Assessment of parallel precipitation measurements networks in Piedmont, Italy

Assessment of parallel precipitation measurements networks in Piedmont, Italy

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Abstract: Long historical climate records usually contain non-climatic changes that can influence the observed behaviour of meteorological variables. The availability of parallel measurements offers an ideal occasion to study these discontinuities as they record the same climate. The transition from manual to automatic measurements has been analysed in this study. The dataset has been obtained from two independent climate networks in the Piedmont region, in Northwest Italy. From this dataset, 17 pairs of stations with up to 17 years of overlapping have been identified. On average the overlapping period is 12 years with 8760 daily data matched for a pair of stations. This dataset has proven valuable because it has made it possible to study a set of independently managed pairs of standard-quality stations, while most previous studies in this field analysed data from well-maintained instruments with the same operator, often at meteorological offices. The transition between two networks has highlighted important differences in the amount of precipitation and in the number of rainy days. On average, the automatic network has measured 12% less precipitation and has recorded 9% more rainy days (8 days) per year than the manual network. Both of these differences produce a spurious change in the precipitation of the analysed area, thus showing the importance of having a homogeneous dataset to identify real climate variations.

Parole Chiave: precipitation; parallel measurements; inhomogeneities; rain gauge

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1 Introduction

Long-term climate datasets are essential to study climate changes. In other words, long series of rainfall are essential for various hydrological applications related to water resource planning, power production, irrigation and flood control. However, these applications require long series of high quality. The observations need to be recorded, transmitted, digitized, quality controlled and then examined by an expert who is familiar with the instruments and climatology (Terzago et al., 2010, 2012; Mekis and Vincent, 2011; Acquaotta et al., 2015).

Italy plays a leading role in the development of meteorological observations. This role can be confirmed considering the invention of some of the most important meteorological instruments (Galileo Galilei's thermometer in 1607, Torricelli's barometer in 1643 and Cusano's hair hygrometer) and the foundation of the first observational network (Accademia del Cimento in 1657). This interest in meteorology over the last three centuries has produced a wealth of observational data of enormous value.

However, this long legacy also means that the Italian networks have undergone many technological, economic and organizational changes, which may have affected the homogeneity of the records (Peterson et al., 1998; Aguilar et al., 2003; Acquaotta et al., 2009). Consequently, studies on non-climatic changes are necessary to be able to reliably interpret any change in the climate records, such as climatic changes (Parker, 1994; Acquaotta and Fratianni, 2014). Inhomogeneities in precipitation gauge measurements can be caused by changes in wind-induced undercatchment, wetting losses (water adhering to the surface of the inner walls) and evaporation losses (Bodtmann and Ruthroff, 1976; Sevruk and Zahlavova, 1994; Sevruk et al., 2009). Also changes in instrument geometry, in the neighbouring environment and in the method of recording can cause inhomogeneities due to undercatchment. The World Meteorological Organization (WMO), and in particular the Commission for instruments and Methods of Observation (CIMO), have recognized the need to conduct a series of intercomparison of instruments in order to highlight and classify these discontinuities in precipitation recordings. Sevruk and Klemm (1989) showed that the major differences between precipitation records depend on the type of instrument, the height above the ground and the level of exposure. In order to establish the true amount of precipitation, it is necessary to calculate the systematic error of the precipitation measurements. These generally amount to 3–15% of the measured precipitation. Goodison et al. (1998) highlighted that the data of solid precipitation for all intercomparison sites should be adjusted to account for errors and biases. The catch efficiency of different gauges can vary to a great extent, for example from 20% up to 70% at 6 m s−1 wind speed. Lanza and Vuerich (2009) studied the first comparison of rainfall intensity in order to evaluate the performance of instruments in field conditions. The study allowed the efficiency of the instruments to be evaluated and indicated that tipping-bucket rain gauges and weighing gauges were the most accurate instruments.

These studies have shown and estimated the variations in the recording of precipitations in situ through special field studies, but what occurs in a region when a precipitation network is replaced? Is it possible to evaluate the systematic error of precipitation whenever the weather stations are not checked sufficiently? Baciu et al. (2005) and Boroneant et al. (2006). with reference to the transition to automatic weather stations (AWS) in Romania, have shown that the magnitude of the breaks differed to a great extent according to the location; some locations showed hardly any difference, whereas others showed clear inhomogeneity. The aim of this study is to analyse the effects of the recent transition to automatic precipitation measurement instrumentation in Italy, in particular in the Piedmont region where there are two independent meteorological networks, managed by two independent Institutes. An important feature of this study is that it is based on 17 pairs of stations located close to each other, with an overlapping period of 17 years (from 1987 to 2003). This offers an ideal opportunity for a unique study of inhomogeneities in long-term series.

The paper is structured as follows. A brief description of the climatic features of the studied area is given in Section 2. The networks and their instruments are introduced in Section 3 and it is also explained how the pairs are built and their properties are described. The methodology that has been adopted between the pairs is presented in Section 4. The paper finishes with the presentation of the most important results and a discussion on the importance of knowing the quality and the history of a series.

2 Geography of the Piedmont region

Piedmont covers an area of 25 399 km2 and has about 4.3 million inhabitants. It borders Switzerland and France, and in Italy it borders the regions of Lombardy, the Aosta Valley, Liguria and Emilia-Romagna.

From a geomorphological point of view, Piedmont can be divided into three large areas: an outer mountain arc (Western Alps and Apennine mountains) that covers about 48.7 % of the entire region, the Piedmont Plain (25.4%) and the extensive hilly area of Monferrato and the Langhe (25.9%) (Figures 1 and 4).

Two major factors, internal and external, determine the thermal-pluviometric characteristics of Piedmont. The major internal factor that controls the climate in Piedmont is its orography. The external factor is the circulation of relatively dry continental air flowing in from the Po Valley in the east and relatively moist Mediterranean and Atlantic air coming from the northwest (Fratianni et al., 2005, 2009; Giaccone et al., 2015).

The annual precipitation cycle in Piedmont shows a bimodal pattern with two maxima, one in autumn and one in spring, and two minima, in winter and in summer. On the basis of the position of the main minimum, the main maximum and the secondary maximum, four types of pluviometric regimes can be distinguished in Piedmont. Of these, three are of a continental type (main minimum in winter) and one is of a Mediterranean type (main minimum in summer).

Figure 1, taken from Biancotti et al. (1998), illustrates the relationship between precipitation and elevation in Piedmont: the average annual precipitation profiles show minimum values over the Piedmont Plains and maximum values over the Alps and Apennines.

3 Dataset

3.1 SIMN – Italian Hydrographic Mareographic Service

The first network that has been studied is the Italian Hydrographic Mareographic Service (SIMN), which was founded in 1917 with the aim of standardizing and organizing the pluviometric, thermometric and hydrometric measurements in Italy. This network was closed in 2003 by a national law to reorganize the national weather network. In 1970, the year for which most data is available in Piedmont, the dataset was built on the results of 135 totalizing rain gauges and 149 tipping-bucket rain gauges, while in the analysed period, that is, from 1987 to 2003, only 142 meteorological stations recorded precipitation.

The SIMN rainfall stations use a tipping-bucket rain gauge, UM 8100, with a calibrated mouth (1000 cm2), a bucket and a recording system that writes on diagram paper. Any movement of the lever corresponds to 20 g of water and every click of the pen represents 0.2 mm of rain. The mouth was at a height of 2 m from the ground (Figure 2). The measurement data are collected manually in the SIMN stations. The rain gauge measurements are recorded on a paper roll, which has to be collected weekly in order to manually transcribe the values. The daily amounts of precipitation are calculated from 0800 UTC+1 to 0800 UTC+1.

Long historical precipitation series are available at the SIMN stations. In order to obtain metadata about the historical changes in the area and in the weather station, the authors studied the Hydrological Annals (Hydrographic Mareographic National Service archives), which state, for each year, the geographic coordinates of each station (latitude, longitude and elevation) and the type of instrumentation. Furthermore, the original records on which the potential breaks, changes in location or instrumentation were marked have also been inspected.

Manual quality control (QC) was carried out using the RClimdex software (Zhang and Feng, 2004). The programme highlights any precipitation data that are obviously wrong, such as negative values, and creates plots that allow outliers to be identified. The identification of the outliers and of the maximum values of the daily precipitation in the SIMN stations has been very important because it has made it possible to identify incorrect values due to erroneous transcriptions of the daily data. An example of a typical transcription error is the weekly accumulation being transcribed as the value of one day. Such an error is relatively simple to identify, but it is necessary to re-check the data in the original paper records. Once this type of error had been identified in the selected time period, the daily values were considered as missing data and the cumulative value was dropped.

A statistical test was carried out on the monthly precipitation series from 1961 to 2003 to prevent any undocumented inhomogeneities from falsifying the recording. HOMER (HOMogenization softwarE in R) (Mestre et al., 2013) was used to detect any inhomogeneities. HOMER compares a candidate series with its neighbours in the same climatic area by computing a difference series. These difference series are then tested for discontinuities. Any changes detected on the computed series may have been caused by the candidate or the neighbour. However, if a detected change-point is consistently seen in a set of comparisons of a candidate station with its neighbours, it can be attributed to this candidate station.

3.2 ARPA – Regional Agency for Environmental Protection Piedmont

In 1986, a new automatic hydrographic network began to be set up in Italy. This network has been managed by the Regional Technical Prevention Services by the Legislative Decree no. 112 of 31 March

1998, the 'administrative functions and duties of the State were to be conferred to the regions and local organizations'. For Piedmont, the network is managed by the Regional Agency for Environmental Protection Piedmont (ARPA). In 1986, ARPA had 42 pluviometric stations. It now has 400 automatic stations with a density of one rain gauge per 70 km2 (Cagnazzi et al., 2007).

The instrumentation used by ARPA consists of a tipping-bucket rain gauge, PMB2, with a calibrated mouth (1000 cm2). The overturning of the bucket activates a contact that provides an electrical signal for each 0.2 mm of rain. The mouth is at a height of 1.5 m from the ground (Figure 2). The hourly data is transmitted directly to the database. The hourly ARPA values from 0900 to 0900 were aggregated in order to compare the daily data with the daily SIMN data.

The ARPA stations are relatively new automatic stations that have started to record in 1986. The instruments are subjected to an accurate control and calibration once a year, while the data are subject to an automatic QC. The QC flags are indicated with the alphabetic letters: A, B, C, D, E, R and Z; see Table 1. The flags from A to D indicate values that may be wrong because of missing or suspicious hourly data, E indicates that the data was computed taking the hydrological balance into account and R denotes reconstructed data. Correct data values are indicated with the Z flag. Only data with Z flags have been used in the subsequent analysis.

The ARPA stations are relatively new automatic stations with a good QC, but the instruments can still malfunction or need replacement. The stations with such known problems were removed from the dataset. A homogenization test was also applied to the monthly series to prevent any undocumented discontinuities from falsifying the real behaviour of the variables.

HOMER could not be used for these series because they were not long enough (Lindau and Venema, 2013). In order to evaluate the homogeneity, the behaviour of the annual and monthly ARPA series was compared with the homogeneous monthly SIMN series to visually assess any possible discontinuities between the two series. This first cross-check did not show any undocumented breaks in the ARPA series. Furthermore, the penalized maximal t-test (Wang et al., 2007) was also applied.

3.3 Pairs of stations

In 2002, a national law introduced the unification of the meteorological networks owned by SIMN with those of ARPA. After the unification, ARPA decided to remove to close the SIMN stations on 31/12/2003, which are located very close to ARPA stations for technological and cost-effectiveness reasons.

Therefore, at present precipitation series are recoded from two different meteorological networks in Piedmont; the SIMN network, with daily data being collected from 01/01/1917 to 31/12/2003, and the ARPA automatic station network, which has provided information since 1986. The selected time frame for the analysis of the stations is 1987–2003: this has led to an overlapping period of 17 years, which has been used to study the influence of this transition in detail.

The first selection of pairs of stations was based on three parameters, that is, the overlapping period, the difference in elevation and the distance. Series need to have more than 5 years of overlapping before they can be used to study the influence of transition (Vincent and Mekis, 2009). According to the work by Biancotti et al. (2005) on the precipitation gradient, the difference in elevation between two stations must be less than 200 m. The distance between two stations must be less than 20 km (Isotta et al., 2013).

The second step was to evaluate the exposure of the selected stations and their characteristics, the type of instrumentation, the neighbours and the general conditions. A metadata file was created for each location in which the following are shown: the location of the meteorological stations, the basin they belong to, the latitude, the longitude, the altitude, the type of instrumentation, any changes in location or in the instrumentation, the elevation difference, the distance between two stations, the operating periods and the overlapping period. In addition, cartographical maps with different levels of detail were drawn up for each meteorological station, and photographic documentation was used to complete the information (Table 2 and Figure 3). The photographs make it possible to see the conditions of the instruments. The 1 : 10 000 scale cartography, obtained from the Regional Technical Cartography (CTR), contains topographic and urban planning information. Finally, the pairs of meteorological stations were marked on a 1 : 25 000 topographic map of Italy (Military Geographical Institute, Cartographic State Agency) to show their relative positions.

Considering 1986 as the starting point, 55 municipalities with two meteorological stations were examined in the studied region. These locations are uniformly distributed (Figure 4), and their elevations range between 83 m a.s.l. (Sale) and 1810 m a.s.l. (Malciaussia).

These 55 locations, with a total of 110 daily precipitation series, were quality controlled to identify any anomalies or gaps. A month with less than 80% daily values was considered a gap. If a year had 1 month or more of missing data, that year was considered to be a gap (Klein Tank et al., 2002; Gokturk et al., 2008). Of the 55 pairs of stations, only 20 pairs showed good continuity, a sufficient overlapping period, an adequate distance and a different elevation. The overlapping period on average was equal to 12 years, while the distance ranged between 5 m at Oropa and 2500 m at Carcoforo. Moreover, the elevation differences were not too large, as they ranged between 0 m at Ala di Stura and 140 m at Carcoforo; the aforementioned values are listed in Table 3.

A continuous and accurate history of the stations (metadata) was available for the selected SIMN and ARPA stations. This information was studied to avoid any potential breaks in the series, due either to changes in the location or in the instrumentation.

For the SIMN stations, HOMER showed a break for five stations: Ala di Stura, Luserna S. Giovanni, Oropa, Salbertrand and Valprato Soana. Only for Luserna S. Giovanni did the discontinuity fall into the overlapping period, and this location was therefore dropped from the study (Table 3).

The historical research on 20 SIMN stations highlighted one or two breaks during the operation period. In most cases, the breaks were due to changes in the shown position or to changes in the elevations documented in the original paper record. These breaks did not fall into the overlapping period with the ARPA stations, and the series metadata were therefore considered homogeneous. The visual check of the monthly series and the penalized maximal t-test for the ARPA stations did not highlight any discontinuities.

Another two pairs of stations, Bra and Piedicavallo, were also dropped from this group of 19 locations (Table 3). The Bra location was deleted because of the differences in location and exposure. The SIMN station is a very old meteorological station that was set up in 1862 and which has been replaced by an automatic station. The SIMN station was located on the roof of a building, while the new ARPA station is in the garden and is surrounded by trees, one of which is close to the instrumentation. As far as Piedicavallo is concerned, the two stations utilize different types of rain gauges. The SIMN station uses totalized rain gauges, while the ARPA station utilizes a tipping-bucket rain gauge. Therefore, out of a total of 55 pairs of stations, only 17 pairs were analysed.

4 Methodology

In order to be able to make a direct comparison between the daily pluviometric series, any values that were missing in one series were also set to be missing in its counterpart before the monthly statistics were computed. Moreover, the daily precipitation values of less than 1 mm in the series were dropped to prevent a set of small values that reflected changes in the measuring precision from influencing the recording (Wang et al., 2010). Averagely in an year, the daily precipitation less than 1 mm was excluded in the study corresponding to 10.0 mm (1.2% of annual rain for SIMN stations), and to 10.6 mm (1.3% for ARPA stations).

The ARPA series were considered in this analysis as the reference series because they are still operating and they satisfy the measurement criteria recommended by WMO. Moreover, their instruments are subject to constant maintenance.

Non-parametric tests were applied to the daily values to evaluate the preliminary relationships between the pairs of series. The root mean square error (RMSE) was used to identify the mean difference between the two series, while the Spearman correlation coefficient was used to evaluate the correlation coefficient. The Kolmogorov–Smirnov test (KS) was applied to determine whether two datasets could have come from the same distribution, while the Wilcoxon rank sum test (W) was considered to establish whether two samples had identical population medians. A p = 5% significance level was used for all the tests.

The monthly precipitation sums were then analysed. A two-factorial analysis of variance (ANOVA) test was applied to the pairs of series. One factor was the month and the other factor was the network: SIMN or ARPA. Data need to be normally distributed for an ANOVA test. For this reason, the Shapiro–Wilk test was first applied. This test establishes the null hypothesis that a sample comes from a normally distributed population (Filliben, 1975; Ricci, 2005).

The percentage relative error, e, (Lanza and Stagi, 2012) was also calculated from the monthly precipitation data in order to identify the months or seasons with the greatest differences.

$$e\,[\%] = \frac{R_{\mathrm{SIMN}} - R_{\mathrm{ARPA}}}{R_{\mathrm{ARDA}}} \times 100$$

A value of e > 0 shows an overestimation of monthly precipitation of SIMN stations while e < 0 highlights an underestimation of monthly SIMN precipitation, with respect to the monthly ARPA rain considered as reference series. Also the trend in the percentage relative errors is studied. The non-parametric trends were computed using the Theil–Sen approach (TSA) (Sen 1968; Zhang et al., 2000; Toreti and Desiato 2008). The Mann–Kendall test for the trend is then run on the resulting time series to compute the level of significance. TSA is preferred to the linear least square that is more vulnerable to outliers and has a confidence interval more sensitive to the non-normality of the distribution.

The thresholds by percentile were calculated on a daily scale to identify the different precipitation types. The percentiles were calculated on the ARPA series, that is, the reference series, and five classes of precipitation were established: weak (w_r), medium (m_r), heavy (h_r), very heavy (R95p) and extremely heavy (R99p), see Table 4. The number of events and the cumulative amount of rain were calculated for each class and for each pair of series.

Only the days that had measurements of the same precipitation events were selected for each class and for each pair of series. An error of the rain amount equal to ±15%, which corresponds to the maximum systematic error of the precipitation measurement, SEP (Sevruk and Klemm, 1989; WMO (CIMO), 2008; Sevruk et al., 2009), was calculated for these events, and then the number of common events included in these ranges was estimated. This methodology has made it possible to show the percentage of precipitation events that can be considered equal between the pairs of series and, at the same time, to highlight the type of events that can induce the greater difference between the two stations.

5 Results

The statistical analyses with the Kolmogorov–Smirnov test show similar probability distributions between most pairs of stations (Table 5). Only in four stations, Boves, Carcoforo, Locana L. Valsoera and Valprato

Soana, did the test show statistically significant differences. The root means square error (RMSE) was also very large for these stations, ranging between 10 mm at Valprato Soana and 32 mm at Boves, while the RMSE in the statistical tests was around 5 mm in the pairs of series, thus showing a good result.

All the rank correlations were larger than 0.80, except for five locations: Casale M.to, Boves, Carcoforo, Valprato Soana and Bardonecchia (Table 5). The scatter plot of the correlation coefficient and the distance do not show any clear relationships (not reported). Moreover, no obvious relationship can be seen between the correlation coefficient and the difference in elevation (not reported).

In most cases, the SIMN rain gauges measured larger precipitation amounts than the ARPA stations; see Table 3. On average, the SIMN stations measured 12% more precipitation. Only in three locations, that is, Cumiana, Lanzo T.se and Torino, was the opposite observed. In these three locations, ARPA measured 11% more precipitation.

The Shapiro–Wilk test did not reject the hypothesis that the monthly precipitation series had a normal distribution. Only in the SIMN Oropa series was the test almost significant ($p = 0.07$).

The variable 'month' in the two-factorial ANOVA test for the amount of rain was statistically significant for all the locations. All the stations showed a seasonal cycle in the mean precipitation amounts. A continental pluviometric regime was identified in all the stations, with a minimum in winter and a maximum in spring or autumn (Terzago et al., 2010; Acquaotta and Fratianni, 2013).

The variable 'network' differed from location to location (Table 5). In seven locations, that is, Bardonecchia, Ceresole Reale, Cumiana, Salbertrand, Susa, Valprato Soana and Varallo Sesia, the monthly precipitation series did not depend on the network, according to the ANOVA test. The two meteorological networks recorded about the same monthly precipitation amounts. In these locations, the monthly percentage relative error was on average equal to 8%. The month that recorded the greatest difference is February, with a mean percentage relative error of 24%. These sites are situated in the Cozie Alps (Bardonecchia, Salbertrand and Cumiana) in the Graie Alps (Ceresole Reale, Susa and Locana) and in the Pennine Alps (Varallo Sesia). The distance ranges between 2040 m for Varallo Sesia and 465 m for Valprato Soana, while the difference in elevation ranges between 103 m for Bardonecchia and 5 m for Valprato Soana.

In the remaining ten locations, the recorded monthly precipitation amounts depended on the network. The mean monthly percentage relative error was equal to 17%. In particular, the largest deviations were obtained for the Casale M.to, Boves and Locana L. Valsoera sites, where the mean monthly percentage relative error was 39% (Figure 5). The differences in height and distance again do not seem to be important to explain the differences in the monthly precipitation. The stations are located in the Piedmont Hills (Mondovì, Casale M.to, Boves and Torino), in the Piedmont Plains (Vercelli), in the Graie Alps (Ala di Stura and Locana L. Valsoera), in the Cozie Alps (Lanzo T.se) and in the Pennine Alps (Oropa and Carcoforo). The distance ranges between 2500 m for Carcoforo and 5 m for Oropa, while the difference in elevations ranges between 140 m for Carcoforo and 0 m for Ala di Stura.

The SIMN stations on average recorded 13 mm per month more than the ARPA stations for these locations. The largest differences were once again recorded in the winter months. The mean monthly percentage relative error was 42% for December, 32% for February and 26% for January.

The trends calculated on percentage relative error do not highlight a systematic long-term change in the quality between the pairs of series. In ten locations the trend is positive. The average trend of these ten locations is 0.11%/month, while in the other seven locations it is negative (−0.08%/month). Only in five locations is the trend statistically significant. In two locations it is positive while in the other three it is negative (Table 5, Figure 6).

The analysis of precipitation events into five classes had shown similar behaviours not from station to station but for the type of the rain events. The weak and medium classes show the same characteristics (Table 6). The ARPA stations recorded a greater number of events. The ARPA stations on average recorded 411 events for the weak class throughout the entire analysed period, while the SIMN stations measured −14% of events. Only 53% of the events were recorded in the same days, and 32% of these events were included in the maximum systematic error of the precipitation measurement equal ±15% of the daily rain amount. The medium rain class presents the same features. The ARPA stations recorded a greater number of events, that is, 5% more, and only 56% of the events were measured in the same days, but the main precipitation events did not fall within the maximum systematic error of the precipitation measurement.

For the heavy, very heavy and extremely heavy rain, the opposite is true. The SIMN stations recorded a greater number of events. The main differences were calculated for the extremely heavy and very heavy precipitation events. The SMN stations recorded 52% more of extremely heavy rain events. For these events, only 71% were recorded in the same days, but 55% of the events showed less of a difference than ±15% of the rain amount. For the very heavy precipitation events, the SIMN stations recorded 22% more of events, while only 50% of the cases were included in the error range for the events in the same days.

A scatter plot, divided into two location classes, that is, Susa and Locana L. Valsoera, is shown in Figure 7 as an example. These locations were selected because the pairs of series examined during the analysis presented different results. Locana L. Valsoera was chosen since the monthly analysis showed large differences between the two series, while Susa was chosen because of its good results. Despite these differences, the class analysis shows the same results. The ARPA rain gauge measured a greater number of events for the weak rain and medium rain events, while the opposite situation was observed for the heavy, very heavy and extremely heavy rain events. The two networks recorded the precipitation events in two different ways, thus producing an intrinsic discontinuity in the pairs of series.

6 Conclusions

An important non-climatic change in precipitation records has been studied in this paper. The transition from one network, the SIMN, to another network, the ARPA, has been studied in the Piedmont region, Northwest Italy. This instrumental transition is typical for all of Italy. Infact, with LD 112, 1998, was agreed that the departmental offices of SIMN would be transferred to the regions. As a result, the new regional hydrographic weather network was equipped with new instruments (tipping-bucket rain gauges), which can provide real-time measurements with high temporal details, because of their advanced technology content, and which was destined to progressively be substituted by the manuals instruments of the SIMN network throughout the entire country.

The question has therefore arisen concerning the correctness of uniting consecutive in time data series but from different instruments. To this aim, locations in the Piedmont region in which both weather station networks were present at the same time have been searched for and identified in order to analyse the impact of the changes in instrumentation and site on the acquired measurements. Piedmont has many long daily precipitation series available and its database contains parallel measurement from 1987 to 2003. This situation is ideal, the meteorological stations are very close and the mean overlapping period is 12 years.

Transition from the old network, SIMN, to the new, ARPA, one in 17 locations has made it possible to have a unique dataset made up of independently measured parallel observations. This has enabled the authors to study to what extent the measurements heritage has been damaged by the closure of the original meteorological stations. The ARPA weather stations have shown 12% less precipitation and 9% more rainy days than the original observations.

The applied methodology has also made it possible to discern the locations with the greatest differences. In these locations, the monthly analyses of the precipitation series have shown variations that are higher than or equal to 30% in both the annual amounts and in the number of rainy days.

The differences have been found to vary from location to location, thus emphasizing the advantages of studying sets of parallel measurements. The disadvantage of the large set is that the instruments are not placed close to each other. However, the statistical analysis did not show any influence of distance (or height) on the differences.

A further advantage of the dataset is that the two networks were maintained independently to each other which means that one measurement did not influence the observations reported for the other. Nevertheless, the analysis has shown common behaviour for all the weather stations. The two networks do not record the precipitation events in the same way. The study of the five precipitation classes, that is, weak, medium, heavy, very heavy and extremely heavy rain, has shown that the ARPA network has measured a greater number of weak and medium precipitation events, while the SIMN network has measured a greater number of heavy, very heavy and extremely heavy events. For the weak and medium rain ARPA recorded averagely 10% in plus of events while for heavy, very heavy and extremely heavy rain the SIMN station measured 27% in plus of events. The greatest differences, 52% of events, was calculated for extremely heavy rain.

The study has clearly highlighted the importance of analysing parallel measurements for the study of non-climatic changes in climate records. This is especially important in the case of precipitation, where the relative statistical homogenization is hampered by low cross-correlations between stations.

The Parallel Observations Science Team (POST) is working on a large database with parallel station measurements of all the essential climatic elements in order to be able to study the characteristics of non-climatic changes in large sets as a function of the local climate (POST, 2015).

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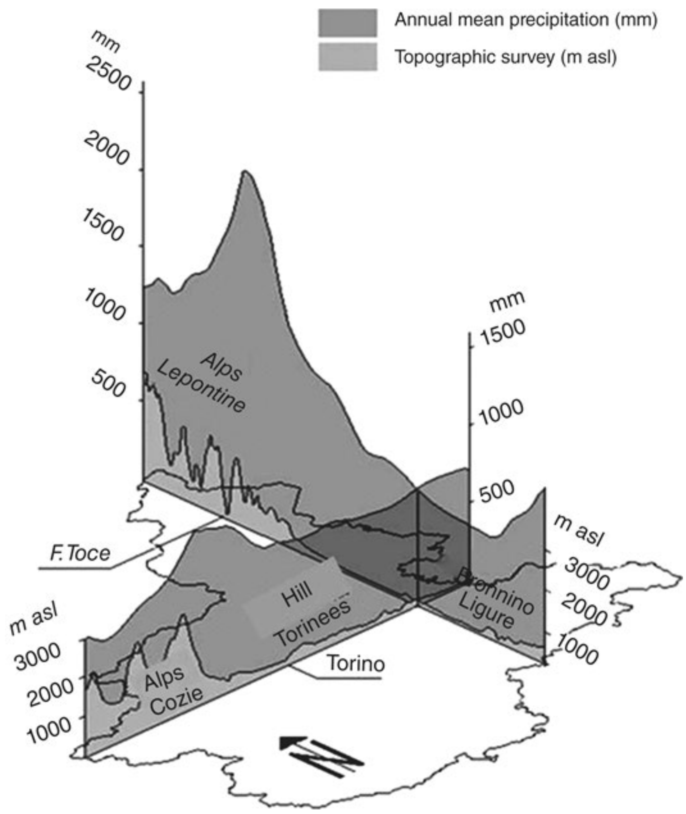

Figure1

Pluviometric and altimetric profiles over two Piedmont sections. Figure by Biancotti et al., 1998.

Figure 2

This is the Authors final copy of the original published: **International Journal of climatology** 36(2016) p. 3963-3974

Left: photo of a tipping-bucket rain gauge, UM8100, used by SIMN. Right: photo of a tipping-bucket rain gauge, PMB2, utilizing by ARPA Piedmont.

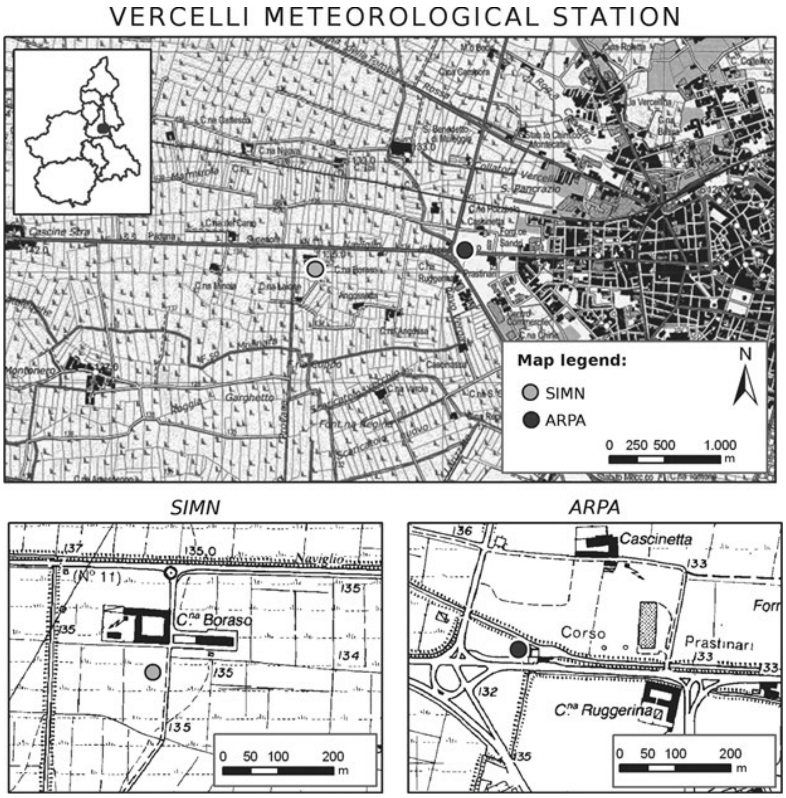

Figure 3

Cartography of two meteorological stations in Vercelli.

Figure 4

The 55 sites with pairs of meteorological stations in Piedmont: the white stars denote the locations that were utilized in the comparison (17 locations).

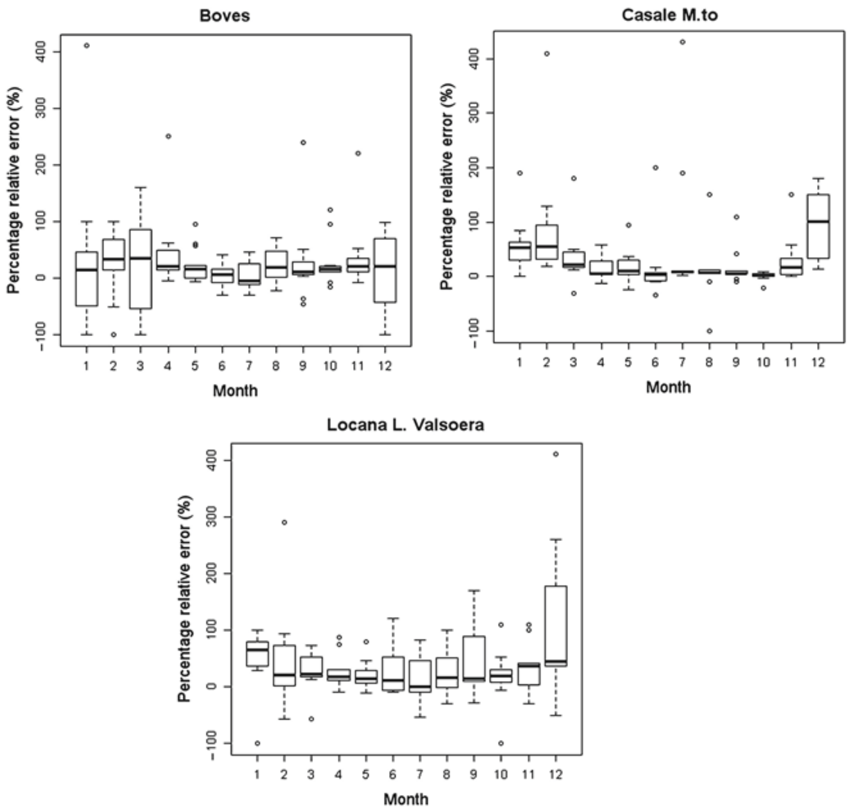

Figure 5

Box-plot of the percentage relative error for Boves, Casale M.to and Locana L. Valsoera.

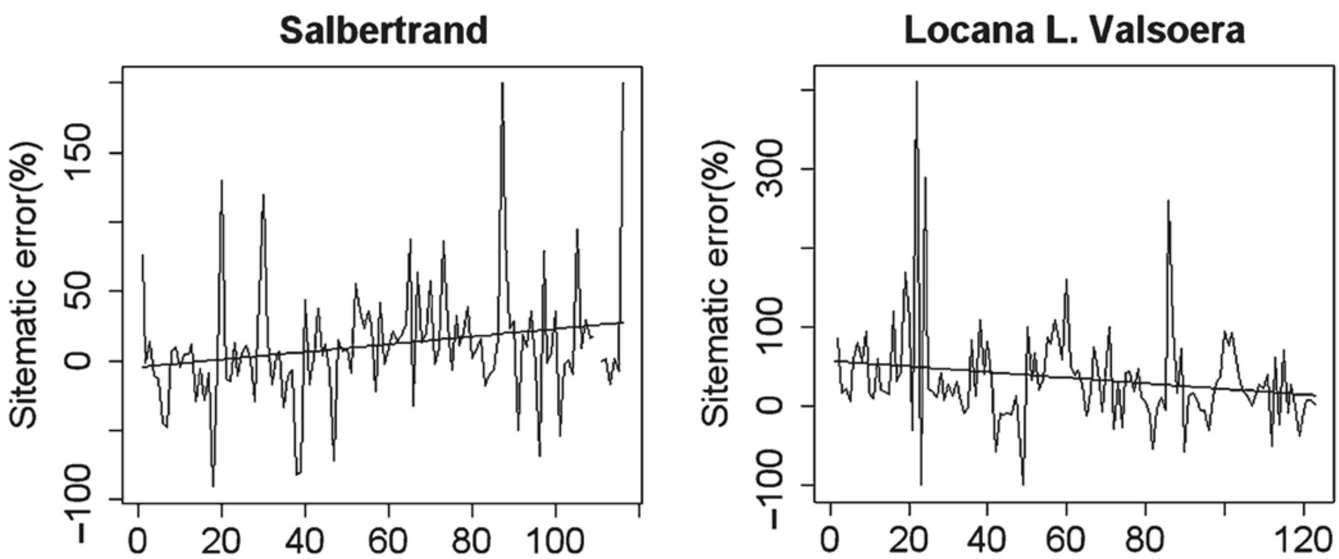

Figure 6

Trend of the percentage relative error, e, calculated for Salbertrand, left, and for Locana L. Valsoera, right. Salbertrand has the largest positive trend, while Locana L. Valsoera has the largest downward trend.

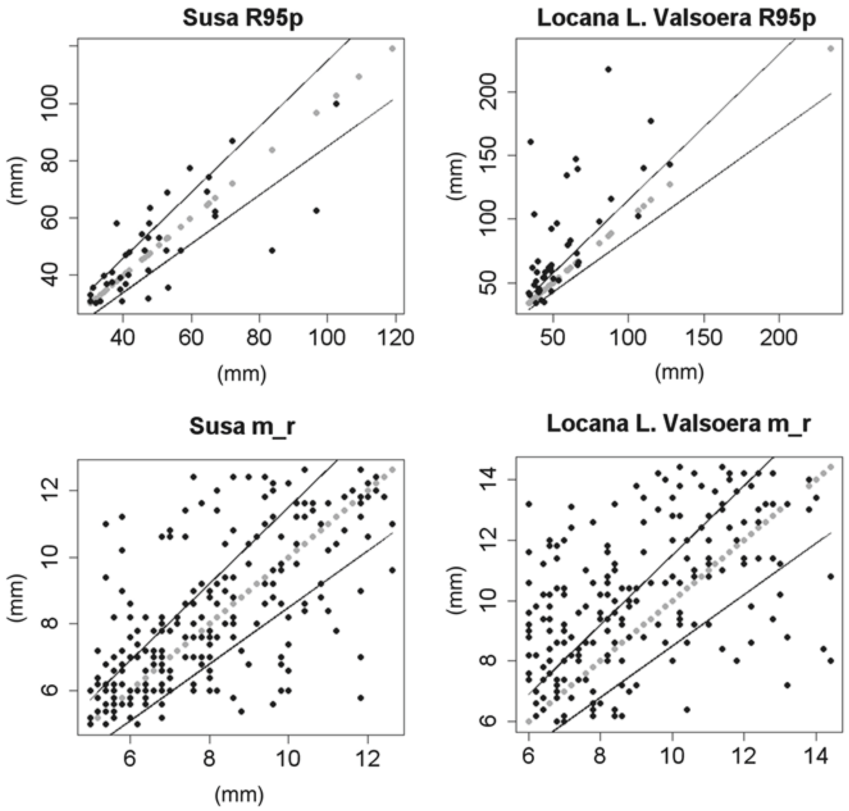

Figure 7

Scatter plot of the ARPA and SIMN rain divide into classes, R95p very heavy rain and m_r medium rain for Susa in the left column and for Locana L. Valsoera in the right column. Only the events measured on the same days are represented in these plots. The ARPA values are shown on the x-axis while the SIMN values are shown on the y-axis. The black line represents a range equal ±15% of the daily rain amount. The ARPA rain is shown in grey, while and the SIMN rain is shown in black.

Table 1. ARPA data flags.

Flag	Definition
A	Aggregation calculated on a percentage of hourly data of less than 75%
B	Aggregation judged unreliable at the time of the interactive validation
C	Aggregation judged suspicious at the time of the interactive validation
D	Aggregation judged very suspicious at the time of the interactive validation
E	Data derived from a hydrological balance with melted snow
R	Data reconstructed using neighbouring stations
Z	Correct data

Table 2. Example of a metadata file for a pair of two meteorological stations in Vercelli.

Vercelli Name or technical code	**SIMN station Stazione risicoltura**	**ARPA station Vercelli – cod 198-**
Municipalities	Vercelli (VC)	Vercelli (VC)
Location	Cascina Boraso	Casello Ruggerina
Basin	Sesia	Sesia
Elevation (m a.s.l.)	135	132
Latitude N	45°19’50”	45°19’32”
Longitude E	8°21’40”	8°23’26”
Coordinate UTM X	319738	452237
Coordinate UTM Y	4994608	5019386
Precipitation (start – sensor type)	1 January 1927 rain gauge UM8100 SIAP	17 June 1993 rain gauge PMB
Precipitation (end)	31 December 2003	Active
Break by HOMER or metadata	–	–
Temperature (start – sensor type)	1 January 1927 thermograph	17 June 1993 thermograph
Temperature (end)	31 December 2003	Active
Break by HOMER or metadata	–	–
Distance (m)	1360	
Difference of elevation (m)	3	
Period of overlap precipitation	1994–2003	
Period of overlap temperature	1994–2003	

Table 3. The 20 locations selected for the comparison of the SIMN precipitation series and ARPA precipitation series: elevation, E, (m a.s.l.); difference in elevation, Diff E, (m); distance, Dist, (m) and overlapping period, Period. The mean annual value of precipitation recorded by SIMN, SIMN_rain, and ARPA, ARPA_rain, are reported for the paired series in millimetres (mm) together with the mean annual number of rainy days for SIMN, SIMN_n, and ARPA, ARPA_n. The locations dropped from the study are shown in bold.

Location	SIMN E (m)	ARPA E (m)	Diff E (m)	Dist (m)	Period	SIMN_rain	ARPA_rain	SIMN_*n*	ARPA_*n*
Ala di Stura	1006	1006	0	70	1993–2003	1079.9	969.9	91	92
Bardonecchia	1250	1353	103	800	1991–2003	686.6	682.2	89	91
Boves	590	575	15	1240	1988–2003	1322.9	1106.9	52	82
Bra	**290**	**285**	**5**	**15**	**1993–2003**	**731.0**	**616.0**	**68**	**61**
Carcoforo	1150	1290	140	2500	1997–2003	953.6	802.4	66	96
Casale M.to	113	118	5	20	1988–2000	479.7	409.0	63	61
Ceresole Reale	2260	2304	44	920	1996–2003	971.6	889.2	99	101
Cumiana	289	327	38	2800	1988–2003	828.9	863.9	69	71
Lanzo T.se	540	580	40	2200	1989–1999	1098.3	1438.3	73	93
Locana - L.Valsoera	2410	2365	45	250	1987–2003	1109.4	846.6	99	94
Luserna S. Giovanni	**478**	**475**	**3**	**760**	**1988–2003**	**1037**	**1090**	**77**	**84**

Location	SIMN E (m)	ARPA E (m)	Diff E (m)	Dist (m)	Period	SIMN_rain	ARPA_rain	SIMN_*n*	ARPA_*n*
Mondovi	440	422	18	390	1993–2003	643.1	577.5	65	65
Oropa	1180	1186	6	5	1991–2002	2057.4	1794.3	105	100
Piedicavallo	**1050**	**1040**	**10**	**180**	**1996–2003**	**1798.0**	**1736.0**	**93**	**106**
Salbeltrand	1031	1010	21	1250	1991–2002	568.0	541.1	84	87
Susa	510	520	10	820	1991–2003	718.6	695.0	75	76
Torino	270	240	30	850	1990–2003	824.3	860.7	69	73
Valprato Soana	1550	1555	5	465	1993–1999	1166.2	1128.1	102	111
Varallo Sesia	453	470	17	2040	1989–2003	1845.4	1698.4	95	94
Vercelli	135	132	3	1360	1994–2003	625.1	577.7	69	67

Table 4. Names and ranges of the five precipitation classes. The thresholds were calculated from the percentiles estimated on the reference ARPA series

Class	Range
Weak rain (w_r)	$R < 50$th
Medium rain (m_r)	50th $\leq R <$ 80th
Heavy rain (h_r)	80th $\leq R \leq$ 95th
Very heavy rain (R95p)	R > 95p

Class	Range
Extremely heavy rain (R99p)	R > 99p

Table 5. Results, p-values, of the statistical tests applied to the daily values of the pairs of stations. KS test, Kolmogorov–Smirnov test; W test, Wilcoxon rank sum test; Sp corr, Spearman correlation coefficient; RMSE, root mean square error. The results obtained from the two-factorial ANOVA test on a monthly scale are also shown. The differences are statistically significant when $p < 0.05$. The last two columns report the estimated trend in the percentage relative error, trend, and the p-value of Mann–Kendall trend test. The trends are statistically significant when $p < 0.05$.

Location	KS test	W test	Sp corr	RMSE (mm)	Two ANOVA Rain	Trend	*p*-value
Ala di Stura	0.10	0.05	0.83	10	<0.001	−0.17	0.08
Bardonecchia	0.94	0.84	0.79	5.1	0.95	−0.05	0.61
Boves	<0.001	<0.001	0.57	32	<0.001	−0.03	0.82
Carcoforo	≪0.001	≪0.001	0.60	26	<0.001	0.05	0.40
Casale M.to	0.37	0.20	0.33	13	<0.001	0.02	0.77
Ceresole Reale	0.60	0.26	0.82	8.3	0.23	0.53	≪0.001
Cumiana	0.91	0.91	0.84	8.3	0.12	0.02	0.80
Lanzo T.se	0.44	0.52	0.84	9.9	<0.001	0.09	0.20
Locana – L.Valsoera	0.04	0.01	0.83	12	<0.001	−0.17	0.05
Mondovi	0.53	0.51	0.92	7	0.04	0.03	0.20
Oropa	0.63	0.30	0.93	9.7	<0.001	−0.10	0.01
Salbeltrand	0.62	0.25	0.81	5.5	0.51	0.16	0.01
Susa	0.85	0.61	0.85	5.6	0.16	0.03	0.37
Torino	0.99	0.79	0.95	5.8	0.007	−0.01	0.47

Location	KS test	W test	Sp corr	RMSE (mm)	Two ANOVA Rain	Trend	*p*-value
Valprato Soana	0.03	0.04	0.70	10	0.76	0.14	0.39
Varallo Sesia	0.50	0.76	0.94	11	0.06	0.05	0.25
Vercelli	0.84	0.53	0.92	5.1	0.02	−0.06	0.87

Table 6. The mean values estimated from the five precipitation event classes: w_r = weak rain, m_r = medium rain, h_r = heavy rain, R95p = very heavy rain and R99p = extremely heavy rain. Rain mean, mean rain amount of the class in (mm); %_ARPA_n, percentage of events recorded in plus or minus by the ARPA instruments; % Events_ common, percentage of events identified in the same days; ±15%_events, number of event that fall within in the maximum systematic error of the precipitation measurement.

Class	Rain mean	%_ARPA_*n*	% Events_common	±15%_events
w_r	2.9	14	53	32
m_r	10.3	5	56	49
h_r	25.4	−8	60	56
R95p	67.4	−22	73	50
R99p	109.9	−52	71	55

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