Daily precipitation variability in the southern Alps since the late 19th century

Yuri Brugnara[1 2] and Maurizio Maugeri[3 4]

[1]Oeschger Centre for Climate Change Research, University of Bern, Switzerland
[2]Institute of Geography, University of Bern, Switzerland
[3]Department of Environmental Science and Policy, Universitá degli Studi di Milano, Italy
[4]Istituto di Scienze dell'Atmosfera e del Clima, CNR, Bologna, Italy

Corresponding author

Yuri Brugnara
Institute of Geography – University of Bern
Hallerstrasse 12
CH-3012 Bern
Switzerland
Tel.: +41 (031) 631 85 24
yuri.brugnara@giub.unibe.ch

Abstract

We analysed a dataset of 18 homogenised daily precipitation series from the southern European Alps, covering approximately the last 150 years. Previously available data from stations in northern Italy have been extended considerably by recent digitisation work, and, for the first time, they have been combined with daily data from Swiss stations on a centennial scale.

Precipitation frequency in the southern Alps decreased significantly over the period 1890–2017. We show that this trend is related to a step-like reduction in cyclonic weather types over central Europe that occurred around 1940. This decrease is an example of the large variability that affects precipitation in the region over many different time scales. In particular, strong trends on a decadal scale are related to the Atlantic Multidecadal Oscillation and the North Atlantic Oscillation, although the influence of the latter is present only in the recent decades.

Trends in heavy precipitation indices do not show a coherent pattern across the study area. We find a significant increase in heavy precipitation in Switzerland, while a decrease affects the southeastern subset in spring.

Keywords: Observational data analysis, Centennial, Mountain, Data rescue

1 Introduction

Understanding precipitation variability is crucial for many sectors, including agriculture, water management, insurance and infrastructure planning. Yet, scientific confidence in the temporal variability of precipitation in the past is still generally low (Hartmann et al., 2013). Precipitation is highly variable in space and time, and therefore a dense coverage of long, highly resolved and high-quality precipitation data series is necessary to fully disentangle precipitation variability on its multiple scales. Although we are still far from a global dataset that fulfills these requirements, it is already possible to build dense datasets that cover more than one century on a regional scale (particularly in Europe).

Precipitation in the Alps is very important in the European context. Alpine runoff water is used in much of Europe for drinking, irrigation, industry and electricity generation. The southern slope of the Alps, in particular, has been recognized as the most important water source in Europe because of the water needs of the lowland basin (Viviroli et al., 2007), which includes the densely populated Po Valley in northern Italy. Moreover, heavy precipitation in the southern Alps is often a hazard leading to damage and casualties, with large-scale floods occurring nearly every decade (Guzzetti et al., 2005).

Currently, dense meteorological station networks are located widely throughout the Alps and highly resolved datasets for the last few decades are available (e.g., Isotta et al., 2014; Crespi et al., 2018; Pavan et al., 2018). For earlier periods, however, daily data availability in the southern Alps is still relatively scarce when compared to the large amount of measurements that were carried out in that area since the late 19th century.

Until 1918, the southern Alps were shared by three countries: Switzerland, Austria-Hungary, and Italy. Switzerland and Austria-Hungary, in particular, possessed two of the most well-developed national weather networks in the world at the time. In Italy, and particularly in the Italian Alps, meteorological observations were often carried out on voluntary basis at cloisters and other religious institutes under the umbrella of the Italian Meteorological Society (see e.g. Brugnara et al., 2016). After the dissolution of the Austro-Hungarian Empire, the newborn Italian national hydrographic office promptly reactivated the stations in the territories annexed by Italy and kept them operative throughout the 20th century. An enormous amount of meteorological data from the late 19th and early 20th century, however, ended up forgotten in archives in various countries. This includes hydrological data (precipitation and snow cover), which were measured at thousands of stations across central and eastern Europe when World War I broke out. In this paper, we make use of recently digitised daily precipitation data that have allowed us to roughly triple the number of long series in the southern Alps reaching back to the 19th century.

Previous studies found a decrease in total precipitation in the southern Alps during the 20th century (Brunetti et al., 2006b; Brugnara et al., 2012) similar to that observed on average in the Mediterranean basin (Hoerling et al., 2012; Mariotti et al., 2015), which is believed to be at least in part of anthropogenic origin (Hoerling et al., 2012). Studies on extremes are still rare and have focused on relatively short periods and/or on small study areas (often limited by political borders). For example, Scherrer et al. (2016) found significant increases in daily extreme precipitation indices at several stations in the southern Alpine sector of Switzerland over 1901–2014, while Uboldi and Lussana (2018) found a significant increase in daily and sub-daily extreme precipitation in a small area in northeastern Lombardy over the second half of the 20th century. No study exists for the southern Alps as a whole. On the continental scale, numerous studies have analysed trends in heavy or extreme precipitation (e.g., Van den Besselaar et al., 2013; Fischer and Knutti, 2016), finding a predominance of positive trends since 1950. In the Mediterranean basin (which includes the southern Alps), however, signals in extremes are less spatially coherent (Ulbrich et al., 2012). For instance, no significant trends are observed in the northwestern Apennines (Brunetti et al., 2018), a region with strong climatic similarities to the southern Alps (Brunetti et al., 2006b).

In the present paper, we analyse changes in both mean and extreme precipitation indices in the southern Alps. After a description of the study area (Sect. 2) and the dataset (Sect. 3), we explain the data processing and define the indices in Sect. 4. The results are in Sect. 5 and are then discussed in Sect. 6. Finally, we draw our conclusions in Sect. 7.

2 Study area

We define the southern Alps as the mountainous area south of the main Alpine watershed, between 8-14°E longitude. This corresponds to the "NEN" region defined by Brunetti et al. (2006a) by means of a Principal Component Analysis of Italian and Swiss monthly precipitation series. The main Alpine watershed roughly follows the political border of Italy, reaching into south-eastern Switzerland (cantons of Ticino and part of Grisons) and southern Austria (East Tyrol and part of Carinthia).

In an Alpine context, the main characteristic of the climate of the southern Alps is the large influence of the Mediterranean Sea. This implies higher temperatures than in the northern Alps, and higher orographically-driven precipitation due to the greater water content of the air. However, some of the valleys close to the watershed (inner Alpine valleys) have a relatively dry climate, especially in winter (Isotta et al., 2014; Crespi et al., 2018).

Precipitation in the southern Alps is concentrated during considerably fewer days than in the northern Alps, yet it leads to similar annual totals. Therefore, the average precipitation intensity is much higher, reaching values greater than 20 mm day^{-1} in the precipitation "hot spots" of Lake Maggiore and the Julian Alps (Isotta et al., 2014).

3 Data

We analyse daily precipitation data from 18 stations located in the cantons of Ticino and Grisons in Switzerland, and in the regions of Piedmont, Lombardy, Veneto, and Trentino-South Tyrol in Italy. These series were selected because of their length, completeness, and good data quality. Table 1 summarises the characteristics of the series.

We use 523 additional monthly precipitation series (with monthly number of wet days, i.e. number of days with at least 1 mm of precipitation, available for 92% of the total station time) as reference for the homogenisation of the 18 target series. Figure 1 shows the geographical distribution of the stations and the length of each series.

3.1 Previously existing data

There are numerous data providers due to the highly fragmented station network management in Italy. Despite this, the measurement standards are fairly consistent across stations. Manual observations were carried out in the early morning hours at all stations, and in most cases, the definition of the hydrological day did not change after the transition to automatic rain gauges. There are, however, inconsistencies in the calendar day to which the daily amount is assigned (either to the day of the observation or to the day before), which depend not only on the station but also on the year considered, because there are often different data providers for different sub-periods of the same series (most stations in Italy have belonged to more than one network in the course of their history).

Data for the central-eastern Alps referring to years later than 1920 were already homogenised by Brugnara et al. (2012) using a dense station network. We use the same homogenised data in this paper.

3.2 Newly rescued data

Until recently, only a few centennial daily precipitation series existed for the southern Alps outside Switzerland, none of which were publicly available. Most of the digitised records started in 1921 or later, such as those analysed in Brugnara et al. (2012).

Over the last few years, significant digitisation work has been undertaken at the University of Bern (with collaborations from the Royal Netherlands Meteorological Institute and the Austrian Zentralanstalt für Meteorologie und Geodynamik) through the initiative “Before 1921” (`http://before1921.wordpress.com`). The aim of this project is to recover the great amount of meteorological data available for the territories of the southern Alps that were part of Austria-Hungary until World War I.

Even though (at the time of writing) the digitisation work is far from complete, in the present study we already make use of over 1500 station years of newly digitised daily data (of which about 350 years are part of the analysed series), reaching back to 1872. The data sources include the yearbooks of the Austro-Hungarian meteorological and hydrographic offices, as well as the original station registers. The digitised data are available without restrictions in public international databases.

4 Methods

4.1 Data quality, homogenisation and gap filling

To verify the quality of the data, we followed a semi-automatic procedure in which we compared each of the 18 series with a reconstructed daily series based on multiple linear regression taking as input data from neighbouring stations (Simolo et al., 2010). Large differences between the original data and the reconstruction were then investigated manually. This led to the correction of 43 daily values (mostly involving the addition of a flag for cumulated values, i.e. when the total precipitation of multi-day events had been assigned to one day), while we set 253 erroneous values to missing. In addition, we discarded all data for the stations of Bellinzona and Segl-Maria before 1887 (i.e., 23 years) and 1890 (26 years), respectively, because of their generally poor quality.

The most significant correction affected the highest value on record at the station of Segl-Maria (108 mm on 3 November 2000): this value was not only incompatible with the much smaller amounts measured at nearby locations, but also with the 12-hour totals (available at Swiss stations for the last few decades) observed at the same station. We replaced the value with the sum of the two 12-hour values (21.6 mm).

This kind of quality control is not sufficient to guarantee data homogeneity over time, because the instruments, observers, and positions of the stations cannot remain the same for over one century. Therefore, we homogenised the data series by applying the same procedure described in Brugnara et al. (2012). Breakpoints were detected visually using the Craddock's test (Craddock, 1979), both on the monthly precipitation totals and the monthly number of wet days. Daily adjustments were obtained from a trigonometric fit of monthly adjustments, in turn estimated from highly correlated reference series. Five series (Bellinzona, Locarno, Rovereto, Segl-Maria, Trento) were found to be sufficiently homogeneous and did not require any adjustment. In the others, we found 1.8 breakpoints on average (including those already adjusted by Brugnara et al. (2012)), with a maximum of 8 breakpoints in the series of Sondrio.

We reconstructed missing data in the homogenised series using the algorithm of Simolo et al. (2010). We filled only those missing values found in partially incomplete months. This allowed us to fill cumulated values, for which we rescaled the reconstructed values so that their sum would match the multi-day observation. A total of 1887 values in our dataset were reconstructed, corresponding to less than 0.25% of the analysed observations.

4.2 Indices and trend analysis

We studied the annual (December to November) and seasonal indices listed in Table 2, selected from those recommended by the World Meteorological Organization (Klein-Tank et al., 2009).

We also studied the relationship between precipitation in the southern Alps and the main large-scale atmospheric and oceanic indices in the North Atlantic region; in particular, we use updates of the North Atlantic Oscillation (NAO) index by Jones et al. (1997) and the Atlantic Multidecadal Oscillation (AMO) index by Enfield et al. (2001). In addition, we use the recent reconstruction by Schwander et al. (2017), who estimated the frequency of 7 weather types in central Europe since 1763 using long temperature and pressure series.

Trends were evaluated by means of a robust linear regression using a so-called M-estimator (Venables and Ripley, 2002), specifically by minimizing the Huber's loss function (Huber and Ronchetti, 2009) instead of the squared residuals as in ordinary least squares, in order to reduce the influence of outliers. Trends were considered significant if the null-hypothesis of the Mann-Kendall test (Sneyers, 1990) was rejected at the 5% level.

5 Results

5.1 Climatological characterization of heavy precipitation events

Table 3 reports the mean seasonal precipitation for each analysed station, as well as the largest RX1day and RX5day values on record. All stations have a precipitation minimum in winter, while the annual totals are highly dependent on topography and range from less than 700 to more than 1800 mm. The most extreme RX5day is found in autumn at most stations, with some exceptions in summer or late spring. The most extreme RX1day indices are more spread over the year but are commonly found in late summer, when local-scale deep convection provides an important contribution. Notably, extremely high precipitation amounts can be observed even in winter, when the expected climatological amount of the whole season can be exceeded in less than 24 hours. One particularly remarkable episode is that of 1 February 1986, which caused the largest daily precipitation on record at 3 different stations (an analysis of this and other recent winter extreme precipitation episodes can be found in Panziera and Hoskins, 2008).

Figure 2 shows, for each station, how frequently annual maxima are observed in each month and season during the period 1890–2017 (chosen to assure a reasonable completeness of all series, i.e. $< 15\%$ missing data, see Table 1). From the distribution of the indices over the year we can identify three clusters of stations (see also Fig. 1 and Table 3). The first cluster (represented by shades of blue in the figures), mainly consisting of stations in the eastern part of the study area (but also including Domodossola in the west), has a clear maximum in late autumn (October-November) and a small summer contribution; moreover, the contribution from winter is relatively high, even higher than summer for some stations. The second cluster (red), which includes the Swiss stations, also peaks in autumn but shows a much larger role of summer (the maximum is between August and September). Finally, the station of Brixen (green) is the only instance of a peak in mid-summer for both indices. This is the driest station of our dataset, with the most prominent summer maximum in the precipitation climatology (Table 3), well representing the climate of an inner Alpine valley.

5.2 Linear trends

Annual TP decreased at almost all stations over the period 1890–2017 (Fig. 3a), but the trends are significant only in the south-east (Trentino). Seasonally, winter and spring have a clear prevalence of negative trends in the east (Fig. 4a). A more extended decrease emerges by analysing the annual WD (Fig. 3b), significant at 5 stations, of which 2 are in Switzerland. A prevalence of negative trends in WD is observed in every season but winter (Fig. 4b), with spring and autumn showing the highest spatial coherence. On the other hand, there is no coherent regional signal for SDII, neither annually (Fig. 3c) nor seasonally (Fig. 4c). The western stations have mostly positive trends (4 of these show a significant trend in spring), whereas the eastern stations have mostly negative annual trends.

The trends for R10mm (Fig. 3d) and R20mm (Fig. 3e) are mostly consistent with those of WD. The main difference is the stronger decrease for R20mm in spring (Fig. 4e), which exceeds 50% century^{-1} at most stations in the south-east (4 significant trends). Moreover, the two northernmost stations have positive trends (one significant for R20mm).

An increase in CDD is observed at most stations in spring and autumn (Fig. 4f). However, the trends are significant at only 1 station in spring and at none in autumn. A prevalence of negative trends is observed in summer (significant at 1 station). No clear pattern emerges on the annual scale (Fig. 3f).

RX1day shows an increase at most stations, especially in the west, with significant trends at 2 stations (Fig. 3g). The increase affects all stations in autumn (significant at 1 station), whereas a decrease is prevalent in spring (Fig. 4g). Results are similar for RX5day (Fig. 3h): significant negative trends occur in spring at 3 south-eastern stations. Figure 4h also shows a clear prevalence of positive trends in summer. Again, the largest trends are in the south-east, where they are significant at 2 stations.

5.3 Decadal variability

Figure 5 shows the regional time series of TP and WD for each season, calculated by averaging the anomaly series of all stations. The most striking feature is the sudden drop in the annual WD around 1940: in the first half of the study period, precipitation occurred about 10% more often than during the last 70 years. The precipitation amount shows a similar behaviour, although the signal is less clear because of greater interannual variability. The most affected season is spring.

The decadal variability is linked to the frequency of certain weather types, in particular those bringing a cyclonic flow with a southern component towards the Alps. In Fig. 5 the frequency of the CAP7 cyclonic weather types, namely, WSW (west-southwest), or N (north) or WC (westerly flow over Southern Europe) from Schwander et al. (2017) is superposed on the precipitation series, showing large correlations with the regional mean ($R^2 > 0.3$ for TP and $R^2 > 0.4$ for WD) in all seasons except summer. About 30% of the total WD in our dataset occur with the type WC, but this percentage is higher if summer is not considered (Fig. 6). According to (Schwander et al., 2017), the frequency of the type WC dropped by about 20% after 1940. A similar behaviour, although with a smaller reduction, was observed for the types WSW and N. Note that many of the names of the CAP7 weather types refer to the mean flow over Switzerland; in particular, the type N is related to a low-pressure minimum over northern Italy, which can bring a south-easterly flow to the southern Alps.

In winter, precipitation in the southern Alps is known to be inversely correlated with the NAO index (e.g., López-Moreno et al., 2011). Our results confirm this relationship only for the later part of the study period (Fig. 7); in particular, the long dry spell between the 1980s and 1990s is related, in part, to a persistent positive phase of the NAO. Before the climate "shift" in 1940, however, we generally find no significant correlation between the NAO index and precipitation in the southern Alps. Interestingly, TP at the station of Bivio is positively correlated with the NAO, even though WD are negatively correlated. In the later part of the study period, we can also see differences in the magnitude of the correlation between the stations in the inner valleys and those closer to the Prealps that are consistent with a change of sign of the correlation across the Alpine watershed (López-Moreno et al., 2011).

TP in spring shows a pronounced multidecadal variability that anti-correlates with the AMO index. Spring precipitation between the 1920s-1930s and 1970s-1980s (i.e., close to the last two minima of the AMO) were on average 20 to 50% higher than during the last few decades. Due to the relatively long period of the AMO, much longer data series than those analysed here would be required to evaluate the temporal stability of the correlation.

Figure 5 also shows the 10 most extreme regional multi-day events over the last 140 years (blue triangles), calculated by averaging the RX5day values observed at all available stations (normalized by the respective annual climatological totals). Six of these events were observed between 1882–1888 and 1920–1928, and 3 of the 5 largest 5-day events all happened in the 1920s (1920, 1926, 1928). We also find that 8 of the 25 largest 5-day events in the last 140 years occurred in pairs separated by less than two years (1888–1889, 1926, 1928, 2000). In 1928 and 2000, two distinct extreme events were separated by only a few days. By season, the largest regional events occurred 29 January–2 February 1986, 13–17 May 1926, 9–13 July 1890, and 13–17 September 1882 (dates may differ slightly at some stations).

We find a similar clustering of extreme dry periods (red triangles): for instance, the 2 highest regional values of CDD (where the regional value is the median of the station values) occurred within just 4 years in the winters of 1988/1989 and 1992/1993. High regional values of CDD in spring follow the multidecadal variability of TP and WD: the empirical probability of a dry spell longer than 30 days to occur at half of the stations is nearly doubled during the positive phase of the AMO with respect to the negative phase (21% - 12%). In summer, the last 50 years have been remarkably deficient in extreme dry periods, with the 5 longest on record all occurring before 1950. This is further explored in Fig. 8, which shows the evolution in time of summer CDD. Even though long dry spells occur regularly at isolated stations, dry spells longer than 15 days that affect at least half of the stations have become much less frequent in the last few decades.

6 Discussion

Precipitation in the southern Alps show a drying trend similar to that observed on average in the northern Mediterranean basin (e.g., Mariotti et al., 2015). The trend is mainly caused by a step-wise climate shift around 1940, which can be explained by a similar behaviour in the frequency of cyclonic weather types over central Europe. This suggests that the precipitation decrease in the southern Alps can, in large part, be ascribed to natural variability, although the attribution of trends is out of the scope of the present paper.

The decrease in precipitation especially affects the eastern part of the study area and the spring season. According to climate projections, however, summer will be more significantly affected by climate change over the next decades in the Mediterranean region (e.g., Mariotti et al., 2015). In the southern Alps, a reduction of summer TP up to 50% is expected by the end of the century (depending on the scenario and the model used) (Gobiet et al., 2014; Fischer et al., 2015; Rajczak and Schär, 2017), although the trends might be lower at higher elevations (Giorgi et al., 2016). Whether this reduction materialises in the observations also depends on natural variability (Maraun, 2013; Mariotti et al., 2015). Our results indicate that widespread extreme dry spells were unusually rare during summer over the last 50 years when compared to the previous 80 years, even though local dry spells were not infrequent, which might be an indication of increased atmospheric instability. However, this does not imply that droughts have become less common or less severe, since dry conditions also depend on temperature (e.g., Vicente-Serrano et al., 2014). Given the high correlation between the frequency of cyclonic weather types and precipitation in the southern Alps during the last 120-130 years, we can consider the reconstruction of Schwander et al. (2017) to be a good proxy for extending precipitation variability back to the 18th century. Interestingly, the frequency of cyclonic weather types has never been as low as in the recent decades, suggesting that the second half of the 20th century has probably been the driest period in the southern Alps in the last 250 years, at least during spring and autumn (when the correlation is higher). This conclusion has important implications, for instance, for the study of glacier mass balance.

The AMO may have exacerbated the trends during spring over the last few decades. In fact, we find a decrease in spring TP of the order of 20% when analysing the last 40 years. A similar decrease had already occurred between ca. 1930–1970 (previous positive phase of the AMO), followed by a rapid increase, suggesting that a future increase in spring precipitation is likely. There is no guarantee, however, that the link will hold in the future, nor that the AMO will continue to behave like it did in the recent past (see e.g., Murphy et al., 2017).

An influence of the AMO on precipitation has been observed in different parts of the world (e.g., Enfield et al., 2001; Zhang and Delworth, 2006; Sutton and Dong, 2012). Sutton and Dong (2012) found a relationship with precipitation in northern Italy that is consistent with our analysis. The influence of the AMO on precipitation is related to changes in the frequency of weather types (Zampieri et al., 2017), but a robust physical interpretation is still missing.

The climate shift in 1940 coincides with a change in influence of the NAO. The negative correlation between the NAO index and WD in the southern Alps, which is statistically significant from the 1950s onward at most stations, is not observed in the early 20th century. This is particularly relevant because many studies about NAO impacts are based on datasets beginning in 1950 or later (e.g., López-Moreno et al., 2011); moreover, stability of the NAO influence is sometime assumed for the interpretation of climate reconstructions (e.g., Scholz et al., 2012). The NAO influence on precipitation was found to be highly variable in the northern Alps as well (Brunetti et al., 2006b).

Our analysis of heavy precipitation events extend the results of Scherrer et al. (2016) out of the Swiss borders and show that the behaviour of annual precipitation maxima in the southern Alps is more complex than in Switzerland (where an increase is observed everywhere). In particular, there is no detectable increase of annual indices of heavy precipitation events in the south-eastern Alps, similarly to what is found for other regions in northern Italy (e.g., Brunetti et al., 2018). The prevalent climatological occurrence of extreme events (late summer / early autumn in the west, late autumn in the east) is arguably one of the factors driving these differences. In fact, precipitation extremes occurring in summer or early autumn have a much higher contribution from local convective processes, suggesting that the magnitude of convective precipitation extremes is increasing. This is also supported by the significant increases in heavy precipitation indices observed at some of the stations in the south-eastern Alps in summer (Fig. 4).

7 Conclusions

We compiled a new dataset of daily precipitation for the southern Alps covering the last 150 years, which complements the previously available Swiss series through the recent digitisation of a large amount of data from Italy.

Precipitation amount and frequency significantly decreased at some of the stations over the period 1890–2017, particularly those in the south-eastern part of the study area. This trend is caused by a step-like shift around 1940, when the mean annual precipitation and the number of wet days suddenly dropped by nearly 10%. We could ascribe this change to a reduction in the frequency of cyclonic weather types in central Europe.

The evolution of precipitation over time is also affected by large variability on the decadal scale, which makes the use of long data series particularly important. We could confirm the previously described relationship with the NAO index in winter and the AMO index in spring, both inversely correlated with precipitation in the southern Alps. For the former index, however, we found that the correlation is not stationary and disappears before 1950.

We also studied the changes in several daily precipitation indices. The behaviour of some of these indices changes significantly with longitude, in particular for heavy precipitation events. We detected a coherent increasing pattern of annual precipitation maxima in the western part of the study area, where these maxima are usually observed in late summer when the contribution of local convection is larger. In the eastern part, on the other hand, we did not find significant trends except for a general decrease of heavy precipitation events in spring and local increases in summer. Extremely long dry spells became less frequent in summer during the last 50 years, with 9 of the 10 longest spells on record occurring before 1962. In spring, dry spells are modulated by the AMO.

Our findings indicate that the synoptic conditions conducive to extreme precipitation events in the southern Alps tend to occur with anomalous high frequency during certain time periods that can last up to a few years, and with anomalous low frequency during others. In other words, the occurrence of an extreme precipitation event increases the probability of another similar event within a relatively short time. This applies both to extremely wet and dry spells.

Our results show that long daily time series (possibly longer than 100 years) are necessary to sufficiently represent precipitation variability in the Alps. More research is needed to understand the processes driving the low-frequency natural variability that is of comparable magnitude with the expected future anthropogenic changes for some indices.

Acknowledgments

Data for Italy were provided by the regional weather services (ARPAs) of Aosta Valley, Piedmont, Lombardy, Veneto, Friuli-Venezia Giulia, and of the autonomous Provinces of Trento (MeteoTrentino) and Bolzano (Hydrographic Office); by the Central Office of Agronomical Ecology (UCEA, now CREA), the Italian Meteorological Society (SMI), the Italian electrical board (ENEL), the Italian Air Force, and the Fondazione Museo Civico di Rovereto. Data for Switzerland were provided by the Swiss national weather service (MeteoSwiss). We thank the personnel of the library of the Franciscan cloister San Bernardino in Trento and of the Zentralanstalt für Meteorologie und Geodynamik in Vienna for their precious help in organising the digitisation of the relevant weather registers. We also thank Stefan Brönnimann and Michele Brunetti for their feedbacks on an earlier version of the manuscript, and Alena Giesche for language editing.

References

Brugnara, Y., Brunetti, M., Maugeri, M., Nanni, T., and Simolo, C.: High-resolution analysis of daily precipitation trends in the central Alps over the last century, International Journal of Climatology, 32, 1406–1422, doi:10.1002/joc.2363, 2012.

Brugnara, Y., Auchmann, R., Brönnimann, S., Bozzo, A., Berro, D. C., and Mercalli, L.: Trends of mean and extreme temperature indices since 1874 at low-elevation sites in the southern Alps, Journal of Geophysical Research, 121, 3304–3325, doi:10.1002/2015JD024582, 2016.

Brunetti, M., Maugeri, M., Monti, F., and Nanni, T.: Temperature and precipitation variability in Italy in the last two centuries from homogenised instrumental time series, International Journal of Climatology, 26, 345–381, doi:10.1002/joc.1251, 2006a.

Brunetti, M., Maugeri, M., Nanni, T., Auer, I., Böhm, R., and Schöner, W.: Precipitation variability and changes in the greater Alpine region over the 1800–2003 period, Journal of Geophysical Research, 111, doi:10.1029/2005JD006674, 2006b.

Brunetti, M., Bertolini, A., Soldati, M., and Maugeri, M.: High-resolution analysis of 1-day extreme precipitation in a wet area centered over eastern Liguria, Italy, Theoretical and Applied Climatology, pp. 1–13, doi:10.1007/s00704-018-2380-1, 2018.

Craddock, J.: Methods of comparing annual rainfall records for climatic purposes, Weather, 34, 332–346, doi:10.1002/j.1477-8696.1979.tb03465.x, 1979.

Crespi, A., Brunetti, M., Lentini, G., and Maugeri, M.: 1961–1990 high-resolution monthly precipitation climatologies for Italy, International Journal of Climatology, 38, 878–895, doi:10.1002/joc.5217, 2018.

Enfield, D. B., Mestas-Nunez, A. M., Trimble, P. J., et al.: The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U. S., Geophysical Research Letters, 28, 2077–2080, doi:10.1029/2000GL012745, 2001.

Fischer, A., Keller, D., Liniger, M., Rajczak, J., Schär, C., and Appenzeller, C.: Projected changes in precipitation intensity and frequency in Switzerland: a multi-model perspective, International Journal of Climatology, 35, 3204–3219, doi:10.1002/joc.4162, 2015.

Fischer, E. M. and Knutti, R.: Observed heavy precipitation increase confirms theory and early models, Nature Climate Change, 6, 986, doi:10.1038/nclimate3110, 2016.

Giorgi, F., Torma, C., Coppola, E., Ban, N., Schär, C., and Somot, S.: Enhanced summer convective rainfall at Alpine high elevations in response to climate warming, Nature Geoscience, 9, 584, doi:10.1038/ngeo2761, 2016.

Gobiet, A., Kotlarski, S., Beniston, M., Heinrich, G., Rajczak, J., and Stoffel, M.: 21st century climate change in the European Alps–a review, Science of the Total Environment, 493, 1138–1151, doi:10.1016/j.scitotenv.2013.07.050, 2014.

Guzzetti, F., Stark, C. P., and Salvati, P.: Evaluation of flood and landslide risk to the population of Italy, Environmental Management, 36, 15–36, doi:10.1007/s00267-003-0257-1, 2005.

Hartmann, D., Klein Tank, A., Rusticucci, M., Alexander, L., Brönnimann, S., Charabi, Y., Dentener, F., Dlugokencky, E., Easterling, D., Kaplan, A., Soden, B., Thorne, P., Wild, M., and Zhai, P.: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, chap. Observations: Atmosphere and Surface, Cambridge University Press, Cambridge, UK and New York, NY, USA, 2013.

Hoerling, M., Eischeid, J., Perlwitz, J., Quan, X., Zhang, T., and Pegion, P.: On the increased frequency of Mediterranean drought, Journal of Climate, 25, 2146–2161, doi:10.1175/jcli-d-11-00296.1, 2012.

Huber, P. J. and Ronchetti, E. M.: Robust statistics, second edition, Wiley, 2009.

Isotta, F. A., Frei, C., Weilguni, V., Perčec Tadić, M., Lassegues, P., Rudolf, B., Pavan, V., Cacciamani, C., Antolini, G., Ratto, S. M., et al.: The climate of daily precipitation in the Alps: development and analysis of a high-resolution grid dataset from pan-Alpine rain-gauge data, International Journal of Climatology, 34, 1657–1675, doi:10.1002/joc.3794, 2014.

Jones, P., Jonsson, T., and Wheeler, D.: Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and south-west Iceland, International Journal of Climatology, 17, 1433–1450, doi:10.1002/(SICI)1097-0088(19971115) 17:13⟨1433::AID-JOC203⟩3.0.CO;2-P, 1997.

Klein-Tank, A. M., Zwiers, F. W., and Zhang, X.: Guidelines on analysis of extremes in a changing climate in support of informed decisions for adaptation, no. 1500 in WMO-TD, World Meteorological Organization, Geneva, Switzerland, 2009.

López-Moreno, J., Vicente-Serrano, S., Morán-Tejeda, E., Lorenzo-Lacruz, J., Kenawy, A., and Beniston, M.: Effects of the North Atlantic Oscillation (NAO) on combined temperature and precipitation winter modes in the Mediterranean mountains: observed relationships and projections for the 21st century, Global and Planetary Change, 77, 62–76, doi:10.1016/j.gloplacha.2011.03.003, 2011.

Maraun, D.: When will trends in European mean and heavy daily precipitation emerge?, Environmental Research Letters, 8, 014 004, doi:10.1088/1748-9326/8/1/014004, 2013.

Mariotti, A., Pan, Y., Zeng, N., and Alessandri, A.: Long-term climate change in the Mediterranean region in the midst of decadal variability, Climate Dynamics, 44, 1437–1456, doi:10.1007/s00382-015-2487-3, 2015.

Murphy, L. N., Bellomo, K., Cane, M., and Clement, A.: The role of historical forcings in simulating the observed Atlantic multidecadal oscillation, Geophysical Research Letters, 44, 2472–2480, doi:10.1002/2016GL071337, 2017.

Panziera, L. and Hoskins, B.: Large snowfall events in the south-eastern Alps, Weather, 63, 88–93, doi:10.1002/wea.178, 2008.

Pavan, V., Antolini, G., Barbiero, R., Berni, N., Brunier, F., Cacciamani, C., Cagnati, A., Cazzuli, O., Cicogna, A., De Luigi, C., Di Carlo, E., Francioni, M., Maraldo, L., Marigo, G., Micheletti, S., Onorato, L., Panettieri, E., Pellegrini, U., Pelosini, R., Piccinini, D., Ratto, S., Ronchi, C., Rusca, L., Sofia, S., Stelluti, M., Tomozeiu, R., and Torrigiani Malaspina, T.: High resolution climate precipitation analysis for north-central Italy, 1961–2015, Climate Dynamics, doi:10.1007/s00382-018-4337-6, 2018.

Rajczak, J. and Schär, C.: Projections of future precipitation extremes over Europe: A multimodel assessment of climate simulations, Journal of Geophysical Research, 122, doi:10.1002/2017JD027176, 2017.

Scherrer, S. C., Fischer, E. M., Posselt, R., Liniger, M. A., Croci-Maspoli, M., and Knutti, R.: Emerging trends in heavy precipitation and hot temperature extremes in Switzerland, Journal of Geophysical Research, 121, 2626–2637, doi:10.1002/2015JD024634, 2016.

Scholz, D., Frisia, S., Borsato, A., Spötl, C., Fohlmeister, J., Mudelsee, M., Miorandi, R., and Mangini, A.: Holocene climate variability in north-eastern Italy: potential influence of the NAO and solar activity recorded by speleothem data, Climate of the Past, 8, 1367–1383, doi:10.5194/cp-8-1367-2012, 2012.

Schwander, M., Brönnimann, S., Delaygue, G., Rohrer, M., Auchmann, R., and Brugnara, Y.: Reconstruction of Central European daily weather types back to 1763, International Journal of Climatology, 37, 30–44, doi:10.1002/joc.4974, 2017.

Simolo, C., Brunetti, M., Maugeri, M., and Nanni, T.: Improving estimation of missing values in daily precipitation series by a probability density function-preserving approach, International Journal of Climatology, 30, 1564–1576, doi:10.1002/joc.1992, 2010.

Sneyers, R.: On the statistical analysis of series of observations, no. 143 in WMO Technical note, World Meteorological Organization, Geneva, 1990.

Sutton, R. T. and Dong, B.: Atlantic Ocean influence on a shift in European climate in the 1990s, Nature Geoscience, 5, 788, doi:10.1038/ngeo1595, 2012.

Uboldi, F. and Lussana, C.: Evidence of non-stationarity in a local climatology of rainfall extremes in northern Italy, International Journal of Climatology, 38, 506–516, doi:10.1002/joc.5183, 2018.

Ulbrich, U., Lionello, P., Belušić, D., Jacobeit, J., Knippertz, P., Kuglitsch, F. G., Leckebusch, G. C., Luterbacher, J., Maugeri, M., Maheras, P., et al.: Climate of the Mediterranean: synoptic patterns, temperature, precipitation, winds, and their extremes, in: The Climate of the Mediterranean Region, pp. 301–346, Elsevier, 2012.

Van den Besselaar, E., Klein Tank, A., and Buishand, T.: Trends in European precipitation extremes over 1951–2010, International Journal of Climatology, 33, 2682–2689, doi:10.1002/joc.3619, 2013.

Venables, W. and Ripley, B.: Modern Applied Statistics Using S, Springer, New York, 2002.

Vicente-Serrano, S. M., Lopez-Moreno, J.-I., Beguería, S., Lorenzo-Lacruz, J., Sanchez-Lorenzo, A., García-Ruiz, J. M., Azorin-Molina, C., Morán-Tejeda, E., Revuelto, J., Trigo, R., et al.: Evidence of increasing drought severity caused by temperature rise in southern Europe, Environmental Research Letters, 9, 044 001, doi:10.1088/1748-9326/9/4/044001, 2014.

Viviroli, D., Dürr, H. H., Messerli, B., Meybeck, M., and Weingartner, R.: Mountains of the world, water towers for humanity: Typology, mapping, and global significance, Water Resources Research, 43, doi:10.1029/2006WR005653, 2007.

Zampieri, M., Toreti, A., Schindler, A., Scoccimarro, E., and Gualdi, S.: Atlantic multi-decadal oscillation influence on weather regimes over Europe and the Mediterranean in spring and summer, Global and Planetary Change, 151, 92–100, doi:10.1016/j.gloplacha.2016.08.014, 2017.

Zhang, R. and Delworth, T. L.: Impact of Atlantic multidecadal oscillations on India/Sahel rainfall and Atlantic hurricanes, Geophysical Research Letters, 33, doi:10.1029/2006GL026267, 2006.

Table 1: Stations that have been homogenised and used in the analysis (Lon = longitude in degrees East; Lat = latitude in degrees North; Elev = elevation in metres). The "+" sign separates the station names before and after a major station relocation (distance > 1 km or elevation difference > 100 m); coordinates refer to the current station location.

Name	**Abbr.**	**Lon**	**Lat**	**Elev**	**Period**	**% missing**
Bellinzona	BLZ	9.000	46.180	224	1887–2017	1.3
Bivio	BIV	9.667	46.467	1856	1892–2017	0.0
Brixen	BRX	11.644	46.731	584	1878–2017	3.0
Cavalese	CAV	11.452	46.285	958	1882–2017	0.4
Cortina	COR	12.127	46.537	1271	1895–2017	6.0
Domodossola	DOM	8.288	46.113	284	1871–2017	1.7
Gries + Bozen	BZG	11.313	46.498	254	1884–2017	11.7
Locarno + Monti	LOM	8.783	46.167	367	1882–2017	0.7
Lugano	LUG	8.967	46.000	273	1864–2017	0.0
Marienberg	MAR	10.520	46.706	1335	1890–2017	3.8
Pergine	PER	11.240	46.053	458	1887–2017	9.3
Riva + Torbole	RIT	10.877	45.870	90	1872–2017	3.0
Rovereto	ROV	11.044	45.896	203	1882–2017	3.4
Segl-Maria	SIA	9.767	46.433	1804	1890–2017	0.8
Soglio	SOG	9.533	46.350	1086	1884–2017	0.1
Sondrio	SND	9.852	46.167	298	1894–2017	7.5
Tione	TIO	10.731	46.041	533	1895–2017	9.2
Trento + Laste	TNL	11.136	46.072	312	1893–2017	4.1

Table 2: Annual and seasonal precipitation indices analysed in this study.

Index	**Unit**	**Description**
TP	mm	Total precipitation amount
WD	days	Number of wet days (≥ 1 mm)
SDII	mm day^{-1}	Simple daily intensity ($^{TP}/_{WD}$)
R10mm	days	Number of days with precipitation ≥ 10 mm
R20mm	days	Number of days with precipitation ≥ 20 mm
CDD	days	Maximum number of consecutive dry days (< 1 mm)
RX1day	mm	Maximum daily precipitation
RX5day	mm	Maximum 5-day precipitation

Table 3: Seasonal mean TP over the period 1981–2010 and largest RX1day and RX5day values on record (after homogenisation) for the analysed stations (values are in mm). The first column indicates the cluster to which the stations are assigned according to the distribution of RX1day and RX5day by season of occurrence (b = blue, r = red, g = green; see Fig. 2).

		Normals 1981–2010					**RX1day**		**RX5day**	
Cl	Abbr	DJF	MAM	JJA	SON	Year	Value	Month	Value	Month
r	BLZ	183	413	518	454	1568	217	08/1942	372	11/2002
r	BIV	192	290	385	337	1203	124	11/2002	308	11/2002
g	BRX	58	143	297	169	666	103	06/1924	138	06/1924
r	CAV	87	187	271	227	772	118	02/1986	220	09/1882
b	COR	136	229	355	319	1039	136	11/1987	227	11/1966
b	DOM	189	426	296	445	1355	248	08/1987	447	10/2000
r	BZG	73	160	256	203	692	112	02/1986	167	09/1888
r	LOM	209	492	572	574	1848	318	09/1991	483	09/1991
r	LUG	192	429	473	451	1545	241	08/1911	356	08/1911
r	MAR	99	131	248	193	671	89	08/1954	158	05/1983
b	PER	125	226	274	312	936	150	09/1960	302	09/1960
b	RIT	152	229	263	304	947	103	08/1933	202	11/1951
b	ROV	157	223	267	291	938	136	03/1898	279	09/1882
r	SIA	139	222	348	282	991	99	05/1981	251	11/2002
r	SOG	164	363	467	426	1420	137	09/1991	346	11/2002
b	SND	122	208	245	268	844	186	09/1988	235	09/1988
b	TIO	197	290	290	364	1141	138	11/2003	276	11/2002
b	TNL	135	224	260	303	923	121	02/1986	233	11/1951

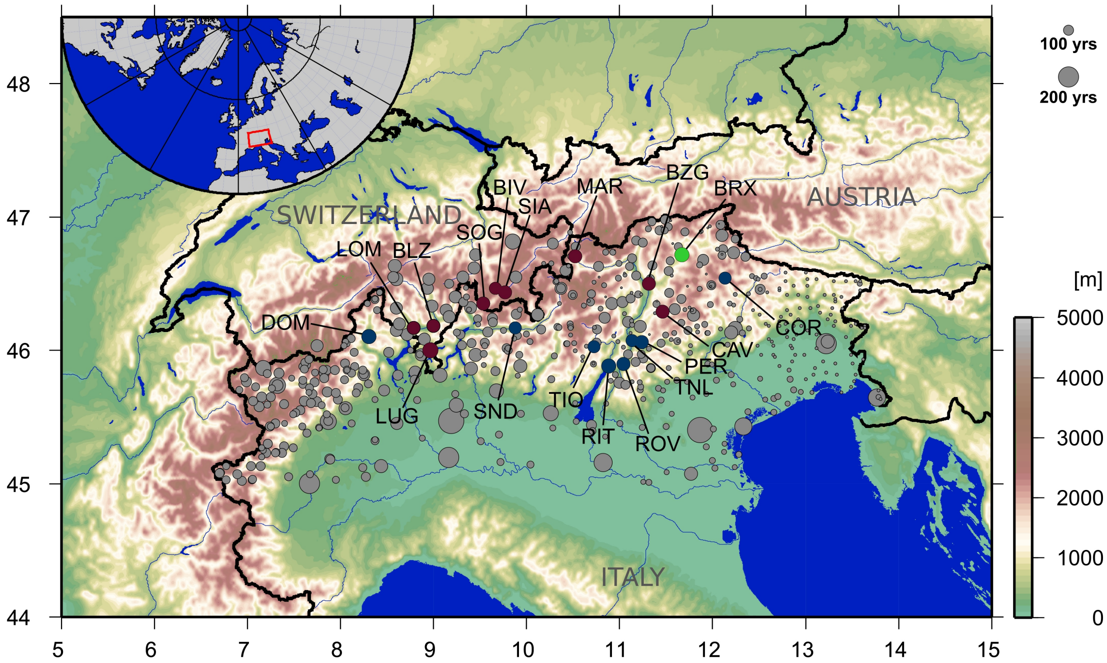

Figure 1: Map of the stations used in this work. Coloured points indicate the analysed series (the colours indicate the station clusters according to the distribution of RX1day and RX5day by season of occurrence, see Fig. 2), gray points indicate the additional reference series. The diameter of the points is proportional to the length of the series. The background colour scale represents elevation above mean sea level.

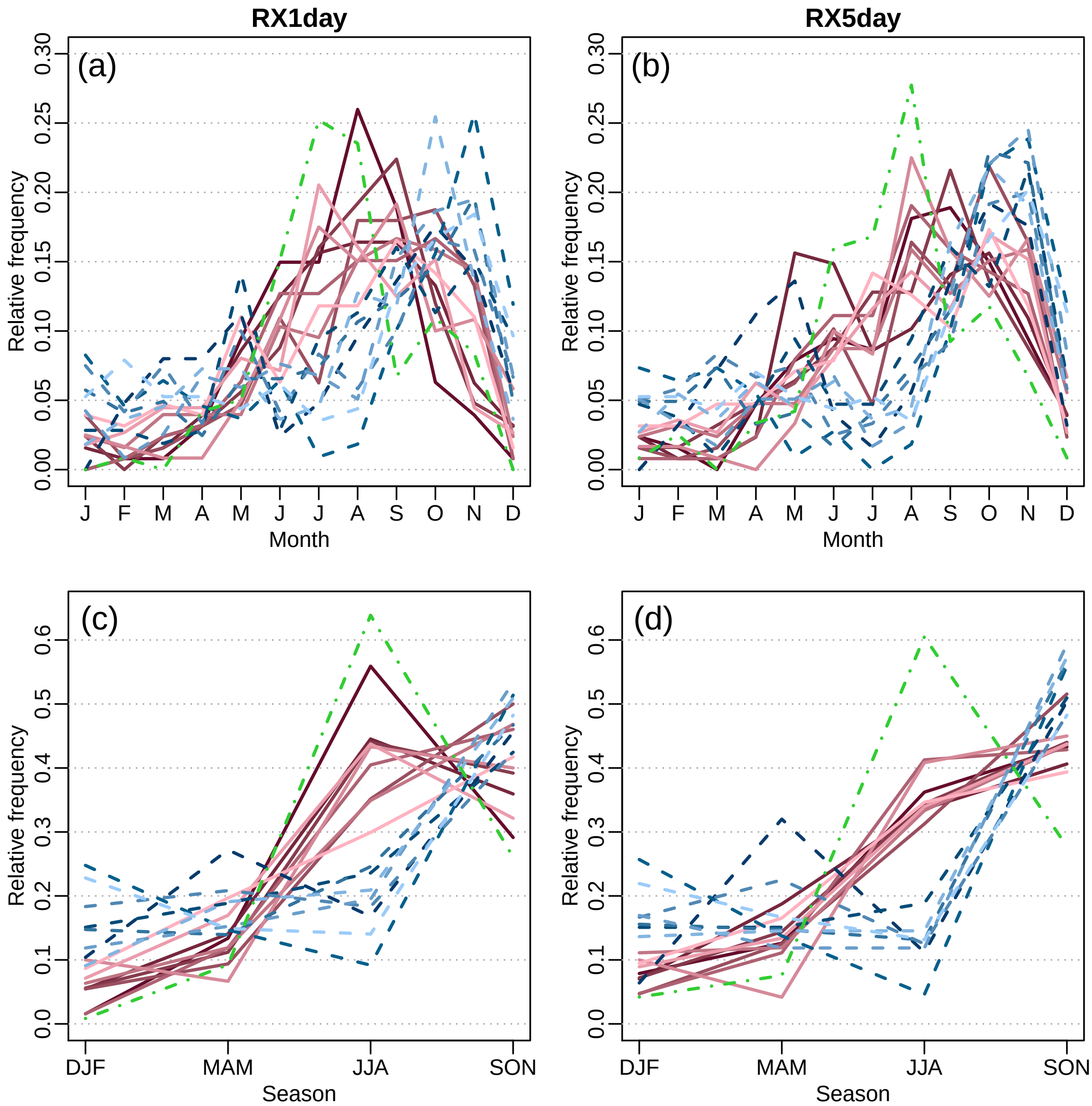

Figure 2: Distribution of RX1day (a, c) and RX5day (b, d) by month (a, b) and season (c, d) of occurrence. For RX5day the central day is considered. The colours identify the three main station clusters, the shade of the lines depends on the longitude of the stations (the darker the colour, the lower the longitude).

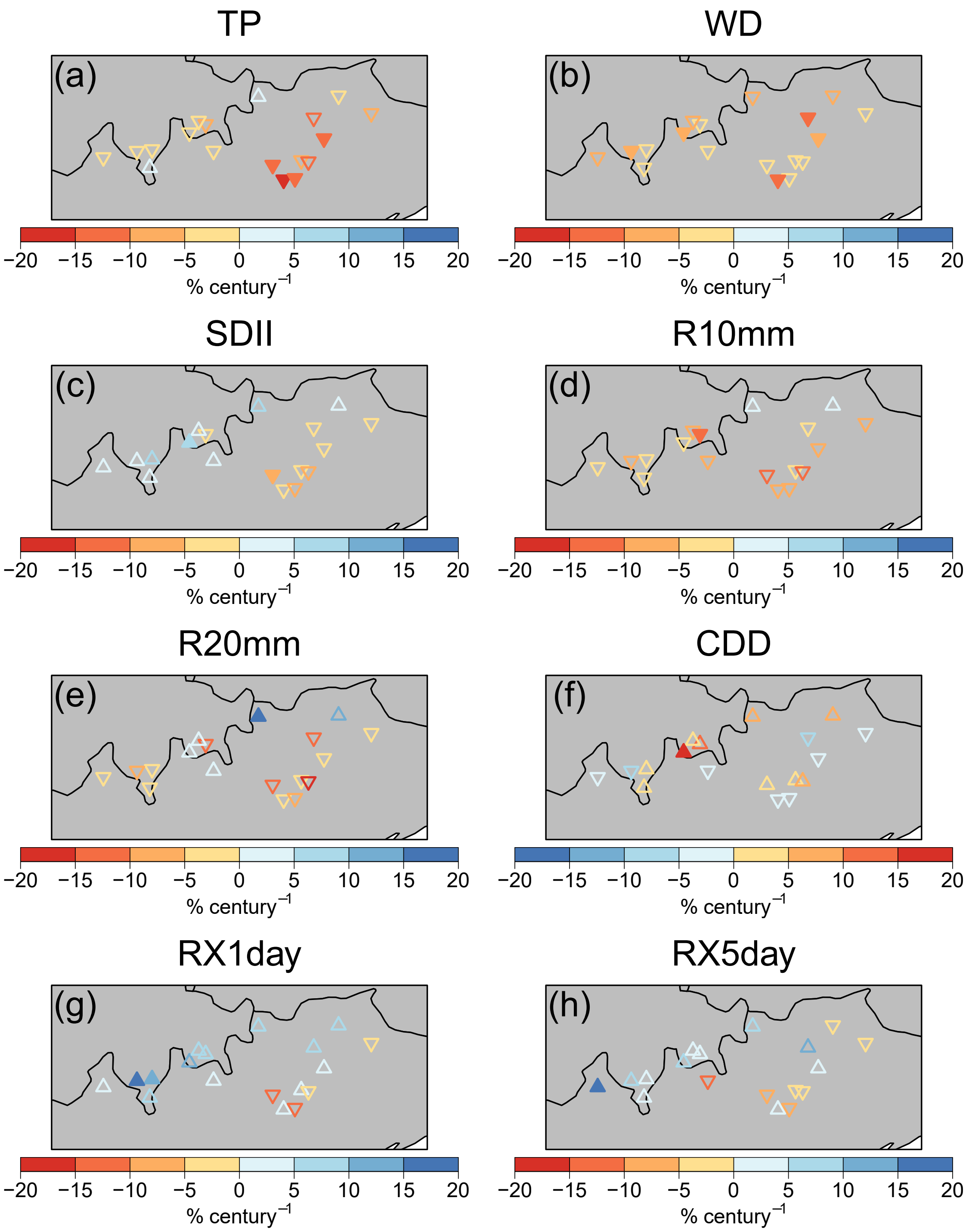

Figure 3: Annual linear trends over the period 1890–2017 for: (a) TP, (b) WD, (c) SDII, (d) R10mm, (e) R20mm, (f) CDD, (g) RX1day, (h) RX5day. Filled circles indicate significant trends.

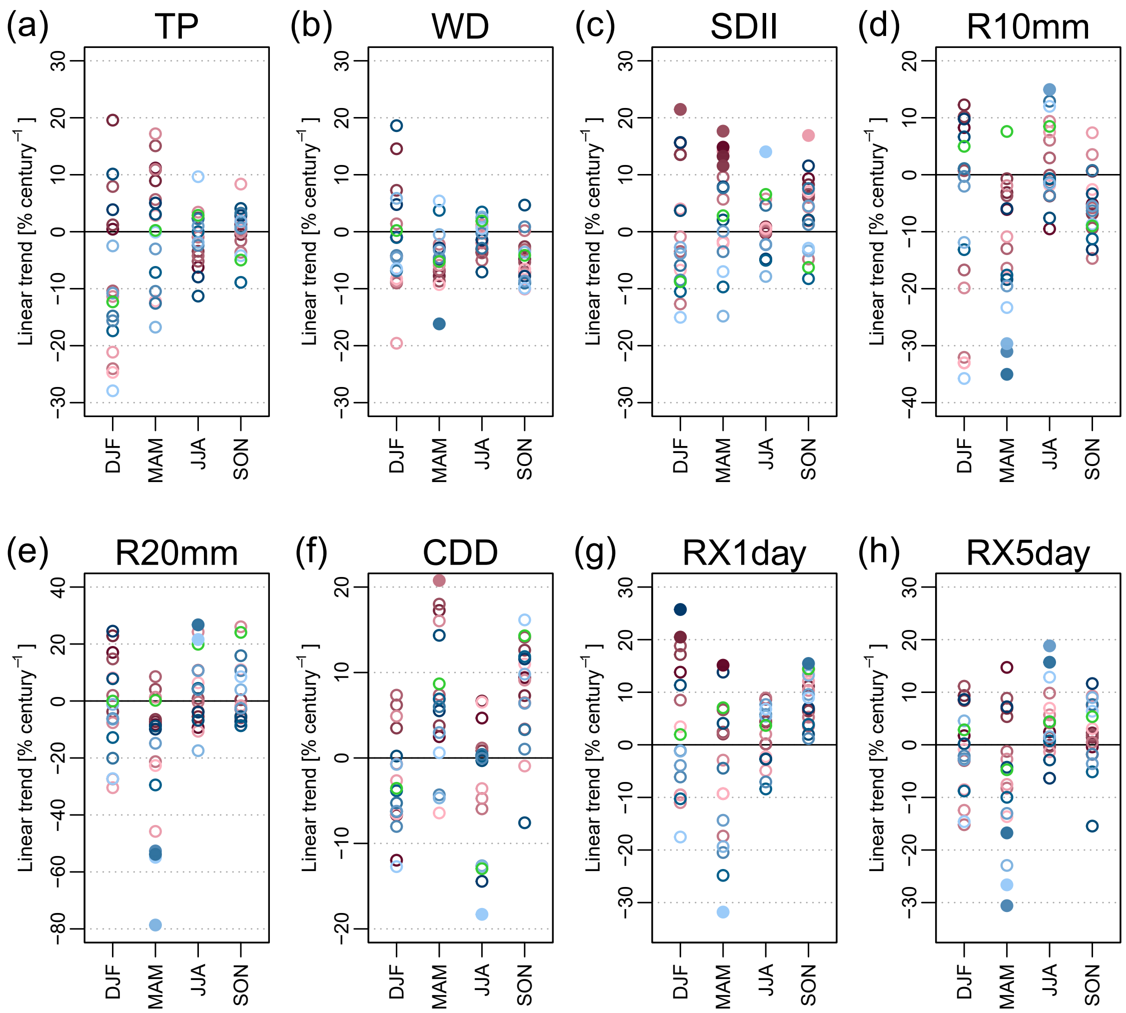

Figure 4: Seasonal linear trends over the period 1890–2017 for: (a) TP, (b) WD, (c) SDII, (d) R10mm, (e) R20mm, (f) CDD, (g) RX1day, (h) RX5day. Colours are as in Fig. 2, filled points indicate significant trends.

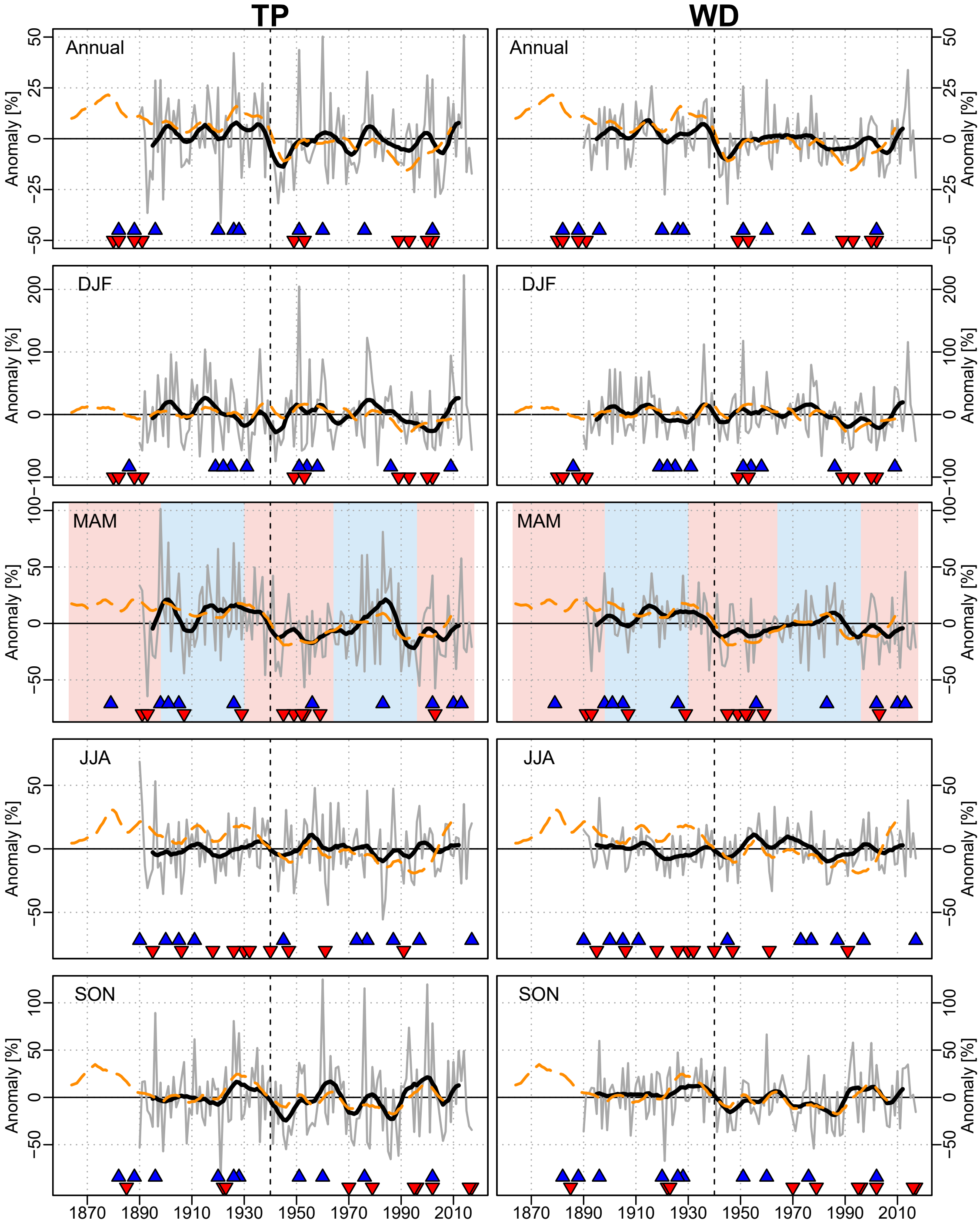

Figure 5: Annual and seasonal regional mean time series for TP (left) and WD (right), in the form of anomalies with respect to the period 1901–2000. The black lines show the low frequency variability (11-year Gaussian filter with $\sigma = 3$ years), the orange lines represent the number of days characterised by either the WSW, N, or WC weather type as defined by Schwander et al. (2017). The blue triangles indicate the 10 years in the period 1878–2017 with the highest regional RX5day; the red triangles similarly indicate the 10 years with the highest regional CDD. In the spring season panels, red and blue backgrounds indicate the periods with positive and negative phase of the AMO, respectively. The vertical dashed line marks the year 1940.

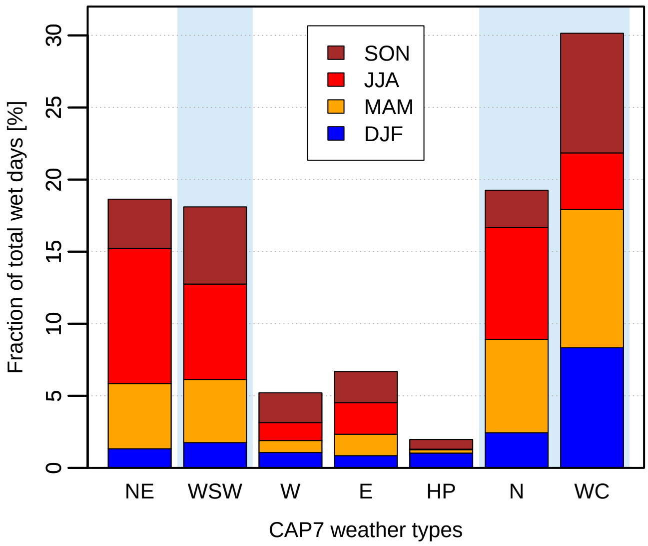

Figure 6: Distribution of WD by weather type and season, when considering data from all stations over the period 1890–2017 (the sum of the bars is 100%). The blue background indicates cyclonic weather types. For the definition of the weather types the reader is referred to Schwander et al. (2017).

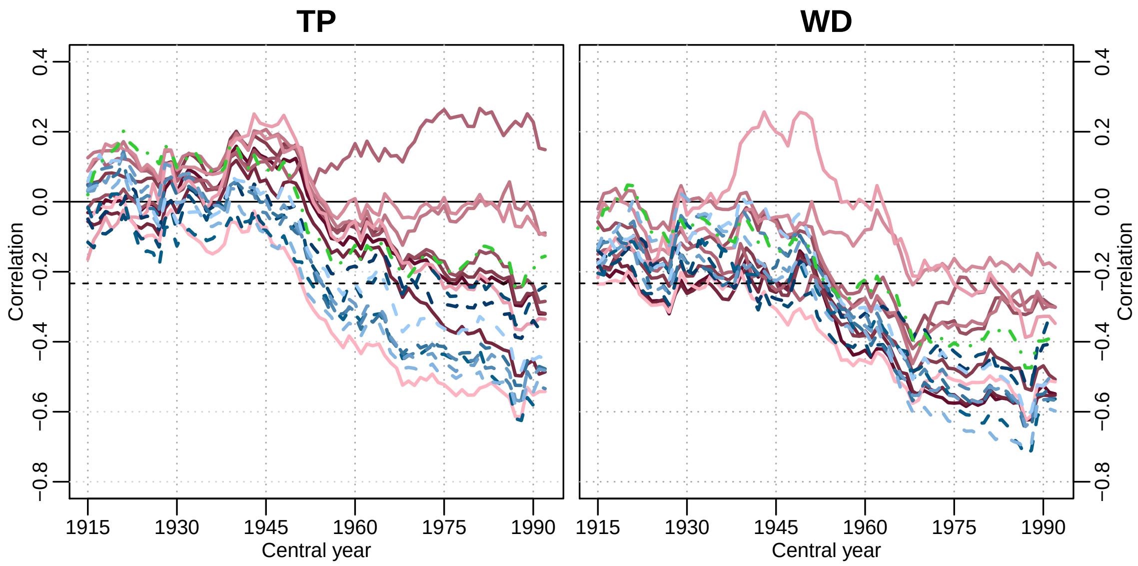

Figure 7: 51-year running Spearman correlation coefficient between winter precipitation and the winter NAO index. The dashed line represents the average 5% significance level of 18 one-tailed permutation tests (one for each series). Colours are as in Fig. 2.

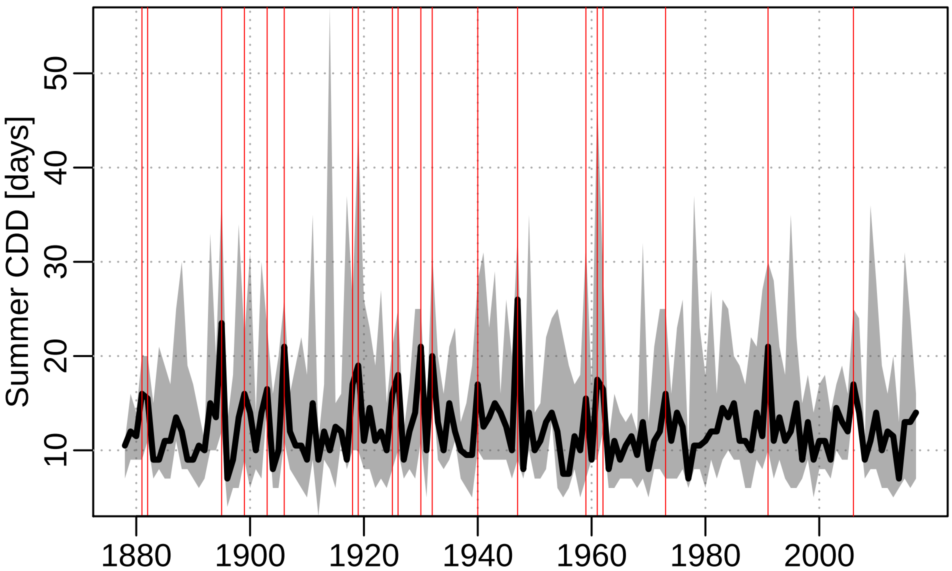

Figure 8: Median of CDD when considering summer months only (JJA). The gray shading encompasses the values of all stations, the red vertical lines indicate values > 15 days.