Three centuries of daily precipitation in Padua, Italy, 1713-2018. Part I: history, relocations, gaps and homogeneity

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Abstract
Long instrumental records are fundamental to study climate changes, but their reliability and quality have to be checked before any statistical research. Moreover, when metadata are used to solve some problems, data interpretation may change and require further work to refine the series. A thorough revision of the three-century precipitation series in Padua (1713-2018) shows that the results of previous analyses were affected by serious biases. This paper clarifies key features concerning early instruments, exposure, relocation and observational protocols. The daily analysis pointed out a number of problems, bias, irregular sampling and underestimations that have passed unobserved so far. A comparison with the parallel series of Bologna and Venice made it possible to distinguish bias from the climate signal or to reconstruct missing data. The instrumental threshold was recognized to be fundamental to determine the frequency of precipitation, but less important with respect to its amount. This paper provides a methodological example to test the goodness of long instrumental series, in particular to identify problems related to metadata and observations, which is the preliminary step to perform a sound correction and obtain a reliable series.

Keywords. Climate change, Precipitation, Early instruments, Raingauge, Long instrumental series, History of meteorology

1. Introduction

The mathematical analysis of long instrumental records is the basis of our knowledge on climate change. However, the scientific and technological progress occurred from the early period and other circumstances may have affected in different ways the data quality. Long records may be composed of readings with uneven quality, but this is not always evident and biases may be interpreted for climate signal. Statistical tools are available to detect discontinuities in a series, but they don't give any indication on how to correct data, a delicate operation that has to be performed coupling mathematical results with metadata. The long precipitation series of Padua, Italy, constitutes a methodological example to identify problems and find solutions.

In the antiquity, the raingauge was known in India and Palestine, and in the middle age in China and Korea, but not in Europe. At the Padua University, where Galileo Galilei and Santorio Santorio invented and improved the thermoscope (Camuffo 2019), Benedetto Castelli was a student of Galileo and in 1639 "invented" the raingauge (Castelli 1639). In 1709, in the same University, Marquis Giovanni Poleni, Professor of Astronomy and Meteors (with reference to the Aristotle's books of Meteors), built thermometers and barometers (Poleni 1709) and began to take meteorological observations, but irregularly, until he joined the network of the Royal Society, London (Jurin, 1723). This record was continued by Giovan Battista Morgagni, Giuseppe Toaldo, Vincenzo Chiminello and others, and is still going on. The series is almost unbroken over 3 centuries, with only 1.8% missing data, potentially recoverable from qualitative daily weather Logs of other observers in Padua or daily records taken in neighbouring towns. All original Logs and related documents are preserved in the Historical Archive of the Astronomical Observatory (HAAO), Padua, and the Marciana Library, Venice.

The series constitutes a mine of historical and climate information. Over the centuries, it was studied and commented by several scientists, most of them based in the same building where measurements were taken, therefore they could have examined most details. In the past, the main studies were performed by Toaldo (1770), Zantedeschi (1869), Lorenzoni (1872), Millosevich (1881), Favaro (1906), Padova (1913), Eredia (1921) and Crestani (1926a, b, 1935). In recent times, the research has continued intensively regarding: precipitation (Camuffo 1984; Marani and Zanetti 2015), historical context (Camuffo 2000, 2002a, 2019), temperature series and early thermometers (Camuffo 2002b, c; Cocheo and Camuffo 2002; Camuffo and Bertolin 2012), air pressure (Camuffo et al. 2006), relative humidity and early hygrometers (Camuffo et al. 2014).

Despite the previous publications, precipitation remains still obscure for a number of unsolved problems related to instruments, exposure, incorrect or irregular sampling, that will be considered in this paper. More precisely, Camuffo (1984) recovered from the original Logs and analysed monthly precipitation. However, it was not possible to evaluate and separate the climate signal from observations and instrumental bias because: (i) the monthly resolution was too low; (ii) it was unknown that the observational protocol was disregarded by some observers; (iii) no other contemporary series was available in the same geographic area for comparison.

After that, a lot of drawbacks and obscure items were pointed out, that made necessary the revision (with correction or integration) of several decades of the record, as specified later. In addition, the study of the contemporary series of Bologna (Camuffo et al. 2016, 2017, 2019) and Venice (Pollaroli 1764-67) made it possible to clarify and reconstruct the obscure periods and conclude this long study with a methodological effort described in this paper.

Marani and Zanetti (2015) recovered the data from the original records as they were, without caring the history of the datasets selected to compose the series. The original raw data are affected by inconsistencies and thus include heterogeneous sources of uncertainties that may affect the results of statistical analyses.

This paper is devoted to the recovery and revision of data and metadata (e.g. the most likely description of the earliest instruments, their location and exposure that were unknown in the early period), and individuate observational errors, in order to investigate non-homogeneous periods and turning points, provide methods to correct the series and fill gaps, taking advantage of contemporary sources. The aim is to produce a high quality daily series, carefully checked and corrected for observational errors and obscure periods. A second part will follow, with the corrected dataset of this precipitation series and the analysis of the climate signal.

2. Main periods of the precipitation series

An overview of the series and the location of the stations are reported in Fig.1.

1709-1718. The earliest observations by Giovanni Poleni

Giovanni Poleni knew the Castelli raingauge, i.e. a simple glass vessel with cylindrical shape and open top, about 30 cm deep and 15 cm in diameter exposed on the free land, and knew that Towneley from 1677 to 1704 and Derham from 1697 to 1716 measured precipitation with a funnel fixed to the roof and a pipe transporting water to a reservoir in a room under it. However, he never specified his preferred exposure, either at ground level or on the roof. It is possible that till 1718 Poleni used a simple vessel or a metal box to collect rain. A metal box with open top was the most popular solution for funnels in the XVIII century because cubic funnels were easy to build respecting a selected size and were very effective in catching snow and hail, without splash-in and splash-out. The building location is also unknown, except that it was at his first house, left in 1718, about 1 mile (1.6 km) far from his new house (CF 1725) (label 1 in Fig.2).

The readings from 1709 to 1715 were lost and only the yearly precipitation for 1713 and 1714 are known because they were reported in a copy of a confidential letter, marked CF (1725) and

addressed to Andrea Forzadura (Fig.ESM1). From 1716 to 1725, a Log exists, written in Italian, with columns for observations of air pressure, temperature, precipitation and weather notes (Fig.ESM2) (Poleni 1716-1725). However, only a few pages are filled, i.e. from January to 9 July 1716, from 12 October 1716 to 2 May 1717, and then some random measurements from February to August 1718 when he changed house. The empty pages do not imply that Poleni missed his observations, and the CF letter specifies that Poleni wanted to keep confidential his observations. He intended to produce a complete, well ordered record, but this was never done.
In the CF letter, the amounts are reported without the unit. However, the monthly totals of January to April 1725 differ from the corresponding values in the Log, certainly written in London inch (25.40 mm) and become identical if the values in the CF letter are read as Paris inch (27.07 mm). The yearly precipitation was 715 mm in 1713 and 617 mm in 1714.

January-December 1724. Giovanni Poleni and the invitation of the Royal Society, London

In 1724, Poleni started regular weather observations following the invitation by Jurin (1723) to join the meteorological network of the Royal Society, London. Jurin gave instructions concerning instruments and reading protocols. The funnel was required to be 2 or 3 feet wide (i.e. with square section) and exposed in a fully open location without obstruction of trees or buildings. It should be connected with a reservoir, and any leakage or evaporation loss should be minimized. The collected water should be measured with a cylindrical vessel graduated in inches and decimal parts. The ratio between the sections of the funnel and the cylinder should magnify 100 times the rain depth. Snow should be melted and then measured.
In his letters to the Royal Society, Poleni described his thermometer and barometer (Poleni 1731, 1738) because they differed from the Jurin protocol. The raingauge was not described and one should assume that it complied with the instructions, at least broadly.
Poleni house was a three-storey building, with a big garden, located in San Giacomo District (1 in Fig.2, Fig.ESM3). The raingauge exposure was not specified. Only the yearly total (532 mm) is known, having been reported in the CF letter (Fig.ESM1).

January 1725-March 1764. Giovanni and Francesco Poleni: the regular series, part of the network of the Royal Society, London

In his new house, Giovanni Poleni took regular measurements from 1725 to his death in 1761 and reported the readings in a Log (Poleni and Poleni 1716-1763) kept in HAAO. The Log is in Latin, in good order, with data in columns, one month each page, one reading a day and very clear handwriting (Fig.ESM4). In the XVIII century, the classical language for scholars was Latin and Italian was used for notes or personal use. Poleni published the first decades in the Transactions of the Royal Society (Poleni 1731, 1738) and the Academy of St Petersburg (Poleni 1740).
Poleni made personally his observations, but instructed a servant to perform readings when he was absent, e.g. in the hot July or August. His son Abbot Francesco assisted Giovanni and continued from his death until April 1764, when he moved to the convent of the Filippini Fathers (3 in Fig.2). In the new location, the temperature readings became different and Giuseppe Toaldo, the new Professor of Astronomy and Meteorology, discouraged Francesco from continuing, causing a gap.
Neither Giovanni nor Francesco gave indication about the raingauge, its location and exposure. Toaldo who had close contacts with Francesco and saw the instrument, specified that the funnel was a box with square section and flat bottom, and that Poleni measured the collected water by dipping a graduated rod into the vessel (Fig.2a) (Toaldo 1770).
Poleni certainly measured at home (Camuffo 1984, 2002a) because: (i) he taught at home; (ii) barometer and thermometer were kept in his library; (iii) all the observations were taken simultaneously; (iv) readings continued till the last day of life, and beyond with Francesco; (v) Toaldo saw the instrument. The raingauge could be located in the garden, following Castelli style. This required to locate the instrument in an uncomfortable position far from the house. In addition, the Bovetta canal, flowing on the side (Fig.ESM3a,c), sometimes flooded the garden and some

rooms. The other option was the funnel on the roof, as Lorenzoni (1873) and Crestani (1935) believed, but without explaining why. Toaldo saw the raingauge exposure, but not mentioned it because he considered it obvious: this leads to suppose that was the same exposure that Toaldo kept later, i.e. the roof that had free horizon in all directions. This responded to the Jurin request, and followed Towneley and Derham. The roof exposure was typical in the XVIII century and was recommended by the *Societas Meteorologica Palatina*, Mannheim (Hemmer 1783; Camuffo 2019). Cotte (1788) illustrated the method: the funnel was fixed on the top of the chimney, a pipe descended through the chimney and reached a collecting vessel located in a room (Fig.3a). For Poleni, the most likely position (Fig.3b) was the chimney above the library on the first floor, where he kept barometer and thermometer, and never made fire, as recommended by Jurin (1723), so that the pipe was compatible with the chimney. The eastern chimney had also the advantage of minimizing the building disturbance, because in Padua most of the rain comes from North-East (Camuffo et al. 1988) (Fig.ESM3d).

1740-1768. Morgagni and his parallel observations

Giovan Battista Morgagni was a good friend of Poleni and assisted him in 1709, when he built his thermometers and barometers. In 1740, he decided to start a parallel series with indoor/outdoor readings for medical purposes. Morgagni observed at home, in S. Massimo Street, one mile from Poleni house (2 in Fig.2). The Log (Morgagni 1740-68) was in Italian and the handwriting was good in the early period, but worsened with the age. Time was computed in Italian style, i.e. the new day started at sunset, and the observing time, i.e. sunrise and two hours after noon, apparently changed over the calendar year. The Log is composed of pages with columns for date and hour (two readings a day, plus a note for the night), barometer, external and internal thermometers, and weather notes from which it is possible to know whether the day was clear, cloudy, foggy, rainy, snowy or dewing, with some specifications and adjectives useful to classify intensity, amount or duration (e.g. a few drops, drizzle, light rain, rain, continuous rain, heavy rain) and distinguish precipitation from condensation (Fig.ESM5).

The main gap: April 1764 – December 1767

From April 1st, 1764, when Francesco Poleni moved, till 1768, when Toaldo started his observations, nobody recorded the daily amounts. However, these are reported in black ink inside the Morgagni Log, as if Morgagni had continued using the raingauge of his dead friend. Toaldo acknowledged of having filled himself the gap from April 1764 to December 1767, by writing the amounts of months with equal precipitation frequency (Toaldo 1770). This is equivalent to suppose a constant ratio between frequency and amount. Crestani (1935) tested this approach and found that it was not good. In the last part of his life, Crestani worked to recover the contemporary observations, but could not publish them.

Two methods exist to fill the 1764-67 gap: using indexes or a nearby station. In the former method, the accurate descriptions in the Morgagni Log can be transformed into an index and quantitative values, using for calibration the observed amounts in the Poleni record over the 24-year common period. This method follows a long tradition for documentary sources (Rodrigo et al. 1994; Brázdil 1996; Alcoforado et al. 2000; Diodato 2007; Domínguez-Castro et al. 2008, 2012, 2019; Camuffo et al. 2011; Fernández-Fernández et al. 2014; Santos et al. 2015). The second method is based on contemporary records from nearby sites, and Venice, 37 km East of Padua, was the closest one. In this period, the *Giornale di Medicina* (Medicine Journal) published monthly weather tables with daily observations made by Tomaso Temanza (April to July 1764) and Nicolò Pollaroli (August 1764 to December 1767) (Fig.ESM6). They used a very simple raingauge: a cubic box made of copper, with flat bottom and vertical walls. In the literature, several long precipitation series were obtained by combining records taken at different sites in the same geographic area and/or at different levels from the ground, although this opens issues concerning the homogeneity of the resulting series (Wales-Smith 1971; Craddock 1976, 1979; Craddock and Craddock 1977;

Craddock and Wales-Smith 1977; Wigley et al. 1984; Wigley and Jones 1987; Demarée et al 2002; Alcoforado et al. 2012; Burt and Ferranti 2012; Todd et al. 2015; Murphy et al. 2018; Burt and Burt, 2019).

On the yearly or monthly timescale, the precipitation in Venice is highly correlated to Padua and is 8% less; however, on the daily scale, local phenomena may lower the correlation. A critical comment on the two approaches will be made in a future paper.

January 1768- July? 1771. Toaldo at the Specola during the refurbishment works

In 1764, Giuseppe Toaldo was appointed to the chair of Astronomy and Meteorology. He was charged to adapt the main Tower of the mediaeval castle of the Carraresi and transform it in Astronomical Observatory, called the Specola. During the refurbishment works, thermometers and barometer were relocated, but no mention was found about raingauge relocations, neither in Toaldo papers, nor in the handwritten documents of HAAO, nor in Lorenzoni (1872). The most probable position can be deduced from the time flow of works that started from the top of the main Tower (Lorenzoni 1921). In September 1767, the masonry works for the upper Observatory on the top of the Tower were concluded and a temporary pavement for the terrace above it was set in place. In this terrace (Fig.4a, Fig.ESM7), three small towers for the astronomical observations were built between May and September 1771. From January 1768 to May 1771, this terrace was the only possible exposure, with completely free horizon. It was 50 m above ground level, but uncomfortable due to the too many steps to climb.

The raingauge (Toaldo 1770, 1781, 1786, 1797) (Fig.3b) was composed of a cubic vessel collector, 1 Paris foot side length, and another narrow vessel, where the collected rain passed, closed around to avoid evaporation loss. The measurement was made using three cubic cups (Fig.3c) with 1, 2, and 3 inch side length, having 1, 8 and 27 inch^3 capacity. The small cup corresponded to 1/12 line or 1/144 inch of precipitated water (0.188 mm).

Toaldo considered precipitation "any form of water falling from the sky, i.e. rain, snow, hail, dew, fog or any other type" (Toaldo 1770), i.e. when the raingauge collected some water, even originated by condensation (e.g. dew and fog). It should be noted that in the WMO definition of precipitation (WMO 1966, 1975, 1992), dew and fog are excluded, and they are not recorded by the modern raingauges with heated funnel. In long series, this critical factor may introduce discontinuities: it may markedly change the precipitation frequency, less the amount.

August 1771- December 1811. Toaldo and Chiminello at the Specola, and the Societas Meteorologica Palatina, Mannheim

In August 1771, the works on the eastern terrace at mid Tower level (24 m above ground) were concluded (Lorenzoni 1921). The terrace was planned to host the raingauge on a protruding border of its eastern side, between two small turrets located on the corners (Fig.3a, Fig.ESM7).

Toaldo started his observations with the aim of continuing the Poleni series (Toaldo 1770) and worked alone till 1777. After, he had an excellent co-worker, his nephew Vincenzo Chiminello. Toaldo was a good and accurate scientist but his handwritings are not always clear or in good order Fig.ESM8a,b). Chiminello was very accurate and precise (Fig.ESM9). In 1783, they adhered to the network of the *Societas Meteorologica Palatina*, Mannheim (Hemmer 1783; Toaldo 1794). Toaldo ceased taking observations 3 days before his death, the 11st November 1797. After, Chiminello was appointed to the same chair and became Director of the Specola. The assistant astronomer Giovanni Santini and the technician Giovanni Battista Rodella were charged of the meteorological observations, and the assistant astronomer Francesco Bertirossi-Busata of the astronomical calculations. When in 1811 Chiminello had the second apopleptic fit, he was unable to teach, lost the control of the activities, abandoned the Specola and died in 1815. Although he was officially the Director, in 1812 the chair of Astronomy was unofficially assigned to Santini. This introduced a formal gap in the direction and the data quality of the series started worsening.

Toaldo Log is in Italian, but the period 1780-86 was later published in Latin, with comments and notes under the Padua Academy (Toaldo 1786; Toaldo and Chiminello 1789, 1794). Although with some exceptions, Toaldo gave clear indication about the instruments and their location (Toaldo 1781, 1797) in the yearly *Giornale Astro-Meteorologico* (Journal about Astronomy and Meteorology, see ESM).

January 1812- August 1836. The sickness of Bertirossi-Busata and Conti

In 1812, Santini charged Bertirossi-Busata of the weather observations. However, from 1816 he suffered gallbladder and liver sickness and was less disposed to climb the long stair and observe the collected water under the rain. Observations were prevalently made when the rain stopped: they became irregular, most amounts were referred to the water collected in the previous day and the delayed reading increased the evaporation loss. Bertirossi-Busata operated alone and in the last two months of his life, September and October 1825, observations are missing. Rodella continued the observations until a new assistant, Carlo Conti, was in charge from 1827 to 1842. However, the quality of the observations remained low. In the precipitation column, the frequency of days with rain amount was penalized. Rainy days can be recognized from the column of the weather notes, because the observers correctly reported short descriptions, e.g. rain, light rain, a few drops, intense rain, snow, snowflakes and other details, but without the correspondent amount in the precipitation column. The irregular sampling had a minor effect on the monthly totals, but generated false extreme events when the cumulative amount of one, two, three or even more days was read.

The Log (Fig.ESM10) is apparently in good order, but reports contradictory values and notes, e.g. rainy days without precipitation amount or huge amounts in clear days. A precious support is given by the yearly climate reports published by the medicine doctor Jacopo Penada in the *Giornale Astro-Meteorologico* and in other publications where he linked medicine with climate from 1786 to 1827.

The raingauge (Fig.2d) was built by Rodella under the supervision of Chiminello (HAAO document Contabilità, b. XLVI, Ledger I). The funnel was a cubic box, made of copper, 1 Paris foot side length, as before. The water percolated through a small hole into a cylindrical, vertical vessel, whose internal diameter was about 64 lines, i.e. 144 mm. The two sections were 144 and 22.33 inch^2, and the precipitated depth was magnified 6.45 times (Lorenzoni 1872). A glass tube was connected to the bottom of the vertical cylinder, parallel to it, to make the level of the water inside the cylinder visible. A graduated scale was placed behind the tube. With the above magnification, 1/12 of Paris line of precipitated water was equal to 1.2 mm in the glass tube. This was a useful technological advancement to make readings easier. Similar raingauges (Fig.2e) were in use at Zwanenburg, The Netherlands, from 1735 to 1861, designed by Petrus van Musschenbroek who took inspiration from Poleni (Burnings 1789). In reality, Poleni never built such an instrument, but discussed this principle, i.e. the equilibrium of liquids in communicating vessels with different sections (Poleni 1709; Fig.2f). The raingauge exposure was unchanged.

September 1836 - December 1837. The works on the terrace. In September 1836, Santini decided to demolish the two turrets on the eastern terrace (Fig.4a; Fig.ESM7) and in the middle between them, in the position where the raingauge was located, he built a Meridian Circle Room with octagonal section (Fig.4b-f). The eastern terrace was small (9.30 m x 4.60 m) and during the works the raingauge had to be moved because it constituted an obstacle to workmen, the funnel would have been filled with lime dust and the reading glass tube would have been obscured. Neither Lorenzoni (1872), nor other sources mention if and where the raingauge was moved. The Log has neither gaps nor comments. This suggests that the displacement was close and easy. The most probable location (Fig.4ab, Fig.ESM7) is the small terrace surrounding the main Tower, 38 m above ground level. Another possibility is the 1768-71 uncomfortable position on the top of the Tower, but this is hardly credible because the observer Conti minimized any effort for meteorological observations.

January 1838- December 1877. The dome used as water collector

The octagonal Meridian Circle Room was finished in June 1837 and Santini decided to use the metal dome as an enormous funnel, 27.485 m^2 (Fig.4c-f). In November 1838, the dome was connected with a metal piping system and measurements started from January 1838 (HAAO documents; Lorenzoni 1872; Favaro 1906; Crestani 1935). The collected water was transported via gutters into a copper-lined wooden box with 1.482 m^2 section, so that the precipitation depth was magnified 18.55 times (Fig.ESM11). The dome was convex with 25 deg average slope and was not convenient to catch hail, windborne snow, drizzle or showers with strong wind; however, it was very big and its performance was better than the previous small cubic funnel. The level was 27-28 m above ground.

The Log bookbinding missed the pages from May to December 1838. In this period, the astronomical logs and the *Giornale Astro-Meteorologico* report the monthly totals and daily notes including the frequency (Fig.ESM12). However, the daily amounts are lost.

Examining the Logs, readings continued to be performed after the end of the precipitation, e.g. the day after, or collecting together the amounts of two or more precipitation days (Fig.ESM13). The reading delay continued even in days of persistent rain, and the first amount was reported the second precipitation day and the last amount the first clear day.

In the 1860s, when Italy was reunited, an effort was made to organize a national weather service, homogenize observations and send them to the Central Office, Rome. In 1865, Lorenzoni was charged of this responsibility and the situation was improved from 1867 to 1871. Since 1867 the readings followed the schedule of the Central Office and were published on the journal *Meteorologia Italiana* (Italian Meteorology).

January 1878-1937. The roof of the building next to the Specola and the end of the meteorological records

When Lorenzoni became Director of the Specola, abandoned the dome and installed new funnels on the top of the roof of the building next to the tower (the so-called Astronomer House), 18 m east of it, 20.7 m above ground level (Fig.5f). A pipe transported the collected water in the underlying room, 5 m under the funnel, where it was measured.

The first raingauge was built by the technician Giuseppe Cavignato in copper, brass and iron frames (HAAO document, Contabilità, b. XLVI, Ledger III); the funnel was pyramidal with square base of 0.4 m^2 (Fig.ESM14) (Favaro 1906; Crestani 1935). A pipe transported the collected water into a cylindrical vessel located in the room below it. The ratio between the sections of the funnel and the collecting vessel magnified it 22 times. The bottom of the cylinder had connected a vertical glass tube to measure the precipitation depth. The diameter of the glass tube was 10 mm to avoid capillarity. It had a discharge tip. It was installed and calibrated in 1877, but the regular record started in 1878.

In this period, an effort was made to homogenize the Italian weather observations and the Direction for Agrarian Meteorology, Rome, sent a standard raingauge, Agrarian Model (see later), 1000 cm^2 funnel section, to substitute the Cavignato gauge. It was used from 1880 to 1910.

In October 1910, the Hydrographic Bureau of the Water Magistrate sent a self-recording raingauge (Fig.3g). This was the siphon self-discharging instrument invented by Hellmann and improved by Palazzo (Camuffo 2109). Lorenzoni added a funnel, with conic shape and 36 cm internal diameter (Fig.ESM15), connected via a pipe to the recording instrument. The two funnels were located close to each other and the two measuring instruments were in the same underlying room.

In 1937, the meteorological records were definitively stopped because the Director Giovanni Silva decided to abandon the astronomical observations in Padua and build another Observatory in Asiago, on the Alps, where the sky was clearer. The project was approved in 1933 and the new Observatory became operative in 1942.

1920-1996. Meteorological Observatory of the Water Magistrate

In 1920, a new Meteorological Observatory of the Water Magistrate entitled to Giovanni Magrini (Fig.6a) was located in Sorio Street, about 750 m west of the Specola, at the edge of the town (5 in Fig.2). The best period was under the direction of Augusto Levi in 1920 and Giuseppe Crestani from 1921 to 1958. Some years later, the Observatory was downgraded to warehouse and peripheral unit with unattended recording instruments that operated till 1996, but with worsened data quality. In its best period, this Meteorological Observatory tested different raingauges and compared their readings and their difference when height changed (Crestani 1935). Three raingauges were installed on the grassland (Fig.6b): UIRMA model, Agrarian model and Tipping Bucket, with the funnel 1.20 m above ground. The operating principles are sketched in Fig.6c-d-e. In 1921, a Palazzo raingauge was installed on the upper building terrace and operated till 1934. The funnel was 11.30 m above ground and was connected to the recording raingauge in the underlying room with a pipe 8 m long. In 1934, the funnel was moved to the lower terrace, 8.5 m above ground. The departure between the instruments on the terrace and those in the garden was less than 10%, the highest values being reached with strong wind. The observation day started at 0 a.m.

1951-1990. The Meteorological Service of the Italian Air Force at the Padua Airport

The Padua Airport (6 in Fig.2) was founded in 1926, but it is small and devoted to small aircrafts and helicopters. Weather observations, according the WMO standard, were regularly taken and digitized from 1951 to 1990. The observation day started at 0 UTC, i.e. 1 a.m. After the Veneto Region established a new public weather network, controlled by the Regional Agency for the Prevention and Protection of the Environment in the Veneto Region (ARPAV), this service stopped gathering weather records for external use.

1980-today. Botanical Garden: Padua University and ARPAV

In 1979, the Department of Biology of the Padua University installed a weather station in the historical Botanical Garden, located in the city centre (7 in Fig.2). It includes a tipping bucket raingauge, with continuous record. Today the station is under the control of ARPAV and data are taken hourly according the WMO standard.

3. Inhomogeneous periods

1737-1742. Poleni (1738) and Toaldo (1770) wrote that the instruments were always kept in the same position. Nevertheless, starting from October 1735, in the cold seasons the thermometer was moved to another room as specified in the Poleni Log (Camuffo 2002). A graphical test of the cumulative precipitation amount (Fig.6a) reveals that from 1736 to 1742 the slope is different from the previous and subsequent periods. This might be explained either with a climate signal or with a funnel relocation. The former should be excluded because the same test applied to the contemporary series by Beccari (Camuffo et al. 2019) in Bologna, 130 km south of Padua, doesn't reveal any change (Fig.6b). The funnel relocation may be justified for personal reasons. In a letter, Poleni (1737) wrote that in the last two years he lost a son and his wife. In the XVIII century, it was not usual to heat buildings but, in the case of sickness, a more comfortable climate was needed because unheated rooms fall below the freezing point. This required the ignition of the fireplace in the library, but this was not compatible with the thermometer and especially the funnel and pipe inside the chimney. Poleni was obliged to relocate the instruments. Every winter from 1734 to 1742, the Log reports a note that "he moved to the kitchen" (Camuffo 2002), that evidently was not used because the fire was lighted in another room. The kitchen is on the western side of the building. Looking at the values of the slopes of the cumulative plot, from 1737 to 1742 the collecting efficiency was reduced by 31% and this is compatible with a funnel more distant from the roof edge, i.e. the edge from which the wind blows (Fig.ESM3d). Whatever the reason and passed the emergency, after 1742 the funnel returned to the initial position as demonstrated by the same angular coefficient of the interpolation lines.

1812-1871. Starting from the Bertirossi-Busata period, the plot of the daily precipitation (Fig.6c) shows lower density of dots especially for amounts smaller than 10 mm. If amounts are represented with vertical lines (Fig.6d), the lines cover the empty space under the dots and the bias is masked. Marani and Zanetti (2015**)** used lines and didn't recognize the bias. This bias can be also evidenced analysing the yearly frequency of precipitation below and above selected thresholds. The result is that in 1812-37 the majority of the light rain disappeared. An example for 5 mm threshold is in Fig.6e. Two periods can be identified: 1812-1837 (Bertirossi-Busata and Conti period) and 1838-69±2yr when observations were made using the dome (Santini period). The last turning point is not precisely defined and occurs before the Meridian Circle was dismissed in 1877 (Favaro 1906). The 1867-71 transition cannot be explained with a change of instrument, but with more accurate observations by Lorenzoni, as discussed before.
The loss of lighter rains is explained with the irregular sampling, collecting the amounts of two or three days together, and longer evaporation loss. The above is confirmed analysing the distribution of the precipitation lasting for 1, 2, 3 or more days. The normalized precipitation frequencies of the critical periods 1812-1837 and 1838-1864 have been compared with the ones of the 1768-1811 and 1878-1937 reliable periods taken as references (Fig.6f). In the reference periods, some 20% of the total time it rained only 1 single day and 10% two consecutive days. In 1812-1864, the percentages changed drastically: single day exceeded 50%, while three and four consecutive rainy days were underestimated respect to the reference periods.
Homogeneity tests (von Neumann 1941; Pettitt 1979; Buishand 1982; Alexandersson 1986) pointed out turning points in 1810 or 1812, and 1843, but missed 1867-71 (ESM). However, the 1737 and 1742 turning points were not found because the change was too weak for these tests. In order to investigate the sensitivity of the above statistical tests, a century of the Padua series that resulted homogeneous was considered: the first half was left unchanged, the second half was modified in order to simulate changes. The first test was made by multiplying readings by a constant factor to simulate what happens when the raingauge is substituted with another one characterized by different funnel size or if it is moved to a different level. In this case study, the homogeneity tests revealed a turning point with a multiplicative factor greater than 1.05 or lower than 0.9. The second test was made with an additive transformation that simulates what may happen if, in the selected year, the raingauge was substituted with another one characterized by a different threshold and it catches a little more or less. The thresholds found were 0.65 mm in additive and 130 mm in subtractive mode.
The problem concerning the change of scheduled observation time is discussed in ESM and illustrated in Fig.ESM16 and Fig.ESM17abcd.

Conclusions

All long instrumental series include uneven periods. Although the Padua series is among the most accurate and best-documented ones, a careful integrated mathematical and historical analysis, with site inspections and study of archival documents and old photographs, clarified some issues, but also revealed a number of unexpected problems. A comparison with other contemporary records in Venice and Bologna allowed to fill gaps and discover some crucial items related to the instruments, their thresholds, exposure and relocation, or due to poor observation regularity. Observations made one or more days after the end of precipitation reduced the frequency and increased evaporation losses. Moreover, the association of the amount of two or three consecutive rainy days affected the distribution, decreasing the light rains and increasing the abundant ones with the risk of creating false extremes. This bias severely affected the results based on daily precipitation, less the monthly ones.
Graphical tests (cumulative amounts, consecutive rainy days) and statistical homogeneity tests (von Neumann, Pettitt, Buishand, SNHT) were applied. Graphical tests resulted more sensitive and homogeneity tests required a certain inhomogeneity threshold to respond. When both tests provided results, they were consistent between them.

This analysis pointed out some critical periods for a total of 70 years. Slightly reduced amounts were caught in 1737-42, when Poleni changed the funnel position. The comparison with the Bologna series confirmed that this was an instrumental bias, not a climate signal. This effect was corrected after the reduced sensitivity factor was recognized.
The 1764-67 gap can be filled either (i) from the notes enclosed on the Morgagni daily records, after having transformed them into quantitative values, using for calibration the observed amounts in the Poleni record over the 24-year common period; or (ii) using the contemporary Pollaroli record in Venice. Then, the homogeneity criteria are helpful to verify which method is the most convenient one.
The two periods: 1812-25, when Bertirossi-Busata was sick and could not take regular readings, and 1826-71, when the next observers continued with irregular sampling, have been recognized and can be (partially) corrected with the help of the daily weather notes and with an evaluation of the evaporation loss.
This research has identified instruments, exposures, observers, observation protocols, different data reporting styles, biases and obscure periods and how to remedy them. Corrections and the climate analysis will be discussed in another paper.

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Figure Captions

Fig.1 Overview of the precipitation series.

Fig.2 Map of Padua in the 18th century (Valle 1781) with the station locations. Before 1718, Giovanni Poleni inhabited somewhere in proximity of the dashed arc, most likely the cyan sector, 1 mile (1.6 km) from his second house (indicated 1). Padova has grown over time and the modern stations 5 and 6 are now inside the city.

Fig.3 (a) Poleni raingauge, 1724-1764. Precipitation was measured dipping a graduated rod. (b) Toaldo and Chiminello raingauge, 1768-1813. Precipitation was measured with three cups. (c) The original measuring cups. (d) Raingauge built in 1811 by Rodella under the direction of Chiminello, used 1814-1837. Precipitation was read on an external glass tube. (e) Raingauge designed by van Musschenbroek (Brunings 1789). (f) Communicating vessels with different sections (Poleni 1709) that inspired the external tube. (g) Palazzo siphon self-recording raingauge (Specola from 1910 to 1937, Water Magistrate from 1921 to 1934).

Fig.4 (a) Scheme of indoor raingauge, pipe connection through a chimney and funnel on the top (Cotte 1788). (b) Poleni house in S. Giacomo District and the most likely position of the funnel on the roof, 15 m above ground level. (1) The chimney above the room, (2) the library with weather instruments at the first floor.

Fig.5 (a) Raingauge exposures on the Specola Tower, before the construction of the Meridian Circle (MC) room (Valle 1781). (b) The Specola today and the various exposures over time. (c) MC in a shot from south-east in 1840. The pyramidal dome was used as funnel 1838-1877. (d) A scheme of the collecting system. (e) The dome today, with added sliding shutters, viewed from the upper terrace. (f) A bird view (1885) from north-east with the pyramidal funnel on the roof, used 1878-1937 (PF arrow). MT northern terrace with meteorological instruments.

Fig.6 (a) A view of the Magrini Observatory of the Water Magistrate in 1920s with the two terraces where the funnels of the Palazzo raingauge were located (Crestani 1926a). (b) Raingauges in the garden of the Magrini Observatory of the Water Magistrate. U UIRMA model, A Agrarian model, T tipping bucket. (c) Operating principle of the UIRMA model: after precipitation, the funnel is removed, the raingauge is tilted, the water is transferred to another bucket and measured. (d) Agrarian model: opening the tap the water flows into a measuring tube and the depth is detected with a graduated rod. (e) Tipping bucket: the bucket movements are recorded with an ink pen in a rotating chart strip drum.

Fig.7 (a) Cumulative plot of the precipitation in Padua. The observations in 1725-36 and 1743-63 (blue line) have the same slope (red best-fit line) while in 1737-42 (cyan line highlighted in the yellow rectangle) the slope is 31% lower. (b) Cumulative plot of the precipitation in Bologna and best-fit line. Plot of the daily precipitation amounts (limited to 60 mm to increase resolution). BC Bertirossi-Busata and Conti period, S Santini period. (d) Daily amounts are represented with vertical lines. (e) Yearly frequency of precipitation with amount lower than, or greater than, 5 mm. (f) Distribution of consecutive rainy days: comparison between the 1812-1837 and 1838-1864 critical periods and the 1768-1811 and 1878-1937 reference periods.

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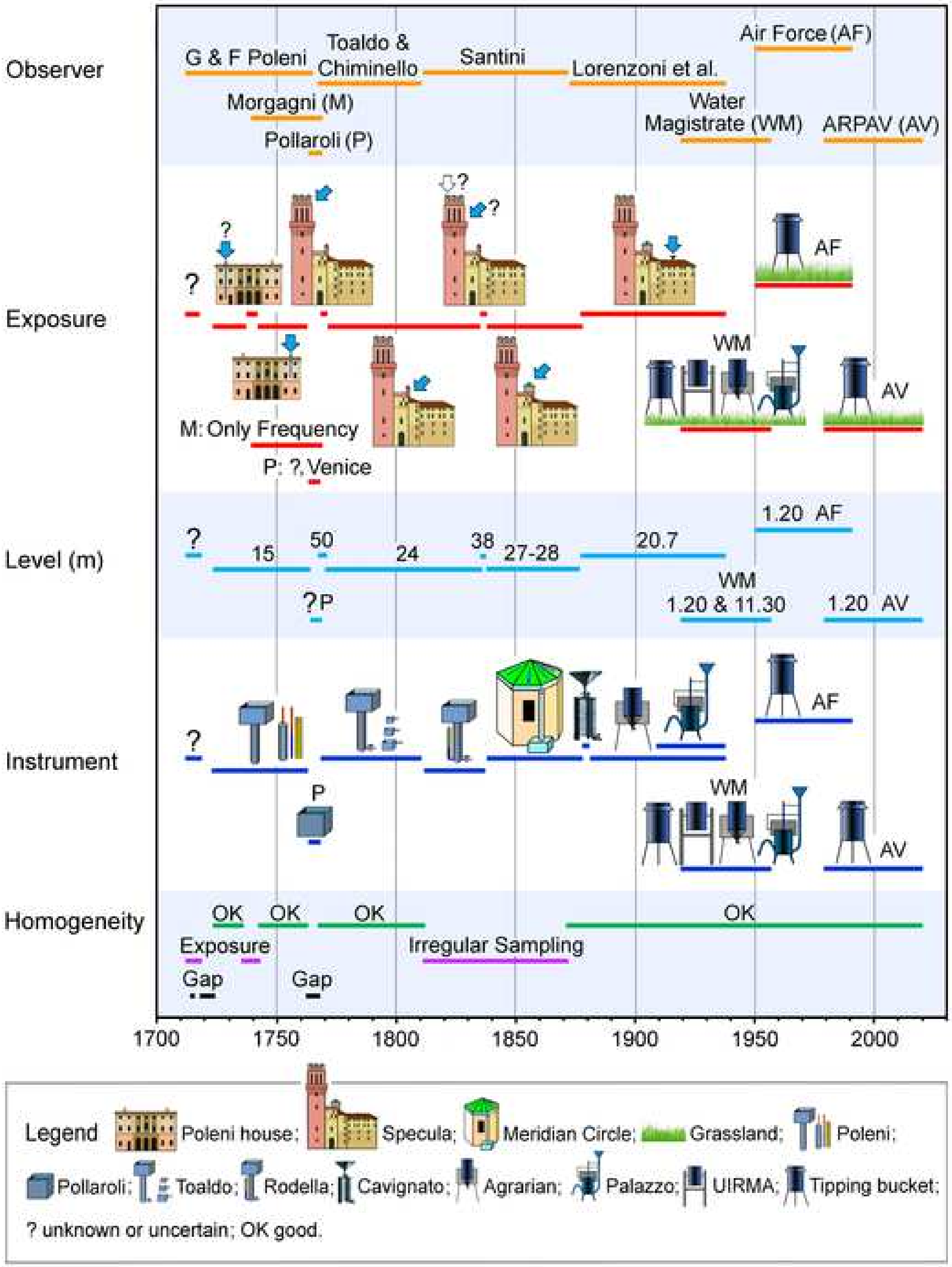
Figure 1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Specula;
Meridian Circle;
Grassland;
Poleni;
Pollaroli;
Toaldo;
Rodella;
Cavignato;
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Figure 2

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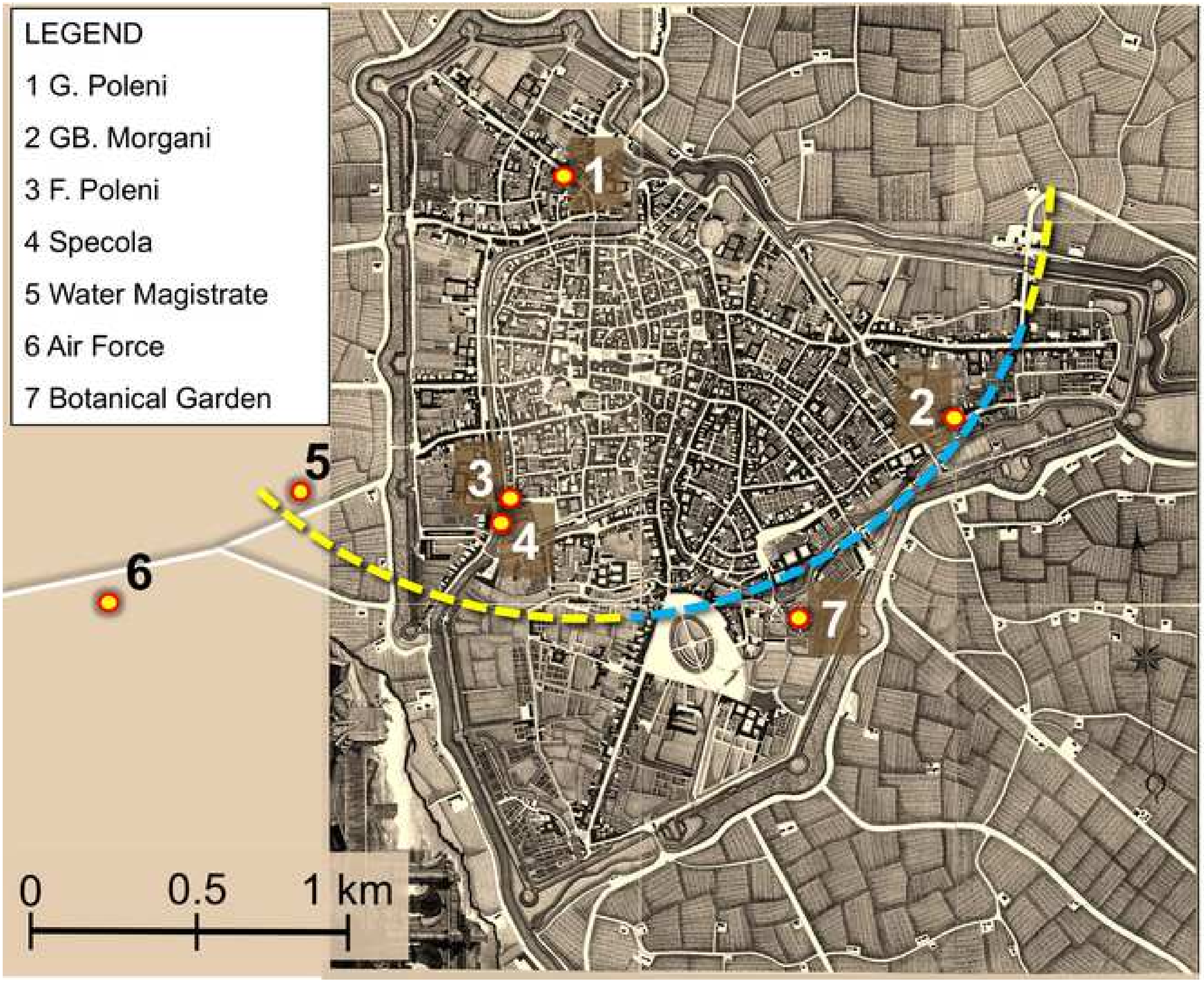

Figure 3

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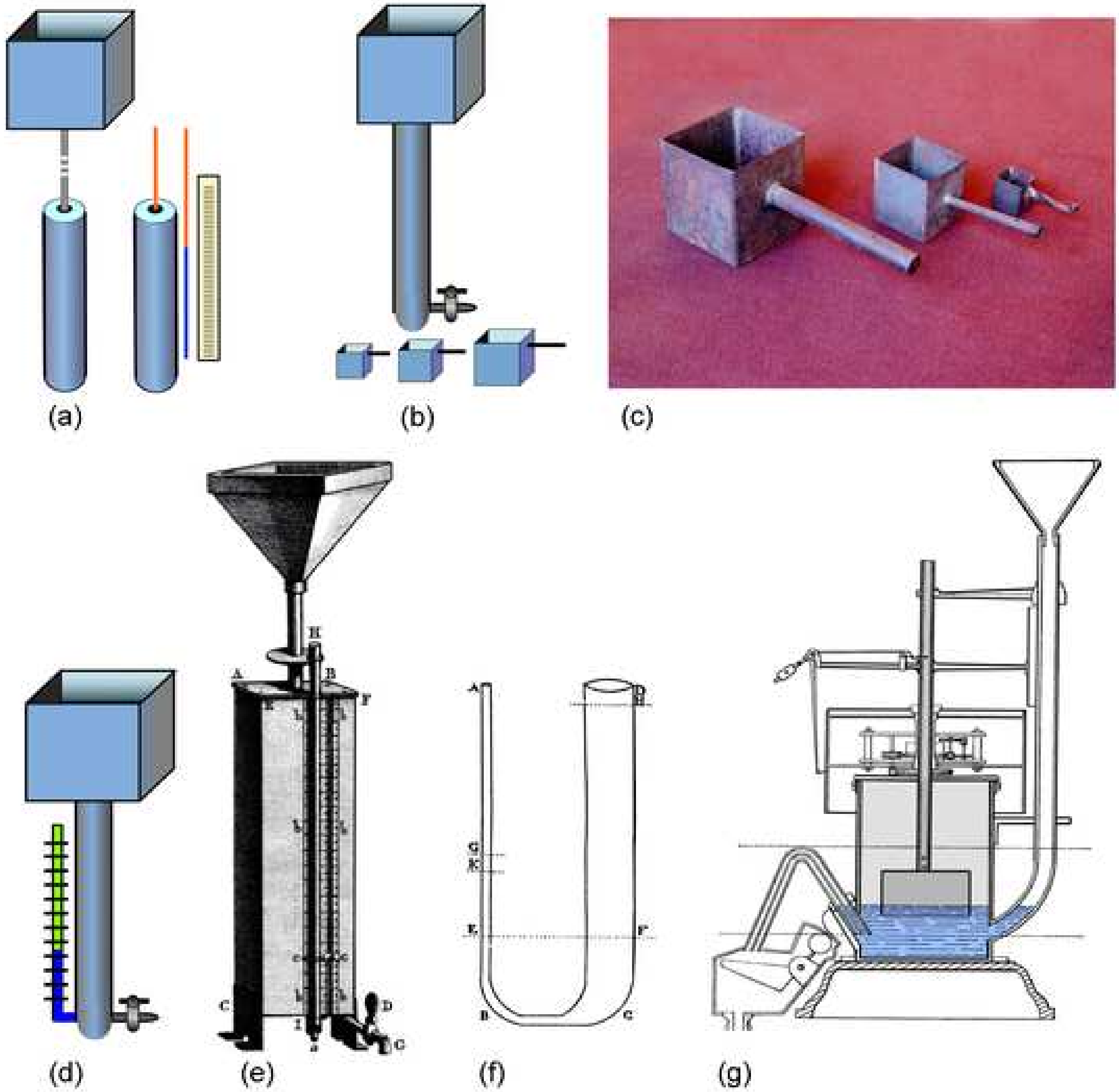

Figure 4

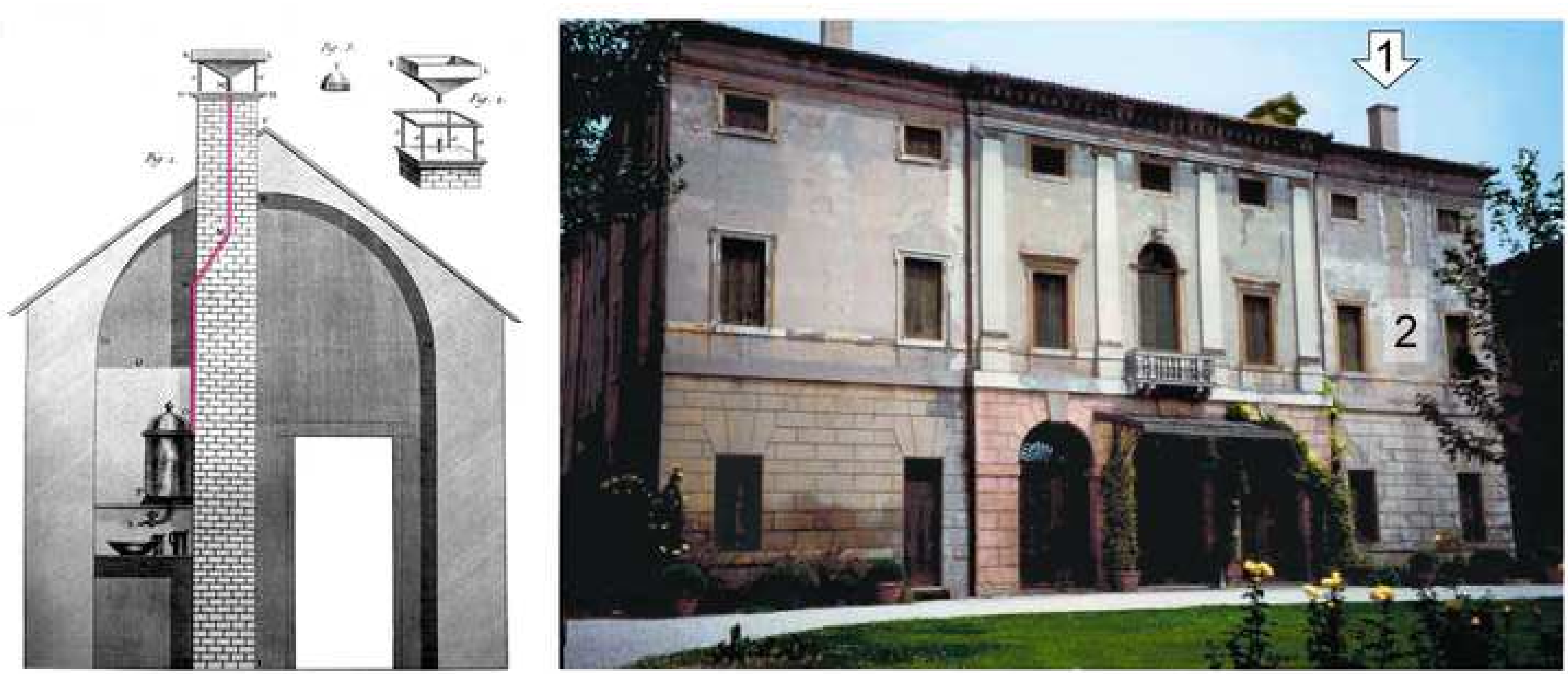

Figure 5

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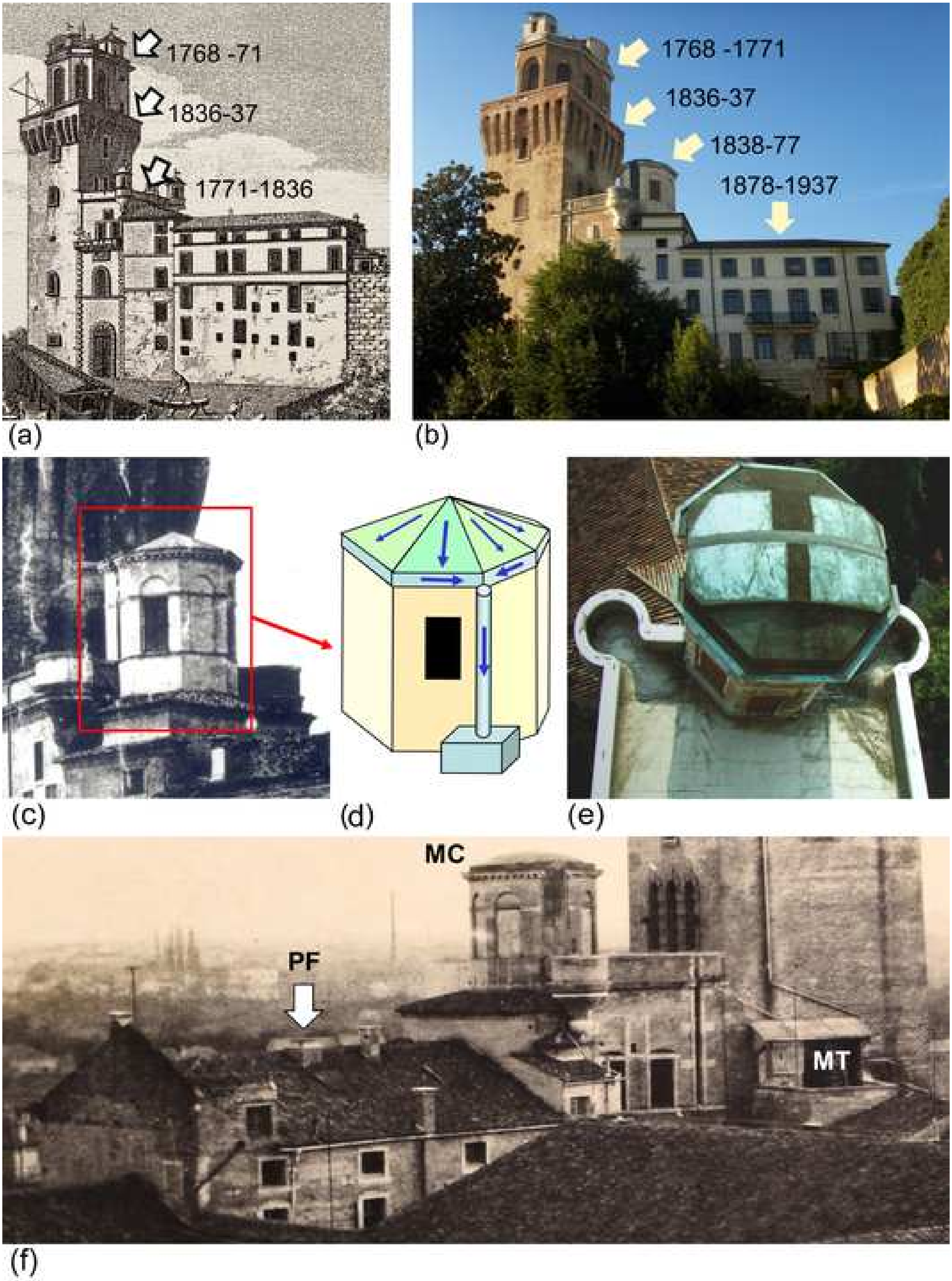

Figure 6

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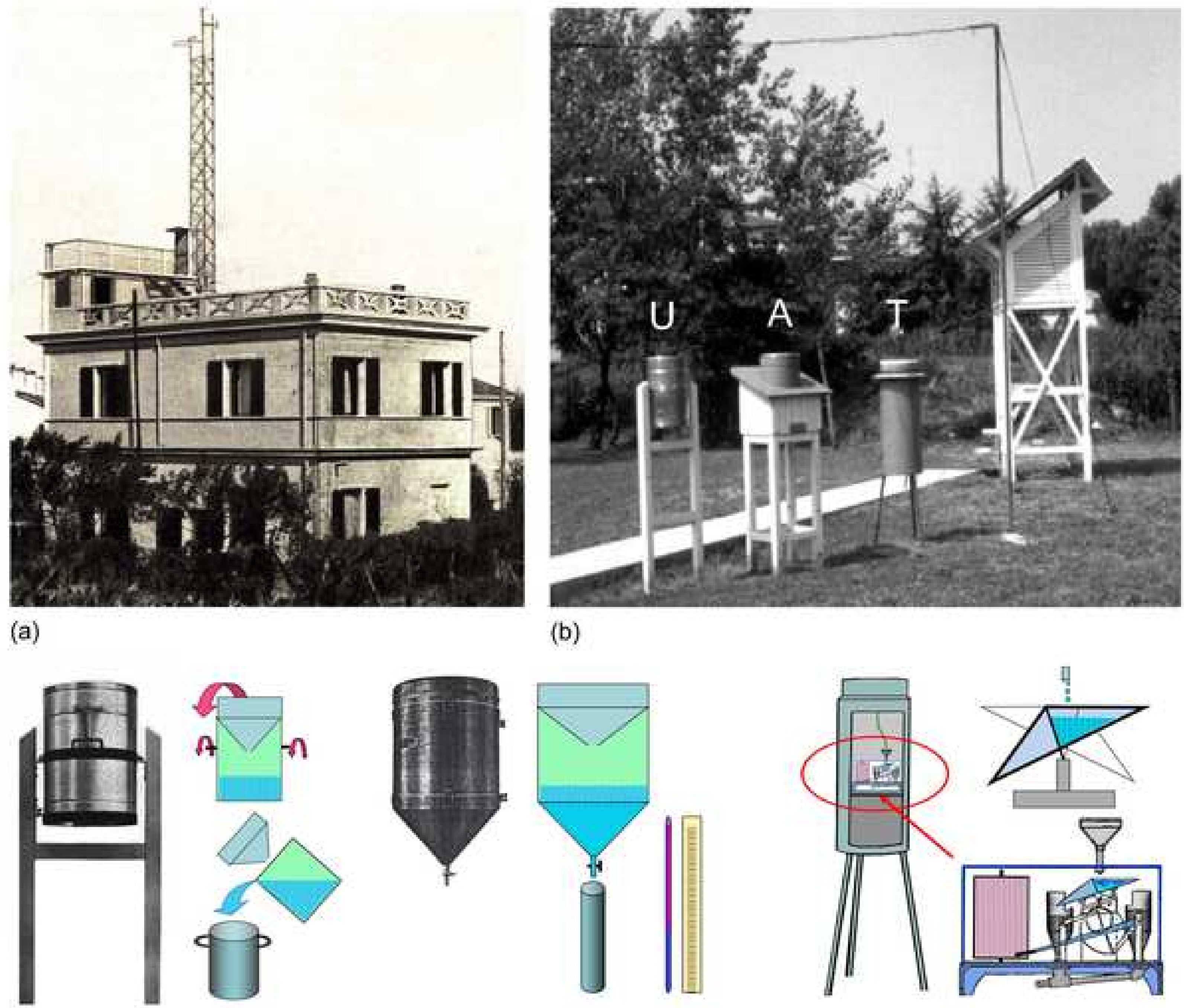

(a)

(b)

(c)

(d)

(e)

Figure 7

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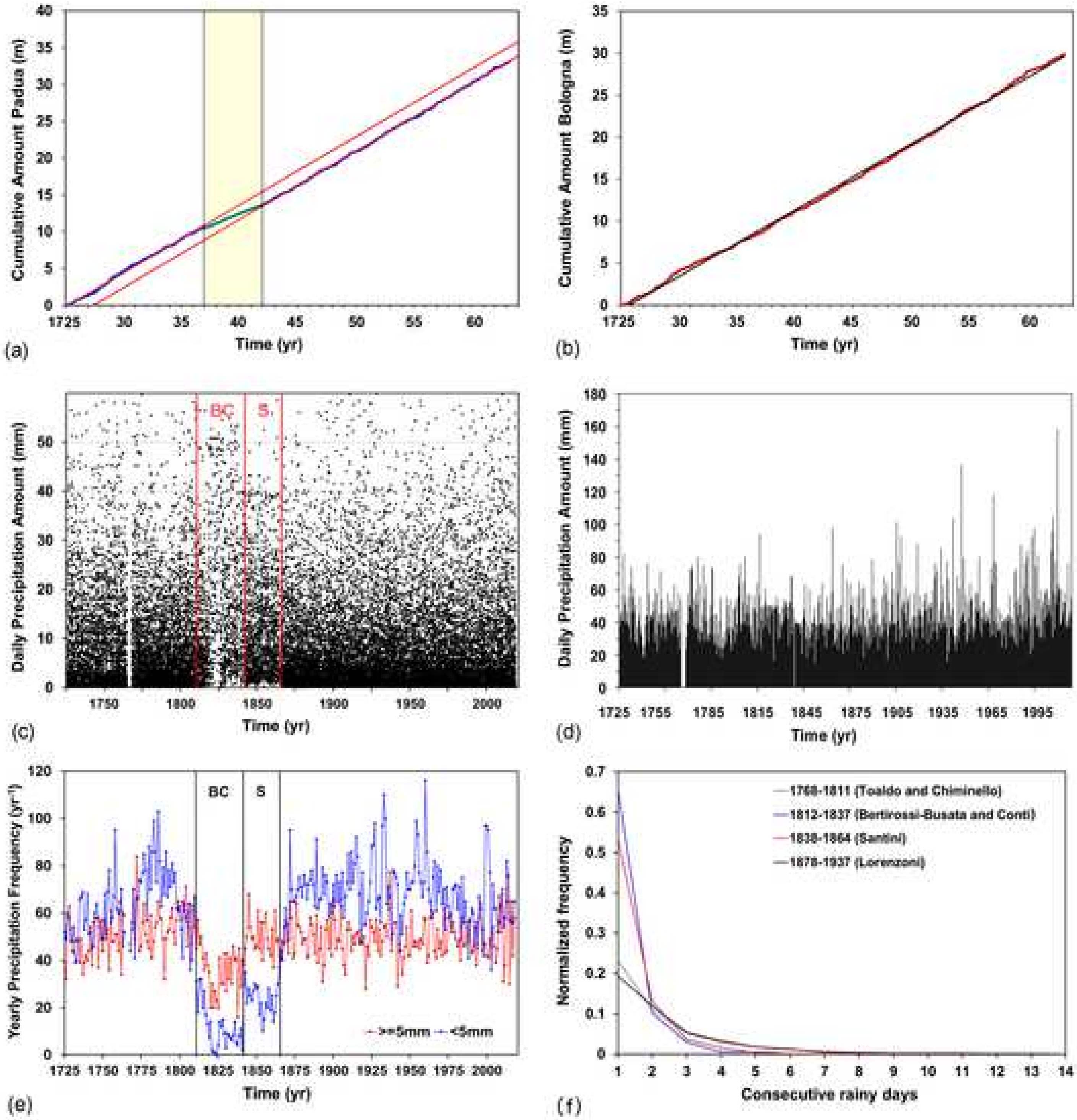

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