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Discussions

Trends and variability in extreme precipitation indices over Maghreb countries

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Abstract

Maghreb countries located in North Africa are highly vulnerable to extreme hydrological events, such as floods and droughts, driven by the strong variability of precipitation. While several studies have analyzed the presence of trends in precipitation records for the Euro-Mediterranean Basin, this study provides the first regional assessment of trends on its southernmost shores. A database of 22 stations located in Algeria, Morocco and Tunisia with between 33 and 59 yr of daily precipitation records is considered. The change points and trends are analyzed for eleven climate indices describing several features of the precipitation regime. The issue of conducting multiple hypothesis tests is addressed through the implementation of a false discovery rate procedure. The spatial and inter-annual variability of the precipitation indices at the different stations are analyzed and compared with large scale atmospheric circulation patterns, including the North Atlantic Oscillation (NAO), Western Mediterranean Oscillation (WEMO), Mediterranean Oscillation (MO) and El Niño Southern Oscillation (ENSO). Results show a strong tendency towards a decrease of precipitation totals and wet days together with an increase in the duration of dry periods, mainly for Morocco and western Algeria. On the opposite, only a few significant trends are detected for heavy precipitation indices. The NAO and MO patterns are well correlated with precipitation indices describing precipitation amounts, the number of dry days and the length of wet and dry periods, whereas heavy precipitation indices exhibit a strong spatial variability and are only moderately correlated with large scale atmospheric circulation patterns.

1 Introduction

Maghreb countries (Algeria, Morocco and Tunisia) in Northern Africa are vulnerable to extreme hydrological events such as floods and droughts. Like other Mediterranean countries they are prone to violent flood episodes caused by torrential rainfall, usually catastrophic with a very high number of casualties (Llasat et al., 2010). The deadliest events that occurred in the three countries during the last 50 yr were the 2001 flood near Algiers (Algeria) that caused more than 700 fatalities (Argence et al., 2008), the 1969 floods in the region of Kairouan (Tunisia), with between 150 and 400 fatalities (Poncet, 1970; Guillaud and Trabelsi, 1991) and the 1995 flood in the Ourika valley (Morocco) with over than 200 fatalities (Saidi et al., 2003). On the opposite, the strong inter-annual variability of precipitation, which is one of the most important feature of the Mediterranean climate (Lionello, 2012), is also causing dry spells of varying length threatening the water resources in these countries. Since the last two decades, there is a growing awareness about these extreme events (Bouaicha and Benabdelfadel 2010), and a questioning about the possible increase in their intensity or occurrence (Douglas et al., 2008). In particular for floods, as a significant increase in the vulnerability of the populations was observed in Maghreb countries during the last decades (Fig. 1), similar to what observed in the whole African continent by Di Baldassarre et al. (2010).

In the Maghreb region, there is limited data coverage and most of the rivers are regulated for either water resources or flood protection. Therefore, daily precipitation data is an interesting proxy to analyze long terms trends and variability of precipitation that are causing floods or drought periods. Several studies have analyzed the regional precipitation trends in large datasets over Europe (Moberg and Jones, 2005), West Africa (Servat et al., 1999) or South Africa (New et al., 2006) during the last decades. However no such regional trend analysis exists for North Africa, yet one of the most vulnerable regions of the Mediterranean Basin (Schilling et al., 2012). Previous research on precipitation in Maghreb countries has mainly focused on the inter-annual variability and the relationships with large-scale circulation such as the North Atlantic Oscillation (NAO) or El Niño Southern Oscillation (ENSO), for water resource management purposes (El Hamly and Sebbari, 1998; Kingumbi et al., 2005; Knippertz et al., 2003; Driouech et al., 2010; Mebarki, 2010; Meddi et al., 2010; Ouachani et al., 2013). Indeed, several studies have shown that precipitation in the Mediterranean Basin is influenced by local characteristics, such as elevation and topography (Hidalgo-Muñoz et al., 2011; Acero et al., 2011; Lionello, 2012), but also by large scale circulation such as the NAO (Xoplaki et al., 2004; Mariotti and Dell'Aquila, 2012; Angulo-Martínez and Beguería, 2012), the MO (Conte et al., 1989), the WEMO (Martín-Vide and Lopez-Bustins, 2006) and ENSO (Meddi et al., 2010; Ouachani et al., 2013). Meddi et al. (2010) observed a decrease in precipitation totals in northwest Algeria after 1970 related to the ENSO index. In Morocco, very dry years have been also observed after 1970, in relation with positive NAO anomalies (El Hamly et al., 1998; Knippertz et al., 2003). Tramblay et al. (2012) noted the absence of trends in annual maximum precipitation in Morocco and the dependence of annual maximum precipitation in some stations with the NAO and Mediterranean Oscillation (MO) indexes. In Tunisia Kingumbi et al. (2005) reported a reduction of annual rainfall between 1976 and 1989 and Ouachani et al. (2013) observed a link between precipitation variability and the ENSO index.

For the Mediterranean Basin, several studies observed an increase in the occurrence and the severity of droughts (Sousa et al., 2011; Hoerling et al., 2012). However in the western part of the Mediterranean Basin, precipitations do not show a homogeneous tendency in the last decades. Alpert et al. (2002) reported an increase in heavy precipitation in Italy and Spain but Toreti et al. (2010) observed for six locations in France, Italy, Greece, and Cyprus a negative trend towards a decrease of the number of heavy precipitation events. Reiser and Kutiel (2010) found no significant trends in precipitation indices in 40 sites across the Mediterranean Basin, with the notable exception of Algier (Algeria) were they observed a decrease in the number of rain spells and total precipitation. In Spain, several studies observed a general decrease in annual precipitation, in the number of rainy days, precipitation intensity and an increase in the duration of dry spells. On the contrary, the frequency of heavy rainfall events and their contribution to annual precipitation events did not change at most observatories, or showed a decreasing trend (Lopez-Moreno et al., 2010; Rodrigo, 2010; Gallego et al., 2011). However, Hidalgo-Muñoz et al. (2010) and Acero et al. (2011) reported positive trends in the heavy rainfall event's magnitude over the south-eastern Mediterranean

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coast, corresponding to the region of Andalusia. In Italy, Brunetti et al. (2004) reported a decrease in wet days associated with an increase in precipitation intensity and Bonaccorso et al. (2005) or Caloiero et al. (2011) observed in southern Italy negative trends in winter rainfall amounts and in annual maximum daily precipitation. In the south of Portugal, Costa and Soares (2009) noted an increase in the length of dry spells but no significant trends in heavy precipitation. Similarly, in southern France Pujol et al. (2007) or Tramblay et al. (2013) did not detect changes or trends in heavy rainfall events during the last 50 yr.

The main objective of this study is to analyze the trends in precipitation during the last 50 yr, with a focus on extreme dry and wet events, in long time series of precipitation in Maghreb countries. It is necessary to distinguish the possible climate change signal from the observed increased vulnerability, in order to improve the mitigation and adaptation strategies. In addition to the trend detection, the dependence of different precipitation characteristics with large scale atmospheric circulation is also analyzed, in an attempt to characterize their variability. The two main questions addressed by this study are: (i) is the stationary hypothesis valid on the long term for different precipitations indices? and (ii) can the observed interannual variability be explained by large scale circulation, such as the NAO, WEMO, MO or ENSO? The trend analysis and the dependences with large scale atmospheric circulation are investigated using robust statistics, taking into account the serial and cross correlations in the dataset and also the issue of repeating multiple statistical tests. The following section describes the different datasets considered for this study. The Sect. 3 details the statistical tests applied to the precipitation data and the Sect. 4 presents the results.

2 Study area and datasets

In the present study are considered the long daily precipitation series maintained by the governmental hydrological services of Algeria, Morocco and Tunisia, who are in charge of dams and all the water regulation structures (Fig. 2). The precipitation data have been provided by the hydrological services of Algeria (Agence Nationale des Resources Hydrauliques, ANRH), Morocco (Direction de la Recherche et de la Planification de l'Eau, DRPE), and Tunisia (Direction Générale des Ressources en Eau, DGRE). The longest data series available between 1950 and 2009 have been provided; these stations are usually located near dams, reservoirs, or other water regulation structures. They are routinely used to estimate the return levels for extreme precipitation as well as to evaluate the inter-annual water resources availability. The daily data form the Melilla station (Spain) located in North Morocco was downloaded from ECA&D, the data and metadata is available at http://eca.knmi.nl.

The raw data record went under a data quality control procedure, to check for missing data records and measurements errors such as the reporting of unfeasible precipitation values. Each station data has been carefully manually scrutinized, in particular to look for obvious breaks, absurd values and missing data by visual inspection. The stations that were subsequently selected did not have more than 5 % missing days between September and May. The years with more than 5 % missing days during this period have been removed. In the whole area, there is a strong seasonality signal with most of the precipitation during late fall and winter. The summer months of June, July and August are not considered in the analysis since there is almost no precipitation during these months in all the stations and they have a very large number of missing data. After this quality check, 22 stations were selected in the three countries (Table 1). The median length of records is 45 yr, with complete data in almost all of the stations between 1970 and 2002 (Fig. 3). Most stations are located in the northern part of Africa, the rainiest and most populated area. As shown on the map of flood events together with the stations (Fig. 2), this is the area where several major flood events have been reported between 1984 and 2012. Therefore it is important to assess the stationarity of precipitation extremes over time, a feature that is very important and useful for water resources management.

In addition, different climatic indexes have been considered in an attempt to explain the observed interannual variability of precipitation. They include the NAO (Hurrell,

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1995), MO (Conte et al., 1989), WEMO indexes (Martín-Vide and Lopez-Bustins, 2006). These indexes have been computed from daily sea level pressure grids by Angulo-Martínez and Beguería (2012). The North Atlantic Oscillation index (NAOi) was calculated as the normalized difference between time series of sea level pressure recorded at two points in the southwest Iberian Peninsula (Gibraltar, 35° N, 5° W) and southwest Iceland (Reykjavik, 65° N, 20° W). The MOi, as defined by Palutikof (2003), was calculated as the daily normalized difference between the SLP at Gibraltar (35° N, 5° W) and Lod, Israel (30° N, 35° E). The WEMOi was calculated as the daily normalized difference between the SLP at Gibraltar (35° N, 5° W) and Parma (45° N, 10° E). For the ENSO, since different versions of the index exist (Ouachani et al., 2013), here is considered the Multivariate ENSO Index (MEi) proposed by Wolter and Timlin (2011) and available online at http://www.esrl.noaa.gov/psd/enso/mei/. The MEi integrates more information than other ENSO indices and it better reflects the nature of the coupled ocean-atmosphere system in the ENSO phenomenon.

3 Methodology

3.1 Precipitation indices

In this study are considered different precipitation indices, similar to those of ETCCDI (Klein Tank et al., 2002; New et al., 2006 and http://http://etccdi.pacificclimate.org/). The selected indices include:

1. The total precipitation (PRCPTOT).
2. The ratio of wet days (R1 mm).
3. The simple daily precipitation intensity (SDII).
4. The Annual maximum precipitation (RX1day).
5. The 95th percentile of daily precipitation (Prec95p).

6. Fraction of the annual total precipitation above Prec95p (R95pTOT).

7. The maximum length of dry spells (CDD).

8. The mean length of dry spells (CDDm).

9. The maximum length of wet spells (CWD).

10. The mean length of wet spells (CWDm).

11. Number of events above Prec95p (R95p).

The indices have been computed for wet days, i.e. when the daily precipitation is exceeding 1 mm during the hydrological years (from September to May). The R1 mm and PRCPTOT indices are not strictly describing extreme precipitation, however they are frequently used to assess the homogeneity of precipitation data series (Wijngaard et al., 2003), and this is the reason why they are included in the analysis. Figure 4 show the box plots of these two variables together with the annual maximum precipitation. The most striking feature in all the stations is the strong interannual variability of precipitation, with great variations in precipitation amounts and extremes depending on the year.

A temporal declustering scheme has been adopted for the computation of the R95p to ensure the independence of consecutive threshold exceedances (Tramblay et al., 2013). Indeed the trend and change point results could be questioned if the observations are dependent (Khaliq et al., 2009) i.e. if several days that are in fact belonging to the same extreme event are considered in analysis. On average, the number of consecutive days exceeding the threshold of Prec95p in all the stations is 1.73 days (maximum 2.18 and minimum 1.37). Therefore a minimum of 2 days in between consecutive threshold exceedances is adopted for the computation of R95p in each station. Thresholds above the 95th percentiles have been also tested (for example the 99th percentile) however due to the strong interannual variability they lead to a very low annual number of threshold exceedances that are concentrated only on a few years. Consequently, thresholds above the 95th percentile are not considered in the present study.

3.2 Pettitt test for change points

There is no homogeneity correction method specifically designed for daily precipitation time series and no consensus about the best method to use (Beaulieu et al., 2007; Toreti et al., 2010). However, homogeneity is a crucial aspect when dealing with trend detection or temporal analysis. If the monotonic trends are likely caused by long term climate change, step changes in precipitation series may be considered doubtful and possibly caused by station relocation or changes in the station instrumentation. The Pettitt (1979) test is able to detect potential change points in the mean of time series; it has been widely used with precipitation data (Servat et al., 1999; Klein Tank et al., 2002; Wijngaard et al., 2003; Beaulieu et al., 2007; Villarini et al., 2011). To test the null hypothesis H_0 of "no change in the mean of the series tested", the statistical significance of the test is computed using the approximate limiting distribution for continuous distributions provided by Pettitt (1979).

3.3 Mann–Kendall test for trends

The Mann–Kendall (MK) test (Mann, 1945) is used for the trend detection. For large sample sizes, Mann and Kendall have documented that the test statistic S is approximately normally distributed. The null hypothesis H_0 for the test is "there is no trend in the time series". Several studies have shown that the presence of serial correlation in the data may affect the results of trend analysis by increasing the variance of S (Douglas et al., 2000; Khaliq et al., 2009; Renard et al., 2008). Hamed and Rao (1998) proposed correcting the variance of the MK test statistic S by using an effective sample size that reflects the effect of serial correlation. This correction was applied in the present study, with the serial correlation estimated from the detrended series as recommended by Yue and Wang (2004). Khaliq et al. (2009) have shown that this

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approach is able to handle not only the Autoregressive of order 1 structure (AR(1)) but also higher order serial dependencies.

In addition the method of Sen (1968) is considered to estimate the magnitude of the slope of detected trends:

$$b_{sen} = \text{Median}\left[(Y_i - Y_j)/(i - j)\right] \quad (1)$$

where Y_i and Y_j are data points i and j. With N values in the time series, there is as many as $n = N(N-1)/2$ slope estimates and b_{sen} is the median of these n values.

3.4 Correlations with atmospheric circulation indices

The correlations between the precipitation indexes and large scale indicators are investigated by means of the nonparametric Spearman's (1904) test. It is a special case of the Pearson's correlation coefficient, in which the data are replaced by their ranks. This test is well suited for monotonically related variables, even when their relationship is not linear, as it is required in the case of Pearson's correlation coefficient. The null hypothesis H_0 for the test is "there is no correlation in between the two variables".

3.5 False discovery rate and field significance of trend results

The significance level, α, for a statistical test is the probability of committing Type I error, i.e. rejecting the null hypothesis when it is true. Nevertheless, this probability is related to a single test and is no longer valid when multiple tests are conducted (Livezey and Chen, 1983; Ventura et al., 2004). Consequently, as the number of tests being conducted increase, more significant values are found. The p values of different independent tests follows a binomial distribution with sample size n and the probability of correctly accepting the null hypothesis is $1 - \alpha$. The purpose of the False Discovery Rate (FDR) procedure (Benjamini and Hochberg, 1995) is to identify a set of at-site significant tests by controlling the expected proportion of falsely rejected null hypotheses that are actually true (Renard et al., 2008; Khaliq et al., 2009).

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In addition to the issue of repeating several times the same statistical test, the presence of cross-correlation may also affect the test results, by artificially increasing the number of significant trends, and consequently it requires field significance testing (Douglas et al., 2000; Pujol et al., 2007). Field significance testing allows the determination of the percentage of tests that are expected to show a trend, at a given local significance level, purely by chance. Wilks (2006), Renard et al. (2008) and Khaliq et al. (2009) demonstrated that the original FDR procedure of Benjamini and Hochberg (1995) is robust to positive cross correlations and can work with any statistical test for which one can generate a p value.

Therefore the FDR procedure of Benjamini and Hochberg (1995) is used here to identify the stations where the statistical tests results are field significant: consider testing H_1, $H_2, \ldots H_m$ based on the corresponding p values P_1, $P_2, \ldots P_m$. Let $P_{(1)} \leq P_{(2)} \leq \ldots \leq P_{(m)}$ be the ordered p values and denotes by $H_{(i)}$ the null hypothesis corresponding to $P_{(i)}$. Let k be the largest i for which:

$$P_{(i)} \leq \frac{i}{m}\alpha_{\text{global}} \tag{2}$$

Then reject all $H_{(i)}$ for $i = 1, 2, \ldots k$.

α_{global} is the global significance level, it is set here to 0.05, the same as the local confidence level considered for the Pettitt, Mann–Kendall and Spearman tests. The field significance is declared by this method when at least one null hypothesis is rejected at the global significance level.

4 Results

4.1 Serial and cross correlations

The presence of autocorrelation in time series may affect the change point (Beaulieu et al., 2012) or trend detection test results (Douglas et al., 2000; Khaliq et al., 2009)

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by increasing the possibility of the null hypothesis to be rejected. Consequently, the presence of lag-1 autocorrelation in the time series of the different indices is first tested. Results indicate that a very limited number of stations exhibit an autocorrelation signal, only in Berkane and Tanger for R1 mm and in Rechaiga for PRCPTOT. In all cases, it is a significant positive lag-1 autocorrelation. The indices of extremes such as RX1day, Prec95p or CDD do not exhibit any serial correlations. Therefore, there is a very limited influence of autocorrelation in the present analysis.

To evaluate the spatial structure of dependence of the different precipitation indices, for each of the 11 indices a cross-correlation matrix was build for the period 1970–2002, when most stations have complete years. There are significant cross correlations for most indices, with higher correlations among the stations for PRCPTOT, R1 mm and CDDm by comparison with heavy precipitation indices (RX1day or Prec95p). The spatial correlations for the different indices have been also analyzed with climatological variograms (Bastin et al., 1984). For each index and each year between 1970 and 2002, a variogram scaled by the variance of the field is computed. The mean variogram obtained for each precipitation index is then fitted with a spherical model, which is a convenient tool for precipitation kriging since it provides a value of the decorrelation distance, given by the value of the range (Lebel and Laborde, 1988). The climatological variograms are presented in Fig. 5. Overall, while the indices describing intense precipitation (SDII, RX1day, Prec95p, R95pTOT, R95p) show high temporal and spatial variability, with ranges less than 150 km, the indices describing rainfall amounts or the duration of dry and wet periods (PRCPTOT, R1 mm, CDD, CDDm, CWD, CWDm) exhibit less temporal variability and a much greater decorrelation distance, up to 350 km for R1 mm and CDDm.

Significant correlations also exist between the different precipitation indices. The mean PRCPTOT and the mean R1 mm at the different stations are well positively correlated, with $\rho = 0.93$ between the two variables. There is also a strong correlation between the annual precipitation totals (PRCPTOT) and annual daily maximums (RX1day). The Spearman correlation coefficient between the two variables is significant

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at the 5 % significance level in every station, with an average value $\rho = 0.58$ (with minimum and maximum values respectively of 0.36 and 0.86). The correlation coefficient is itself an inverse function of the mean annual precipitation, with highest values for stations with low annual precipitation. For the most arid stations where the mean annual precipitation is below 200 mm (Gabes and Gafsa), the annual maximum daily precipitation can represents up to 25 % of the annual precipitation totals. When considering the fraction of the annual total precipitation above the 95th percentile, this ratio rises up to 58 % of the annual totals. The same ratio was observed by Toreti et al. (2010) in the Euro-Mediterranean region.

4.2 Change points and trends

The presence of change points, indicating possible homogeneity breaks, has been tested with the Pettitt test. A special focus is put on the PRCPTOT and R1 mm indices, since they are often used to check the homogeneity of precipitation data (Wijngaard et al., 2003). In cases when both a significant monotonic trend and a change point are detected, the Pettitt test is applied on the detrended series, since the presence of a monotonic trend could lead to the false detection of a change point. To remove the trends, the least-squares fit of a straight line to the data is computed and the resulting function is subtracted from the data. For PRCPTOT and R1 mm this procedure has been applied to the stations of Rechaiga, Ponteba Bab Ouender, Beni Mellal, El Kansera and Larache where a monotonic trend was present. For the two indices, the smallest local p value (0.05) is obtained for R1 mm at the Berkane station, yet non significant at the 5 % level. Therefore no significant change points are detected and the hypothesis of homogeneity is valid for all the stations selected. The same conclusion holds true for the other indices.

The trend test results are presented in Table 2, showing the Sen slope estimates for each station and each index, if local or global trends are significant. As expected by the FQR approach, there are fewer significant trends at the global significance level (in bold) than at the local significance level. There is a strong evidence of

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a global drying tendency in most of the stations. The trends are more pronounced in the western part of the study area, including Morocco and West Algeria (Fig. 6). The trend test results indicate an increase of the number of dry days (R1 mm), the duration of dry spells (CDD, CDDm) a decrease of precipitation totals (PRCPTOT) and of the duration of precipitation episodes (CWD, CWDm). In particular, field significant trends at the global level are identified for R1 mm in 9 stations, out of 11 with local significant trends, for CDDm in 8 stations and for PRCPTOT in 5 stations (Table 2). On the opposite, fewer significant trends are detected for heavy precipitation indices. However, in several stations there is a negative Sen slope for these indices, indicating a decrease in precipitation intensity (SDII), annual maximum precipitation (RX1day), in the 95th percentile of precipitation (Prec95p) and in the relative part of the heavy precipitation events in annual precipitation totals (R95pTOT). For the annual maximum precipitation, there is a significant trend towards a decrease only for the Rechaiga station (Table 2). Therefore, the hypothesis of stationarity for annual maximums is valid for most stations (Fig. 7). There are a few stations with a negative tendency in the probability of observing a heavy rainfall event (R95p), as observed in other parts of the Mediterranean Basin by Toreti et al. (2010). However the only station for which field significance at the 5 % level is achieved is Rechaiga. These trend results are consistent with those obtained in Algiers by Reiser and Kutiel (2010).

4.3 Relationships with large scale circulation indices

The correlations between the different precipitation indices and the NAOi, WEMOi, MOi and MEi have been analyzed. The presence of trends may affect the correlation analysis and since the focus here is on the co-variability of the different precipitation and large scale circulation indices, the indices have been detrended if a significant trend was present. This is the case of the NAOi and MOi, which are showing a long-term positive trend in particular since the 1970s (Mariotti and Dell'Aquila, 2012). Different time aggregation periods for the computation of the climate indices have been tested. When considering annual averages of the large scale circulation indices (from

September to August), almost no significant correlations with precipitation indices are found. The largest number of significant correlations is obtained when considering extended winter season (from November to March) averages of the NAOi, WEMOi, MOi and MEi. The results are presented in Fig. 8, showing for each precipitation indices the number of local and global significant correlations with the different climatic indices. The PRCPTOT and R1 mm indices and to a lesser extend SDII, CWD and CWDm, show significant correlations with NAOi and MOi. For PRCPTOT and R1 mm the correlations with NAOi or MOi are significant in almost half of the stations (Fig. 9), mostly in Morocco (Bab Ouender, Mjaara, Beni Mellal, El Kansera, Larache, Tanger stations), Algeria (Ponteba station) but also in Tunisia with the MOi (Jendouba, Tunis stations). On average, the mean Spearman correlation coefficient between PRCPTOT at the different stations and NAOi is equal to −0.51 and −0.47 with the MOi. For R1 mm, the average correlation coefficient with NAOi is −0.5 and −0.48 with MOi.

On the contrary, heavy precipitation indices such as RX1day, Prec95p or R95pTOT are not strongly correlated with large scale circulation indices. Only a few field-significant correlations with the NAOi are detected for these indices, mainly in Morocco (Larache, Mjaara, Bab Ouender). It must be noted that similar correlation results have been obtained when averaging the different atmospheric indices from November to March or from December to February, indicating the robustness of the signal during the extended winter season. Born et al. (2010) previously noted that large scale variability, caused by the NAO or ENSO, controls Moroccan rainfall variability towards a detectable but relatively small range. Thus, they concluded that one should not expect these indices to deliver sufficient results for an assessment of seasonal rainfall prediction. A reasonable part of rainfall variability remains stochastic and can only be assessed by applying more complex atmospheric climate or weather prediction models (Born et al., 2010).

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5 Conclusions

This study provides the first assessment of trends in precipitation indices at the regional scale over Maghreb countries. Several precipitation indices describing precipitation amounts, heavy rainfall, and the duration of dry and wet periods have been computed for 22 stations having long data records of daily precipitation. There is a strong temporal and spatial variability, in particular for the indices describing the heavy precipitation events. On the opposite, the indices representing precipitations amounts or dry periods, such as the number of dry days or the duration of dry spells, show a greater spatial consistency, indicating that droughts periods are simultaneously impacting large areas when they occur. The influence of autocorrelation is found to be limited in the present analysis but several indices show significant cross-correlations among stations indicating the need to assess the field significance of trend results. The trend analysis indicates an increase of the dry episodes duration and magnitude, together with a decrease in the number of wet days and annual precipitation. For the heavy precipitation events there is no such a strong signal towards a decrease or an increase, therefore the hypotheses of stationarity remain valid in most stations. These trends are significant at the regional scale and mostly affect Algeria and Northern Morocco, when only a few local trends are detected in Tunisia. The detected trends for northern Africa are consistent with those found in other studies across the Mediterranean region (Brunetti et al., 2004; Costa and Soares, 2009; Meddi et al., 2010; Reiser and Kutiel, 2010; Caloiero et al., 2011; Schilling et al., 2012).

The precipitation indices considered in this study only show a moderate correlation with the various large scale circulation indices considered. There is a dependence of annual precipitation or wet day's frequency with NAO and MO indices in almost half of the stations, but a very little correlation signal with the indices representing the heavy rainfall events magnitude or occurrence. Since heavy precipitation also exhibit a strong spatial variability among the different stations, it is hypothesized that these extreme events are more influenced by local climatic processes and topography. Although some spatial patterns for the different precipitation indices could be identified in the present analysis, to identify homogeneous regions there is a need to include more stations, even with shorter record length. These regional approaches could be useful to better analyze the influence of large scale atmospheric circulation or to build robust downscaling methods for the assessment of future climate change impacts.

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Table 1. Stations with precipitation data (the full years are those with less than 5 % missing data during the hydrological year).

ID	Name	Country	Altitude (m)	Beginning	End	Number of full years
1	Rechaiga	Algeria	830	1948	2005	39
2	Alger	Algeria	140	1951	2005	46
3	Ain Arnat	Algeria	1100	1970	2005	37
4	Bouhadjar	Algeria	0	1945	2005	37
5	Ghrib	Algeria	460	1968	2005	36
6	Ponteba	Algeria	140	1968	2005	38
7	Bab Ouender	Morocco	312	1956	2006	44
8	M'jaara	Morocco	96	1958	2006	45
9	Beni Mellal	Morocco	537	1950	2007	54
10	Berkane	Morocco	160	1959	2006	44
11	El Kansera	Morocco	100	1950	2006	44
12	Homadi	Morocco	230	1950	2004	46
13	Tamalaht	Morocco	275	1970	2005	34
14	Larrache	Morocco	5	1942	2011	49
15	Tanger	Morocco	5	1972	2006	33
16	Mellila	Morocco	47	1907	2009	46
17	Gabes	Tunisia	4	1950	2009	57
18	Gafsa	Tunisia	300	1950	2009	58
19	Jendouba	Tunisia	143	1950	2009	59
20	Kairouan	Tunisia	55	1950	2009	58
21	Ksour	Tunisia	720	1950	2009	49
22	Tunis	Tunisia	66	1950	2009	58

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Table 2. Sen slope estimates for each station and each indices, when the trend is significant at the local 5 % level. Among them, the field-significant trends at the global 5 % level are in bold.

Stations	R1 mm (%)	PRCPTOT (mm)	SDII (mm day^{-1})	RX1day (mm)	Prec95p (mm)	R95pTOT (%)	CDD (days)	CDDm (days)	CWD (days)	CWDm (days)	R95p (days)
Rechaiga	**−0.0023**	**−4.9667**		**−0.4615**	−0.1604	**−0.0019**		**0.15441**	**−0.0455**	−0.00635	**−0.0625**
Algier		−4.5793									−0.0385
AinArnat					0.2110						
Bouhadjar	**−0.0023**						**0.5**	**0.07902**	−0.0667		
Ghrib	**−0.0015**	−2.7342									
Ponteba	**−0.0024**	**−5.5714**		−0.3778	−0.1363	−0.0014		**0.09225**	**−0.0500**	−0.00579	−0.0625
BabOuender	**−0.0018**	**−11.8136**	−0.0790	−0.6254			0.29412	**0.06737**			−0.0455
Mjaara	−0.0013	−4.5714					0.34549	**0.05891**			
BeniMellal	**−0.0015**	**−4.8200**		−0.2114			0.25	**0.07955**	−0.0256	−0.0042	−0.0263
Berkane		−1.8227									
ElKansera	**−0.0018**	**−4.3449**					**0.54545**	**0.08162**			
Homadi											
Tamalaht								**0.09766**			
Larache	**−0.0018**	−3.5182	**0.0266**							−0.00755	
Tanger					−0.1935						
Melilla			0.0557								
Gabes											
Gafsa											
Jendouba	**−0.0006**							0.01883			
Kairouan											
Ksour											
Tunis	−0.00030							0.0205			

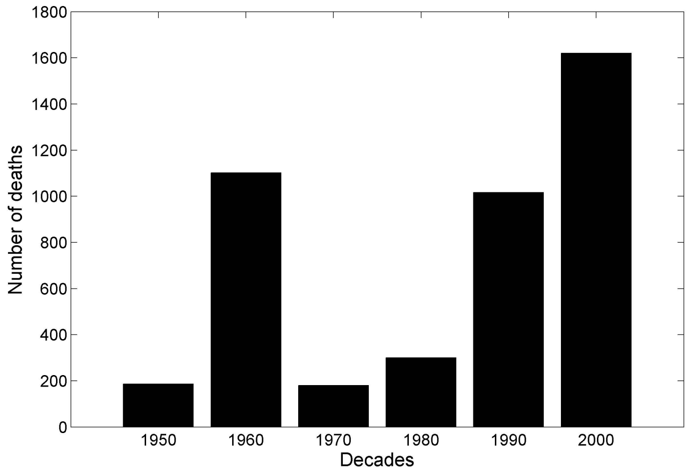

Fig. 1. Fatalities caused be floods between 1950 and 2009 in Algeria, Morocco and Tunisia (data from EM-DAT: the OFDA/CRED International Disaster Database – http://www.emdat.be/ – Université catholique de Louvain – Brussels – Belgium).

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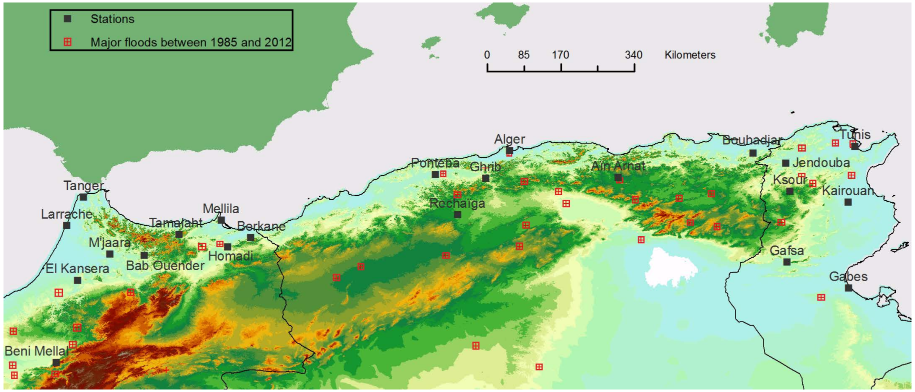

Fig. 2. Map of the selected stations and centroids of the areas affected by floods between 1984 and 2012 (data from G. R. Brakenridge, "Global Active Archive of Large Flood Events", Dartmouth Flood Observatory, University of Colorado, http://floodobservatory.colorado.edu/Archives/index.html).

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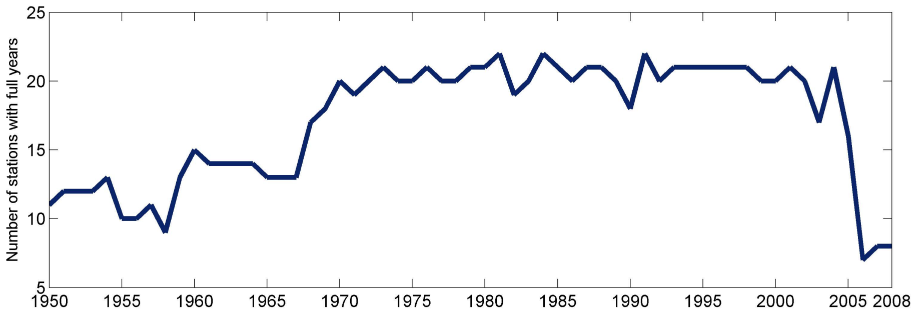

Fig. 3. Number of stations with full years (less than 5 % missing data) between 1950 and 2008.

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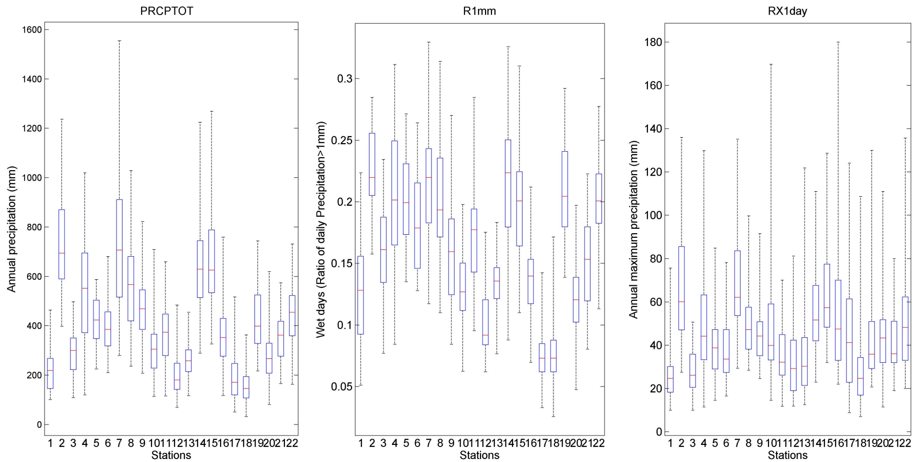

Fig. 4. Box plots showing the PRCPTOT, R1 mm and RX1day precipitation indices for the 22 rain gauges considered in this study. The boxes have lines at the lower quartile, median and upper quartile values; the whiskers extend from each end to the most extreme values.

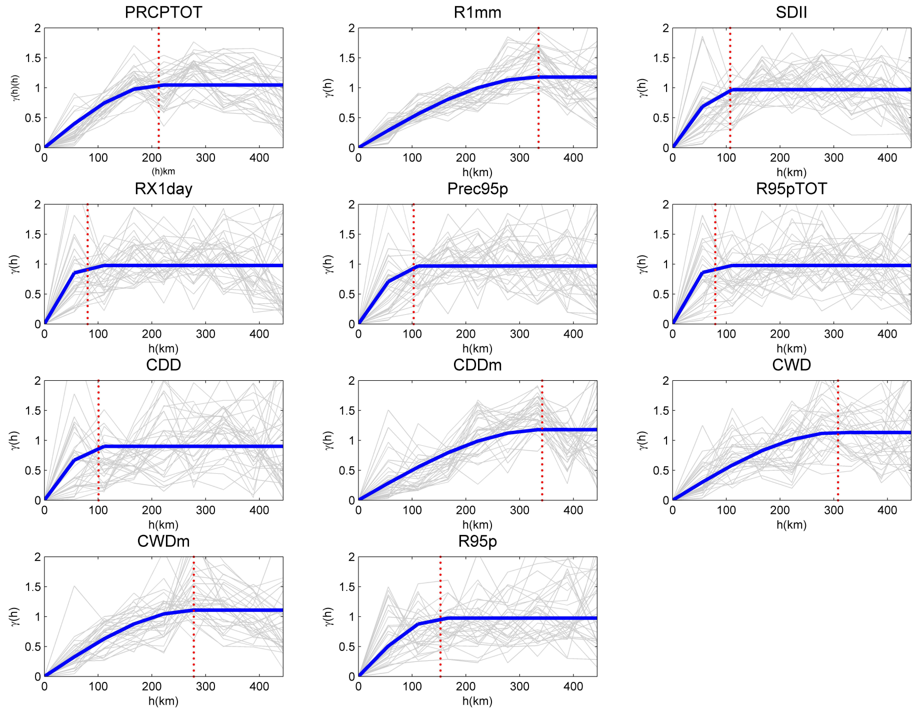

Fig. 5. Climatological variograms computed for the indices each year (grey lines). The thick blue lines represent the fitted spherical variogram models and the red dotted lines are the ranges of the fitted variograms.

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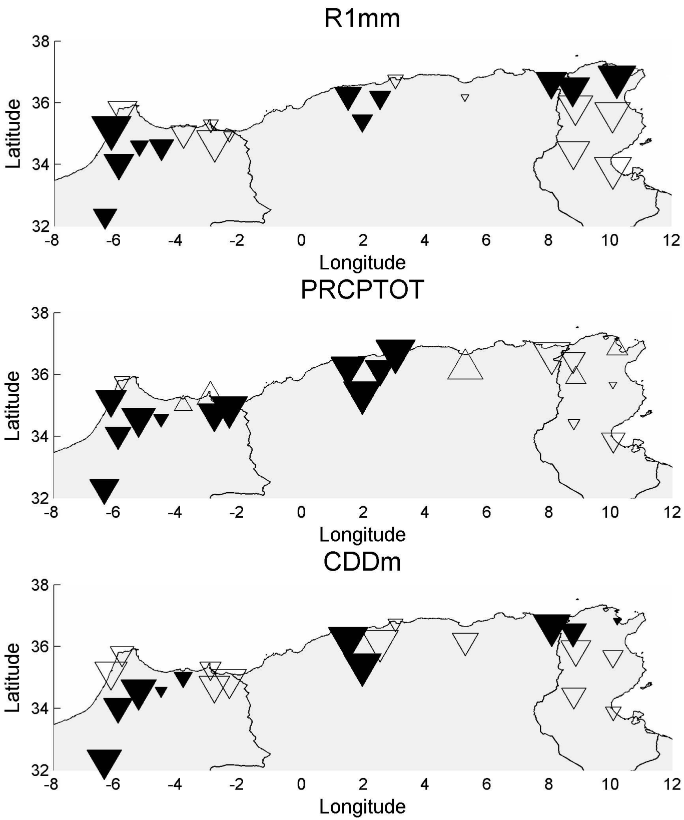

Fig. 6. Maps of the long term trends detected for the indices R1 mm, PRCPTOT and CDDm. The size of the triangles is proportional to the Sen slopes computed on the full length of the time series. The triangles filled with black are the stations where the trend is significant at the 5 % level according to the Mann–Kendall test. The actual values of the Sen slopes are in Table 2.

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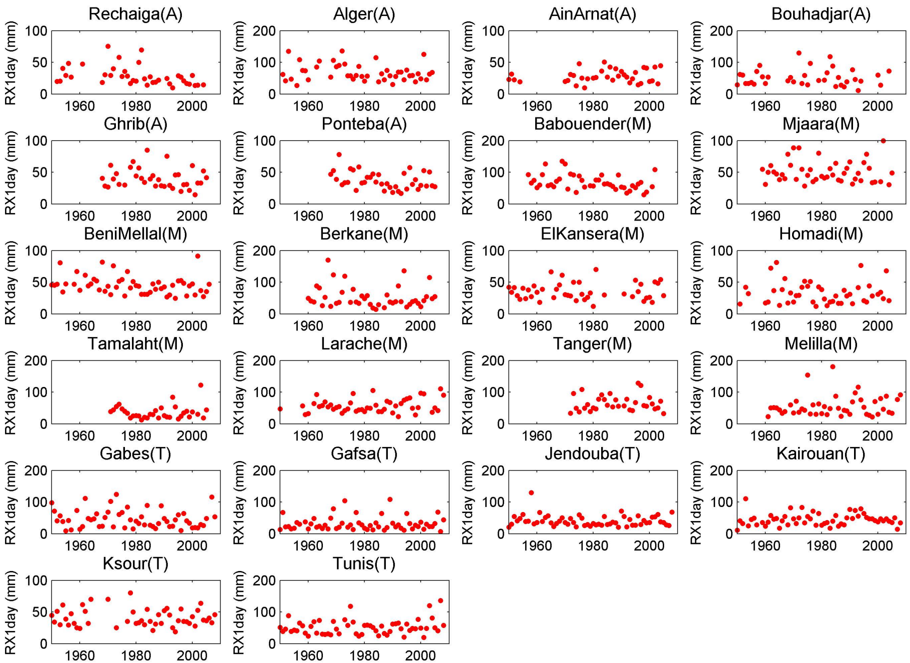

Fig. 7. Times series of the annual maximum daily precipitation (RX1day) at the different stations.

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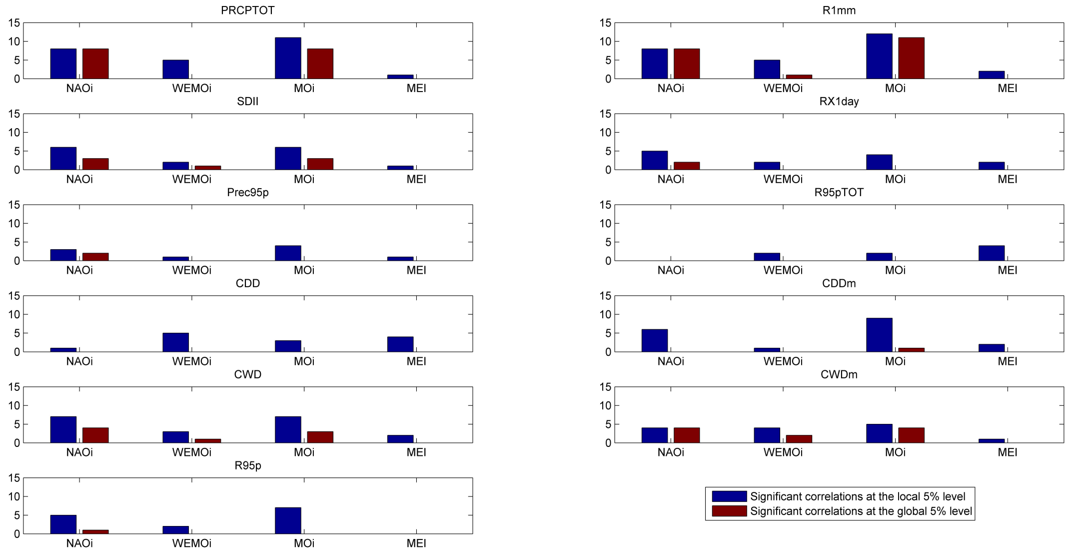

Fig. 8. Number of stations with significant correlations with the NAOi, WEMOi, MOi and MEi indices at the 5 % local and global levels.

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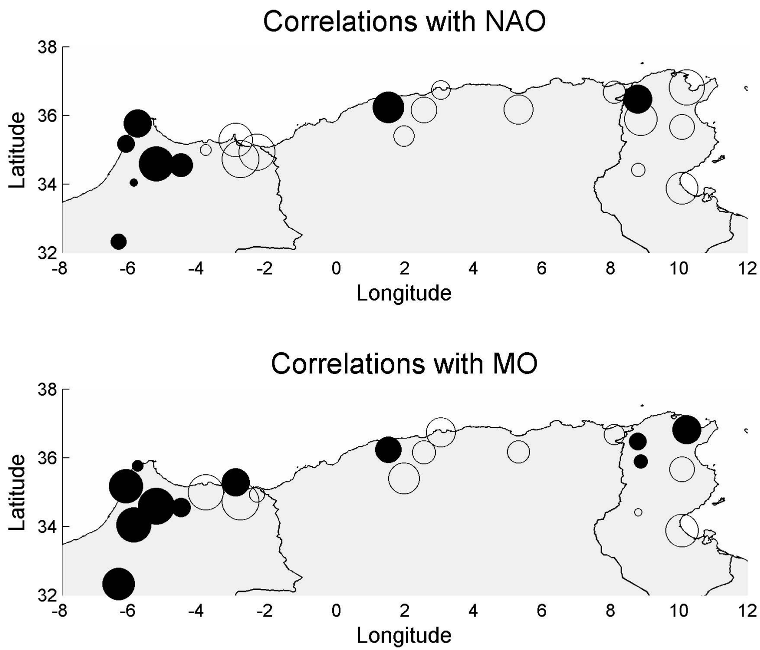

Fig. 9. Correlation between annual precipitation (PRCPTOT) and the NAOi and MOi indices at the different stations. The size of the circles is proportional to the Spearman correlation coefficients. The circles filled with black are the stations where the correlation is significant at the 5 % level.