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Climatology of Mediterranean cyclones using the ERA-40 dataset

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Abstract

The generation of cyclone climatologies has recently received a renewed interest. Cyclones are closely related to the climate of certain regions, and thus, their variability is one of the key points in current climate research. The Mediterranean is a region with high density of cyclones, but due to its location and its particular morphology, cyclones are subject to large spatial and seasonal variability. Moreover, some cyclones are related to hazardous weather events, in particular heavy precipitation and strong winds. Improved knowledge of Mediterranean cyclones would contribute to the improvement of the forecasts of such damaging events.

In this study, objective detection and tracking algorithms are used on the ERA-40 reanalysis to derive a climatology of surface cyclones for the Mediterranean region. The detection algorithm is also applied at various vertical levels, characterizing the three-dimensional structure of the cyclones, and allowing to derive their vertical thickness. The relatively high spatial resolution, but mainly the long period (45 years) makes the ERA-40 reanalysis especially suitable for the generation of a cyclone climatology.

The aim of this study is twofold. Firstly, a detailed description of the Mediterranean surface cyclones is obtained. This includes the spatial and seasonal variability and some of their main individual features, like the intensity, size, vertical thickness and life cycle. Moreover, some regions with a large cyclogenetic frequency are studied in detail. Secondly, the results of the present climatology are compared with many other studies. The qualitative comparison indicates a general agreement with most of previous climatologies. However, as a consequence of the ERA-40 resolution, the comparison with high resolution cyclone datasets shows a shortcoming related to the detection of small cyclones. Nevertheless, it is concluded that the current climatology depicts a comprehensive view of the synoptic and sub-synoptic cyclonic activity in the Mediterranean.

KEYWORDS: cyclone climatology, Mediterranean, ERA-40 reanalysis.

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1 Introduction

The weather and climate are strongly influenced by anticyclones and cyclones. Especially, the cyclone tracks yield the location of precipitation, and changes of the mean tracks, caused either by the long-term natural variability or by anthropogenic causes, influence strongly the regional climates (Lionello et al., 2006; Ueno 1993). Besides, cyclones are a potential source of high impact weather, because of their association with strong winds, intense precipitation, high wind waves and storm surges (Radinovic 1987; Jansà et al., 2001b; Lionello et al., 2006). In a general sense, there is a close link between cyclones and rainfall. Synoptic cyclones evolve in a context of ascending motions and thus favourable to the generation of large areas of precipitation (on their eastward and poleward sectors). In the Mediterranean, cyclones contribute to organizing the low-level flow of warm and moist air which feeds precipitation systems. This flow interacts with the orography or any local convergence zone, resulting both of them in upward motions. However, the relationship between cyclones and precipitation is not simple and it could differ from one region to another (Pinto et al., 1999; Romero et al., 1999). In Trigo and Davis (2000), the decrease in total winter rainfall for the Northern Mediterranean regions was attributed to the average decrease in cyclone intensity, rather than their frequency. Jansà et al., (2001b) show that in most of the heavy rain events registered in the Western Mediterranean, a nearby cyclone centre was detected, in such a way that the associated circulation enhanced the moist air flow towards the region affected by heavy rain. Jansà et al. (2001b) also show that not only deep and synoptic cyclones contribute to heavy rain, but so do weak and meso-scale lows. Similar relationships were found for different Mediterranean regions (Kahana et al., 2002). Therefore, variations in the cyclone tracks and cyclone intensity affect the distribution of precipitation, which in addition could have serious consequences in several Mediterranean areas. Contrasting changes have been observed in Mediterranean precipitation 1951-1995 trends: on the one hand a decrease in the total annual rainfall and on the other hand an increase in frequency and contribution to the total of heavy/torrential daily rainfall events (Alpert et al., 2002; Brunetti et al., 2004). These variations are important for two different reasons. First, there are many Mediterranean regions under water stress because of their small total precipitation amounts, and second, the potential damage that torrential rain could produce.

Sitting at intermediate latitude, between about 30º and 45º North, the Mediterranean region is affected by both tropical and mid-latitude systems. The Mediterranean basin is surrounded by complex orography, with high mountain ranges such as the Atlas or the Alps (Figure 1). Besides, the Mediterranean Sea is an almost enclosed basin, which acts as a reservoir of heat and moisture, with a remarkable land-sea contrast. These features bear important consequences on the atmospheric regional circulations and they indeed determine largely their spatial and seasonal variability, where meso-scale structures, and particularly low-pressure centres, play an important role (Radinovic, 1987).

In previous climatological studies of cyclones in the Northern Hemisphere, the importance of the so-called Mediterranean storm-track has been underlined, in particular in winter (Petterssen, 1956; Hoskins and Hodges, 2002). Other studies focused on the Mediterranean, show that cyclogenesis occurs at preferred regions, being the gulf of Genoa and Cyprus, the two most frequent regions (Alpert et al., 1990; Maheras et al., 2001; Flocas et al., 2001). These studies were performed employing low resolution datasets, and so focusing on synoptic-scale systems. As the horizontal resolution increases other regions with high frequency of cyclone centres appear and the importance of the sub-synoptic cyclones arises. Hence, in Trigo et al., (1999) cyclones in northern Africa, southern Italy, the Aegean and Black seas, and the Iberian peninsula were analysed. The predominant role of meso-scale features in the Mediterranean was already pointed out by Radinovic (1978). Further on, this result has been corroborated in other studies (Picornell et al., 2001; Gil et al., 2002; Campins et al., 2006).

Recently, several reanalysis projects have produced homogeneous datasets covering long periods of time. By using a fixed data assimilation system, they render the best available homogeneous four-dimensional dataset to be used for the study of atmospheric processes and climate. Some of them, as the ERA-15 (Gibson et al., 1997) and the ERA-40 (Uppala et al., 2005) from the European Centre for Medium-Range Weather Forecast (ECMWF) or the National Centres for Environmental Prediction-National Centre for Atmospheric Research (NCEP-NCAR) reanalysis (Kalnay et al., 1996), have been used to derive the synoptic-scale cyclonic activity over long periods and large regions. Cyclone climatologies derived from different reanalyses are found to be in reasonably good agreement over the Northern Hemisphere in general, and the Euro-Atlantic sector in particular (Hodges et al., 2003; Wang et al., 2006; Hanson et al., 2004; Trigo, 2006). Nevertheless, all the aforementioned studies also agree in that ECMWF reanalyses (both ERA-15 and ERA-40) resolve better the location of cyclone centres in the Mediterranean than the NCEP-NCAR reanalysis. This is a consequence of the higher horizontal resolution of ECMWF reanalyses compared to the NCEP-NCAR data, and hence a better performance for sub-synoptic systems.

The MEDiterranean EXperiment on cyclones that produce high impact weather in the Mediterranean (MEDEX, http://medex.aemet.uib.es) is a project endorsed initially (first phase) by the World Weather Research Project of the World Meteorological Organization, and currently (second phase) in THe Observing system and Research and Predictability EXperiment (THORPEX). In order to improve the knowledge and forecasting of the cyclones that produce high impact in the Mediterranean, the implementation of a dynamically oriented climatology of cyclones was established as one of the initial goals in the first phase (Jansà et al., 2001a). To do that, cyclones and high impact events had to be collected in a systematic way, and later, both types of data could be cross-referenced. Objective and automated catalogues of cyclones have been derived from high resolution operational objective analyses (from HIRLAM-INM in Picornell et al., 2001 and Campins et al., 2006 and from ECMWF in Gil et al., 2002) and for short period of 4-8 years. Besides, cyclone databases have been cross-referenced with high impact weather events (heavy rain and strong wind) for some specific Mediterranean regions (Campins et al., 2007). However, from a climatological point of view, the robustness of the results demands the use of a long period of time. This can only be achieved by using a reanalysis dataset. Hence, in the MEDEX framework an objective catalogue of cyclones was derived from ERA-40 reanalyses for the whole Mediterranean basin. The most intense cyclonic events of this catalogue has been analysed in Genovés et al., (2006). Intense cyclones have been also used as a proxy of hazardous weather events, to conduct sensitivity studies of such events (Homar et al., 2007; Garcies and Homar, 2009). All the aforementioned Mediterranean cyclone databases (HIRLAM-INM, ECMWF and ERA-40) are public and available in the MEDEX website (http://medex.aemet.uib.es).

The main goal of the present study is to present a comprehensive and coherent cyclone climatology for the Mediterranean region by means of the ERA-40 dataset. The results are compared with other available climatologies, stressing the main similarities and discrepancies. The data and methodology used to build the climatology are explained in Section 2. Results are presented in three separated sections. First, the general characteristics of Mediterranean cyclones are depicted in Section 3. Afterwards, in Section 4, the seasonal features of such cyclones are analysed. In Section 5, the cyclones originated in the main cyclogenetic regions are studied in detail. Section 6 is devoted to compare qualitatively the present cyclone climatology with other ones and to discuss the results of the comparison. Finally, the most remarkable results are summarised in Section 7.

2 Data and methodology

The ERA-40 data has a spectral resolution of T159, which has been interpolated to a regular 1.125º x 1.125º latitude-longitude grid (~ 125 km), the temporal resolution is 6 hours and the dataset encompasses analyses from September 1957 to August 2002 (45 years). The ERA-40 reanalysis has been produced with a fixed three-dimensional variational assimilation system; but as the atmospheric system has been improved along the period, ERA-40 dataset is not fully consistent, especially from the introduction of the satellite observing system. However, as shown by Bengtsson et al. (2004), the differences between pre-satellite period (1957-1978) and satellite period (1979-2002) in the mean intensity of extratropical cyclones are seen to be relatively small in the Northern Hemisphere. Thus, cyclone climatologies for the Mediterranean derived from ERA-40 can safely be considered as homogeneous.

The methodology follows a three-step algorithm. First, surface cyclones are detected from mean sea level pressure (MSLP) fields, available every 6 hours. Next, the vertical extension of a surface cyclone is explored by means of the geopotential height at the levels of 1000, 925, 850, 700, 500 and 300 hPa. Finally, each cyclone centre is tracked along time to produce a cyclonic event. Similar detection and tracking methods were applied to a set of HIRLAM-INN analyses to produce two distinct cyclone climatologies for the Western Mediterranean (Picornell et al., 2001 and Campins et al., 2006). Following, a brief description of the algorithms is given, but the reader is referred to both aforementioned papers for a more in-depth description and discussion. The study domain includes the entire Mediterranean, from 48.375º N to 25.875º N and from 11.250º W to 38.250º E (Figure 1).

2.1 Detection of surface cyclones

Algorithms used to compile cyclone climatologies are usually performed at low levels, from MSLP fields (Petterssen, 1956; Whittaker and Horn, 1984; Nielsen and Dole, 1992; Simmonds and Murray, 1999; Simmonds and Keay, 2000; Gulev et al., 2001; Maheras et al., 2001; Hanson et al., 2004; Wang et al., 2006; Wernli and Schwierz, 2006) or from the geopotential field at 1000 hPa (Alpert et al., 1990; Sinclair, 1997; Blender et al., 1997; Trigo et al., 1999; Sickmöller et al., 2000). Cyclones are detected as minima in MSLP or 1000 hPa geopotential fields. There are various drawbacks in using these fields. MSLP and geopotential at 1000 hPa fields are strongly influenced by large spatial scales and strong background flows. This might result in a bias favouring the large-scale, slow-moving systems, and on the contrary weak, fast-moving ones can be masked. Besides, MSLP is an extrapolated field and may be sensitive to the extrapolation procedure, mainly over elevated regions. For these reasons, the vorticity could be a better variable than the pressure field to identify surface cyclones, in particular in the early stages of their development (Sinclair 1997; Flocas et al., 2001). But when high resolution datasets are used, the vorticity is a very noisy field and a smoothing or a reduction of resolution is necessary.

In spite of the aforementioned drawbacks there are large amounts of cyclone climatologies built upon the MSLP, and they form a valuable basis for comparison. Furthermore, Hoskins and Hodges (2002) investigated the suitability of a large number of variables for cyclone detection in the Northern Hemisphere, at both lower and upper levels. In particular, MSLP and 850 hPa vorticity fields produced similar results, although the latter better described the smaller-scale systems. Accordingly, and due to the relatively high horizontal resolution of the ERA-40 dataset, in the present study MSLP field will be used to detect surface cyclones. Nevertheless, the geostrophic vorticity will be used to calculate the cyclone domain. To avoid a very noisy vorticity field, the MSLP field is previously smoothed by means a Cressman filter, with an influence radius of 200 km (Cressman, 1959). Therefore, a cyclone centre is determined as a local minimum in the smoothed MSLP field, that is a grid point is initially considered as cyclone centre if its MSLP value is smaller than each of its eight neighbouring grid points. Very weak cyclone centres are removed by means of an additional criterion, based on the pressure gradient: a cyclone centre is rejected if the pressure gradient around it is lower than 0.5 hPa/100 km. The cyclone domain is defined as the region around the pressure minimum with positive geostrophic vorticity. To calculate the cyclone domain, the distance from the centre of the cyclone to the zero vorticity line is looked for radially along sixteen directions. The mean radius (R), defined as the average of the sixteen radial radii around the cyclone domain, will be used as an approximate measure of the cyclone size. Since Mediterranean cyclones are not expected to be large systems, an upper bound of 850 km to each radial radius is imposed.

In previous studies, the intensity of cyclones has been measured with several parameters. Some authors use the central MSLP (Gulev et al., 2001; Maheras et al., 2001; Lambert et al., 2002). Others prefer the pressure gradient around the cyclone centre (Nielsen and Dole, 1992; Trigo et al., 1999; Sickmöller et al., 2000), the laplacian of MSLP or the vorticity (Serreze et al., 1997; Wang et al., 2006). As the laplacian of MSLP or the vorticity are very dependent on the spatial resolution of the fields, Simmonds and Keay (2000) scaled the MSLP laplacian ($\nabla^2 p$) with the square of mean cyclone radius (R), defined as cyclone depth D (= $1/4\nabla^2 pR^2$). A similar cyclone intensity measure is based on the circulation around the cyclone centre (Sinclair, 1997). As it is explained in detail in Sinclair (1997), the circulation takes into account both the vorticity and the size of the cyclone, and it is not as dependent on the resolution as the vorticity. The circulation was already applied to measure Mediterranean cyclone intensity in Picornell et al. (2001) and Campins et al. (2006), and it has been applied in the present study as well. Therefore, the cyclone intensity is calculated by means of the geostrophic circulation (GC), that is, the areal integral of the geostrophic vorticity within the cyclone domain (for further details see the Appendix in Campins et al., 2006). Intensity values are given in GC units (GCU), being 1 GCU = 10^7 m^2 s^{-1}.

2.2 Vertical extension

As previously mentioned, most of cyclone climatologies focus on the low levels, but only few of them account for the upper levels (Bell and Bosart, 1989; Levefre and Nielsen-Gammon, 1995). In Hoskins and Hodges (2002) lower and upper cyclonic features in the Northern Hemisphere have been studied by means of several variables. The vertical structure of composite surface cyclones in three regions of enhanced cyclonic activity of the Mediterranean (the gulf of Genoa, the southern Italy and Cyprus) was studied by Maheras et al. (2002). In Lim and Simmonds (2007) a climatology of Southern Hemisphere winter extratropical cyclones in 1979-2001 was derived by means the ERA-40 reanalysis data. In that climatology the vertical structure of cyclones was obtained from six levels, and results revealed that about 52 % of that MSLP cyclones have a well organized vertical structure. For the Western Mediterranean, in Campins et al. (2006) the vertical structure of each individual surface cyclone was also characterized. For the present cyclone climatology, the same methodology as in Campins et al. (2006) is used, and briefly reviewed hereafter.

In order to define the vertical extension of a surface cyclone, a two-step algorithm is used. First, cyclone centres are detected independently at each pressure level (i.e. 1000, 925, 850, 700, 500 and 300 hPa). Detection at a pressure level follows the detection procedure at surface, that is, to identify local minima in the geopotential field. However, not only closed centres are allowed, but also open ones are recorded. An open centre is defined by means of a local maximum in the geostrophic vorticity field. In a second step, each surface cyclone centre is traced in the vertical. To do that, the presence of a cyclone centre is looked for in the upper-next pressure level, up to 300 hPa. The search is performed inside a circular domain, centred at the low pressure minimum (or the geostrophic vorticity maximum). The searching domain increases as the pressure level decreases, from 200 km at 1000 hPa to 500 km at 300 hPa (see Table 1 in Campins et al., 2006). This search is repeated until no cyclone centre is found or the 300 hPa level is reached. Closed cyclone centres are preferred rather than open ones. If two or more cyclone centres are found into the searching domain, the most intense one (that is with the highest GC) is selected. As a result, the cyclone centre thickness, that is, the lowest pressure level where the cyclone centre is detected, is obtained. A cyclone centre is considered as shallow if its vertical extension ranges from surface up to 850 hPa, middle-deep up to 500 hPa and finally deep when the cyclone extends throughout the whole troposphere (that is up to 300 hPa).

2.3 Tracking in time

A wide variety of tracking procedures has been proposed to derive cyclone trajectories and lifetimes. The most used algorithm, as well as the simplest, is the nearest-neighbour search procedure (Trigo et al., 1999; Blender et al., 1997; Serreze et al., 1997). Other procedures make use of more complex matching techniques, as those based on the comparison of the projected position of a cyclone with the one detected at an earlier time. The projection of the cyclone position can be derived from the earlier cyclone position (Wernli and Schwierz, 2007) or from a weighted combination of the current cyclone trajectory, the climatologically preferred movement and an estimate of the central geopotential height (Murray and Simmonds, 1991). To avoid unlikely matches all tracking schemes impose constrains, usually a threshold on the cyclone track length or on the velocity of the cyclone.

In the present study, the tracking algorithm firstly described in Picornell et al., (2001), and afterwards applied in Campins et al., (2006) has been used. This procedure is based on the one described by Alpert et al., (1990). In short, for a certain cyclone centre, the presence of another cyclone centre at the next analysis is looked for. The 700 hPa level is assumed to be the steering level of the movement of a cyclone, that is, the wind at 700 hPa determines the most probable direction of movement for the cyclone. A searching domain is defined as the elliptical area which extends from the cyclone centre along the 700 hPa horizontal wind. If a cyclone centre is found into the searching domain, then it is flagged as the same cyclone, otherwise it is assumed that the cyclone has vanished. As a result, cyclones are collected as a set of 6-hourly linked low pressure centres, spanning from the initial appearance (cyclogenesis) to the last appearance (cyclolysis). For each cyclone, the genesis and lysis location, lifetime and track length are derived.

3 General characteristics

3.1 Spatial distribution

For the whole study period 81762 cyclone centres are detected, that is an average of 1817 centres per year. These centres are not uniformly distributed (Figure 2), on the contrary they are located at preferred regions, with two outstanding maxima: Cyprus and the gulf of Genoa. Other regions with an appreciable number of cyclone centres are the Sahara (with two distinct maxima), the Adriatic and the Aegean Seas, the gulf of Cadis and the Algerian Sea. Other regions with less number of centres are also noteworthy: the Iberian peninsula, the Balearic, the Tyrrhenian and the Ionian Seas and the eastern part of the Black Sea. As most of the regions with a large number of cyclone events are placed very close to prominent mountain ranges, it is reasonable to suppose that the spatial distribution of cyclone centres in the Mediterranean is largely shaped by the orography. This is the case of many shallow, weak and stationary lee cyclones, which are generated as a result of the interaction of the air flow with the orography (Bessemoulin et al., 1993). However, in some cases, as the Genoa cyclogenesis, lee depressions evolve into intense and deep cyclones, where lower and upper levels interact in rather complex processes (Buzzi and Tibaldi, 1978).

3.2 Thickness, size and intensity

The relative frequency of cyclone thickness for the whole period and the entire region is presented in Figure 3. The bar graph shows that shallow and deep lows dominate, although middle deep depressions also accounts for a noticeable frequency. The number of shallow and deep lows is very similar, slightly higher for the formers. The main differences with the cyclone catalogue presented in Campins et al., (2006) concern shallow depressions, which are more frequent in that study than in the present one (51.1 % and 42.1 % respectively) and middle-deep ones, which are less frequent (11.1 % and 18.1 % respectively). The frequency of deep depressions is very similar (37.8 % and 39.8 %) for both climatologies. This suggests that deep cyclones are well captured in the present climatology, but on the contrary shallow depressions can be misrepresented.

As Figure 4a shows, most of cyclone centres exhibit a mean radius (R) comprised between 350 and 700 km, with an average value of 518 km. These results can be first compared with those obtained in Trigo et al., (1999). In that paper, a Mediterranean cyclone climatology was performed using ECMWF initialised reanalyses with a similar horizontal resolution (the T106 spectral resolution, which was interpolated to a 1.125º x 1.125º latitude-longitude grid) and the same temporal resolution (6 hours). The cyclone radius was calculated as the distance between the central position and the nearest saddle point in the 1000 hPa geopotential field. For each cyclone that lasted a minimum of 12 hours, the maximum radius along its whole life was used as a measure of the cyclone size. In Trigo et al., (1999) an average maximum radius of less than 500 km was obtained, and more than 65 % of the cyclones had a maximum radius of less than 550 km. Our results generally agree with these ones, probably due to the similar horizontal resolution used. Nevertheless, the maximum radius distribution in Trigo et al., (1999) is more skewed than the present one, as a greater portion of smaller and larger cyclones were found (see Fig. 3 in Trigo et al., 1999). In fact, in the present climatology only very few large cyclones (R >= 750 km) are detected. As the maximum radius is bounded to 850 km (see subsection 2.1), larger cyclone centres are probably a little misrepresented. Small cyclones (R < 250 km) are also poorly detected. It is probably due to the different methodology used to derive the cyclone radius, but also to the smoothing of MSLP fields (see subsection 2.1) performed in the present study. This low skill to detect small cyclones is even more evident when these results are compared against other cyclone catalogues, which were achieved by means of higher resolution datasets. In Picornell et al. (2001) Western Mediterranean cyclones were detected over a 0.5º x 0.5º latitude-longitude grid (~ 50 km) from HIRLAM-INM analyses and for a 4-year period (June 1995 to May 1999). Cyclones were featured as minima in non-smoothed MSLP field. However, to calculate the cyclone domain, the MSLP field was previously smoothed by means the Cressman filter, with an influence radius of 100 km. Results showed a mean cyclone radius of 236 km, that is, most of the detected cyclones were small-scale lows. In Campins et al., (2006) the same HIRLAM-INM analyses that in Picornell et al. (2001), were used, but for a longer period (8-years, from June 1995 to May 2003). Moreover, the MSLP field was previously smoothed with the Cressman filter and with an influence radius of 200 km. Therefore, although the horizontal resolution was initially the same as in Picornell et al., (2001), the smoothing implied in fact that a lower horizontal effective resolution was used. As a consequence, in Campins et al., (2006) the mean cyclone radius was 410 km. Hence, small-scale cyclones are still present, but the increase in the smoothing in spite of the high horizontal resolution of the original data results in a bias towards larger cyclones.

Concerning cyclone intensity, as shown in Figure 4b, most of the cyclone centres exhibit a GC around the mean value (4.0 GCU). The frequency of weak (i.e. GC < 2 GCU) and intense cyclones (i.e. GC >= 7 GCU) is small (8.0 and 6.3 % respectively). Weak cyclones are much more frequent (16.0 %) in Campins et al., (2006), but above all (53.0 %) in Picornell et al., (2001). However, the frequency of intense depressions is small and rather similar in both studies (4.5 % and 4.3 % respectively). As a result, moderate and intense cyclones seem to be correctly captured in the present ERA-40 climatology, but weak depressions seem to be clearly misrepresented.

In fact, the cyclone intensity is closely related to the cyclone size. For the present cyclone dataset the correlation coefficient between GC and R is 0.77. That means, weak cyclones are small and intense ones are large. A similar relationship between intensity and radius of Mediterranean cyclones is also present in Trigo et al. (1999). Therefore, the shortcoming to correctly detected weak cyclones is related to the low skill to detect small-scale cyclones, already discussed.

3.3 Life cycle

Once the tracking algorithm is applied, the identified minima are grouped as cyclones. The 81762 cyclone centres detected for the whole study period and along the whole study domain correspond to 34612 cyclones; that is a mean of 769 cyclones per year. The cyclone lifetime and track length are next examined. Other parameters as the maximum intensity and size, as well as the cyclogenesis regions and cyclone tracks will be analysed in the following sections.

The mean lifetime (t) of Mediterranean cyclones is 14.2 hours. This small value is mainly due to the fact that most of the cyclones (49.5 %) are detected only once, that is t= 6 hours (Figure 5a). The very short-lived cyclones are real systems, usually weak and small, which can be observed in daily analysis weather maps and influence the local weather. The portion of cyclones with duration equal or longer than 24 hours is 18.0 %. When very short-lived cyclones (i.e. t = 6 hours) are excluded, the mean lifetime increases to 22.2 hours. To calculate the track length (d) only cyclones lasting at least 12 hours are considered. Within this constrain, Mediterranean cyclones travel an average distance of 350 km. This relatively low value is partially due to the fact that a large frequency of cyclones (10.8 %) are non-moving, that is d= 0 km. However track length exhibits a large spread and an important number of cyclones moves large (in the scale of the basin) distances (Figure 5b).

These results are rather similar to those obtained by Trigo et al. (1999). In that paper, where cyclones were tracked by means of a different algorithm, 60 % of the cyclones lasted only 6 hours. When very short-lived cyclones were excluded, the mean lifetime was 28 hours. Life cycle parameters also agree with those obtained in Picornell et al., (2001), where a mean lifetime of 12 hours (all cyclones included) and a mean track length of 207 km (cyclones with t >= 12 hours) were obtained.

Nielsen and Dole (1992) distinguished between travelling and stationary cyclones for the population of cyclones that formed over North America and the adjacent Atlantic Ocean during the Genesis of Atlantic Lows Experiment (GALE). Travelling (stationary) cyclones were defined as those depressions whose cyclolysis positions, from their cyclogenesis ones, were greater or equal (lesser) than 400 km. When the same criteria is used for the Mediterranean, results show that more than two thirds (69.5 %) of the cyclones are stationary, and the remaining (30.5 %) are travelling ones. Another way to prove that most of the Mediterranean cyclones are stationary is by comparing the genesis and lysis distributions, which resemble to each other (not shown).

4. Seasonal distribution

Once the general features of Mediterranean cyclones have been stressed, the following sections describe the seasonal variations of those parameters. In this study, summer refers to the months of June, July and August; autumn to September, October and November; winter to December, January and February; and finally spring to March, April and May.

4.1 Spatial distribution

The spatial distribution of Mediterranean cyclones shows a strong seasonal signal (Figure 6). Summer and winter exhibit contrasting patterns, with spring and autumn as transitional seasons, keeping some features of both the warmest and coldest seasons. Cyclone centres locate at preferred regions depending on the season and only in the south-side of the Alps and, in a lesser extent, around Cyprus, cyclone centres are significantly present throughout the year.

In summer a prominent maximum in Cyprus stands out. The large number of cyclone centres makes the Cyprus cyclones a quasi permanent feature for this season. High frequency of cyclones is also found in the Sahara and, to a lesser extent, in the Iberian peninsula, the gulf of Cadis, the gulf of Genoa and the Algerian Sea. The presence of many cyclone centres over land during the warmest season indicates that the strong sensible heating plays an important role in the genesis and maintenance of such depressions.

During autumn the highest concentration of cyclone centres is located in the gulf of Genoa and the surrounding seas. Many cyclone centres are also detected over the Sahara, although not as many as during the warmest season. Finally the Algerian Sea and the gulf of Cadis in the Western basin, together with Cyprus and the Aegean Sea in the Eastern basin still keep a significant number of centres.

Cyclones locate mainly over the sea during the coldest season. The maximum over the gulf of Genoa again stands up, but other regions are also highlighted such as the Adriatic, the Tyrrhenian, the Ionian, the Aegean and the Black Seas and Cyprus. This pattern is likely related to a thermal effect of the relative warm sea surrounded by cold land. However other effects as lee cyclogenesis and baroclinic instability are also related to winter cyclogenesis in the Mediterranean (Buzzi and Tibaldi, 1978; Speranza et al. 1985). Trigo et al. (2002) showed that cyclogenesis over three northern Mediterranean regions (gulf of Genoa, Aegean Sea and Black Sea) in winter may occur as the result of the same synoptic system which crosses the northern Mediterranean border.

The cyclone distribution for spring shares characteristics with both extreme seasons. On one hand the presence of cyclone centres over the sea is still notable (i.e. the gulf of Genoa and surrounding waters and the Aegean Sea). On the other hand, many other cyclones form over land in certain areas such as over the Sahara and, to a lesser extent, over Turkey. Thermal heating over land likely contributes to the genesis of such depressions, but other mechanisms as the southward excursion of upper-level troughs can trigger deep cyclones in the lee of the Atlas (Egger et al., 1995; Thorncroft and Flocas, 1997).

4.2 Thickness, size and intensity

The cyclone thickness also exhibits contrasting differences between seasons (Figure 3). Thus, in summer most depressions are shallow (62.0 %) and only a few (21.4 %) reach the 300 hPa level. In contrast, low pressure centres in winter are mainly deep (55.1 %), but the frequency of shallow centres is still noticeable (26.2 %). During transitional seasons, frequencies of shallow and deep centres are similar.

Important seasonal differences in cyclone size and intensity are also found (Table 1). In summer, cyclone centres are significantly smaller than in winter, with mean values of R of 475 and 565 km respectively. Mean values of GC vary significantly between the warmest and coldest seasons: 3.3 and 4.9 GCU respectively. Additionally, very few intense summer cyclones are detected (1.5 %), but the frequency increases notably in winter (14.4 %). Mean values of both R and GC in autumn and spring rank within the summer and winter extremes. Similar seasonal variations were also described in Picornell et al., (2001) and Campins et al. (2006).

Nevertheless, the misrepresentation of small-scale and weak cyclones remains a concern in all the seasons, especially in summer.

4.3 Life cycle

Further differences between cyclones detected in summer and in winter emerge regarding their life cycle (Table 1). Most of the summer low pressure centres are very short-lived: more than 50 % are detected only once (that is, t = 6 hours) and only 11.8 % last a day or more. Despite the portion of very short-lived winter cyclones is high (42.6 %), the frequency of depressions lasting a day or more increases significantly (25.1 %). This fact is reflected by the mean lifetime of all cyclones detected each season: 12.2 hours in summer and 16.6 hours in winter (19.4 and 24.5 hours for cyclones with t >= 12 hours). Moreover, in summer most cyclones are stationary or move a little from the genesis location. On the contrary, although the frequency of winter stationary cyclones is still high, cyclones which move far away from their genesis region is noticeable. When only cyclones lasting more than 6 hours are considered, mean track length in summer is d= 230 km and d= 451 km in winter. This contrasting behaviour is due not only to the different lifetime (for longer t larger d can be expected), but also to the different frequency of stationary lows (for larger frequency of stationary cyclones lower d). As mentioned before, cyclone characteristics in spring and autumn lay between the extreme seasons.

5 Cyclogenetical regions

After a first sketch of the main features of Mediterranean cyclones, where a strong spatial and seasonal variability is found, a deeper analysis of cyclones generated in some specific regions is described here. Figure 7 depicts the mean frequency distribution of the location of the first detection (cyclogenesis) for such cyclones. The gulf of Genoa and Cyprus comprise two outstanding maxima in the Mediterranean, but other secondary cyclogenetic areas such as the two Saharan maxima, the Iberian peninsula and the Aegean and Algerian Seas can be also underlined. The main features of the cyclones generated within these regions are studied in detail, especially those related to their life cycle. For this reason, only cyclones with a lifetime equal or longer than 12 hours will be considered. In addition, the monthly variation of the cyclones characteristics is also analysed. However, only the annual and the four mid-season monthly (January, April, July and October) averages are presented in Table 2.

As many studies reveal, the most important cyclogenetic mechanisms in the Mediterranean are orography, baroclinity, sensible heat fluxes, latent heat release and upper-level precursor troughs (Petterssen, 1956; HMSO 1962; Radinovic 1987; Trigo et al., 2002; Lionello et al., 2006). Different mechanisms can act at the same time, but usually their relative importance change over the cyclone lifetime. For each region, some of these mechanisms will be next briefly discussed. Note that an extensive study of cyclogenetic mechanisms in the Mediterranean is beyond the scope of this paper and could be the subject of another paper.

5.1 Gulf of Genoa

The gulf of Genoa region includes the south-side of the Alpine range. This region exhibits the highest frequency of cyclogenesis in the Mediterranean, with a mean number of 37.4 events per year. Cyclogenesis occur throughout the year, but March and April stand out. The Genoa cyclones are mainly deep depressions, mostly in the cold season (Table 2) and at the most intense stage (Table 3). However the portion of shallow or middle-deep centres is not negligible, mainly in the early stages of development and in summer. Mean cyclone lifetime is around 25 hours, longer in the cold months and shorter in the warm ones. The mean track length also presents important seasonal differences. Depressions travel longer distances in the cold months than in the warm ones. Consequently, stationary cyclones prevail in summer, while in winter the mobile ones dominate. These mobile cyclones can move far away: southeastwards along the Tyrrhenian Sea and east-southeastwards along the Adriatic Sea (Figure 8). Most Genoa cyclones reach moderate intensity, but intense ones are also detected, especially in winter. During summer, cyclones are weak or moderate depressions, and rarely intense lows develop. These two well differentiated seasons are connected by two transitional periods, which extend longer for autumn (September and October) than for spring (May).

The notable differences between the cold and the warm season Genoa depressions suggest different predominant cyclogenetic mechanisms for both seasons. In summer cyclones are stationary and shallow depressions, most of them weak or moderate. A great part of these cyclones could be generated by thermal and orographic effects. On the contrary in winter, cyclones are well-developed depressions, covering the whole troposphere, sometimes very intense and usually they move far away from the origin. This last pattern clearly fits with the well-known Genoa cyclogenesis described, among others, by Buzzi and Tibaldi (1978) and McGinley, (1982).

5.2 Cyprus

This region shows a large frequency of cyclogenesis, with a mean of 36.8 events per year, and together with the gulf of Genoa constitute the two outstanding cyclogenetic Mediterranean. As previously mentioned, cyclones in Cyprus develop mainly in summer, from June to August, even though Cyprus cyclone can be found anytime throughout the year. Similarly to the Genoa cyclones, Cyprus depressions show well-defined differences between cold and warm seasons (Table 2). In summer most Cyprus lows are shallow and weak to moderate depressions. On the contrary, the portion of deep cyclones increases in winter, especially at the most intense stage. Cold season cyclones last for longer times and reach significantly higher intensities than the warm season ones. In spite of an increase of the mean track length for cold season cyclones compared with summer ones, most of the Cyprus lows are stationary, and only few of them move far away from their genesis location. However, due to the closeness of Cyprus region to the boundary of the detection region, probably the small number of mobile cyclones is fairly misrepresented. Nevertheless, mobile cyclones evolve towards the Near East or inland Turkey (Figure 8).

The Cyprus low during summer is associated with the Persian trough, an extension of the Indian monsoon (Bitan and Saaroni, 1992). This surface trough is associated with a strong upper-level Subtropical High, preventing ascending motion. Similar conclusions can be achieved when the mean distribution of relative vorticity is looked for (Flocas et al., 2001). In summer, cyclonic vorticity is relatively high at 1000 hPa in the Eastern Mediterranean, providing evidence of the influence of the Persian trough, but weaker values are detected at 850 hPa. On the contrary, anticyclonic vorticity prevails at 500 hPa.

Winter cyclones are less frequent over Cyprus, but a few develop into very intense depressions. These lows initiate as baroclinic depressions, but the warm sea and the latent heat release have also been described to significantly contribute to the development of Cyprus cyclones (Nicolaides et al., 2006). For example, the intense Cyprus low which produced torrential rains in Israel in December 2001 (Krichak et al., 2007) can be mentioned.

5.3 Sahara

Two distinct cyclogenetic regions emerge over the Sahara: one located close to highest slopes of the Atlas range, south of Morocco, and the other one in the high plain of central Sahara. In spite of the similarities between cyclones originated in both regions, differences are so relevant to study them separately. Hereafter these two regions will be called as western and eastern Sahara respectively. Saharan cyclones are sometimes referred to as Sharav or north-west African depressions.

Western Sahara region exhibits a rather small number of events (16.8 per year). It is partially due to the fact that most cyclones are confined within a short period of time, from March to June, and a relative maximum in October. At the genesis stage, shallow cyclones predominate, but afterwards some depressions increase their vertical thickness (Table 3). Sahara lows are large depressions, with moderate or strong intensity (Table 2). Stationary cyclones are the most frequent ones, particularly in May and June, though mobile depressions can also be found, mostly in March and April. Travelling cyclones can move far away from the genesis region, northeastwards, inland or even to the Ionian Sea (Figure 9). Their well-defined diurnal cycle (not shown) suggest the important role of the thermal heating in the genesis and maintenance of these depressions. Besides, the proximity of this maximum to the high slopes of the Atlas mountains could reveal the generation of lee cyclones.

Eastern Sahara cyclones are one of the most prominent maximum for the Mediterranean region, with a mean of 29.4 cyclones per year. But unlike their gulf of Genoa and Cyprus counterparts, these lows only develop during the warm season, from March to October, and rarely occur in the cold months. For a better analysis, this period can be divided into two: spring (March to May) and summer through early autumn (June to October). In spring most depressions are shallow, but a noticeable portion of them develop throughout the troposphere, especially at the most intense stage (Table 3). Spring depressions last for a long time, and both stationary and mobile lows could be found. As for the cyclones generated in the western Sahara, the preferred track is northeastwards, to the Ionian Sea, and it could be considered as a prolongation of that cyclone track (Figure 9). These lows could achieve moderate or even strong intensity, being relatively small (Table 2). On the contrary, in summer and early autumn, shallow, stationary and weak to moderate lows predominate (Table 2). The proximity of this maximum to the southernmost border of the study domain could affect the correct description of these cyclones, mainly in the warmest months, where a permanent heat low at lower latitudes is observed (Barry and Chorley, 1987).

In summer the thermal forcing and, in a lesser extent, the orographic forcing seem to prevail as cyclogenetic mechanisms of the Saharan lows. However, in spring, a wider range of mechanisms seem to be involved in the generation and maintenance of such depressions. In spring, the Mediterranean frontal zone is located well south into the western Sahara (HMSO, 1962). Moreover, the equatorward extension of the upper-level troughs at the end of the Atlantic stormtrack is not an unusual feature in such season. Both factors, low-level baroclinity and upper-level vorticity advection, were pointed out as the most important factors in a detailed description of the synoptic conditions associated with the genesis of the Saharan depressions (Prezerakos, 1985, 1990; Prezerakos et al., 1990). In Thorncroft and Flocas (1997), a case of Saharan cyclogenesis was studied by means of the interaction of an upper-level potential vorticity anomaly with low-level baroclinity. The role of the orography in the generation of the Saharan depressions was studied from a numerical point of view in Egger et al., (1995) and for an intense event in Horvath et al., (2006).

5.4 Iberian peninsula

The Iberian peninsula is one of the predominant cyclogenetic regions in summer (Figure 6a). Most of the cyclones generated in the Iberian peninsula develop in the warm season (from May to August), with an outstanding maximum in July. The major part of these low pressure centres are weak, shallow, short-lived (Table 2) and stationary depressions (Figure 9). These lows exhibit a pronounced diurnal cycle, as most of them originate at 12 or 18 UTC, dissipate at 00 UTC and reach their maximum intensity at 18 UTC (not shown). All the aforementioned features point to the thermal heating as the main cyclogenetic mechanism. The thermal low of the Iberian peninsula is a well-described feature of such region in summer (Alonso et al., 1994; Portela and Castro, 1996; Hoinka and Castro, 2003).

Despite the small portion of cyclones detected along the cold season over the Iberian peninsula, and the large spread of their main features, the contrasting characteristics with their warm season counterparts make a brief comment mandatory. Cold season cyclones are deep, long-lived and mobile depressions. These lows can move far away from their origin and could develop into intense cyclones. The proximity of this region to the western border of the study domain suggests that these lows could be related with intense Atlantic depressions, which enter into the Mediterranean, and move towards the east.

5.5 Aegean Sea

Unlike other regions, cyclones that originate in the Aegean Sea predominate along the cold season, from November to May. Most of these depressions are deep (Table 2), although at the early stages of development the portion of shallow lows is noticeable (Table 3). These cyclones are large and moderate or even intense centres (Table 2). Stationary cyclones prevail, although a high portion of these lows moves far away. Two main tracks are found (Figure 10): southward or southeastward to Cyprus and northeastward to the Back Sea. Most of these features are more pronounced in the coldest months, that is, in December and January.

The synoptic situations that favour the cyclogenesis over the Aegean Sea were investigated in Flocas and Karakostas (1996). Based on circulation patterns at 500 hPa, six categories were described. In their study, cyclogenesis over the Aegean Sea appeared to occur predominantly throughout the cold months (from October to May), and to be a rather short-lived and weak phenomena. The thermal contrast between cold air masses that cross the Aegean Sea and the warm sea surface during winter was also pointed out as factors that contribute to cyclogenesis (HMSO, 1962; Trigo et al., 2002). An intense case of cyclogenesis over the Aegean Sea was investigated by means of potential vorticity diagnostics in Flocas (2000), which showed that in the early stages of the cyclogenesis, a large-scale development, associated with an upper-level potential vorticity anomaly, had a preponderant role. However, at later stages a smaller-scale development was generated, which was associated with a low-level potential vorticity anomaly and a surface warm anomaly.

5.6 Algerian Sea

This region is a rather active region, with a mean of 20.2 events per year. These cyclones are found along most part of the year, from March to December, with special incidence during the warm season. As observed in other regions, warm and cold season cyclones differ in mean characteristics (Table 2). In summer, cyclones generated in the Algerian Sea are weak, shallow, stationary and short-lived. In spring and late autumn, though the presence of weak, shallow and stationary lows is still noticeable, the frequency of intense, deep and mobile cyclones increases. The mean lifetime also increases and cyclones could move far away from their origin (for instance in November t= 27.2 hours and d= 460 km), northeastward along the Western Mediterranean (Figure 10). This cyclone track is very significant, especially in autumn, since in some cases these cyclones are related to heavy rain events along the coastal Spanish regions (Jansà et al., 2001b; Romero et al., 2000). However, in this region, cyclones related to heavy rain events are usually small-scale low pressure centres or even pressure troughs, sometimes secondary lows of a larger north African depression (Jansà et al., 2001b; Romero et al., 1999). Therefore, due to the horizontal resolution, such lows are probably misrepresented in the present climatology. It is worth mentioning that very intense and deep lows can also develop in this region in late autumn or early winter. For example, one of the most intense and disastrous cyclone occurred in the Mediterranean during the ERA-40 time span developed in November 2001 in this region (Hamadache et al., 2003; Genovés et al., 2006).

6 Comparison with other cyclone climatologies

The results of the present climatology are compared with other similar cyclone climatologies. Comparisons will be mostly made based on the frequency of cyclone centres, the genesis and lysis regions or the cyclone tracks. The wide range of study periods, data resolutions and methodologies used to compile cyclone statistics make comparisons only valid in a qualitative sense. Our results will be first compared against cyclone climatologies performed for the Northern Hemisphere. Secondly, comparisons with cyclone climatologies which cover the entire Mediterranean will allow a more accurate description of the similarities and differences between different climatologies. Finally, cyclone datasets focused only in the Western Mediterranean basin will complete the comparisons.

6.1 Northern Hemisphere climatologies

The cyclone climatology of Petterssen (1956) for the Northern Hemisphere is widely referenced as one of the first works which highlighted the importance of the Mediterranean as a cyclogenetic region in winter. Petterssen, based on the Historical Weather Map from 1899 to 1939, calculated the frequency of occurrence of cyclogenesis and cyclone centres in winter and in summer. Cyclones were detected when and where a closed isobar was found on the sea level pressure charts (drawn at intervals of 5 hPa), available once a day. Results were presented in 100,000 km^2. In winter, the gulf of Genoa and in a lesser extent Cyprus stood up as regions with a high frequency of occurrence of cyclone centres and cyclogenesis. However, no other secondary regions, as the Aegean Sea, were detected in the climatology of Petterssen. In summer, only the relative maximum in the Iberian peninsula and also in the western North Africa (but further south) are in coincidence; but the outstanding maximum in Cyprus, as well as in the gulf of Genoa, find out in the present study are not captured in the Petterssen's climatology. The coarse resolution in space and time could explain most of these discrepancies.

Hoskins and Hodges (2002, hereafter HH02) used the ERA-15 reanalysis and ECMWF operational analysis for the period 1979-1993 to analyse cyclone density, cyclogenesis and cyclolysis regions and track density for the Northern Hemisphere in winter. Their objective was to identify synoptic-scale features, and therefore the primary data was truncated to a T42 spectral resolution. Cyclones at low levels were obtained as minima in MSLP or maxima in the vorticity at 850 hPa fields. Winter cyclones move along the Mediterranean, from West to East, along the so-called Mediterranean storm-track (Fig. 14 in HH02). Our results agree with those of HH02 in the sense that the synoptic-scale cyclones are correctly represented, but the more detailed description depicted in the present study can not be compared against those of HH02, since meso-scale features were filtered in their analysis.

In a recent study, Wernli and Schwierz (2006, hereafter WS06) presented a climatology of surface cyclones from the ERA-40 dataset. In that paper, a novel method was used to generate a climatology of extratropical cyclones from MSLP fields at both the Northern and Southern Hemispheres. Cyclones were also tracked along their life cycle, and hence, genesis and lysis regions were also derived. The comparison of such climatology against our study is very interesting as the primary data is the same 6 hourly ERA-40 reanalyses, although interpolated on 1º x 1º latitude-longitude grid. In the Mediterranean and in winter cyclone densities agree in a general sense. Two maxima were found in WS06, the largest over Italy, and a secondary one close to Cyprus. In summer, only a large and spread maximum over the Sahara is in coincidence with our result, although rather to the south. Concerning cyclogenetic and cyclolytic regions, in the Mediterranean, results in WS06 roughly agree with ours. However, it must be taken into account that in such cases only cyclones with a lifetime of at least 1 day were selected. In winter, the gulf of Genoa was highlighted as a region of genesis, and a great portion of such cyclones died in the eastern Mediterranean. In summer, the Iberian peninsula as well as the Sahara arose as regions of both genesis and lysis, and therefore stationary features. That result agrees with ours, where heat lows develop over the continents. In summary, results in WS06 and our study are very similar. Differences can be attributed to the different methodology of detection and tracking algorithm, and especially to the fact that WS06 excluded short-lived cyclones from their analysis.

6.2 Climatologies for the Mediterranean

One of the first objective climatologies of cyclones for the entire Mediterranean was carried out by Alpert et al. (1990). In that study, initialised ECMWF analyses for a 5-year period (1983-1987) were used.

Cyclones were detected as local minima on the 1000 hPa field. Despite the low spatial and temporal resolutions (2.5º x 2.5º latitude-longitude and 12 hours), and the short study period (5 years), it is interesting to compare some of such results with those achieved in the present paper. As for most climatologies in Alpert et al. (1990), the gulf of Genoa and Cyprus regions stand up. Cyclones in both regions were detected along the whole year, with a maximum in summer. In winter the number of cyclones in both regions was similar, but in summer Cyprus centres clearly dominated. In our study, Cyprus cyclones are also more frequent than Genoa ones in summer, but in winter the opposite is found. In spite of the coarse resolution of the data used in Alpert et al. (1990), other secondary regions with a high frequency of cyclone centres or cyclogenesis were found. This is the case of Aegean Sea in winter, the Algerian Sea in summer or the eastern Sahara in spring and summer. These regions are also found in the present climatology, and accordingly, the seasonal cyclone distribution for both climatologies is rather similar (the Iberian peninsula and the western Sahara were not included in their study domain). The presence of secondary regions in the study of Alpert et al., (1990), not present in other climatologies, is probably due to the fact that no criterion was applied to selected cyclone centres (except that neighbouring centres were not allowed). When a pressure gradient of 0.5 hPa/500 km was required to select a cyclone, the number of lows was considerable reduced, especially in summer and at night.

The objective climatology of surface cyclones in the Mediterranean performed by Maheras et al. (2001, hereafter Ma01) constitutes another complete study on the spatial and temporal variations of such features. Cyclones were detected as low pressure centres on MSLP fields of the NCEP-NCAR reanalyses. Data was available four times a day (at 00, 06, 12 and 18 UTC), over a 40-year period (1958-1997) and on a grid of 2.5º x 2.5º latitude-longitude. Despite the different horizontal resolution, Ma01 climatology and the present one compare rather well in a qualitative sense. That is, the spatial distribution for each season outlines the same regions of high frequency of cyclone centres in both studies. However, differences lie in total number of cyclone centres, much lower in Ma01than in the present study, and also in the relative number of cyclone centres in some regions. For example, in Ma01 the number of cyclones in Cyprus and in the gulf of Genoa in summer was rather similar, but in our study the Cyprus maximum is clearly larger than the gulf of Genoa one. As it was also found in Alpert et al. (1990), in Ma01 other secondary regions with an appreciable frequency of cyclones were also detected. These regions are, in principle, favourable to sub-synoptic cyclones, but they were detected even with a coarser resolution. This unexpected result is probably due to the criterion used to detect cyclones. In Ma01, cyclones were derived as local minimum and only neighbouring centres were removed (no pressure gradient was required). This fact, despite the low horizontal resolution, allowed detecting some sub-synoptic cyclones, which were present in the low resolution data as weak and larger depressions. However, neither the number of sub-synoptic lows nor the cyclone features (such as intensity and size) were properly gathered.

The most similar climatology of Mediterranean cyclones with the present study is the one performed by Trigo et al. (1999). In their study, the ECMWF initialised reanalyses for the period 1979-1996 were used. The spatial resolution derive from T106 spectral representation, interpolated on the same regular grid as the one used in this study for ERA-40, that is 1.125º x 1.125º latitude-longitude. Also the same 6-h temporal resolution was used. The region study in Trigo et al. (1999) also includes the whole Mediterranean basin, although larger than ours (in particular to the south and to the east). The spatial distribution of cyclone centres for different months showed the same regions with higher frequency of cyclone centres than in our study. Moreover, mean characteristics of cyclones (such as size and lifetime) in different regions also agree with our findings (Section 3). In that study, the ability to detect sub-synoptic cyclones was emphasized, and it was shown that Mediterranean lows were generally associated with smaller spatial scales and shorter lifetimes than Atlantic synoptic systems. In Trigo et al. (1999), cyclone trajectories were derived from a k-means cluster analysis of the cyclone locations. That analysis depicted the main tracks of mobile cyclones and also underlined the role of stationary cyclones in some regions and certain seasons. The results of Trigo et al. (1999) agree with our findings, likely due to the similar spatial resolution, despite the different detecting and tracking algorithms.

6.3 Climatologies for the Western Mediterranean

So far, only cyclone climatologies performed by means of lower or even similar horizontal resolution have been qualitatively compared with the current one. These comparisons indicate that in general our results agree with most of previous climatologies, and therefore, the principal features of synoptic and sub-synoptic cyclones in the Mediterranean are well captured in the present climatology. But, in the present study the use of reanalysis data to objectively detect and track cyclones, as well as the inclusion of the cyclone vertical thickness, allowed to achieve a more accurate, homogeneous and precise picture of such depressions. However, as already discussed, the Mediterranean is a region prone to develop meso-scale cyclones, and therefore, it is necessary to compare the current climatology with others performed with higher horizontal resolutions. Recently two objective cyclone catalogues for the Western Mediterranean were built from high-resolution numerical analysis of MSLP by Picornell et al. (2001, hereafter Pi01) and Campins et al. (2006, hereafter Ca06). As previously mentioned, both studies were performed with the same methodology than the used for the present work. Both studies (Pi01 and Ca06) were based on the same analyses: the high-resolution 0.5º x 0.5º latitude-longitude operational analyses of the HIRLAM-INM, but for different time periods. And besides, cyclone detection was carried out from different MSLP fields: the original ones in Pi01 and smoothed ones in Ca06. As a consequence, the resolution in Pi01 is higher than in Ca06, and the latter is higher than the current work.

When comparing the spatial and seasonal distribution of western Mediterranean cyclones derived from Ca06 with the current results, rather similar features are observed. However, in Ca06 the total number of cyclone centres was clearly higher than those detected in the current climatology and the lows were smaller and shallower. These differences are even clearer when the comparison is made against cyclone centres detected in Pi01. In this case, all regions with high frequency of cyclone centres obtained with ERA-40 reanalyses were also present in Pi01. However, new regions such as the south-side of the Pyrenees appeared. Furthermore, as mentioned in section 3.2, cyclones were smaller and weaker than those detected in the current climatology. As the methodology used to compile cyclones is the same in all three catalogues (Pi01, Ca06 and the present one), the differences must be mostly attributed to the different horizontal resolution and to the smoothing of objective analyses. As expected, the higher the resolution the higher the number of small-scale depressions, and on the contrary, the stronger the smoothing, the lower the number of lows.

As a consequence, the current climatology exhibits a clear shortcoming in detecting meso-scale cyclones. This result agrees with those of Condron et al. (2006), where polar mesocyclones detected by means of the ERA-40 reanalysis were compared with mesocyclones detected in satellite imagery over the northeast Atlantic. In their study, although the results showed a similar trend in monthly cyclone number and a similar spatial distribution, ERA-40 appeared unable to resolve a substantial proportion of polar mesocyclones (i.e. with a radius less than 250 km).

7 Conclusions and further remarks

In the present study objective detection and tracking algorithms have been applied on the ERA-40 reanalysis to derive surface cyclone climatology for the entire Mediterranean basin. A similar methodology was already applied on an operational dataset for a shorter period and for the Western Mediterranean (Picornell et al., 2001; Campins et al., 2006), but the long period of time of the ERA-40 reanalysis (45 years) allows to achieve a precise and homogeneous picture of the cyclone climatology for the entire Mediterranean. Moreover, the detection algorithm has been also applied to different vertical levels, which allowed calculating the cyclone vertical thickness.

A cyclone centre has been detected as a minimum in the MSLP field, which overcomes a pressure gradient threshold. Each low pressure centre has been characterised by means of a set of variables, such as date, latitude-longitude coordinates, mean radius and intensity. Besides, for each cyclone centre we have calculated its vertical thickness, which helps discriminating between shallow, middle-deep and deep cyclones. Finally, cyclone centres have been tracked along their life cycles. Thus, the regions of first appearance (cyclogenesis) and last appearance (cyclolysis), and the most preferred cyclone tracks were derived. Other parameters as lifetime, and track length have been also stored.

Results show that most of the Mediterranean cyclones are weak, shallow, stationary and short-lived depressions, but some of them evolve into intense, deep, long-lived and mobile ones. However, a significant seasonal variability must be pointed out. Therefore, in summer the frequency of short-lived, weak and shallow cyclones is even more marked. On the contrary, in winter, and in a lesser extent in spring, the number of long-lived, mobile, intense and deep cyclones notably increases. Thus, summer and winter are two contrasting seasons, whereas spring and autumn can be considered as transitional seasons between both extremes.

Mediterranean cyclones locate at preferred regions, being the gulf of Genoa in the Western basin and

Cyprus in the Eastern basin the two outstanding regions. Other important cyclogenetic regions are located in western North Africa (with two distinct maxima), the Iberian peninsula, the Aegean Sea and the Algerian Sea. The detailed study of the cyclones which originate in each of these regions allowed to identify the seasonal variability as well as the main cyclone characteristics of their life cycle and tracks. Furthermore, the main mechanisms acting on the genesis and evolution of Mediterranean cyclones have been sketched. The orography and the thermal heating seem to be the principal factors, but others such as the upper-level troughs and the low-level baroclinity have been also underlined.

A second part of the present study was devoted to compare the obtained results against other available cyclone climatologies. In spite of the variety of study periods, study regions, datasets and methodologies, it can be concluded that in a general sense the results of the present climatology agree with those derived in many other synoptic or sub-synoptic cyclone climatologies. However, the comparison against other higher resolution cyclone catalogues shows that the climatology based on ERA-40 data is not able to correctly detect most of the meso-scale depressions. As meso-scale features play a main role in the Mediterranean, this shortcoming constitutes a serious drawback and it must be taken into account in further applications.

Nevertheless, the methodology and the results of the cyclone database used to derive the present cyclone climatology can be utilized for several future applications. Some of them are outlined here:

i) The cyclone detection and tracking algorithms can be applied to general circulation models (GCMs) datasets. The consistency of the different reanalysis (in space and in time) in the Northern Hemisphere, and in particular the skill of ERA-40 over the Mediterranean make the present cyclone climatology adequate to validate the ability to GCMs to assess synoptic and sub-synoptic cyclone activity in such region.

ii) The interannual variability of Mediterranean cyclones can be investigated, as well as its links to the principal modes of atmospheric variability.

iii) To improve our knowledge about the relationships between cyclones and other meteorological phenomena is another possible application of the cyclone database. A better knowledge of the links between Mediterranean cyclones and precipitation is a major task to properly understand the current and the future climates.

iv) Special categories of Mediterranean cyclones, like intense depressions, thermal lows or Saharan cyclones can be studied in detail. That means, for instance, their seasonal and interannual variability, genesis and lysis regions and main tracks.

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Tables

	Year	Winter	Spring	Summer	Autumn
GC	4.0	4.9	4.1	3.3	3.9
R	518	565	521	475	519
T	14.2	16.6	14.5	12.2	14.3
t*	22.2	24.5	22.6	19.4	23.1
d*	350	451	387	230	354
t = 6 h	49.5	42.6	48.7	54.1	50.8
t >= 12 h	50.5	57.4	51.3	45.9	49.2
t >= 24 h	18.0	25.1	19.1	11.8	18.5
t >= 48 h	3.9	5.8	4.1	2.1	4.1
Stationary*	69.5	57.6	66.1	83.4	68.1
Travelling*	30.5	42.4	33.9	16.6	31.9

Table 1. Mean values of geostrophic circulation (GC, in GCU), mean radius (R, in km), lifetime (t, in hours), track length (d, in km), relative frequency (%) of different cyclone lifetimes and relative frequency (%) of stationary and travelling cyclones for all cyclones and grouped in seasons. * Only cyclones with lifetime equal or greater than 12 hours are considered.

Region		Year	January	April	July	October
G. Genoa	N	37.4	3.0	4.4	2.9	2.5

Region		Year	January	April	July	October
	t	25.2	26.4	26.5	17.9	24.7
	d	410	500	386	242	392
	GC	4.8	5.6	4.7	3.3	4.8
	R	514	568	508	448	527
	Shallow	27	27	27	38	25
	Deep	55	55	58	37	57
Cyprus	N	36.8	2.4	1.4	9.2	1.3
	t	19.2	22.1	21.0	18.8	18.3
	d	209	299	320	162	190
	GC	4.0	5.4	4.5	3.7	4.7
	R	497	564	521	470	518
	Shallow	50	30	27	65	39
	Deep	33	52	58	18	51
W. Sahara	N	16.8	-	3.4	-	1.2
	t	23.4	-	28.1	-	22.0
	d	353	-	539	-	315
	GC	6.1	-	6.3	-	5.0
	R	581	-	582	-	555
	Shallow	40	-	33	-	39
	Deep	29	-	38	-	51
E. Sahara	N	29.3	-	2.9	3.3	2.0
	t	26.4	-	25.3	24.5	27.1
	d	399	-	544	23.5	383
	GC	4.8	-	5.4	4.4	4.1
	R	538	-	556	526	520
	Shallow	61	-	47	75	52
	Deep	18	-	25	3	26

Table 2. For different cyclogenetic regions: mean values of the number of cyclones (N), lifetime (t, in hours), track length (d, in km), maximum geostrophic circulation (GC, in GCU), mean radius at the maximum intensity stage (R, in km) and relative frequency (in %) of shallow and deep cyclone centres for the whole year and for the mid-season months.

Iberian p.	N	16.0	-	-	4.3	-
	T	18.0	-	-	16.5	-
	D	217	-	-	187	-
	GC	3.3	-	-	3.1	-
	R	489	-	-	470	-
	Shallow	59	-	-	70	-
	Deep	27	-	-	15	-
Aegean Sea	N	17.0	2.5	1.4	-	-
	T	23.4	27.2	19.4	-	-
	D	407	516	294	-	-
	GC	5.0	6.0	4.3	-	-
	R	573	600	553	-	-
	Shallow	27	20	27	-	-
	Deep	52	57	58	-	-
Algerian Sea	N	20.2	-	1.4	3.5	1.4
	T	19.2	-	20.1	16.5	19.7
	D	292	-	308	233	317
	GC	3.4	-	3.7	2.8	3.5
	R	477	-	490	444	479
	Shallow	52	-	39	77	45
	Deep	33	-	46	11	38

Table 2 (Cont.)

Region	Genesis		Maximum intensity	
	Shallow	Deep	Shallow	Deep
G. Genoa	39	36	30	53
Cyprus	58	25	55	29
W. Sahara	53	20	43	29
E. Sahara	76	9	68	14
Iberian p.	69	17	65	21
Aegean Sea	37	38	29	52
Algerian Sea	69	17	59	26

Table 3. For different cyclogenetic regions: mean annual relative frequency (in %) of shallow, and deep cyclone centres at the genesis and maximum intensity stages.

Figure captions

Figure 1: Mediterranean region, with the geographical names referred to in the text and the orography in the ERA-40 reanalysis (shaded each 250 m).

Figure 2: Mean number of cyclone centres in 2.25º x 2.25º latitude/longitude boxes. Contour intervals: 5, 10, 20, 40 and 60 centres per year.

Figure 3: Relative frequency (%) of cyclone centre thickness for the whole year and for each season.

Figure 4: Histograms of (a) mean radius (R, in km) and of (b) geostrophic circulation (GC, in GCU) of all the cyclone centres.

Figure 5: (a) Histogram of lifetime (t, in hours) of all the cyclones. (b) Histogram of track length (d, in km) of all the cyclones with a lifetime of at least 12 hours.

Figure 6: Seasonal mean number of cyclone centres in 2.25º x 2.25º latitude/longitude boxes, for (a) summer, (b) autumn, (c) winter and (d) spring. Contour intervals: 2.5, 5, 10, 20 and 40 centres per season.

Figure 7: Mean number of cyclogenesis events in 2.25º x 2.25º latitude/longitude boxes. Contour intervals: 1, 2.5, 5, 10 and 20 cyclones per year. The selected regions are marked with boxes.

Figure 8: Track density for cyclones originated in the gulf of Genoa and in Cyprus. Events counted in 2.25º x 2.25º latitude/longitude boxes. Contour intervals: 0.25, 0.5, 1, 2.5, 5, 10 and 20 cyclones per year.

Figure 9: As Figure 8 for cyclones originated in western and eastern Sahara and in the Iberian peninsula.

Figure 10: As Figure 8 for cyclones originated in the Algerian and in the Aegean Seas.

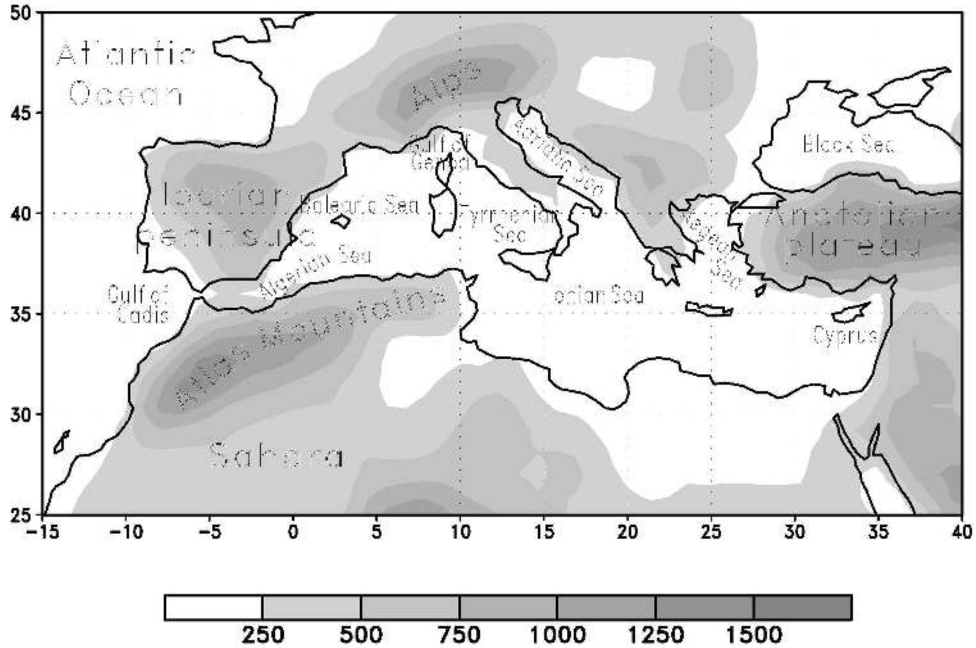

Figure 1: Mediterranean region, with the geographical names referred to in the text and the orography in the ERA-40 reanalysis (shaded each 250 m).
163x110mm (600 x 600 DPI)

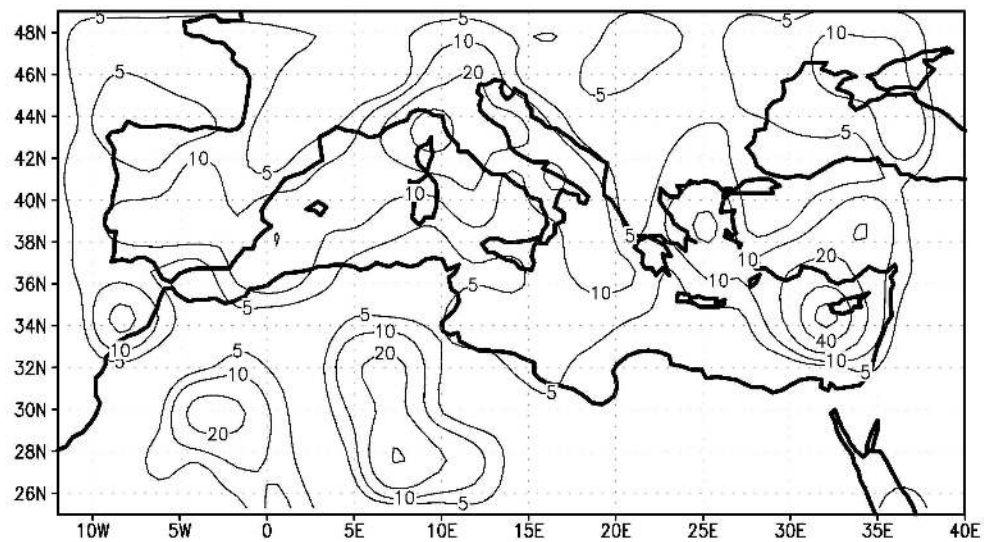

Figure 2: Mean number of cyclone centres in 2.25şx2.25ş latitude/longitude boxes. Contour intervals: 5, 10, 20, 40 and 60 centres per year.
191x127mm (600 x 600 DPI)

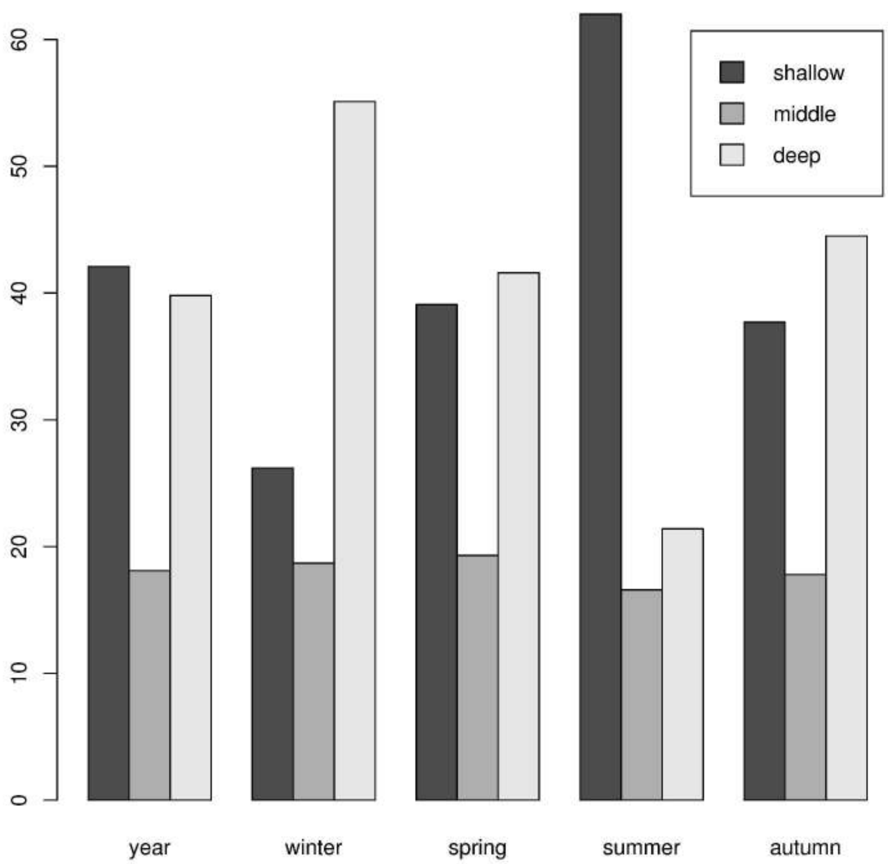

Figure 3: Relative frequency (%) of cyclone centre thickness for the whole year and for each season.
197x203mm (600 x 600 DPI)

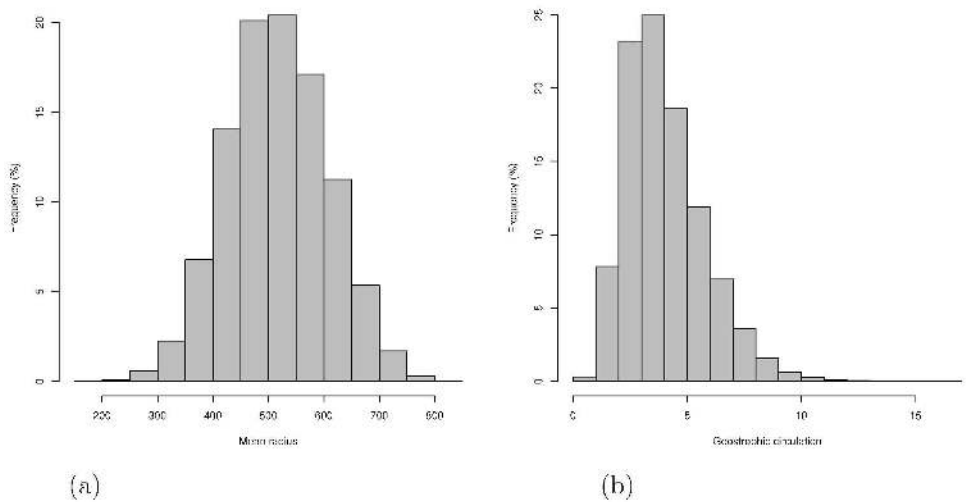

Figure 4: Histograms of (a) mean radius (R, in km) and of (b) geostrophic circulation (GC, in GCU) of all the cyclone centres.
160x89mm (600 x 600 DPI)

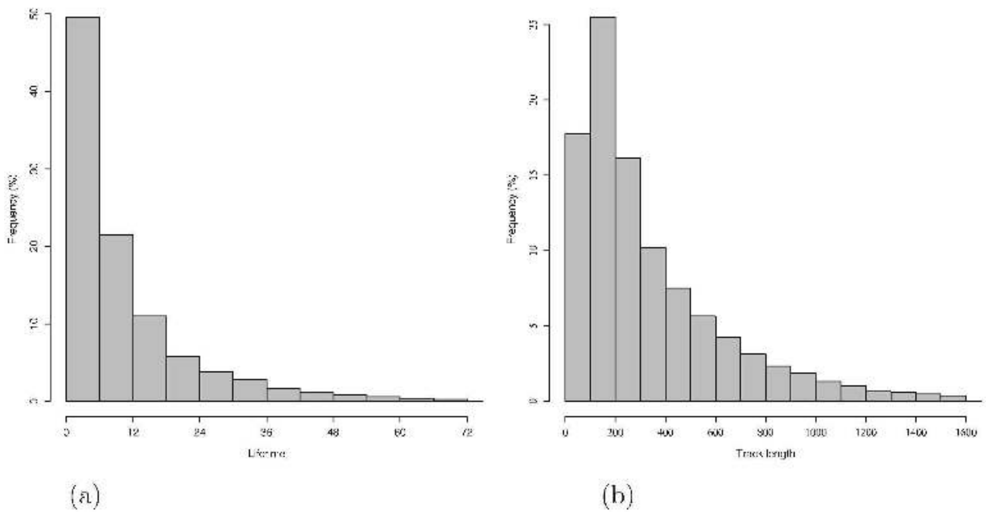

Figure 5: (a) Histogram of lifetime (t, in hours) of all the cyclones. (b) Histogram of track length (d, in km) of all the cyclones with a lifetime of at least 12 hours.
160x89mm (600 x 600 DPI)

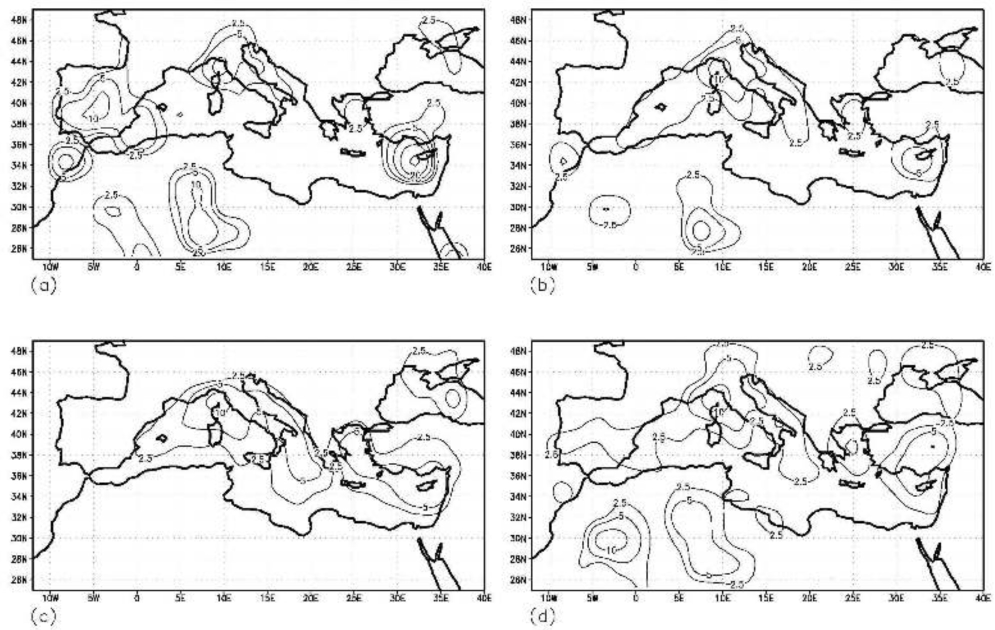

Figure 6: Seasonal mean number of cyclone centres in 2.25şx2.25ş latitude/longitude boxes, for (a) summer, (b) autumn, (c) winter and (d) spring. Contour intervals: 2.5, 5, 10, 20 and 40 centres per season.
160x106mm (600 x 600 DPI)

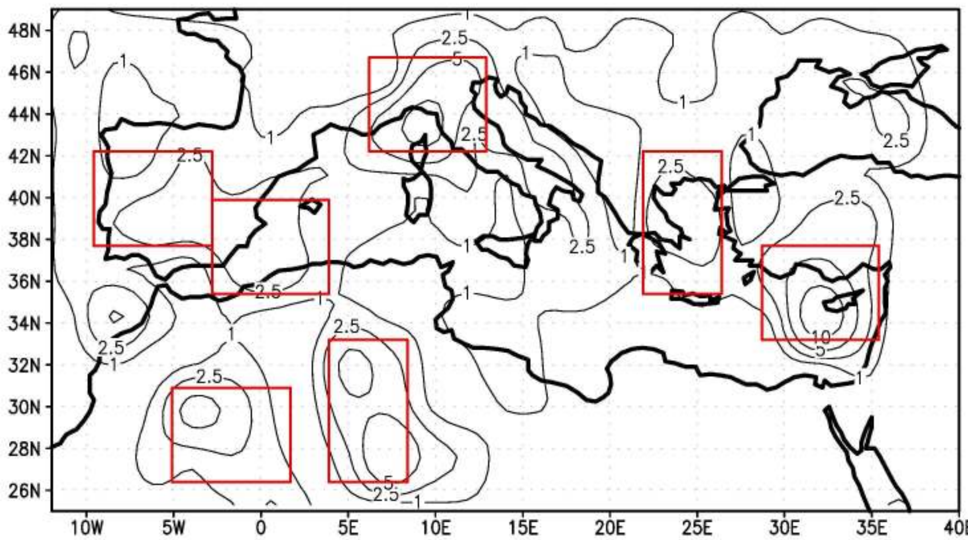

Figure 7: Mean number of cyclogenesis events in 2.25şx2.25ş latitude/longitude boxes. Contourn intervals:1, 2.5, 5, 10 and 20 cyclones per year. The selected regions are marked with boxes.
191x127mm (600 x 600 DPI)

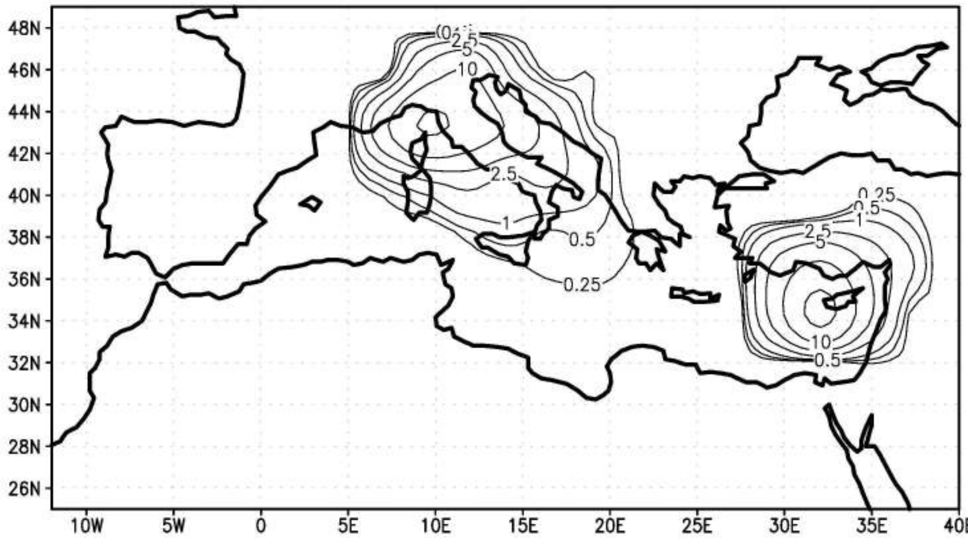

Figure 8: Track density for cyclones originated in the gulf of Genoa and in Cyprus. Events counted in 2.25şx2.25ş latitude/logitude boxes. Contourn intervals: 0.25, 0.5, 1, 2.5, 5, 10 and 20 cyclones per year.
191x127mm (600 x 600 DPI)

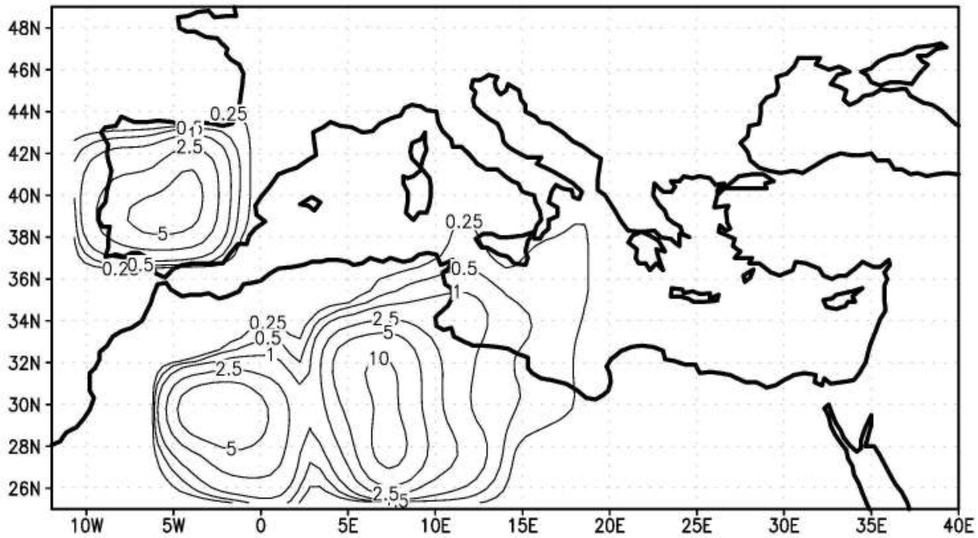

Figure 9: As Figure 8 for cyclones originated in western and eastern Sahara and in the Iberian peninsula.
191x127mm (600 x 600 DPI)

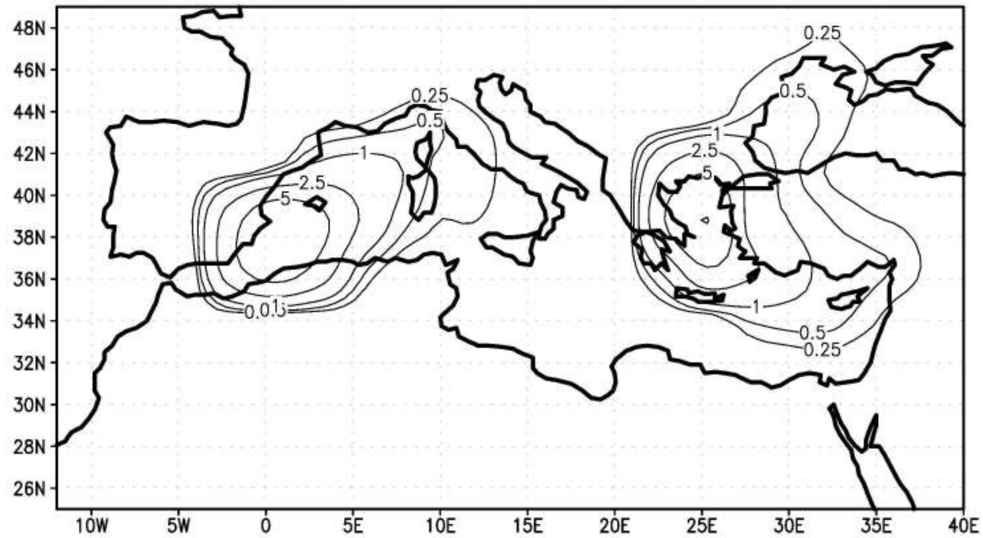

Figure 10: As Figure 8 for cyclones originated in the Algerian and in the Aegean Seas.
191x127mm (600 x 600 DPI)