Long-term Oscillations in Rainfall Extremes in a 268-year Daily Time Series

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Abstract. We analyze long-term fluctuations of rainfall extremes in 268 years of daily observations (Padova, Italy, 1725-2006), to our knowledge the longest existing instrumental time series of its kind. We identify multidecadal oscillations in extremes estimated by fitting the GEV distribution, with approximate periodicities of about 17-21 years, 30-38 years, 49-68 years, 85-94 years, and 145-172 years. The amplitudes of these oscillations far exceed the changes associated with the observed trend in intensity. This finding implies that, even if climatic trends are absent or negligible, rainfall and its extremes exhibit an apparent non-stationarity if analyzed over time intervals shorter than the longest periodicity in the data (about 170 years for the case analyzed here). These results suggest that, because long-term periodicities may likely be present elsewhere, in the absence of observational time series with length comparable to such periodicities (possibly exceeding one century), past observations cannot be considered to be representative of future extremes. We also find that observed fluctuations in extreme events in Padova are linked to the North Atlantic Oscillation: increases in the NAO Index are on average associated with an intensification of daily extreme rainfall events. This link with the NAO global pattern is highly suggestive of implications of general relevance: long-term fluctuations in rainfall extremes connected with large-scale oscillating atmospheric patterns are likely to be widely present, and undermine the very basic idea of using a single stationary distribution to infer future extremes from past observations.

1. Introduction

Multicentennial instrumental observations of daily precipitation are precious direct documentation of the statistical properties of rainfall, with particular regard to high-return period extremes and changes in climatic regimes [*Katz*, 1999; *Koutsoyiannis and Montanari*, 2007; *Groisman et al.*, 1999; *Buffoni et al.*, 1999; *Brunetti et al.*, 2000; *Schonwiese and Rapp*, 1997]. The analysis of long rainfall time series also allows quantitative assessments of the possible limitations of the stationarity hypothesis, which underlies current approaches to rainfall statistical analysis and engineering practices [*Milly et al.*, 2008].

Here we recover, by digitization of the original historical archives, and analyze for the first time daily precipitation observations performed in Padova (Italy) for a total of 268 complete years. Observations at the Padova astronomical observatory, *La Specola*, started in 1725 and, with few instrumental changes and relocations, continue to our days. The time series has been previously and independently reconstructed [*Camuffo*, 1984], but only monthly averages have been analyzed, and no analysis at the daily time scale has been performed. Here we use the original data to document daily extreme events and their possible changes over multicentennial time scales. The objectives of this paper are: 1) to quantitatively characterize long-term interannual variabilities in rainfall statistical properties in general, and extremes in particular, and to explore their implications for the stationarity assumption; 2) evaluate the relative importance of fluctuations in large-scale circulation patterns and of systematic trends associated with climate change in inducing variations in observed rainfall extremes.

2. Materials and Method

2.1. Data recovery and preliminary analysis

The daily rainfall observations analyzed here have been acquired in Padova between 1725 and 2006 using different, though structurally similar, instruments at three different locations, all falling within a 1 km-radius circle. Five main data collection periods can be identified [*Camuffo*, 1984, e.g.]:

1) 1725-1768. Giovanni Poleni collects data on the roof of his house (10m above ground) with a raingauge constructed according to the indications of The Royal Society;

2) 1768-1813. Data are collected at the astronomical observatory, *La Specola*, using a raingauge located 25 m above the ground, by Giuseppe Toaldo and, later, by Vincenzo Chiminello.

3) 1814-1877. Giovanni Santini succeeds Chiminello as the new director of La Specola. Observations are sometimes not systematic in this period and we excluded the data from 1815-1822 for their sparsity and for the presence of uncertain and interpolated values. Starting in 1838 the entire roof of the observatory ($27.5\,m^2$) is used as a funnel. This may have induced some degree of underestimation of small rain rates, due to the amount of rain retained by the roof surface and because of evaporation. However, evaporation over the large receiver is not likely to affect the observation of extreme events. Three years (1838-1840) are missing from this period.

4) 1878-1934. Giuseppe Lorenzoni installs a new raingauge with an area of $0.4\,m^2$, 21 m above the ground. Subsequently, the observations proceed under different directors (Antoniazzi and Silva, after Lorenzoni) to end in 1934.

5) 1935-1996. Measurements continue at a new station, run by the Venice Water Authority, located about 800 m away from La Specola.

6) 1997-present. A hourly raingauge station is activated at the Padua Botanical Gardens, currently the reference station for Padova and run by the Veneto Region Environmental Agency, 1 km away from La Specola and about 1.8 km from the Venice Water Authority station (now of uncertain maintenance).

In summary, except for 52 missing daily data that have been interpolated from neighboring stations, only 14 years are missing from the record (1765-1767, 1815-1822, 1838-1840), which consists of 268 full years of daily data. The historical observations were recovered from the original registries, which were all photographed, to avoid handling the historical records, and were manually digitized. Values recorded before 1864 were expressed in French inches (=27.07 mm) and were converted to millimeters. Instrument changes and relocations can potentially generate spurious variations in observed statistical properties [*Potter*, 1976]. However, the observational time series (Figure 1 and 2) does not display evident variations, nor abrupt differences, associated with instrumental changes. In paticular, no sharp changes in the annual totals (Figure 2a) or in the annual number of wet days (Figure 2b) are visually detectable. 30-year running means are computed for yearly totals and number of wet days. Solid lines in Figure 2 indicate averaging windows falling entirely within a period in which rainfall was measured with the same instrument, while dotted lines correspond to averaging windows containing observations from different instruments or different locations. The comparison of values at two ends of a dotted line do not show significant differences for annual totals or wet day numbers, suggesting small effects associated with instrumental changes. A relatively large difference is present only between the last values of the 'Santini' period and the first values of the 'Lorenzoni' period, particularly in the number of wet days. However, the observations within the 'Santini' period indicate a rather steep increasing trend, which is consistent with the values measured at the beginning of the 'Lorenzoni' period.

Overall, annual precipitation amounts decrease over the almost three centuries considered, while the number of wet days shows large fluctuations but no evident trend.

2.2. Extreme event analysis

We use a moving-window approach to estimate time-dependent rainfall extremes with return periods of 100 and 200 years. For each window we determine the set of annual maxima and estimate the parameters of a Generalized Extreme Value distribution (GEV) [*Frechet*, 1927; *Fisher and Tippett*, 1928; *Gnedenko*, 1943; *Gumbel*, 1954; *Jenkinson*, 1955] using a Maximum Likelihood (ML) estimator [*Martins and Stedinger*, 2000]. While the ML estimator for the GEV is potentially problematic with small samples and large quantiles [*Hosking*, 1985], we use here a relatively large sample (n=30), such that ML is known to perform comparably to other estimators [*Coles and Dixon*, 1999; *Martins and Stedinger*, 2000; *Smith et al.*, 2011].

We have experimented with overlapping and non-overlapping windows of different lengths, from 10 to 50 years. A longer window allows more accurate estimates of extreme events, but reduces the ”‘resolution”’ with which changes in extremes can be detected, particularly if the overlap between successive windows is small. A large overlap can raise the problem of serial correlation in the estimated extremes, while a small overlap, again reduces the resolution with which extremes oscillations are described. We find that the time scales of fluctuation of extremes detected using different combinations of window length and overlap are quite robust (see the periodogram discussion below) and we will chiefly discuss in the following the results obtained using windows of 30 years with overlap of 29 years (Figure 3). This analysis shows that estimated 100-year estremes vary between less than 70 mm and more than 200 mm over the entire observation period. 200-year extremes vary between about 70 mm and almost 280 mm. Such large fluctuations have apparent practical implications, as changes of up to 100% in the estimated extremes are seen in just few years. One can also observe that extremes tend to be more intense in recent years (at a rate of about 0.25 mm/year), though this trend is partly obscured by the large interannual oscillations.

To address the possible presence of characteristic time scales of fluctuation in rainfall extremes we analyze the time series of events with an estimated 200 year return period using the Lomb-Scargle normalized periodogram [*Lomb*, 1976; *Press et al.*, 2007]. The use of this approach instead of the more conventional discrete Fourier Transform was dictated by the presence of missing years, such that the time series of estimated rainfall extremes is not equally-spaced. The Lomb-Scargle periodogram allows the detection of characteristic periodicities, even when time series spacing is not homogeneous, by use of a least square fit of sinusoidal functions. The values in the resulting normalized periodogram (Figure 4a-c) are not numerically comparable to a traditional Fourier spectral density function, but similarly provide a quantitative measure of the relative importance of different periodicities in the time series. In fact, we find several distinct periodicities, evidenced by peaks in the periodogram, between about 17 years and 172 years. We explored different combinations of window lengths (10-50 years) and overlaps between windows (from zero overlap to almost complete overlap) to evaluate the possible effects of 1) the correlation induced by window overlap and 2) the low resolution with which non-overlapping windows describe extreme events change over time. We find that analyses with non-overlapping windows confirm results from overlapping windows, but do not allow to resolve short-scale periodicities (e.g. compare Figures 4a and 4b-c). Overall, the peaks emerging in the normalized periodograms obtained from different combinations of window length and overlap, show characteristic scales of fluctuation in the following ranges: 17-21 years (not detectable at overlap = 0 years), 30-38 years, 49-68 (most energetic peak), 85-94 years, and 145-172 years.

The implications of this finding are relevant for the estimation of extremes in a climate with strong interannual variability. The presence of high-amplitude cycles occurring over scales shorter (17-172 years in this case) than the return period being considered (200 years in this case) makes a proper definition of return period problematic, because of the stationarity assumption underlying the operational definition of return period as the average time between two successive exceedances of the set threshold.

2.3. NAO index and daily precipitation

The North Atlantic Oscillation (NAO) is one of the most prominent global patterns of atmospheric circulation variability in the Northern Hemisphere. The related NAO Index (NAOI) is usually defined as the normalized pressure difference between a station in the Azores and one in Iceland, and is a measure of the northward displacement of Atlantic storm tracks [*Hurrel*, 1995], which largely control synoptic scale events over Europe.

We are here interested in exploring the possible relationship between rainfall amounts, occurrences, and extremes, and the NAOI, which exhibits complex cycles, but no evident trends [*Jones et al.*, 1997].

Figure 4d shows that the NAOI posesses significant cyclicities at relatively short scales (11-13 years), a well established notion [*Hurrel*, 1995]. Longer periodicities also emerge in Figure 4d, at 30-31 years, 38 years, and 63-68 years. Periodicities in the NAOI show some correspondence with those observed for anomalies in extremes, suggesting a possible relation between the two. However, such correspondence could be coincidental, and needs to be investigated further. In order to explore this possible relation, we first isolate extreme rainfall fluctuations from mean tendencies, by computing the anomalies of yearly rainfall, wet fraction, and 200-year rainfall extremes (see Figure 5a-c) with respect to the overall linear trend computed on the entire period. These anomalies are then comparatively analyzed with yearly and seasonal NAOI values [*Jones et al.*, 1997] (see Figure 5d). We plot the November-December-January (NDJ) precipitation vs. the NDJ NAOI, obtained by averaging the monthly NAOI over the NDJ period. The choice of this period is due to the fact that most rainfall events in NDJ in Padova are originated by Atlantic storms, significantly driven by the NAO phase [*Hurrel*, 1995]. In fact, we find NDJ rainfall (Figure 6a) and the fraction of dry days (Figure 6b) to be highly correlated with NAOI. Even more interesting, also the intensity of 200-year rainfall events is correlated with both the annual and the NDJ NAOI (Figure 7). While there is a significant scatter when single 30-year windows are considered, a clear trend emerges when the range of NAOI values is divided into discrete intervals and the 200-year event intensity is averaged within each such "‘bin"’ (solid circles in Figure 7).

3. Summary and Conclusions

Our analyses of daily rainfall observed in Padova since 1725, possibly the longest existing rainfall time series from direct instrumental observations, allow us to draw conclusions of some general relevance.

The dominant feature of extreme events with return periods of 100 and 200 years is constituted by large oscillations (almost 100% range with respect to the long-term mean) which overwhelmingly dominate a more subtle intensification trend. Our analyses show the presence of energetic oscillations with rather distinct periods between about 17 years and 172 years.

A correlation between extremes and the North Atlantic Oscillation also emerges. This correlation is interpreted by considering that the latitudinal location, and activity, of the Atlantic storm track is a primary control of rainfall intensity in the Northern Hemisphere, and in Europe in particular []*Bartolini et al.* [2009]; *Brandimarte et al.* [2011]. This established relation between local extremes and global-scale oscillating atmospheric patterns also suggests that periodicities in extreme rainfall events should be a general feature, beyond the particular case analyzed here.

The analysis of this particularly long time series (268 years) supports further considerations. The characteristic periods identified here (up to about 172 years) are decisively longer than the length of the rainfall time series usually available for climatic and hydrologic analyses. The predictive horizon of interest for climate studies, as well as for engineering applications, is often 100 years or longer. Our results show that, even in the absence of trends, reliable extreme event estimates cannot be inferred over such an horizon on the basis of normally available rainfall observations. The extreme events that are ’seen’ in short records, in fact, come from a different statistical population than those occurring in the subsequent 100 years, due to the presence of long-term periodic-like oscillations. For example, in the Padova time series, estimates based on a 30-year record at the end of the 19th Century are very different from the extreme events actually occuring at the beginning of the 20th Century. Importantly, these considerations imply that stationarity (or, more precisely, cyclostationarity), even if trends were absent, could only be invoked if observations over time intervals spanning several times the longest periodicity in the data (172 years) were available.

Long-term fluctuations and cycles are also found in yearly totals and dry days fraction. Such fluctuations are consistent with those observed in the North Atlantic Oscillation as represented by the NAOI. High values of the NAO Index are associated with lower precipitation amounts and a greater number of dry days. This may be interpreted by noting that higher NAOI values correspond to more northward storm tracks, and hence to a reduced number of storms and lower period totals. However, lower period totals do not imply less intense events, as evidenced by the positive correlation between the intensity of rainfall extremes and the NAOI. Hence, the NAO affects rainfall extremes through a control both on the number of Atlantic storms investing Southern Europe and on the intensity of individual storms. In particular, the potential attenuation of extremes due to a decreased number of events during positive NAOI phases is more than compensated by an increase in event intensity, resulting in an overall increase in the intensity of extremes with a fixed return period.

Our results also suggest that the effects of climatic fluctuations will be aggravated by the probable effects of projected changes: the increase in positive NAOI phases expected in the next century [*Randall et al.*, 2007; *Goodkin et al.*, 2008; *Ulbrich and Christoph*, 1999] is likely to cause an intensification of rainfall extremes at the daily scale in the study area (which is representative of conditions in mediterranean Europe, e.g. *Bartolini et al.* [2009]).

In summary, our analysis of a multicentennial rainfall time series shows that past extremes, observed through records of typically available length (i.e. at most 100 year long, in the best of cases) are not reliable predictors of future ones, and points to the need for a statistical theory of extremes incorporating time-varying probability distributions and modelling of large-scale atmospheric patterns.

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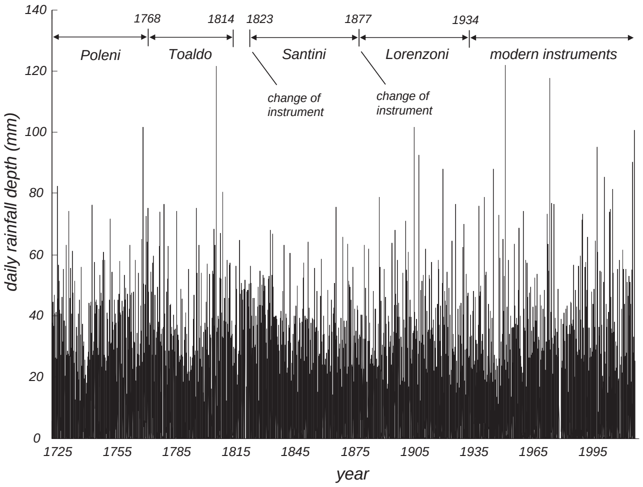

Figure 1. The 1725-2006 daily rainfall observations in Padova (Italy). Periods in which rainfall was measured at a same location using the same raingauge are indicated with the name of the director of the Observatory.

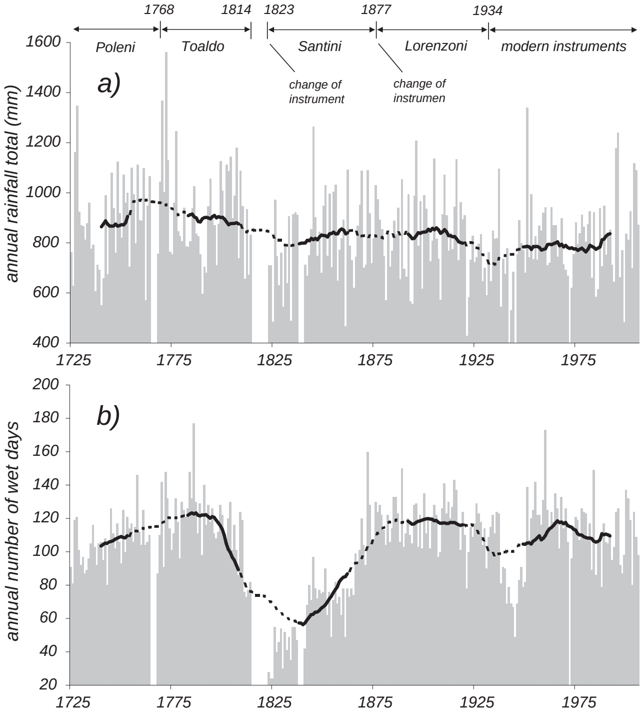

Figure 2. Annual rainfall amounts and number of wet days. Moving averages over windows of 30 years are indicated as a solid line when the window lies entirely within a homogeneous period (same location and raingauge) and as a dotted line when the window spans different observational periods. Values are indexed using the year at which the corresponding moving window starts.

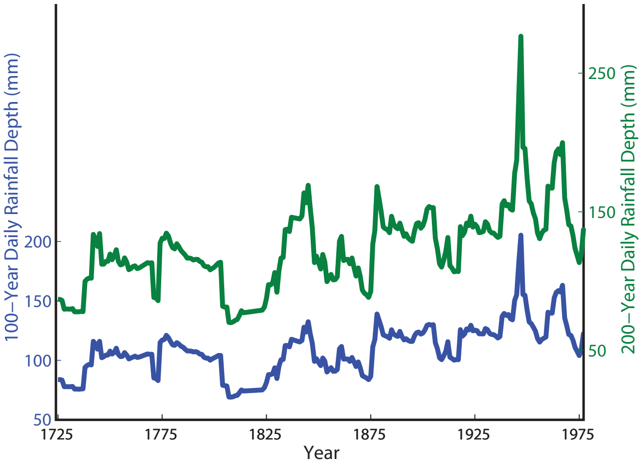

Figure 3. 100- and 200-year recurrence rainfall extremes as obtained from a Generalize Extreme Value analysis performed over 30-year long moving windows. Windows are indexed using the start year.

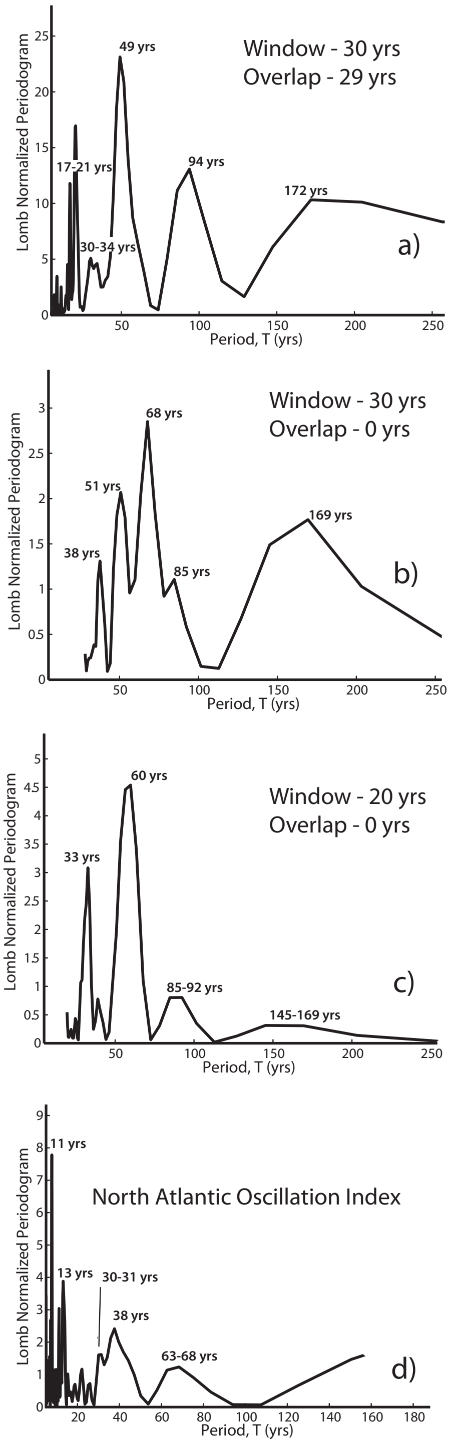

Figure 4. Lomb-Scargle periodograms of 200-year return period rainfall: a) 30-year windows with 29 years of overlap; b) 30-year windows with no overlap; c) 20-year windows with no overlap; d) Lomb Scargle periodogram of the annual North Atlantic Oscillation Index.

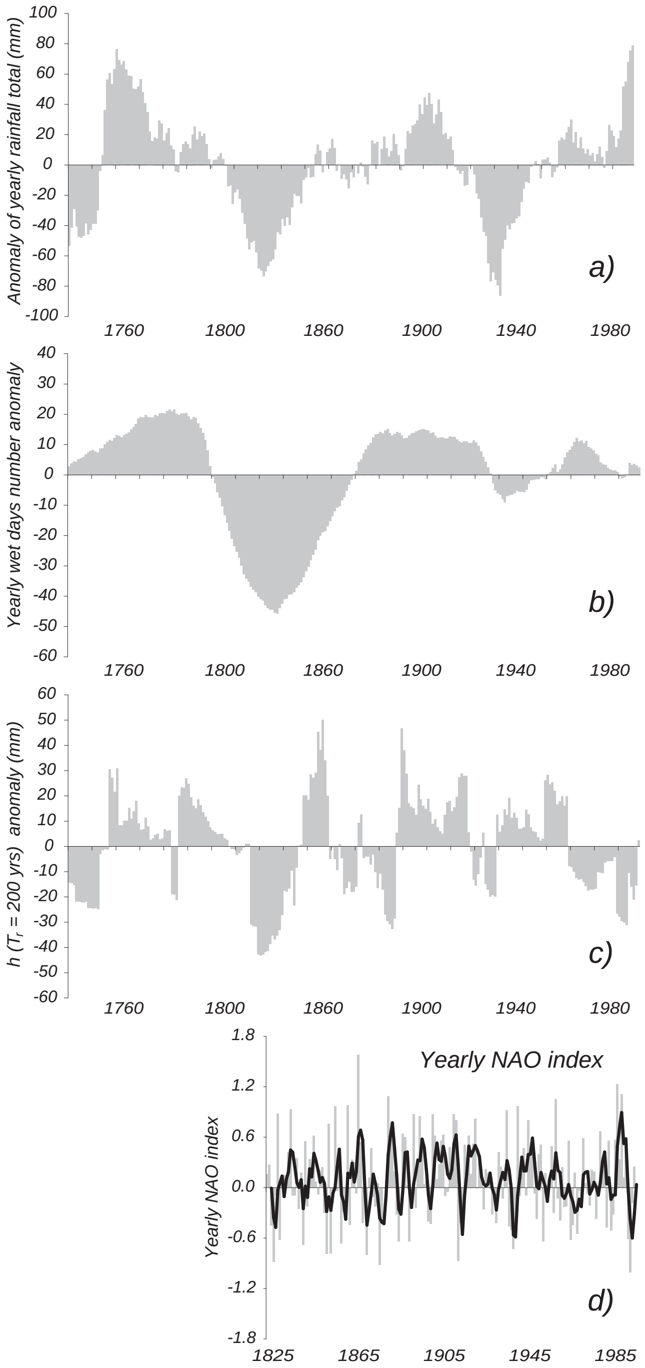

Figure 5. Anomalies of yearly rainfall (a), annual wet days number (b), and 200-year rainfall extreme (c), with respect to the overall linear trend of these variables computed on data in Figures 2 and 3. d) shows the annual NAOI value reconstructed starting from 1825 (grey) [*Jones et al.*, 1997] and its 30-year moving average (solid line).

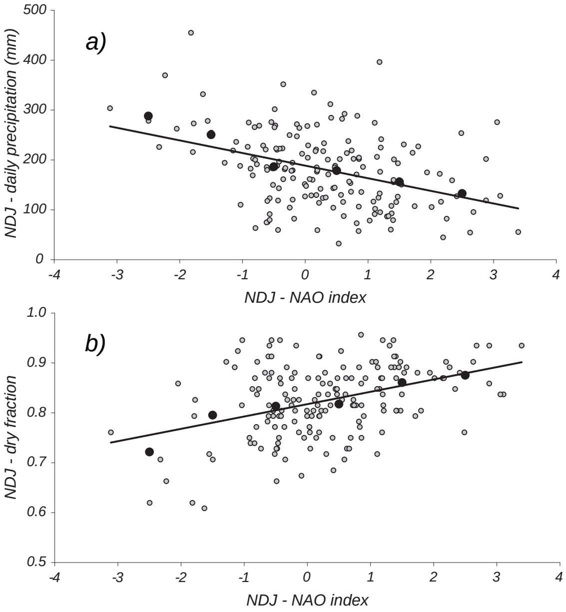

Figure 6. November-December-January (NDJ) correlation analysis between mean daily rainfall (a) and mean dry-day fraction (b) vs. NAOI value. Larger closed circles indicate mean values computed over data points falling within intervals of NAOI values of unit length. This "'binning"' analysis shows that correlation emerges more clearly when random fluctuations are averaged out.

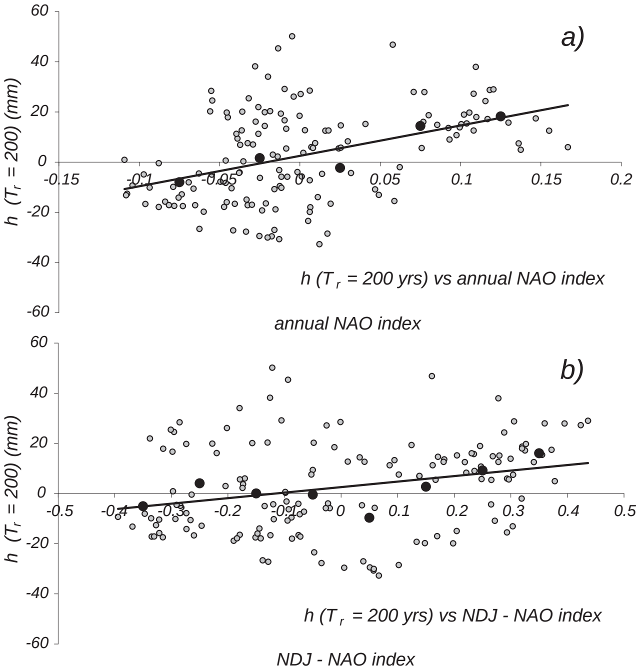

Figure 7. Correlation analysis of 200-year rainfall extremes and yearly (a) and NDJ NAOI (b). Larger closed circles indicate mean values computed over data points falling within intervals of NAOI values of unit length. This ”‘binning”’ analysis shows that correlation emerges more clearly when random fluctuations are averaged out.