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Invited review article

Reviews and perspectives of high impact atmospheric processes in the Mediterranean

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A R T I C L E I N F O

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A B S T R A C T

The Mediterranean region is a unique area characterized by a large spectrum of atmospheric phenomena, some of which have a high impact on many aspects of human activities, safety and wellbeing. The area is long considered as a hot spot of such atmospheric phenomena deserving multidisciplinary scientific attention. The scientific research that has been carried out on these high impact atmospheric processes that occur in the Mediterranean area is indeed widespread and the available international literature is very extensive. The paper touches initially the temperature and precipitation regimes, followed by a discussion of floods and droughts. The exciting cyclogenetic patterns of explosive cyclones and medicanes are presented in separate sections. The lightning activity and the presence of dust and other pollutants are also presented herein. The atmospheric chemistry of the region which is increasingly becoming of utmost importance for the area under study is distinctly discussed. Attempts to modify the weather (the precipitation, in particular) are outlined too. The effects of climatic change on various atmospheric processes are considered throughout this paper, in addition to a dedicated section on temperature and precipitation.

1. Introduction

Any attempt to delineate and comprehend the complex atmospheric processes that are observed in the Mediterranean region, unavoidably ought to start with a portrayal of the multifaceted and intensively interacting characteristics of this geographical area. In many respects, it is these characteristics and their interplay that make this area a unique ground of atmospheric-related phenomena. Hence, this review paper starts with this introductory section in which a brief overview is given of the characteristics of the Mediterranean region which set the scene for the study of high impact atmospheric phenomena and hydro-meteorological hazards experienced in the region.

The Mediterranean Sea is virtually embraced by three continental bodies, namely Europe to the north, Asia to the east and Africa to the south. It is a water body which is almost isolated from the other oceanic bodies of the Earth since the only connection to a much larger oceanic water mass, namely the Atlantic Ocean, is through the Strait of Gibraltar through which a mass exchange in terms of replenishing the

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Mediterranean Sea is accomplished.

The area surrounding the Mediterranean Sea is characterized by a mixture of land cover (i.e., the physical material that covers the surface): in brief, extensive desert areas exist to the south and east with narrow vegetated areas around the coast; in contrast, vegetated areas are present to the north. On the one hand, the contribution of atmospheric processes to this land cover formation is of course decisive (c.f., temperature, precipitation and wind regimes). On the other hand, the feedback of the land cover and its interactions with the atmospheric processes must always be borne in mind.

The morphological characteristics of this area have a large influence on the complexity and richness of atmospheric phenomena (see Lionello et al., 2012). Indeed, this influence is considered to have such an extent at which this morphology may be held accountable for the onset and sustainability of some high impact atmospheric phenomena. The Mediterranean Sea is surrounded by complex mountain ranges; in many cases, they extend to high altitudes, essentially modifying the underlying dynamic characteristics of the atmospheric flow at various scales, thus playing a critical role in the regional and local climatology.

Energy and moisture fluxes between the water surface of the Mediterranean Sea and the overlying atmosphere constitute important driving factors for atmospheric processes, not only of relevance to the region but also well beyond it (see Rowell, 2003).

The geographical position of the Mediterranean places the region under the influence of a large spectrum of large-scale atmospheric patterns of the general circulation. Indeed, from the north, the region is prone to influences from circulations associated with the mid-latitudes (see Trigo et al., 2006). The northern part of the region is more frequently affected by the polar front and its latitudinal movement during the year with diverse seasonal variations in both the frequency and intensity of related atmospheric phenomena. The variability of the atmospheric phenomena especially over the north part of the Mediterranean region is linked to the North Atlantic Oscillation[1] (NAO) (e.g., Xoplaki et al., 2003, 2004; Krichak and Alpert, 2005a). Researchers have also investigated the influence of a multitude of other northern hemisphere teleconnection indices on the weather in the Mediterranean, such SCAND, EA and EAWR: the Scandinavian index, the East Atlantic and the East-Atlantic/West-Russian indices, respectively (see e.g., Krichak and Alpert, 2005b; Trigo et al., 2008; Nissen et al., 2010).

From the south, the Mediterranean basin is subjected to strong influences from circulations of tropical and subtropical origin (Alpert et al., 2006). Most notable is the influence of the descending limb of the Hadley cell which during most of the year maintains dry weather conditions with occasional wet spells. The area is even affected by quite distant patterns of the southern hemisphere, such as the that of the El Niño Southern Oscillation (ENSO) which has been held accountable for influencing the variability of weather in the Mediterranean with focus on precipitation (see Price et al., 1998; Mariotti et al., 2002; Alpert et al., 2006). In addition, the Asian monsoon circulation has a westward protruding extension during summer, thus largely influencing the prevailing lower level circulation of the eastern Mediterranean (EM) and the associated weather (see Raicich et al., 2003; Tyrlis et al., 2013).

The area is alternately exposed to air masses of different origin. Tropical continental air, often quite rich in particulate matter originating from the extensive dry deserts of north Africa, is quite frequently affecting large parts of the region (see Michaelides et al., 1999a). Intrusions of continental air of polar or sub-polar origin from the north and northeast are also noted, particularly during the cold periods of the year. In the same periods, polar air masses of maritime origin may sometimes affect the area, though quite modified when they reach the Mediterranean. The proximity of the Atlantic Ocean enriches the variety and interaction of the air masses affecting the area, with frequent intrusions of maritime air masses from the west and southwest.

It has long been realized that the Mediterranean area is affected by two tropospheric jet-streams. The first is the subtropical jet-stream which is a westerly stream forming on the poleward side of the Hadley cell, the existence of which is largely ascribed to conservation of angular momentum (see Reiter, 1963). The other jet-stream is commonly known as the polar front jet-stream accompanying mid-latitude baroclinic disturbances and whose existence is attributed to the large horizontal temperature gradients in the lower troposphere. Both jet-streams are subjected to seasonal north-south displacements, following the seasonal displacement of the meridional large-scale circulations. The synergistic interaction between the polar the subtropical jet-streams is considered as a possible mechanism triggering explosive cyclogenesis in the region (see Conte et al., 1997).

The complex topography and coastline of the Mediterranean region interact with the global atmospheric circulation, inducing regional patterns of high temporal and spatial variability When interacting with the global atmospheric circulation, the characteristic morphology of the Mediterranean region induces regional features such as areas of preferred cyclogenesis and cyclonic rejuvenation (c.f., cyclonic developments bearing the geographic names of the Gulf of Genoa and the island of Cyprus). Storm tracks are also largely determined by the Mediterranean area morphology and thermal characteristics of the underlying surface. The above have important consequences for regional storminess and precipitation regimes (Luterbacher and Xoplaki, 2003).

The Mediterranean region is a unique area characterized as a climate change hotspot, a region whose climate is especially responsive to global change (Giorgi, 2006). Additionally, as already mentioned above, the location of the Mediterranean in a transitional band between the subtropical and the midlatitude zones renders the climatic modeling of this region a very challenging task (Planton et al., 2012).

This review paper aims at presenting in a comprehensive manner the phenomena that are significant in terms of impacting the weather and related hydro-meteorological hazards in the Mediterranean but it focuses primarily on the topics that are pertinent to the issues discussed in separate papers in this Special Issue. In the selection of topics to be reviewed here, the spatiotemporal extent of the respective processes is also taken into consideration, focusing on those which are identified at the synoptic scale. The processes considered here are widely affecting the area of the Mediterranean basin receiving much public and research interest. Localized phenomena or those which are not conducive to much attention from the public or the scientific community are not exclusively reviewed. For example, tornadoes and waterspouts are not considered as a separate topic in this review paper, despite their considerable societal and economic impact, because they generally receive very little attention from the public, meteorologists, researchers and emergency managers (see Antonescu et al., 2017).

This introduction is followed by eleven sections, as follows. The temperature and precipitation regimes over the region are discussed in Sections 2 and 3, respectively. Floods and droughts are specifically discussed in Sections 4 and 5, respectively. Sections 6 and 7 focus on explosive cyclones and medicanes, respectively. Section 8 focuses on lightning activity and Section 9 on dust and air pollution in the area. Section 10 discusses aspects of atmospheric Chemistry. Projects on weather modification that have been undertaken in countries in the Mediterranean are outlined in Section 11. Finally, Section 12 reviews aspects of climate change with particular emphasis on temperature and precipitation.

The literature surveyed in this review paper is by no means exhaustive. The objective of this paper is to review a reasonable amount of existing literature on the respective topics, especially the most recently available and subsequently proceed by scrutinizing the perspectives on these topics.

[1] All symbols and abbreviations are tabulated in the Appendix A.

2. Temperature regime

Due to the high climatic variability of subtropical latitudes and the complex topography of the Mediterranean region, this area is affected by both cold temperature events (mainly during the winter months) as well as extreme hot conditions (especially during the summer season).

2.1. Observed climate, trends and extreme events

Efthymiadis et al. (2011) used two recently-available daily gridded datasets covering the 1950–2009 period to investigate trends in Mediterranean temperature extremes since the mid-20th century, while Hertig et al. (2010) used daily station series. It was found that while the western Mediterranean experienced warming, the eastern parts of the Mediterranean area were affected by cooling trends despite the overall tendency of global warming but with a near reversal of this cooling in the last two decades. This inter-basin discrepancy was clearer in winter, while in summer changes were more uniform and the west-east difference was restricted to the rate of increase of warm/hot extremes, which was higher in central and eastern parts of the Mediterranean over recent decades (Efthymiadis et al., 2011).

For the EM, Kostopoulou et al. (2014) found, using observations during 1961–1990, that the spatial distribution of recent temporal trends in temperature indicates strong increasing in minimum temperature over the eastern Balkan Peninsula, Turkey and the Arabian Peninsula. The rate of warming reaches 0.4–0.5 °C decade^{-1} in a large part of the domain, while warming is observed to be strongest in summer (0.6–0.7 °C decade^{-1}) in the eastern Balkans and western Turkey.

Brunetti et al. (2006) suggest a positive trend for mean temperature of about 1 °C per century all over Italy with the maximum temperature trend being stronger than that of the minimum temperature. This has led to a negative trend in the daily temperature range which has been reversed in the last 50 years.

Upper and lower temperature percentiles increased during the 20th century over mainland Spain, but changes in daytime extreme temperatures were larger than changes in night-time extreme temperatures. This pattern, however, shifted slightly in the recent period of strong warming, with more similar rates of change among daytime and night-time extreme temperatures (Brunet et al., 2007). Generally speaking, air masses leading to temperature extremes are first transported from the north Atlantic towards Europe for all categories. While there is a clear relation to large-scale circulation patterns in winter, the Iberian thermal low, i.e., the low-level depression, directly related with a positive temperature anomaly, is important in summer (Santos et al., 2015).

For northeastern Spain in particular, El Kenawy et al. (2011), analyzing data for the period 1990–2006, indicated a significant increase in the frequency and intensity of most of the hot temperature extremes. An increase in warm nights, warm days, tropical nights and the annual high maximum temperature was detected in the 47-year period. In contrast, most of the indices related to cold temperature extremes (e.g., cold days, cold nights, very cold days and frost days) demonstrated a decreasing but statistically insignificant trend.

2.2. Future climate trends and extreme events

Best accordance among climate models regarding future projections can be found in seasonal temperatures with lower rates of warming in winter and spring and, in most cases, higher ones in summer and autumn with respect to the present climate. Different results are obtained for the intra-annual range of extreme temperatures, but high-temperature conditions are generally expected to increase (Jacobeit et al., 2014).

Diffenbaugh et al. (2007) state that increased greenhouse gas concentrations dramatically increase heat stress risk in the Mediterranean region, with the occurrence of heat extremes increasing by 200 to 500% throughout the region. This heat stress intensification is due to preferential warming of the hot tail of the daily temperature distribution, dictated in large part by a surface moisture feedback, with areas of greatest warm-season drying showing the greatest increases in hot temperature extremes. Fine-scale topographic and humidity effects help to further dictate the spatial variability of the heat stress response, with increases in hazardous heat indices magnified in coastal areas due to the combined effects of high temperature and humidity.

Giorgi and Lionello (2008) projected a pronounced warming over the Mediterranean maximum in the summer season. Interannual variability was projected to mostly increase especially in summer, which, along with the mean warming, would lead to a greater occurrence of extremely high temperature events. Similarly, Hertig and Jacobeit (2008) showed a temperature increase for the whole Mediterranean area for all months of the year in the period 2071–2100 compared to 1990–2019. The assessed temperature rise varied depending on region and season, but overall substantial temperature changes of locally > 4 °C by the end of this century had to be anticipated under enhanced greenhouse warming conditions. Moreover, hot summer conditions that rarely occurred in the reference period may become the norm by the middle and the end of the 21st century (Founda and Giannakopoulos, 2009; Tolika et al., 2009; Bador et al., 2017).

In the western Mediterranean strong increases, some in excess of 4 °C, are indicated in early and late summer for the 2071–2100 period [namely, the B2 scenario according to the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES)], compared to the 1990–2019 period. Temperature rise is more uniform in the transitional seasons with values around 3 °C in spring and 4 °C in autumn (Jacobeit et al., 2014). In northwestern Mediterranean, temperature is expected to rise in all considered scenarios (up to 1.4 °C for the annual mean) and particularly during summertime and at high altitude areas (Barrera-Escoda et al., 2014).

The IPCC SRES A1B scenario suggests a gradual and relatively strong warming of about 3.5–7 °C between the 1961–1990 reference period and the period 2070–2099 for the EM. Kostopoulou et al. (2014) indicated a future statistically significant warming trend for the EM region over the last 30 years of the 21st century. The annual trend patterns for both minimum and maximum temperature show warming rates of approximately 0.4–0.6 °C decade^{-1}. Summer temperatures reveal a gradual warming (0.5–0.9 °C decade^{-1}) over much of the region. Lelieveld et al. (2014) also indicated increasing hot weather extremes and heatwaves using model projections for the 21st century. Across the Balkan Peninsula and Turkey, climate change is particularly rapid and especially summer temperatures are expected to increase strongly (Lelieveld et al., 2012). Temperature rise can be amplified by depletion of soil moisture, which limits evaporative cooling (Zittis et al., 2014; Bador et al., 2017).

A recent study for future projections based on transient high resolution regional climate simulations (10 × 10 km) is reported by Zanis et al. (2015). In this study, it is also pointed that the number of hot days, warm nights, and continuous dry spell days and length of the growing season are projected to increase slightly in the near-future period, but markedly and consistently in the late 21st century future period in accordance with the generally warmer and drier climate projected from the high-resolution simulation.

By 2050, Cyprus regional modeling results show significant warming of 1 °C in winter to 2 °C in the summer for both maximum and minimum temperatures. Very hot days are expected to increase by > 2 weeks per year and tropical nights by 1 month per year (Hadjinicolaou et al., 2011).

Giannakopoulos et al. (2011) noted that climate change is expected to result in warmer temperatures in urban areas, which translate into more hot days with maximum temperature above 35 °C and night temperatures exceeding the 20 °C. High temperatures and relative humidity combined with the lack of green spaces will increase the discomfort for the people living in large cities. For instance, several Greek cities are expected to experience up to 20 more hot days and almost an additional month with night-time temperatures higher than 20 °C.

3. Rainfall regime

The Mediterranean area is susceptible to changes in precipitation, particularly concerning extreme events and has been identified as a climate change hot spot (Giorgi, 2006). The spatial complexity of the Mediterranean region (Lionello et al., 2012) and the associated complexity of the dynamical and physical processes that lead to extreme precipitation, however, translate into the difficulty in analyzing the region as a whole. This is reflected in numerous studies focusing on the description of the synoptic systems that trigger extreme precipitation events in various sub-regions of the Mediterranean area.

3.1. Observed climate trends and extreme events

Mehta and Yang (2008) examined the climatological features over the Mediterranean region using the Tropical Rainfall Measuring Mission (TRMM) precipitation products. Results show considerable regional and seasonal differences of rainfall over the Mediterranean region. The maximum rainfall (up to 3000 mm year^{-1}) occurs over the mountainous regions of Europe (Isotta et al., 2014), while the minimum rainfall (180 mm year^{-1}) is observed over North Africa (Mehta and Yang, 2008). The main rainy season over the Mediterranean Sea extends from October to March, with maximum rainfall occurring during November–December. Over the Mediterranean Sea, an average rain rate of 1–2 mm day^{-1} is observed, but during the rainy season there is 20% higher rainfall over the western than over the EM. During the rainy season, mesoscale rain systems propagate generally from west to east and from north to south, mostly associated with Mediterranean cyclonic disturbances resulting from interactions among large-scale circulation, orography and land-sea temperature contrast. Similarly, Flaounas et al. (2013) state that in winter, maximum rainfall is mainly observed over the mountainous regions surrounding the Mediterranean Sea due to forced orographic lifting of moist air advected by strong winds of maritime origin. In summer, strong precipitation is frequent in the European continental plains due to thermal convection and along the slope of the major mountain ridges (e.g., the Alps) due to the thermally driven circulation between the European Alps and the alpine foreland.

Lelieveld et al. (2012) studied the climatology of the east Mediterranean - Middle East region (EMME) and concluded that the large north–south contrast is evident in both annual and seasonal rainfall patterns. In the northern EMME, the average total annual precipitation during the 1961–1990 reference period ranges from approximately 500 mm in the east to > 1000 mm in the west. The Dinaric Alps in the western Balkans and locations along the southern coast of the Black Sea receive the greatest rainfall amounts, averaging > 1000 mm year^{-1}. Other parts of the Balkan Peninsula and western Turkey receive rainfall amounts to about 600–700 mm year^{-1}. In Cyprus, total annual precipitation is approximately 300–400 mm year^{-1}, while in north Africa the total annual precipitation does not exceed 200 mm year^{-1}. Subsequently, Lelieveld et al. (2012) calculated the number of days with heavy precipitation exceeding 10 mm day^{-1}. Along the western edge of the Balkan Peninsula and other high-elevation areas, heavy precipitation occurs about 40 days per year. About 25 heavy precipitation days per year occur over the Taurus mountain range in southern Turkey. The same authors have also derived the number of dry days with precipitation < 1 mm day^{-1}. The above mentioned wet regions have the least dry days, i.e., 160 to 200 per year, while in lower-elevation and northern coastal Mediterranean regions this ranges between 250 and 300 per year. The driest areas are located in the southern EMME, with up to 300 dry days per year in several countries of north Africa. Kostopoulou et al. (2014) showed that EMME has seen a decrease in spring precipitation, while decrease in winter precipitation was mainly found to be statistically significant over Turkey. In contrast, some western parts of the EMME region have seen an increase in winter and autumn precipitation.

The observed annual mean precipitation for 1971–2000 over the northwestern Mediterranean (Barrera-Escoda et al., 2014) peaks at the highest mountain areas (above 1400 mm year^{-1}). Some coastal areas are also characterized by large precipitation amounts, exceeding 800 mm year^{-1}. The flat inland region constitutes the driest area, with annual mean rainfall around 400 mm year^{-1}. The region's precipitation in the same period shows a high intra-annual and spatial variability. Wintertime precipitation peaks at high altitude locations (above 400 mm). However, flat inland areas are much drier (below 100 mm). Rain is more abundant in those regions in autumn and spring, frequently above 150 mm. The Mediterranean coast is also characterized by values of accumulated precipitation around 150 mm. Summertime constitutes the driest season, with maximum precipitation amounts registered on the Pyrenees below 350 mm.

Regarding mean precipitation amounts, an analysis by Philandras et al. (2011) showed that statistically significant (95% confidence level) negative trends of the annual precipitation totals exist in the majority of Mediterranean regions during the period 1901–2009, with the exception of northern Africa, southern Italy and western Iberian Peninsula, where slight positive trends (not statistically significant at the 95% confidence level) appear. Concerning the annual number of rain days, a pronounced decrease of 20%, statistically significant at the 95% confidence level, appears in representative meteorological stations of the EM, while the trends are insignificant for the west and central Mediterranean. Additionally, the NAO index was found to be anticorrelated with the precipitation totals and with the number of rain days in Spain, southern France, Italy and Greece. These correlations are higher in the rain season (October–March) than the entire year. The results by Sousa et al. (2011) indicate a clear trend towards drier conditions during the 20th century in most western and central Mediterranean regions, especially during winter and spring with the exceptions of northwestern Iberia and most of Turkey that are exposed to an increase of moisture availability.

Shohami et al. (2011) studied the climate trends of the EM for 39 years, at the transition zone between the Mediterranean and the semi-arid/arid climates. The main findings of their analysis are: 1) changes of atmospheric conditions during summer and the transitional seasons (mainly autumn) support a warmer climate over the EM and this change is already statistically evident in surface temperatures having exhibited positive trends of 0.2–1 °C decade^{-1}; 2) changes of atmospheric conditions during winter and the transitional seasons support drier conditions due to a drop in cyclogenesis and specific humidity over the EM, but this change is not yet statistically evident in surface station rain data, presumably because of the high natural precipitation variability masking such a change. The overall conclusion of this study is that the EM region is under the influence of a climate change leading to warmer and drier conditions.

Regarding extremes, Toreti et al. (2010) present an analysis of daily extreme precipitation events for the extended winter season (October–March) at 20 Mediterranean coastal sites, covering the period 1950–2006. Precipitation extremes are mainly associated with cyclone activity, which represents > 50% of the annual rainfall over the Mediterranean (Flaounas et al., 2015). Three stations (one in the western Mediterranean and the others in the eastern basin) have a 5-year return level above 100 mm, while the lowest value (estimated for two Italian data series) is equal to 58 mm. As for the 50-year return level, an Italian station (Genoa) has the highest value of 264 mm, while the other values range from 82 to 200 mm. Furthermore, six series (from stations located in France, Italy, Greece and Cyprus) show a significant negative tendency in the probability of observing an extreme event. In the western Mediterranean, the anomalous southwesterly surface to mid-tropospheric flow is connected with enhanced moisture transport from the Atlantic and leads to the development of severe precipitation events. For the EM extreme precipitation events, the identified anomaly patterns suggest warm air advection connected with anomalous ascent motions and an increase of the low- to mid-tropospheric moisture (Toreti et al., 2010).

Other researchers have performed trend analysis at various locations around the Mediterranean, such as the study of de Lima et al. (2013) who found that seasonal precipitation in Portugal exhibits significant decreasing trends in spring precipitation, while extreme heavy precipitation events, in terms of both magnitude and frequency, have become more pronounced in autumn. Similarly, Founda et al. (2013) studied the 150-year long precipitation records for Athens in Greece and concluded that the number of rainy days per decade exhibits negative anomalies during the last three decades with respect to the long-term climatic value. A pronounced increase in the percentage of precipitation amount due to heavy ($> 30\,\mathrm{mm\,day^{-1}}$) and extreme ($> 50\,\mathrm{mm\,day^{-1}}$) precipitation was also observed during the last decade. Burić et al. (2015) showed that in Montenegro the number of days with precipitation decreased while rainfall intensity increased, particularly in south-western parts of the country. Vergni et al. (2016) concluded that the expectation of extreme drought event occurrence doubled or even tripled over a 30-year time span in central Italy.

3.2. Future climate trends and extreme events

Summarizing the results for the Mediterranean area as a whole, on the one hand, statistical downscaling assessments point to predominating rainfall reductions in spring, summer and autumn, whereas, widespread increases in rainfall up to the end of the twenty-first century are expected for the Mediterranean winter season (Jacobeit et al., 2014). Regional climate models, on the other hand, indicate higher winter rainfall only for the northernmost parts of the Mediterranean area (Gao et al., 2006; Giorgi and Lionello, 2008; Giorgi and Coppola, 2009), probably due to an anticipated increased cyclone activity in this region (Lionello and Giorgi, 2007; Hertig and Jacobeit, 2008). The EM area reveals another seasonal pattern in statistical downscaling assessments, that of exhibiting precipitation increases in summer and autumn, in contrast to rainfall decreases in winter (Jacobeit et al., 2014).

Concerning future dry period durations in the Mediterranean region, the predominant climate change signals point to their increase. However, there are also indications for sub-regional decreases in the maximum number of consecutive dry days, e.g., in parts of the northern and western area in spring, in the Ionian and Aegean Seas in summer, in the north-central and eastern area in autumn and in the western part in winter. Giannakopoulos et al. (2009) found that one week of additional dry days will be evident in 2031–2060 along the coast and in the already dry southeast basin. Over land areas in the northern part, up to and over three weeks of additional dry days are projected. The dry season tends to shift towards autumn, with the exception of the south of France and Algeria, where it starts and ends two weeks earlier, on average. Oikonomou et al. (2008) report that the highest increase of dry spell length is expected during the period 2071–2100 in winter in the southern part of the EM basin, as well as in spring, reaching up to about seven days.

Hertig et al. (2014) used global models to show that precipitation extremes results yield mainly decreases over many parts of the Mediterranean area in spring. In summer, increases are assessed around the Tyrrhenian Sea, the Ionian and Aegean Seas, whereas decreases are projected for most of the western and northern Mediterranean regions. In autumn, reductions of heavy rainfall occur over many parts of the western and central areas. In winter, distinct increases are widespread in the Mediterranean area. Also, in winter, the increases of the frequency and seasonal amount of extreme precipitation events over the western Mediterranean area are primarily related to changes of local scale thermodynamic conditions whereas mainly decreases arise from large scale circulation changes alone. In contrast, the winter time increases over the central-northern Mediterranean area are more strongly connected to large-scale circulation changes, while the change in local scale thermodynamic factors results in decreases over this area.

Paxian et al. (2014, 2015) using regional climate models extending up to 2050 showed that in summer, a prominent drying prevails mainly over the northern parts of the Mediterranean basin. This drying comes along with a weakening of heavy rain events but with some exceptions, especially over southeast Europe, where precipitation extremes intensify considerably. In winter, the situation is different: the majority of the land grid boxes may also experience a drying, most significant over the southern areas, but positive precipitation trends predominate around the Black Sea and in parts of the Balkans and northern Spain. In addition to weakening rainfall extremes over the southern part, there is a distinct tendency towards more intense precipitation extremes in many northern Mediterranean regions, particularly over the Iberian Peninsula and Turkey. Thus, regions with reduced precipitation amounts will be confronted with heavier individual events.

Hertig et al. (2014) concluded that in autumn reductions of the number of events exceeding the 95th percentile of daily precipitation (R95N) will occur over many parts of the western and central Mediterranean area. In the EM area, a widespread rise of the frequency is assessed, in particular over southern Turkey and southern Greece with values of up to about three days. In winter, distinct increases of R95N can be seen for many parts of the Mediterranean area, most pronounced over the north-western Iberian Peninsula, the northern Dinaric Alps, around the northern Aegean Sea and the southern coast of Turkey with a maximum of about four days. Also, for northern Morocco, central and southern Italy increases are foreseen. In contrast, for the Mediterranean coast of Tunisia, the EM area and parts of Turkey decreases of the number of precipitation extremes are modelled. However, in the EM, even the areas that will experience winter increases will experience longer droughts in spring and summer (Lelieveld et al., 2012).

Barrera-Escoda et al. (2014) reported that reductions in precipitation for the 2021–2050 period in comparison to the 1971–2000 period are consistently shown among scenarios for winter and autumn over high mountain ranges in the Mediterranean.

Several regional and country-based studies also exist such as the studies by Giannakopoulos et al. (2011) reporting increased autumn precipitation in eastern continental Greece and that of Hadjinicolaou et al. (2011) reporting that mountainous areas of Cyprus may receive more extreme precipitation in the future by 2050.

3.3. Snow related extremes in the Mediterranean region

Regions under Mediterranean climate receive during winter a considerable portion of their annual precipitation (Fayad et al., 2017; López-Moreno et al., 2017). For this reason, snowfall is frequent at high elevation sites; however, it occasionally occurs even at low elevations (López-Moreno et al., 2011a; Buisan et al., 2015; Gascón et al., 2015a). Thus, in many Mediterranean mountains a persistent snowpack exists that controls many ecological processes (López-Moreno et al., 2013) and it represents a valuable source of freshwater for covering the needs during the long and persistent dry and warm season (García-Ruiz et al., 2011; Morán-Tejeda et al., 2011). Several studies have focused on the effort to understand how snowmelt in Mediterranean area influences the availability of surface and groundwater resources (López-Moreno et al., 2008; Akyurek et al., 2011; Koeniger et al., 2016) and the timing of the spring peak flows (Maurer et al., 2010; Morán-Tejeda et al., 2014; Valdés-Pineda et al., 2014; Sanmiguel-Vallelado et al., 2017). However, much less attention has been paid to study extreme events related with snow. Heavy snowfall affects traffic (Datla and Sharma, 2008), causes large economic and environmental damage (Strasser, 2008) and increases the frequency of avalanches (Höller, 2009). In addition, rain on snow events is also relevant risks that frequently trigger widespread and significant floods in Mediterranean mountainous regions (Corripio and

López-Moreno, 2017).

The existing literature does not report any study about snow extremes for the Mediterranean region as a whole. Long-term studies based on observational data have been basically limited to the Alps and the Pyrenees. López-Moreno et al. (2011a) used combined precipitation and temperature quantiles from reanalysis as a proxy to analyze the temporal evolution of snow abundant (wet and cold years) years in 15 mountain areas in Mediterranean Europe, Morocco, Turkey and Lebanon. Relating the annual variability of wet and cold winters to the North Atlantic Oscillation (NAO) index. It was possible to confirm that NAO exerts substantial influence on the annual anomalies of temperatures and/or precipitation during winter. Thus, NAO induces differences between wet or dry winters in the Iberian Peninsula, Atlas Mountains, the Balkans and Greece (all of them showing a negative association with NAO), while it influences the occurrence of warm or cold winters in the Alps, Taurus and Lebanon mountains through a positive association. The opposite relations would explain the occurrence of poor snow years (warm and dry years). These results have been corroborated using snow observations, with a statistically significant negative correlation between accumulated snow and occurrence of snow days with NAO in the Pyrenees (López-Moreno and Vicente-Serrano, 2007; Añel et al., 2014; Buisan et al., 2015), as well as the Italian (Bocchiola, 2016) and French Alps (Durand et al., 2009). Just focusing on heavy snowfall and avalanche activities, a statistically negative correlation with the NAO and the Western Mediterranean Oscillation (WEMO) index was found in eastern Pyrenees (García-Sellés et al., 2009) and in the country of Andorra (Esteban et al., 2005). In the French Alps, the NAO and the Atlantic Multidecadal Oscillation (AMO), were demonstrated to have an influence on the inter-annual variability of winter maximum snowfall all over the French Alps for the 1958–2012 period (Nicolet et al., 2016).

Climate projections for the rest of the 21st century point out towards warming trends for the region and also an increased frequency of positive anomalies of the NAO that will likely reduce winter precipitation in the Southern Mediterranean areas while lead to warmer winters in the Alps, Lebanon Mountains and Turkey (López-Moreno et al., 2011), compared to the 20th century, superimposed to large interannual and decadal variability (Vicente-Serrano and López-Moreno, 2008). These projections represent a continuation of reported trends in the last decades in the Mediterranean and are generally driven by higher temperatures and lower precipitation (García-Ruiz et al., 2011). Such trends have caused a general decrease in snow accumulation and snow duration in the French (Durand et al., 2009) and Italian Alps (Valt and Cianfarra, 2010), the Pyrenees (López-Moreno, 2005; Morán-Tejeda et al., 2014); Slovakia (Vojtek et al., 2003) and northern Greece (Baltas, 2007). Very little information is available on changes in the frequency of heavy snowfall events; from the relevant studies, a decrease in the frequency of heavy snowfall in the Pyrenees (García-Sellés et al., 2009) and the Alps (Marty and Blanchet, 2012) is concluded. However, the generalized decrease on accumulated snowpack reported in the Mediterranean and some punctual studies on extreme snowfalls do not necessarily imply that the frequency and intensity of snow storms have decreased or will do so everywhere. Thus, there are areas in the Mediterranean region where extreme precipitation in winter is likely to increase (as portrayed elsewhere in this review paper) and some parts of the mountains will be elevated enough so that the corresponding rain/snow ratio will be insensitive to temperature warming (Laternser and Schneebeli, 2003; López-Moreno et al., 2009). Thus, López-Moreno et al. (2011b) reported that climate change is expected to lead to decreasing frequency of heavy snowfalls by the end of the 21st century in the Pyrenees below 2000 m above sea level (asl), but to increased frequency above this threshold. The possible contrasted trend in heavy snowfall events depending on the elevation might explain the negative temporal trend in the spatial dependence of extreme snowfall found in the French (Nicolet et al., 2016) and Swiss Alps (Blanchet and Davison, 2011).

Regarding the occurrence of rain on snow events, there is an almost lack of studies in the Mediterranean region, despite their importance in explaining floods in mountainous rivers (Corripio and López-Moreno, 2017). A recent work conducted in the Swiss Alps (Morán-Tejeda et al., 2016) illustrates that the opposite sign in air temperature (positive) and snow duration (negative) trends explain the fact that overall rain on snow (ROS) events have actually decreased in Switzerland, being less (more) frequent at low (high) elevations. The same elevational gradient was found for the next decades, as it will continue to decrease at < 2000 m asl until 2055, according to all phase 5 of the Coupled Model Intercomparison Project (CMIP5; Meehl et al., 2009) climatic projections for the next decades. On the other side, an increase in ROS events is projected during winter at higher elevation (> 2000 m asl). Results obtained in this study are likely to extrapolate to the Mediterranean mountains, where a shift to higher ratio of rain versus snowfall and a shorter snow duration is expected due to climate warming (López-Moreno et al., 2017).

3.4. Anomalies in atmospheric fields related to hailstorm

Hailfall is one of the most frequent severe weather phenomena in the Mediterranean region. Thus, numerous studies on different aspects of hailfall have been conducted in the Mediterranean area: in France (Dessens et al., 2007; Sánchez et al., 2009; Berthet et al., 2011; Berthet et al., 2013; Merino et al., 2014; Hermida et al., 2015), Spain (Sánchez et al., 2003; Merino et al., 2013; García-Ortega et al., 2014; Gascón et al., 2015b), Italy (Giaiotti et al., 2003; Manzato, 2012; Eccel et al., 2012; Baldi et al., 2014), the Balkan Peninsula (Mesinger and Mesinger, 1992; Mitic et al., 2009; Počakal, 2011), Greece (Sioutas et al., 2009; Sioutas, 2011), Turkey (Kahraman et al., 2011) and Cyprus (Michaelides et al., 2008).

One of the main problems in the study of hailstorms is obtaining datasets of hailfalls, due to the small spatial and temporal scales in which they appear. Published works have used different methods to obtain hailfall data: damage data (Eccel et al., 2012), meteorological stations (Burcea et al., 2016; Ćurić and Janc, 2016), radar detection (Kaltenboeck and Steinheimer, 2014), or hailpad networks (Manzato, 2012; Sánchez et al., 2009). However, most of these methods do not allow for the collection of long, homogenous and extensive data series, which are needed to analyze trends in the frequency and intensity of these phenomena.

Various authors have sought to find relationships between hailfalls and atmospheric characteristics at synoptic (Sioutas and Flocas, 2003; García-Ortega et al., 2011; Berthet et al., 2013), mesoscale (García-Ortega et al., 2014; Merino et al., 2013, 2014) and thermodynamic levels (Gascón et al., 2015a), so as to infer hailfall. In this sense, the investigation of atmospheric field anomalies that are representative of the state of the atmosphere during hail days provides valuable information on the mechanisms involved in the development of these events.

One of the longest, most extensive and homogenous hailfall databases in the Mediterranean region is one that the Association Nationale d'Etude et de Lutte contre les Fléaux Atmosphériques (ANELFA) maintains in the south of France. This database contains hailfall information collected using > 1000 hailpads distributed throughout four zones in the region (Atlantic, Pyrenees, Mediterranean and Central; see Berthet et al., 2011). The ANELFA network has been in continuous operation since 1989. For further details of this hailpad network, see Berthet et al. (2011).

After thoroughly filtering the cases, in the present paper, those hail days (HDs, subsequently defined) were selected from the ANELFA database for hail seasons (May to September) from 1989 to 2014 for Pyrenees zones and from 1994 to 2014 for the Mediterranean zone. The Central zone was excluded from this study owing to a low number of cases. HDs were defined as days with at least one hailpad impact in one of the three studied zones. Thus, 402 and 161 HDs were selected for

Pyrenees and Mediterranean zone respectively.

Once the HDs were extracted for each of the zones, atmospheric conditions in the study area were characterized by daily 1948–2015 gridded reanalysis data from the National Centers for Environmental Prediction (NCEP), with spatial resolution of 2.5° × 2.5° (Kalnay et al., 1996). The study area is between 30°N–55°N and 25°W–10°E. This area was selected in line with the objectives of this study and to determine, at synoptic scale, the influence of circulation features of hailfall in the study area. The dynamic and thermodynamic state of the atmosphere was described using the following fields:

- Geopotential height at 500 hPa level (G500)
- Sea level pressure (SLP)
- Temperature difference between 850 and 500 hPa levels (lapse rate)

These fields describe the state of the atmosphere at low and mid-levels and permit assessment of thermal and dynamic instability. Obviously, with the three fields used we do not have a complete description of the structure of the atmosphere, but many authors have used these fields as the most representative at the synoptic-scale associated with environmental conditions conducive to convective development and have been extensively related to synoptic environments favoring the formation of severe convection and hailstorms in numerous regions. García-Ortega et al. (2014) used the fields of geopotential height and temperature at 850 and 500 hPa, in addition to the lapse rate between these both levels, to characterize the anomalies and trends in synoptic environments linked with hail in the Ebro Valley. Sioutas and Flocas (2003) characterized the synoptic patterns of atmospheric circulation related to hailstorms in northern Greece using sea level pressure and geopotential height at 500 hPa. To study the climatology of hail over central Europe, Suwała and Bednorz (2013) used the fields of sea level pressure, geopotential height at 500 hPa and temperature at 850 and 500 hPa.

In the present paper, anomalies at synoptic scale during HDs were calculated in each of the study areas based on the fields SLP, G500 and lapse rate, computed at monthly scale. First, monthly means of synoptic fields were computed for the period 1948–2015. Then, the fields' anomalies were extracted for each HD and the averages by zones are depicted, in Fig. 1 for the Pyrenean zone and in Fig. 2 for the Mediterranean zone. In the G500 field, a clear area of negative anomalies in the range of − 40 to − 50 geopotential meters (gpm) can be seen in the northwest Iberian Peninsula, with deeper anomalies in September. In the SLP field, September once again had anomalies of greater magnitude (− 5 to − 6 hPa) whereas anomalies in the central months of the hail season fluctuated between − 3 and − 4 hPa. These anomalies were located over the Cantabrian Sea in all months. Finally, with respect to lapse rate, the anomalies had a positive sign and generally extended from the western Mediterranean to cover all of France, with values around 2.5–3 °C. Finally, anomalies present during HDs in the Mediterranean zone were very different from observations in the Pyrenees zone. The negative anomalies for G500 and SLP were very prominent in May, August and September, whereas, in June and July, barely any significant anomalies can be seen. Thus, the maximum anomalies in G500 surpassed − 80 to − 90 gpm. These were located in the northern Iberian Peninsula in May and shifted northward in August and September. With respect to SLP, a negative anomaly centered over the inland area of France can be seen in May, with values up to − 4 to − 5 hPa; in August and September, the anomaly also moved north, reaching − 8 to − 10 hPa. Finally, for the lapse rate, anomalies between 2 °C and 3 °C emerged around the western Mediterranean, covering areas further north than in the other two zones.

The anomalies found in these fields are associated with environmental conditions conducive to convective development: an increase in the dynamic and thermal instability during HDs. The negative anomalies in G500 and SLP suggest that cyclonic circulation at low and middle levels are located, so that rising motion at synoptic scale are favored over the studied zones. Also, positive anomalies in the lapse rate indicates the presence of elevated vertical thermal gradients, being one of the fundamental factors for the convection development. In the final months of spring and first months of autumn, anomalies related to dynamic instability (in both G500 and SLP) predominate, whereas, in the mid-months of the hail season, anomalies related to thermal instability are predominant. This was observed by Merino et al. (2014), who found that hailstorms in May were associated with the passage of fronts and baroclinic disturbances related to jet-stream undulations. These authors also found that in summer months, strong warm surface advection that caused strong thermal instability was more important. The anomalies found here indicate the formation of cut-off lows or troughs over the Atlantic that favor south-southwest flow over the south of France and a cold maritime air mass entering over Aquitaine the Pyrenees at mid-levels above a warm southern flow at the surface and low levels, which produced an increase in the lapse rate between 850 and 500 hPa. These conditions have been previously described as the most propitious for the development of hailstorms in the region (Berthet et al., 2011, 2013).

4. Floods in the Mediterranean area

As mentioned in the Introduction, the Mediterranean area is characterized by complex topography with steep mountains close to the coastlines, a nearly enclosed sea and a highly varying land-water distribution. The Mediterranean Sea that is a source of heat and moisture on the one hand, with the surrounding complex orography on the other hand, not only modulate but also favor heavy precipitation and subsequent floods and mainly flash floods. Indeed, the numerous steep small catchments in the Mediterranean region favor rapid concentration times and generate runoff that can rapidly result in devastating floods (Garambois et al., 2014). The Mediterranean littorals are highly urbanized, with important infrastructure and settlements with historical value, increasing thus the vulnerability of these areas to floods and flash floods.

Flash floods in the Mediterranean were found to be related with heavy precipitation produced by intense and sometimes explosive cyclone activity (Homar et al., 2002b; Genovés et al., 2006; Lagouvardos et al., 1996, 2007; Kouroutzoglou et al., 2011a; Flaounas et al., 2016), but also by less intense cyclones with relatively long lasting embedded mesocale convective systems that interact with the complex topography of the area (Buzzi et al., 1998; Kotroni et al., 1999; Romero et al., 2000; Kotroni et al., 2005; Nuissier et al., 2008; Davolio et al., 2009a; Demirtas, 2016). During the last 20–25 years, a large number of catastrophic floods have occurred across the Mediterranean that were associated not only with damages on the infrastructures (power and telephone grids, buildings, road network, bridges and vehicles) but also with human casualties. A non-exhaustive list of the catastrophic floods that gave rise to numerous studies in the literature, going from the west towards the east are:

- on 3 November 1987, at Gandia (Spain) with > 800 mm in 24 h (Llasat and Puigcerver, 1994; Peñarrocha et al., 2002)
- on 7 August 1996, at Biescas (Spain) with 80 to 100 people killed (Soula et al., 1998)
- on 10 October 1994, in Catalonia (Spain), with 400 mm in 24 h (Ramis et al., 1998)
- on 22 September 1992, at Vaison-la-Romaine (France) with 300 mm in 24 h (Senesi et al., 1996; Nuissier et al., 2008)
- on 12–13 November 1999, in the Aude region (France) with 485 mm in 18 h (Ducrocq et al., 2003; Nuissier et al., 2008)
- on 8–9 September 2002, in the Gard region (France) with 600–700 mm in 24 h (Delrieu et al., 2005; Nuissier et al., 2008)
- on 10 November 2001, in Algiers (Algeria) with > 280 mm in 24 h (Hamadache et al., 2002; Tripoli et al., 2005)
- on 3–5 November 1966, the "century" flood strongly affected

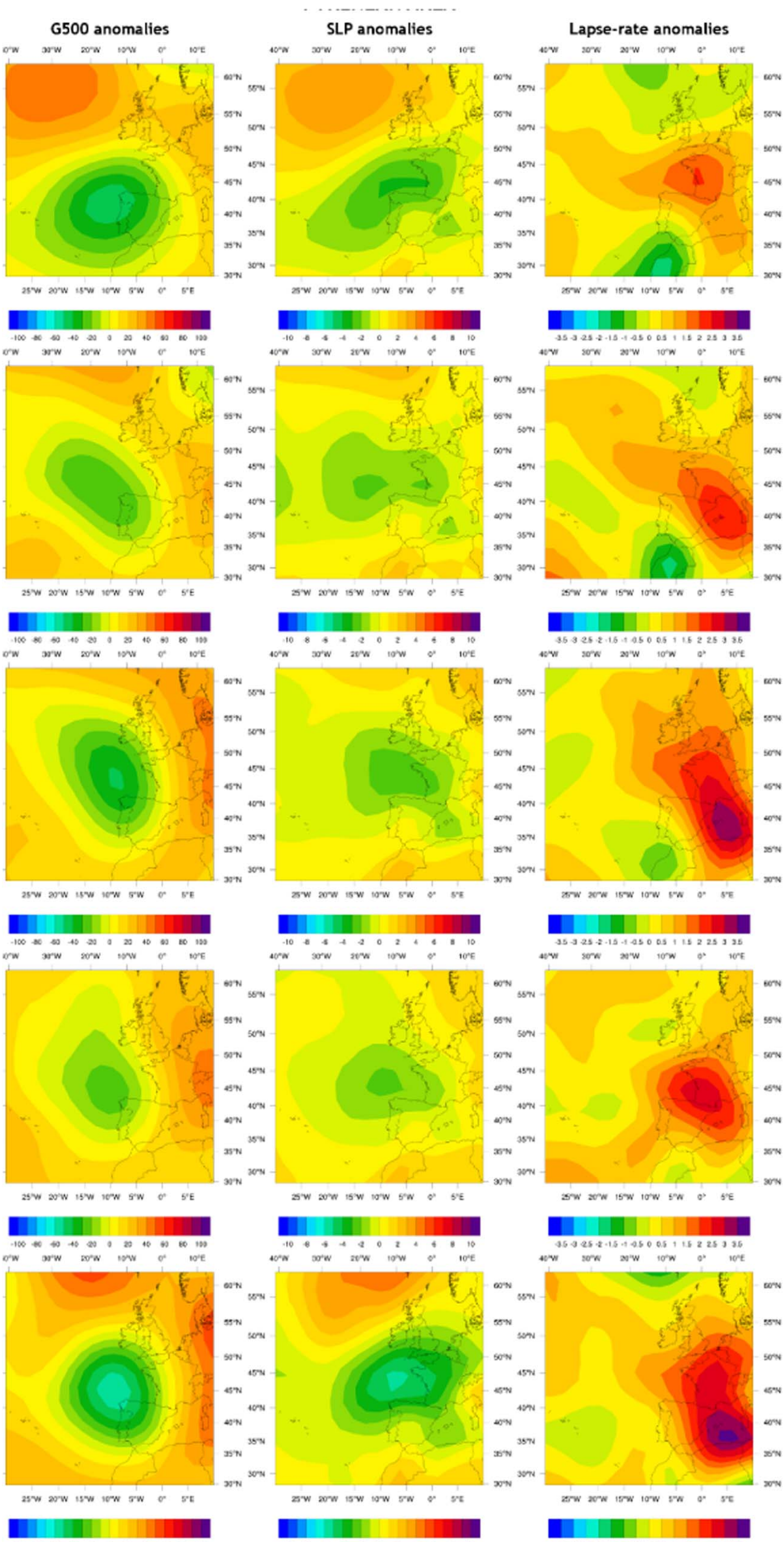

Fig. 1. Monthly anomalies at synoptic scale during hail days in the Pyrenean area based on the fields SLP, G500 and lapse rate, computed at monthly scale.

northeastern and central Italy with a peak precipitation value of 751 mm in 48 h at Barcis in northern Italy (Malguzzi et al., 2006; Cavaleri et al., 2010)

- on 4–5 November 1994, in Piedmont region (Italy) with > 300 mm in 24 h (Buzzi et al., 1998; Ferretti et al., 2000; Rotunno and Ferretti, 2001);
- on 13–16 October 2000, in Piedmont region (Italy) with 740 mm in 4 days and daily values ranging from 100 to 250 mm (Gabella and Mantonvani, 2001; Turato et al., 2004),
- on 8 October 1970, in Genoa (Italy) with 453 mm in 24 h and 44

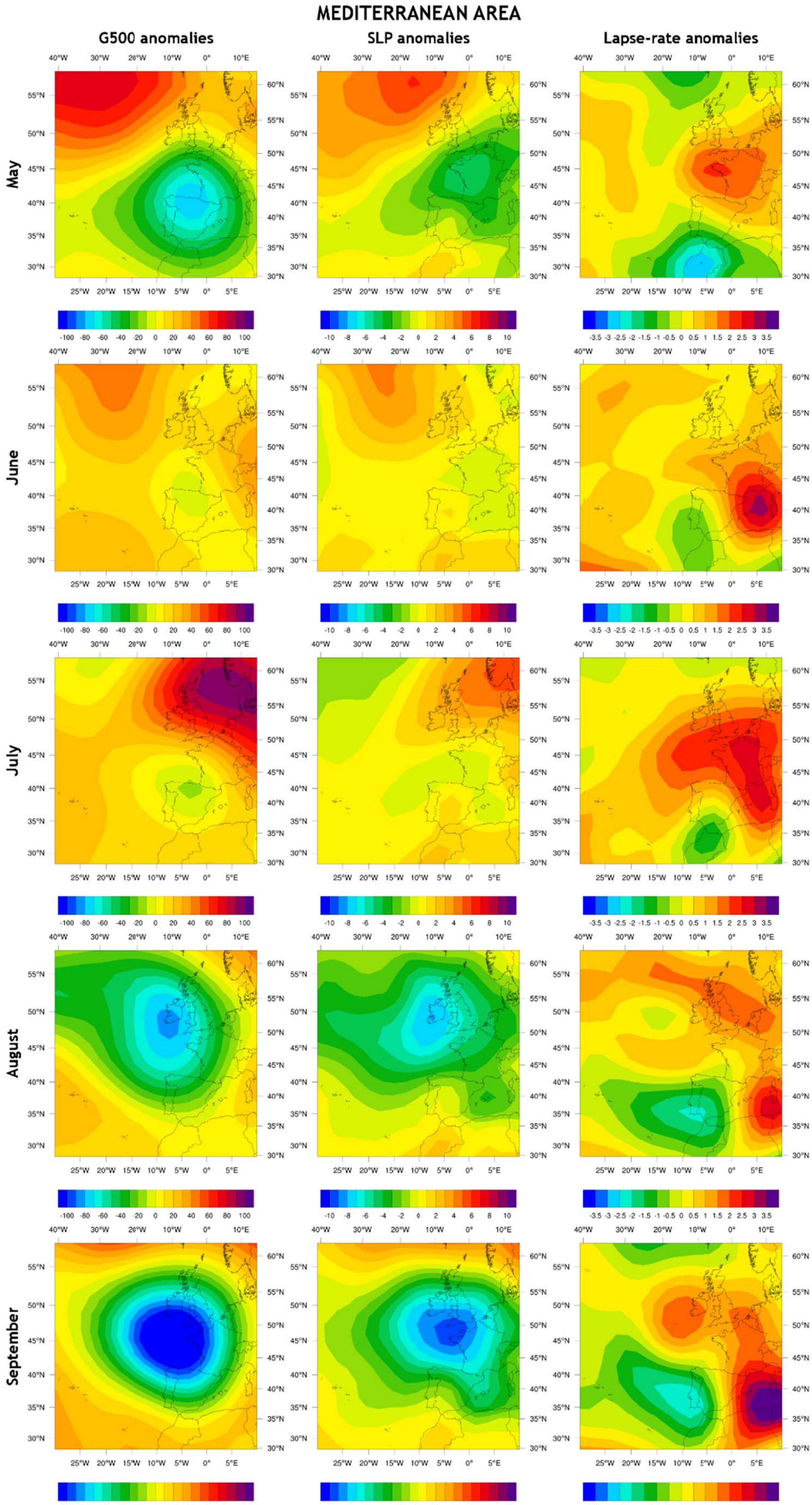

Fig. 2. Monthly anomalies at synoptic scale during hail days in the Mediterranean area based on the fields SLP, G500 and lapse rate, computed at monthly scale.

fatalities in the metropolitan area of Genoa (Faccini et al., 2016)

- on 4–5 November 2011, in Genoa (Italy) with 500 mm in 6 h and 6 fatalities (Fiori et al., 2014)
- on 21–22 October 1994, in Greece with major impacts in the greater Athens area with areas with > 150 mm in 24 h (Lagouvardos et al., 1996; Petroliagis et al., 1996)
- on 11–12 January 1997, in southern Greece with > 300 mm in 24 h (Kotroni et al., 1999)
- on 15–16 July 2014, in Thessaloniki (Greece) with 98.5 mm in 15 h and 107.3 in 24 h (Pakalidou and Karacosta, 2017; Pytharoulis et al., 2016; Tolika et al., 2017).
- on 6 November 2005, in Cyprus with 115 mm in 24 h (Nicolaides et al., 2009)
- on 24 December 1988 in Cyprus with 126 mm; 9 January 1989 with 144.6 mm; 21 November 1994 with 140.7 mm; 18 January 2010 with 162.5 mm; all in 24 h (Table 2 in Zittis et al., 2017)
- on 4–5 December 2001, in Israel with 250 mm in total and > 200 mm in 6 h (Krichak et al., 2007)
- on 5 December 2002, in Antalya (Turkey) with 230 mm in 24 h (Kotroni et al., 2005)
- on 9 October 2011, in the Gulf of Antalya (Turkey) with 238 mm in 6 h (Demirtas, 2016)

Floods have received an increasing interest during the last decades due to the important impacts they induce on the environment but also on the society and the economy. Various scientists and projects have been devoted in the collection and cataloguing of disastrous weather events including floods and many efforts have been devoted to the creation of flood databases. For that reason, data from national and regional databases, newspapers, web-portals, social-media, questionnaires, insurance companies, historical documentation, scientific and technical reports have been used along with the available hydrometeorological information (precipitation amounts and discharges). The problem that arises from the use of these various sources is the lack of homogeneity in the resulting databases (Petrucci, 2012). At international level, the Centre for Research on the Epidemiology of Disasters at Leuven University operates the EM-DAT database (http://www.emdat.be), which focuses only on highly catastrophic disasters (criteria that include > 10 reported fatalities, > 100 people affected, declaration of a state of emergency and call for international assistance). Also, international in terms of coverage (but with somehow less severe criteria for an event to be reported) is the NatCatService database (MunichRe, 2016). The aforementioned databases are very useful but their major shortcoming is that they provide information only for the catastrophic or even extremely catastrophic events, so they are not exhaustive over all categories of flood events.

At the European level, it is worth mentioning the European Severe Storms Laboratory (ESSL) initiated in 2006 (Dotzek et al., 2009) that covers severe storms with increased level of meteorological details reported by networks of voluntary observers, meteorological services and the general public. In this database flood producing heavy precipitation events are included. At national level, there is a number of open databases such as the PRIM.NET in France that includes the catastrophic events since 1900 (MEDDTL, 2012), the database of the Spanish Civil Protection that includes the major floods from 1995 to 2010, the AVI database in Italy that includes the floods and landslides of the 20th century (Guzzetti et al., 1994), the database of the National Observatory of Athens that includes the high impact weather events in Greece since 2001 that is continuously updated (Papagiannaki et al., 2013) and which has been extended back to 1980 for the flood events.

Many international collaborations have been devoted, among others, to the improvement of the understanding and better forecasting of high impact weather in the Mediterranean and mainly to flood inducing heavy precipitation, while also the climatology of these events and the study of their socio-economic impact has been also studied. Among these projects, the MEDiterranean Experiment (MEDEX) has operated from 2000 to 2010 on the improvement of the understanding and forecasting of cyclones that produce high impact weather in the Mediterranean area (Jansà et al., 2014). MEDEX has produced, among others, a database in order to support the climatological and physical process studies that included a catalogue of cyclones that induced high impact weather including floods. This database comprised initially the period 1996–2001 and was extended to cover the period 1990–2006 in the frame of the European funded project FLASH (Price et al., 2011a). This database was the basis for the FLOODHYMEX database (Llasat et al., 2013; Papagiannaki et al., 2013) that was later produced in the frame of the Hydrological Cycle in Mediterranean Experiment (HyMeX - www.hymex.org). Indeed, HYMEX is an international effort spanning over a decade (2010 – 2020) with the aim to advance the scientific knowledge of the water cycle variability and some of its specific tasks consist of improving our understanding of the water cycle, with emphasis on hydrometeorological extremes, assessing the socio-economic vulnerability to these extremes and the adaptation capacity of the territories and the population (Drobinski et al., 2014).

Indeed, in the frame of HYMEX, a large effort has been devoted to homogenizing regional databases of flood events in the Mediterranean in a common database. The regions included are Catalonia and the Balearic Islands in Spain, Languedoc-Roussillon, Midi-Pyrenees and Provence-Alpes Cote d'Azur in France and Calabria in Italy; the respective study period is 1981–2010. The resulting database is the FLOODHYMEX database (Llasat et al., 2013) that has been recently updated to include Greece and to expand the period up to 2015. It is shown that in the Northwest Mediterranean the most flood-prone season is autumn, except in Calabria where the flood-prone season is winter. Papagiannaki et al. (2013) in their study of high impact weather events in Greece for the period 2001–2011, also found that high impact weather events are more frequent in October and November and that ~50% of the fatalities due to weather related natural hazards were related to floods, while flooding is the most common weather related natural hazard with a percentage of occurrence of ~65%. An example of the visualization of the content of the FLOODHYMEX database is given in Fig. 3.

All the aforementioned efforts to populate and extend (both geographically and temporally) the databases of flood events are of paramount importance in the frame of climate change, since they permit to identify trends in the occurrence and severity of floods in the Mediterranean area. Therefore, this endeavor has to be maintained and prioritized by the relevant agencies/service/research centers since it will provide the necessary information for climate-change studies related to the flood events in this area. Future climate trends in precipitation and extreme precipitation events, which frequently lead to floods, have been addressed in Section 3.2.

5. Drought in the Mediterranean area

According to the World Meteorological Organization (WMO), drought is a hydro-meteorological hazard characterized by lower than normal precipitation (WMO, 2006). Prolonged lack of rainfall results in conditions where water resources may not be able to meet the demands of the environment or of human activities. Drought is a relative rather than an absolute condition, unlike aridity or well-defined dry seasons, which are permanent climate features. It is difficult to know when drought begins and when it ends and there are no exact or universally accepted definitions (WMO, 2006). Droughts are often classified in four different categories, related to their impacts (e.g., Mishra and Singh, 2010): meteorological drought (precipitation deficits), agricultural drought (soil moisture deficits impacting crop production), hydrological drought (stream flow deficits impacting water levels in natural water bodies and reservoirs) and socioeconomic droughts (a deficit of economic goods, as a result of the previous three droughts, impacting the quality of life).

Indicators to assess and quantify droughts have been reviewed by

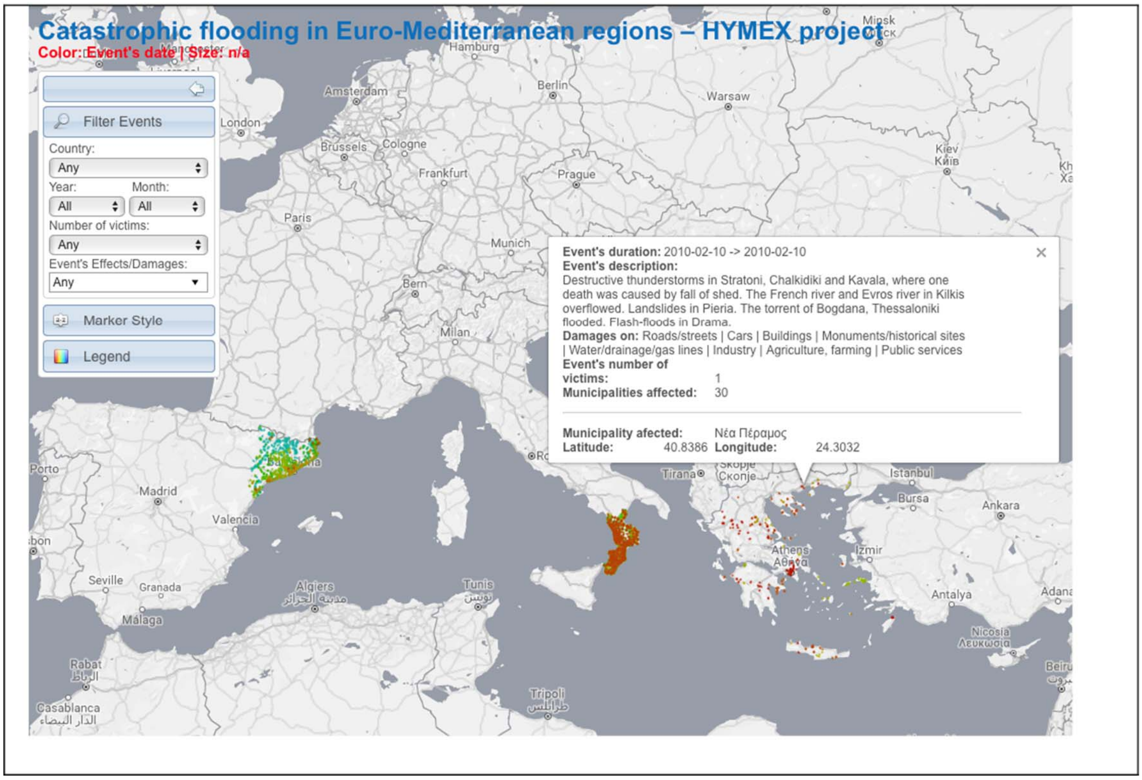

Fig. 3. A platform constructed for the visualization of the flood events that populate the FLOODHYMEX database. Points on the interactive map correspond to the municipalities affected by the catastrophic events. Information includes: start and end date of the event, short description, weather-related phenomena, number of fatalities and damaged elements (http://stratus.meteo.noa.gr/events_europe).

various authors (e.g., Heim, 2002; Mishra and Singh, 2010; Hao and Singh, 2015; Vicente-Serrano et al., 2015). The World Meteorological Organization (WMO) recommends the use of the Standardized Precipitation Index (SPI) as a universal drought index (Hayes et al., 2011). The SPI is based on monthly precipitation data and analyses the precipitation deviation of the mean, using a Gamma distribution (McKee et al., 1993). The SPI can be calculated on different time-scales (e.g., monthly, 3-monthly, annual) to represent the different response times of hydrological variables to precipitation deficits. A weakness of the SPI is its inability to analyze moisture availability related to atmospheric evaporative demand. This is especially important for the Mediterranean, where droughts are driven both by lack of precipitation and high evaporation rates (Sousa et al., 2011), as well as for climate change studies.

Several investigators have included atmospheric evaporative demand into drought indicators. These include the well-established Palmer Drought Severity Index (PDSI) and the more recent Standardized Precipitation Evapotranspiration index (SPEI) (Palmer, 1965; Vicente-Serrano et al., 2010; Beguería et al., 2014). The PDSI calculates a water budget system based on precipitation, evapotranspiration demand and soil characteristics (Palmer, 1965). Wells et al. (2004) developed a self-calibrating PDSI (SC-PDSI), where the empirical constants in the index are automatically replaced with local, dynamically calculated values. The SPEI is similar to the SPI, but uses the difference between precipitation and reference evapotranspiration as input (Vicente-Serrano et al., 2010).

AghaKouchak et al. (2015) reviewed satellite-based remote sensing of drought-related variables, relevant current and future satellite missions and development of multi-parameter drought indicators. The authors indicate various future opportunities, including the use of microwave emissivity to assess surface soil moisture and vegetation water content, combination of microwave and optical vegetation monitoring and integration of data uncertainty. However, they also point out that the length of record of many satellite observations may not allow the analysis of drought from a climate perspective. The European Drought Observatory (http://edo.jrc.ec.europa.eu/edov2/php/index.php?id=1000) computes a combined 10-daily drought indicator, based on the 1- and 3-month SPI, soil moisture anomalies from a hydrological model and anomalies of the fraction of absorbed photosynthetically active radiation, obtained from SPOT-satellite images (De Jager and Vogt, 2015).

Analysis of gridded precipitation data sets for 1902–2010 has shown that the Mediterranean region has undergone substantial drying with more frequent droughts since the 1970s (Hoerling et al., 2012). Time series analysis showed that ten of the driest winters since 1902 occurred in the last 20 years. Long-term average annual precipitation (October–September) over Cyprus (Fig. 4) showed a very similar pattern as the November–April rainfall over the Mediterranean (30°–45° N, 10°W–40°E). These authors compared atmospheric general circulation model simulations with observed and forced sea surface temperatures, as well as unforced (pre-industrial) and externally-forced coupled ocean-atmosphere general circulation model simulations. Results indicated that anthropogenic greenhouse gas and aerosol forcing could explain only part of the strong Mediterranean drying after the 1970s. It is likely that sea surface temperature anomalies over the Indian Ocean and a positive NAO response have played a role in this drying (Hoerling et al., 2012).

Sousa et al. (2011) analyzed monthly precipitation, the PDSI and the SC-PDSI for the period 1901–2000 for the entire Mediterranean basin and specific sub-domains. They used non-parametric trend analysis corrected for serial correlation. Similar to other studies, they found a decrease in precipitation and water availability for the region, except for northwest Iberia, the extreme south of Italy and parts of Turkey. They found that the main driver of the SC-PDSI in the western and central Mediterranean areas is the winter NAO pattern that is also relevant during the following spring and summer seasons. The second

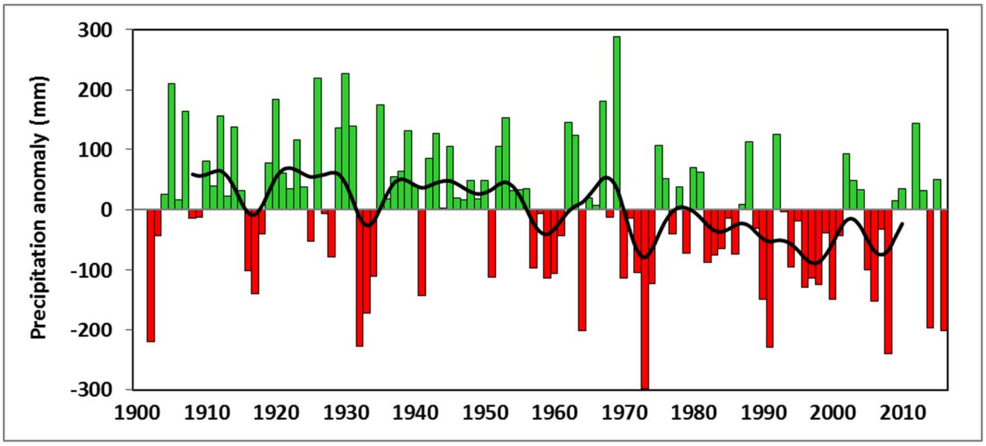

Fig. 4. Anomalies of the average annual rainfall over Cyprus (October–September) for the 1901–1902 to 2015–2016 period with a low-pass 13-weight filter (black line); data from the Cyprus Department of Meteorology. This filter removes fluctuations on less than decadal time scales and has also been used by the fourth IPCC assessment (Trenberth et al., 2007).

most important mode corresponds to the Scandinavian Pattern that is significantly associated to the SC-PDSI between winter and summer over central Mediterranean. Sousa et al. (2011) also used the teleconnection and sea surface temperature analysis to develop a regression to forecast summer drought conditions six months in advance.

Altava-Ortiz et al. (2011) analyzed precipitation records (70 to 150 years) in four Mediterranean regions: the French and Spanish Mediterranean coasts, Sardinia Island and the Calabrian region, in Italy. They found that the 1984/1985 to 1994/1995 and 1994/1995 to 2004/2005 decades were some of the driest in the record. They found that the low precipitation amounts in the Central Mediterranean were caused by a decrease in winter rainfall, whereas a decrease in spring and winter rainfall was the cause of the driest periods in the western Mediterranean. They indicated that the high frequency of positive seasonal phases of winter, spring and autumn NAO at the end of the 20th century and beginning of the 21st could be a possible dynamic mechanism causing the dry last decades.

García-Herrera et al. (2007) analyzed the 2004/2005 drought over the Iberian Peninsula. The spatially averaged precipitation over Iberia between October 2004 and June 2005 was roughly 45% less than the 1961–1990 climatological average. Several stations with long-term precipitation series across central Spain and Portugal recorded the worst drought episode since the late nineteenth century (e.g., Madrid since 1859; Lisbon since 1865; Sevilla since 1876). They attributed the 2004/05 Iberia drought to three main factors that occurred successively: positive NAO indexes from November to January, a positive East Atlantic (EA) pattern in February and an anomalous blocking episode in March associated with negative NAO values.

Spinoni et al. (2015) analyzed the biggest European drought events during 1950–2012. They computed three drought indicators, the SPI, SPEI and the Reconnaissance Drought Index and merged these into a combined indicator at 3-month scale for meteorological and 12-month for hydrological droughts. The indicators were calculated using the E-OBS gridded data (0.25° × 0.25°). Monthly reference evapotranspiration was computed using the Thornthwaite equation. Large-scale 12-month droughts in the southern Europe and the Mediterranean occurred in 1989–1991, 1995, 1991–2001, 2003, 2004–2005, 2007–2008. On the contrary, northern and eastern Europe experienced the highest drought frequency and severity from the early 1950s to the mid-1970s.

Spinoni et al. (2017) investigated how seasonal drought trends have evolved over Europe from 1950 to 2015 during winter, spring, summer and autumn. They used the same data as Spinoni et al. (2015), except that reference evapotranspiration was computed with the Hargreaves-Samani equation. Analysis of the 1950–2014 period showed an increase in the frequency and severity of droughts in winter for the Iberian Peninsula, south France and Italy, Greece, Turkey and Cyprus (both SPI and SPEI). In spring droughts were more frequent and severe in the Iberian Peninsula (both SPI and SPEI) and in Greece, Turkey and Cyprus (SPEI only). In summer, more frequent and severe droughts were found for all above mentioned regions plus the Balkan, but for the SPEI only. For the 1981–2014 period, only the summer SPEI showed more frequent and severe droughts in all regions. In fall, less frequent and severe droughts (SPI only) were found in the Iberian Peninsula, south France and Italy for 1981–2014. These results indicate a drier Mediterranean region after the 1980s.

Cook et al. (2016) used 106 tree ring chronologies, with the oldest going back to the year 1100, to construct a SC-PDSI map for the June–August period of the Mediterranean. They found that the 1998–2012 period in the Levant is likely (89% likelihood) the driest 15-year period in the region since the twelfth century. On the contrary, recent droughts in the western Mediterranean and Greece were not found to be outside the range of the last 900 years of natural variability.

Orlowsky and Seneviratne (2013) found that CMPI5 projections of changes in the frequencies of future drought events display detectable trends towards more frequent drought before the end of the 21st century in the Mediterranean. Pascale et al. (2016) analyzed changes in rainfall under the RCP8.5 emission scenario, projected by 24 models of CMIP5. They found high inter-model agreement over the Mediterranean, with a strong increase in the number of dry days (up to 1 month), by the end of the twenty-first century. Lehner et al. (2017) analyzed the PDSI from a set of ensemble simulations with the Community Earth System Model (CESM). They found that, at 1.5 °C and 2 °C warming, the Mediterranean experiences substantially elevated risk of consecutive drought years, compared to present day. The simulations showed that the additional 0.5 °C of the 2 °C climate lead to significantly higher drought risk.

6. Explosive cyclones

6.1. Definition -classification - consequences

The explosive cyclones, or meteorological bombs (Sanders and Gyakum, 1980), are high-impact cold-season, synoptic or sub-synoptic scale lows, mainly of maritime origin that occur in both hemispheres (Sinclair, 1995; Lim and Simmonds, 2002), including the Mediterranean Sea (Conte et al., 1997). Their most distinct feature is the large and rapid pressure drop at sea-level.

In a pioneering study, Sanders and Gyakum (1980) defined them as the extratropical cyclones in which the central mean sea-level pressure (mslp) falls at least by 1 hPa h^{-1} for 24 h at 60°N, or by the geostrophically equivalent threshold of 24 hPa × (sinφ/sin60°) in 24 h at latitude φ (1 bergeron; hereafter 1B). The equivalent deepening of the central mslp in a 12 h period has also been considered in order to define an explosive cyclone (e.g., Gyakum and Barker, 1988; Kouroutzoglou et al., 2011a; Maheras et al., 2001; Roebber, 1984; Rogers and Bosart, 1986; Sanders and Gyakum, 1980). Kouroutzoglou et al. (2011a) showed that more than half (57.6%) of the explosive cyclones in the Mediterranean attain explosive deepening in a 12 h period. As an alternative definition to that based on the central pressure change, Lim and Simmonds (2002) proposed the use of the relative change of central pressure which is calculated after the removal of the climatological sea-level pressure.

Sanders (1986) classified the explosive cyclones of west-central north Atlantic Ocean, as weak (for 24 h deepening of 1–1.2 B), moderate (1.3–1.8 B) and strong (> 1.8 B). Conte et al. (1997) introduced four categories: C1 (1–1.15 B), C2 (1.16–1.30 B), C3 (1.31–1.45 B) and C4 (> 1.45 B), for the Mediterranean explosive cyclones. The lower limits in the latter systems are consistent with the fact that the cyclones in the Mediterranean, even the most intense ones, are generally weaker than over the oceans (e.g., Čampa and Wernli, 2012; Flaounas et al., 2015; Trigo et al., 1999). Trigo (2006) found considerably larger fraction of explosive cyclones with very rapid pressure drop (> 1.83 B) in the Atlantic (10%) than in the Mediterranean (1%).

The explosive cyclones are associated with hazardous phenomena, like strong winds and high waves, torrential precipitation and floods, snowfall and blizzards, thunderstorms and lightning activity (e.g., Bech et al., 2013; Capaldo et al., 1980; Conte et al., 2002; Homar et al., 2002a; Lagouvardos et al., 2007; Sanders and Gyakum, 1980). They have also been associated with intercontinental transport of air pollution from northern America to Europe (Stohl et al., 2003). Thus, they pose a significant threat to life, property and environment, especially in the maritime and coastal regions. It needs to be clarified that according to MEDEX experiment, heavy precipitation in the Mediterranean basin does not only occur in explosive, or other intense cyclones, but it may be associated with weak/moderate cyclones (Jansà et al., 2014 and references therein). The latter systems are able to organize properly the low-level inflow of warm and moist maritime air masses, promoting deep convection, especially in regions with steep topography.

6.2. Mechanisms of explosive cyclogenesis

Two main types of explosive cyclogenesis have been recognized to prevail in the Mediterranean, denoted by KF [Karacostas-Flocas] and CC [Conte-Capaldo] (Conte et al., 2002). The KF type follows the mechanism presented by Karacostas and Flocas (1983), for an explosive cyclone which appeared over the Mediterranean basin in March 1981 and set a new record minimum atmospheric pressure at the National Observatory of Athens, Greece (~970 hPa, since 1858) and the Aristotle University of Thessaloniki, Greece (980 hPa, since 1931). The cyclone developed as a result of the interaction of an upper-air baroclinic long wave with an unstable short wave created by a dynamically unstable ridge together with a jet stream. This cyclone was further studied by Flocas (1990) and Prezerakos and Michaelides (1989). The latter showed the important role of dynamical processes relative to diabatic heating, for the energy balance, during its deepening phase. The CC mechanism is based on the processes discussed in a study by Capaldo et al. (1980), for a severe storm which caused flood, deaths and significant damages at the region of Trapani (western Sicily), in November 1976. Explosive cyclones of CC type develop over the Mediterranean, through the interaction of a sub-synoptic African low with a cold mid-latitude synoptic-scale depression penetrating from the north or northwest.

Kouroutzoglou et al. (2011a) have shown that 60% and 38% of the Mediterranean explosive cyclones, are of KF and CC type, respectively. The KF or CC type mechanisms seem to be necessary, but not sufficient conditions for the vast majority of explosive cyclogenesis in the Mediterranean, since they also explain cyclogenesis of regular lows. Their synergy with some additional processes is likely to trigger rapid deepening (Conte et al., 1997; Karacostas and Flocas, 1983). These include strong surface heat and moisture fluxes, latent heating, synergy of the polar with the subtropical jet-stream and stratospheric air intrusions associated with tropopause dynamic anomalies. Flaounas et al. (2015) has concluded that an upper-air Potential Vorticity (PV) streamer precedes the genesis of the intense Mediterranean cyclones.

The Mediterranean Sea is surrounded by complex topography. Therefore, the orographic (or lee) cyclogenesis (Buzzi and Speranza, 1983) also needs to be considered since maximum deepening rates of the Mediterranean explosive cyclones are exhibited in the lee of mountain ranges; with the most important being the Alps. Lee cyclogenesis takes place due to the interaction of a synoptic-scale low with the orography. The latter is crucial in determining the location and/or timing of cyclogenesis (Tibaldi et al., 1990). Shallow low-level depressions that form by orography (Horvath et al., 2006; Lionello et al., 2006) may interact with an approaching upper-level trough, creating a deep cyclone. Buzzi and Tibaldi (1978) have provided a detailed synoptic and dynamic analysis of a deep cyclogenesis event in the lee of the Alps describing also the processes responsible for this phenomenon. The ALPine EXPeriment of the Global Atmospheric Research Programme (see, ALPEX-GARP in the joint World Meteorological Organization - International Council of Scientific Unions publication: WMO-ICSU, 1986), with its field phase in 1982, had been specifically devoted to study orographic cyclogenesis in the lee of the Alps and provided significant measurements. The large number of observational and theoretical studies on these data (e.g., Alpert et al., 1996; Buzzi and Speranza, 1986; Radinovic, 1986; Speranza et al., 1985; Tafferner and Egger, 1990; WMO-ICSU, 1986) promoted the understanding of this phenomenon (also see Tibaldi et al., 1990 for a thorough critical review). Moreover, ALPEX motivated further research on this topic in the coming years (e.g., Buzzi et al., 1987; Pierrehumbert, 1985; Smith, 1986). Pichler and Steinacker (1987) using the ALPEX dataset identified two types of orographic cyclogenesis over the Alps: the northwesterly and the southwesterly upper-level flow type. Actually, in the former type there is not a new formation of a low in the lee of the Alps, but usually a re-intensification under a favourable baroclinic flow.

Regarding the energetics of the explosive cyclones, Michaelides et al. (1999b) investigated a case of rapid cyclogenesis that strongly affected central-eastern Mediterranean with maximum precipitation amount of 266.7 mm in 2.5 days at Rhodes island, Greece (see also, Prezerakos et al., 1997). Barotropic and baroclinic energy conversions were important in the initial and later phases, respectively, of its rapid deepening, while appreciable energy was transferred from the surrounding area.

Table 1
The lifetime, radius, deepening rate and annual number of the regular lows, explosive cyclones and medicanes. The sources are also included.

	Average lifetime	Average radius	Deepening rate	Annual number
Ordinary cyclones (Kouroutzoglou et al., 2014)	1–2 days (38%) 2–3 days (27%)	1.4–1.9° lat.	–	1445
All cyclones (Trigo et al., 1999)	28 h	< 500 km	− 1 to − 2 hPa/6 h	660
Explosive cyclones (Kouroutzoglou et al., 2011b, 2014)	5 days	1.6–2.2° lat.	20.49 (34–35) hPa/24 h on average (max)	5.7
Medicanes (Tous and Romero, 2013)	12–24 h	< 100-200 km	− 10 to − 20 hPa/6 h	1–3

6.3. Climatology of explosive cyclones in the Mediterranean

The explosive cyclogenesis in the Mediterranean is a relatively rare event, since an average of almost 6 explosive cyclones form each year (Table 1), corresponding to the 0.4% of all the cyclones in this basin (Kouroutzoglou et al., 2014). They exhibit a well-defined seasonal cycle, with the vast majority appearing from November to April, having a peak in December, according to Conte et al. (2002) and Kouroutzoglou et al. (2014). The last authors have also shown that their mean lifetime is about 5 days and their average radius is between 1.6 and 2.2° of latitude (Table 1), with the largest forming over the southern and eastern Mediterranean Sea. A comparison with the regular lows shows that the explosive cyclones are generally larger in size and longer-lived systems. Their maximum deepening rate is 20.49 hPa/24 h, on average, while it has reached 34–35 hPa/24 h (Kouroutzoglou et al., 2011b).

The explosive cyclones exhibit maximum deepening rates mainly along the northern Mediterranean coast (Gulf of Genoa, Ligurian Sea, Tyrrhenian Sea, Adriatic Sea, Gulf of Lions, Balearic Sea, Aegean Sea) and over the Ionian Sea, the Levantine Sea and the lee of Atlas Mountains (Kouroutzoglou et al., 2011b; Maheras et al., 2001). Therefore, they tend to deepen rapidly mainly near the strongest sea-surface temperature (SST) gradients (Conte et al., 1997; Kouroutzoglou et al., 2011a), in agreement with Sanders and Gyakum (1980) for the explosive cyclones in the Atlantic and Pacific oceans. In addition, the above regions and especially northern Italy, point to the importance of orography, particularly of the Alps massif (Conte et al., 2002). The western Mediterranean explosive cyclones tend to move eastward/southeastward, the Alpine ones move primarily south-southeastward, those of the Balkans mainly follow a northward track and the ones of northwestern Africa exhibit an eastward path (Kouroutzoglou et al., 2014). Kouroutzoglou et al. (2012) showed that during explosive deepening they display a clear westward tilt with height, confirming the importance of baroclinic instability. Finally, Kouroutzoglou et al. (2014) and Conte et al. (1997) found a negative trend in their density and annual number (respectively), in line with Trigo (2006) for the number of intense lows of the northern Mediterranean in the December–March period.

6.4. Cases of explosive cyclogenesis

The “Queen Elizabeth II storm” over the north Atlantic in September 1978 (Gyakum, 1983), the “President's Day Snowstorm” over the eastern United States in February 1979 (Bosart, 1981) and the “Great Storm” of October 1987 over southern England with at least 18 fatalities (Burt and Mansfield, 1988) are a few examples of high-impact explosive cyclones worldwide. Regarding the Mediterranean, various cases appear in the literature. For example, a deep explosive cyclone caused serious damages to Palermo Harbor of Sicily in October 1973 (Conte et al., 2002). More recently, the eastern Mediterranean explosive cyclone of 21–22 January 2004 was associated with serious damages in the infrastructure and power supply network in the Aegean Sea (Brikas et al., 2012; Lagouvardos et al., 2007).

The explosive cyclone of 2004 is presented in more detail, because it was one of the deepest cyclones over the Mediterranean in the MEDEX database for the last 40 years (Lagouvardos et al., 2007). The explosive deepening lasted for 24 h until 12:00 UTC 22/1/2004. At that time, the minimum mslp dropped to 976.4 hPa (Katsafados et al., 2011), which is very close to the 977 hPa measured at Samos island in the eastern Aegean Sea. The pressure fall of about 23 hPa/24 h (~1.4 B; Katsafados et al., 2011; Lagouvardos et al., 2007) classifies it in the C3 (very disruptive explosive cyclone) category of the classification by Conte et al. (1997). Although a station on Ikaria Island (just west of Samos) reported an even lower mslp of 972 hPa (Brikas, 2006), this measurement is treated with caution.

Gale force winds prevailed over the Aegean Sea. The reported sustained winds in the Aegean Sea exceeded 20 m s^{-1} on 22 January and at Naxos island they reached 32 m s^{-1} with gusts up to 41 m s^{-1} (Brikas, 2006). Snowfall and even blizzards were observed in the eastern mainland of Greece, the northern Aegean Sea and northwestern Turkey, while important lightning activity affected the Aegean Sea, the surrounding coastal regions and Cyprus (Lagouvardos et al., 2007).

The development of the cyclone was associated with two upper-air troughs which interacted during the rapid deepening. The southern trough was a 500 hPa cut-off low that emerged over the sea from Libya, while the other one penetrated the central Mediterranean over Italy and the Ionian Sea from the north. Both were associated with significant dynamic tropopause anomalies towards the mid-troposphere. Brikas (2006) suggested that the polar and subtropical jet-streams contributed to the explosive deepening, through their associated secondary ageostrophic circulations.

In an experimental simulation of the January 2004 explosive cyclogenesis with the MM5 model, the modification of the upper-air PV field resulted in a shallower low that did not move at the correct track (Lagouvardos et al., 2007). In another experiment, these investigators turned off the surface sensible and latent heat fluxes and the model predicted an intense and rapidly deepening cyclone, but of weaker intensity than in the control run, in agreement with Pytharoulis (2008) who used the SKIRON/Eta model. Finally, Katsafados et al. (2011) showed that different SST datasets modified the surface heat fluxes and affected the spatiotemporal distribution of precipitation, but not the explosive deepening or the cyclone's track. In conclusion, the upper-air dynamic forcing assumed primary role in the explosive cyclogenesis of this system, contrary to the surface heat fluxes.

7. Medicanes

Cyclones have a central role in the definition of the weather and climate of the Mediterranean region, especially for the characterization of meteorological extremes (Radinovic, 1987; Lionello et al., 2006). Indeed, the connection between Mediterranean cyclones and hazardous weather phenomena has been the subject of research efforts for several decades; the reader is referred to Jansà et al. (2014) for an extensive review of literature and projects dealing with Mediterranean cyclones. With the advent of satellite meteorology in 1960s, a relatively rare type of Mediterranean cyclones got the attention of the atmospheric science community for their morphological similarity with tropical cyclones, namely, the presence of a warm core, axisymmetry and cloud-free eye (see Ernst and Matson, 1983). For these reasons, these systems have been coined *Medicanes* (Mediterranean Hurricanes; Fig. 5; Emanuel, 2005). The identification of medicanes offered a possible interpretation for extreme but short-lasting cyclonic wind records and narrow V-shape signals occasionally observed on barograms (Homar et al., 2003; Moscatello et al., 2008).

Medicanes are relatively small in size and associated with strong winds and often with heavy rain showers (Rasmussen and Zick, 1987; Lagouvardos et al., 1999; Pytharoulis et al., 2000; Homar et al., 2003; Fita et al., 2007; Moscatello et al., 2008; Buzzi, 2010; Tous et al., 2013). Some authors classify these cyclones as a subclass of polar lows (Businger and Reed, 1989), not only for their aesthetic appearance in satellite and radar images (as vigorous highly concentric convective cloud bands wrapped around a central eye; e.g., Moscatello et al., 2008; Tous and Romero, 2013) but also for the warm-core and small-scale nature linked to the fundamental action of sea-to-air heat fluxes and latent heat release within the core of the storm. Medicanes also rely on the availability of initial dynamical forcing and the development of marked sea – atmosphere temperature contrasts; therefore, a necessary but certainly not sufficient condition for their genesis is the presence of a cold core low in the upper and mid troposphere (Emanuel, 2005; Tous and Romero, 2013; Cavicchia et al., 2014a). Over the Mediterranean, such a synoptic setting is more frequent in the fall and early winter, hence these are the seasons exhibiting the peak medicane occurrence.

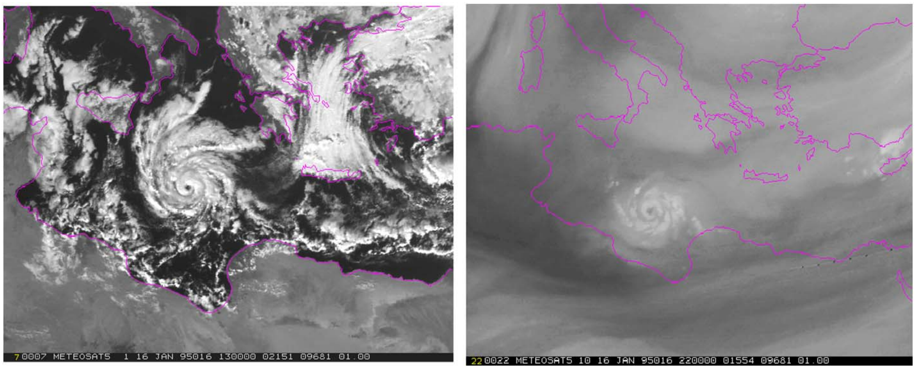

Fig. 5. Meteosat 5 images for 16 January 1995. Left: Visible channel at 13:00 UTC. Right: Water vapor (10.8 μm) channel at 22:00 UTC.

Despite the rich body of literature analyzing tropical-like cyclones in the Mediterranean from different perspectives, there is still a need for consensus on a clear and practical definition of a medicane. Romero and Emanuel (2013) state that there is a "*great difficulty in formulating a clear-cut distinction between medicanes and the broad spectrum of Mediterranean low-pressure systems, a significant fraction of which appear to be hybrid cyclonic storms that combine in different proportions the physical mechanisms of ordinary extratropical disturbances (e.g., frontal dynamics) with* those [of tropical systems]". Using an effect-based definition, like the one for hurricanes at the NHC (i.e., *tropical cyclones with maximum sustained surface winds of 33 m s^{-1} or more*), combined with some broad features on satellite images, like a high degree of symmetry around a more or less defined central eye, would misclassify hybrid and even some baroclinic extratropical systems as medicanes, rendering a scientifically useless solution.In this sense, two competing approaches to set an objective medicane definition are currently under active scientific debate: an observation-based definition versus a physical-processes-based definition. On the one hand, several authors propose the use of morphological criteria established over different observational sources: satellite images QuickSCAT (Fita et al., 2007); AMSU (Claud et al., 2010); MSG-SEVIRI (Conte et al., 2011), Meteosat-VIS (Tous and Romero, 2013), sea level pressure and/or wind records (Ernst and Matson, 1983), radar reflectivity maps and even lightning data (De Luque et al., 2007; Fita et al., 2009; Miglietta et al., 2013). The common idea underlying these definitions is to identify a cloud-free eye surrounded by a quasi-continuous convective eyewall, axisymmetric shape of the cyclone with spiral rainfall bands, abrupt and deep V-shape signals of sea level pressure, fast surface wind-veering including a calm period and other similar-to-hurricane genuine characteristics. On the other hand, quantitative criteria on the size and lifespan (e.g., "*the order of 100 km,… lasting few hours*") have been used (Miglietta et al., 2015). An ambitious attempt to define medicanes systematically according to morphological criteria is presented by Tous and Romero (2013) who visually inspected 32 years of Meteosat images screening for symmetric cyclones over the Mediterranean region presenting continuous cloud cover, an eyewall, a size < 300 km in diameter and a lifespan of 6 h or more. They identified six "clear" medicanes and complemented the database with six additional cases collected from studies reported in the literature. Miglietta et al. (2013) identified fourteen cases of medicanes over a 13-year period, based on satellite images combined with high resolution simulations. These authors recognized that the derived annual rate of medicanes was rather low owing to the very strict definition criteria used.

An alternative definition of medicane is the more fundamental processes-based approach, which focus on the similarities of the physical mechanisms acting on the genesis and maintenance of medicanes compared to those of tropical cyclones. Admittedly, this approach hampers an agile and automatic detection of medicanes based on observations or analysis fields; however, it abides by the identification of hurricane-like energetic and dynamic processes. In this sense, the consensus conceptual model for the intensification and maintenance of medicanes is similar to that of tropical cyclones, being governed by surface energy fluxes within pre-existing organized cyclonic environments, although with a critical requirement at Mediterranean latitudes: the presence of an upper-level cold trough that contributes to cool and moisten the low and mid-tropospheric environment, thus increasing the air-sea gradient of saturation moist static energy (Emanuel, 2005). This sets an apparent paradox: the presence of an upper-level trough favors the classical baroclinic cyclogenesis by differential vorticity advection and thermal gradient, while it is also a tropical-like cyclone prone environment, especially during the mature and late phases of development of the synoptic scale system, when the vertical wind shear -both directional and in magnitude- tends to decrease. The rarity of medicanes, as opposed to the commonness of synoptic troughs affecting the region, is an obvious indication that further conditions must be met for medicane formation (Tous and Romero, 2013). In agreement with the idea of a continuous spectrum of cases (Romero and Emanuel, 2013) and as highlighted by Cioni et al. (2016), the physical mechanisms determining the sea-level pressure fall alternate and even coexist in the same area and period of time, thus making the attempt to classify some systems within pure baroclinic (i.e., extratropical) or diabatically driven (i.e., tropical-like) classes a daring and unrealistic objective. This clearly depicts the inherently hybrid nature of most medicanes. Some baroclinic cyclones evolve into symmetrical structures during the occlusion phase, with intense latent heat release around the core, posing a serious forecast challenge similar to that found in the so-called extratropical transition of tropical cyclones, but in the reverse direction. The role of air-sea interaction as a necessary driver for medicane formation and maintenance, along with high values of mid-tropospheric relative humidity and low values of wind shear is extensively proven in the literature (Rasmussen and Zick, 1987; Lagouvardos et al., 1999; Pytharoulis et al., 1999; Pytharoulis et al., 2000; Homar et al., 2003). Experiments with varying sea surface heat fluxes, like modifying SST temperatures or directly prescribing the sensible and latent heat fluxes (see Tous et al., 2013), clearly show the essential role of air-sea interactions in favoring the overcome of convective inhibition and enhancing the genesis and intensification of the medicane.

The forecasting challenges posed by these rare, small and highly dependent on non-linear processes Mediterranean cyclones, which initiate and evolve over directly undersampled maritime areas, are not minor. Despite the recent examples of skillfull simulations of medicane cases (e.g., Davolio et al., 2009b; Carrió et al., 2017; Pytharoulis, 2017; Pytharoulis et al., 2017), the number of false alarms, missed cases and significant errors on their timing, location and intensity are still too high in operational high-resolution forecasts. In principle, ensemble data-assimilation forecasting techniques proposed to improve the accuracy of the forecast of extreme phenomena over Mediterranean coastal areas (e.g., Carrió and Homar, 2016) are applicable for medicane formation, intensification, evolution and decay. Given the recent restrictive funding policies for in-situ routine observations over the sea, a key factor to untap the potential to better medicane predictions in the near future is the transference of more precise atmospheric information

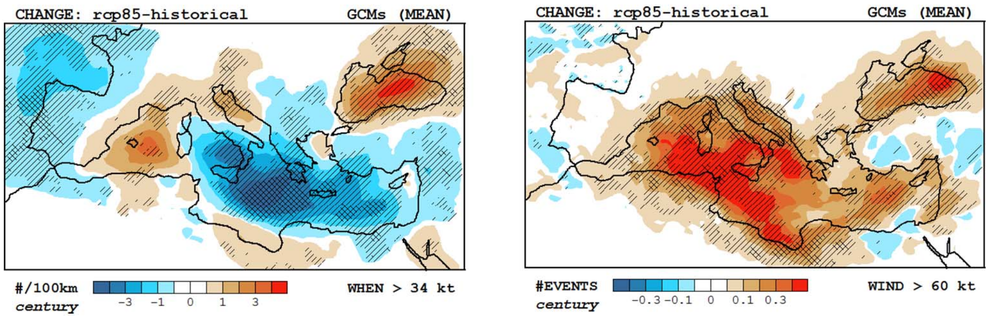

Fig. 6. Left: Present-to-future change in medicane track density (density defined as number storms per century within a radius of 100 km). Right: Present-to-future change in the probability of medicane-induced winds above 60 knots or equivalently 31 ms^{-1} (probability defined as local number of these extreme wind events per century). For both maps, model consensus at 66% and 80% levels on the sign of change (positive in reddish areas, negative in bluish areas) is indicated as hatched and cross-hatched, respectively.
(Based on Romero and Emanuel, 2017 ©American Meteorological Society. Used with permission.)

from coastal lands towards maritime areas by means of data assimilation cycling systems, an aspect favored by the limited spatial extent of the Mediterranean Sea.

As for other extreme phenomena, there is some concern about the way medicanes could respond to human-induced global warming (e.g., possible changes in frequency, intensity or regional variability of storms). This interest on the future climatology of storms has motivated specific research during the last decade. Based on parallel studies like those by Cavicchia (2013) and Cavicchia et al. (2014a), Romero and Emanuel (2013) estimated an average genesis of only two medicanes per year under the present climate, considering the geographical domain shown in Fig. 6. Therefore, the identification of recent and projected climatological patterns and long-term changes, as well as a proper representation of the uncertainty of any derived climatic signal, appears as a challenging task for the case of medicanes, simply because satellite observations and traditional simulation techniques will yield too few events to evaluate, given the low natural frequency of the phenomenon [see Frei and Schär, 2001 and Klein Tank and Können, 2003 for the issue of dealing with rare events]. In addition, results could be contaminated by the aforementioned problem of the hybrid nature of some Mediterranean cyclones, which impedes a clear-cut distinction between genuine medicanes and other types of low-pressure systems.

In principle, one could explore the present-to-future changes in large-scale ingredients that in present-day weather analyses tend to accompany the genesis of storms, in analogy with the practice followed by some authors for the analysis of polar low environments: Zahn and von Storch (2008, 2010) used the simplified vertical stability parameter; Kolstad (2011) and Kolstad and Bracegirdle (2008) employed the so-called marine cold air outbreak proxy parameter. For the Mediterranean, Tous and Romero (2013) showed that the potential incubation of medicanes is simultaneous with high values of an empirical index of genesis that was formulated by Emanuel and Nolan (2004) for the tropical regions:

$$GEN = (10^5\eta)^{3/2}\left(\frac{RH}{50}\right)^3\left(\frac{PI}{70}\right)^3(1 + 0.1V_{shear})^{-2} \quad (1)$$

This index depends positively on potential intensity (*PI*; Emanuel, 1986), absolute vorticity at low levels (η) and mid-tropospheric relative humidity (*RH*) and inversely on vertical wind shear across the troposphere (V_{shear}). The *GEN* index summarizes the most relevant factors of the medicane-prone cyclonic environments that are established at synoptic scale over the Mediterranean Sea when a baroclinic system, maturing into a cold cut-off low at mid- to upper-tropospheric levels, approaches the region or develops in situ (Emanuel, 2005). Under these circumstances, upward air motion forced through a deep tropospheric layer will increase the relative humidity, inhibiting the formation of intense convective downdrafts; in contrast, a well-known disturbing factor for the genesis of hurricane-like storms (vertical wind shear) will be reduced under well-mature upper-level disturbances; finally, large air–sea enthalpy contrasts and the presence of cold air aloft will together enhance, through the *PI* ingredient, the local thermodynamic potential for "hurricanes" according to the air-sea interaction theory of storms (Emanuel, 1986).

The problem with *GEN* and other climatologically derived parameters is their mere quality as necessary, but not sufficient, ingredients for a full development of a medicane. In addition, the application of these large-scale proxies (e.g., calculated from the output of a General Circulation Model (GCM) transient climate simulation) will only assist in approaching the issue regarding the future frequency of medicanes; quantitative projections of changes in intensity will need to rely on alternative methods almost exclusively based on some kind of high-resolution application of a numerical–physical model. Note that medicanes, owing to their small scale, are poorly represented in routine observational and reanalysis data and of course in the vast majority of GCMs available today.

During the last decade, there have been intermittent applications of nested Regional Climate Models (RCMs) to the problem of medicanes, although the high computational cost of these tools has prevented the analysis of as many climate scenarios (i.e., an ensemble of parent global models and emission scenarios) as would be desirable. Gaertner et al. (2007) used a multimodel ensemble of nine RCMs (with resolutions of 50–55 km) forced with a single GCM and found an enhanced future risk of "tropical" cyclone development over the Mediterranean Sea. In a more recent work, Gaertner et al. (2017) concluded that the availability nowadays of large ensembles of RCM simulations configured at higher resolutions (up to 12.5 km) and even in ocean-atmosphere coupled mode, like those performed in the EURO-CORDEX and MED-CORDEX projects (see Jacob et al., 2014 and Ruti et al., 2016, respectively) can impact positively on the estimation of the frequency of medicanes, although other important aspects of these storms, particularly their maximum intensity (which is generally underestimated), will still remain elusive. The previous downscaling studies discriminate medicanes from other cyclonic signatures using the objective cyclone detection method of Picornell et al. (2001), combined with the cyclone phase space diagram of Hart (2003) that quantifies the degree of symmetry, depth and warm or cold characteristics of the detected lows.

Cavicchia et al. (2014b) extended for the Mediterranean the approach originally devised by Zahn and von Storch (2010) for the problem of polar lows; that is, they applied another ad-hoc cyclone detection algorithm to dynamically downscaled results conducted with a single GCM–RCM couple forced with three IPCC AR4 emission scenarios. They found a decreasing trend in the frequency of medicanes but a moderate increase of storms intensity towards the end of the 21st century. Walsh et al. (2014) implemented a storm detection and tracking algorithm to the results of another single GCM–RCM modeling system and concluded that the number of Mediterranean warm-core low pressure systems could decrease in a future warmer world, particularly in winter. Tous et al. (2016) also found that the projected effects of climate change on medicanes could be a decrease in the number of events accompanied by an increase in their typical intensity; instead of nesting a RCM, this work made direct use of a high-resolution (aprox. 25 km) global climate model (the HadGEM3N512 model).

Trying to overcome some of the limitations of traditional techniques, Romero and Emanuel (2013) went a step further and adapted for the Mediterranean the method originally devised by Emanuel (2006) for the tropical regions. This approach entails the generation of trajectories and radial distributions of wind for storms embedded in a large number of randomly generated synthetic environments that operate as analogs of actual GCM-simulated synoptic evolutions. The trajectories are initiated in medicane-prone areas, as indicated by the *GEN* index and checked for intensification using an axisymmetric numerical model involving both atmospheric and oceanic elements and operating with very high resolution in the storm core, where it is needed. The overall method is computationally very efficient, thus enabling the production of thousands of synthetic storms for each GCM -or reanalysis- and emission scenario considered, from which the current and future medicane risk can be assessed with great statistical robustness. Initially, Romero and Emanuel (2013) illustrated the potential of this technique using four models of the phase 3 of the Coupled Model Intercomparison Project (CMIP3), from which they projected fewer medicanes at the end of the century but a higher number of violent storms compared to present.

Recently, Romero and Emanuel (2017) extended the statistical–deterministic approach to the exploration of the CMIP5 scenarios, producing the most ambitious –at least in terms of model representativeness and uncertainty assessment– medicane projections to date. Thousands of synthetic storms compatible with the "climates" provided by 30 CMIP5 models in both historical and RCP85 simulations were generated and the climatologies of downscaled medicanes obtained using the ERA-interim and National Centers for Environmental Prediction (NCEP) National Center for Atmospheric Research (NCAR) reanalyses were used as reference. Their results indicate that the future trends in the number of medicanes are unclear (half of the models show increases, while the other half show decreases; on average, the total frequency of storms decreases by only 5%). However, an unambiguous tendency is found regarding the storm maximum intensity: the number of moderate and violent medicanes clearly increases towards the end of the century, at the expense of "ordinary" storms. Once again, the idea of a future climate with more severe medicanes evolving over the Mediterranean waters prevails as a consistent feature in the existing literature. Spatially, the method of Romero and Emanuel (2017) projects an increased occurrence of medicanes in the western Mediterranean and Black Sea that is balanced by a reduction of storm tracks in the central and eastern Mediterranean. In contrast, future extreme events (e.g., occurrences of surface winds above 60 kt (60 knots, or equivalently 31 ms^{-1}) exhibit a homogeneous signal, becoming more probable in all sub-basins (see Fig. 6, relative to the ensemble mean).

8. Lightning activity

Lightning, as a natural phenomenon, has a strong impact on human life (i.e., causing deaths, property damages and power system breakdowns). Therefore, research on lighting activity is necessary to focus on the development of effective tools for monitoring and forecasting (in terms of alerts). So far, researchers have been able to study the mechanisms for understanding discharge processes and development of detection sensors.

Nowadays, researchers are able to answer questions regarding lightning occurrence and thunderstorm processes that generate lightning. Hence, the study of lightning is focused on the establishment of relationship between the electrical characteristics of storms and precipitation, convection and severe weather. Several types of instrumentation have been designed and developed covering a range of ground-based, airborne and spaceborne sensors. Most of these sensors are capable not only to detect lightning but also to provide necessary information regarding its characterization.

Research on lighting has gained considerable attention in the field of climate change. The importance of lightning for climate studies is increasingly recognized. New measurements of global lightning from the ground and from space have greatly stimulated the application and integration of lightning in climate studies (Williams, 2005). Atmospheric electrical studies naturally focus on extremes of convection and extremes in lightning.

Several studies have been focused on the analysis of the spatio-temporal distribution of lightning over the Mediterranean region (Altaratz et al., 2003; Anderson and Klugmann, 2014; Chronis, 2012; Defer et al., 2005; Holt et al., 2001; Katsanos et al., 2007a; Kotroni and Lagouvardos, 2014; Nastos et al., 2014; Matsangouras et al., 2016; Petrova et al., 2014; Shalev et al., 2011; Tomás et al., 2004; Feudale and Manzato, 2014). In most cases, it was shown that lightning occurs mainly over the Mediterranean Sea during the coldest months, while in the warmest months it occurs mainly over land.

In a recent study, Kotroni and Lagouvardos (2016) presented an analysis of lightning activity over the Mediterranean, based on a 10-year long dataset (2005–2014) provided by the ZEUS long-range lightning detection system. They found that the yearly lightning density peaks up to 5 lightning strokes $km^{-2}\,y^{-1}$ over land (close to the main topographic features of the area) and up to 4–5 lightning strokes $km^{-2}\,y^{-1}$ over the sea (with the highest density found over Adriatic and Ionian Seas). Relatively low lightning stroke density was detected over the Gulf of Lion, the coastal areas of Egypt and Libya and major part of the Black Sea, while scattered highest lightning stroke density over maritime areas could be attributed to individual severe thunderstorms. Regarding the number of lightning days, they found that maxima is noticed mainly in the area of northeastern Italy, Austria and Slovenia, while hot spots are also detected over the Italian and Greek peninsulas, as well as over the high mountains of the Balkan countries.

Other studies (Yair et al., 2010; Altaratz et al., 2003; Ziv et al., 2009) in the eastern Mediterranean Basin concluded that lightning activity occurs almost exclusively in the winter season and almost never in the summer. Synoptic conditions favoring thunderstorm occurrence in the eastern Mediterranean can be found in Levin et al. (1996) and Shalev et al. (2011). Ben Ami et al. (2015) showed that the electrical activity over the eastern Mediterranean takes place during fall and winter and not during summertime.

The EU FP6 FLASH project was focused on using lightning observations to better understand and predict convective storms that result in flash floods in the Mediterranean region (Price et al., 2011a, 2011b). Through this project, tools were developed to forecast severe thunderstorms. A linkage between lightning and convective storms was established by Yair et al. (2010) and Lynn and Yair (2010). They developed an algorithm-derived index that could be used as a good predictor of flash floods. Two synoptic indices, one indicating potential for lightning activity and one indicating heavy rain that might be attributed as a precursor of flash floods were developed by Harats et al. (2010), while evaluation of these indicators was performed by Ziv et al. (2016). The index for intense lightning activity was successfully tested, although it incorporated a high rate of false indications. Also, the index indicating heavy rain was potentially promising, hence, it could be used to predict flash floods caused by such rain in the Mediterranean region. In the same EU project, Michaelides et al. (2009, 2010) studied also relationships between lightning and rainfall over Cyprus, using a rectangular grid-box methodology.

During the first special observation period (SOP1) of the HyMeX (HYdrological cycle in the Mediterranean EXperiment) project, four lightning locating systems, ATDNET (Gaffard et al., 2008), EUCLID, LINET (Betz et al., 2009) and ZEUS (Kotroni and Lagouvardos, 2008) and the HyMeX Lightning Mapping Array (HyLMA) were used to locate and characterize the lightning activity over the southeastern Mediterranean (Defer et al., 2015; Drobinski et al., 2014; Ribaud et al., 2016).

A number of studies have also dealt with exploring the relationship between lightning and orography. Feudale and Manzato (2014) showed that cloud-to-ground (CG) lightning activity varied within three different areas in NE Italy and the surrounding regions having different types of topography. Galanaki et al. (2015) found that the orography and the terrain slope affect the distribution of lightning as retrieved from ZEUS system in the Eastern Mediterranean. Kotroni and Lagouvardos (2008) indicated a strong correlation between the lightning activity as derived from the ZEUS system in the Mediterranean and the terrain slope. Mazarakis et al. (2008) found that the lightning activity over Greece during the warm season (May–September) of the years 2003–06 increases with elevation along the slopes of terrain features. Santos et al. (2013) indicated that the lightning activity over the Iberian Peninsula occurs predominantly over land and is associated with orographic lifting, during the warmest months, while it occurs over the Mediterranean Sea and is linked with near-surface thermal contrasts, during the coldest months. Soriano et al. (2001, 2005) highlighted the dependence of lightning with orography in Castilla-–Leon (Spain), and the strong correlation between the distribution of CG lightning activity and orography over the Iberian Peninsula, respectively. The relationship between lightning activity and sea surface temperature (SST) was examined by Kotroni and Lagouvardos (2016) presenting evidence of a positive trend in the number of lightning strokes with increasing SST.

The relationship between lightning activity and rainfall, that frequently coexist in thunderstorms, has been studied by several researchers (Koutroulis et al., 2012; Iordanidou et al., 2016; Katsanos et al., 2007b; Mazarakis et al., 2008; Pineda et al., 2007; Soula and Chauzy, 2001). Pineda et al. (2007) found a positive correlation between the rainfall volume and the total number of CG flashes. Soula and Chauzy (2001) found in their study that the overall spatial correlation between rain and lightning occurrence to be very consistent for all lightning types. Koutroulis et al. (2012) found that the effective radius giving the higher results in correlation was set to 15 km around the gauge station and the optimal time lag is achieved when the flash count to is 15 min prior to the rain accumulation. Iordanidou et al. (2016) showed that lightning and rainfall are closely related, with the association of these two physical phenomena not being random and depending on the distance and the number of flashes of the storm from the region of interest. They found that the area mostly influenced by rain due to the appearance of a group of lightning activity is within a 30-km radius from the center of the group.

Tropical Rainfall Measuring Mission (TRMM) data has also been used for exploring the relationship between lightning activity and rainfall (Kummerow et al., 1998). The relations established in several studies showed a positive correlation (Siingh et al., 2013, 2014). However, Adamo et al. (2009) report that the relationships between lightning occurrence and precipitation and/or upwelling microwave/infrared brightness temperatures are not valid over the Mediterranean Basin. Reasons are associated with the fact that the convection is less intense in this area regarding to other places that such studies were conducted, while Mediterranean Sea represents one of the major centers of winter electrical activity in the Northern Hemisphere. Price and Federmesser (2006) analyzed lightning and rainfall data from the TRMM satellite for a period of six years (1998–2003) in the central and eastern Mediterranean. They found that Rainfall amounts increase during the winter months, with the maximum precipitation occurring during December, while lightning activity has a maximum during November. Analysis of seasonal rainfall and lightning activity showed a strong correlation with ENSO events, while monthly and seasonal correlation coefficients between rainfall and lightning were found to vary between 0.81 and 0.98, respectively.

Another significant component assisting our understanding of lightning activity is the employment of Numerical Weather Prediction models that are capable to provide short and medium range forecasts of thunderstorms and lightning events (Giannaros et al., 2015; Karagiannidis et al., 2016; Lynn et al., 2012; Wong et al., 2013; Yair et al., 2010). For example, Giannaros et al. (2015) evaluated the Price and Rind lightning parameterization introduced in the Weather Research and Forecasting (WRF) model for ten different single-day events that took place in Greece during the period 2010 to 2013. They concluded that the WRF model could be used for real-time lightning prediction applications provided that the lightning parameterization is properly adapted. Yair et al. (2010) investigated the use of the lightning potential index for predicting lightning density. They found that in several case studies, using WRF model with explicit microphysics that the LPI is highly correlated with observed lightning, suggesting that the LPI may be a useful parameter for predicting lightning as well as a tool for improving weather forecasting of convective storms and heavy rainfall.

Although results from studies based on the lightning-rainfall relationship concluded that this relationship is of great significance assisting the improvements in heavy-rain nowcasts and short-term severe weather warnings (Price and Federmesser, 2006; Soula et al., 1998; Tapia et al., 1998) and in the estimation of rainfall amount (Garcia et al., 2013; Soula and Chauzy, 2000; Tapia et al., 1998; Xu et al., 2013, 2014), there is still ground for exploring this scientific topic.

This sub-section concludes with a brief reference to another phenomenon which is strongly related to stormy weather, namely, the occurrence of tornadic events. Tornadoes occur more frequently during autumn and early winter over southern Europe, which reflects the occurrence of waterspouts in the Mediterranean Sea. Despite causing fatalities, injuries and damages, they have long been considered as posing a small threat to the wider community, due to their local character (see Antonescu et al., 2017).

9. Dust and air pollution

Air pollution has become an increasingly important environmental issue at a global scale. Both natural and anthropogenic components of air pollution have long been recognized and investigated. The presence of particulate matter (PM) in the atmosphere is recognized as one of the most significant environmental health risk factors in the European Union (European Environment Agency, 2014).

Aerosol parameters can be measured in situ or remotely sensed from ground, aircraft or satellite. Conventional techniques of particulate matter measurements define regional air quality on a rather local sense. Modeling approaches embrace uncertainties associated to the use of emissions inventories and/or sparse point ground measurements to characterize initial conditions. For a proper consideration of the aerosols in air quality monitoring efforts, vertical profiling of aerosols is required (Ansmann et al., 2017).

Sunphotometer networks such as the AERONET (AErosol RObotic NETwork), providing integrated observations of aerosol optical, microphysical and radiative properties, have also become widely used (Holben et al., 1998). AERONET observations offer the advantage of continuous, high-temporal resolution measurements over a given location where satellite coverage might not always be available. Such measurements provide useful information about local trends that are unavailable through other means. Aerosol Optical Depth (AOD) measurements provide estimates of the vertically integrated aerosol loading in the atmosphere (Calvello et al., 2010), while the Ångström exponent could assist in the characterization of aerosol types, as for example, the seasonal variability of the atmospheric aerosol loading over the western basin of the Mediterranean Sea (Pace et al., 2006; Masmoudi et al., 2003; El-Metwally et al., 2008, 2010). Sunphotometers and LIDAR systems are found to be suitable tools for assisting air pollution monitoring studies (Ansmann et al., 2012; Amiridis et al., 2009a; Engel-Cox et al., 2006; Papayannis et al., 2007a, 2007b; Pitari et al., 2013). Additionally, two fundamentally different lidar-/photometer-based methods have been developed within ACTRIS (Aerosols Clouds and Trace Gases Network). These methods are the LIRIC [Lidar/Radiometer Inversion Codes] (Chaikovsky et al., 2012; Lopatin et al., 2013) and a more robust technique, the POLIPHON [Polarization-lidar photometer networking] approach (Ansmann et al., 2012; Mamouri and Ansmann, 2017).

Remote sensing of aerosols has a long history and a wide range of techniques have been developed using various sensors and various parts of the electromagnetic spectrum. AOD is one of the most important properties of atmospheric aerosols.

Satellite remote sensing has been used for recording aerosol since the late 1970s. The Advanced Very High-Resolution Radiometer (AVHRR) onboard NOAA (National Oceanic and Atmospheric Administration) satellite was mostly used for deriving aerosol properties, especially over the oceans (Holben et al., 1992; Ignatov et al., 1995; Stowe and Ignatov, 1997), followed by TOMS (Total Ozone Mapping Spectrometer). Its capability was the detection of elevated absorbing aerosols over both land and ocean by using ultraviolet (UV) spectrum in the range 0.34–0.38 μm (Hsu et al., 1996; Herman et al., 1997). TOMS data have been systematically used in studying the spatial distribution of dust particles (Hsu et al., 1999; Torres et al., 2002). Aerosol assessment in terms of the absorption Aerosol Index (AI) taken from OMI-Aura (Ozone Monitoring Instrument) measurements has also been examined for several years (Torres et al., 2007).

Aerosol remote sensing products are well summarized and compared in the works of King et al. (1999) and Kokhanovsky et al. (2007). Such aerosols products are derived from a variety of satellite sensors such as MODIS [Moderate Resolution Imaging Spectroradiometer] (Chu et al., 2002), MERIS [Medium Resolution Imaging Spectrometer] (Vidot et al., 2008), MISR [Multi-angle Imaging Spectroradiometer] (Kahn et al., 2005), AATSR [Advanced Along-Track Scanning Radiometer] (Bevan et al., 2009; Grey et al., 2006), CHRIS PROBA (Davies et al., 2010) and POLDER [Polarization and Directionality of the Earth's Reflectances] (Goloub et al., 1999). Furthermore, active remote sensors as lidars, provide the aerosol's vertical dimension of global distribution. Such data are available today due to the launch of the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument on board the Cloud- Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission of NASA/CNES in June 2006 (Winker et al., 2009). Ever since, CALIPSO provides global aerosol and cloud vertical distributions to the scientific community which will be continuing in the future through the EARTH-Care satellite mission.

Desert dust pollution, particles emitted mainly by urban and industrial activities, marine aerosols formed continuously over the Mediterranean, and volcanic emissions (to a lesser degree) are the dominant types of aerosol over the Mediterranean area.

9.1. Dust

Mineral dust is a major component of the atmospheric aerosol system, uniquely influencing climatic and environmental conditions. The main geographical areas responsible for the formation of coarse desert dust particles are the north of Africa (Sahara and Sahel), the Middle East region (Saudi Arabia) and eastern Asia (Gobi Desert in the south Mongolia/northern China area). Their contribution is higher during the spring and the summer seasons, with AOD values generally higher than 0.5, however, reaching under extreme conditions values higher that 5.0 (Mamouri et al., 2016), usually associated with medium and long-range transport events. The Sahara and its margins contribute to more than half of the global dust emissions (Huneeus et al., 2011; IPCC, 2013). A regional effect on particle concentrations in the Mediterranean region, including the Iberian Peninsula due to the north African dust was noted by Pandolfi et al. (2011) and Rodríguez et al. (2001).

Turbulent exchange processes at the interface between the free troposphere and the planetary boundary layer lead to efficient downward mixing of dust towards the surface. Emissions from arid (non-desert) and semi-arid regions and areas with strong agricultural activities also contribute to the dust load over Europe.

For a better consideration of mineral dust in climate and air quality modeling, vertical profiling of dust with the potential to distinguish between fine-mode and coarse-mode dust is required (Kok, 2011; Zhang et al., 2013). The fine mode covers the particle size spectrum up to 1 μm in diameter, whereas the coarse mode contains the supermicrometer dust particles (diameters > 1 μm). Fine and coarse dust particles influence the Earth's radiation budget, cloud processes and environmental conditions in different ways (Nabat et al., 2012; Mahowald et al., 2014). The optical properties and radiative impact are widely controlled by coarse-mode dust particles. However, 20–40% of the dust-related optical depth is caused by fine-mode dust according to Aerosol Robotic Network (AERONET) sun/sky photometer observations (Mamouri and Ansmann, 2014).

Aerosols affect the Earth's climate system by altering the radiative properties of the atmosphere. They influence the Earth's radiation budget directly through scattering and absorbing solar radiation and indirectly through affecting cloud properties. Studies of the optical properties of aerosols are crucial to fully understand their radiative effects. A review of the aerosol optical properties and radiative effects is provided by Liu et al. (2014). Dust particles have an effect on the heating/cooling rates in the atmosphere. Moreover, they can also have an impact on the modification of atmospheric dynamics and large-scale atmospheric circulations like monsoons, cloud properties and precipitation (Gkikas et al., 2016).

Regarding the influence on cloud processes, coarse dust particles belong to the most favourable cloud condensation and ice nuclei (DeMott et al., 2010). Fine-mode dust particles, on the other hand, can significantly impact air quality, defined in PM (particulate matter) aerosol levels and may even sometimes dominate PM1.0 (particles with diameter < 1.0 μm) observations at sites close to deserts, such as Cyprus.

In their study, Gkikas et al. (2016) used MODIS data to identify strong and extreme desert dust episodes, over the period March 2000–February 2013, affecting the broader Mediterranean Basin. They found that strong desert dust episodes occur more frequently over the western Mediterranean, while in contrast to their frequency, dust episodes are more intense over the central and eastern Mediterranean Sea, off the northern African coasts. Moreover, in their study on occurrence of African dust outbreaks over the whole Mediterranean Basin for the period 2001–2011, Pey et al. (2013) concluded that the African dust appears as the largest PM10 source in regional background southern sites of the Mediterranean (35–50% of PM10), with seasonal peak contributions to PM10 up to 80% of the total mass.

The influence of Saharan dust outbreak, as transported in plumes across the Mediterranean Sea, is responsible for the increase in PM10 surface concentration (Meloni et al., 2007; Bouchlaghem et al., 2009; Salvador et al., 2013). However, dust originated from other desert regions, such as those of the Middle East, has also attracted scientific interest, particularly for countries in the southeast Mediterranean region, such as Cyprus (Retalis and Michaelides, 2009; Mamouri et al., 2013; Nisantzi et al., 2015; Mamouri et al., 2016). A detailed description on the existing knowledge about the dust outbreaks sources and the mechanisms of transportation, in terms of favourable synoptic conditions, of the dust aerosols over the Mediterranean is given in Solomos et al. (2017), Abdelkader et al. (2015) and Choobari et al. (2014).

Volcanic eruptions are also an important natural source of primary and secondary aerosols. Revuelta et al. (2012) commented on emissions from the Eyjafjallajökull eruption (in Iceland, 2010) and its impacts which flow of a volcanic plume caused serious disruptions in aviation in Europe. Adame et al. (2015) presented a study to estimate the probability of arrival of ash plumes in Spain emitted from volcanoes located within its area of influence as a part of a broader scale forecast system for air navigation in a volcanic crisis. Sellitto et al. (2016) indicated that even a relatively weak volcanic eruption, such as the moderate eruption of Mount Etna occurred on 25–27 October 2013, may produce an observable effect on the aerosol properties at the regional scale. The downwind impact of Mount Etna's sulfur emissions in the central Mediterranean estimated over the period 2000–2013, based on the synergy of sulfur dioxide concentrations, aerosol Ångström exponent and dispersion model data, was presented by Sellitto et al. (2017).

Hence, the characterization of decadal impact of Mount Etna's sulfur emissions on the sulfur dioxide and the aerosol microphysical/optical properties in the central Mediterranean was exploited.

9.2. Anthropogenic aerosols

Finer anthropogenic aerosols are associated with regional urban and industrial pollution and can be found mainly in developed, developing or densely populated regions; in most cases, a specific pattern of higher summertime aerosol loadings and lower in the winter could be met in global climatology studies (Holben et al., 2001; Ichoku et al., 2004; Remer et al., 2008). Other studies, however, showed that different seasonal patterns are recognized (Kambezidis and Kaskaoutis, 2008; Kaskaoutis et al., 2007). These diverse findings could be attributed to a higher influence of local and regional emission sources and meteorological parameters.

In the literature, analyses of local sun-photometer observations over the Mediterranean report AOD values in the range 0.1–0.5 in the spectral range of 440 to 550 nm for pollution particles (see Mallet et al., 2013). In their study, based on the data analysis resulted from 22 Mediterranean sun photometer stations, they concluded that daily averaged aerosol absorption optical depth values obtained from sun photometer observations over the Mediterranean at 440 nm ranged from 0.024 ± 0.010 to 0.050 ± 0.010 for urban sites.

Koçak et al. (2009) presented a short literature review about the evaluation of the anthropogenic contribution to ambient PM10 in both Western and Eastern Mediterranean. Findings presented concluded that PM10 concentrations in the Western Mediterranean atmosphere increase from rural to kerbside, while the contribution to PM10 of anthropogenic sources decreases from urban/industrialized/kerbside sites towards rural sites. However, PM10 levels observed both in rural and urban sites are considerably affected by high mineral dust concentrations during African dust outbreaks. On the other hand, PM10 levels at regional background sites within the boundary layer in the Eastern Mediterranean are mainly related to the proximity of sampling sites to arid regions (e.g., the Sahara Desert and the Middle East).

Current research focusing on the study of regional and intercontinental transport of air pollutants, such as particulate matter (PM10, PM2.5), points to a need for additional data sources to monitor air pollution in multiple dimensions, both spatially and temporally. To address this issue, Earth observations from satellite sensors can be a valuable tool for monitoring air pollution due to their ability to provide complete and synoptic views of large areas.

Examples of satellite retrievals to monitor urban air pollution in different geographical areas in the Mediterranean has received considerable attention from researchers (Chu et al., 2003; Kacenelenbogen et al., 2006). Chu et al. (2003) showed that for the case of northern Italy the MODIS-derived AOD has an accuracy of ± 0.05 ± 0.2AOD and is subject to the spatial sensitivity of the retrievals. The correlation established between the AERONET daily averaged AOD and 24-hour PM10 concentration ($\mu g/m^3$) was found to be encouraging with a correlation coefficient of about 0.82. Grosso and Paronis (2012) presented a contrast reduction algorithm designed for the MODIS sensor and applied it to a set of about 192 images acquired for the year 2005 at areas around five European AERONET stations (Barcelona, Lille, Lisbon, Modena, Paris). Comparison with AERONET AOD data showed a good agreement with a correlation coefficient of 0.78, which was also similar to that resulting from comparing AERONET measurements and MODIS aerosol standard product.

One year (2003–2004) of Terra MODIS, TOMS, and MOPITT data over the open ocean were are used in conjunction with the Goddard Chemistry Transport Model (GOCART) to characterize differing aerosol types as a function of satellite observable parameters (Jones and Christopher, 2007). It was found that the annually averaged estimates for anthropogenic MODIS fine mode fraction was 0.84 ± 0.04, which was in agreement with or slightly lower than previous estimates. Kacenelenbogen et al. (2006) concluded that the comparison between collocated daily averaged PM2.5 and POLDER derived AOD over France during the period April and October 2003 showed a lot of scattering, which might be due to the influence of the vertical distribution of the aerosol in the atmosphere, although a fairly well correlation (~0.55) over the 28 stations (with a maximum value of 0.80 for particular sites) was established.

Koelemeijer et al. (2006) presented a comparison for Europe of spatio-temporal variations of PM with those of MODIS AOD retrievals for 2003. It was found that major aerosol source regions were recognized in Northern Italy, Southern Poland, and the Belgium/Netherlands/Ruhr area, as well as individual large cities and industrialized valleys (Rhone, Danube), while smaller scale features were found at several major cities like Rome, Paris, and Athens; also, the Rhone-valley was clearly distinguishable. A differential textural analysis (DTA) code was applied to MERIS-ENVISAT (Retalis and Sifakis, 2010), NOAA-AVHRR (Retalis et al., 2003) and Landsat (Retalis et al., 1999) imagery to assess spatial distribution of aerosols over urban areas, such as the Athens, Greece. High positive correlation values between satellite AOD retrievals and PM10 measurements were establish with coefficient values in the range of 0.71 to 0.90.

A global satellite-based estimate of surface PM2.5 at a spatial resolution of approximately 10 km × 10 km was developed by van Donkelaar et al. (2010). They combined MODIS and MISR AOD into a single improved estimate of AOD and calculated then the AOD–PM2.5 conversion factors with the aid of a global chemical transport model. These global PM2.5 concentrations estimates were validated with in-situ observations. They indicated a global population-weighted geometric mean PM2.5 concentration of 20 $\mu g/m^3$.

Most of the work developed to estimate PM concentrations from satellite AOD derives from statistical/empirical models based on variations of this theoretical relation. These mainly consist of linear regression approaches (see Michaelides et al., 2017), although some nonlinear and neural network based models have also been developed (Gupta and Christopher, 2009; Michaelides et al., 2011). Thus, taking advantage of the correlation between AOD and PM, the use of satellite AOD retrievals data for air quality monitoring at a regional scale has become a topical challenge.

It is very important to have a complete picture of aerosol events over the entire Mediterranean basin based on long term monitoring means in order to better understand the mechanisms and processes associated with air quality issues. The use of satellite sensors on air pollution studies is highlighted above, especially their ability for systematic monitoring and synoptic coverage.

9.3. Recent ground-based remote sensing activities in the Mediterranean

The central position of the eastern Mediterranean in the global dust belt and its close proximity to several African and Middle East deserts make it an ideal place for the study of dust properties and dust transport. From the European mainland, anthropogenic pollution is advected, mixing in with the dust emissions and creating a complex aerosol situation in the eastern Mediterranean area. Moreover, Southern Europe and Mediterranean, is frequently affected by volcanic ash emissions from three active volcanoes (Etna, Stromboli and Vulcano) (Pappalardo et al., 2014; Mona et al., 2012).

Over the recent years, the eastern Mediterranean evolved as a hot spot of studies about dust properties and the interrelation between aerosols and radiative impact (Nisantzi et al., 2015; Mamouri and Ansmann, 2014; Mamouri et al., 2016). Recently, the interaction between aerosols, in-cloud dynamics and cloud microphysics and precipitation formation has come into focus (Rosenfeld and Farbstein, 1992; Rosenfeld, 1997; Andreae and Rosenfeld, 2008; Rosenfeld et al., 2008; Mamouri and Ansmann, 2015). Especially, the issue of how the presence of ice nucleating aerosol particles (INP) and ice formation in clouds are related is of special interest.

The properties of desert dust that has been transported over long distances has been studied with Raman Polarization lidar for a long time (Ansmann et al., 2011; Ansmann et al., 2017). A manifold of remote-sensing activities has been established in the eastern Mediterranean over the past decade. Different groups at Athens and Thessaloniki in Greece and at Limassol in Cyprus have been using combinations of Raman lidar and sun photometer in order to study the properties of aerosols in the area, covering a large spectrum of relative scientific topics. Amiridis et al. (2005) observed yearly cycles of aerosol properties. Dust storms that play a major role in the region were studied in detail with combinations of remote sensing methods and modeling (Pérez et al., 2006; Amiridis et al., 2009b; Mamouri et al., 2016; Ansmann et al., 2017). The injection of dust into the atmosphere due to fire events has been noted by Nisantzi et al. (2014). State-of the art methods for the separation of the coarse dust and the fine dust (Mamouri and Ansmann, 2014; Mamouri and Ansmann, 2017), as well as the estimation of number concentrations of ice nucleating particles (INP) from Raman/Polarization lidar measurements (Mamouri and Ansmann, 2017), have been developed recently and enable, for the first time, detailed long-term studies of the process of ice nucleation in the atmosphere on the basis remote-sensing measurements. Spaceborne active remote sensing sensors have been used repeatedly over the eastern Mediterranean to study the dynamics of dust (Abdelkader et al., 2015) or its three-dimensional distribution (Liu et al., 2008; Marinou et al., 2016). Current operational observations with the Polly^{XT} Raman-Lidar network (Engelmann et al., 2016) at Finokalia, Crete and from Limassol, Cyprus will yield an unprecedented dataset of dust properties in the eastern Mediterranean. During the last years, lidar systems were widely used to study volcanic aerosol clouds produced by major volcanic eruptions (e.g., Papayannis et al., 2012). Moreover, the possibility to discriminate volcanic ash from desert dust could have a strong influence on air-traffic decision management.

9.4. Combined ground-based active remote sensing

Raman LIDAR and cloud radar are an ideal combination for atmospheric studies focused on the interaction between aerosols, clouds and atmospheric dynamics. In general, a remote sensing instrument is most sensitive to particles in the range of its operation wavelength. The Raman lidar, operating in the visible wavelength range, is best suited to detect aerosol particles around 100–1000 nm. Different techniques for the retrieval of particle properties can be applied, e.g., to derive the mass concentration of dust particles (Tesche et al., 2011; Mamouri and Ansmann, 2014) or the number concentrations of Cloud Condensation Nuclei (CCN) and INP. Cloud radars, operating in the microwave regime, detect cloud droplets (~15 μm radius) or larger ice crystals and water particles.

In Europe, two major networks for ground-based remote sensing exist, namely, the European Aerosol Raman Lidar Network [EARLINET; Pappalardo et al., 2014] and Cloudnet (Illingworth et al., 2007). Both are combined under the roof of the Aerosol, Clouds and Trace gases Infrastructure (ACTRIS). The advanced processing algorithms of Cloudnet are used to derive the liquid water content [LWC; Merk et al., 2016], ice water content [IWC; Hogan et al., 2006] and ice particles' shape (Bühl et al., 2016; Myagkov et al., 2016). These cloud microphysical parameters, combined with automated retrievals of aerosol properties (Baars et al., 2016) permit a study of the interaction between aerosols and clouds. Furthermore, the rain rate at ground level is measured with a disdrometer with high temporal resolution, allowing the combination of ground-based observations of rain with remote-sensing observations for an in-depth aerosol-cloud-precipitation interaction study.

Since October 2016, the eastern Mediterranean is in the focus of the Cyprus Clouds Aerosols and Rain Experiment (CyCARE) of the Leibniz-Institut für Troposphärenforschung e.V., Leipzig, Germany in collaboration with the Cyprus University of Technology. In the framework of this project, the Leipzig Aerosol and Clouds Remote Observations System (LACROS) has been established in Limassol, in the premises of the Cyprus University of Technology. LACROS has the capability to carry out detailed and quantitative observations of clouds in addition to the properties of the aerosols. The main remote-sensing instruments of LACROS are a Polly^{XT} Raman Lidar, a MIRA-35 cloud radar, a HATPRO microwave radiometer, a Doppler lidar and a disdrometer.

Beside the CyCARE campaign in Cyprus, several remote sensing combined activities take place in Mediterranean, mainly related with ACTRIS activities. The PRE-TECT (http://pre-tect.space.noa.gr/) experiment took place in Crete, Greece, focuses on desert dust microphysical characterization from remote sensing, employing advanced inversion techniques developed in the framework of ACTRIS, focusing on aerosol absorption. Specifically, the aim of the campaign is to validate the remote sensing retrievals against surface and airborne in-situ measurements. The experiment includes a temporary Cloudnet station at Finokalia in Crete, Greece and the deployment of an additional Polly^{XT} Raman lidar to Technion Haifa, Israel. Furthermore, in the West Mediterranean the SLOPE II (Sierra Nevada Lidar AerOsol Profiling Experiment) (http://atmosfera2.ugr.es/en/) is a campaign in the framework of ACTRIS designed for gathering data useful for testing the microphysical retrieval schemes through inversion of remote sensing observations using absorption coefficient profiling. The campaign combines active and passive remote sensing of the vertical column with in-situ measurements at several levels in the northern slope of Sierra Nevada, Spain. With this combination of instruments and their geographical distribution, a large-scale coverage of the eastern Mediterranean is guaranteed. In Fig. 7, the aerosol and cloud classification based on the combined lidar and Cloudnet observations is given. This is an example that nicely illustrates the potential of the integrated aerosol - cloud - rain monitoring by LACROS during the Cy-CARE campaign over Limassol, Cyprus.

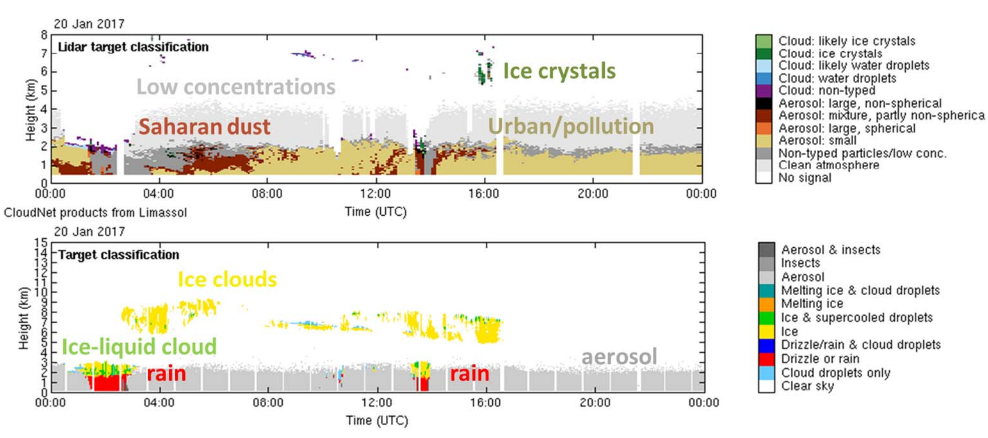

Fig. 7. Multiwavelength lidar aerosol classification (top) and Cloudnet classification (bottom) retrieved on 10 January 2017 by LACROS observations (classification based on, cloud radar, disdrometer, microwave radiometer, PollyXT Lidar, Doppler Lidar) over Limassol, Cyprus during the Cy-CARE campaign.

10. Atmospheric chemistry characteristics

10.1. General characteristics

The Mediterranean is an area of great scientific interest as far as its atmospheric chemical composition, with the climatic patterns and geographic characteristics of the region playing an important role in generating air-quality patterns with notable spatiotemporal variability. In winter, the eastward movement of frontal systems influences the weather and climate in the region, while during spring, the mid-latitude baroclinic zone moves northwards; in summer, the region is subjected to tropical and south Asian monsoon influences, leading to enhanced subsidence that suppresses clouds and rain (Maheras et al., 2001; Xoplaki et al., 2004; Tyrlis et al., 2013). It is characteristic that the area is subject to large variability of the total O_3 column which is associated to changes in the location of the sub-tropical front (Ladstätter-Weißenmayer et al., 2007).

The Mediterranean is one of the regions worldwide where elevated concentrations of primary and secondary gaseous air pollutants as well as particulate pollutants have been frequently reported, while it presents among the highest levels of tropospheric ozone and aerosol optical depths (AODs) in the world especially during the warm period of the year (Lelieveld et al., 2002; Zerefos et al., 2002; Georgoulias et al., 2016; Mallet et al., 2016). Satellite observations of tropospheric O_3, NO_2 and AOD over the Mediterranean clearly show the regional tropospheric O_3 column maximum over the Mediterranean Sea as well as the high NO_2 columns in the urban pollution agglomerations that surround the basin (Papadimas et al., 2008; Kanakidou et al., 2011; Doche et al., 2014). The findings from the satellite observations are corroborated by ground based and profile measurements at stations of the east Mediterranean (EM) participating in European and global observing networks, such as EMEP (European Monitoring and Evaluation Programme - www.emep.int) and AIRBASE (https://www.eea.europa.eu) as well as the AERONET and EARLINET netwoks indicated in Section 9. Commonly, the Mediterranean basin is recognized as a crossroads where air masses with different chemical characteristics originating from different sources and continents meet up and mix within the troposphere, while the intense photochemical activity support its role as the 'pressure-cooker' of transported air pollution (Lelieveld et al., 2002; Zerefos et al., 2002; Millán et al., 2002; Pace et al., 2006; Kallos et al., 2007; Hildebrandt et al., 2010; Kanakidou et al., 2011; Di Biagio et al., 2015). The importance of long range transport of pollutants for the air quality in the Mediterranean indicates that improvements of air quality require coordinated efforts inside the region and beyond (Gangoiti et al., 2001; Ravetta et al., 2007).

Furthermore, the Mediterranean and especially the eastern part of the basin is a region that mixing of stratospheric with tropospheric air is preferential as it is a global "hot spot" of summertime tropopause fold activity in the vicinity of the subtropical jet with the rare deeper folds penetrating towards the Levantine region (Tyrlis et al., 2014; Akritidis et al., 2016) while it is also a favourable ending spot for deep stratospheric intrusions extending south-eastward from the typical position of the polar front jet (Sprenger and Wernli, 2003; Galani et al., 2003). Last but not least, the Mediterranean is a region with intense photochemical activity, especially in the warm period of the year which strengthens photooxidation processes and biogenic emissions (Zerefos et al., 2002; Kanakidou et al., 2011; Im et al., 2011; Alexandri et al., 2015; Bossioli et al., 2016). In contrast to central and northern Europe, photochemical episodes can also occur during winter since at these latitudes solar radiation is intensive year-around, driving photochemical reactions that favor air pollution (Kanakidou et al., 2011). However, the number of baseline stations monitoring the chemical composition over the Mediterranean region is limited with sparse spatial coverage. Furthermore, there is limited systematic monitoring of the vertical distribution of tropospheric ozone while baseline measurements of gas phase pollutants such as inorganic reactive nitrogen compounds, non-methane volatile organic compounds (NMVOCs) and CO are sparse (Michoud et al., 2017). As pointed by Kanakidou et al. (2011) there is a clear need of reliable and systematic measurements of NMVOCs, NO_x and CO in the region to support modeling of air pollution and climate impacts since the available information on these species is limited despite their key role for O_3 production and the build-up of air pollution.

10.2. Chemical characteristics in the lower troposphere/atmospheric boundary layer

The annual cycles of the observed near-surface ozone at baseline EMEP stations across the Mediterranean basin show some similarities and some differences. Two baseline stations in the eastern Mediterranean (Finokalia, Greece and Agia Marina, Cyprus) present a broad spring/summer maximum peaking in summer (Gerasopoulos et al., 2005; Kleanthous et al., 2014). Over the central Mediterranean (Gozo, Malta) and western Mediterranean (Cabo de Creus, Spain) there is also broad spring-summer maximum but the peak is in spring (Saliba et al., 2008; Zanis et al., 2014).The Mt. Cimone WMO Global Atmosphere Watch (GAW) global station (Italy) which can be considered as a continental baseline station for the Mediterranean basin also presents a broad spring/summer maximum as a combination of background "hemispheric-scale" impact and photochemical production from regional emissions (Cristofanelli et al., 2015). The ozone concentration at near surface often exceed the EU air quality standard for human health protection especially during summer. This has been shown by measurements at rural and baseline stations located upwind of urban areas (Kalabokas et al., 2000; Kouvarakis et al., 2000; Kalabokas and Repapis, 2004; Gerasopoulos et al., 2005) as well as measurements during field campaigns over the Aegean (Kourtidis et al., 2002; Kouvarakis et al., 2002). Furthermore ground-based observations over the Mediterranean show high concentrations of aerosols, in both PM10 and PM2.5 fractions, presenting a similar seasonal behavior with maxima in spring and fall due to African dust transport (Querol et al., 2009a, 2009b).

In the lower troposphere often gaseous pollutants (NO_x, SO_2 and O_3) and anthropogenic or biomass burning aerosols (mainly sulfate, nitrate and carbonaceous aerosols) are being transported from European sources with northwesterly to northerly flow where can mix up with marine aerosols from the Mediterranean Sea and dust aerosols from the Sahara and the Middle East in dust outbreak events (Kallos et al., 1993; Lelieveld et al., 2002; Balis et al., 2003; Mihalopoulos et al., 2007; Sciare et al., 2008; Amiridis et al., 2009a; Hatzianastassiou et al., 2009; Georgoulias et al., 2016; Marinou et al., 2017). Various studies in the past have identified the paths and scales of transport and transformation of air pollutants released from Europe towards the Mediterranean region (Katsoulis and Whelpdale, 1990; Luria et al., 1996; Millán et al., 1997; Millán et al., 2000, 2002; Kallos et al., 2007). On an annual mean basis, PM10 contains about 8–12 mg m^{-3} of transported mineral dust and an additional 5–10 mg m^{-3} is attributed to transported anthropogenic regional sources and to sea-spray loads (Querol et al., 2009a, 2009b). High sulfate background loadings in the eastern Mediterranean (EM)are mostly attributed to the long-range transport of SO_2 (Zerefos et al., 2000) with marine biogenic emissions contributing up to 20% to the total sulfate production in a yearly basis (Kouvarakis and Mihalopoulos, 2002).

Kanakidou et al. (2011) reviewed the impact of local pollution sources from several large urban agglomerations, including the two megacities (Cairo, Egypt and Istanbul, Turkey) pointing out that air pollution transported to the area is of similar importance to local sources for the regional background air pollution levels in the EM. Im and Kanakidou (2012) showed further the importance of long range transport of pollutants for the air quality in the east Mediterranean for both winter and summer suggesting that improvements of air quality in the east Mediterranean require coordinated efforts inside the region and beyond. Drori et al. (2012) calculated that transport of air masses from eastern Europe and Turkey to the EM can contribute up to 50% of surface CO in the area. Myriokefalitakis et al. (2016) using a CTM (Chemistry Transport Model) reported that local anthropogenic sources are found to have relatively small impact on regional air quality in the area, contributing by about 8% and 18% to surface levels of O_3 and CO, respectively.

There are a number of observational data analysis and modeling studies that shed light on the controlling mechanisms for the high lower troposphere ozone levels over the Mediterranean. An important meteorological factor associated with the elevated boundary layer and near surface ozone levels is the dominating anticyclonic conditions over the central Mediterranean and the Balkans leading to enhanced photochemical ozone production but also large-scale subsidence from the upper troposphere, which is a characteristic feature of the Mediterranean summer circulation (Kalabokas et al., 2007, 2008, 2013). Another important factor is the long-range transport of air masses from Europe, which are rich in ozone and ozone precursors, towards the sunlit Mediterranean region in addition to emissions from local sources (Zerefos et al., 2002; Kouvarakis et al., 2002). Especially note should be made for the Etesians, which dominate the circulation during the summer and early autumn over the Aegean Sea and EM, with persistent northerly winds in the lower troposphere, thus setting up the typical transport regime for the EM (Tyrlis and Lelieveld, 2013). The dynamics of the Etesians are tightly interwoven with the large-scale subsidence observed over the EM and both are interconnected manifestations of the remote south Asian Monsoon forcing (Rodwell and Hoskins, 1996; Tyrlis et al., 2013).

Within the atmospheric boundary layer, results from Chemistry Transport Models (CTMs) and Air Quality Models (AQMs) indicate that long-distance pollution transport and photochemical processes dominate for the ozone budget in the Mediterranean (Lelieveld et al., 2002; Zanis et al., 2014; Safieddine et al., 2014; Akritidis et al., 2014). Furthermore, a number of CTM simulations pointed that the largest portion of this regional high ozone over the EM is beyond local emission controls (Zerefos et al., 2002) and that ozone and its precursors originate mainly from the European continent (Roelofs et al., 2003). Myriokefalitakis et al. (2016) using a CTM reported that the most important source of polluted air masses for the eastern Mediterranean boundary layer is the free troposphere with about 40% of O_3 and of CO while the western Mediterranean boundary layer receives 4 times lower amounts of O_3 from the free troposphere than the eastern basin. This modeling result corroborates the findings from the observational study of Gerasopoulos et al. (2006) who showed that the dominating factor for the maximum ozone values during summer at Finokalia station (Crete, Greece) is the entrainment of ozone rich air masses from the free troposphere. In support of this, Zanis et al. (2014) attributed the discrepancy between modelled with a CTM and observed near surface ozone at four baseline Mediterranean stations to overestimated modelled photochemical ozone production during summer, related to the coarse horizontal resolution, thus masking partially the contribution of downward transport and entrainment from the free troposphere to the boundary layer. The overestimation of local photochemical ozone production for Mediterranean continental stations during summer was also implied in the study of Katragkou et al. (2015a) based on MACC (Monitoring Atmospheric Composition and Climate) reanalysis near surface ozone. Furthermore, in line with the above, simulations with a regional AQM showed an underestimation of surface ozone during summer at baseline stations over the EM due to the limited vertical domain (top at around 6 km) and hence the lack of realistic middle tropospheric conditions to simulate the effects of subsidence on near surface ozone (Akritidis et al., 2013). A few modeling studies highlighted also the contribution of biogenic emissions on the summertime high ozone levels in the lower troposphere of the Mediterranean Basin due to their temperature sensitivity (Liakakou et al., 2007; Im et al., 2011; Richards et al., 2013).

10.3. Chemical characteristics in the middle/upper troposphere

In the middle troposphere, where westerly winds prevail, Asian and to a lesser extent north American pollution affects the CO levels over Mediterranean with long-range transport, while in the upper troposphere Asian pollution from the east has the greatest impact associated with the Asian monsoon outflow (Lelieveld et al., 2002; Sheeren et al., 2003). Satellite measurements of CH_4 indicated that although it is a long-lived tracer, an east–west gradient in CH_4 is observed and modelled in the mid-to-upper troposphere with a maximum in the western Mediterranean basin in all seasons except in summer when CH_4 accumulates above the EM basin due to the circulation and dynamical characteristics of EM and the impact of the Asian monsoon outflow (Ricaud et al., 2014). In line with the above, the pool structure with high ozone values is also characteristic in the free troposphere over EM during the warm part of the year, associated with the large-scale circulation (Li et al., 2001; Zanis et al., 2014).

Furthermore, enhanced levels of ozone have been reported in the lower and middle troposphere over the Mediterranean with maximum over EM region during summer from satellite measurements based on the Tropospheric Emission Spectrometer (TES), the Global Ozone Monitoring Experiment-2 (GOME-2) and the thermal Infrared Atmospheric Sounding Interferometer (IASI) satellite instruments (Richards et al., 2013; Doche et al., 2014; Safieddine et al., 2014). Already in earlier observational studies, vertical profiles from the MOZAIC program on commercial aircraft indicated high summer mixing ratios over the area in the middle and upper troposphere (Marenco et al., 1998; Stohl et al., 2001). Zanis et al. (2014) characterized this "hot-spot" of high free-tropospheric ozone levels during summer over the eastern Mediterranean/Middle East as an ozone pool.

In the free troposphere, there are several modeling studies investigating the high ozone levels (Li et al., 2001; Roelofs et al., 2003; Liu et al., 2009, 2011). Li et al. (2001) concluded that the anticyclonic circulation in the middle and upper troposphere over the Middle East funnels northern midlatitude pollution, transported in the westerly subtropical jet as well as lightning NOx from the Asian monsoon and pollution from eastern Asia transported in the Tropical Easterly Jet (TEJ). Liu et al. (2011) reported that the interannual variations of ozone transported from Asia and other regions are linked to the position and strength of the subtropical westerly jet over central Asia. Richards et al. (2013) highlighted also the role of the south Asian monsoon outflow in the high ozone concentrations in the middle and upper troposphere over the EM. Roelofs et al. (2003) reported substantial contributions on the free troposphere high ozone levels by transport from the stratosphere. Zanis et al. (2014) proposed that the dominant mechanism causing the free-tropospheric ozone pool is the downward transport from the upper troposphere and lower stratosphere, in association with tropopause folds, the enhanced subsidence and the limited horizontal divergence at the middle troposphere observed over the region. Recently, Akritidis et al. (2016) indicated further the links of high free tropospheric ozone levels with the fold activity in the region and they also pointed the relation of the interannual variability of near-surface ozone at EM during summer with both tropopause folds and ozone in the free troposphere.

11. Weather modification activities in the Mediterranean

For many years, people have sought to modify weather and climate by enhancing water resources and mitigating severe weather, since water is becoming an ever more scarce and precious commodity around the world. The potential societal benefits of precipitation enhancement and hail suppression are therefore too important to be ignored, hence, coordinated strategies and research programs have been developed to provide a sound scientific basis for precipitation enhancement and hail suppression programs.

On the objective to provide information concerning the scientific weather modification activities around the Mediterranean area, emphasis was given to these countries which support, throughout the years, such organized research programs, spanning from the western to eastern Mediterranean.

11.1. Spain

The weather modification activities in Spain are focused mostly on hail suppression. According to List et al. (1996), three operational, nonrandomized hail suppression projects have been conducted since 1969 in the Ebro river valley in northeastern Spain. Two hundred and ninety ground based generators were used for the seeding, aiming to cover and protect an area of about 20,000 km^2. Their evaluation was relied upon crop damage comparisons, which resulted to about 50% decrease in hail damage, not at a significant level.

In 1976, a new hail suppression programme was initiated in the Middle Ebro Valley area of Catalonia, by transferring methodology and technology (ground based generators) from ANELFA in south of France (Dessens et al., 2016). A small network of 70 hailpads was used for the study of hailstones' characteristics and evaluation purposes. In the frame of this program, a "piggy-back" venture took place, with the aim to investigate the trend of the summer precipitation within the area (Mosmann et al., 2003). Sánchez et al. (1998, 1999) reported that no effect on summer precipitation from seeding was found. Additional analyses of rain water, collected under seeding and no seeding conditions were performed, showing that Ag concentrations were well below the maxima recommended by regulation standards (Sánchez et al., 1999).

A new 5-year phase of the program started in 2000, adopting the model developed by Fraile et al. (1999). In this phase, a network of meteorological stations was installed and the hailpad network expanded to 165 hailpads, placed in a 5-km mesh, aiming to assess hail suppression with AgI ground generators, as in southern France (Dessens, 1998). Moreover, in 2001, a weather radar was also installed, to study hailstorm characteristics, improve hail forecasting models and better understand the severe convection processes (López et al., 2007; López and Sánchez, 2009).

In 2005, although the hail suppression activities were halted, the operational hailpad network was maintained, thus providing hailfall data during periods with no AgI seeding, suitable for comparison purposes.

11.2. France

The weather modification activities in France are focused on hail suppression and have been conducted mainly in the southern regions, by non-profit organizations, such as the Association Nationale d'Etude et de Lutte contre les Fléaux Atmosphériques (ANELFA) and the "Association Climatologique de Moyenne Garonne" (ACMG).

ANELFA is operating continuously since 1952 and is still involved in an operational hail suppression programme, without many changes in its principle, which consists of the preventive seeding of the developing hailstorms with ice-forming AgI nuclei released from ground based AgI vortex generators with acetone combustion (Dessens, 1953). According to Dessens et al. (2016), in 2015, the ANELFA operated its 64th hail research and prevention season, making this program to be the longest-lasting weather modification activity around the world. The number of ground generator stations and the total covered and protected area increased over the years: i.e., from the 455 vortex generator stations covering an operational area of 55,000 km^2 in 1984 (Dessens et al., 2006, 2009, 2016; Berthet et al., 2011), they increased to 838 and about 70,000 km^2 in 2015 (Dessens et al., 2016), respectively. The operational period is from April to September–October and each generator burns 1.1 $l h^{-1}$ of AgI–0.5 NaI acetonic solution at 8 g of AgI per liter, which means, 8.6 $g h^{-1}$ of AgI and produces 2×10^{11} s^{-1} ice-forming nuclei, active at −15 °C. In a general sense and for the previous years, the total AgI consumption was estimated to about 1200 kg $year^{-1}$ (List et al., 1996). However, in recent years, the total AgI consumption was decreased, because the number of emitting days per year had been reduced due to forecast improvements (Dessens et al., 2016).

For many years, the evaluation was essentially based on cloud physics measurements and insurance costs, insured value and loss reimbursement (Dessens, 1986a). In 1988, hailpad networks were added to the generator networks; after 8 years of combined exploitation, correlations were detected between the amount of seeding delivered to the hailstorms and the severity of the hailfalls (Dessens, 1998). A second data set, obtained a few years later, allowed to refine the first results and to improve the efficiency control by performing a geographical partition in the data processing (Dessens et al., 2003; Sánchez et al., 2009). This nonrandomized weather modification project, using the double-ratio calculations of the hailstones size parameter between the target and control data (Dessens, 1986b, 1998), depicts a hail decrease of 41%, for the correctly seeded events. Moreover, using the hailstone kinetic energy parameter, the double-ratio accounts to 50.2%, significant at the 0.01 level (Dessens et al., 2006). These findings actually mean: 41% fewer hailstones larger than 0.7 cm and 50.2% less hailstone kinetic energy. According to Dessens (1986b), these findings, represent a benefit of 104 million Francs; when compared to the 4.3 million Francs of the seeding cost, the project's benefit-to-cost ratio is about 24.

ACMG operated another hail reduction cloud seeding program for the period 1995–1999 in Moyenne-Garonne (southwest of France). The hail reduction hypothesis was based upon early rainout concept, which robs the hail formation regions of supercooled liquid water and upon increase in ice concentration at the −10 °C level, reduces the mean altitude of the center of gravity of the storm (Berthoumieu, 2003; List et al., 1996).

The experimental area was 8000 km^2, equipped with 472 hailpads (3 km grid) and 114 rain gauges, with 12 automatic weather stations. A 5 cm C-band weather radar was used for storm data collection and for directing the seeding aircrafts at the updraughts regions to release hygroscopic material (Berthoumieu, 2003).

The objective and expectation was to detect a decrease, due to seeding, of the average altitude of the high reflectivity zones, that correlate well with surface hail reports. Due to the poor storm and hail events during the operational periods, no conclusions have been reported.

11.3. Italy

The weather modification activities in Italy are focused on precipitation enhancement project. The "Progetto Pioggia" was a randomized rain enhancement experiment, with two alternating target areas, a buffer zone in-between and two additional control areas, carried out during 1988–1994, in Puglia area, on the Adriatic coast (Dell' Angelo et al., 1994; List et al., 1999). The experiment was proposed and designed by Abraham Gagin, as a replication of the Israel technology (List et al., 1999), to test the static seeding method, by establishing the viability of the crossover design (Shimborsky, 1988). The randomized seeding began in 1988 and continued with interruptions until 1994. Seeding aircrafts were flown, just below the base of convective clouds, along predetermined flight tracks of about 40 km and dispersed AgI nuclei at a seeding rate of 500 g h^{-1}, by burning a AgI–NaI in acetone solution. This adopted method incorporated several features from the two Israeli experiments (Gabriel, 1967; Gagin and Neumann, 1974, 1981; Gabriel and Rosenfeld, 1990), by transferring the Israel technology.

The experiment was controlled from an operation center at the Italian air force base at Bari, which was equipped with a C-band radar and facilities for radar data processing, meteorological and satellite data receiving and preparation of the silver iodide solution for the burners (List et al., 1999). Analyses and comparisons of radar data and rain gauge measurements have been presented by Nania (1994, 1996).

The established Scientific Committee (1993) relied upon the root double ratio (RDR) and root regression ratio (RRR) analyses (Gabriel, 1991, 1999) to suggest the termination of the "Progetto Pioggia" (List et al., 1999), because the desirable and required 15% rain increase, out of the expected 303 rainy days (Shimborsky, 1988), at a significance level of 0.05, could not be reached. This unforeseen result was also indicated in preliminary exploratory studies, where the two target areas might had been affected differently by seeding and that an apparent substantial seeding effect occurred in the Bari area, as opposed to Canosa, probably due to their geomorphological situation relative to the Gulf of Taranto and the inhomogeneities of the Apennines.

11.4. Greece

The Greek National Hail Suppression Programme (NHSP) is the first and only weather modification activity in Greece. The overall design, presented by Karacostas (1984, 1989), comprises a five-year (1984–1988: 3-year exploratory and 2-year confirmatory phase) randomized, target-control, crossover research experiment, which was designed as a "piggy-back" venture on the overall operational project; From 1989 till today, the Greek NHSP is only operational. Through the years, the Greek NHSP protected two to four distinct areas, totaling of > 5000 km^2. When the protected areas were further apart and the research project was on, four (4) seeding aircrafts and a research-seeder aircraft were used. Otherwise, three seeding aircrafts were sufficient on covering the protected areas. It should be noticed that the information provided hereafter are based upon the research part of Greek NHSP (1984–1988).

The cloud seeding hypothesis was relied upon the conceptual model of the "beneficial competition of hailstone embryos" (Foote and Knight, 1977) and the seeding was conducted, either at cloud top, within the layer between the − 8 °C and − 15 °C at a rate of one to two 20 g droppable flares every 5 s, or at cloud base at a rate of one to two end-burning flares every 4 min (Karacostas, 1984, 1989).

The majority of the convective cells were short lived and not very well developed, which means that their potential as hail producers was not very high (Karacostas, 1991). Limited microphysical observations indicated conical graupel embryos, continental droplet size distributions at cloud base and cloud base temperatures around 10 °C (Karacostas, 1989, 2003).

The hailpad network was consisted of 130 hailpads, covering the total study area of the research program with an average linear spacing of 4 km (~2400 km^2). Two additional "dense" networks of 65 hailpads each (with a linear spacing of 1 km), were implemented on either side of the buffer zone, providing additional information (Dalezios et al., 1991).

Several detailed studies, mainly in a "case study", or relatively short time period approach, have been pursued, concerning the NHSP (Flueck et al., 1986; Rudolph et al., 1989; Foris et al., 2006; Sioutas and Flocas, 2003; Sioutas et al., 2009).

The statistical evaluation of the programme was conducted by Karacostas (2002), using the modern Ratio Statistics theory (Gabriel, 1999), non-parametric statistics and graphical demonstrations (Wilks, 1995). It relied upon objective hailpad measurements, taking into consideration terrain constraints, proximity to international borders and possible contamination effects. Concerning the research part of the Greek NHSP, it was finally proven (18 out of the 21 examined parameters) that they exhibit a positive treatment effect -ranging between 35% and 72%- with probability values being accepted within the 5% confidence limit (Karacostas, 2002, 2003).

11.5. Israel

History suggests that the weather modification activities in Israel were due to the very intense water deficit in this country. This is considered the reason for the first weather modification project around Mediterranean to be developed in Israel.

The first randomized, crossover, airborne cloud seeding project (Israel I) was conducted during the 1961–1967 rainfall seasons (November–April), in two target areas, situated at the north-central Israel (Gabriel, 1963; Gagin, 1965). Gabriel (1963, 1970) pursued the evaluation of the project, resulting to an increase in rain at the order of ~15% for the target areas and ~22% for interior areas.

The second randomized, crossover cloud seeding experiment (Israel II) follow up the Israel I, being conducted for the period 1969–1975, with the objective to examine the possibilities of precipitation enhancement in the catchment areas close to the principal national reservoir (Neumann et al., 1967; Gagin and Neumann, 1976). The statistical evaluation indicated positive overall results of 13% to 18% increase of rainfall. These findings of the Israeli experiment (I and II) were resulted from clouds with top temperatures ranging from − 12 °C to − 26 °C, with the maximum effect between − 16 °C and − 21 °C (Gagin and Neumann, 1981), which resembles similarities with the Whitetop project results (Flueck, 1971).

The Israeli experiments where considered the most promising rain enhancement projects around the world and for this reason they were criticized. Gagin and Neumann (1981) support the argument that the positive seeding effect resulted from static seeding of convective cold-based continental clouds. Rangno and Hobbs (1995) have questioned the validity of the conclusions of the Israeli experiments, claiming that a type I statistical error -that is, to consider the incorrect rejection of a true null hypothesis- was the reasoning for the positive effect in the Israel I. Moreover, they consider the natural variability as the reasoning for the resulted higher precipitation in the north target area for Israel II. In addition, Rosenfeld and Farbstein (1992) argued that the incursion of desert dust could be the reasoning for encountering less rainfall in the south target area compared to the north target area, in Israeli II. They suggested that desert dust contains more cloud condensation nuclei and ice forming nuclei, which can provide coalescence embryos and cloud droplets, enhancing thus a more efficient collision–coalescence process in clouds. In addition, the original thought that clouds in Israel were continental with small ice particle concentrations for cloud tops warmer than − 12 °C, with neither coalescence nor ice multiplication process operating, has also been questioned by Rangno and Hobbs (1995) and Levin (1992), who presented evidence for the existence of large supercooled droplets and high ice concentrations at relatively warm temperatures in these clouds.

Although the aforementioned arguments and referred measurements represented a limited number of cases, it somewhat wears down the earlier perception that clouds over Israel were highly susceptible to seeding (Gagin, 1986; Gagin and Neumann, 1974). The initial criticisms of Rangno and Hobbs (1995) have generated a number of responses in the scientific literature (Rosenfeld, 1997; Rangno and Hobbs, 1997a; Woodley, 1997; Rangno and Hobbs, 1997b; Ben-Zvi, 1997; Rangno and Hobbs, 1997c; Dennis and Orville, 1997; Rangno and Hobbs, 1997d).

12. Regional climate projections

12.1. Challenges in projecting the Euro-Mediterranean climate

The interaction of different components of the climate system is very crucial for the understanding of the Mediterranean climate and its future projection. Air-sea interactions produce the deep Mediterranean water at different locations with intense mesoscale variability, strong seasonal cycle and interannual variability at fine spatial scales (CIESM, 2009). The water surface provides a lower boundary for the atmosphere which controls the exchange of heat, water and chemical compounds, while serving as a long-term storage of those quantities, thus constituting a significant memory component of the climate system. Similarly, land provides another boundary for the atmosphere which controls seasonal to interannual climate variability along three main paths: soil-moisture-temperature, soil moisture-precipitation and vegetation-climate interactions (Seneviratne and Stöckli, 2008). Finally, the atmospheric composition of the Mediterranean region, rich in atmospheric trace gases and aerosol of anthropogenic and natural origin (Lelieveld et al., 2012), features another important forcing of the regional climate by interacting with short and longwave radiation components and altering the energy, water budget and the circulation of the atmosphere (Nabat et al., 2014, 2015; Zanis et al., 2012).

Given those complex interactions and multiple feedbacks, it is obvious that the modeling efforts contributing to the understanding and projection of the Mediterranean climate are very demanding. One major challenge is the coupling of several climate system components (ocean, land, atmosphere, chemistry) ideally into one Earth System Model, accounting for air-sea-land-chemistry interactions and feedbacks. The second one is the high temporal and spatial resolution, which is required to capture the fine variability patterns of the Mediterranean climate. The third challenge is the transition from individual scientific efforts to coordinated ensembles and international intercomparison projects to foster the knowledge exchange between experts and the provision of coherent datasets for the study of climate change.

12.2. Coordinated regional climate downscaling experiments

Past intercomparison projects focusing on downscaling global climate simulations over the Euro-Mediterranean region include STARDEX (Goodess et al., 2005), PRUDENCE (Christensen et al., 2007), ENSEMBLES (van der Linden and Mitchell, 1990) and CIRCE (Gualdi et al., 2013). The initiative running currently and aiming to coordinate regional downscaling activities is CORDEX (Giorgi and Gutowski, 2015). CORDEX is one of the World Climate Research Program (WCRP) core projects and will serve as a diagnostic Model Intercomparison Project (MIP) for the phase 6 of the Coupled Model Intercomparison Project (CMIP6) ensuring a close and structured collaboration with the global climate community (Gutowski et al., 2016). Three regional CORDEX domains cover the Mediterranean region, the European, the Mediterranean and the Middle-East North-African, denoted hereafter as EURO- CORDEX, MED- CORDEX and MENA-CORDEX, respectively (see Ruti et al., 2016).

Below a summary is provided of recent regional downscaling activities with focus on the work published within the dynamical downscaling activities of CORDEX, which includes state-of-the-art downscaled ensembles, higher resolution experiments and the new pathways adopted by the Intergovernmental Panel on Climate Change (IPCC) for the 5th Assessment Report (AR5), namely the Representative Concentration Pathways (RCPs) (Moss et al., 2010) superseding the SRES scenarios (IPCC, 2000) used in AR4.

12.3. Advances in regional climate model simulations

In comparison to past ensemble modeling exercises (ENSEMBLES), the current CORDEX simulations show similarity in the large-scale patterns and difference in regional details, with more obvious differences seen for the seasonal mean changes in heavy precipitation (Jacob et al., 2014). This feature can be partly attributed to the changes in the ensemble model resolution, which strongly affect precipitation amounts, regardless of the external or local forcings (Giorgi and Marinucci, 1996).

The higher spatial resolution simulations (12 km) were found to better reproduce the mean and extreme precipitation for almost all regions and seasons over Europe, because of the improved topographic representation and the ability of models to better resolve dynamical processes (Prein et al., 2015). Other studies were not very conclusive about the impact of resolution on the correctness of the representation of extreme events, with the exception of some improvements, especially along coastlines (e.g., analysis of Vautard et al., 2013 on heat-waves).

The bias ranges of EURO-CORDEX mostly correspond to those of the ENSEMBLES simulations, with some improvements in model performance; seasonal and regionally averaged temperature biases were mostly smaller than 1.5 °C, while precipitation biases were typical located in the ± 40% range (Kotlarski et al., 2014). Studies with multivariable analysis, showcased that satisfactory model performance can be occasionally a result of error compensation and not a correct representation of the physical system (García-Díez et al., 2015; Katragkou et al., 2015b).

Characterization of model performance and identification of systematic model errors is very crucial in climate modeling. Boberg and Christensen (2012) demonstrated that projections of intense mean summer warming partly result from model deficiencies; when corrected for, the Mediterranean summer temperature projections are reduced by up to one degree, on average by 10–20%.

12.4. Patterns of climate change in the Euro-Mediterranean region

According to the 5th Assessment Report (AR5) of the IPCC, there is a high confidence in model projections of mean temperature from global to regional scale (IPCC, 2013) and evidence that temperature increase and effects on extreme temperature and precipitation is attributed to anthropogenic forcing (Bindoff et al., 2013). It is very likely that temperature will continue to increase through the 21st century over the Mediterranean region, with a more intense summer warming. The length, frequency and intensity of warm spells or heat waves are assessed to be very likely to increase. A decrease of precipitation is likely in the same region. The range of changes in land temperature is expected in the range 1 to 4 °C (1 to 6 °C) until the end of the century in winter-DJF (summer-JJA), depending on the future scenario adopted [Fig. 8, source: IPCC, 2013]. Similarly, precipitation is projected to decrease from a few to 10% during the cold period of the year (October to March) and up to 25% during the warm months (April to September) [Fig. 9, source: IPCC, 2013]. Increasing heat extremes with projections to accelerate in future will characterize the MENA domain according to Lelieveld et al. (2016), with a sharp increase of warm days and nights; for the most pessimistic RCP8.5 scenario, the maximum temperature will rise from 43 °C to about 46 °C by the middle of the century and reach almost 50 °C by the end of the century.

Despite the fact that global climate projections provide a useful reference on the response of the climate system to natural and anthropogenic forcings, they cannot provide accurate descriptions of extreme events. Their coarse spatial resolution and uncertainties in parameterized processes (e.g., convection) prevents them from capturing accurately local forcings which modulate climate at local scales. Projections in precipitation are even more regionally variable than changes in temperature. Based on HyMeX (Drobinski et al., 2014) and MED-CORDEX datasets, Drobinski et al. (2016) found that the change in precipitation extremes with respect to temperature is robust and consistent in the Mediterranean region, with a slope following the Clausius-Clapeyron scaling at lower temperatures and a negative slope at high temperatures; they also noted that the temperature break point appears to be shifting to higher temperatures towards the end of the century. A negative slope was reported in the arid regions, with implications for the scaling of precipitation extremes, expected to be weaker at highest temperature due to water limitation. Using a high-resolution (0.11°) multi-model EURO-CORDEX ensemble, Jacob et al. (2014) reported a temperature increase in the range of 1–4.5 °C for RCP4.5 and 2.5–5.5 °C for RCP8.5, with greater annual mean warming and a decreasing trend for annual precipitation in the Mediterranean parts of Europe. Their projections based on the RCP8.5 projection included a possible decrease in heavy summer precipitation by about 25% over some parts of the Iberian Peninsula and southern France, accompanied by regional increases in parts of the Iberian Peninsula.

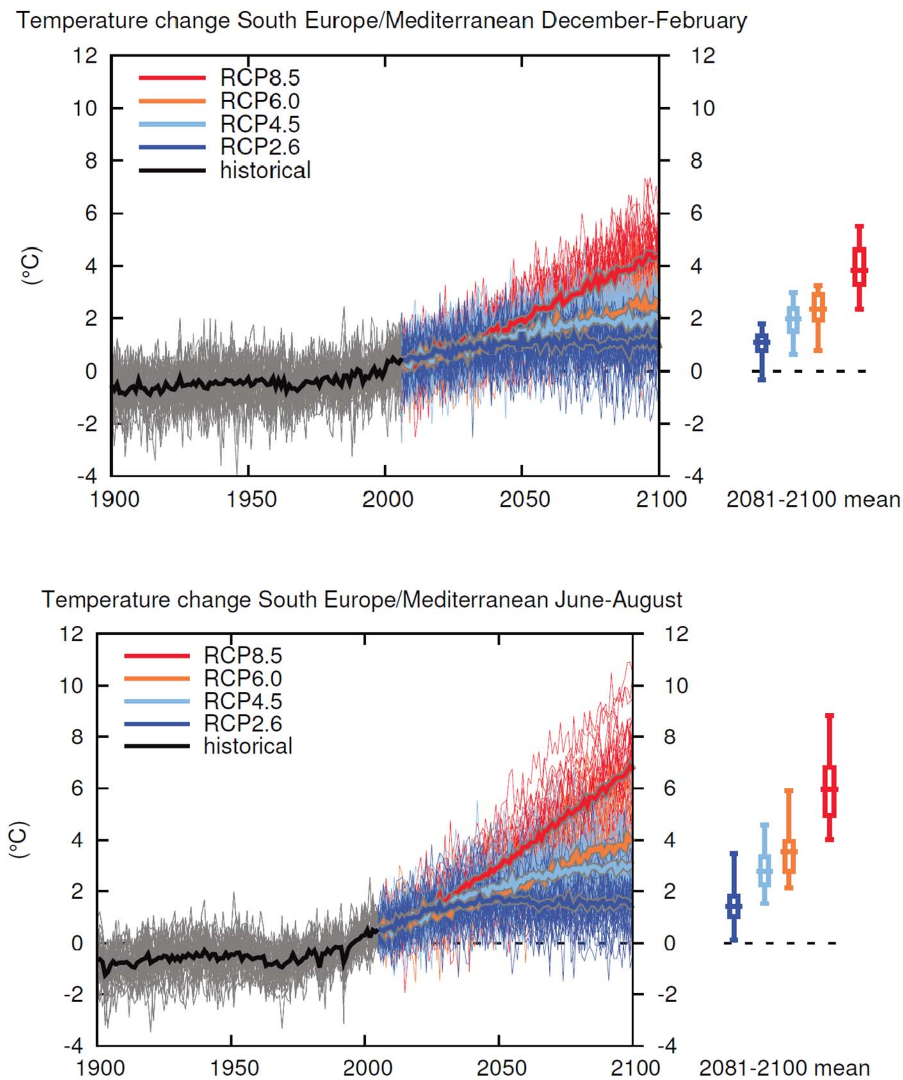

Fig. 8. Time series of temperature change relative to 1986–2005 averaged over land grid points in the region south Europe/Mediterranean (30°N to 45°N, 10°W to 40°E) in December to February (top) and June to August (bottom). Thin lines denote one ensemble member per model, thick lines the CMIP5 multi-model mean. On the right-hand side the 5th, 25th, 50th (median), 75th and 95th percentiles of the distribution of 20-year mean changes are given for 2081–2100 in the four RCP scenarios.
[Source: IPCC, 2013, Annex I, Figs. AI.40 and 41].

12.5. Regional processes and uncertainties in regional climate simulations

The amplified warming of the eastern Mediterranean region is generally associated with the soil-moisture-atmosphere feedback mechanism. According to Knist et al. (2017), the spread in soil-moisture in regional climate model ensemble can be very large, even for models using the same land surface model, thus affecting decisively the land-atmosphere coupling strength over regions. Other model processes affecting strongly the European heatwaves were attributed to the selection of convective scheme (Vautard et al., 2013). Stegehuis et al. (2013) quantified the uncertainty of European temperature changes stemming from land-atmosphere processes and reported that the uncertainty can be reduced (up to 40% for France and the Balkans) with the use of observation-based heat flux data.

13. Concluding remarks

In this paper, processes that are significant in terms of impacting the weather and related hydro-meteorological hazards in the Mediterranean, along with some current related research activities have been reviewed. The topics reviewed were selected on the basis of their spatiotemporal extent, focusing on those which are identifiable at the synoptic scale but also those which widely affect the Mediterranean basin and are conducive to much attention from the public or the scientific community. Also, future perspectives of such processes have been presented with focus on future climatic trends.

Near future scientific advances in the regional modeling community will be driven by thematic ensembles, which will investigate the importance of regional scale forcings (aerosols, land-use change, vegetation, etc.) on regional climate (e.g., CORDEX-Flagship Pilot Studies). The modeling exercises will be augmented by Earth observations including satellites and in situ sensors containing the geophysical information needed to analyze the climate change indicators in a consistent and harmonized way, providing guidance for the evolution of climate services. Higher resolution climate simulations will aim to address more accurately the changes to high impact processes like severe precipitation events and droughts. The possibilities and constraints of increasing the resolution of the simulations will be investigated even further by shifting towards convective permitting ensembles with spatial resolution < 5 km. Together with a better integration of statistical downscaling methods and improvements in the techniques of building ensembles (Benestad et al., 2017), regional climate information will be enhanced in the near future, providing more robust datasets which will be extremely useful for the climate impact assessment community.

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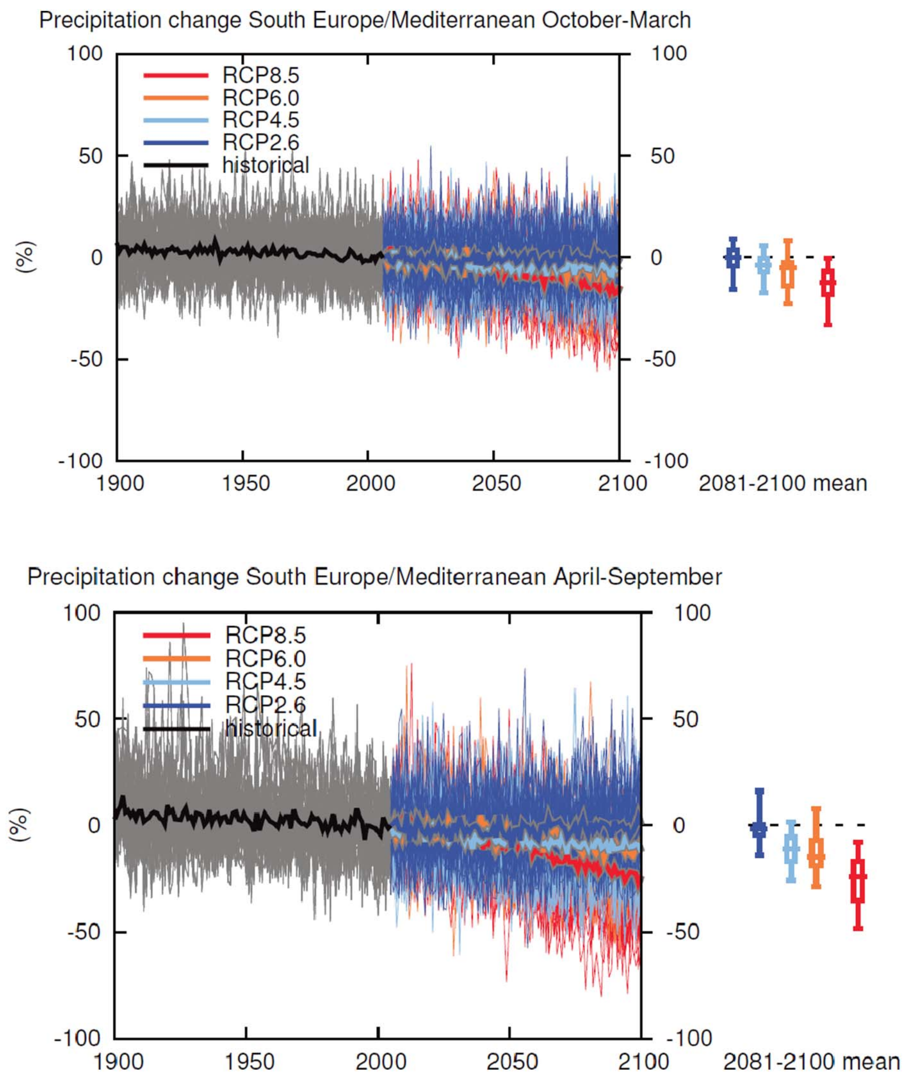

Fig. 9. Time series of relative change relative to 1986–2005 in precipitation averaged over land grid points in the region south Europe/Mediterranean (30°N to 45°N, 10°W to 40°E) in October to March (top) and April to September (bottom). Thin lines denote one ensemble member per model, thick lines the CMIP5 multi-model mean. On the right-hand side the 5th, 25th, 50th (median), 75th and 95th percentiles of the distribution of 20-year mean changes are given for 2081–2100 in the four RCP scenarios.

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Appendix A

A.1. List of symbols and abbreviations

asl	above sea level
AATSR	Advanced Along-Track Scanning Radiometer
ACMG	Association Climatologique de Moyenne Garonne
ACTRIS	Aerosol, Clouds and Trace gases Infrastructure
AERONET	AErosol RObotic NETwork
AI	Aerosol Index
AIRBASE	Air quality database hosted by the European Environment Agency (EEA)
AMO	Atlantic Multidecadal Oscillation
ANELFA	Association Nationale d'Etude et de Lutte contre les Fléaux Atmosphériques

AOD	Aerosol Optical Depth
AQM	Air Quality Model
AR4	4th IPCC Assessment Report
AR5	5th IPCC Assessment Report
AVHRR	Advanced Very High-Resolution Radiometer
B	Bergeron
CC	Conte-Capaldo type of explosive cyclogenesis
CCN	Cloud Condensation Nucleus (Nuclei)
CESM	Community Earth System Model
CG	cloud-to-ground
CMIP3	Coupled Model Intercomparison Project – Phase 3
CMIP5	Coupled Model Intercomparison Project – Phase 5
CMIP6	Coupled Model Intercomparison Project – Phase 6
CORDEX	Coordinated Regional Downscaling Experiment
CTM	Chemistry Transport Model
CyCARE	Cyprus Clouds Aerosols and Rain Experiment
EA	East Atlantic index
EARLINET	European Aerosol Raman Lidar Network
EAWR	East-Atlantic/West-Russian index
EEA	European Environment Agency
EM	East Mediterranean
EMEP	European Monitoring and Evaluation Programme
EMME	East Mediterranean-Middle East region
ENSO	El Niño Southern Oscillation
ESSL	European Severe Storms Laboratory
EU	European Union
G500	geopotential height at 500 hPa level
GAW	Global Atmosphere Watch
GCM –	General Circulation Model
GEN	Medicane generation index
GOME-2	Global Ozone Monitoring Experiment-2
gpm	geopotential meter
HD	Hail days
HyLMA	HyMeX Lightning Mapping Array
HyMeX	Hydrological Cycle in Mediterranean Experiment
IASI	Infrared Atmospheric Sounding Interferometer
ICSU	International Council of Scientific Unions
INP	ice nucleating aerosol particles
IPCC	Intergovernmental Panel on Climate Change
IWC	ice water content
KF	Karacostas-Flocas type of explosive cyclogenesis
LACROS	Leipzig Aerosol and Clouds Remote Observations System
LIRIC	Lidar/Radiometer Inversion Codes
LWC	liquid water content
MEDEX	MEDiterranean Experiment
MERIS	Medium Resolution Imaging Spectrometer
MIP	Model Intercomparison Project
MISR	Multi-angle Imaging Spectroradiometer
mslp	mean sea-level pressure
NAO	North Atlantic Oscillation
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NHC	National Hurricane Center
NHSP	Greek National Hail Suppression Programme
NMVOCs	Non-methane volatile organic compounds
NOAA	National Oceanic and Atmospheric Administration
OMI-Aura	Ozone Monitoring Instrument
PDSI	Palmer Drought Severity Index
PI	potential intensity
PM	particulate matter
PM1.0	particulate matter with aerodynamic diameter ≤ 1.0 μm
PM10	particulate matter with aerodynamic diameter ≤ 10 μm
PM2.5	particulate matter with aerodynamic diameter ≤ 2.5 μm
POLDER	polarization and directionality of the Earth's reflectances
PV	potential vorticity
RCM	Regional Climate Model

RCP	Representative Concentration Pathway
RDR	root double ratio
RH	mid-tropospheric relative humidity
ROS	rain on snow events
RRR	root regression ratio
SCAND	Scandinavian index
SC-PDSI	self-calibrating PDSI
SLP	sea level pressure
SOP1	first special observation period of HyMeX
SPEI	Standardized Precipitation Evapotranspiration Index
SPI	Standardized Precipitation Index
SPOT	Satellites Pour l'Observation de la Terre
SRES	Special Report on Emissions Scenarios
SST	sea-surface temperature
TEJ	Tropical Easterly Jet
TES	Tropospheric Emission Spectrometer
TOMS	Total Ozone Mapping Spectrometer
TRMM	Tropical Rainfall Measuring Mission
UTC	Universal Time Coordinated
UV	ultraviolet radiation
V_{shear}	vertical wind shear across the troposphere
WCRP	World Climate Research
WEMO	Western Mediterranean Oscillation
WMO	World Meteorological Organization
η	absolute vorticity at low levels

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