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The earliest temperature observations in the world: the Medici Network (1654–1670)

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Abstract This paper presents the earliest temperature observations, scheduled every 3–4 h in the 1654–1670 period, which have been recovered and analysed for the first time. The observations belong to the Medici Network, the first international network of meteorological observations, based on eleven stations, the two main ones being Florence and Vallombrosa, Italy. All observations were made with identical thermometers and operational methodology, including outdoor exposure in the shade and in the sunshine to evaluate solar heating, state of the sky, wind direction and precipitation frequency. This paper will consider only the regular temperature series taken in the shade. The observations were made with the newly invented spirit-in-glass thermometer, also known as Little Florentine Thermometer (LFT). The readings have been transformed into modern units of temperature (°C) and time (TMEC). The LFT has been analysed in detail: how it was made, its linearity, calibration and performances. Since the middle of the LIA, the climate in Florence has shown less than 0.18°C warming. However, although the yearly average showed little change, the seasonal departures are greater, i.e. warmer summers, colder winters and unstable mid seasons. The temperature in the Vallombrosa mountain station, 1,000 m a.m.s.l, apparently rose more, i.e. 1.41°C. A discussion is made on the interpretation of this finding: how much it is affected by climate change or bias. A continuous swinging of the temperature was observed in the Mediterranean area, as documented by the long instrumental observations over the 1654–2009 period. However, changes in vegetation, or exposure bias might have contributed to reduce the homogeneity of the series over the centuries.

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1 Introduction

The first aim of this paper is to present for the first time the daily temperature observations taken in a number of sites coordinated within the Medici Network for the time span from 1654 to 1667, but continued till 1670 in the two main stations, located in Florence and Vallombrosa, Italy. These observations were made some years after the discovery and the full development of the thermometer and constitute the earliest set of instrumental readings in the world.

Although a number of studies have been conducted to know and reconstruct the history of the observations made within the Medici Network (Boffito 1926; Cantù 1985; Maracchi 1991; Galluzzi 2001; Vergari 2006; Borchi and Macii 2009) and to recover the readings of temperature for over two centuries, i.e. in Florence since 1889 (Crisci et al. 1998; Kumar et al. 2005) and Vallombrosa since 1872 (Gandolfo and Sulli 1990), nobody has till now recovered and analysed the earliest period—1654–1670—due to the difficulty of retrieving the data. The main problem was the catastrophic flood of the Arno River that invaded Florence on 3rd–4th November 1966 and affected libraries and archives where original logs and related documents were preserved. It took many years to restore the documents and organize public access to them. The original data and metadata have been searched in public and private archives, libraries, research institutions and museums of science potentially interested in preserving documents concerning Galileo and the scientific activity in Tuscany in the 16th and 17th centuries. In the remote possibility that the documents were improperly catalogued and not easily identifiable, we sought for original logs also in the archives and headquarters of religious orders that had observations in charge. Thanks to a very kind cooperation, we had access to most originals either in paper support or digital reproduction. Some sheets with unknown or apparently lost data (accounting for some months) were found in the Archives of the Central National Library, Florence. Now the original readings have been recovered.

The second aim is to transform these earliest temperature observations into modern units of time, i.e. calendar year (year beginning from January 1st) and WET time (hours starting from midnight), and temperature (°C), and in addition to assess the data quality. Generally speaking, a series of readings available without any knowledge about instrument features, calibration, sampling time, exposure and location, is a useless collection of numbers. In order to appreciate and interpret such data and their quality, a preliminary analysis was made of the scientific context in which the instruments were created and the observations made. Useful documentation has been found after the analysis of the 17th and 18th century scientific literature, written in Latin, Italian, French and English. This study was useful to clarify some obscure points that characterised the dawn of the meteorology and the scientific research in Italy. The fundamental question is: are these readings reliable or a mere historical curiosity? At the dawn of meteorology, were the early scientists able to do a good job, acceptable from the point of view of modern WMO standards?

The third aim is to analyze the thermometer used for these early observations, i.e. the so-called Little Florentine Thermometer invented in 1641 or earlier. This was a spirit-in-glass thermometer, the first instrument able to supply precise quantitative temperature readings after the invention of the thermoscope. The thermoscope, invented by Galileo Galilei in 1593, and later improved by Santorio Santorio in 1612–1615 with the addition of a scale, responded to both air temperature and pressure changes and was not able to provide real temperature readings. These became possible with the spirit-in-glass thermometer, because the tube was sealed on the top, so that any influence from atmospheric pressure ceased.

We finally intend to analyze and comment, for the first time, the earliest instrumental temperature readings, i.e. from 1654 to 1670, i.e. in the middle of the Little Ice Age (LIA).

2 Stations and activity of the Medici Network (1654–1670)

Galileo, his pupils, the Grand Duke Ferdinand II de' Medici and his brother Prince Leopold had the intuition that Nature could be known by means of direct instrumental observations and experiments. Nature was considered as a book, written by God in numbers and mathematical terms, paralleling the Holy Bible, written in words to announce the history of human salvation. In their observational activity, these scientists discovered some key meteorological parameters, e.g. temperature, pressure and humidity; they invented instruments to measure them, looked at their distribution in time and space, and discovered some fundamental laws of physics, biology and other sciences. In addition to the thermometer, in 1639 Castelli invented the raingauge and the evaporimeter (Castelli 1639), in 1643 Torricelli invented the barometer (Marsenne 1647; Magalotti 1666; Viviani 1717 posthumous) and in 1655 Ferdinand II devised the condensation hygrometer (Magalotti 1666; Viviani 1717 posthumous). These facts and the experiments were day by day carefully described in the "*Diario Grande*" (i.e. *Main Diary*) of the *Accademia del Cimento* (i.e. the *Experiment Academy*, active from 1657 to 1667). The *Diary* was written by the two Secretaries of the Academy, i.e. Alessandro Segni (from 19 June 1657 to 19 May 1660) and Lorenzo Magalotti (from 20 May 1660 to 1667) who were coworkers and direct witnesses of this activity. The original manuscript of the *Diary* (Segni and Magalotti 1657–1667) is still preserved at the National Central Library, Florence, and several parts and summaries of it have been published by Magalotti (1666) and two leading Florentine historians with direct access to the original sources, i.e. Targioni Tozzetti (1780) and Antinori (1841).

In order to extend the observational activity outside the geographical limits of Florence, Prince Leopold and the Grand Duke decided to organise an international network of well-coordinated observations, performed with identical instruments, exposure, schedule and protocols. This was the first meteorological network, called the "Medici Network" composed of 11 stations in Europe (Online Resource 1) including seven in Italy (Fig. 1) and flourished from 1654 to 1667.

The Network was created to know the main climatic features of some localities, and especially to give an answer to the following and many other questions. What is the difference in temperature in various countries, on the plain and the mountains, in middle and higher latitudes? Does ice always melt at the same temperature, disregarding geographical or height differences? How much does the density of liquids change with temperature? What is the difference in temperature between sunshine and shade?

The Network was organised and lead by a Secretary, Father Luigi Antinori, who was chancellor of the Jesuit Fathers and chaplain of the Grand Duke (Targioni Tozzetti 1780; Antinori 1858). The task of Antinori was to provide the instruments, identical to each other to get comparable results and to provide instructions on how to operate. Observers were committed to hang a thermometer on a wall facing North and another thermometer on a wall facing South, to see the air temperature, the effect of sunshine and verify a claimed cooling/heating effect of winds from North (i.e. *Borea*) and South (i.e. *Austrum*).

All readings followed a precise time schedule, including diurnal and nocturnal observations. Observers were Monks belonging to the Camaldolense Benedectine Order in Florence and Vallombrosa, and Jesuit Fathers in other stations. The choice of religious observers was dictated by the fact that Monks and Fathers had a high cultural level, were

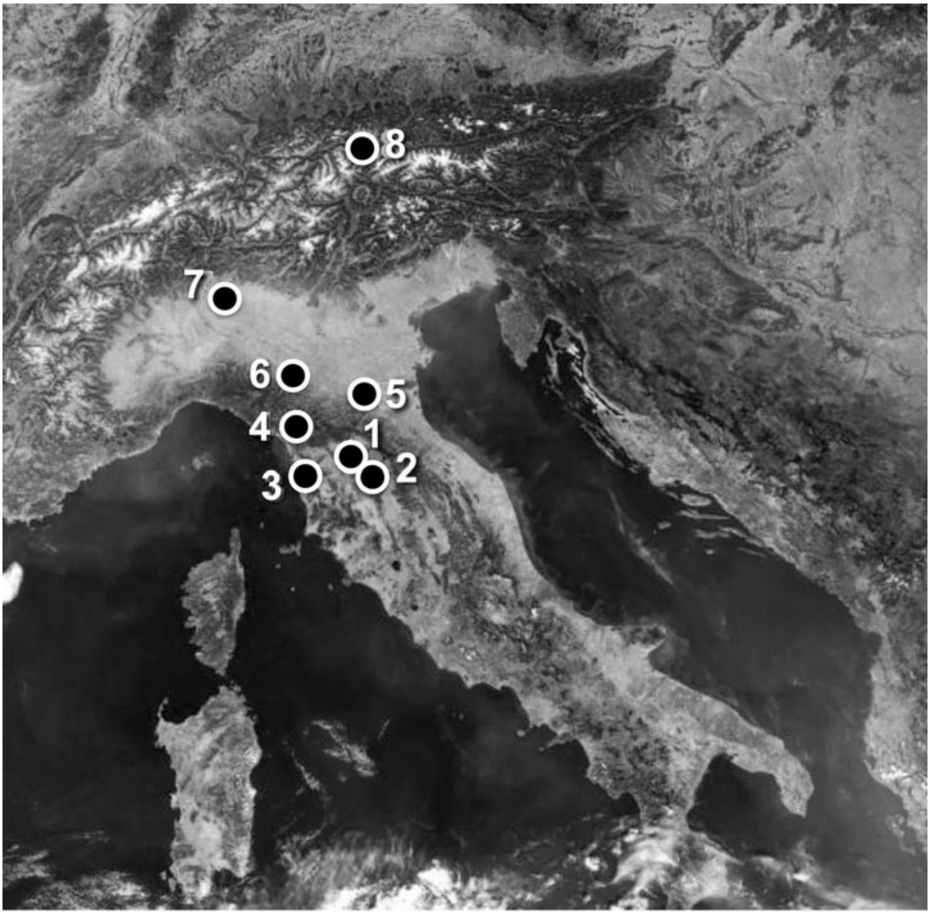


Fig. 1 Map of the seven Italian stations of the Medici Network formally active for the 1654–1667 period and in practice from 1654 to 1670, i.e. 1-Florence, 2-Vallombrosa, 3-Pisa, 4-Cutigliano, 5-Bologna, 6-Parma and 7-Milan (station 8 is outside Italy)

always on the site, free from civil business, and were able to perform regular readings by day and by night, at monastic hours in which prayers and observations were scheduled.

The stations of the Network are described in Table 1, where geographic position, altitude above mean sea level (amsl), periods of observations and name of the observers are reported. The activity was concentrated on two primary stations, i.e. Florence and Vallombrosa, which operated continuously with several observations by day and by night and ceased their activity 3 years after the Network was closed. Other stations were considered secondary, and generally operated in summer and winter to investigate the extremes of the temperature range.

Florence was the main station, under the strict control of the Grand Duke. Observations were taken at the Pitti Palace, the Boboli Gardens and in the Convent of St. Mary of Angels (nicknamed "*Convent of Angels*") in the city centre. The observations in the Convent of Angels constitute the main series we will analyse it in this paper. The observers were unknown but from the change of the handwriting we recognize that a number of observers were taken on over the years. From Guglielmo Libri della Somaia (Libri 1830) we read that

Table 1 Stations active in the Medici Network

	Location	Lat E	Long N	Altitude amsl	Period	Observer
1	Florence	43°47′	11°15′	50 m	15-12-1654 31-03-1670	Unknown
2	Vallombrosa	43°44′	11°34′	980 m	01-01-1656 31-05-1670	Petronio Paceschi, Filiberto Casini and Nicola Signorini
3	Pisa	43°43′	10°24′	4 m	26-11-1657 08-05-1658	Alfonso Borelli and Vincenzo Viviani
4	Cutigliano	44°6′	10°45′	678 m	06-03-1658 31-03-1659	Unknown
5	Bologna	44°29′	11°20′	54 m	01-12-1654 31-03-1656	Giovan Battista Riccioli
6	Parma	44°48′	10°20′	57 m	23-12-1654 31-12-1660	Antonio Terrillo
7	Milan	45°27′	9°11′	137 m	17-02-1655 30-04-1656	Giulio del Re
8	Innsbruck	47°16′	11°23′	574 m	06-03-1655 30-04-1655	Unknown
9	Warsaw	52°13′	21°00′	97 m	10-05-1655 16-05-1655	Unknown
10	Osnabrück	52°17′	8°03′	63 m	Readings lost	Unknown
11	Paris	48°51′	2°20′	33 m	05-1658 09-1660	Ismaël Boulliau

the observer was Father Vincenzo Renieri, but this is wrong because Renieri, active in astronomical observations, died several years before the Network was founded.

The second main station, very accurate, was located in the Benedictine Convent in Vallombrosa, on the mountain slope, 1,000 m amsl. Fathers Filiberto Casini and Petronio Paceschi performed up to eight readings a day.

Secondary stations had a shorter, fragmentary activity, mainly focused on recording the seasonal extremes, i.e. hot in summer and cold in winter. The interest of the Grand Duke for summer and winter was not only to know extremes, but also to deduce what was called "*the Temperate*", i.e. the temperature in the middle between the warmest and the coldest weather, that was supposed to be the basic temperature of the region. The medium level of the range was preferred to the average value, probably because it was easier to obtain and did not require many regular sampling. In the secondary stations, sampling was less frequent than in comparison with the two main stations, but generally from five to eight readings a day.

Pisa was the only station that measured atmospheric pressure, observed by Vincenzo Viviani and Giovanni Alfonso Borelli for the period November 1657–May 1658 (Borelli 1686; Ramazzini 1695; Antinori 1841). These were the very first regular pressure readings in Europe. Readings were generally taken three to four times a day and have been used to recognize the feature of the 1657/58 winter (Camuffo et al. 2009).

Milan had Giulio del Re as observer (Borchi and Macii 2009). Libri (1830) stated that the observers were Father Bonaventura Cavalieri and Ticcioli. Cavalieri should be excluded because he died years before the institution of the Network. No other information exists about Ticcioli, but probably was a misprint for Riccioli, and a mistake because Riccioli took observations in Bologna (Antinori 1841).

Paris needs a further comment. The queen of Poland, Marie Louise (named Ludwika Maria) Gonzaga de Nevers, was in touch with the Grand Duke of Florence and joined the Network with the station in Warsaw that had been operative since 1655. In 1657, she sent the physicist Tito Livio Burattini to the Grand Duke, and he returned with some LFT as a gift. One of these LFT was given to the astronomer Father Ismaël Boulliau to use it in Paris. Although late, Paris was formally part of the Network and Boulliau made observations from 25 May 1658 to 19 September 1660 in *rue des Poitevins* at the *hôtel de Thou*, which later became the headquarters of the *Sociétés Savantes* (Society of Savants) (Maze 1895a). These observations were reported in some tables with the comment: “readings made in Paris, year 1658, with a Florentine Thermometer”, while readings made with a mercury thermometer with the same shape and dimension as the LFT can be found in another column of the logs.

All readings in all stations were daily collected in a form with all the observations of the same day (Online Resource 2), and sent daily, or weekly, depending on the distance, to the Grand Duke. A copy of the readings was kept at the stations. This practice of sending a duplicate saved several of the readings that reached us. All the stations used two LFT sent by the Grand Duke represented by the secretary Luigi Antinori, as we know from the correspondence between the observer Terillo (1654) and Antinori.

The Medici Network was officially closed in 1667 for political reasons, being considered closely related to the Galileo’s dangerous ideas that substituted instrumental observations to the Bible when interpreting Nature. Only the Convent of Angels, particularly close to the Grand Duke, and Vallombrosa continued to operate after the official closure of the Network. Regular observations were made there till 1670, when the Grand Duke died, and this was the end of any activity.

3 The Little Florentine Thermometer

The history of the thermometer, and several details about the LFT are extensively reported in Middleton (1966). We will not repeat the content of this milestone book, but we will focus on the key items necessary to the interpretation of the readings taken within the Medici Network.

3.1 From the thermoscope to the spirit-in-glass thermometer

The development of the thermoscope lead to the air thermometer, and the two instruments derived from it were the Amontons (1702) and the Stancari (invented 1707 but unpublished; Baiada 1986) thermometers. The spirit-in-glass thermometer was a totally revolutionary instrument with a different origin. The thermoscope was based on the discovery that gases expand when heated; the liquid-in-glass thermometer on the discovery that also liquids are subject to thermal expansion although their expansion coefficient is much smaller than that of gases. Vincenzio Viviani, pupil and biographer of Galileo, wrote that Galileo invented “the thermometer with air and water” (i.e. the thermoscope) in Padua and that the Grand Duke invented the spirit-in-glass thermometer in Florence (Magalotti 1666; Lana 1670; Viviani 1717 posthumous) known as Florentine Thermometer (Fig. 2). Actually, he mentioned only the Grand Duke for obsequiousness but the invention was due to a synergism between the Grand Duke and Torricelli, who would also discover atmospheric pressure 2 years later (i.e. 1643) and the barometer as well. We don’t exactly know when

Fig. 2 Little Florentine Thermometers with 50°G scale marked with black and white glass enamel beads sealed on the glass tube. By courtesy of MG-IMHS, Florence

the Florentine Thermometer was invented; however, we know that the *Diary* at the date 12 December 1657 reports that the Academicians sectioned and analyzed a spirit-in-glass thermometer built 16 years before, i.e. in 1641 that was the last year of Galileo's life.

The spirit-in-glass thermometer was derived from the study made by Galileo, his pupils and the Grand Duke on the quality of spring waters and other liquids. This study induced the Florentine scientists to invent the "*Aerometer*", also called "*Densitometer*", i.e. an instrument that was designed to measure the density (originally called "*specific gravity*") of liquids from the buoyancy of a graduated cylinder immersed on it (Segni and Magalotti 1657–1667; Magalotti 1666; Targioni Tozzetti 1780: Antinori 1841). It was recognised that the density of liquids varied with temperature, and this suggested to Galileo the idea of building a thermometer based on this principle, the "*Termometro Infingardo*" (i.e. "*Sluggish Thermometer*", literally: which takes time to react) for its long response time.

The "*Sluggish Thermometer*" is based on the fact that the variation of density induced by temperature changes generates a variation of buoyancy. The thermometer is composed of a number of glass spheres with the same size but with slightly different weight (i.e. selected density levels) immersed in spirit. Spirit decreases density with increasing temperature and vice-versa. The glass spheres will rise or fall depending on the density reached by the surrounding liquid that determines the buoyancy of each sphere. Each glass sphere reaches neutral buoyancy at selected spirit temperatures, while all the other spheres sink or float. From the colour, or label, of the floating sphere we know the temperature of the thermometric liquid, supposed to be in equilibrium with the air. The mass of liquid to heat is quite large and requires a long time to reach equilibrium, hence the name "*Sluggish*" (Segni and Magalotti 1657–1667; Magalotti 1666; Targioni Tozzetti 1780; Antinori 1841). This instrument, based on the change of density of a liquid, was the father of the spirit-in-glass thermometer.

The expansion of spirit was modest and another, alternative way of observing it was to magnify the expansion. The solution was inspired by the thermoscope, i.e. a large air pocket kept aloft and a thin vertical tube immersed into a vessel with water or other liquids. When the air pocket changed volume with temperature, the water column in the capillary rose or descended, magnifying the change in volume of the air. The magnification depended on the ratio between the sections of the ampulla and the tube. This was equivalent to turn upside-down, like a standing bottle, a smaller thermoscope with the ampulla on the bottom filled of spirit. However, the spirit evaporated fast from the open top. A bottle with spirit is topped with a cork. The sealed top solved the problem of evaporation of spirit, ensured repeatability and made the instrument easily portable and independent from its position. Some air at atmospheric pressure was left inside the tube because the builder had no other choice, but some atmospheric pressure was necessary to prevent the spirit from boiling. This instrument, based on the change of density of a liquid, was the first spirit-in-glass thermometer.

After the *Accademia del Cimento* was closed, the instruments were preserved in the Pitti palace, headquarters of the Academy, and Leopold sent some of them to Pope Alexander VII. In 1737, the instruments which survived in Florence were given to Philippe Vayringe, Professor of Physics at the court of Francis I of Lorraine, Grand Duke of Tuscany. At Vayringe's death, in 1746, some of the old instruments returned back to Pitti palace, some were sent to Vienna's Theresianum College. Finally, the instruments that remained in Pitti palace were moved to the Museo Galileo-Institute and Museum of History of Science (MG-IMHS), Florence, forgotten and finally discovered by Vincenzo Antinori in 1829 (Libri 1830; Antinori 1841). The MG-IMHS still preserves a number of Florentine thermometers, 17 of them being LFT, and we had the possibility to observe them and make some measurements of their dimensions. Libri made a gift of two original Florentine Thermometers to the *Académie Royale des Sciences*, where he had a lecture in 1830.

The main advantage of the LFT was that it was entirely made only of glass, apart the thermometric liquid. The scale was made with glass beads directly welded on the glass tube. In practice, the LFT was very resistant outdoors, no matter the weather, being unaffected by dampness, rain, sunshine or frost. Outside Florence, thermometers were built with a poor technology, i.e. tube and bulb were made of glass, but they were fixed to a wooden tablet with an iron wire (Fig. 3); the scale too was separated, glued to or painted on the tablet. The problem is that wood shrinks and swells depending on the equilibrium with the relative humidity in air, sunshine or precipitation. Dryness and wooden shrinkage decreased the tension of the iron wire, with the consequence that the tube slipped down changing reference with the scale. Dampness and wooden swelling increased the wire tension with the risk of breaking the tube. Briefly, it was impossible that thermometers supported on wooden tablets were kept outdoors, and indoor observations were necessarily preferred. This choice, which was dominant for most of the 18th century, was in addition supported by the fact that in 1660, John Locke, an English medicine doctor and empiric philosopher, made indoor observations related to people's health. This was a further reason why the directives of the Network of the Royal Society, London, leaded by the medicine doctor James Jurin recommended indoor observations (Jurin 1723).

The next generation of thermometers able to withstand exposure to weather without damage was with the "*Societas Meteorologica Palatina*", Mannheim (1780–1795) that (partially) abandoned the wooden tablet and used metal, glass, or ceramic supports for tube

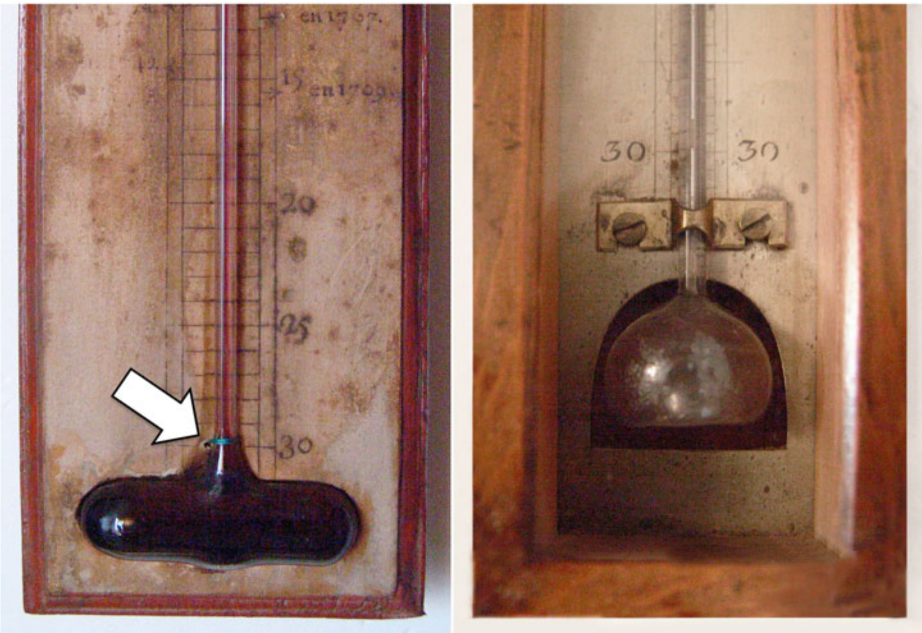


Fig. 3 Evolution of the technology in building thermometers in the 18th century and at the turn with the 19th century. On the left, an early Réaumur thermometer had the glass tube fixed to the wooden tablet with an iron wire passing through holes (*arrow*). The glasswork could slip or be broken by the tension of the wire when the wooden tablet was swollen when wet. Now the wire has been substituted with a gentle rope for conservation purposes. The scale is drawn in ink on a paper sheet, glued to the wooden tablet. The ink was not resistant to water. On the top, the extreme cold in 1709 i.e. −15.5 °R and 1767 i.e. −12.5 °R have been reported as a reference. On the right, the Réaumur thermometer with improved technology had the tube safely fixed with a bridge and screws to a metal support with engraved scale. By courtesy of MG-IMHS, Florence

and scale. At this point the thermometers returned to be weatherproof and could be exposed outdoors.

Robert Boyle was impressed by the studies of Galileo and his pupils and passed the winter 1641–1642 in Florence to join the flourishing scientific activity and learn from Galileo, who unfortunately was at the last days of his life. He had the possibility of observing the earliest spirit-in-glass thermometers, including the LFT. Twenty years later, in 1661, Robert Southwell brought to England a LFT. Boyle, who at that time was President of the Royal Society, made a duplicate of this LFT (Hellmann 1908) and used it for his study about the perfect gases (Boyle 1662).

3.2 The choice of the thermometric liquid

After numerous tests to characterise the density of various liquids, Galileo and the Florentine Academicians recognised that pure spirit was highly sensitive to temperature changes and was a good candidate for thermometers. The first reason to use spirit was motivated by the fact that spirit does not freeze in winter and does not break thermometers, differently from water (Segni and Magalotti 1657–1667; Magalotti 1666; Targioni Tozzetti 1780: Antinori 1841). Another strong point was that spirit does not adhere too much to the tube, thus making good readings possible. Also mercury was tested but it was observed that the mercury had lower expansion and the thermometers lower resolution (Segni and Magalotti 1657–1667; Targioni Tozzetti 1780). Finally, for the relevant size of the ampulla, the thermometer using spirit was much lighter than that with mercury.

Spirit (Ethyl Alcohol, or Ethanol) was distilled from wine grapes or from wine, e.g. *eau-de-vie*, *cognac*. The typical percentage of Ethyl alcohol by volume (ABV) of these drinks is 42% ABV. After successive distillations it is possible to increase the percentage of alcohol, as described in the *Dictionary* of the *Accademia della Crusca* (1612), reaching 80% ABV or more. This highly concentrated solution of alcohol after refinement was called "*acquarzente*" and was used as spirit for thermometers (Segni and Magalotti 1657–1667; Redi 1660; Magalotti 1666; Legati 1677; Targioni Tozzetti 1780).

The instrument resolution and sensitivity were proportional to the percentage in Ethyl alcohol and it was crucial to use "*acquarzente*", with exactly the same ABV percentage, to build instruments that were identical to each other. All the LFT had the same response: this means that they were filled with the spirit of the same production or with spirits with the same refinement.

3.3 Building a Florentine thermometer

We found in contemporary and later but reliable sources precise information about the instrument and how it was built. The most important sources are Segni and Magalotti (1657–1667) and Magalotti (1666) who dedicated several pages to the fabrication and calibration of Florentine thermometers. The text by Magalotti is closely followed by Targioni Tozzetti (1780) and Antinori (1841). Further documentation was provided by Redi (1660); Legati (1677), Bartolo (1679), Du Hamel (1681) and Crivelli (1744).

The Florentine thermometers were built by Antonio Alamanni and Jacopo Giuseppe Mariani, both nicknamed "*il Gonfia*", i.e. "*the Blower*". Alamanni was top quality, as documented in the *Diary* of the Academy; Mariani was also skilled although at a lower level, but he is better known because he also built some lenses for Galileo (i.e. the telescope) and was mentioned by three historians, i.e. Fabroni (1773), Targioni Tozzetti (1780) and Antinori (1841). The Florentine thermometers were a masterpiece of science and technology. In particular, Fabroni (1773), followed by Antinori (1841), commenting a letter of Prince Leopold to Borrelli, added the note that the famous French physicist Abbé Jean Antoine Nollet (born 1700- died 1770) was highly impressed by the ability of *the Blower* Mariani in performing the glass thermometers. Several types of spirit-in-glass thermometers were built, most of them with scientific purposes and some as amazing artworks, in the shape of a frog for example. The scientific thermometers had a very large bulb at the bottom and a capillary tube that was graduated to read the temperature. The tube was either rectilinear or spiralling to reduce the occupied space, with the scale subdivided into 50, 100, 300 and 400 parts. All the instruments having the same number of subdivisions were almost identical to each other and provided almost the same readings, but the units were different for the 50, 100, 300 and 400 scales. Of course, sensitivity increased with the number of subdivisions in the scale.

The Grand Duke had in mind the problem that all thermometers should have the same scale to cross compare and interpret the readings. For this reason he ordered a number of thermometers identical to each other. This goal was possible only with the 50-degree scale thermometer, called Little Florentine Thermometer (LFT). To be interchangeable, all LFT were made identically, with the same scale based on the range of temperature in Florence. All of them were an excellent replica of a reference instrument, the LFT that the Grand Duke always had in his pockets, protected by a wooden case. In the following, we will strictly report and summarize the descriptions by Magalotti (1666), Targioni Tozzetti (1780) and Antinori (1841).

The manufacturer, i.e. *the Blower* prepared a number of empty glass spheres, identical to each other, which were the bulbs. Most of the spheres were sized 16 mm in diameter, i.e. the standard LFT. *The Blower* prepared also the same number of capillary tubes some 10 cm long, with 1.1–1.2 mm internal diameter. Then he sealed the capillaries to the bulbs with lampworking, i.e. warming glass at melting temperature with the flame. The sealing at glass melting temperature was perfect, except for two thermometers. Recently, this became evident after the Arno River was flooded in Florence, in 1966. Thermometers were left immersed into flooding water and in two thermometers some water was sucked in by the spirit through the sealing porosity, and almost completely filled the tube.

Once tubes and spheres were combined forming the thermometer glasswork, *the Blower* added the scale on the tube, divided into 50 not numbered levels, marked with one white enamel bead for every nine black beads (Fig. 2). The spacing between beads was even, i.e. 1.8 mm, made at naked eye and corresponded to one degree of this scale, named "°G" in honour of Galileo.

Then *the Blower* filled the thermometer with repeated operations. First he heated the sphere very much to expand the air inside, reversed the glasswork upside-down and immersed the open top of the capillary into the refined spirit. When the sphere returned to room temperature, the contraction of the air pocket caused the suction of a certain amount of spirit inside the bulb, passing through the narrow capillary. It was crucial that the spirit filled the bulb and reached a certain selected level in the capillary. The level was adjusted adding or subtracting with a smaller capillary the needed amount.

The Blower verified if the instruments responded in the same way immersing them into baths at arbitrary temperatures and tuning them adding or removing spirit until their levels were perfectly correspondent (see next section). Once the spirit level was adjusted to the appropriate level, *the Blower* sealed the top of the capillary with lampworking pressing and turning the softened glass on the top with pliers. At this point the thermometer was completed.

Magalotti (1666) and other writers specified that *the Blower* was so skilled, that after having built many LFT he was able to combine different size of the sphere, with appropriate size of the capillary and spirit level. As a consequence, most of the bulbs were sized 16 mm; some others deviate within 10%; a few have a much larger diameter, i.e. about 30 mm, and were made later.

All of the LFT have the same scale and calibration, i.e. they provided the same readings and were really interchangeable instruments. A test made by Vittori and Mestitz (1981) recognized that the standard deviation (STDEV) of 15 LFT which survived at the MG-IMHS, Florence, is STDEV=0.5°C. Other Florentine thermometers, more complex, were less comparable between each other.

A weak point was, however, that the spirit was transparent and it was difficult to read the height of the column under pale light. Attempts were made to use coloured spirit, but dye deposits soon soiled the glass worsening the situation. It was preferred to use regular refined spirit without addition of colouring substances and pay attention in reading. In particular, it was verified that the thermometer with 100 scale subdivisions, and especially the type with 50 subdivisions, were not sensitive to the light of a lantern or a candle during readings, as reported by Magalotti (1666). Only the 300 and 400 subdivision types were sensitive to it, and were not convenient for nocturnal reading.

3.4 Original calibration and scale of the LFT

The calibration, as we can imagine it today, and the existence of fixed points was unknown. Fixed points were discovered after experiments made with the newly invented thermometers, e.g. the study of freezing water and melting ice.

The aim was to produce thermometers with the same response. The methodology could not be based on an accurate calibration, but on an accurate replica of the glassworks and a tuning of the thermometer response, reached after patient regulation made by adjusting the quantity of spirit in it (Magalotti 1666; Targioni Tozzetti 1780; Antinori 1841). Sebastiano Bartolo, living in Naples but making experiments with the LFT, described the instrument, how this was made and calibrated. He clearly stated that the calibration was made with three reference points: extreme cold, i.e. snow, extreme hot and ambient temperature (Bartolo 1679). In practice, Magalotti (1666) explained that the *Blower* used three points at arbitrary temperatures to check and adjust the correspondence between thermometers. The aim was not to find a correspondence between a fixed point and a specific level of the scale, but that the spirit in the column of the newly produced thermometer had the same levels as the reference LFT when immersed into baths at arbitrary temperatures. To verify the accuracy in the lower, medium and upper part of the range, *the Blower* immersed the bulb into snow or ice for cold (this bath corresponded to 20°G in the 100 subdivision scale or 13.5°G in the LFT); he then used a bath with the water of the Arno River; finally, he exposed the LFT to summer sunshine (corresponding to 80°G in the 100 subdivision scale or 40°G in the LFT). We should note that only the bulb was immersed (this is confirmed by the sources), because the capillary with the scale was necessarily outside the bath to allow readings.

We should consider that the LFT was the first thermometer in the world, and it necessarily had a fully arbitrary scale. It was dimensioned to include the full range of temperatures in Florence, from extreme winter cold to the heat experienced after noon in summer, exposed to sunshine. The comparability between the readings was necessary because the Grand Duke wanted to distribute the instruments to observers in different sites throughout Europe, on the plain and on the mountains, to determine the differences in the local climates. The regularity of replicas and the instrumental precision show an incredibly advanced technological level.

An important finding was that ice melted always at 13.5°G. This finding was later used for a fixed calibration point. It is known that in 1665 the Dutch astronomer Christian Huygens suggested the melting and boiling points of water as calibration points, but this happened 24 years after the invention of the LFT. The same proposal was made in 1694 by Carlo Renaldini, formerly member of the *Accademia del Cimento* and later Professor of Philosophy at the University of Padua (Renaldini 1694). However, this suggestion remained unattended per years because the boiling point was considered unstable (depending on atmospheric pressure) or not convenient.

3.5 Later calibration of LFT

We know scales and calibrations of the LFT with similar results (Table 2). The first scale was published by Father Louis Cotte (1774) in his famous *Traité de Météorologie* (i.e. Treatise of Meteorology). He published a drawing that compared side-by-side fifteen different scales in use at his time. The LFT scale is linearly interpolated between the two extremes. The first real calibration we know was made in 1829–1830, when Libri compared seventeen LFT found in 1829 in the Museum of Science now MG-IMHS,

Table 2 Known scales of the Little Florentine Thermometer (LFT) by Cotte (1774), Libri (1830), Schouw (1839), Meucci (1873), Maze (1895a, b) and Vittori and Mestitz (1981)

Scale	Year	1 (°G) in °C
Cotte	1774	1.40°C
Libri (T<0°C)	1830	1.39°C
Libri (T>0°C)	1830	1.51°C
Schouw (T<0°C)	1839	1.39°C
Schouw (T>0°C)	1839	1.51°C
Meucci (T<0°C)	1873	1.39°C
Meucci (T>0°C)	1873	1.51°C
Maze (T<0°C)	1895	1.39°C
Maze (T>0°C)	1895	1.51°C
Vittori & Mestitz	1981	1.43°C

Florence, with a Réaumur thermometer performing some 200 readings (Libri 1830). He found 0°G=−18.75°C, 13.5°G=0°C and 50°G=55.00°C and noted that the melting point is not exactly on the same straight line passing for the two extremes, i.e. the scale is not exactly linear. Joachim Frederik Schouw (1839) commented the calibration by Libri under the light of some other literature existing in the Museum of Science, Florence. In conclusion, he closely followed Libri, and fixed the melting point at 13.45°G. In 1873, Francesco Meucci, director of the Museum of Science, Florence, where the instruments were kept, repeated the calibration with a Celsius thermometer checking the ice melting point and other temperature levels obtained with selected mixtures of cold and hot water. He confirmed the calibration by Libri except for the melting ice that was just a bit (not better specified) below 13.5°G (Meucci 1873). Maze (1895a, b) reported the calibration made by Libri and discussed the non-linearity.

All calibrations show that the LFT had a very small departure from linearity. Some non-linearity was suspected since the times of the Academy because the scientists considered that at high temperatures the reduced volume of the air pocket entrapped inside the thermometer produced a compression that opposed the free expansion of spirit. They were not aware that ethyl alcohol strongly departs from linearity and its expansion coefficient is variable with T. In normal spirit-in-glass thermometers the non-linearity is a problem when fixed points are 0° and 100°C and the scale is obtained as interpolation from these two fixed points. The problem is much smaller when the calibration is made at shorter intervals. This means that the intervals −10° to 0°C and 0°to 35°C that cover the typical range of temperature in Florence and Vallombrosa are reasonably well represented by straight lines, although the −10° to 0°C and the 0°to 35°C interpolations are slightly different between them.

In 1981, Vittori and Mestitz made a careful calibration of the fifteen Little Florentine Thermometers still preserved in good conditions at the MG-IMHS, Florence, using a high-precision calibration bath but limited to the temperature above the freezing point, i.e. 0°, 10°, 14°, 20° and 34°C, to avoid risking any harm to the preservation of these precious instruments (Vittori and Mestitz 1981). These thermometers were the same that Libri analyzed 150 years before, except for the two thermometers damaged during the flood of the Arno River in 1966.

All the calibrations confirm that melting ice is coincident or very close to 13.5°C and all calibrations are very similar between them especially in the range of the observations (Fig. 4). We could suppose that the earliest scale, i.e. Cotte (1774), is preferable for historical reasons and especially because glass and spirit might have undergone transformations over the centuries due to ageing. Libri (1830) and Meucci (1873) made real

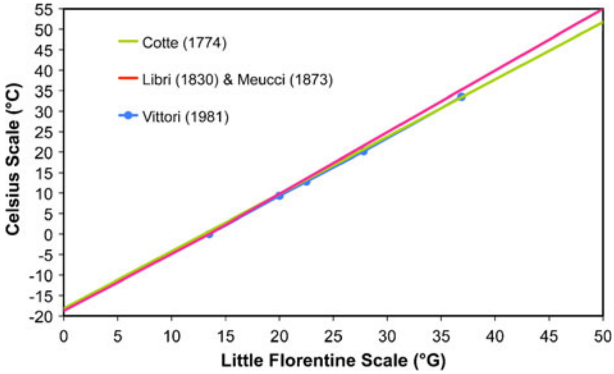


Fig. 4 The key calibrations of the Little Florentine Thermometer (LFT). Father Louis Cotte (1774), Libri (1830), Meucci (1873) and Vittori and Mestitz (1981)

calibrations although we don't know the accuracy of the reference thermometer. Vittori and Mestitz (1981) made an accurate calibration, only above the ice melting point. Libri, Meucci, Vittori and Mestitz calibrated the same thermometers, very probably different from those considered by Cotte. In conclusion we considered an average value of all the calibrations, i.e. 1°G=1.44°C for temperatures above the freezing point and 1°G=1.395°C below it. The fact that the instrument response was substantially unchanged after 150 years means that the drift due to glass and spirit ageing was very modest.

3.6 Thermometer exposure and location

Thermometers were in the free air without direct contact with supports, being hung with a rope, and far from any surface able to reflect solar radiation (Antinori 1841). The Secretary Lorenzo Antinori explicitly required that thermometers were hung one in a North-facing wall (i.e. "*ad Boream*") and another in a South-facing wall (i.e. "*ad Austrum*"), directly exposed to solar radiation (Terillo 1654). In particular, when solar beams hit a thermometer, this was indicated on the form with the symbol ⊙ drawn on the side of the reading.

The readings on the South-facing wall were obviously higher than those in the shade. However, they don't directly represent solar radiation intensity because both the spirit and the glass are transparent to visible radiation and absorb only some infrared bands; in addition, the temperature of the air in close proximity to the surface of the wall hit by solar radiation is influenced by the local overheating. Again, these observations cannot be used to study any difference between sunny and shaded areas, as made e.g. by Petralli et al. (2009), because to this aim the thermometers in the sunny areas should be accurately shielded against solar radiation. Therefore, a comparison between North and South facing thermometers is of little help and is outside the scope of this paper. In this paper we used only readings from the thermometer in the shade, which are the only useful observations for climatic purposes.

The exact position where the thermometers were located is unknown. Certainly the thermometer was inside the Convent area because in the night it was risky to go outside its protective walls for the presence of wild animals and bandits. We should consider that the observer made readings during day and night under any weather condition. This leads to suppose that the thermometer was easily reachable, possibly in the way between the cells and the church where the observer went for diurnal and nocturnal services, or close to it. All sites had the church at ground floor, connected with cloisters, making possible to hang thermometers on the Northern and the Southern walls of the cloister. However, Florence and Vallombrosa had no walls facing North and South but only North-East, South-East, South West and North West, as we have verified on the site and controlled in old maps and studies on the

Convent history (Ciardi 1999; Savelli and Nencioni 2008). We could hypothesize that thermometers were hung on the Northern and the Southern corners of the cloister. However, the data analysis shows that things were different. In the summer, a North-facing wall is reached by direct radiation in the early morning and late afternoon, and this happens on the readings, confirming that the wall was really facing North and had no shadow from obstacles. However, from the equations representing the solar motion and the beams crossing the cloisters it was evident that the North facing corner was never reached by the sun, and the South facing corner only near midday, being shielded by the loggias on both sides. As opposed, the readings shown that the South-facing thermometer had no obstacles, and that the solar beams reached the North-facing thermometer in early morning and late afternoon in the warm season, as confirmed by the higher temperature and the symbol ⊙ reported on the side of the reading. This excluded the cloister location and the use of existing walls oriented towards the secondary cardinal points. We should necessarily conclude that the Fathers built to this aim a wall external to the cloister but internal to the convent, and the only possibility was inside the vegetable garden.

In addition, we know that the spirit was transparent and reading the thermometer required sharp eye (Magalotti 1666) and staying close to it with the face. As a consequence, the thermometer needed to be hung at eye height (i.e. 1.5 m above soil) in order to make easier readings. Nocturnal readings made with the help of a lantern, because the glass shielded it against wind and in addition it stopped the IR from the flame without overheating the thermometers (Magalotti 1666).

4 Available data and methods for data analysis

4.1 Transformation of original data into modern units; verification of temperature readings

The readings are reported in daily forms, which include five columns with date and reading time (i.e. 5–8 readings a day), temperature on the North-facing thermometer, on the South-facing thermometer, and state of the sky and/or precipitation and/or other special weather events. The forms were produced some 10 years before Robert Hooke drew in 1663 the first standardized weather log in use in UK, later used as worldwide model. Per each station, readings are available for the periods indicated in Table 1.

It should be considered that original forms are written with faded ink on yellowish paper. They cannot be automatically read with existing software for character recognition, and require the expert eye of a person especially trained on it, who operates on digital reproductions of the sheets kindly supplied by the *National Central Library*, Florence, in order to electronically improve magnification, luminosity, and contrast in order to be sure of each reading. The data recovery has been particularly care and time consuming, if you consider that any single column is composed of 5–8 readings per 365 days per 15 years for a total of 30,000–40,000 readings. We will shortly describe each single column.

1st column: date The Medici series is characterized by a particular Calendar Style in use during the 17th century when Italy was divided into a number of small states and dukedoms, each of which had their own calendar. Florence used the '*Incarnation style*' (Camuffo and Enzi 1992) with the 25th March as starting day, i.e. postponed by 84 days in comparison to the modern dating style. All dates were transformed into modern calendar dating.

2nd column: reading time Before the French Revolution, 1789, clocks were based on the so-called Italian Time, (Camuffo 2002) regulated by monastic activity. Following the Italian

Time, the day began at twilight with the monastic celebration of "*Compieta*", i.e. "*The Angelus*", about half an hour after sunset. All the subsequent hours were counted starting from this moment that varied day-by-day during the calendar year. Observations were made at twilight, continued at midnight, at "*Matutinum*", i.e. the celebration before sunrise, and then at regular intervals during the day.

For this reason a necessary step was to recalculate all reading hours from astronomical formulae of the apparent position of the Sun for each station of the Medici network following a procedure already established for the early observations in Padua (Camuffo 2002). In this way for each observing day we calculated the Civil Twilight, i.e. when the Sun is 6° below the horizon and the visual perception is strongly reduced. This was considered the end of the day and the start of the new one. The Italian Style Time was converted into West European Time adding to each day of the calendar year the difference between midnight and twilight.

3rd and 4th columns: North and South facing thermometers Readings were transformed from the original Galileo degrees (°G) into Celsius degrees (°C) as discussed above. In a few cases the third column, i.e. North-facing thermometer, registered a higher temperature compared with the thermometer on the wall facing South (fourth column). This was frequent near sunrise and sunset in the warm season, when sunrise is between North East and East, and sunset between West and North-West. In such a case, the reading was associated with the symbol ⊙. In other cases, this was due to a misleading transcription of readings in the columns. Whatever the reason, we copied both columns and per every sampling time we automatically selected the lower temperature reading to be certain of using the observation taken in the shade.

5th column: notes on weather This column provides a qualitative description of the state of the sky, wind direction, precipitation and other weather events. It has been useful in interpreting the data in their context.

4.2 From hourly readings to daily averages

The schedule was uneven, with readings more frequent during the day-time and less during night-time. For this reason it was decided to adopt the style in use in a number of early series, and that was verified to be quite accurate at least in Italy, i.e. to obtain the daily average as the half-sum of the maximum and the minimum daily temperatures. The average difference between the mean daily temperature computed after 24 hourly readings and after the maximum and minimum daily readings is 0.26°C in Padua, Italy; the largest difference being 0.6°C reached in winter. In a number of Italian stations this difference was evaluated to range between −0.1 and −0.2°C at yearly level. (Camuffo 2002). The series were therefore expressed in terms of daily values computed after the daily maxima and minima.

4.3 Filling gaps

The Florence and Vallombrosa daily series were affected by some minor gaps as reported in Online Resource 3. The gaps have been filled with the help of the transfer equations relating one series to another. Matched series have been considered for the common periods only, i.e. discarding readings falling in periods affected by gaps either in Florence or Vallombrosa. These equations have been obtained by plotting in abscissa the daily readings of the reference series, and in ordinate the related readings of the other series. A robust plot of over 30,000 matched daily values from the two stations was obtained, from which the transfer equation (TE) was calculated by interpolation with the least square regression analysis available in Excel©. The determination coefficient R^2 was also calculated, to assess the accuracy of the TE. This methodology is commonly found in literature, e.g. Crisci et al. 1998; Cocheo and Camuffo 2002; Bergström and Moberg 2002; Demarée et al. 2002.

The TE we used to fill gaps in the Florence and Vallombrosa series are, respectively:

$\langle T_{VA} \rangle = 0.8151 \langle T_{FL} \rangle - 4.0149$ to fill Vallombrosa gaps with Florence daily data (Online Resource 4).
$\langle T_{FL} \rangle = 1.0936 \langle T_{VA} \rangle + 6.0131$ to fill Florence gaps with Vallombrosa daily data
$\langle T_{FL} \rangle = 1.1491 \langle T_{CU} \rangle + 3.5426$ to fill Florence gaps with Cutigliano daily data

where the <brackets> indicate the average daily values per each station and the label VA is for Vallombrosa, FL for Florence, and CU for Cutigliano. From the scatter of dots we obtained the best-fit transfer function with $R^2=0.89$ for Florence to Vallombrosa and vice-versa. Similarly for Cutigliano to Florence, we obtained $R^2=0.90$ with actual observations transformed in °C and $R^2=0.45$ with data transformed in terms of anomaly.

We should note that the TE are slightly different in the case daily or monthly averages are used, because the least square regression includes non-linear operators. For instance, the equation to fill gaps in the Vallombrosa series (T_{VA}) using Florence monthly data becomes

$$\langle T_{VA} \rangle = 0.8092 \langle T_{FL} \rangle - 3.7319$$

where now the <brackets> indicate the average monthly values per each station. The monthly equation is close to the daily but shifted by some 0.3°C and the two regression lines are almost overlapping and hardly distinguishable from each other.

5 Results and discussions

The time series of the seasonal averages in Florence are reported in Fig. 5 together with the 1961–1990 averages. No trends are visible, but some variability appears. Summers were

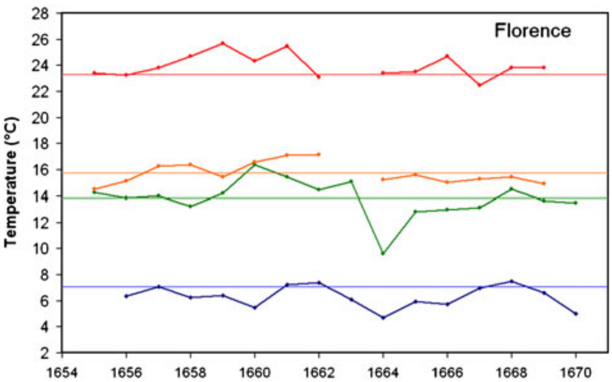


Fig. 5 Time series of seasonal temperature in Florence from 1655 to 1670. The *horizontal lines* refer to the seasonal averages in the 1961–1990 reference period

generally warmer than in the 1961–1990 reference period and winters generally colder. The bulk average temperature was 14.74°C.

The time series of mean daily temperature anomaly in Florence for the 1654–1670 period is reported in Fig. 6. The anomaly has been expressed in expanded scale to be more

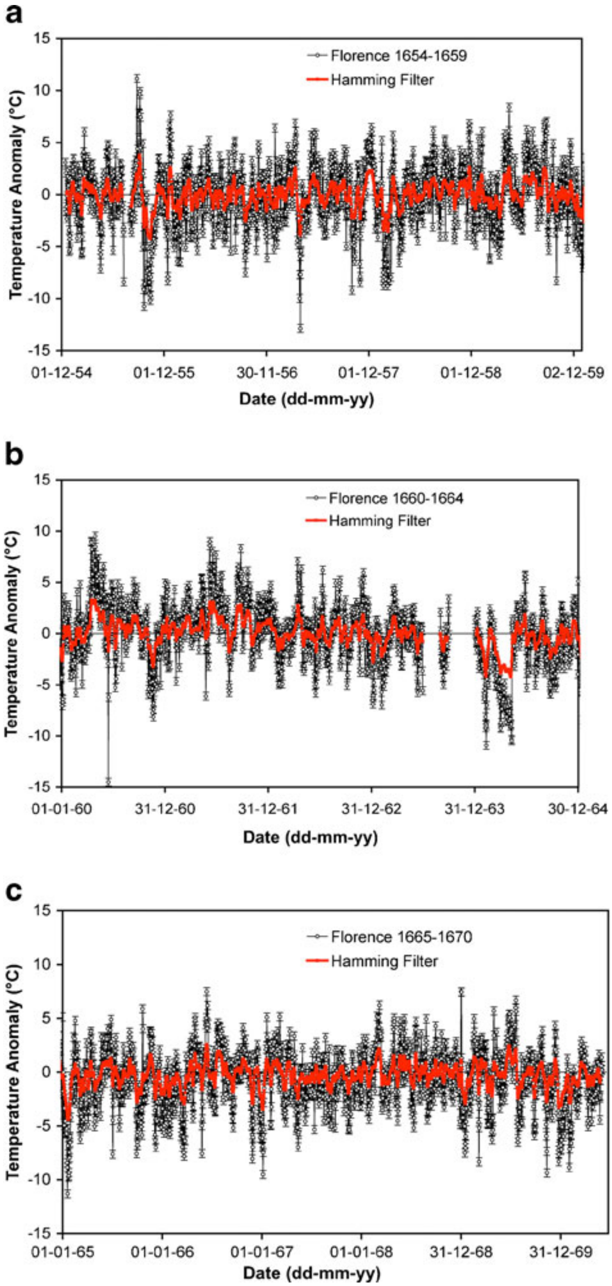


Fig. 6 Time series of daily temperature anomaly (reference period 1961–1990) in the 1654–1670 period, Florence. The Hamming filter with 11-day windows is reported (*thick line*) in order to pinpoint the smoother anomaly. Error bars: ±0.35°C

readable. In addition to the daily data, a low-pass bell shaped filter was applied, i.e. Hamming filter (Wei 1990):

$$D(\tau) = \begin{cases} 0.54 + 0.46 \cdot \cos\frac{\pi\tau}{\tau_m}, |\tau| \leq \tau_m \\ 0, |\tau| > \tau_m \end{cases}$$

where $\tau_{\mathrm{m}}=11$ days is the window and τ the running time variable (1 day resolution). The persistence of values scattered around the same level is a further demonstration that the series are homogeneous, without drift, and that the temporary departures are really due to extreme weather conditions. The hottest days were in summer 1655. The most severe cold happened in January 1665. Among the highest summer temperatures reported in Table 3, the lowest one was in June 1663. The two mildest winters were in 1662 and 1668 in Florence.

We can determine the climate change by comparing the average of the whole set of early data with the 1961–1990 modern data, taken at the Ximenian Observatory, in the centre of Florence, close to the Convent of Angels, i.e. 400 m from it, and at the rural site of the Florence airport, i.e. Peretola, 5 km from Florence. The historical centre of Florence has been left practically unchanged since the times of the Grand Duke except for an expansion of the town outskirts and of traffic. Also the landscape around Florence is controlled by a specific Agency for the preservation of cultural heritage, and landscape transformations have been relatively modest. However, the early observations at the Convent of Angels were made at ground level, whereas they are now made in the Ximenian Observatory on the meteorological brickwork tower located 25 m above the soil and 15 m above roof level. This elevated location attenuates the effect of urban heat island and constitutes an underestimate of the climate change in the city. The 1654–1670 observations in the Convent of Angels are 0.18°C lower than the average of the observations at the Ximenian Observatory in the 1961–1990 reference period.

The temperature in Peretola is 0.36°C lower than the Ximenian Observatory for the 1961–90 reference period (as well as for 1975–1997, Crisci et al. 1998). The difference between the 1654–1670 temperature at the Convent of Angels, Florence, and the 1961–1990 average in Peretola is 0.18°C.

We can determine the climate change in Florence in a totally different way, based on the frequency distribution of extreme events, if the distribution has not changed too much in the meantime. This has been verified by comparing the distributions in 1655–1670 and in 1961–1990, obtained from observations of the Ximenian Observatory (Fig. 7). Days are distributed by temperatures following a slightly asymmetrical bell-shaped distribution, with a bimodal top. In the same graph, the minimum and the maximum of the 1961–1990 monthly averages, i.e. January and July are also reported as a reference. Most of the daily readings fall within this range; the number of coldest days

Table 3 Seasonal extremes. The warmest day of the year in Florence (1654–1670) reached during the hottest and the freshest summers

Hot	Year	1655	1661	1659	1662
	T (°C)	33.7	31.02	30.84	30.84
Fresh	Year	1663	1667	1665	1668
	T (°C)	24.36	26.88	28.14	28.32

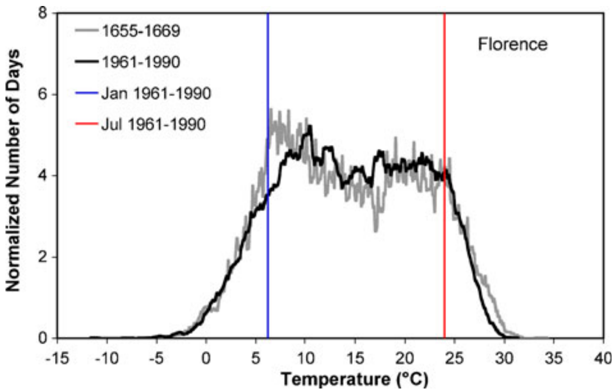


Fig. 7 Frequency distribution of days by temperatures in Florence for the 1655–1669 and the 1961–1990 reference periods, normalised for the different number of years. *Grey* refers to 1655–1669 and black to 1961–1990. The scatter of data was reduced with an 11-day moving average. The two *vertical lines* refer to the 1961–1990 average for January (*left*) and July (*right*), and the interval between them indicates the range of the monthly averages

falling outside is 14% of the total population, and the number of the hottest days exceeding the above range is 13%.

Let us verify how the frequency distribution of extremes in Florence and Vallombrosa will vary as a consequence of small simulated climate changes. The effect of climate change can be simulated shifting by small temperature steps the above bimodal frequency distribution (1961–1990 reference period) but leaving the 1961–1990 January and July averages unchanged, for reference. For each positive shift (i.e. warming) or negative shift (i.e. cooling), we can obtain the total number of the cold days (C), colder than the 1961–1990 January average, or the hot days (H), warmer than the 1961–1990 July average. These are reported in Fig. 8 together with their ratio (HCR). If we suppose that the climate will go towards global warming, the expected distribution will shift towards higher temperatures, increasing the number of hottest days, and similarly decreasing the number of coldest days, and vice-versa in the case of global cooling. In Florence, in the 1961–1990 reference period, HCR was 0.85, corresponding to 0°C simulated climate change. In 1654–1670 HCR was 0.91 and corresponds to −0.20°C with reference to the 1961–1990 period, similarly to the above finding with Peretola. All methods show that the climate in Florence had warmed less than 0.20°C since the middle of the LIA.

The seasonal character of the temperature in Florence can be recognized by calculating the average anomaly and temperature of each running day of the calendar year with reference to the average of the 30 values of the same day in the 1961–1990 period (Fig. 9 and Online Resource 5). In the 1654–1670 period, Florence experienced summers similar to the 1961–1990 period but with two hot peaks and winters generally colder. Florence also

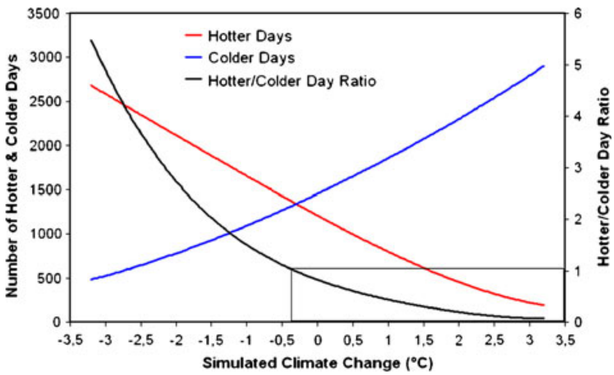


Fig. 8 Computed number of days that were colder than the 1961–1990 January average (*blue line*) and those warmer than the 1961–1990 July average (*red line*) and ratio of the hot to cold days (HCR, *thick black line*) in Florence. Simulation described in the text. *Thin black lines* outline the situation during the Medici Network

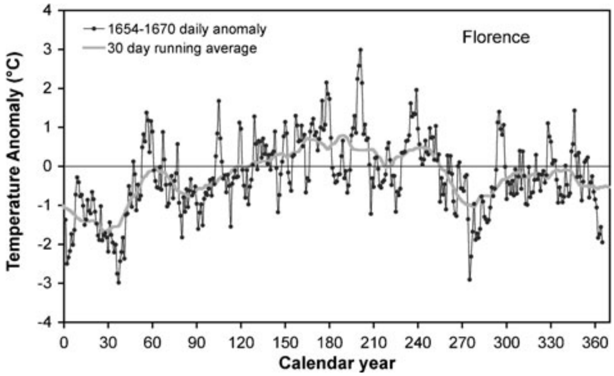


Fig. 9 Calendar year distribution of the daily temperature anomaly in the 1654–1670 period in Florence. Daily averages: *dots and thin black line*, 30-day running average: *thick grey line*

had higher variability in the mid seasons, i.e. two peaks, one in the transition between February and March and one between November and December, and two drops, i.e. one between March and April and one between September and October.

Tables 3, 4, 5 and 6 reports the most extreme mean daily temperatures experienced in winter and summer in Florence and Vallombrosa. The top extremes were reached in the years 1655, 1662, 1663, and 1665 in Florence, and 1655, 1663 and 1668 in Vallombrosa, with similar but not coincidental extremes.

The time series of the seasonal averages in Vallombrosa (Fig. 10) show that both the summers and the winters were colder than today, while the mid seasons were swinging. The time series of the mean daily temperature anomaly in Vallombrosa for the 1655–1669 period is reported in Fig. 11. No trends are visible. The 1961–1990 reference period exceeds the average of all the 1654–1669 observations by +1.41°C. The main difference in comparison with Florence is found in summer. The average temperature in Vallombrosa was 7.83°C and the difference with Florence was 6.90°C. The vertical gradient was 6.9°C/1000 m, very close to the NACA (National Advisory Committee for Aeronautics) standard atmosphere, i.e. 6.5°C/1,000 m (List 1971) or the dry adiabatic lapse rate in the International Standard Atmosphere (ISA), i.e. 6.49°C/1,000 m. In the 1961–1990 reference period the difference between the two stations was 5.67°C, i.e. 1.23°C departure from 1654 to 1670.

The interpretation of the above results suffers for some uncertainties, mainly determined by changes in vegetation, or exposure bias. Possible explanations might be related to the different geographical position of two stations, i.e. Florence on the plain and Vallombrosa on a mountain slope, and to changes in albedo. In the 17th century the plain around the mountain foot was covered with woods, but now most of the trees have been cut. The site around the Convent had some minor transformations (i.e. some deforestation, new asphalted roads, construction of new buildings for tourism and related business not far from the monastery) that might have increased the summer temperature, now 1.4° higher than at the Grand Duke's times. Another explanation might be related to the thermometer

Table 4 Seasonal extremes. The coldest day of the year in Florence (1654–1670) reached during the most severe and the mildest winters

Severe	Year	1665	1667	1664	1670
	T (°C)	−5.52	−3.43	−2.75	−1.86
Mild	Year	1662	1668	1659	1655
	T (°C)	2.78	2.78	1.88	1.52

Table 5 Seasonal extremes. The warmest day of the year in Vallombrosa (1654–1670) reached during the hottest and the freshest summers

Hot	Year	1655	1657	1660	1666
	T (°C)	23.46	22.93	22.93	21.85
Fresh	Year	1663	1664	1665	1667
	T (°C)	15.84	18.61	18.61	18.61

screen. Böhm et al. (2009) evaluated a warm bias in early series, largest during June (between 0.21° and 0.93°C) with a cold bias of up to 0.3°C in February, considering a bad sheltering compared with the modern Stevenson screen. However, in the case of the Medici Network, the thermometers were in the free air, in the shade of a North-facing wall and did not suffer for screen overheating. On the other hand, if we make a comparison with the 1961–1990, we should consider that the standard reference period, as all modern series, is affected by the bias of the Stevenson screen. In the Italian climate the Stevenson screen has been evaluated to overheat up to 1.5°C in sunny, windless summer days, and cool up to −0.5°C in clear nights (Cicala 1970). Although the average effect is smaller, this may affect the comparison with our data. In the case of the shady Vallombrosa (literally: "Valley in the shade") the screen disturbance was smaller, and this is confirmed by the very small difference between thermometers exposed to North and to South in this particular site. Another problem is that in Vallombrosa the weather station and all instruments were destroyed in 1945, at the end of suffered for the World War II. In addition, in November 1966 the station was relocated 20 m higher, i.e. on the tower of the Convent and this changed a bit the data quality. The readings of this series ended in 1970. Fortunately, in 1928 the *Stazione Sperimentale di Selvicultura* (SSS), Florence, installed a second, parallel station located close to the external walls of the Convent. Gandolfo and Sulli (1990), who produced the series for the 1872–1989 period, found some inhomogeneities. For this reason, Gandolfo and Sulli preferred to use the original series till 1944, and the SSS station for the subsequent period. Consequently, the 1961–1990 reference period is composed of post relocation readings.

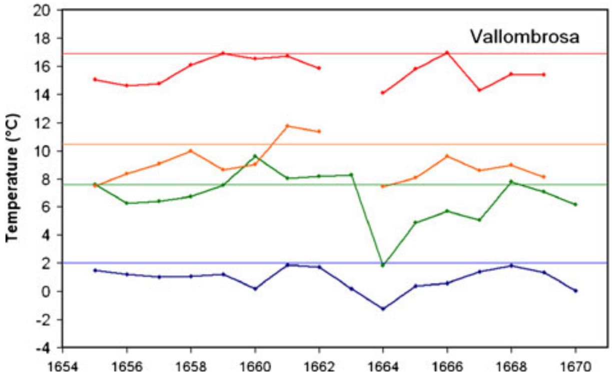
The frequency distribution by temperatures to establish climate change in Vallombrosa (Fig. 12) shows that in 1655–1670 the climate was colder with both the hot and cold extremes at temperature lower than in the 1961–1990 reference period. The seasonal character in this mountain site can be recognized from the average of the anomaly and the temperature of each running day of the calendar year (Fig. 13 and Online Resource 6). In the middle of the LIA the climate in Vallombrosa was generally colder than today, especially in summer and winter.

The secondary stations of the Medici Network were mainly aimed to investigate the seasonal extremes and operated for a limited period, i.e. December 1654–1660, as reported in Fig. 14a. Readings were more frequent in winter than in summer because scientists investigated whether ice always formed at the same temperature in the various countries,

Table 6 Seasonal extremes. The coldest day of the year in Vallombrosa (1654–1670) reached during the most severe and the mildest winters

Severe	Year	1663	1665	1664	1667
	T (°C)	−10.23	−8.84	−7.44	−5.70
Mild	Year	1668	1659	1662	1655
	T (°C)	−1.74	−2.47	−2.56	−2.77

Fig. 10 Time series of seasonal temperature in Vallombrosa from 1655 to 1670. The *horizontal lines* refer to the seasonal averages in the 1961–1990 reference period



irrespective of the geographical position and height. The data form a consistent set of readings, but are too few for any climate analysis. The days that were colder than January 1961–1990 and the days that were warmer than July 1961–1990 have been reported in Fig. 14b. The second mountain site, i.e. Cutigliano, shows a lower temperature compared with those on the plain. The days exceeding the 1961–1990 reference period are almost symmetrically distributed for hot and for cold. No major climate changes are visible, at least for the year 1658 and the winter 1659. In the Parma and Bologna stations, the number of summers and winters is uneven, but in any case the number of cold days per winter falling outside the band is larger than the corresponding number of hot days per summer. The Pisa station only has winter readings and is of little help. December 1659 was the coldest month. Fig. 14b might seem to suggest that the partially documented LIA period was slightly colder than the 1961–1990 reference; however, the real problem is the scarcity of summer readings.

A cross comparison between the individual series of the primary and secondary stations has been made for the individual overlapping periods by calculating the determination coefficients R_{ij}^2 between stations (e.g. Florence & Vallombrosa, Florence & Cutigliano, Florence & Pisa) that we will indicate with the i and j labels. Figure 15 has been made selecting Florence as reference station and shows that R_{ij}^2 exponentially decreases when the distance (d_{ij}) from Florence increases, following the equations

$$R_{ij}^2 = 1.00 \exp\left(-0.0015\ d_{ij}\right) \text{ if we impose that } R_{ij}^2 = 1 \text{ when } d_{ij} = 0$$
$$R_{ij}^2 = 0.96 \exp\left(-0.0014\ d_{ij}\right) \text{ if we prefer the best fit.}$$

The exponential fit is characterized by an elevated value of R^2, i.e. R^2=0.89 in the first equation and R^2=0.92 in the second. Some scatter is justified by the different altitude of the stations, some of them being located on the mountains and others on the plain. The exponential decrease is a further demonstration of the data quality; if the quality were bad, a random distribution would have been expected.

6 Conclusions

This paper presents for the first time the earliest meteorological observations taken within the Medici Network, from 1654 to 1670, five to eight readings a day. The series of the seven Italian stations that joined the Network, either unbroken series (i.e. Florence and Vallombrosa) or fragments, have been recovered, verified and transformed into modern

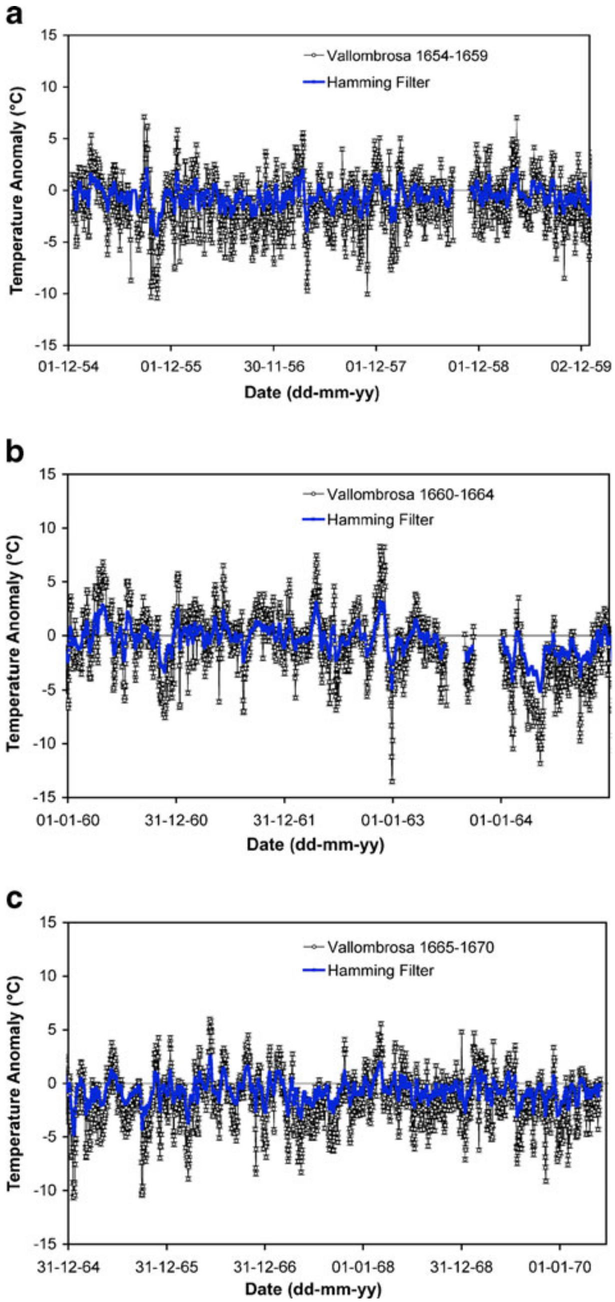


Fig. 11 Time series of daily temperature anomaly (reference period 1961–1990) in the 1654–1670 period, Vallombrosa. The Hamming filter with 11-day windows is reported (*thick line*) in order to pinpoint the smoother anomaly. *Error bars*: ±0.35°C

units of time and temperature. All the series of the Network are consistent and well related to each other, with the determination coefficient exponentially decreasing with increasing distance between stations. The small scatter shows that the quality of instruments was good as well as the observational modalities.

The analysis of these observations extends our knowledge of past climate back to the middle of the LIA. In that period, the climate in Florence was close to the 1961–1990

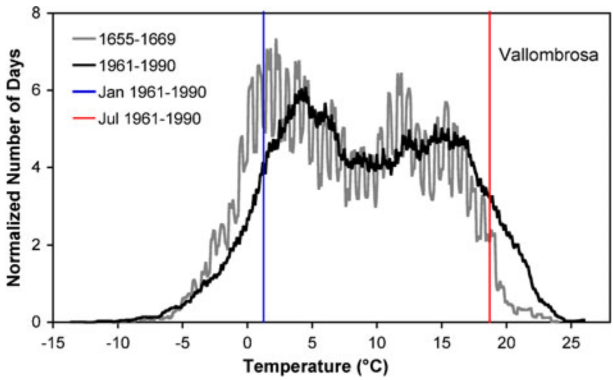


Fig. 12 Distribution of daily temperatures in Vallombrosa for the 1655–1669 and the 1961–1990 reference periods, normalised for the different number of years. *Grey* refers to 1655–1669 and black to 1961–1990. The scatter of data was reduced with an 11-day moving average. The two *vertical lines* refer to the 1961–1990 average for January (*left*) and July (*right*), and the interval between them indicates the range of the monthly averages

reference period, except for winters that were colder and for a few hot peaks in summer. Today the tendency is for an increase in hot peak frequency (Bartolini et al. 2008).

The climate on the Vallombrosa mountain site was 1.4°C colder than the 1961–1990 reference period with frequent departures from seasonal averages. The vertical gradient between Florence and Vallombrosa was 6.9°C/1,000 m, close to the NACA standard atmosphere, i.e. 6.5°C/1,000 m, but larger than the 5.7°C/1,000 m found in the 1961–1990 reference period.

Climate signal or bias? Not easy to answer. From one side we can suppose that changes in vegetation, exposure or location biases might have contributed to obscure our findings. From another side, we can consider that a small anomaly was observed in a number of stations in the subsequent period when other observations became available. In Padua, located some 200 km North of Florence, the 1716–1760 period was characterized by cold winters and chilly springs, opposed to hot summers and warm autumns, but the mid seasons having some variability (Camuffo and Bertolin 2010). The same was observed in Bologna (1716–1774) located midway between Florence and Padua (paper in preparation). Also in France the temperature observed since 1676 was continually swinging from higher to lower levels (Camuffo et al. 2010a), and only in recent times (i.e. after 1850) the climate signal is similar to the well-known "hockey stick" typical of the global warming. The long instrumental series in the Mediterranean area show that the LIA was characterized by temperature swings that followed the Bruckner and the Hale cycles, i.e. 35 and 23 years respectively, and the rainfall was also characterized by swings, but with longer periodicity, i.e. 70 years. The combination of these two cycles led to a variety of wet & cold or wet & warm or dry & cold or dry & warm

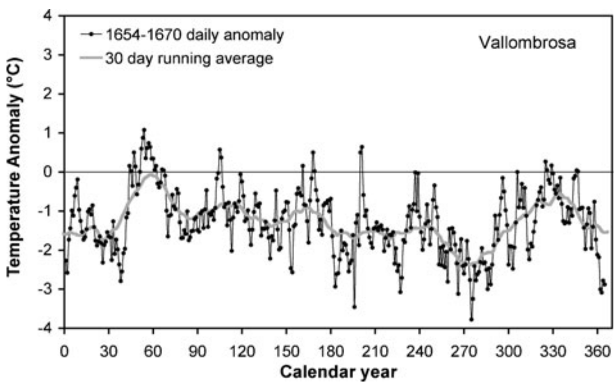


Fig. 13 Calendar year distribution of the daily temperature anomaly in the 1654–1670 period in Vallombrosa. Daily averages: *dots and black thin line*, 30-day running average: *thick grey line*

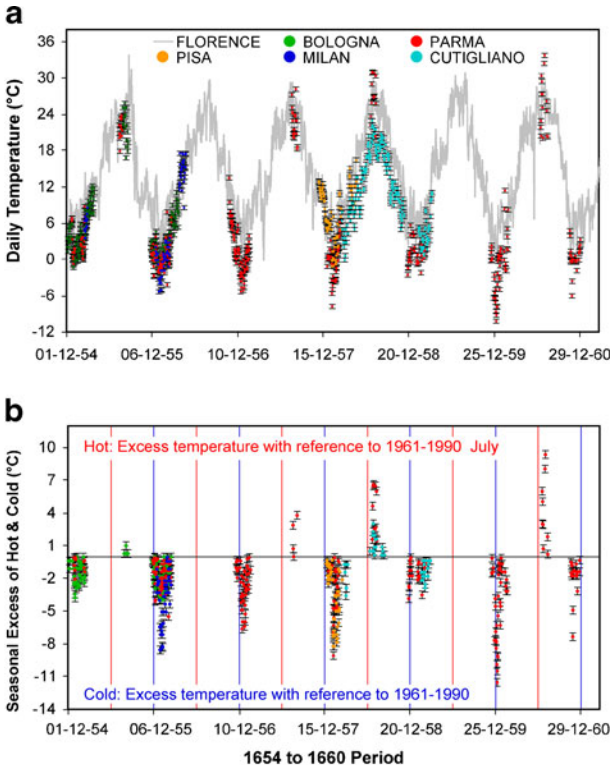


Fig. 14 **a** Fragmented series of daily temperature in the secondary stations: Bologna (*green*), Cutigliano (*cyan*), Milan (*blue*), Parma (*red*) and Pisa (*orange*). Florence (*light grey*) is reported as a reference of the climate at that time. **b** Extreme days warmer than the 1961–1990 July average (i.e. 1654–1670 temperature peaks) and colder than the 1961–1990 January average (i.e. 1654–1670 temperature drops) in Bologna (*green*), Cutigliano (*cyan*), Milan (*blue*), Parma (*red*) and Pisa (*orange*). The scale represents the difference in temperature between the observed values and the respective reference average, i.e. January or July 1961–1990

intervals, which have characterized the period from the Medici Network to nowadays. It is only since 1930 that the Italian climate and, more generally, the Western Mediterranean, are strictly connected with the Northern Hemisphere and Global Warming (Camuffo et al. 2010b). However, further research is needed to confirm the above critical items.

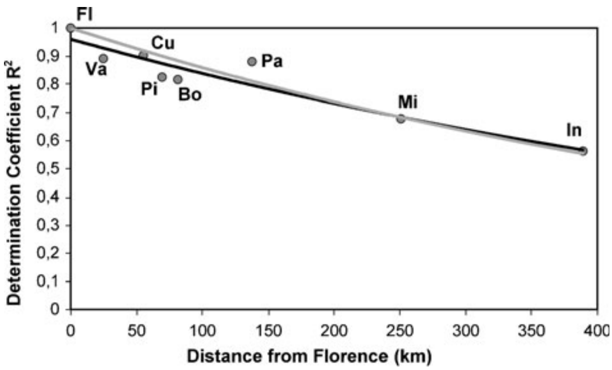


Fig. 15 Cross comparison between individual series of the Medici Network, i.e. Vallombrosa (Va), Cutigliano (Cu), Pisa (Pi), Bologna (Bo), Parma (Pa), Milan (Mi) and Innsbruck (In), with Florence (Fl), headquarter of the Network. The determination coefficient R_{ij}^2 obtained from the comparison between Florence and the other stations is plotted versus the distance from Florence. The *grey interpolation line* represents the exponential fit if we impose that $R_{ij}^2 = 1$ at the origin. The *black line* is the best fit that maximizes the determination coefficient R^2

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The earliest temperature observations in the World: the Medici Network (1654-1670)

Climatic Change

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Online Resource 1: Map of the eleven European stations of the Medici Network, formally active for the 1654-1667 period. Stations outside Italy were: 8-Innsbruck, 9- Warsaw, 10-Osnabruck and 11-Paris.

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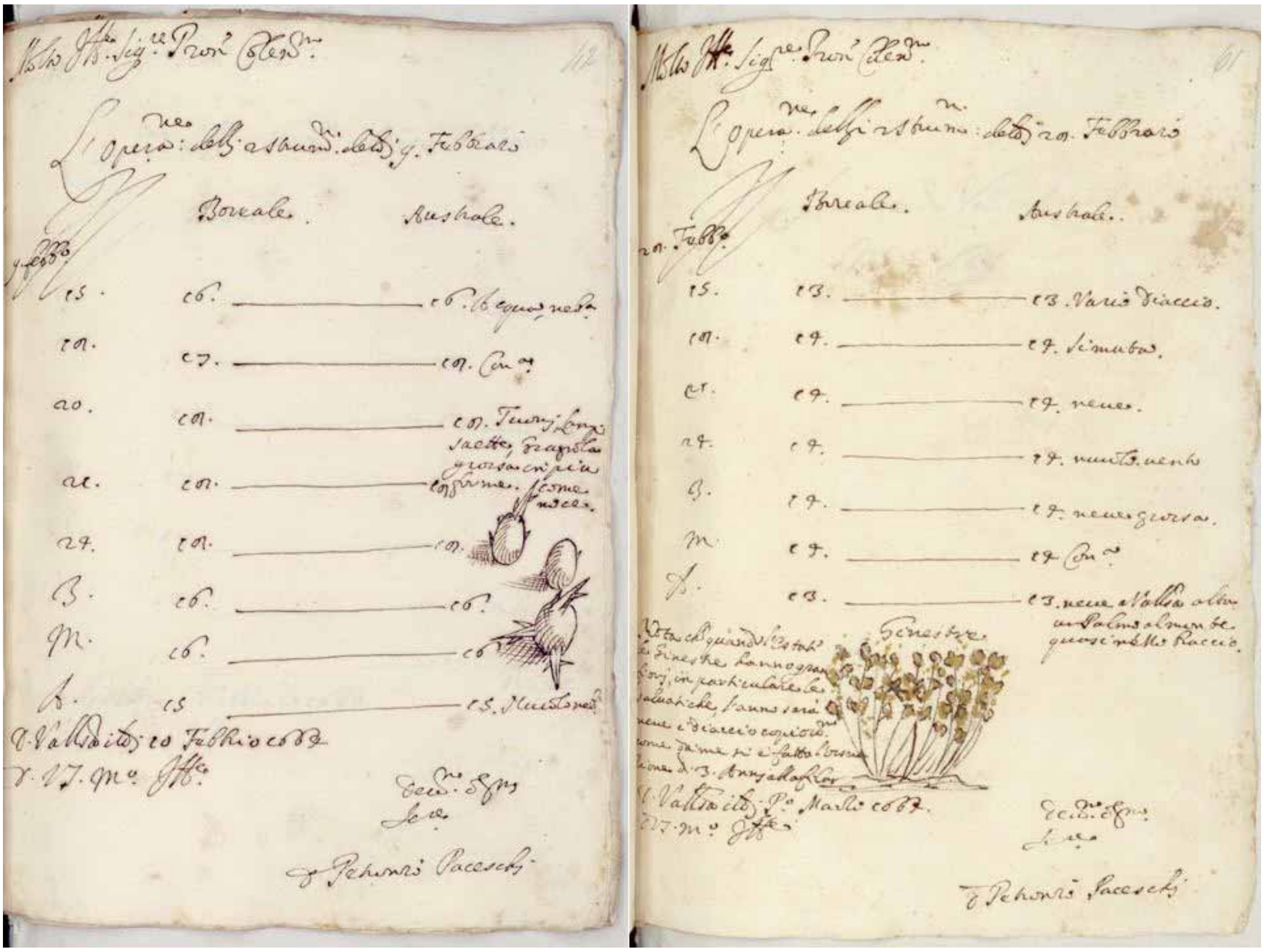

Online Resource 2: Two letters with observations from Vallombrosa: (a) with hailstones, (b) with blooming flowers. Readings were generally taken five to eight times a day, depending on the sites, but at hours that varied with the seasons, because the new day started at twilight. By courtesy of National Central Library (BNCF), Florence.

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Online Resource 3a: Gaps in the Florence series filled using other series, i.e. Vallombrosa (VA), and Cutigliano (CU)

1-1-1657 to 31-1-1657, VA	2-4-1657 to 30-4-1657 VA	15-6-1657 to 19-6-1657 VA
25 and 26-6-1658 CU	2-9-1658 to 31-10-1658 CU	25 and 26-11-1658 CU
2-8-1660 to 30-9-1660 VA	2-5-1661 to 31-5-1661 VA	2-8-1661 to 31-8-1661 VA
1-3-1662 to 31-3-1662 VA	1-1-1664 to 10-5-1664 VA	1-1-1670 to 31-5-1670 VA

Online Resource 3b: Gaps in the Vallombrosa series filled using the Florence series

15-12-1654 to 31-1-1655	25 and 26-8-1657	11-9-1657 to 19-9-1657
27-11-1657 to 29-11-1657	1-1-1658 to1-9-1658	1-11-1658 to 31-12-1659
2-10-1662 to 31-10-1662	1-1-1663 to 30-6-1663	9-9-1663 to 1-10-1663
1-1-1668 to 31-3-1670		

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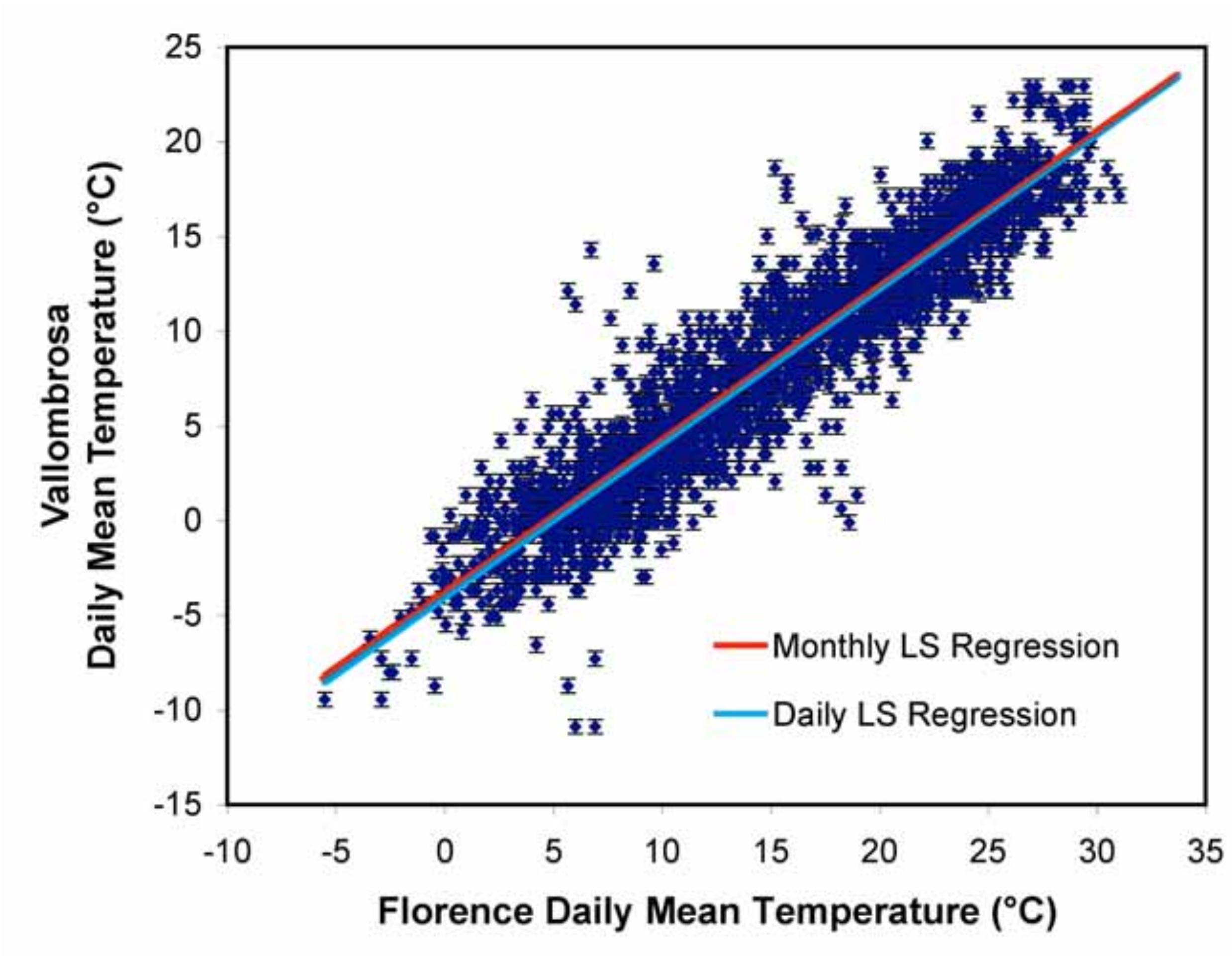

Online Resource 4: Least squares (LS) regression obtained by plotting in abscissa the daily readings of the reference series (Florence) and in ordinate the related readings of Vallombrosa. Daily average regression: cyan line; Monthly average regression: red line. The two regression lines are almost overlapping and hardly distinguishable.

The earliest temperature observations in the World: the Medici Network (1654-1670)

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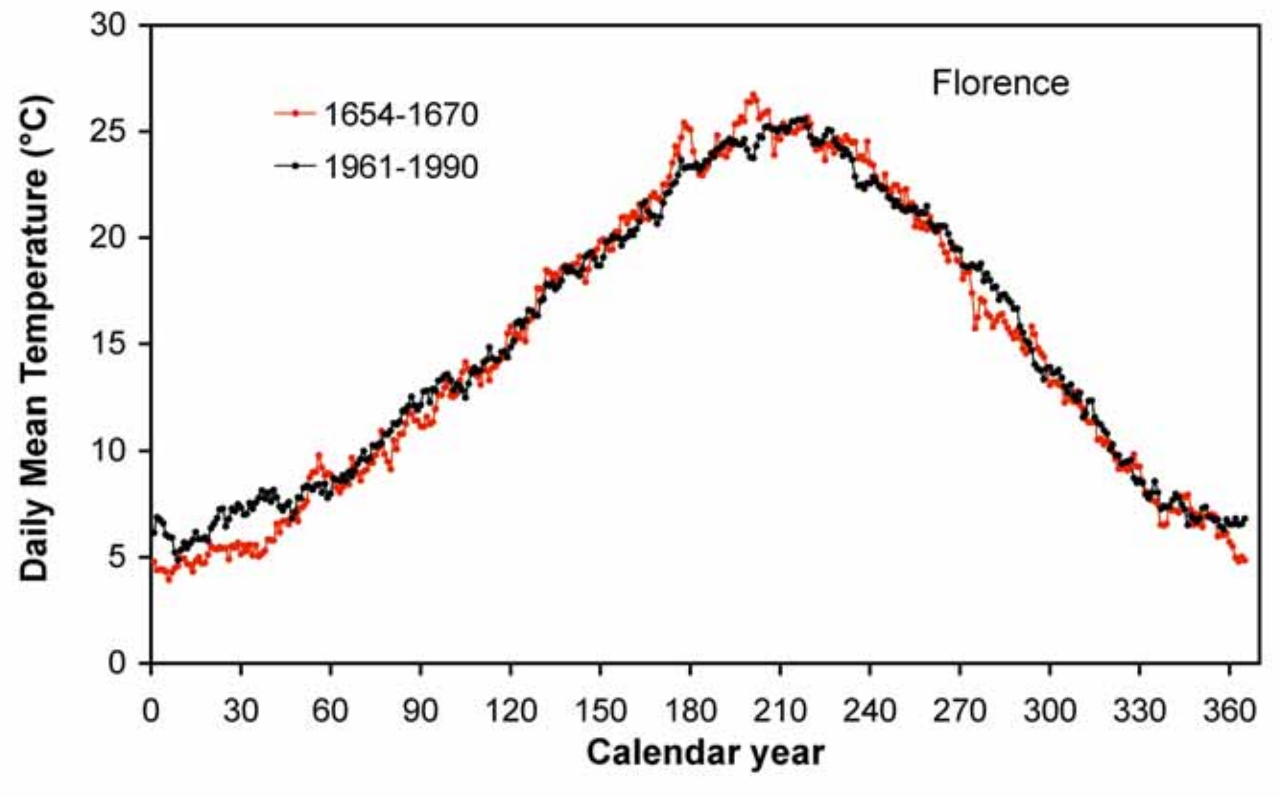

Online Resource 5: Calendar year distribution of the daily temperature in the 1654-1670 (red) and 1961-1990 reference period (black) in Florence.

The earliest temperature observations in the World: the Medici Network (1654-1670)

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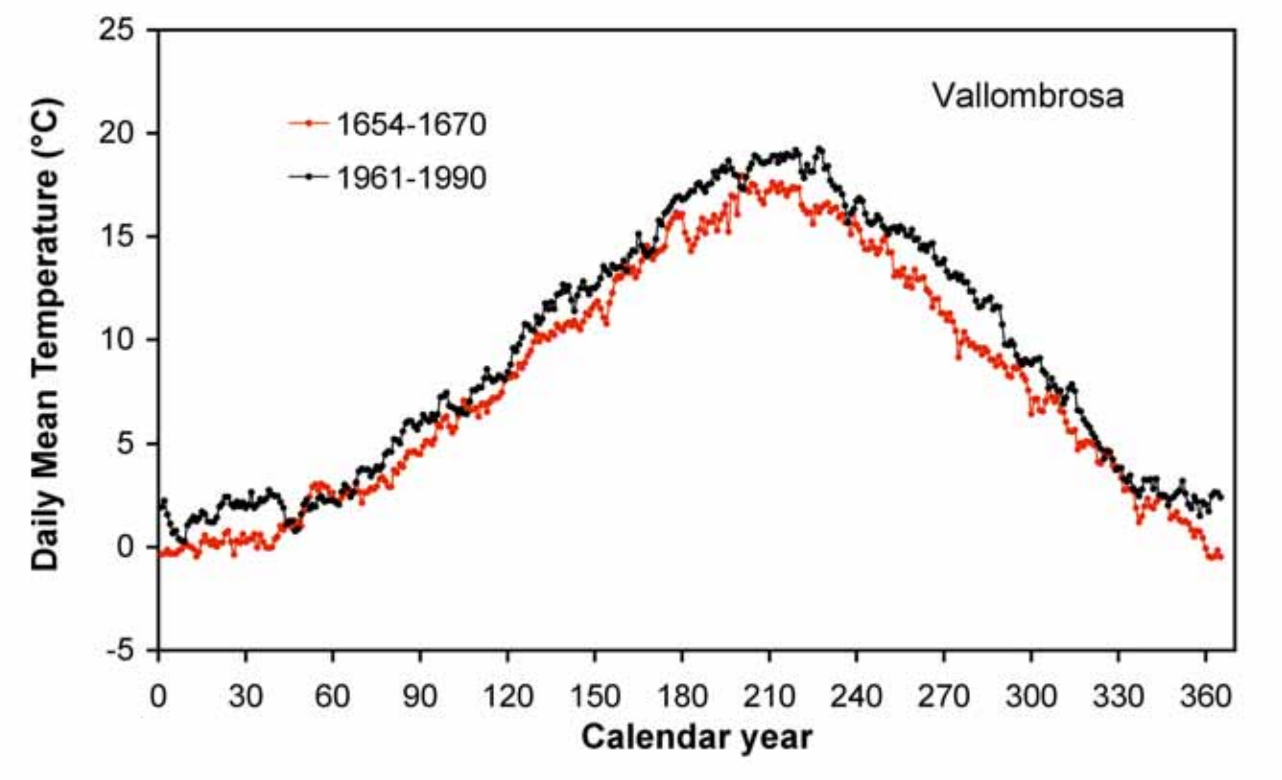

Online Resource 6: Calendar year distribution of the daily temperatures in the 1654-1670 (red) and 1961-1990 reference period (black) in Vallombrosa.

The earliest temperature observations in the World: the Medici Network (1654-1670)

Climatic Change

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Online Resource 1: Map of the eleven European stations of the Medici Network, formally active for the 1654-1667 period. Stations outside Italy were: 8-Innsbruck, 9- Warsaw, 10-Osnabruck and 11-Paris.

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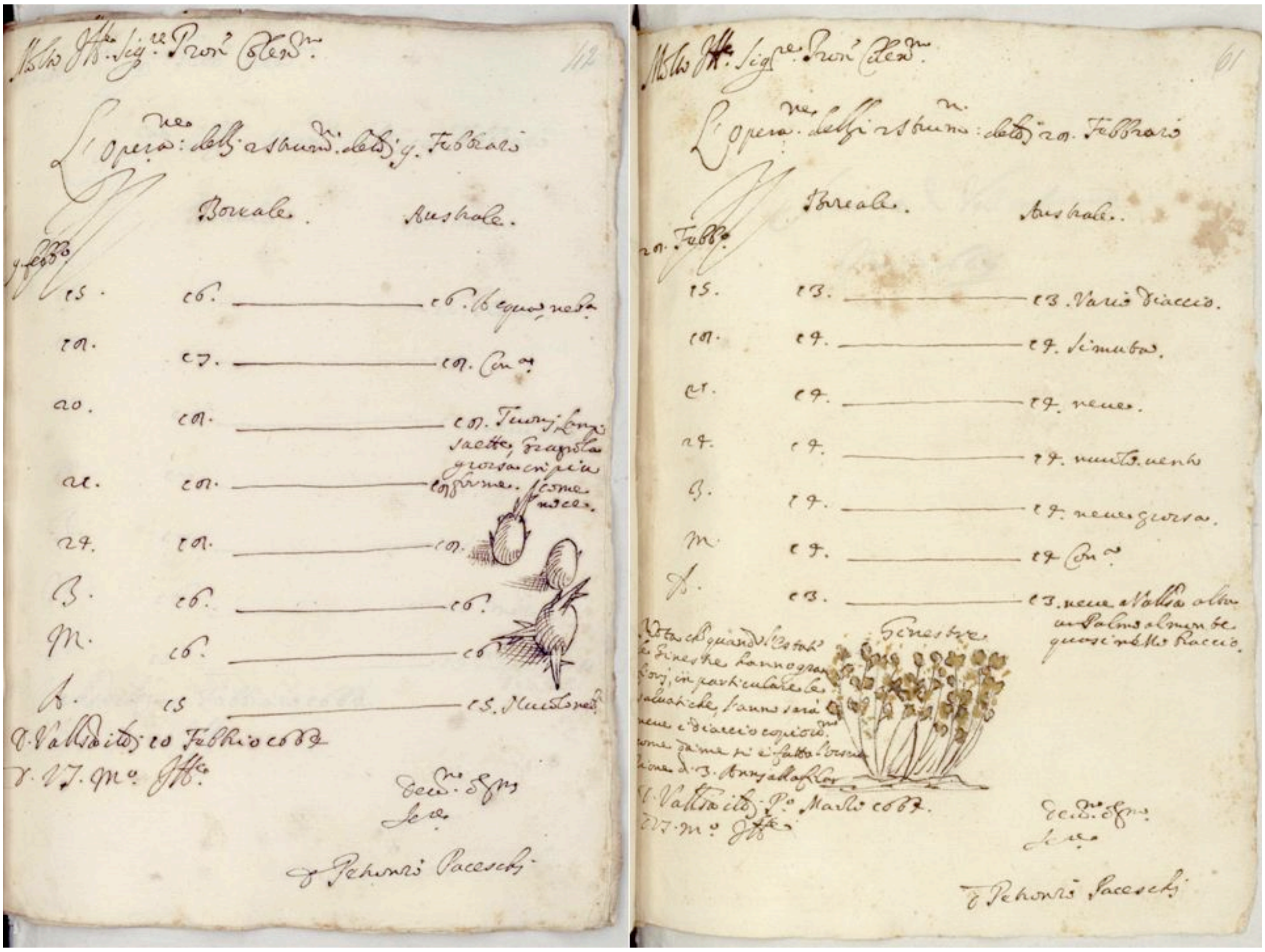

Online Resource 2: Two letters with observations from Vallombrosa: (a) with hailstones, (b) with blooming flowers. Readings were generally taken five to eight times a day, depending on the sites, but at hours that varied with the seasons, because the new day started at twilight. By courtesy of National Central Library (BNCF), Florence.

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Online Resource 3a: Gaps in the Florence series filled using other series, i.e. Vallombrosa (VA), and Cutigliano (CU)

1-1-1657 to 31-1-1657, VA	2-4-1657 to 30-4-1657 VA	15-6-1657 to 19-6-1657 VA
25 and 26-6-1658 CU	2-9-1658 to 31-10-1658 CU	25 and 26-11-1658 CU
2-8-1660 to 30-9-1660 VA	2-5-1661 to 31-5-1661 VA	2-8-1661 to 31-8-1661 VA
1-3-1662 to 31-3-1662 VA	1-1-1664 to 10-5-1664 VA	1-1-1670 to 31-5-1670 VA

Online Resource 3b: Gaps in the Vallombrosa series filled using the Florence series

15-12-1654 to 31-1-1655	25 and 26-8-1657	11-9-1657 to 19-9-1657
27-11-1657 to 29-11-1657	1-1-1658 to1-9-1658	1-11-1658 to 31-12-1659
2-10-1662 to 31-10-1662	1-1-1663 to 30-6-1663	9-9-1663 to 1-10-1663
1-1-1668 to 31-3-1670		

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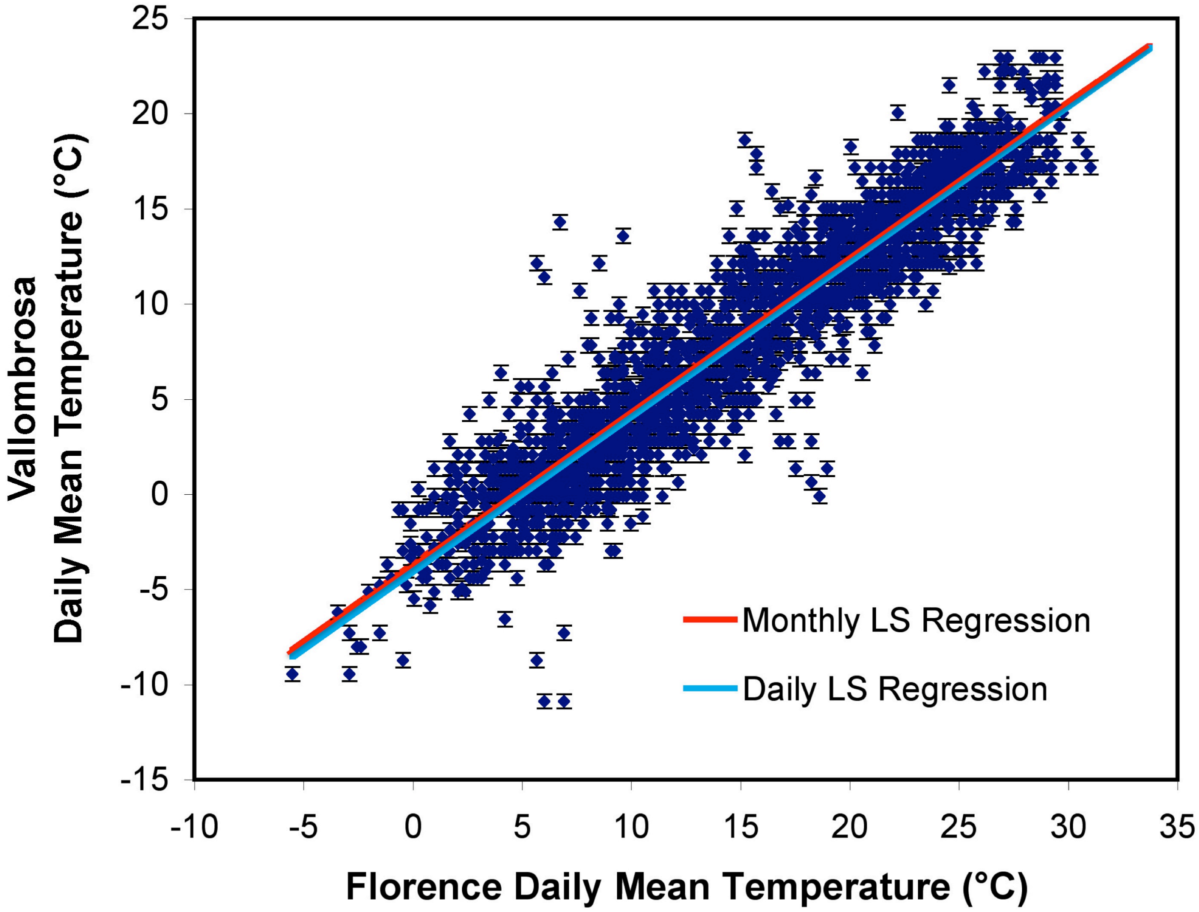

Online Resource 4: Least squares (LS) regression obtained by plotting in abscissa the daily readings of the reference series (Florence) and in ordinate the related readings of Vallombrosa. Daily average regression: cyan line; Monthly average regression: red line. The two regression lines are almost overlapping and hardly distinguishable.

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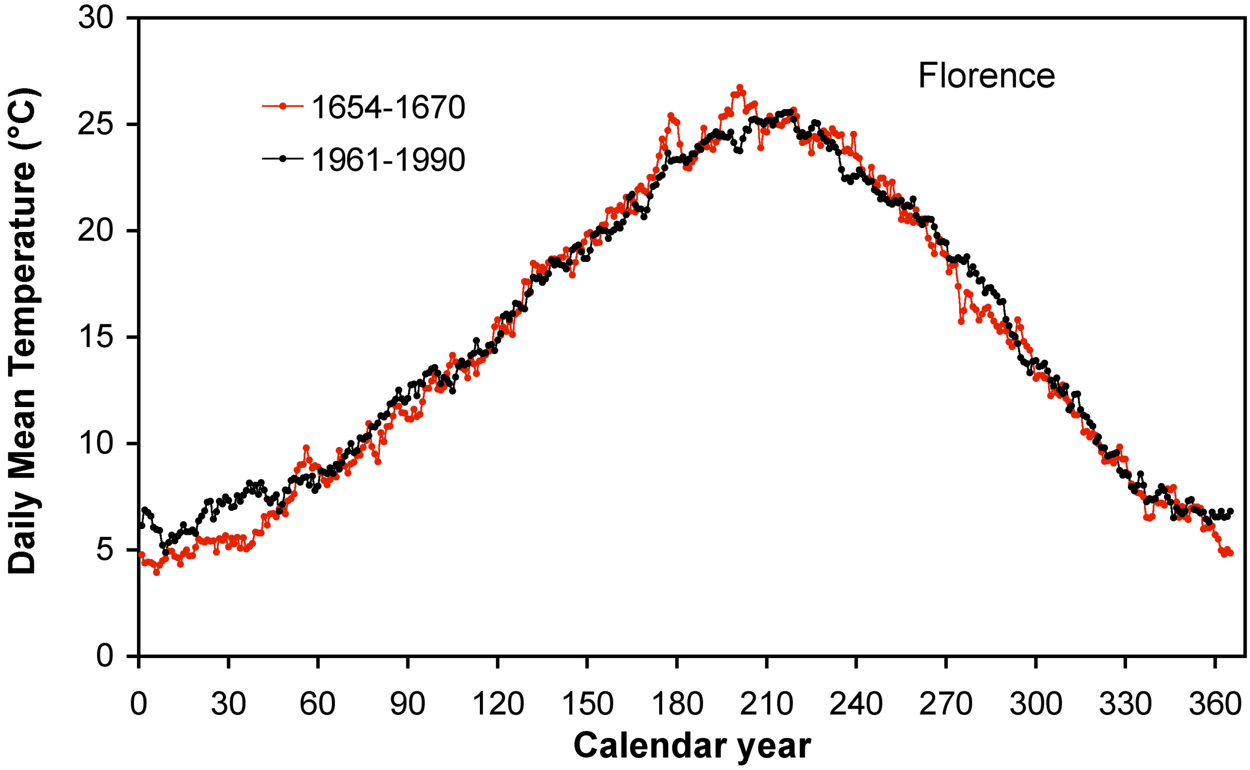

Online Resource 5: Calendar year distribution of the daily temperature in the 1654-1670 (red) and 1961-1990 reference period (black) in Florence.

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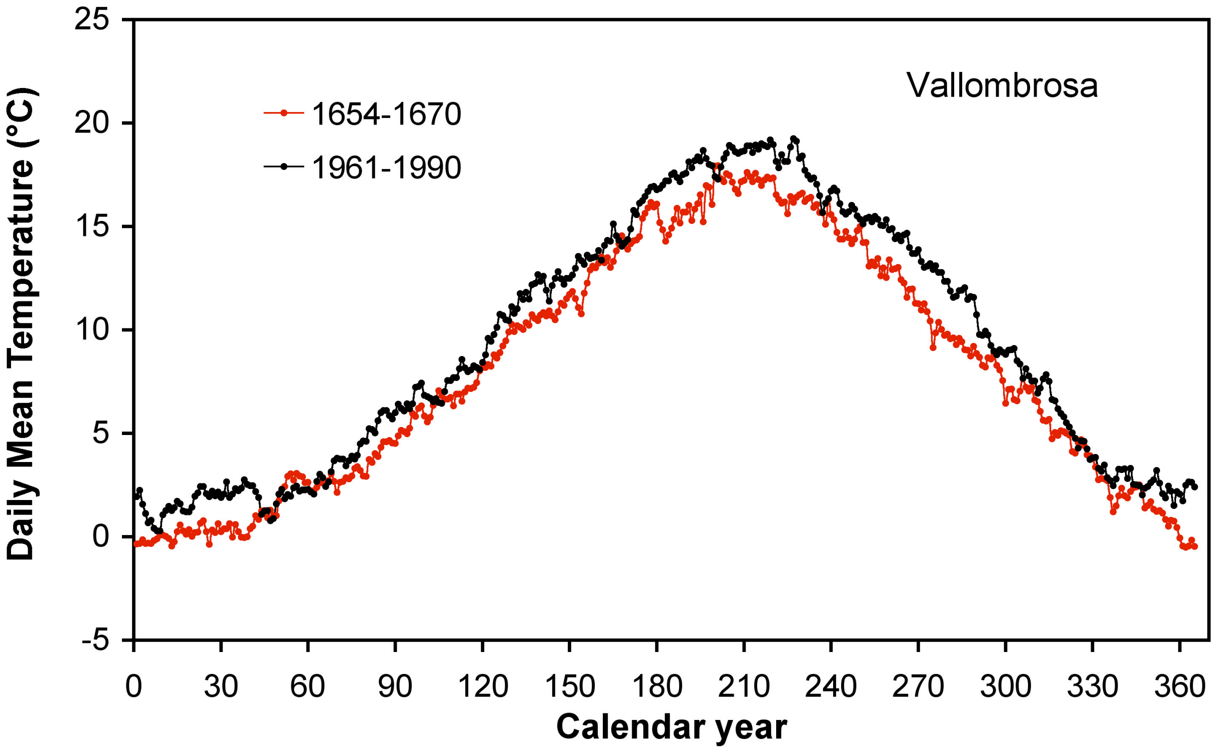

Online Resource 6: Calendar year distribution of the daily temperatures in the 1654-1670 (red) and 1961-1990 reference period (black) in Vallombrosa.