *apparent solar time* and at *average solar time*. An example is reported in Figure 2 for the difference between air temperatures measured following these two styles in the morning at 8.00 and in the evening at 20.00 hr. The differences closely follow the oscillation of the equation of time. In the morning the departure is more marked, exceeding 0.4 °C in autumn, whereas in the evening it hardly exceeds 0.15 °C. The evening difference is small because the temperature drops at a very slow rate. In particular, the observation at 20.00 hr was thought to be especially important because (Flammarion, 1888), for each month, the average daily temperature was noted to be close to the average of temperature readings taken at 20.00 hr (apparent solar time). Therefore, a measurement taken at that time was regarded as being a reasonably good approximation ($\Delta T < 0.1\,^{\circ}C$) of the average temperature of the day.

The graph in Figure 2 is representative of the inhomogeneity derived from the passage from apparent solar time to average solar time. In the 18th century and for part of the 19th century, time was regulated daily, on the basis of the local culmination of the sun. As a consequence, the equation of time was respected day by day and observations were always in the same phase with the position of the sun. An important change appeared when it was no longer necessary to adjust clocks daily on the basis of the passage of the sun across the local meridian, and clocks were regulated on the basis of average solar time, due to the forward movement of the spring mechanism. When this change of reference occurred, all measurements taken at the same hour underwent a positive, or a negative displacement from -14.26 to $+16.33$ min plus the difference of longitude with a departure in the climate signal that will be discussed later.

5. Errors Inherent to the Temporal Determination of Measurements

The daily temperature cycle, under typical conditions found on a clear day, can be approximately reproduced using polynomial or other mathematical equations. In Italy, where solar radiation is strong, a sinusoid may describe the heating period mainly governed by solar radiation from early morning to noon, and an exponential attenuation may represent the late afternoon and nocturnal cooling for infrared emission. On perturbed days, departures may occur, which might also be marked, as a result of forcing factors (e.g., precipitation, passage of fronts, etc). Over long time periods, however, the average hourly distribution indicates that departures are randomly distributed and tend, statistically, to compensate for each other so that the average follows the same distribution, but with reduced amplitude. This average includes all the perturbations due to both synoptic and local effects. Once the equation representative of the daily cycle is known for each month, after the actual observations, it is possible to calculate the expected value at a slightly different time, and homogenise the series for changes at observation times. In reality, making reference to the mean daily cycle may introduce an error of first order approximation with individual days; the error vanishes when monthly averages are considered. Fortunately, for most climate analyses, working on a monthly basis is not a great limitation, and working on individual days is a reasonable approximation.

First of all, it is necessary to evaluate the error that is induced in the temperature series when an observation has been made at, or attributed to, an inexact time. This is relevant in assessing reliability of the data, especially those of the 18th century. In fact, it is reasonable to suppose the measurements taken by Poleni, Morgagni and

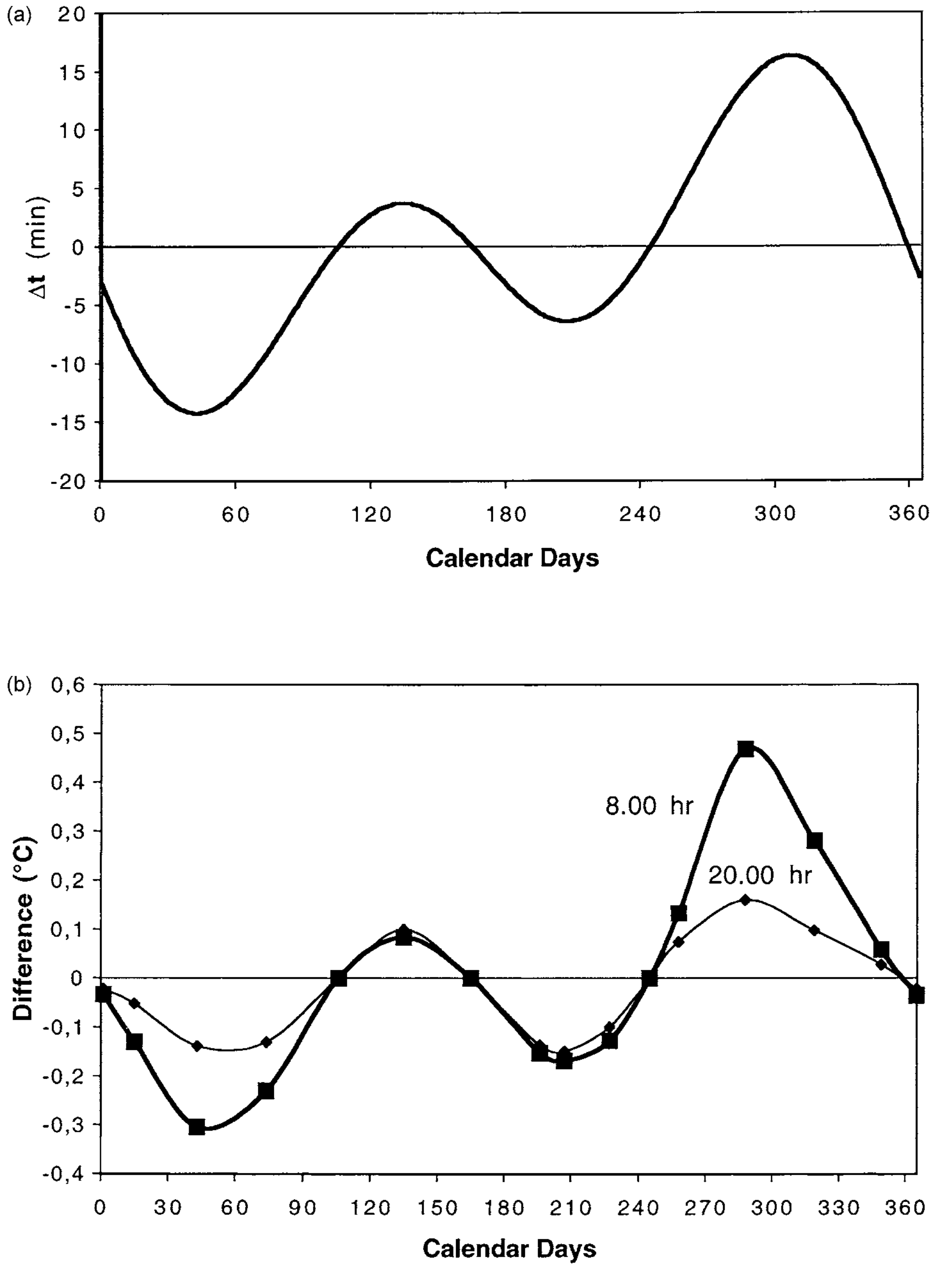

Figure 2. (a) Equation of time. (b) Difference between temperatures observed at apparent solar time and at average solar time. Example at 8.00 hr (thick line) and 20.00 hr.

Toaldo could have been displaced in time by about 15 min or more. The error due to a poor approximation of the time of observation is linked to the instantaneous change rate dT/dt of air temperature T(t). The principal maximum of the absolute value of dT/dt occurs in mid- or late morning; a secondary maximum is found in the cooling period during the afternoon. Two minima of dT/dt occur when T(t) is near the daily minimum, i.e., at dawn, and the maximum, i.e., 2–3 hours after noon. The distribution of the monthly average of the hourly rate dT/dt is shown in Figure 3 for January and July, in order to show the most critical hours and the more reliable ones for taking temperature measurements at the two seasonal extremes. In the plot at 10 m, where the influence of the soil is attenuated, the daily range is smaller than at 2 m, and the daily maximum is reached later. In summer, the diurnal superadiabatic layer and the nocturnal inversion at 2 m are more marked than in winter, when solar irradiation is weaker and fog is frequent during the night. In the same graph, the letters P, M, T and H indicate the time of the observations by Poleni (P), Morgagni (M), Toaldo (T), and Hemmer (H). The observing schedule followed by Toaldo was fairly similar to Morgagni's.

Examining the graphs, dT/dt increases following the seasonal cycle of air temperature. In the summer, when solar radiation is intense, dT/dt reaches very high values, and in July the main maximum (about 1.8 °C/hr) is twice the winter one. A symmetrical trend is found for the afternoon minimum. The morning maximum arrives early, from about 12.00 hr in the winter to about 8.00 hr in the summer, while the minimum is delayed from about 16.00 hr in December to 18.00 hr in the summer. The early morning period in which dT/dt is close to zero follows the seasonal shift of dawn (from 7–8 hr in winter to about 5.00 hr in summer). In the central part of the day, the period in which dT/dt is close to zero is rather stationary, lying around 14.00 hr throughout the year. As a result, if a measurement is taken at 8.00 hr, it corresponds to dawn in the winter months and therefore at a time when dT/dt is close to 0 and any imprecision about the time of measurement has negligible effects. In the summer, on the other hand, it would correspond to a time when the temperature rises particularly fast and therefore dT/dt is at its main maximum, which could lead to a considerable error in T(t).

The dT/dt values relating to measurements taken at 12.00 hr lie between 0.75 °C/hr in winter and 0.4 °C/hr in summer. However, it is not advisable to apply these results directly in the case of Poleni, because he took measurements inside and not outside.

Morgagni's measurements were generally taken one hour after dawn and at 14.00 hr. Both of these hours were appropriate for observations. In the early morning, dT/dt was close to 0 in the cold season and on overcast days, but increased when solar radiation was stronger. Temporal precision in Morgagni's readings was not particularly important. Toaldo followed a similar schedule, but much more irregularly. Therefore, Morgagni's observations are at first approximation representative of the daily minimum and maximum. The problem is that the measurements were affected by the thermal inertia of the building, so that it is impossible to

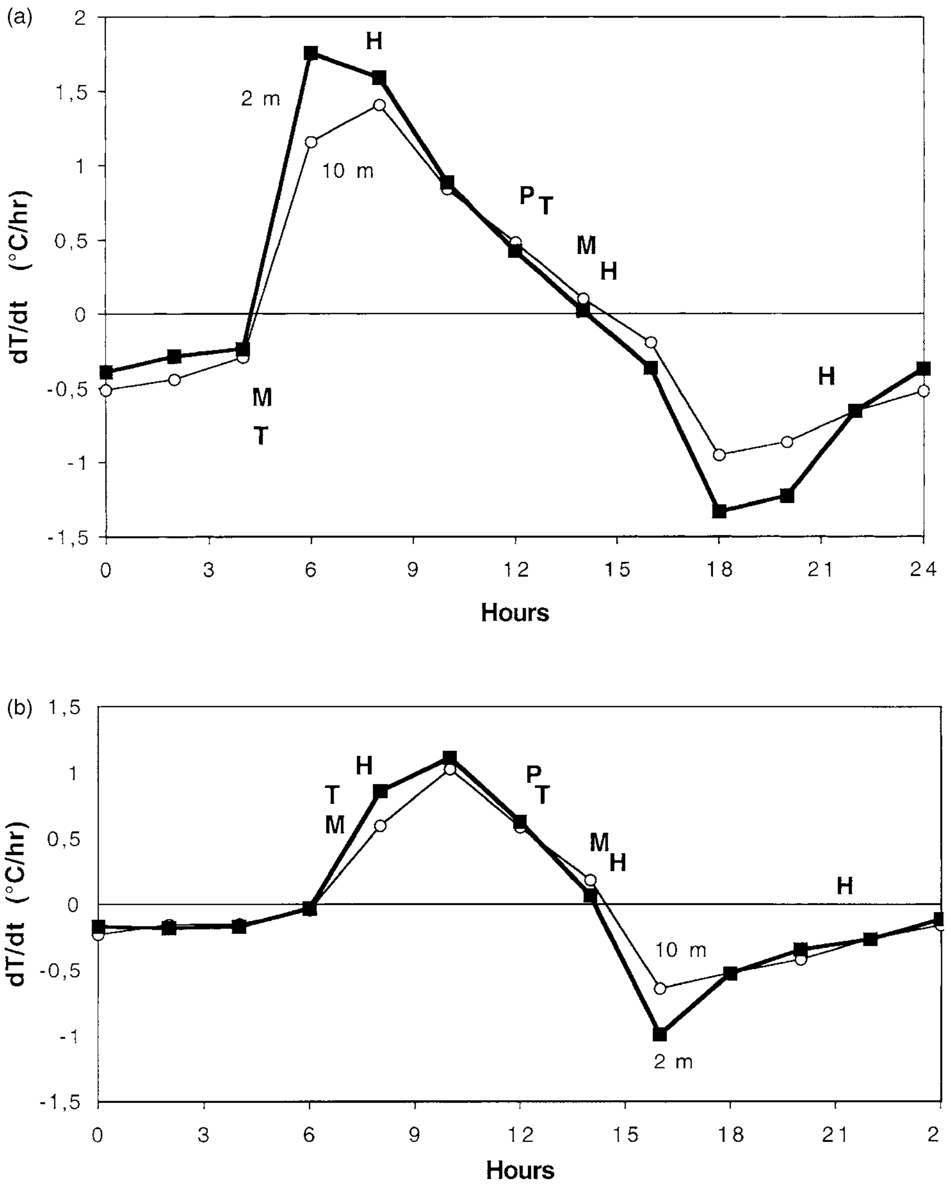

Figure 3. Monthly average of the hourly rate of the change in air temperature dT/dt (°C/hr) in January (top) and July (bottom), measured at 2 m (thick line) and 10 m (thin line). The letters P, M, T and H indicate the time of the observations by Poleni (P), Morgagni (M), Toaldo (T), and *the Meteorologica Societas Palatina*, Mannheim, as suggested by Hemmer (H).

define the daily range and also obtain a reasonable approximation of the average daily value.

Hemmer (1783), secretary of the *Societas Meteorologica Palatina*, Mannheim, suggested readings at 7.00, 14.00 and 21.00 hr mean solar time. With reference to the observation at 7.00 hr, dT/dt was about 0 in the winter months while it increased considerably in the summer, and reached 1.7 °C/hr in July. A time shift of 15 min in taking the reading could lead to an error of ± 0.4 °C, but late or early readings amounting to some 30 min should not be excluded. From this point of view, the choice of time was not appropriate. In terms of the evening reading at 21.00, dT/dt lies between −0.3 °C/hr in winter and −0.9 °C/hr in summer.

6. Calculation of the Mean Temperature after a Given Number of Observations

When only a few observations were taken in a day, they may or not be useful, depending on the choice of the time of the readings. It is thus necessary to subdivide each series into parts which are homogeneous for the number and the schedule of observations, and then proceed separately to correct and homogenise each part. In this section the general problem of assessing the representativeness of the data will be considered, i.e., may the existing data be reasonably used to estimate the maximum, minimum and mean daily values and to model the hourly temperature distribution? The following cases, from one to more daily observations, will be considered.

One Daily Observation

Only one observation was taken with the aim of getting a rough value, representative of mean daily temperature. This happened centuries ago, when Jurin (1723), on behalf of the *Royal Society*, recommended measuring indoors, probably supposing that the thermal capacity of buildings would filter out short time temperature variations and measure smoothed values. These data were considered representative of the daily average, although we cannot define the real averaging period. Giovanni and Francesco Poleni followed these recommendations from 1725 to 1764. Some years later, Toaldo evaluated the error in this approximation. He measured the difference between a filtered value measured in a room of Poleni's house and the actual average of the external temperature. He wrote at the beginning of Poleni's register, as well as in other publications (Toaldo, 1770, 1781), that the temperature indicated by Poleni overestimated the actual mean at least by two or three degrees Réaumur (Camuffo, 2002a). This is the only correction that we might do today, as Poleni's house was restored, the heat exchanges and the penetration of air through the windows are not the same, and the actual owners, living there, would not appreciate no heating at all, as Poleni did, to measure this departure. Unfortunately, Toaldo did not add further details on the seasonal distribution of this error.

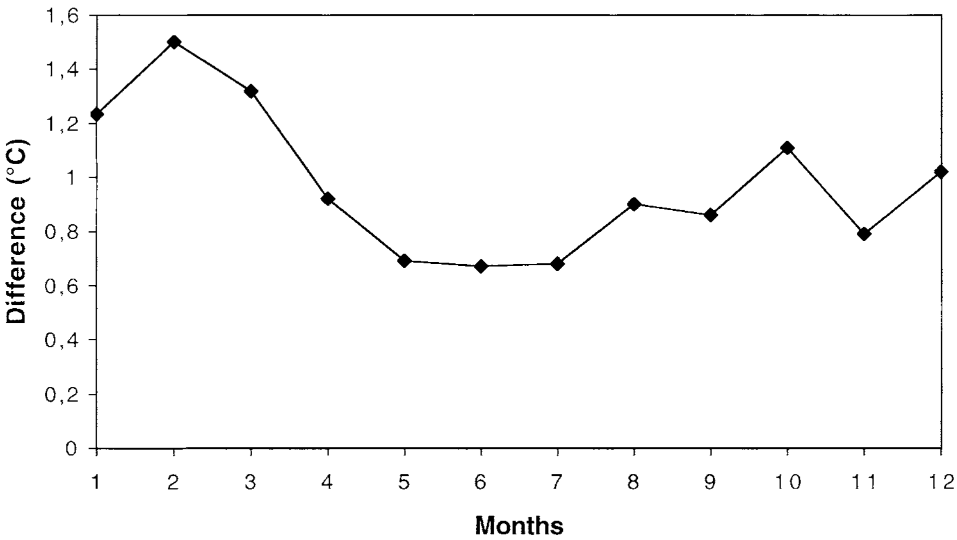

Figure 4. Monthly average of the difference between the daily maximum and the actual value of the air temperature at noon.

In the case of only one daily observation, it is impossible to reconstruct the hourly cycle of air temperature, unless based on some hypotheses. One is to assume, for every day of the year, that the amplitudes of daily cycles are close to present day ones. Another possibility, with only observations performed at time h', is to analyse the series of data taken at the time h', which indicates the climatic variability occurred at the same reference time. If the available measurements correspond to the daily maximum, or the minimum near sunrise, or the mean temperature at 20.00 hr, then the series has greater utility. In fact, the trend of the daily maximum, or minimum, or mean temperatures over the centuries can be correctly calculated, and this type of information is very important.

A fixed observation time implies seasonal changes due to the phase of solar input. Let us consider the case of measurements taken around noon, as Poleni did, but outdoors. At noon the temperature is near its maximum in summer, and more distant in winter. For every month ($j = 1 \ldots 12$) the difference D_j can be expressed in terms of the normalised index

$$D_j = [T_{\max} - T(h')]_j / \Delta T_j$$

where $T(h')$ represents the average temperature at the time $h' = 12.00$ hr, $T_{\max}$ and $T_{\min}$ the mean maximum daily temperatures, and $\Delta T_j = [T_{\max} - T_{\min}]_j$ the average daily temperature range during the j-th month of the year. The monthly average of the difference between the daily maximum and the actual value of air temperature at noon is reported in Figure 4. This difference ranges between 0.7 °C and 1.5 °C, the maximum being reached in the heart of the winter.

Two Daily Observations
In the past, an empirical method used to obtain the average daily temperature T_{ave} consisted in taking two readings close to the daily minimum and maximum, then summing these two values and subsequently dividing the total by two. This practice was adopted by Morgagni and Toaldo (even though Morgagni never recorded his average values), and was widely used throughout the 19th century. A famous treatise on the atmosphere written more than a century later, stated that 'in general, the half-sum of the maximum and minimum temperature (i.e., the one at 2 after midday and at sunrise) hardly differs from the real [calculated] average of the 24 hours' (Flammarion, 1888). Fifty years later, in the stations of the Italian meteorological network, under the control of the *Water Magistrate*, only extreme temperatures were recorded, and therefore, the only possible average was the half-sum of the maximum and minimum temperatures (Ceconi, 1939), i.e.,

$$T_{ave,2} = (T_{max} + T_{min})/2 .$$

For every month, we can evaluate day by day the error $E_{2,j}$ due to the empirical practice of computing the mean temperature by using only two data instead of all the hourly data, i.e.,

$$E_{2,j} = T_{ave,j} - 0.5(T_{max} + T_{min})_j ,$$

where the label j indicates the month. The monthly averages of $E_{2,j}$ in Padova are shown in Figure 5. In practice, this method gives a good approximation in the intermediate seasons. The largest error (exceeding 0.6 °C) is negative and was found in the cold season, with a positive error in late spring and early summer (maximum $E_{2,j} = 0.4$ °C in July); the best approximation was found in April, June and August ($|E_{2,j}| < 0.2$ °C). Ceconi (1939) calculated this difference for a number of stations; in Padova the departure in summer was 0.2° and in winter −0.6 °C. The error $E_{2,j}$ is practically the same in Padova as in Venice (the distance between the two cities is 37 km), but differs in other sites.

In the annual average, monthly errors tend to compensate each other for $E_{2,j}$ varies seasonally becoming positive and negative. The yearly error $E_{2,y}$ calculated from recent CNR data used for Figure 5 gives a departure of −0.26 °C. A similar analysis over an earlier ten-year period (Water Magistrate data) was $E_{2,y} = -0.18$ °C. Favaro (1906) calculated the annual deviation for the year 1881, using a Hipp thermograph and obtained $E_{2,y} = -0.1$ °C.

In conclusion, daily values may have important errors; errors for monthly averages do not exceed 0.6 °C and the annual average is quite accurate.

Readings were not always made at the appropriate time, and the error may be corrected when the daily temperature cycle from which we extrapolate the minimum and the maximum value is known. It is necessary to assume, as a first approximation, that the general shape of the unknown temperature cycle in the past was governed by the same equation as today, except for the amplitude. From two hourly values we can compute the whole by imposing a curve fitted to the two

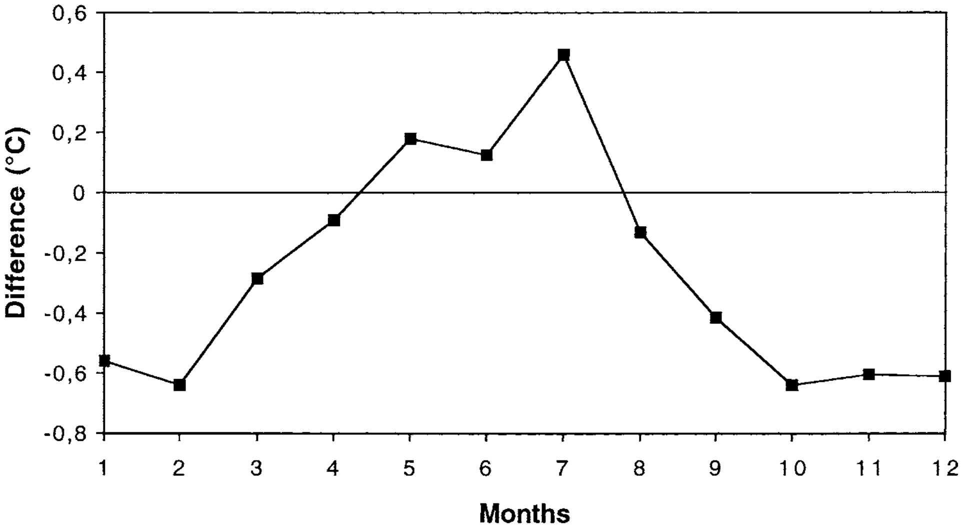

Figure 5. Monthly average of the difference between the mean temperature computed after all the hourly data and after the daily maximum and minimum.

observations. This method gives reasonable values only when the two readings fall respectively near sunrise and a couple of hours after noon. It is not applicable when the two observations are spaced within too short a time interval, or when one has been made in the morning and one in the afternoon, but at similar air temperatures. In these cases, it is impossible to calculate the amplitude of the daily cycle, as in the above case with only one observation.

In order to quantify this problem, an index of the representativity Rj of a pair of hours chosen for the two readings, has been introduced per month, as defined by the following:

$$R_j = [T(h'') - T(h')]_j / \Delta T_j$$

where $T(h'')$ and $T(h')$ are the temperatures observed at the hours h' and h'' and ΔT_j is the mean daily range for the j-th month. This index shows to what extent the readings are useful in obtaining the true amplitude of the daily temperature cycle. The absolute value of R_j lies between 1 (whenever the two readings are made close to the daily maximum and minimum), and 0 (when the two readings have the same temperature). For every month of the year, it is possible to calculate the corresponding values of R_j for each pair of hours h′ and h″. An example for July has been reported in Table I.

The values corresponding to Morgagni's readings have been indicated with the letter *M* on the graphs. Morgagni took his measurements twice a day, but not at fixed times. After transformation from *Italian Time* the readings were found to have been made, in general, one about half an hour after dawn and the second some two hours after mid-day. The first measurement was, therefore, taken

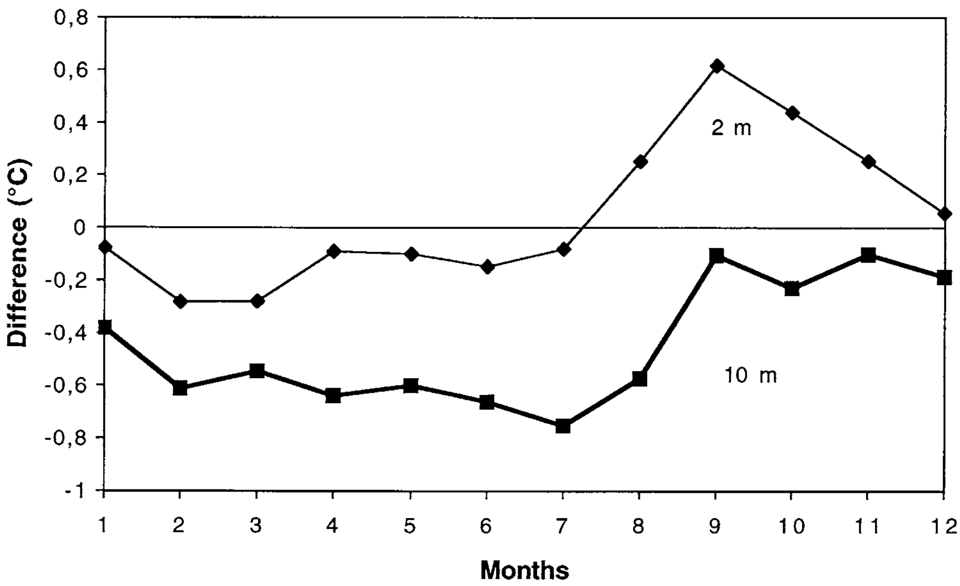

Figure 6. Monthly average of the difference between the daily average and the temperature observed at 20.00 hr. Thin line: sensor at 2 m; thick line at 10 m.

a little after the daily minimum temperature, while the second corresponded to the maximum. Thus, the R_j index, which has a value of a little less than unity $(0.9 < R_j < 1)$, shows that Morgagni had chosen his two observations times fairly well. The situation was similar with respect to Toaldo's observations, in that he took his measurements more or less at the same times, but with less regularity.

Three Daily Observations

The average based on two readings was rather good, but unrepresentative in the case of the occurrence of short-term meteorological phenomena. It became clear that it was necessary to increase the number of daily readings. As already mentioned, the evening observation at 20.00 hr, $T(20)$, equals, or is very close to, the daily mean (Figure 6). At the level of standard weather stations (2 m) this rule of thumb is quite accurate to obtain the monthly average, except for in the autumn rainy season, in which observations at 10 m give a better approximation. Therefore, this measurement at 20.00 hr was considered useful, as it practically introduced another independent average, which increased the statistical representativity of the computed average. Therefore, a new empirical approximation was introduced, by combining two ways of computing the daily mean, i.e., the weighted sum of the daily minimum and maximum, and the evening value close to the mean, that is:

$$T_{ave,3} = [T_{max} + T_{min} + T(20)]/3$$

This method is characterised by one measurement taken at a fixed time, i.e., $T(20)$, another at a time which slightly varies with the season (i.e., T_{max} which was observed more or less 2 hr after noon) and a third of a more pronounced seasonal character (i.e., T_{min} which was linked to sunrise). It was impossible to establish a clear and simple international recommendation for a schedule of observation. Thus, Hemmer (1783) on behalf of the *Societas Meteorologica Palatina*, Mannheim, preferred a standard practice, irrespective of seasonality, always reading all instruments at the same hours, at 7.00, 14.00 and 21.00 hr, to avoid the risk of non-simultaneous readings by the observers. This choice introduced an error in computing the average temperature. The main error was in the morning observation: this reading was late in the summer, and this overestimation was only partially mitigated by reading the thermometer one hour later in the evening, i.e., at 21.00 instead of 20.00 hr.

In practice, or at least in Padova, the readings were actually taken at randomly variable times, always specified in the registers, close to the internationally agreed ones, with variations of up to 30 min.

A frequent combination was characterised by a longer delay in the morning, i.e., at 8.00, 14.00, 20.00 hr. The error $E_3[8; 14; 20]_j$ made by taking three readings at these hours is:

$$E_3[8; 14; 20]_j = T_{ave} - [T(8) + T(14) + T(20)]_j/3$$

The results obtained with CNR data measured at a 2 m and 10 m level are shown in Figure 7. The deviation was always negative; it was smaller in the cold season ($E_3 = -0.4\,°C$) and greater in the hot season ($E_3 = -1.4\,°C$). The annual error was $E_3 = -0.9\,°C$. The under-estimation of the data, especially the summer ones, was because the morning measurement was taken too late after dawn.

Comparing the values of $E_3[8; 14; 20]_j$ in Padova and Venice, the seasonal variation is similar, with the greatest error in summer, but individual errors are greater in Padova than in Venice. The largest error found using data collected by the Water Magistrate over a ten-year period was $E_3 = -2.2\,°C$ in Padova and $E_3 = -1.0\,°C$ in Venice. Ceconi (1939) evaluated the error made using the above formula but for the hours 8.00, 14.00, 19.00 in Padova and other three stations, and he found substantial errors; the maximum error was in summer when $E_3[8; 14; 20]_j$ generally exceeded $-2\,°C$ (the largest error was found in August 1927 with $-2.5\,°C$); the minimum error was around $-0.5\,°C$ in January.

A comparison of $E_3[8; 14; 20]_j$ with $E_{2,j}$ shows that the method of obtaining $T_{ave,2}$ with two daily observations, i.e., T_{max} and T_{min}, gives better results. The reason is that $T(20)$ introduced unreliability, as meteorological events which occur in the afternoon (e.g., summer thunderstorms, passage of fronts) are responsible for strong departures.

From 1868 to 1920, all meteorological observations were made at the times recommended by the *Ufficio Centrale di Meteorologia e Geodinamica*, Rome, which shifted the observations to a later hour, especially in the morning, i.e., at 9.00, 15.00 and 21.00 hr. These times were expressed in the style of the local average time from 1868 to 1893 and since 1 January 1894 were expressed in WET.

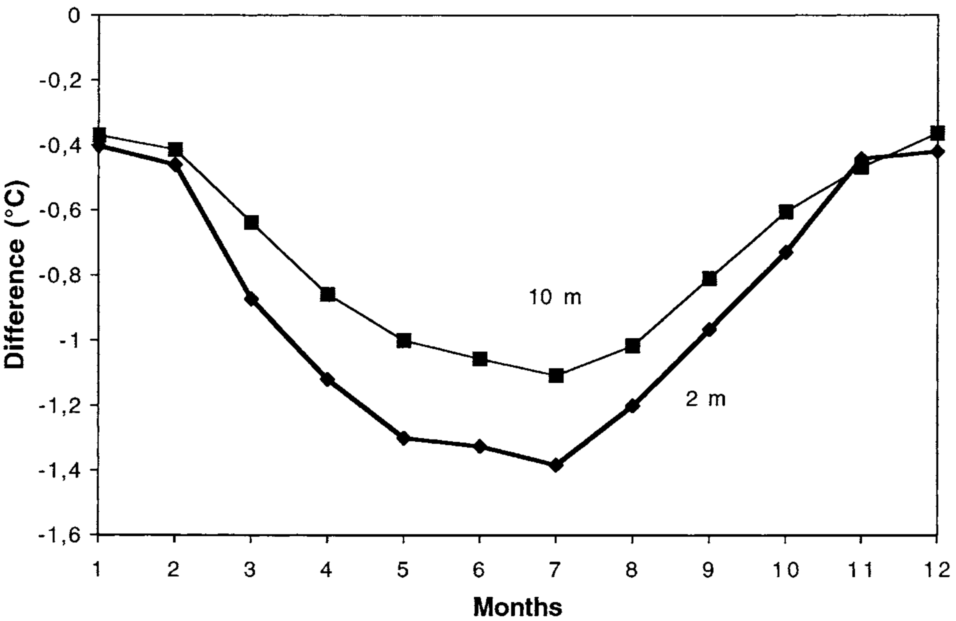

Figure 7. Monthly average of the error $E_3[8; 14; 20]_j$ made by calculating the daily average after three observations at 8.00, 14.00 and 20.00 hr. Thick line: observations at 2 m; thin line at 10 m.

Therefore, since 1894, all the observations in Padova were brought forward by 12 min 30 s with respect to the previous observations made at the same time under local average time, with a systematic error that lies between -0.3 °C and $+0.5$ °C, depending on the time of day and the season.

With an analytic expression of the daily temperature cycle with the three daily readings, it is possible to evaluate the error for every station and the choice of observation times, whatever it was.

Four Daily Observations

Four readings were used to increase the statistical representativity and reduce the error associated with three readings at fixed times, thus reducing over-evaluation. In particular, in the three years from 1865–1867, the *Specola* in Padova took four readings per day following the recommendation of A. Secchi, that is, at 7.00, 12.00, 15.00 and 21.00 hr, at average local time. In practice, this schedule was aimed to improve the schedule suggested by Hemmer (1783) and followed by the observers of the *Societas Meteorologica Palatina*, but with the central observation at 14.00 hr split into two, i.e., at 12.00 and 15.00 hr.

In the second half of the 19th century, the average daily value, in Venice, was calculated according to the Cantoni formula. Cantoni introduced an observation with a slightly greater value than $T_{\min}$ and one slightly smaller than T_{ave}, i.e.:

$$T_{\text{ave},4} = [T_{\min} + T_{\max} + T(9) + T(21)]/4 ,$$

which was similar to the method based on $[T_{max} + T_{min} + T(20)]$ except the over-evaluation of the first three terms was not completely compensated by the slight under-evaluation of the last (Crestani, 1933). As in several stations the mean daily temperature was mainly computed as $T_{ave,2}$, which was substituted around the turn of the century by the Cantoni formula, a number of climatologists computed the difference between these two averages. For example, Capra (1939) obtained for Bologna monthly differences, which seasonally varied from 0.38 °C (winter minimum in January) to 0.7 °C (summer maximum in June). For Milan $T_{ave,2} - T_{ave,4} \approx 0.3$ °C (Ferretti et al., 1993; Maugeri et al., 2002).

Ceconi (1939) evaluated the error made in Padova using the above formula but for the hours 8.00, 19.00. He found that the error was generally small; generally lying from +0.2 °C to +0.3 °C in summer and from −0.2°C to −0.4 °C in winter, although some departures occurred.

Five Daily Observations

Five readings were taken in one of the last periods of the *Specola* observations, using the formula:

$$T_{ave,5} = [T_{max} + T_{min} + T(9) + T(15) + T(21)]/5 ,$$

which can be expressed as a linear combination of the two formulae already discussed, i.e.:

$$T_{ave,5} = (2/5)T_{ave,2} + (3/5)T_{ave,3}$$

$$= (2/5)[(T_{max} + T_{min})/2] + (3/5)\{[T(9) + T(15) + T(21)]/3\} .$$

According to the theory of error propagation, the same formula can be used to compute this error as a linear combination of the individual ones.

Many Daily Observations

In the case of many daily readings, it is possible to accurately compute the mean and extreme values as well as their variance and other mathematical properties in accordance with the principles of modern statistics. From this experimental basis, the analytical expression of the daily cycle in the different seasons and weather types can be calculated, as can the accuracy of the various approximations.

The daily averages of the *G. Magrini* Observatory in Padova (1920 onwards) were computed as the mean of the 12 readings taken at even hours. In practice, however, the average was computed with 13 readings, because the two midnight values, at the beginning and end of the day, were included each with half weight.

7. Conclusions

This study suggests that a critical analysis of the history of the long series is absolutely necessary, as all the long series are composed of a number of inhomogeneous parts, each of them with the mean daily values computed in different ways. Also observations were taken at different times, or with the time expressed in different styles. The same change in temporal reference, from the ancient *Italian time*, *apparent solar time*, *mean solar time*, *local time* and *French time* (which were regulated on the passage of the actual sun across the local meridian) to the modern WET (which was regulated on the passage of the fictitious average solar motion on the reference meridian 15° East), introduced spurious seasonal changes. In certain months, the departure is of the same order of magnitude as is the natural warming of the last century found by Jones et al. (1986).

Not only in the early period of the long meteorological series, but also in more recent times, do we meet the practice of taking a limited number of daily observations. The aim was to obtain average values with little effort in the field, and to avoid time-consuming calculations with too many numbers, especially before the advent of computers. This practice has limited our knowledge and the possibility of reconstructing the past daily temperature cycle. This is especially true when the choice of the times for readings was inappropriate, and in particular when the observations were performed less closely to the daily minimum and maximum. Paradoxically, in the early period with Morgagni and Toaldo, the choice of observation schedule was good; later, the introduction of new observations, not always established at the most appropriate time, reduced the representativeness of the data.

In the past, average values were obtained by taking only a few daily measurements, and each of these had its own degree of approximation, which introduced a different error. The first problem was to reconstruct the daily cycle from which to extrapolate the hourly temperatures needed to evaluate the daily minimum, maximum and average values homogeneously. All of these corrections are absolutely necessary to obtain a homogeneous time series.

Each time the operational methodology, or the general directives, or the style of computing time was changed, an inhomogeneity in the series was introduced, which can be misinterpreted as an apparent climate change. Imprecise clocks, little care for the exact time established for meteorological readings, changing style of evaluation time, inappropriate choice of observation times, too few readings to compute a daily average, have all been relevant errors. Although they are rarely considered, they have caused significant departures in time series that can be misinterpreted as climate signals.

The role of national, and especially, international recommendations was particularly important. In fact, they were simultaneously applied in a large number of sites, causing inhomogeneity everywhere, which may be misinterpreted for a well-documented, widespread climate change.

Acknowledgements

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Note: Essential information is found in the issues: *Annali dell'Ufficio Centrale di Meteorologia*, Rome, period: 1879–1887. *Annali dell'Ufficio Centrale di Meteorologia e di Geodinamica*, Rome, period: 1887–1924. *Bollettino Idrografico Mensile* of the Ufficio Idrografico del Magistrato alle Acque, Ministry of Public Works, Rome. Period: 1912–onwards.

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Recovery of the early period of long instrumental time series of air temperature in Padua, Italy (1716–2007)

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ABSTRACT

The longest series of instrumental observations have a number of problems in the early period. This paper is focused on the recovery of early indoor and outdoor observations in Padua and their transformation in terms of a modern series. The Padua series was started by Giovanni Poleni with outdoor observations in 1716–1718, but soon, the readings passed indoors (1725–1764) to join the directives of the Royal Society, London. The indoor readings were recovered within the EU project IMPROVE, but it was necessary to transform indoor observations into outdoor ones, and this was possible thanks to the presence of simultaneous indoor and outdoor observations by Morgagni in Padua and Beccari in Bologna. These parallel series were also useful to fill a short gap. Another problem was to reconstruct the calibration of the Amontons thermometer, which changed when Poleni moved to a new house. Also the problem of the use of variable and/or different sampling times was solved making reference to the trend of the daily cycles in the different seasons and under diverse weather conditions. The data analysis has shown a trend that appears similar to the well-known results (IPCC 2007) for the last 160 yr but a less marked recent warming for winter and autumn. The 18th century was characterized by cold winters (culminated 1709 and 1740) and springs, and warm summers and autumns. A well-marked Bruckner cycle (35.8 yr), continually repeated and attenuated, is visible for the period 1716–1930. The wide time scale and the repetition of warmer and colder periods over two-thirds of the series noted in Padua and other Mediterranean stations may induce us to suppose that such cycles could continue in the future, at least on the local scale.

1. Introduction

The early period of instrumental meteorological observations is extremely relevant, because it furnishes extremely rare and unexploited quantitative information about the past climate. On the other hand, early observations were taken with instruments and methodologies, which were not always according to the present-day practice, and for this reason, a huge effort is needed to remove all obscure items, check the quality, interpret, correct, homogenise and analyse the data.

Under the EU funded project IMPROVE (Camuffo, 2002a,b,c; Cocheo and Camuffo, 2002; Camuffo et al., 2006), the daily meteorological observations made in Padua by Giovanni Poleni (born 1683–died 1761) and his son Francesco in the 1725–1769 period have been recovered from the original registers preserved in the old library of the Astronomic Observatory of the University of Padua and published. However, some problems were left unresolved, i.e. (i) indoor observations, (ii) only one reading a day, (iii) the use of variable and/or different sampling times. In this paper, the 1725–1761 indoor observations have been transformed into outdoor ones with the help of the simultaneous indoor and 1740–1768 outdoor observations made by Giovan Battista Morgagni (b 1682–d 1771) in Padua, one mile from the Poleni house. The problem of only one reading a day taken at different times has been solved, and the data have been expressed in terms of anomaly, i.e. difference from the 1961–1990 period.

In addition, newly recovered data have been analysed. First, the daily data by Giovanni Poleni for the 1716–1718 period were copied from the original log preserved at the Marciana Library in Venice (Poleni, 1716–1725). Second, the monthly averages of the readings made by Francesco Poleni for the 1765–1769 period, found in a publication by Giuseppe Toaldo (1770, 1781).

Details about instruments, their calibration, location, exposure and observational modalities have already been illustrated and discussed in a special issue of Climate Change (Camuffo, 2002a,b,c; Cocheo and Camuffo, 2002) to which we make reference.

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Simultaneously, in Bologna, 120 km far from Padua (Fig. 1), Jacopo Bartolomeo Beccari (b 1682–d 1766) was performing similar observations at the local Science Academy, first only with indoor readings, later with both indoor and outdoor ones (Baiada, 1986). This fortunate combination gave us the opportunity for cross controls to check the data quality and to fill a short gap in the Padua series.

The main thermometer used in Padua was an Amontons thermometer built by Poleni in Venice, in 1709 (Poleni, 1709), shortly before he moved to Padova, being appointed teacher of Astronomy and Atmospheric Phenomena to the University. He started regular daily observations in 1716, at his first home in an unknown address where he taught too. In 1718, he moved to another house, in Pellegrino Street, where he made observations till his death in 1761. His son Francesco continued readings till 1769. For the subsequent history, we make reference to the above IMPROVE publications.

The Amontons thermometer (Amontons, 1695, 1699, 1702) is the natural evolution of the thermoscope, which was more or less simultaneously and independently invented and developed by

Fig. 1. View of Italy with indication of the locations: Padua (P) and Bologna (B).

some scientists in the turn between the 16th and 17th century, i.e. Galileo in 1593, Santorio in 1612–1615, Fludd or Drebbel and maybe somebody else (Middleton 1966, Frisinger, 1983). The prototype first used by Galileo was a glass ampulla sized like an egg, filled with air and fitted to a vertical glass tube whose lower extremity was immersed into a vessel containing some water or red wine, to better show to his students the height of the column of liquid in the tube when the ampulla was heated or cooled. When the ampulla was heated, the air expanded, and the liquid column lowered; when cooled, the liquid column rose until it reached equilibrium. Santorio made some improvements and added a scale, which allowed the transformation of qualitative observations on the expansion of gases to a quantitative evaluation of the heat supplied. However, the free surface of the water in the bottom vessel was subject to atmospheric pressure, and when this increased, the air in the ampulla was compressed, and the liquid in the column was raised, and vice versa. In practice, this instrument was at the same time a thermometer and a barometer, so it was impossible to distinguish the two contributions. A number of different solutions were found. One of these was discovered by Amontons, about one century after the first experience by Galileo.

The Amontons thermometer (Fig. 2) was composed of two independent instruments, a thermoscope and a barometer, in order to compensate the effect of atmospheric pressure on the thermoscope with the pressure readings. Both the thermoscope and the barometer were about 1 m long. Both instruments being filled with mercury and the Amontons thermometer was heavy and hardly portable on short distances. For these reasons, after an initial popularity in the first half of the 18th century, it was abandoned. A detailed discussion about characteristics and problems of this air thermometer is found in Camuffo (2002b).

The thermoscope devised by Amontons was composed of an ampulla connected to a J-shaped tube open in the upper top. Inside the ampulla was a pocket of air, which was compressed by the column of mercury in the glass tube and the atmospheric pressure active on the open top. The latter is known after the associated reading of a barometer, and the actual temperature is obtained as the sum of the two mercury columns in the thermoscope and the barometer. In the case of the instrument built by Poleni in 1709, the sum of the two heights was expressed in Poleni degrees

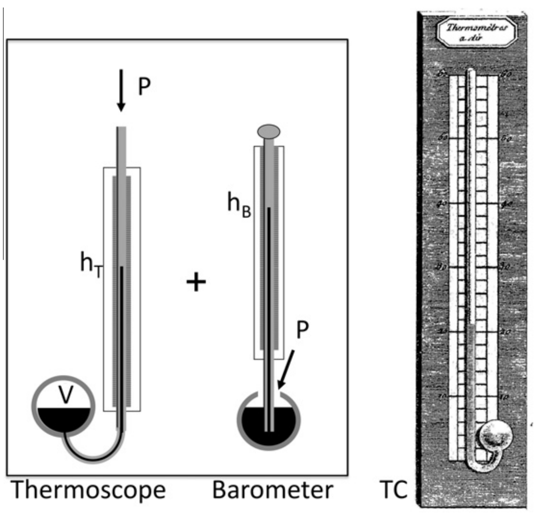

Fig. 2. The Amontons thermometer composed of a thermoscope and a barometer. Both the air pocket *V* in the ampulla of the thermoscope and barometer respond to atmospheric pressure *P*. The actual temperature is the sum of the two mercury columns: h_T and h_B. *P* is the atmospheric pressure acting on the mercury. On the right, TC is the image of an Amontons thermoscope illustrated by Cotte (1774), Table III, Fig. 4).

($°Po_{1716–1718}$) expressed in Paris inches in the first period, i.e. 1716–1718, and London inches for the second one, i.e. 1725–1769 ($°Po_{1725–1769}$). When Poleni moved in 1718, he removed the mercury for transport, so that the air pocket and the scale changed. Therefore, the degrees $°Po_{1716–1718}$ are different from $°Po_{1725–1769}$.

The complete Padua series will improve our knowledge especially for the 18th century, a poorly understood but relevant period of the Little Ice Age, subsequent to the Maunder Minimum of Solar Activity (1645–1715). In fact, only a few long instrumental series that reach three centuries exist.

2. Data recovery, discussion and analysis

2.1. Daily outdoor temperature readings 1716–1718

Giovanni Poleni made outdoor temperature readings with his thermometer hung on a north-facing wall, following the Italian traditional style established by Luigi Antinori in 1653 for the Medici Meteorological Network (1654–1670) (Antinori, 1841). The observations were reported in a log, with monthly tables and daily rows from 1716 to 1725, but regularly filled for the period 1716–1718 and limited to the warm and cold seasons, the observer being particularly interested in knowing the seasonal extremes. The log had columns for date (i.e. day of the month), hour, wind vane direction, barometer height, thermometer height, state of the sky and precipitation amount, either rainfall or snowmelt. The hour was calculated from twilight, following the Italian style, and the observations were made at scattered times in the morning. Sometimes two readings were made in the same day. From the consistency of data, it was possible to establish that the figures reported in the log temperature column were the actual sum of the thermoscope and the barometer readings, i.e. the true Amontons temperature, as later used in the register for the period 1725 onwards.

Observations were practically stopped, or rarely made, after Poleni moved to his next house in Contrada San Giacomo, now Beato Pellegrino street, number 5, one mile away. In 1725, he began a new regular series of indoor observations (1725–1769) to follow the invitation by Jurin (1723) to join the network of the Royal Society, London. Poleni used the same instruments, i.e. thermometer and barometer built in Venice, for both 1716–1718 and 1725–1769 periods. However, at each move, he removed the mercury from the ampulla of the Amontons thermometer and when the ampulla was filled again, the air pocket was different, thus changing the instrument response and needing a new calibration. We know the first Amontons calibration made in Venice (Poleni, 1709) and the third calibration for the 1725–1769 period; no information was found about the 1716 calibration. For 1716–1718 readings and the later loose readings, the units were in Paris inches; in 1725–1769, in London inches to publish data in the Philosophical Transactions. In 1725, Poleni changed the instrument scales that were probably strips of paper glued to the walnut tablet supporting the glass tube and the ampulla.

In the Venice period (1709), we know two calibration points of the Amontons thermometer. However, for the gas thermometers, only one calibration point is necessary, the equation being determined by the perfect gas law, although the problem is a little complicated for the ratio of the tube to the ampulla diameters. This equation was determined on the ground of the sizes obtained from Poleni's drawings and the other calibrations. A previous study on this instrument and its calibration (Camuffo, 2002b) confirmed that the instrument used in Venice and in Padua was the same, except for the air pocket that determined the instrument response, i.e. its transfer equation. We needed at least one key calibration point for the first Padua period (1716–1718). In this paper, we established this point by looking at the days with snowfall alone or mixed to rain, i.e. 15 days in total. A problem arose when the temperature was read in the morning and the precipitation was during the night. For this reason, we considered only the seven cases in January, when the daily temperature range is smallest. The temperature 0 °C corresponded to 44.47 Paris inches, and the boiling point was calculated to be 60.75 inches. Briefly, 1°Po$_{1716-1718}$ = 6.15 °C. In 1716–1718, readings were expressed in Paris mercury inches, lines and fractions of lines (e.g. ½). A Paris inch was divided into 12 lines. In 1725–1769, readings were in London inches, and a inch was divided into 10 lines.

In 1716–1718, Poleni made his outdoor readings at different times, mainly between 7:00 and 16:00 with a frequency peak between 8:00 and 10:00 (Fig. 3). The problem of such scattered data can be easily solved in terms of anomaly, making the difference between the observed value and the corresponding one at the same hour and the same day of the calendar year averaged over the 1961–1990 reference period. This is equivalent to transforming such an irregular sampling into a regular one representative of the daily average, i.e. supposedly made at the time in which, for each individual month, the instantaneous value of the temperature cycle equals the daily average. To this aim, for each month, the daily cycle was computed on the ground of high frequency sampling (10 min) performed from 1985 to 2008. From these data, the temperature difference between each sampling time and the daily average was calculated, following a procedure similar to that described in the next section (see later Fig. 6). A distinction was made for the cloud cover, i.e. (i) clear or partially overcast sky and (ii) thick cloud cover, with or without precipitation. The appropriate correction was possible, because the state of the sky and the precipitation were reported in Poleni's original log. Each individual original reading was transformed into a modern daily average with a correction based on the original specific sampling time and cloud cover of the day.

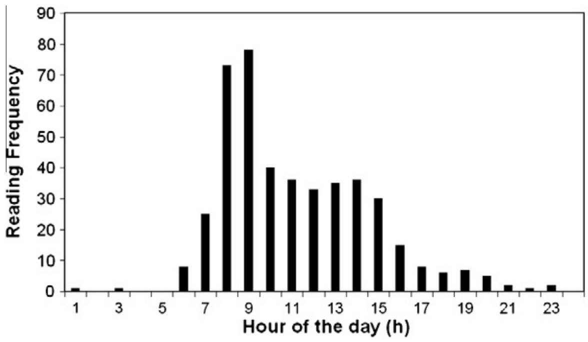

Fig. 3. Sampling time performed by Giovanni Poleni for his outdoor readings in 1716–1718. The most frequent reading time was around 8–9 in the morning.

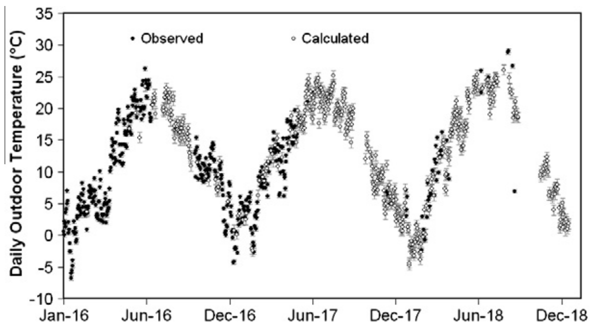

Fig. 4. Mean daily outdoor temperature observed by Poleni in Padua in the years 1716–1718 (black) and gaps filled by means of a transfer function (white). Estimated error bar as in Table 1.

The early Poleni observations have gaps in some months, i.e. August and September 1716, from July to November 1717, May and June 1718 and after August 1718. From the simultaneous indoor and outdoor observations made by Beccari in Bologna, it was possible to establish the transfer function, i.e. the key to transform indoor into outdoor readings. Beccari made three meteorological readings a day, sampled at 8:00, 14:00 and 21:00, from which it was possible to calculate a daily average taking into account the thermal inertia of the building. The Bologna series will be discussed and presented in another paper. A cross-comparison between the Poleni and Beccari readings lead to the equation $T_P = 0.9942\,T_B - 11.017$ where T_P is for Poleni's and T_B is for Beccari's readings; $R^2 = 0.82$ with good agreement. With this equation, it was possible to fill the gaps in the Padua series. However, in the Beccari indoor observations, the variance is reduced compared to the outdoor observations in Padua because of the damping due to the inertia of the building envelope. The damping should not be evaluated from the simple standard deviation (Std. Dev.) of the actual readings because the seasonality influences it. The seasonality can be eliminated by considering the temperature difference between consecutive days, i.e. the inter-diurnal Std. Dev. The outdoor observations by Poleni have Std. Dev. 2.1, the indoor ones by Beccari 1.5 and the calculated data to fill the gaps, which suffer in lower variability from the damping on the mother series, have 1.5. The smoothing for the building inertia may be a problem with high frequency resolution, not with monthly averages. The series obtained for the 1716–1718 period is reported in Figs. 4 and 5. From the data, we see that the 1716–1718 period had substantially the same temperature level as the 1961–1990 reference period, and the daily temperature was scattered in the range ±9 °C.

An estimate of the errors in this period is reported in Table 1 taking into account the specific instrumental errors of the two series and the error introduced by the transfer function from Bologna to Padua in the case of gaps. Poleni measured on a north-facing wall with an Amontons thermometer with a 0.3 °C estimated error. Beccari used a Stancari thermometer with a 0.25 °C estimated instrumental error. The uncertainty for Bologna indoors to Padua outdoors transformation is 0.55 °C as deduced from the scatter of the corresponding data in the period the two series overlap. The total error in filling gaps is 0.8 °C. In the reconstructed periods of which we have only fragments in Padua (black dots in Figs. 4 and 5), observed data fit well with calculated ones (white dots). Passing from daily data to monthly averages, the uncertainty is reduced in correspondence with the number of samplings per month (Parker and Horton, 2005).

2.2. Transformation from indoor to outdoor readings for the 1725–1764 period

In 1725, Poleni started a long series of regular daily observations accepting the invitation by Jurin (1723) to join the Royal

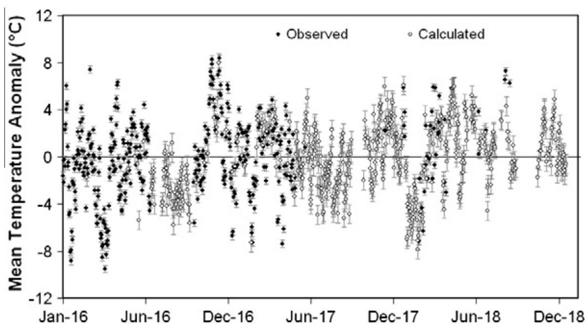

Fig. 5. Daily temperature anomaly for the period 1716–1718 in Padua. Observed temperature: black, calculated: white. Estimated error bar as in Table 1.

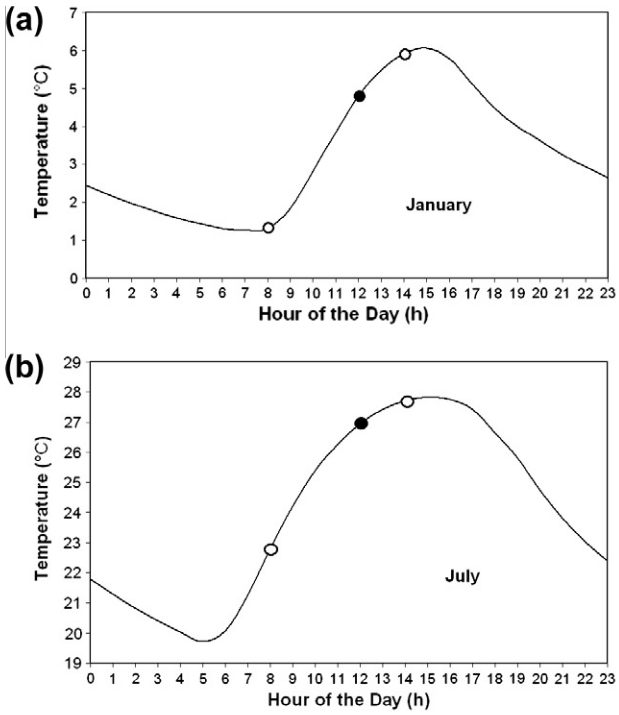

Fig. 6. Daily temperature cycle in January (a) and July (b), Padua, period 1980–2007. White dots: the two Morgagni reading times (8 am and 2 pm); black dot: temperature at 12 am.

Society, London. The instructions were to follow the style suggested by John Locke, with the instrument located indoor in a room without fire. Poleni made readings after having well ventilated the room for some time (half an hour or more) compensating in some way the low-pass filter operated by the building envelope.

Poleni used the same instrument as for the previous period but with a new calibration for the air pocket after the move in 1718. Fortunately, the two calibration points were reported in the log, and the new scale corresponded to $1°Po_{1725-1764} = 6.33$ °C.

Some years later, in 1740, Morgagni initiated another parallel series with two Réaumur thermometers, one exposed indoors and one outdoors. Morgagni's readings were scheduled at 8 am and 2 pm. An example of how the scheduled sampling time fits with the diurnal cycle is reported in Fig. 6a and b for two selected months. From the Morgagni readings, and the shape of the daily temperature cycle, it has been possible, month by month, to calculate the expected reading at 12 am, i.e. Poleni's sampling time.

From the observations in the common period 1740–1764, it has been possible to cross-compare Poleni's indoor observations with Morgagni's outdoor ones calculated for the same sampling time. The transfer function is $T_{out} = 1.116\ T_{in} - 5.737$ where T_{out} is for Poleni's outdoor reading and T_{in} the indoor one. The determination coefficient is $R^2 = 0.97$. The Std. Dev. for the Poleni indoor readings, but in a well-ventilated room, is Std. Dev. = 1; for Morgagni outdoor readings, Std. Dev. = 1.2, and for Poleni's calculated outdoor readings, Std. Dev. = 1.1, with close values. In this way, we got a corrected series of external data from 1725 to 1764, with daily readings as they were sampled at noon. However, the next step is to see of which time this sampling is representative, because it is affected by the inertia of the building envelope that acts as a low-pass filter.

In order to evaluate how this filter cuts high frequencies, we have calculated first the difference between each day and the previous one and then the variance of this difference (Cocheo and Camuffo, 2002). Today, in Padua, the variance of outdoor inter-diurnal temperature variability is around 10, and in the case of the Poleni observations, it is 1. This means that the building inertia filters most of the day by day variability, which is reduced by 1/3. From the attenuation of the amplitude of the daily temperature cycle, the averaging period is about 2 days. We obtained the same result by looking at the indoor–outdoor readings correlation and then repeating this exercise by shifting the outdoor readings by 1, 2, 3 ... days. The simultaneous indoor–outdoor observations are highly correlated, i.e. $R = 0.98$, but the highest correlation, i.e. $R = 0.987$, was found with a 2-day delay, showing that the building structure introduces some delay, as expected. Lowering the variance of the high frequency signal introduces a smoothing to daily variability but becomes an advantage when passing from a specific sampling time to the daily average.

The indoor–outdoor transformation can easily be made once the transfer function is known after the long, homogeneous 1740–1764 period in which the two Poleni and Morgagni series overlap. The limit is that it reduces the daily variance, but it has no relevant effect when we pass from the daily to the monthly scale.

The main problem is for exceptional short periods of very cold or warm air invasions because the building envelope damps the high frequency variability. This was recognized in the middle of an invasion of very cold air in February 1740. Therefore, exceptional short periods of extreme temperature are badly represented by indoor readings at daily resolution. In theory, this becomes irrelevant at monthly resolution. In practice, Poleni was aware of this problem and, in the case of exceptional cold, he made additional external samplings.

The building envelope acts as a low-pass filter that is representative of the last 2 days, but the open windows update the internal temperature. In conclusion, the readings are approximately representative of the last day and are slightly affected by the choice of the particular sampling time.

Table 1
Sub-periods in which the early part of the Padua series can be subdivided, corrections and transformations applied and estimated error for each sub-period.

Sub-period	Comments	Estimated error (°C)
1716–1718 fragments	Outdoor readings on a north-facing wall. Sampling at scattered times in the morning. Corrected day by day. Statistically good correction at monthly level	0.2
1716–1718 fragments filled gaps	Gaps filled with two conversions, i.e. indoor to outdoor and Bologna to Padua conversion	0.55
1719–1724	Indoor readings. Two conversions applied, i.e. indoor to outdoor and Bologna to Padua conversion	0.55
1725–1740	Indoor readings corrected within the EU Improve Project. Indoor to outdoor conversion based on the simultaneous indoor–outdoor readings in the 1740–1764 period	0.29
1740–1764	Precise operational methodology. Simultaneous indoor (G. Poleni) and outdoor (Morgagni) readings in Padua used for calibration of the 1725–1740 indoor to outdoor conversion	0.2
1765–1769	Relocation of indoor readings (F. Poleni). Unchanged outdoor readings (Morgagni). Simultaneous indoor (F. Poleni) and outdoor (Morgagni) readings in the 1765–1768 period. 1768–1769 transformed indoor to outdoor	0.35

In this paper, they have been expressed in terms of daily averages (Fig. 7). We see that the most severe winter was that of 1740, followed by 1745, and that a consistent number of mild winters was found, even in the mid of the Little Ice Age. The anomaly (Fig. 8) shows that this period was on average very similar to the reference period 1961–1990, but with frequent, marked departures, especially due to the cold.

An estimate of the errors in this period is reported in Table 1. Please note that this is the evaluation of the actual errors and does not include all problems concerning the raw data and the instrument that have already been adequately corrected and homogenised as extensively discussed in specific papers (Camuffo, 2002a,b,c; Cocheo and Camuffo, 2002). These included: transformation from the Italian time (beginning at twilight) to Western European time, selected sampling time, sampling made at different times, conversion from original temperature units to °C, calibration of the Amontons thermometer at the two fixed points (the 0 °C was made in winter with crushed ice or snow, the barometer being at the same temperature; the 100 °C was necessarily in the same season, but with the barometer at a different temperature), barometric corrections especially for temperature and height above sea level, the latitude not being necessary because Padua is lat. 45°, drift of the instrument, building influence, path of solar beams in relation to window and wall exposure, shrinkage and swelling of the wooden board with the scale, homogenisation control after cross-comparison with other daily series.

2.3. Daily minimum values of outdoor temperature in February 1740

In a letter to De Pompeiis, Poleni (1740) wrote some observations in the occasion of an Aurora Borealis on 29th March 1739,

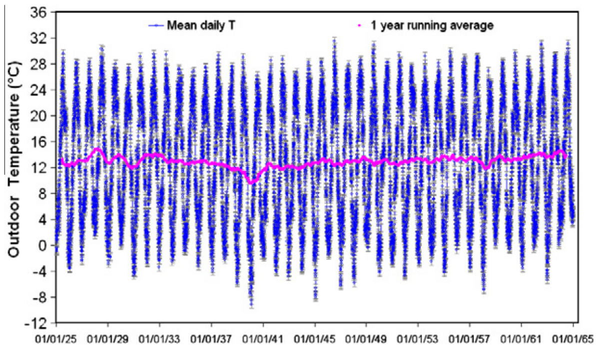

Fig. 7. Outdoor temperature for the 1725–1764 period. Daily readings: open dots and thin black line, with estimated error bars as in Table 1. 12-month moving average: thick black line.

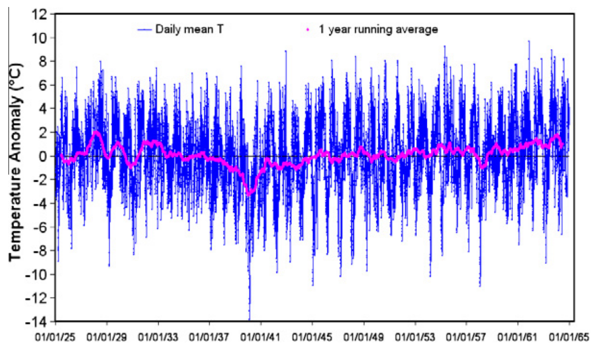

Fig. 8. Outdoor temperature anomaly for the 1725–1764 period. Daily readings: full dots and black line. 12-month moving average: thick grey line. Severe cold is evident in 1740 and 1758.

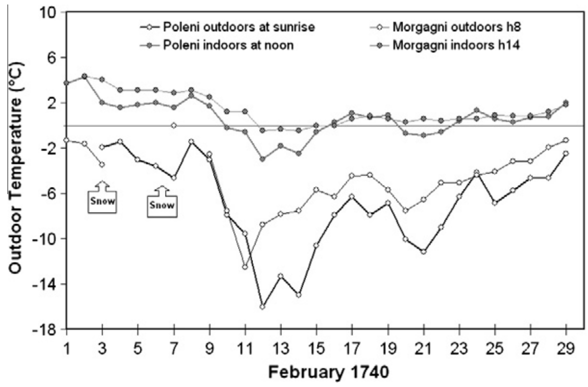

Fig. 9. Outdoor and indoor readings by Poleni and Morgagni in February 1740. White dots: outdoor readings; Full dots: indoor readings; Thick line: Poleni readings; thin line: Morgagni readings. Arrows: snowy days.

a solar eclipse on 30th December 1739, a lunar eclipse on 13th January 1740 and, in addition, meteorological observations made outdoors for the whole month of February 1740, which was anomalous for the severe cold. After the first week with rain and snow, the air arrived from the north bringing cold air and clear sky. Poleni wanted to record the exceptional cold of this period, and for this reason, he installed a mercury-in-glass Fahrenheit thermometer outside, outdoors, hung on a north-facing wall, following the early Antinori recommendations. The readings were taken before sunrise to record the absolute minima. It is interesting to compare all the indoor and outdoor readings made in Padua during this cold air invasion (Fig. 9). A minor difference is found between the indoor readings taken by Poleni (Amontons thermometer, noon readings) and Morgagni (Réaumur thermometer, slightly affected by home life). In the first week of observations, characterized by rainfall and snowfall, all measurements show a certain coherence. A major difference is found between indoor and outdoor observations, as well as between outdoor ones during the cold air invasion. Outdoor observations by Poleni were made externally, with a thermometer that was well exposed to ventilation, before sunrise and this explains why they generally constitute the absolute minimum. The outdoor thermometer used by Morgagni was hung to the window-jamb, partially affected from the milder building envelope. In addition, the Morgagni readings were made at 8:00, i.e. 60 min after sunrise at the beginning of the month and 90 min after, at the end. This justifies why Poleni readings depart so much from the others during the extreme cold. The departure was particularly relevant during the most severe spell, i.e. 12, 13 and 14 February, when the difference between the two Poleni readings reached 13 °C, which largely exceeds the diurnal range. Therefore, the short periods of extreme temperature are badly represented by indoor readings.

2.4. Monthly temperature values collected by Francesco Poleni (1765–1769)

After Giovanni Poleni died (14th November 1761), his son Francesco continued the observations with the same modalities till 26th April 1764 when he moved to the convent of the Philipine Fathers in San Tomaso Street, this site being 1260 m south of the previous house in Beato Pellegrino Street. He continued to observe indoors till 31st December 1769. In this period, the 1765–1769 average was different from the 1725–1764 average, and we evaluated that it was 1 °C higher. For this reason, Francesco Poleni, under the influence of Giuseppe Toaldo, who was Professor of Astronomy and Meteorology at the University of Padua, was convinced that there was something wrong, and the reason was attributed to the escape of some air bubbles from the air pocket in the ampulla during the move. The readings were considered to be affected by error and thrown away, although a simple recalibration of the instrument would have been sufficient. However, we should reject the Toaldo hypothesis for three reasons: (i) air can escape from the ampulla only in the case the Amontons thermometer is rotated more than 90°, and this is unrealistic; (ii) in the case of loss of air, the thermometer would have provided lower temperature readings (not higher). In such a case we should hypothesize the entrance of external air; however, it is quite impossible that external air can cross the whole tube filled with mercury and then enter the ampulla. (iii) Francesco Poleni was extremely accurate and made regular observations even on the day of his father's death; for this reason, it is unbelievable that he damaged the instrument during the move. We should conclude that the thermometer did not suffer losses of air for the move and that the calibration was unchanged and that the difference was due to either relocation or natural climate variability, as we will discuss later.

Francesco Poleni's readings were later published by Toaldo (1770, 1781) as monthly total of Poleni degrees accumulated day by day above or below the whole 1725–1764 average. For each month, Toaldo separately summed the positive and the negative deviations from the 1725–1764 average and divided the total by the number of days. These values were called "Sums of Hot" in the case they were positive and "Sums of Cold" if negative and represent something like a positive or negative anomaly expressed in terms of degrees-day above or below the average (Camuffo, 2002a). In this paper, the "Sums of Hot" and the "Sums of Cold" originated from $°Po_{1725–1764}$ have been transformed into modern units, i.e. monthly averages in °C. The transformation was made month by month, by calculating the degrees making reference to the whole 1725–1764 period average. The obtained data were then referred to the monthly averages of the simultaneous outdoor readings by Morgagni, to transform them as if they had been observed outdoors, as described in the previous sections.

The 1719–1724 gap has been filled, thanks to the simultaneous and unbroken measurements by Beccari in Bologna, once the transfer function for the common period $T_P = 1.0434\, T_B - 1.6606$ with $R^2 = 0.97$ was established where T_B is the monthly mean temperature measured by Beccari and T_P by Poleni.

The whole series of monthly temperature and anomaly averages for the 1716–1769 period are reported respectively in Figs. 10 and 11, together with the yearly and the 11-yr running average. This period had a number of oscillations around the 1961–1990 average, but substantially it had the same mean temperature. Cold reached an extreme value in 1740, but it was compensated by a number of mild winters. Summer temperature departed much less from the modern values.

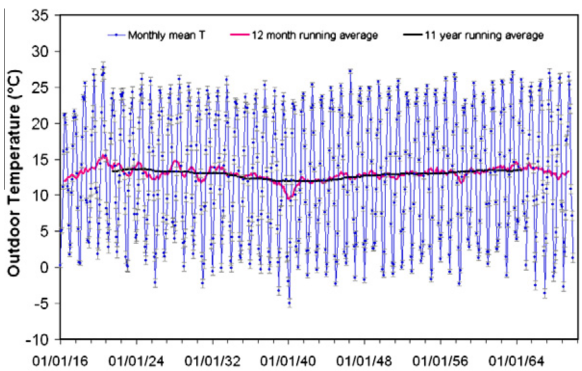

Fig. 10. Outdoor monthly temperature for the period 1716–1769 in Padua. Thin black line with white dot: observations by Giovanni and Francesco Poleni; thick black line: 12-month moving average; thick white line: 11-year moving average.

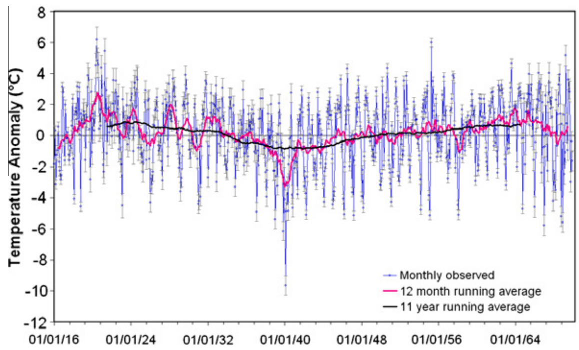

Fig. 11. Outdoor monthly temperature anomaly for the 1716–1769 period in Padua. Thin black line with white dots: observations by Giovanni and Francesco Poleni; thick black line: 12-month moving average; thick white line: 11-year moving average.

An estimate of the error bars in Figs.10 and 11 is reported in Table 1. The Standard Normal Homogeneity Test for Single Shift (SNHTss) (Alexanderson and Moberg, 1997) is of little help in showing discontinuities, because the interval to test is too short and too close to the end of the series. This forced us to use another approach, i.e. the Cumulative Values Test of the actual series, e.g. Padua, versus a reference series, e.g. Bologna. In the case there are no discontinuities, we obtain a bent straight-line, otherwise the line continues with a change in slope after the discontinuity. We applied it to the series of monthly averages in Padua and Bologna. No changes were observed, and the data should be considered homogeneous.

3. Climate change discussion and analysis

The seasonal temperature anomaly computed for winter (months DJF), spring (MAM), summer (JJA) and autumn (SON) and referred as usual to the 1961–1990 period is reported in Fig. 12. Severe cold characterized most of the winters in the 18th century with a peak in 1740. Please note that the Great winter in 1709 is not included in these regular observations. The 1709 winter reached −18 °C (Biancolini, 1749) i.e. about 20 °C below the average monthly temperature in January in the reference period. In the same figure, spring in the 18th century was characterized by a similar, but less severe trend as the one described for winter. In the most recent 50 yr, some warming is visible: in winter, no or rare severe cold is found; in spring, an exceptional warm season occurred in the last decades. The 18th century was anomalous for the warm season too, indeed several hot summers were repeated up to 1760. Similarly, autumn was generally warmer in the same period but with a cold peak in 1740. Summer shows a marked warming, similar to spring in the last decades. Autumn had no specific trend. The main anomalies were in the period before 1760 with cold winters and springs opposed to hot summers and autumns; a general warming is evident in the last decades.

If we consider the yearly averages (Fig. 13), the situation changes. Seven oscillations were repeated from the origin to 1930, although there was an amplitude attenuation going on in time. The average period of this smoothed oscillation studied with Fourier analysis (Fig. 14) gives 35.8 yr and 23.9 yr. The 35.8-yr oscillation is the Bruckner cycle, interpreted as the results of the non-linear effect of solar activity on climatic processes (Raspopov et al., 2000). The 35.8-yr cycle exceeds the red noise level in the yearly average of the Padua temperature, but not in each individual season. In winter, this oscillation is absent, whilst in spring, sum-

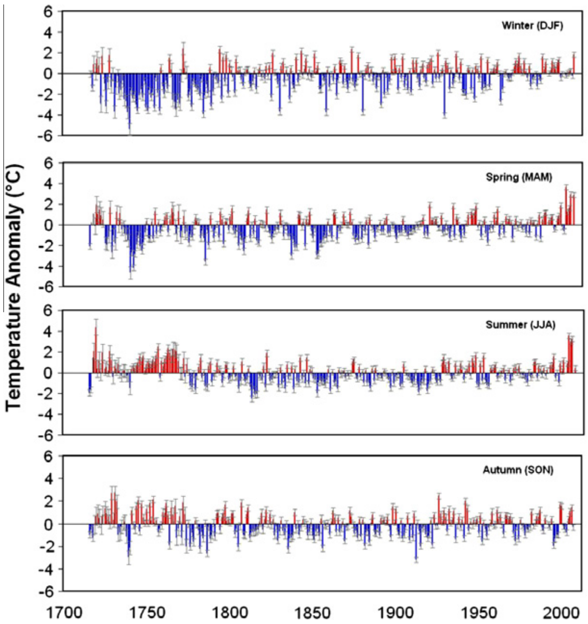

Fig. 12. Outdoor seasonal temperature anomaly for the Padua series (1716–2007). Blue/red: colder/warmer years compared with the reference period 1961–1990.

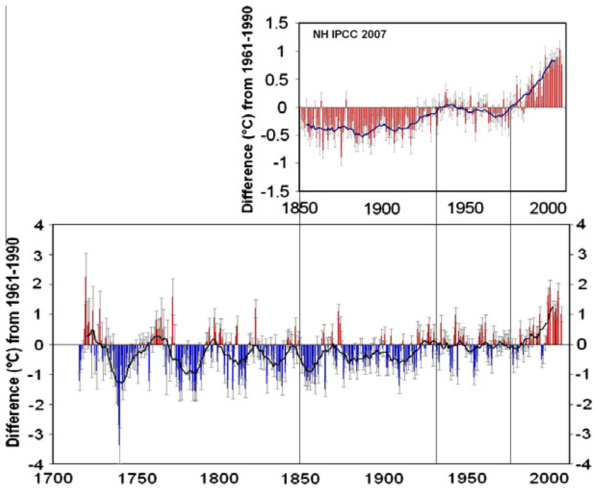

Fig. 13. Top: yearly temperature anomaly for the Northern Hemisphere after IPCC 2007 (Le Treut et al., 2007, WP1, data HadCRUT3). Thick line: binomial filter giving near-decadal average. Bottom: yearly temperature anomaly for the Padua series (1716–2007), Blue/red: colder/warmer years compared with the reference period 1961–1990. Thick line: 11-yr moving average.

mer and autumn, it is visible but below the red noise level. Once the partial contributions are combined to form the yearly averages, the peak exceeds the red noise level. The 23.9-yr oscillation lightly exceeds the red noise and is the well-known Hale cycle of magnetic solar activity.

From 1930 to 1980, all oscillations are almost completely damped, and a rise in temperature is visible since 1980. The above situation reflects, for the common period 1850–2007, the general trend of the famous temperature difference from 1961 to 1990 reported in Fig. 3.6 WP1 in IPCC 2007 (Le Treut et al., 2007) for the instrumental readings in the Northern Hemisphere (Fig. 13). In the IPCC 2007 graph, the general impression is of continual warming with some intervals of temporary stagnation, the whole period being concluded with a sharp final warming.

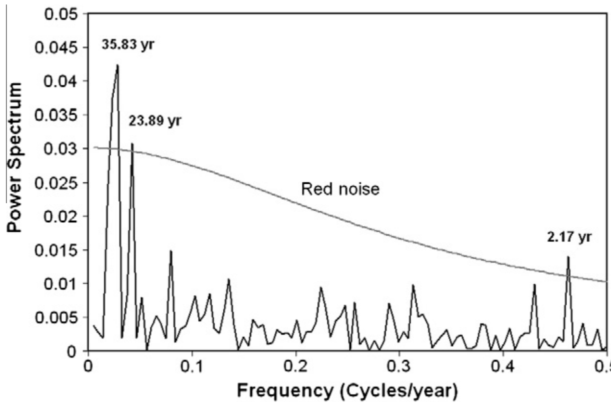

Fig. 14. Power Spectrum to investigate periodicity in the Padua series for the 1716–1930 period. 35.8 yr (Brückner), 23.9 yr (Hale) and 2.2 yr cycles exceed the red noise level.

4. Conclusions

This study extends back to 1716 the long daily temperature series in Padua with the addition of newly recovered data and the transformation of initially obscure indoor readings into outdoor observations in terms of modern units and observational methodology. This long work was justified by the scarcity of information about the early instrumental period and the exceptional contribution they can provide to our knowledge. In this study, we fortunately found a number of parallel, simultaneous observations, both indoors and outdoors, performed by independent observers in locations that were close to each other. These gave us the possibility to check the high quality of the data, to find the indoor–outdoor transfer function and to fill short gaps.

This study extends back our knowledge about the climate in Padua in the 18th century, when winters and springs were characterized by prevailing cold, with their absolute minima in 1709 and 1740, as opposed to the summers and autumns that were warm except for 1740.

In the 1716–1930 period, the climate oscillated following a marked Bruckner cycle (35.8 yr) and a weak Hale cycle (23.9 yr). The climate oscillations were attenuated with progressing time, and their amplitude was almost completely damped for the 1930–1980 period, after which the present-day warming started.

It is clear that Padua is only one station and cannot be compared with multi-station graphs representative of a wide scale. Nevertheless, it is interesting to see how this station is responding to climate changes and global warming and to compare it with the well-known trend of the Northern Hemisphere produced by IPCC 2007 (Le Treut et al., 2007). The comparison shows that, after 1860, Padua generally follows what is happening in the Northern Hemisphere, with marked warming after 1980 in spring and summer, but less in winter and autumn. The Padua series, adding some 150 yrs before the IPCC 2007 report, gives the opportunity to observe the almost regular oscillation that has preceded the 1850–2007 period. A wider time scale and the repetition of warmer and colder periods over two-thirds of the series seem to suggest that such cycles might be repeated in the future too. The same has been observed for the Mediterranean Basin (Camuffo et al., 2010a,b). We agree that the problem is very complex, with many open questions (Jones and Moberg, 2003; Parker and Horton, 2005; Frank et al., 2007) and that no general hypotheses can be drawn on the ground of what has happened on a local scale for its limited representativeness. However, this may be a further, interesting newly opened question.

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