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A comparison between different methods to fill gaps in early precipitation series

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Abstract

The aim of this work is to analyse and compare different methodologies to fill gaps in early precipitation series, and to evaluate which time resolution is reachable, i.e. monthly or daily one. The following methods are applied and tested to fill the 1764–1767 gap in the precipitation series of Padua: (1) using a relationship between monthly amounts and frequencies; (2) transforming a daily log with visual observations into numerical values through analysis, classification, and calibration; (3) substituting the missing values with an instrumental record from a nearby, contemporary station in the same climatic area. To apply the second method, the descriptions reported in the Morgagni Logs are grouped in 37 classes and transformed into numerical values, using for calibration the observed amounts in the Poleni record over the 24-year common period. As a third method, the series of Temanza and Pollaroli in Venice is used to fill the gap, and the application of a factor scale based on the ratio Padua/Venice is attempted. The results of these three methods are discussed and commented.

Keywords Daily precipitation · Missing values · Early instrumental meteorological series · Descriptive observations · Documentary sources · Climate reconstruction

Introduction

Extended datasets of past weather conditions are extremely valuable for the assessment of climate change and related consequences. The growing need for high-resolution, high-quality and long-term continuous records has required an enormous effort to recover and reconstruct early precipitation series. Documentary evidence and early instrumental records constitute an important source of data for historical climatology.

Almost all long instrumental series are affected by gaps, due to different reasons, such as instruments malfunctions, poor health or even death of the observer, political changes, wars, and so on. This leads to exclude periods with gaps

from data analysis. Another approach is to try to reconstruct missing values, or validate uncertain records. This is particularly important especially in the early instrumental periods, when the data are scarce, but their recovery, correction and reconstruction are crucial for climate studies.

The problem with precipitation is twofold, since both frequency and amount have to be reconstructed. A number of techniques have been developed over the decades aimed at estimating missing values in precipitation time series, and their performance evaluated. Most of these techniques are hardly applicable to early series, in particular to reach daily resolution, due to a number of difficulties that will be discussed in the next sections.

In fact, when dealing with early series, the task is more challenging, as generally data have to be carefully interpreted and validated, and gaps are quite large (i.e. years). Moreover, most of the methods described in literature requires contemporary datasets from other stations, a condition that is quite rare for early series. Therefore, the choice of the gap-filling method depends strongly on the nature and amount of data and/or metadata available. This paper considers the following methods:

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1. Relationship between monthly amounts and frequencies. Historically, this was the first attempt and it was based on the monthly relation between the total precipitation amount and the number of rainy days. In the presence of gaps, when the frequency was known from narrative sources, the missing amount was substituted with the matched value based on different criteria, e.g. similarities, return periods and so forth (Toaldo 1770; Crestani 1926, 1933). This method was applied at monthly and daily resolution.
2. Transformation of narrative sources into numerical values through analysis, classification, and calibration. The transformation from the narrative format to numerical proxy values is a challenging task, not only because of the difficulties in recovering and interpreting the historical sources, but for the very nature and quality of the proxy. The use of indices or categories in historical climatology follows a long tradition: different scales of indices for series of temperature and precipitation have been developed, and a number of protocols tailored for the typical climate of each specific climatic area have been established (Brazdil et al. 2019; Pfister et al. 2018; Dominguez-Castro et al. 2015a; Fernández-Fernández et al. 2015; Santos et al. 2015; Camuffo et al. 2013; Diodato 2007; Gimmi et al. 2006; Alcoforado et al. 2000; Rodrigo et al. 1994; Ge et al. 2005; Harvey-Fishenden and Macdonald 2021). The reverse approach, i.e. the transformation of reconstructed values into index form to make them comparable to weather descriptions, has also been studied (Bronnimann 2020). The indexation method has been applied to both normal and extreme events (e.g. droughts, storms, floods). This latter application is favoured by the natural tendency to document unusual weather/hydrological phenomena (Brázdil et al. 2012; Domínguez-Castro et al. 2012, 2015b; Barrera et al. 2006; Santorelli et al. 2003; Brunetti et al. 2002). The used scale is generally monthly, seasonal or yearly, and there are very few cases of daily resolution. Dominguez-Castro et al. (2015a) devised a 4-category rainfall index at daily scale, using also sub-daily information. Ge et al. (2005) converted qualitative description into quantitative values using precipitation events in which both were documented, but then the precipitation series was reconstructed at monthly level. In this paper, for the first time, the content analysis has not been limited to the indexation, and the reconstruction of daily amounts has been attempted.
3. Using records from one or more stations in the same climatic area. Several long series have been reconstructed, or had their gaps filled using data from one or more neighbouring contemporary stations, e.g. in the Alpine Region (Auer et al. 2007), in England and Wales (Cradock 1976; Lough et al. 1984; Simpson and Jones 2012);

Iberian Peninsula (Prohom et al. 2016); Portugal (Alcoforado et al. 2000); Poland (Przybylak 2010); Switzerland (Pfister et al. 2019, 2020); Australia (Shubham et al. 2019; Gergis and Ashcroft 2013). In case of long gaps, the missing values in the target location have been calculated by interpolating a number of contemporary observations from surrounding stations using different methods (Kanda et al. 2018; Wollesenbet et al. 2017; Young 1992; Teegavarapu and Chandramouli 2005; Eischeid et al. 2000; Creutin and Obled 1982; Gentilucci et al. 2018; Ruane et al. 2015; Hasan and Croke 2013; Kim and Ryu 2016). The first problem is that more than one simultaneous record must be available in nearby sites with similar climate, and this is very unlikely in the early period, when only a few stations operated. It must be considered, however, that precipitation has high time and space variability, and a great density of stations is needed to assess statistically significant precipitation patterns. In addition, the quality and homogeneity of the datasets is a crucial element (Lanza and Causeruccio 2022). The second key item is the choice of the interpolation method. When only one neighbouring station is available, a high correlation between the two datasets is required to give good predictions (Caldera et al. 2016).

This paper is part of a wider study devoted to the recovery and revision of the Padua series of precipitation from 1713 to 2018. In particular, the following step will be focussed on the period from 1812 to 1864 (Bertirossi-Busatta and Santini periods), for which the major problem was the irregular sampling that generated false extremes at daily level and increased the evaporation loss.

The aims of this paper are: (1) fill a gap of an early series, for which different methodologies can be applied; (2) ascertain the pros and cons of these methodologies; (3) reach the daily resolution. More precisely, this paper compares and discusses the three different methodologies above mentioned to fill a four-year gap in the mid-eighteenth century Padua series (Camuffo et al. 2020) at daily resolution, using contemporary sources. In the same period, in Padua, Morgagni left a precise visual observation and description of the precipitation. In Venice, some 30 km west of Padua, a parallel instrumental record was taken. This fortunate situation gives the possibility of applying and testing different methodologies to the same case study. Another aim is to see whether it is possible to reach the daily resolution, or only the monthly one, and at what confidence level. This is the first time that different procedures are compared to reconstruct the daily rainfall amounts in an early precipitation series.

Materials and methods

Padua dataset: Poleni and Morgagni observations

The history of the three-century daily precipitation series in Padua has been described elsewhere, including data, instruments, exposure, relocation and observational protocols (Camuffo et al. 2020). However, the reader may find useful a short summary to compare the situation in Padua with Venice.

Besides some occasional observations from 1709 to 1718, Giovanni Poleni performed regular weather observations on the roof of his house, from 1725, when he joined the Network of the Royal Society, London, to his death in 1761. His son Abbot Francesco continued until March 1763. From 1768, Giuseppe Toaldo carried out regular instrumental observations on the tower of the Specola.

Giovan Battista Morgagni, a good friend of Poleni made a parallel series with indoor/outdoor readings for medical purposes from 1740 to 1768. Morgagni observed at home, 1 mile from Poleni's house. However, he did not measure daily rain amount, but included in his Log some weather notes, 2 or 3 times per day, specifying whether the day was clear, cloudy, foggy, rainy, snowy or dewing, adding several adjectives useful to classify intensity, amount or duration (e.g. a few drops, drizzle, light rain, rain, continuous rain, heavy rain) and to distinguish liquid and solid precipitation from condensation.

The precipitation series has a gap from 1 April 1764 to 31 December 1767 (Camuffo et al. 2020). The Morgagni Log is apparently regularly filled from 1 April 1764 (Fig. ESM1) to 31 October 1765 (with the exception of April 1765 that is missing), but this was a late reconstruction made by Toaldo. The daily amounts are reported in a column without heading, on the right border of each page, written with a lighter ink, with the same handwriting used in a note at the bottom of the page of April 1764, stating: "NB The measurements of precipitation are estimated, in inches and decimals of the English foot, as Mr. Marquis Poleni used". Toaldo explained (1770) that he analysed the relation between monthly amount and frequency of the Poleni series and then estimated the daily amounts considering the frequency given by Morgagni. The method used for matching frequency and amount is not fully clear, as explained in "Results and discussion".

Both Poleni and Toaldo used cubic funnels. The former had unspecified side length; the latter 1 Paris foot. To reduce evaporation, they fixed a tube to the flat bottom and carried the collected water into a vessel located below. Poleni used a cylindrical vessel and measured the precipitation depth plunging a graduated rod. The reading was amplified by the ratio between the funnel opening and the

vase cross sections, obtaining 0.6 mm resolution. Toaldo measured the volume of the collected water with three calibrated cups with cubic shape (1-, 2- and 3-inch side length), and divided the collected volume by the cross section of the catching funnel (Toaldo 1770). His resolution was 1/12 of line, i.e. 1/144 Paris inch = 0.19 mm.

Venice dataset: Temanza and Pollaroli instrumental series

The period of the Padua gap has contemporary observations in Venice published by Orteschi (1762), Pollaroli (1764) and Temanza (1751). Temanza observed the first part, i.e. 9% of the total gap, and Pollaroli the remaining, i.e. 91%. The former is responsible for a small fraction of the gap, but is particularly relevant because had established the methodology that the latter followed.

Tommaso Temanza was a Venetian architect, engineer and art historian. He studied at the University of Padua, and his most leading teacher was Giovanni Poleni. As Poleni taught at his house, Temanza had the opportunity to become familiar with the Poleni's instruments and he too used an Amontons air thermometer, a barometer, and a rain gauge with cubic funnel. Temanza became chief architect of the Magistrate of the Waterways of the Most Serene Republic of Venice. His interests included the measurement of meteorological variables and the sea level. Temanza was highly regarded and Toaldo reported his data on several occasions, complimenting the author (Toaldo 1770, 1797).

The location and the exposure were not specified. It is very likely that his instruments were at his house, following his reference Poleni. In Venice, the exposure had a very limited choice: a typical terrace to dry laundry on roofs, named "altana" (see Fig. ESM2), or a balcony. Temanza knew well that Poleni measured on his roof, and very likely followed his example. Like Poleni, Temanza observed near noon, when he returned home for lunch, following the astronomers' practice of setting the clock with culmination. Temanza dipped the graduated rod directly into the collecting vessel, and therefore he was not interested in knowing the cross section exactly. However, in the absence of amplification, the resolution was limited to ounces and lines, and was 2.4 mm.

Around the end of 1762, Temanza began to conclude his local business, and decided to leave Venice with his wife for a long cultural trip through Italy, i.e. Florence, Rome, Naples, Ercolano and Bologna (Negri 1830). This explains why at the end of July 1763 Temanza interrupted the series of his meteorological observations published in the *Giornale di Medicina*, and why the Editor Orteschi replaced such a famous person with Pollaroli, who was a normal level professional.

Temanza Logs From 1751 to 1755, the handwritten log is in monthly tabular form reporting the daily readings (Fig. ESM3). The original is preserved in the Historical Archive of the INAF-Astronomical Observatory of Padua (Temanza 1751–1755). Toaldo (1770) published the daily values of the year 1755 and a summary for the 1751–1755 period. Toaldo (1797) witnessed that Temanza made accurate observations, except that he observed once a day, near noon. From 1 January 1761 to 30 April 1762, Temanza published in monthly tabular form the daily readings (Temanza 1762) together with a short note about the yearly totals from 1751 to 1761, but with a gap for 1758–1759 (not observed). From 1 Jan 1762 to 31 July 1763, he published in monthly tabular form the daily readings in the *Giornale di Medicina* (Medicine Journal) edited by Orteschi (Temanza 1762–1763).

Niccolò Pollaroli was a Venetian physician, with interests in meteorology and other environmental factors related to the public health. He published some notes on this topic on the *Giornale di Medicina*, but his meteorological observations were never mentioned by his contemporaries.

Pollaroli succeeded Temanza in the publication of the monthly weather tables from 1 August 1763 to 31 December 1769 and added some notes about public health (Pollaroli 1764–1770). The *Giornale di Medicina* had a gap and returned again in 1773 with the monthly tables published by another Venetian physician, Jacopo Panzani, who also added some comments about the public health.

In the *Giornale di Medicina*, the measurements taken by Pollaroli are presented without metadata (Pollaroli 1764). This suggests that the type of instrument, exposure and reading time were kept unchanged, except for the location that became the Pollaroli's house, which is unknown. The resolution of the precipitation readings, i.e. 2.4 mm, is the same of Temanza, and this confirms that Pollaroli used the same type of rain gauge, i.e. a basic cubic box into with a graduated rod. If the funnel had mouth larger than the flat bottom, the resolution would have been different, i.e. multiplied by the ratio of top to the bottom section. When a few years later Panzani adopted a more sophisticated pluviometer composed of a big cylindrical vessel with a funnel inserted inside to divide the volume in two parts and reduce the evaporation, he reported the characteristics of his instruments in a note to his record (Panzani 1773). At least in the Venice area, rain gauges, constituted a simple cubic catching box, were popularly used by scientists not specifically specialist in meteorology, till the end of the eighteenth century, as confirmed by Trevisan (1793), another physician who published his measurements in the New Series of the *Giornale di Medicina* describing his instruments.

Pollaroli Logs The original handwritten logs are lost. The data have been preserved in form of printed tables in the *Giornale di Medicina*. Each table is composed of columns ordered as follows: day of the month; lunar phases;

barometer; thermometer; weather notes; prevailing wind; rain (Fig. ESM4).

The observations made by Temanza and Pollaroli from 1 April 1764 to 31 December 1767 have been rescued for the aims of this paper, and are available in ESM 6 and 7.

The 1st method: relationship between monthly frequency and amount

Historically, the first approach used to reconstruct missing daily precipitation amounts was based on the relationship between monthly frequency and amount (Camuffo et al. 2020). Toaldo (1770) devised this method to fill the gap from 1 April 1764 to 31 October 1765, and used the Poleni dataset. The method assumes that there is a strong relationship between the known monthly frequency (from local documentary sources) and the unknown amount. However, the amount was not derived by the simple linear relationship with frequency, but it was reconstructed following the observed 9-year periodicity of precipitation based on lunar cycle (Toaldo 1781). Toaldo made a further passage from monthly to daily values and reproduced previous rain sequences. His method is not fully clear and Toaldo himself declared that “the monthly precipitation amount did not correspond always to the number of rainy days, as it might rain for several days, but in small amount”. He concluded that “it is necessary to measure the precipitation amount to establish if a year or month was rainy or not” (Toaldo 1770). Crestani (1935) severely criticised Toaldo's method, even at monthly level.

Over the time, several studies have been carried out to characterise the relationships between rainfall amount, duration and frequency in locations belonging to different climatic areas (Gamez-Balmaceda et al. 2020; Praveen et al. 2020; Nandargi and Mulye 2012; Dairaku et al. 2004; Kral and Knight 1998), with the main aim to deepen the understanding of the rainfall distribution and variability, and in particular to predict extreme events (Kao and Ganguly 2011; Myhre et al. 2019). However, no attempt has been made to provide methods to reconstruct missing values.

The 2nd method: conversion of contemporary weather notes into quantitative values

This method is based on the conversion of contemporary weather notes into quantitative values. The unbroken and accurate descriptions that Morgagni reported in his Logs can be transformed into quantitative values, using for calibration the observed amounts in the Poleni record over the 24-year common period. Calibration is a challenging item, because weather notes depend on the skill and accuracy of the observer, the modality of observation and/or recording, and perception of the weather phenomena.

A difficulty is the exact time correspondence between Poleni and Morgagni observations. Poleni observed at noon, but his rain gauge recorded over the previous 24 h. Morgagni observed three times a day, i.e. one hour after sunrise, two after noon, plus a note for the night. However, the sunrise and the sunset changed over the calendar year, in Padua the night is 1/3 of the day at the summer solstice and 2/3 at the winter solstice, and very likely Morgagni missed the situation over night when he was sleeping.

The precipitation series by Poleni (instrumental) and Morgagni (visual, but with event classification) are analysed over the common period 1740–1763. The comparison of the frequencies is useful to test the accuracy of the visual observations. Overall, there is very good agreement in the occurrence of the precipitation events according to the two series, with the lowest difference in winter and the highest in summer (Fig. 1). The lower frequency of the Poleni's series in summer may be explained by the fact that he passed the hottest months in a countryside locality with better climate than Padua, and charged a trained servant to take note of the weather record. Evidently, this person was not very accurate. Finally, it should be considered that several summer months are missing in the Morgagni series.

The analysis of the contemporary precipitation events of the two series allows to calibrate the method, associating to the weather notes reported by Morgagni the daily precipitation amounts measured by Poleni.

Morgagni wrote several (i.e. two or even three) comments a day, often different between them according to the weather variability.

The daily precipitation amount (DPA) is given by the integral of the precipitation intensity (PIN(t)) over time (t), i.e.

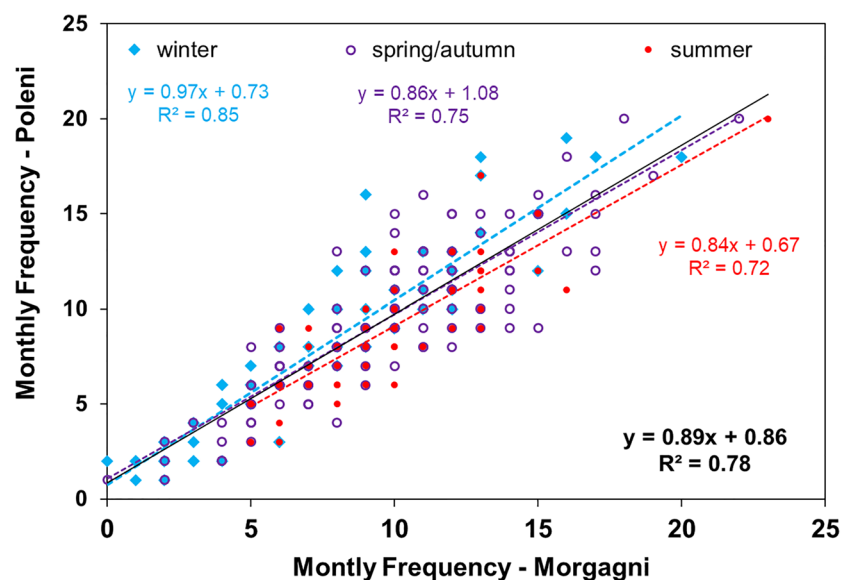
$$\text{DPA} = \int_{t_0}^{t_{\text{fin}}} \text{PIN}(t) dt,$$

where t_0 and t_{fin} are initial and final times of the precipitation event. Poleni measured the daily amounts DPA. Morgagni made an effort to give an accurate evaluation of PIN, using a number of different adjectives and adverbs, including a variety of their combinations, therefore it was not easy to extract classes from them, and sometimes the “label” of the class itself was composed by more than one adjective and/or adverb. Sometimes PIN is represented by the precipitation type, e.g. drizzle, rain, shower. Less clear is the duration, i.e. t_0 and t_{fin} . Morgagni often referred to the duration in terms of “long”, “continuously”, “ceaseless”, without specifying the exact number of hours.

Some weather notes include only PIN; some others include some information about the duration. Therefore, it was necessary to adopt two classifications: one for PIN alone, and another for the combination of the two variables, e.g. “continuous little rain” was considered a different class than “little rain”. When duration is missing, that is the majority of the cases, the events characterised by the same intensity are considered within the same class (PIN alone) and supposed to have the same duration. This leads to apparent paradoxes when matching the Morgagni definitions to the Poleni DPA, e.g. a continuous drizzle, defined simply “drizzle” by Morgagni, but lasting over the whole day, could be associated to the same large amount of an intense but short shower, even if a shower belongs to an intensity class greater than drizzle.

In total, 37 classes are recognised (Table. ESM1). To increase the representativeness of the statistical approach, when an original definition is used only a few times, the related events are merged with classes with similar

Fig. 1 Scatter plot of the precipitation monthly frequency observed by Poleni versus Morgagni over the common period 1740–1760 and linear regressions. The seasons are indicated with different symbols and colours: winter with blue diamond, summer with red dots, spring/autumn with violet circles



definition, based on slightly different terms, but with the same meaning. Every class is identified with one or two letters. The English translation of the Italian original definitions is only indicative, as it is impossible to find the precise correspondence of the many diminutives, nicknames and terms of endearment, of which the Italian language is extremely prolific.

The most populated class, i.e. 47% of the cases, is “rain” (N), without further specification. Then, the most numerous classes are “light rain” (U) 11% of the total, and “big rain” (G), 6%. According to this result, about a half of the daily amount reconstructed using this method are characterised by the same value, the one associated to class U.

Once each precipitation event is attributed to a specific class, the next step is to associate a quantitative value to each class. Each class is composed of the ensemble of the matched amounts, i.e. those read by Poleni in the days when precipitation events belonging to that class occurred. This establishes for each class a broad and skew distribution, characterised by a specific mode, median and mean. The mode is scarcely representative, being determined by the most frequent precipitation type, i.e. fine and light rains. The mean and the median are better representative to distinguish one class from another, and are represented in (Fig. ESM6).

The 3rd method: use of a contemporary record of a nearby location

This method is based on the use of a contemporary record of a nearby location of the same climatic region. In the early instrumental period, it is not always possible to find a satisfactory solution, or even another record. 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 method 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). The choice of the most suitable interpolation method depends on the number of neighbouring stations available for use and their correlation with the particular station where data are being reconstructed (Caldera et al. 2016). The two problems in applying this methodology in the early instrumental period, are, as we have already pointed out: (1) the lack of contemporary data, (2) the lack of homogeneity between the datasets. In our fortunate case, observations were made in the same period in Venice, 37 km east of Padua. In addition, the measurements benefit of a basic homogeneity, because the first observer, Temanza, made his best to follow the protocol

of his former teacher and friend Poleni, and the second, Pollaro, made his best to follow Temanza. All observers used a cubic funnel, very likely on the roof, and read at noon. However, precipitation is a local phenomenon, so even if two cities are quite close together it is possible that the frequency and intensity of precipitation is quite different (Berndtsson 1988; Li et al. 2014). In addition, the wind field distortion caused by each particular roof could be responsible of unpredictable departures.

The gap in the Padua series can be filled with the contemporary observations by Temanza from 1st April to 31st July 1764 and by Pollaro from 1st August 1764 to 31st December 1767. A correction factor may be due, because the precipitation in Padua and Venice is very similar, but not exactly the same.

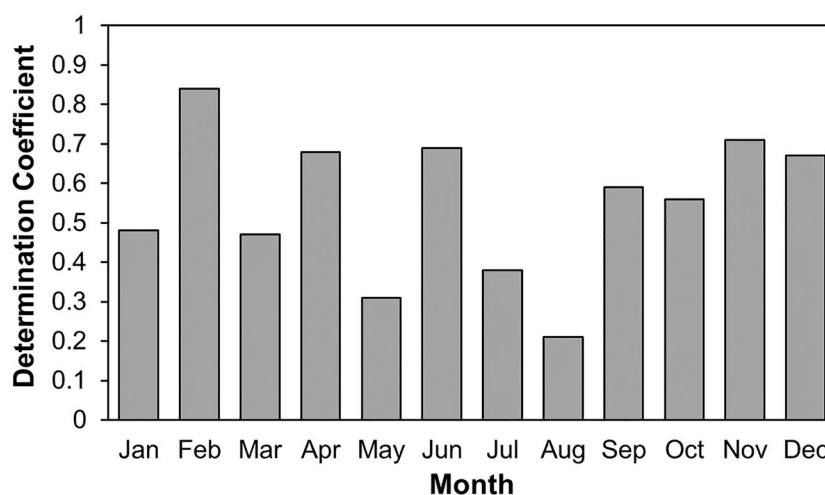
Therefore, the ratio Padua/Venice is calculated over a common period. It must be said, however, that on the yearly or monthly timescale, the precipitation in Venice is highly correlated to Padua; whilst, on the daily scale, local phenomena may lower the correlation.

Results and discussion

The 1st method: relation between precipitation frequency and amount

The relation between precipitation frequency and amount depends strongly on the specific precipitation regime of the location under study. In tropical areas, characterised by the monsoon regime, a relationship between average seasonal rainfall amount and mean daily intensity can be easily found (Nandargi and Mulye 2012). The regime of the precipitation in Padua is different and extremely variable over the calendar year, i.e. heavy and long-lasting precipitation in spring and autumn, when the Atlantic perturbations reach northern Italy; dryness interrupted by heavy showers in summer; light winter precipitation, with some episodes of intense precipitation for a few days when the Sirocco wind is blowing from Africa. Therefore, we have investigated the relation between precipitation frequency and amount in the Poleni dataset for each month separately. We make the scatter plot of the monthly amount versus the frequency (Fig. ESM5), and then apply a linear regression. The monthly averages of the values of the determination coefficient R^2 are reported in Fig. 2. The values range between $R^2 = 0.84$ in February and 0.21 in August, and the average over the 1725–1760 period is 0.55. This suggests that at monthly level this reconstruction may be acceptable for February, April, June, November and December, and not acceptable at all in May, July and August. Finally, there is no way to pass from monthly to daily resolution.

Fig. 2 Determination coefficient R^2 between monthly precipitation frequency and amount in the 1725–1760 Poleni dataset



The 2nd method: conversion of contemporary weather notes into quantitative value

The results for the three most numerous classes, i.e. “big rain”, “rain” and “light rain”, are shown in Fig. 3 with the indication of the most significant statistical values, i.e. median, mean and mode. The precipitation amounts associated to each class are quite scattered and the mode does not seem to be the best representative of each class. For example, according to the results, the mode of the class “rain” is lower than the mode of the class “light rain”, i.e. in a rainy day the amount of rain collected is lower than in the case of light rain. This is not reliable from an objective point of view, and it can be explained because the information concerning the duration of each event was missing; therefore, it is likely that if a light rain lasted for enough time, the daily total amount can be even higher than the amount collected in a rainy day.

Between the mean and the median, the choice may be subjective. In this paper, we assume the latter as representative of each class.

The daily precipitation amounts with the values in the gap reconstructed using all the 37 classes are shown in Fig. 4. The result is not fully satisfactory because the method misses the lowest and highest values.

The 3rd method: use of a contemporary record of a nearby location

Comparison of precipitation frequency and amounts in Padua and Venice

The study of the relationships between the two cities, more specifically how the monthly precipitation frequencies and amounts may differ in Venice and Padua, indicates that in the 1764–1767 period, there were about 424 rainy days in

Padua, 421 rainy days in Venice, of which 302 (about 70%) occurred simultaneously in the two cities, the main differences being in the summer months, explained by local instability and cumulus cloud development (Fig. 5).

Moreover, the correlation coefficient between the two datasets is quite low (0.3). Therefore, the linear regression method, that is one of the most suitable ones in case of only one neighbouring station available (Caldera et al. 2016), does not give good predictions.

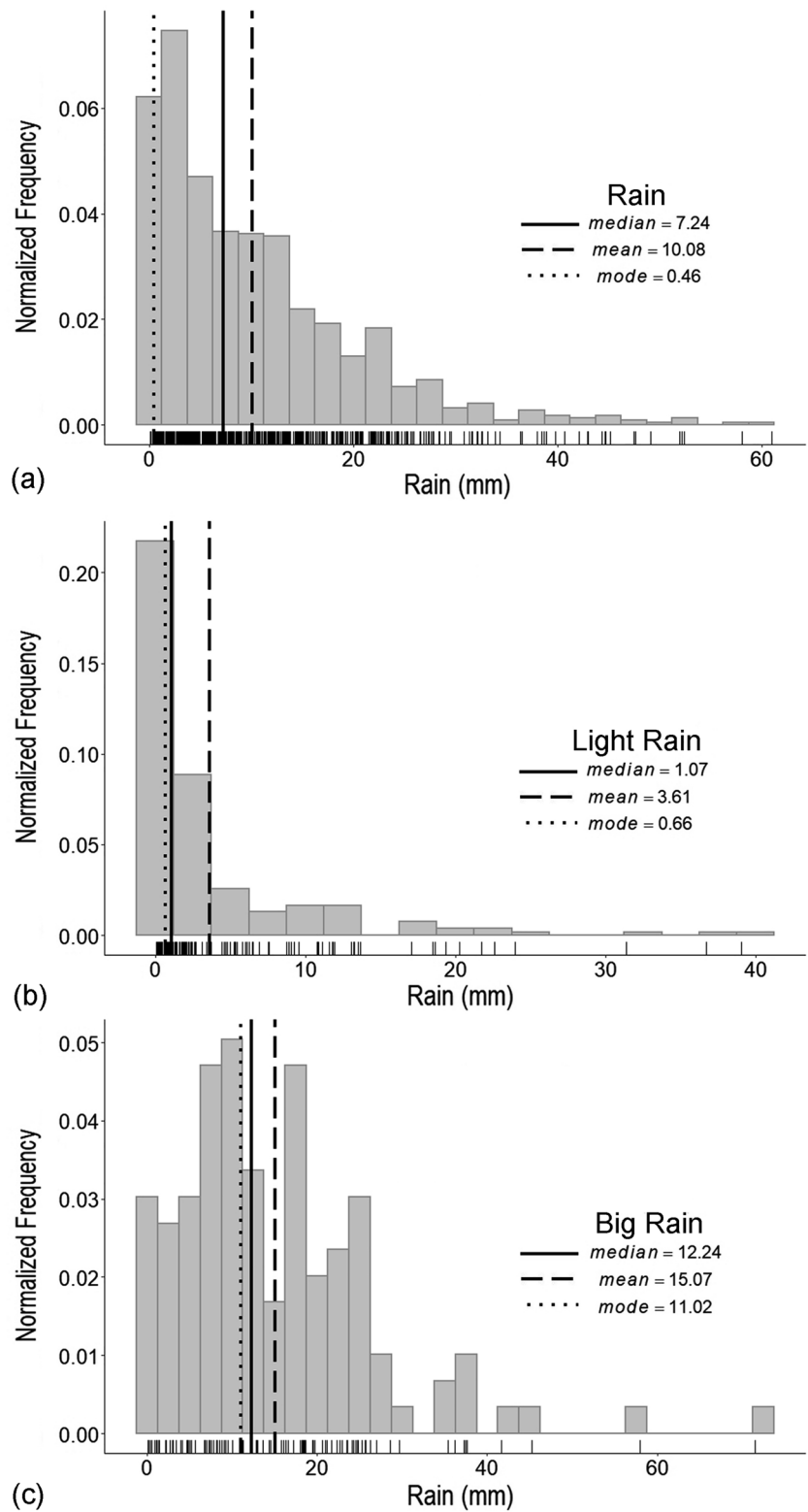
The plot of the daily precipitation amounts in Padua over the wider 1725–1811 period is shown in Fig. 6a, with the 1764–1767 gap filled with the Venice data. The two highest values of the whole series occurred in the gap, i.e. recorded in Venice, but both the days had intense rain in Padua. In fact, on the 14 September 1764 Pollaroli measured 92 mm and Morgagni wrote “*gran pioggia*” (great rain), and on the 10 July 1765 Pollaroli measured 130 mm and Morgagni reported “*coperto poi vento grandissimo con pioggia e tuoni*” (overcast, then strong wind and thunderstorm with rain). If the amounts are represented with dots instead of vertical lines (Fig. 6b), it is evident that the resolution of the instrument used by Pollaroli is lower than the ones used by Poleni before and Toaldo after (as discussed in “Materials and methods”), resulting in a less variability in the daily values. This result confirms that the use of the Venice data is not the best solution to fill the Padua gap at daily resolution.

The 4-year gap is too short to apply homogeneity tests to the series, as well to analyse the cumulative values of Padua vs Venice. The same can be said for the calculation of the yearly percentiles from the 10th- to the 90th-ile of the reconstructed series (Fig. 6c) (Camuffo et al. 2021).

The Padua/Venice ratio as scaling factor

A challenging problem is to scale the daily amounts of the Venice series with the ratio Padua/Venice (PD/VE). Tests

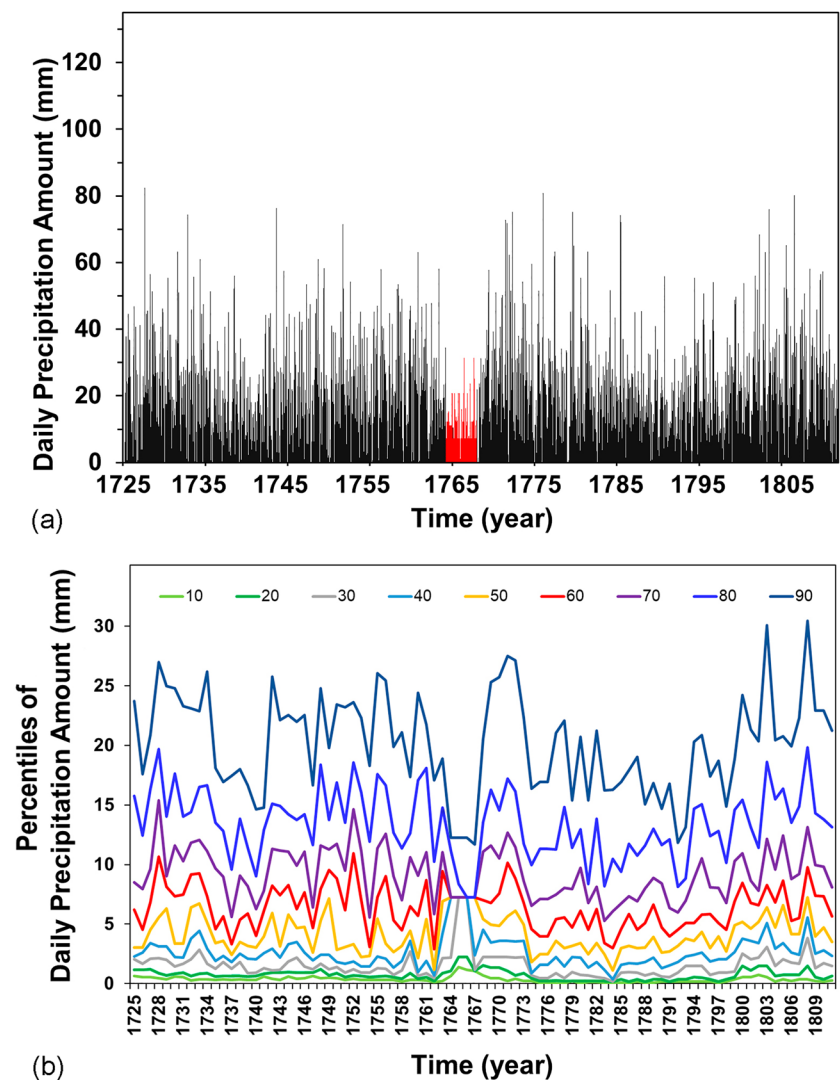
Fig. 3 Normalised frequency of daily precipitation amounts (mm) of the three most numerous classes: **a** rain; **b** light rain; **c** big rain



made over different sub-periods, determined by the homogeneity and availability of data, show that $PD/VE=0.95$ for the period 1751–1758 (this study); $PD/VE=1.24$ for 1880–1895 (Eredia 1908); $PD/VE=1.10$ for 1920–1932

(Crestani 1933); $PD/VE=1.01$ for 1960–1990 (this study) (Table. ESM2). All of these sub-periods have a different instrument and exposure either in Padua, Venice, or both, showing that several contributing factors alter considerably

Fig. 4 **a** Daily precipitation amount in Padua in the period 1725–1811, with the indication (in red) of the data reconstructed considering each class, represented by its median. **b** Percentiles of the series



the result, e.g. local roof turbulence, elevation, influence of wind drag, rain gauge threshold, wetting (i.e. dew) and evaporative losses. Only in modern times the precipitation is measured according to the WMO (2018) recommendations to make possible a reliable comparison between two sites. Wind field deformation can account for 2–10% underestimation, which can exceed 50% for solid precipitation (Goodison et al. 1998; WMO 2018). Wetting loss in the collector walls and measuring cylinder when it is emptied can reach the 15% in summer. Evaporation from the container can be responsible of the loss of another 4%, in- and out-splashing up to 2%. These errors were arguably larger in the earliest instrumental periods (Brugnara et al. 2020). Any change in the instrumental threshold has a dramatic impact on the precipitation frequency, much higher than on the amount, in particular for the fine and light rains, that are dominant (Camuffo et al. 2021). For example, if only the precipitation values above 10 mm are considered, 70% of the data will remain undetected, but they are responsible for the 25% of

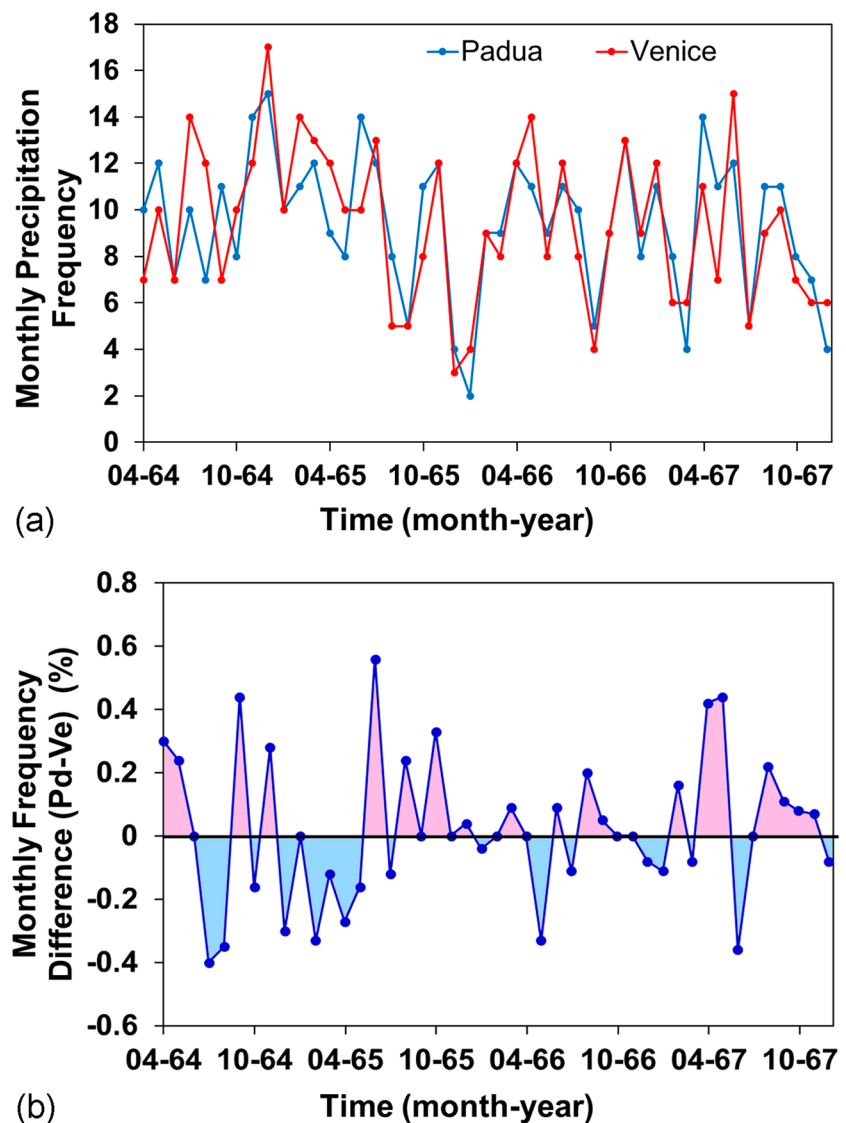
the total amount. In conclusion, considering that the PD/VE ratio is around 1, but the exact value depends by different factors, and the main part of the Padua gap (i.e. 91%) is covered by the Pollaroli series that cannot be calibrated with other contemporary records, the application of a scaling factor to adjust the daily values of Venice would be affected by subjectivity and not justified.

Conclusion

In this paper, three different methodologies are applied and compared to reconstruct the rainfall daily amounts of the 1764–1767 gap in the Padua series, taking into account the availability of only one contemporary series from a location about 30 km far from Padua, i.e. the Venice series.

The first approach is based on the relationship between monthly frequency and amount. Results indicate that a linear relation is acceptable only at monthly level, and limitedly

Fig. 5 **a** Monthly precipitation frequency in Padua and in Venice over the common period 1764–1767. **b** Difference between Padua and Venice represented as a percentage respect to Padua



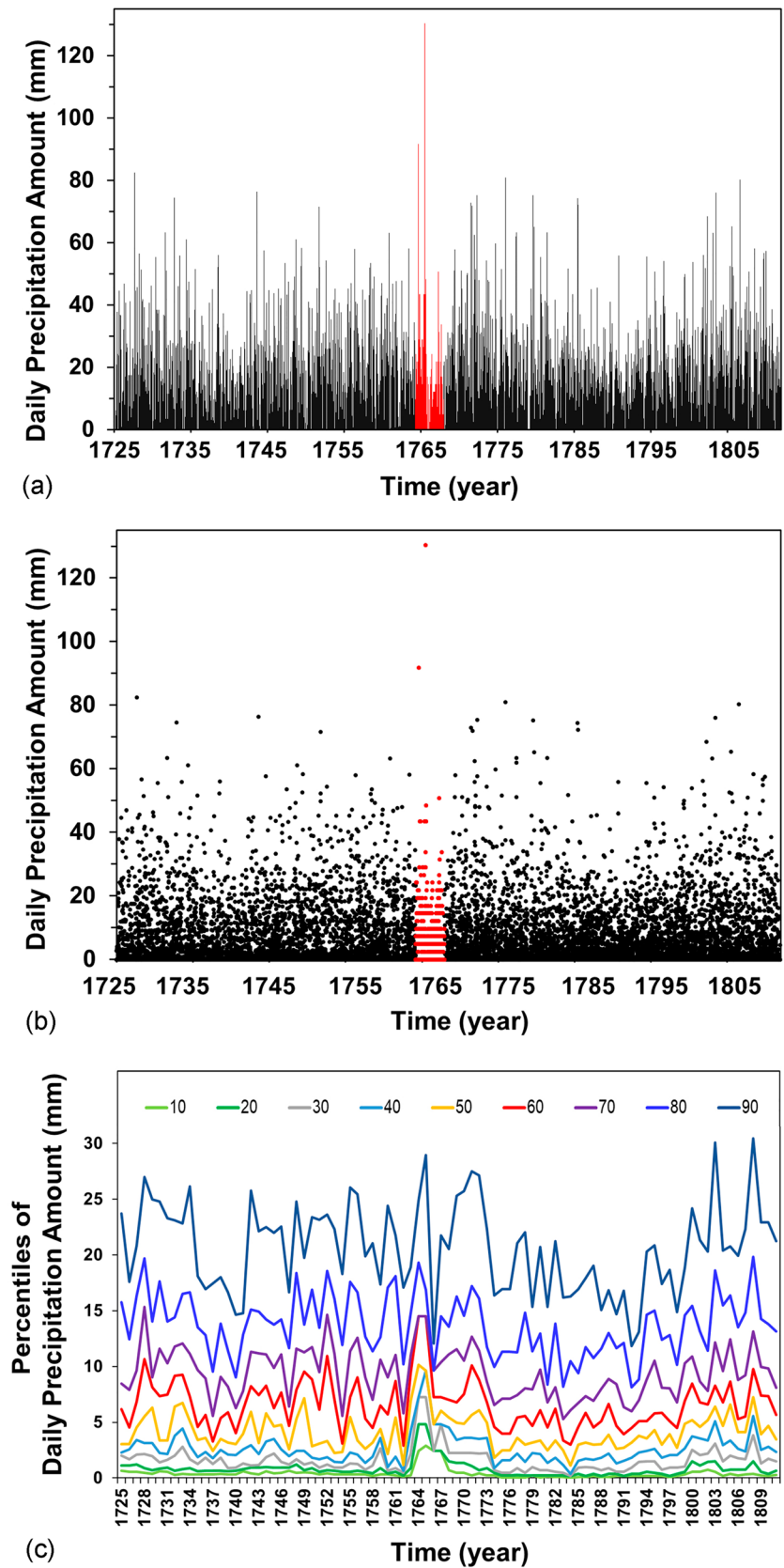
to some months, as the regime of the precipitation in Padua has a marked seasonal character, with maxima in spring and autumn.

The second method tries the conversion of contemporary weather notes into quantitative values. The unbroken and accurate descriptions reported in the Morgagni Logs are transformed into numerical values, using for calibration the observed amounts in the Poleni record over the 24-year common period. The comparison of the rain frequencies of the two series over that period indicates that Morgagni's visual observations were quite accurate, with the highest difference with Poleni records in summer. The analysis of the contemporary precipitation events allows establishing 37 classes of precipitation. Every class has a wide range of values and our tests indicated the median as better representative of each class than the mean and mode. The daily values reconstructed even on the ground of an accurate daily

description of the rain intensity are not fully satisfactory. The main disadvantage of this method is that the Morgagni's descriptions are based on the precipitation intensity at the moment of the observation, but the duration of the event is missing; this is misleading, because a long-lasting rain of light intensity may cumulate a higher amount of a more intense, but shorter precipitation.

The third method consists of filling the missing values with a record from a nearby, contemporary station in the same climatic area, i.e. the series of Temanza and Pollaroli in Venice. In these two nearby cities, at monthly level, the precipitation values are closely related between them, both in frequency and amount. However, at daily level, this method shows some problems: (1) the precipitation may differ from one site to another, due to the local character of the rainfall; (2) the two records are not homogeneous, as observations were taken by different observers with different instruments;

Fig. 6 **a** Plot of the daily precipitation amounts in Padua in the period 1725–1811, with the indication (in red) of the Venice data; **b** as in **a** but represented with dots; **c** Percentiles of the reconstructed series



(3) the application of a scaling factor does not improve the results. In particular, a scaling factor cannot be uniquely determined, as it depends strongly on a number of variables related to the period in which is calculated. Therefore, if this last method may be acceptable at monthly level, it is not reliable at daily resolution. Results clearly show that, in case of early series, the use of nearby, contemporary series has to be evaluated carefully, as any change in the instrumental threshold has a dramatic impact on the precipitation frequency, much higher than on the amount, in particular for the fine and light rains, that are dominant.

In conclusion, notwithstanding the limits discussed in this study, the 2nd method, based on the transformation of contemporary weather notes into quantitative precipitation depths, is the best option to fill the 1764–1767 gap in the Padua precipitation series at daily resolution. The best ever technique for daily precipitation reconstruction in early series cannot be assessed, as it is strongly dependent on the quality and quantity of data and metadata available, so every case needs to be considered individually.

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Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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