WEATHER REGIMES AND THEIR CONNECTION TO THE WINTER RAINFALL IN PORTUGAL

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ABSTRACT

Wintertime rainfall over Portugal is strongly coupled with the large-scale atmospheric flow in the Euro-Atlantic sector. A $K$-means cluster analysis, on the space spanned by a subset of the empirical orthogonal functions of the daily mean sea-level pressure fields, is performed aiming to isolate the weather regimes responsible for the interannual variability of the winter precipitation. Each daily circulation pattern is keyed to a set of five weather regimes (C, W, NAO−, NAO+ and E). The dynamical structure of each regime substantiates the statistical properties of the respective rainfall distribution and validates the clustering technique. The C regime is related to low-pressure systems over the North Atlantic that induce southwesterly and westerly moist winds over the country. The W regime is characterized by westerly disturbed weather associated with low-pressure systems mainly located over northern Europe. The NAO− regime is manifested by weak low-pressure systems near Portugal. The NAO+ regime corresponds to a well-developed Azores high with generally settled and dry weather conditions. Finally, the E regime is related to anomalous strong easterly winds and rather dry conditions. Although the variability in the frequencies of occurrence of the C and NAO− regimes is largely dominant in the interannual variability of the winter rainfall throughout Portugal, the C regime is particularly meaningful over northern Portugal and the NAO− regime acquires higher relevance over southern Portugal. The inclusion of the W regime improves the description of the variability over northern and central Portugal. Dry weather conditions prevail in both the NAO+ and E regimes, with hardly any exceptions. The occurrence of the NAO+ and the NAO− regimes is also strongly coupled with the North Atlantic oscillation. Copyright © 2005 Royal Meteorological Society.

KEY WORDS: winter precipitation; rainfall regimes; large-scale circulation; Portugal; $K$-means

1. INTRODUCTION

Rainfall is of the utmost importance, as it is a primary variable in most hydrological models. Owing to the Mediterranean-type climatic conditions that prevail in Portugal, winter precipitation is the determining factor in the budgets of the hydrological cycle. Moreover, wintertime rainfall amounts play a key role in triggering drought episodes, because although natural and socio-economic systems are already prepared to cope with the Mediterranean summer dryness, they are not prepared for a lack of winter rainfall. In addition, from a statistical viewpoint, the study of summer rainfall in Portugal is quite complex owing to its sporadic character and irregularity.

Changes in the large-scale atmospheric flow have an important impact on the winter precipitation variability over the Mediterranean basin (Corte-Real et al., 1995a; Dünkeloh and Jacobtet, 2003; Fernandez et al., 2003). Furthermore, the development and movement of synoptic weather systems that originate over the North Atlantic explain most of the winter precipitation variability over western Europe (Murphy, 1999). Many earlier

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studies also developed relationships between large-scale atmospheric circulation and precipitation over Iberia (Zorita et al., 1992; Corte-Real et al., 1995b; Rodó et al., 1997; Esteban-Parra et al., 1998; Rodriguez-Puebla et al., 1998; Rocha, 1999; Romero et al., 1999; González-Rouco et al., 2000; Muñoz-Díaz and Rodrigo, 2003; Sumner et al., 2003). Cyclones located to the west of the British Isles clearly favour winter precipitation over Portugal through strong advection of maritime air masses along their southern flank (Ulbrich et al., 1999; Wibig, 1999; Goodess and Jones, 2002). Furthermore, changes in the frequencies of occurrence of a number of large-scale atmospheric circulation patterns in the Euro-Atlantic sector have a strong impact on Portuguese rainfall (Corte-Real et al., 1995b, 1998, 1999; Trigo and DuCamara, 2000).

The strong wintertime connection between several climate variables over Europe and the North Atlantic oscillation (NAO) is widely recognized (Hurrell and van Loon, 1997; Qian et al., 2000a,b; Hurrell et al., 2001; Trigo et al., 2002). The NAO pattern in the mean sea-level pressure (MSLP) field displays a renowned dipolar structure, which is characterized by one ‘centre of action’ located over the Iceland region and another, of opposite sign, located near the Azores (Wallace and Gutzler, 1981; Barnston and Livezey, 1987; Hurrell, 1996). The NAO is frequently measured by a two-station index (Jones et al., 1997; Rogers, 1997; Pozo-Vázquez et al., 2001; Goodess and Jones, 2002), and the Gibraltar–Iceland (G–I) index (Jones et al., 1997) is particularly suitable for monitoring the winter NAO (Osborn et al., 1999).

Owing to the importance of winter precipitation in Portugal, and making an allowance to the studies referred to above, the main aims of the present work concern the identification, characterization and intercomparison of the different weather regimes specifically associated with Portuguese winter rainfall. Section 2 describes the data and methods used to achieve the latter purposes. The results are presented and discussed in Section 3. The main conclusions are ultimately summarized in Section 4.

2. DATA AND METHODOLOGY

The recent-past atmospheric conditions were monitored using the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis data (Kalnay et al., 1996). The present study employed the daily fields of the MSLP, geopotential height at 500 hPa, zonal and meridional wind components at 850 hPa and specific humidity at 850 hPa. All these datasets are defined over a 2.5° latitude × 2.5° longitude grid. The time period was chosen to begin in the International Geophysical Year (1957) and to end in 1998, and the winter season corresponds to the months of December, January and February.

In order to relate the frequencies of occurrence of the different weather regimes with the NAO, the G–I index was used. This index was provided by the Climatic Research Unit, University of East Anglia, Norwich, UK (http://www.cru.uea.ac.uk/). The historical time series of the gridded monthly precipitation produced by the latter unit (Hulme, 1992, 1994; Hulme et al., 1998) were also used in this study. The geographical locations of the three grid boxes (P1, P2 and P3) that cover the entire mainland of Portugal are shown in Figure 1. This gridded precipitation dataset provides full coverage of the interannual variability of the winter precipitation over Portugal. The relationships between the statistical properties of station and gridded data were analysed in detail by Osborn and Hulme (1997). In addition, the gridded observed precipitation is generally more reliable than the reanalysed precipitation, though high correlations are found between them (Wilby and Wigley, 2000).

An automatic classification scheme was developed so that each day was keyed to a particular weather regime. The weather regimes were isolated by a $K$-means cluster analysis on a subspace spanned by a subset of empirical orthogonal functions (EOFs) of the daily MSLP. With this procedure, both a prefiltering and a data reduction were achieved. The $K$-means algorithm starts with a preset number of clusters $K$ and then moves objects between clusters with the goal of, first, minimizing the variance within clusters and, second, maximizing the variance between clusters. The classification of weather regimes by the $K$-means cluster analysis has been used extensively (e.g. Solman and Menendez, 2003).

The pressure anomalies were previously weighted so that every grid point had contributions to the covariance estimates proportional to its representative area (the anomalies at each grid point were multiplied by the square root of the respective latitude’s cosine). A principal component analysis (PCA) was then applied to the
covariance matrix of the winter daily MSLP weighted-anomalies defined within a Euro-Atlantic sector with
the following coordinates: (25–60°N; 30°W–10°E). Next, the first few principal components (PCs) were
used as input variables for the clustering analysis.

The classification was carried out on the daily MSLP fields due to the wide range of applications provided by
this variable when compared with other candidates, such as the geopotential height at 850 hPa. First, the daily
MSLP fields are more widely available (both in space and in time) and more reliable than other competitive
variables, which enables the extension of the same statistical approach, based on the same climate variable, to
areas or time periods where other variables are unavailable or unreliable. Second, most numerical models are
reasonably skilful in reproducing the daily MSLP fields, which allows a straightforward expansion of the study
to model data. Third, this variable has already been applied successfully in previous classification procedures
in the same geographical area (e.g. Corte-Real et al., 1998; Trigo and DaCamara, 2000). It is still worth
emphasizing that a combination of variables is not possible in this particular case, since the input variables
in the K-means method are the non-standardized PCs. Therefore, a combination of different variables with
different physical dimensions is not appropriate. On the other hand, the standardization gives all the PCs the
same weight, which is an unrealistic assumption.

Aiming to identify weather regimes clearly related to the rainfall over Portugal, an information measure, Inf,
was defined as a function of a previously specified threshold, thr, and of the number of clusters K in the
following manner:

\[
\text{Inf}(\text{thr}, K) = \sum_{i=1}^{K} |n_{ri}(\text{thr}) - p_{ri}| n_{i}
\]

where \( n_{ri}(\text{thr}) \) is the number of rainy days within the \( i \)th cluster with a rainfall amount beyond the threshold
\( \text{thr} \); \( n_{i} \) is the total number of days within the same cluster; and \( p_{r} \) is the probability of a rainfall total above
the specified threshold in all time realizations of the full series. For each specific threshold, \( \text{thr} \), the optimal
number of clusters (the number of clusters that best differentiates between the precipitation regimes with
amounts above and below the specified threshold) maximizes the function \( \text{Inf}(\text{thr}, K) \). A simpler version of
this information measure was previously developed by Corte-Real et al. (1998).

The dependence of the solution on the seeding of the K-means algorithm (Michelangeli et al., 1995) was
taken into account by selecting the seeding that maximizes the information measure for a given threshold and
for a preselected number of clusters. The seeding that maximizes the 1 mm threshold is the most appropriate

choice, since this threshold enables a clear differentiation between wet and dry days. It is still worth noting that other classifications based on Lamb’s weather types (Trigo and DaCamara, 2000; Goodess and Jones, 2002) are not specifically developed taking into account local precipitation amounts. Therefore, these latter weather types are not optimal rainfall regimes.

The mathematical literature related to this method commonly refers to a ‘pseudo-$F$’ test, based on the analysis of variance, as a proper indicator of the optimal number of clusters. Nevertheless, this measure is less suitable when the aim is to identify weather regimes that discriminate the values of a particular time series associated with a specific climate variable (e.g. precipitation). Despite the different nature of these measures, the present analysis revealed that the solution that maximizes the information measure nearly maximizes the ‘pseudo-$F$’ statistic.

The gridded dataset only comprises monthly data, and so the time series of the daily rainfall recorded at Porto, Bragança, Lisbon and Beja were thereby used to compute the information measure. These daily time series were provided by the European Climate Assessment project (Klein Tank et al., 2002). The geographical locations of these four stations are depicted in Figure 1. Herein, the stations of Porto and Bragança represent the conditions over northern Portugal, and Lisbon and Beja represent the conditions over southern Portugal.

Although the daily time series and the gridded precipitation are obtained from different sources, the total winter precipitation recorded at each station is highly correlated with the time series in the nearest grid boxes (Table I). All these coefficients are statistically significant at the 1% significance level, which is also clear proof of the dominance of the large-scale forcing of winter precipitation throughout the country; the local and regional processes are not strong enough to weaken these correlations.

3. REGIMES

The first three orthogonal modes cumulatively represent about 80% of the total variance and are statistically significant according to North’s rule-of-thumb (von Storch and Zwiers, 1999) and to other widely used criteria based on Monte Carlo approaches (Prohaska, 1976; Overland and Preisendorfer, 1982; Leite, 1991).

Cluster analysis was applied afterwards in order to identify the weather regimes in the current atmospheric state. The selection of the optimal number of clusters (weather regimes) was undertaken by computing the aforementioned information measure for each of the daily precipitation time series in Portugal (Porto, Bragança, Lisbon and Beja). The information measures (for several threshold values) were expressed as a percentage of their absolute maximum value, which is reached when the number of clusters equals the sample size. Therefore, each information measure exhibits an upward trend and the first pronounced local maximum indicates the optimal number of clusters for the corresponding threshold.

A detailed analysis of the scores of these information measures suggested that five is the appropriate number of weather regimes at the four stations. As an illustration, the information measure at Porto has a clear local maximum for five clusters, and for all but the 5 mm threshold (Figure 2). Additionally, the results revealed that the information measure for all thresholds is almost invariant when the number of retained PCs is higher than three (higher PCs have lower fractions of variance represented). Consequently, following both

Table I. Correlation coefficients ($r \times 100$) between the single-station winter precipitation at Porto, Bragança, Lisbon and Beja and the gridded precipitation in the P1, P2 and P3 grid boxes. All these correlations are statistically significant at a significance level of 1%. The highest coefficient for each station is given in bold

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the parsimony principle and the statistical significance of the orthogonal modes, only the first three PCs were retained as input variables for clustering purposes.

In order to get an integrated view of the dynamical structure of each weather regime, and to stress the differences between them, composites of the following daily climate variables were performed: MSLP, geopotential height at 500 hPa, relative vertical vorticity at 850 hPa and the total humidity advection at 850 hPa. The last two variables were computed using both the zonal and meridional wind components (vorticity and advection) and the specific humidity at 850 hPa (advection). As will be shown below, the differences in the spatial features of the composites referred to above for each regime constitute a validation of the clustering technique.

These composites can actually be interpreted as typical circulation patterns of each weather regime and will henceforth be presented. The frequencies of occurrence of the weather regimes and some relevant statistics are also listed in Table II.

### 3.1. Cyclonic regime

The cyclonic regime (C regime) is the least frequent (14%; Table II). However, the high interannual variability can occasionally turn it into the dominant regime. From a physical viewpoint, the C regime is associated with a high density of cyclonic systems, mainly located just to the west of the British Isles, whereas
the Azores high is almost absent (Figure 3(a)). The anomaly composite of the geopotential height at 500 hPa level shows dynamically consistent negative anomalies over the North Atlantic (Figure 3(d)).

Strong cyclonic (positive) vorticity over the same area was also found (Figure 3(e)), which is related to a high density of extratropical cyclonic systems. The vorticity values over Portugal are nearly zero, which means that neither significant large-scale air rising nor strong baroclinicity occur over Portugal; the rainfall generation is indeed linked to travelling frontal systems (e.g. cold fronts) that usually extend to latitudes to the

![Figure 3. Absolute composites of the reanalysed daily MSLP for the C regime, in the winters from 1957–58 to 1997–98, for: (a) all winter days; (b) rainy days (R ≥ 10 mm) at Porto; (c) rainy days (R ≥ 10 mm) at Beja (contour intervals of 4 hPa). Corresponding anomaly composites of the: (d) geopotential height at the 500 hPa level (contour interval of 30 gpm); (e) vertical vorticity at the 850 hPa level (contour interval of 5 × 10^{-6} s^{-1}); (f) total humidity advection at the 850 hPa level (contour interval of 10 g kg^{-1} m s^{-1} and the arrows represent the anomalies in the zonal and meridional components of the total advection). Shaded areas represent absolute anomalies above 20 g kg^{-1} m s^{-1} (statistically significant at least at a confidence level of 99%).](image-url)
The average wind direction and the average rainfall on a rainy day for the full time series are also shown (hollow squares) south of Portugal in winter. In fact, the humidity advection anomalies highlight their key role in explaining the occurrence of rainfall (Figure 3(f)). Strong humidity advection is associated with westerly and southwesterly winds from the North Atlantic that occur over Portugal along the southern flank of the cyclonic systems, which have a high moisture content, particularly over northern and central Portugal. The dominance of the large-scale southwesterly and westerly winds during the wet days of this regime is apparent in the scatter plot of the wind directions on a rainy day at Porto (Figure 4(a)).

The latter physical description is confirmed by well-above-average rainfall probabilities throughout Portugal (Table II). Furthermore, the C regime gives the largest contributions to the total winter rainfall; they range from 34 to 40% (Table II). The precipitation rates are also well above the climate mean values; the average rainfall on a rainy day is of about 1.5 times its climatic mean. These properties suggest that the C regime plays a leading role in governing the winter rainfall variability over Portugal, despite being the least frequent regime. This assumption will be more objectively quantified in Section 3.7.

The rain-generating conditions can be overridden because not all days within a regime are actually rainy days. This can be overcome by conditioning the composites (conditional composites) to the occurrence of a rainfall amount in excess of 10 mm, recorded at a specific station. Owing to Portuguese climate heterogeneity, the conditional composites for rainfall at Porto (northern Portugal) and at Beja (southern Portugal) are presented here. Although both conditional composites (Figure 3(b) and (c)) are very similar to the total composite (Figure 3(a)), the most remarkable rain-generating patterns tend to have a southeastwardly displaced low-pressure centre. In fact, the closer the low-pressure centre is to Portugal (weaker Azores high), the more favourable the conditions are to the rainfall occurrence.

3.2. Westerly regime

In the westerly disturbed weather regime (W regime), the Iceland low is southeastwardly displaced and the Azores high undergoes a southward displacement (Figure 5(a)). The MSLP values north of the British Isles can be more than 20 hPa below the mean values (not shown). The typical ridge of the Azores high over Iberia is absent or very weakened, and a more westerly flow prevails. A dynamically coherent enhancement of the north–south contrast in the mid-tropospheric flow is also noteworthy (Figure 5(d)). This feature is related to anomalously strong cyclonic vorticity near the British Isles (Figure 5(e)), which reflects an anomalously high density of extratropical cyclonic systems over this region. The vorticity over Portugal is slightly negative, which means that the rainfall generation in the W regime, as in the C regime, must be linked to travelling frontal systems that extend as far to the south as Portugal. As for the C regime, humidity advection has a leading role in explaining the rainfall occurrence (Figure 5(f)). The high humidity advection anomalies are now associated with westerly and northwesterly winds (Figure 4(b)) along the southern flank of the cyclonic systems centred over northern Europe, and their effects are particularly clear over northern Portugal; the strong north–south gradient over Portugal is worth emphasizing. For instance, the probability of occurrence of a rainy day is about 71% at Porto and it is only 33% at Beja, a value slightly higher than the climate mean value of 31% (Table II). Moreover, the relative average rainfall at Porto (1.1) is narrowly higher than its
climate mean value, whereas the rates are lower than average at all the other stations. Although the W regime is more frequent than the C regime (19% against 14%), the contributions of the W regime for the winter rainfall at all stations are much lower than the corresponding contributions of the C regime; its contributions are much higher over northern Portugal (Porto, 31%) than over southern Portugal (Beja, 14%).

The rain-generating conditions are clearly connected to a pressure trough that extends from the British Isles towards Iberia and the western Mediterranean for both northern and southern Portugal (Figure 5(b) and (c)). As expected, the pressure trough is deeper for Beja than for Porto, and the presence of the Azores high, almost absent in the C regime, is another noticeable feature of the W regime.

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3.3. NAO− regime

The third regime is linked to the negative phase of the NAO (NAO− regime). Its frequency of occurrence is 17% (Table II) and its typical pattern is remarkably different from the patterns of the aforementioned regimes (Figure 6(a)). Both the Iceland low and the Azores high are particularly weak; over the Iceland-low region the average anomalies are positive and higher than 16 hPa and over the whole of Iberia the anomalies are negative and higher than 8 hPa. This north–south inverted dipolar structure clarifies its connection with the negative phase of the NAO. The correlation coefficient between its frequency of occurrence and the G−I index is −0.78 (statistically significant at the 99% confidence level). The rainfall probabilities nearly fall within the range from 50 to 60% (Table II). Although the mean precipitation on a rainy day is higher over northern Portugal, the relative precipitation rates are higher over southern Portugal (1.3 at Beja). Also, the contribution
of the NAO− regime to the total winter precipitation is higher over southern Portugal (35% at Beja and 21% at Porto). The anomalies in the mid-tropospheric flow (Figure 6(d)) are a result of the more southerly path of the westerlies, and anomalous strong cyclonic vorticity that occurs over Iberia (Figure 6(e)). Therefore, during the NAO− regime the occurrence of weak cyclones (relatively low vorticity anomalies) in the vicinity of Iberia is apparent, with an average vorticity maximum just off the Portuguese coast. The near-average values of humidity advection over Portugal suggest that the rainfall generation in the NAO− regime must be, in large part, attributed to large-scale air rising and baroclinic instability over Portugal (Figure 6(f)). The cyclonic circulation over Portugal is also plainly resolved (Figure 6(f)).

In contrast to the scatter plots of the wind direction on a rainy day in the C and W regimes (Figure 4), the scatter plot for the NAO− regime (Figure 7) displays a high scattering of the rainy days with the large-scale wind direction, though the rainfall at Porto is more likely to occur in the presence of westerly winds. Therefore, the cyclones located to the north of Portugal (westerly winds at Porto) establish the highest rain-generating conditions over northern Portugal, whereas over southern Portugal the rain-generating conditions are almost independent of the cyclone’s position.

The conditional composites emphasize the inverted dipolar structure (Figure 6(b) and (c)). On a smaller scale, the key rain-generating systems tend to be located near the station, but with their cores located to the north (mesoscale westerly winds). Therefore, the low-pressure systems located off the Portuguese coast (small core in Figure 6(c)) are more relevant to the rainfall occurrence at Beja than at Porto. Conversely, low-pressure systems located to the north of Iberia are more significant to the rainfall occurrence at Porto. A meridional pressure gradient (MPG) between the centres of the inverted dipole was computed. The geographical coordinates of the poles are (62.5° N, 11.25° W) and (40° N, 11.25° W). Only less than 3% of the days at both stations have MPG scores below average, and at Beja the heaviest rainy days tend to be related with higher scores (Figure 8). These latter outcomes corroborate the high relevance of the inverted dipolar structure in the rainfall generation under the NAO− regime. This relationship between the MPG and rainfall is not observed in the other regimes.

Figure 7. Scatter plots between the winter daily rainfall on a rainy day and the wind direction (a) at Porto and (b) at Beja in the NAO− regime. The average wind direction and the average rainfall on a rainy day for the full time series are also shown (hollow squares)

Figure 8. Scatter plot between the daily precipitation (a) at Porto and (b) at Beja and the north–south pressure gradient (MPG). The vertical solid line corresponds to the mean gradient (−16.3 hPa)
3.4. NAO+ regime

The NAO+ regime is strongly linked to the positive phase of the NAO and is the most common regime, with a frequency of occurrence of 28% (Table II). The correlation coefficient between its frequency of occurrence and the G–I index is 0.75 (statistically significant at the 99% confidence level). The Azores high is enhanced and presents a well-defined ridge over Iberia (Figure 9(a)). As a result of the sinking and divergence of the surface winds during this regime, Portugal usually experiences very settled and fairly dry weather conditions.

The mid-tropospheric ridge over western Europe is enhanced and the westerlies follow wavy paths (Figure 9(d)). The opposite dipolar structures of the anomalies between the NAO− and the NAO+ regime are quite clear (Figures 6(d) and 9(d)). The anomalous high anticyclonic vorticity over Portugal is in clear

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dynamical conformity with the above-stated dynamical features (Figure 9(e)). The easterly and northeasterly advection anomalies reinforce the dry and settled weather conditions (Figure 9(f)).

The probabilities of rain clearly fall behind the climatic mean values for every station (Table II). The average rainfall on a rainy day is about one half its climatic mean value, and the contributions to the winter rainfall are only nearly 10% throughout the country.

A more detailed inspection of the few rainy days in this weather regime led to the conclusion that they are essentially due to mesoscale processes (e.g. cold fronts), which are not properly resolved by the coarse grid of the dataset and are smoothed out by daily means. The majority of the rainy days are connected to cyclones located far to the north of Portugal, but with well-developed frontal systems that briefly interrupt the Azores high (Figure 9(b) and (c)). In some cases, the mean fields are indeed indistinguishable from others related to dry weather conditions. Furthermore, despite the occurrence of precipitation over Portugal, both the Azores high and the Iceland low are generally strong (positive phase of the NAO).

3.5. Easterly regime

Lastly, in the easterly regime (E regime), is the presence of high pressure over the western European basin and the British Isles that are unprecedented in the other regimes (Figure 10(a)). This is the driest regime and occurs on roughly 22% of the winter days (Table II). During this regime the mid-tropospheric ridge over western Europe is strongly enhanced (Figure 10(d)).

The vorticity is anomalously low near the British Isles, near average over northern and central Portugal and slightly higher than average over southern Portugal (Figure 10(e)). The easterly wind anomalies weaken the advection of maritime air masses over the country (Figure 10(f)), which further enhance the dryness of this regime. The prevailing easterly winds over Portugal justify the name of this regime.

The rainfall probabilities over northern Portugal are much lower than in the NAO+ regime (Table II). Nevertheless, despite the lack of rainy days, the rainfall probabilities and the mean rainfall on a rainy day over southern Portugal are slightly higher than in the NAO+ regime. In actual fact, the E regime explains 8% of the total winter rainfall at Beja (the same value as for the NAO+ regime), whereas, over northern Portugal it explains only 3% of this value. This can be explained by occasional cyclonic systems located southward or southwestward of Portugal that can lead to heavy rainfall events and to severe storms over southern Portugal, despite being extremely rare events. The presence of these cyclones is manifested in the conditional pattern for Beja by the weak pressure minimum over Madeira (Figure 10(c)).

Sporadically, when an eastward moving trough over North Africa (along the southern flank of the high-pressure system) reaches the Atlantic waters it develops and can be accompanied by an upper level cold-core cyclone, supplying the required conditions for the generation of strong local convective rainfall (Tullot, 1983). This Iberian–African trough plays an essential role in the rainfall generation over northwestern Africa (Knippertz et al., 2003; Knippertz, 2004). With the purpose of identifying these cold-core lows in the E regime, the conditional composites of the geopotential height anomalies at 500 hPa and of the vorticity anomalies at 850 hPa for a rainy day ($R \geq 10$ mm) at Beja (most affected station) were computed. The enhancement of the negative mid-tropospheric anomalies over the Madeira area is a manifestation of the equivalent barotropic structure of these lows (Figure 11(a)). Furthermore, the high vorticity anomalies southwestward of Portugal plainly confirm the presence of these systems during rainy episodes in the E regime (Figure 11(b)). However, it must be kept in mind that these events are extremely scarce and their differentiation within an automated classification scheme, with a small number of regimes, is virtually impossible.

3.6. Intercomparison of the regimes

Even though the previously described weather regimes effectively discriminate rainy days from dry days, a discrimination of the rainfall amounts must also be accomplished. The probabilities of exceeding a stated daily rainfall amount within each weather regime can highlight this issue.

At Porto, the C regime is clearly the moistest regime (Figure 12(a)). In fact, the decrease in its distribution function is slow, which means that intermediate and heavy rainfall days are relatively frequent; about 40% of the rainy days have rainfall values over 15.0 mm. For instance, the recorded maximum daily rainfall
(84.4 mm) occurred in this regime. The NAO− and W regimes present similar distributions that are also very close to the distribution of the full time series. For the NAO+ and E regimes, the frequencies of occurrence are all clearly below average. For both regimes, about half of the rainy days have rainfall values equal or below 2.0 mm, and only roughly 10% of the days have rainfall values above 15.0 mm.

At Beja, the C regime is less dominant than at Porto (Figure 12(b)); the decrease in the distribution function is steeper than at Porto and is actually very similar to the corresponding curve of the NAO− regime. The distribution function of the W regime is always below the mean curve at Beja, which explains the differences in its statistics at Porto and at Beja (Table II). The NAO− regime plays a greater role over southern Portugal, whereas the W regime plays a more secondary role.
Figure 11. Conditional composites for the E regime of the (a) geopotential height anomalies at 500 hPa and of the (b) vorticity anomalies at 850 hPa on a rainy day ($R \geq 10$ mm) at Beja.

Figure 12. Probabilities (as a percentage) of exceeding a stated daily precipitation, $F(R)$, on a rainy day (a) at Porto and (b) at Beja for the entire time series (solid curves) and for each regime separately.

The C regime at Porto is responsible for the occurrence of most of the stormy days with rainfall amounts above 40 mm (Figure 13(a)). For intermediate rainfall events (15–40 mm) the C and W regimes show similar contributions. The NAO$-$ regime has lower contributions in almost all classes. Although the contributions of the C regime are similar at both stations, the contributions of the NAO$-$ regime are superior at Beja (Figure 13(b)). At Beja, the W regime is only significant in the occurrence of light rainfall values (lesser than 15 mm). The NAO$+$ and E regimes still have relevant contributions for light precipitation; about 40% (Porto) or 30% (Beja) of the days with rainfall amounts below 5 mm are keyed to these two regimes. The rainfall extremes at Porto are related to the C, W and NAO$-$ regimes, whereas only the C and NAO$-$ regimes are relevant in the occurrence of extremes at Beja. As was already noted, the E regime can lead to sporadic heavy rain events over southern Portugal related to the development of cold-core lows near Madeira. However, at Beja, the high contribution (50%) of this regime in the class centred at 47.5 mm can be misleading, since it corresponds to a single E regime event that evidently does not have an important impact on the winter rainfall as a whole; it is a rather abnormal event.

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3.7. Interannual variability

With the aim of quantifying the relevance of each regime in the interannual variability of the winter precipitation over Portugal, a linear regression model was individually fitted to the winter precipitation at each grid box (P1, P2 and P3). The frequencies of occurrence of the C, W and NAO− regimes for each winter were considered as predictors, because these regimes are clearly connected to winter daily precipitation over Portugal and the introduction of the other two regimes (NAO+ and E) brings redundancy to the models. Moreover, the W regime does not give a significant contribution to the precipitation modelling in the P3 box, and was thus removed from the corresponding model.

The application of conventional hypothesis testing to the coefficients led to the conclusion that all the coefficients are statistically significant at the 99% confidence level. In addition, the $F$-test highlights a strong linear relationship between predictors and precipitation. The errors (residuals) are statistically independent, according to the Durbin–Watson test, and are normally distributed. A cross-validation was performed in order to remove the artificial skill from each model (von Storch and Zwiers, 1999). In this procedure, a complete winter was omitted at each step and all the analyses were fully repeated for the remaining period. The values omitted were successively modelled and, at the end of this process, a synthetic time series was obtained for each grid box.

The correlation coefficients between the synthetic and observed time series are: 0.83 (P1), 0.87 (P2) and 0.80 (P3). All these coefficients are statistically significant at a confidence level of 99%. The skill scores of the regression models (Wilks, 1995) show that about two-thirds or more of the variance is explained by the model at every grid box: 69% (P1), 75% (P2) and 64% (P3). The regression coefficients estimated for each grid box (models without intercept) represent a ‘typical daily precipitation amount’ of each weather regime and are expressed in precipitation units (Table III). The C regime is the most significant in explaining the interannual variability of the precipitation in the P1 and P2 boxes, whereas the NAO− regime is dominant in the P3 box. The strong decrease in the relevance of the W regime and the increasing relevance of the NAO−
regime towards the south are still noteworthy. In every grid box, the C and NAO− regimes are crucial in explaining the interannual variability of precipitation.

6. SUMMARY AND CONCLUSIONS

Owing to the strong connection between winter rainfall over Portugal and the large-scale circulation patterns, a keying of the days into a set of non-overlapping large-scale rainfall regimes is particularly meaningful. Therefore, a $K$-means cluster analysis over the first three PCs of the daily MSLP weighted-anomalies was performed. An information measure was computed so that a maximum discrimination of the rainfall amounts amongst the weather regimes could be achieved. Five weather regimes (C, W, NAO−, NAO+ and E) were isolated in this manner, and both their statistical and dynamical properties enabled a validation of the clustering strategy.

The C regime is characterized by low-pressure systems centred to the west of the British Isles. This feature leads to the prevalence of the westerlies and frontal systems over the country, which transport maritime air masses (mT and mP) and establish rain-generating conditions. The NAO− regime is strongly linked to the negative phase of the NAO; its main feature is an inverted dipolar structure, with a mean low-pressure centre over Iberia. The presence of local cyclones provides anomalously high levels of baroclinic instability and they constitute the main precipitation source during this regime.

On the whole, the occurrence of both the C and NAO− regimes is largely dominant in the interannual variability of winter rainfall over Portugal. The C regime is particularly meaningful over northern Portugal, whereas the NAO− regime plays a more relevant role over southern Portugal. The W regime is characterized by the presence of low-pressure systems over the North Atlantic and northern Europe and by a weakened Azores high. It allows an improvement in the description of the winter rainfall variability over northern and central Portugal. These three regimes jointly explain more than 60% of the total variance of winter precipitation over the entire mainland of Portugal. It is still worth mentioning that the precipitation in both the C and W regimes tends to be associated with remote cyclones (centred northward or northwestward of the Iberian Peninsula), whereas the precipitation in the NAO− regime tends to be linked to local cyclones.

The NAO+ regime is strongly coupled with the positive phase of the NAO; its principal feature is an enhanced Azores high, with a ridge that extends widely over Iberia, leading to generally settled and dry weather conditions. The E regime is clearly associated with a high-pressure area northward of Iberia. During this regime, easterly advection of continental air masses (cT and cP) over Portugal usually yields dry weather conditions.

This study also revealed that the frequencies of occurrence of the C, NAO− and W regimes are skilful predictors of winter rainfall over Portugal. In this manner, a significant prediction potential is available. In a subsequent study, under final development, the frequencies of occurrence of these weather regimes are used to build up a downscaling strategy for the assessment of future rainfall scenarios in Portugal.

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