Climatic Change
https://doi.org/10.1007/s10584-019-02482-x

The Beccari series of precipitation in Bologna, Italy, from 1723 to 1765

Dario Camuffo[1] · Francesca Becherini[1] · Antonio della Valle[1,2]

Received: 14 March 2019 / Accepted: 18 June 2019/Published online: 03 July 2019

Abstract
The precipitation record taken by J.B. Beccari in Bologna from 1723 to 1765, with three observations a day, has been recovered from the original Logs and analysed. Although metadata are scarce or even missing, a thorough investigation of the contemporary sources, the interactions between Beccari, his colleagues in Padua, and the Royal Society London, as well as the record analysis, have allowed reconstruction of most of the information concerning the instrument, its location and exposure, the measuring protocol and units. Daily, monthly and yearly amounts and frequencies, as well as extreme events, have been analysed. The first decade (i.e. 1723–1733) was drier than the 1961–1990 reference period and the subsequent decades wetter. During the calendar year, summer was dryer and October was characterized by a stronger activity of Atlantic perturbations.

Keywords Climate change · Precipitation · Early instrumental measurements · Little Ice Age

1 Introduction

Early meteorological records provide a unique opportunity to document the climate of the last period of the Little Ice Age and merit any effort to be recovered and analysed. At the beginning of the XVIII century, in Bologna, Italy, Jacopo Bartolomeo Beccari (1682–1766) started a long series of observations that he continued till the end of his life. He started in 1715 with temperature and pressure, and in 1723 he added precipitation readings. He left his original writings, constituted by hardly readable daily Logs and few yearly summaries, but metadata (e.g. co-workers, instrument characteristics, location and exposure) are completely missing

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s10584-019-02482-x) contains supplementary material, which is available to authorized users.

✉ Francesca Becherini
f.becherini@isac.cnr.it

[1] National Research Council (CNR), Institute of Atmospheric Sciences and Climate (ISAC), Corso Stati Uniti 4, 35127 Padua, Italy

[2] Secondary School Romano Bruni, Via Fiorazzo 5, 35129 Padua, Italy

although some scattered information may be found in the contemporary documents or deduced from the data analysis. In the 1980s, some researchers of the National Research Council of Italy (CNR) established a long-term programme to recover, even in the absence of a specific financial coverage, the earliest Italian meteorological series at daily resolution. An extensive historical research concerning the main ones was performed, e.g. the Medici Network including Florence and Vallombrosa (1654–1670) (Camuffo and Bertolin 2012a, b), Bologna (1715–today) (Baiada 1986; Comani 1986; Brunetti et al. 2001; Camuffo et al. 2016, 2017), Padua (1725–today) (Camuffo and Jones 2002), Milan (1763–today) (Maugeri et al. 2002) and Rome (1782–today) (Colacino and Rovelli 1983).

As far as Bologna in the XVIII century is concerned, the study of the temperature series has been recently concluded (Camuffo et al. 2016, 2017), but precipitation needed further research. In the accurate historical research made by Baiada (1986), the complete lack of information about instruments, locations and assistant observers was underlined. Ferrario (1840) analysed the first volume of the Logs from 1716 to 1726 and published the monthly values, including precipitation of the period in which it was observed, i.e. 1723–1726. In the 1980s, the precipitation record was recovered by CNR in IBM punch cards, but the data were not validated. Silvia Comani (1986) started to analyse the monthly and yearly totals, but the research was interrupted for lack of funds and the punch cards with the data were deteriorated and dispersed. The yearly totals found by Ferrario and Comani were different, from 3 to 14% (Sect. 3.1 and Electronic Supplementary Material). In order to conclude the study, the Beccari original Logs had to be recovered once again. The new recovery at sub-daily resolution made possible to identify eventual drawbacks in the series and correct them, and to analyse the validated data.

The aim of this paper is to recover and study the 1723–1765 precipitation record by Beccari. The research is divided in two parts: the first is mainly historical and concerns observers, Logs, instruments, exposure and other metadata on the ground of documentary sources and the interpretation of recovered readings; the second is focused on the precipitation data analysis.

The well-checked data are used to investigate daily, monthly and yearly precipitation regimes in that period and to make comparison with the XX century data in order to assess the climate anomaly. The collected data will be the first step to complete as much as possible the Bologna series that at present is available since 1813 (Brunetti et al. 2001).

2 Metadata analysis

2.1 The observer or observers?

Jacopo Bartolomeo Beccari (born 1682, died 1766) (Beccari 1724, 1725 and 1726; Mazzucchelli 1760; Scarselli 1766; Fantuzzi 1782, 1784, 1790) was one of the most leading scientists in Bologna in the first half of the XVIII century. Graduated Doctor of Philosophy and Medicine at the Bologna University in 1704, he became member of the *Accademia degli Inquieti* (Restless-spirit Academy). In 1709, he had lectureships in Logic, and in 1712, he became Professor of Medicine. At the end of 1711, Luigi Ferdinando Marsigli established the Institute and Academy of Sciences and Arts (IASA) that joined the scientific legacy of the *Accademia degli Inquieti* to the Clementine Academy of Fine Arts dedicated to Pope Clemens XI. IASA became operative in 1714 and included several disciplines: Beccari was named head of the Natural Sciences Department with assistant Gusmano Galeazzi, and he was appointed to the chair of Experimental Physics at IASA. In 1724, he was elected President of the Academy of Sciences, Bologna, a position took also in 1735, 1740 and 1750. In 1728, he became member of the Royal Society, London. In 1737, he was named the first Professor of Chemistry at any Italian University (Bologna). In 1740, he became member of the Benedictine Academy, in honour of Pope Benedict XIV. After 40 years of teaching, in 1749, he was named Emeritus Professor and continued teaching at home.

Besides teaching, he carried out a wide scientific activity, mainly in disciplines related to medicine, such as physiology, pathology, dietetics and food science. He is mainly known as the discovery of the gluten in wheat flour. He also performed studies in other fields, such as hydrology, meteorology, chemistry and physics. In particular, he carried out important research on the phosphorescence of body and on the effect of light on silver salts.

Beccari took regular meteorological readings since 1715 and wrote personally his Logs till the very last day of his life, the 18th January 1766 (Electronic Supplementary Material, Fig. ESM.1). This was confirmed by the contemporary sources (Scarselli 1766) and by the worsening of his handwriting with his progressing ageing and illness. Neither Beccari nor the historical sources mention that the meteorological series involved any other observer, except Gusmano Galeazzi who cared the Stancari thermometer readings at IASA. Precipitation was recorded from 1723 to 18 January 1766, forming an unbroken, homogeneous series 43-year long. However, an exception is the period between 9 April and 3 December 1740 when the precipitation was reported with different handwriting, style and unit (see Sect. 2.5). This is the only discontinuity noted, and the conclusion is that Beccari charged another trained person to substitute him for this limited period. After Beccari died, his pupil Francesco Maria Galli Bibiena continued the observations until 1774, but he did not record any precipitation amount.

2.2 Original records

The first Log is for the year 1715 (Camuffo et al. 2017), with the daily readings of temperature and pressure, as well as notes about weather in Bologna by Jacopo Bartolomeo Beccari, and readings of pressure in Florence by his brother Johannes Gualbertus Beccari (Beccari and Beccari 1715). The Log is in Latin and time is in Italian notation (i.e. day starting at twilight). It is kept in the *Archiginnasio* Municipal Library, Bologna. However, it does not include precipitation as well as the subsequent Logs till 1723, when the precipitation record started. To the aim of this study, only the Logs and other documents from 1723 to January 1766 are concerned.

All original Logs, summaries, correspondence and related items from 1716 to 18 January 1766, and the Logs by Galli Bibiena until 1774 are kept in the Library of the Astronomical Observatory, Padua. These documents had been gathered in 1781 by Giuseppe Toaldo, Director of the Astronomical Observatory, Padua. In that period, Toaldo was making similar observations, and charged his colleague Petronio Matteucci, Director of the Astronomical Observatory, Bologna, to seek for and buy the whole series of observations by Beccari and his pupils, that were dispersed among various academicians. The original documents are bound together in volumes with hardcover book form. The Logs with the daily observations were called "*Effemeridi*" (Ephemerides) (Beccari 1716–1766) and gave this name to the whole collection. Particularly useful are three summaries for the years 1724, 1725 and 1726, with extended title "*Observationum meteorologicarum* *compendium anni XXX*" (i.e. Outline of meteorological observations of the year XXX), short name "*Compendia*" (Beccari 1724, 1725 and 1726), that provide an introduction to the observations. Probably, they were conceived to be sent to the Royal Society, London. The 1724 summary contains a precious introduction, with some fundamental information concerning thermometers and barometers, but not the rain gauge. Ephemerides and *Compendia* were handwritten in Latin, that was the official scientific language at that time, but have the appearance of crude drafts, with colloquial style. A problem to be faced is that the Beccari handwriting is hardly readable (Fig. 1), even to his contemporary colleagues as Giuseppe Toaldo witnessed: "I bought at a high price the Beccari observations, collected together in several thick volumes, but written with characters that are difficult to decipher even to a fortune teller" (Toaldo 1788). A general description of the documents has been reported elsewhere (Camuffo et al. 2017), except for precipitation, that requires further specification, as follows.

In 1723, James Jurin, secretary of the Royal Society of Medicine, London, established an international network of meteorological observations (Jurin 1723) and wrote a plea to the most leading scientists to join the Network. In Italy, Beccari in Bologna, Giovanni Poleni in Padua, Carlo Taglini in Pisa and Nicolò Cirillo in Naples adhered to the network; however, only Poleni sent regular observations to the Philosophical Transactions (Poleni 1731, 1738). When Beccari decided to adhere, re-edited in fair copy the draft Logs of the years 1716–1726, following the tabular style in columns used by the Network of the Royal Society. This text too was handwritten, in Latin, one page per month. The columns reported: day of the month, sampling time, barometric pressure, temperature recorded using various thermometers, wind, other weather notes, and precipitation (Electronic Supplementary Material, Fig.ESM.2a,b).

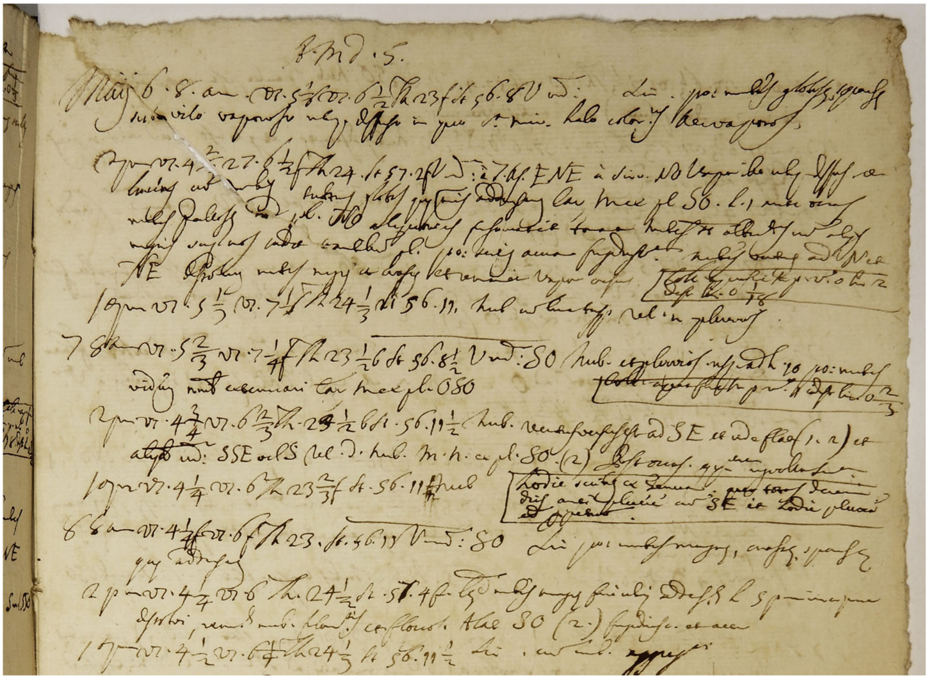

Fig. 1 Detail of the Beccari 1729 handwritten Log. The precipitation is in between the text inside a rectangle

Sometimes, a summary of the previous years was made in tabular form. However, Beccari never sent his weather records. Nonetheless, he had strict contacts with the Royal Society, in 1728, he was appointed member of it and published other works. In the 1723–1726 period, pages are divided into two columns, one with temperature and pressure readings, the other with precipitation and short notes (Electronic Supplementary Material, Fig.ESM.3). Each page reports the indication of year, month, day, reading time (generally at 08:00, 14:00, 22:00 local astronomical time) and observations. The text is written in horizontal paragraphs, and each paragraph reports the observation of 1 day, in running style, not in tabular form, and the different variables are indicated with an abbreviation. The information related to precipitation starts with "*Coll. Aqua*" (*Collecta aqua*, i.e. collected water). The sampling time may change from day to day, e.g. once a day or two/three times a day, depending on the needs or the precipitation intensity, but this is not a problem when the daily amount is calculated. Since 1727, Logs were not re-edited, but were written in columns, following a more ordered structure (Electronic Supplementary Material, Fig.ESM.4). The 1729 Log represents an exception to this rule: the columns disappeared and Beccari returned to the running style with horizontal rows. The precipitation was reported within the text among other things, often in a random position, again indicated with "*Coll. Aqua*" and usually included in a rectangle (Fig. 1). The 1740 Log has the usual structure, but some differences due to the partial contribution of a substitute observer, as mentioned before.

2.3 The instrument

The Log with the daily observations and the yearly summaries do not include descriptions of the instruments used and their location. The explanation should be considered from the cultural point of view of that time. (i) Log and summaries were written for personal use and the author had not to explain to himself what he did. (ii) There was no need to write what was considered obvious. This principle was followed even in the case of publications. An unspecified item means that it was obvious, and/or was in line with the official specifications. (iii) The observers followed the basic idea that they were measuring a certain atmospheric variable, and this was independent of how it was observed, including the instrument and the location. (iv) Last but not least, the observers were leading scientists, and some of them were noblemen too; therefore, there was no doubt that they always applied the best solution, and they had to account for details.

The next step is to determine what could be a "normal" rain gauge and a normal location to the Beccari's eyes, i.e. the reference model.

The key reference was the invitation made by James Jurin (1723) to join the network of the Royal Society, London. As we said (Sect. 2.2), to this invitation adhered both Giovanni Poleni in Padua, who was very diligent and perseverant, and Beccari in Bologna, who made observations and started to put them in good order, but stopped soon and never sent his readings to the Royal Society.

Jurin (1723) recommended to observe the depth of rain, or dissolved snow, at least once a day, and to report the readings in a diary, as follows. The rain gauge should be composed of a collecting vessel, 2 or 3 ft wide. It is not specified whether the funnel section should be a square or a circle. However, the square is more likely because "wide" applies to squares, and "diameter" to circles. The choice of a square funnel was dictated by a practical reason: to easily build a funnel with known catching area, without decimals. Jurin indicated that the rain gauge should have a second vessel to receive the water from the collector, and a cylindrical measure with a gauge, divided into (London) inches and decimal parts. The collecting vessel should be located in a position where no part of the rain may be intercepted, either by the building or other obstacles, whatever wind blows. The vessel that acted as a reservoir should be closely shut to avoid evaporation, having only a small hole to receive the water from the funnel.

When Beccari started the precipitation records in January 1723, the Jurin protocol was not yet published, because it appeared in the September–October issue of the Philosophical Transactions of the same year. It may be logical to suppose that Jurin had preliminary contacts with the potential observers, and that the Beccari instrument was in line with the simple requests made by Jurin, or was adapted to meet the requirements when this protocol was published (Fig. 2).

Giovanni Poleni also adhered to the Jurin plea, but used a cubic funnel as collecting vessel, 1 London foot in side, that he used before. The cubic shape was more convenient to catch hail and snow. Poleni started some irregular weather measurements in 1713, 1714, 1716, 1717, 1718 and 1724 (without specifications about instruments and location) and then a regular record of temperature, pressure, precipitation and wind from 1725, following the invitation of Jurin (1723). Poleni published many details about the construction and calibration of the thermometers and barometers (1709), but was very sparing with the rain gauge, probably because it was considered an instrument too simple and because he substantially followed the Jurin protocol. Poleni was a key reference for Beccari, especially because they had a close friend in common, also interested in weather, Giovan Battista Morgagni who moved from the University of Bologna to the University of Padua (Camuffo 2002). Similar rain gauges with cubic funnel were used by Giuseppe Toaldo, Vincenzo Chiminello and others in Padua, who continued Poleni series. It is very likely that Beccari used the cubic funnel as his friend Poleni. The typical rain gauge in use in the second half XXVIII century follows Jurin recommendations and the funnel had square section. The funnel shape was either a rectangular parallelepiped as used in the Palatina Meteorological Society (Electronic Supplementary Material, Fig.ESM.5) Mannheim (Hemmer 1783), or pyramidal, as documented by Louis Cotte (1774) (Electronic Supplementary Material, Fig.ESM.6). Funnels had square cross section until the XIX century, when the conic shape prevailed. Snow was melted and measured as liquid water, as recommended by Jurin (1723) and indicated in the Logs.

2.4 Location and exposure

As most observers lived and operated in an urban environment, the roof position was considered the only that could satisfy the request of an unobstructed horizon. From Lorenzoni (1872), we know that Poleni kept the instrument (or at least the funnel) on the roof of his house, a three-storey building, although he had a big garden, but with some trees. However, placing the funnel on the roof and not far from the building made the measurements easier, avoiding of being wetted when it was raining.

Theoretically, two locations are possible for the rain gauge: (i) Poggi Palace, 33 Zamboni street, seat of IASA, where Beccari worked from 1711 to 1749; (ii) his house, 8 San Petronio Vecchio street.

In Poggi Palace, the rain gauge could have been located on the roof. The astronomical tower of IASA was built in 1727 and is another possible candidate after that date. The Palace had internal courtyards, but they did not constitute the best location for the disturbance to the wind field and because the instrument could not be adequately protected. The scheduled

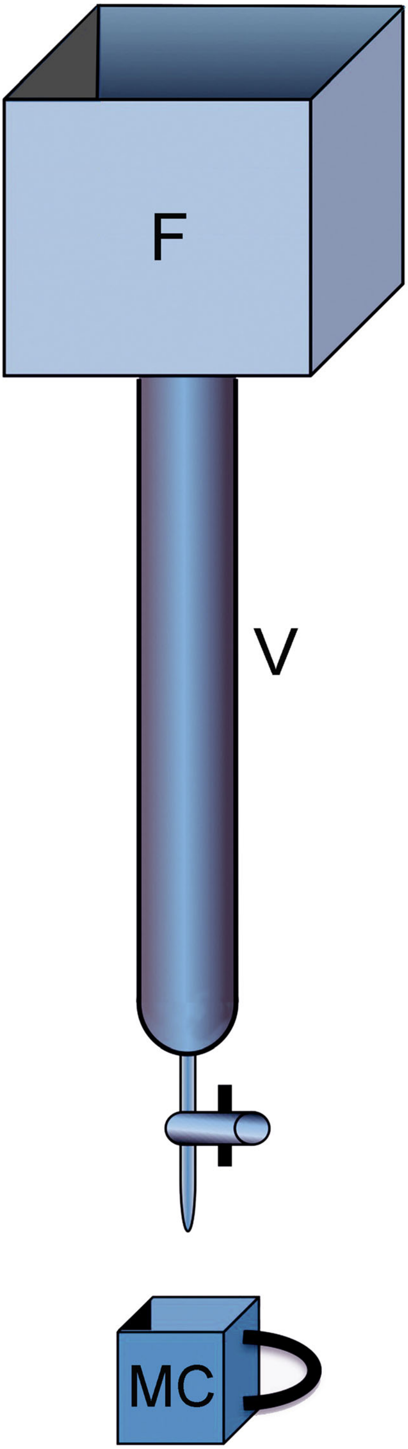

Fig. 2 Most likely reconstruction of the Beccari rain gauge, in line with Poleni and Toaldo. F funnel, V vessel, MC measuring cup

reading times were uncomfortable, especially for the nocturnal observations that were more convenient for an astronomer. It has been demonstrated (Camuffo et al. 2016, 2017) that the readings of the Stancari thermometers and one of the two barometers were made at IASA by his assistant Gusmano Galeazzi (from 1716 to 1726) and then by the astronomer Eustachio Zanotti (from 1727 to 1738) until he became Director of the Astronomical Observatory. It is unlikely that Beccari had delegated all measurements in Poggi Palace except precipitation. In addition, this location becomes not sustainable after Beccari retired in 1749 and continued his lessons at home.

Beccari house was a three-storey building, facing the street that is aligned from north-west to south-east. The map of Bologna by Ferratini (1743) (Electronic Supplementary Material, Fig.ESM.7) and the historical description by Guidicini (1872) show that at that time the buildings were located a little away from the centre, and in particular Beccari house, were surrounded by big vegetable gardens.

The precipitation record is unbroken from 1723 to 1765, and the record is homogeneous. In the case of change of level or location in an urban context, the cumulative precipitation plot would have changed slope (Electronic Supplementary Material, Fig.ESM.8). Such a homogeneous and continuous plot gives no evidence of changes when he retired in 1749 and strongly suggests an unchanged site. As in the last period, he surely observed at home, even if the location has never been specified, the data analysis in combination with the historical sources lead to identify the measuring site with Beccari house.

There is no documentation to support the roof or the garden exposure; however, the roof is more likely for historical reasons, especially the similarity with Poleni, and it was easier to manage. The home location was a key factor, the only compatible with the nocturnal observations, or when Beccari became old and ill. Last but not least, home observations were explicitly recommended by the Jurin (1723) protocol. This style was very popular during the XVIII century and was recommended by another key network: the Meteorological Palatina Society, Mannheim, from 1781 to 1792 (Hemmer 1783). In conclusion, the more reasonable exposure for the funnel was the roof.

2.5 Units used to express the precipitation amount

Toaldo (1770) explained that, in the XVIII century, the precipitation amount could be measured with one of these three methods: (i) using a length unit, dipping a graduated rod into the vessel that received the water from the funnel, as Poleni did; (ii) using a capacity unit, counting the number of larger and smaller volumes that could be filled by emptying the vessel, as Toaldo and many others did; (iii) using a weight unit, weighing the collected water. The weighting method was a theoretical possibility, because measurements made with cups of known volume were preferred to the use of a balance that is more complex, especially considering the variability of the precipitated amount and the consequent ratio with the tare. Another problem raised against this method was that the density of water changed with temperature and this affected the effective height reached by the precipitated water. As usual, Beccari did not specify the method he used. In the "*Observationum meteorologicarum compendium anni 1724*" (Beccari 1724, 1725 and 1726) Beccari reported that he measured the precipitation in Paris lines, but the Logs generally report readings in two units, i.e. the "mensura parva" (MP) (i.e. small unit of measurement) and Paris lines. The Paris unit system of length is indicated in Table 1, as well as the conversion factors and the use made by Beccari.

There is no indication whether MP is a small unit of length, volume or weight. The fact that Beccari sometimes used the double unit of measurement, i.e. MP, a totally unknown unit, and Paris lines, a known unit, suggests that he took his measurements in a practical but obscure unit and then transformed it into Paris lines to be understood. It is unlikely that MP was a length, because it was easier to graduate directly the rod in lines than to calculate the transformation from lines to MP each time. It is also unlikely that MP was a weight, because nobody used this method. The most likely conclusion is that Beccari measured the collected water with a smaller vessel (i.e. the MP) whose capacity corresponded to a precipitation height equal to 2/3 of Paris line, i.e. 1 Paris line = 1.5 MP. In 1739 and subsequent years, MP is further divided in 24 intervals, each one corresponding to 1/36 of Paris line. The conversion factor is clear in the summaries of the years 1723 and 1724 and some individual days in the years ’23-’26, ’39-’41, ’59-’65, where the double notation is present (Electronic Supplementary Material, Fig.ESM.9). Baiada (1986) arrived to the same conclusion.

In the period from 9 April to 3 December 1740, the Log reports the precipitation in a different style, i.e. “dig” and “lin”, written by a different person (Electronic Supplementary Material, Fig.ESM.10). However, the precipitated amount is exceedingly high, by orders of magnitude, whatever the reference for inches and lines, e.g. Paris, London or Bologna. There are no notes to explain the change of style, nor the usual double notation with reference to MP and the solution was found after the data analysis.

3 Data analysis

3.1 Interpretation of the unit used in 1740

In the 1740 Log, the most likely explanation for the inconsistency of the declared unit is that the person who substituted Beccari, e.g. a servant, as Poleni did, was not adequately trained and less familiar with the French units: he always used the lowest unit, even for large values, and misnamed it. This person misnamed “dig” the lowest unit, i.e. the “point”, that in reality is $(1/12)^2$ of digit (Table 1). In the Log, the reading in “dig” was followed by an entire number (i.e. 3, 4, 6 or 9) called “lin” that indicated the sub-multiple of the previous unit. This means that 3 lin should be interpreted as 3/12 of point. Under the assumption of misnamed units and use of the lowest one, all adds up.

A useful reference to verify this assumption is that Toaldo (1770) wrote that in Padua (about 130 km far from Bologna), the year 1740 was exceptionally dry, similar to 1762 when the totals were 570 mm. In Bologna too, the precipitation total amounts of the years 1740 and

Table 1 Length unit system used by Beccari and conversion factors

Original name (French)	English translation	Latin name	Short name in the Beccari’s Log	Ratio with the basic unit	SI value
Pied du Roy	King’s foot	pes		1	324.8 mm
Pounce	Paris inch	digit	dig	1/12	27.07 mm
Ligne	Paris line	linea	lin	$1/12^2$	2.256 mm
Point	Paris point	punctum		$1/12^3$	0.188 mm

Beccari preferred not to mention “points”, but to use fractional numbers instead, e.g. 3 points were indicated as 3/12 or 1/4 (i.e. 3 points are 3/12 of line, but he omitted to specify “lin”). For 1740, see text

1762 are similar (Electronic Supplementary Material, Fig.ESM.11a,b) and are among the lowest ones. Ferrario's results (1840) for 1723 to 1726 are in agreement with the findings of this study, while the Comani's ones(1986) present some departures, especially in 1734 and 1740. All departures have been carefully controlled and confirmed.

A further argument is the comparison between the precipitation amounts in Bologna and Padua, for that period. In Bologna, the yearly precipitation was a bit lower than in Padua, i.e. 92% as a result of the linear regression over the 1724–1763 common period (Fig. 3). If one applies this ratio to the 1740 value in Padua, one obtains 570 mm × 92% = 524 mm, that is close to the observed value in Bologna, i.e. 541 mm.

3.2 Daily, monthly and yearly amounts

The 1723–1765 daily precipitation readings in Bologna are shown in Fig. 4a. Only 64 days over 43 years are missing, i.e. less than 1% of the total. No sharp changes are detectable. The 1723–1727 period might be uncertain because the precipitation amount never exceeded 40 mm. The reason is unclear. It might be due to a particular climate without intense rains, or to an instrumental bias. The hypothesis of particular climate may be viable because other periods had no intense rain, e.g. the 90th percentile of 1729–1733 is even lower. On the other hand, a possible bias explanation might be the fact that these were among the earliest regular measurements and the collecting vessel was not big enough to keep amounts exceeding this threshold. This required an instrument improvement. However, after this start, the record becomes homogeneous, and suggests that no relocations have occurred. In 1749, Beccari became emeritus and continued teaching and taking observations at home. If he had changed instrument location, this would have been recognized as a turning point in the trend of the cumulative amount. Contrariwise, the series does not show any turning point, neither in this, or any other year (Electronic Supplementary Material, Fig.ESM.8). This confirms that the instrument was always at his home.

The 90th percentile is a particular threshold, suggested by IPCC (2014) for extreme events. Figure 4a shows that every year includes ten of such events, with too low return period, and is

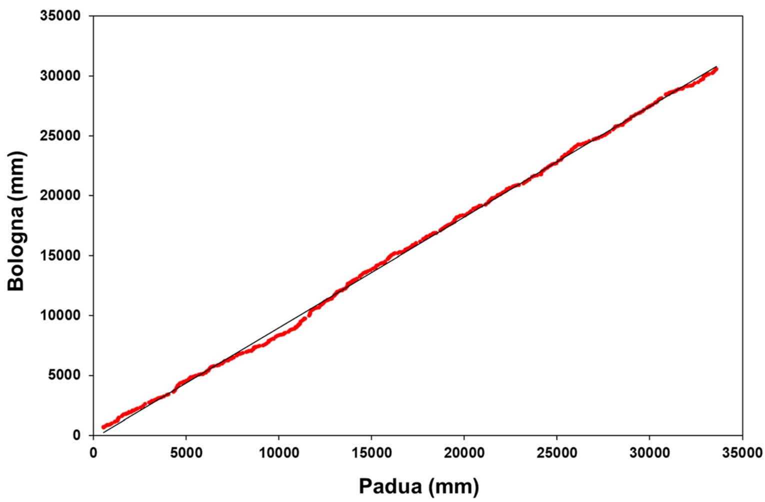

Fig. 3 Cumulative monthly precipitation amount of Bologna versus Padua over the 1724–1763 common period

no convenient to define a real "extreme" event (Camuffo et al. 2018). Passing from the daily to the yearly scale, the precipitation amount that exceeds the 90th percentile is reported in Fig. 4b. The average value is 335 mm, the highest 612 mm, the lowest 155 mm, showing a wide range. The most abundant precipitation occurred in 1729 and 1764; the less in 1760.

3.3 Frequency of the consecutive rainy days and regularity of the sub-daily observations

A test has been made on the frequency of single and consecutive rainy days. This test is useful to characterize the length of the rainy weather situations in Bologna and to verify the regularity of the observations. The Log generally reports observations three times a day, but it may be possible that Beccari was engaged in other business and missed some sub-daily or even daily rain gauge reading. This does not affect the precipitation amount, but the frequency, because two consecutive rainy days may be registered as they were only one, three as they were two, and so forth. The frequency distribution of single and consecutive rainy days has been computed for Beccari and the 1961–1990 reference period (Fig. 5). In interpreting the results, it should be noted that the thresholds of the modern and Beccari rain gauge may be different,

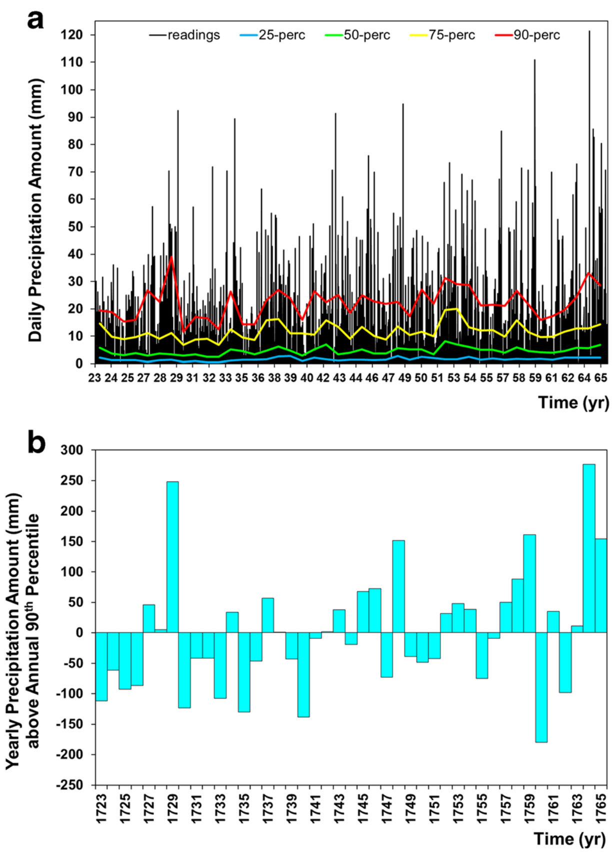

Fig. 4 **a** Daily precipitation amount in Bologna in the period 1723–1765, with the indication of selected yearly percentile levels (25-, 50-, 75- and 90-ile). **b** Yearly precipitation amount above the annual 90th percentile level. The zero of the *y*-axis is fixed at the 1723–1765 average level of the 90th percentile, i.e. 335 mm

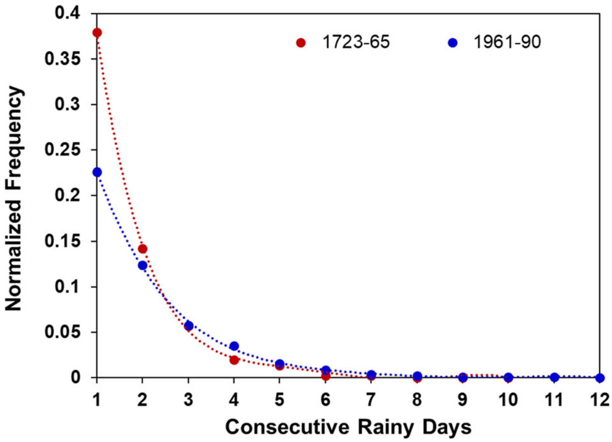

Fig. 5 Normalized frequency of consecutive rainy days: comparison between Beccari series and 30-year reference period 1961–1990

and, in particular, modern ones are heated to exclude false signals for condensation. In the XVIII century, it was believed that the precipitation consisted in "all forms of water from the sky, including rain, snow, hail, dew and fog" (Toaldo 1786). This definition added a few spurious cases of light nocturnal precipitation, that in reality were dew. In addition, it should be taken into account that the particular choice of the reading hour may be influential on the frequency. A test made with a modern station in Bologna, for 1990–2018 (Electronic Supplementary Material, Fig.ESM.12) showed that the difference in the number of rainy days computed from 0:00 a.m. or 8:00 a.m. was randomly distributed over time, and its range varied with the selected instrumental threshold. From the above tests, the conclusion is that Beccari was in general very accurate in taking observations, except a few days in which he was off, and the single-day difference between his observations and the 1961–1990 reference is partly due to the observer, partly to nocturnal condensation and other factors.

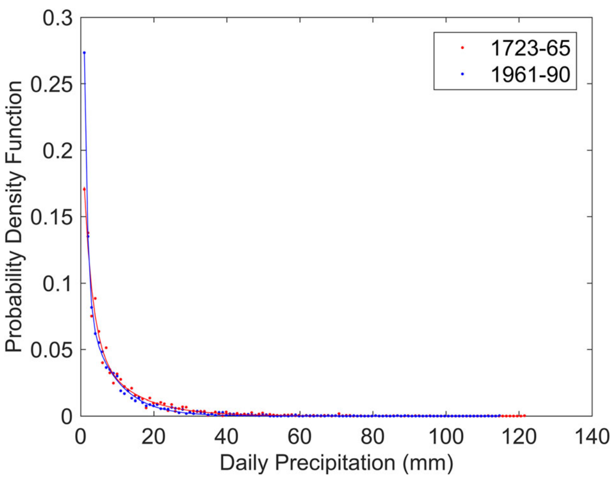

Fig. 6 Double exponential probability density function applied to the daily precipitation amount: comparison between the 1723–1765 Beccari series and 1961–1990 reference period

Table 2 Coefficients and parameters of the double exponential function

Period	Coefficients				Parameters	
	a^*	b^*	c^*	d^*	R-square	RMSE
1723–1765	0.1782	−0.4337	0.06199	−0.09031	0.9834	0.003092
1961–1990	0.6013	−1.159	0.09558	−0.1284	0.9985	0.001187

3.4 Frequency distribution of daily precipitation amount

The frequency distribution of the precipitation collected every day in the period 1723–1765 has been plotted in a normalised scale versus the daily precipitation amount, as well as the 1961–1990 reference period. A variety of models can be found in literature that describe the distribution of the precipitation amounts, the integration period being extremely relevant in determining the shape (Wilks 2011). The dataset was interpolated with different functions, e.g. Gamma, Weibull, double exponential. The Gamma distribution is frequently used as it provides flexible representation of a variety of distribution shape using only two parameters; therefore, it can be applied to many precipitation regimes with reasonable accuracy. However, in this case, it gave not the best result (Electronic Supplementary Material, Fig.ESM.13). For both the series, the best interpolation was obtained with the probability density function represented by a double exponential (Fig. 6):

$$f(x) = a^*\exp(b^*x) + c^*\exp(d^*x)$$

with coefficients and parameters specified in Table 2.

The fits obtained with the above probability density function of the Beccari and the reference series are in agreement between them (Fig. 6). The main difference is related to the lowest precipitation amount as already discussed (Sect. 3.3).

3.5 Extreme events

The distribution of the extreme events in the Beccari period was considered. This constitutes a useful case study to investigate the extreme events in the Little Ice Age. Following the peak-over-threshold (POT) theory, a number of thresholds established at selected percentile levels were considered in the time record. The starting threshold was 90th-percentile following the IPCC (2014) definition. The results are reported in Table 3.

Table 3 Thresholds, extreme precipitation, occurrence and return periods related to the Beccari's series

Percentile threshold (%)	Precipitation amount (mm)	Events above threshold (number)	Return period (years)	Return period (day)
90	22.56	373	0.12	42
95	31.58	200	0.22	78
99	57.14	40	1.08	392
99.9	91.47	4	10.7	3924
99.95	95.56	2	21.5	7847
99.99	117.33	1	43	15695

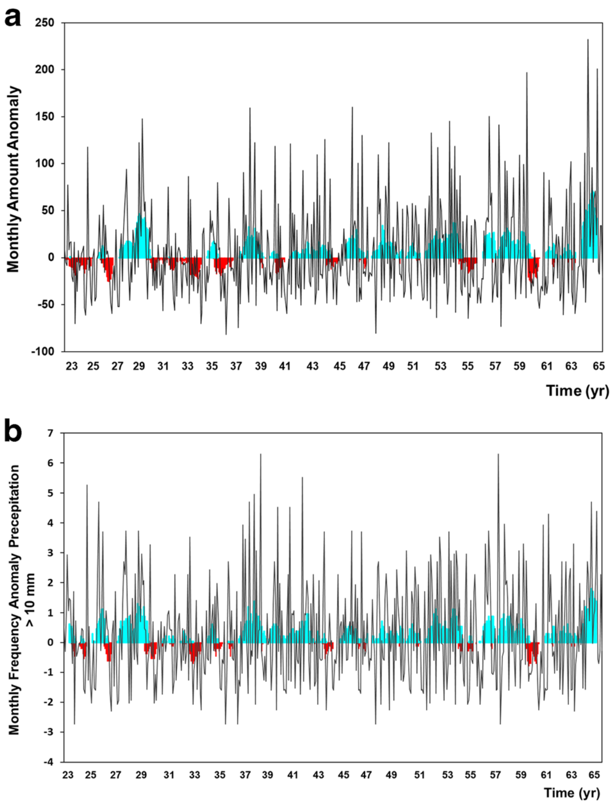

Fig. 7 **a** Monthly amount anomaly (difference from the 1961–1990 reference period). Positive (blue) and negative (red) values of the 12-month moving average are indicated. **b** Monthly frequency anomaly (difference from the 1961–1990 reference period) of the daily amounts above the threshold of 10 mm. Positive (blue) and negative (red) values of the 12-month moving average are indicated

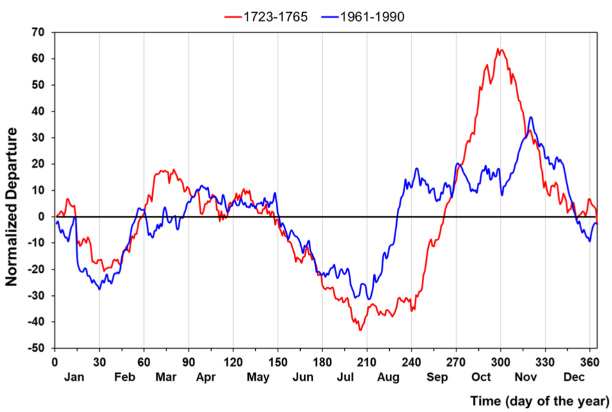

Fig. 8 Precipitation amounts over the calendar year in 1723–1765 and 1961–1990. Normalized departure of the 30-day moving average from the average over the whole recording period. Red line: 1723–1765; blue line: 1961–1990

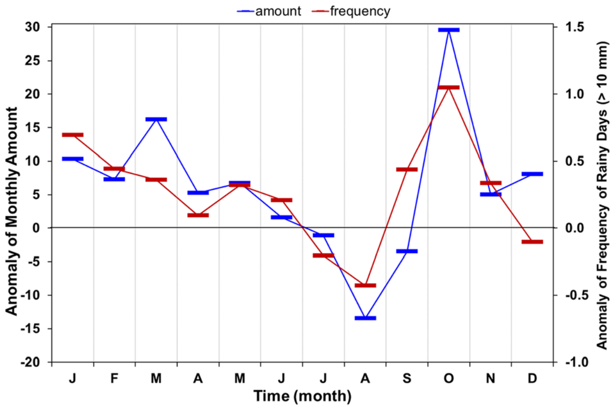

Fig. 9 Anomaly (difference from the 1961–1990 reference period) of amount (blue) and frequency of precipitation > 10 mm (red). The data related to the same month of the different years have been averaged in the whole period 1723–1765

The table shows that the 90th percentile is a too low threshold to define an extreme precipitation because the related daily amount is 22 mm, with 42-day return period (Electronic Supplementary Material, Supplement to Section 3.5).

3.6 Anomalies

In order to investigate changes in the precipitation regime between the first half of the XVII century and the 1961–1990 reference period, the anomaly was calculated for both the amount and the frequency at monthly resolution. The yearly window was also considered with a 12-month moving average (Fig. 7a, b). For the yearly anomaly of the precipitation amount, see the Electronic Supplementary Material, Fig.ESM.14.

The comparison with the analogous data during the 1961–1990 reference period shows that the 1723–1765 period had generally higher monthly amounts (Fig. 7a), as well as higher frequency of rainy days (Fig. 7b). In the long series, the frequency of light precipitation may be strongly affected by different instrumental thresholds and/or occult precipitation (e.g. dew, fog condensation). As the Beccari threshold is unknown, the light rain (i.e. < 10 mm) has been excluded to avoid the uncertainties mentioned above and point out a clear climate signal. Lower amount and frequency occurred from 1723 till 1736, in 1755 and in 1760. Apart from some exceptions in the first decade (Electronic Supplementary Material, Supplement to Section 3.6), the Beccari series shows a more humid climate in agreement with previous findings (Camuffo et al. 2013; Santos et al. 2015).

The seasonal variability of the anomaly was also investigated. The precipitation in Bologna is bimodal, with a broad maximum in spring and a peak in autumn for the penetration of Atlantic perturbations. Winter and summer have a continental character, and the summer precipitation is mainly due to thermo-convective cells, often thunderstorms, for soil heating (Fig. 8).

The monthly anomaly (Fig. 9) indicates that summer had less precipitation both in amount and frequency. This may be explained with the fact that in the XVII century the land was more vegetated and generated less powerful convective cells. As opposed, the rest of the year was wetter, with a remarkable peak in October. This explanation is of climate nature, with enhanced Atlantic influence.

4 Conclusions

Beccari was taking temperature and pressure readings since 8 years when Jurin made his famous invitation to join the meteorological network of the Royal Society, London. Following this invitation, Beccari added the precipitation; however, he never sent his results to London. Beccari started one of the longest weather records in the world, but his Logs are very difficult to read and interpret, especially for the handwriting and lack of metadata. However, after a long and patient analysis of all the documents, the records, and the activity of his friends and colleagues, it has been possible to reconstruct the various pieces of the puzzle. For instance, the rain gauge and its location had not been described, but it was possible to conclude that: the location was his home; the instrument followed the Jurin's directives and the use of Poleni and Toaldo in Padua, with a cubic funnel to catch snow and hail, fixed to the roof to have the horizon free of obstacles. It has also been possible to reconstruct that Beccari measured the precipitation amount with a small cup (*mensura parva*) and then transformed this unit in Paris lines. For some months, in 1740, he was off and probably a servant took the readings also in Paris units, but with swapped name. Fortunately, the reconstruction could be confirmed for other witness who described that year with scarce precipitation and compared the yearly amount with another year. Except the drawbacks mentioned, Beccari was very accurate in his observations. He regularly read three times a day, and this accuracy was ascertained with some tests, e.g. distribution of consecutive rainy days.

The Beccari record covers 43 years in the late of the Little Ice Age. The data analysis shows that the first decade was drier than the 1961–1990 reference period, and the rest of the series wetter. The seasonal distribution of precipitation shows that summer showers were less frequent, very likely for the more widespread vegetation that reduced soil overheating and the formation of thermo-convective currents and clouds. As opposed, the rest of the year was wetter, with a marked peak in October for a more intense activity of Atlantic perturbations.

The analysis of the extreme events confirmed that the threshold of the 90th percentile established by IPCC (2014) is too low for precipitation, because the associated return period is around 1 month and a half.

Acknowledgements The authors are grateful to Gaston R. Demarée and to Maria de Fátima Nunes for their constructive comments which helped improve the manuscript. They are indebted to Valeria Zanini, INAF – Astronomical Observatory, Padua, and the Archiginnasio Library, Bologna, for having favoured document consultation. They furthermore thank ARPA ER, Emilia-Romagna Region, for the provision of modern data of the 1961–1990 reference period.

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Electronic Supplementary Material

Article Title:

The Beccari Series of Precipitation in Bologna, Italy, from 1723 to 1765

Journal name: Climatic Change

Author names: Dario Camuffo[1], Francesca Becherini[1], Antonio della Valle[1,2]

Affiliation: 1: National Research Council of Italy (CNR), Institute of Atmospheric Sciences and Climate (ISAC), Padua, Italy

2: Secondary School Romano Bruni, Padua, Italy

E-mail address Corresponding Author: f.becherini@isac.cnr.it

Supplement to Section 2: Metadata Analysis

The second half of the XVIII century, the period of Enlightenments, gave a strong impulse to the meteorological observations finalised to the social use (Venturi 1969). This renewed interest in meteorology was related to the application of meteorology to health and to agriculture, as well as to the development of experimental physics. Meteorological observations were carried out with the main aim of understanding the effect of weather on human health, following the neo-Hippocratic hypothesis concerning the close relationship between climate and human health (Demarée 1996).

In Padua, Italy, the astronomer Giuseppe Toaldo studied if it was possible to establish statistical relationships between meteorological variables, weather extremes, solar and lunar forcing, agriculture, yield and farming activity, diseases, number of died or born people. To this aim he wrote a famous book (Toaldo 1770) including a table with the number of people died over the calendar year, and made an attempt to relate diseases and agricolture to climate. Toaldo stimulated an own network, and adhered to the other networks that were under development in Europe.

Following this example, in Paris, Felix Vicq d' Azyr, physician of Louis XIV, with Father Louis Cotte, set up a network on behalf of the newly founded Societé Royale de Médecine (Royal Society of Medicine), Paris (Garnier 2009). The network was composed of 22 stations, active 1777–1786, and their aim was to establish a link between weather and health, by collecting meteorological records and medical reports concerning man and animal epidemics happened in France and other countries, and summaries of the meteorological records were published in the official journal of the Society, named "*Histoire*" (i.e., History).

In Germany, the Prince Elector Karl Theodor von Pfalz and his secretary John Jacob Hemmer, founded the *Societas Meteorologica Palatina* (Palatine Meteorological Society), Mannheim (Hemmer 1783). This international network, active from 1781 to 1792, was composed of 39 sites, most of them over Europe and some in Russia, Greenland and America.

The Palatine Meteorological Society influenced significantly most early Portuguese meteorologists. In 1815 Marino Miguel Franzini started the first continuous meteorological observations in Lisbon (Alcoforado et al. 1997). Following the tradition of the 18th century enlightenment movement, he took a keen interest in Nature and Sciences, particularly in the influence of weather and climate on health and agriculture (Alcoforado and Nunes 2013, Alcoforado et al. 2015). Franzini was member of the Lisbon Academy of Sciences founded in 1799 (Alcoforado et al. 1997) and he established a link with the European scientists (Alcoforado et al. 1999, Alcoforado et al. 2012). Following Toaldo's example, he gathered meteorological data and collected from parishes the number of dead people. He then published his findings in the Journal of Medical Sciences and the Lisbon Gazette.

Supplement to Sections 2.1 and 2.2: Selected examples of original documents

Fig.ESM.1 Last page of the Beccari record with the very last readings by Beccari before his death occurred on January 18th 1766. (By courtesy of Valeria Zanini, *Historical Archive of INAF-Astronomical Observatory*, Padua. Photo Archive Collection, © Used with permission)

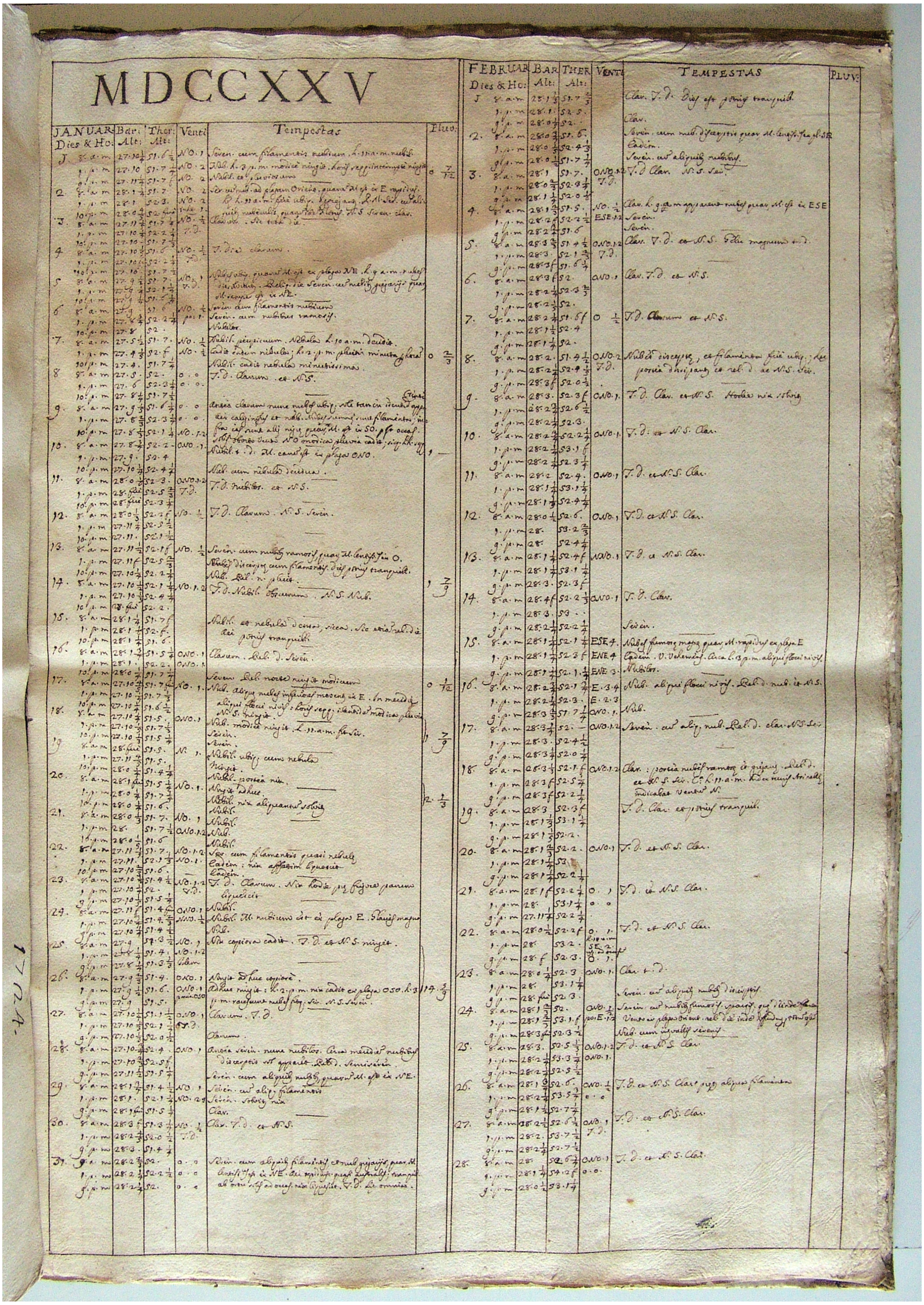


Fig.ESM.2a The re-edited copy, called "Compendium", of the 1725 Log, put in good order. (By courtesy of Valeria Zanini, *Historical Archive of INAF-Astronomical Observatory*, Padua. Photo Archive Collection, © Used with permission)

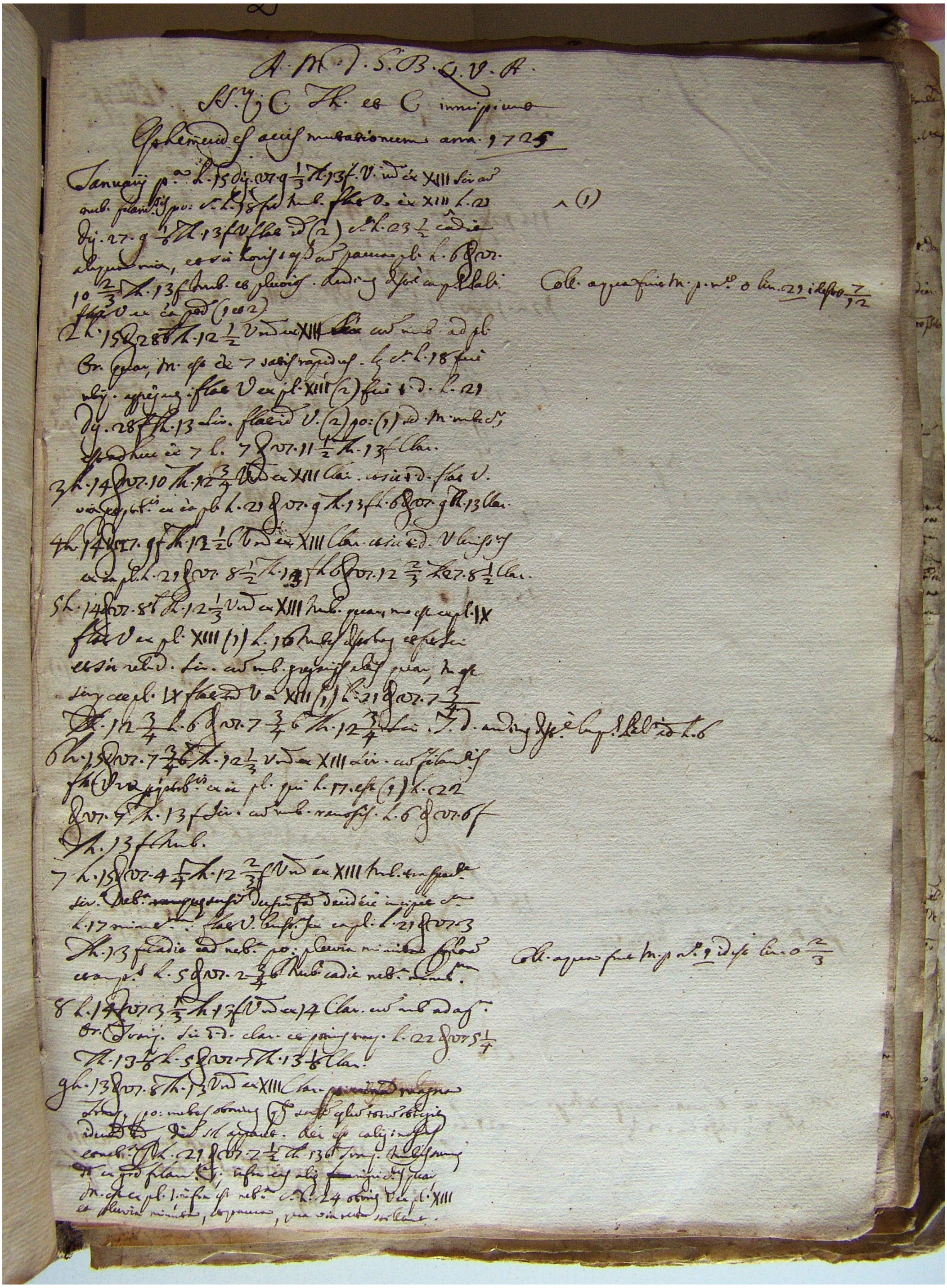


Fig.ESM.2b The original version of the 1725 Log. (By courtesy of Valeria Zanini, *Historical Archive of INAF-Astronomical Observatory*, Padua. Photo Archive Collection, © Used with permission)

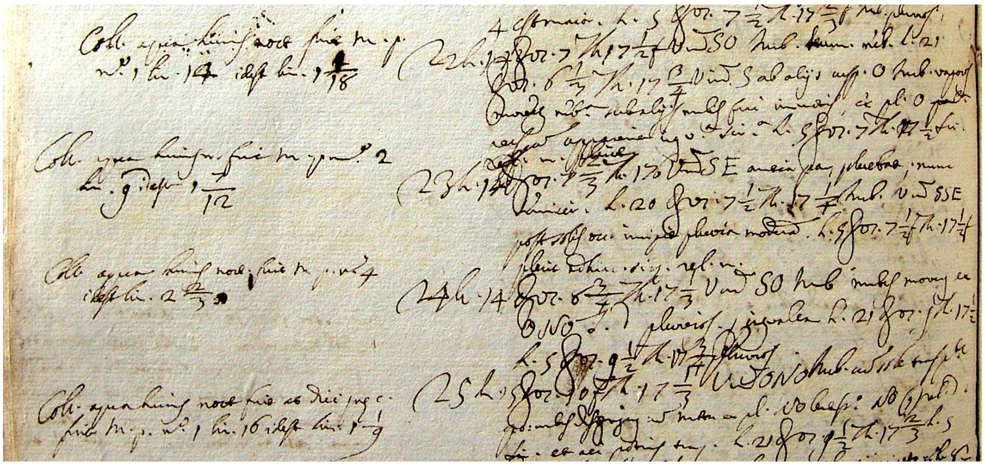


Fig.ESM.3 Detail of the Beccari 1726 handwritten Log. The precipitation is in a separate column with notes, and indicated as "*Coll. Aqua*" (i.e., collected water). (By courtesy of Valeria Zanini, *Historical Archive of INAF-Astronomical Observatory*, Padua. Photo Archive Collection, © Used with permission)

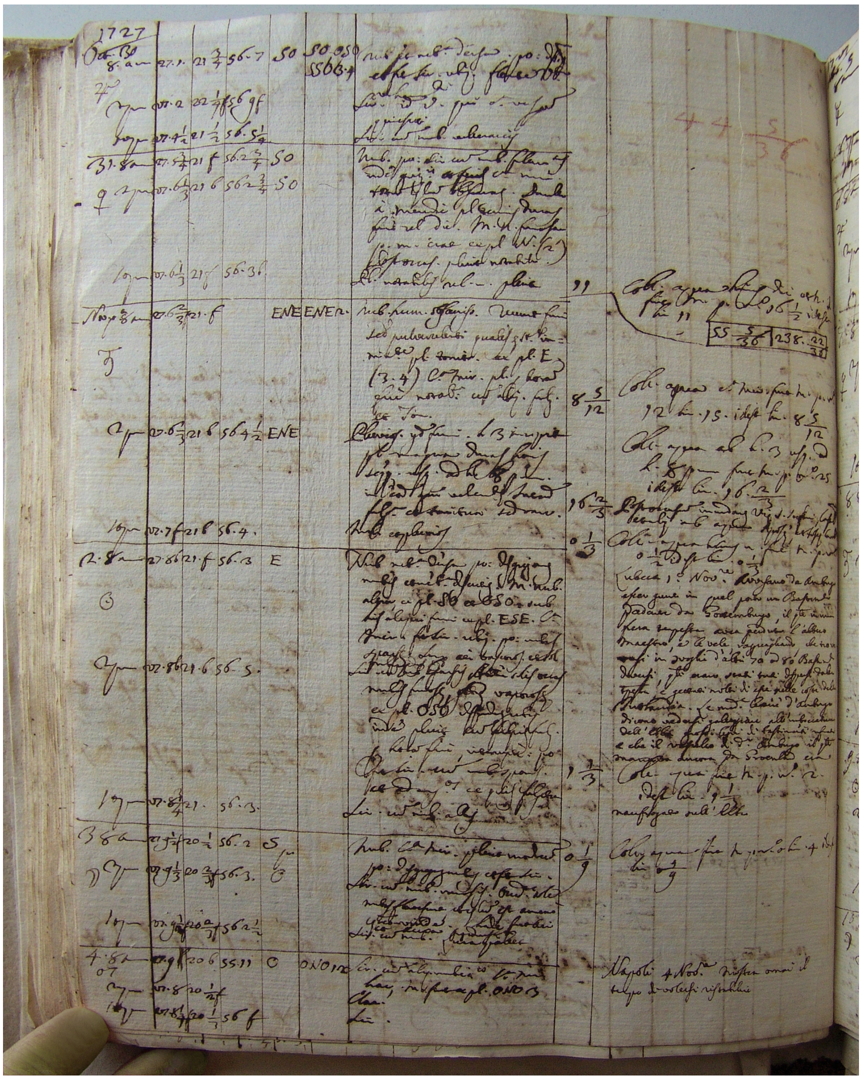


Fig.ESM.4 Detail of the handwritten Ephemerides for 1727, directly written in tabular form. (By courtesy of Valeria Zanini, *Historical Archive of INAF-Astronomical Observatory*, Padua. Photo Archive Collection, © Used with permission)

Supplement to Section 2.3: Examples of XVIII century rain gauges

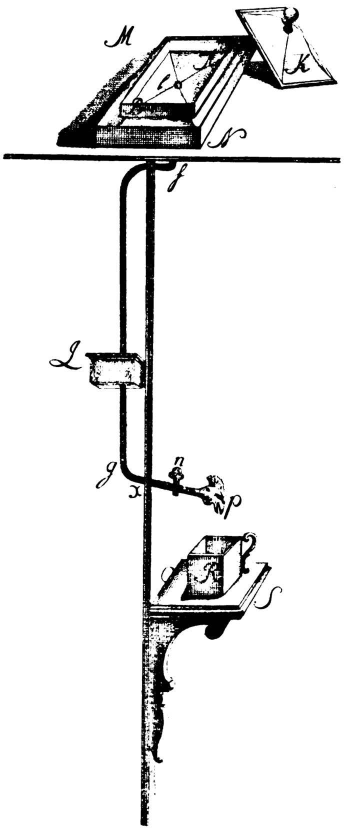


Fig.ESM.5 Rain gauge with rectangular parallelepiped funnel used in the Palatina Meteorological Society (Hemmer, 1783)

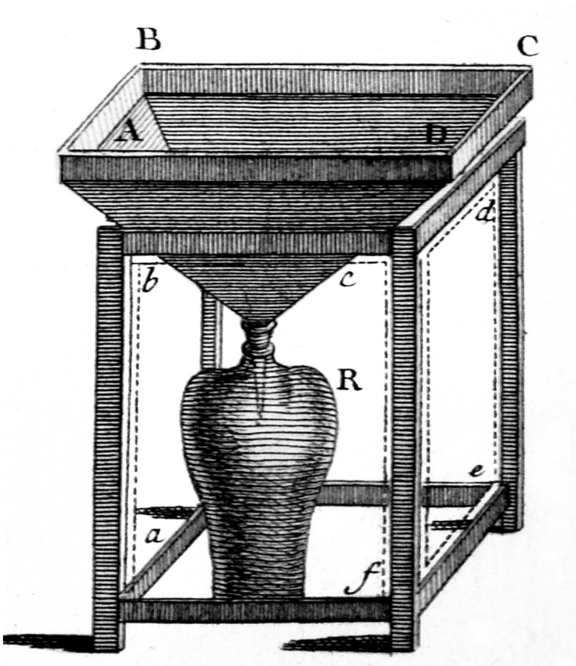
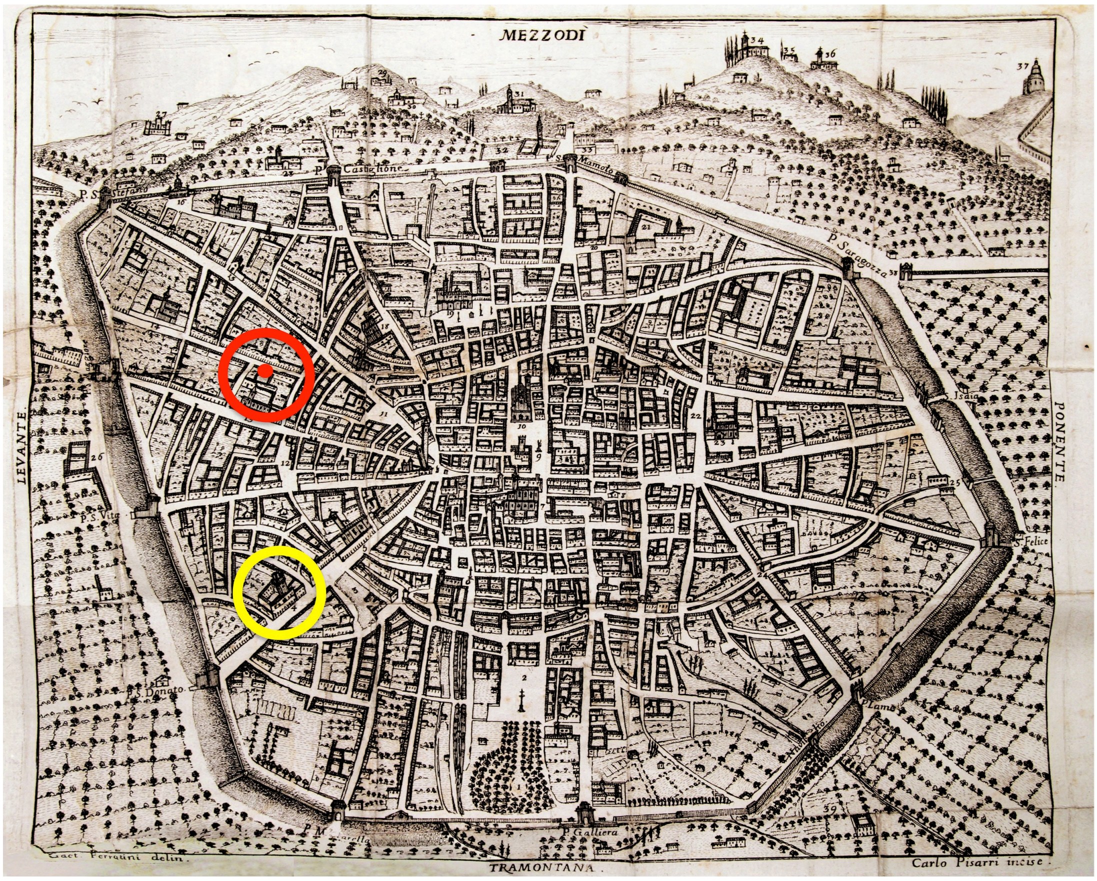
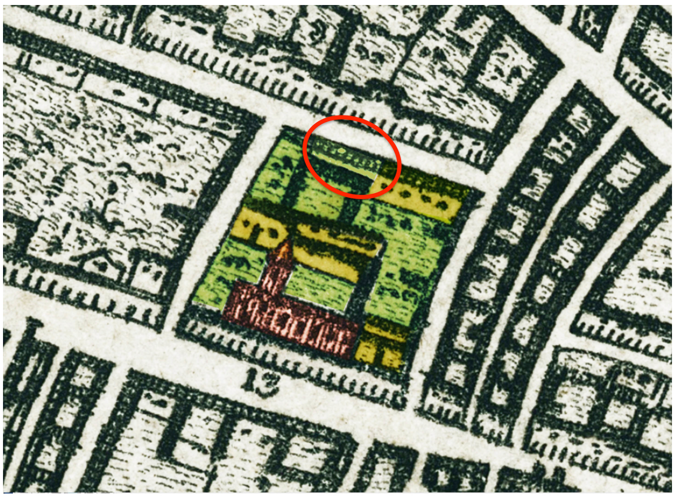


Fig.ESM.6 Rain gauge with pyramidal funnel in the second half of the XVIII century (Cotte, 1774)

Supplement to Section 2.4: Location of the Beccari rain gauge



a)



b)

Fig.ESM.7 Map of Bologna by Ferrarini (1743) with: **a)** the indication of the Beccari house (red circle) and Poggi Palace with the Astronomic Tower, seat of IASA (yellow circle); **b)** a magnification of the location of Beccari house in St. Petronio the Elder street. Please note that the map is rotated by 180 degrees, i.e., south on the top and west on the right. Also note that location and appearance of churches and main palaces are accurately reported; minor buildings are not individually characterized

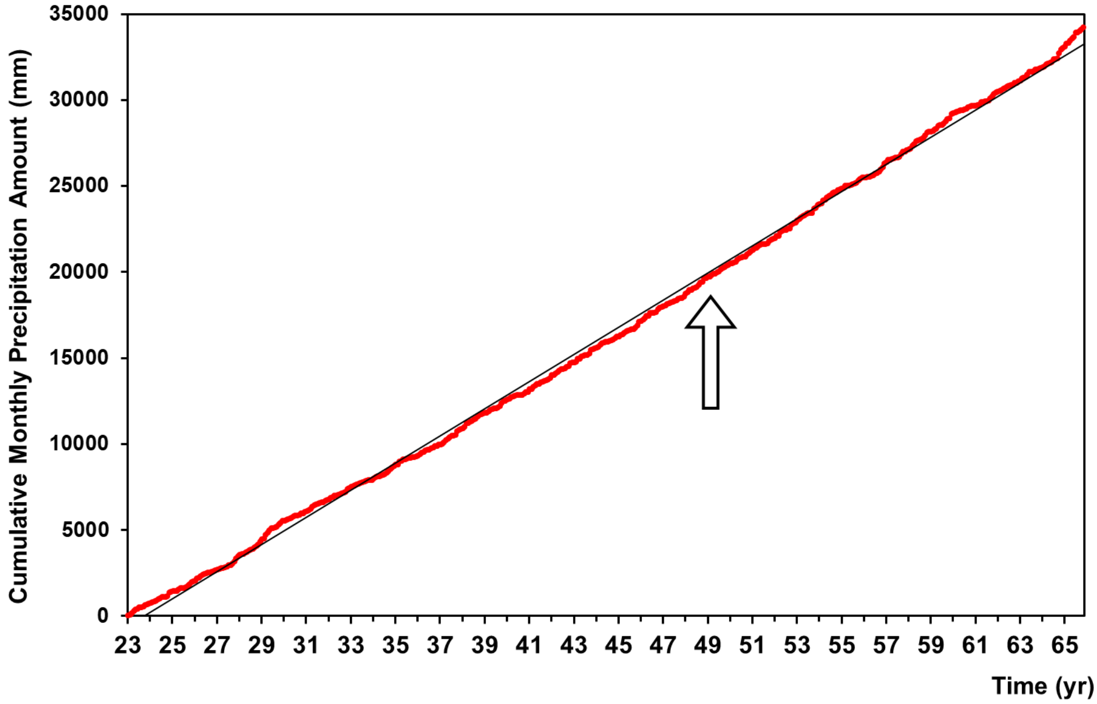


Fig.ESM.8 Cumulative monthly precipitation amount. The year 1749, when Beccari retired, is indicated with an arrow. No change of funnel level or location occurred that year, nor in other periods. Any change in height or location in an urban context would be recognizable as a change of slope in this plot

Supplement to Section 2.5: Examples of units used in original documents

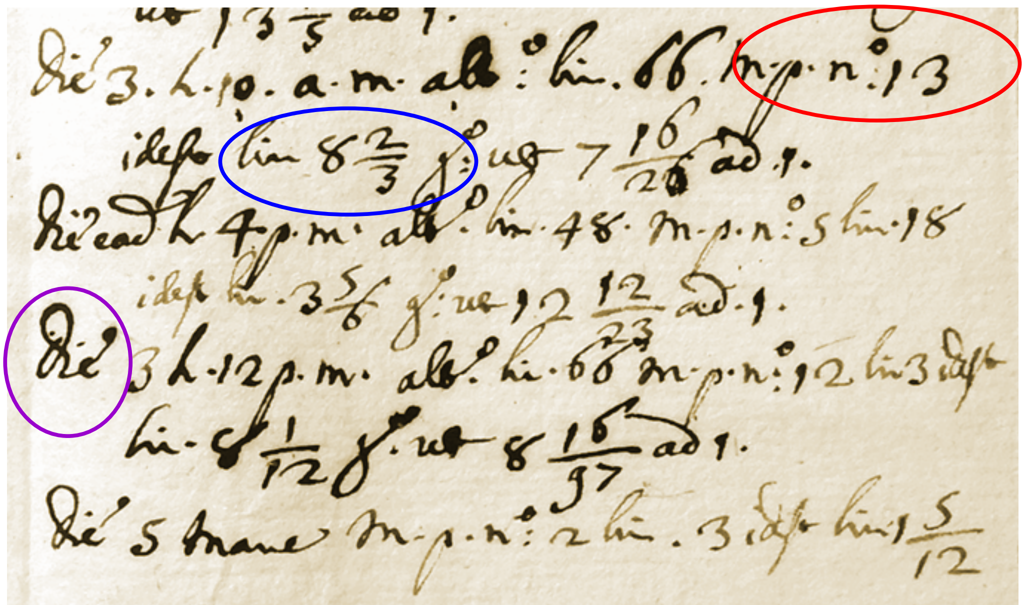


Fig.ESM.9 Example of double notation in MP (red circle) and Paris line (blue circle). "Die" (i.e. "day") is circled violet to be compared with "Digit" in Fig.ESM.10. Only one line has been highlighted. (By courtesy of Valeria Zanini, *Historical Archive of INAF-Astronomical Observatory*, Padua. Photo Archive Collection, © Used with permission)

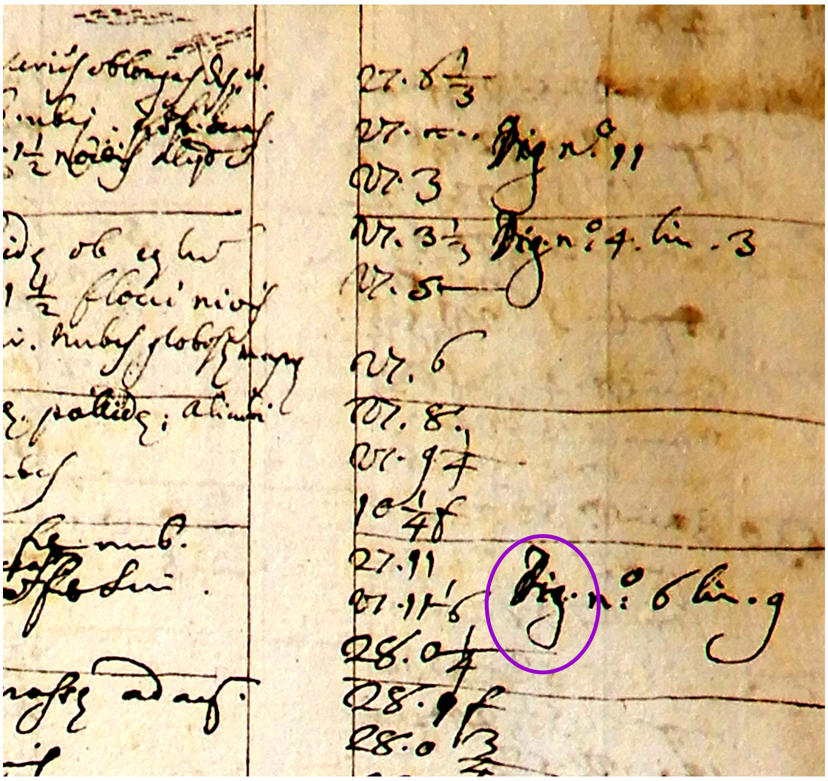


Fig.ESM.10 Detail of the 1740 handwritten Log reporting the precipitation in a different style (i.e., Dig and lin) and writing (e.g., compare letter "D" of Dig (violet circle) in this figure and "Die" in Fig. ESM.9). (By courtesy of Valeria Zanini, *Historical Archive of INAF-Astronomical Observatory*, Padua. Photo Archive Collection, © Used with permission)

Supplement to Section 3.1: Departures from previous studies

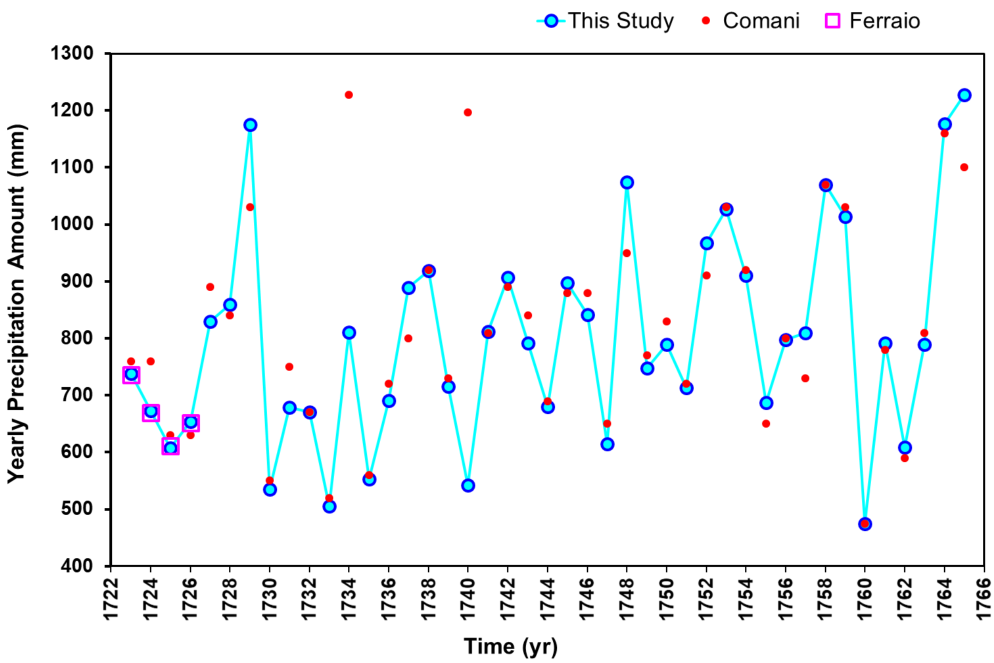


Fig.ESM.11a Yearly precipitation amounts recovered in this study (blue circles with cyan line); compared with those by Ferrario (1840) from 1723 to 1726 (pink squares) and Comani (1986) (red dots)

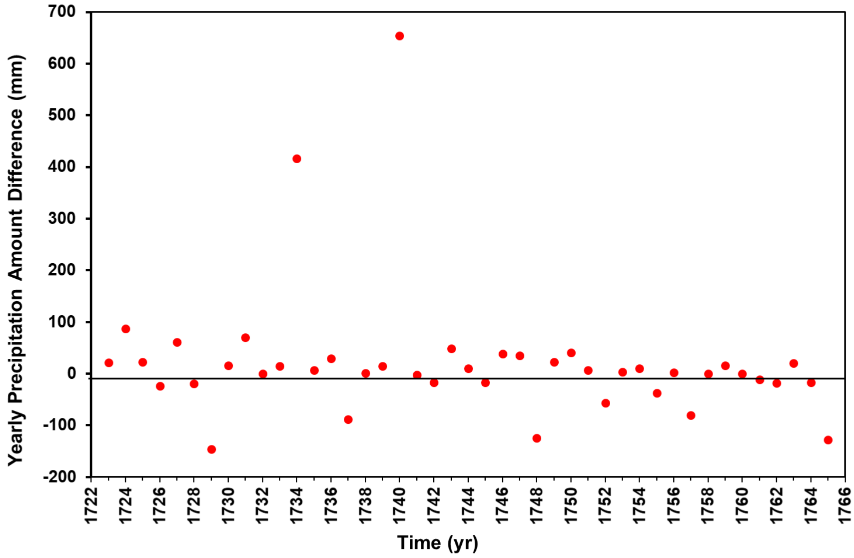


Fig.ESM.11b Difference between the yearly precipitation amounts reported by Comani and those recovered in this study. The main departures refer to 1734 and 1740. Concerning 1734, probably the total was calculated using "*mensura parva*" (Latin for small unit) as unit. In fact, if the yearly total is converted from "*mensura parva*" to Paris line the result is 814 mm, close to this study (826 mm). The total measured in Padua in the same year (i.e., 947 mm) is closer to this reconstruction. Concerning 1740, the anomalous unit "dig" was probably misinterpreted (section 3.1)

Supplement to Section 3.3: Consequence when changing the start of the sampling period

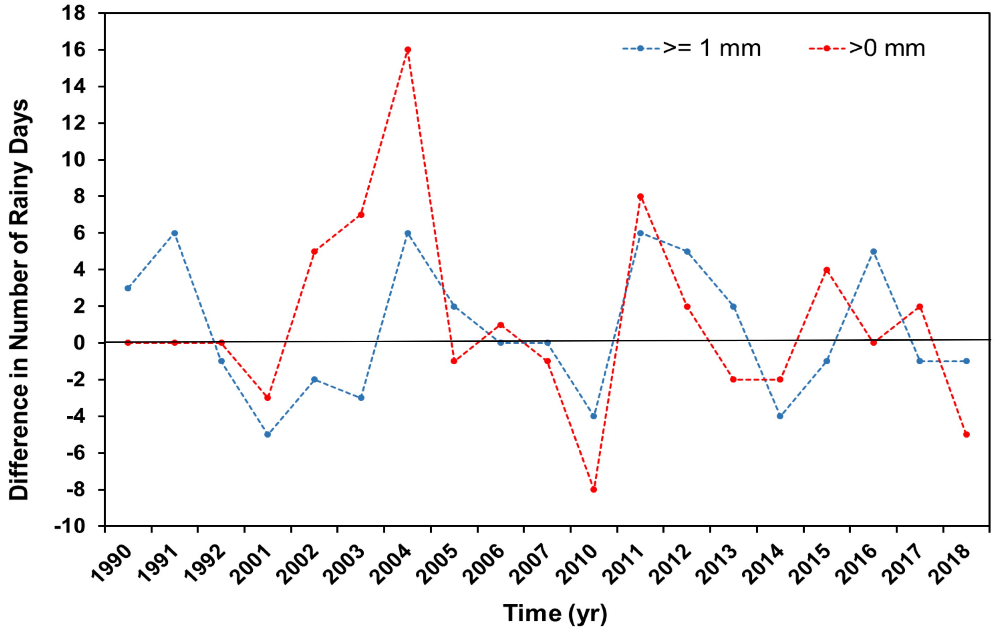


Fig.ESM.12 Difference in the yearly number of rainy day when a rainy day is computed starting from 0:00 a.m. and 8:00 am. This test has been performed with a modern record (1990-2018) in Bologna. Considering that the threshold of the Beccari rain gauge is unknown, two thresholds are considered: ≥ 1 mm (blue line and dots); >0 mm (red line and dots). At 0 mm threshold, the rainy day difference is higher

Supplement to Section 3.4: Gamma distribution

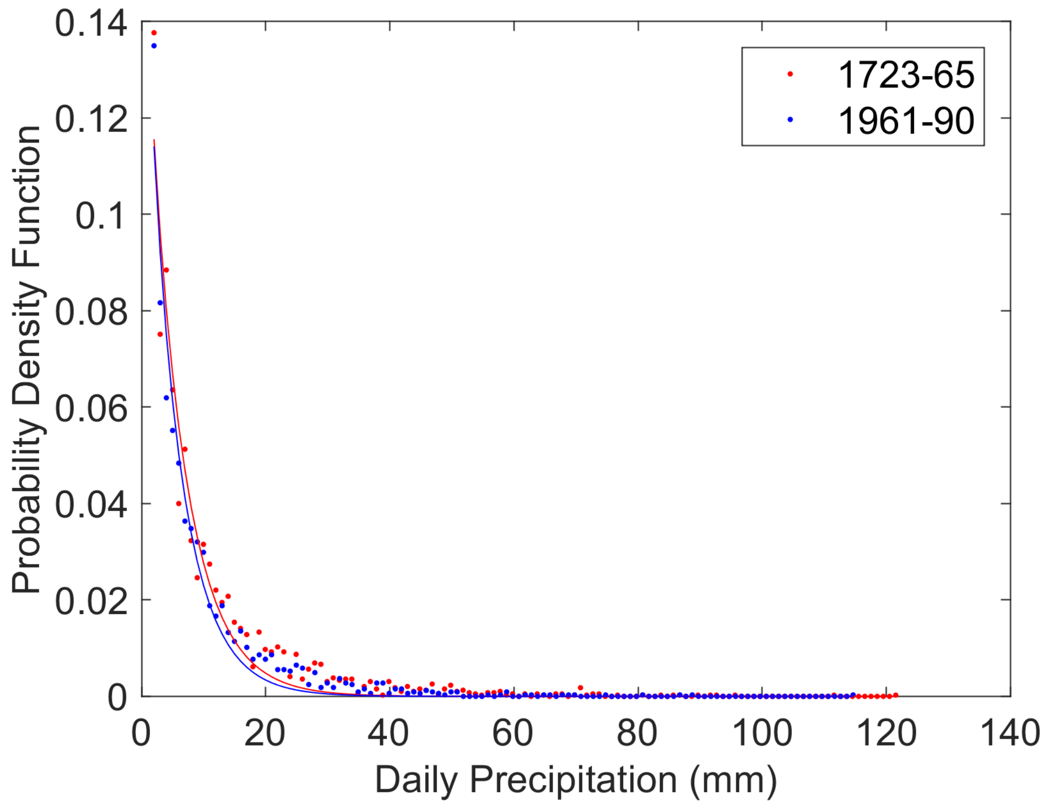


Fig.ESM.13 Probability density function (PDF) of daily precipitation amount and fit with gamma distribution: comparison between Beccari series (red line) and 1961-1990 reference period (blue line). The reference record shows higher PDF at lower amounts

Table.ESM.1 Coefficients and parameters of the Gamma function

f(x) = (x)^(α-1)*exp(-x/β)/β^(2-α)*gamma(α)	α	β	R-square	RMSE
Beccari 1723-65	0.9635	4.979	0.9649	0.004438
Reference 1961-90	0.002339	39.152	0.9963	0.001858

The fit of the Beccari series with a 4-parameter probability density function (double exponential function) results better than the one obtained with the 2-parameter probability density function (gamma distribution), as proved by R-square values (i.e., 0.9834 versus 0.9649), but in the former case the estimated 4 parameters are characterized by a wider 95% confidence interval, therefore by larger variability in the parameter space.

Supplement to Section 3.5: Return period

For precipitation, the return period (RP) is a critical issue because it may vary depending on the way the daily precipitation amount is considered. There are two main alternatives, as follows.

(1) All the readings are considered, as they are supplied by the measuring instrument. Therefore, they may be either 0 or greater than zero. These values are used in the subsequent analysis. Rainy days are days in which the reading is greater than zero, and determine the precipitation frequency and the total amount at the end of the month, or the year. The yearly series is composed of 365 daily values of which 36 exceed the 90-percentile. In such a case, the RP of precipitation exceeding the 90-percentile is 10 days, irrespectively of the specific record under study, be it Beccari or any other. This approach is not useful to characterize a certain climate period, as shown in a previous paper (Camuffo et al., 2018).

(2) Only the daily amounts greater than zero are considered. The precipitation frequency and amount at the end of the month, or the year, are the same as the previous case. However, the yearly series is composed of less than 365 values and the percentile distribution is different, having been rejected the values equal to zero. In such a case, the return period of values exceeding 90-percentile is variable and depends on the record under study. This approach does provide results useful to characterize a certain climate period, and has been used in this paper. In this context, in the Beccari series, the 90-percentile RP was 42 days, to be compared with the 1961-90 reference period characterized by average frequency of 81 rainy days/year and 45-day RP. However, this difference might be affected by the different threshold between the Beccari instrument and the modern ones.

Supplement to Section 3.6: Yearly Precipitation Amount Anomaly

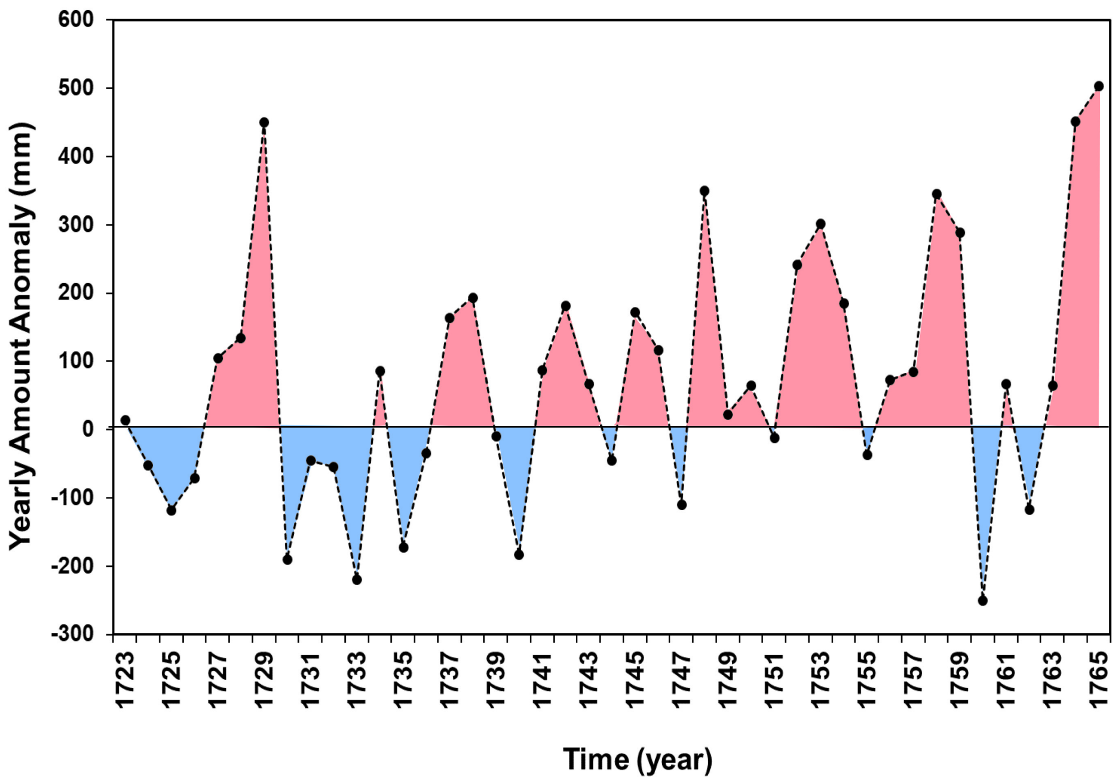


Fig.ESM.14 Yearly amount anomaly (difference between the total yearly amount and the average yearly amount of the 1961-1990 reference period)

Concerning further evidence on dryness in the Beccari period, there are two sources related to the same geographic area, i.e., Bernardino Fiandrini (1794) and Giuseppe Toaldo (1770). The information reported, however, does not point out extreme events.

Fiandrini mentioned a famine that occurred in Ravenna (70 km east of Bologna) in 1736 for food shortness and a severe dryness in May 1756. The dryness over Europe in 1779 is out of the period of interest for the Beccari series.

Toaldo, relying on Poleni observations, noted that the driest years in Padua (130 km north of Bologna) were 1740 and 1762, followed by 1726, 1737 and 1741.

Therefore, the observed negative anomaly is a result of the analysis of instrumental record and it is not specifically mentioned in documentary sources, probably because it did not reach enough severity to cause remarkable social impact.

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