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Discussions

Review Article: Atmospheric conditions inducing extreme precipitation over the Eastern and Western Mediterranean

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Abstract

This review discusses published studies of heavy rainfall events over the Mediterranean Basin, combining them in a more general picture of the dynamic and thermodynamic factors and processes producing heavy rain storms. It distinguishes the Western and Eastern Mediterranean in order to point at specific regional peculiarities. The crucial moisture for developing intensive convection over these regions can be originated not only from the adjacent Mediterranean Sea but also from distant upwind sources. Transport from remote sources is usually in the mid-tropospheric layers and associated with specific features and patterns of the larger scale circulations. The synoptic systems (tropical and extra-tropical) accounting for most of the major extreme precipitation events and the coupling of circulation and extreme rainfall patterns are presented. Heavy rainfall over the Mediterranean Basin is caused at times in concert by several atmospheric processes working at different atmospheric scales, such as local convection, upper-level synoptic-scale troughs, and meso-scale convective systems. Under tropical air mass intrusions, convection generated by static instability seems to play a more important role than synoptic-scale vertical motions. Locally, the occurrence of torrential rains and their intensity is dependent on factors such as temperature profiles and implied instability, atmospheric moisture, and lower-level convergence.

1 Introduction

Extreme precipitation events can lead to flooding and pose a threat on human lives and infrastructure. Several factors can contribute to the development and occurrence of heavy rainfall inducing floods over the Mediterranean Region (MR), such as meso-scale convective systems (Dayan et al., 2001; Delrieu et al., 2005), cyclones (Alpert et al., 1990a; Homar and Stensrud, 2004), upper level troughs (Kotroni et al., 2006; Knippertz, 2007) and large-scale circulation teleconnection patterns (Xoplaki et al., 2004; Krichak and Alpert, 2005; Feldstein and Dayan, 2008). However two essential ingredients are required to generate extreme precipitation. The water vapor content of the atmosphere must be high and the onset of rain must be triggered by a thermodynamic or dynamic process.

In this study we review the scientific literature dealing with the conditions that can lead to extreme precipitation events in the Eastern and Western Mediterranean (EM, WM) regions. Following the description of the climatological background of the region (Sect. 2), the moisture sources for developing intensive convection over the basin are specified (Sect. 3). Next, the interaction between the tropics and extratropics manifested by several atmospheric processes is discussed (Sect. 4). This discussion is followed by a description of the mechanisms governing the rainfall variability (Sect. 5). The next two sections review the scientific literature dealing with the spatial distribution of deep convective precipitation over the MR resulting from the synoptic patterns inducing rain over both parts of this region (Sects. 6 and 7). Next, we identify the dynamic and thermodynamic factors in the upper level and at the surface involved in producing heavy rain storms over the study region (Sect. 8). In Sect. 9 the main findings and conclusions are summarized.

2 Mean rainfall over the Mediterranean Region

There are substantial regional differences in rain rates over the MR. The maximum rainfall rate (3–5 mm day^{-1}) occurs over the mountainous regions of Europe, while the minimum rainfall rate is over North Africa ($\sim$ 0.5 mm day^{-1}). An average rain rate of $\sim$ 1–2 mm day^{-1} is observed over the whole region with a maximum over its western part (Alpert et al., 2002; Raveh-Rubin and Wernli, 2015). The climate over the MR, defined by Koeppen as "Interior Mediterranean" (Csa), is temperate with winter rain on most of its parts. During the summer, the Subtropical High drifts northward and eastward covering the whole African coast. During this season, sinking air produces a strong upper level subsiding inversion (Dayan and Rodnizki, 1999; Dayan et al., 2002). In winter the Subtropical High pressure cell moves south, enhancing the

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probability of a penetration of rain-producing mid-latitude synoptic systems as well as the development of extra-tropical cyclones in the Mediterranean Basin (MB). The main tracks of lows migrating into the Mediterranean in winter are found over the northern part of this basin (Fig. 1).

Penetrating cyclones may deepen over the warm Mediterranean waters, while cyclones forming are focused on four cyclogenetic centers, with a dominating region in the Gulf of Genoa, and secondary centers in south Italy, Crete and the Cyprus Island (Fig. 2). The latter center is characterized by a stronger baroclinic character as compared with other MB cyclogenetic centers (Maheras et al., 2002).

Penetrating frontal lows are the main cause for a significant amount of summer rainfall over the north-western part of the MR, amounting about a quarter of the yearly sum (Romero et al., 1998). Over the east and south-east MR, summer cyclonic activity vanishes due to the predominance of the Subtropical High aloft leading to subsidence. Consequently, all regions featured by a Mediterranean climate regime: E. Spain, S. France, South and Central Italy, Greece, Southern Turkey, Syria, Lebanon and Israel are characterized by winter rains only (Raveh-Rubin and Wernli, 2015) (Fig. 3). Northern Italy and the northern Adriatic feature maximum rain amounts during fall, caused by an air mass destabilization over the warmer sea surface temperature (Ventura et al., 2002). Maximum rain amounts during spring are typical for the internal continental regions such as the Anatoly Plateau (Turkey), and Central Spain. They are caused by strong free convection conditions in these regions.

A contributing factor to the Mediterranean cyclogenesis are the relatively high sea surface temperatures (SST) as compared to the colder layer of air above it during the fall and the winter, which increases the instability of shallow atmospheric layers enhancing the generation of lows over the sea (Marullo et al., 1999; Flocas et al., 2010).The satellite SST shows that during the winter the sea SST is warmer and more homogeneously distributed than the ground temperature, spanning from ~ 12 to 18 °C) (Fig. 4).

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3 Moisture sources

Even though North Atlantic moisture sources may be important in controlling the interannual variability of heavy precipitation events (Drumond et al., 2011) in the MB, the moisture generated within this basin is the major moisture supply associated with winter Mediterranean cyclones especially whenever long fetch of regional winds, e.g., Sirocco, are associated with abundant moisture (De Zolt et al., 2006; Winschall et al., 2014). Over the EM, however, this source is less effective as a moisture supplier during the transitional seasons featured by southeasterly flows at low tropospheric layers. Levy et al. (2008) have indicated that such easterlies amounted to nearly 40 % of the total surface flow in winter. Earlier studies by Dayan and Sharon (1980), Krichak et al. (1997), and Saaroni et al. (1998) have shown, for example, that the area over the Red Sea quite often serves as a corridor for transporting air masses from the Arabian Sea and Tropical Africa into the southeastern Mediterranean. The air coming from the south, still warm, absorbs large quantities of water vapor while crossing the northern part of the Red Sea up to the EM. The crucial moisture for the developing convection under such situation is confined to the mid-tropospheric layers. Moisture from remote origins, such as the Inter-Tropical Convergence Zone (ITCZ) is playing an additional role, as shown for a specific rainstorm event by Krichak and Alpert (1998). Both observations and numerical experiments confirmed a major moisture source associated with intensified tropical convection over Eastern Africa. Evidence was given that both moisture sources were not independent. The enhanced convection contributed to the intensification of the Subtropical jet (STJ) over the Red Sea, which in turn triggered the development of the low level trough. Independent of the Red Sea source, moisture from the African part of the ITCZ played a role in a spring rainstorm (March 1985) over the EM region. Zangvil and Isakson (1995) found that the moisture originated from Tropical Africa and that the maximum transport took place in the 850–700 hPa layer. Dayan et al. (2001), using satellite water vapor imagery, showed that moisture originating from western Tropical Africa was transported within the

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midtroposphere to the southern Levant during a severe autumn storm (October 1997) that stroke the southern parts of the EM and stimulated intense convection under conditional instability associated with synoptic-scale forcing. Ziv (2001), in an analysis of a rainstorm over Egypt and southeastern Israel associated with a tropical plume, also found that the moisture originated from western Equatorial Africa. It was transported eastward at the midlevels above the dry planetary boundary layer of Sahara to the EM.

For the western parts of the MR, the role of remote moisture sources for extreme rainfall events has been demonstrated by Knippertz and Martin (2005), for example. They discuss a case of extreme precipitation in the Atlas Mountains associated with a plume of moisture from low latitudes advected along the West African coastline. Even for events in the Central Mediterranean, a significant role of moisture import into the basin was detected. Pinto et al. (2013) found that moisture advection from the North Atlantic plays a relevant role in the magnitude of the extraordinary rainfall events over Northwest Italy, while humidity transports from the North Atlantic are less important for weaker events in the same region. These results show that a significant, if not the major part of moisture necessary for developing intensive convection over the MR can be originated from distant upwind sources and transported at elevated tropospheric layers. As found by Knippertz and Wernli (2010, their Fig. 1), there is a maximum of tropospheric poleward moisture transport in the vicinity of the Atlas Mountains, though weaker than the respective meridional moisture transports in other regions of the world. They also show that outbreaks of tropical moisture over the western and central Atlantic can affect the Mediterranean as the track may turn eastward in conjunction with the STJ (Knippertz and Martin, 2005), thus making the Tropical Atlantic a relevant moisture source (Duffourg and Ducrocq, 2011; Raveh-Rubin and Wernli, 2015). Drumond et al. (2011) analyzed the variation in moisture sources related to drier and wetter conditions in regions around the MB using the Lagrangian 3-D FLEXPART model for backward trajectories. They conducted a seasonal analysis, identifying years with the lowest/highest rates of precipitation averaged over eight different continental regions (Iberian Peninsula, France, Italian Peninsula, Balkan

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Peninsula, Eastern and Western Mediterranean, Central and East North Africa). The results show that the Iberian Peninsula is mostly influenced by moisture from the Mediterranean and Atlantic (western European coast to the Subtropical-Tropical North Atlantic, STNA). France is influenced by moisture from Western Europe and STNA. The Italian and Balkan Peninsulas are affected by moisture originating in the MB.

4 Tropical extra-tropical interactions

Interactions between the tropics and extratropics is manifested by several atmospheric processes, such as deep upper-level troughs penetrating into the tropics or Rossby waves connecting mid and low latitudes. Sometimes, during transitional seasons, especially in autumn, the global systems deviate from the long term seasonal climatology and the EM, being on the edge of subtropical and mid-latitude climate, can be affected by the interaction of tropical and extra-tropical systems (Dayan et al., 2001). A typical phenomenon manifesting the transport of tropical moisture to the extra-tropics is the "Tropical Plume" (TP). These plumes are referred to elongated cloud bands at mid and upper atmospheric levels extending from the tropics into subtropics. Kuhnel (1989) classified cloud bands crossing Africa into two separate bands: the Saharan (i.e., West African) and the East African band, both with frequency maxima in winter. The Saharan cloud band, about three times more frequent than the East African band, occurs between October to March whereas the latter is most frequent between February and May. The East African band, affecting mainly the eastern MR, was not studied in depth. Observations of the rainfall associated with the tropical cloud development related to such jet streams extending from the tropics into the subtropics analyzed by Tubi and Dayan (2014) as well as in previous studies in this region (e.g., Dayan and Abramski, 1983; Ziv, 2001; Rubin et al., 2007) indicate that their contribution to the water budget in the Middle East, particularly in arid and semiarid locations is important. Dayan and Abramski (1983) described a major and fatal flooding event caused by very heavy showers which occurred over the south-eastern parts of the

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MB. The involved TP originating from Western Africa was attributed to a pronounced disturbance in the STJ over Northeastern Africa. Ziv (2001) examined a rainstorm associated with a TP over Eastern Africa and the Middle East and pointed at wind flow acceleration at the jet entrance contributing to tropical convection and near-tropospheric divergence in the inflection point ahead of the accompanying subtropical upper-level trough. The main canonical characteristics of rain producing TPs over Eastern North Africa were identified by Rubin et al. (2007) while investigating ten selected plumes between 1988 and 2005. They have shown that the moisture supply for the rain production is composed of horizontal moisture convergence near the TP origin and a fast and effective mobilization along the plume toward the target area (i.e., the EM). Their analysis has put in context the efficiency of TPs in the long range transport of mid-level moisture and their role as rain contributors over desert regions. In their recent study, Tubi and Dayan (2014) identified a new TP cluster originating in Central to Eastern Africa, referred to “southern” plumes, of a shorter fetch. In this TP category, the STJ is accompanied by an anti-cyclonic flow over the south of the Arabian Peninsula, which serves as an essential vehicle transporting moisture from Central to East African sources. An objective climatology of tropical plumes (Fröhlich et al., 2013, their Fig. 7) suggests that in particular the number of Atlantic plumes greatly exceeds those occurring south of the MB. They can also affect the MR when moisture advection turns eastward in conjunction with the subtropical jet (e.g. Knippertz and Wernli, 2010). The typical structural characteristics of TPs were summarized by Knippertz (2007) and are displayed in Fig. 5. TPs typically exhibit a poleward and eastward orientation with an anticyclonic curvature in the subtropics. Most TPs originate from an active segment of the ITCZ and are located at the eastern side of an upper level trough, which penetrates into the tropics. It should be noted that relevant moisture outbreaks from the low latitudes and the occurrence of extreme rainfall events over the MR have also been observed in conjunction with Atlantic hurricanes (Reale et al., 2001; Turato et al., 2004).

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Lavers and Villarini (2013) have shown that TPs, they refer to as an Atmospheric River (AR), do cause extreme rainfall over the WM particularly in fall and winter. Based on a latitude dependent integrated vapor transport threshold calculated between 1000 and 300 hPa, and daily observed gauge-based precipitation for 1979–2011 they further showed that about 10 % of the annual maximum daily precipitation events in fall and winter are related to ARs.

5 Mechanisms governing extreme rainfall variability

In the EM, the synoptic-scale system responsible for about 90 % of the annual rainfall is an extratropical cyclone – the Cyprus Low (Goldreich, 2003). The surface low over the EM featuring the heaviest rainfall days is generally accompanied by high pressure over the WM (Fig. 6a). The concurrent upper-level system (Fig. 6b) consists of a pronounced trough extending toward southwestern Turkey.

An analysis performed by Ziv et al., (2006) based on rainfall time series for December, January and February for the period of 1950–2002 over the EM revealed that an upper level trough extending from East Europe toward the EM is closely linked with the seasonal rainfall over this part of the MR, as expressed by a correlation of −0.74 between the 500 hPa gph at 32.5° N, 35° E and the rainfall. Location of the Cyprus low over the EM is an important contributing factor to extreme rainfall over the region. Saaroni et al. (2010) indicated that deep Cyprus Lows, located to the north and east of Israel, produce the highest amounts of daily rainfall as compared to other synoptic systems, averaging to 16.4 and 10.9 mm d^{-1} respectively for November–March of 1954–2004. In a regional context, wet rainfall conditions were found to be characterized by negative pressure departures and westerly circulation over the EM. Moreover, in many cases dry conditions over the EM were associated with below normal pressure conditions over Central or Western Europe, while wet conditions with above normal conditions over the same region, thus, reflecting the so-called Mediterranean Oscillation (MO) (Kutiel and Paz, 1998; Tornros, 2013). Aiming

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to determine the Eurasian pressure patterns which are associated with dry or wet conditions over the EM, Krichak et al. (2000) found that during dry spells positive SLP and H-500 anomaly patterns prevail over Eastern Europe while negative SLP and H-500 anomalies are found over southwestern and Western Europe. The impact of the North Atlantic Oscillation (NAO, Hurrell et al., 2003), is large over the WM but weak and opposite in phase in the Levant (Kelley et al., 2012). This is manifested by the EM precipitation response to this oscillation which is weak and in anti-phase to that in most of the rest of the Mediterranean (Kelley et al., 2012). A further step toward understanding the association of rainfall anomalies with large scale, high amplitude North Atlantic anomalies was undertaken by Eshel and Farrell (2000). They analyzed the mechanisms of EM rainfall variability as controlled by modulations of the relative intensity of the climatological subtropical high and sub polar low, namely, the NAO. Based on rainfall monthly data spanning 1940–1994 for 16 stations over the EM, they examined the differences in large scale dynamical atmospheric state between the five driest and five rainiest years. They found that elevated Greenland pressure (i.e., negative NAO phase) is accompanied by an anomalous cyclone over the MB. These anomalies result in anomalous southerlies which warm the EM and enhance air mass ascendance which lead to intensive precipitation. Evidence for influence of the Pacific El Niño/Southern Oscillation (ENSO) was found and studied by several investigators (Price et al., 1998; Mariotti et al., 2002, 2005). Alpert et al. (2002) found that torrential rainfall categories ($> 64\,\mathrm{mm\,d^{-1}}$) tend to peak in El-Nino years mainly over Central Mediterranean (Italy) for the El-Nino years 1953, 1965, 1982/83, and 1986/87. However, the influence, over the EM is seasonally dependent, small, and intermittent (Ziv et al., 2006). In order to assess the global circulation anomalies with which the WM rainfall is associated, Mariotti et al. (2002) analyzed the interannual variations of rainfall over this part of the basin in relation to major ENSO events based on SST anomalies. They found a positive correlation between CRU rainfall, NCEP rainfall and NCEP moisture flux and the Nino3.4 index in autumn (Fig. 7).

Dünkeloh and Jacobeit (2003) used a canonical correlation analysis to identify the main coupled circulation – rainfall patterns in the Mediterranean based on CRU gridded rainfall data and geopotential height fields from the NCEP reanalysis data set. The most important pattern throughout the year, they identified, is the seasonal cycle of the MO, a pattern that is well correlated with both the Arctic Oscillation and the NAO.

With respect to the most western part of the WM, Zorita et al. (1992) analyzed the interaction of atmospheric circulation and SST in the North Atlantic area in winter with precipitation variability over Iberia. They found that the most dominant process responsible for the variability of rainfall appear to be the intensity of the westerlies and the frequency of storms imbedded in it rather than the presence of regional or remote SST anomalies. However the role of the SST in the development of torrential rain events is controversial. Millan et al. (1995) argued that enhanced evaporation resulting from temperature differences between European continental air and the relative warm Mediterranean Sea in autumn can become a key factor in determining the onset of torrential precipitation. Fernandez et al. (1997) stress the importance of knowledge of SST as critical factor for an accurate model forecasting of Mesoscale Convective Systems (MCS) over the WM in fall. Pastor et al. (2001), based on numerical simulations using a mesoscale model point on SST's influence on two torrential rain episodes while using different SST datasets derived from satellite data. In a recent study, Pastor et al. (2015) have shown that regions of high heat/moisture air sea exchange over the MB are prone for enhancing convection leading to torrential rain. An investigation of the link between atmospheric circulation patterns and Iberian rainfall for the period 1958–1997 lead by Goodess and Jones (2002) revealed that the NAO negative mode produces high-pressure blocking in the northeast Atlantic, and a more meridional circulation than the opposite, NAO positive mode, consistent with Moses et al. (1987). Moreover, upper-air troughs and incursions of polar air over the Mediterranean are more frequent and the Atlantic storm tracks are displaced south. They suggest that all these factors are conducive to wetter conditions in the WM. This is in line with Toreti et al. (2010), who analyzed daily extreme precipitation events

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during the winter season at 20 Mediterranean coastal sites covering the period 1950–2006. They showed that Western Mediterranean anomaly patterns (GPH at 500 hPa and SLP) associated with extreme precipitation events show dipole structures favoring mid-tropospheric southwesterly/westerly flow, which indicates moisture transport from the Atlantic. Other evidence on the role of the NAO on heavy precipitation was demonstrated and studied by Scaife et al. (2008) who found a statistically significant negative correlation between precipitation events exceeding the 90th percentile and the NAO, for the WM region, using the (EMULATE) database described by Moberg et al. (2006) (Fig. 8).

Using the NCEP data set for the winter season, a study by Yiou and Nogaj (2004) confirms this result. Similar patterns of influence for the NAO on extreme precipitation during winter are also found by Kenyon and Hegerl (2010), using station based climate indices. However, as mentioned previously, the relationship of the NAO and rainfall is not uniform over the whole MB. Cullen and deMenocal (2000) showed that rainfall is negatively correlated with the NAO over most of the basin, while its southeastern parts exhibit a positive correlation. Brandimarte et al. (2011) checked this relationship over two regions in the basin: Southern Italy, and the Nile Delta (Egypt) representing western and eastern parts of the MB respectively. Their results showed a negative correlation over southern Italy and a low, though significant positive correlation over the Nile Delta which are consistent with Cullen and deMenocal (2000). The results obtained recently by Krichak et al. (2014) based on a correlation between monthly NAO index and the frequency of days that have extreme values (using the 90 % threshold value) of precipitation over Western Europe are consistent with the previous studies. However practically no NAO role in determining frequency of days of extreme precipitation was detected in the EM.

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6 Spatial distribution of deep convective precipitation over the MR

The moisture content of an air parcel is critical in knowing if conditional instability contains the potential for this parcel to become buoyant. The main origin of buoyant instability is both latent and sensible heat produced at low atmospheric levels caused by solar heating and evaporation. Intense convection can then produce an intense precipitation event (Massacand et al., 1998).

There is no universal meteorological definition of when a rainfall event should get the attribute "severe". Based on the statistical distribution of large rainfall amounts, Boni et al. (2006) distinguished ordinary and extraordinary values, thus finding a more objective way of classification applied to station data. For events associated with intense deep convection, it is possible to consider satellite radiation measurements to obtain information about the spatial distribution of intense convective rainfall events. Such an approach was suggested by Funatsu et al. (2009). It is based on measurements with the AMSU B microwave radiometer onboard of NOAA satellites. AMSU-B features 3 channels designed to measure atmospheric moisture. These moisture channels (3, 4, and 5) detect the presence of hydrometeors through the scattering of radiation which lowers the brightness temperature compared to its surroundings. Based on these data, Funatsu et al. (2009) identify and detect areas of deep convection. They suggest a deep convective threshold (DCT) corresponding to an accumulated rainfall of at least 20 mm in 3 h in 50 % of the cases in the MR. This threshold was validated by Funatsu et al. (2007a, b) with radar and rain gauges from meteorological ground stations for selected heavy precipitating events. The spatial distribution of deep convection (Fig. 9) features a pronounced seasonal signal with convective events more frequent over land in summer; these spots of DCT migrate toward the sea in autumn, becoming most frequent over the sea in winter. Most active regions for deep convection are the Alps, the western Croatian coast, the south of France and the area of Tunisia. Some of these regions coincide with areas characterized as vulnerable to heavy precipitation inducing floods over the MR (Haratz

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et al., 2010). Claud et al. (2012) and Alhammoud et al. (2014) have extended the data set using measurements from the AMSU-B and the Microwave Humidity Sensor instruments onboard additional NOAA satellites. They found that interannual variability of deep convection is strongest along the northern coasts of the MB. While there is less variability over the sea. Alhammoud et al. (2014) found a maximum frequency of deep convection over the MB in September–October and a minimum one in June and July, which is consistent with Funatsu et al. (2009) and Melani et al. (2013).

7 Synoptic circulation patterns inducing heavy rain

Several studies analyzing the important role of synoptic forcing on the generation of extreme precipitation over the MR have been conducted previously, (e.g., Lionello et al., 2006; Ulbrich et al., 2012; Xoplaki et al., 2012). The typical ingredients leading to heavy rainfall are an unstable air mass, a moist low-level jet, the presence of orography orthogonal to the flow and a slowly-evolving cyclonic synoptic pattern (Doswell, 1998; Miglietta and Rotuno, 2010). Even though occurrence of heavy precipitation events are not always attributed directly to intense cyclones, for most of the cases, a surface cyclone is usually positioned at a distance of few hundreds of kilometers to the heavy rain region (e.g., Jansa et al., 2001; Reale and Lionello, 2013; Raveh-Rubin and Wernli, 2015). For this sake getting insights on the synoptic climatology of cyclones for the whole MB (i.e., seasonal frequency, spatial distribution and regions favoring cyclogenesis) is important. A significant contribution to this task is the comprehensive paper (Campins et al., 2011) and the MEDEX data base as part of the MEDEX program (Jansa et al., 2014).

In the EM high rain depths are often associated with active cold fronts, in turn linked to midlatitude extra-tropical cold lows originating over the eastern part of the basin (e.g., the Cyprus Lows; Fig. 6a). The flow associated with these lows may lead to heavy precipitation over the Levant region as a result of forced convection while crossing mountain ridges. Intensive rainfall in the southernmost parts of the EM is

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generated mainly by a derivative of the Cyprus Low – the Syrian Low. Syrian Lows (SL) are Mediterranean mid-latitude cyclones that deepen while approaching Syria (Kahana et al., 2002). SLs are the second most frequent synoptic-scale cyclone type, producing major floods over the southern part of the region (Kahana et al., 2002, 2004). An objective selection of all EM cyclones for four consecutive winters (1982–1986) undertaken by Alpert and Neeman (1992) found that such Syrian cold cyclones are slightly more baroclinic and feature larger than average latent heat fluxes, indicating the importance of local convection. In contrast to the Mediterranean midlatitude cyclones, the Red Sea Trough (RST) is a tropical system incursion, characterized by a low barometric trough extending northward from Equatorial Africa, crossing the Red Sea and the EM regions. Occasionally, under specific upper air support conditions, this synoptic scale system can become active and generate stormy weather with intense precipitation, referred hereafter as an Active Red Sea Trough (ARST) (Dayan and Morin, 2006). This tropical system, accounting for most of the major floods over the southeastern EM (Kahana et al., 2002) occurs mainly during fall (Dayan et al., 2001). The ensuing destabilization of the lower troposphere leads to a rapid formation of deep convective clouds imbedded in severe Mesoscale Convective Systems (MCSs) producing heavy precipitation and thunderstorms (Fig. 10a and b).

The southerly winds over the EM at the 500 hPa level were found to be essential for moisture transport of tropical origin to the region. The knowledge gained from detailed synoptic-scale analysis of several rainstorms associated with an ARST that have impacted the southern EM (Dayan et al., 2001; Ziv et al., 2004; Krichak et al., 2012) provides a basis for the generalization of the main characteristics of this synoptic system. In all cases, the storm was initiated while hot and dry air blew from the east at lower levels, leading to a buildup of conditional instability throughout the troposphere. All these storms, in their initial stage, were characterized by a MCS with an intensive warm core moving from Sinai Peninsula northward over the Negev Desert and the Dead Sea Basin (Fig. 10b). The physical characteristics of MCSs were defined on the basis of enhanced infrared satellite imagery developed by Maddox (1980) and

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appear as a large circular region composed of high clouds that gradually become colder and higher toward the center of the system (Fig. 10b). Such precipitative elements crossing the south-eastern parts of the EM can produce intense rainfall, inducing floods due to their large aerial extent and long duration. As stated in Sect. 3 over the southeastern Mediterranean the STJ can serve as a conveyor belt of moisture in mid- and upper tropospheric layers, often originating from Tropical Africa. In addition to this important role, the synergistic interaction of these jets with the mid-tropospheric diabatic processes assists in intensifying cyclogenesis and contributes significantly to deep synoptic scale ascent over the region (Ziv et al., 2004). Dayan et al. (2001) analyzed an intense rainstorm that struck the EM in October 1997. The storm was manifested by torrential rain with intensities of a 30-year return time that exceeded 100 mm h^{-1} for 10 min over Jericho in the northern part of the Dead Sea, Israel. In addition to the conditional instability established by the preexistence of the Red Sea barometric trough, the upper level divergence imparted by both Polar Jet (PJ) and STJ over the region supported the formation and intensification of this storm. The EM was then situated simultaneously to the left of the STJ exit and to the right of the PJ entrance, implying near tropopause divergence.

As compared to the EM characterized by less frequent cyclogenesis in the fall months, heavy precipitation in the WM usually occurs in the autumn, since the Mediterranean SSTs are still high from the summer heating. Jansa et al. (2000) pointed at the frequent formation of lee depressions and troughs over the warm and humid air filling this part of the basin. The combination of strong synoptic-scale forcing and the contributing topographic features make the WM prone to heavy rains caused by MCSs embedded in synoptic scale systems as confirmed by Rudari et al. (2005) by means of large ensemble of heavy rainfall events and composite statistics. The examination of four heavy rainfall events that occurred in the coastal area of north-eastern Italy, a region fringed by the Alpine barrier to the north of the Adriatic Sea, revealed that synoptic rather than convective settings controlled the observed time scales of these intense rainfall events. The combined convective rainfall rates paired with the synoptic

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durations lead to the exceptionally high rainfall accumulations observed (Barbi et al., 2012). In some particular cases, daily amounts of precipitation of 300, 400, even 800 mm have been reported in that particular region (see, for example, Romero et al., 1997; Ramis et al., 1998). Extreme rainfall events over Northwest Italy were classified taking local station intensities and rainfall durations simultaneously into account (Pinto et al., 2013). The two clusters containing the strongest events were found to be associated with strong and persistent upper air troughs inducing not only moisture advection from the North Atlantic into the WM but also strong northward flow towards the southern Alpine ranges. Other favorable large-scale conditions for the occurrence of deep convection in their target area are the location in front of the upper air trough, and enhanced humidity available over the WM region shortly before the event. A sustained moisture advection towards the southern Alpine ranges is due to a quasi-stationary steering low located near the Bay of Biscay/British Isles, while local cyclogenesis over the WM region is responsible for triggering and focusing the event on a particular area. The authors find their characterization in agreement with investigations of heavy rainfall for Catalonia (Rigo and Llasat, 2007), and Jansa et al. (2001) and Martinez et al. (2008) for the broader WM. Other parts of the WM and the northern parts of the Adriatic Sea are also occasionally affected by very heavy rain (see, for example, Senesi et al., 1996; Buzzi et al., 1998). Ducic et al. (2012) carried out an analysis of the relationship between extreme precipitation events and synoptic circulation types in Montenegro, the wettest Mediterranean region. In their study, they used an efficiency coefficient, expressing the ratio between a relative frequency of a given circulation type in extreme precipitation events to its mean frequency for the period spanning 1951–2007. They found that northerly, easterly and southerly circulation types are more frequent for very wet days. Doswell et al. (1998) examined three heavy precipitation events that occurred over the WM and pointed at the difference among them in spite of their perceived similarities. Although these events were characterized by a southerly flow advecting warm and moist air at the surface accompanied by an eastward movement of a mid-tropospheric trough leading to a positive vorticity over the whole WM, evolutionary

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differences were found among them. The synoptic condition responsible for the heavy rain during the Piedmont event analyzed by Jansa et al. (2000) was the presence of a mid to upper level trough, drifting north-east from Spain forcing an upward motion. A frontal structure at shallow levels provided the additional upward motion. A strong south-westerly flow in the forefront of the frontal structure blew in perpendicular to the local orography. This vigorous upslope forcing imposed by the Apennines and the Maritime Alps combined with the convective instability over the sea were the critical factors for the heavy rain. Jansa et al. (2001) checked the simultaneities existing between heavy rain and surface cyclones over the WM covering the period from December 1991 to November 1996. They found that about 90 % of all heavy rain cases (> 60 mm/24 h) a cyclone center is usually around 300 km to the heavy rain region. Analyzing intense precipitation in winter for 15 coastal sites around the MB, Reale and Lionello (2013) found that the probability of finding a cyclone within a distance of 20° (approx. 200 km) from a precipitation event increases with the intensity of the event. Romero et al. (1999a) investigated the synoptic circulation associated with typical spatial patterns for significant rainfall days for the Spanish Mediterranean area for 1964–1993. Among the 19 derived synoptic types obtained from a cluster analysis of heavy rainfall days and spatial modes of the 500 and 925 hPa gph, they found that the most effective ones are the circulation types during which a large-scale disturbance is located to the west or south of the Iberian Peninsula while generating a moist Atlantic flow enhancing copious rainfall over the WM. Romero et al. (1999b) derived 8 characteristic torrential rainfall patterns (defined when, at least 2 % of the 410 Iberian stations registered more than a daily amount of 50 mm) and found that most torrential rain days occur whenever an accentuated mid-tropospheric trough or a closed cyclone is located to the south or west of the Iberian Peninsula and accompanied by a collocated low at shallow tropospheric layers. Among the numerous baroclinic low pressure systems generating intense precipitation few are tropical-like cyclones which are formed, during the cold season, mainly over the WM referred to as Medicanes. However, the latter are extremely rare (0.75 p.a. over the WM and 0.32 p.a. over the

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Ionian Sea) (Miglietta et al., 2013; Cavicchia et al., 2014). Numerous diagnostic and numerical studies, reflecting similar synoptic conditions inducing heavy rain over this part of the MR were published (e.g., Doswell et al., 1998; Ramis et al., 1994, 1999, 2009; Homar and Stensrud, 2004). Nuissier et al. (2008) best summarize this section as deduced from their study examining the simulation of three torrential rain events over southeastern France while stating: "even though synoptic-scale ingredients (upper-level PV anomalies, strong low-level moisture advection, CAPE, etc.) can provide the necessary ingredients for the convective activity, other important mesoscale factors and/or finer-scale processes contribute to continuously focus the activity over the same specific region (the necessary forced ascent to trigger and/or maintain the convection)". Moreover, simulations of extreme rainfall events are very sensitive to the details and precise timing of these mesoscale factors, despite their being imbedded in large-scale synoptic system (Argence et al., 2008; Ducrocq et al., 2008; Fiori et al., 2014).

8 Thermodynamic and dynamic predictors of heavy precipitation

The occurrence of torrential rains and thunderstorms and their intensity depends on a combination of factors, such as temperature profiles and implied instability, atmospheric moisture, lower-level convergence etc. In order to evaluate the probability and intensity of the rainstorm various predictors should be combined to estimate the necessary conditions for its occurrence. In a first attempt, Dayan and Sharon (1980) found that indices of instability were the most efficient determinants over the EM, as is the qualitatively defined synoptic situation. Vorticity and water content of the air proved to be similar for widespread and spotty types of storms. Predictors for the ARST and the Syrian Low (see Sect. 7 above) were examined by Kahana et al., 2004 For the ARST synoptic condition, most of the predictors were found at the 500 hPa level, with the most powerful being the v/u ratio, which represents the southerly wind component that is responsible for the transport of moist tropical air masses towards the EM. Two new indices, aimed to assess the potential for heavy precipitation and flash-floods over the EM were proposed and evaluated by Harats et al. (2010). The first is the MKI, which is a modified version of the KI index (Mortimer et al., 1980).

$$\mathrm{MKI} = (T_{500} - T_{850}) \cdot \mathrm{RH}_{850,\,700} + \mathrm{Td}_{850} - (T_{700} - \mathrm{Td}_{700}), \tag{1}$$

where T and Td are the dry bulb and dew point temperatures, respectively, and the subscripts refer to the respective pressure level (hPa). The 1st term reflects the lapse rate throughout the lower- and mid-troposphere (the lapse-rate term) which is multiplied by the average RH of the 850 and 700 hPa levels, the 2nd represents the lower-level moisture and the 3rd the saturation deficit in the mid-troposphere. The applied index gives more weight to the lower- and mid-level relative humidity. The second index suggested by Harats et al. (2010) is a rain index, the RDI, which is the integrated product of specific humidity and vertical velocity.

$$\mathrm{RDI} = \int_{Z_{(925\,\mathrm{hPa})}}^{Z_{(300\,\mathrm{hPa})}} wq\,\mathrm{d}z, \tag{2}$$

where w is vertical velocity, q is specific humidity and z is elevation. This index comprises the precipitable water and the dynamic conditions necessary to convert it to rain. Figure 11 displays the spatial distribution of these two indices as calculated for the torrential rain event that occurred on 1 April 2006 along a northwest-southeast orientated line extending from the central coast of Israel (Wadi-Ara) to the northern end of the Dead-Sea. Based on the few cases analyzed in this study Harats et al. (2010) suggest that the tentative values of 25 for the MKI and of 20 for the RDI might be referred as preliminary thresholds for rain storm and potential flash-flood over the EM.

As compared to the EM for which heavy precipitation are associated mostly with frontal thunderstorms, occurring mainly in winter, the central and WM are often affected by non-frontal (air mass) thunderstorms. Such convective weather events and especially heavy rains are frequent during the autumn. Forecasting these severe

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weather conditions is based, among other tools, on a broad range of stability indices and thermodynamic parameters. Jacovides and Yonetani (1990) used a coastal and inland location in the MR to evaluate the skill of a combination of indices, namely, the humidity index (Litynska et al., 1976), the Pickup index (Pickup, 1982), and the K-stability index (Reap and Foster, 1979) and compared them to the modified Yonetani index. This last index, combines information about the lapse rates of the 900–850 and 850–500 hPa layers, with a measure of the mean relative humidity of the 900–850 hPa layer. They have shown, after adding the flow curvature at 500 hPa, that the Yonetani index is more successful than the others in the forecast of air mass thunderstorms over the MR. Several researchers (e.g., Neuman and Nicholson, 1972; Fuelberg and Biggar, 1994;) made attempts to classify convective events into separated groups, based on the observed event (hail, heavy rain, "dry" storms, storms with heavy rain, and tornadoes) while using single stability indices to differentiate between groups. The usage of such classic stability indices did not provided good guidance for discriminating environments associated with each group of events. An alternative approach to classify the environments in which significant convective events occur has been made by Tuduri and Ramis, (1997). In their study, soundings have been defined by means of 34 variables that include the vertical distribution of temperature, humidity, instability, helicity, and precipitable water. The k-means clustering method has been used to determine four different environments including a "heavy rain" category. Their results point at particular environments characterizing the different events. In such a way, heavy rain events occur with warm, humid air in all the troposphere and warm advection at low levels. Moreover, they demonstrated that convective indices are very sensitive to the location due to the nature of thunderstorm inducing heavy rain which is of a high spatial and temporal variability. Obviously, beside convection and moisture supply, a mechanism for sustaining that convection is necessary in order to originate intense precipitation.

Recently, Korologu et al. (2014) developed an index as predictor of heavy convective rainfall over western Greece. This index referred to as Local Instability Index (LII) takes

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into account the three essential ingredients for thunderstorm and heavy rain initiation: energy, moisture and lifting mechanism. The advantage of the LII is the incorporation of experience-based local weather and knowledge of atmospheric processes associated with severe thunderstorm events. It is, however, not clear if any of the suggested parameters results in a better general performance in indicating a high risk of heavy rainfall events than those developed earlier.

9 Summary

There are substantial regional differences in rain rates over the MR. The maximum rainfall occurs over the mountain regions in the north Mediterranean coasts while the minimum rainfall is over North Africa. The main rainy season over this region extends from October to March, but maximum rainfall occurs during November–December. Over the northern Mediterranean, there is a bimodal rain pattern with spring and autumn seasons having maximum rainfall. The rainy season over Northern Africa (Southern Mediterranean) and the EM is December–January–February, while most heavy precipitation events in the WM occur in fall. In both sub-Mediterranean basins most of the heavy rain events (around 90 are associated with a cyclone in the vicinity that generates a flow of air towards the area affected by heavy rain.The main tracks of migrating lows in winter are over the northern MB whereas in the summer, the blocking effect of the Azoreans High and the subsiding conditions aloft, prevent the movement of cyclones as well as their formation mostly over the EM. Contributing factors to the Mediterranean cyclogenesis are the relatively elevated SST and the diabatic heating from condensation which serves frequently as determinant in Mediterranean cyclones. Most of intense EM rain episodes are associated with the cold fronts of mid-latitude cyclones (i.e. Cyprus Lows and Syrian Lows) affecting the eastern and south-eastern Mediterranean coasts respectively in winter. In fall, the ARST tropical synoptic-scale system accounts for most heavy and localized precipitation events, mainly over the eastern and southern parts of the Levant. In comparison to the EM, autumn is the

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season of frequent heavy precipitation spells over the WM. These events are often associated with lee cyclogenesis over the relatively warm and moist air filling this part of the basin. The typical synoptic configuration of a heavy precipitation episode is an eastward advancing trough leading to positive vorticity advection at mid-tropospheric layer accompanied by a deep cyclone positioned over the WM at the surface generating a strong and moist flow blowing in perpendicular to the local orography. The spatial distribution of deep convection detected objectively by remote sensing and validated with radar and rain gauges over the MR points at a pronounced seasonal signal with convective events more frequent over land in summer, which migrate toward the sea in the fall and are most frequent over the sea in winter. Most frequent regions of deep convection are the western Croatian coast, the south of France and the Tunisian coast. Moisture not originating from the Mediterranean Sea is a major moisture supply for heavy rain events associated with winter Mediterranean cyclones over the EM. During winter, conveyor belt of moisture in mid tropospheric layers, called tropical plumes/atmospheric rivers, often originating from Tropical Africa might also play an important role. During the transitional seasons, the Red Sea quite often serves as a corridor for transporting moist air masses from the Arabian Sea and Tropical Africa into the southeastern Mediterranean. Over the WM, for most cases, the circumstance under which moisture is supplied is a southerly flow at all atmospheric levels blowing at the forefront of a sharp and slow moving mid-tropospheric synoptic scale trough. Under these conditions air parcel is orographically forced, destabilized and moistened while crossing the relatively warm Mediterranean Sea which produces the heavy precipitation events. During autumn and winter about 10 % of heavy precipitation events in the WM are associated with moisture from tropical origin transported into the region by TPs. With respect to large-scale teleconnection pattern related to heavy precipitation in the MR it is widely accepted that the most important pattern throughout the year is the seasonal cycle of the MO. The MO is in turn linked to both, the AO and the NAO. The influence of the NAO is large over the WM but weak and opposite in phase over the

EM. The inter-annual variation of rainfall, manifested by moisture flux anomalies over the WM was also found to be related to major ENSO events in autumn.

Meteorological indices, developed mainly for forecasting severe weather inducing torrential rain, are combinations of variables, taking into account instability, atmospheric moisture, and lower-level convergence. Such indices often depend on the resolution of the data set and the location they are applied to, but can be useful to predict timing and spatial distribution of heavy precipitation events. In tropical rain bearing circulation systems over the EM, such as the ARST, the southerly wind component at mid-tropospheric levels responsible for the transport of moist tropical air masses (essential for convection) was found as the most powerful for intense rain events. One of the essential ingredient leading torrential rains over the WM as reflected in most of the indices, point at onshore unstable flow, as a major contribution. This indicates that the favorable conditions for torrential rains occur whenever onshore flow of unstable air, encounters the mountain ridges in the vicinity of the WM coasts.

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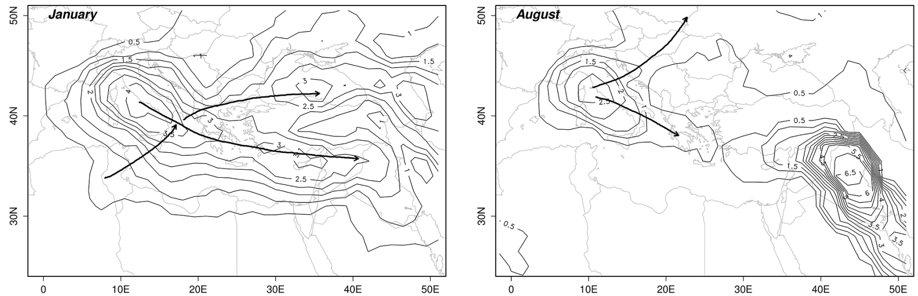

Figure 1. Isolines: average number of tracks passing within a radius of 250 km from the center of each cell counted on a 1.5° × 1.5° grid in the ERA-Interim data set (i.e. cyclone track density). Arrows (taken from Alpert et al., 1990b): the main tracks of migrating lows over the MB during winter (January) and summer (August).

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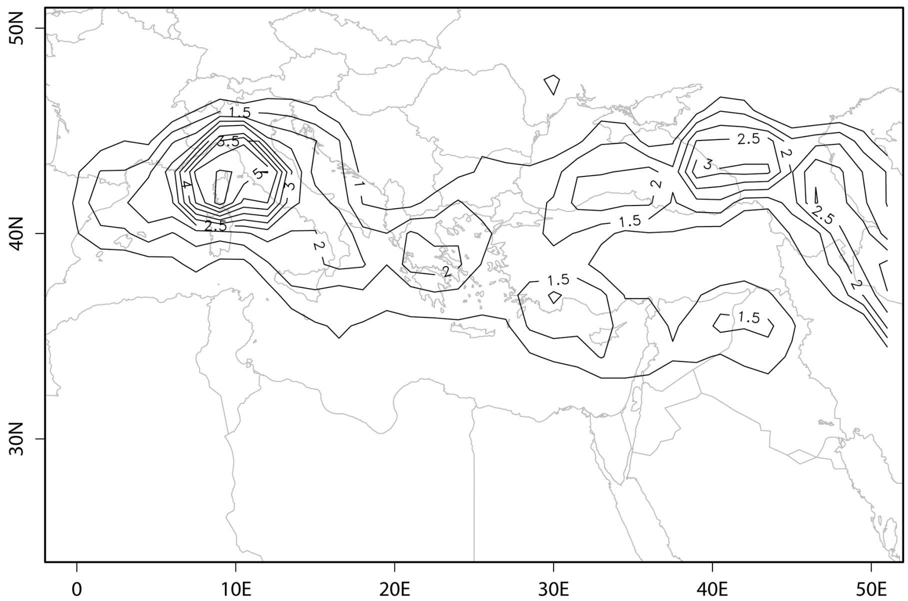

Figure 2. Cyclogenetic regions over the MB in winter (DJF) determined using the ERA Interim reanalysis data set for the period 1979–2012. Contour interval 0.5 cyclone/winter, first contour is 1.

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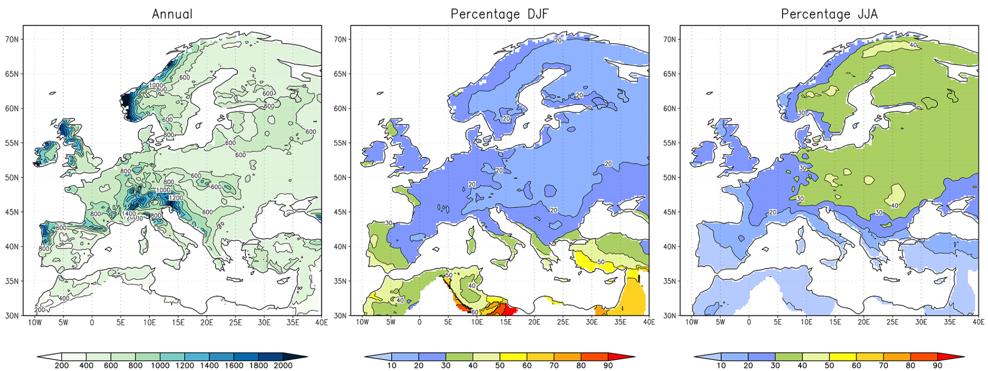

Figure 3. Precipitation in Europe and the Mediterranean region computed from the E-OBS data set (Haylock et al., 2008). Left: annual mean rainfall, contour interval 200 mm. Middle and right: percentage of the annual precipitation falling in winter (December, January and February), and in summer (June, July and August), respectively. Contour interval 10 %.

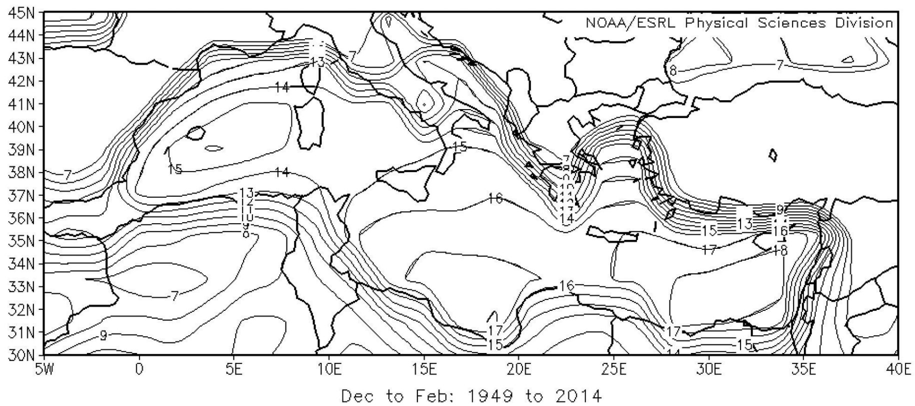

Figure 4. Long Term Mean SST over the MB for winter (December–February) 1949–2014. (Extracted from: http://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl.)

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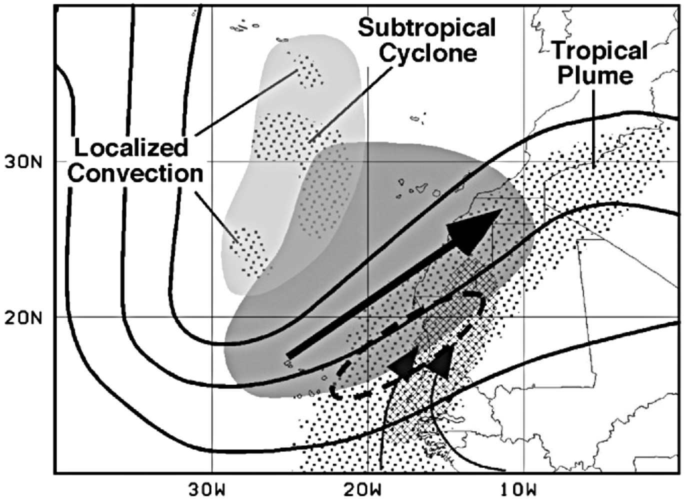

Figure 5. Schematic depiction of the synoptic situation during precipitation events over West Africa in connection with tropical plumes. Thick black lines delineate the low-latitude upper-trough and the thick arrow indicates the associated subtropical jet streak. Thin arrows show midlevel moisture transports from the deep Tropics. Stippled regions indicate high clouds and hatching delineates the major precipitation zone. Light (dark) grey shading depicts the region of convective instability under the coldest air at upper-levels (positive quasi-geostrophic forcing for midlevel ascent). The dashed lines bound a region of upper-level inertial instability along the anticyclonic shear-side of the jet (from: Knippertz, 2007, reprinted with permission of Elsevier).

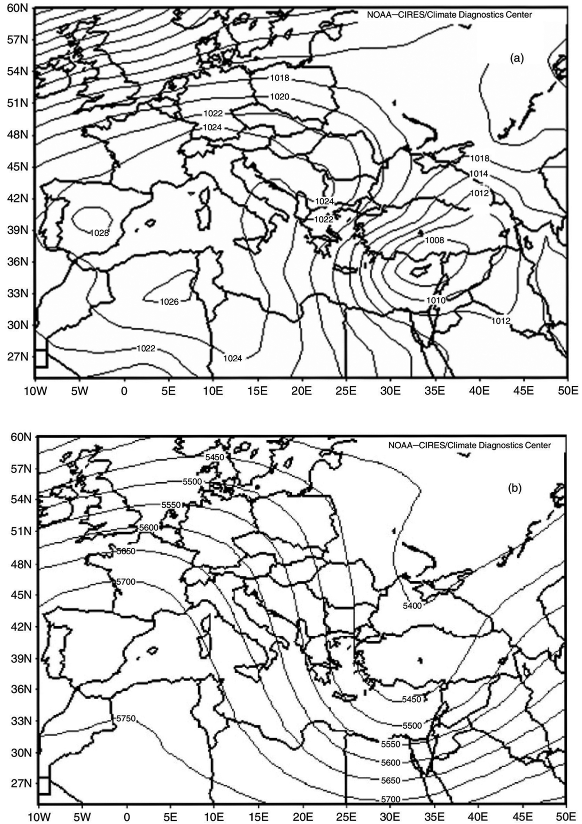

Figure 6. Composite maps for the ten heaviest rainfall days in Israel for the period (1950–2002): **(a)** SLP (hPa), **(b)** 500 hPa gph (m) (from: Ziv et al., 2006, reprinted with permission of John Wiley and Sons).

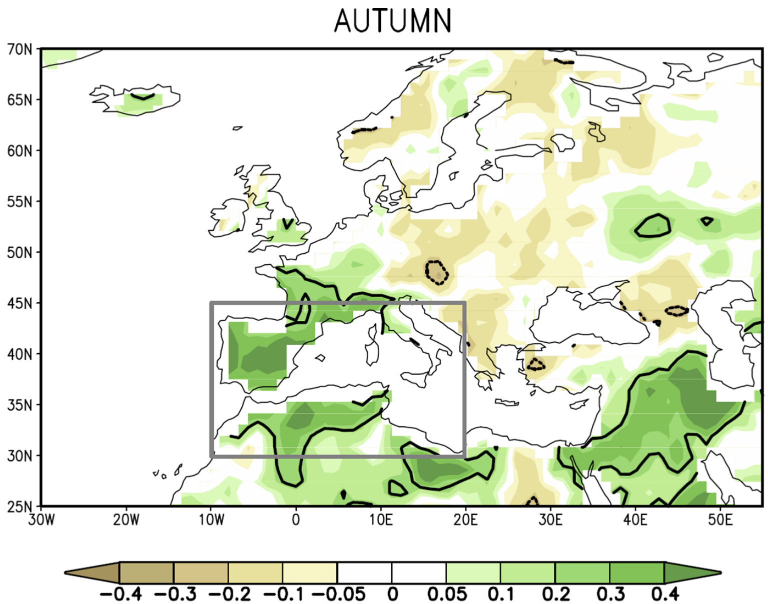

Figure 7. Correlation of rainfall over the WM in autumn and the Nino3.4 index for the period 1948–1996 (from: Mariotti et al., 2002, reprinted with permission of John Wiley and Sons).

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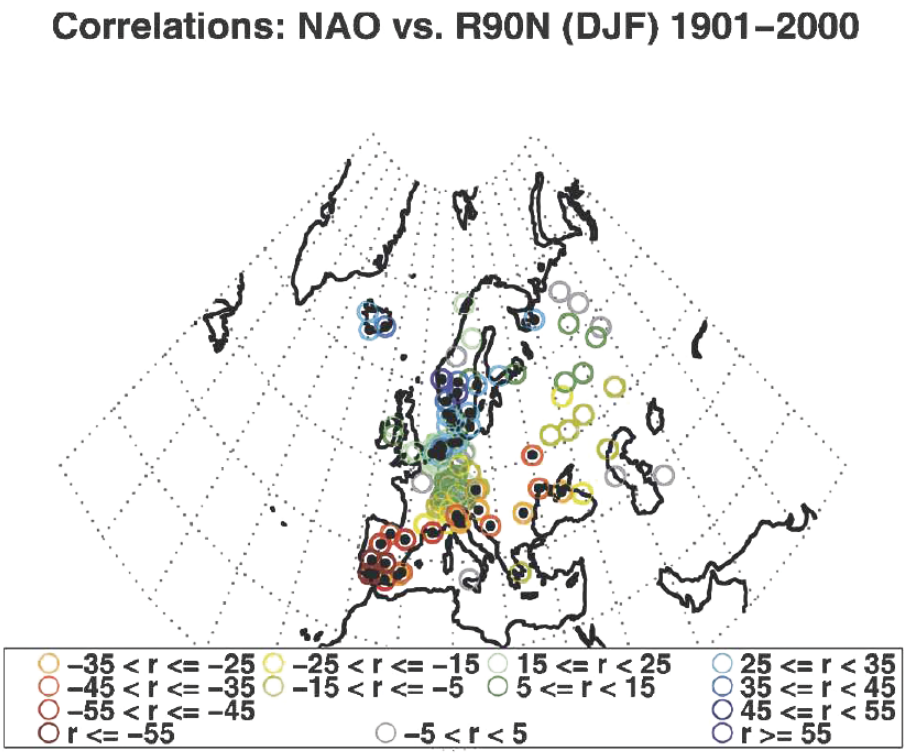

Figure 8. Correlations (×100) over the whole twentieth century between the NAO and the frequency of above 90th percentile daily rainfall events. Black dots show stations with correlations significant at the 99 % level accounting for autocorrelation and percentiles are defined over 1961–1990. All stations are used that have at least 15 years of 90th percentile precipitation data in each 20-year block (1901–1920, 1921–1940,. . . ,1981–2000) west of 60° E in the European and North Atlantic Daily to Multidecadal Climate Variability project (EMULATE) database described by Moberg et al. (2006) (from: Scaife et al., 2008, ©American Meteorological Society, used with permission).

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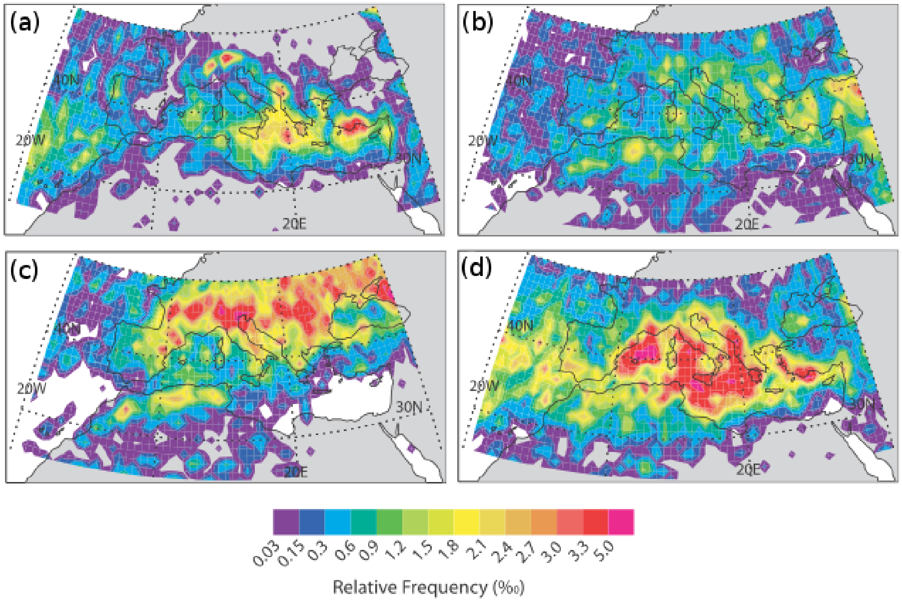

Figure 9. Spatial distribution of the 7 yr average seasonal relative frequency of deep convection for the period 2001–07 over the MB. **(a)** December–January–February, **(b)** March–April–May, **(c)** June–July–August, and **(d)** September–October–November (from: Funatsu et al., 2009, ©American Meteorological Society, used with permission).

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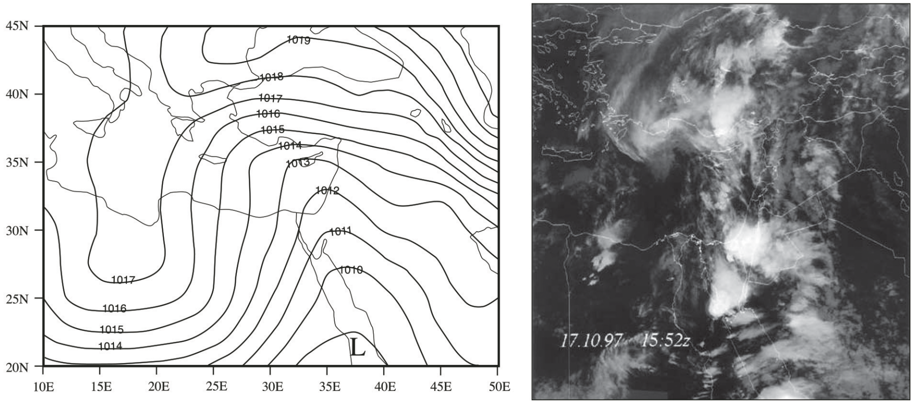

Figure 10. (Left) Composite SLP with 1 hPa interval for all flash flood cases resulting from the ARST synoptic category. (Right) U.S. National Oceanic and Atmospheric Administration satellite IR image (NOAA Satellite and Information Service) for a developing Mesoscale Convective System over the southeastern MB at 15:52 UTC 17 October 1997 (from: Dayan and Morin, 2006, with permission to reprint from the Geological Society of America).

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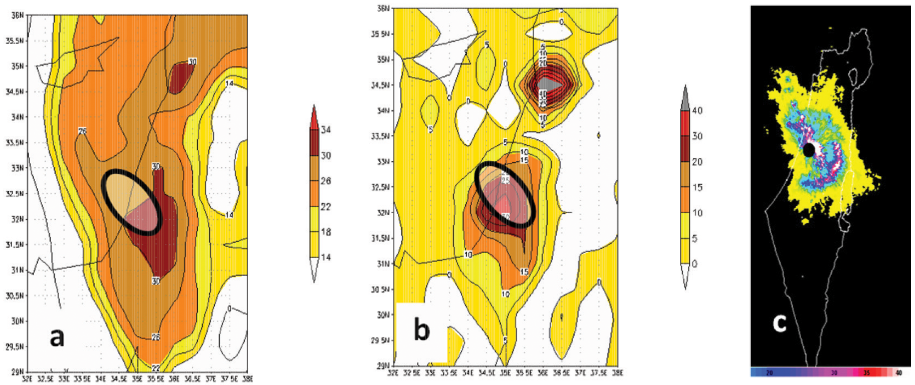

Figure 11. Spatial distribution of **(a)** MKI, **(b)** RDI, both for 2 April 2006, 00:00 UTC, **(c)** uncalibrated rain totals derived from the radar reflectivity over the period 1 April 2006, 23:00 UTC–2 April 2006, 01:00 UTC. The bold ellipses in **(a)** and **(b)** represent the core of the rain system (from: Harats et al., 2010; Open Access).