The Variability of Cyclonic Activity in the Mediterranean Area in the last 40 Years and its Impact on Precipitation

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ABSTRACT

The influence of cyclonic activity and water vapour advection on winter precipitation variability in the Mediterranean is investigated by means of correlation and composite studies. Main focus is put on Portugal, Italy and Greece. For Portugal, the influence of Atlantic lows on precipitation is found to be decisive, as for rainy months precipitation is associated with an enhanced number of deep and medium cyclones (core pressures below 1000 hPa) between Newfoundland and the British Isles. For Italy, months with high precipitation amounts show an increased number of shallow cyclones in the vicinity of the Italian Peninsula. These cyclones are generally formed over the Mediterranean itself. Atlantic cyclones affect Italian precipitation indirectly through enhanced humidity advection into the Western Mediterranean and by inducing lee cyclogenesis in the lee of the Alps. In some cases Atlantic cyclones move into the Mediterranean Basin and influence local precipitation directly. For Greece, high precipitation is connected with increased cyclone counts over the Central and Eastern Mediterranean.

It is concluded that for Portugal large-scale effects like the advection of humid air associated with distant cyclones (typically located near the Gulf of Biscay) are the main contribution to precipitation. Local effects play a minor role. For Italy and Greece, the main physical mechanisms steering precipitation variability are related to synoptic and orographic lifting due to local cyclonic activity.

1 INTRODUCTION

Within the Mediterranean area, several subclimatic regions can be distinguished with regard to precipitation and temperature variability. Goosens (1985, 1986) and Maheras (1989) proposed subdivisions of the Mediterranean region which suggest a succession of sectors mainly from the eastern to the western part of the basin. In agreement with the regionalization of precipitation by Goosens (1985) and long term precipitation variability (e.g. Maheras, 1988; Palmieri *et al.*, 1991; Maheras *et al.*, 1992; Mendes, 1993), we have chosen three areas to be investigated: the first corresponds to a region with a rather west-european coastal climate (Portugal), the second to a region in the central Mediterranean characterised with rainy summers (Italy) and the third one to a region on the eastern Mediterranean with long and dry summers (Greece). For all three regions most of the annual precipitation occurs in the winter half-year.

Our objective was to investigate the relationship between winter (December to February) rainfall over these areas in the Mediterranean region and the large scale atmospheric circulation. The general patterns of the relationships between precipitation variability and cyclone distributions, cyclone tracks and water vapour advection is investigated on a monthly time-scale. Emphasis is put on the underlying physical mechanisms of these relationships, like synoptic lifting, orographic forcing and large-scale water vapour advection induced by cyclones. We also investigated in how far the influence of Atlantic cyclones can be detected.

Data and methods used for this study are presented in part 2. Part 3 presents the results obtained for the 3 investigation areas (Portugal, Italy and Greece), followed by a short discussion of our results.

2 DATA and METHODS

The precipitation data used consists of monthly time series for 3 groups of stations, hereafter defined as Portugal, Italy and Greece, for periods around 30 winters (see Table 1). The datasets were obtained from the Climate Research Unit, East Anglia, U.K., the I.C.A.T., Lisbon, Portugal, and the E.R.S.A.L., Milan, Italy.

Principal Component Analysis (Preisendorfer, 1988) is used to identify leading modes of precipitation variability in the chosen areas. The annual cycle was removed from the data series, and missing values (maximum 1-2%) were substituted by the cimatological mean for the correspondent month for that station. Using the rule N from Preisendorfer (1988), significant EOFs were identified. The leading Principal Component (PC1) is used as representative for precipitation variability in the area. Based on the extreme values of PC1, with a threshold of $\pm$ 1 standard deviation, composites were built for other variables, for example cyclone distribution. Each of the resulting composites included 13 to 16 fields, depending on the region, from a total of 120.

Table 1. Number of stations and period considered for each region.

Region	N. Stations	Period
Portugal	15	1958-1990
Italy	16	1958-1988
Greece	16	1958-1987

All atmospheric variables were taken from NCEP-Reanalysis (spatial resolution of 2.5˚ x 2.5˚, 6-hourly) for the period January 1958 to April 1998. The moisture fields in the NCEP-Reanalysis are found to be in good agreement with observations in our region of interest (see Trenberth and Guillemot, 1998). Water vapour advection was computed for 2 levels, 700 and 850 hPa, both zonal and meridional components. Only results for the 850 hPa level are presented, as no difference is found with respect to the qualitative interpretation of the results.

Automatic methods have been used to identify and track cyclones in the Mediterranean region (see Alpert *et al.*, 1990a, 1990b, Trigo *et al.*, 1999). We identified the cyclones from 6-hourly Sea Level Pressure (SLP) data using the methodology of Haak and Ulbrich (1996). The results were cross-validated with an alternative code from Murray and Simmonds (1991). Both methods use bicubic splines to interpolate the original data onto a finer grid (0.25˚ x 0.25˚), before minima search is initiated. As results from both methods are equivalent, only output obtained with the Haak and Ulbrich (1996) routine is presented here. For this study only minima fulfilling the following conditions are considered: 1) pressure rises monotonously from the centre to a radius of 330 km, and 2) central pressure is the absolute minimum within a radius of 660 km. Cyclones were afterwards separated in classes based on their central pressure. Climatologies and monthly distributions of cyclones were constructed using 5˚ x 10˚ lat.-lon. boxes, and the total count is given to the centre of the box.

Cyclone Tracks were computed from cyclone identification results, using Murray and Simmonds (1991) tracking routine. Only cyclone tracks lasting at least 2 days were considered. As the life span of Mediterranean cyclones is in average shorter (e.g. Trigo *et al.*, 1999), they are considered if their tracks last at least 24 hours. The general characteristics of preferred cyclone tracks in winter agree with results presented by Alpert *et al.* (1990b).

3 RESULTS

For Portugal, Principal Component Analysis of precipitation show one significant PC, explaining over 83% of the total variance (cf. Table 2). The correspondent EOF shows a maximum over the mountains in the interior north (Fig 1a). For the Greek area only one PC is significant, with a corresponding EOF revealing increasing values over the West Coast of Anatolia (Fig 1c).

Table 2. Explained and accumulated variance of the first 3 PCs for Portugal, Italy and Greece. Significant PCs are marked with '*'(see text).

EOF	Portugal	Italy	Greece
1	83.3 (83,3) *	34,5 (34,5) *	61,8 (61,8) *
2	8.6 (91,8)	15,6 (50,0) *	10,0 (71,7)
3	2,4 (94,2)	12,1 (62,1) *	6,8 (78,5)

For these two regions the PC1 is found to be a good approximation for precipitation variability. Although for Italy three significant PCs are found (Table 2), we restrict our considerations to PC1, which explains about one third of the precipitation variability. The corresponding EOF shows a maximum in the Liguria region (Fig. 1b).

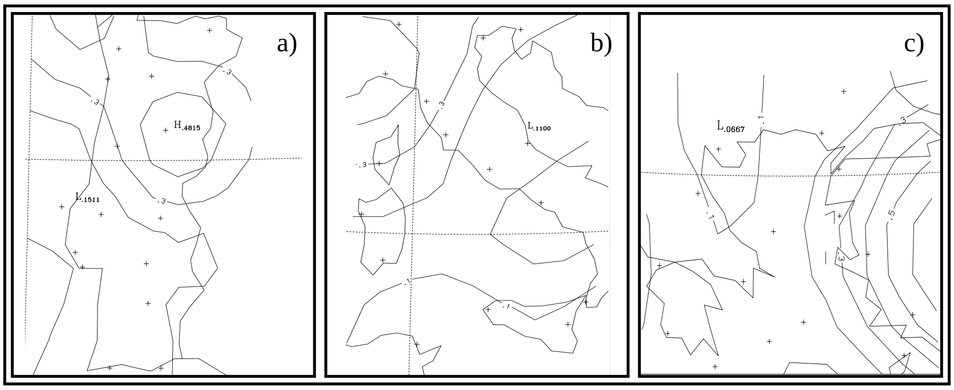

Fig 1 Non-seasonal EOF1 of precipitation for Portugal (left panel), Italy (central panel) and Greece (right panel). '+' indicate the location of stations. Contour interval is 0.1.

Based on the extremes of the first PC for Portugal, composites of cyclone distributions were computed for Portugal. Three classes with different core pressure ranges were chosen: a) below 980 hPa, b) 980 - 1000 hPa, and c) 1000 - 1010 hPa. The difference composites (positive - negative) for deep and medium cyclones are shown in Figs. 2 and 3. For deep cyclones, an increased number of counts is found in a band around 50° N, with a maximum at 20° W (see Fig. 2). A reduced number of cyclones is found further north. Enhanced precipitation in Portugal is therefore connected with a shift of the position of deep cyclones further to the south. For medium cyclones (Fig. 3) a higher number of cores is found northwest and over the Iberian Peninsula, with a maximum near the Gulf of Biscay. In this case we find an enhancement of cyclonic activity rather than a shift.

The anomaly distribution of weak cyclones (cores between 1000 and 1010 hPa) shows an increased number of counts over the Iberian Peninsula and further west (not shown). The fact that, for a given humidity advection, rainfall amounts for months with local cyclone cores over the region tend to exceed those without, reveals the separated influence of these cyclones on precipitation (see Ulbrich *et al.*, 1999).

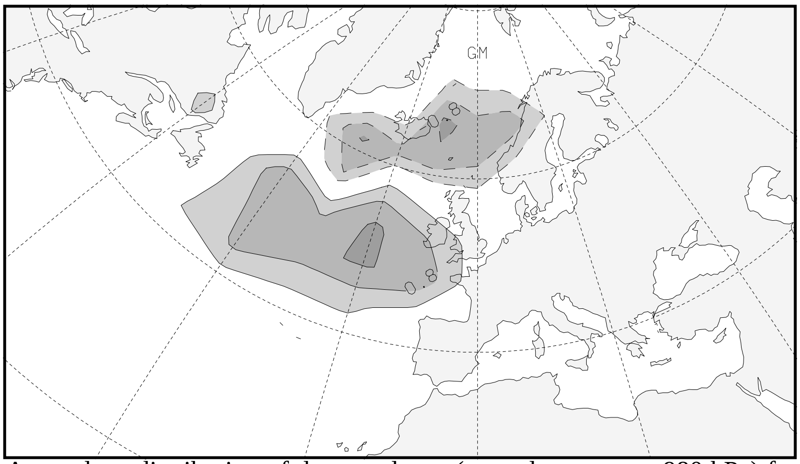

Fig. 2: Anomalous distribution of deep cyclones (central pressure < 980 hPa) for Portugal. Contour interval is 0.4 cyclones/month.

In months with high (low) precipitation in Portugal, cyclone tracks are shifted to the south (north) over the whole North Atlantic (not shown). This corresponds to the anomaly distribution of deep cyclones based on the extremes of precipitation (Fig. 2).

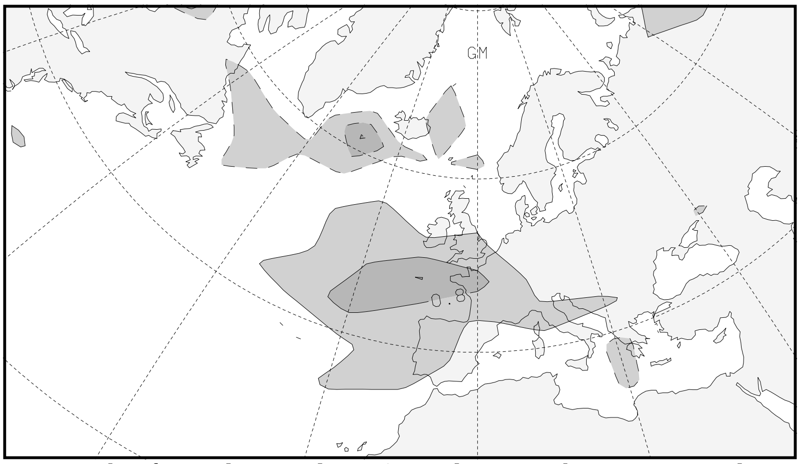

Fig. 3: As Fig. 2 but for medium cyclones (central pressure between 980 and 1000 hPa).

In order to evaluate the contribution of humidity advection to precipitation, composites were computed for the zonal and meridional components in analogy to the cyclone counts. The anomalous distribution of the humidity advection is given by the vectors in Fig. 4, whose components correspond to the zonal and meridional humidity advection. A strong anomaly of westerly advection is found over the Atlantic, west of the Iberian Peninsula, turning to southwest over the Peninsula itself. The position of the vortex of anomaly advection is coherent with the position of the maximum of deep cyclone counts (cf. Fig. 2). The total humidity advection is dominated by the zonal component, with high correlations to PC1 in a band extending over the Atlantic around 40˚ N (cf. Fig. 4), and a maximum correlation of 0.93 over Portugal (40˚ N, 7.5˚ W). This result is in agreement with earlier studies (Zorita *et al.*, 1992; Zhang *et al.*, 1997; Ulbrich *et al.*, 1999).

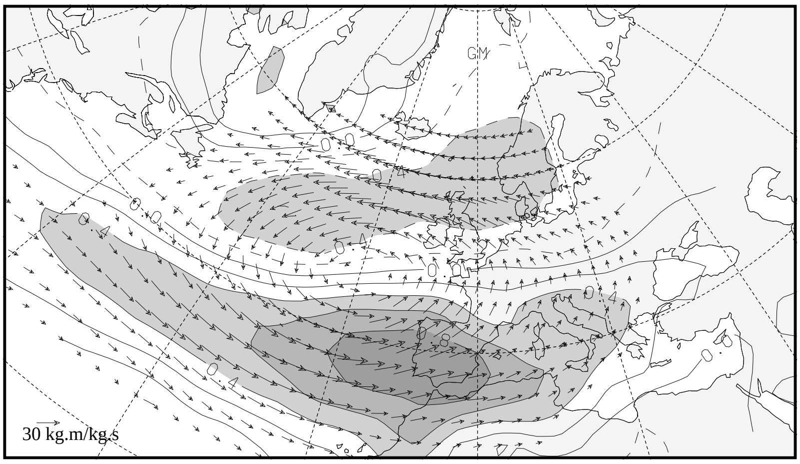

Fig. 4: Anomalous distribution of humidity advection in 850 hPa (vectors) and correlation chart between humidity advection and precipitation PC1 (isolines) for Portugal. Vectors representing values below 10 kg.m/kg.s are suppressed. Isoline contour is 0.2.

For Italy we distinguish between two cyclone classes: a) core pressure below 990 hPa, and b) core pressure between 990 and 1010 hPa. This choice of class boundaries is found to provide a better interpretability of the cyclone count distributions for this area. Note that the class ranges differ from the ones for Portugal. The difference between the positive and the negative composites of these cyclone classes are shown in Figs. 5 and 6. For deeper cyclones a higher number of counts is found north of the Iberian Peninsula, near the British Isles. An equivalent anomaly is found when composites of the geopotential height at 1000 or 500 hPa are considered (not shown).

The relevance of these features for precipitation in Italy lead us to consider the following possibilities: 1) the enhanced counts of cyclones influence precipitation in Italy indirectly by contributing to humidity advection into the Mediterranean; 2) the cyclones may eventually cross over to the Mediterranean (note that some cyclones might not be assigned to the same class further downstream, if core pressure rises above 990 hPa) and induce precipitation locally; 3) the cyclones may induce cyclogenesis in the lee of the Alps (see Buzzi and Tibaldi, 1978; Radinovic, 1986) as they cross over Western Europe at correspondent latitudes. During this investigation we found examples of all three cases, but the comparatively low numbers of the latter two cases (see below) suggests that the most relevant effect of these cyclones is their contribution to humidity advection.

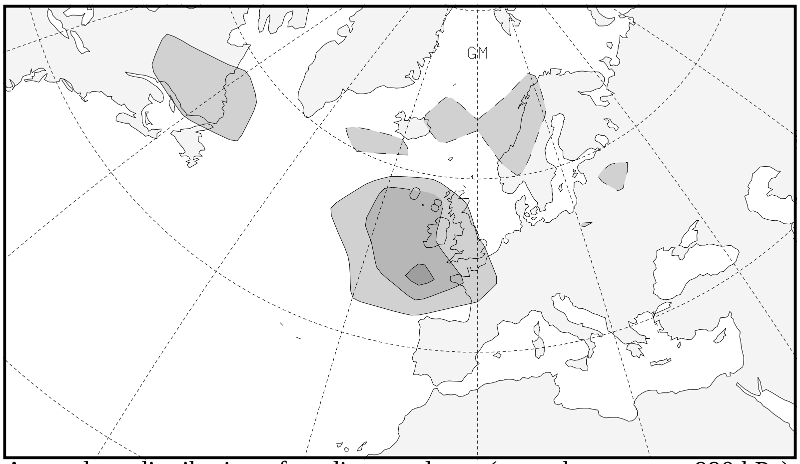

Fig. 5: Anomalous distribution of medium cyclones (central pressure < 990 hPa) for Italy. Contour interval is 0.4 cyclones/month.

With respect to shallow cyclones, enhanced counts are found for the Western Mediterranean, with a maximum near the Italian Peninsula. Reduced activity is found further to the east, especially near the Black and Caspian Seas.

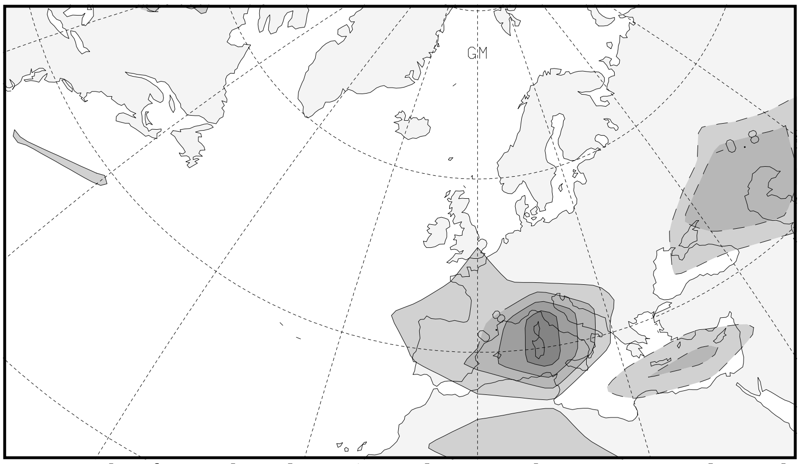

Fig. 6: As Fig. 5 but for weak cyclones (central pressure between 990 and 1010 hPa).

Furthermore, we investigated cyclone tracks for months with high and low precipitation amounts. We show results from two particular months that represent typical features from each composite (positive: December 1959; negative: January 1981).

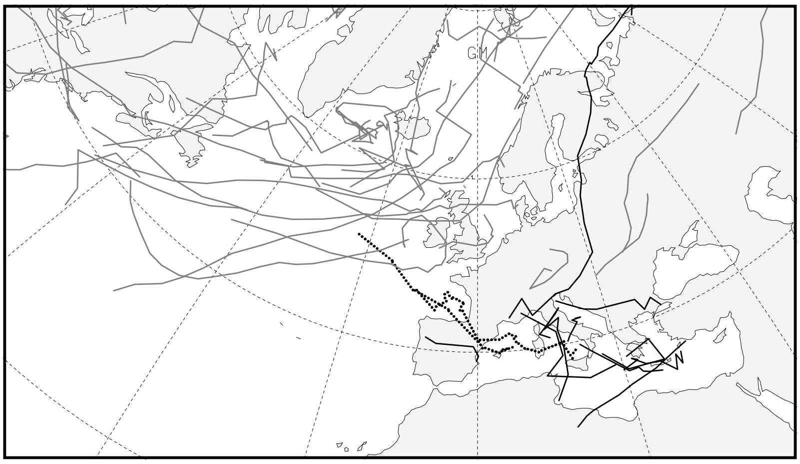

Fig. 7: Cyclone tracks for December 1959; dotted lines: Atlantic cyclones moving into the Mediterranean; solid lines: Mediterranean cyclones; gray lines: other cyclones.

Cyclone tracks for December 1959 (Fig. 7) show strong cyclonic activity in the vicinity of the Italian Peninsula and two Atlantic cyclones moving into the Mediterranean (dotted lines). The cyclone tracks in the Atlantic are further south than average, with cyclones moving around 50˚ N towards the British Isles. There are several cyclone tracks starting in the Gulf of Genoa. An inspection of weather maps for these cases makes clear that lee cyclogenesis was induced by the cyclones crossing over Northwestern Europe. In January 1981, the Atlantic tracks are shifted further to the north, with the tracks typically starting near Newfoundland and extending to Iceland and North Scandinavia (not shown). Very few cyclone tracks are found over the Mediterranean Basin.

In order to evaluate the role of humidity advection, the zonal and meridional anomaly humidity advection were computed based on the extremes of the first PC for Italy. A strong westerly anomaly is found for the region near Gibraltar, and a southerly anomaly near the Italian Peninsula (Fig. 8). The position of the vortex of anomaly advection is coherent with the position of the maximum of anomaly of deeper cyclones counts (cores below 990 hPa; cf. Fig. 5).

The correlation chart between the PC1 for Italy and total humidity advection shows two maxima: one near Gibraltar (dominated by the zonal component) and another over the Italian Peninsula (dominated by the meridional component). Maximum correlation found between total humidity advection and PC1 for precipitation is 0.70 (45˚ N, 17.5˚ E). Considering only the meridional component (not shown), we find a maximum correlation of 0.85 over Italy (45˚ N, 15˚ E).

The difference between the positive and the negative composites is found to be significant at the 95% significance level for the area near the Italian Peninsula.

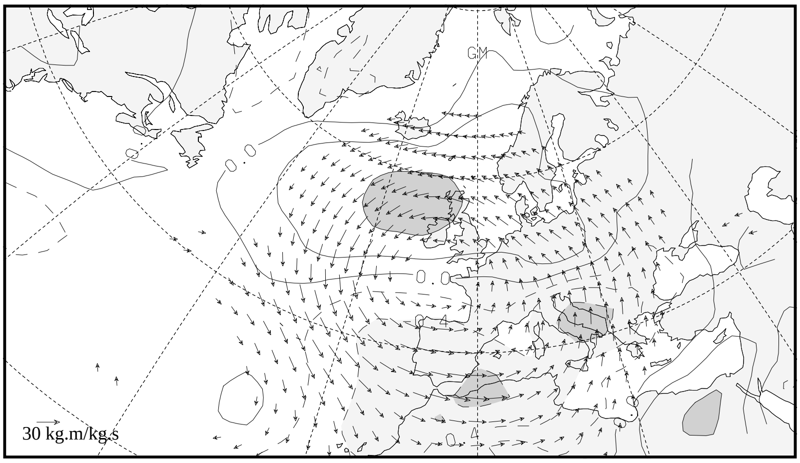

Fig. 8: As Fig. 4 but for Italy. Isoline contour is 0.2.

For Greece we considered the two cyclone classes already used for Italy. The distribution of deeper cyclones in the positive and negative composites are in fact similar, and the only significant feature of the anomaly field is a reduced number of cyclone counts for the region near Newfoundland (not shown). Therefore it is suggested that precipitation in Greece is in general rarely affected by the Atlantic weather systems.

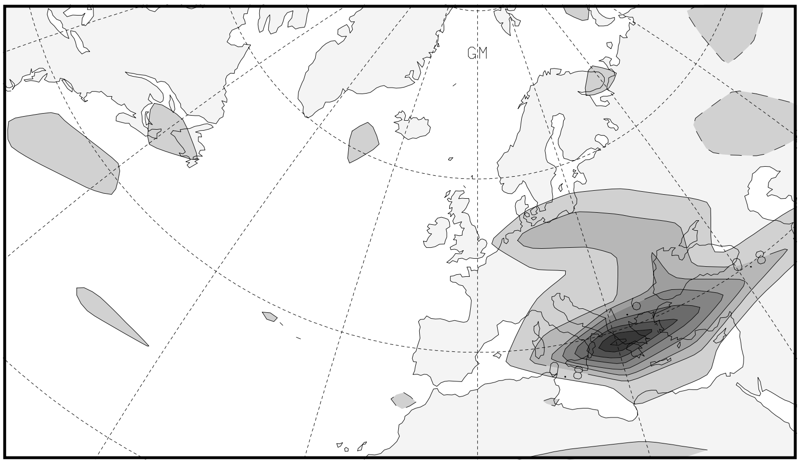

Fig. 9: Anomalous distribution of weak cyclones (central pressure between 990 and 1010 hPa). Contour interval is 0.4 cyclones/month.

However, in some cases, like a ‘cutoff high situation‘ (see Petterssen, 1956;

also known in German literature as an ‘Ω-Wetterlage‘, cf. Kurz, 1990), their influence may reach the Eastern Mediterranean (see Alpert and Reisin, 1986). These situations are characterised by long persistent weather conditions, which endure often more than a week.

Looking at the anomaly distribution of weaker cyclones, strong enhanced activity is found for the Central and Eastern Mediterranean (Fig. 9). A similar result is found for cyclone tracks; larger track density is diagnosed for months corresponding to the positive composite than for the negative one, when often very little activity over the Eastern Mediterranean is found (not shown). This seems to be caused by stronger cyclogenesis over the Central and Eastern Mediterranean, reinforced in some cases by enhanced cyclogenesis over the Atlas region. The strong variability of Atlantic cyclone tracks within the composites and the small differences between the positive and negative phases suggests that they are in general not relevant for precipitation in Greece.

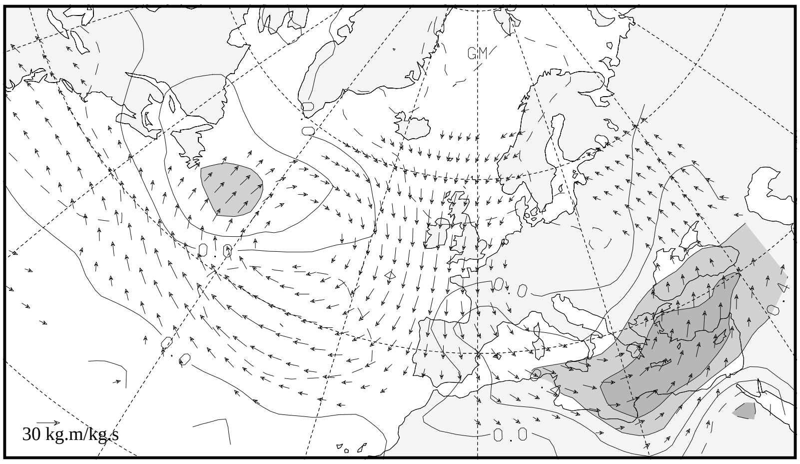

Fig. 10: As Fig. 4 but for Greece. Isoline contour is 0.2.

The anomalous distribution of humidity advection for Greece is shown if Fig. 10. A strong southwest anomaly is found near the Greek peninsula, which is in this case related to the anomaly distribution of shallow cyclones shown in Fig. 9. The maximum correlation between PC1 of precipitation and total humidity advection is 0.75 (35˚ N, 30.˚ E).

4 DISCUSSION

Our investigations demonstrated that the relationship between regional rainfall and the large-scale atmospheric circulation (notably cyclone counts and tracks, and water vapour advection) differs for Portugal, Italy and Greece. The influence of Atlantic (Mediterranean) cyclones on precipitation decreases from the Portuguese area, where they are extremely (rarely) relevant, to the Greek region, where they are rarely (extremely) relevant.

Humidity advection is found to be the main precipitation mechanism for Portugal, with a maximum explained variance of 86.6%. The distant lows do not influence precipitation directly, but rather contribute to humidity advection at their southern flanks. Shallow systems, located close to the Iberian Peninsula may contribute additionally to precipitation with large-scale vertical lifting produced by their fronts or cores (see Ulbrich *et al.*, 1999).

For Italy the distant lows contribute to southwesterly advection of humidity into the Mediterranean region. Some of these Atlantic cyclones may cross over into the Mediterranean, normally over Southern France or Gibraltar, or induce Genoa cyclogenesis as they track over Central Europe (see Buzzi and Tibaldi, 1978; Radinovic, 1986). However, the main precipitation sources are local cyclones, which induce precipitation due to synoptic and orographic lifting. These Mediterranean cyclones contribute additionally to southwesterly advection of water vapour towards the Italian Peninsula.

For Greece, only Mediterranean cyclones are in general important to precipitation. Cyclogenesis is especially relevant over the Central and Eastern Mediterranean. Only in special cases, like cutoff situations, there is a decisive influence from middle latitude air masses on precipitation in the Eastern Mediterranean (see Alpert and Reisin, 1986). The main precipitation mechanisms are orographic effects and lifting related to shallow cyclones. The moisture advection, enhancing the content of precipitable water in the region, is controlled by the shallow Mediterranean cyclones.

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