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New Azores archipelago daily precipitation dataset and its links with large-scale modes of climate variability

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ABSTRACT: Within the scope of the two major international projects of long-term reanalysis for the 20th century coordinated by the National Oceanic and Atmospheric Administration and European Centre for Medium-Range Weather Forecasts, the Instituto Dom Luiz from the University of Lisbon has digitized a large number of long-term daily and monthly climate records from stations in Portugal and former Portuguese colonies. We have recently finished the digitization of precipitation values from Ponta Delgada (capital of the Azores Archipelago), obtaining an almost complete daily precipitation series, with the exception of some years (1864–1872; 1878–1879; 1888–1905; 1931; 1936; and 1938) for which only monthly values are available. At daily resolution, we have used a comprehensive assessment on different characteristics of rain spells (consecutive days with rainfall accumulation). The distribution of precipitation presents an evident seasonal pattern and reveals large inter-annual and intra-annual variability, increasing considerably in the last 3 decades. The frequency of dry years decreases almost by half between the first and the second part of the record, whereas wet years increase up to three times. This is mainly due to more intense events that are reflected by higher rain-spell yields (amount of precipitation) and rain-spell intensity (amount of precipitation per day) values. Most of the extreme precipitation events occurred during the last 2 decades, and they generally correspond to dates with cyclonic conditions over the North Atlantic. We have also looked into the influence of large-scale modes of climate variability on the precipitation regime of the Azores Archipelago. As expected, theNorth Atlantic Oscillation (NAO) has a major impact on the precipitation regime of Ponta Delgada both in winter and summer. However, our results show a non-stationary NAO influence and the impact of other large-scale modes (including the Atlantic Multidecadal Oscillation and El Niño-Southern Oscillation) increases when this influence becomes weaker.

KEY WORDS daily precipitation; Azores Archipelago; teleconnection; seasonality; North Atlantic Ocean

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1. Introduction

Long-term climate datasets are essential for understanding climate changes (Compo *et al.,* 2011). However, the currently limited availability of long-term instrumental climate records hampers our ability to conduct more reliable assessments of climate variability and change (Trenberth *et al.,* 2007). Present access to daily digital climate data is scarce over many parts of the world, particularly in oceanic regions, and this limited coverage of instrumental data obstructs the ability to better understand climate changes and its forcing factors (Brunet and Jones, 2011). In this sense and within the scope of the two major international projects of long-term reanalysis for the 20th century coordinated by the NOAA (Compo *et al.,* 2011) and ECMWF (Hersbach *et al.,* 2013), the Instituto Dom Luiz (IDL) from the University of Lisbon has digitized a large number of long-term stations records from Portugal and former Portuguese colonies (Stickler *et al.,* 2014).

Island environments are very sensitive to externally induced changes, and the limited area and resources available to island states can make it difficult to apply adaptation methods (IPCC, 2014, WG3). In particular, small islands, like those in the Macaronesian region in the eastern North Atlantic (Figure 1(a)), have long been identified among the most vulnerable to climate change and climate extremes (Nurse *et al.,* 2014) due to the potential implications in the relocation of resources and activities (Santos *et al.,* 2004). Changes in precipitation are of particular concern as precipitation, or a significant lack of it, can be responsible for flash floods, landslides and droughts. The Azores Archipelago (Figure 1(a)) is usually under the direct influence of the semi-permanent, high-pressure Azores anticyclone. During most of the year (September–March), if this high-pressure centre is dissipated or displaced latitudinally, then the Azores region is frequently crossed by the North Atlantic storm track, the main path of rain-producing weather systems (Trigo

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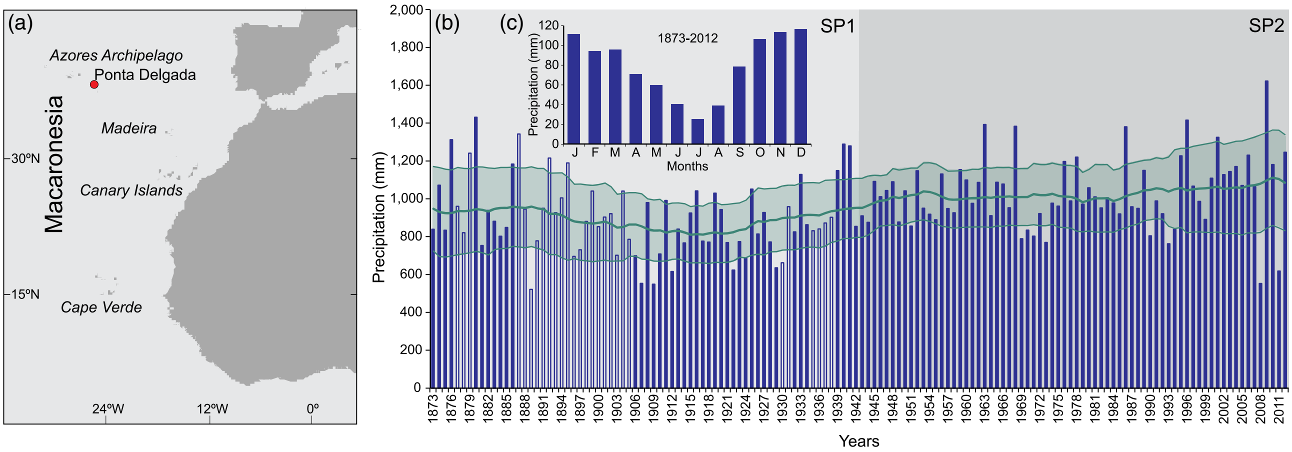

Figure 1. (a) Map of the Macaronesian region showing the Azores Archipelago and Ponta Delgada location. (b) Annual and (c) monthly mean precipitation (mm), 1873–2012. Annual series of precipitation were calculated by summing daily values if no more than two values per month were missing (solid bars). When this occurs, series were completed using monthly data sets from previously digitised monthly series already used by other authors (e.g. Cropper and Hanna, 2014) covering this time period (open bars). The thick line represents a 31-point moving mean, which emphasizes the low-frequency variability of the annual precipitation series and the shadow indicates the corresponding 31-point moving standard deviation. Note that the values obtained for both ends were calculated using as many years as possible in the moving average when the number of years was less than 31.

et al., 2004). Conversely, during late spring and summer, the Azores climate is mainly dominated by the Azores anticyclone (Agostinho, 1948; Santos *et al.,* 2004; Azevedo, 2006). Thus, the rainfall regime from Ponta Delgada (São Miguel Island, Azores Archipelago, Portugal) displays a strong seasonal cycle and large inter-annual variability (Marques *et al.,* 2008). The changes in precipitation are usually larger than temperature or pressure variations, and long-term records are essential to accurately present the local rainfall regime (e.g. Esteban-Parra *et al.,* 1998; Kutiel and Trigo, 2014). Variations in total precipitation can be caused by changes in the characteristics of the constituting rain events, including their timing, intensity and some aspects of the dryness conditions between rainfall episodes (e.g. Paz and Kutiel, 2003). Therefore, in order to improve the understanding of precipitation behaviour as an indicator of climate changes in the last century, daily precipitation series must be analysed (Brunetti *et al.,* 2001).

Some authors (e.g. Andrade *et al.,* 2008; Marques *et al.,* 2008; Cropper and Hanna, 2014) have previously analysed long-term characteristics of precipitation for Ponta Delgada and its relationship with the main large-scale modes in the North Atlantic sector, the North Atlantic Oscillation (NAO). However, these studies have used shorter and/or lower-resolution time series, and to the best of our knowledge, there is no work evaluating the evolution of daily precipitation time-series characteristics starting in the second half of the 19th century. Uninterrupted monthly precipitation values from Ponta Delgada are currently available since 1865 without missing data (Cropper and Hanna, 2014), and a new, almost complete, corresponding daily precipitation series, with the exception of some years, has recently been digitized at IDL.

A large fraction of the inter-annual variability of precipitation observed in the Azores Archipelago has previously been ascribed to the NAO influence during winter (Andrade *et al.,* 2008; Marques *et al.,* 2008; Cropper and Hanna, 2014). The NAO is the leading mode of climate variability in the North Atlantic region and is manifested as a meridional dipole anomaly in sea-level pressure, with the two centres of action located approximately over Iceland and the Azores (Hurrell, 1995; Trigo *et al.,* 2004). However, besides the NAO, there are other large-scale modes, such as the East Atlantic pattern (EA), the Scandinavian pattern (SCAND), the Arctic Oscillation (AO), the Atlantic Multidecadal Oscillation (AMO), the Pacific Decadal Oscillation (PDO) and the El Niño-Southern Oscillation (ENSO), that may also contribute significantly to the North Atlantic region's precipitation regime (e.g. Thompson and Wallace, 1998; Pozo-Vázquez *et al.,* 2005; Sutton and Hodson, 2005; Trigo *et al.,* 2008; Comas-Bru and McDermott, 2014). Furthermore, it is worth noting the existence of inter- and intra-annual variations in the impact of these large-scale modes on the climate throughout long periods. In particular, the correlation between the NAO and precipitation in the Macaronesian region shows a non-stationary behaviour over time (Cropper and Hanna, 2014), and therefore, studies of the long-term influence of large-scale modes on rainfall variability are required. However, despite the increasing understanding of the impact of large-scale modes on the North Atlantic region climate, to our knowledge, the impact of other large-scale modes on the rainfall regime of the Azores Archipelago has not previously been explored.

The influence of large-scale modes on the variability of North Atlantic storms has been the focus of several previous works (e.g. Kossin *et al.,* 2010). Intense precipitation greatly affects human activities as it can cause catastrophic floods or landslides among other impacts. The analysis of the behaviour of extreme rainfall and its links to large-scale modes is essential to better understand their impact on human endeavours. Days with extreme values of precipitation are potential triggers of catastrophic episodes, and previous studies of the Azores Archipelago (e.g. Andrade *et al.,* 2008; Marques *et al.,* 2008) have focussed their efforts on establishing links between cyclones and the NAO pattern.

Our study aims to contribute to the understanding of the rainfall regime in the Azores Archipelago by investigating daily precipitation data recorded at Ponta Delgada. Changes in precipitation in the period 1873–2012 (~140 years) were studied using a methodological approach based on different characteristics of rain spells (e.g. Reiser and Kutiel, 2008). This method has been shown to perform well when analysing the different parameters related to the rainfall regime in other parts of the world with strongly seasonal precipitation behaviour, such as the Mediterranean region (e.g. Reiser and Kutiel, 2007). Additionally, the influence of the large-scale modes on the inter-annual precipitation variability as well as on the severe rainfall events was investigated. We also analysed the trajectory of significant North Atlantic tropical storms that are shown to sometimes influence extreme precipitation across the Azores Archipelago.

2. Data and methods

2.1. Datasets

Daily rainfall data from 1873 until 2012 from the Ponta Delgada station (37°44’N, 25°40’W, 77 m) have been digitized from meteorological annals and then quality controlled according to the framework presented in Stickler *et al.* (2014). Additionally, we tested the quality control of daily data with RClimDex_extraQC routines (Aguilar and Prohom, 2011). Data from 1873 to 1946 were obtained from the ‘Annaes do Observatório Infante D. Luiz’ (see Valente *et al.,* 2008 and Stickler *et al.,* 2014) and for 1947 to 2012 were supplied by the Instituto Português do Mar e da Atmosfera (IPMA). Thus, we obtained a new daily precipitation series from 1873 to 2012, with the exception of some years (1878–1879; 1888–1905; 1931; 1936; and 1938). In addition, annual and monthly series of precipitation were calculated by summing daily values if no more than two values per month were missing. When this occurs, monthly and annual series were completed using the monthly datasets from previously digitized monthly series (IDL-IPMA) covering this time period (Cropper and Hanna, 2014)

Long-term climate time series have been influenced by non-climatic factors quite often, mainly related to changes in instrumentation, instrumental exposure, station locations and local environments, observing practices and/or data processing (e.g. Aguilar *et al.,* 2003; Trewin, 2010). All these factors can introduce gradual or abrupt breaks in the homogeneity of climate records.

To detect and estimate adjustments for these problems, the Ponta Delgada annual and monthly precipitation series were examined for homogeneity using the software package HOMER (Mestre *et al.,* 2013) to detect possible breaks in the homogeneity of series. As HOMER is a relative homogenization method, we have used some long-term precipitation series available for the Azores Archipelago as references [Terceira (Angra do Heroismo, 1873–2012) and São Miguel Island (Furnas, 1935–2012; Casado José, 1935–2012; Santana, 1947–2012)]. We applied annual pair-wise detection and joint detection to estimate homogeneity breaks and to determine potential change points. Then, metadata records for each station were used to confirm break points. Two homogeneity breaks were detected in the Ponta Delgada precipitation series for the years 1888 and 1936, the first one coinciding with the beginning of a period that was filled with the newly digitized monthly data (1888–1905) and the second with a station relocation (1936). The adjustment of inhomogeneities was done with the option log ratio multiplicative correction for cumulative parameters in HOMER. This type of adjustment by multiplicative ratio is normally used to homogenize precipitation series, which is different from the additive factors used in temperature series (Alexandersson, 1986; Venema *et al.,* 2012).To adjust daily data, we have chosen the scheme developed by Vincent *et al.* (2002). This approach attempts to provide a better time-interpolation procedure that preserves monthly values and does not introduce artificial discontinuities at the beginning and end of calendar months. The impact of this homogeneity adjustment is relatively small, and it affects only the period previous to 1936. Between 1889 and 1936, the monthly impact of the adjustment is ~10 mm on average compared with the original data, whereas for the earlier period, 1872–1888, the average difference is ~5 mm.

This study has been performed with data from an Azorean meteorological station, and therefore, an extended daily (1850 to present) station-based NAO index, based on the reconstructed Azores sea-level pressure data presented by Cropper *et al.* (2015), has been employed. The temporal evolution of the other large-scale modes was obtained through the numerical indices stored at the Climate Prediction Center of the National Oceanic and Atmospheric Administration (http://www.cpc.ncep.noaa.gov). Monthly resolution datasets were employed with different durations according to the available data (Table S1, Supporting Information). The Atlantic tropical storms data were retrieved from the National Hurricane Center from the National Oceanic and Atmospheric Administration (http://www.nhc.noaa.gov/).

2.2. Rainfall analyses

The daily rainfall regime was explored using a specially designed statistical model, entitled the Rainfall Uncertainty Evaluation Model (RUEM; Reiser and Kutiel, 2008).

To avoid splitting the Azores rainy period into two different years, we use the hydrological year rather than the traditional meteorological year. Most definitions for a hydrological year start on September 1 or October 1. However, in this study, we will use the hydrological year definition starting on 1 July and ending on 30 June of the next calendar year as proposed by Reiser and Kutiel

(2008) for regions with dry summers and long wet seasons. The number of the year refers to when it started, e.g. 1873 refers to the period that spans between 1 July 1873 and 30 June 1874.

For our analysis, we focussed on rain spells instead of rainy days as the former better accommodates the total length of any rainy period. A rain spell is defined as a period of consecutive days with rainfall above a given predetermined daily rainfall threshold (e.g. Reiser and Kutiel, 2012). Each rain spell is preceded and followed by at least one dry day or a day with a rainfall amount less than the daily rainfall threshold (1.0 mm in this study). For each rain spell, its duration (RSD), yield (RSY, the total rainfall accumulated during the rain spell) and mean intensity (RSI, the average daily rainfall in the rain spell) were calculated. Additionally, the total number of rain spells (NRS) and the rainy season length (RSL) in each year was also considered. The RSL is defined as the number of days elapsed between the beginning and the end of the rainy season. The beginning and the end dates are when 10 and 90% of the annual rainfall were accumulated, respectively. These dates vary from year to year, and the RSL varies accordingly. This was done in order to avoid some sporadic rains with minute amounts at the beginning and/or end of the rainy season that will cause a very long RSL consisting of long dry periods in between (Reiser and Kutiel, 2009). Following Kutiel and Trigo (2014), annual totals in all years/seasons were standardized, and the years/seasons were categorized accordingly into five categories: very dry ($z < -1$), dry ($-1 \leq z < -0.5$), normal ($-0.5 \leq z \leq 0.5$), wet ($0.5 < z \leq 1$) and very wet ($1 < z$). For each category, the above rain-spell parameters were also calculated separately.

Intra-annual variability was analysed by calculating and comparing the dates of accumulated rainfall percentage. For each day in each hydrological year, the accumulated percentage of the total annual rainfall of that year was calculated, and these values were then sorted in an ascending order for each Julian day, thus enabling the values to be presented in a probabilistic way.

Dryness was analysed using the dry days since last rain (DDSLR) approach (e.g. Kutiel, 1985; Aviad *et al.,* 2009; Lana *et al.,* 2012; Kutiel and Trigo, 2014). According to the DDSLR methodology, each rainy day is attributed a ' 0' value, the first dry day is attributed a '1' value, the next consecutive dry day a '2' value and so on until the next rainy day, which is again attributed a '0; value. Values carry over from 1 year to the next. Once all days in the analysed period were attributed with a value that describes the distance in days of that specific day from the last rainy day, all values for each Julian day were sorted in an ascending order, thus enabling the values to be presented again in a probabilistic way.

The long-term inter-annual rainfall evolution throughout the entire period (1873–2012) was studied by applying a 31-point moving mean window to the annual mean precipitation calculated from the daily time series (Figure 1(b)). In addition, this period was divided into two halves that correspond to a regime change in precipitation (Figure 1(b)). This break point (1942–1943) was chosen as it corresponds to a potential precipitation regime change in the regional series (Cropper and Hanna, 2014). Additionally, it was also a suitable point as the Subperiod 1 (SP1) and Subperiod 2 (SP2) needed to be of near similar lengths. The first half (SP1) spans from 1873 until 1942 but only comprises 42 years (out of a possible 70) due to the lack of data; the second half (SP2) spans from 1943 until 2012, including all 70 years. To evaluate the representativeness of the 42 years in the first period, appropriate statistical *t*- and *F*-tests were applied to the mean and standard deviation values of SP1 obtained with the different length (70-year *vs* 42-year) datasets. Results do not show significant differences between the monthly (70-year) and daily (42-yr) datasets with a confidence level of 99%, which suggests it is feasible to make valid comparisons between the daily precipitation regime of SP1 (42-year) and SP2 (70-year).

The rainfall regime in the Azores Archipelago at daily resolution comprises a time window of 140 years (1873–2012) with five gaps lacking daily data (1878–1879; 1888–1905; 1931; 1936; and 1938). Thus, 117 years were initially available, and, as we used hydrological years instead of meteorological years, a total of 112 hydrological years (July 1–30) could be analysed with the RUEM. We decided to reproduce the RUEM analysis for the entire period, the two subperiods and the categorised very dry to very wet years.

2.3. Atmospheric circulation patterns' influence on rainfall regime

The extended winter (DJFM) and summer (JJAS) influence of each considered large-scale mode (NAO, EA, SCAND, AO, AMO, PDO and ENSO) on precipitation has been explored. This was performed according to Spearman's rank correlation coefficients (ρ) and associated p-values. Unless otherwise stated, significance (p-value) is always discussed at $p < 0.01$.

3. Overall rainfall regime

The rainfall regime in Ponta Delgada shows clear inter-annual and intra-annual variability (Figures 1(b) and (c)). The mean annual precipitation for 1873–2012 is 960.6 mm, with a standard deviation of 201 mm, and almost 75% of the total precipitation was accumulated between October and March. The mean rainy season length is 277 days (Table 1). Although the Azores Archipelago is geographically distant from the Mediterranean basin, the rainfall regime presents some similar characteristics with the Mediterranean region, with maximum precipitation during the cold season and minimum precipitation during summers (Reiser and Kutiel, 2009). Precipitation occurred (on average) in ~122 rainy days consisting of 60 rain spells with a mean duration of ~2 days. Each rain spell yields 16 mm on average with a mean rate of 7.9 mm day^{-1}. About 42% of the annual total is due to rain spells longer than 3 days (Table 1).

Table 1. Mean, standard deviation and coefficient of variation for the different precipitation indices used in this study for the entire series length (1873–2012), subperiods 1 (1873–1942) and 2 (1943–2012), and the categorized very dry to very wet years. Also shown is the ratio of the means between subperiod 1 and 2, between dry and wet and very dry and very wet years for each precipitation index.

	1873–2012 (112 years)		1873–1942 SP1 (42 years)		1943–2012 SP2 (70 years)		Very dry (<760 mm) (13 years)		Dry (760–860 mm) (23 years)		Normal (860–1061 mm) (47 years)		Wet (1061–1162 mm) (13 years)		Very wet (>1162 mm) (16 years)		Ratio SP2/SP1	Ratio W/D	Ratio VW/VD
	$\overline{X}$	SD	$\overline{X}$	SD	$\overline{X}$	SD	$\overline{X}$	SD	$\overline{X}$	SD	$\overline{X}$	SD	$\overline{X}$	SD	$\overline{X}$	SD			
Annual rainfall (mm)	960.6	201.0	893.3	211.5	1000.9	184.4	643.5	80.9	810.0	33.0	963.0	61.3	1114.2	25.1	1302.5	113.6	1.12	1.38	2.02
Number of rain days (NRD)	121	15	119	16	122	14	103	7	117	10	120	11	131	10	141	13	1.03	1.13	1.37
Number of rain spells (NRS)	60	5	59	5	61	5	60	6	59	6	60	4	64	7	62	4	1.03	1.08	1.04
Number of rain spells longer the 3 days (NRS >3)	8	3	8	3	8	2	5	2	8	2	8	2	9	2	10	2	1.03	1.21	2.12
Rainy season length (RSL, days)	277	31	283	27	273	32	280	35	278	35	277	28	270	24	276	34	0.97	0.97	0.99
Rain spell duration (RSD, days)	2.0	0.2	2.0	0.2	2.0	0.2	1.7	1.3	2.0	0.2	2.0	0.2	2.1	0.2	2.3	0.2	1.00	1.05	1.35
Rain spell yield (RSY, mm)	16.0	3.3	15.1	3.4	16.6	3.2	10.9	1.6	13.9	1.5	16.2	1.6	17.7	2.2	21.1	2.2	1.10	1.27	1.94
Rain spell intensity (RSI, mm/day)	7.9	1.2	7.5	1.2	8.3	1.1	6.3	0.9	7.0	0.6	8.1	0.9	8.5	0.7	9.3	0.7	1.11	1.21	1.48
Relative contribution of rain spells longer than 3 days (%)	41.9	11.8	42.5	11.5	41.2	12.1	32.0	10.7	41.4	9.8	41.9	11.9	44.7	13.2	48.4	9.4	0.97	1.08	1.51

The precipitation record shows an increase in the rainfall conditions between a drier earlier period (1873–1942; SP1) and a wetter recent period (1943–2012; SP2). The mean annual total of SP1 is 893.3 mm, whereas SP2 shows a value of 1001 mm, but with the RSL, it reduced by 9 days. The precipitation increase is mainly a consequence of an increase of the RSY, RSI and, to a lesser extent, in the NRS. Conversely, the RSD is unchanged between the two periods (Table 1). The mean values of all the analysed parameters (with the exception of the RSL and RSD) are slightly higher during SP2 but present a lower coefficient of variation, which highlights a larger heterogeneity and variability of the rainfall regime throughout SP1.

As mentioned above, the Ponta Delgada precipitation regime displays similar characteristics with Mediterranean climate behaviour (e.g. Reiser and Kutiel, 2009) in spite of the ca. 3000 km between them, although both regions are within similar latitudinal bands. Wigley and Farmer (1982) defined the Mediterranean climate as having winter season rainfall more than three times that of summer. Kutiel and Trigo (2014) later defined this as the Mediterranean Climate Index (MCI). The MCI is an index that describes the level of seasonality of the rainfall. This index calculates the ratio between winter and summer rains. According to it, an $MCI < 1$ means summer wetter than winter, $1 \leq MCI < 3$ winter slightly wetter than summer, $3 \leq MCI < 10$ dry summer and $10 \leq MCI$ extremely dry summer. A location with an $MCI \geq 3$ is considered to have a so-called Mediterranean climate. The MCI in Ponta Delgada is 3.02 and therefore, fits well, albeit by a minimal margin, within the definition of the Mediterranean climate type previously defined. The MCI of SP1 is 2.69, whereas SP2 shows a MCI of 3.34, indicating a change towards more 'Mediterranean' conditions, with a larger concentration of precipitation in winter.

A priori, dryness is not a problem in the Azores Archipelago, but islands are very sensitive to climate changes, especially to changes in the hydrological availability. Thus, the dryness conditions (severity, consistency and temporal uncertainty) were analysed using the DDSLR approach [see Kutiel and Trigo (2014) for further details]. In Ponta Delgada, the longest DDSLR (severity) occurs at the end of August and the beginning of September, and it spans 63 days (Figure S1, Supplementary Information). We can expect a DDSLR longer than 30 days on average once every 25 years. The temporal uncertainty, i.e. the span of time when such a DDSLR has been observed, is from 14 April to 21 September, over a period of 161 days. Similarly, the only observed example of a DDSLR longer than 60 days occurred during the 3 days 30 August–1 September, and therefore, the most likely time for very high DDSLR values would be late August/early September (Figure S1). The dry period started 60 days earlier (around the end of June or beginning of July) and reached its maximum (more than 60 days) during these 3 days. These DDSLR values are considerably lower compared with those obtained for Lisbon (Kutiel and Trigo, 2014), indicating wetter conditions in Ponta Delgada.

4. Inter-annual variability

Table 1 presents the analysed precipitation parameters studied for the five 'wetness/dryness' categories (Section 2.2). It can be observed that the mean total rainfall during very wet years was 1302 mm, around twice the mean of the very dry years, which had a mean of 644 mm. All parameters, with the exception of the RSL, show an increase from the very dry years towards the very wet years. The NRS has the lowest very wet/very dry ratio with values of 1.04. This means there was a slight mean increase of 4% in the number of rain spells. In contrast, when only long rain spells (RSD >3) were considered, their number increased considerably, from a mean of 4.9 in the very dry years to 10.4 in the very wet years, corresponding to an increase of more than two times. These long rain spells, which consist only of 28.6% of the total NRS in the very dry years, nearly doubled their percentage to 42.4% in the very wet years (Figure 2). The RSD and RSI represent a moderate increase between those two categories of years between 1.3 and 1.5. The RSY represents the highest ratio between the two (besides the NRS >3) and was doubled in the very wet years compared with the very dry years, 21.1 and 10.9 mm, respectively. Hence, these five categories have very different RSY values. However, even though their NRS values slightly increase from very dry to very wet years, they overlap to a large extent (Figure 3). This implies that while the RSY can be used as a good index of the rainfall variability, the NRS cannot serve as an indicator to differentiate between these years and has an insignificant impact on the annual total.

The percentage of the total rainfall contributed by rain spells of various durations is represented by the relative contribution. The relative contribution of long rain spells (RSD > 3 days) is usually higher in more humid stations, whereas, in drier locations, the main contribution to the annual total is made by very short rain spells of 1 or 2 days (Reiser and Kutiel, 2012; Kutiel and Trigo, 2014; Kutiel *et al.,* 2014). This is reflected in this study by dividing the entire dataset into five rainfall categories as explained earlier. Although Ponta Delgada is considered to be a humid location, the maximum contribution varies according to the different categories. In very dry or dry years, the maximum contribution is by rain spells of 1 day as in arid regions, whereas in normal, wet and very wet years, the distributions resemble humid regions (Figure 2).

If we compare the relative contribution of short rain spells ($RSD \leq 3$ days) and very long rain spells ($RSD > 7$ days), we find that the first decreases from more than two-thirds (65.2%) in very dry years to slightly over half (51.3%) in very wet years. By contrast, the relative contribution of very long rain spells is doubled from 4.8% in very dry years to 9.5% in very wet ones (Figure 2).

These results are in agreement with those obtained recently by Reiser and Kutiel (2012) with an application for the entire Mediterranean area, but considering a much shorter period, and by Kutiel and Trigo (2014) for a similar long-term period in Lisbon. This means that wet or

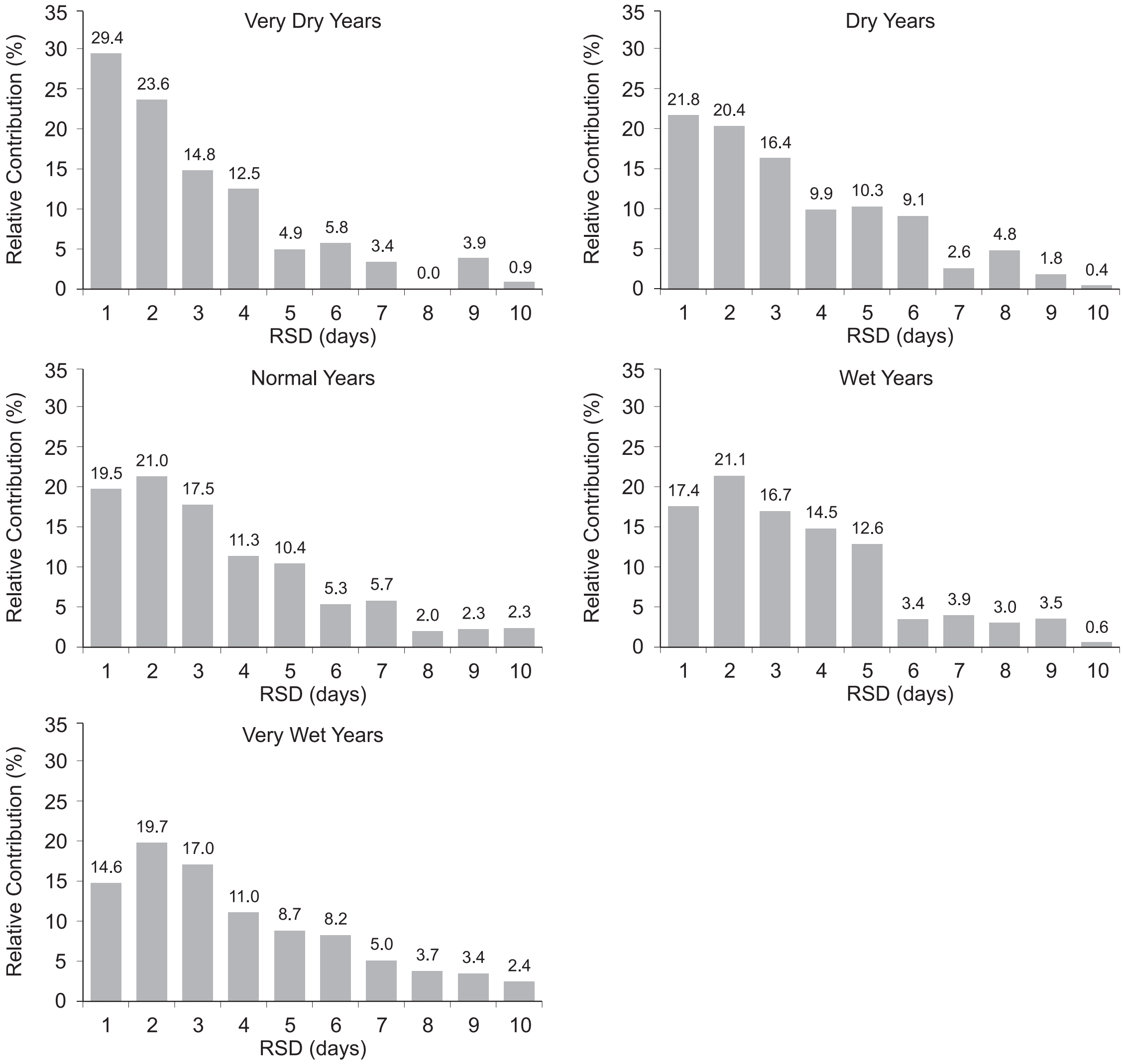

Figure 2. Mean relative contribution of rain spells of various durations in the very dry, dry, normal, wet and very wet years.

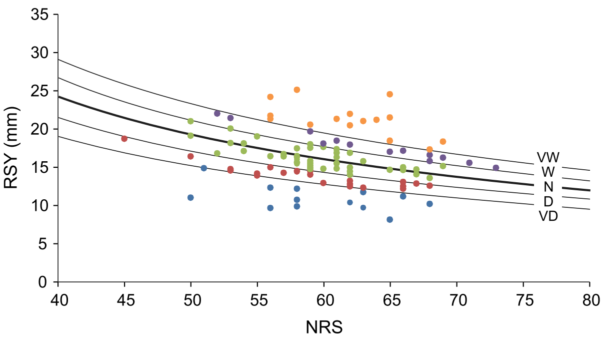

Figure 3. The distribution of very dry, dry, normal, wet and very wet years according to their NRS and RSY. The curved lines represent isohyets of annual rainfall delimiting very dry, dry, normal, wet and very wet conditions.

very wet years in Ponta Delgada are caused primarily by a considerable increase in the RSY or vice versa, whereas dry or very dry years are caused mainly by a considerable reduction of the RSY and not so much by a strong reduction of the NRS.

5. Intra-annual variability

Previous works (e.g. Paz and Kutiel, 2003; Kutiel and Trigo, 2014) have presented the range of dates for which a certain rainfall percentage was accumulated and/or the range of accumulated percentage obtained for a given date of the hydrological year. This kind of analysis allows us to extract a considerable amount of information from the daily series (it would be unfeasible with monthly values only) and represents a highly instructive way to analyse the intra-annual rainfall variability.

In Ponta Delgada, the median date when 50% of the annual (hydrological year) rainfall was accumulated (mid-season date) is 1 January. However, the range of the dates, from the year when the accumulation of 50% was the earliest to the year when it happened latest, ranged from 16 October to 21 February. This means that the mid-season date varied over a range of 128 days, or more than 4 months, which is almost half of the entire rainy season in Ponta Delgada. However, when this range is examined between more conservative percentiles (10th and the 90th), its temporal span is reduced by half and

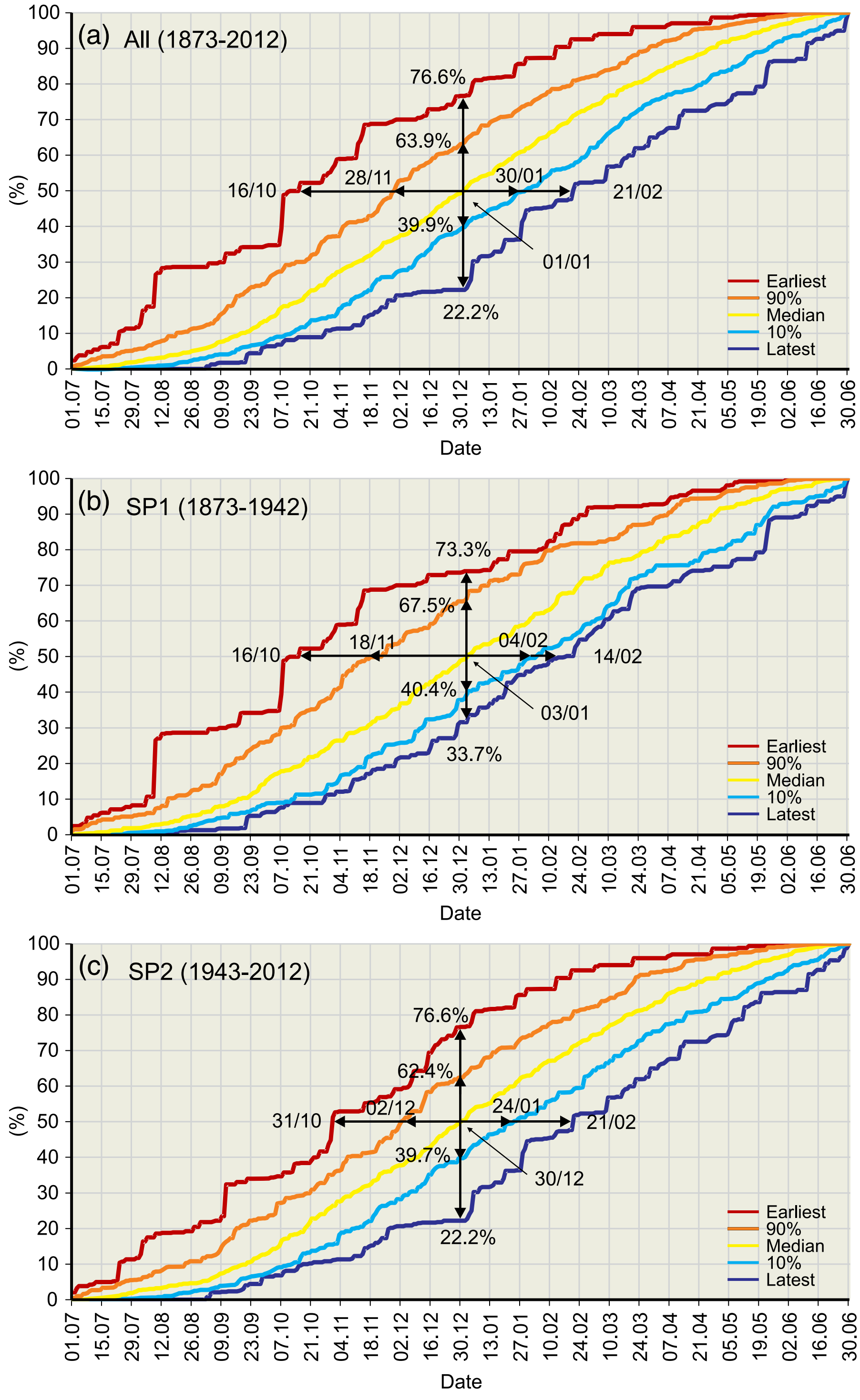

Figure 4. Mid-season dates of earliest, 10%, median, 90% and latest years and the respectively accumulated percentages, for (a) the entire period (1873–2012), (b) SP1 (1873–1942) and (c) SP2 (1943–2012).

varies between 28 November and 30 January, around 2 months (Figure 4).

The intra-annual variability can also be analysed by examining the range of accumulated percentage for any given date, e.g. at the mid-season date. When the entire range of years are considered, in the first half of the rainy season, between 22.2 and 76.6% of the annual total was accumulated, i.e. a range of 54.4% of the annual rainfall for that date. For the range of the 10th and 90th percentiles, this span of percentages is reduced to less than half (24%), varying from 39.9 to 63.9% (Figure 4).

These results show that when the intra-annual variability is examined – without the influence of the earliest and latest 10th percentile years – the series variability is reduced. There is an uncertainty of 2 months in the occurrence of the mid-season date and about a quarter of the annual total by the median mid-season date. Nonetheless, when all years are considered, these ranges are doubled,

Table 2. Spearman's rank correlation coefficients associated with seasonal series of precipitation and large-scale modes (only large-scale modes with significant values are shown).

Precipitation	1873–2012		1873–2012		1900–2012		1873–2012	
	NAO	|NAO| > 0.5	AMO	|AMO| > 0.5	PDO	|PDO| > 0.5	ENSO	|ENSO| > 0.5
Winter (DJFM)	**−0.66**	**−0.74**	0.14	0.17	−0.06	−0.10	0.13	0.09
Summer (JJAS)	**−0.37**	**−0.51**	**0.21**	**0.23**	0.17	0.19	0.18	0.19

Grey, regular and bold numbers indicate values at $p > 0.05$, $p < 0.05$ and $p < 0.01$, respectively.

representing slightly more than 4 months in the occurrence of the mid-season date and more than half of the annual total by the median mid-season date. Therefore, the variability induced by 20% of the extreme years is almost equal to that induced by the remaining 80% (Figure 4).

Differences in the mid-season date between SP1 and SP2 are significant (Figure 4). These differences are especially accentuated in the range of the dates of the mid-season date and in the range of rainfall percentage accumulated by that date. Despite the smaller number of years included, SP1 shows higher ranges of variability of the dates of the mid-season date than SP2. This range is 78 days when it is calculated between the 10 and 90% percentiles and 121 days if the extreme years, from the earliest to the latest, are also included. These values decrease considerably to 53 and 113 days, respectively, for SP2. If the accumulated rainfall by the median mid-season date is considered, SP1 displays a higher range (27.1%), without the 10% earliest and latest years, than SP2 (22.7%). However, if we consider all the years, the SP2 range is higher (54.4%) than the SP1 range (39.6%). Thus, the range of the dates of the mid-season date for SP1 presents a ratio of 1.55 between all the years and disregards the 10% earliest and latest years, whereas this ratio is 2.13 for SP2. Similarly, the range of rainfall percentage accumulated by the median mid-season date for SP1 shows a ratio of 1.46 between all the years and rejects the 10th and the 90th percentiles, whereas this ratio is 2.40 for SP2. This would mean and confirm that the so-called 'normal' conditions are more unstable for SP1, while the extreme years are more variable and uncertain for SP2 (Figure 4).

6. Impact of large-scale modes of climate variability on rainfall regime

Spearman's correlation coefficients (ρ) between the extended (DJFM and JJAS) seasonal large-scale modes and precipitation were computed with the seasonal data of all the available years (Table S1). However, only large-scale modes displaying significant correlations (p-value < 0.05) are presented and discussed (Table 2). In addition, we defined the seasonal high and low large-scale mode composites to be constituted by all winters and summers, with the corresponding indices higher than 0.5 and lower than −0.5, respectively, i.e. non-neutral conditions.

The NAO index (NAOi) shows the highest correlations of all the large-scale modes with ρ values of −0.66 for winter and −0.37 for summer (Figures 5(a) and (b)). These ρ values rise to −0.74 and −0.51 if only seasons with non-neutral NAOi values are considered. The second large-scale mode with significant correlation coefficients is the AMO index (AMOi). The ρ value between the AMOi and the DJFM precipitation is 0.14 (p-value < 0.05), rising to 0.17 (p-value < 0.05) if only seasons with non-neutral AMOi values are taken into account. The JJAS ρ values obtained with the AMOi are higher, with $\rho = 0.21$ and $\rho = 0.23$, respectively. The PDO index (PDOi) also displays relatively small albeit significant correlations (p-value < 0.05) but only for JJAS with ρ values of 0.17 and 0.19 if we consider all the summers or only the summers with non-neutral PDOi values, respectively. Finally, the ENSO index (ENSOi) is the last large-scale mode that shows significant correlation (p-value < 0.05) with seasonal precipitation in Ponta Delgada. The summer precipitation correlates positively with the ENSOi both if we consider every summer ($\rho = 0.18$) and if we consider only the summers with non-neutral ENSOi values ($\rho = 0.19$). By contrast, the EA, the SCAND and the AO indexes do not show any significant correlation between them and the seasonal precipitation. This lack in the influence of the EA and SCAND is a major difference to what can be seen over the Iberian Peninsula where these two large-scale mode patterns play a major role in shaping the climate, as shown with low (Trigo *et al.,* 2008) and high (Jerez and Trigo, 2013) resolution climate datasets. This may simply reflect the fact that the SCAND major regions of influence are located too far from the Azores Archipelago and also that the island falls inside the area of neutral influence of the EA pattern, i.e. the area where the influence of EA in precipitation switches from positive to negative.

Nevertheless, the link between the Ponta Delgada precipitation and the large-scale modes has not been constant through time (Figures 6(a) and (b)). The non-stationary relationship between the NAOi and environmental variables has already been pointed out in the Azores Archipelago (Cropper and Hanna, 2014), the North Atlantic sector (García Molinos and Donohue, 2014) and continental Europe (e.g. Trigo *et al.,* 2004; Vicente-Serrano and Lopez-Moreno, 2008). Here, we also identify a non-stationary pattern on the precipitation–NAOi relationships. The running correlation (19-year sliding window) between the winter (Figure 6(a)) and summer (Figure 6(b)) Ponta Delgada precipitation and the NAOi illustrates a clear non-stationary behaviour of the relationship. The winter NAOi–precipitation correlation shows a fairly constant

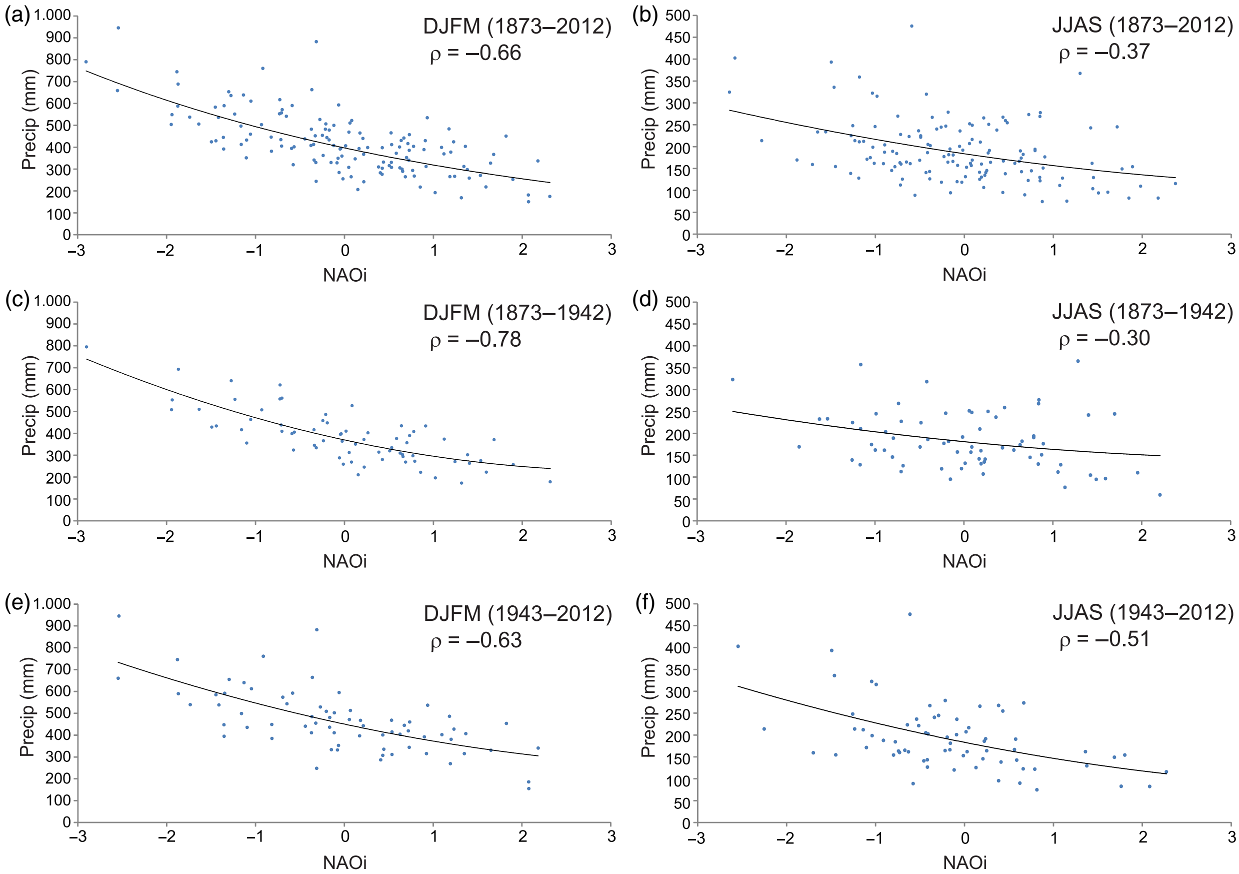

Figure 5. Correlation between extended winter (DJFM) and summer (JJAS) precipitation (mm) and NAOi for the entire studied period (a and b), SP1 (c and d) and SP2 (e and f).

behaviour until approximately 1930 before declining for the following 20 years. The lowest values of correlation are observed around the 1950s, with a minimum of −0.37. After 1950, an increasing trend is recorded, achieving the maximum correlation values (−0.84) in 1975 followed by a period of weaker correlations with the values rising again since 2000. The temporal evolution of the correlation coefficient between summer precipitation and NAOi is more oscillatory. These correlations are also negative but with smaller values, with more restricted significant periods between 1886–1909 and 1941–1997. An increasing trend can be observed from 1886 to 1897 before declining until 1909. A similar pattern can be seen from 1941 to 1997 with an increasing trend until 1970 and a continuous weakening until the end of the record. The range of significant correlations is from −0.35 to −0.72 and −0.35 to −0.84, respectively. Several authors (e.g. Pauling *et al.,* 2006; Comas-Bru and McDermott, 2014) linked this changing nature to variations in the spatial configuration of the NAO and the increment of the role played by the other climatic circulation modes. The role of the other significant large-scale modes (AMO, ENSO and PDO) for periods of lower NAO impact seems clear for the North Atlantic sector in summer. Figure 6(b) highlights the fact that when the NAO impact does not achieve a statistically significant role, other large-scale modes increase their influence on the precipitation. This behaviour can be observed during the first decades (1910–1940) and the last years (1997–2005). Conversely, the large influence of the NAO on winter precipitation seems to mask the role played by the other large-scale modes for winter. Only prompt peaks of AMO influence over winter precipitation (around 1905, 1965, 1988 and 1995) seem to overlap with the winter NAO impact, while the impact of the ENSO and PDO on the winter precipitation is much lower (Figure 6(a)).

As previous works (e.g. Trigo *et al.,* 2008; Bladé *et al.,* 2012; Comas-Bru and McDermott, 2014) pointed out, the NAO is the main large-scale mode controlling the seasonal precipitation over the North Atlantic region. Our results highlight this fact, showing that up to 50% of the variance of the winter precipitation can be explained by the NAO for winters with positive and negative values. In summer, the NAO role is also significant although it is less prominent, and the role of other large-scale modes (AMO, ENSO and PDO) should not be neglected. These results also highlight the non-stationary behaviour of the NAO and precipitation relationship in the Azores Archipelago, which was already pointed out for other climate variables (i.e. temperature) in previous works (e.g. Cropper and Hanna, 2014).

6.1. The seasonal NAO influence

As outlined above, the ρ values for extended winter and summer precipitation in Ponta Delgada and the corresponding NAOi are −0.66 and −0.37 for the 140-year

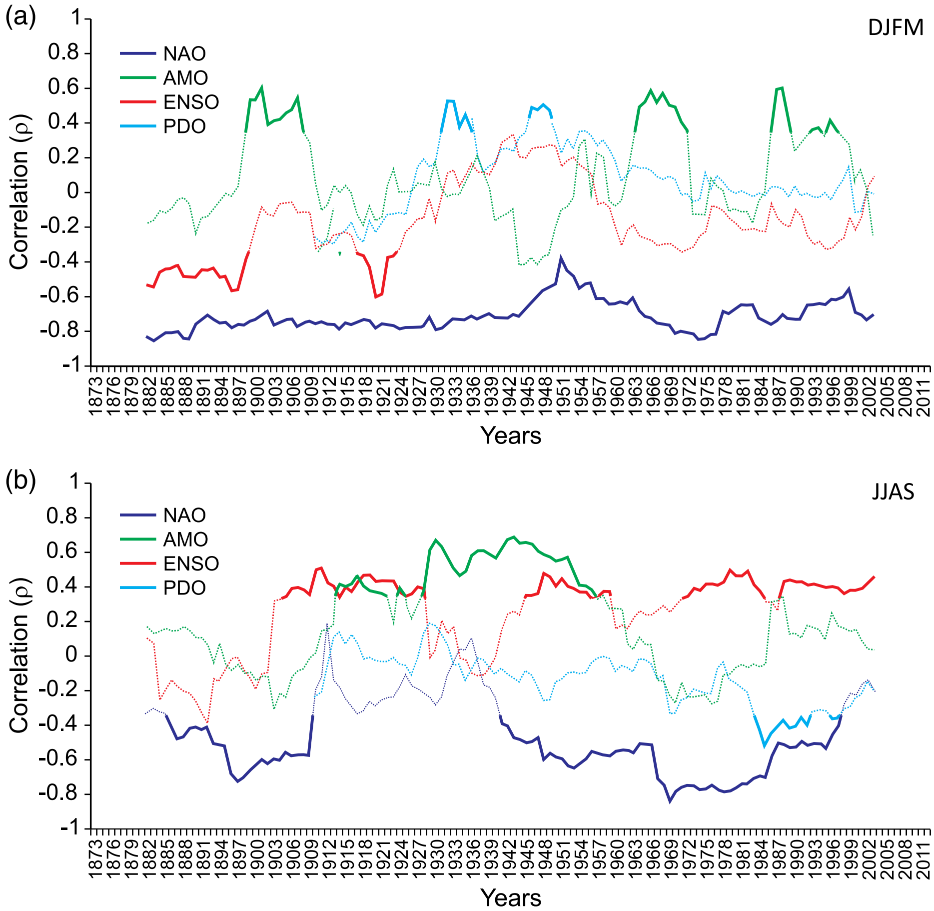

Figure 6. Running correlation (19-year sliding window) between (a) extended winter (DJFM) and (b) summer (JJAS) precipitation and the corresponding seasonal NAO, AMO, ENSO and PDO indexes. Dotted lines indicate no significant values.

period (from 1873 to 2012). These values are similar to those previously presented by Cropper and Hanna (2014) for winter and summer (−0.64 and −0.31). The results obtained here with extended precipitation and NAOi data (~150 years) are in better agreement with the results from the Portuguese mainland area (Trigo *et al.,* 2004; Trigo *et al.,* 2005) than the values previously obtained from the Azores Archipelago (Marques *et al.,* 2008) with shorter datasets (~65 years).

Figure 5 shows the linear correlation between NAOi and precipitation time series. The correlations between winter NAOi and precipitation for SP1 and SP2 are −0.78 and −0.63, respectively (Figures 5(c) and (d)). The correlations between summer NAOi and precipitation are much lower with values of −0.30 and −0.51 for SP1 and SP2, respectively (Figures 5(e) and (f)). It is important to note that the relationship between these time series is better represented by a non-linear, second-degree polynomial curve. This is due to the non-stationary shape of the precipitation distribution moving from high to low NAO index classes similar to those obtained for mainland Portugal by other authors (e.g. Trigo *et al.,* 2005).

In addition, between 1873 and 2012, the number of winter seasons with high NAOi (49; SP1 = 26 and SP2 = 23) is higher than the number characterized by a low NAOi (42; SP1 = 21 and SP2 = 21), whereas the number of summer seasons with high NAOi (37; SP1 = 22 and SP2 = 15) is lower than the number distinguished by a low NAOi (44; SP1 = 20 and SP2 = 24) (Table 3). These results unveil a higher prevalence of positive NAO phases (NAO^+) during winter and a higher occurrence of negative NAO (NAO^-) during summer.

Table 3 also summarizes the distribution of the categorized seasons (very dry, dry, normal, wet and very wet) associated with both positive and negative NAO composites throughout the entire analysed period (1873–2012), SP1 (1873–1942) and SP2 (1942–2012). It can be observed that there are no very wet winters and only one wet winter with NAO^+. However, up to 27 dry and very dry winters occur with NAO^+ and most of them (67%) during SP1. On the contrary, the probability of a very dry or dry winter during the negative phase of the NAO is almost zero, with only one dry winter occurring during SP1, while wet and very wet winters are common. Very wet winters account for almost 60% of all NAO^- years during SP2. Although a similar pattern is depicted for summer, the NAO influence is less apparent during this season. Summers with NAO^+ are rarely wet or very wet (total period = 16%; SP1 = 22% and SP2 = 7%), and they are usually very dry or dry (total period = 57%; SP1 = 50% and SP2 = 67%). Summers with NAO^- are usually normal (50%) but with more than double the occurrence of very

Table 3. Number of very dry, dry, normal, wet and very wet seasons of negative and positive phases of the NAO for the entire period (1873–2012) and the sub periods 1 (1873–1942) and 2 (1943–2012).

		Winter (DJFM)				Summer (JJAS)		
		1873–2012	1873–1942 SP1	1943–2012 SP2		1873–2012	1873–1942 SP1	1943–2012 SP2
NAO > +0.5	VD (<284 mm)	14	11	3	VD (<117 mm)	12	7	5
	D (284–353 mm)	13	7	6	D (117–152 mm)	9	4	5
	N (353–493 mm)	21	8	13	N (152–223 mm)	10	6	4
	W (493–562 mm)	1	0	1	W (223–259 mm)	2	2	0
	VW (>562 mm)	0	0	0	VW (>259 mm)	4	3	1
		$N = 49$	$N = 26$	$N = 23$		$N = 37$	$N = 22$	$N = 15$
NAO < −0.5	VD (<284 mm)	0	0	0	VD (<117 mm)	2	1	1
	D (284–329 mm)	1	1	0	D (117–152 mm)	4	4	0
	N (353–493 mm)	14	9	5	N (152–223 mm)	22	7	15
	W (493–562 mm)	11	7	4	W (223–259 mm)	7	5	2
	VW (>562 mm)	16	4	12	VW (>259 mm)	9	3	6
		$N = 42$	$N = 21$	$N = 21$		$N = 44$	$N = 20$	$N = 24$

wet and wet summers (36%) than very dry and dry (14%) ones. This contrast is much clearer for SP2 with only 4% of very dry and dry years, while the summers with NAO$^-$ during SP1 show up to 25% of very dry and dry years.

Hence, the results obtained here prove that a large fraction of the inter-annual variability of seasonal precipitation in the region is largely modulated by the NAO mode. Thus, as it is expected, seasons (winters and summers) dominated by negative NAO phases present higher mean precipitation values than the corresponding positive NAO phases, with the obtained differences being very significant (mean differences of 38% for winter and 29% for summer). However, it is worth noting that the negative NAO phase influence in summer is unclear, and its role could be different during the early 20th century (Table 3 and Figure 6(b)).

6.2. Extreme rainfall events and links with the NAO

The characterization of the severe precipitation events has been performed at two temporal scales; days and months with precipitation values above 75 and 250 mm (roughly above the percentile 99th), respectively, have been selected to explore the NAO influence on them.

Table 4 shows the recorded 21 months with precipitation values over 250 mm. The month with the highest precipitation (502.3 mm) was recorded in the 19th century (November 1879). However, only 6 months are from the previously defined SP1, whereas 15 months are distributed through the second half of the record (1943–2012), with 4 months of extreme precipitation during the last decade. This pattern highlights a clear increase of severe precipitation months from the last decades of the 19th century towards the present.

The NRD for this set of months is highly variable with values between 8 and 27 distributed in rain spells with a mean duration ranging between 1 and 9 days. The RSY oscillates between 31 and 114 mm, and values of RSI (mm day^{-1}) range between 10 and 39.3. The characterization of these extreme rainfall months is, therefore, difficult as there is no clear pattern. There are months mainly characterized by continuous precipitation through the entire month and, conversely, months with few but very intense days of precipitation (Table 4). Nonetheless, the NAOi values present a high negative correlation ($\rho = -0.79$) with the RSD; in other words, the more negative the NAOi, the less concentrated the precipitation (Figure 7(a)). This pattern is confirmed by the positive correlation between the NAOi and the intensity of precipitation (RSI) shown by the Figure 7(b), where months with more negative NAOi values display, mostly, smaller amounts of precipitation per day. Hence, on monthly scales, severe precipitation conditions (>250 mm) are directly linked to NAO negative conditions, following a clear pattern of a stronger (negative) NAOi leading to a more regular distribution of precipitation throughout the month.

On the other hand, there are several months where a large amount of precipitation (>75 mm) is accumulated in a single day. The daily extreme precipitation is also clearly associated with the NAO signal but not with the NAO magnitude (Figures 7(c) and (d)). Thus, more than 69% of the days with precipitation over 75 mm correspond to months with negative phases of the NAO (Figure 7(c)). This clear relationship is even stronger at daily resolution, with 82% of the days coinciding with negative values of the NAOi (Figure 7(d)). In contrast, there is no clear relationship between the amount of precipitation and the NAO magnitude (Figures 7(c) and (d)).

Long-term variability of these extreme precipitation days follows a similar pattern to the monthly scale extreme rainfall events. An increasing recurrence of the extreme precipitation days is reflected through the entire studied period (1873–2012), with almost 35% of the cases concentrated in the last 2 decades. The last decades have seen an enhancement of very extreme precipitation events (often associated with tropical storms including a few hurricanes) over the North Atlantic sector. This increase in the frequency and intensity of Atlantic tropical cyclones has been linked to the global rise of the sea-surface temperatures in the current global warming context (Emanuel,

Table 4. Amount of precipitation (mm), number of rain days, number of rain spells, rain spell duration (days), rain spell yield (mm), rain spell intensity (mm/day) and monthly NAO index for months ($n = 22$) with extreme values of precipitation (>250 mm).

Months with precipitation above 250 mm	11/1879	1/1881	10/1887	08/1919	12/1925	10/1933	12/1961	11/1963	10/1966	10/1968	11/1980
Precipitation (mm)	502.3	341.7	439.5	290.3	287.0	439.5	302.5	266.9	304.0	251.0	282.0
Number of rain days	ND	27	14	9	22	17	25	16	15	14	16
Number of rain spells	ND	3	6	6	6	6	6	6	6	8	8
Rain spell duration (days)	ND	9	2	2	4	3	4	3	3	2	2
Rain spell yield (mm)	ND	113.9	73.3	48.4	47.8	73.3	50.4	44.5	50.7	31.4	35.3
Rain spell intensity (mm day^{-1})	ND	12.7	31.4	32.3	13.0	25.9	12.1	16.7	20.3	17.9	17.6
Monthly NAO index	−3.96	−6.03	−3.13	0.77	−3.85	−1.87	−4.11	−1.21	−3.08	−2.54	−2.84

Months with precipitation above 250 mm	11/1981	1/1987	10/1993	12/1996	9/1997	12/2001	3/2005	12/2009	3/2010	12/2010
Precipitation (mm)	251.0	288.2	253.8	350.4	314.0	454.8	254.0	252.4	308.9	385.6
Number of rain days	15	19	16	22	8	20	20	25	20	27
Number of rain spells	7	4	7	4	6	5	7	6	8	4
Rain spell duration (days)	2	5	2	6	1	4	3	4	3	7
Rain spell yield (mm)	35.9	72.1	36.3	87.6	52.3	91.0	36.3	42.1	38.6	96.4
Rain spell intensity (mm day^{-1})	16.7	15.2	15.9	11.4	39.3	22.7	12.7	10.1	15.4	14.3
Monthly NAO index	−0.93	−3.67	−3.20	−3.27	−0.87	−3.72	−3.23	−3.99	−1.74	−4.98

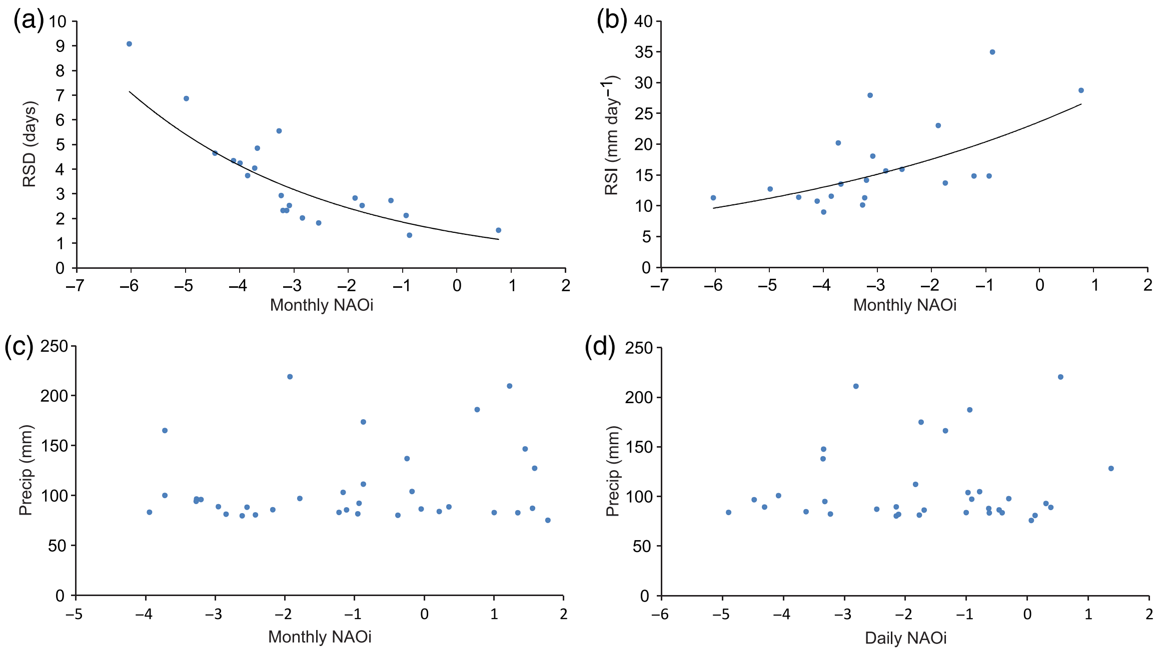

Figure 7. Relationship of the NAOi and the RSD (a) or the RSI (b) for months ($n = 21$) with precipitation above 250 mm. Relationship between the precipitation (mm) of days ($n = 35$) above 75 mm and the monthly (c) or daily (d) NAOi.

2005; Elsner *et al.,* 2008). From Ponta Delgada precipitation records, 6 out of 10 days of maximum precipitation (>110 mm) correspond to dates with tropical storms over the North Atlantic sector, and nearly half of the days with precipitation above 75 mm are concurrent with detected cyclonic conditions (Table 5 and Figure 8). Previous studies (e.g. Kossin *et al.,* 2010) illustrated the role of the NAO influence, among other factors, on the North Atlantic hurricanes. These authors related the May–June NAOi with an increased hurricane occurrence, increasing the number of storms as the NAO tends towards its negative phase. However, as it has been pointed out above, in our case, the extreme precipitation days are not directly related to the NAO magnitude but to the sign of the NAOi. This is clear with the extreme precipitation events triggered by tropical cyclone conditions (Table 5). The link between negative NAO phases and this type of days is higher on a daily scale, decreasing if we consider the NAO conditions during the month when the days are recorded and/or the same year May–June NAO values. Thus, the relationship between the hurricane conditions and the daily extreme precipitation in the Azores Archipelago seems clear, but the type,

Table 5. Date and amount of precipitation (mm); date, type and name of the hurricane; and values of daily, monthly and May–June NAO index for extreme rainfall days (>75 mm) corresponding with tropical cyclonic conditions over the North Atlantic.

Year	Precipitation date	Precipitation (mm)	Hurricane date	Maximum type	Name	Mean daily NAOi	Mean monthly NAOi	Mean May–June NAOi
1933	14/10	218.8	01/10–09/10	3		−1.29	−1.92	1.35
1934	23/10	82.8	19/10–23/10	TS		−0.41	1.01	0.60
1948	11/10	127.2	03/10–16/10	4		0.21	1.65	−0.11
1956	02/11	146.6	30/10–07/11	4	GRETA	−1.79	1.45	3.04
1966	08/09	83	21/08–07/09	2	FAITH	−0.41	−1.13	1.72
1968	15/10	88.2	13/10–21/10	1	GLADIS	−0.66	−2.58	0.00
1978	16/10	80.1	13/10–17/10	TD		−1.68	−0.37	1.34
1980	27/11	81.3	25/11–28/11	1	KARL	−1.38	−2.71	−0.24
1981	03/11	92.1	29/10–02/11	TS	JOSE	0.62	0.80	−0.95
1986	15/08	83.2	13/08–30/08	1	CHARLEY	−2.46	−3.78	1.51
1996	21/10	87.1	14/10–29/10	3	LILI	0.39	1.55	−0.58
1997	10/09	173.6	03/09–19/09	3	ERIKA	−0.53	−0.73	−2.52
1997	11/09	111.3	03/09–19/09	3	ERIKA	−0.53	−0.73	−2.52
1998	01/10	209.6	21/09–04/10	2	JEANNE	−1.44	1.03	−0.63

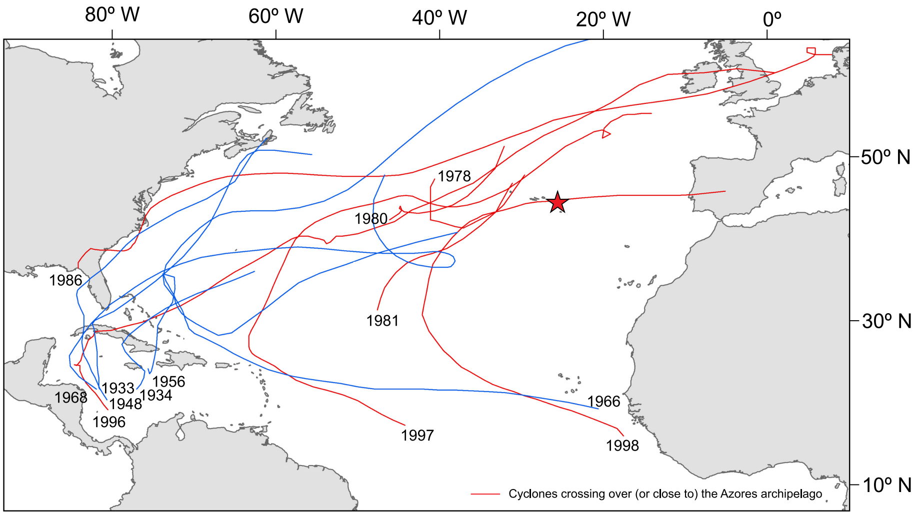

Figure 8. Tracks of tropical cyclones linked to days of severe precipitation (>75 mm).

duration and trajectory of the related hurricanes are variable, making it difficult to establish a clear pattern.

7. Conclusions

The central goal of the present study was to give a detailed view of the precipitation trends and changes in the Azores Archipelago, on daily/monthly scales, using the recently digitized long (∼140 years) daily dataset from Ponta Delgada. Additionally, we aimed to test the influence of a high number of large-scale modes over the rainfall regime.

The main conclusions of the present study may be summarised as follows:

- The rainfall conditions evolved from a drier (893.3 mm year^{-1}) first half (1873–1942) to a wetter (1001 mm year^{-1}) second half of the record (1943–2012) with a larger heterogeneity and variability in the rainfall regime during the former. The relative occurrence of very dry and dry years decreases almost by half between the first and the second half of the record, whereas the relative presence of wet and very wet years increases up to three times. The precipitation increase results, to a large extent, from a considerable rise of the intensity of the precipitation rather than the number and duration of the rain spells.
- The recurrence of dry periods longer than a month is, on average, once in 25 years, whereas dry periods longer than 2 months are very rare (around once in a century). The range of time when dry periods can be expected is from the middle of spring until the middle of summer. Despite being located in the mid-Atlantic, the Ponta Delgada precipitation regime is very similar to the Mediterranean climate type seasonal distribution with the rainfall during the winter season being more than three times that of summer, and therefore, similar sustainability policies should be considered for the studied region than the ones discussed for the Mediterranean regions.
- The intra-annual variability of precipitation is large and mainly accounted for by extreme years (those which

fall in the 10th and 90th percentiles). The range of variation of the extreme years (20% of the years) is almost the same than the one induced by the remaining years (80% of the years). The intra-annual baseline conditions are more unstable for the earlier studied subperiod (1873–1942). Conversely, the extreme years are more variable and uncertain for the second subperiod (1943–2012).

- Most of the months with the highest values of precipitation (>250 mm) are distributed through the second half of the record (1943–2012) with five of them occurring during the last decade. Severe precipitation days (>75 mm) follow a similar pattern to the monthly scale extreme rainfall events with more than a third of the cases in the last 2 decades. Most of days (6 of 10) with severe precipitation correspond to dates with cyclonic conditions over the North Atlantic.
- The large-scale modes exert a discernible influence on the rainfall regime of the Azores Archipelago. The results show that up to 50% of the winter precipitation variance can be explained by the NAO. In summer, although less prominent, the NAO influence is also significant. Besides the NAO, the role of a few other large-scale modes of climate variability (AMO, ENSO and PDO) should not be ignored. Nevertheless, we must acknowledge that other large-scale modes that play an important role in southwestern Europe, such as EA and SCAN, do not significantly influence the precipitation regime in the Azores Archipelago. Seasons dominated by negative NAO phases present higher mean precipitation values than the corresponding positive NAO phases. Nonetheless, the negative NAO phase influence in summer is unclear, and its role could be different during the early 20th century. Furthermore, when the NAO influence becomes weaker, other large-scale modes' influences appear to increase, highlighting the non-stationary influence of the large-scale modes on precipitation.
- Severe precipitation conditions are usually consistent with negative NAO phases. In general, more negative values of NAO are associated to more continuous, but not necessarily intense, rainfall events. There is no clear link between the amount of precipitation on rainy days and the magnitude of the NAO index.

Our study of daily precipitation data from Ponta Delgada has extended significantly in time for the assessment of the precipitation regime in the Azores Archipelago, particularly in what concerns the comprehensive analysis of the new daily precipitation since 1873. The results become more relevant owing to the limited availability of long-term daily instrumental precipitation records, particularly in oceanic regions. We are confident that this study delves into unknown aspects of its short-term rainfall characteristics, including changes throughout time and the non-stationary impacts of the large-scale modes of variability on these rainfall characteristics.

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Supporting Information

The following supporting information is available as part of the online article:

Figure S1. The distribution and characteristics of the DDSLR for the entire analysis period (1873–2012).

Table S1. Summary of the all datasets used in this work.

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