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DEPENDENCE OF WINTER PRECIPITATION OVER PORTUGAL ON NAO AND BAROCLINIC WAVE ACTIVITY

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ABSTRACT

The relationship between winter (DJF) rainfall over Portugal and the variable large scale circulation is addressed. It is shown that the poles of the sea level pressure (SLP) field variability associated with rainfall variability are shifted about 15° northward with respect to those used in standard definitions of the North Atlantic Oscillation (NAO). It is suggested that the influence of NAO on rainfall dominantly arises from the associated advection of humidity from the Atlantic Ocean. Rainfall is also related to different aspects of baroclinic wave activity, the variability of the latter quantity in turn being largely dependent on the NAO.

A negative NAO index (leading to increased westerly surface geostrophic winds into Portugal) is associated with an increased number of deep ($p_s < 980$ hPa) surface lows over the central North Atlantic and of intermediate ($980 < p_s < 1000$ hPa) surface lows over North-western Europe. It is suggested that these distant surface lows have no direct influence on local Portuguese precipitation, but rather contribute to advection at their southern flanks. The other aspect of baroclinic wave activity varying with the NAO is the mid-tropospheric storm track (defined by the 500 hPa bandpass-filtered geopotential height variance). A possible local influence of the storm track due to vertical motions ahead of the upper air troughs cannot be unambiguously separated from the effect of advection.

A separate influence of local surface cyclones over the Iberian peninsula which may, for instance, arise from the large scale ascent of air, is revealed by the statistics: for a given advection, rainfall amounts for months with local cyclone cores over the considered region tend to exceed those without. Copyright © 1999 Royal Meteorological Society.

KEY WORDS: precipitation; North Atlantic Oscillation; Portugal; surface low; storm track; baroclinic wave; EOF-analysis

1. INTRODUCTION

Rainfall over the western part of the Iberian peninsula is known to be related to the large scale sea level pressure field and thus to advection of humidity into this area. Zorita *et al.* (1992) (subsequently referred to as ZKS) showed that intense winter rainfall over the Iberian peninsula is connected with a negative sea level pressure (SLP) anomaly over the eastern North Atlantic which induces intensified westerly winds over South-western Europe. Another aspect elucidating the importance of westerly advection for rainfall in this region is presented by Zhang *et al.* (1997) (see also Mendes, 1993). They found that reduced occurrence of a certain circulation pattern generating westerly advection of humidity caused the decrease of rainfall over Portugal in the winters of 1981–1990 compared with the 30-year reference period 1951–1980.

The SLP variability pattern associated with rainfall over South-western Europe is known to bear strong similarities to that of the North Atlantic Oscillation (NAO) (Wallace and Gutzler, 1981; Rogers, 1990;

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Deser and Blackmon, 1993; Hurrell, 1995). The NAO, in turn, is a feature that is also reflected by shifts in the surface (Rogers, 1997) and upper air baroclinic wave activity (Hurrell and van Loon, 1997). Baroclinic waves, however, have a potential influence on rainfall due to their frontal systems and also due to the large scale vertical motions associated with them. In this paper we investigate, on a statistical basis, to what extent two processes, namely mean advection of humidity and baroclinic wave activity, influence rainfall over Portugal. With respect to the baroclinic waves we distinguish between mid-tropospheric geopotential height standard deviations (the 'storm track') and the core pressure and position of surface cyclones. We identify common variability modes of the mean flow and of synoptic-scale activity, and give evidence for an independent influence of these two factors on regional rainfall.

2. DATASETS

This work is based on monthly mean precipitation time series taken from 15 stations in Portugal (see map in Figure 1 and Table I) covering the period 1946–1990, made available by the Instituto da Água in Portugal. Time series of rainfall at these stations provides a good representation of Portuguese precipitation. Missing values (less than 0.2%) are attributed the climatological value for this period.

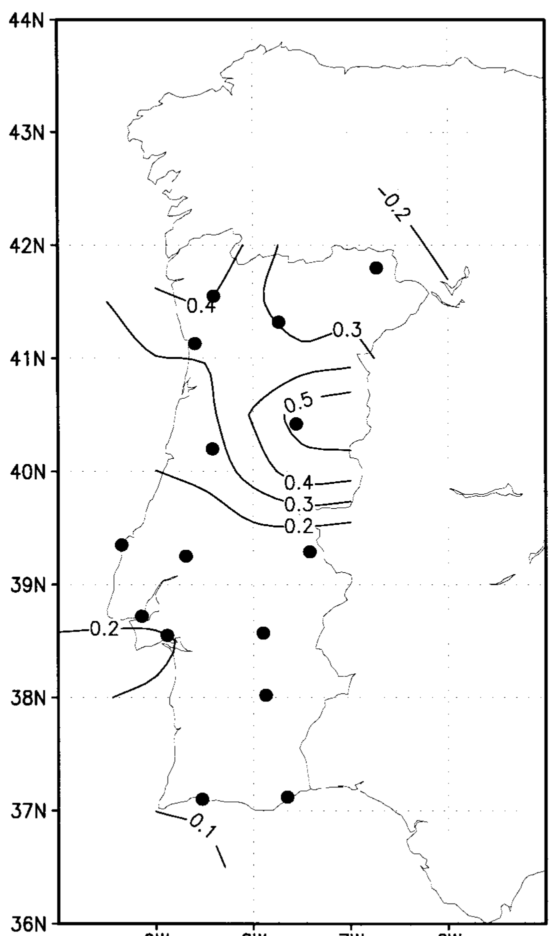

Figure 1. Leading EOF of winter precipitation (December through February) in Portugal for the winters 1946/47–1989/90, based on monthly data at 15 stations. Dots indicate the location of the 15 stations used

Table I. List of 15 Portuguese stations used for EOF analysis

Station	Longitude	Latitude	Elevation (m)
Bragança	6°44′W	41°48′N	690
Braga	8°24′W	41°33′N	190
Régua	7°48′W	41°10′N	65
Porto	8°36′W	41°08′N	93
Penhas Douradas	7°33′W	40°25′N	1380
Coimbra	8°25′W	40°12′N	141
Cabo Carvoeiro	9°24′W	39°21′N	32
Alter do Chão	7°39′W	39°12′N	270
Santarém	8°42′W	39°15′N	54
Lisboa	9°09′W	38°43′N	77
Évora	7°54′W	38°34′N	309
Vila Nog. De Azeitão	9°01′W	38°31′N	120
Beja	7°52′W	38°01′N	246
Praia da Rocha	8°32′W	37°07′N	21
Tavira	7°39′W	37°07′N	25

For the atmosphere we make use of the NCEP (National Center for Environmental Prediction, formerly National Meteorological Center) Northern Hemisphere monthly mean SLP and daily geopotential height (500 hPa) analyses for the period December 1946 to February 1990. Temporal data gaps in the height analyses were filled (Christoph *et al.*, 1997). The NCEP fields are interpolated from the original octagonal grid to a regular $5° \times 5°$ latitude–longitude grid. The domain extends from 20°N to 85°N. Bandpass filtering (half power cut-off periods: 2.5 and 8 days; see Christoph *et al.*, 1995) of daily geopotential height fields for individual winter months and subsequent computation of the standard deviation $\sigma_{ij}(Z_{500})$ at each grid point (i, j) result in a set of 129 storm track charts. Averaging over individual winter seasons (DJF) yields another set of 43 storm track charts. As we consider variations on an interannual (boreal winter mean) and, in addition, on a month-to-month timescale, the linear trend and long term variations (>10 years) are removed prior to statistical computations. Anomalies are formed with respect to the mean annual cycle.

The cyclone-core identification is performed using numerically analysed daily surface pressure data on a regular $5° \times 10°$ latitude–longitude grid. The identification scheme (Haak, 1993; Haak and Ulbrich, 1996) is based on a bicubic spline interpolation. For the present study, only lows with monotonous pressure increase within some 700 km radius from their centre are taken into account. The data origin for this part of the investigation is the German Weather Service (DWD) and data are provided by the University of Bonn, Germany. Quality-checks of this dataset were performed by Born and Flohn (1997) and, with respect to cyclone climatologies, by our own comparisons with results produced on the basis of ECMWF reanalyses. It should be noted that only data starting in the winter of 1967/1968 are considered since for the preceding years data gaps may hamper the quality of the cyclone identification procedure. The cyclone-count time series ends in the winter of 1989/1990 in order to match the period covered by NCEP data.

3. RAINFALL OVER PORTUGAL

The variability of precipitation in Portugal is characterized by a strong annual cycle. The maximum rainfall occurs in winter, with additional significant contributions coming from late autumn and early spring. Summer months contribute only little to the total amounts (e.g. 7.7% at Braga in the north of Portugal, 4.1% at Beja in the South). The significant negative trend in March rainfall (e.g. Mendes, 1993) which Zhang *et al.* (1997) found to be associated with a decrease of westerly circulation weather types after 1960, does not affect our results regarding DJF rainfall.

A quantitative description of the dominant modes of rainfall variability over Portugal can be obtained from an EOF (Empirical Orthogonal Function)-analysis (Kutzbach, 1967; Preisendorfer, 1988). The eigenvectors, based on 15 Portuguese stations, are computed for winter months (December, January, February). The first EOF obtained from monthly data after removal of the annual cycle explains 82% of the total rainfall variability in winter (Figure 1). It is characterized by a monopole pattern with a maximum in the mountainous regions of North-eastern Portugal. We performed checks in how far our subsequent results depend on the single station at 40.42°N, 7.55°W which dominates the monopole (Figure 1). It turns out that the rainfall time series from Southern Portuguese stations are highly correlated with the first principal component of rainfall, i.e. abundant or poor winter rainfall according to PC1 largely affects the entire country. Thus, the choice of the PC1 time series as a representative of Portuguese rainfall has no systematic impact on our results. Possible local effects at individual stations, however, are removed by the EOF technique. In the subsequent sections, we use the temporal coefficients of single winter months (not shown) and of averages over individual winters (Figure 2, solid line).

3.1. Rainfall and the North Atlantic Oscillation

A pronounced influence of the NAO on precipitation has been identified for the North African coast (Lamb and Peppler, 1987) and the southern parts of the Iberian peninsula (ZKS, their Figure 13; Rodo *et al.*, 1997, their Figure 3). Low index values (which are associated with high precipitation in this area) are associated with increased westerly advection.

In order to confirm the relation of the rainfall and NAO for the first EOF of Portuguese rainfall, we correlated the first rainfall PC (Figure 2, solid line) with two different NAO indices: NAO-A is computed as the difference of normalized SLP between Azores (Ponta Delgada) and Iceland, following Rogers (1984), while NAO-L (following Hurrell, 1995) replaces the Azores with Lisbon. The correlation of these indices with the precipitation time series is $r = -0.66$ for NAO-A and $r = -0.68$ for NAO-L. As the definition of these indices was partly motivated to obtain the longest possible time series of the NAO, they may not be optimally representing the SLP variability associated with the rainfall time series for Portugal. Thus, we computed the correlation pattern of PC1 with the time series of winter mean SLP at individual grid points (Figure 3), additionally shading areas where the influence is quantitatively strong (absolute values of linear regression coefficients between the PC1 of precipitation and the time series of SLP exceeding 0.015 hPa/mm · month). Anomalously low pressure off the north-western tip of the Iberian peninsula and another centre of opposite sign north of Iceland are connected with increased rainfall over Portugal. A similar result, with somewhat lower correlations, is obtained on the basis of monthly data (not shown).

The reference stations of standard NAO indices (NAO-L and NAO-A) are located about 15° southward of the areas of maximum correlation in Figure 3. Thus, the standard indices are indeed not optimally representing the dependence of Portuguese rainfall on mean SLP variability. We define a new index

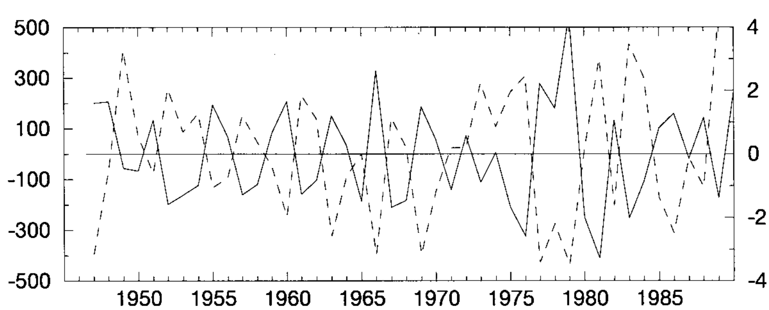

Figure 2. Winter time series (December–February, 1946/47–1989/90) of the first principal component of precipitation (PC1) in Portugal (explained variance: 82%) obtained from an EOF-analysis in (mm/month) (solid line, left y-axis) and of the North Atlantic Oscillation (NAO-P) index (no units) (dashed line, right y-axis) based on the difference of NCEP normalized sea level pressure anomalies between two area averages: (40–45°N, 10–15°W) and (70–75°N, 10–15°W)

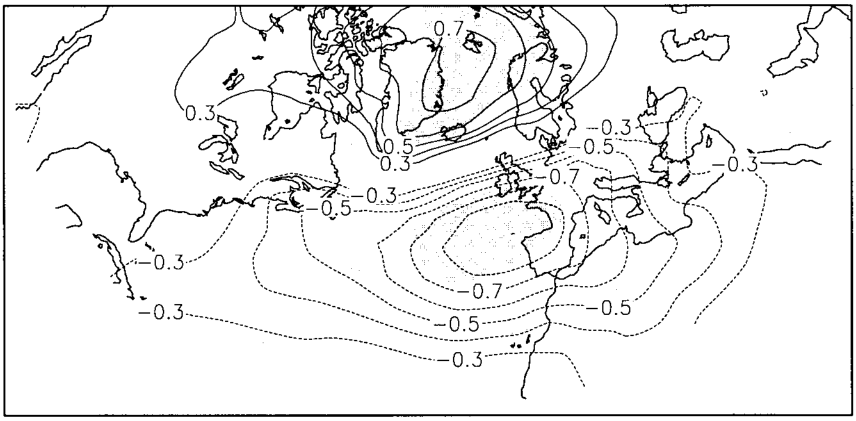

Figure 3. Distribution of correlation coefficients between the first principal component of precipitation in Portugal and sea level pressure at individual grid points in DJF. Correlations above 0.3 (below − 0.3) are significant at the 95% confidence level. Contour interval is 0.1. Shading highlights areas with a regression coefficient above 0.015 hPa/mm · month (below − 0.015 hPa/mm · month)

named 'NAO-P' as the difference of normalized SLPs of two area averages (40–45°N, 10–15°W and 70–75°N, 10–15°W, respectively). The time series of this index (Figure 2, dashed line) has a correlation coefficient $r = -0.85$ with the precipitation-PC1 (significance level 99%). Not unexpectedly, this correlation is higher than the correlation produced with the standard NAO indices. Subsequently we will utilize the NAO-P index for quantifying the NAO variability associated with rainfall.

3.2. Influence of baroclinic wave activity

Baroclinic wave systems can have a strong impact on rainfall in Portugal due to a number of processes. One of them is enhanced advection of maritime air which occurs south of the cores of surface cyclones. With respect to rain generation, the frontal systems associated with cyclones are important. Another factor may be the large scale upward air motion above the surface lows and ahead of upper air troughs. Large scale ascent of air is responsible for condensation, provided that there is enough water vapour in the air. Approaching cold upper air troughs may also be associated with a destabilization of the local air column eventually leading to latent heat release.

In order to gain greater insight into the role of surface lows, we investigated their anomalous distribution during winter months with large and small rainfall amounts (threshold $\pm$ one standard deviation of PC1). Figure 4 shows that there is an increased number of deep lows with central pressures below 980 hPa over the central North Atlantic between Newfoundland and Ireland, and reduced numbers in the Norwegian Sea. Intermediate depressions with a central pressure between 980 and 1000 hPa are more numerous over the North Sea and the eastern Atlantic when the same selection of months is considered (Figure 5).

The occurrence of deep and intermediate lows over the North Atlantic is largely limited to the higher latitudes, so that no clear local signal over Portugal can be expected. During the 69 winter months no cyclones with pressures below 980 hPa and only 27 with pressure below 1000 hPa are found directly over the Iberian peninsula (35°N–45°N, 0–10°W). None of them occurred during the 11 months with smallest rainfall amounts and five during the 11 months with large rainfall amounts. The position of anomalies in Figures 4 and 5 suggests that the impact of these systems on rainfall is mainly due to the enhanced westerly advection south of their cores. During months with large rainfall, deep lows occur south of their climatological maximum in the central Atlantic so that the associated winds may become relevant for Portugal. Concerning the intermediate lows (parts of which may have already been counted as deep lows at an upstream position), an influence on westerly advection into Iberia can only be expected when these systems are close to Europe, as the lateral extension of cyclones can be assumed to be related to their depth. Thus, it is not unexpected that the cyclone count anomalies are confined to the East Atlantic and Europe.

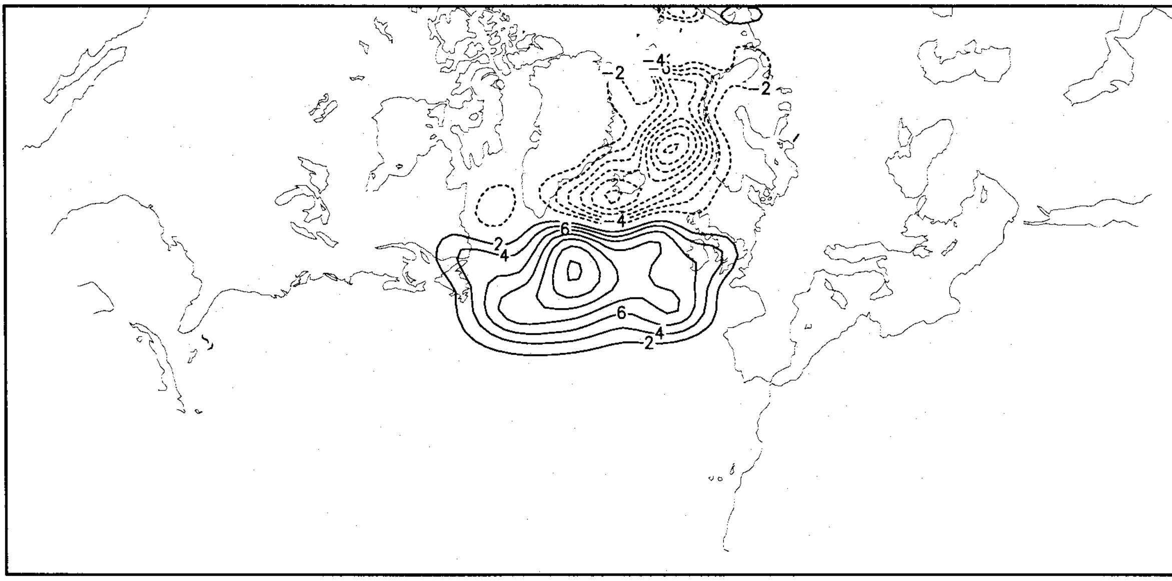

Figure 4. Anomalous distribution of deep-cyclone counts (central pressure < 980 hPa). Anomalies are defined as the difference in total cyclone counts during individual winter months with high and low PC1-values (threshold ± one standard deviation). Contour interval is 2 cyclones

With respect to weak depressions (between 1000 and 1010 hPa) identified by our scheme, the composite difference indicates an enhanced number of cyclone counts north of, south of, and over the Iberian peninsula (not shown). Hence the anomalous distribution does not support a picture where weak cyclones also add to precipitation by purely enhancing moisture advection. Instead, it suggests that large scale rising of air associated with surface lows is a potential rainfall producing mechanism. Note that no such systems are encountered over the Iberian peninsula during months with poorest rainfall, but eight out of a total of 35 during months with largest rainfall amounts.

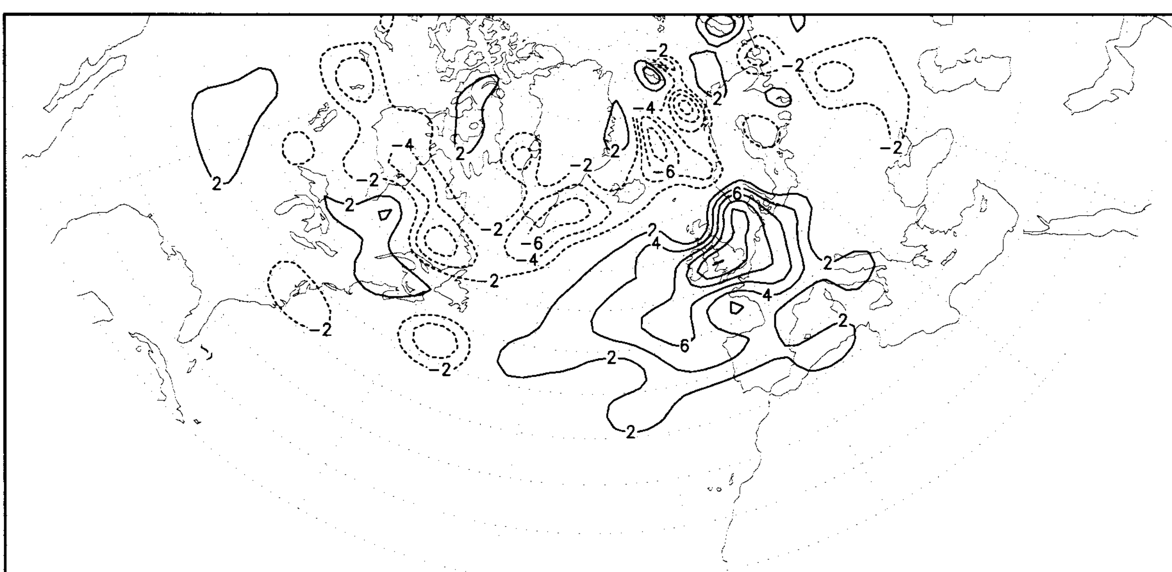

Figure 5. Anomalous distribution of weaker-cyclone counts (980 hPa ≤ central pressure ≤ 1000 hPa). Anomalies are defined as the difference in total cyclone counts during individual winter months with high and low PC1-values (threshold ± one standard deviation). Contour interval is 2 cyclones

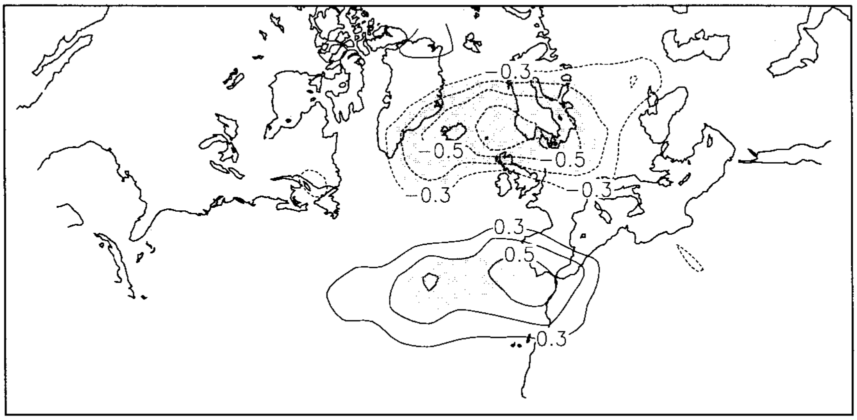

Figure 6. Distribution of correlation coefficients between the first principal component of precipitation in Portugal and storm tracks at individual grid points in DJF. Correlations above 0.3 (below -0.3) are significant at the 95% confidence level. Contour interval is 0.1. Shading highlights most influential areas with a regression coefficient above 0.015 gpm/mm · month (below -0.015 gpm/mm · month)

The second aspect of baroclinic waves that we consider, the mid-tropospheric wave activity, is computed as the bandpass filtered 500 hPa geopotential height variance (the storm track, e.g. Blackmon, 1976; Christoph *et al.*, 1995). We correlate this quantity with the first principal component of rainfall. The resulting distribution of correlation coefficients (Figure 6) shows that enhanced rainfall in Portugal is associated with anomalously high activity over Portugal and adjacent areas to the west. As mentioned before, this could be due to the vertical motions associated with the mid-tropospheric waves, thereby enhancing condensation in front of the upper air troughs. However, Figure 6 also reveals negative correlations over the Norwegian Sea. The absolute correlation values of PC1 and the storm track intensity at these gridpoints have values of about 0.6 and thus are at least as high as those over Portugal. Clearly this indicates that a shift of the Atlantic storm track (and not a purely local intensification or weakening of storm track intensity over Portugal) is associated with rainfall variability. This finding is consistent with our aforementioned result of southward shifted cyclone tracks during high rainfall over Portugal.

3.3. Baroclinic wave influence versus westerly advection

The results described in the previous sections suggest that the intensity of humidity advection into Portugal (as, for example found by ZKS) is the most important factor for local rainfall. The deep and intermediate surface cyclone count anomalies were found to be consistent with an enhanced humidity advection from the Atlantic Ocean for months with enhanced rainfall. Counts of weak lows and the correlation of mid-tropospheric storm track intensity suggest that the large scale rising of air may also contribute, but correlations (for the storm track) and absolute counts (for the cyclone cores) are rather low. It could be that either the effect of large scale ascent of air associated with cyclones or upper air waves is small, or that the relation of these factors to rainfall is merely a statistical one. In particular this would mean that the observed anomalies in the distribution of weak cyclones and storm tracks are statistically related to the changes in advection, but do not exert a physical effect themselves.

In order to identify an independent influence of baroclinic wave activity on rainfall we first quantified the effect of westerly advection on Portuguese rainfall with a very simple approach, assuming that humidity advection is proportional to the unnormalized difference in SLP between two grid points (35°N, 10°W and 45°N, 10°W). A scatter-diagram depicting monthly mean PC1 values versus the above introduced north–south pressure gradient over Portugal shows a highly linear relationship (Figure 7). The correlation coefficient is $r = 0.81$. We repeated the correlation between rainfall PC1 and pressure-gradient using differently defined estimates of the latter (choice of grid points, absolute gradients including the east–west component), but the highest correlation was obtained for westerly advection.

The independent role of cyclone cores over the Iberian peninsula and the adjacent parts of the Atlantic Ocean (36°N–42°N, 0–30°W) is revealed by distribution of those winter months with cyclone cores located over Iberia. All months with three or more cyclone counts over the Iberian peninsula (see filled squares in Figure 7) are characterized by rainfall amounts larger than or, in one case, equal to that expected from linear regression.

The existence of an advection-independent influence from local cyclone cores can also be elucidated by removing the linear influence of the north–south gradient from the time series of rainfall. Months with very high and low values of residual-PC1 were compared with respect to surface cyclone locations. Figure 8 shows that the main difference is the occurrence of an enhanced number of weak (central pressure between 1000 and 1010 hPa) cores in an east–west orientated band at the latitude of Portugal. For the intermediate cyclones (central pressure between 980 and 1000 hPa), the number of cores in this region is increased for the high–low residual PC1 months (no plot shown) compared with the use of the original PC1 (Figure 5). Nevertheless, the maximum of occurrence for this class of cores is found north of Portugal. We interpret this as an indication for the superposition of two effects in this class of cyclone: enhanced advection *and* large scale ascent of air.

In order to identify an independent role of the mid-tropospheric storm track intensity we marked months with particularly high and low storm track intensity over Portugal (threshold $\pm$ one standard deviation) in a scatter-diagram depicting the relationship between rainfall PC1 and westerly advection (Figure 9). Low (high) local storm track activities tend to be associated with low (high) pressure gradients and low (high) rainfall amounts, but apart from this linear relation there is no indication for excessive rainfall due to high storm track intensity. Next we removed the linear influence of the north–south gradient from both the time series of rainfall (PC1) and of storm track intensity at all gridpoints. The remaining correlation of rain and storm track intensity is below 0.3 over Portugal (not shown), while it was above 0.5 before (Figure 6). Thus, there is still a positive correlation of local storm track intensity and the residual PC1, but it explains little variance. We conclude that there is no large independent contribution of local storm track intensity to rainfall over Portugal.

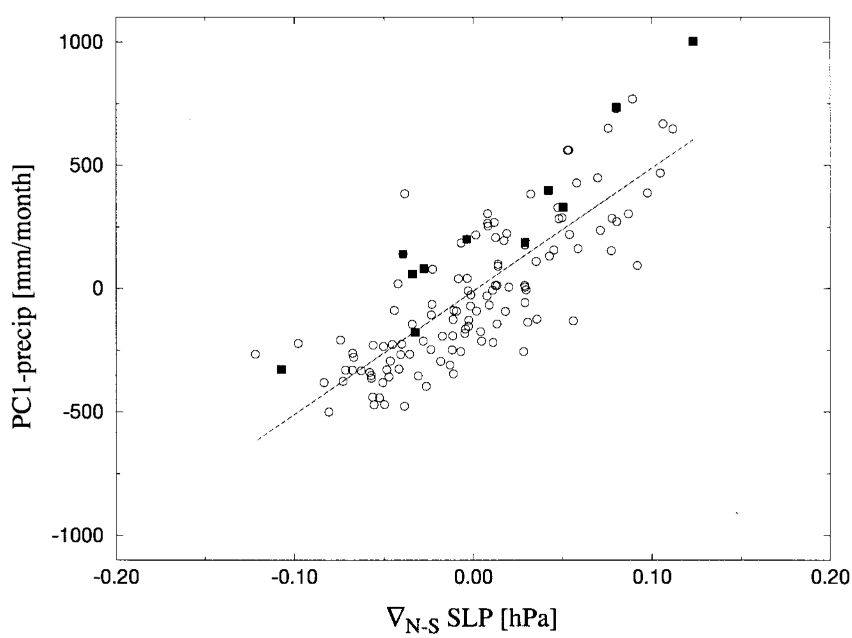

Figure 7. Scatter-diagram of first principal component of precipitation in Portugal versus north–south sea level pressure gradient over Portugal in (hPa) for individual winter months (denoted by circles). Thin line marks linear regression. Filled squares highlight those winter months when three or more cyclone cores are found over Iberia and adjacent parts of the Atlantic Ocean (36–42°N; 0–30°W)

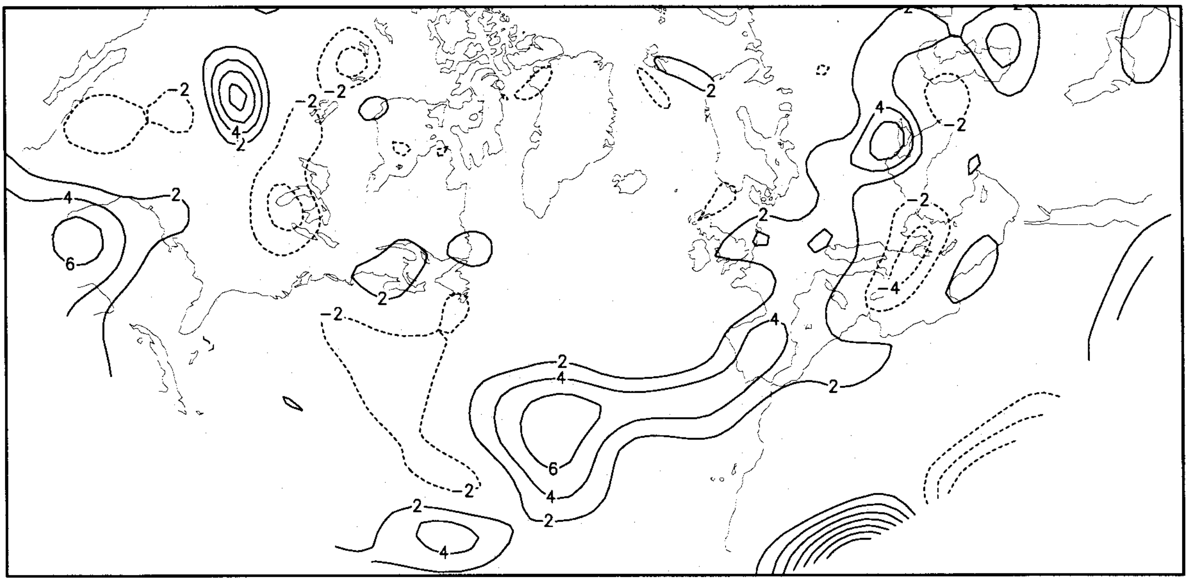

Figure 8. Anomalous distribution of weak-cyclone counts (1000 hPa ≤ central pressure ≤ 1010 hPa). Anomalies are defined as the difference in total cyclone counts during individual winter months with high and low PC1-values (threshold ± one standard deviation) and under the constraint that influence from westerly advection is eliminated linearly. Contour interval is 2 cyclones

It appears that the possible importance of the storm track intensity for rainfall is tied to the variable westerly advection and thus to the meridional pressure gradient. The close relation of these two quantities is confirmed in Figure 10. In fact, the correlations between pressure gradient and storm track intensity over Portugal are higher than those between rainfall and the local storm track. Taking into account the

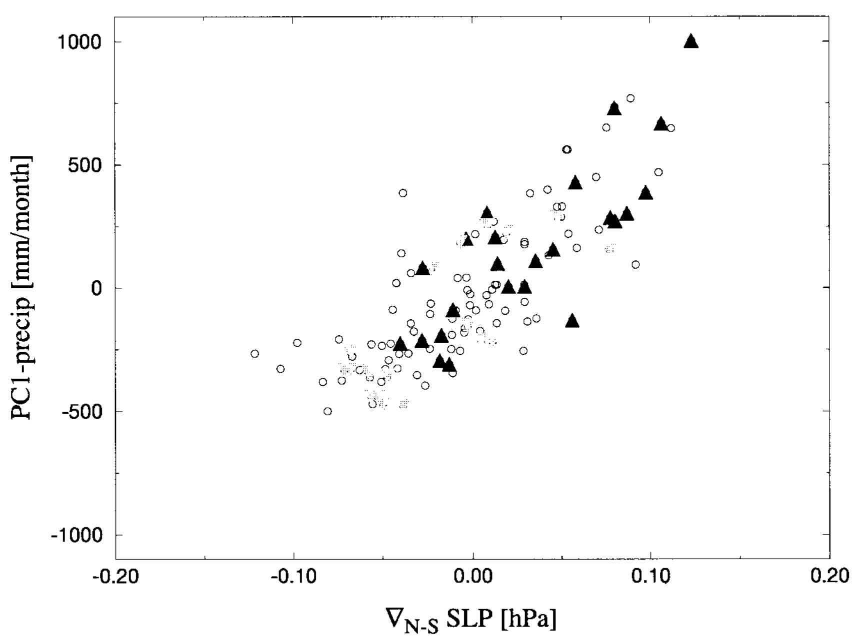

Figure 9. Scatter-diagram of first principal component of precipitation in Portugal versus north–south sea level pressure gradient over Portugal in (hPa) for individual winter months (denoted by circles). 'Black triangles up' and 'grey triangles down' highlight those months with particularly high and low stormtrack activities (threshold ± one standard deviation) over Portugal, respectively

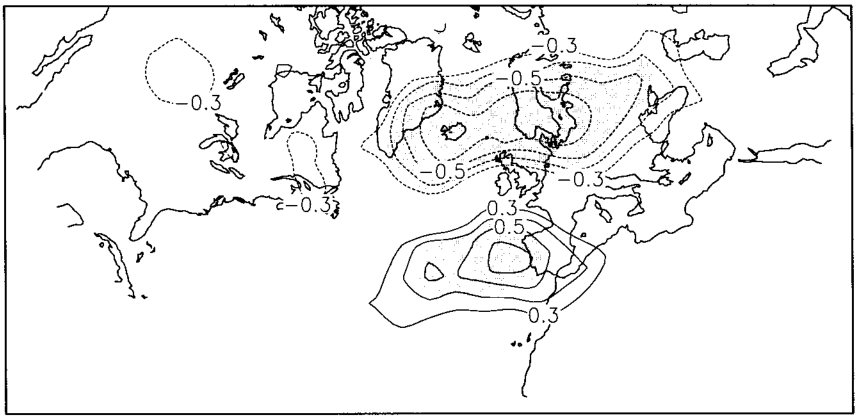

Figure 10. Distribution of correlation coefficients between the meridional pressure gradient over Portugal and storm tracks at individual grid points in DJF. Correlations above 0.3 (below −0.3) are significant at the 95% confidence level. Contour interval is 0.1. Shading highlights most influential areas with a regression coefficient above 0.9 gpm/hPa (below −0.9 gpm/hPa)

results of Hurrell and van Loon (1997) regarding the relationship between NAO and storm tracks, we believe that the role of the local storm track variability must be seen as part of the NAO-dependence of rainfall described earlier in this paper.

4. CONCLUSIONS

Our results confirm the importance of the North Atlantic Oscillation for the variability of Portuguese rainfall, a fact which is imposed by the NAO's close relationship with humidity advection, cyclone occurrence, and upper air variability (see also ZKS; Rogers, 1990; Hurrell and van Loon, 1997). The highest correlation with rainfall is found for the NAO-P pressure variability pattern which is quite similar to the standard NAO patterns as defined by Hurrell (1995) and Rogers (1984) except for a 15° northward shift of the NAO-P dipole. This suggests that the prime factor induced by the NAO surface pressure variability is the humidity advection from the Atlantic Ocean which is connected to the NAO-P pattern by the geostrophic wind relation.

Changes in the occurrence of deep ($p_s < 980$ hPa) and intermediate ($980 < p_s < 1000$ hPa) cyclone cores associated with rainfall variability are found mainly over the eastern North Atlantic and North-western Europe. This is consistent with results from studies relating NAO and cyclone occurrence (e.g. Rogers, 1990), as well as with findings of ZKS (their Figure 10) that submonthly SLP variance is enhanced over the central North Atlantic (rather than over Portugal) for the ten wettest winters in the Iberian peninsula. These anomalies are indicative of an enhancement of advection south of the cyclone cores rather than of processes related to local cyclones inducing rainfall, e.g. large scale ascent of air or destabilization.

The relative importance of local cyclones as an additional independent factor for rainfall over Portugal emerges from the fact that in their presence, monthly precipitation amounts are higher than expected from advection only. We expect this excessive rain to depend on the number and strength of cyclones crossing the Iberian peninsula, both factors being related to the intensity of the local processes within a month, e.g. large scale rising of air. Deep cyclones are, however, rarely encountered in the area of Portugal's latitudes which hampers a more detailed statistical investigation of this matter.

The fact, however, that the largest anomalies of cyclone-core counts are found north of Portugal, does not mean that the influence of these cyclones is limited to the effect of enhanced humidity advection. Depending on the position of the cores, the local effects of cyclones mentioned before may be superimposed on advection. Also, we did not consider secondary depressions which frequently develop along the frontal zones of deep cores. These pressure minima don't meet the identification scheme's criterion of a monotonous pressure rise within a 700 km radius due to the related large core in a more northerly position. Secondary systems, however, can have a strong impact on rainfall when located over Portugal. Thus cyclone-count anomalies of the deeper cores may be partly related to rain-producing local effects of the secondary systems rather than to advection only.

Furthermore, the influence of local cyclones over Portugal may be underestimated due to the low spatial and temporal resolution of the data used for cyclone identification. Intermediate ($980 < p_s < 1000$ hPa) and weak ($1000 < p_s < 1010$ hPa) cyclones (these are among the most frequently observed ones over Portugal) may not be resolved by the data and thus be missed by the identification scheme. The restriction of the temporal resolution to daily values may also lead to a missing of cores passing through the area within less than 24 h.

We find a correlation maximum of rainfall and local upper air geopotential height variability (the storm track) over Portugal. This parameter could be assumed to be important for rainfall variability due to the associated upward vertical air motions in front of approaching troughs. However, as storm track variability and NAO (and thus also westerly advection of humidity) are also closely related (see also Hurrell and van Loon, 1997), there is no strong evidence for an independent role of storm track variability on rainfall. Cut-off lows which sometimes produce large amounts of rainfall at Iberian latitudes, have not been considered in this paper. Generally speaking they do not appear in sea level pressure charts and also contribute little to the storm track variability due to their episodic occurrence.

Up to this point we have only considered the first principal component of Portuguese rainfall. The second and higher principal components of precipitation show significant correlation neither with the storm track intensity nor with the NAO index. Note that we used winter means rather than individual winter months for producing the correlation maps, while individual months were used for the scatter-diagrams and the cyclone count statistics. Repeating the correlation procedures for individual winter months and with different lags leads to very similar spatial distributions. Absolute values of correlation coefficients are highest at zero lag but generally somewhat lower than when using winter means. The lower correlations found are probably due to the fact that the NAO on a monthly basis is strongly influenced by individual Icelandic lows which do not necessarily describe the characteristic flow patterns encountered for enhanced Portuguese rainfall.

We used a rather limited set of basic variables (i.e., surface pressure and geopotential height) for our statistics. Despite these restrictions we were able to identify and largely quantify the dependences of winter precipitation for a specific area. Although relations among basic variables might be different in other regions, our study could be used as a guideline indicating to what extent large-scale parameters potentially relevant to rainfall are interrelated. Such relations should also be considered in GCM downscaling efforts where confidence in model-produced rainfall rates on a regional scale (<2000–4000 km) is rather low (von Storch *et al.*, 1993).

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