How the Rain-Gauge Threshold Affects the Precipitation Frequency and Amount

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How the rain-gauge threshold affects the precipitation frequency and amount

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Abstract

After an overview of the problems concerning the early rain-gauges and their thresholds, a study is made to investigate the impact that the instrumental threshold of a rain-gauge has on the distribution of precipitation frequency and amount. Some tests have been performed using two historic datasets, i.e. the observations by Giovanni Poleni in Padua from 1725 to 1760, and Jacopo Bartolomeo Beccari in Bologna from 1723 to 1765, and two modern rain-gauge records, i.e. taken at the Botanical Garden, Padua, and at the Hydrographic, Bologna, from 1990 to 2019. The tests consisted in applying a filter to the datasets to simulate the action of an instrumental threshold. The result is that the threshold has an enormous impact on the frequency, and a smaller one on the total amount. The study included how the threshold affects the percentile distribution of precipitation amounts. The results provide indications to correct and interpret early records, and to test their quality. Moreover, they are useful in the analysis of long time series composed by datasets derived from different instruments for climate studies.

1. Introduction

In hydrology, climate analysis, and environmental protection, a huge effort has been devoted to study and recover early instrumental records or to reconstruct precipitation series from rogation ceremonies, weather diaries and other documentary sources (Barriendos 1997, 2010; Rodrigo et al. 1999; Alcoforrado et al. 2000; Slonosky 2002; Garcia Herrera 2003; Auer et al. 2005; Brázdil et al. 2005, 2018, 2019; Ge et al. 2005; Gimmi et al. 2007; Dominguez-Castro et al. 2008, 2012, 2015; Camuffo et al. 2010, 2013; Santos et al. 2015; Wetter 2017; Harvey-Fishenden and Macdonald 2021; Pfister et al. 2019). In early records, the problem is the use of different instruments with unknown characteristics. In the documentary approach, the problem is to pass form qualitative information to a quantitative assessment, or to pass from a frequency of occurrence of rainy days to a precipitation amount. So far it is not clear whether a progress can be made with a refinement of the existing techniques, or with a thorough revision of the early instruments, the relationship existing between frequency and amount, and what may pass unobserved. This paper is aimed to clarify this complex issue, starting from the analysis of early instruments and their records, and in particular the different thresholds.

Precipitation events that are beyond the threshold of the specific gauges are considered as trace precipitation. It has evaluated that at latitudes higher than 45°N, the precipitation lost is small in summer (10%), and very large in winter (80–120%) because of the increased effect of wind on gauge that has difficulty in catching snowfall (Yang et al. 2005). Wind speed greatly affects the efficiency of catching rain too (Dingman 2015), and the impact is larger for fine and small droplets. The cumulative value and the upper limit of trace precipitation are determined by the combination of the actual distribution of precipitation and the instrumental threshold. In literature, the distribution of the precipitation amounts is described with different model functions, i.e. Gamma, Weibull and double exponential (Wilks 2011; WMO 2011), that depend on the climatic precipitation regime, instrument response and integration period. The common feature is that these functions reproduce a sharp peak immediately after the threshold, followed by a continuous decrease when the amount increases. If the highest frequency is detected in correspondence of the lowest precipitation amount, it is clear that a change of threshold will severely affect the frequency and, secondarily, the amount. A key question is to evaluate this bias in the measurement of the precipitation frequency and amount. This paper is focused to evaluate how a change in the rain-gauge affects the dataset, and to refine the homogeneity criteria for long precipitation records.

2. Overview of the threshold of the most popular early instruments

Especially in the case of drizzle or light precipitation, the first droplets adhere to the surface of the funnel of the rain-gauge, and a certain critical mass must be reached before the precipitated water enters the measuring apparatus, or reaches the collecting vessel where it will be measured with daily (or other) frequency. Surface adhesion of droplets and the type of measuring device determine a threshold for the measurable precipitation depth. Less than 0.1 mm (0.2 mm in the United States) is generally referred to as a trace (WMO 2008, Chapter 6). In some instruments the threshold equals the resolution, e.g. tipping bucket, siphon; in some others, the threshold is not related to the resolution, e.g. drops adhering to the surface, or to the amount of water necessary to move a float. The variety of instruments and the complexity of this matter lead to the conclusion: «threshold for light precipitation may vary» (WMO 2008, Chapter 14). Therefore, 0.1-0.2 mm may be considered the lowest threshold for modern instruments. Moreover, every instrument has a particular basic threshold T_B due to the droplets adhering to the glossy or oxidized surface of the funnel, and the water amount needed to reach and activate the measuring apparatus. The latter is determined by the type, construction and assembly of the various parts of the instruments. A special mention should be made to the connection between the funnel and the storage vessel, or the measuring apparatus. In the past, it was common to install the funnel on the roof of buildings (Fig.1ab) to get an unobstructed horizon, and transport the collected water in a room located one or two floors below it, where measurements were made in a more comfortable environment. For instance, this practice was recommended within the Network of the Palatina Meteorological Society, Mannheim (Hemmer 1783) (Fig.1a). With one or two floors, the pipe length was some 3 or 6 m, and the film of water, or the drops adhering to the pipe surface increased the threshold.

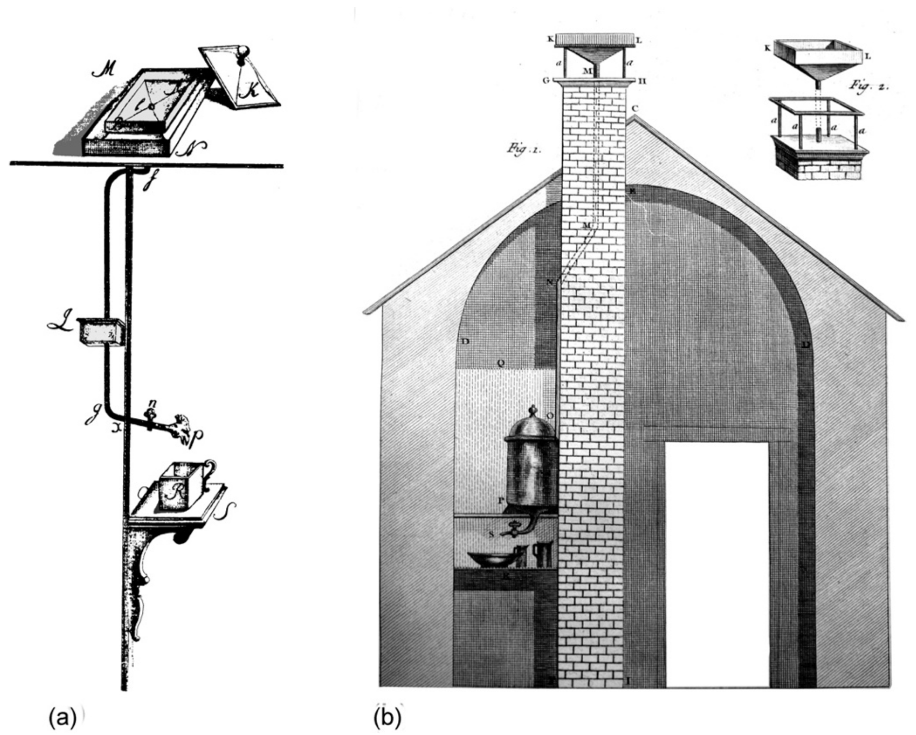

Fig.1 (a) Scheme of roof mounting of the rain-gauge recommended by the Palatina Meteorological Society. On the roof, the funnel (M) had rectangular shape, with vertical rim walls. A cover (K) was used to avoid deposition of dry leaves and other, and debris in the dry periods. The collected water was stored in a reservoir (L) with a tap (p) and measured with a graduated cup (R) located in a room below it (Hemmer 1783). (b) Example of roof mounting, using the chimney (Cotte 1788).

Several types of rain-gauges have been invented, based on different measuring principles, resolution and threshold (Camuffo 2019). Nowadays more than 40 rain-gauge designs are used throughout the world (Linacre 1992) and a short comment concerning the most popular types used in the historical series is made.

The earliest rain-gauges are found in Palestine, 2nd century BCE, followed by China in 1247 CE, and Korea, in 1441 CE (Srinivasan 1976; Strangeways 2010). As well as the type invented in Europe by Benedetto Castelli (1639), they consisted of a simple rectangular or cylindrical vessel with vertical walls and open top. This type is illustrated in Fig.2ab, but the models found in the catalogues Negretti & Zambra (1864), Casella (1871) and others are more advanced because they insert a funnel inside to create a lower and an upper volume and reduce evaporation. The traditional "five-inch" rain-gauge still used by the UK Meteorological Office is an advanced version of the cylindrical type. The water collected inside was in the ratio of 1:1 making reference to the undisturbed precipitated water, so there was no magnification of readings. The basic threshold T_B of the instrument and its resolution depended on the graduated measuring stick dipped inside the collector to measure the precipitation depth. It was soon evident that it was possible to magnify the reading by using a large funnel with cross-section S_{FU} and using a graduated measuring cylinder with cross-section S_{MC}, the magnification factor MF being

$$MF = \frac{S_{FU}}{S_{MC}} \qquad (1a)$$

For instance, Jurin (1723) recommended that the diameter of the collecting vessel was 1/10 of the funnel to obtain the magnification ratio 1:100. The effective threshold T_{eff} became

$$T_{Eff} = \frac{T_B}{MF} = T_B \frac{S_{MC}}{S_{FU}} \quad (2)$$

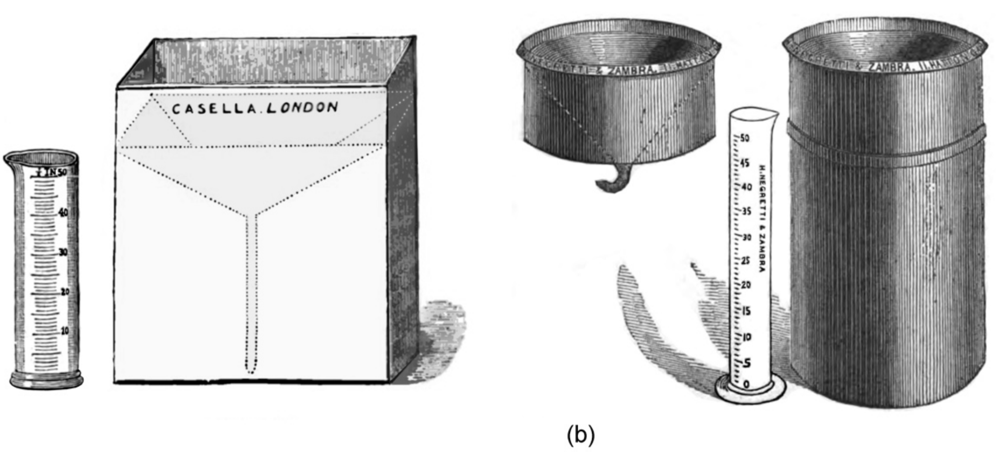

Fig.2 (a) Box shaped rain-gauge with a square funnel inside to reduce evaporation. The diameter of the measuring cylinder magnifies 1:20 (Casella 1871). (b) A cylindrical rain-gauge 5-inch diameter (Negretti & Zambra 1864).

The rain-gauges with side tube (Fig.3ab) were characterized by an external glass tube for direct reading. Parallel to the storage vessel, and communicating with it at the bottom, there was a graduated glass tube that allowed reading the precipitated depth. However, this instrument required a small volume of stagnant water (Fig.3c) to connect the zero level in the storage vessel to the related zero level on the glass tube. This constituted an additional threshold T_A. Therefore,

$$T_{Eff} = \frac{T_B + T_A}{MF} \quad (3)$$

where MF is calculated with the cross-section S_{SV} of the storage vessel, i.e.

$$MF = \frac{S_{FU}}{S_{SV}} \quad (1b)$$

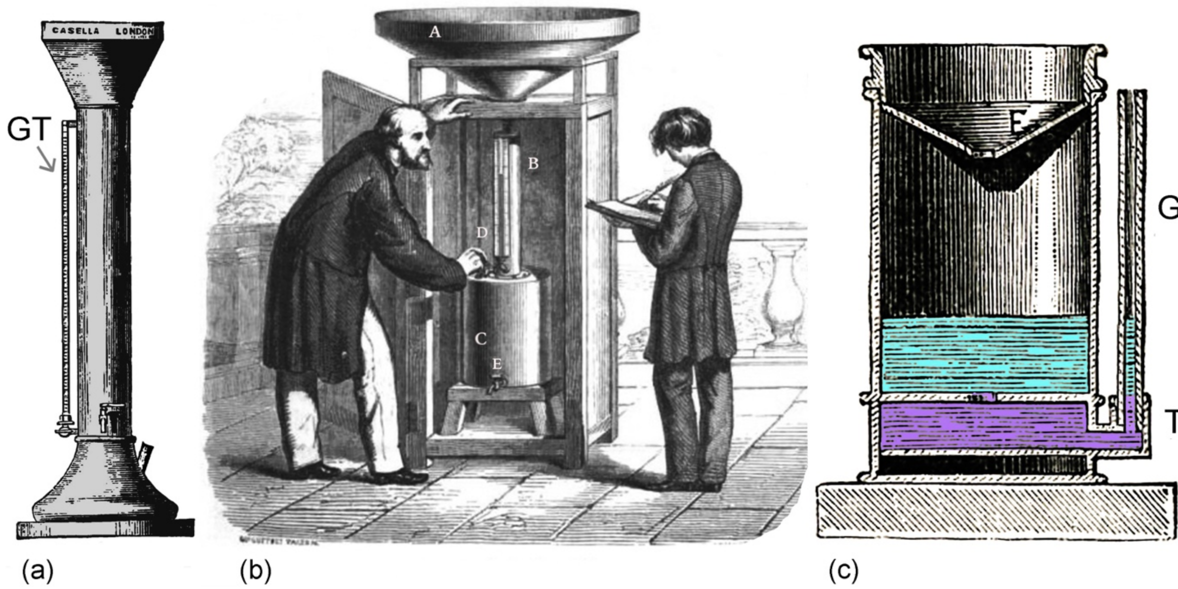

Fig.3 (a) Rain-gauge with external glass tube (GT) for direct readings of the collected water (Casella 1871). (b) The Hervé-Mangon model with internal vessel (B) and reading glass tube (D). In the bottom, it had a reservoir (C) to cumulate precipitation. The magnification factor is 1:100 (Mangin 1865). (c) A cross section showing the water collected and visible in the glass tube (cyan) and the stagnant water (violet) necessary to connect the storage vessel to the related zero level on GT. This stagnant water determines the threshold T_A. F is the funnel. (Ganot 1860).

The tipping bucket rain-gauge is based on a tipping bucket fed by the funnel and a counter (e.g. a mechanical counter, an electrical contact, or a pulse-generating reed switch), that is operated each time the bucket tips (Fig. 4ab). WMO (2008, Chapter 6) recommends that the amount of rain necessary to tip the bucket should not exceed 0.2 mm if detailed records are required. The effective threshold is determined by the volume of water V_W necessary to tip the bucket and is inversely proportional to the magnification due to the funnel section S_{FU}

$$T_{Eff} = \frac{V_W}{S_{FU}} \quad (4)$$

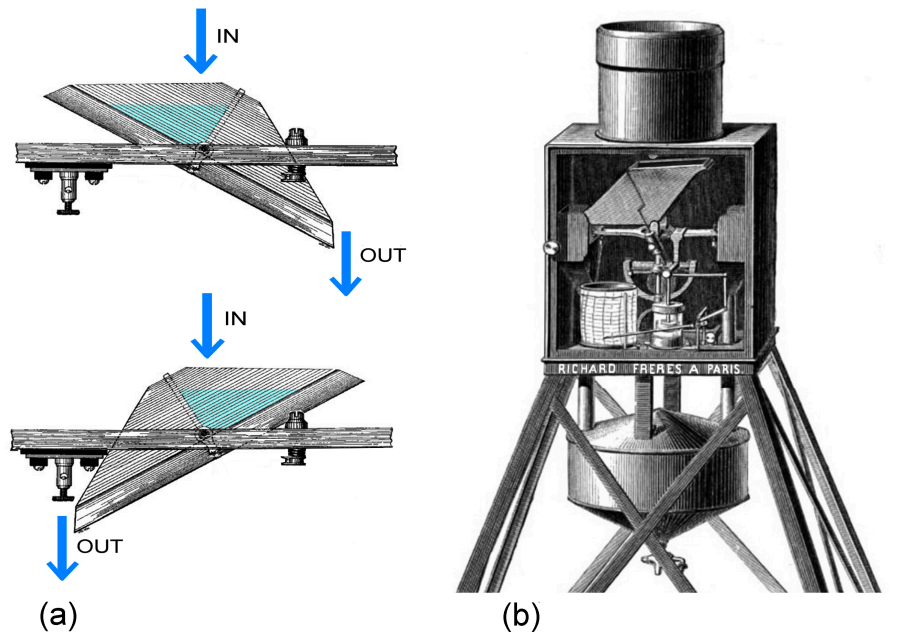

Fig.4 (a) The two phases of a tipping bucket. Arrows show the water input and discharge (Marvin 1894). (b) The tipping bucket rain-gauge Frères Richard, Paris. On the bottom, a reservoir to cumulate precipitation and measure it manually (Richard Frères 1889).

The float rain-gauge is an instrument for direct observations. It is constituted of a float chamber, i.e. a cylindrical collecting vessel that receives the precipitated water from the funnel and lifts a float connected to a graduated rod. A model (Fig.5a) is conceived to stand leaning on a terrace or a garden; another (Fig.5b) to be located in a gauge well dug in the ground to reduce overheating and evaporation loss. The depth of the water collected is read on the graduated rod at the level where it emerges from the instrument. As the float responds to the cumulated water, the instrument is a totalizer. However, when the float approaches the top, it is necessary to empty the cylinder and return to the initial position. This operation is done manually. The effective threshold is determined by the level of water L_W necessary to create buoyancy and start to lift the float (Fig.5c). For the Archimedes principle, the buoyancy level L_W is reached when the volume of water displaced by the float equals the weight W_{FR} of the float and the rod. If the float is a cylinder, with section S_{FL}, the threshold is

$$L_W = \frac{W_{FR}}{S_{FL}} \quad (5)$$

$$T_{eff} = L_W \frac{S_{FC}}{S_{FU}} = \frac{W_{FR}}{S_{FL}} \frac{S_{FC}}{S_{FU}} \approx \frac{W_{FR}}{S_{FU}} \quad (6)$$

where S_{FC} is the section of the float chamber that is slightly larger than the float section, i.e. $S_{FC} \approx S_{FL}$. The result is that the effective threshold is proportional to the weight of the float and the rod, and inversely to the funnel section, and is almost independent from the cross sections of the float chamber and the float, if their difference is small.

However, this instrument is subject to blockage of the intake pipe and sometimes the discharge opening for sediment of debris, due to the close proximity to the ground. This may affect the operation and the threshold.

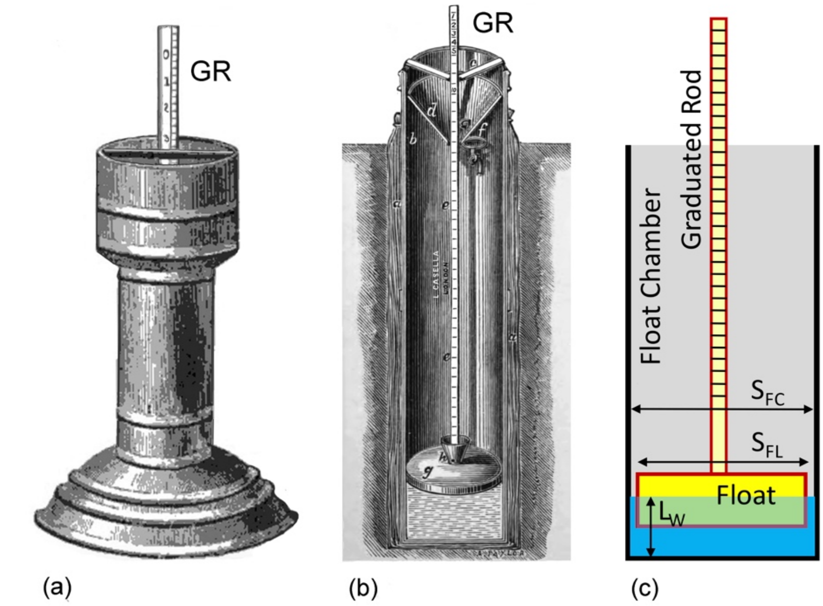

Fig.5 (a) Float rain-gauge with graduated rod (GR) for terraces or gardens (McAllister & Brother 1855). (b) Vertical section of a float rain-gauge by Casella, London. The instrument is sited into a well, dug in the ground (Moore 1894). (c) Scheme of the float chamber and key abbreviations used in the mathematical formulae

The siphon rain-gauge is a recording instrument, derived from the float gauge but with automatic discharge, invented by Hellman and improved by Palazzo (Fig.6ab). The recording pen is driven by a float lifted by the collected precipitation. A siphon mechanism is added for an automatic discharge when the collected water reaches the siphon level. The float follows the instantaneous precipitation, while the siphon acts as a totalizer, because it is triggered every time a certain level (i.e. a certain precipitation depth) is reached inside the float chamber. The diagram is like a saw-tooth and peaks (i.e. siphon discharges) and can be easily counted to determine the monthly totals. The triangle (label L) visible on the top of Fig.6a is not a tipping bucket, but the section of a conical lid, like a reversed funnel, to release water from the border and percolate it along the vertical wall (blue arrow in Fig.6a) to reduce internal turbulence. In fact, the siphon discharge may be anticipated by internal oscillations, as it may occur during heavy rains. In other models, the collected water enters from a pipe located on the cylinder bottom. The siphon rain-gauge has two thresholds: the lower (L_W) is related to the float buoyancy and lift (Fig.5c), and concerns light rains or the initial period of a precipitation; the higher to trigger the siphon discharge (Fig 6a, label S), i.e. the upper level of the discharge siphon tube. The amount of water necessary to activate the siphon drainage is fixed for every instrument; however, the instrument responds to the water cumulated inside, and part of it may be due to precipitation occurred in previous days. This must be taken into account when precipitation totals are considered. The effective threshold for fine or light rains is determined by the level of water L_W necessary to reach the float buoyancy, the weight of the float and is inversely proportional to the funnel size, as explained for the float rain-gauge.

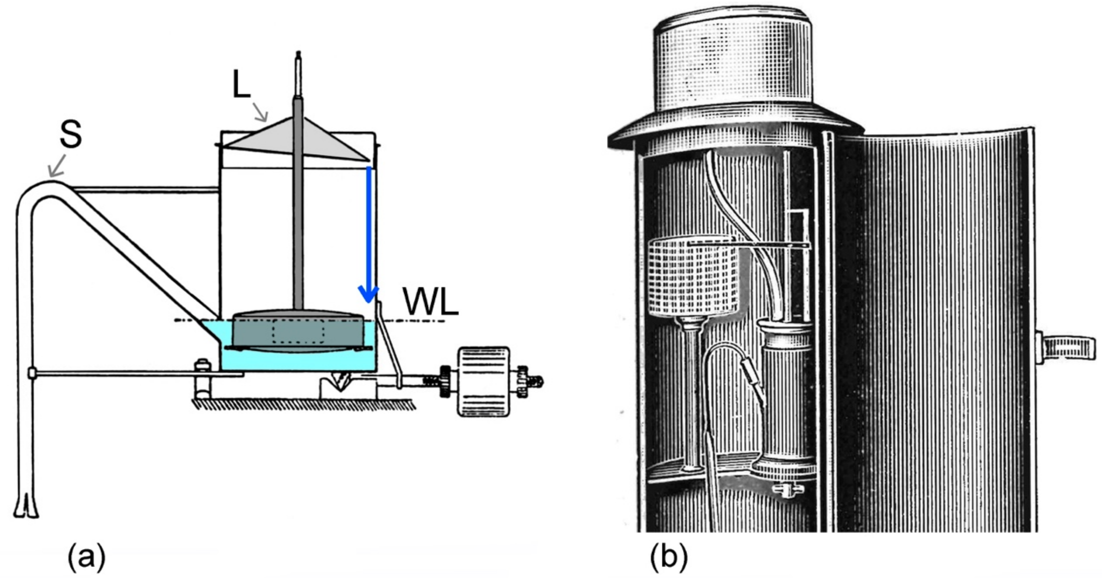

Fig.6 (a) Measuring apparatus of the syphon rain-gauge Palazzo. L is a conical lid on the top, to percolate the collected water along the wall (blue arrow); WL the water level inside the float chamber; S the level needed to trigger the siphon. (Eredia 1922). (b) The syphon rain-gauge Hellman (Vercelli 1933).

Every instrument has a particular threshold. A problem is that the long meteorological series are composed of a number of periods in which different instruments, with different thresholds were used (Camuffo et al. 2020a). Every change of instrument is associated with a change in threshold, and this affects the homogeneity of the series.

3. Data and method

In this paper, the analysis has been made using four daily datasets: two historic datasets of the 18th century and two modern ones for reference. The first historic record was taken in Padua by Giovanni Poleni on his roof, from 1725 to 1760, with a square box funnel and magnification 1:100. The second historic record was taken in Bologna by Jacopo Bartolomeo Beccari at his home, from 1723 to 1765. The instrument characteristics and exposure are unknown but likely similar to Poleni because both adhered to the network of the Royal Society, London, based on the Jurin (1723) protocol. The history of the Padua series has been published in Camuffo et al. (2020a); Bologna in Camuffo et al. (2019).

The two modern records used as a reference were taken with standard tipping-bucket rain-gauges according the WMO (2008, 2011) recommendations. The first reference record was collected at the Botanical Garden, Padua, a station of the Environmental Agency of the Veneto Region, ARPAV; the second one at the Hydrographic, Bologna, a station of the Environmental Agency of the Emilia-Romagna Region, ARPAE. Both reference records are from 1990 to 2019, and both instruments have 0.2 mm threshold.

In order to investigate how a record may be affected by an instrument with higher threshold, we have proceeded by steps. The first step has been to investigate how the dataset would have been affected if the instrumental threshold was 1 mm. This means to remove from the record all readings with value lower than 1mm. Then, in the original dataset, it has been computed how many precipitation days, and what precipitation amount would have passed unobserved with this higher threshold. After, the threshold has been moved to 2 mm, 3 mm, and so forth up to 10 mm, and the above calculations have been repeated each time, acting as a high-pass filter with cut-off at the selected thresholds. For both quantities (i.e. frequency and amount) results are expressed in % of the yearly average over each dataset, i.e. 100% represents unaffected readings, and the departure represents the impact.

4 Results and discussions

4.1. Impact on the precipitation frequency and amount

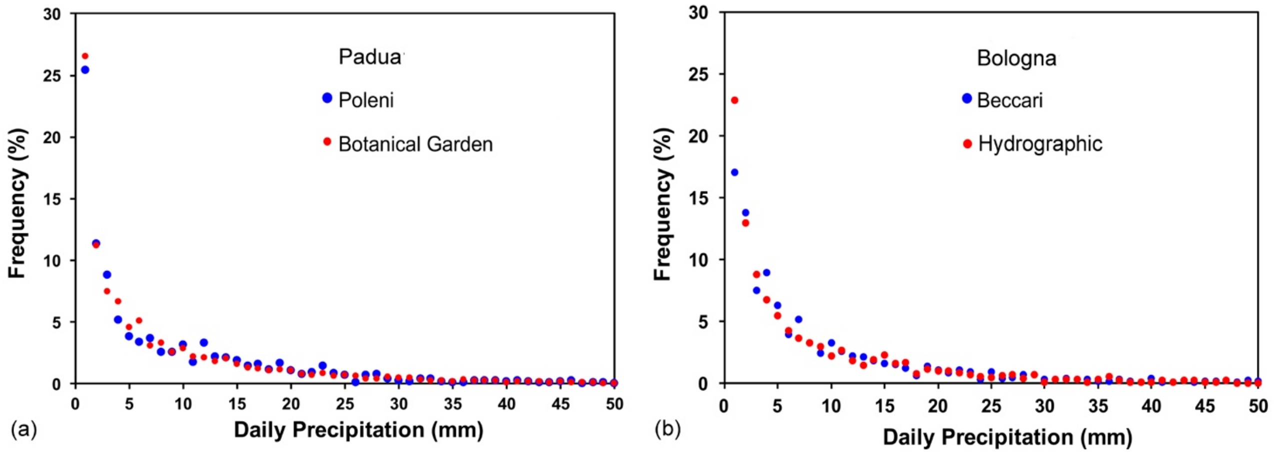

Fig.7 Frequency distribution of historic and modern records of daily precipitation (a) Padua datasets: Poleni and Botanical Garden. (b) Bologna datasets: Beccari and Hydrographic. The X axes have been truncated at 50 mm to magnify and make better readable the interval of fine, light and medium precipitation.

The first test was to check the relationship between frequency and daily amount in the historic records compared to the modern reference ones (Fig.7). The plots of both historic records show a distribution similar to the modern ones, with a sharply peaked maximum after the threshold, followed by a continually decreasing line. This suggests that, if the threshold is increased, the high frequency of fine and light rains will be dramatically reduced, and this is the objective of the next simulation.

The simulations have been calculated by filtering the Poleni and Botanical Garden datasets in Padua, and Beccari and Hydrographic in Bologna, with increasing threshold values. The simulations for the precipitation frequency are reported in Fig.8a for Padua and Fig.8c for Bologna. To improve clarity, this figure has two scales: on the left, the detected frequency (DF) that is actually measured with the selected threshold; on the right, the undetected frequency (UF) that passes unobserved. The results have been normalized to 100 to be expressed in percentage. This applies for any statistically representative dataset, either expressed in yearly, seasonal or monthly totals. Of course, UF = 100 - DF. The four datasets show very similar results, and point out an impressive impact of thresholds: 1 mm threshold is sufficient to pass undetected some 20% of the (light) rain days; 4 mm some 50% of the frequency; and 10 mm some 70%. This fact is explained with the very high frequency of light rains.

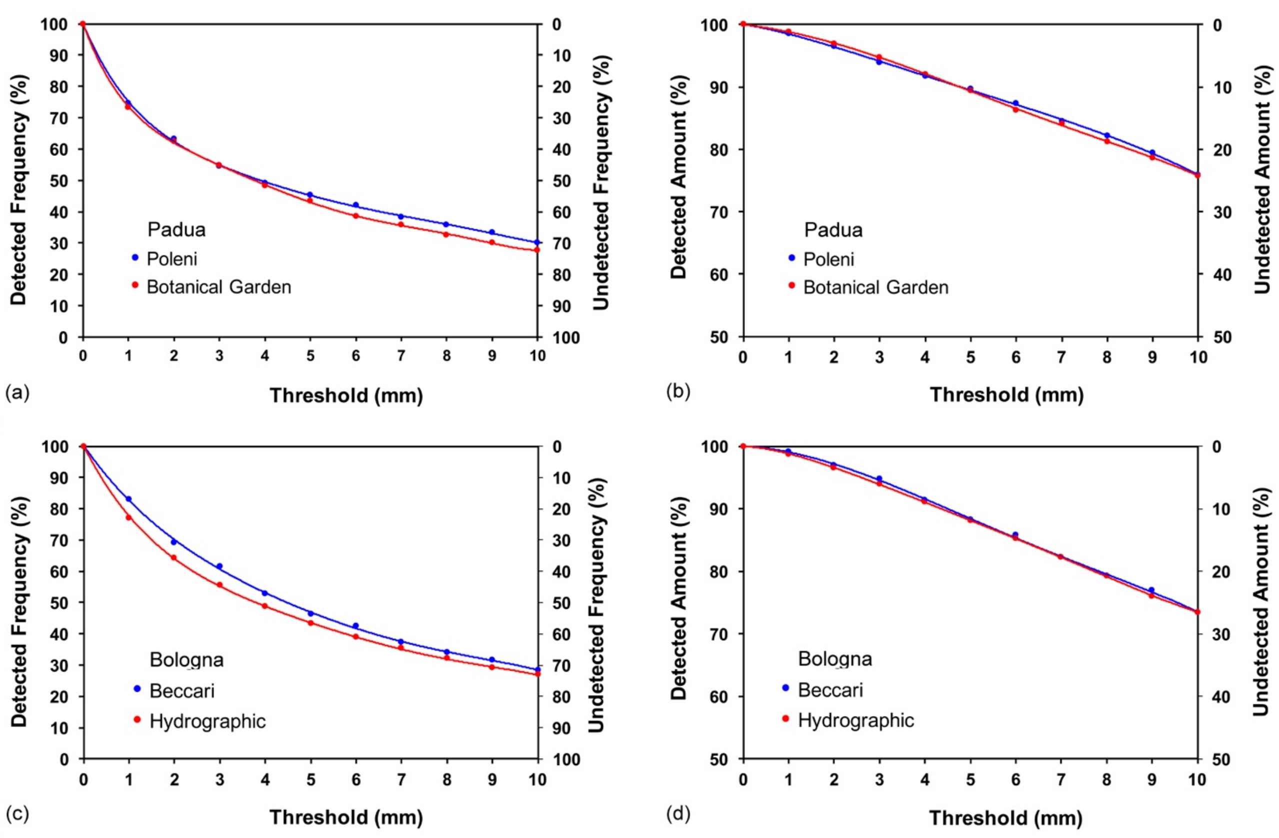

Fig.8 Simulation to detect changes in precipitation frequency and amount when an instrumental threshold is applied. (a) Frequency, Poleni and Botanical Garden; (b) amount, Poleni and Botanical Garden; (c) frequency, Beccari and Hydrographic; (d) amount, Beccari and Hydrographic.

The simulations for the precipitation amount are reported in Fig.8b for Padua and Fig.8d for Bologna. Also in this case, the four datasets provide results very similar between them. However, the percentage of undetected amounts is much smaller than observed for frequency. When the threshold is 5 mm, only 10% of precipitation amount is lost, and when is 10 mm, the undetected amount is around 25%. This is explained because light rains are very frequent, but their contribution to the total precipitation depth is small. The most relevant contributions to the yearly totals are given by precipitation exceeding 5 mm/day. The most extreme cases in the records are around 150 mm/day.

4.2. Impact on the percentile distribution

4.2.1 Percentiles of a uniform, linearly distributed dataset

Another key question is how the percentile distribution may be affected by the instrumental threshold. To make easier the presentation, let us start with the simple example of a dataset composed of a population with uniform, linear distribution and proceed by steps.

The first step is to considered a selected dataset and perform the analysis of the percentile distribution, without applying filters (i.e. no threshold, in the plot in Fig.9b indicated as Threshold 0). The second step is to remove from the selected dataset the lowest 10-ile of the data and calculate the resulting percentile distribution over the 90% of the population survived (i.e. the subset from the 10- to 100-ile of the original) (Fig.9a). The next step is to remove the data within the 20-ile of the original dataset and calculating the resulting percentile distribution over the 80% of the population survived (Fig.9b). Similar steps are repeated, each time excluding 10% of the original dataset, and the result is shown in Fig.9c.

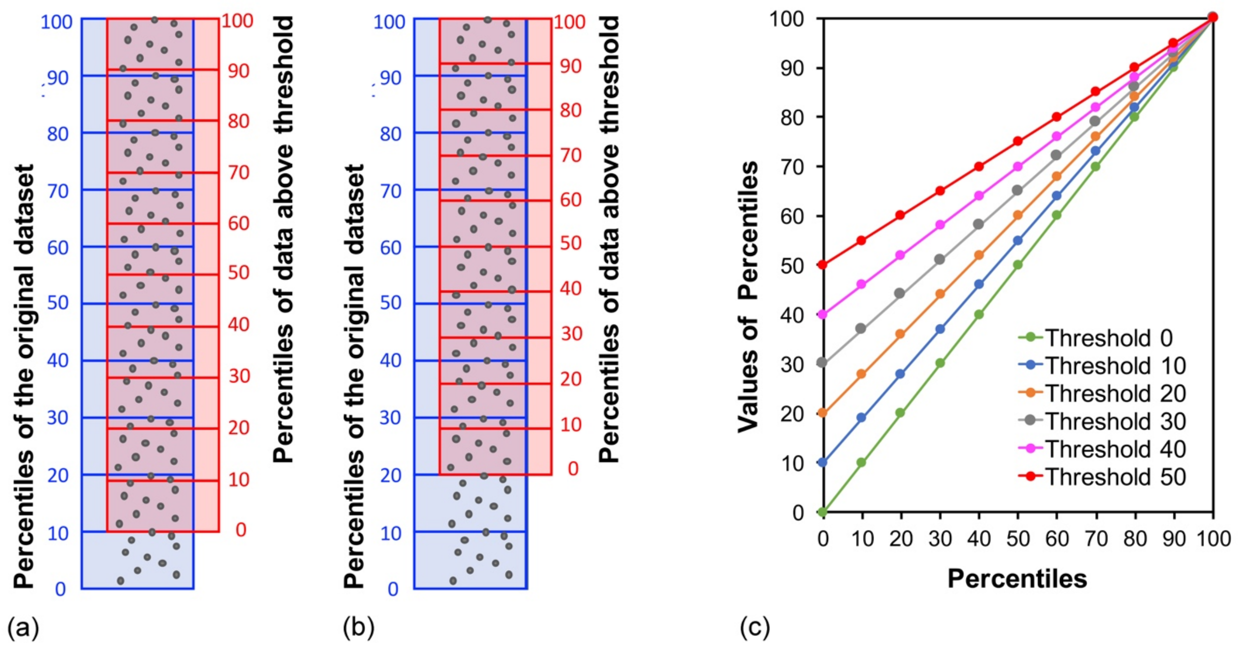

Fig.9 (a) Example of the method used to study the impact that a change of threshold may have on a percentile distribution. A threshold (i.e. 10-ile) is applied to a dataset (with percentiles in blue, left scale). The data below the threshold are removed and new percentiles (in red, right scale) are calculated for the survived data. (b) The same process is repeated for threshold 20-ile. (c) Values assumed by the percentiles calculated for the population of a dataset after the data below selected thresholds have been removed. Threshold 0 is for the original dataset.

It can be easily recognized that, given an original dataset whose population is linearly distributed with percentiles $P_{Oi,}$, if one removes all the data with values below a selected threshold T_i (as shown in Fig.9a), the survived population has the final percentiles P_{Fi} (Fig.9b) is given by the general equation

$$P_{Fi} = P_{Oi}\frac{100-T_i}{100} + T_i \quad (7)$$

The coefficient of the first term determines the slope and its linearly related to the threshold. The intercept is the threshold. The percentiles are linearly distributed and linearly related between them. It is trivial that the lowest percentile equals, or is close to the applied threshold, while the highest percentile, i.e. 100-ile, remains unchanged.

4.2.2 Percentiles of real precipitation datasets

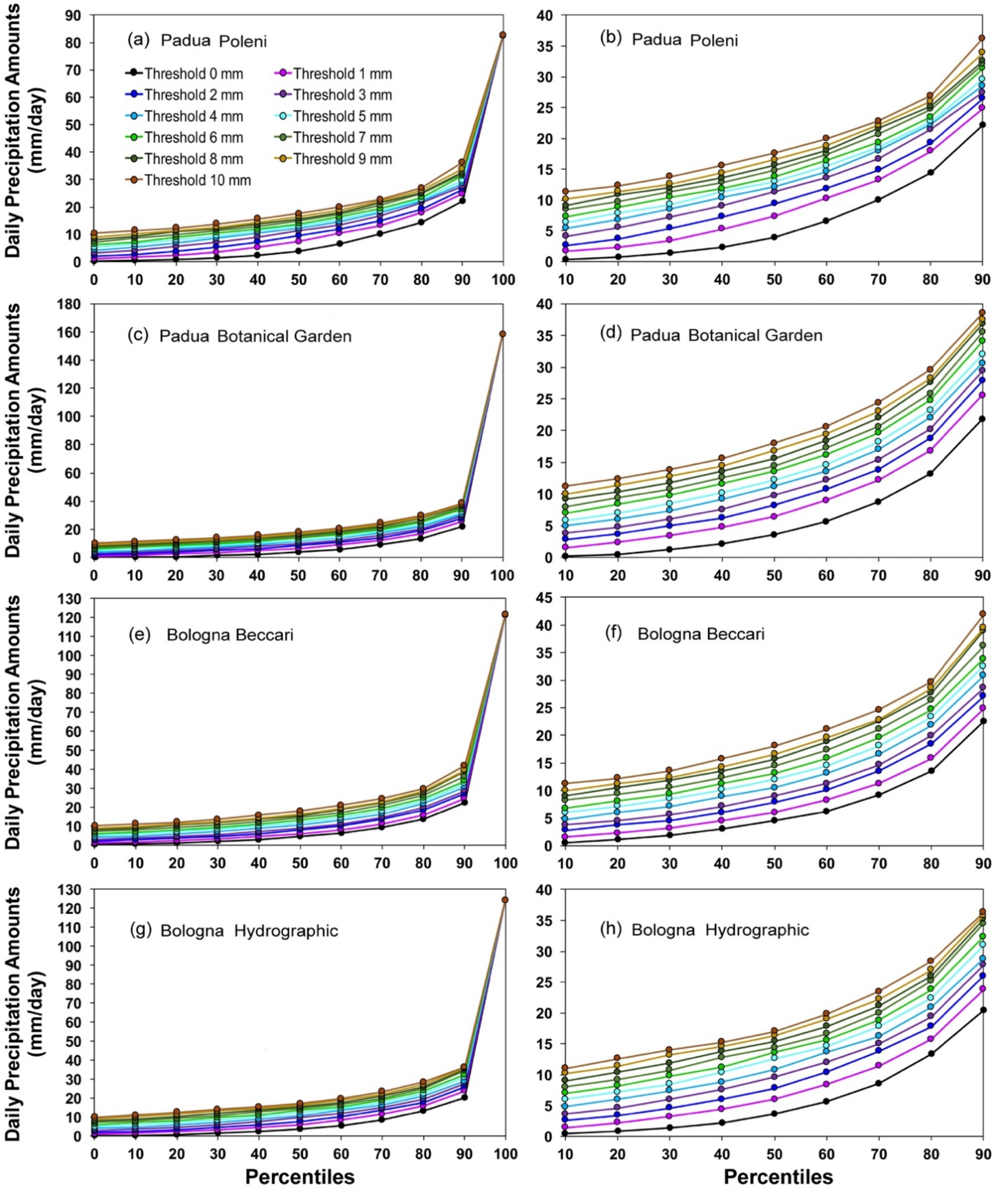

Fig.10 Change of the percentiles values when an instrumental threshold is applied. The first column is for the whole range from 0 to 100-ile; the second for the magnification of the 10 – 90-ile interval. (a), (b): Poleni; (c), (d): Botanical Garden; (e), (f): Beccari; (g), (h): Hydrographic.

The percentile distributions of the real datasets of Poleni and Botanical Garden in Padua and Beccari and the Hydrographic in Bologna are now considered. The simulation has been made by calculating the values of the percentile distribution without filter (Threshold 0) and with the high-pass filters 1, 2, 3 and so forth up to 10 mm.

The percentiles over the entire range (Fig.10a,c) show a hockey stick trend, where the sharp bend from 90- to 100-ile is due to the extreme precipitation events (Camuffo et al. 2020b,c). In the interval from 10- to 90-ile (Fig.10b,d) the percentile distribution of the observed data without filter is bent (Poleni may be represented with a fourth-degree polynomial). After the application of the threshold filter, the distribution is shifted upward by a vale that equals the threshold the lowest percentiles. This is clearly shown in Fig.11 that represents the difference between the values of the 0 to 90 percentiles of the datasets in Padua and Bologna calculated with a 10 mm threshold and without threshold. The results are different from the simple case of a homogeneous distribution discussed in Fig7b where all percentiles tend to reduce the difference introduced by the threshold. In the Botanical Garden, that can be considered a good standard reference, at the 0-ile, the difference between the values calculated with a threshold and those without threshold equals the threshold, as before. However, this difference increases linearly up to the 90-ile where is 6.7 mm higher. The Hydrographic has a similar trend, but with slightly curved plot. The final increase at the 90-ile is 5.9 mm. The Beccari trend is very similar to the Botanical Garden, but with a departure at the 90-ile. The Poleni trend starts to deviate at the 60-ile. After the 90-ile the situation changes dramatically for the particular distribution of the extreme precipitation. In the 90- to 100-ile interval, (Fig.10a,d), a strong convergence develops the and all lines converge and join together at 100-ile. The main difference between the regular Botanical Garden and the historic records concerns the highest percentiles and especially the 100-ile extreme, and the Poleni record has the lowest extreme. This may be explained because the Poleni funnel was on the roof chimney, more exposed to strong winds, thus penalizing stormy showers.

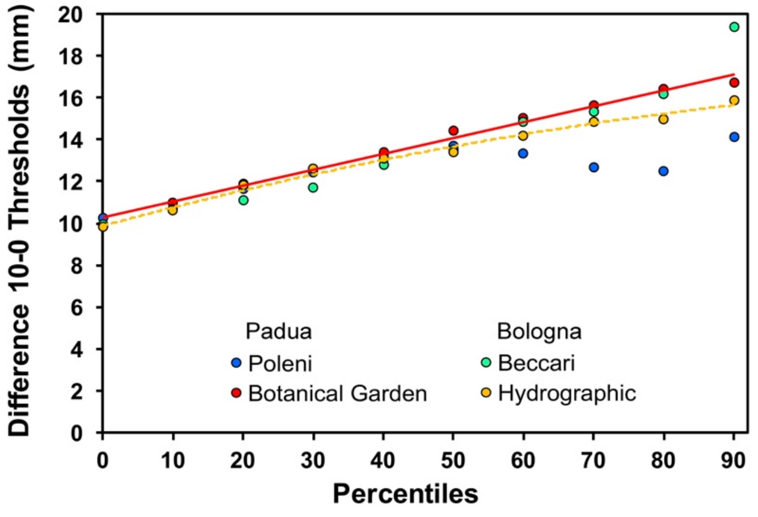

Fig.11 Difference between the values of the 0-90-iles of the datasets in Padua and Bologna calculated with a 10 mm threshold and without threshold.

5. Conclusions

In climate analysis, a crucial point is the interpretation of a result as climate change signal or instrumental bias. This problem is especially relevant for the historic records, taken with uncertain methodology and poorly documented with metadata. The methodology to analyze the low precipitation discussed in this paper has proven to be a powerful system to assess the quality and the homogeneity of early records.

Especially in the past, every instrument had its own threshold, and whenever an instrument was changed, this introduced a discontinuity that affects the homogeneity of the series. Under this aspect, the observations made by in the 18^{th} century by Giovanni Poleni and Jacopo Bartolomeo Beccari, always with the same instrument, have been recognized to be of high quality, being in several aspects homogenous to, or not much different, from those performed with a modern rain-gauge in line with the WMO standards.

Every change in the instrumental threshold has a dramatic impact on the (monthly, seasonal, yearly) precipitation frequency, especially for fine and light rains that remain largely undetected. On the other hand, the impact on the total precipitation amount is small, because fine and light rains give a modest contribution to the total.

In a precipitation record, the use of instruments with higher thresholds will shift upward all percentiles from 0- to 90-ile by a value that at the lowest percentile equals the instrumental threshold; after, it linearly (or almost linearly) grows with the percentile level. However, a turning point occurs after the 90-ile for the distribution of the extreme precipitation, and all lines converge to the most extreme value.

The comparison between historical records is a difficult task because different instruments will filter in different ways the fine and light rains, that are dominant. Any comparison should be made for values unaffected by cut-off thresholds. When this is not possible, it is advisable to make comparisons above selected thresholds unaffected by the change of instruments, although this will dramatically reduce the dataset population. For instance, if in a dataset only the precipitation values above 10 mm are considered, only some 30% of the data will survive, but they are responsible for the 75% of the precipitation total.

Precipitation frequency and amount are not related between them with a simple relationship, and the frequency alone cannot be considered representative of a missed amount. In the case of gaps or reconstruction of early series, the method of reconstructing monthly, or yearly amounts starting from diaries or newspapers reporting the list of rainy days, may hardly reach reliable results.

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