



Temperature observations in Florence, Italy, after the end of the Medici Network (1654–1670): the Grifoni record (1751–1766)

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Abstract

This paper deals with the earliest meteorological observations in Florence after the Medici Network (1654–1670), i.e., from mid-seventeenth to mid-eighteenth century, and puts them in the context of the history of meteorology in Florence. After the gap caused by the Inquisition, observations started again in the eighteenth century, made by Cipriano Antonino Targioni (1728–1748), Giovanni Targioni-Tozzetti (1737–1740), Pietro Gaetano Grifoni (1751–1766), Leonardo Ximenes (1752), and Luca Martini (1756–1772). The first two records were lost, and this paper considers those by Grifoni and Ximenes. The latter is affected by severe bias; the former is of good quality and has been recovered and analyzed. Both the observers made only one reading a day and the metadata are scarce. The paper discusses several issues: the conversion from the apparent solar time to the Central Europe Time; the transformation from a single reading to a daily average; the identification of the thermometric liquid and the scale; the test made with the snow benchmark; the comparison with the contemporary series in Bologna. The comparison of the reconstructed series with other periods, i.e., 1654–1670, 1881–1910, 1961–1990, and 1991–2017, reveals that in mid-eighteenth century the temperature reached the lowest levels, especially in summer, and showed a sudden warming in the most recent decades.

Keywords Temperature series · Early instrumental records · History of meteorology · Climate change

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1 Introduction

The scientific passion and motivation of the Grand Duke Ferdinand II de' Medici and his brother Prince Leopold led to the creation of an important scholarly institution, the *Accademia del Cimento*, i.e., Academy of Experiments (1657–1667), considered the first experimental European scientific society (Magalotti 1666; Middleton 1971; Vergari 2006; Beretta et al. 2009). It was composed of the most leading men of science and letters including some foreign correspondent members. It was focused on knowing and understanding natural phenomena through direct quantitative observations made with scientific instruments and repeated tests. This was a clear cut with Aristotle heritage and any other unproved ideas, as well as the tradition that the Church was the only authoritative interpret of the world, the universe and all natural phenomena cited in the Holy Bible. Quantitative measurements were considered the key to understand Nature. New instruments were devised to this aim. This established the passage from the dark of Middle Age to the dawn of modern science based on objective research.

The Grand Duke and his Academicians invented the liquid-in-glass thermometer, the barometer, the condensation hygrometer, and the rain gauge. In 1654, the Grand Duke instituted the first meteorological network, the Medici Network (Camuffo and Bertolin 2012a, b), an event of fundamental importance for the development of meteorology. An international network of well-coordinated observations, performed with identical instruments, exposure, schedule, and protocols, flourished from 1654 to 1670. This network provided the earliest temperature record and Florence was the primary station, under the strict control of the Grand Duke (Targioni-Tozzetti 1780; Antinori 1858). The Medici Network was composed of 11 stations in Europe, the majority of them (7 out of 11) located in Italy. The records of this network have been already recovered and analyzed (Camuffo and Bertolin 2012a, b; Rousseau 2013; Camuffo et al. 2020).

The astronomical discoveries and other investigations made by Galileo and the Academicians entered in conflict with the theological beliefs of the time. The church considered the Bible as the only source of knowledge, directly inspired by God, while Galileo and the *Accademia del Cimento* proposed another independent source, i.e., the direct observation of the nature (Galilei 1615; Viviani 1717). The astronomical and meteorological observations were disliked by the Holy See after the Galileo trial in 1633. However, the Academy and the meteorological network resisted more than 10 years under the protection of the Gran Duke and his brother. A turning point was in 1666, when Lorenzo Magalotti, secretary of the Academy, published a fundamental book: “*Saggi di Naturali Esperienze*”, i.e., Essay on Experiments on Nature, that was the story of the research in Florence, with records of the activity performed, including discussions and scientific explanations (Magalotti 1666). The dissemination of this book inspired by the new philosophy of Nature, based on scientific research, was considered extremely dangerous for the authority of the Church. The Holy See proposed to close the Academy as an exchange to promote Prince Leopold to the level of Cardinal, which happened on 12 December 1667. The natural investigations were considered on suspicion of heresy; the Academy and the Network were diplomatically closed and all the Academicians dispersed (Fabroni 1769; Targioni-Tozzetti 1780).

The political situation required time for a new equilibrium. It was improved with the advent of Pope Clement XI (1700–1721) and became good with Benedict XIV (1740–1758). These two Popes encouraged the research, especially in Bologna that was under the political and administrative control of the Pope. Florence was under the protection of the Grand Duke of

Tuscany, belonging to the powerful *de' Medici* Family related to the *Asburgo-Lorena* Family, and new scientific observations could start, continuing the legacy of the former *Accademia del Cimento*. In Italy, the renewed interest on climate, as well as the attention to extreme weather events and meteorological observations, gained trust as a key for agriculture, to interpret seasonal epidemics and protect against river floods, and this practical approach continued in the following century (Ramazzini 1718; Targioni-Tozzetti 1767; Toaldo 1770; Camuffo 2002a, b, c).

The aim of this paper is to reconstruct the history of the meteorological observations made in Florence from the Medici Network to mid-eighteenth century, and to analyze the earliest two survived records, still unexploited, by Grifoni from 1751 to 1766, and Ximenes in 1752. In particular, the paper addresses the issue of the uncertainties related to the early series, frequently mentioned but rarely solved in the literature. From the climatic point of view, it integrates the knowledge of air temperature in Florence presented by Kumar et al. (2005).

2 Lost and survived observations in Florence from mid-seventeenth to mid-eighteenth century

After the Medici Network and the gap caused by the Inquisition, the observations in Florence started again in the second decade of the eighteenth century and continued for 50 years, as follows.

Cipriano Antonino Targioni (1672–1748): observations from 1728 to 1748 The Grand Duke Cosimo III *de' Medici* appointed the medicine doctor and botanist Cipriano Antonino Targioni to coordinate the observations and physical experiments in the renewed Academy. This included the weather records and Cipriano made regular observations from 1728 to the end of his life in April 1748 (Targioni 1773; S.P.I.R. 1774). Unfortunately, this record was dispersed.

Giovanni Targioni-Tozzetti (1712–1783): observations from 1737 to 1740 He was a medicine doctor and botanist like his uncle Cipriano Antonino. He observed temperature and pressure till 1740, when a dramatic flood of the Arno River invaded his house and destroyed all documents (Targioni-Tozzetti 1767; Vergari 2006). Targioni-Tozzetti published two books rich of climate history and information:

- *Alimurgia* (Targioni-Tozzetti 1767) where he reported the description of the climate in Tuscany, famines, plagues, and extreme weather events since 1765. He also added some temperature and pressure readings taken by his colleague Luca Martini;
- *Notizie degli aggrandimenti delle scienze fisiche accaduti in Toscana nel corso degli anni LX del secolo XVII* (Targioni-Tozzetti 1780) where he reported the activity of the *Accademia del Cimento*.

Leonardo Ximenes (1716–1786): observations only for 1752 He was an astronomer and a Jesuit Father. He published tables with ephemerides, meteorological and astronomical observations for the year 1752 (Ximenes 1753) (Fig. ESM1), performed at the College of San Giovanni Evangelista, nowadays known as Ximenian Institute, in the city center (Fig. 1a, Fig.

ESM2). For a total 107 days over the year, he read the barometer and thermometer in the morning, generally from 7 to 10 a.m., but more frequently at 8 a.m. In Ximenes (1753) there was no specification about the thermometer used and its exposure. Readings were expressed in degrees and tenths, but without indicating either Réaumur or Celsius degrees.

Pietro Gaetano Grifoni (1710–1772): observations from 1751 to 1766 He was a Florentine patrician; he taught physics and made experiments with physical machines and equipment at his palace, as it was usual at that time. His pupil Carlo Alfonso Guadagni, a doctor in natural philosophy and medicine, wrote a paper (Guadagni 1767) to describe a new portable barometer invented by Grifoni. In addition, he reported the meteorological observations made by Grifoni at his home (Section 3.1), analyzed in this paper.

Luca Martini (birth and death dates unknown): observations from 1756 to 1772 He was a medicine doctor at the *Santa Maria Nuova* Hospital and secretary of the Botanical Society, Florence. During the observation period, Martini changed house, moving from Ginori Street to Pitti Square in 1765. He took readings using two Réaumur thermometers, one filled with mercury and another with spirit, both indoors and outdoors, but at different sampling times (Targioni-Tozzetti 1767; Targioni 1773). The data related to the 1765–1772 period are affected by remarkable inhomogeneity with respect to the previous period. The Martini series is potentially interesting but problematic. It was severely criticized by Schouw (1839) and needs a thorough analysis that may be the aim of a future work. In this paper, it has been used only to identify the thermometric liquid used by Grifoni.

However, in the absence of better references for validation, the comparison with the uncorrected Martini readings, the overlapping year of Ximenes, the contemporary series in Bologna (Camuffo et al. 2017a), and the natural benchmark when it was snowing, may help data interpretation and correction. When dealing with rare early instrumental data, such as the eighteenth century ones, it is not always possible to reach the quality required by the modern international standards (WMO 2008), but it is necessary to make any effort to recover and interpret such records that require a very careful work, but constitute a unique opportunity to reconstruct past climate.

3 Location and exposure, reading time, and the log

3.1 Location and exposure

In the eighteenth century, the earliest available record in Florence is by Grifoni, who observed from January 1751 to December 1766 in the city center as shown in the contemporary map of Florence by Fausto Amidei (1761) (Fig. 1a). The palace was built by the architect Bartolomeo Ammannati and was located in the corner between the street *dei Servi* and the square *Santissima Annunziata*.

The Grifoni palace had a big private garden with a loggia, as shown in a map by Stefano Buonsignori (1584) (Fig. 1b and Fig. ESM3), so the most likely location of the thermometer was at ground floor under the loggia, in a position sheltered from rain, following the authoritative example of the Medici Network in Florence. The loggia was convenient because the thermometers built in the first half of the eighteenth century had the glassware fixed with an iron wire to a wooden tablet and could not be exposed to rain, e.g., outside a window

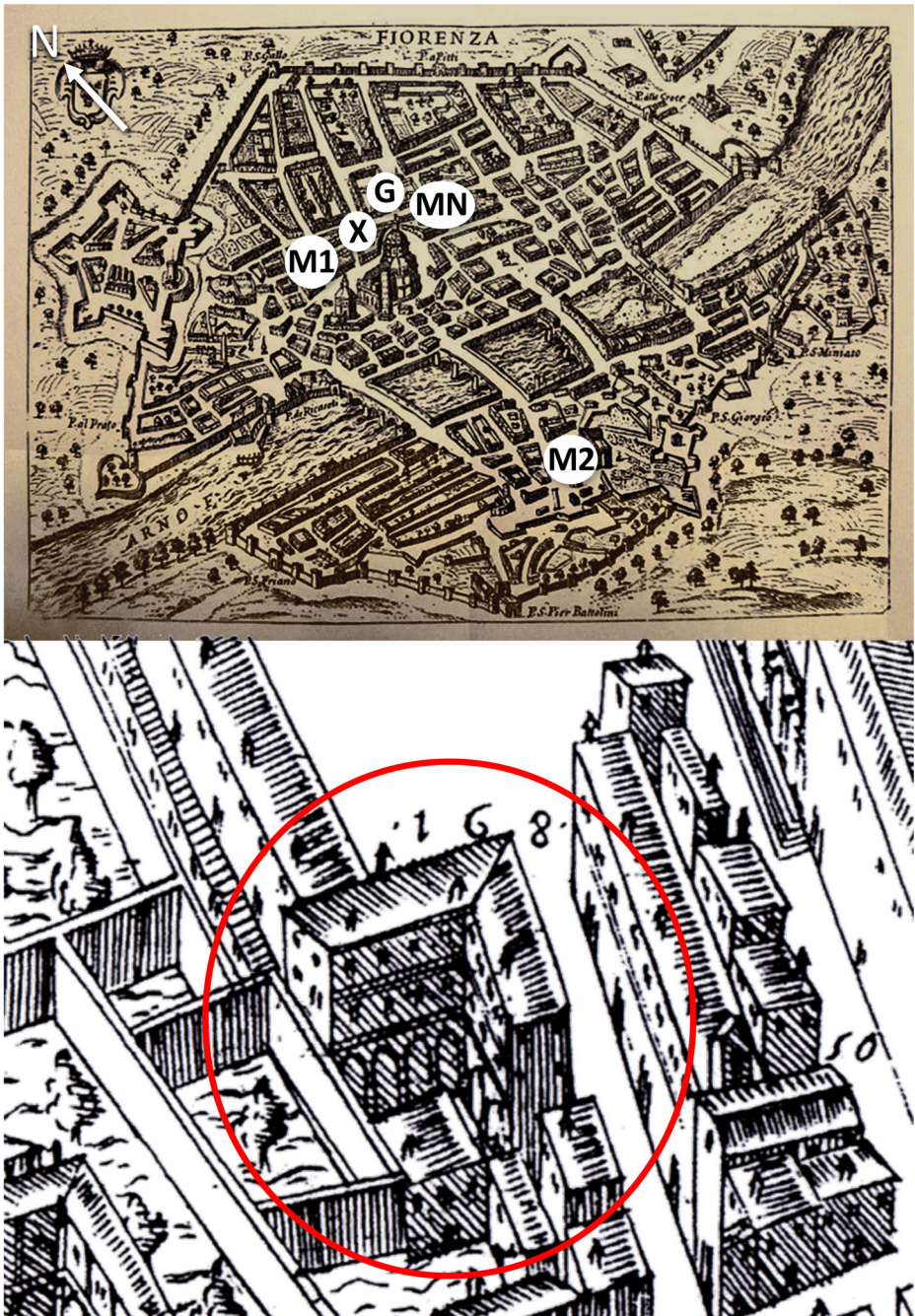


Fig. 1 **a** The cited locations of the Florentine observations in a contemporary map of Florence by Amidei (1761). MN, Medici Network; G, Grifoni; X, Ximenes; M1 Martini in Ginori Street; M2 Martini in Pitti Square. **b** Grifoni palace with internal garden and loggia as it was originally (Buonsignori 1584)

(Camuffo and Bertolin 2012a, b; Camuffo 2019). In addition, it was more comfortable to take readings in bad weather conditions. The selected site had excellent ventilation as evidenced by the large day-by-day temperature variability (Fig. ESM4ab), reconstructed as explained in Section 4.3.

The only information reported by Guadagni (1767) is that the thermometer was Réaumur, exposed to “open air”, that should be interpreted for outside, in contrast with “in a room,” facing north (Fig. ESM5). According to Middleton (1971), thermometer screens started to be applied in 1835. The well-known summer temperature bias due to thermometers insufficiently shielded or hung on north-facing windows where the solar radiation could arrive in summer, was frequent in the period prior to 1850–1870, but not everywhere (Moberg et al. 2003; Frank et al. 2007; Böhm et al. 2010; Luterbacher et al. 2016). In the network of the *Societas Meteorologica Palatina*, Mannheim, thermometers were exposed in the shade, away from the building walls (Hemmer 1783). In Italy the situation was better. For instance, in 1770, Toaldo applied a cardboard to shield his thermometer exposed outside a north facing wall of the astronomical tower (Camuffo 2002a). In the Medici Network (1654–1670) thermometers were exposed 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 thermometer of this network in Florence was exposed to north, inside a loggia of the Convent of *S. Maria degli Angeli* where the solar radiation was completely intercepted over the whole year (Camuffo and Bertolin 2012a). For the specific case of Grifoni, the intensity of the radiation reaching a north facing wall has been calculated (ESM2.5) for the summer solstice, when the Sun is nearest to the northern sector and reaches the highest elevation above the horizon (Fig. ESM6). In the most critical day of the year, Grifoni observed 1 h after the sun had disappeared and the bias for an unshielded thermometer was minimal.

3.2 Reading time

Grifoni took readings 3 h before noon, i.e., 9 a.m. It was normal that meteorological readings were taken once or a few times a day, because this was considered something in addition to the normal activity of the observer. It was known that the minimum temperature was near sunrise and the maximum in the early afternoon (Jurin 1723), and the concept of mean was strictly related to the Aristotle’s median, i.e., the middle position between the maximum and the minimum values.

Therefore, readings taken at 9 a.m. were considered highly representative of the daily average. In the next century, investigations were made to establish the most representative reading time. As a result of careful investigations in several geographic localities, it was established that the readings taken around 8 or 9 a.m., depending on the location, closely approached the mean daily temperature and it was recommended to take only one observation a day at this specific time (Brewster 1826; Pécelet 1838; Arago 1858). Several series of the nineteenth century were based on this recommendation. The departure for Padua has been evaluated elsewhere (Camuffo 2002b). Nowadays this method is not acceptable, but the Grifoni choice may be considered a good start that requires a small correction to calculate the daily average.

The real problem was not the choice of the hour, but how it was measured. In the eighteenth century the quality of mechanical clocks was quite low and the recommendation was “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 1770). The clock was regulated every

day with the culmination (i.e., the passage of the sun across the local meridian), but this was impossible when the sky was overcast; therefore, this caused a severe uncertainty in the time scheduled for readings, especially those in the morning that were the most distant from the previous calibration. An alternative was the use of a sundial based on the gnomon shadow, but this method too had a poor resolution and it was impossible to use in case of overcast sky. As a consequence, the time reference was affected by uncertainty that was added to the time uncertainty introduced by the observer that might have done his reading at any time around the scheduled one. In conclusion, time uncertainties of the order of 30' should not be considered exceptional.

A further problem was that in the eighteenth century the time was regulated on the apparent solar motion and the day duration changed some minutes during the calendar year, while today the average time measured with precise clocks is considered. This may introduce a bias when early and modern data are compared. However, this is a minor problem, as the difference is of the order of magnitude of some minutes, as discussed later.

3.3 Grifoni log

Grifoni published his logs in Italian and each page contains the observations related to 4 months, organized in 5 columns (Fig. ESM5). The first column reported the day of the month, and the other four ones the temperatures recorded in the same day of 4 subsequent months. Readings were reported with 0.25 °R (i.e., 0.31 °C) resolution. Decimal places were represented with dots, each dot indicating one quarter of degree. The freezing point was indicated “oo” and negative values were preceded by an asterisk “*” instead of the minus sign. Some symbols were added to indicate the weather and other phenomena in Florence, e.g., snow (N, *neve* in Italian), hail (G, *grandine*), thunder (T, *tuono*), and earthquake (Tr, *Tremoto*, old word for *Terremoto*). Only 485 days over 15 years are missing, i.e., about the 8% of the total.

4 The Réaumur thermometer

Guadagni (1767) wrote that Grifoni used a Réaumur thermometer without further specification. The original Réaumur thermometer (Réaumur 1730, 1731) was built and calibrated filling with spirit of wine (WS) the bulb and part of the tube up to the zero level, and then adding equal amounts of WS to mark the scale. The calibration was based on a single fixed point, i.e., the freezing point of water, and the addition of known volumes of spirit under isothermal conditions, added with small phials (Fig. ESM7). Réaumur found that the response was determined by the purity of alcohol, i.e., the mixture between spirit (ethyl alcohol) and water, and this was recognizable from the boiling temperature at which the WS boiled that was around 78 °C depending on the proportion of water diluted in the spirit.

In the early 1730s, Réaumur and his assistant Jean Antoine Nollet built a few such thermometers. As several types of scales were adopted over time (Du Crest 1765; Nollet 1770; De Luc 1772; Martine 1772; Cotte 1774; Toaldo 1775; van Swinden 1778; Gausson 1789; Wildt 1825; Birembaut 1958; Middleton 1971; Talas 2002; Chang 2004; Gauvin 2012; Brugnara et al. 2020), the following sections are devoted to identify the instrument used by Grifoni. Informal identification labels will be added to distinguish scales characterized by the lower or the upper calibration point (i.e., R_F related to freezing ice and R_M to melting ice), the thermometric liquid (i.e., R_{WS} , R_{Hg} related to WS or mercury), or other features.

4.1 The upper calibration point

The original 1730 scale (called “true Réaumur” R_T) was based on the observation that the volume of the thermometric liquid increased by 80/1000 between freezing water (considered $0\text{ }^\circ R_T$) and boiling spirit (considered $80\text{ }^\circ R_T$). Therefore, Réaumur divided this interval into 80 equal parts to obtain the scale. Considering that spirit boils at $78.4\text{ }^\circ\text{C}$, i.e., $80\text{ }^\circ R_T$, this scale is similar to Celsius, with $-3.5\text{ }^\circ\text{C}$ departure in summer and $\pm 1\text{ }^\circ\text{C}$ in winter (Fig. [ESM8](#), Fig. [ESM9](#)) and the point of boiling water at $100.4\text{ }^\circ R_T$ (De Luc [1772](#); Toaldo [1775](#); Van Swinden [1778](#)). However, in the Réaumur experiments, the boiling point of WS was neither easily detectable nor constant because he operated with an open tube and the boiling point depended on the purity of the WS and the atmospheric pressure. In some cases, personalized scales were introduced to account for the peculiar alcoholic degree of WS, e.g., $82\text{ }^\circ R$ (Van Swinden [1778](#)), $85\text{ }^\circ R$ (Messier [1779](#)), and $87\text{ }^\circ R$ (De Sauvage [1778](#)).

Following Fahrenheit ([1724](#)), some intermediate reference points were added to complete calibration, i.e., a cold mixture of ice with marine salt or ammonium chloride, and the body temperature; in addition, he added the temperature of the caves of the Meteorological Observatory, Paris, inspired by La Hire (Réaumur [1730](#); De Luc [1772](#); Van Swinden [1778](#); Gaussen [1789](#)).

Later, following the popular tradition after Huygens ([1665](#)), Renaldini ([1694](#)), and Amontons ([1702](#)), the upper point $80\text{ }^\circ R$ was referred to boiling water. However, the atmospheric pressure affected the boiling point of water: weather contributed for $\pm 0.5\text{ }^\circ\text{C}$; the mountain elevation (e.g., Switzerland) lowered the boiling point, around $-1\text{ }^\circ\text{C}$ every 300-m altitude.

4.2 The lower calibration point

In the earliest Réaumur thermometers, till 1732, the lower calibration point was the freezing point of artificial ice obtained with a mixture of salts (Réaumur [1730](#)). Calibration became possible even in the warm season, but was imprecise. Nollet built several thermometers with scale starting from the freezing point $0\text{ }^\circ R_F$, and they were called “true Réaumur” (not to be confused with the previous “true” R_T). De Luc found that the freezing point $0\text{ }^\circ R_F$ was below the melting point $0.8\text{ }^\circ R_F$ (De Luc [1772](#)). In theory, the equilibrium between the liquid and the solid phases of water is a well-determined point, but with the early technology it was difficult to ascertain when ice crystals started to form or when ice started to melt, and this required a certain temperature difference.

The interval between the freezing point ($0\text{ }^\circ R_F = -1\text{ }^\circ\text{C}$) and boiling water ($80\text{ }^\circ R_F = 100\text{ }^\circ\text{C}$) was divided into $80\text{ }^\circ R_F$, with $1\text{ }^\circ R_F = 1.2625\text{ }^\circ\text{C}$ (De Luc [1772](#); Gaussen [1789](#); Avogadro [1840](#)). The conversion from this scale to Celsius is:

$$Y(^{\circ}\text{C}) = \frac{101}{80} X(^{\circ}R_F) - 1 \quad (1)$$

In 1732, Nollet persuaded Réaumur to adopt as the ice melting point ($0\text{ }^\circ R_M = 0\text{ }^\circ\text{C} = +0.8\text{ }^\circ R_F$) obtained from natural ice or snow that was more stable (Abbe [1888](#)). The interval between $0\text{ }^\circ R_M$ and boiling water ($80\text{ }^\circ R_M = 100\text{ }^\circ\text{C}$) was divided into $80\text{ }^\circ R_M$, with $1\text{ }^\circ R_M = 1.25\text{ }^\circ\text{C}$. This scale had the further advantage that the conversion to Celsius was easy, being based on a simple proportionality factor:

$$Y(^{\circ}C) = \frac{100}{80}X(^{\circ}R_M) \quad (2)$$

and soon became the official Réaumur scale (Du Crest 1741) (Fig. ESM10).

Unfortunately, the complex development of this thermometer generated confusion, except when the conversion factor was indicated. The difference between R_F and the traditional R_M was more perceptible in winter (e.g., $-1^{\circ}C$ difference at $0^{\circ}C$), less in summer (e.g., $-0.5^{\circ}C$ difference at $30^{\circ}C$). However, depending on calibration accuracy, this difference was often reduced or even tended to disappear.

4.3 The thermometric liquid

A key problem is that Réaumur recommended to use WS and this liquid departs from linearity, while mercury very little. Indicating R_{WS} the readings on a thermometer using WS and R_{Hg} those on one using mercury, calibrated in the same way, the R_{WS} and R_{Hg} values were similar near the calibration points, but in general they differed between them, especially in summer. The departure varied with the dilution of water in ethyl alcohol (Du Crest 1741, 1765; De Luc 1772; Gausson 1789; Wildt 1825). In summer, the departure could reach $4\text{--}5^{\circ}C$ or even more (Camuffo and della Valle 2016, ESM 4.3).

Some WS thermometers were calibrated to provide the same readings as mercury, i.e., $R_{WS} = R_{Hg}$. The method consisted in dipping in the same bath the WS that needed calibration and the reference mercury thermometer. The bath was initially filled with hot water and was left to cool slowly, thus reporting on the WS scale the readings of the mercury thermometer (Toaldo 1775). With this procedure, all spirit thermometers became comparable between them, as well as with the mercury thermometers (Fig. ESM12), and this method was continued for a century (Ganot 1860).

In 1740 Réaumur ceased to improve thermometers (Birembaut 1958). The name Réaumur became a brand, and indicated thermometers, either WS or Hg, calibrated at melting ice, boiling water, and without linearity distortion. Mercury thermometers were largely dominant and only a few scientists used WS, possibly calibrated with mercury.

5 Data analysis

5.1 Thermometers used in Italy

The thermometer used by Grifoni was simply defined “Réaumur” that means that this definition was perfectly understandable by the contemporaries; i.e., it was the thermometer most popularly used by Italian scientists at that time. The most renowned observers of the eighteenth century and their instruments are listed in Table 1, showing that the glorious Florentine thermometer was running out of time and the new century started with innovative air thermometers, i.e., Amontons and Stancari. Réaumur thermometers appeared in 1740 and continued to be largely dominant for a century and a half.

All Réaumur thermometers in Italy were calibrated with ice ($0^{\circ}R$) and boiling water ($80^{\circ}R$). The specification either freezing or melting ice (R_F or R_M) was generally missing. The exact attribution is uncertain, but it might be recognized with the snow benchmark (Section 5.2). Grifoni bought or built his thermometer in 1750, 10 years after Morgagni and

Table 1 The most renowned observers of the eighteenth century and their thermometers

Date	Site	Observer	Thermometer	Reference
1715–1737	Bologna	Beccari and Galeazzi	2 Stancari	Camuffo and della Valle 2016
1723–1765	Bologna	Beccari	2 Florence	Camuffo et al. 2017a
1725–1764	Padua	Poleni	Amontons	Camuffo 2002a
1727–1732	Naples	Cyrillus	Hauksbee	Cyrillus 1734
1740–1768	Padua	Morgagni	2 R_{Hg}	Camuffo 2002a
1741–1765	Bologna	Beccari	2 R_{Hg}	Camuffo et al. 2017a
1751–1766	Florence	Grifoni	R_7	Guadagni 1767
1752–1757	Florence	Ximenes	2 R_{Hg}	Ximenes 1757
1756–1793	Turin	Somis	R_7	Somis 1758
1755–1764	Venice	Temanza	Amontons	Toaldo 1770
1756–1775	Florence	Martini	$R_{Hg} + R_{WS}$	Targioni-Tozzetti 1767
1763–1799	Milan	La Grange, Reggio and Cesaris	R_{Hg}	Cesaris 1820; Maugeri et al. 2002
1766–1799	Padua	Toaldo and Chiminello	R_{Hg}	Camuffo 2002a
1764–1767	Venice	Pollaroli	Scale R_7 and Fahrenheit	Pollaroli 1764
1776–1774	Bologna	Galli Bibiena	3 R_{Hg}	Camuffo et al. 2017a
1769–1775	Pisa	Tilli	R_{WS}	Tilli 1776
1782–1784	Bologna	Matteucci	2 R_{Hg}	Camuffo et al. 2017a
1782–1799	Bologna	Ranuzzi-Cospi	R_{WS}	Camuffo et al. 2017a
1782–1799	Rome	Calandrelli & Conti	R_{Hg}	Calandrelli and Conti 1803; Colacino and Rovelli 1983
1789–1799	Turin	Vassalli-Eandi	R_{Hg}	Vassalli-Eandi 1815
1794	Florence	Bicchierai	Fahrenheit	Bicchierai 1795

R_{Hg} , Réaumur mercury; R_{WS} , Réaumur WS; R_7 , Réaumur without specification

Beccari, and in the same period of Ximenes. As metadata are not sufficient to clarify the thermometric liquid and calibration, it is necessary to test all possibilities, as in the next sections.

5.2 The snow benchmark

Snowflakes are constituted of ice crystals that may be a useful benchmark to recognize whether Grifoni used the R_M or R_F scale, and/or to verify if readings were compatible with the presence of snow. If a few exceptions are found, one might consider that Grifoni reported the temperature at 9 a.m. and added the note of snow, but without specifying whether it was snowing at that moment, or if it snowed during the night when the temperature was lower. Again, the note “snow” might have referred to the appearance of white-capped mountains, as Florence lies on the foot of the Apennine Chain, or to the falling of some snowflakes in Florence, but that had melted away quickly. As opposed, if in the snow days the temperature was systematically too high, this may be an index of a bias, either related to the thermometer or its exposure. For instance, the thermometer was hung with a nail to a wall, in contact with it, and the wall had a temperature higher than the free air, especially for the protection of the loggia. In addition, the Grifoni palace was located in the city center that may have been affected by the urban heat island (Petralli et al. 2011).

Snowflakes are expected to fall at temperatures below the ice melting point, except in dry air conditions, when the latent heat released for sublimation (that equals to the sum of the latent

heats of fusion and of vaporization) keeps the snowflake at the freezing point. Therefore, snow might fall at above freezing temperature, the value of the excess temperature depending on the relative humidity (RH). Direct observations and theoretical calculations have determined two combined T-RH thresholds topping the area of the snow domain (i.e., snowflakes only), a mostly-snow transition band, followed by a rain domain (i.e., only water drops) (Matsuo and Sasyo 1980, 1981; Camuffo 2019). The snow benchmark was used to verify the temperature records in Padua and Bologna during the eighteenth century (Camuffo 2002c; Camuffo et al. 2017a). A likely hypothesis for this climatic region is that in the snow days RH was generally higher than 70–75%, which implies a temperature not higher than 2.5 °C. The Grifoni data were compared with the temperatures associated to the reference value RH = 65%, considering that the precipitation may have occurred before the reading, and in the meantime the temperature could have risen, lowering RH.

If the scale was R_M (Fig. 2a), 14 snow cases out of 30 (i.e., 47%) occurred in days with too high temperature and should fall in the rain or transition domain. If the scale was R_F (Fig. 2b), only 6 cases (i.e., 20%) exceed the snow domain, but 4 of them are in the mostly snow transition domain and only 2 reach 4 °C in the rain domain, which implies that RH should be around 50% to be compatible with snow.

The snow benchmark test suggests two conclusions: (i) the scale was closer to R_F ; (ii) in winter, there was a small inconsistency between snowfall and *loggia* microclimate. Likely, the thermometer response was due to a combination of an imprecise calibration and microclimate distortion. The conversion was made with equation (1) that minimizes the overall bias. If the readings are further lowered by 0.5 °C, all the snow day temperatures become consistent.

5.3 Reconstruction of daily average temperatures

The first step was to calculate the departure between the apparent solar time (AST) in Florence, as measured with a sundial or the culmination of the sun, and the average time measured with a clock, referred as Central European Time (CET). This involves two contributions (ESM4). The first is the so-called equation of time that represents the astronomical effect of the eccentricity of the Earth orbit and the obliquity of the ecliptic; as a result, the Sun is behind by 14 min 6 s (around February 11) and ahead by 16 min 33 s (around November 3). Next, the longitude of Florence 11° 14' 46" (min and sec of arc) East, implies – 15 min (of time) in comparison with the First Meridian taken as reference for Central Europe.

For every day j of the calendar year, the time departure $CET-AST = \Delta t_j$ has been calculated in order to pass from 9 AST to 9 CET = 9 AST + Δt_j (Fig. ESM13). Then, for every day j , the difference of temperature $\Delta T_{j,CET-AST}$ between these two particular times (i.e., 9 CET and 9 AST) has been evaluated for the records of Florence in the 1961–1990 reference period (Fig. 3a). As the Grifoni clock might have had 30 min uncertainty in the determination of sampling time (see Section 3.2), the band of error related to this difference in the modern data has been evaluated considering that the readings might have been performed between 8 h 30 min and 9 h 30 min. The former gives underestimation; the latter overestimation.

The average correction of the bias for the AST time reference (Fig. 3a, black dots) was + 0.3 °C; in the rainy period from October to December the bias was null; the maximum bias was reached in summer, in the turn between July and August, i.e., up to 0.7 °C. These results are consistent with the calculations made for Padua (Camuffo 2002b).

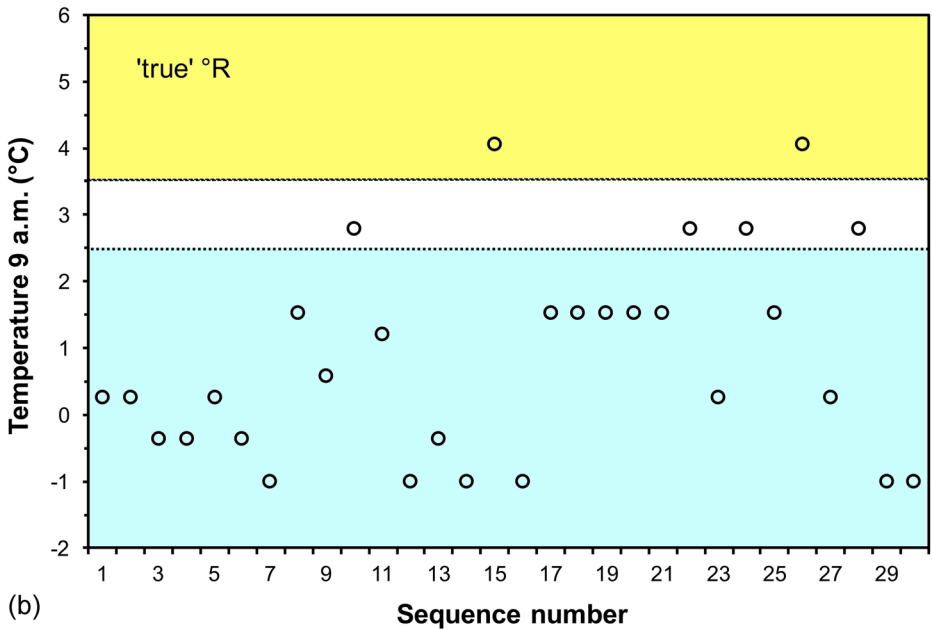
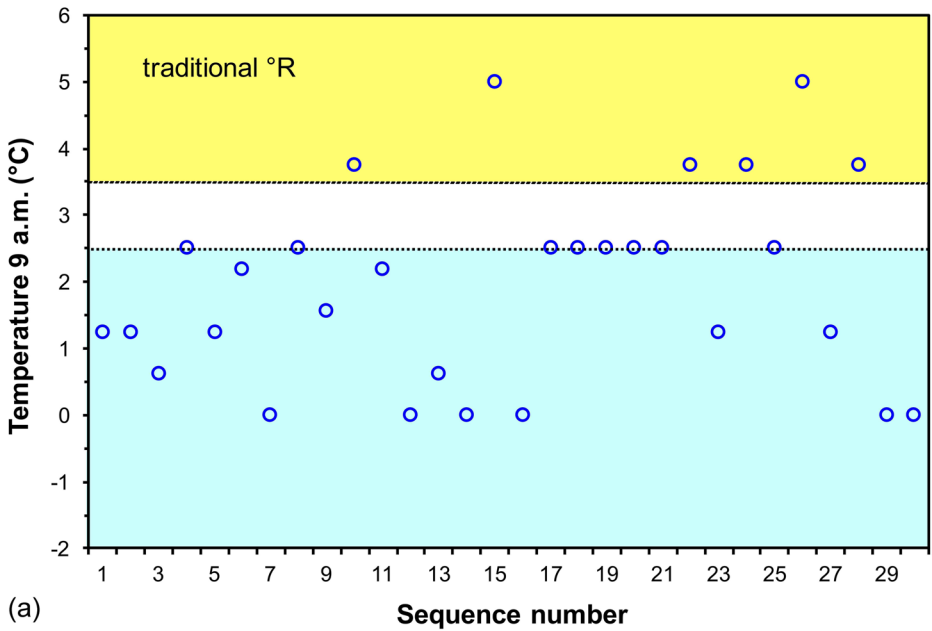


Fig. 2 **a** Temperature readings at 9 a.m. AST in snow days in Florence for the period 1751–1766 under the hypothesis of a R_M scale; **b** the same but for R_F scale. Cyan area: snow domain; white: mostly snow transition; yellow: rain domain calculated for $RH=65\%$

The bias for the clock uncertainty was high when Grifoni made delayed readings (Fig. 3a, red dots) and a little smaller for earlier ones (Fig. 3a, blue dots). However, as the uncertainty in the time determination made equally probable earlier and delayed

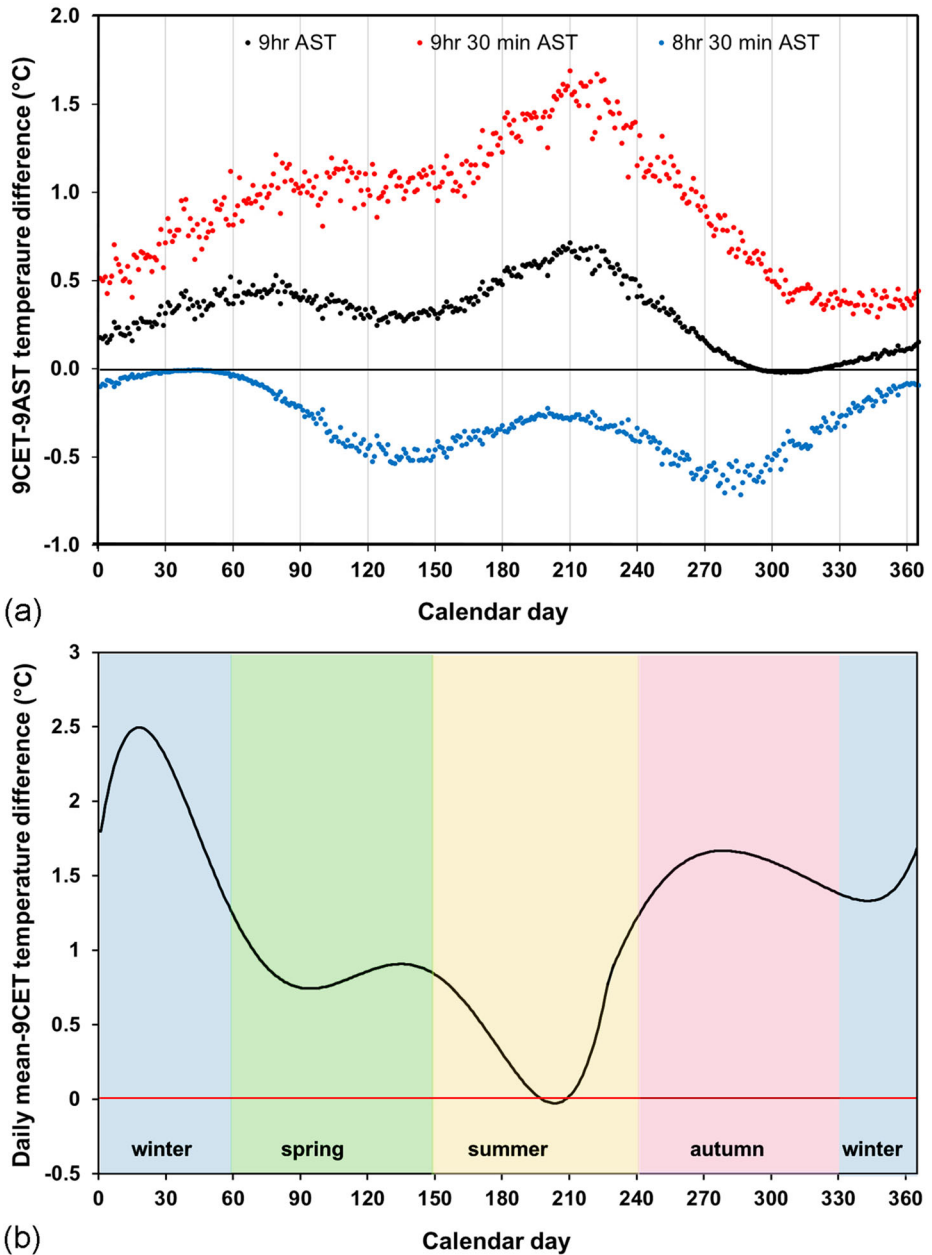


Fig. 3 **a** Bias for the AST and CET time reference. Mean temperature difference calculated over the calendar year between readings taken at 9 CET (modern clock) and 9 AST (Grifoni with sundial) in Florence (black dots) for the reference period 1961–1990. Red dots: reading at 9 h 30 min AST; blue dots: reading at 8 h 30 min AST. **b** Difference between the average daily temperature and the temperature at 9 CET over the calendar year for the reference period 1961–1990

readings, the combination of the random departures tends to compensate each other at monthly or yearly level and vanishes the bias.

Once the original dataset was corrected for the bias due to the AST time reference and then transformed in CET time reference, for every day j the difference between the mean daily temperature and the temperature read at 9 CET, i.e., $\Delta T_{j,mean-9CET} = T_{j,mean} - T_{j,9CET}$, was calculated (Fig. 3b). This calculation has been made with the reference dataset of Florence (1961–1990).

The average correction is small, around 1 °C, with the maximum departure in January and the minimum one in summer, with almost no correction in the turn between July and August. The small value of this correction indicated that Grifoni made a good choice of sampling time, quite representative of the daily mean; in addition, if the correction is small, the bias for the correction is even smaller.

In practice, the mean daily temperature of the calendar day j of the year y ($T_{j,y}$) has been obtained from the original Grifoni reading of the same day ($T_{j,y,AST}$) with the equation:

$$T_{j,y} = T_{j,y,AST} + \Delta T_{j,CET-AST} + \Delta T_{j,mean-9CET}$$

that corresponds to the algebraic sum of the values reported in the plots of Fig. 3a, b.

The daily mean temperatures calculated for every calendar day j (1–365) and for every year y (1751–1766) are reported in Fig. 4.

5.4 Comparison with Ximenes

Ximenes (1753) did not mention the scale in which his readings were expressed and the only logical explanation is that it was not necessary. In addition, Ximenes (1753) did not specify whether the thermometric liquid was mercury or wine spirit. A few years later, Ximenes (1757) published a book about astronomical observations and instruments with the indication of the air temperature during his tests and specified that he had two Réaumur thermometers, both of mercury.

The thermometer could have been exposed either outdoors or indoors. It is not easy to guess because Poleni in Padua (Camuffo 2002a), Beccari in Bologna (Camuffo et al. 2017a) and the

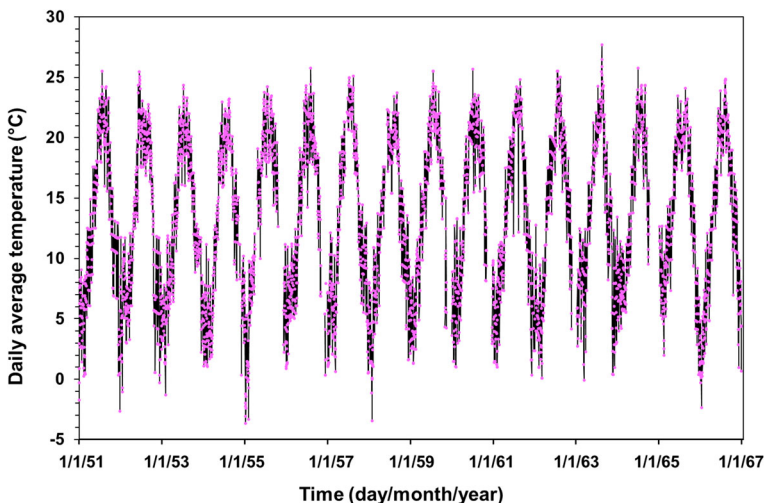


Fig. 4 Daily temperatures reconstructed after the Grifoni record

whole Network of the Royal Society, London (Jurin 1723), measured indoors; Morgagni in Padua (Camuffo 2002a), Grifoni and Martini in Florence measured both indoors and outdoors.

Comparing the records of Ximenes and Grifoni (Fig. 5), Ximenes readings follow the positive peaks of the fluctuations of the Grifoni record and show a slightly higher temperature over the year, with largest departure in the cold season. This may be consistent with a room heated in winter, possibly with walls and roof exposed to solar radiation, e.g., the astronomical turret on the roof of the building, or a room of the top floor, that was surely warmer than the Grifoni loggia. A likely location was the astronomical turret on the roof of the building, or a room of the top floor of the convent, and Ximenes (1757) reports that a thermometer was normally kept in the Chapel of the Holy Cross.

The departure from the Grifoni and the Ximenes readings in winter suggests that the bias for indoor heating is around 5 °C. If this bias is removed to the Ximenes record, the winter minimum is lowered, passing from 9 to 4 °C and the range of the yearly cycle becomes 18.5 °C, close to the 1961–1990 reference period, i.e., 18.3 °C.

Ximenes temperature readings are affected by severe bias, especially in winter, and cannot be used for quantitative climate analysis. Indeed, Ximenes (1753) wrote that he observed for a number of years, but stopped publishing because nobody was interested to his records. As opposed, the meteorological tables published by Grifoni and Martini were highly considered by their contemporaries.

5.5 Comparison with Bologna and climate change

The monthly temperatures in Florence and Bologna (Camuffo et al. 2017a) have been compared in the common period 1751–1766 (Fig. 6, Fig. ESM14) as well as in other reference periods distributed over time (Fig. 6). In Florence, it has been possible to add the early period 1654–1670 (Camuffo and Bertolin 2012a) to get an overview over a longer time span.

The comparison between Florence and Bologna (Fig. 6a) shows that, in the eighteenth century, from April to September, the two cities had similar temperatures, but departed in the cold season, with maximum in January, when Florence was some 4 °C milder. The same

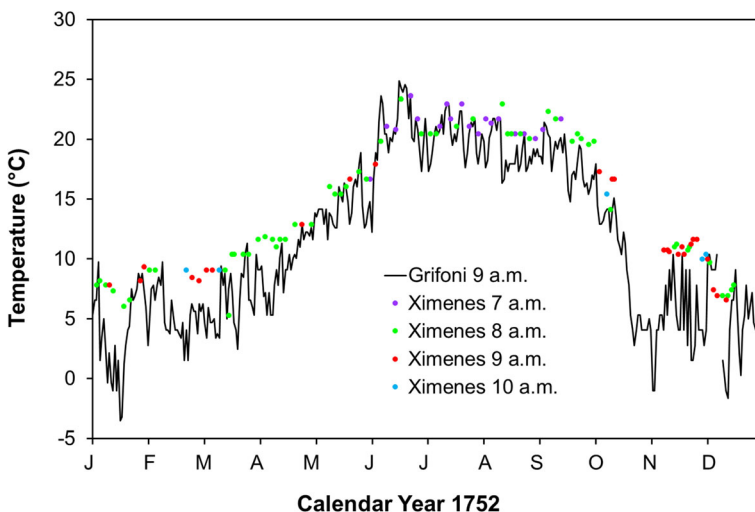


Fig. 5 Comparison of Ximenes and Grifoni readings for the year 1752

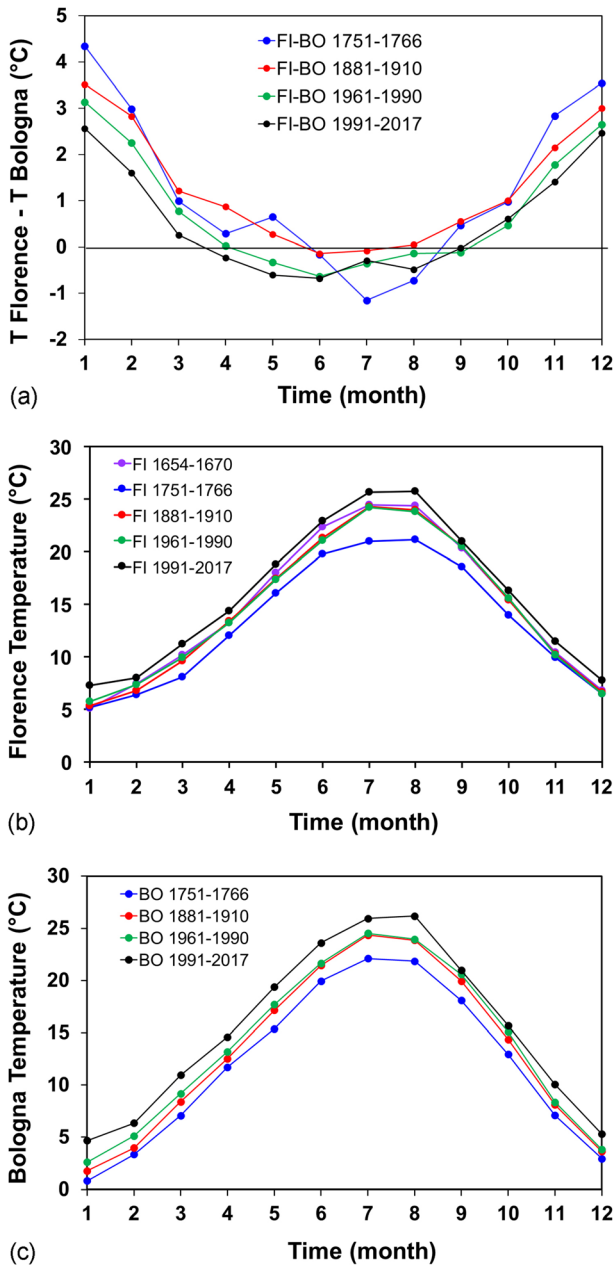


Fig. 6 **a** Difference between the monthly temperatures in Florence and Bologna 1751–1766, 1881–1910, 1961–1990, and 1991–2017; **b** monthly temperatures in Florence in 1654–1670, 1751–1766, 1881–1910, 1961–1990, and 1991–2017; **c** monthly temperatures in Bologna in 1751–1766, 1881–1910, 1961–1990, and 1991–2017

comparison for the periods 1881–1910, 1961–1990, and 1991–2017 shows a similar behavior, but the winter difference is gradually reduced over time. These periods show more regular trends for being obtained considering twice the number of years, i.e., 30 instead of 15. One might suspect that the differences in the eighteenth century might be due to an unknown bias

affecting either Florence or Bologna, or both. The separate analysis of the two cities may clarify if it is a climate signal (i.e., same behavior in two independent stations) or it is due to other issues.

In Florence (Fig. 6b), the temperature in 1751–1766 was a few degrees lower, especially in summer. In 1654–1670, 1881–1910, and 1961–1990, the related monthly values were very similar between them. In 1991–2017 the temperature was slightly higher throughout the year. In winter, the difference between the various periods is very small. The Grifoni record suggests that in the middle of the eighteenth century the warm season was characterized by perturbed weather. The fact that Grifoni summer temperatures were the lowest ones is a further confirmation that they were not affected by overheating for unshielded thermometer.

The temperature in Bologna (Fig. 6c) had the same behavior, showing a marked increase from 1751–1766 to 1881–1910, a very small winter increase and a stationary summer level compared with 1961–1990, and a marked increase to 1991–2017.

Bologna and Florence are two independent datasets and both show the same behavior over time. Therefore, the perturbed summer weather in the middle of the eighteenth century is a climate signal, being present in both the datasets. The particular cold of the eighteenth century has been confirmed by the long series of Padua and Bologna (Camuffo and Bertolin 2012c; Camuffo et al. 2017a), as well as of Venice, where the lagoon was frozen over with unparalleled frequency (Camuffo et al. 2017b). Both series show a marked warming in the most recent decades.

5.6 Uncertainties affecting the Grifoni series

The time departure passing from AST to CET, as well as the contribution due to the geographical location of Florence with reference to the First Meridian, was exactly calculated with astronomical equations. The average value of the correction to transform temperature readings from 9 AST to 9 CET is ± 0.3 °C. Even in the case that a large relative error is prudentially assumed, e.g., 30% of the value, the uncertainty is < 0.1 °C.

Grifoni specified the reading hours without minutes. This suggests that the precision of his clock (either mechanical or sundial) was quite low. Consequently, the sampling time declared by Grifoni should be intended ± 30 min. The temperature bias for reading 30 min earlier or later ranges from 0.5 °C in winter to 1.3 °C in summer. Under the above prudential assumption, the uncertainty is < 0.4 °C. However, this bias is randomly distributed; its impact on monthly averages is strongly reduced and is irrelevant for climate conclusions over the 15-year period.

The average correction due for the transformation from the temperature at 9 CET to the daily average is around 1 °C. Under the same assumption, the uncertainty is < 0.3 °C. At daily level the bias may be relevant; however, it is randomly distributed and its impact on monthly averages and climate conclusions is irrelevant.

The initial uncertainty related to the thermometer, whether the liquid was mercury or wine spirit, affects especially the summer temperature, as discussed in the text and [ESM](#). However, once the thermometric liquid has been recognized, this uncertainty drops.

Another initial uncertainty was related to the type of Réaumur scale, i.e., R_M or R_F . The difference ranges between 1 °C in winter and 0.5 °C in summer. The snow benchmark was an objective element that allowed to identify the scale and avoid this bias.

The thermometer exposure and the representativeness of the location still constitute a source of uncertainty. The tests based on the day-by-day variability have shown that the

exposure site was well ventilated, and the model to calculate the solar radiation impinging on a north-facing wall has shown that there was no bias in case of unshielded thermometer. The snow benchmark suggests that in winter the loggia microclimate could have been 0.5 °C milder than the free outdoor air. However, this correction cannot be objectively demonstrated; therefore, it was not applied.

The comparison with the parallel series in Bologna has not revealed biases.

6 Conclusions

Instrumental records of the eighteenth century are very rare and extremely important to determine the climate in one of the most crucial periods of the Little Ice Age. They need, however, a careful work of correction and validation to be transformed into an accurate series, like the modern standards, correcting them for a number of biases determined by the particular choice of the sampling time, instrumental scale, departures from linearity, exposure in urban environment, and other problems. This study constitutes a methodological example on how to identify, evaluate, and manage uncertainties related to early series, that are frequently mentioned, but rarely addressed and solved in the literature.

Our research has shown that the Réaumur thermometer, especially the mercury type, has become largely popular in Italy since 1740, and continued to be the dominant one even in the next century.

The temperature record taken by Ximenes in 1752 has been recognized to have missed two-thirds of the days, to be indoors and in a heated room. Therefore, it is of no particular interest.

This study has recovered, corrected, and analyzed the 1751–1766 Grifoni series, the first available record in Florence after the Medici Network. The reconstruction work has included the calculation and application of the astronomical correction to pass from AST to CET time, as well as the evaluation of the incoming solar radiation and the potential bias due to an unshielded thermometer. The snow benchmark has been useful to recognize the thermometer scale and liquid. The latter was supported by the comparison with other contemporary observations in Florence, i.e., Ximenes and Martini, that were not so accurate to provide other climate records, but sufficient to make a choice between two hypotheses.

The comparison between representative observation periods in Florence in 1654–1670, 1751–1766, 1881–1910, 1961–1990, and 1991–2017 has shown that the mid-eighteenth century was generally colder, and in particular the warm season was characterized by perturbed weather. The temperature in the periods 1881–1910 and 1961–1990 resulted very similar, while the most recent decades were affected by global warming. These results are consistent with Kumar et al. (2005). The comparison with the contemporary part of the Bologna series that started in 1715 has confirmed the above results.

The whole dataset has been made available in [ESM](#) to allow further use of this series for scientific purposes.

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