Climate Dynamics (2019) 52:3435–3453
https://doi.org/10.1007/s00382-018-4337-6

High resolution climate precipitation analysis for north-central Italy, 1961–2015

Valentina Pavan[1] · Gabriele Antolini[1] · Roberto Barbiero[2] · Nicola Berni[3] · Fabio Brunier[5] · Carlo Cacciamani[1,6] · Anselmo Cagnati[7] · Orietta Cazzuli[8] · Andrea Cicogna[9] · Chiara De Luigi[14] · Enzo Di Carlo[10] · Marco Francioni[3] · Luca Maraldo[13] · Gianni Marigo[7] · Stefano Micheletti[9] · Luca Onorato[4] · Elvio Panettieri[2] · Umberto Pellegrini[5,8] · Renata Pelosini[14] · David Piccinini[15] · Sara Ratto[5] · Christian Ronchi[14] · Luca Rusca[4] · Stefano Sofia[15] · Marco Stelluti[16] · Rodica Tomozeiu[1] · Tommaso Torrigiani Malaspina[11,12]

Received: 15 November 2017 / Accepted: 25 June 2018 / Published online: 28 June 2018

Abstract

Observational daily precipitation data from a group of 1762 stations over north-central Italy and adjacent areas are used to produce a high resolution daily gridded precipitation analysis covering the period from 1961 to 2015. Input data are checked for quality, time consistency, synchronicity and statistical homogeneity and the final result has been used to describe the spatial and temporal variability of precipitation over the area. Data are interpolated using a modified Shepard scheme and the interpolation errors are compatible with those presented in Isotta et al. (Int J Climatol 34(5):1657–1675, 2014). The analysis is compared with other similar products available over the area considered, and differences and similarities are described, taking into account the impacts of different spatial resolution and time coverage. The data set is used to describe local climate with respect to precipitation, including mean values and seasonality, by using a group of climate annual and seasonal indices: cumulated precipitation, maximum number of consecutive dry days, frequency of wet days, mean precipitation intensity and 50th and 90th percentile of daily precipitation over a season. The linear trends over the full period of these indices are described and compared. It is shown that although the time series of area average total annual precipitation over north-central Italy does not show significant linear trends, these are present locally. In particular, significant negative trends of annual total precipitation are found in central Italy and in the inner part of northern plains, while significant positive linear trends are present in several areas over the Alps and over the Liguria coast. The seasons most affected by changes in precipitation are summer and autumn, which, in most areas, are the driest and wettest seasons. In summer, significant positive trends in total precipitation have been found in areas close to the northern national borders, while significant negative trends are located elsewhere. The number of wet days is significantly decreasing over most of the domain, but the 90th percentile of precipitation is significantly increasing over most of the Alpine area and northern Po Valley. Over the southern part of the Po Valley and central Italy summer precipitation is significantly becoming less frequent and, generally, less intense. In autumn, total precipitation is characterised by significant positive trends over large areas in Northern Italy and by significant negative trends in inner areas of the Central Apennines. The trend patterns present great similarities with those of the 90th percentile of daily precipitation for the same season. The maximum length of dry spell is significantly decreasing in autumn over most areas, including central Italy, while the number of wet days presents negative but mostly non significant trends over the whole domain.

1 Introduction

The description of local climate is the first step towards understanding its dynamics and the relation between local climate anomalies and their local impacts. Furthermore, it is essential in the process of planning new infrastructures, and increasing resilience to climate extremes. This is even more crucial in a territory like the Italian Peninsula,

✉ Valentina Pavan
vpavan@arpae.it

Extended author information available on the last page of the article

characterised by a complex topography, extended coastlines, areas with very high population density and a general high vulnerability to intense and extreme events (Castellari and Artale 2009).

The present work focuses on aspects of local climate linked to precipitation and has been produced by a group of Italian local administrations contributing to the ARCIS (ARchivio Climatologico per l'Italia centro-Settentrionale) consortium (Pavan et al. 2013). It is meant to provide an instrument able to describe weather and climate variability on a daily time scale at the highest possible spatial resolution over several decades, so as to address the needs of impact studies and of new generation of regional climate models, reaching spatial resolutions between 5 and 10 km (Bucchignani et al. 2016; Giorgi et al. 2009, 2012). The choice to provide daily precipitation data allows to extend the climate description to all climate indices based on daily precipitation data, typically addressed in studies on observational time series analysis (Bartolini et al. 2017; Ciccarelli et al. 2009; Pavan et al. 2008).

The consortium has also decided to extend the data collection effort to several local data providers, working over the same territory but outside the consortium, so as to extend further the observational data-set and increase station density. The final product can describe the great spatial variability of local climate, ranging from Alpine, to Continental Temperate and Mediterranean climate; it can also represent the frequency of large-scale climate events, like droughts and large-basin floods, and the frequency of intense local convective events known to be recurrent over the area (Nuissier et al. 2016; Buzzi et al. 2014; Davolio et al. 2012, 2013).

The input data were selected so as to reduce as much as possible the impact on the final products of artificial causes of variability, like local changes in station density, substantial modifications in stations locations, drifts or other problems in data recording. This goal was reached by creating long times series of multiple stations not overlapping in time, which passed strict homogeneity statistical tests as done in several other climate studies (Toreti et al. 2010; Alexander et al. 2006). The effort in selecting input data has made the present data-set as much as possible usable not only to describe mean values, but also the variability of local climate indices, an essential ingredient in validating climate models. The data-set includes daily precipitation fields on a regular grid of about 5 km in resolution, similarly to the EURO4M data-set by Isotta et al. (2014), and it covers the Italian territory above latitude of 42°20′. This allows to produce a description of the local climatology over all the territories covered by the administrations contributing to the present consortium, and to be easily used as input for local climate and impact studies.

Finally, this data-set was designed to be updated regularly by the institutions participating to the consortium, allowing more flexible climate comparisons and assuring synergies in network improvement and maintenance.

Section 2 offers a description of the data, of the methods used to select and control them, and furthermore an overview of the characteristics of the interpolation procedure. In Sect. 3 it is presented a description of the mean values of annual precipitation and a detailed comparison with three other available data-sets covering the study area. Section 4 highlights the precipitation seasonality over the ARCIS domain through the mean seasonal values of several climate indices, paying particular attention to summer and autumn. Section 5 focuses on trends of the same climate indices over the considered period. Section 6 presents the descriptions offered by the present data-set of few historical weather events relevant to the ARCIS community either for their great intensity, or for the combination of intensity and extension to a large fraction of the domain. The last Section includes a summary of all results and a discussion.

2 Methodology

2.1 Data collection and validation

The observational data used as input of the analysis include daily records from non conventional stations located over the territories of the ARCIS consortium, and from stations belonging to foreign National Meteorological Services, located close to the Italian borders. These stations were included to reduce the boundary effects on interpolation over the ARCIS domain. With respect to Italian data, in the first few decades, the data-set includes records collected by the ex-National Hydrological Service, while in recent decades it includes records collected by several services, such as local Hydrological Services, Agro-Meteorological Services, and Regional/Local Meteorological Services. In several regions, the effort dedicated to collect data from different sources allowed to improve the density of long time series, and the resolution at which climate processes are described.

All data cover the period from 1961 to 2015, and almost all Italian input data consist of 24 h cumulated precipitation from 9 to 9 a.m. (local solar time), apart from the data from Marche and Umbria after 1991. At present, these last data are available only as daily cumulated precipitation from 0 to 24 and have been shifted of 1 day in order to maximise the overlap between the data reporting periods of adjacent regions. The methods used to build the data set, to check the quality of input data and to interpolate them onto the final gridded data-set are similar to those adopted in Antolini et al. (2016).

First, all available data are checked for the occurrence of spurious dry persistence in locations where all other stations recorded the presence of some rain. These spurious persistence are sometimes the result of low quality data digitalization and are eliminated from the data-set. The second step is constructing time series of data, each from one or more observational stations, so that all retained series cover at least 80% of the whole period. All time overlapping between stations contributing to the same time series have been eliminated and stations within the same series should be close enough in both space and height, with greater tolerance for the distance between stations located in plain areas. Each station contributes to the analysis at its specific location. This approach has allowed to reach a greater and more uniform density of input observations: in several cases, maintaining the same location for the historical stations was either not of high priority for the local monitoring service, or not possible due to changes in the station environments, making the historical location not representative of its surroundings. All time series satisfying the above requirements were checked for homogeneity using the SNHT test and the Craddock and Vincent tests in support, discarding those not passing the tests. These tests were applied to each time series by building a reference series, as combination of the data of four different stations surrounding the tested location. Only stations passing the homogeneity tests have been used to build reference time series. A total number of 1762 stations contribute to form the 1048 time series used as input of the analysis, 118 of which refer to stations located outside the Italian border.

In station selection, well maintained new automatic stations are preferred to old mechanical stations, even if still present at their historical location. Although the station position is unaltered, the surrounding environment has often changed due to modifications in land use. Furthermore, although properly maintained, old mechanical instruments are becoming less and less dependable. The use of these old instruments in recent years is mostly linked to the tight economical constraints imposed on public offices.

Figure 1 presents in panel (a) the map of the stations contributing to the present analysis (black dots) and those discarded after the homogeneity checks (light blue dots). In panel (b) it is presented the time series of the number of stations contributing to the analysis in each year from 1961 to 2015. The station density changes from region to region and it is in general higher over mountains than over the plain. Although much effort has been put in choosing the observational time-series, in the last decade there is a reduction in the number of observational points which could be used in this analysis. This decline could still be partially reduced in the years to come, since public offices spending ability are slightly improving. It is also possible that additional time series could be recovered in areas with low station density, considering that the current meteorological regional monitoring networks include more measuring points not included in the present data-base. Furthermore more effort could be spent in contacting other local monitoring services.

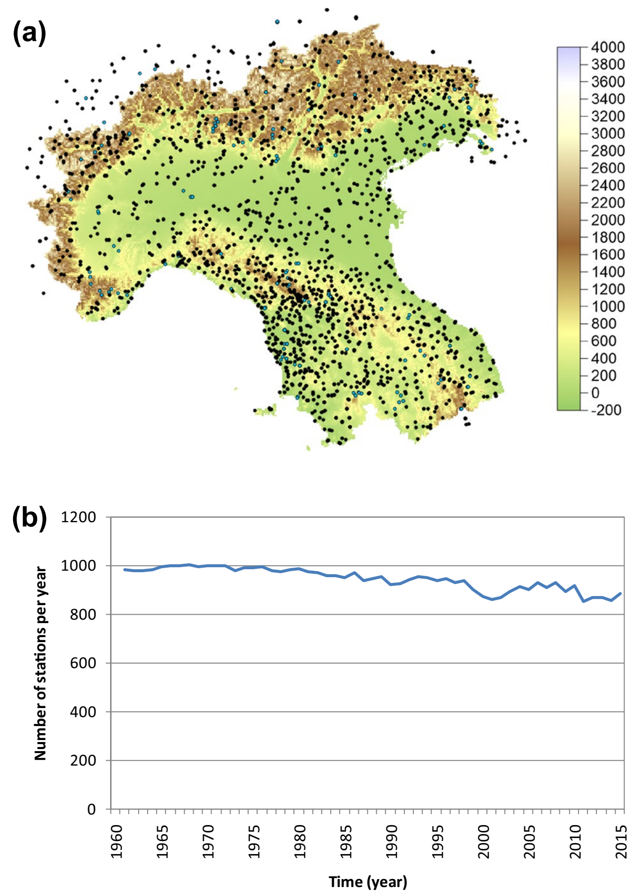
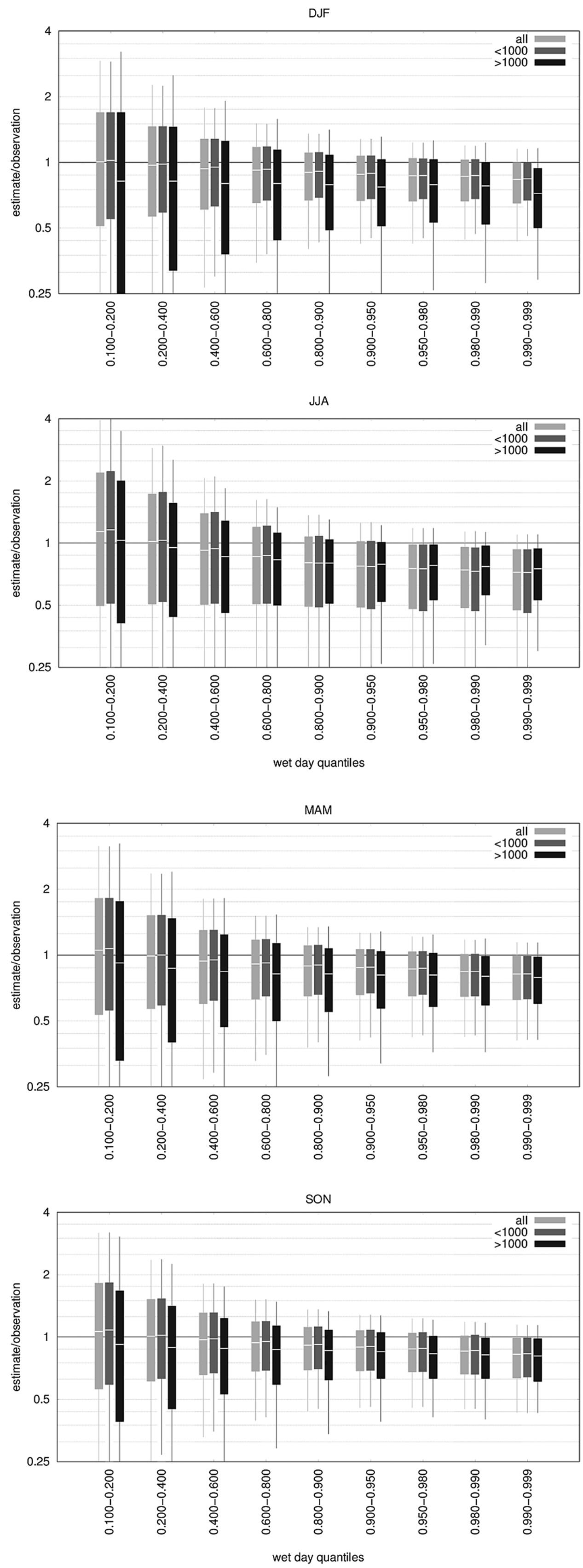


Fig. 1 **a** Map of the territory covered by ARCIS analysis (height with respect to sea level in m) and of the stations contributing to the ARCIS dataset. Black dots represent stations contributing to the analysis, blue dots represent stations contributing to discarded time-series. **b** Number of stations contributing to the analysis as a function of time in years

The series chosen as input of the analysis were checked for their synchronicity, to detect whether the data are all referred to the same observational time window. This test consists in comparing the time series of synchronous and 1 or 2 days lagged yearly correlation coefficients between a tested station and each station of a group located in the surroundings. If in one or more years the lagged correlation with several of the surrounding stations is higher than the synchronous, then the data of the tested series are shifted so as to make the synchronous correlation higher. A detailed description of the methods used to identify initial and final date of the data to be corrected can be found in Antolini et al. (2016). Although most of the used data have already been validated and checked, still some asynchronicities could be detected at several stations.

Fig. 2 Plots of the distribution of the ratio between estimated and ▶ observed daily precipitation in cross-validation as a function of the quantile of observed daily precipitation intensity over the period 1961 to 2015 over the whole ARCIS domain for winter (DJF), spring (MAM), summer (JJA) and autumn (SON) and for different group of stations (all, below and above 1000 m). Box plots extends to the second and third quartiles, the horizontal thick white line represents the median and the whiskers extends to the whole distribution



2.2 Data interpolation and validation

Observational daily data are interpolated on a regular grid with an approximate 5×5 km resolution. The interpolation method used to produce the gridded data-set is a Shepard scheme modified as in Antolini et al. (2016), to take into account topographic distances between locations. As in Antolini et al. (2016) and in Isotta et al. (2014), the interpolation errors were quantified using the relative errors, that is the ratio between the daily interpolated and the observed values, for all positive values of observed precipitation, computed by applying the leave-one-out cross-validation technique. The relative error distributions over the full period, classed depending on the observed daily intensity, and also separately for two classes of elevation (above and below 1000 m), are presented in Fig. 2 for all seasons. Low intensity events (first quantile) are overestimated at low elevations in all seasons but winter, while higher intensity events, greater than the 40th percentile, are mostly underestimated at all elevations. Values for winter and summer are compatible with those presented in Isotta et al. (2014). In winter, when a substantial portion of the precipitation is due to large scale processes, the errors are similar to those presented in Antolini et al. (2016). In summer, interpolation errors for events between the 80th and the 99th percentile are smaller in the present analysis, possibly thanks to the high station density in areas characterised by high frequency of convective events like Tuscany and part of the Alpine region. Dependence of these results on station elevation show that at higher locations the present interpolation method produces more frequent underestimates at all intensities with respect to lower locations. In winter at high elevations, the error distribution shows a larger spread and a more negative bias than at low elevations, while the error distributions at different heights are comparable in summer. Results from the other two seasons show intermediate values with respect to winter and summer.

Table 1 presents the values of several performance indices describing the characteristics of the present product. All indices are obtained by applying a leave-one-out cross validation method, averaging over the ARCIS domain and over the whole period covered by the data-set for three classes of stations: all stations, only those located below 1000 m and only those located over 1000 m. Performance indices include mean absolute error (MAE), mean bias error (MBE),

Table 1 Mean values of mean absolute error (MAE), mean bias (MBE, in mm), root mean square error (RMSR, in mm), correlation (R2), HR (hit rate), false alarm rate (FAR) and percent of correct (POC) for all stations, only for station located lower than 1000 m, and only for those located over 1000 m

	MAE	MBE	RMSE	R2	HR	FAR	POC
All stations	3.59	− 0.01	7.34	0.73	0.87	0.20	0.71
< 1000 m	3.57	0.04	7.34	0.74	0.87	0.20	0.71
> 1000 m	3.79	− 0.37	7.46	0.68	0.87	0.22	0.70

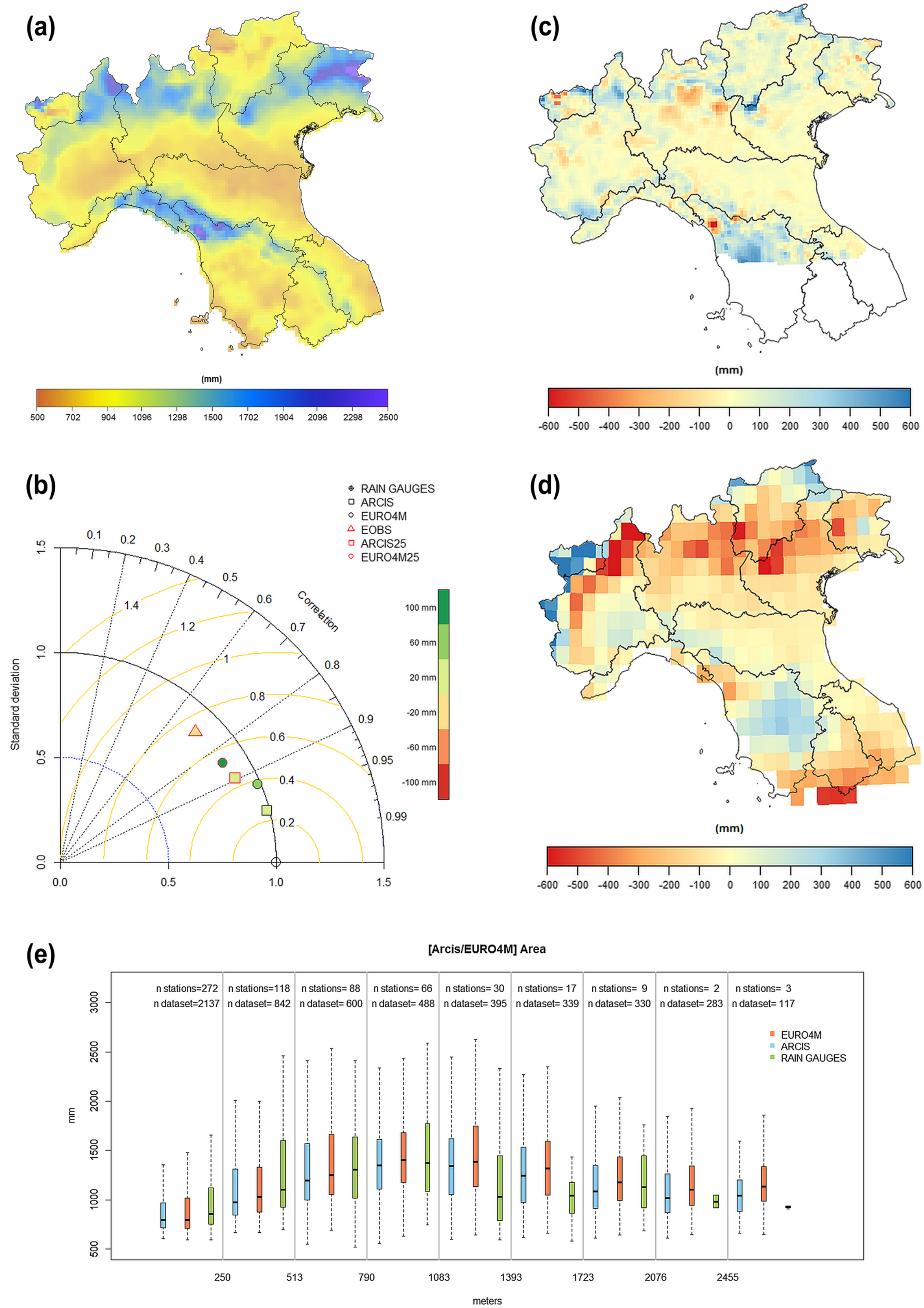
root mean squared error (RMSE), coefficient of determination (R2), hit rate (HR), false alarm rate (FAR) and percent of correct (POC). The first four performance indices are computed only for positive values of precipitation, while the remaining three are computed starting from contingency tables using the same threshold for observed and estimated values. The only index presenting substantial differences for elevation greater than 1000 m with respect to lower ones is the MBE, but the impact of a substantially greater bias than average at higher elevations is reduced by the smaller number of stations located over 1000 m with respect to those located under this elevation threshold.

Next, the present data-set is compared with two other daily precipitation data-sets covering Northern Italy over the common period 1971–2008: the EURO4M data-set (Isotta et al. 2014), available on a 5 × 5 km regular grid covering the whole Alpine region for the period 1971–2008, and the E-OBS data set (Haylock et al. 2008) available on a regular grid of 0.25° × 0.25° resolution covering the Euro-Mediterranean land region for the period 1961 to present. Finally ARCIS climate normals are compared with those presented in Crespi et al. (2018, CRESPI hereafter). This data-set consists of a monthly climatology 1961–1990 for total precipitation over Italy. The fields are provided at regular grid cells with 30-arc-second-resolution (~ 800 m) of the GTOPO30 DEM (USGS 1996).

Each time a lower resolution data-set is compared with a higher resolution data-set, the higher resolution one is up-scaled onto the coarser grid, following Casanueva et al. (2016). In this way, it is possible to highlight the actual differences between data-sets, without punishing the lower resolution product for its resolution choice.

3 Mean climate

Figure 3 presents a comparison between the total annual precipitation averaged over the common period 1971–2008 obtained from three observational daily data-sets covering Northern Italy: ARCIS, EURO4M and E-OBS analyses. In panel (3c), differences with respect to EURO4M are mostly due to differences in the choice and availability of input stations at specific locations: some stations are not included in ARCIS analysis because they contribute to statistically non-homogeneous time series, others were added to the ARCIS data-set after the EURO4M analysis was produced, especially in Toscana and Marche, but also at other scattered locations over Northern Italy, where data were recovered and added to the data-set only recently. Panel (3b) presents the Taylor diagram for the mean annual precipitation over the period considered, comparing rain gauges with ARCIS and EURO4M at their original resolutions and their upscaled counterparts over the E-OBS grid together with the E-OBS products. In the diagram, the angle with the horizontal is proportional to the correlation between stations and the closest analysis grid-point of each product, this being equal to 1.0 for stations themselves; the distance from the origin represents the ratio between each data-set standard deviation and that of the stations; the distance from the rain gauge point represents the root mean square error (yellow circles centred on rain gauges) and the inner shade of the symbol represents the mean bias with respect to rain gauges. The impact on the final climatological product of reduced resolution is a substantial reduction in correlation and a reduction in standard deviation ratio for both ARCIS and EURO4M. In general, ARCIS presents a higher mean correlation value, a lower root mean square error and a standard deviation similar to the stations, with respect to EURO4M. Focusing only on low resolution products, E-OBS is the only product presenting a negative mean bias and it presents a substantially lower correlation and higher relative root mean square error with respect to the other low resolution products, possibly due to the much lower density of input stations. This seems to be confirmed also by the large differences in the map of panel (3d) suggesting that the E-OBS data-set at present has some problem in representing some detailed aspects of the climatology of the region. Panel (e) presents a comparison between stations, ARCIS and EURO4M mean annual precipitation averaged over different elevation intervals. The EURO4M analysis has not been included in this comparison as it uses a much smaller number of stations data in input with respect to the present input data-set. At elevations lower than 1000 m, the analyses present a general underestimate with respect to the stations, with differences being greater for ARCIS than for EURO4M, probably due to the different interpolation methods, while both products present an


(a)
(mm)
500 702 904 1096 1298 1500 1702 1904 2096 2298 2500
(c)
(mm)
-600 -500 -400 -300 -200 -100 0 100 200 300 400 500 600
(b)
RAIN GAUGES
ARCIS
EURO4M
EOBS
ARCIS25
EURO4M25
Standard deviation
Correlation
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 0.95 0.99
1.4 1.2 1 0.8 0.6 0.4 0.2
0.0 0.5 1.0 1.5
100 mm
60 mm
20 mm
-20 mm
-60 mm
-100 mm
(d)
(mm)
-600 -500 -400 -300 -200 -100 0 100 200 300 400 500 600
(e)
[Arcis/EURO4M] Area
n stations=272 n dataset=2137
n stations=118 n dataset= 842
n stations= 88 n dataset= 600
n stations= 66 n dataset= 488
n stations= 30 n dataset= 395
n stations= 17 n dataset= 339
n stations= 9 n dataset= 330
n stations= 2 n dataset= 283
n stations= 3 n dataset= 117
EURO4M
ARCIS
RAIN GAUGES
mm
500 1000 1500 2000 2500 3000
250 513 790 1083 1393 1723 2076 2455
meters

◂**Fig. 3** **a** Mean annual precipitation (mm) over the ARCIS domain averaged over the period 1971–2008 for ARCIS analysis; **b** Taylor diagram for mean annual precipitation as represented by stations, ARCIS and EURO4M analysis at their original resolution, E-OBS analysis together with ARCIS and EURO4M at E-OBS resolution. Inner colour of the symbols represent the mean bias over the common area (mm); **c** differences (mm) between EURO4M and ARCIS mean annual precipitation; **d** same as **c** but between E-OBS and ARCIS. **e** Box plots of mean annual precipitation averaged over the common period as a function of elevation. Boxes represent the interquartile range, with medians as thick black lines, whiskers the minimum–maximum values. Total number of stations and grid-points in each elevation intervals is specified in the upper part of the figure

apparent overestimate at higher locations between 1000 and 1700 m. An analysis carried out distinguishing areas characterised by different precipitation regimes (not shown) reveals that the overestimate is mainly present over the central-eastern Alpine area, while Apennines results are similar to those for lower elevations and consistent with those obtained in cross-validation, indicating the presence of an underestimate at all elevations. This apparent overestimate over the Alpine area is linked to the spatial distribution of stations located at elevations between 1000 and 2000 m and to their limited number in the current data-set. As it is, in the Alpine areas these stations are mostly located in inner valley, further away from the plain areas, while the majority of grid-points with elevation within this same interval are located much closer to the plains. Although located at the same elevation, these last areas are much more rainy than those surrounding the stations used for this analysis, resulting in different descriptions of the dependence of total precipitation on elevation in rain gauges and analyses. In particular we think that having an extended data-set of observational input data could highlight the presence of an underestimate of the analyses with respect to observations also at these elevation intervals, as it is the case over the Appennine areas. Figure 4 is similar to Fig. 3, but compares ARCIS with CRESPI annual mean precipitation over the period 1961–1990. In the Taylor diagram, CRESPI up-scaled version and ARCIS are very similar, but, at its native resolution, CRESPI presents a greater value of correlation with observational data and a smaller root mean squared error. A more detailed description of the CRESPI data-set with respect to its own input data, more extended with respect to those used here, can be found in Crespi et al. (2018). Maps of differences in mean climatological values (Fig. 4b) present smaller values than those obtained for EURO4M, and an overall similar pattern, with the exception of central regions, where EURO4M had a very low input station density. In these last areas, and especially in eastern Liguria and northern Toscana are concentrated some of the greatest differences between ARCIS and CRESPI, indicating a greater variability in ARCIS with respect to CRESPI. Finally, a comparison between the dependence of mean annual precipitation on elevation over the ARCIS domain confirms the great similarity of the two data-sets with respect to mean annual values (Fig. 4c).

It is possible that the present comparison between datasets is partly influenced by the use of the input ARCIS observational data as reference. An extended climatological dataset, possibly obtained using reconstructed monthly data to fill in the gap of too short time-series, as done in CRESPI, could possibly produce different results, especially in the case of the box-plot diagrams. In particular, it is expected that such an exercise would highlight the presence of an under-estimate at all elevations of analysis products with respect to observed data, especially for the ARCIS data-set, coherently with the cross-validation results in Fig. 2. In the present work, it is decided not to reconstruct missing daily data prior to the analysis and these results can be considered not only a description of the characteristics of the analysis data-set with respect to input observational data, but also a description of the characteristics (and limitations) of the local climate observational data currently available, which can only partly be mended by the applied interpolation method. In this respect, the analysis products represent an improvement with respect to the original input data.

4 Mean seasonality

The seasonality of the regional climate is described in the following, starting from total annual precipitation and seasonal precipitation indices averaged over the full period covered by the ARCIS data-set, namely 1961–2015. The indices include total precipitation (P_{tot}), the 50th percentile of daily precipitation (PX50), the 90th percentile of daily precipitation (PX90), the maximum number of continuous dry days (CDD), the number of rainy days (NRD) and the mean precipitation intensity (mean precipitation amount in rainy days, MPI). In the definitions above, a day is considered dry (rainy) if daily precipitation is less than (greater or equal to) 1.0 mm, while only days with precipitation greater than 0.2 were considered in order to identify percentiles.

As can be seen from Fig. 3a, highest locations are more rainy, due to orographic amplification phenomena, but also exposition and distance from the coast influence the local amount of total precipitation. In particular, the most rainy areas are the north-eastern alpine areas of Friuli Venezia Giulia (with average values over 2900 mm) and the northern Apennines slopes facing the Ligurian sea (2500 mm). On average, total precipitation over the plains and lower hill areas both in Northern and Central Italy are the lowest, with values between 600 and 1000 mm per year. These values are consistent with those presented in several works describing the regional climatology, as Crespi et al. (2018), Manzato et al. (2016), Antolini et al. (2016) and Toreti et al. (2009).

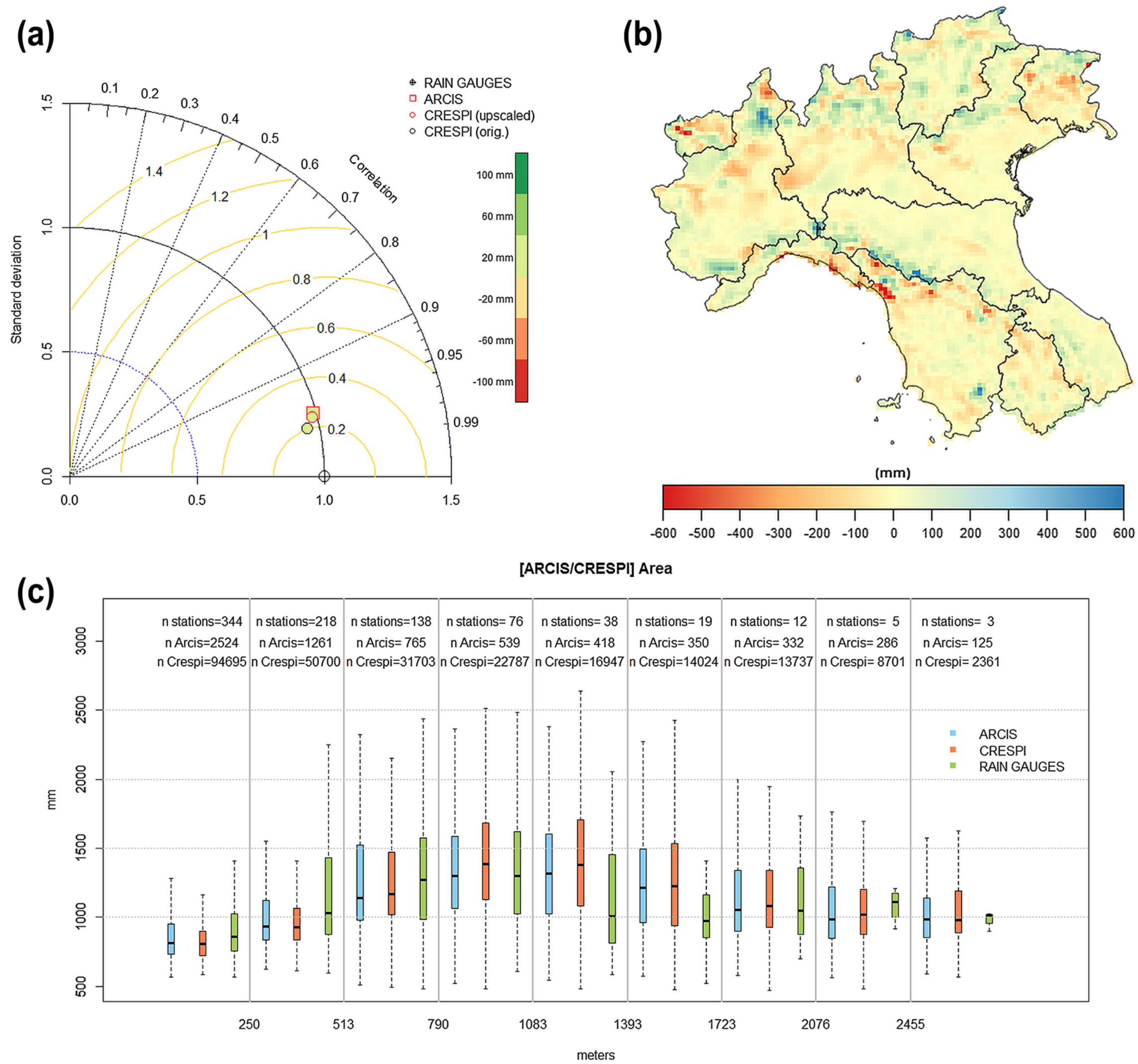


Fig. 4 **a** Same as Fig. 3b but for the comparison between CRESPI and ARCIS over the period 1961–1990; **b** same as Fig. 3c, but for the difference between CRESPI and ARCIS; **c** as Fig. 3e but for rain gauges, ARCIS and CRESPI

Precipitation seasonality depends on the location considered (Fig. 5). Over a large portion of the domain, the most rainy season is autumn, but in the westernmost alpine areas it is spring. In the northern tip, the Bolzano province, summer is wetter than the other seasons, while almost everywhere in central Italy winter is as wet as autumn. The driest season is winter in most areas north of the Apennines while it is summer in central Italy, part of the Po valley, and western Liguria. These results are consistent with those presented in Crespi et al. (2018), describing the seasonality of monthly precipitation over Italy over the period 1961–1990.

Figure 6 presents autumn and summer maps of PX50, PX90, CDD, NRD and MPI averaged over the period 1961–2015. Over the whole territory, both PX50 and PX90 have greater values in autumn than in summer. The areas with the highest values of PX90 are located over the mountains and in particular over the Alps, where it exceeds 35.0 mm in summer and 70.0 mm in autumn. In autumn, also the southern flanks of the Northern Apennines present PX50 values comparable to the Alps. Minimum values of PX90 between 10.0 and 15.0 mm are observed in Central Italy, over the northern tips of the Alps, and, only in autumn, around the eastern and lowest part of the Po valley. In the other seasons, not shown here for brevity, values are mostly intermediate between these two seasons, with PX90 maxima just exceeding 40.0 mm in spring and 60.0 mm in winter. In all seasons, the geographical distribution of these fields is similar to correspondent cumulated seasonal precipitation. Finally, in summer in most areas PX90 is about 4–5 times the value of PX50, but in Liguria and in the northern tip of Piedmont it is more than six times PX50. In autumn the PX90 may be six or even seven times PX50 over the Alps

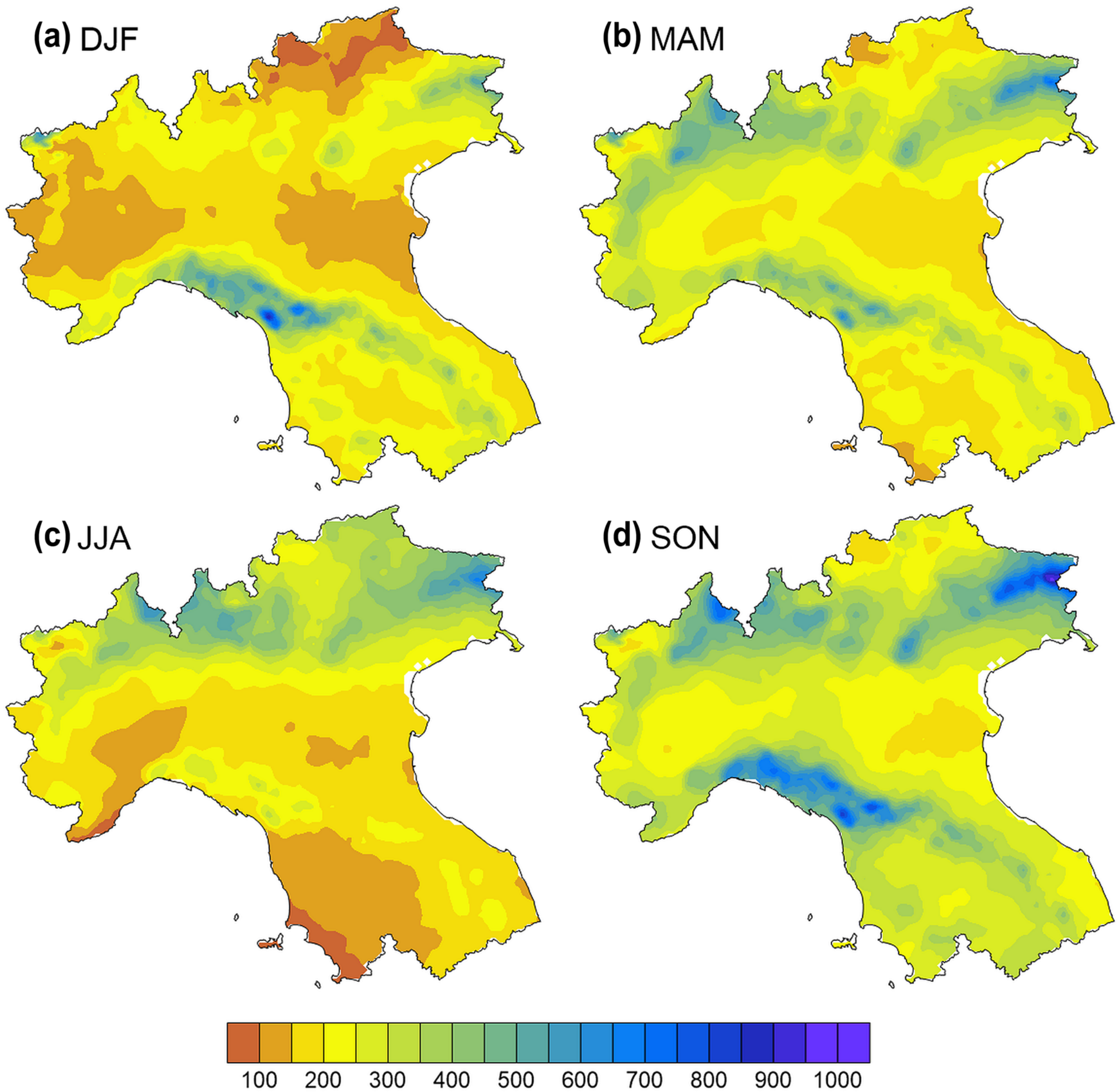


Fig. 5 Total seasonal precipitation (mm) averaged over the period 1961–2015

and in Liguria, but only about four times PX50 over the remaining areas. This indicates that, in several areas and seasons, the distribution characteristics of daily precipitation values can substantially vary, making intense daily values more probable. The number of rainy days (Fig. 6g, h) is greater in summer than in autumn over the Alps, reaching here maximum values greater than 45 days over the season, while the opposite is true elsewhere over the domain; the mean precipitation intensity (Fig. 6i, j) is everywhere greater or equal in autumn than in summer, reaching in the rainy seasons values greater than 24.0 mm in the Eastern Alps.

As for the CDD index, maximum seasonal values are observed in summer, and minima in autumn or spring. In summer, the index seems to present a negative correlation with the latitude, with maximum values of more than 40 days occurring along the southern Tyrrhenian coast. In autumn, the geographical distribution is very different and the variations are much smaller, with maxima just exceeding 25 days in the western part of the Po valley and minima slightly under 15 days in central Italy. As for the other seasons, not shown for brevity, this index has a geographical distribution similar to that in summer, minima over the innermost part of northern and central Apennines, with values between 10 and 35 days in winter, between 5 and 25 days in spring.

The previous description suggests that the Italian climate is characterised by a strong seasonal and geographical variability due to the complexity of the terrain, to the proximity of the sea and to its meridian extension. In some areas, the presence of complex orography induces an amplification of precipitation intensity, while protecting others from rain, depending on the season, on the weather pattern and on the area considered.

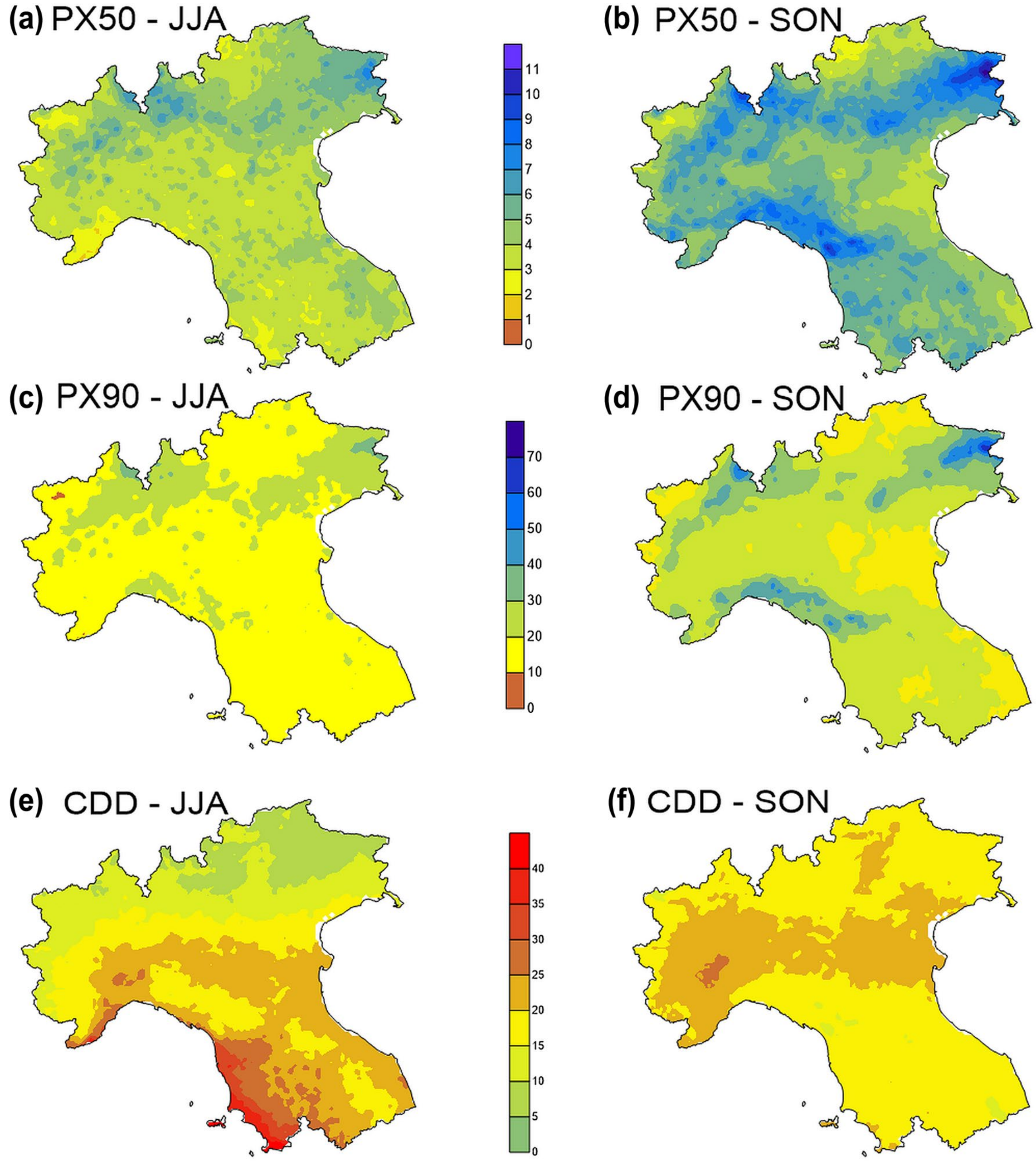


Fig. 6 Maps of seasonal climate indices averaged over the period 1961–2015: PX50 (mm) in summer (**a**) and autumn (**b**), PX90 (mm) in summer (**c**) and autumn (**d**), CDD (days) in summer (**e**) and autumn (**f**), NRD (days) in summer (**g**) and autumn (**h**); MPI (mm) in summer (**i**) and autumn (**j**)

This variability, leads to oscillations of the local climate between intense droughts and extreme abundances of water within the same year or between one year and the next. In the next section, the description will focus on the time variability of these indices depending on the season.

5 Trends and climate variability

Figure 7a shows the time series of the total annual precipitation averaged over the ARCIS domain. It presents a

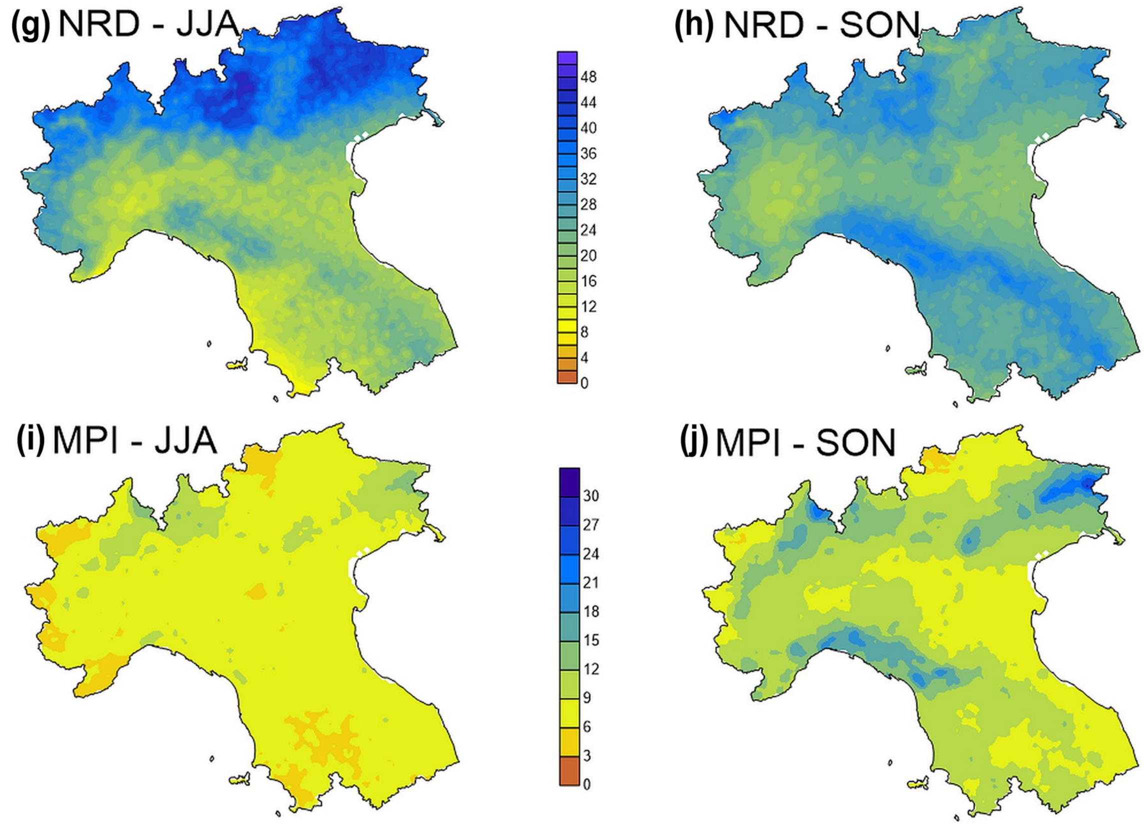
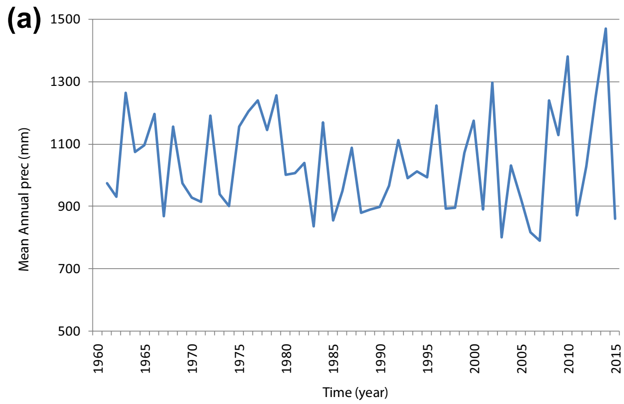


Fig. 6 (continued)

great time variability at different scales and no significant linear trend. This can be partly a consequence of the large spatial variability of the field, as can be seen in Fig. 7b, showing the map of linear trend of annual precipitation from 1961 to 2015. Different areas receive precipitation depending on the frequencies of different weather regimes, so total precipitation in each of them can be characterised by a different variation in time (Cacciamani et al. 1994). Notwithstanding the high spatial variability, it is possible to identify large areas characterised by similar time dependence of this index. In particular, several areas over the Alps and over the Liguria coast are characterised by statistically significant increases (confidence level of 95%) of total annual precipitation, while several areas of Central Italy, of the western part of the Po valley and of the northern slopes of the Northern Apennines are characterised by a significant decrease. As for other trend maps that will be shown in the following, these maps are characterised by a great spatial variability and some areas present trend intensities greater than their surroundings. In the present data-set, great attention has been paid to exclude as much as possible sources of un-natural variability by applying homogeneity tests to the original input observational time series and imposing strict consistency thresholds. As a result, all these local trend anomalies are supported by two or more stations independently producing similar results. This is the case for example for the positive trends observed in central Liguria or the negative trends in the Apennines between Marche and Umbria. Excluding these input station data, would make for sure the trend maps smoother, but the final product would possibly fail in capturing a specific characteristic of the Italian climate: the distribution of climate anomalies is often strongly related to the complexity of the Italian territory, making specific locations more likely than others to be exposed to extreme or intense events. In other parts of the Italian territory geographical differences are less intense and trends are smoother.

Like the mean climatological values, these long term changes are characterised by a large seasonality, implying a great variety of impacts, even for similar changes in total annual precipitation. For these reasons, the seasonal linear trends and their significance are shown in Fig. 8. The seasons characterised by stronger and more significant trends are summer and autumn, while trends in winter and spring are weaker, and significant only over more restricted areas. In particular, in winter, important changes can be spotted only in few scattered areas with negative trend in Piedmont,



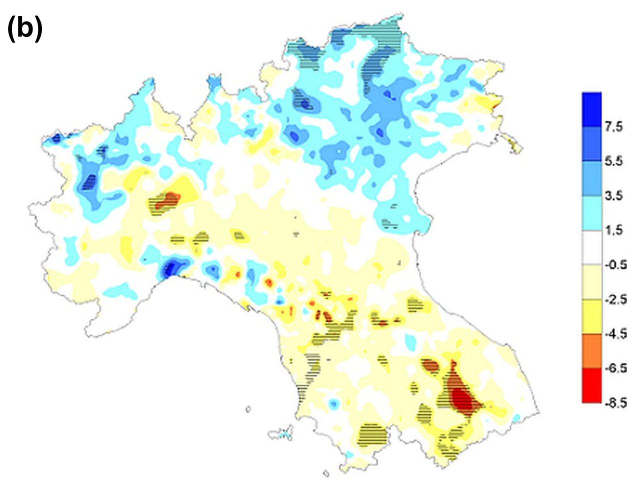


Fig. 7 **a** Time dependence of total annual precipitation averaged over ARCIS domain; **b** map of linear trend of total annual precipitation over the period 1961–2015 (shading). Hatched areas are characterised by significant trends over 95% significance levels

in the southernmost areas of the ARCIS domain, and in few small areas with positive trends over the Alps. In spring, there are areas characterised by significant decreases in total precipitation over the central Alps, over the southern flank of the northern Apennines and in inner areas of the central regions, while increases are detected in north-western Alps, in the plains facing the Adriatic sea and along the southern border of the ARCIS domain, with only few spots characterised by statistical significance.

In general, significant trends in total annual precipitation are mostly linked to the presence of significant trends in seasonal precipitation detected in the two extreme seasons: summer and autumn. The maps of trends in autumn and summer total precipitation present patterns of opposite sign almost everywhere over northern Italy, while remaining similar in central Italy, especially in Umbria where they are both negative, and over the alpine territories close to the northern Italian borders, where total precipitation is increasing both in summer and in autumn. In summer, total precipitation is decreasing almost everywhere, with large areas characterised by significant trends, apart from the areas along the northern national border, where precipitation is significantly increasing. In autumn, precipitation is significantly increasing in several parts of northern Italy, especially over north-eastern areas and on the southern flanks of the Northern Apennines, but significantly decreasing in the inner parts of the Central Apennines. The areas where significant trends have opposite signs in different seasons result in weaker non significant trends in total annual precipitation.

The significant changes in total precipitation in summer and autumn could be due either to changes in the frequency of rainy days or in the intensity of daily precipitation. For this reason, it is interesting to check how the PX50, the PX90, CDD, NRD and MPI indices for these two seasons change in time (Fig. 9). In areas between the most western part of the Po valley, through Emilia-Romagna to the eastern part of Central Italy and in Friuli Venezia Giulia, significant decreases in summer total precipitation are linked to significant decreases in NRD, increases in CDD and to a general reduction (locally significant) of the daily rain intensity, both in its median, mean and intense values. So, in these areas, in summer it rains less frequently, dry spell are becoming longer and the amount of precipitation received in rainy days is decreasing. In the central part of Northern Italy, including Veneto plain areas, the reduction in total precipitation is mainly linked to a decrease in rain frequency (decreases in NRD, increases in CDD) although it can be observed a significant increase in mean precipitation intensity (MPI) and a significant increase in the amplitude of intense events (PX90). This behaviour is also observed very locally in some areas in Toscana, in agreement with what observed in Bartolini et al. (2014a). In these areas, it rains less and less frequently but with greater precipitation intensity. Finally, the increase in total summer precipitation close to the northern Italian border (Aosta Valley, northern Piemonte, Trento and Bolzano Provinces) seems to be linked to greater precipitation intensities: trend maps show more intense significant increases in PX90 than in MPI and PX50 and, locally, in northern part of Piemonte, significant decreases in the number of rainy days (NRD).

Figure 8d shows the map of trends in autumn precipitation total, with extended areas of increases over the northern regions, reaching statistical significance over some areas. A comparison between this map and those in Fig. 9 suggests that, in north-eastern regions, significant increases in total precipitation are related to significant increases in mean precipitation intensity (MPI), more due to intense events (PX90) than for average intensity event (PX50). Increases in the intensity of extreme events over these areas have also been documented by Uboldi and Lussana (2018), a study focussed on annual intensity maxima over different cumulation time intervals including 24 h. In that study, it was noted that in the majority of

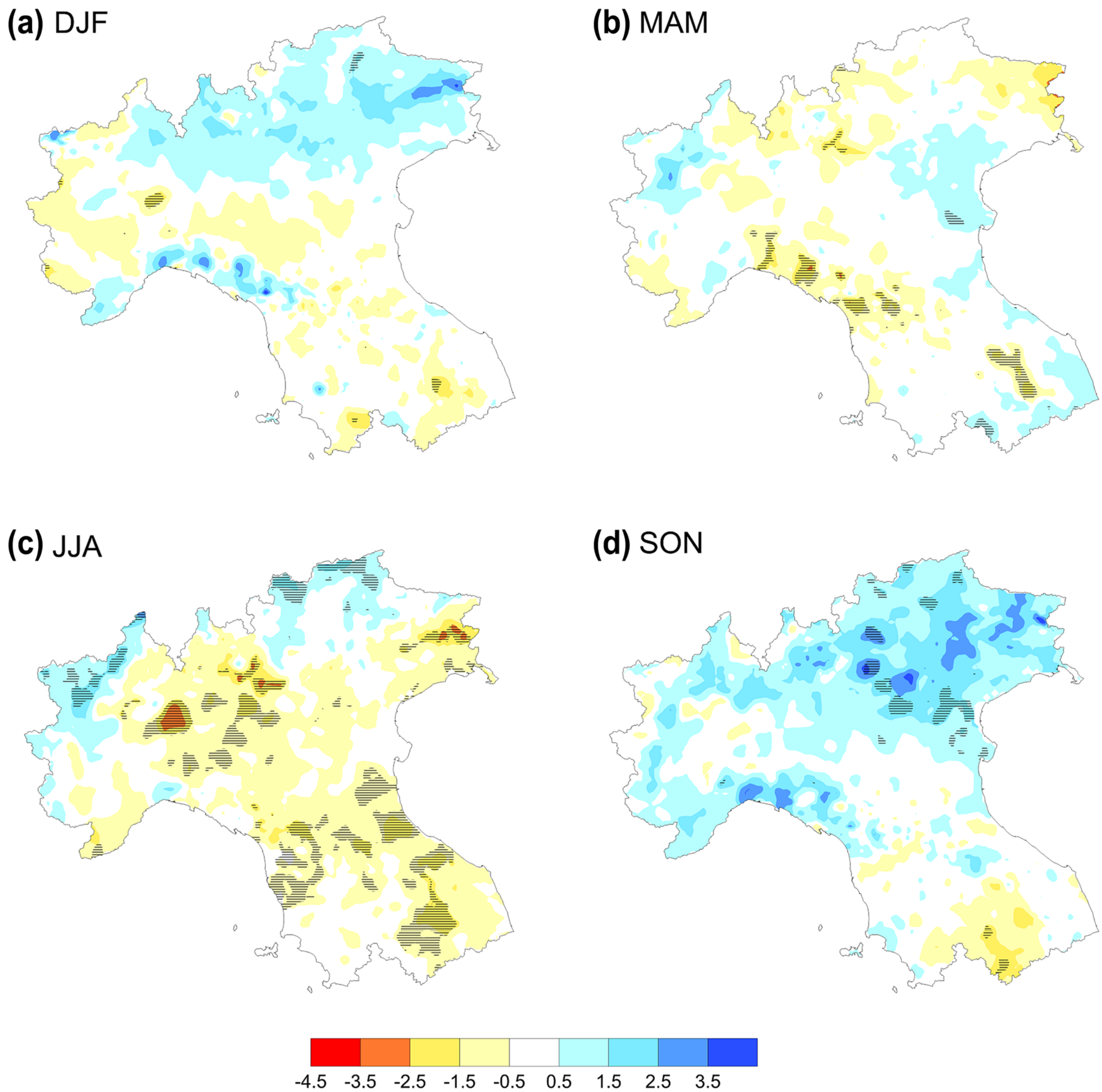


Fig. 8 Maps of linear trends of seasonal precipitation (shading in mm per year) and of their statistical significance over 95% level (hatching) over the period 1961–2015

cases more intense extreme events occur in autumn. Over these areas, it is also observed a general decrease in the length of dry spells, mostly falling below the 95% significance level, while the number of rainy days (NRD) presents mixed signals. Close to the Adriatic coast, it is also present a significant decrease in the length of dry spells (CDD), which is not, anyway, associated with a significant trend on the number of rainy days. In general, in this season CDD and NRD seems to undergo independent changes in time, not being necessarily anti-correlated; this could be due to the fact that in this season the two indices may be linked to dynamically independent weather regimes. However, a more detailed analysis of these results is out of the scope of the present paper. In north-western Italy, changes in total autumn precipitations are small and not significant, although in some local areas close to the western border, the data-set indicates the presence of significant decreases in precipitation at all daily intensity (PX50, PX90 and MPI). In Liguria, only non significant increases in total autumn precipitation are observed, and no significant signal can be detected, a part from a significant decrease in the length of dry spells (CDD). Finally, Emilia-Romagna shows slight not significant increases, while Central Italy shows slight decreases in total autumn precipitation, becoming significant in the southernmost ARCIS domain areas of Central Apennines (Umbria). These changes are linked to significant and diffuse decreases in the daily rain amount at all intensities received during the season (PX50, PX50 and MPI). In Umbria the number of rainy days is significantly decreeasing, but over the whole central

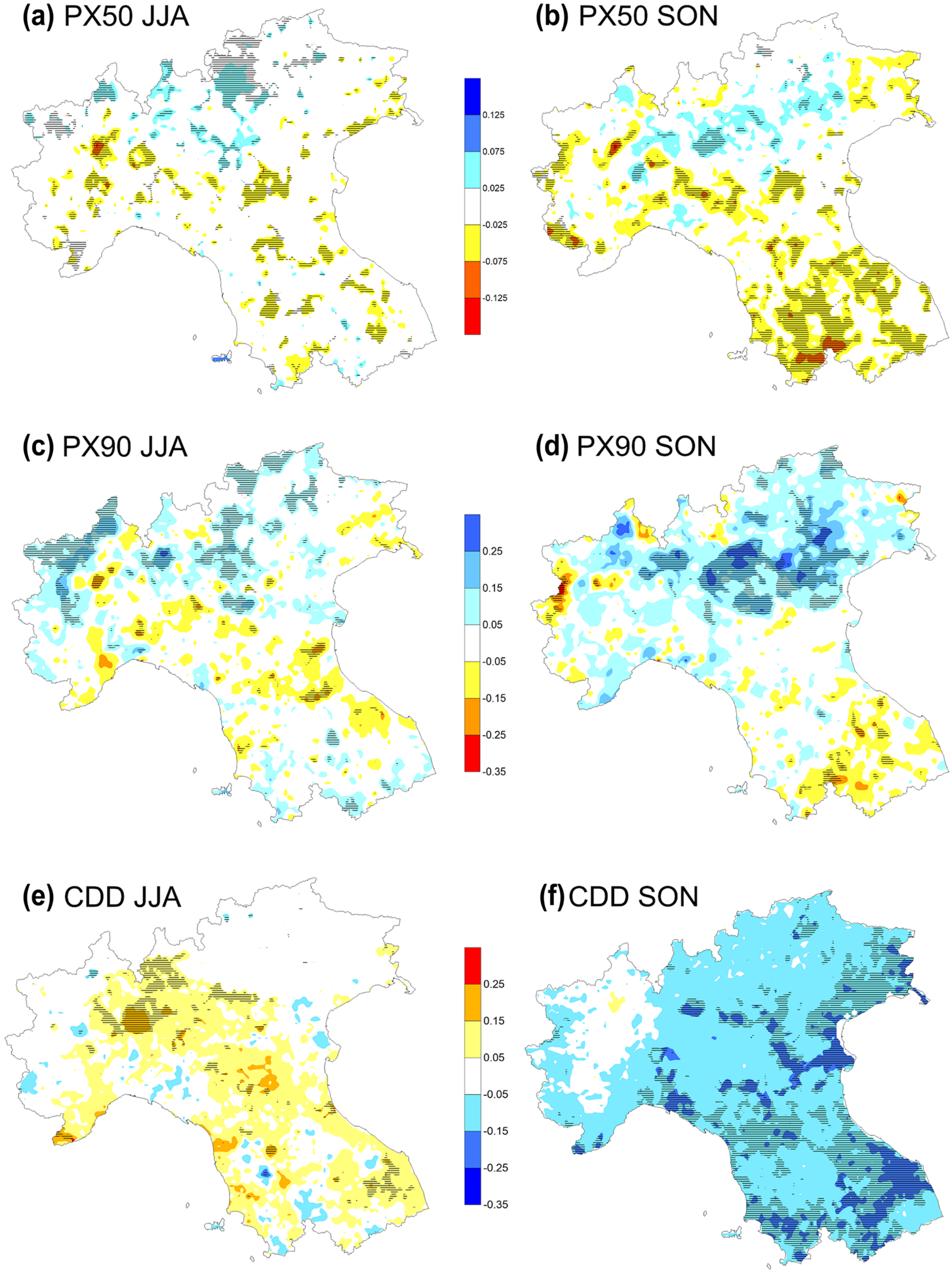


Fig. 9 Maps of linear trends (shading) and of their 95% level significance (hatching) over the period 1961–2015 for PX50 (**a, b** in mm/year), PX90 (**c, d** in mm/year), CDD (**e, f** in days/year), NRD (**g, h** in days/year) and MPI (**i, j** in mm/year)

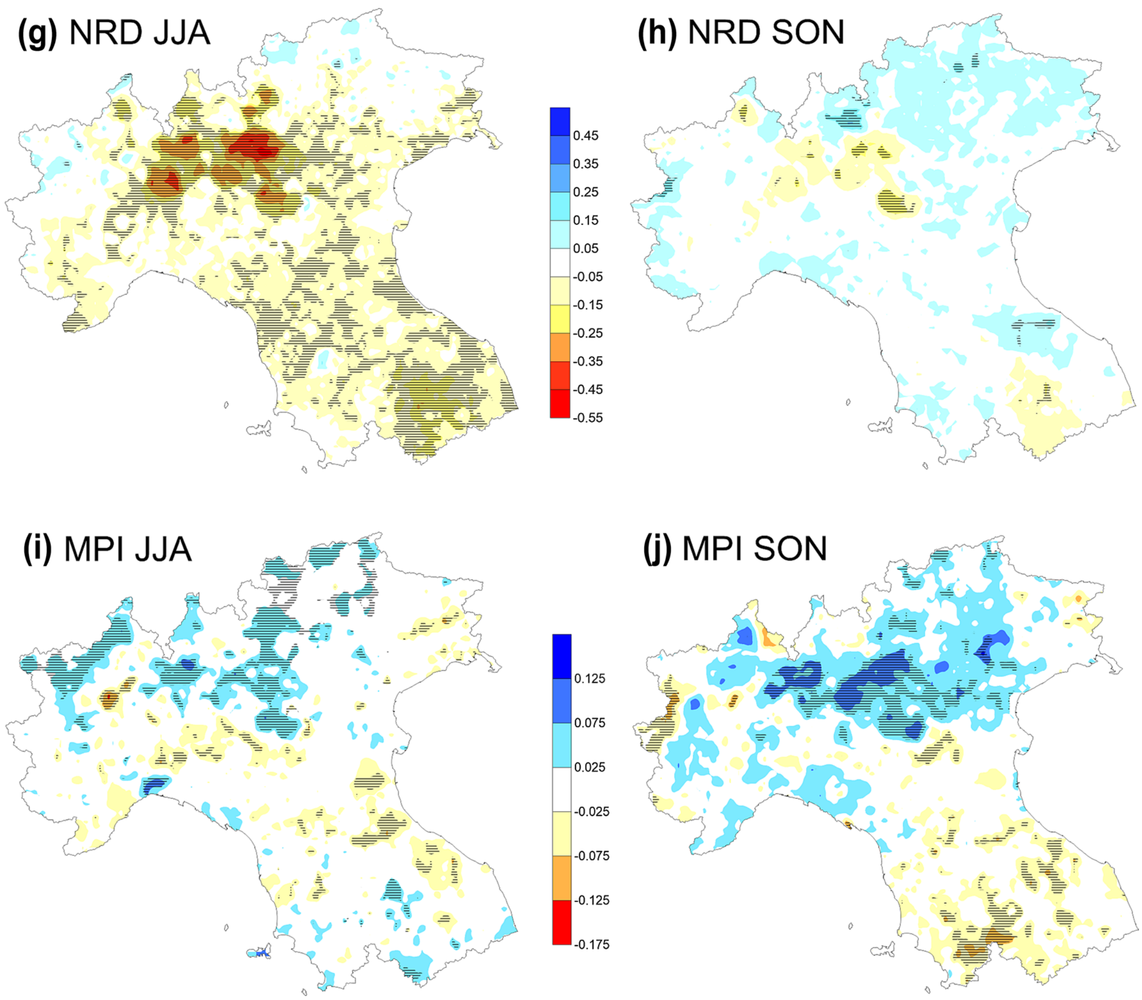


Fig. 9 (continued)

Italy the same signal coexists with very diffuse significant decreases in the length of dry spells (CDD).

It must be noticed that the map of the CDD index trend for autumn shows a completely different pattern and sign than in all other seasons, with negative and significant values almost everywhere in central Italy, and in the central and eastern plains of Northern Italy, but some local positive not significant values over the western and central Alps, with maxima in the western part. In all other seasons, the same index presents large areas of positive and significant trends indicating an increase in the length of dry spells.

6 Extreme events

The present analysis has been specifically built in order to represent as correctly as possible the interannual and long term variability of precipitation, discarding a fraction of data of stations which were only active for few years. As a result, it properly represents the time variability of climate indices, including those based on daily data. It is still usable to describe specific and intense precipitation events, extended to one or more days, although an improved description of such events could be obtained by using all precipitation data available on those dates. Still, the interest of the local climate community on these extremes events is quite great, so in the following it is given a description of three extreme precipitation events, known either for their extreme local intensity or for the substantial amplitude extended to a large fraction of the ARCIS domain: the 'Florence' flood occurred on the 4–5 of November 1966, the most intense flood ever among the several Genoa ones, occurred on the 8–9 October 1970, and the Piedmont flood on the 14–17 of October 2000.

Figure 10 shows the maps for these three events, combining the cumulated precipitation over the whole events as observed at local stations and estimated by the ARCIS grid. Building these cumulated values, it was necessary to take into account that the present data consists of 9-to-9

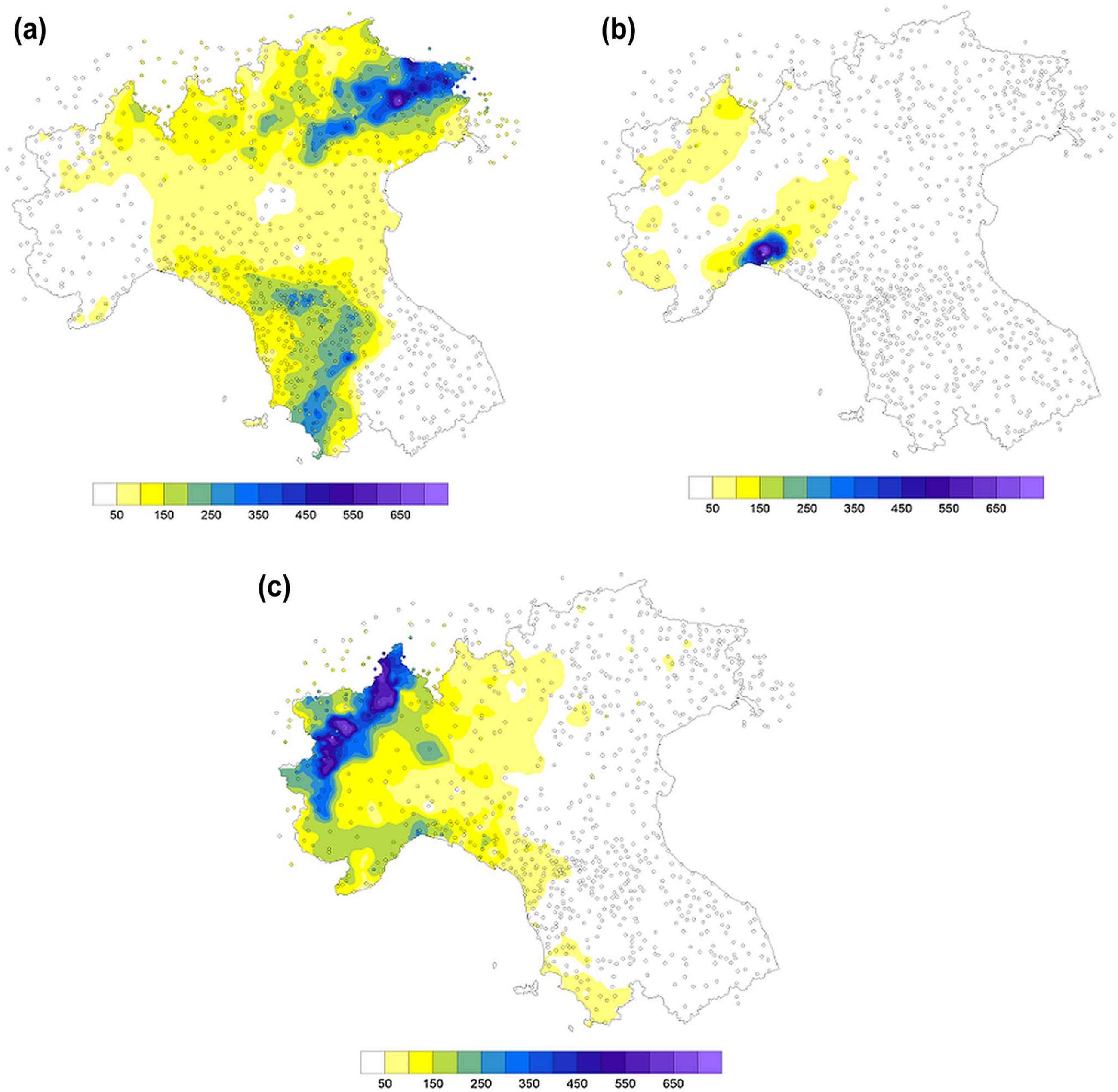


Fig. 10 Cumulated precipitation for the periods of 4–5 November 1966 (**a**), 8–9 October 1970 (**b**), and 14–17 October 2000 (**c**) for stations (coloured dots) and ARCIS grid (shading). All values in mm

cumulated data (am-readers) and that the daily cumulated value is attributed at the last instant of the accumulation period.

The maps show that the analysis presents a larger underestimate of precipitation maxima when the event is more localized, like in the case of the 1970 Genoa flood, currently considered the most intense documented precipitation event over the territory. For extended events, like the Florence flood in 1966 and the Piedmont flood in 2000, the intensity of precipitation maxima of station values and analysis are generally more comparable.

7 Conclusions

The present work describes a daily gridded high resolution data-set of precipitation over north-central Italy from 1961 to 2015. The data-set was generated by interpolating observational data from a high density climate monitoring network, managed by different Administrations. Input data are checked for quality, time consistency, statistical homogeneity and synchronicity. The data-set can be used to study the interannual and climate variability over the area also with respect to the frequency of local scale weather events.

The data-set is used to show and describe mean values and mean seasonality of a group of precipitation climate indices based on daily data. Maps of total annual and seasonal precipitation are discussed together with maps of other five climate indices, obtaining results comparable to those described in several works (Crespi et al. 2018; Bartolini et al. 2014a; Antolini et al. 2016; Isotta et al. 2014; Ciccarelli et al. 2009; Pavan et al. 2008). In particular, it's found that the distribution of daily precipitation values can vary greatly depending on the season and on the location considered, with the autumn PX90 index being locally on long term average from 4 to 7–8 times the PX50 index, depending on elevation, distance from the coastline and slope orientation. Generally, in autumn, precipitation presents a much greater orographic amplification effect than in summer, while the continuous dry day index (CDD) shows very different spatial distributions in these two seasons.

The data-set is also used to study how precipitation has changed in time over north-central Italy from 1961 to 2015. The annual total precipitation averaged over the whole domain does not show a significant linear trend in time, although locally it has undergone significant linear changes. Trends are unevenly distributed over the seasons, so that similar annual changes at different locations may lead to different impacts on the territory and on the local population depending on their seasonality. In particular, significant decreases in total precipitation can be observed in summer everywhere apart from the northern alpine territory close to the Italian border.

The linear trends for summer PX50, PX90, CDD, NRD and MPI indices show that in general the number of rainy days is significantly decreasing and that in large areas, between the north-western Po Valley and eastern central Italy, and in north-eastern territories, significant decreases in seasonal precipitation are linked both to an increase in the length of dry spells and to a general decrease in the amount of daily precipitation at all intensities. In the western part of Central Italy, the situation is similar although, locally, there may be signals of an increase in the amplitude of intense precipitation events, consistently with what observed by Bartolini et al. (2014b). In the north-central part of the Po Valley, significant decreases in summer precipitation are linked with a decrease in the number of rainy days (NRD) and an increase in the length of dry spells, although the PX50 and PX90 indices point towards an increase in intensity of daily amount, greater for intense events (PX90). Finally, the increases in total precipitation close to the northern Italian border are linked to increases in the amount of precipitation, particularly great and significant for the intense event (PX90) influencing also the mean precipitation intensity (MPI).

Total autumn precipitation increases are observed over large areas in the north eastern part of the domain and in Liguria, while significant decreases are observed in the inner area of the Central Apennines. The analysis of the precipitation climate indices shows that in this season, unlike the others, there is a decrease in the length of dry spells everywhere but in the north-western areas of the ARCIS domain. This signal is not always accompanied by a correspondent increase in the number of rainy days, suggesting that in this season the two indices are driven by different weather regimes. The decreases in total precipitation over central Italy are mostly due to decreases in the amount of daily precipitation, more significant and intense for the PX50 than for the PX90 index. In general, the pattern of changes of the total precipitation in this season is very similar to that of the PX90 index, describing the amplitude of intense events. The analysis presented in this paper is made available to the public and to the scientific community through the official web sites of all institutions participating to the ARCIS consortium and through the official web site of the consortium http://www.arcis.it/.

Acknowledgements We thank Météo-France, MeteoSwiss, the Zentralanstalt für Meteorologie und Geodynamik (ZAMG) and the Meteorological Service of Slovenia for making available to the ARCIS consortium daily precipitation data for the period 1960–2015 at several stations close to the Italian border. We acknowledge the use of E-OBS dataset from the EU-FP6 project ENSEMBLES (http://ensembles-eu.metoffice.com) and the data providers in the ECAD project (http://www.ecad.eu). We thank Regione Friuli Venezia Giulia - Servizio Gestione Risorse Idriche, Agenzia Regionale per la Protezione dell'Ambiente della Valle d'Aosta and Agenzia Regionale per lo Sviluppo e l'Innovazione del settore Agricolo forestale della Toscana for providing part of the daily observational data used within this work. Finally, we thank three anonymous reviewers for helping us to improve the quality of this paper.

References

Alexander LV, Zhang X, Peterson TC, Caesar J, Gleason B, Klein Tank AMG, Haylock M, Collins D, Trewin B, Rahimzadeh F, Tagipour A, Rupa Kumar K, Revadekar J, Griffiths G, Vincent L, Stephenson DB, Burn J, Aguilar E, Brunet M, Taylor M, New M, Zhai P, Rusticucci M, Vazquez-Aguirre JL (2006) Global observed changes in daily climate extremes of temperature and precipitation. J Geophys Res 111:D05109. https://doi.org/10.1029/2005JD006290

Antolini G, Auteri L, Pavan V, Tomei F, Tomozeiu R, Marletto V (2016) A daily high-resolution gridded climatic data set for Emilia-Romagna, Italy, during 1961–2010. Int J Climatol 36(4):1970–1986

Bartolini G, Messeri A, Grifoni D, Mannini D, Orlandini S (2014a) Recent trends in seasonal and annual precipitation indices in

Tuscany (Italy). Theor Appl Climatol 118(1–2):147–157. https://doi.org/10.1007/s00704-013-1053-3
Bartolini G, Grifoni D, Torrigiani Malaspina T, Vallorani R, Meneguzzo F, Gozzini B (2014b) Precipitation changes from two long-term hourly dataset in Tuscany (Italy). Int J Climatol 34:3977–3985. https://doi.org/10.1002/joc.3956
Bartolini G, Grifoni D, Magno R, Torrigiani T, Gozzini B (2017) Changes in temporal distribution of precipitation in a Mediterranean area (Tuscany, Italy) 1955–2013. Int J Climatol. https://doi.org/10.1002/joc.5251
Bucchignani E, Montesarchio M, Zollo AL, Mercogliano P (2016) High-resolution climate simulations with COSMO-CLM over Italy: performance evaluation and climate projections for the 21st century. Int J Climatol 36(2):735–756. https://doi.org/10.1002/joc.4379
Buzzi A, Davolio S, Malguzzi P, Drofa O, Mastrangelo D (2014) Heavy rainfall episodes over Liguria of autumn 2011: numerical forecasting experiments. Nat Hazard Earth Syst Sc 14:1325–1340
Cacciamani C, Nanni S, Tibaldi S (1994) Mesoclimatology of winter temperature and precipitation in the Po Valley of Northern Italy. Int J Climatol 14:777–814
Casanueva A, Kotlarski S, Herrera S, Fernández J, Gutiérrez JM, Boberg F, Colette A, Christensen OB, Goergen K, Jacob D, Keuler K, Nikulin G, Teichmann C, Vautard (2016) Daily precipitation statistics in a EURO–CORDEX RCM ensemble: added value of raw and bias-corrected high-resolution simulations. Clim Dyn 47:719–737
Catellari S, Artale V (eds) (2009) I cambiamenti climatici in Italia: evidenze, vulnerabilità e impatti. Bononia University Press, Bologna, Italy
Ciccarelli N, von Hardenberg J, Provenzale A, Ronchi C, Vargiu A (2009) Climate variability in north-western Italy during the second half of the 20th century. Glob Planet Change 63:185–195
Crespi A, Brunetti M, Lentini G, Maugeri M (2018) 1961–1990 high-resolution monthly precipitation climatologies for Italy. Int J Climatol 38:878–895. https://doi.org/10.1002/joc.5217
Davolio S, Diomede T, Marsigli C, Miglietta MM, Montani A, Morgillo A (2012) Comparing different meteorological ensemble approaches: hydrological predictions for a flood episode in Northern Italy. Adv Sci Res 8:33–37
Davolio S, Miglietta MM, Diomede T, Marsigli C, Montani A (2013) A flood episode in Northern Italy: multi-model and single-model mesoscale meteorological ensembles for hydrological predictions. Hydrol Earth Sys Sci 17:2107–2120
Giorgi F, Jones C, Asrar GR (2009) Addressing climate information needs at the regional level: the CORDEX framework. WMO Bull 58(3):175–183
Giorgi F, Coppola E, Solmon F, Mariotti L, Sylla MB, Bi X, Elguindi N, Diro GT, Nair V, Giuliani G, Cozzini S, Güttler I, O'Brien TA, Tawfik AB, Shalaby A, Zakey AS, Steiner AL, Stordal F, Sloan LC, Brankovic C (2012) RegCM4: model description and preliminary tests over multiple CORDEX domains. Clim Res 52:7–29
Haylock MR, Hofstra N, Klein Tank AMG, Klok EJ, Jones PD, New M (2008) A European daily high-resolution gridded dataset of surface temperature and precipitation. J Geophys Res 113:D20119. https://doi.org/10.1029/2008JD10201
Isotta FA, Frei C, Weilguni V, Percec Tadic M, Lassegues P, Rudolf B, Pavan V, Cacciamani C, Antolini G, Ratto SM, Munari M, Micheletti S, Bonati V, Lussana C, Ronchi C, Panettieri E, Marigo G, Vertacnik G (2014) The climate of daily precipitation in the Alps: development and analysis of a high-resolution grid dataset from pan-Alpine rain-gauge data. Int J Climatol 34(5):1657–1675
Manzato A, Cicogna A, Pucillo A (2016) 6-hour maximum rain in Friuli Venezia Giulia: Climatology and ECMWF-based forecasts. Atm Res 169B:465–484
Nuissier O, Marsigli C, Vincendon B, Hally A, Bouttier F, Montani A, Paccagnella T (2016) Evaluation of two convection-permitting ensemble systems in the HyMeX Special Observation Period (SOP1) framework. QJR Meteorol Soc 142:404–418. https://doi.org/10.1002/qj.2859
Pavan V, Tomozeiu R, Cacciamani C, Di Lorenzo M (2008) Daily precipitation observations over Emilia-Romagna: mean values and extremes. Int J Climatol 28:2065–2079
Pavan V, Antolini G, Agrillo G, Auteri L, Barbiero R, Bonati V, Brunier F, Cacciamani C, Cazzuli O, Cicogna A, De Luigi C, Maraldo L, Marigo G, Millini R, Panettieri E, Ratto S, Ronchi C, Saibanti S, Sulis A, Tomei F, Tomozeiu R, Torlai I, Villani G (2013) The ARCIS project. Ital J Agrometeorol 2(2013):51–55
Toreti A, Fioravanti G, Perconti W, Desiato F (2009) Annual and seasonal precipitation over Italy from 1961 to 2006. Int J Climatol 29:1976–1987
Toreti A, Xoplaki E, Maraun D, Kuglitsch FG, Wanner H, Luterbacher J (2010) Characterisation of extreme winter precipitation in Mediterranean coastal sites and associated anomalous atmospheric circulation patterns. Nat Hazard Earth Syst Sci 10:1037–1050
Uboldi F, Lussana C (2018) Evidence of non-stationarity in a local climatology of rainfall extremes in northern Italy. Int J Climatol 38:506–516. https://doi.org/10.1002/joc.5183
USGS-United States Geological Survey (1996) GTOPO30 documentation. http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/gtopo30_info

Affiliations

Valentina Pavan[1] · Gabriele Antolini[1] · Roberto Barbiero[2] · Nicola Berni[3] · Fabio Brunier[5] · Carlo Cacciamani[1,6] · Anselmo Cagnati[7] · Orietta Cazzuli[8] · Andrea Cicogna[9] · Chiara De Luigi[14] · Enzo Di Carlo[10] · Marco Francioni[3] · Luca Maraldo[13] · Gianni Marigo[7] · Stefano Micheletti[9] · Luca Onorato[4] · Elvio Panettieri[2] · Umberto Pellegrini[5,8] · Renata Pelosini[14] · David Piccinini[15] · Sara Ratto[5] · Christian Ronchi[14] · Luca Rusca[4] · Stefano Sofia[15] · Marco Stelluti[16] · Rodica Tomozeiu[1] · Tommaso Torrigiani Malaspina[11,12]

1 ARPAE-SIMC, Bologna, Italy

2 Centro Funzionale Provincia Autonoma di Trento, Trento, Italy

3 Centro Funzionale Regione Umbria, Foligno, Italy

4 ARPA Liguria, Genova, Italy

5 Centro Funzionale Regionale, Regione Autonoma Valle d'Aosta, Aosta, Italy

6 Dipartimento di Protezione Civile Nazionale, Roma, Italy

7 ARPA Veneto, Arabba, Italy

8 ARPA Lombardia, Milano, Italy

[9] ARPA Friuli Venezia Giulia, Palmanova, Italy

[10] Centro Funzionale Regione Toscana-Settore Idrologico, Pisa, Italy

[11] Consorzio LaMMA, Sesto Fiorentino, Italy

[12] IBIMET-CNR, Sesto Fiorentino, Italy

[13] Ufficio idrografico-Agenzia per la Protezione civile della Provincia Autonoma di Bolzano, Bozano, Italy

[14] ARPA Piemonte, Torino, Italy

[15] Centro Funzionale Regione Marche, Ancona, Italy

[16] Servizio Idrografico Regione Umbria, Perugia, Italy