Theor. Appl. Climatol. 71, 199–217 (2002)

Theoretical
and Applied
Climatology

© Springer-Verlag 2002
Printed in Austria

[1] Department of Meteorology and Climatology, University of Thessaloniki, Greece,
[2] Laboratory of Meteorology, Department of Applied Physics, University of Athens, Greece
[3] Division of Hydraulics, Faculty of Technology, University of Thessaloniki, Greece

On the vertical structure of composite surface cyclones in the Mediterranean region

P. Maheras[1], **H. A. Flocas**[2], **Chr. Anagnostopoulou**[1], and **I. Patrikas**[3]

With 13 Figures

Received November 7, 2000
Revised July 14, 2001

Summary

The average pressure distribution at mean sea level and the vertical structure of synoptic scale surface cyclones (with central pressure less than 1000 hPa) that occur in the Mediterranean region is studied for a 40 year period (1958–1997) on a seasonal and daily basis. The cyclonic occurrences are studied in three regions of enhanced cyclonic activity: gulf of Genoa, Southern Italy and Cyprus. The cyclones are identified with the aid of an objective method based on grid point values, available every 6 hours. The analysis revealed different characteristics of the cyclones that occur in the three regions, reflecting the different mechanisms that are responsible for their occurrence in each region. For the Genoa region the cyclone pressure minimum is located over the gulf, associated with orographic forcing, while surface dynamics occur further south. Over Southern Italy, the pressure minimum covers a wide area, whilst the surface dynamics are found to act in the same region, becoming more important in winter and spring. The pressure minimum of cyclones over Cyprus is located over the land during winter and spring and is influenced by surface dynamics and orography.

1. Introduction

Mediterranean basin is well known as a favourable region for cyclone formation while it is also affected by moving depressions from the Atlantic ocean or from the Sahara region. The frequency of depressions and cyclonic tracks in the Mediterranean has been the subject of climatological research (e.g. Radinovic, 1965; Maheras, 1983a, b; Flocas, 1988; Flocas and Karacostas, 1996). In these studies manual methods of cyclone identification and classification are used based on synoptic charts. More recently, Alpert et al. (1990a), Trigo et al. (2000), Maheras et al. (2001) and Flocas et al. (2001) evaluated cyclone characteristics in the Mediterranean with the aid of objective methods, for periods of 5, 18 and 40 years, respectively. According to these studies, the areas of Genoa, Southern Italy and Cyprus are centers of maximum frequency of Mediterranean cyclones.

The present study performs a climatological analysis of the spatial distribution and temporal variation of the average mean sea level pressure for Mediterranean cyclones with central pressure less than 1000 hPa, for period of 40 years. Furthermore, the vertical distribution of the departures of geopotential from the average seasonal value (namely, anomalies) is studied for the composite cyclones that occur in the mentioned three regions above in relation to the vertical profile of the mean relative vorticity (Flocas et al., 2001), to obtain a better insight into the dynamic background that controls the surface cyclones in the Mediterranean.

2. Data-methodology

The data used are the time series of 6-hourly SLP producing from the NCEP/NCAR 40-year

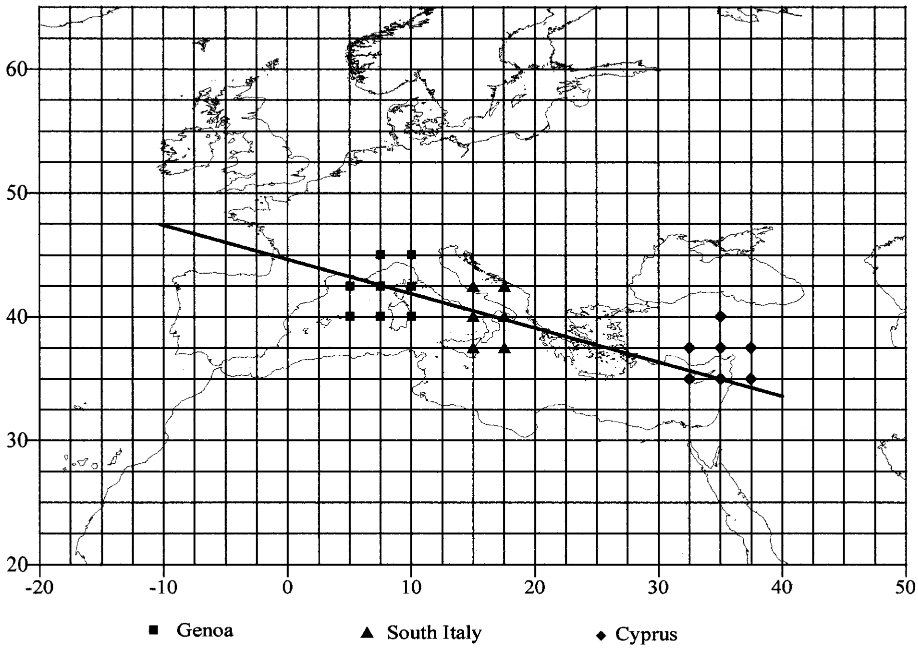


Fig. 1. Domain of study. The grid points, which are consisting of the Gulf of Genoa (see text), the South Italy and the Cyprus cyclonic center, are indicated by squares, triangles and rhombus, correspondingly. The line of the vertical cross-section in Figs. 5, 9 and 13 is indicated

Table 1. Number of cyclonic cases, with central pressure less than 1000 hPa, that are considered in the regions of Genoa, South Italy and Cyprus for each season at 00 and 12 UTC

	Winter		Spring		Summer		Autumn	
	00 UTC	12 UTC	00 UTC	12 UTC	00 UTC	12 UTC	00 UTC	12 UTC
Genoa	101	93	59	64	5	1	54	45
South Italy	96	101	41	47	0	0	24	26
Cyprus	34	43	49	65	20	31	4	4

reanalysis project (Kalnay et al., 1996). The data set consists of grid-point values of mean sea level pressure and geopotential height at all significant isobaric levels for the North Hemisphere in a grid of $2.5° \times 2.5°$. A period of 40 years (1958–1997) is covered at 0000, 0600, 1200 and 1800 UTC. A cyclonic center is detected following the objective method used by Maheras et al. (2001). The study focuses on the cyclones that form in the Gulf of Genoa (Western Mediterranean), Southern Italy (Central Mediterranean) and the area of Cyprus (Eastern Mediterranean). Furthermore, only surface cyclones with central pressure less than 1000 hPa are considered, thus excluding weak cases, following the classification of Mediterranean cyclones according to central pressure as used by Maheras et al. (2001). The geostrophic relative vorticity is calculated from geopotential height data, on the basis of a finite difference method, taking into account the variation of the grid point distances with latitude. The grid points representing the area of Genoa, Southern Italy and Cyprus are shown in Fig. 1. The vertical cross sections are taken along the line shown in Fig. 1 through the three centers. Table 1 presents the total number of cases considered for the three regions and for each season at 00 and 12 UTC.

3. Cyclones over Genoa

Figure 2 shows the distribution of the average pressure at mean sea level corresponding to cyclonic occurrences (central pressure <1000 hPa) detected in the Gulf of Genoa region (see Table 1). In winter, minimum pressure is located over the gulf of Genoa extending to the south over Sardinia and Corsica, without exhibiting any

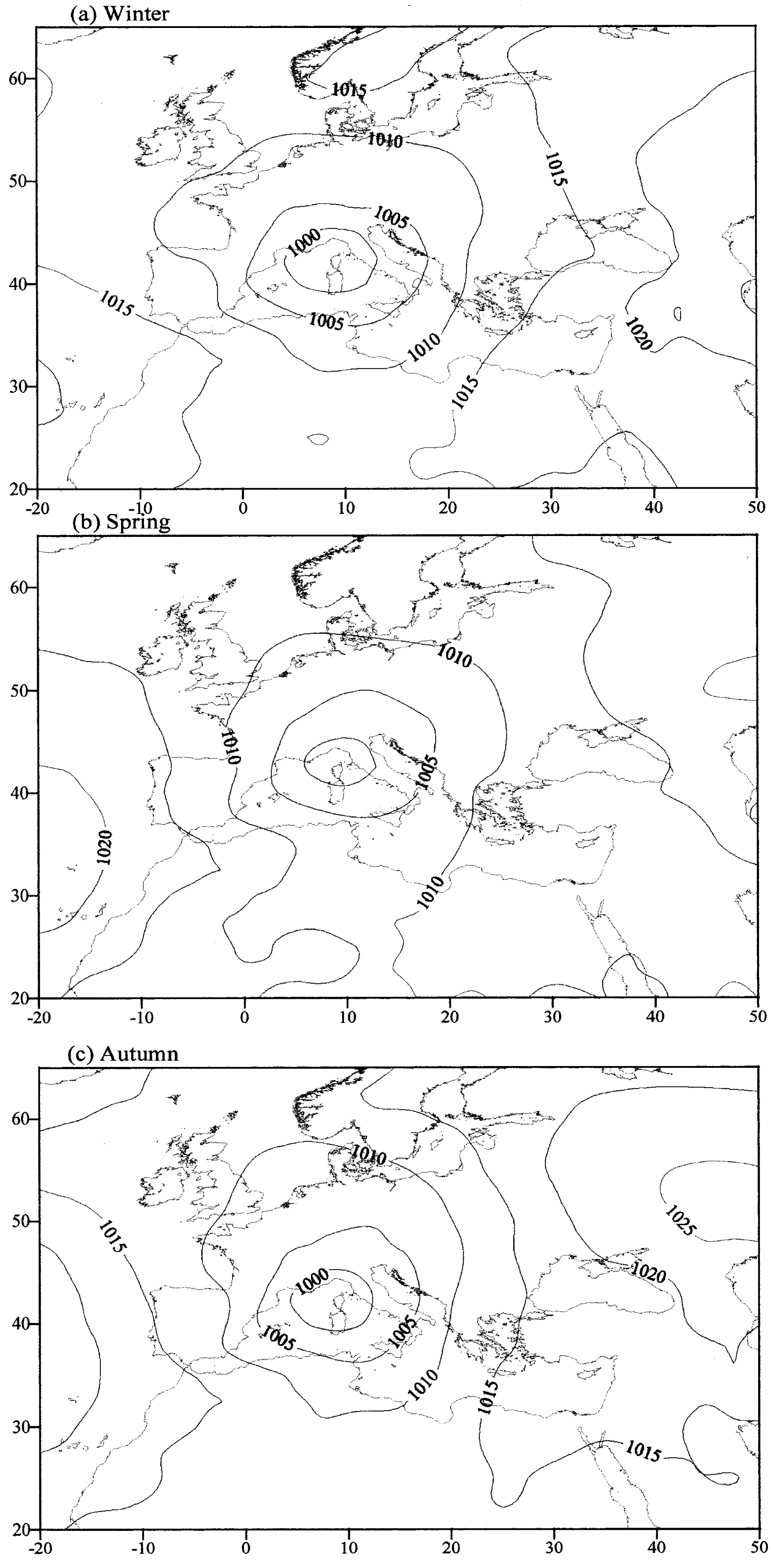


Fig. 2. Distribution of average mean sea level pressure corresponding to Genoa cyclones with central pressure less than 1000 hPa at 00 UTC, for **a**) winter, **b**) spring, **c**) autumn

diurnal changes (Fig. 2a). At the same time, the 1000 hPa vorticity center, of $7 \times 10^{-5}\,s^{-1}$, at 00 and 12 UTC, is found over the islands of Corsica and Sardinia (Fig. 3a), implying that the surface dynamic factor responsible for cyclonic events does not act over the Gulf of Genoa, but further to the south. The geopotential anomaly at 500 hPa is found to the southwest over the Balearic islands (Fig. 4a). During the daytime, the geopotential anomaly weakens while enhancing along a NW-SE axis (not shown).

In spring the pressure minimum (Fig. 2b) extends further northeast than during other seasons, covering northern Italy and the gulf of Venice. The 500 hPa geopotential anomaly (Fig. 4b) strengthens slightly compared to winter. Moreover, the 1000 hPa vorticity center weakens (Fig. 3b), especially at 12 UTC (not shown) and is more confined over Corsica, where a cyclonic path prevails from the Balearic islands during this season (Trigo et al., 2000).

In summer, the number of cyclonic cases in Genoa is very limited (see Table 1) and therefore no reliable results could be obtained. This was expected because in summer the center of the maximum frequency of Genoa cyclones shifts to the north over the warmer land and so do the 1000 and 850 hPa vorticity maxima (Maheras et al., 2001; Flocas et al., 2001). This is also enhanced by the favourable cyclone track over the gulf of Biscay (Alpert et al., 1990b).

The autumn pressure pattern (Fig. 2c) is very similar to that in winter. The 1000 hPa vorticity center is found at the winter location (Fig. 3c), with the same magnitude. The 500 hPa geopotential anomaly (Fig. 4c) is stronger compared to winter and spring throughout the whole day, because the climatological mean value of the geopotential height at 500 hPa is high over Mediterranean during this season (Prezerakos, 1978).

Tables 2 and 3 summarise the seasonal and diurnal characteristics derived from the vertical cross sections of the negative geopotential anomalies. Figure 5a shows the vertical structure of the negative geopotential anomalies corresponding to the surface cyclones in Genoa in winter. It can be seen that four centers predominate in the vertical: at 1000, 850, 500 and 300 hPa, exhibiting a westward tilt with height, with a slope of $-7.1°$, that is indicative of the baroclinic character of the Genoa cyclones. All four centers are found to be statistically significant at the 0.05 level. The surface and 850 hPa anomalies are the strongest ones. The surface anomaly located at 10° E is associated with the strongest vorticity maximum (Flocas et al., 2001), suggesting that the surface cyclones are very intense during this season and are connected to the thermal contrast between sea and air that is at a maximum during winter (Reiter, 1975). This supports the increased number of cyclogenetic events at the surface in winter (Trigo et al., 2000). The 850 hPa anomoly more likely reflects the orographic effect. The two upper level anomalies are related to the deepening of the upper level trough that is observed during Alpine cyclogenesis (Tibaldi et al., 1980). It should be noted that in the vicinity of the Alps a 500 hPa local maximum with closed cyclonic centers was identified by Bell and Bosart (1989), south of the jet stream axis during the cold period of the year. The vertical profile is not characterised by any diurnal variation (Table 2), except that the absolute value of the negative slope reduces during daytime (see Table 3), since the temperature difference between the sea and land decreases.

In spring three geopotential center anomalies appear. These are statistically significant (at level 0.05: at surface, 850 and 700 hPa (Fig. 5b), each one corresponding to a vorticity maximum (Flocas et al., 2001). On the contrary, no anomaly is apparent in the upper levels, which is consistent with the weakening and the northward shift of the 500 hPa closed cyclonic center observed by Bell and Bosart (1989). Nevertheless, the vorticity increases aloft, resulting in the formation of a strong vorticity maximum at 300 hPa (Flocas et al., 2001), suggest that the upper level dynamics are active in spring. The surface anomaly center continues to be the strongest one, in relation to a strong vorticity maximum, despite the weakening of the air-sea thermal contrast in spring. This might be due to the increase in the frequency of lows moving from southwest towards the Gulf of Genoa (Trigo et al., 2000). It is characteristic that all geopotential anomalies strengthen considerably compared to winter (see Table 2). This could be explained by the increase of the climatological reference value of the geopotential at all isobaric levels over WM in spring, compared to winter. The anomalies are

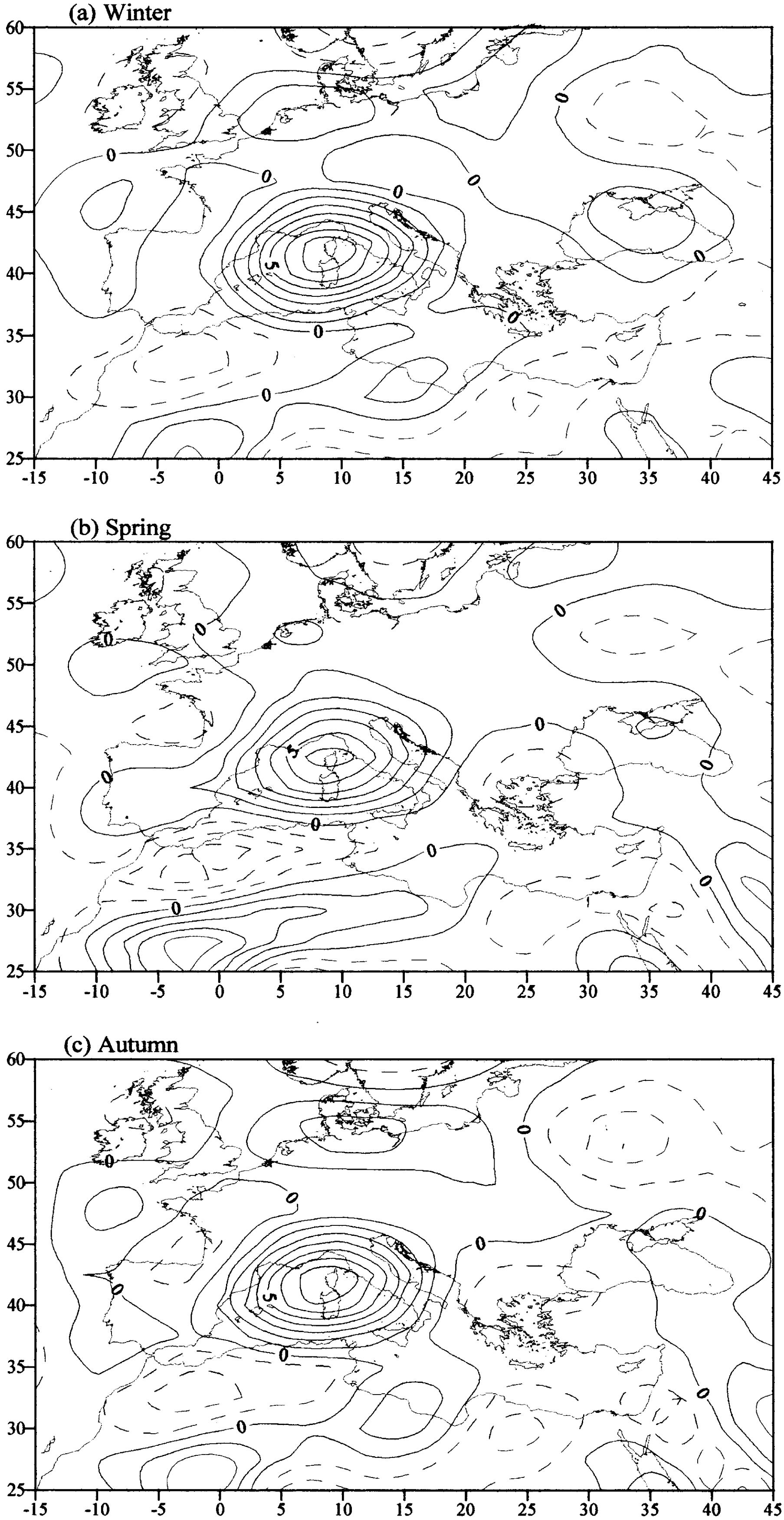


Fig. 3. Distribution of average mean geostrophic relative vorticity at 1000 hPa corresponding to Genoa cyclones with central pressure less than 1000 hPa at 00 UTC for **a**) winter, **b**) spring, **c**) autumn

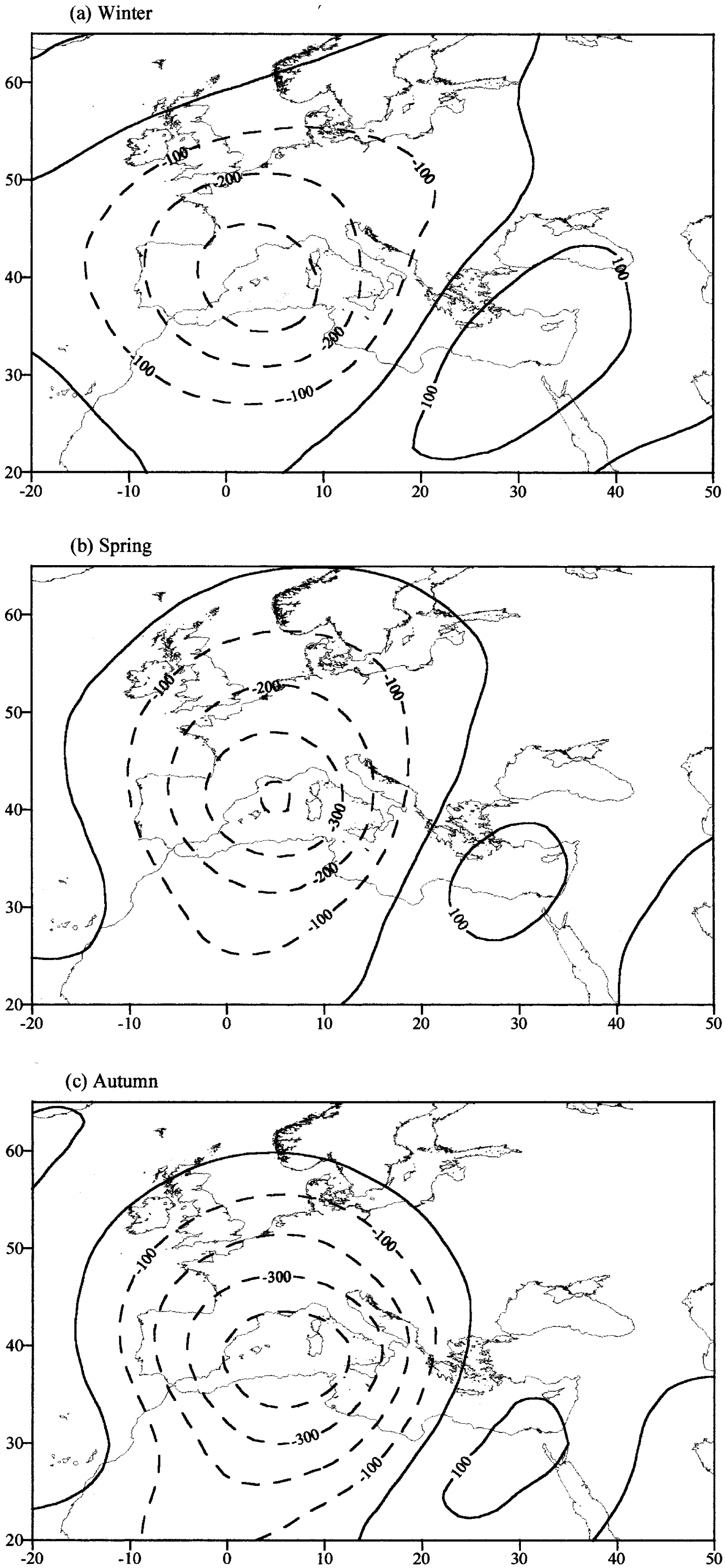


Fig. 4. Distribution of average geopotential anomalies ($\times 100$) at the isobaric level of 500 hPa corresponding to Genoa cyclones with central pressure less than 1000 hPa at 00 UTC for **a**) winter, **b**) spring, **c**) autumn

Table 2. The isobaric levels (hPa) where peaks of the negative geopotential anomalies that are statistically significant (at level 0.05) appear for the three cyclonic centers at 00 and 12 UTC for each season. The number in the parentheses represent the magnitude (×100) of the negative anomaly at each level. The levels in bold indicate the level where the strongest vorticity maximum is observed

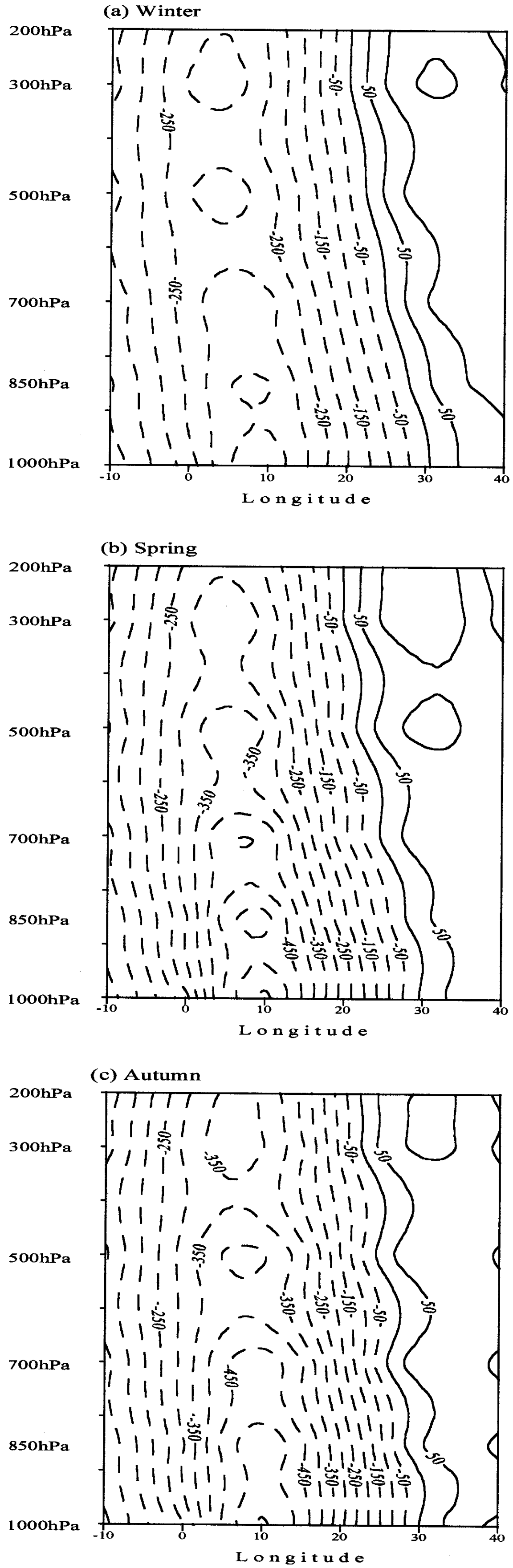
		Genoa	South Italy	Cyprus
Winter	00 UTC	**1000 hPa** (−350) 850 hPa (−350) 500 hPa (−300) 300 hPa (−300)	**1000 hPa** (−400) 700 hPa (−350) 500 hPa (−300) **300 hPa**	1000 hPa (−600) 850 hPa (−600) 500 hPa (−450) **300 hPa** (−400)
	12 UTC	**1000 hPa** (−350) 850 hPa (−350) 500 hPa (−300) 300 hPa (−300)	700 hPa (−400) **300 hPa**	1000 hPa (−600) 850 hPa (−600) 500 hPa (−450) **300 hPa** (−350)
Spring	00 UTC	1000 hPa (−550) 850 hPa (−450) 700 hPa (−450) **300 hPa**	1000 hPa (−550) **300 hPa** (−300)	1000 hPa (−550) 850 hPa (−550) 500 hPa (−400) **300 hPa** (−350)
	12 UTC	1000 hPa (−550) 850 hPa (−500) **300 hPa**	1000 hPa (−550) 700 hPa (−400) 500 hPa (−300) **300 hPa** (−300)	1000 hPa (−550) 850 hPa (−550) **300 hPa** (−300)
Summer	00 UTC			850 hPa (−500) 700 hPa (−550) 500 hPa (−450) **300 hPa** (−400)
	12 UTC			1000 hPa (−400) 500 hPa (−350) **300 hPa**
Autumn	00 UTC	**1000 hPa** (−550) 500 hPa (−400)	1000 hPa (−650) 850 hPa (−700) 700 hPa (−650) 500 hPa (−550) **300 hPa** (−450)	
	12 UTC	1000 hPa (−550) 500 hPa (−400) **300 hPa**	850 hPa (−650) 700 hPa (−600) **300 hPa** (−350)	

Table 3. Negative slope (in degrees) of the vertical profile of the negative geopotential anomalies as estimated from the vertical cross sections at the three locations at 00 and 12 UTC

	Winter		Spring		Summer		Autumn	
	00 UTC	12 UTC	00 UTC	12 UTC	00 UTC	12 UTC	00 UTC	12 UTC
Genoa	−7.1	−5.9	−7.4	−7			−4.7	−5.8
South Italy	−5.2	–	−5.7	−5.0			−5	−4
Cyprus	−8.7	−8.8	−6	−5.2	−3	−4.2		

still characterised by a westward tilting with height (slope −7.4°). Table 2 shows that during daytime the 700 hPa anomaly center vanishes, while the 850 hPa strengthens, along with the corresponding vorticity maximum (Flocas et al., 2001). This could indicate that the orographic effect becomes more active during spring in daytime.

While the vertical distribution of vorticity in autumn resembles that of spring (Flocas et al., 2001), the vertical structure of the negative geopotential anomalies presents different features



(Fig. 5c). There are two main statistically significant anomalies (at the level 0.05) at 00 and 12 UTC: one near the surface (with the highest magnitude, corresponding to the strongest vorticity maximum) and the second at 500 hPa (with a linking to a 300 hPa vorticity maximum). Of interest is the absence of the 850 hPa geopotential anomaly, although the vorticity remains high at this level. Therefore, it seems that the orographic forcing is weaker during this season. In general, the magnitude of the anomalies is very close to those in spring. Unlike the other two seasons, it is characteristic that the anomalies lie in almost the same vertical plane (the slope is $-4.7°$), while the absolute value of slope increases during daytime (see Table 3). This could be attributed to the weakening of the horizontal thermal gradient during autumn, especially during nighttime.

4. Southern Italy cyclones

In winter, the pressure minimum at mean sea level is rather extensive, covering the gulf of Taranto, central and south Italy, and the southern Adriatic sea (Fig. 6a), and does not exhibit any diurnal changes. The 1000 hPa vorticity maximum (Fig. 7a), equal to $8 \times 10^{-5}\,s^{-1}$, coincides with the pressure minimum, however it is more localised over southern Italy, implying that the surface dynamics act in the same area as where the cyclones occur. The 500 hPa geopotential anomaly is slightly displaced to the southwest relative to the surface pressure minimum, covering Sicily (Fig. 8a), especially at 1200 UTC.

In spring (Fig. 6b) and autumn (Fig. 6c) the mean sea level pressure and vorticity patterns are very similar to those in winter, with the following exceptions; in spring, the pressure minimum is not as broad as in winter being confined over southern Italy and the vorticity maximum has weakened (Fig. 7b); in autumn, the 1000 hPa vorticity center (Fig. 7c), has moved to the northwest over the land although it coincides with the pressure minimum. The 500 hPa geopotential anomaly in spring (Fig. 8b) has shifted to the southwest,

Fig. 5. Vertical profile of geopotential anomalies ($\times 100$) for Genoa cyclones with central pressure less than 1000 hPa along the axis shown in Fig. 1 at 00 UTC for **a**) winter, **b**) spring, and **c**) autumn

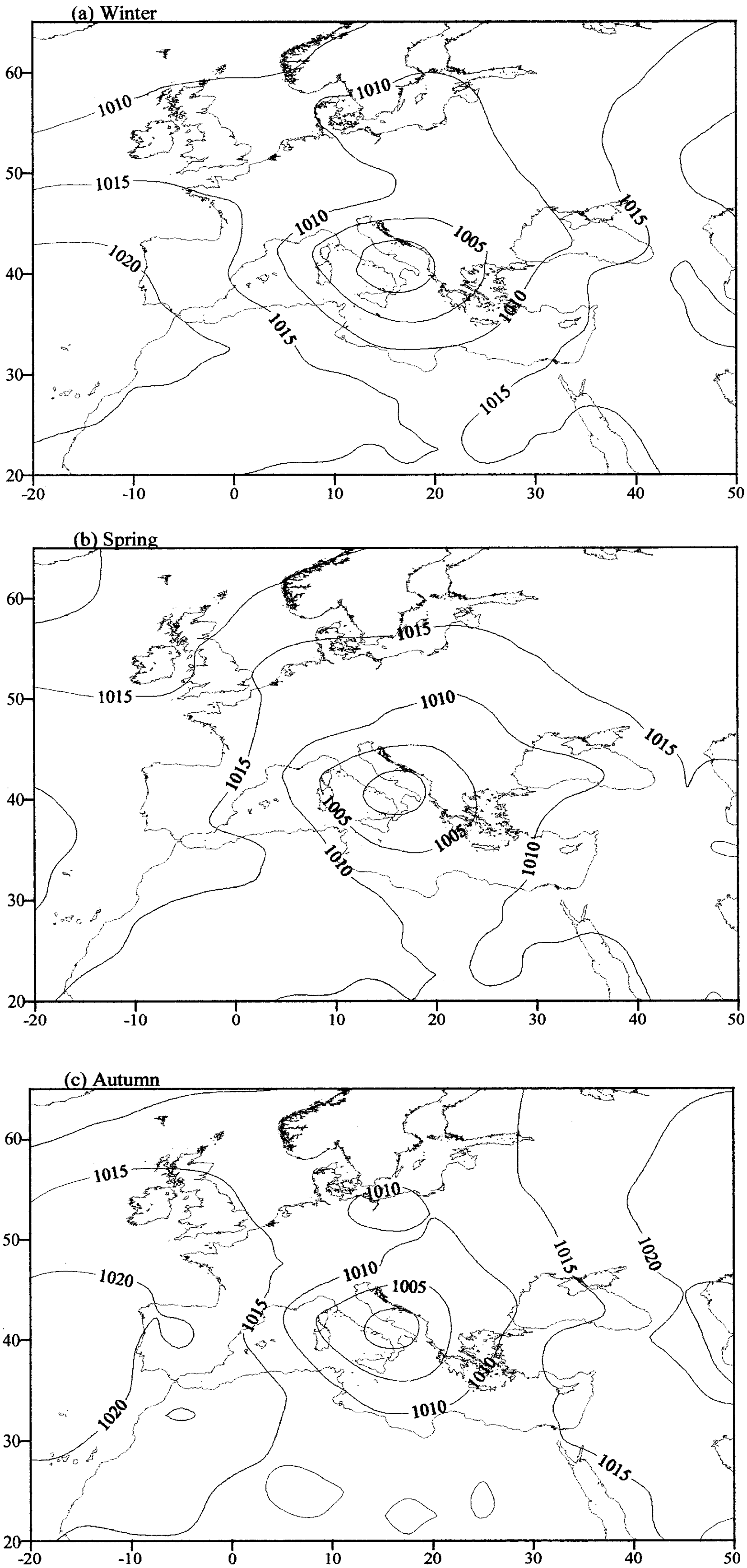


Fig. 6. As in Fig. 2, but for South Italy cyclones for **a**) winter **b**) spring and **c**) autumn

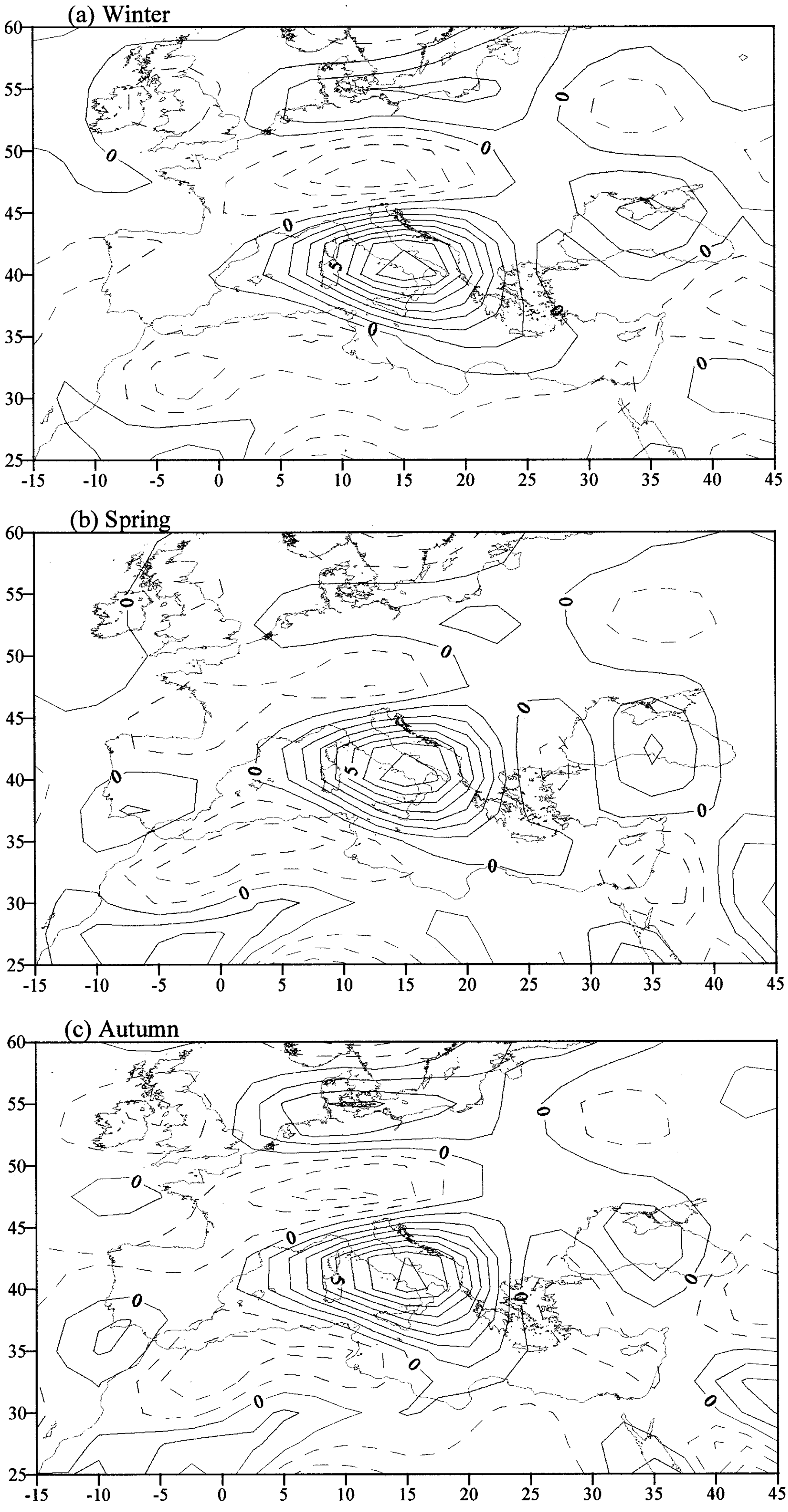


Fig. 7. As in Fig. 3, but for South Italy cyclones for **a**) winter **b**) spring and **c**) autumn

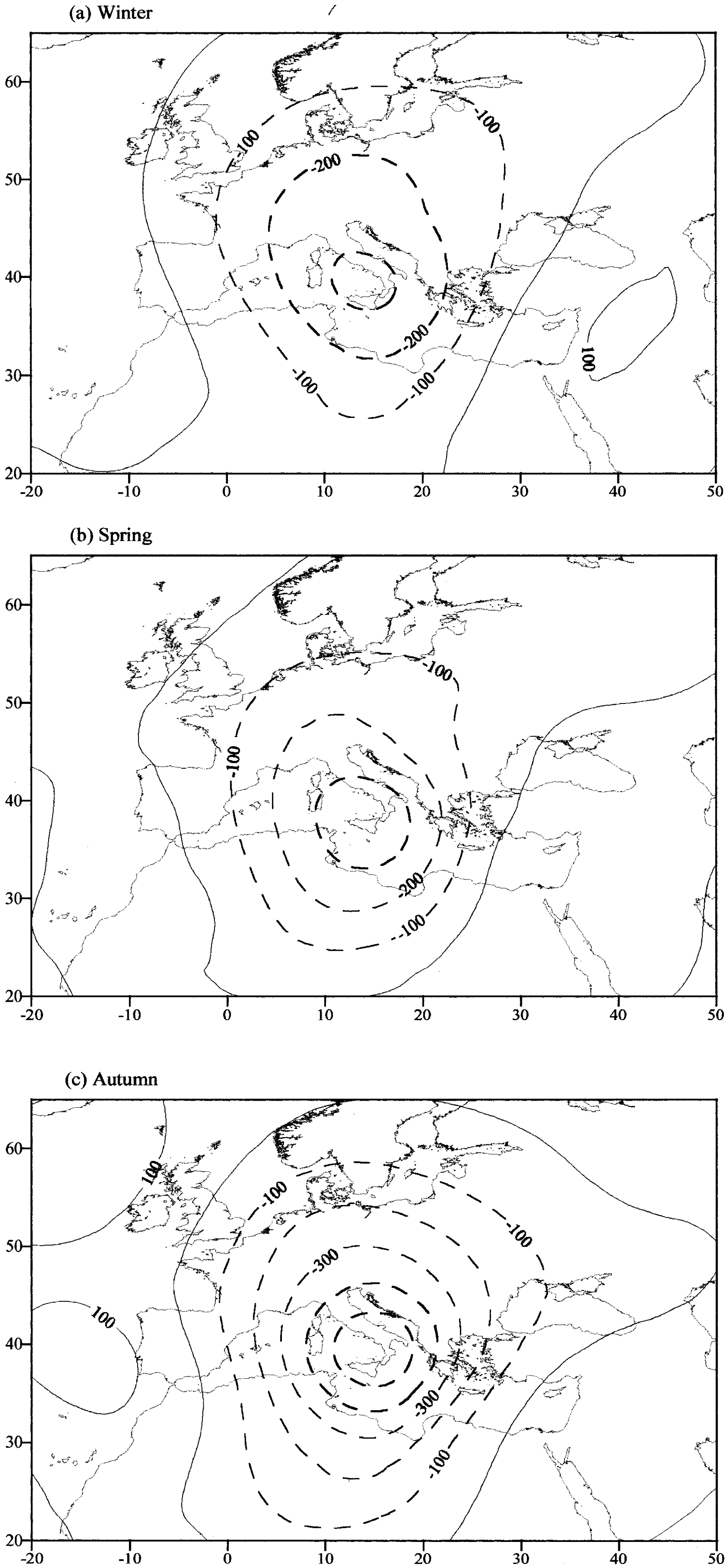


Fig. 8. As in Fig. 4, but for South Italy cyclones for **a**) winter **b**) spring and **c**) autumn

centered over Sicily, and is significantly stronger at 00 UTC, while in autumn (Fig. 8c) it is found in the winter position. As with the Genoa cyclones the geopotential anomaly corresponding to Southern Italy cyclones strengthens in spring and especially in autumn.

In summer, no cyclonic cases were detected in the region of Southern Italy (see Table 1) due to the influence of the subtropical high in the south or of a broad ridge built up across west-central Europe, extending from the Azores high, being accompanied by warm advection (Maheras et al., 1999).

The vertical cross section of the geopotential anomaly in winter (Fig. 9a) shows that there are three statistically significant anomaly centers (at level 0.05): at 1000, 700, 500 hPa. Table 2 shows that the surface anomaly is characterised by the highest value and is also associated with the strongest vorticity maximum. This is associated not only with the frequent cyclogenesis over this area (Radinovic, 1965) but also with the preferred southeastern route of Genoa cyclones through Southern Italy in winter (Alpert et al., 1990b; Trigo et al., 2000). It is worth noting that both surface anomalies and vorticity maxima appear stronger than the corresponding events for Genoa cyclones in winter. This implies that surface dynamics are more important for surface cyclones in Southern Italy, resulting in greater deepening than the Genoa cyclones. At the upper levels, the geopotential anomaly forms at 500 hPa while the strongest vorticity maximum appears at 300 hPa (Flocas et al., 2001), suggesting the important role of the upper level forcing in surface development (Karein, 1979; Prezerakos et al., 1997). Of interest is that the geopotential anomalies exhibit a slight westward tilt with height, as derived from the small negative slope (−5.2°) compared to the other two regions (see Table 3), implying weaker baroclinic character of the winter cyclones in Southern Italy. During the daytime there is neither a localised geopotential anomaly near the surface nor at 500 hPa (see Table 2). Nevertheless, the upper level vorticity maximum continues to constitute a significant feature.

In spring, the vertical structure of geopotential anomalies (Fig. 9b) shows an anomaly at 300 hPa while the geopotential anomaly near the surface strengthens in comparison with the surface

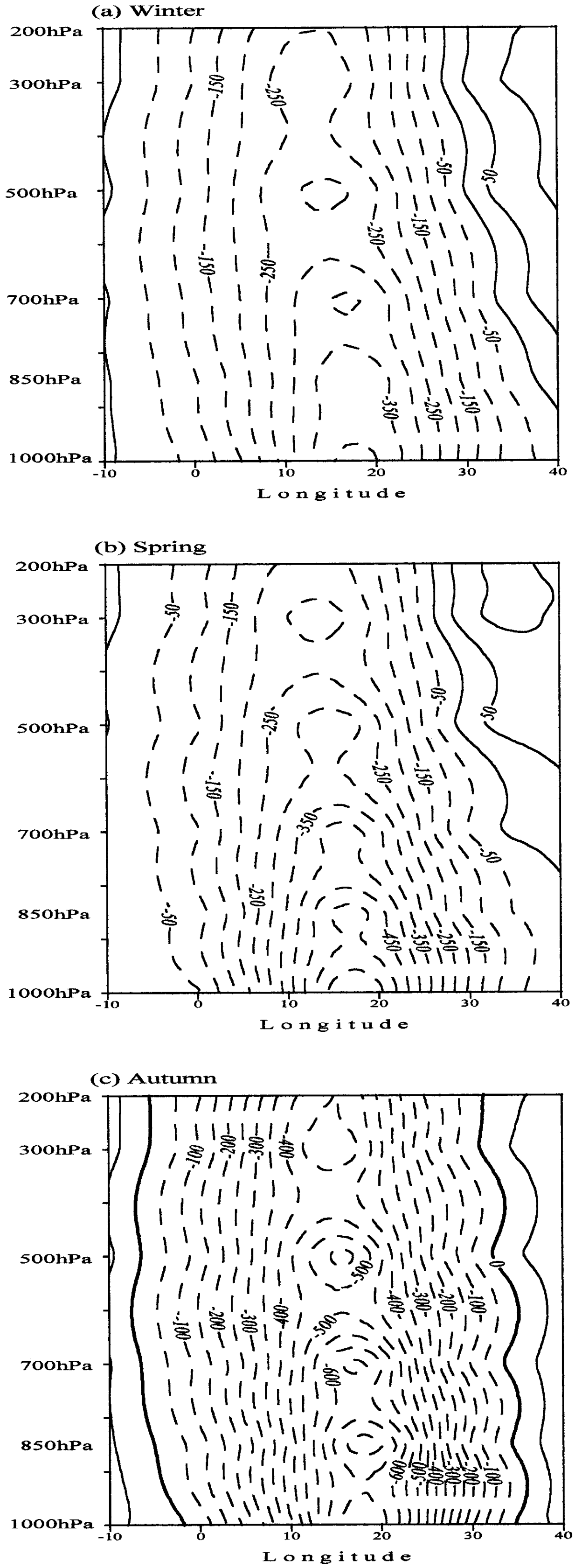


Fig. 9. As in Fig. 5, but for South Italy cyclones for **a**) winter **b**) spring and **c**) autumn

winter anomaly. This could be attributed to the development of a major northeastward path of Saharan depressions over Southern Italy in April and May (Trigo et al., 2000), resulting in the considerable number of cyclonic occurrences in Southern Italy (Maheras et al., 2001). The surface anomaly corresponds to an intense vorticity maximum, while the vorticity reaches a maximum at 300 hPa during the nighttime as well as during the daytime. As can be seen in Table 3, the baroclinic character of the cyclones becomes more prominent in spring, especially during nighttime. The vertical profile of the anomalies does not present any variation at 12 UTC, except that two new peaks form at 700 and 500 hPa.

In autumn, there is a geopotential anomaly center near the surface (Fig. 9c). The vorticity maximum intensifies near the surface and reaches the winter value (Flocas et al., 2001), suggesting that the surface dynamics remain active over the sea, despite the observed decrease in the frequency of cyclones. Four other statistically significant anomalies (at level 0.05) are present at 850, 700, 500 and 300 hPa that are considerably stronger compared to the other seasons. Also indicative of the very important role of the upper levels during this season is the remarkable increase in cyclonic vorticity at 500 and, especially at 300 hPa. The westward tilt of the anomalies with altitude persists and is reduced during daytime (see Table 3). Furthermore, it should be noted that during daytime the 1000 and 500 hPa geopotential anomalies disappear, while all vorticity maxima weaken considerably.

5. Cyclones over Cyprus

In winter the mean sea level pressure minimum (Fig. 10a) along with the 1000 hPa vorticity maximum ($9 \times 10^{-5}\,s^{-1}$) of the Cyprus cyclones (Fig. 11a) originates over the southeastern Turkish coast at 0000 UTC in the lee of the Taurus mountain, although the highest frequency of Cyprus cyclones was located over the sea (Maheras et al., 2001). This suggests that while the influence of the sea seems to favour cyclonic occurrences in the Cyprus area, the lee effect seems to contribute to the intensification of Cyprus cyclones. At 1200 UTC the pressure minimum is extended to the north, covering inland Asia Minor (not shown). The geopotential anomaly at the 500 hPa level is positioned slightly to the west of the pressure minimum, without diurnal changes in location and intensity (Fig. 12a). This anomaly seems to be associated with upper air positive vorticity advection and cold air invasion (Kallos and Metaxas, 1980).

In spring, the distribution of the mean sea level pressure (Fig. 10b) and 1000 hPa vorticity (Fig. 11b) looks the winter situation. However, the 1000 hPa vorticity maximum decreases to $7 \times 10^{-5}\,s^{-1}$ since the sea surface fluxes are not as vigorous as in winter. The 500 hPa geopotential anomaly migrates southwards from its winter location near the coast of Egypt during the night (see Fig. 12b), while it is observed at the winter position during the daytime (not shown).

In summer, there is no localised pressure minimum but rather an extended zone of low pressure that extends to the gulf of Adana (Fig. 10c). This is due to the extension of the Persian gulf trough that predominates from June to September (Bitan and Sa'aroni, 1992). For the same reason, despite the reduced cyclonic activity, the 1000 hPa vorticity is relatively high (Fig. 11c), appearing as a localised maximum over the southern Turkish coast. It should be noted that the combination of the extension of the Persian gulf trough and the anticyclonic circulation over the Balkan peninsula results in the frequent generation of the northerly ''etesians'' over the Aegean sea in summer (Arseni-Papadimitriou et al., 1988). Furthermore, the stronger the Cyprus depressions become, the stronger northerly winds that prevail over the Aegean sea become (Maheras, 1980; Bartzokas and Lolis, 2000). A 500 hPa geopotential anomaly forms in summer to the NW over Asia Minor and the eastern Aegean sea that is especially strong at 0000 UTC (Fig. 12c), in accordance with the large number of troughs over the same area (Jacobeit, 1987). It should be noted that the geopotential anomaly is located in the north of the main core of the subtropical jet, over the latitude 40° (Prezerakos, 1978), coincident with the strong cyclonic NW circulation (from Scandinavia to Black Sea) during this season (Maheras, 1983a, b).

In autumn, according to Table 1, the number of cyclonic cases with central pressure less than 1000 hPa, is very low, and thus the corresponding analysis is not incorporated. The remarkable

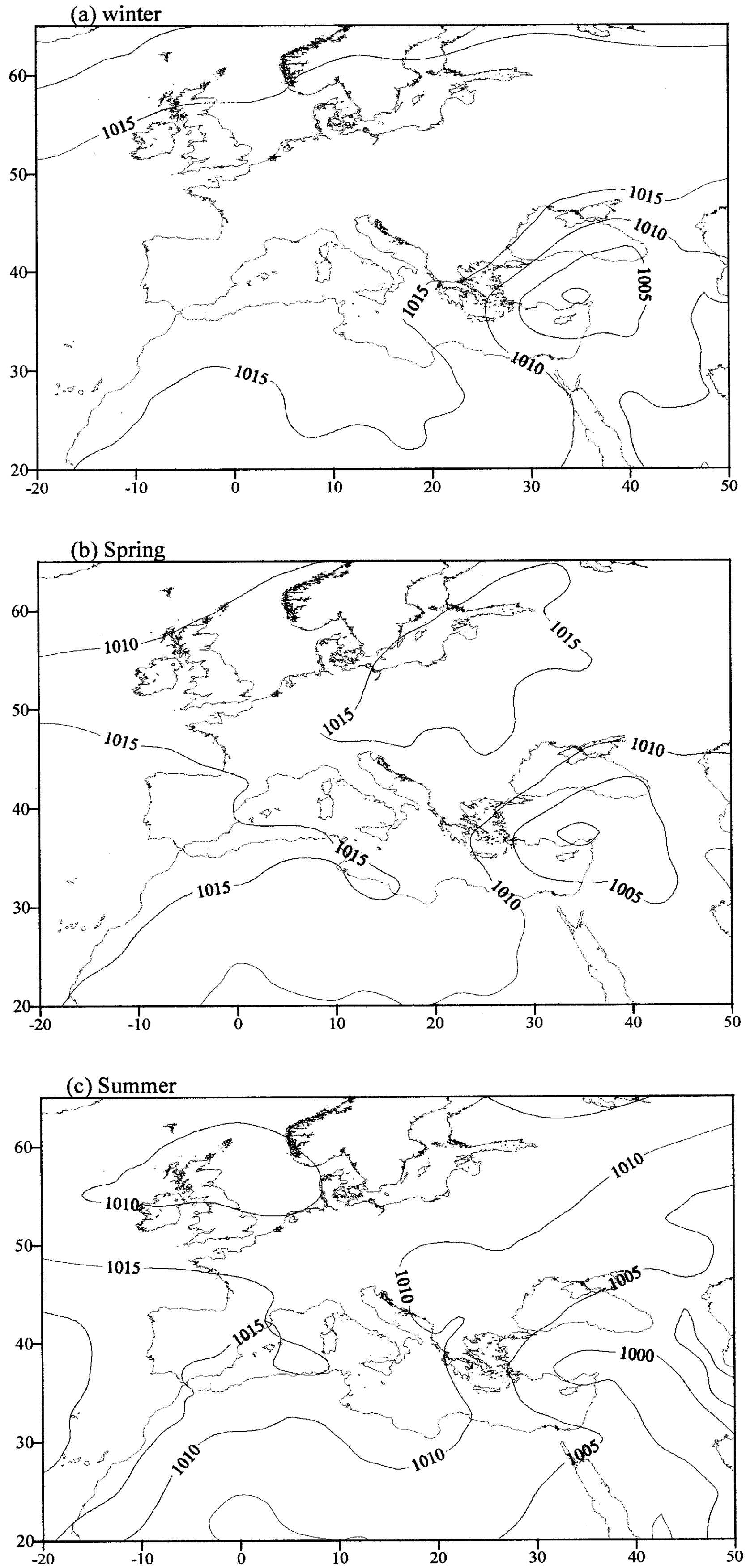


Fig. 10. As in Fig. 2, but for Cyprus cyclones, for **a**) winter **b**) spring and **c**) summer

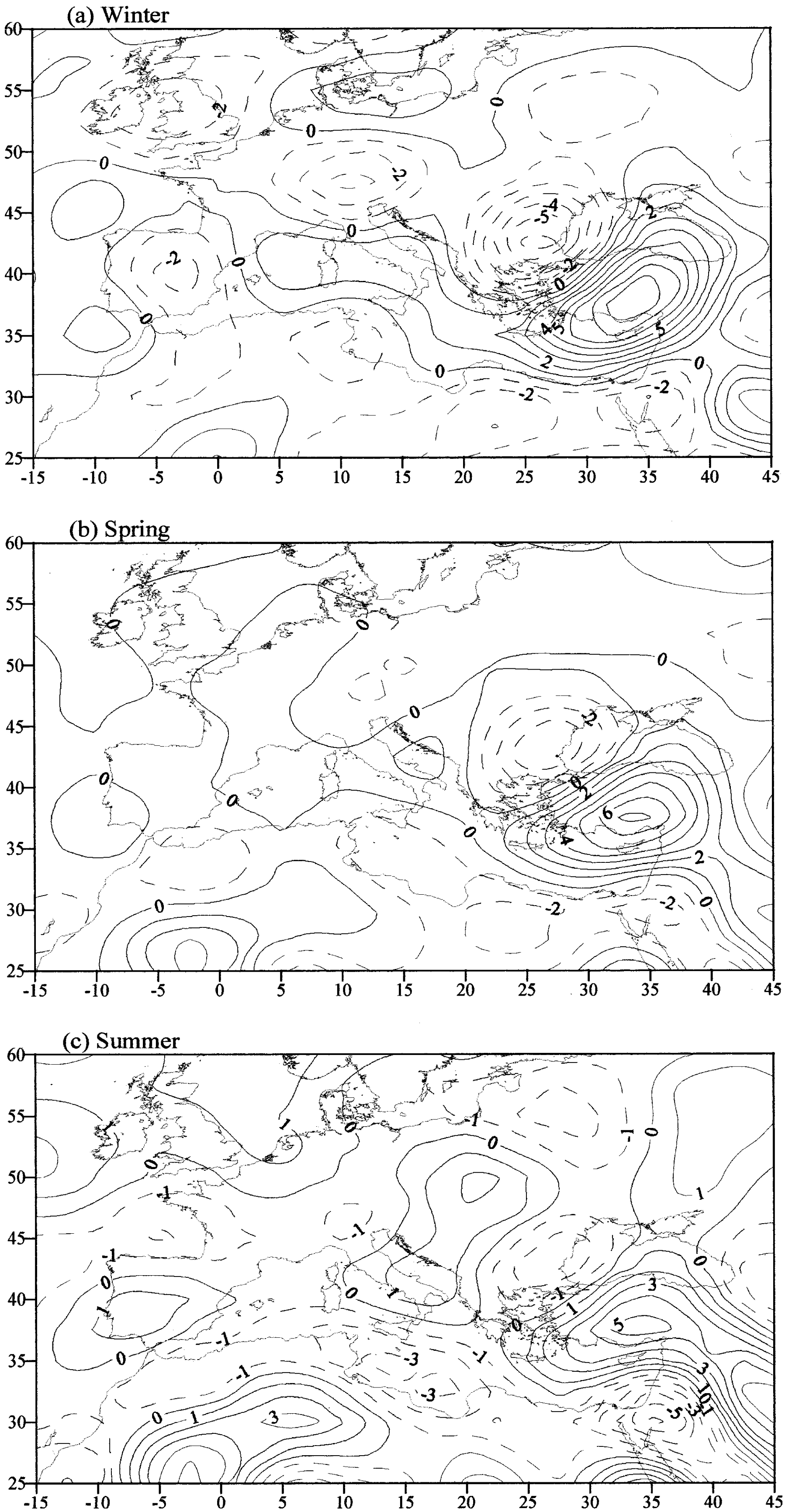


Fig. 11. As in Fig. 3, but for Cyprus cyclones for **a**) winter **b**) spring and **c**) summer

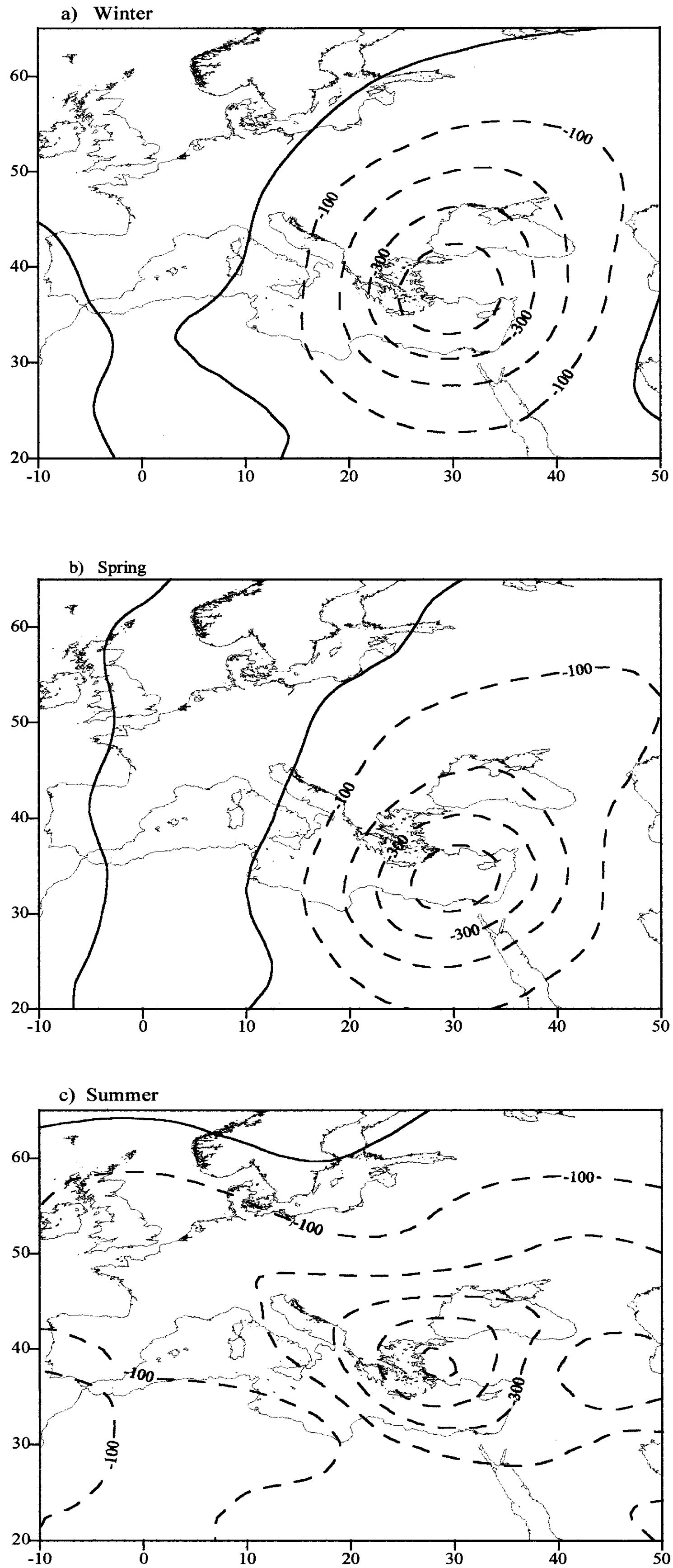


Fig. 12. As in Fig. 4, but for Cyprus cyclones for **a**) winter **b**) spring and **c**) summer

decline in the number of cyclones in the area of Cyprus examined could be attributed to the weakening of the Persian gulf trough (Bitan and Sa'araoni, 1992) and the frequent formation of blocking systems over the Eastern Mediterranean during this period (Prezerakos, 1978).

In winter, the vertical profile of the geopotential anomalies of Cyprus cyclones exhibits four pronounced statistically significant (at level 0.05) maxima (Fig. 13a) with magnitudes that are substantially larger than the Genoa and Southern Italy cyclones. The first anomaly center is located near the surface, being centerd at around 36° N, 32° E (Antalya gulf), that corresponds to an intense vorticity maximum. This could be associated to the strong sea surface fluxes that are produced due to the large thermal contrast between the cold dry air and the warm sea, as was found for a composite Cyprus low (Shay-El and Alpert, 1991), since the Eastern Mediterranean is frequently influenced by cold air flow from Asia in winter (Maheras et al., 1999). The second anomaly center at 850 hPa is also connected with a vorticity maximum (Flocas et al., 2001) and seems to be associated with the lee effect of the Taurus mountains of southern Turkey (Brody and Nestor, 1980). It should be noted that the surface and the 850 hPa geopotential anomalies are the strongest during this season. At the upper levels the geopotential anomaly forms at 500 hPa while the last anomaly is found at 300 hPa, along with the strongest vorticity maximum, and seems to be controlled by the polar front jet stream that descends to the south (Karein, 1979). Besides, Shay-El and Alpert (1991) indicated that there is a relation between Cyprus-low activity and the subtropical jet that is positioned at a latitude of 30° N. From Table 3 it can be seen that the absolute value of negative slope is as high as 8.7°, and therefore the westward tilt with height is considerably more pronounced as compared to the Genoa and Southern Italy cyclones.

In spring, the vertical profile of the geopotential negative anomalies (Fig. 13b) exhibits statistically significant (at level 0.05) peaks at the same altitudes as on the winter profile, however, with slightly reduced magnitude, that compare

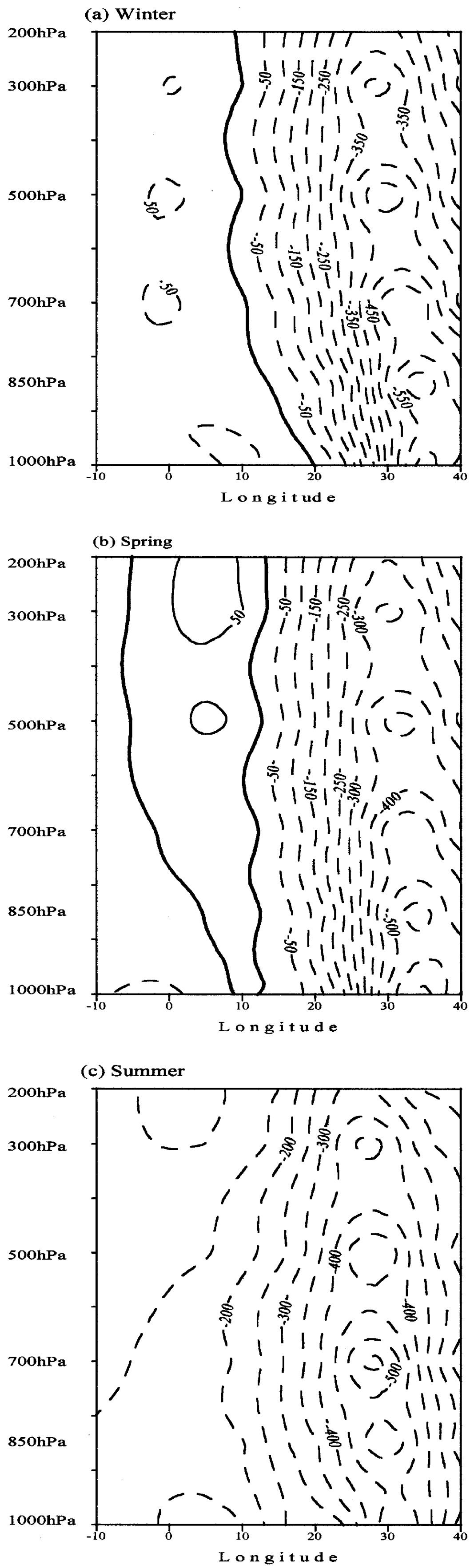


Fig. 13. As in Fig. 5, but for Cyprus cyclones **a**) winter, **b**) spring, **c**) summer

well with the winter anomalies (see Table 2). Also, according to Table 3, the slope reduces substantially, especially during daytime. In the vertical vorticity profile the strongest maximum continues to appear at 300 hPa throughout the whole day while the low level maxima are weaker compared to those in winter (Flocas et al., 2001). During the daytime the 1000 hPa geopotential anomaly remains intense, the 500 hPa geopotential anomaly vanishes and the 300 hPa anomaly slightly weakens.

In summer (Fig. 13c) there is no geopotential anomaly center near the surface during nighttime, and it is accompanied by a further decline of the low level vorticity. On the contrary, a strong anomaly forms at 700 hPa while the 500 and 300 hPa anomalies remain as strong as in winter and spring, being linked with an intense vorticity maximum at 300 hPa (Flocas et al., 2001). It should be noted that the three anomalies are found to be statistically significant at the 0.05 level. From Table 2, it becomes evident that there appear significant changes in the vertical structure at 1200 UTC, including the overall weakening of all geopotential anomalies, and especially those at 850 hPa, 700 hPa and 300 hPa which are accompanied by similar weakening of the vorticity maxima. The barotropic character of the Cyprus cyclones is notable during summer, as can be deduced from the remarkable decrease of the slope between winter and summer (see Table 3).

6. Concluding remarks

A climatological study of the mean sea level pressure patterns and the vertical structure of composite Mediterranean cyclones with central pressure less than 1000 hPa has been performed for a period 40 years on a seasonal and daily basis. The analysis revealed different characteristics for the cyclones that occur in the region of Genoa (representing the western basin), Southern Italy (representing the central basin) and Cyprus (representing the eastern basin). These differences reflect the different mechanisms that are responsible for cyclone formation in each region. The limited number of cyclonic cases detected did not allow a drawing of representative results for cyclones over Genoa and Southern Italy in summer and for Cyprus in autumn.

The minimum average mean sea level pressure for Genoa cyclones mostly originated over the gulf, with some north-south migration, without exhibiting any significant diurnal change. The 1000 hPa vorticity maximum was located further to the south and the 500 hPa geopotential anomaly in the southwest. A westward tilt with attitude height became pronounced in winter and spring. The surface fluxes prevail in all seasons examined, and the upper air dynamics seem to be more important in spring and autumn. The orographic effect, however, seems to contribute more significantly in winter and spring.

For the cyclones that occur in Southern Italy, the pressure minimum is rather broad, especially in winter, covering a wide region of Southern Italy and the Adriatic sea. It was also found that the surface dynamics act in the same region, where the minimum pressure is observed, becoming more important in winter and spring. The upper level dynamics seem to control the surface cyclonic occurrences during winter, spring and autumn, although they are not always associated with geopotential anomalies. The 500 hPa anomaly is positioned slightly to the southwest of the pressure minimum, and exhibits the highest seasonal value in autumn. A more barotropic character of the Southern Italy cyclones becomes evident in winter compared to the other Mediterranean regional cyclones.

Cyclones over Cyprus showed that the pressure minimum originates over the land, in the lee of Taurus mountains, during winter and spring, along with the 1000 hPa vorticity maximum, although the cyclones occur more frequently over the sea. In summer there is no localised minimum, rather a zone of low pressure associated with the Persian gulf trough. At the 500 hPa level the surface cyclones are connected with strong negative geopotential anomalies, even in summer, that are mainly found to the west of the surface pressure minimum, revealing seasonal changes in location and intensity. In winter, Cyprus cyclones are characterised by higher magnitude negative geopotential anomalies at all levels, and a remarkably stronger baroclinic character compared to other Mediterranean region cyclones. The upper level dynamics seem to constitute a dominant feature in winter, spring, and even in summer, while the surface dynamics and the orography are likely to be more significant in winter and spring.

Acknowledgements

This research was funded by the EC project, ACCORD, under contract ENV4-CT-97-0530. The authors would like to express their gratitude to the referees for their constructive comments and suggestions.

References

Alpert P, Neelman BU, Shay-El Y (1990a) Climatological analysis of Mediterranean cyclones using ECMWF data. Tellus 42A: 65–77

Alpert P, Neelman BU, Shay-El Y (1990b) Intermonthly variability of cyclone tracks in the Mediterranean. J Clim 3: 1474–1478

Arseni-Papadimitriou A, Maheras P, Giles BD (1988) Contribution to the study of the strong north winds on Aegean sea in the warm season. Riv di Meteorol Aeron XLVIII (3–4): 3131–138

Bartzokas A, Lolis C (2000) Sea surface temperature-850 hPa vorticity relations in the Mediterranean region during winter. International Conference on the Mediterranean: Cultures, Environment and Society. 22–24 May 2000, Haifa, Israel. (proceedings available in cd-rom)

Bell GD, Bosart LF (1989) A 15 year climatology of northern hemisphere 500 mb closed cyclone and anticyclone centers. Mon Wea Rev 117: 2142–2163

Bitan A, Sa'aroni H (1992) The horizontal and vertical extension of the persian gulf pressure trough. Int J Climatol 12: 733–747

Brody LR, Nestor L (1980) Regional forecasting aids for the Mediterranean basin. Naval Postgraduate School, Monterey, California

Flocas AA (1988) Frontal depressions over the Mediterranean sea and Central Southern Europe. Méditerranée 4: 43–52

Flocas HA, Karacostas TS (1996) Cyclogenesis over the Aegean Sea: Identification and synoptic categories. Meteorol Appl 3: 53–61

Flocas HA, Maheras P, Karacostas Th, Patrikas I, Anagnostopoulou Chr (2001) A 40 year climatological study of relative vorticity distribution over the Mediterranean. Int J Climatol (in press)

Jacobeit J (1987) Variations of trough positions and precipitation patterns in the Mediterranean area. Int J Climatol 7: 453–476

Kallos G, Metaxas A (1980) Synoptic processes for the formation of Cyprus lows. Rivista Meteor Aeron XL (2–3): 121–138

Kalnay E, Kanamitsou M, Kistler R, Collins W, Deaven D, Gandin L, Irebell M, Saha S, White G, Woollen J, Zhu Y, Leetmaa A, Reynolds R, Chelliah M, Ebisuzaki W, Huggins W, Janowiak J, Mo KC, Ropelewski C, Wang J, Jenne R, Joseph D (1996) The NCEP/NCAR 40-year Reanalysis project. Bull Amer Meteor Soc 77: 437–471

Karein AD (1979) The forecasting of cyclogenesis in the Mediterranean region. PhD Thesis, University of Edinburgh, 159 pp

Maheras P (1980) Le probléme des Etésiens. Méditerranée 40: 57–66

Maheras P (1983a) Les types de temps dépressionnaires pertubés au-dessus de la mer Egée. Rivista Meteor Aeron 43 1/2: 13–22

Maheras P (1983b) Les visages cycloniques des saisons et des mois au-dessus de la mer Egée. Rivista Meteor Aeron 43 1/2: 23–30

Maheras P, Xoplaki E, Davies T, Martin-Vide J, Bariendos M, Alcoforado M (1999) Warm and cold monthly anomalies across the Mediterranean basin and their relationship with circulation; 1860–1990. Int J Climatol 19: 1697–1715

Maheras P, Flocas HA, Patrikas I, Anagnostopoulou Chr (2001) A 40 year objective analysis of surface cyclones in the Mediterranean region: Spatial and temporal distribution. Int J Climatol 21: 109–130

Maheras P, Kutiel H, Patrikas I, Flocas HA, Anagnostopoulou Chr (2000) Analyses des fréquences des dépressions en Méditerranée orientale. Publications de l'AIC 12: 359–367

Prezerakos NG (1978) Contribution to study of the blocking over the Greek area. PhD Thesis, University of Thessaloniki, 191 pp

Prezerakos NG, Flocas HA, Michaelides SC (1997) Absolute vorticity advection and potential vorticity of the free troposphere as synthetic tool for the diagnosis and forecasting of cyclogenesis. Atmosphere-Ocean 35: 65–91

Radinovic D (1965) Cyclonic activity in Yugoslavia and surrounding areas. Arch Meteor Geophys Bioklim Ser A 14: 391–408

Reiter ER (1975) Weather phenomena of the Mediterranean basin. Handbook for forecasters in the Mediterranean. Naval Postgraduate School, Monterey, California

Shay-El Y, Alpert P (1991) A diagnostic study of winter diabatic heating in the Mediterranean in relation to the cyclones. Quart J Roy Meteor Soc 117: 715–747

Tibaldi S, Buzzi A, Malguzzi P (1980) Orographically induced cyclogenesis: analysis of numerical experiments. Mon Wea Rev 108: 1302–1314

Trigo IF, Davies TD, Bigg GR (2000) Objective climatology of cyclones in the Mediterranean region. J Climate 12: 1685–1696

Authors' addresses: P. Maheras (e-mail: maheras@-geo.auth.gr, Tel.: 031 998471, Fax: 031 995392), Chr. Anagnostopoulou, Department of Meteorology and Climatology, University of Thessaloniki, Greece; H. A. Flocas, Laboratory of Meteorology, Department of Applied Physics, University of Athens, Greece; I. Patrikas, Division of Hydraulics, Faculty of Technology, University of Thessaloniki, Greece.