Chapter 6

Cyclones in the Mediterranean Region: Climatology and Effects on the Environment

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6.1. Introduction

Cyclones represent the most important manifestation of the mid-latitude high-frequency variability, and play a fundamental role in the atmospheric large-scale horizontal (and vertical) mixing and in modulating the air–sea interaction. Cyclonic circulations, due to their frequency, duration and intensity, play an important role in the weather and climate over the entire Mediterranean region (Radinovic, 1987). A large spectrum of environmental variables and phenomena are associated with cyclones in the Mediterranean region. Wind, pressure, temperature, cloudiness, precipitation, thunderstorms, floods, waves, storm surges, landslides, avalanches, air quality and even the fog and visibility in the Mediterranean are influenced by the formation and passage of cyclonic disturbances. Many phenomena are beneficial from the agricultural, hydrological and economical point of view. However, some of them are damaging and occasionally disastrous (MEDEX, Jansa et al., 2001).

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Cyclones are important when information more complete than that provided by the average geopotential (or sea level pressure) field is required and when aspects of the probability distribution characterizing the statistics of the atmospheric circulation besides its average pattern are investigated. Consequently, statistical analysis of cyclones is important especially for the "tails" of probability distributions, that is the part characterizing extremes values of variables such as precipitation, winds, waves, storm surges. The Mediterranean area, although located to the south of the main Atlantic storm track that more directly affects western and northern Europe, is quite frequently subjected to sudden events of extreme and adverse weather, often having high social and economic impacts. The morphology of the territory, with small and steep river basins and highly populated, industrialized and tourist areas, makes the Mediterranean especially sensitive to the impact of weather phenomena, especially heavy rain and consequent flooding. A report (based on 10 years of data) prepared by the Munich Reinsurance Company collects 166 cases of heavy rainfall and floods and 104 cases of strong wind and storms producing serious damages. The total number of deaths is over 1,900 and the quantified economic losses are over 6,000 MEuro. These figures are certainly underestimates. For Spain alone, and only in four years (1996–1999), the Programme of Natural Hazards of the Spanish Directorate of Civil Defence reported 155 deaths by heavy rain and flood events and 28 deaths by storms and strong winds (Jansa et al., 2001a) in Greece according to the data published by the Hellenic Agricultural Insurance Organization (ELGA) only for the year 2002 the economic losses due to heavy precipitation, floods, hail and extreme winds were over 180 MEuro. Single disastrous events have been recorded, such as the storm of 4 November 1966 which hit central and north eastern Italy, causing more than 50 deaths and widespread, huge damages in the eastern Alps, Florence and Venice (where the damage produced by the surge is estimated to be equivalent to 400 KEuros present-day). Over the sea, significant wave height as large as 10 or 11 m are also reported in extraordinary storms, like the 10–11 November 2001 storm in the Western Mediterranean, that produced the destruction of beaches and coastal flooding in northern Mallorca (Gomez et al., 2002) and the big storm at the end of December 1979, that seriously damaged the port of Oran (Algeria). More examples can be found in the MEDEX list of selected cases, Jansa et al. (2001a). A large portion of such severe weather-related events are associated with cyclones in the Mediterranean (Jansa et al., 2001a).

Since the capability of climate models to reproduce intense cyclones and extreme weather events is limited, it is necessary to determine the links between their probability distribution and large-scale patterns or/and indices.

The identification and analysis of the large-scale patterns associated to the occurrence of cyclones is very important. In fact, as climate models are more accurate in reproducing the large-scale structure of atmospheric circulation than the statistics of cyclones and extreme events, the prediction of the behaviour of large-scale patterns in future climate scenario could be a robust tool for predicting changes in the intensity and characteristics of cyclones and extreme events.

It is important to note that the link between the intensity of cyclones and hazardous extreme events is not simple and different characteristics can be involved as different impacts are considered. The intensity of circulation (winds), precipitation (with consequent floods) and of the cyclone itself (measured as the minimum value of the sea level pressure or the strength of the overall associated circulation) are not necessarily related in a simple (linear) way. An example is the disastrous flood which affected central and Northern Italy during November 1966, characterized by very intense precipitation and high winds, which but whose central minimum pressure was not remarkably low (De Zolt et al., 2005).

Finally, Mediterranean cyclones have also an influence on regions outside their region of origin. Radinovic (1987) suggests that cyclones in the Mediterranean region influence the weather and climate further east in central Europe, in countries such as Hungary, Romania, Ukraine and Russia, and in Asian areas, like Syria, Iraq, Iran, Afghanistan or northern India. At the same time, besides the large amount of cyclones entering the Mediterranean region from the middle latitude storm track, there is evidence of a significant role played by tropical cyclones, which can produce atmospheric circulation patterns advecting moisture into the Mediterranean region and, occasionally, move into it during a later stage of their life cycle after having experienced a transition to extratropical systems (Pinto et al., 2001; Turato et al., 2004).

The introductory Section 6.1 of this chapter consists of Subsection 6.1.1 describing the evolution of research on cyclones in the Mediterranean region and their role on climate. Section 6.2 describes the dynamics responsible for the formation and evolution of cyclones in the Mediterranean region (Subsection 6.2.1), the datasets available for their analysis (Subsection 6.2.2) and the methods for the identification of cyclones and the evaluation of the intensity of their activity (Subsection 6.2.3). Section 6.3 describes the climatology of cyclones, their characteristic spatial scales, seasonality, area and mechanisms of origin (Subsection 6.3.1); the relation between cyclonic activity and large-scale climate patterns (Subsection 6.3.2); and the observed trends (Subsection 6.3.3). Section 6.4 describes the effects of cyclones on the Mediterranean environment; it is divided into five subsections, describing their role on precipitation, winds, storm surge, ocean waves and landslides. For each subsection, a description of the mechanism explaining the effects of cyclones on the specific phenomenon is described, and climate trends are discussed. The concluding Section 6.5 summarizes the available knowledge on cyclones and on their effects in the Mediterranean region. The outlook section 6.6 discusses the main open research issues and subjects of ongoing and future research.

6.1.1. "Historical" Notes

Pioneering studies that include climatology of cyclones and cyclogenesis in the Mediterranean (in the frame of hemispheric studies) are those by Pettersen (1956) and Klein (1957). They are large-scale studies and show, at even this scale, that the western Mediterranean is a distinct and very active area of cyclogenesis and with frequent presence of cyclones in winter, in the northern Hemisphere. These studies are based on hand-made analyses and subjective detection of the cyclones. Subsequent studies, using the same techniques, were able to investigate smaller scales, even including mesoscale features (Radinovic and Lalic, 1959; Radinovic, 1978; Genoves and Jansa, 1989). The annual total number of cyclones detected in the mesoscale studies (Radinovic, 1978 or Genoves and Jansa, 1989) was, as expected, much larger than the number of cyclones found in larger scale analyses. Since 1990 (Alpert et al., 1990), most of the studies on climatology of the Mediterranean cyclones are based on objective analyses and objective techniques aimed at detecting and tracking the cyclones, but there are also studies based on mixed databases, subjective and objective, like Campins et al. (2000). Several studies have focused on the characteristics of the cyclones in the Mediterranean area, on their dynamics, locations, frequency and temporal variability of cyclogenesis (Buzzi and Tosi, 1989; Tosi and Buzzi, 1989; Alpert et al., 1990a,b; Trigo et al., 1999; Campins et al., 2000; Maheras et al., 2001, 2002, Lionello et al., 2002).

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A different category of studies have analysed the link between cyclones and environment. Most studies have been focused on precipitation (Trigo et al., 2000; Jansa et al., 2001; Kahana et al., 2002; Maheras et al., 2002, 2004), but also other aspects such as storm surges, (Trigo and Davies, 2002; Lionello, 2005), and wind waves (Lionello et al., 2002) have been considered.

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The impact of extreme weather conditions on landslides occurrence has been attempted over different areas of the Mediterranean. Recent techniques tend to favour the use of satellite and airborne imagery to assess changes in geomorphology. However the use of historical data obtained form in situ analysis plus local newspapers and interviews is a more reliable tool to establish precise links between the timing of intense rainfall events and concurrent observed landslide episodes (e.g. Zêzere et al., 1999; Polemio and Petrucci, 2003; Trigo et al., 2005)

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6.2. Mediterranean Cyclones: Data, Methods and Dynamics

This section contains a description of the dynamics responsible for formation and evolution of cyclones in the Mediterranean region, and of data and methodologies used for analysing their climatology.

6.2.1. Dynamics of Cyclones in the Mediterranean Region

The cyclones in the Mediterranean region represent a well-distinct element of the global climate. A Mediterranean storm track structure has been put into evidence in different studies and it has been shown that the regular cyclone tracks over the Mediterranean are linked to the baroclinic waveguides (Wallace et al, 1988) and to high rate of alternation between cyclones and anticyclones (Pettersen's, 1956) in the Mediterranean region (Alpert, 1989). The presence of a separate branch of the Northern Hemisphere storm track crossing the Mediterranean region, with areas of more frequent cyclogenesis in the western Mediterranean and of cyclolysis in the central and eastern Mediterranean, though less intense than the storm track in the Atlantic and Pacific, has been confirmed in recent analysis of the Northern hemisphere (Hoskins and Hodges, 2002). At the same time, there are studies showing that the Mediterranean region presents the highest concentration of cyclogenesis in the world (Pettersen, 1956; see also Radinovic, 1987, for a general view) during the northern hemisphere winter. Some of them are so intense that they are classified as ''meteorological bombs'' (Conte, 1986; Homar et al., 2000).

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According to the conceptual model re-proposed by Hoskins et al. (1985), cyclogenesis occurs when and where a high-level PV (Potential Vorticity) positive anomaly overlaps a low-level potential temperature or PV positive anomaly or a frontal zone. The formation of low-level shallow depressions by orography and thermal contrasts is very frequent in the Mediterranean, owing to the complex topography of the region. Therefore hundreds of cyclonic disturbances can be subjectively and objectively detected in the Mediterranean every year (Campins et al., 2000; Picornell et al., 2001). Actually many of them are shallow depressions which cannot be considered deep cyclones, but, they can play a role in the initiation of actual deep cyclogenesis events. There are three kinds of evolution that can be identified in the Mediterranean: (a) The low-level disturbance does not evolve and remains shallow, weak or moderate and nearly stationary if the upper level PV anomaly is absent or too far away to interact with it (Genoves and Jansa, 1991). In this case real or deep cyclogenesis does not develop. (b) An upper level PV anomaly will create cyclogenesis when arriving over a frontal zone, just under the maximum PV advection at high levels, with or without the presence of a depression at low level. Some Mediterranean cyclogenesis could be, at least partially of this type, comprising those cyclones generated at the quasi-permanent Mediterranean border front (Alpert and Ziv, 1989) or at some internal fronts. (c) The low-level disturbance rapidly deepens and cyclogenesis occurs when the upper level perturbation moves close enough to interact with it.

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The Mediterranean region presents geographic factors that can substantially modify the cyclogenesis mechanism. The orography of the region changes quantitatively and qualitatively the baroclinic instability process, usually favouring or "focusing" the cyclogenesis (Speranza et al., 1985). The high frequency of orographically induced low-level disturbances may partially explain the high frequency of real cyclogenesis in the Mediterranean (Genoves and Jansa, 1991, Jansa et al., 1994). Latent heat release usually sustains and intensifies most of the cyclogenesis processes. In the Mediterranean region, this effect seems to be quite important in the Eastern Mediterranean, when a Sharav cyclone arrives there from the desert and intensifies over the sea (Alpert and Ziv, 1989). Some cases in the western Mediterranean also have the same evolution (Homar et al., 2000). Enhanced baroclinic instability in saturated air (Fantini, 1995) influenced by latent heat release in an environment convectively stable can be another process contributing to cyclogenesis. In general, the role of latent heat release and diabatic processes is a key issue in the Mediterranean region, though of secondary importance when intense orographic cyclogenesis, both Alpine (Buzzi and Tibaldi; 1978; Dell'Osso and Radinovic, 1984; Speranza et al., 1985; Tibaldi et al., 1990; Stein and Alpert, 1993; Alpert et al., 1995; Buzzi, 1997) or non-Alpine (Garcia-Moya et al., 1989), takes place.

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Such complicate dynamics and the potential for many different mechanisms favouring cyclogenesis imply that extremely diversified classes of cyclones are present in the Mediterranean region. A tentative list, based partially on the mechanisms producing cyclogenesis and partially on the geographical characteristics, would include lee cyclones, thermal lows, small-scale hurricane-like cyclones, Atlantic systems, African cyclones and Middle East lows.

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Lee cyclones are triggered by the passage of a major synoptic low-pressure system north of the region, so that their generation is expected to be very sensitive to the location of the storm track above Europe. Lee cyclones develop south of the mountain ridges representing the northern boundary of the Mediterranean region. The Gulf of Genoa is the region of most frequent intense cyclogenesis in the Mediterranean, but lee cyclones are also generated in the Adriatic Sea (Flocas and Karacostas, 1994; Ivançan Picek, 1996), in the Cyprus and Aegean Sea areas (Reiter, 1975; Alpert et al., 1990), in the Black Sea, and in several areas of the western Mediterranean sea (Jansa, 1986). The passage of the same synoptic system can be responsible for successive and distinct cyclogenesis in the Gulf of Genoa, Aegean and Black Sea (Trigo et al., 1999). The spatial distribution of the frequency of cyclogenesis presents relative maxima in the Cyprus and Aegean region, in the Adriatic, in the Palos-Algerian sea, in the Catalonian-Balearic sea, and in the Gulf of Lyons (Jansa, 1986).

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Thermal lows are more frequent in spring and summer and their genesis and lysis are modulated by the daily cycle of temperature. Their occurrence is therefore depending on the amplitude of this cycle and on the land–sea temperature contrast. Many of them remain shallow depressions confined to the lower troposphere. Modeling studies suggest that they are also generated over sea in autumn and winter, when the land–sea temperature gradient is reversed.

Small-scale, hurricane-like Mediterranean Lows have been detected over sea. They are a special class of Mediterranean cyclones in which the main source of energy is the great amount of latent heat released in large convective cloud clusters, as in tropical cyclones (Rasmussen and Zick, 1987).They are likely to depend critically on the air–sea temperature difference and on the content of moisture in the atmosphere.

Atlantic systems mostly enter in the Mediterranean region from the west and northwest, and cross the Mediterranean during their attenuation phase. Even when their central pressure minimum does not pass directly above the Mediterranean Sea, they affect the Mediterranean weather as they can cause secondary lee cyclones.

Northern Africa is the source of many cyclones arriving from the south which often form or intensify south of the Atlas Mountains as lee cyclones. Their formation is more likely to occur in spring and summer when static stability is low.

The classification of cyclones in the south-eastern Mediterranean region includes several types of cyclones, with different seasonality and origin, such as the Cyprus Lows, Syrian Lows and Red Sea Troughs. The Cyprus Lows are mostly orographically generated or strengthened. The Syrian low (Kahana et al., 2002) is a particular type of the Cyprus low system so intense that penetrates into some areas of Syria. The Red Sea trough system develops during spring and autumn due to topographic effects in the Red Sea area. Usually it is a warm and shallow trough with a very dry southeasterly flow, but torrential rains occur when an upper cold air trough penetrates southwards above it, due to the extreme instability in this situation (Krichak et al., 1997ab; Krichak and Alpert, 1998)

6.2.2. *Available Sets of Data*

As mentioned before, pioneering studies on the climatology of cyclones in the Mediterranean were based on hand-made subjective analyses. Due to their own nature, the subjective analysis datasets are in general not available except in the institutions where the analyses were prepared, and often not recoverable for subsequent studies. The subjectivity has the advantage that a hand-made analysis can be even more careful and detailed than objective analyses in some areas, due to appropriate conceptual models and complementary information, etc. At the same time, the subjectivity has the disadvantage of being not homogeneous, neither in space nor in time, because some areas and situations can be systematically poorly or incorrectly analysed due to the lack of specific skill and experience of the authors. In general, the quality of objective analyses has improved to the point where their advantages outweigh those of the subjective analyses.

The operational objective analyses are presently the main source of data for performing a climatological analysis of cyclones, although the frequent changes in the procedure (due to changes in the forecasting model, in its resolution, in the data available for its initialization and in the data assimilation method) makes the series quite temporally heterogeneous. Generally, only relatively short samples of operational analyses are homogeneous and can be used for climatic studies. In order to compensate for these inadequacies, homogeneous reanalysis datasets, like ERA15, NCEP or ERA40, have been produced, though with resolution which is coarser than most of the advanced operational analyses (Gibson et al., 1996; Kalnay et al., 1996; Simmons and Gibson, 2000). These homogeneous reanalysis data sets (ERA15, NCEP and ERA40) are the basis for all climatological studies in general and for cyclones in particular. Without them, it would be difficult or even impossible to obtain reliable fields of geopotential or SLP needed for systematic analysis of trends and variability.

As a practical compromise, attempting to exploit both advantages of the high resolution of recent operational analyses and of the homogenous multi-decadal re-analyses, the MEDEX database contains lists of cyclones identified both in operational analyses (HIRLAM/INM, over the Western Mediterranean, and ECMWF over the whole Mediterranean) and reanalyses (ERA40).

Another dataset has been created to investigate the changes and variability in SLP from 1850 as part of the EMULATE project (European and North Atlantic daily to multi-decadal climate variability project). The dataset is a combination of homogenized daily SLP station series, ship observations and previously reconstructed SLP fields (Ansell et al., 2005).

The dataset consists of daily mean sea level data on a 5×5 grid, and it has a lower spatial and temporal resolution than the reanalysis datasets. Though, obviously, it cannot detect mesoscale systems or accurately locate the areas of cyclogenesis, this dataset allows the identification and tracking of synoptic-scale cyclones in the Mediterranean region from 1850.

Extreme cyclones can also be identified by their effects which can be measured or recorded. Instrumental data on surges, waves, floods, and winds can be used for reconstruction of time series of past cyclones. A peculiar example is provided by the records of storm surges in Venice, from past chronicle and archives. The highest surges have been reported with a precision which is sufficient to reconstruct the frequency of past floods since the 8th century AD (Camuffo, 1993). The time series shows a succession of periods of recurrent floods, which were particularly intense in the first half of the 16th and of the 18th century, separated by more quiet periods, and a continuous positive trend during the second half of the 20th century. This last part of the time series is very accurate since the tide gauge records have begun in 1872. This example represents the limits and potential of such local reconstructions. On one side, they are a tool for obtaining very long time series in historical times. On the other side, in general it is very difficult to associate past variability to large-scale regimes and make the distinction between large-scale and local processes (the soil subsidence in this case) for which additional information is needed. Also the homogeneity of the time series along its whole extent can be argued, as its reconstruction often involves subjective criteria which need to account for the temporal changes in the level of vulnerability of society, in human activities, resources and technological capability. Finally, it is difficult to attribute the cause of trends without supplementary information. Though floods of Venice occurred many times during its history, the last 50 years represent an unprecedented period of frequent and intense events. However, this is largely explained by the local loss of relative sea level (a combination of ground subsidence and sea level rise) not associated to a trend of storminess (Lionello, 2005)

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6.2.3. Methodology

In recent years, two distinct approaches have been used to study the storm activity over the North Atlantic and Europe: storm track algorithms and analysis of synoptic variability. Usually, storm track algorithms apply sophisticated methods that can detect the regions of storm development (cyclogenesis) and decay (cyclolysis) as well as the specific paths of each individual storm (Murray and Simmonds, 1991; Serreze et al., 1997; Trigo et al., 1999, 2002; Lionello et al., 2002). Analysis of synoptic variability is a simpler approach, which corresponds to the identification of the synoptic variability using a band-pass filter that retains mainly variability on the 2–8 day period of SLP or 850 or 500 hPa geopotential (Buzzi and Tosi, 1989; Hoskins and Hodges, 2002). This second approach has been widely applied to quantify the synoptic activity associated with a high and low NAO (North Atlantic Oscillation) index (e.g. Rogers, 1997; Ulbrich and Christoph, 1999; Trigo et al., 2002; Krichak and Alpert, 2005a,b). However, the first technique has also been used to show the areas of significant difference in storm activity between winters with high and low NAO index (Serreze et al., 1997). Figure 107, A–D shows the 1,000 hPa geopotental height standard deviation and associated cyclone trajectories. The analysis is applied to the band-pass filtered fields with cut-off periods at 1 and 7 days. Two monthly periods are considered: January 1966 and 1983, which are characterized with a low and high NAO index, respectively. Both approaches show the existence of a major cyclone variability mode, which is strongly associated with NAO (North Atlantic Oscillation).

A climatology of cyclones implies a definition of cyclone and a method of detecting (and describing) it. In both these steps there is a wide margin of arbitrariness, which produces significant differences in the results. When considering subjective analyses and a subjective detection method it was usual to retain a disturbance as a cyclone when it was a minimum of pressure

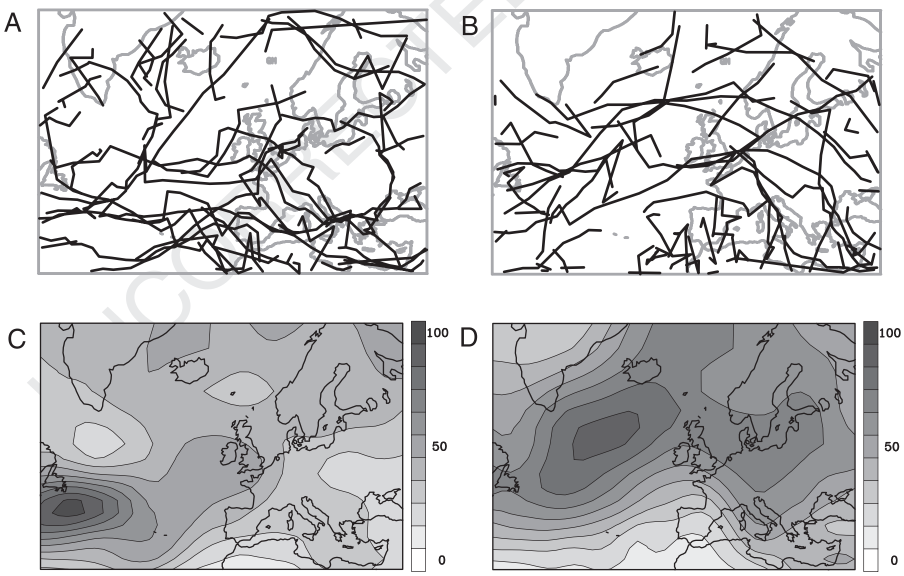

Figure 107: Cyclone trajectories (top panels (A) and (B)) and 1,000 hPA standard deviation (bottom panels (C) and (D)) for low (Jan. 1966, left) and high (Jan 1983, right) monthly NAO index values. Analysis is applied to band-pass filtered data (1 to 7 day window). Only trajectories of cyclones deeper than 25 hPa and with duration longer than one day are shown.

surrounded by a closed isobar. Of course, the results depend on the spacing between isobars and of the scale of the map, so that the more detailed the map, the higher the number of cyclones identified. These situations and problems are not avoided by using objective methods. There are different conceptual ways to define a cyclone. An option is to define a cyclone as a relative maximum of vorticity (relative or geostrophic vorticity). Another definition states that a cyclone is a relative minimum of sea level pressure (or geopotential height). The choice of the definition will produce significantly different number of cyclones, and will affect also other details, like their location. Not all the minima of sea level pressure can be retained as cyclones, because many of them are too weak or too close together, so that restrictions have to be imposed (like a threshold for the minimum pressure gradient, a minimum distance between centres, or other constraints), which introduce arbitrariness in the definition of the cyclone and therefore in the results. Even more critical is the effect of the resolution, since low-resolution analyses will permit the detection of relatively large-scale cyclones, but will miss the smaller mesoscale disturbances, while, on the contrary, high-resolution analyses will permit the detection of many small mesoscale disturbances, but could miss the description of the relatively large-scale disturbances. In fact, the domain of a large-scale cyclone, defined as the area of positive (geostrophic) vorticity, in a region like the Mediterranean characterized by a complex orography and land–sea distribution, is often broken in multiple fragments, without continuity, due to the existence of many high-low small-scale disturbances, with negative–positive vorticity. The maximum detail in the detection and description of small-scale cyclonic disturbances, is achieved by using high-resolution objective analyses directly, but for a good description of larger scale cyclones, lower resolution analyses have to be used or, alternatively, the original fields of the high-resolution analyses have to be spatially smoothed. The results from high-resolution unfiltered fields and from low-resolution or smoothed fields are dramatically different, even with the same definition of cyclones and the same restrictions to the definition. Figure 108 (Gil et al., 2002) is based on a 3-year (Jun 1998 to May 2001) sample of operational analyses from the ECMWF, consisting of four analyses per day at a T319 resolution, which permits 0.5° latitude–longitude gridded maps. From non-smoothed analyses (right-hand side in the figure), 2,248 cyclones are detected in the Eastern Mediterranean (purple frame) and 2,910 in the Western Basin (blue frame). From smoothed fields, using a Cressman filter with a 200 km radius of influence (left side in the figure), these numbers are reduced to 353 cyclones in the East and 437 in the West. Not only the number of cyclones are totally different, but also some details in the distribution: the very important relative maximum south of the Pyrenees obtained from the original fields disappears when the smoothed fields are used.

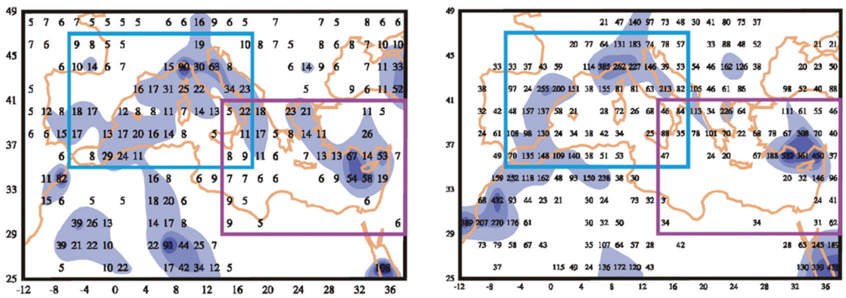

Figure 108: Number of cyclones detected in a three-year (Jun 1998 to May 2001) sample of operational analyses from the ECMWF at T319 resolution. Right panel shows the results of analysing non-smoothed analyses: 2,248 cyclones are detected in the Eastern Mediterranean (purple frame) and 2,910 in the Western Basin (blue frame). Left panel refers to smoothed fields (a Cressman filter of 200 km of radius of influence has been used): 353 cyclones in the East and 437 in the West (from Gil et al., 2002).

6.3. Climatology of Cyclones in the Mediterranean

The climatology of cyclones in the Mediterranean region is highly influenced by the almost enclosed Mediterranean Sea, which represents an important source of energy and moisture for cyclone development; and by its complex land topography, which plays a major role in steering and deflecting air flows. Moreover, being located within the transition between the subtropical high-pressure belt and the mid-latitude westerlies, the Mediterranean is also subject to strong interannual variability of cyclone activity and, consequently of its precipitation regime, water resources.

In the following section, a climatology of Mediterranean cyclones is presented, which decribes the spatial distribution of cyclogenesis and associated mechanisms. The average cyclone characteristics, including their intensity and spatial and temporal scales, as well as their intra- and inter-annual frequency variability, will be described.

6.3.1. Characteristics, Sub-areas of Cyclogenesis, Seasonality and Generation Mechanisms

Mediterranean cyclones are generally characterized by shorter life-cycles and smaller spatial scales than extra-tropical cyclones developed in the Atlantic, as shown in the analysis of storm-tracks derived from 6-hourly near surface fields at T106 (1.125° × 1.125°) resolution, available from ERA-15 (ECMWF ReAnalysis) (Trigo et al., 1999). Over 65% of cyclones are within subsynoptic scales, with radius of the order of 550 km or less, considerably smaller than the 1,000–2,000 km values, typical of Atlantic synoptic systems. If the shortest living cyclones (with duration lower than 12h) are excluded, the average life of cyclones in the Mediterranean region is about 28 h, compared to 3–3.5 days in the Atlantic. Radius and maximum gradient tend to scale with the minimum pressure. In general, cyclones are deeper and have a larger radius in the western than in the Eastern Mediterranean. A recent evaluation (restricted to the western Mediterranean region, Picornell et al., 2001), based on higher resolution fields (computed by HIRLAM at 0.5° resolution) and including short-lived cyclones, produced even smaller space and timescale values. In this dataset the radius of most cyclones is within the 150–350 km range (the mean value is 255 km) and the most intense cyclones have lifetimes of 18–24 h. Deepening rates are mostly lower than 2 hPa $(6h)^{-1}$, though values as high as 10 hPa$(6h)^{-1}$ can be observed. Therefore, also the average deepening rates are smaller than in the Atlantic, although the lower latitude at which Mediterranean cyclones develop should be accounted for. Many cyclones in the Mediterranean region have null or even negative deepening rate, meaning that they originated in neighbouring regions and cross the Mediterranean during their attenuation phase. A very recent comparison between a sample of Atlantic and West Mediterranean cyclones, made by using high-resolution smoothed fields (HIRLAM/INM 0.5° latitude–longitude with Cressman filter of 200 km), confirms the differences indicated above. The average winter geostrophic circulation of the Mediterranean cyclones is 4×10^7 m^2 s^{-1} whereas it is 7×10^7 m^2 s^{-1} for the Atlantic disturbances (Campins et al., 2005). Note that the geostrophic circulation combines the size (area) of the cyclones and their geostrophic vorticity, so that can be considered as a measure of their total magnitude.

The geography of the region, namely the high orography around the Mediterranean Sea and the existence of embayments and inland seas, determines the relatively small areas where cyclogenesis tends to occur (Table 7; Fig. 109) and the variegate mesoscale structure of Mediterranean systems (Alpert et al., 1990a,b; Trigo et al., 1999, 2002; Maheras et al., 2001; Picornell et al., 2001). These structures correspond to the mechanisms discussed in the previous Section 6.2.1. Figure 109 shows that the most active areas include the Gulf of Genoa, Iberia, Southern Italy, Northern Africa, Aegean Sea, Black Sea, Cyprus, Middle East; the respective seasons when these areas are most active are indicated in Table 7.

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Further differentiation can be found inside such areas. In fact, studies based on automated database methods (Campins et al., 2000), have resolved smaller mesoscale structures and identified in the western Mediterranean 7 types of

Table 7: Cyclogenetic regions in the Mediterranean area and respective seasons with significant activity (after Trigo et al., 1999); values represent average cyclone radius (km).

area	seasonality	radius (km)
Sahara	Spring, Summer	530–590
Gulf of Genoa	Whole year	530–380
Southern Italy	Winter	520
Cyprus	Spring, Summer	330–460
Middle East	Spring, Summer	320–460
Aegean Sea	Winter, Spring	500
Black Sea	Whole year	380–400
Iberian Peninsula	Summer	410

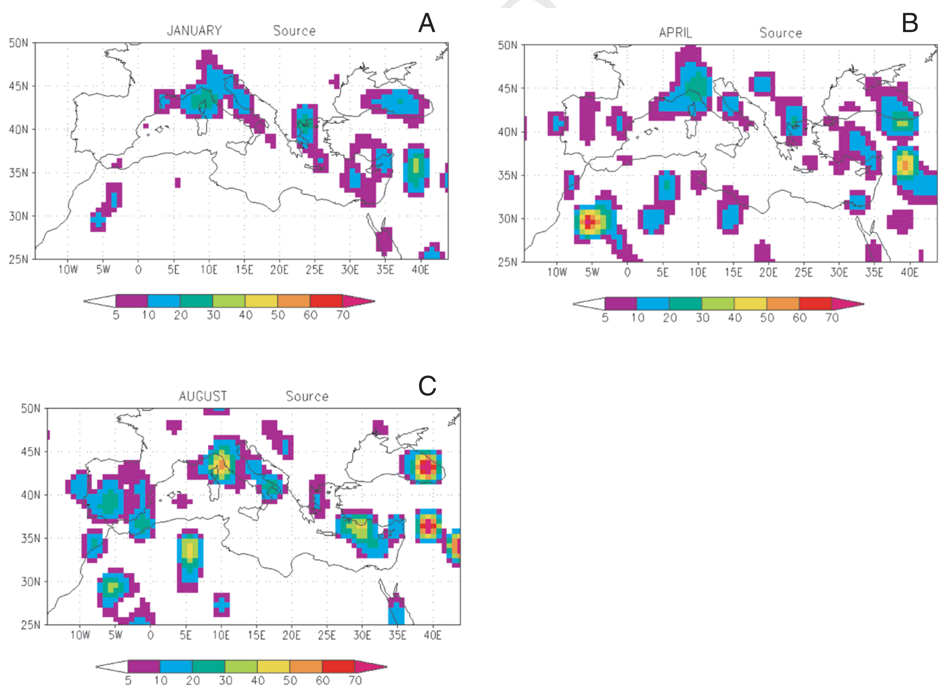

Figure 109: Number of cyclogenesis events detected per 2.25° × 2.25° in January (A), April (B), and August (C) from 1979 to 1996 in ECMWF re-analyses (from Trigo et al., 1999).

cyclones, on the basis of shape and intensity of the associated circulation. However, despite the use of different methodologies, selection criteria and data sets, most studies (e.g. Alpert et al., 1990a,b; Trigo et al., 1999; Campins et al., 2000; Maheras et al., 2001; Picornell et al., 2001) agree on the spatial location of cyclone generation.

The overall synoptic activity over the entire basin has a well-defined annual cycle, being more intense in the period from November to March which corresponds to the so-called storm season (Fig. 110). Though the temporal and spatial distributions of the Mediterranean cyclones present a large intermonthly variability (Alpert et al., 1990a), the analysis favours the definition of three main seasons: winter, spring and summer. Autumn appears as a transitional period with large interannual variability, whose months could be characterized as late summer or early winter.

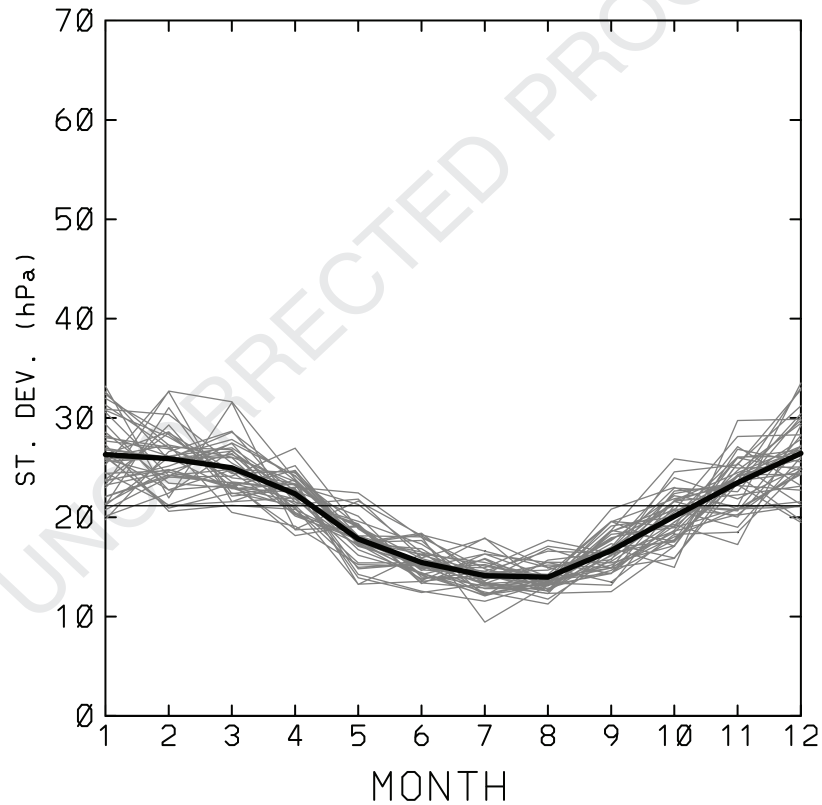

Figure 110: Annual cycle of the standard deviation of the 1,000 hpa geopotential field. The grey lines show individual years, the black thick line the average annual cycle. Values are based on the band-pass filtered fields (1–7day cut-off periods) (Lionello and Zardini, 2005, personal communication)

The mechanisms typical of winter cyclogenesis in the Mediterranean exhibit contrasting characteristics with those most common in spring and summer seasons, with intermediate situations in spring and autumn. The 3D structure of the cyclones gives a first clear indication: in the Mediterranean, only the winter cyclones are mostly deep cyclones (reaching 300 hPa), while in summer they are mostly shallow (reaching 850 hPa or less). The Laplacian of the temperature at low levels, giving the thermal character of the cyclone, is always negative (warm character), but double in magnitude in summer than in winter. The Mediterranean cyclones are in general more similar to the Atlantic cyclones in winter than in summer (Campins et al., 2005). In winter there are strong links between synoptic upper-troughs and local orography and/or low-level baroclinicity observed over the northern Mediterranean coast. In spring and summer, inland cyclogenesis becomes more frequent and also more sensitive to diurnal forcing (Maheras et al., 2001; Picornell et al., 2001; Trigo et al., 2002).

Winter cyclogenesis occurs essentially along the northern coast in three major areas characterized by strong baroclinicity: the lee of the Alps, when an upper-trough is influenced by the mountains, and over the Aegean and Black Seas, when an upper-trough moves over the relatively warm water basins (Trigo et al., 2002). The role of orographic cyclogenesis (Buzzi and Tibaldi, 1978) is not limited to the Alps, being also fundamental in the triggering of lows in the Gulf of Lyons, south of the Pyrenees, and also in Southern Italy, south of the Apennines. Over the south-eastern Mediterranean region, the intensity of cyclogenetic activity is to a large extent controlled by large-scale synoptic systems over Europe, particularly by those characterized by mid- and upper-tropospheric southward air-mass intrusions and tropopause-folding effects (Krichak and Alpert, 2003). These processes are often associated with the formation of three-dimensional potential vorticity structures, jet streaks and low-level jets conditions over the region to the south of Alps (Buzzi and Foschini, 2001; Liniger and Davies, 2003).

In spring, the strengthening of the meridional temperature gradient along the northern African coast favours the development of Saharan depressions. These tend to occur on the lee side of the Atlas mountains, within a region of very weak static stability. Thermal forcing plays an increased role in the genesis and maintenance of Mediterranean Lows in spring and, particularly, in summer. As a result, the life-cycles of summer cyclones, especially those developed over Northern Africa and the Iberian Peninsula, follow the diurnal temperature fluctuations; maximum intensity tends to be reached by late afternoon, and cyclolysis tends to occur mostly by early morning (Maheras et al., 2001; Picornell et al., 2001; Trigo et al., 2002). Also the Middle East trough, which is a semi-permanent feature primarily induced by the Asian monsoon acting on a planetary scale (Rodwell and Hoskins, 1996), exhibits the

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same kind of diurnal see-saw associated with the local thermal cycles (Trigo et al., 2002).

There are several reported cases of very intense storms in autumn–winter and spring months, with severe associated weather (intense rainfall, surges, flash floods), which have either developed or re-intensified over the Mediterranean Sea (e.g. Lee et al., 1988; Ramis, 1994; Lagouvardos, 1996; Lagouvardos, 1999; Doswell III et al., 1999; Pytharoulis et al., 1999). A fraction of these very intense events develop a hurricane-like structure, feeding on the latent heat release at the sea surface; their frequency, space–time distribution, and interannual variability have not been fully investigated, yet (Pytharoulis et al., 1999).

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6.3.2. The Role of Large-scale Climate Patterns on the Mediterranean Cyclones

The Mediterranean region is only partially affected by the North Atlantic storm track, whose main path crosses the Northern Atlantic towards Northern Europe. Consequently, the main mode of the North Atlantic storm track variability, which describes its north–south shift and intensification over the Atlantic, is only marginally related to the frequency and intensity of the cyclones in the Mediterranean region, though Trigo et al. (2000) have demonstrated that an association exists and that it depends on the structural characteristics of the cyclones.

In fact, the analysis of low-frequency SLP variability patterns and the frequency of cyclones in the Mediterranean region shows that there are important patterns than the NAO (Krichak and Alpert (2005a,b)). The link between NAO and the position and strength of the storm track in the central Atlantic implies a link between NAO and the frequency of orographic cyclogenesis which is triggered by the passage of Atlantic cyclones. Instead, the bulk of the variability over Central and Southern Europe and over the Mediterranean region is linked to low-frequency patterns, whose centres of actions are localized over Europe and eastern Atlantic (like the East Atlantic/Western Russia pattern (EAWR), Krichak et al., 2000, 2002; Krichak and Alpert, 2005a,b). It has been demonstrated that, depending on the area of the Mediterranean region, a high level of SLP synoptic-scale variability is associated with the positive phases of the SENA (Southern Europe Northern Atlantic) and, to a minor degree, to the SCAN (SCANdinavian) patterns. Therefore, intensity of the cyclogenetic activity in the eastern Mediterranean region is to a large extent controlled by the large-scale synoptic processes over Europe and especially by those characterized by mid- and upper-tropospheric southward air-mass intrusions and tropopause folding effects (Krichak et al., 2004). The processes are often associated with the formation of three-dimensional PV structures (PV streamers), jet streaks and low-level jets conditions over the region to the south of the Alps (Buzzi and Foschini, 2001; Liniger and Davies, 2003). These conditions tend to stimulate development of mesoscale convective complexes and Mediterranean cyclones. Intensity, location, duration and orientation of the systems as well as their interdecadal trends in association with those of the main European teleconnection patterns appear to be important elements of the eastern Mediterranean weather and climate trends.

Moreover, these teleconnections are defined on a monthly scale, while sub-monthly large-scale features, such as the well known and relatively frequent euro-Atlantic blocking (Tibaldi et al., 1997), can influence the trajectory of storm tracks and their associated precipitation fields (Trigo, 2004). Winter blocking episodes lasting 10–20 days are associated with a large positive anomaly of the 500 hPa geopotential height above the North Sea and with a higher/lower than average number of cyclones in the Mediterranean/North Sea.

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Finally, since such large-scale analyses are generally based on relatively coarse resolution fields where the subsynoptic and mesoscale characteristics of the cyclones in the Mediterranean region are poorly reproduced, important components of their variability might not be well described yet.

6.3.3. *Trends*

A counting of cyclone centres (without any differentiation on intensity), based on the NCEP re-analysis, which covers the period 1958–1997, shows a reduction of the number of cyclones in western Mediterranean and an increase in the East (Maheras et al., 2001). Linear fit to the data leads roughly to a 15% increase/decrease. Changes are not seasonally homogeneous. If only the rainy period (October–March) is considered, a reduction of the number of cyclones is evident also in the Eastern Mediterranean. Other studies suggest a distinction between the increasing trend of weak cyclones and the decreasing trend of strong cyclones in the Western Mediterranean Sea (Trigo et al., 2000). It follows that the positive trend identified in the Northern Hemisphere storm track for the last decades of the 20th century (Chang and Fu, 2002) is not valid in the Mediterranean region.

The negative trend is confirmed by the analysis of longer time series (Della-Marta and Bhend, 2005). A climatology of cyclone activity has been created using a newly compiled dataset of the North Atlantic–European region from 1850 to 2003, which was developed in the European and North Atlantic daily to multi-decadal climate variability project (EMULATE). These data consist of gridded daily mean sea level pressure fields, which are based on land

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and island stations and have been elaborated using Reduced Space Optimal Interpolation (RSOI) on a 5° × 5° degree grid (Ansell et al., 2005). Seasonally averaged statistics of the cyclone dynamics have been computed with an objective locating and tracking system developed by Murray and Simmonds (1991). Commonly to all cyclone tracking algorithms, subjective decisions had to be made regarding the cyclone locating and tracking algorithm parameters. In order to optimize the parameters, tracking results based on EMULATE data (1948–2003) have been compared to tracking results based on daily NCEP data which were transferred to a 5° × 5° grid. The EMULATE reconstructions in the Mediterranean is shown to be reliable because the RSOI error statistics (see Kaplan et al., 2000) are invariant over time and space for the entire 153 years of the reconstruction indicating that the number of predictors (e.g. station-based observations and marine data) are dense enough to reliably reconstruct SLP on the given grid. See Ansell et al. (2005) for more details on the SLP fields. Significant findings are a marked decrease in winter (DJF) cyclone density over most of the western Mediterranean and an increase in cyclone system density in the eastern Mediterranean for the period 1950–2003 (Fig. 111,A). These findings agree with the results of Maheras et al. (2001). In the longer period, 1850–2003, most of the Mediterranean shows a decrease in cyclone system density (Fig. 111,B). Analysis of the cyclone density time series in the form of a Hovmöller plot shows that the frequency of cyclones over the western Mediterranean is highly variable and exhibits large interannual as well as decadal variability over the last 153 years (Fig. 112).

6.4. Weather Patterns and Mediterranean Environment

As it was briefly mentioned in the introduction, cyclones have a deep influence on important environmental variables and, particularly, on the timing and magnitude of their extreme values. In general, although not all the extreme weather events in the Mediterranean are related to cyclones and most of the cyclones do not produce extreme weather, it is plausible to assume that Mediterranean cyclones influence most of the high-impact phenomena. Moreover, the high variability of cyclone frequency and intensity, within the Mediterranean Sea and its immediate environments, results in contrasting weather conditions in the region, ranging from large arid areas (e.g., Thornes, 1998; Trigo et al., 2002) to the greatest annual precipitations totals in Europe, in the Dinaric Alps (Radinovic, 1987; Trigo et al., 2002). This section shows the correlation of cyclones with rain, winds, waves, surges and even landslides, describes the mechanisms involved and discusses variability and trends of the related phenomena.

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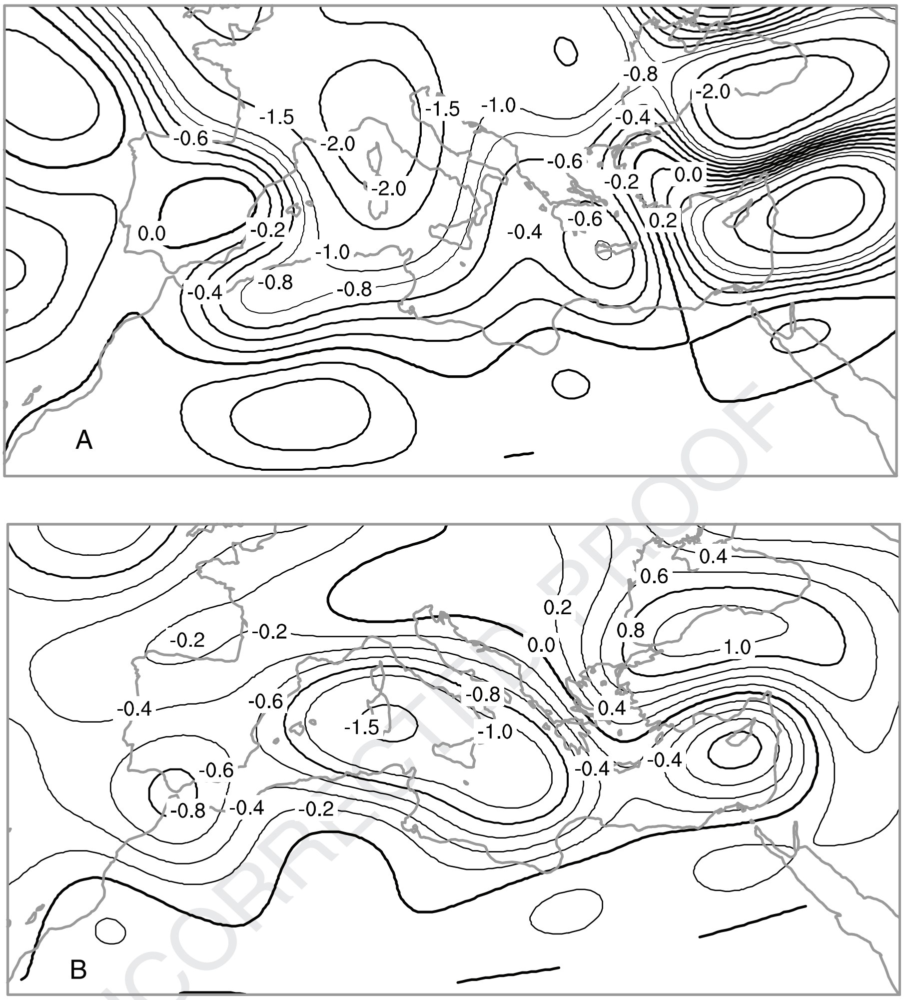

Figure 111: The linear trend in the winter (DJF) cyclone density (A) 1950–2003 and (B) 1850–2003. Cyclone density is the average number of cyclones per unit area at any one time. The trend units are the number of cyclones times 1,000 deg. lat.$^{-2}$ where deg. lat. is a standard length of 1/360th the circumference of the Earth (from Della-Marta and Bhend, 2005, personal communications)

6.4.1. Precipitation

Large quantities of rain require a feeding current of warm and wet air to replace the water removed by precipitation. When vertical stability is close to a critical threshold, such inflow at low levels can favour or lead to instability.

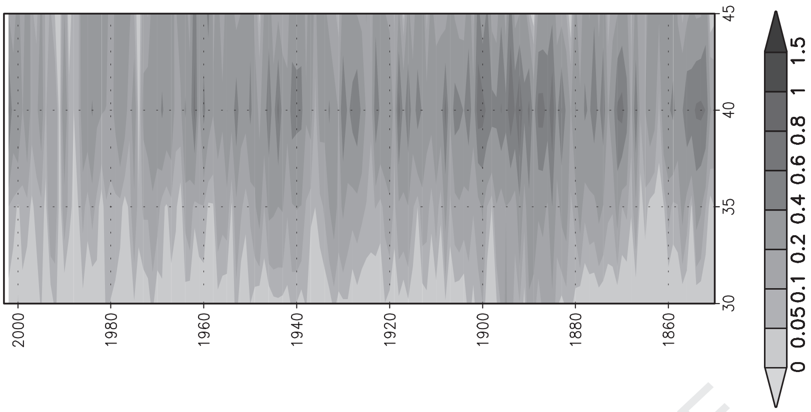

Figure 112: The variability of cyclone density as a function of time and latitude at the longitude of 10°W. The Hovmöller plot *x* axis defines the latitude in degrees North, the *y* axis defines the winter season (DJF) from 1850 (bottom) to 2003 (top). Cyclone density is the average number of cyclones per unit area at any given time. Units are the number of cyclones per deg. lat.$^{-2}$ where deg. lat. is a standard length of 1/360th the circumference of the Earth (from Della-Marta and Bhend, 2005, personal communications).

Therefore, the eastward and poleward sectors of cyclones are suitable places for prolonged and intense precipitation. Moreover, orographic upslope lifting is also very effective for producing ascent of warm humid air and persistent rainfall. In fact, in many places the coastal or inner relief intersects a moisture feeding flow and can force upward motion and orographic rain. The local intensity of the precipitation is very much dependent on the path followed by the cyclone and by the amount of available moisture. The heaviest rain events take place when the cyclone path is in such a position that it produces the local convergence of moist Mediterranean air. In the Western Mediterranean, this feeding flow is southerly for northern Italy and Ticino, south-easterly for France, and easterly for Catalonia, the Balearics and Valencia Murcia (Jansa et al., 2001b). In the Eastern Mediterranean, it is mostly westerly for the Middle East countries and southerly or south-westerly for Greece.

These dynamics explain why heavy rain events are associated with cyclones (only a few events in the eastern Mediterranean and in Northern Italy can be an exception) as humid Mediterranean air is advected against the slopes of the mountain ridges surrounding the basin. In fact, synoptic-scale disturbances have been found responsible for most of the floods both in the Western Mediterranean and in the Eastern Mediterranean. Only a minority of local flash floods has been associated with intense small convective cells, whose presence is not detected in the standard meteorological analysis. It has been established that for most of the cases (around 90%) of heavy rain in the Western Mediterranean there was a cyclone in the vicinity (Jansa et al., 2001b, see Fig. 113, though its intensity could vary from an intense and deep system to quite weak and shallow depressions. In fact, considering the mean value for all cyclones identified in such cases, the average vorticity in a central area of the cyclone of 400 km of radius is $0.8 \times 10^{-4}\ s^{-1}$. In approximately 80% of the events of heavy rain, the location of the cyclonic centre is such that a role of the cyclone in the heavy rain generation and/or location can easily be inferred. The total number of heavy rain events considered is more than 900 (in 5 years, 1992–96). A heavy rain event is defined here as a day with more than 60 mm/day (lowered to 30 mm/day in Algeria) of precipitation in any point of a "territorial unit" (province, department, region or island). Analogously, in Greece about the 92% of rainfall during the rainy period (October–March) is produced by cyclonic patterns (Maheras and Anagnostopoulou, 2003). During the cold season, precipitation in the southern part of the eastern Mediterranean (EM) region is also mainly associated with cyclonic systems of Mediterranean origin. A study carried out for the Negev Desert identified 4 classes of synoptic disturbances responsible for most of the floods, the two most important denoted as the Syrian Low and the Red Sea Trough (Kahana et al., 2002). Therefore cyclones are the cause of most of intense precipitation in the whole Mediterranean region.

From left to right and from up to down S. France, Corsica, Italy, Catalona, Balearics, Sardinia, Valencia, Algeria

The cyclones responsible for precipitation in different areas do not share a common origin and generally a single system affects only part of the Mediterranean region. A study focused on Portugal, Italy and Greece has shown that Atlantic Lows dominate in Portugal, where rainy months are associated with an enhanced number of deep and medium cyclones between Newfoundland and British Isles. Precipitation over Greece is very rarely affected by Atlantic cyclones, but is associated to cyclogenesis inside the Mediterranean region. Italy is influenced from both Atlantic and Mediterranean cyclones, because distant lows sometimes contribute to advection of humidity and some Atlantic cyclones may cross over into the Mediterranean and influence the precipitation over Italy. However, the majority of precipitation sources are Mediterranean cyclones (Pinto et al., 1999). During the cold season, precipitation in the southern part of the eastern Mediterranean (EM) region is mainly associated with cyclonic systems of Mediterranean origin. The cyclones producing intense rain in Israel usually belong to the type of Cyprus Lows or Cyprus Depressions (El-Fandy, 1946; Kallos and Metaxas, 1980; Alpert et al., 1995, 2003; Krichak et al., 2004) and usually start their development in the south-western areas of the Mediterranean Sea, and then migrate to the east. During the migration process, the depressions often weaken, though a very

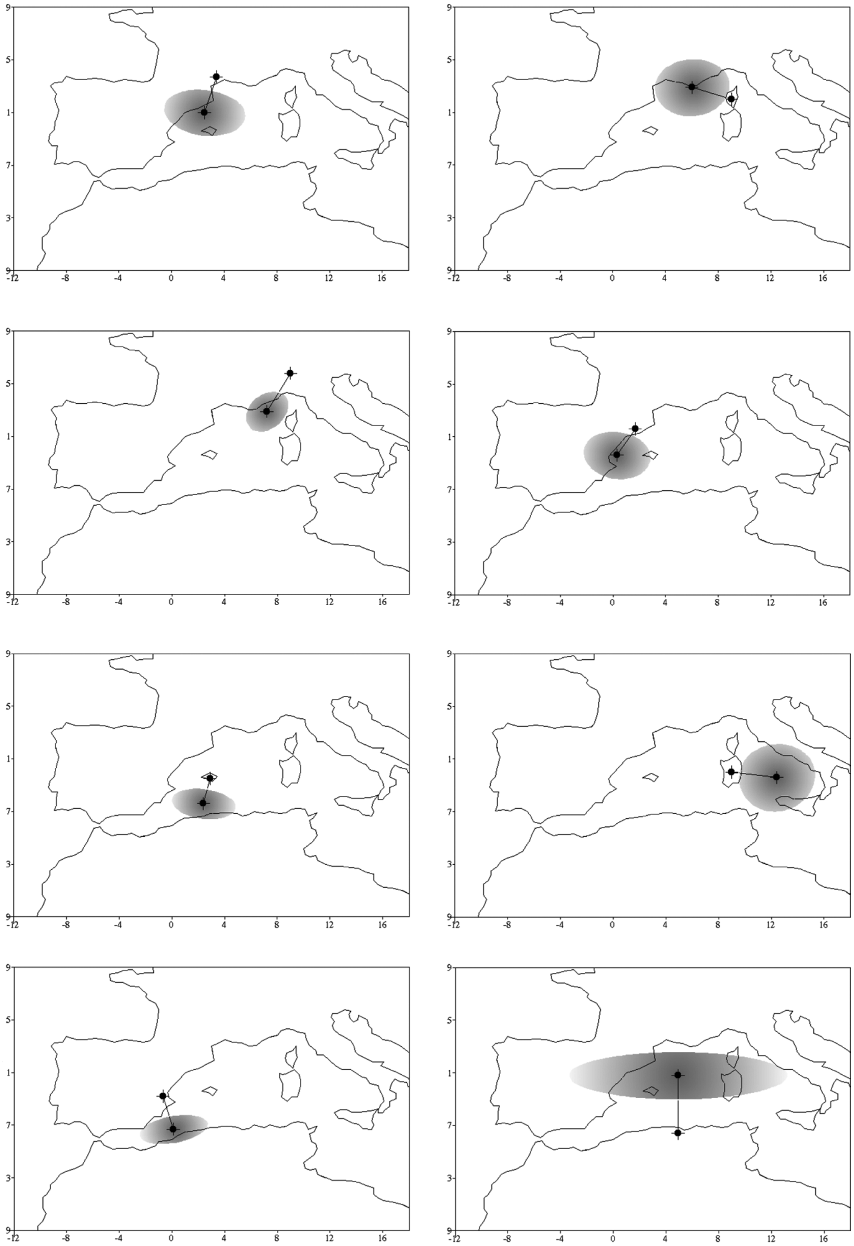

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Figure 113: Most frequent location (elliptic area) of a cyclone in case of heavy rain in some western Mediterranean regions (isolated dot): From left to right and from up to down the locations here considered are (A) SE France, (B) Corsica, (C) North Italy, (D) Catalonia, (E) Balearics, (F) Sardinia, (G) Valencia and (H) Algeria (from Jansà et al., 2001b).

significant strengthening of the cyclones is often observed in the Cyprus area, where the lows regenerate in the lee of the Taurus Mountains of Turkey. This phenomenology corresponds to the key role which cyclones play in the internal redistribution of moisture in the Mediterranean region (Fernandez et al., 2003). The transport of moisture from the Western to the Eastern Mediterranean corresponds to the generation (or intensification) of cyclones in the western Mediterranean and their subsequent eastward motion. Air–sea interaction and significant latent heat flux are likely to play an important role in this process.

In Greece, for the period 1958–2000, precipitation has been analysed considering the frequency of cyclones and the probability of precipitation produced by them. For the majority of stations, in wintertime the decreasing trends of wet-day amount and the probability of rainfall are consistent with the observed changes in frequency of the various types of cyclones. During autumn on the one hand, the probability of rainfall increases for a large number of cyclonic circulation types, which, on the another hand, are characterized by a decrease in frequency. These opposite trends partially compensate, so that the autumn overall amount of precipitation shows a positive trend (Maheras et al., 2004).

An outstanding problem in Western Mediterranean rainfall is the occurrence of catastrophic torrential rains, which tend to occur in the autumn season along coastlines with heavy orography, and the change of relative frequency of moderate/light vs. intense precipitation events. Very little work has been done to link the probability of these events to large-scale extra tropical circulation patterns (Valero et al., 1997), although some analysis of the frequency and intensity of Mediterranean cyclones (Trigo I. et al, 2002) and modeling studies for individual events have been performed (Homar et al., 1999; Romero et al., 1999; Pastor et al., 2001). In the last decades, a tendency for more intense concentration of rainfall seems to have occurred along the Mediterranean coastal areas in Italy and Spain (Brunetti et al., 2001; Alpert et al., 2002; Goodess and Jones, 2002), but this does not seem to be the case for inland areas. In fact, over Italy, results show a negative and significant long-term trend in the number of wet days and a positive one in precipitation intensity, which is significant only in the northern regions (Brunetti et al., 2004). The negative trend in wet days persists since the end of 19th century and is due to the marked decrease in the number of low-intensity precipitation events. An increase in the number of events belonging to the highest intensity interval was observed too, but only in northern regions. The decrease of total precipitation during the wet season in the Northern Mediterranean has been associated with the reduction of intense cyclones (Fig. 114) and to the northward shift of the storm track

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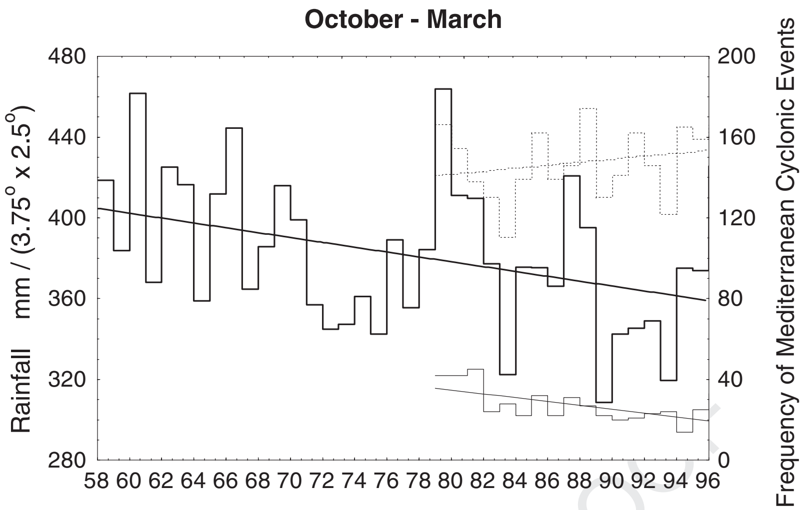

Figure 114: Time series, and respective linear trends, of the total amount of precipitation in the Northern Mediterranean Basin (bold curve, left axis), the total occurrence of intense Mediterranean cyclones (light curve, right axis), and of non-intense cyclones (dotted curve, right axis) for the October–March period (from Trigo and Davies, 2000).

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over Europe in the period from the 1979 onwards (Trigo et al., 2000). However, the analysis of precipitation shows different trends depending on the intensity of the events (Alpert et al., 2002). The torrential rainfall in Italy exceeding 128 mm/day has increased percentage-wise by a factor of 4 during 1951–1995. In Spain, extreme categories at both tails of the distribution (light: 0–4 mm/day and heavy/torrential: 64 mm/day and up) increased significantly. No significant trends were found in Israel, Greece and Cyprus. A detailed analysis of the precipitation in the Valencia Region (Spain) suggests that land use changes in the coastal region result in surface drying, which in turn implies warmer and drier air masses over the coast and higher condensation level and fewer summer storms. It is moreover suggested that higher sea surface temperature can be the cause for the increased number of torrential rain in autumn and winter and that these two factors can be part of a climate mechanism affecting the whole western Mediterranean (Millan et al., 2004, 2005). The consequent redistribution of the daily rainfall categories – torrential/heavy against moderate/light intensities – is of paramount interest particularly in the semi-arid subtropical regions for purposes of water management, soil erosion and flash floods impacts. Specific isolated regions exhibit an increase of extreme rainfall in spite of the reduction of the total amount of precipitation.

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6.4.2. *Strong Winds*

Many strong winds observed in the Mediterranean belong to the category of local winds, like Mistral, Tramontana, Sirocco, Etesian, Bora, Khamsin or Sharav (see H.M.S.O., 1962, or Reiter, 1975, for a general description), that is, they have repetitive location, behaviours and characteristics. Figure 115 shows the location of the main winds in the Mediterranean region.

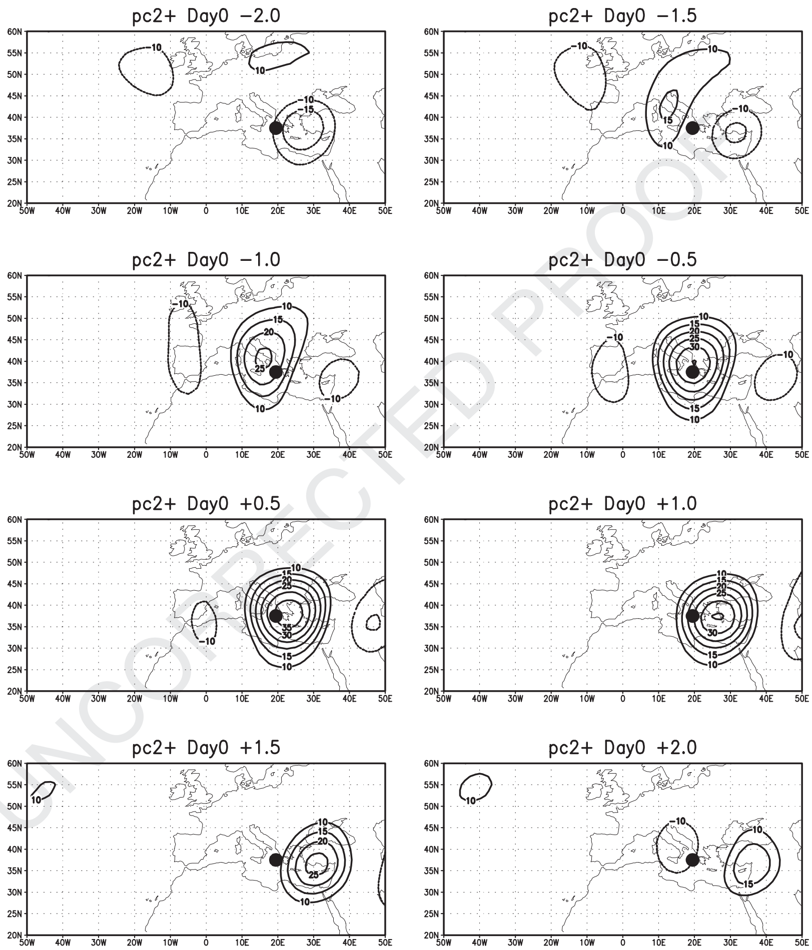

Figure 115: Maps of the lagged correlation with the value in the point indicated by the dot for the 500 hpa synoptic-scale filtered geopotential height. This point is selected as a maximum of explained variance of the precipitation field associated to the EOF describing a moisture transport from western to eastern Mediterranean areas. The maps are meant to describe the evolution of the cyclonic disturbances associated with such transport (From Fernandez et al., 2002).

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In general, there is a connection between the Mediterranean local winds and the Mediterranean cyclones. According to the climatology based on ship observations, the highest frequency of gale storm winds in the Mediterranean occur in the Gulf of Lyons, with large difference with other regions (see, for instance, H.M.S.O., 1962), and they can be identified as winds belonging to the Mistral local wind category. The primary cause for these winds is a cyclone located within the Mediterranean, in or near the Genoa region (together with an anticyclone in France or northwestern Europe) and the high frequency and intensity of the Mistral winds is a consequence of the high frequency and intensity of the Genoa cyclones. Similarly, a low pressure above Italy or west of it produces a Sirocco storms in the Adriatic Sea, where the channelling effect of Apennines and Dinaric Alps strongly intensifies a flow which would otherwise be distributed on a larger front.

The interaction of air flow and orography contributes to the Mediterranean local winds, which can be partially seen as downslope flows or due to channelling effects. The Mediterranean local winds are attributable to orographic mesoscale pressure perturbation induced by the flow–mountain interaction. High- and low-pressure poles of the orographic disturbance (and/or the orographic pressure dipole as a whole) create local areas of strong pressure gradient that provide intense local acceleration, leading to the local wind generation (Campins et al., 1995). The onset of a local wind is, therefore, often quite abrupt. Past the narrow accelerating zone, the winds continue blowing and spreading in an inertial way, although density gradients can contribute to a more efficient wind spreading and extension (Jansa, 1960; Alpert et al., 1982). According to this mechanism, local winds are shallow, only 1.5–2 km deep at most (Jansa, 1933; Campins et al., 1995; Alpert et al., 1998) and may remain quite independent from the basic flow above the mountain.

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On the other hand, the frequent presence of intense cyclones is enough to explain some windstorms blowing within the Mediterranean region and the effect of orographic forcing is not always fundamental. The hot winds blowing from the desert across the Libyan and Egyptian segments of flat coast (Chili, Shimum), the strong easterlies over the Eastern Mediterranean (Saaroni et al., 1998), and the Libeccio storms in the Tyrrhenian Sea, could constitute situations where such interaction is not crucial. Note that the extraordinary storms of December 1979 and November 2001, mentioned in Section 6.0, belong to the category of "intense cyclones". It can be added that the indirect methods of estimating winds (the scatterometers carried by satellite, like in "Quickscat") has given for the sustained winds in one of these storms (November 2001) values as high as 35 m/s. The synergistic combination of both mechanisms, that is the presence of intense cyclone and the generation of local winds, explains the high speed of extreme wind events.

Etesian winds blow over the Aegean Sea and belong to a larger circulation system including northerly winds over the whole Eastern Mediterranean. This Northerly circulation is produced by the combination of a high pressure over Balkan Peninsula or over central Europe and low pressure over eastern Mediterranean and Iraq, generally of thermal origin and corresponding to an extension of the summer Tibetan low to the eastern Mediterranean sea (Repapis et al., 1977). The Etesian winds can be intensified by the presence of a trough in the mid or upper troposphere over eastern Mediterranean. The temperature contrast between land and the Aegean sea can also influence (intensify or weaken) the intensity of the Etesian winds (Maheras, 1980).

It is also worthy to remark that the leading edge of wind streams can act as an internal shallow front. On the other hand, associated with local wind streamers is the formation of orographically generated cyclonic and anticyclonic PV banners, characterized mainly by shear vorticity which often contributes to the Mediterranean cyclogenesis stimulating in some cases the heavy rainfall events (Aëbischer, 1996; Aëbischer and Schär, 1996).

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6.4.3. *Storm Surge*

Storm surge results from the combined action of atmospheric pressure and wind stress on the sea surface. Atmospheric pressure produces what is called the inverse barometric effect, according to which, in steady conditions a low pressure is associated with a sea level increase. Wind stress pushes horizontally the water column and tends to accumulate it at the closed end of a basin. In steady condition, the slope of the sea surface is proportional to wind stress and to the inverse of the water depth. Therefore, the action of wind stress dominates in shallow water and has a large effect in the Northern Adriatic Sea. These dynamics explain the importance of cyclones for storm surges and why the variability of cyclone regimes has an impact on the surge events which, in turn, can be considered an indicator of the cyclones characteristics.

The storm surges in the northern Adriatic, and the consequent flooding of Venice, is caused by intense cyclones in the north-western Mediterranean (Trigo and Davies, 2002; Lionello, 2005). The synoptic patterns determining the surge in the Gulf of Venice present a low-pressure system with a minimum above central Europe or northern Italy (Figs. 116,117) which produces a strong Sirocco wind along the Adriatic Sea. Although these synoptic dynamics are well known, the mechanisms responsible for their frequency and intensity have not been completely understood. It appears that periods with extreme surge events are characterized by a general circulation anomaly, represented by a

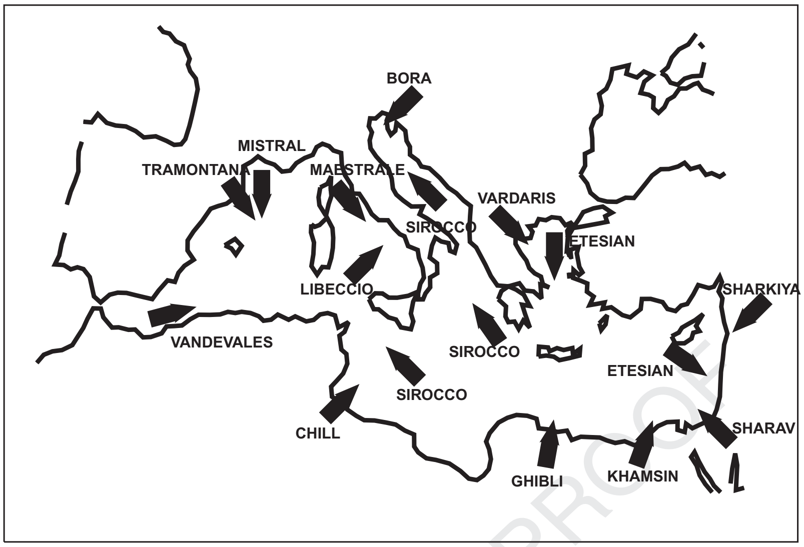

Figure 116: Location and direction of main winds in the Mediterranean region. Note that there are discrepancies between related terms in the different languages. In the French language, Mistral is the northerly wind descending along the Rhone Valley and blowing in the region of Provence, towards the western Mediterranean and Tramontane the northwesterly wind belonging to the same system and blowing in the Roussillon region. In the Italian language Tramontana is a northerly wind and Maestrale the dominant northwesterly wind blowing over most of the western Mediterranean Sea. Tramontana (or Tramuntana) is also the name of the northerly wind (belonging to the Mistral system) in Catalan and Spanish languages, blowing in the north of Catalonia and north of the Balearics.

pattern with a negative centre of action above the Eastern Atlantic, according to which cyclones are deviated south-eastward and penetrate into the Mediterranean Sea from North–West or generate a lee cyclone south of the Alps. This pattern is different from the NAO dipole, whose time behaviour is not correlated with that of the highest surges in the Gulf of Venice. It appears therefore that the storminess associated with the floods of Venice is not related to the NAO (Fig. 118 after Lionello, 2005).

The records of floods in Venice show a clear positive trend, the cause of which is mainly the subsidence of the ground level, whose rate was particularly high in the years from the 1950s to the 1970s, rather than variations in the meteorological

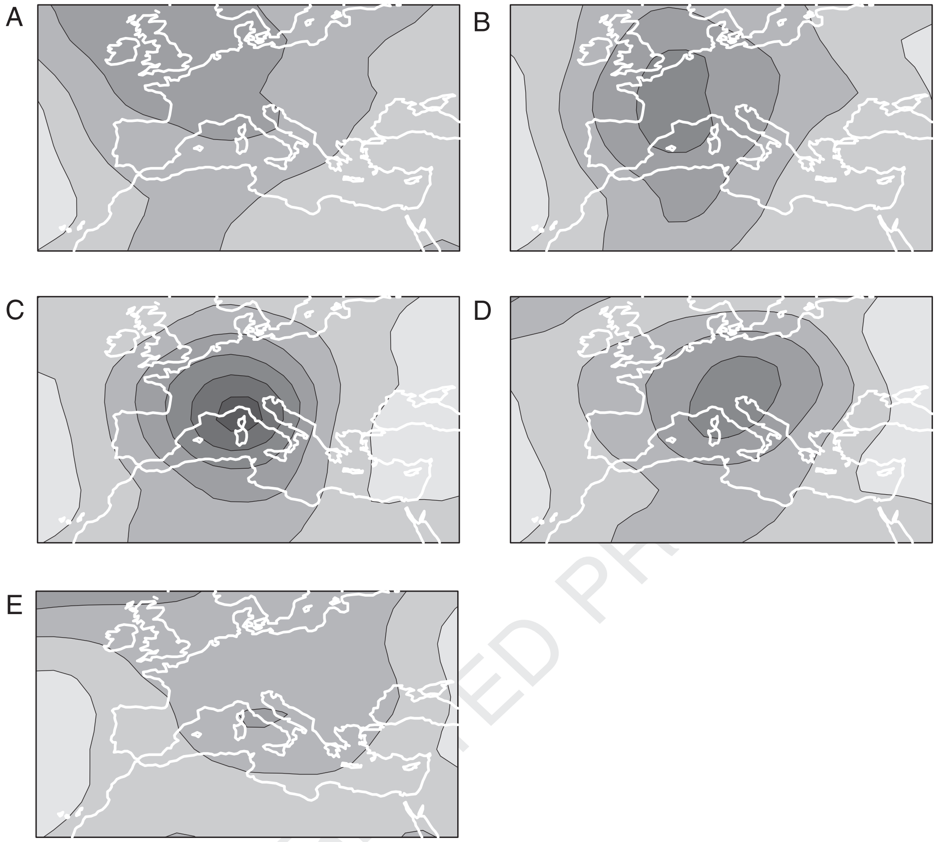

Figure 117: Evolution of the gph1000 field producing the storm surge in Venice. Panels (A) to (E) show the gph1000 composites (in hPa according to the greyscale bar) with a time lag of −48h, −24h, 0h, +24h, +48h with respect to the time of the surge peak. This situation is associated to a main minimum south of the Alps at the time of maximum surge (panel C). The composites are based on events with a peak surge value higher than 70 cm.

forcing fields. If subsidence is excluded, the residual variability, which can be associated with the meteorological forcing, shows trends which are small and dependent on the intensity of the storm surges. During the second half of the 20th century, there is an indication that the frequency of moderate surges is increasing (Pirazzoli and Tomasin, 1999) while major independent surge events do not show large variation (Trigo and Davies, 2002). During the same period, a weak decreasing trend has been identified in the value of extreme levels in Trieste (Raicich, 2003). This behaviour has been shown to be consistent with the variation of the meteorological forcing in the Northern Adriatic area, that is, with

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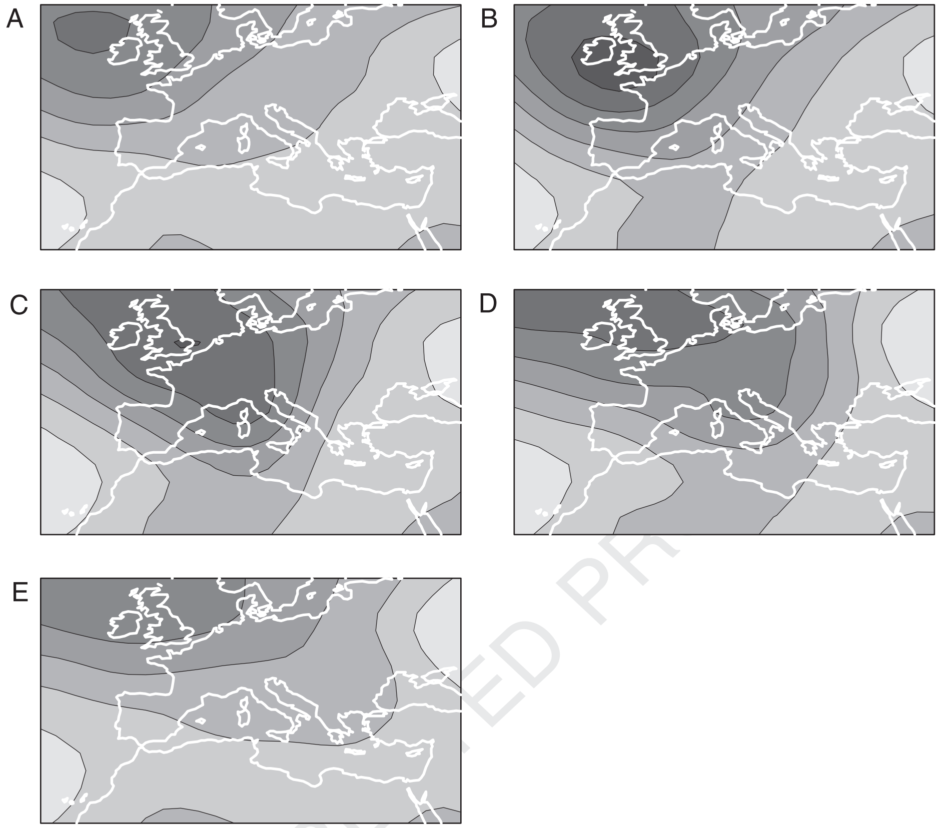

Figure 118: Same as Figure 117, but for a situation associated with a main pressure minimum located north of the Alps at the time of maximum surge (panel C).

more frequent moderate storms and less frequent intense storms. In Venice, there is no evidence of a correlation between extreme surge levels and the ongoing hemispheric warming trend. If the effect of regional sea level rise is subtracted from the data, the record of extremes is dominated by a large interdecadal variability, with respect to which an eventual residual trend is of minor importance (Fig.119, Lionello, 2005). The understanding of this variability, and of its past and future evolution, appears a very interesting scientific and practical issue. It will be important, on one side, to investigate the variability of large-scale patterns associated with it and, on the other side, to find the explanation for its correlation with the periodicity of the sunspot number. This last correlation points to the possible existence of a link between regional climate and external forcing which is not understood yet.

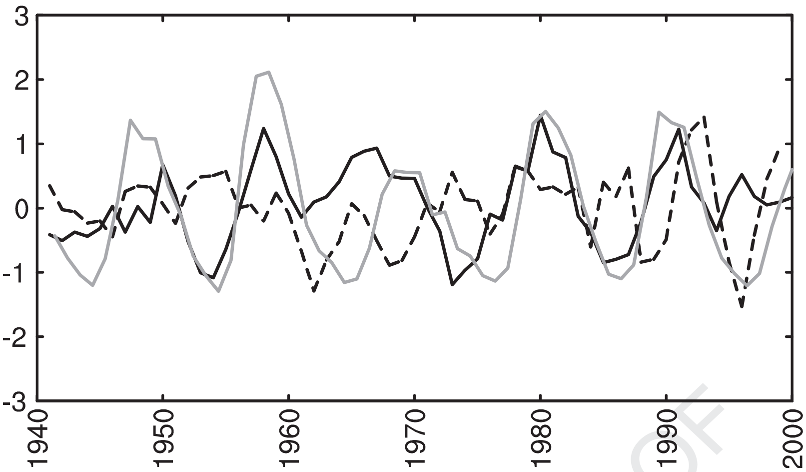

Figure 119: Indexes of the storm surge level time (black continuous), sunspots number (grey continuous), NAO (black dashed) during the 1940–2000 period (years on the *x* axis). NAO and storm surge level data include November and December only. All time series have been smoothed using a 3-year running mean.

6.4.4. Wind Waves

Ocean waves are the consequences of winds, so that intense cyclones are the cause of extreme waves. In this respect storm surges and waves have a common cause. However, waves grow continuously under the action of the wind and their maximum height reflects the average intensity of the wind along the fetch. In other words, waves tend to depend on the integral of the wind stress along their travelling path, while surges are very dependent on its value over the shallow water areas near the coast. Measurements with moored buoys, and models capable of assimilating, analysing and forecasting waves, have demonstrated that high waves (with 5–7 m significant wave height) exist in the Mediterranean, in spite of the relatively short fetches with respect to the Oceanic situations. As already mentioned, analysed SWH (Significant Wave Height) of 10–11 m were encountered in the case of the extraordinary storm of 10–11 November 2001 (Gomez et al., 2002).

It is not simple to reconstruct the wave climatology in the Mediterranean sea because long time-series of instrumental observations are lacking. Buoy observations are mostly available since the 1990s, when national buoy networks were installed. Satellite altimeter data are continuously available only since 1992. Therefore, the analysis of past variability is mostly based on model reconstructions and ship observations. Often, model simulations under-evaluate the SWH,

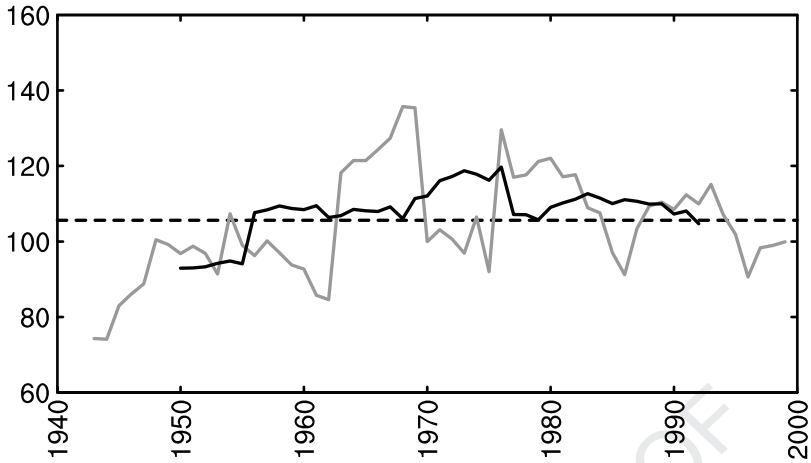

Figure 120: Variation of the 10-year return value (*y* axis, cm.) during the 1940–2000 period. The horizontal dashed line shows the value computed on the basis of the whole 1040–2001 period. The grey and black continuous lines show the values computed using events inside a moving 7-year and 21-year long time window, respectively.

mostly because of lack of accuracy of the forcing wind fields. An example is Fig. 120 which results from a model integration based on the ERA40 reanalysis winds. Figure 120 represents the geographical distribution of maximum SWH values, but presumably does not show the actual height of the more intense events.

There are several compilations and atlas of winds and waves derived from ship observations. There is a big difference between the Atlantic and Mediterranean situation, mainly due to different fetch, which in the Atlantic Ocean is generally larger than in the Mediterranean Sea. Therefore, the Atlantic waves are larger (longer period) than those in the Mediterranean, even when the same wind conditions are considered. Due to the low dissipation in long waves travelling out of the storm area (swell), the Atlantic waves remain relatively high for a long time, and, therefore, the average wave heights in the Atlantic are much higher than in the Mediterranean, where the swell component plays a minor role so that waves are mostly present only in correspondence to strong winds (windsea). In the Gulf of Lyons, in January, the frequency of waves above 1m of SWH is as large as 70%, and the frequency of waves above 2.5 m of SWH south-east of this zone is 20%. The growth of waves with fetch implies that the maximum frequency of high waves is displaced downstream from the maximum frequency of strong winds; for example, the highest waves in the Mediterranean are just downstream of the mistral core. Significant wave heights of 6m or more are reached every year (on average) in this zone of the Mediterranean where their presence is related to the high frequency and intensity of the Genoa cyclones.

Figure 120 confirms the presence of these maxima and shows also other features in the various basins. High waves are present over most of the Mediterranean Sea and tend to reach the highest values where strong wind and long fetch are simultaneously present. The largest maxima are located in the western Mediterranean and in the Ionian Sea, under the action of the Mistral, where the shape of the Mediterranean Sea determines the most effective combination of a long fetch and a strong wind. The Island of Crete interrupts the fetch of the Etesian winds and determines two separated maxima: one in the Aegean and another in the Levantine Basin. Sirocco produces the maximum SWH in the Northern Ionian and in the southern Adriatic. A maximum due to the Bora wind is present in the northern Adriatic Sea, and another due to the Vendavel in the Alboran Sea. In summer, wave height is small over the whole basin and a characteristic maximum is present in the Aegean sea caused by the action of the Etesian winds.

Figure 121 shows the sea level pressure composites associated with high waves in different areas of the Mediterranean Sea. Cyclones located near Cyprus are responsible for high waves in the Levantine Basin, those in the Gulf of Genoa for high waves in the western Mediterranean, while those above Tyrrenian or central Italy produce high waves in the Adriatic and central Mediterranean Sea. Obviously, waves are the result of the action of past winds, so that also

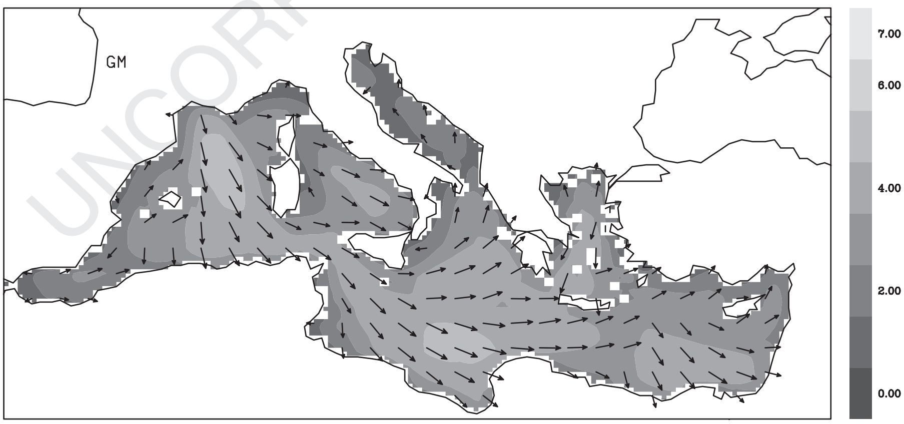

Figure 121: Distribution of maximum wave height as resulting from a 40-year model integration carried out using the ERA-40 re-analysis. Contour levels show the maximum SWH, arrows show the mean wave direction corresponding to SWH maximum (from Sanna and Lionello, 2005).

the past evolution of the synoptic situation contributes to the value and location of the maximum SWH.

Wind wave extremes, obtained from model simulations, show little significant trends. Figure 122 shows the statistically significant variations of maximum SWH in 50 years, on the basis of linear trends derived from the ERA40 reanalysis. The two main features correspond to a reduction in the Ionian and Alboran Sea, which are consistent with a reduction of cyclones in the western Mediterranean. The significant increase is limited to a very small region near the coast of France.

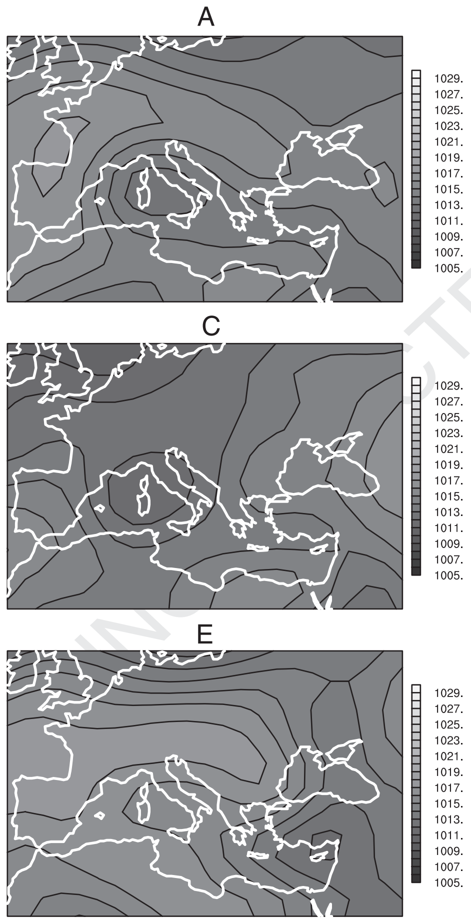

Figure 122: Synoptic patterns associated with extreme significant wave height in different regions of the Mediterranean Sea: (A) Tyrrenian, (B) Adriatic, (C) Balearic, (D) Ionian, (E) Levantine basin (from Sanna and Lionello 2005).

6.4.5. Landslides

Rainfall-induced landslides are usually directly associated with the passage of intense storms of Atlantic or Mediterranean origin. In a recent work, the link between the occurrence of Landslide episodes in Portugal and the storm tracks associated with the NAO pattern has been established (Trigo et al., 2005). Naturally, strong cyclones can produce intense rainfall events that are responsible for the rapid growth of pore pressure and for the loss of the apparent cohesion of thin soils, resulting in failure within the soil material or at the contact with the underlying impermeable bedrock. A different type of association between cyclones and landslides can be found for rainfall periods which are less intense but have a long duration. In this case long-lasting rainfall periods (from 30 days to 90 days), are responsible for the activity of deeper slope movements, such as translational slides, rotational slides and complex and composite slope movements. This is the group of landslide events mostly affected by the large-scale atmospheric circulation mode NAO.

The western Mediterranean Basin is prone to slope instability due to geological, geomorphological and climatic factors. It is widely accepted that high duration/intensity rainfall events (associated with intense cyclone events) are the most important triggering mechanism of landslides worldwide (van Asch et al., 2001). In particular, rainfall-induced landslides have been studied in Portugal (Trigo et al., 2005), Spain (Corominas and Moya, 1999), Italy (Petrucci and Poleminio, 2003) and France (Flageollet et al., 1999). Landslide consequences include damages on property, houses and particularly roads, and can be also related with the increasing human pressure related to urban development throughout the countryside (Trigo et al., 2005).

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6.5. Conclusions

The Mediterranean region is characterized by strong morphological forcing. This characteristic is important for cyclones and their effects. The steep orography surrounding the basin and the complicated land–sea distribution introduce a rich mesoscale structure. On the one hand, these two factors produce a peculiar phenomenology internal to the basin and, on the other hand, they modulate the interaction of the Mediterranean system with global climate patterns by adding sub-regional features. As far as cyclones are concerned, steep orography and complicate land–sea distribution condition the formation and the evolution of cyclones themselves and the effects they produce on the environment.

Mountain ridges are responsible for the presence of many areas with orographic cyclogenesis, land–sea contrast for thermal lows, the presence of moist Mediterranean air with potential for strong diabatic processes conditions the development of cyclonic structures, like small-scale, hurricane-like lows. The triggering mechanism of most Mediterranean cyclones is mostly due to features external to the Mediterranean region, that is mid-latitude (primary) baroclinic waves with high-level potential vorticity anomaly, which interacts with regional structures in the Mediterranean region. The complexity of the mechanisms involved is such that many different categories of cyclones can be identified, according to the region of formation, their seasonality and dominant mechanism of formation. Beside the cyclones entering from the Atlantic sector, there are lee cyclones, thermal lows, African cyclones, mesoscale hurricane-like lows, Middle East cyclones. Further differentiations are possible, as several distinct regions of cyclogenesis exist for lee cyclones and different types of cyclones can be defined in the Middle East. Most cyclones have a radius smaller than 600 km. Seasonality is different for various categories; in general, the overall synoptic activity is higher from November to March, but there are types of cyclones, like thermal lows, Sahara cyclones and Middle East depressions, whose frequency is larger in summer.

Because of this complexity, several large-scale patterns can be associated with cyclones in the Mediterranean area. While the NAO certainly plays an important role (which is dependent on the type of cyclone considered), blocking episodes above central and northern Europe explain a large fraction of variability. Other patterns, like the East Atlantic/Western Russia pattern, exert a significant influence too.

Long-term trend analysis (since 1850) shows a reduction of the cyclone activity over most of the region. During the second half of the 20th century this trend is confirmed for the western part, while an increase of cyclone activity has been observed for the eastern part. However, a very large interannual variability is superimposed on these trend.

Cyclones are associated with many extreme events: precipitation, winds, waves, landslides and surges. Several hazardous weather events take place every year in the Mediterranean region and are a relevant cause of economic losses. In all these events, the geography at regional-scale plays a fundamental role in determining the effects of cyclones on the environment. Prolonged heavy rain episodes take place when a cyclone forces surface currents of humid and warm Mediterranean air to flow over coastal mountain slopes. High waves are produced when the location of the cyclone ensures a long fetch. Strong winds occur when orography locally intensifies the cyclonic circulation around a low-pressure centre. The storm surge in the Northern Adriatic sea takes place when the south-easterly Sirocco wind is channelled along the Adriatic Sea.

This implies that the intensity of the cyclone is not the only factor responsible for its impact, but its position and evolution are also extremely important. Therefore, not only the variability of the cyclone intensity, but also that of its track contributes to the impact on the environment.

In general, extremes present larger variability than average values and, consequently, it is more difficult to identify significant trends. While most of the Mediterranean region, in winter, experiences a decrease in total precipitation and average SWH (Lionello and Sanna, 2005), extremes do not show spatially and temporally coherent trends over the whole Mediterranean region. Extreme SWH levels have become smaller only in part of the Ionian and in the Alboran Sea, while are increasing in a small area close to the coast of France. The frequency of torrential rainfall has been found to increase (percentually wise) in the second half of the 20th century.

6.6. Outlook

This chapter documents the large amount of research which has already been carried out and provides a well-established understanding of many aspects of the Mediterranean cyclones and their effect on the environment. However, in consideration of the importance of these processes, of their potentially damaging effects, and the need for assessing their sensitivity to climate changes, further research is recommended (see also Chapter 8).

A main issue is whether the present archives of data provide an adequate database for the needed analysis. On the centennial timescales it appears that there is an imbalance between regions where phenomena are well documented (e.g. the surge of Venice, Camuffo, 1993), and regions where data are scarce and reconstruction of past events necessarily indirect (e.g. precipitation patterns and extremes on the whole African coast). For the recent decades, where meteorological observations are available worldwide and model reanalysis have been carried out (e.g. NCEP and ERA-40 re-analysis), it has still to be fully investigated whether the subsynoptic and mesoscale characteristics of cyclones in the Mediterranean region are well represented in the available data archives. On this respect, the development of extensive, high-resolution sets of data appears extremely important for addressing unresolved scientific issues. Similar considerations apply for climate change studies. Certainly more work is needed to link modeling of selected events, long-term modeling and observation analysis, with the goal of a coherent long-term climatological perspective. In this respect, interactions between climate and meteorological projects, such as MedCLIVAR (endorsed by the WCRP) and MEDEX (a project of

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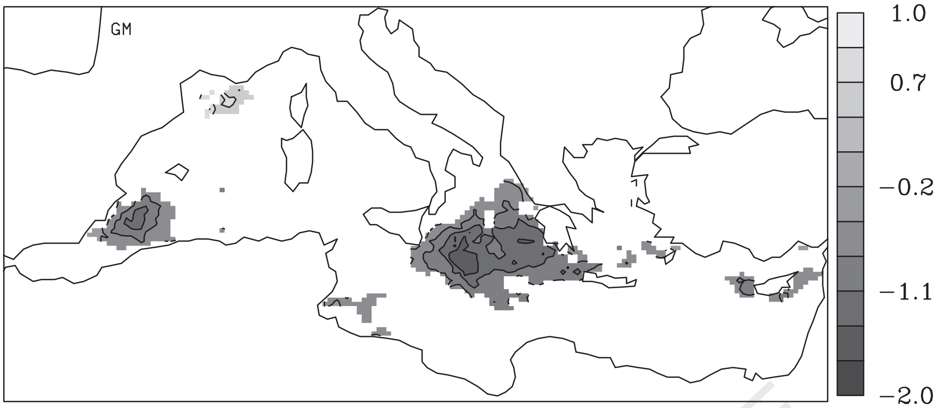

Figure 123: Statistically significant variations of maximum significant wave height in 50 years, based on linear trends evaluated from the results of a 40-year model integration carried out using the ERA-40 re-analysis.

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WMO-WWRP), national initiatives and the involvement of regional institutions are certainly important and potentially fruitful.

The classifications of cyclones should involve an analysis of the sensitivity of the generation mechanisms to climate variability and change, whose identification might help in predicting future scenarios and the change in the frequency and intensity of some specific cyclone types (e.g. the hurricane-like Mediterranean Lows). The availability of regional high-resolution reanalysis, where cyclone structures are well reproduced, might be crucial for this task. Moreover, it is important to identify the deficiencies in the models that account for the inadequacies in simulating the cyclones and their variability. On this point, the connection between the climate of the cyclones in the Mediterranean region and the low-frequency large-scale variability is not sufficiently understood yet. Intensity, location, duration and orientation of the systems as well as their interdecadal trends should be analysed and put in relation with variations of the main European teleconnection patterns. The importance of regional-scale processes (e.g. latent heat release over the sea) and their variability with respect to large-scale forcing (e.g. the meridional shift and/or intensification of the storm track over northern Europe) has not been precisely quantified.

The Mediterranean Sea is characterized by a complex coastline structure, with some highly vulnerable areas (for example, the Niles delta and the Gulf of Venice). Though the main danger for these areas is due to the increased coastal erosion and loss of land that would be produced by sea level rise, the change in storminess is also potentially critical. Variations of the frequency and intensity of sea storms could further increase risks and damages. The analysis of changing wind waves and surge regimes requires detailed impact studies, carried out on

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the basis of sufficiently precise forcing fields, and relies on accurate surface wind field analysis and adequate downscaling techniques.

Variations of cyclone regimes affect the distribution of precipitation. It may be suggested that the variations of the precipitation observed during the last decade over the Mediterranean region are associated with relatively small variations in the transport and characteristics of the air masses. Such changes might be small and not always easily detectable; however, their impact on local climate and climate variability is likely to be large. These variations could have serious consequences for rain intensities in many Mediterranean areas. The danger is twofold. There are areas already under stress because of recurrent water shortage during summer, and areas where torrential rains have produced human casualties and large damages to properties. It is important to identify the factors responsible for the increase in rainfall extremes and reduction of total precipitation A similar understanding is also important for waves, surges and winds

Finally, the links between large-scale patterns and extreme events are not simple, as extreme events are cannot easily associated to extreme values of some large-scale predictors. The characterization of patterns of cyclones, weather extremes and their link to large-scale fields is a topic on which more research is needed.

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