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Climatological analysis of Mediterranean cyclones using ECMWF data

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ABSTRACT

A thoroughly objective method for the definition, selection and tracing of Mediterranean region cyclones is presented. The method is applied to the ECMWF 1982–1987 analyzed datasets to show monthly cyclone frequencies, cyclonic tracks and vertical variation of average relative vorticity. Day-to-night changes and vertical variation of cyclonic frequencies/vorticities indicate the importance of the sea thermal effect in the eastern Mediterranean. In the western Mediterranean and to a lesser extent in the Cyprus region, the lee cyclogenetic effect is very pronounced. Monthly cyclone tracks are presented and they clearly indicate the preferred routes of cyclonic movements.

1. Introduction

The dynamics of atmospheric circulations of the Mediterranean region are of much interest from both dynamical and climatological viewpoints, but unfortunately data were insufficient for the synoptic and particularly the sub-synoptic scale analyses. In recent years, however, more and more unconventional data like automated aircraft wind reports, satellite winds and temperatures (e.g., Bengtsson et al. (1982), Kållberg et al. (1982), Baede et al. (1987)), have been routinely introduced in the regular daily analyses of meteorological data. Kållberg et al. (1982), for instance, have illustrated that the adoption of cloud track wind data had significantly improved the analyses and the forecasts of the ECMWF model especially over the tropics and subtropics where conventional data were severely lacking. In some cases, synoptic circulation systems were only observed by the cloud drift winds. Consequently, such data were incorporated into the routine ECMWF analyses. For example, satellite temperatures down to sea level are incorporated with 500 km resolution starting 1982, and with 250 km resolution starting February 1985.

As indicated by Bengtsson (1988, p. 290), the "new observing systems, such as satellites, now provide a good coverage of data over previously data-sparse regions. In combination with comprehensive data-assimilation systems developed over the last 10 years, this has led to a substantial reduction of the initial error". The Mediterranean region, particularly above the sea and to its south, is a region of relatively few stations. Therefore, the purpose of the present work is to look at the Mediterranean cyclones as analyzed in recent 5 years by the ECMWF system.

The data employed in this study is the 5-year initialized ECMWF analyses for 1983–1987, twice a day at 0000 and 1200 GMT. Actually the data set covers also the period 3 November 1982–31 December 1982. Hence, the November and December averages are based upon 6 years of data. The data consist of 7 mandatory levels at 1000, 850, 700, 500, 300, 200 and 100 mb with an interval of $2.5 \times 2.5°$. The subsynoptic scale is, of course, not resolved with such a resolution, a disadvantage to be mentioned particularly in the highly complex Mediterranean region. However, the treatment here differs from previous studies in few important characteristics as follows: first, an objective method is used to define and select the cyclones; second in contrast to most previous studies we discuss (Section 4) the vertical variation of average vorticity above the Mediterranean; third, the full Mediterranean region is studied. Most of the previous studies including even some atlases of the Mediterranean focused on the western-central parts only (Black, 1969; Weather in the Mediterranean, 1962; Reiter, 1975; Radinovic, 1987). Also, in contrast to most previous studies the day and night cyclone climatologies are compared and discussed.

Although the period of 5 years is too short for obtaining a complete picture of cyclone climatology, the relatively good quality of data used here is believed to give a reliable description of Mediterranean cyclones. Also, the data for that period covers the Mediterranean and surroundings (0–60° N, 0-60° E) with the same data-sources, i.e., ECMWF analysis. Hence, this enables a relatively fair comparison of specific regions. This study focuses on cyclone frequency of occurrences (Section 2), cyclone tracks (Section 3) and vertical variation of the vorticity centres (Section 4). Special emphasis is given to the understanding of the differences between the western and eastern Mediterranean (WM and EM) cyclones. Separate studies are underway including detailed analysis and three-dimensional mesoscale modelling for the investigation of specific case-studies and consequently the understanding of the physical mechanisms of Mediterranean cyclogenesis.

2. Cyclone frequencies

2.1. *Method of objective analysis*

The exact definition of a cyclone is of much significance for statistical studies of cyclones. Hence, we examined the criterion for estimating the number of cyclones and came out with two approaches to be discussed below. A candidate for a cyclone was first defined when the 1000-mb height at a given point was less than or equal to each of the 8 neighboring height-values on the ECMWF analysis grid. Next, the exact location of the cyclone was calculated through the following interpolation steps.

(i) Parabolic interpolation (Koehler, 1977) in the x-direction was performed to obtain the x-location of the cyclone centre.

(ii) The height-value at that point was calculated by the highly accurate bi-parabolic interpolation of the height-values at the neighbouring grid points in the x-direction (Koehler, 1977). Similarly, the height-values of the two points in the positive and negative y-direction were calculated.

(iii) The first step is now repeated in the y-direction.

Next, the square of 500 × 500 km around the cyclone centre was searched for additional cyclones. If another cyclone was indeed found, only the deeper one, i.e., lower height, was kept. In this process, about 6% of the cyclones were eliminated. Hence, the total number of cyclones for the full data set (0–60° N) dropped in this way from 58,286 to 54,654. For the full period data-set, this means that on the average, 14 cyclones were identified on each of the 1000-mb analyzed data sets, (54,654 divided by ~3800).

In the second approach we have applied a filter in which a minimum surface pressure gradient of (0.5 mb/500 km) was checked in the east, west, north and south directions at the distance of 500 km. Results (see below) indicate a considerable decrease of the summer frequencies at night.

2.2. *Annual variation of cyclone frequencies—day and night* (*November 1982–December 1987*)

Figs. 1–3 depict the average monthly number of cyclones $\overline{N}$ at 0000 and 1200 GMT, in the rectangle (0–60° E, 25–60° N) for January, April and July, respectively. The number $\overline{N}$ was normalized to a square area of 250 × 250 km. At the southern boundary where the data were available, $\overline{N}$ was directly calculated, but at the other boundaries the values of $\overline{N}$ was put to zero. Hence, values 2.5° from these boundaries may be distorted.

Since the 0000 and 1200 GMT correspond in the Mediterranean region to (0000–0200) and (1200–1400) LST respectively, the two time periods were assumed to represent in the forthcoming discussion night and day distributions.

Fig. 1 presents the winter (January) distribution of cyclones showing four cyclonic centres: at Cyprus, at Crete, at southern Italy and at the Gulf of Genoa. As expected, the major cyclonic centres are located over the relatively warm sea regions, as for example, the Black Sea and the Caspian Sea maxima. The two more pronounced Mediterranean centres are at the Gulf of Genoa

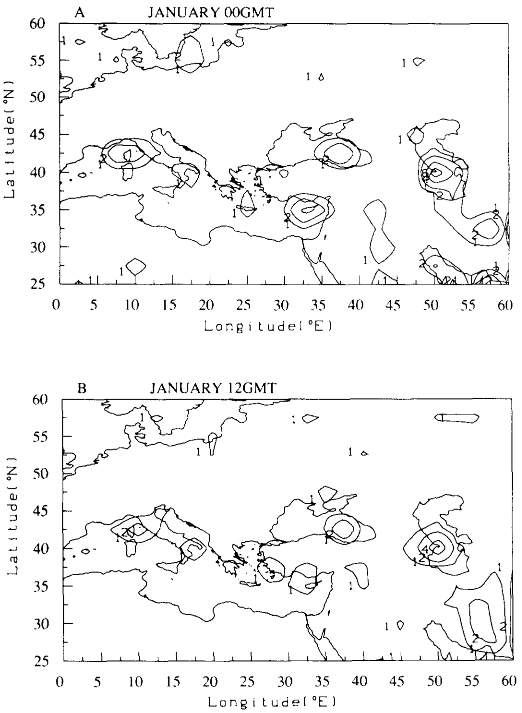

Fig. 1. Isolines of $\overline{N}$, the averaged number of cyclone occurrences, during January (a) 0000 GMT: (b) 1200 GMT, with the values of 1, 2, 4, 6, 10, 14, etc. Based on ECMWF analysis for 1983–87. For method of calculation see text.

with a maximum of 3 and at the Cyprus region with a maximum value of 3.5. The distinction between the two WM centres was not found in earlier synoptic-scale studies but higher mesoscale resolution (Radinovic, 1965, 1987) clearly indicates their existence. In particular, the location of the south Italy centre coincides exactly with that reported by the mesoscale analysis (at the Gulf of Taranto—40° N, 17.5° E). The exact location of the centres as inferred from the present study should be regarded with caution since the data resolution is 2.5°. However, the accuracy in locating the centres is largely increased thanks to the averaging of about 150 maps for each case. At night (Fig. 1a), the cyclonic centres tend to be located above the sea and to be stronger particularly in the two centres in the EM. At day, the EM cyclonic centres are weaker and are found in the lee of the Turkish mountains. This may possibly indicate a thermal effect of the Mediterranean at night and a mountain effect at day particularly in the EM. This point will be later discussed (Section 4).

At spring (April), the cyclonic centres above the sea considerably weaken while land centres strengthen, since the land warms up and the seas are still cool. In particular, the maximum at the lee of the Saharan Atlas Mountains in northwest Africa, strengthens. Spring is the favourable period for the Saharan Depressions (or Sharav Cyclones) responsible for major dust storms, which were recently studied as a baroclinic instability disturbance modified by the strong *surface* baroclinicity between the Mediterranean and the heated north-African land (Alpert and Ziv, 1988). The influence of the Sharav Cyclones go far beyond regional interest because of the huge amounts of dust transported to large horizontal distances (e.g., Westphal et al., 1985). Another interesting feature is the enhanced cyclonic activity from the Persian Gulf toward the EM. Clearly, this is the manifestation of the monsoonal trough which intensifies at spring.

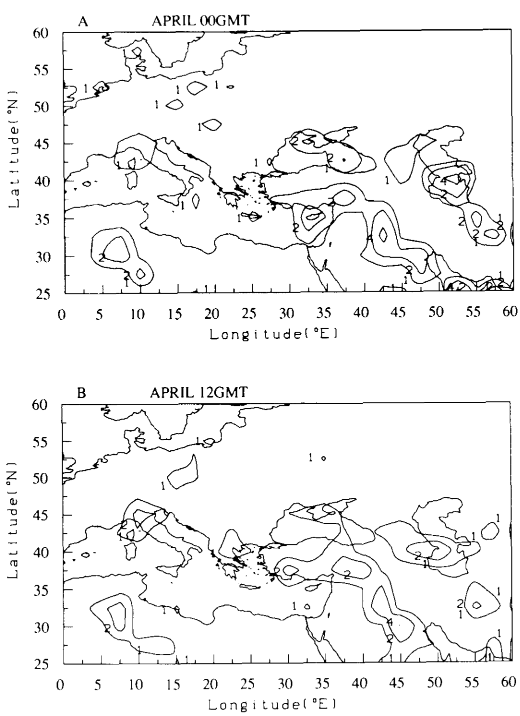

Fig. 2. As in Fig. 1, but for April.

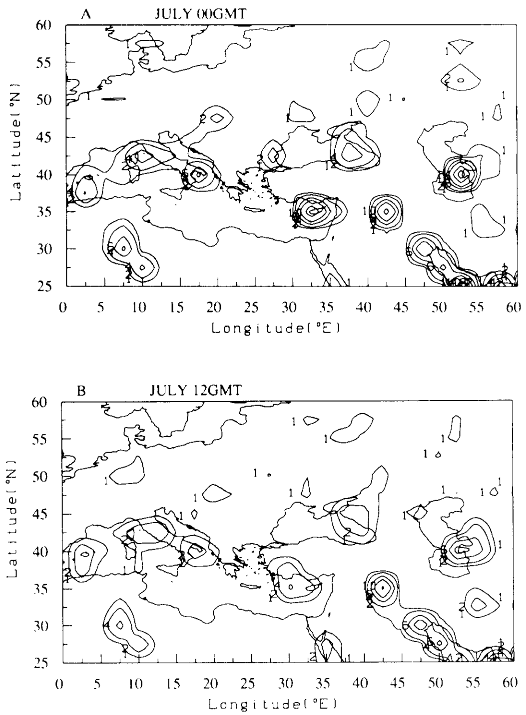

Fig. 3. As in Fig. 1, but for July.

In July (Fig. 3), the relative minimum centres associated with the monsoonal trough from the Persian Gulf dominate the EM region. Their dominance do not reflect cyclonic intensity but rather consistency of the system. The Cyprus centre, for instance, attains a maximum of 14, indicating that every other day in July is typified by a relative minimum centre associated with the Persian Trough, an extension of the Indian monsoon low. This surface trough is associated with a strong upper-level Subtropical High preventing the formation of deep clouds or rain. Petterssen's (1956) classical study of cyclone occurrences does not show these centres at all, probably because they were not deep enough to be included. Also, the lower resolution in Petterssen's (1956) study (100,000 km^2 compared to 62,500 km^2 here) may partly explain that. The strong thermal character of the summer minima is manifested in the considerable diurnal amplitude in their number $\overline{N}$ (compare Fig. 3). The large day to night differences were examined in two different approaches: First, the average 1000 mb ECMWF analyses at 0000 and 1200 GMT were plotted and found to show a distinct minimum at night right over Cyprus. Second, the observed surface pressure at about 50 stations was averaged over a long period of 8 years for day and night separately and these maps were drawn to again show a distinct minimum of 1006.5 mb over east Cyprus (in August) only at night. In addition, 0000 and 1200 GMT detailed surface maps were cautiously examined in few cases during summer and revealed the same feature. The diurnal dependency will be further investigated through the annual cycle (Figs. 4, 5). Interesting to note are three new summer cyclonic centres which could be hardly found at winter: at the western shore of Black Sea, north to the Algerian coast at the WM (2.5°E, 37.5°N) and at the Hungarian Plain (20°E, 47.5°N). Note the high day to night amplitude of the western Black Sea centre.

In October, (not shown), the distribution of cyclone frequencies resembles the July rather than the April distributions. The autumn centres are located more above the Mediterranean and are deeper compared to spring. Probably this reflects the warmer sea in October compared to April, i.e., a maximum SST of about 26 compared to 17°C in April, Reiter (1975).

Radinovic (1987) follows Brody and Nestor (1980) in identifying the cyclogenetic region near Cyprus as that between the Gulf of Antalya at the Turkish coast (31°E, 36°N) and Cyprus (32.5°E, 35°N). It should be noted that throughout the year, the Cyprus centre fluctuates between the two points with a clear tendency at night to Cyprus and by day to the Gulf of Antalya (compare Figs. 1a–3a to 1b–3b). The diurnal fluctuation of the geographical location of the cyclonic centres in the WM, however, is much smaller.

The annual variation of the cyclone frequency of occurrences $\overline{N}$, is shown for the maximum centre near Cyprus, EM, in Fig. 4. Fig. 4a illustrates the effect of the filter on the annual variation of nocturnal frequencies. In July, 00 GMT the number of EM cyclones dropped from $\sim$14 to $\sim$5 applying the filter. This means that about 70% of the nocturnal summer centres are very weak. The corresponding January drop in the cyclone frequencies was only by about 30%.

Night and day variation (full and dotted lines) as well as their differences (dashed) are depicted

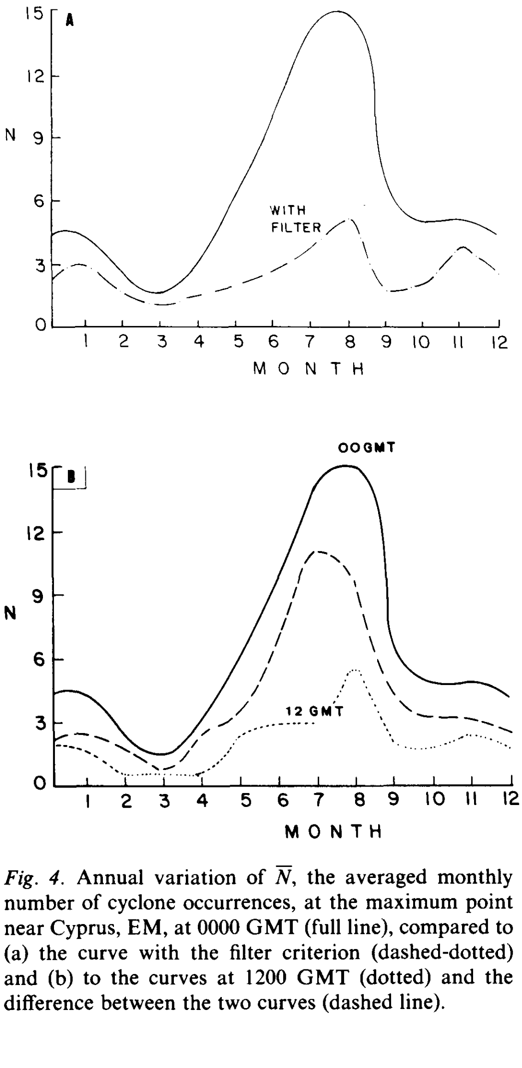

Fig. 4. Annual variation of $\overline{N}$, the averaged monthly number of cyclone occurrences, at the maximum point near Cyprus, EM, at 0000 GMT (full line), compared to (a) the curve with the filter criterion (dashed-dotted) and (b) to the curves at 1200 GMT (dotted) and the difference between the two curves (dashed line).

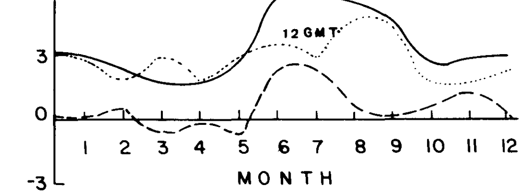

Fig. 5. As in Fig. 4b, except for the maximum point at the Lee of Genoa.

in Fig. 4b. The strong summer maximum of 15 by night and 5 by day is very pronounced. The thermal effect is illustrated by the difference curve attaining a maximum of about 10 in July and dropping to a minimum of about 1 at March, a month when the SST is minimum. In the Gulf of Genoa centre (WM), however (Fig. 5), the situation is remarkably different. Both the seasonal and diurnal amplitudes are smaller. Here the thermal effect is noticed only during the summer months, June to August, and is insignificant during most of the year. When the filter criterion was applied a reduction of the day to night difference in the cyclone frequency from ~2.5 to ~1.5 in June–July was noticed. Following these results, we suggest that the sea thermal processes are more effective at the warmer EM (by at least 5°C, e.g., Reiter (1975)) than at the WM, where other processes like lee cyclogenesis effects play the major role throughout the year.

3. Cyclone tracks

3.1. Method of objective analysis

The search was based on an elliptic domain where the initial cyclone was located at a point on the major axis about one grid point (300 km) upwind. Following a number of experiments with varying axis lengths, the following was applied.

(i) The major axis direction was determined by the direction of the 700 mb wind vector at the starting point (location of a cyclone centre). The 700 mb was shown in various synoptic and dynamic studies to be close to the steering level, see, e.g., the steering level of the Charney instability problem (Gill, 1982).

(ii) The part of the major axis from the starting point downwind (wind at 700 mb), c, was calculated by:

$$c = \max\,(300\text{ km}, 1.8\,A), \tag{1}$$

where

$$A = |V_{700\,\text{mb}}\,(\text{km/h})\cdot 12\text{ h}|. \tag{2}$$

(iii) The upwind segment of the major axis, b, was chosen constant at 300 km. Hence, the equation of the ellipse could be written by:

$$x^2 + \frac{c}{b}y^2 - (c-b)x = bc, \tag{3}$$

where x is the distance along the major axis where the starting point is the coordinate system's origin.

If one cyclonic point for the next data set (12 h later) was found within the ellipse, the starting point was connected with that point to form part of a track and the search continued from the next data set. If two (or more) cyclonic points were found a splitting to two (or more) tracks was assumed. In analogy, if two ellipses associated with different cyclonic points interlap and the pertinent tracks connect to the same point, the tracks were assumed to converge.

The number of cyclonic tracks and their geographical locations found in each experiment were compared to subjectively analyzed tracks prepared for specific periods in winter and spring. For further illustration, Fig. 6a presents the cyclone tracks produced objectively and Fig. 6b those produced subjectively for the period 1–10 January 1987. Isolated points in Fig. 6a indicate cyclone centres for which tracks were not found; most of them are weak or thermally driven so that they are strongly dominated by the diurnal cycle. Although the number of isolated points was large (about 20% for the full period) they were found to have a strong annual and diurnal dependence. Their frequency at night is more than double particularly at the summer months.

Fig. 6 shows that most of the cyclones' tracks were realistically captured. However, the observed cyclone track crossing Europe from the North Sea to the Black Sea was not obtained by the objective method because the cyclone moved very fast, about 12° in 12 h. A further increase of c to 2.5 A in order to include this particular track spoiled other tracks. The value of 1.8 A in (1) was found optimal for the minimization of erroneous track connections on the one hand and maximization of the number of true tracks on the other.

The importance of the elliptic searching domain is illustrated in Fig. 6c where tracks were found for the same period but with a circular searching domain. Right tracks were not connected, i.e., at northern Europe, from south Italy to Greece and from south Greece to north Turkey. In addition wrong connections were done, i.e., from northwest to southwest Turkey. An independent similar comparison of 10 Sharav Cyclone tracks for the period of March–April 1986 to that analyzed subjectively by Alpert and Ziv (1988, Fig. 5) was also found satisfactory (not shown here). It should be emphasized that not all tracks are captured and some tracks identified by the aforementioned method are wrong. The wrong tracks however, are found to be small in percentage, about 5–15% depending on the period considered.

3.2. Monthly cyclonic tracks (1983–1987)

Fig. 7 shows the computed tracks for January, April and July, respectively for the full period (3 November 1982–31 December 1987). The main conclusions to be drawn from these figures follow.

(i) *January* (*Fig. 7a*). The cyclones tend to move along the northern part of the Mediterranean Sea. They leave the Sea in 3 major routes colocated with passages between major mountain ridges. One is between the Swiss and Dinaric Alps, second, most pronounced route, is between the Balkan and Turkish mountains towards the Black Sea and the third route is between the Turkish and Syria/Lebanon mountains to the east of the EM. This was illustrated by a schematic map in Weather in the Mediterranean (1962). Another point to mention is the tendency of the northwest African depressions to move northeastward towards the Sea. In December (not shown) there is a tendency of the cyclones to penetrate to the southern part of the EM. This is a well-known feature of the early winter cyclones (Alpert and Reisin, 1986).

(ii) *April* (*Fig. 7b*). The Saharan Depressions (Sharav Cyclones) tracks increase significantly in number while maritime tracks decrease. The springtime cyclones tend to move along the north-African coast where low level baroclinicity is maximized at spring, Alpert and Ziv (1989). The relatively cold water, 16°C, compared to higher temperatures above land strongly favor the continental tracks. The source of many springtime cyclones can be identified as the lee of the Saharan Atlas mountains. More cyclones in the WM leave the sea towards the northeast or east-northeast and not along the Sea. The Saharan Depressions (Sharav Cyclones) tracks from the lee of the Atlas mountains correspond well with the three typical routes reported by Radinovic (1987): (i) to the northeast, (ii) to the east till Tunisia (10°E, 34°N) then to the north-

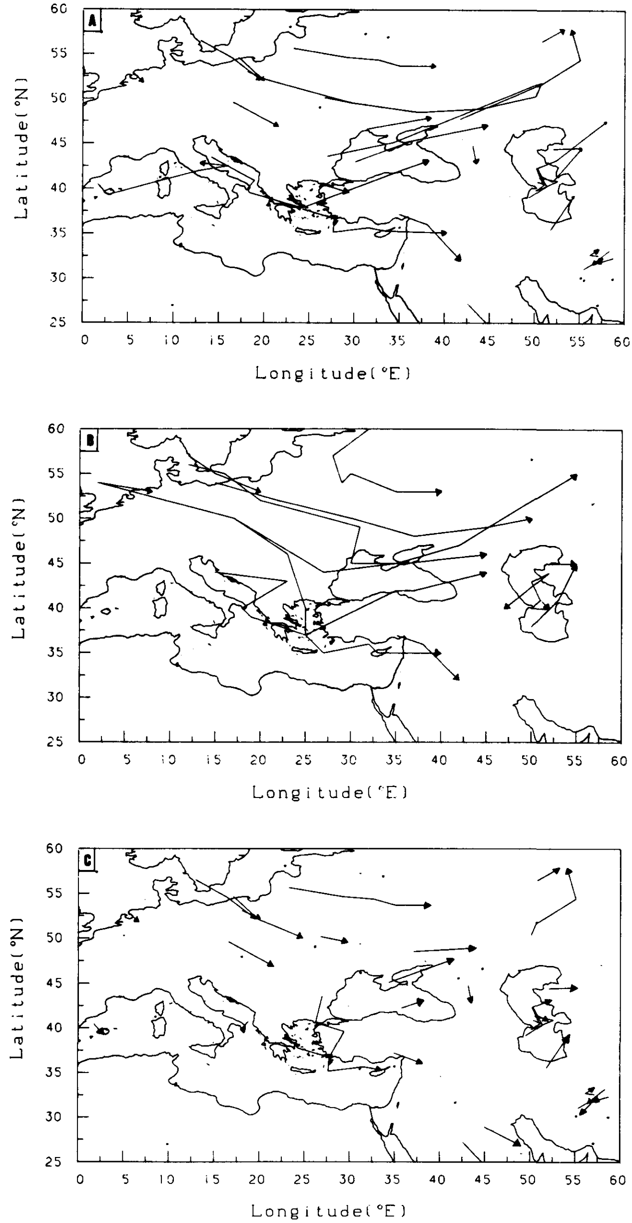

Fig. 6. (a) Objectively and (b) subjectively calculated cyclone tracks for the period 1-10 January 1987. For details of computation see text. Arrows indicate direction of cyclone motion; (c) as in (a) but with a circular searching domain. Isolated points indicate cyclone centres for which tracks were not found.

east and (iii) to the east till the Bay of Sidra (19° E, 31° N) then to the northeast.

(iii) *July* (*Fig. 7c*). There is a fair-weather semi-permanent cyclonic centre in the EM near Cyprus, connected with the Persian trough. It seems that some of the cyclone centres appear over Cyprus at 0000 GMT, tending to move westward and disappear by 1200 GMT. In July,

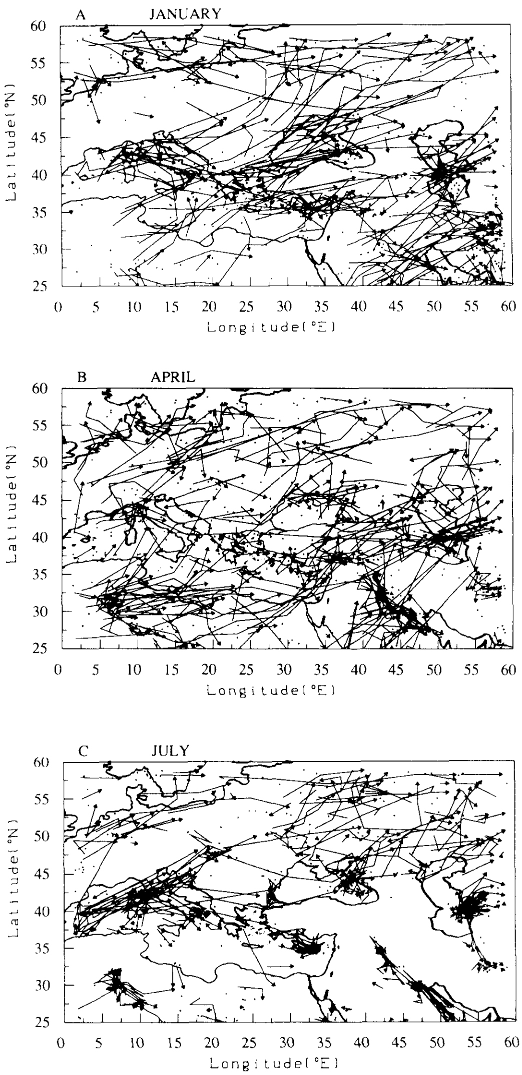

Fig. 7. Objectively calculated cyclonic tracks for January (a), April (b), July (c), during November 1982–December 1987.

travelling cyclones exist only in the WM, and their main route is northeast toward the Po valley and the Hungarian basin.

4. Average vorticity centres (1983–1987)

Up to now, we have discussed cyclonic centres and cyclone tracks based on 1000 mb average analyses where the cyclone was defined by a minimum in the height of the pressure surface. To investigate the height dependence of average cyclonic character the average vorticity distribution was chosen. As discussed earlier the summer cyclones are in general not associated with rain or storms in the EM but with a low-level inversion and nice weather. Hence, this section will focus on the climatic features of the more intense and rain-producing winter cylones, and in particular, on the variation through the troposphere of the average vorticity. First, 5-year January averages over standard isobaric maps will be shown and then vertical cross-section above the Mediterranean will be employed to compare the EM and WM average cyclonic characteristics.

4.1. Isobaric maps

Fig. 8 shows the January, 0000 GMT 5-year relative vorticity averages at 1000, 850, 500 and 300 mb isobaric surfaces respectively. The average 1000 mb vorticity in Fig. 8a is reminiscent of the average cyclonic frequency of occurrences (Fig. 1a). In both maps the water bodies attract the average cyclone or vortex but there are important differences. The positive vorticity tends to cover the seas, even nearly follow the coastal lines while cyclone frequencies concentrate in specific regions. A major difference between this map and Fig. 1a is the relatively weak vorticity centre at Cyprus compared to that at the WM with a factor of about $\frac{1}{3}$ (0.7 at Cyprus to 2.4 at the WM), whereas in number of cyclone occurrences, Fig. 1a, the two centres are nearly equal. Hence, although the number of cyclones in the EM are fairly close to that for the WM the average vortex intensity is higher at the WM.

Comparing Figs. 8a, b, c, d, one notices that while the two lower surfaces, 1000 and 850 mb are similar and correspond to the cyclone distributions at the surface, the two higher-level surfaces, 500 and 300 mb are very different. The 300 mb map presents along with the average vorticity the isotachs in which the subtropical jetstream axis of 40 m s^{-1} at 26–28°N separates the positive and negative vorticities. There are three vorticity centres close to the Mediterranean which seem to be the result of a steady-wave in the upper jet. The interaction between the Atlas mountain at northwest Africa and the subtropical

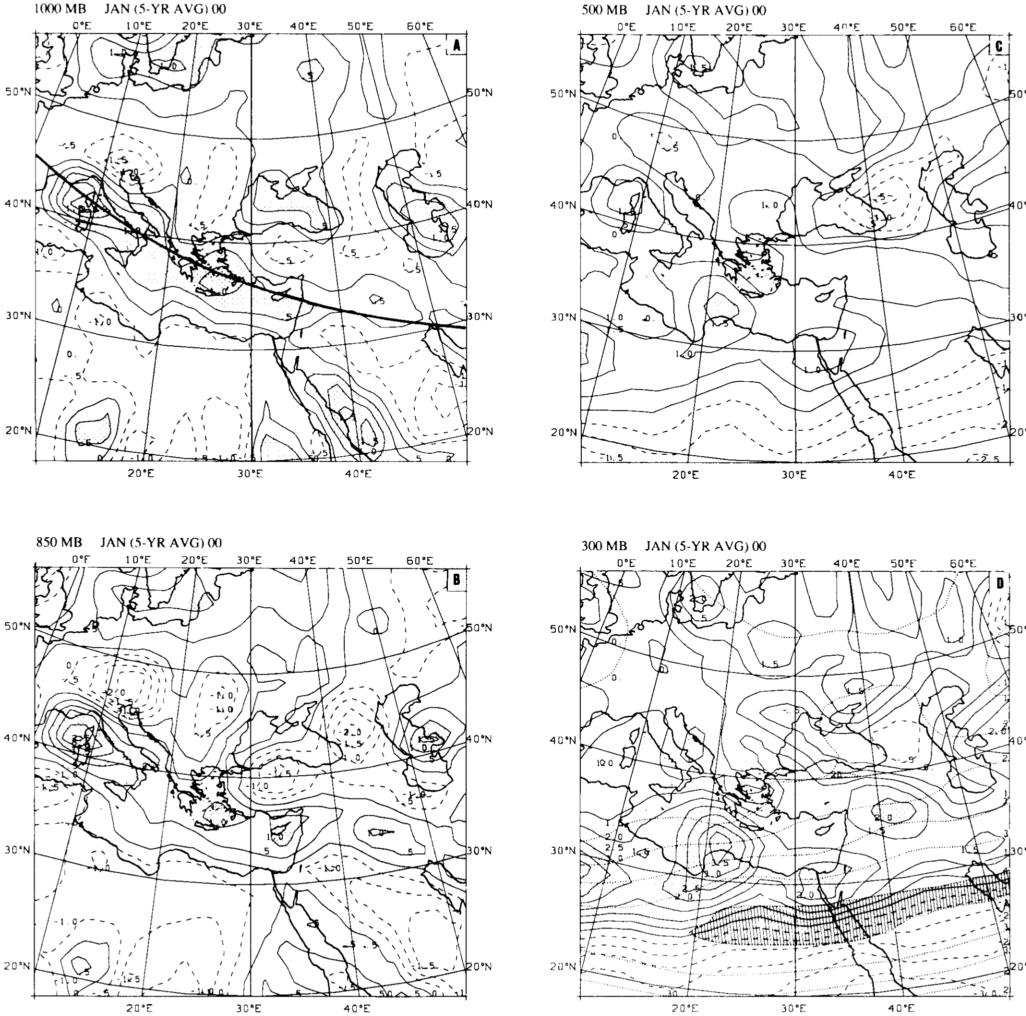

Fig. 8. Distribution of average (a) 1000 mb, (b) 850 mb, (c) 500 mb and (d) 300 mb relative vorticity (10^{-5} s^{-1}) for January 0000 GMT. Averaging period consists of 5 years, 1983–1987. Positive (full line) and negative (dashed line) vorticity in intervals of 0.5. Background contours of coastlines are also drawn. At 300 mb, the isotachs for the total horizontal wind magnitude are drawn (dotted) with an interval of 5 m s^{-1}. Line of the vertical cross-section in Figs. 9 and 10 is indicated in Fig. 8a. Regions exceeding vorticity of 0.5 in (a), 1.0 in (b) and 2.0 (10^{-5} s^{-1}) in (d) are shaded, in dots. In (d), the region exceeding wind vector magnitude of 40 m s^{-1}, indicating the subtropical jet core, is hatched.

jet, may be responsible to that steady-wave and is currently being investigated. One vorticity centre is at the southeastern Mediterranean, a second one above the Libyan coast (22° E, 33° N) and one at northwest Africa—only its eastern part is seen at (28° N, 9° E). Interesting to note is the existence of the Genoa vorticity centre which extends up to 500 mb while the other average vortices are kept only at the lower surfaces. The Black Sea vorticity centre dissipates already at the 850 mb, compare Figs. 8b and 8a.

We present only the nocturnal maps because day to night variations were found small at all levels. The 1000 mb vorticity centres above the Mediterranean are slightly stronger during day (10–20%). At 300 mb, day-night differences above the Mediterranean are in general smaller although the Libyan centre weakens by more than 30% and moves about 2–3° to the southwest.

4.2. Vertical cross-sections of vorticity

To compare the complete vertical character of the average vorticity centres at the EM and WM a southeast–northwest vertical cross-section of average vorticity along the EM and WM centres, was drawn (see Fig. 8a). This is a straight cartesian line connecting points (45° N, 0° E) and (27.5° N, 60° E). Figs. 9a, b present the results of vertically interpolating the vorticity between the 7 given standard levels, for 5-years averaged January vorticity at 0000 and 1200 GMT respectively. Between 1000 and 1050 mb and 100 to 0 mb a linear extrapolation was performed. The high-resolution topography (~0.5°) is drawn at the bottom where 1000 mb represents the sea level height; the islands of Cyprus and Corsica are indicated and could be considered as a rough estimate of the Mediterranean extension in this cross-section.

A major feature of the average vorticity above the Mediterranean is the positive vorticity through the whole troposphere. The 4 aforementioned centres near the surface can be detected but they appear more like two extended centres at the WM and EM. The WM centre is deeper and stronger (about double the intensity) while the EM centre is clearly separated into two parts, one near Cyprus and the other near Crete. The Crete centre is maximized at the surface while the maximum of the Cyprus one is at about 850 mb. The Genoa centre is also maximized at 850 mb which seems to indicate a stronger lee cyclogenesis mechanism compared to a sea-surface cyclogenetic effect dominating the Crete centre. Another interesting difference which could result from the cyclogenetic mechanism is the broader/shallower EM centre as compared to narrower/deeper centre in the WM. A third difference is the separation of the upper-level much stronger vorticity centre at the EM with the value of $2.4 \cdot 10^{-5}\ s^{-1}$ from the lower-level centre. The two centres seem to originate at the EM from different mechanisms, i.e. subtropical jet-stream and surface cyclogenetic mechanisms, as conjectured by Alpert and Warner (1986), while at the WM they seem to be strongly connected with the lower level cyclonic activity. Evidence for that is

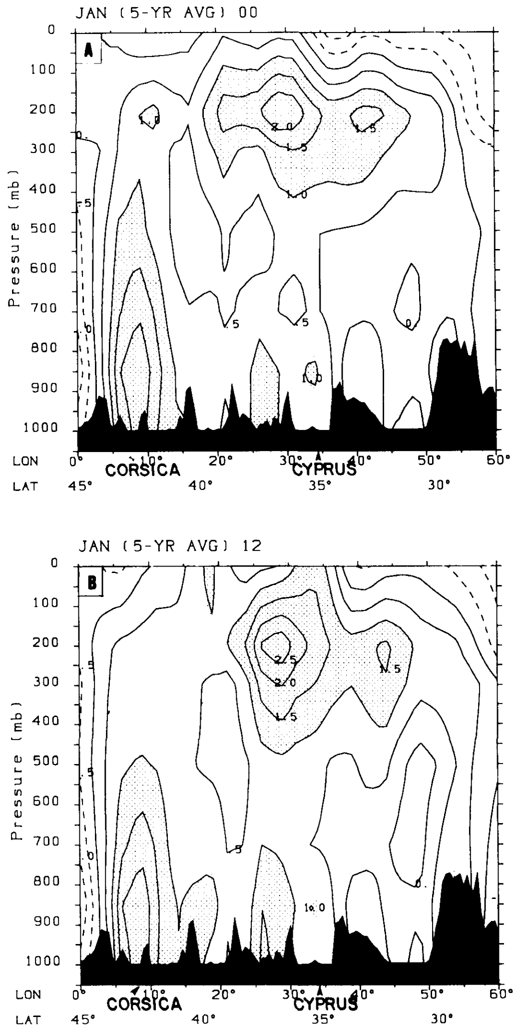

Fig. 9. Vertical distribution of average vorticity ($10^{-5}\ s^{-1}$) through the cross-section indicated in Fig. 8a, for January (a) 0000 GMT and (b) 1200 GMT. Averaging period consists of 5 years, 1983–1987. Positive (full line) and negative (dashed line) vorticity in intervals of 0.5. Topographic altitude is indicated at the bottom with 1000 mb corresponding to zero altitude above MSL. Islands of Cyprus and Corsica are indicated. Regions exceeding vorticity 1.0 ($10^{-5}\ s^{-1}$) are shaded.

found in the opposite sense of the diurnal circulations in the upper level vortices. In the WM the upper level average vortex weakens by day, Fig. 9b, as does the lower level vortex while at the EM the upper level vortex slightly strengthens by day

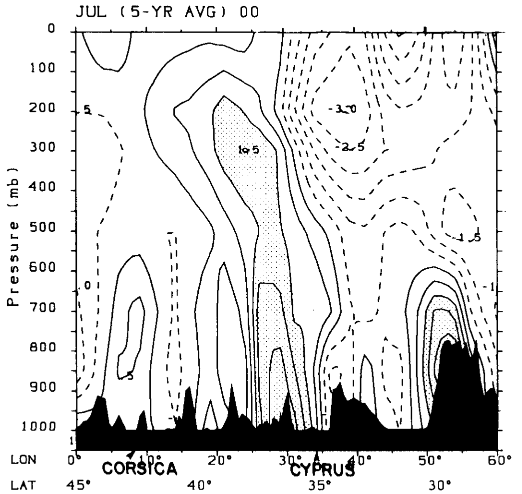

Fig. 10. As in Fig. 9a, but for July at 0000 GMT.

(from 2.4 to $2.8 \cdot 10^{-5}\,s^{-1}$). It should be stressed however that some independent measures would give more confidence in the day-night differences because the accuracy of the data may not be good enough to interpret such differences.

At summer, Fig. 10, the Mediterranean region is influenced by negative-vorticity centres as well and the positive vorticity domain is smaller. One exception is the Crete region where the consistency of the Persian monsoonal trough results in an even higher value of the average vorticity (2.6 compared to $1.3 \cdot 10^{-5}\,s^{-1}$) even though the summer cyclonic activity is much weaker compared to winter. The Genoa vortex maximum rises at night to 700 compared to 850 mb by day (not shown). Again, the EM maximum is right at the surface in contrast to the upper level maximum in the WM. Another interesting feature is the negative-vorticity at the EM coast which changes abruptly eastwards. The high value of the east–west vorticity gradient in Cyprus corresponds to the sharp transit from the surface ridge at the EM coast to the surface Persian trough maximum further in sea.

5. Conclusions

The present analysis of the Mediterranean cyclones includes the following features, as emphasized by Radinovic (1987): objective definition and selection of cyclones, the consideration of the vertical structure of the cyclone and the treatment of the whole Mediterranean domain. The data base of the present study is the ECMWF highly sophisticated analysed data set for the recent 5 years for which major modifications have been introduced in the data assimilation systems.

A few of the important findings of this study follow.

(i) Day-to-night variations along with annual variations in the number of cyclones and in their geographic location indicate the major positive thermal effect of the sea particularly at night and during the summer. At the eastern Mediterranean these effects are much more pronounced than at the western Mediterranean and persist throughout the year. We believe that these day-to-night variations are real and not merely artificial effects due to certain problems in the data assimilation system. Similar variations were also found in a separate data set of observed day and night surface pressures (Subsection 2.2).

(ii) Differences between the eastern and western Mediterranean vertical and horizontal distributions of vorticity indicate that the sea thermal effect is very important in the eastern Mediterranean particularly at the Crete centre. Lee cyclogenesis seems to play an important role in the Gulf of Genoa and also in Cyprus particularly during the winter.

(iii) The results from the current ECMWF analyzed dataset seem to have the ability to exactly locate some subsynoptic cyclonic centres which were not found in earlier synoptic studies. But, the representativeness of the low resolution ECMWF analyses to small-scale structure must be further investigated.

(iv) A realistic method for the objective calculation of cyclone tracks is presented. All cyclone tracks in a 5-year period calculated by this method are shown for January, April and July. The well-known cyclonic tracks in the Mediterranean region are reproduced, but in contrast to earlier studies where a schematic picture was drawn, the actual tracks are depicted.

The current approach to cyclogenesis was based on cyclone frequencies (Subsection 2.3) and vorticity (Subsection 2.4). A more restricted treatment of cyclogenesis, see *Glossary of Meteorology* (1959), accounts only for new formations of cyclones. In the latter sense the eastern Mediterranean is a very weak cyclogenetic region compared to the western Mediterranean, e.g., Reiter (1975, p. 111–27). As early as in Petterssen's (1956) study it was found that by defining cyclogenesis through cyclone frequencies, the eastern Mediterranean is a highly cyclogenetic centre comparable to that of Genoa. Radinovic (1987) who noticed the large difference between the two approaches suggested a proportion factor for the ratio between total number of cyclones and cyclones' new formations and found numbers which increase from 1.9 at Genoa to more than 10 at the Black Sea. Following our results this number at the eastern Mediterranean is also very large ($\gtrsim 10$) because the cyclone frequencies at the eastern and western Mediterranean are similar, even though new formations at the eastern Mediterranean are infrequent.

Future modifications and improvements of the objective method for analyzing cyclones will include the following features. First, the definition/trace of cyclones as well as anticyclones will be based on the three-dimensional structure. Second, the tracing method will be further improved to include the largest number of cyclones possible and eliminate as far as possible wrong tracks. Third, cyclones' speeds and growth-rates will be classified according to their intensities including the distinction between new formation and intensification.

This new objective system could be applied to the study of the various cyclogenetic theories. One example for that is the investigation of the IVP (initial value problem) growth theory, Farrell (1984), and its comparison with classical baroclinic instability theories as based upon a large number of cyclonic evolutions. An important variable for such a comparison is the distribution of the growth-rates for a large number of cyclones in contrast to single cases, e.g., Buzzi and Tibaldi (1978).

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