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Discussing the role of tropical and subtropical moisture sources in cold season extreme precipitation events in the Mediterranean region from a climate change perspective

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Abstract. This paper presents a review of a large number of research studies performed during the last few decades that focused on the investigation of cold season extreme precipitation events (EPEs) in the Mediterranean region (MR). The publications demonstrate the important role of anomalously intense transports of moist air from the tropical and subtropical Atlantic in the occurrence of EPEs in the MR. EPEs in the MR are directly or indirectly connected to narrow bands with a high concentration of moisture in the lower troposphere, i.e., atmospheric rivers, along which a large amount of moisture is transported from the tropics to midlatitudes. Whereas in a significant fraction of the EPEs in the western MR moisture is transported to the MR from the tropical Atlantic, EPEs in the central, and especially the eastern, MR are more often associated with intense tropical moisture transports over North Africa and the Red Sea. The moist air for the EPEs in the latter part of the MR also mainly originates from the tropical Atlantic and Indian oceans, and in many cases it serves as a temporary moisture reservoir for future development. The paper is supplemented by the results of a test for a possible connection between declining Arctic sea ice and the climatology of intense precipitation in the eastern MR. Based on the results of the evaluation supporting those from the earlier climate change analyses and modeling studies, it is concluded that a further anthropogenic global warming may lead a greater risk of higher rainfall totals and therefore larger winter floods in western and central parts of the MR as a consequence of stronger and more numerous Atlantic atmospheric rivers, possibly accompanied by a decline in the number of EPEs in the eastern part of the MR.

1 Introduction

The cold season, which for the Mediterranean region (MR) may be defined as September–May, is characterized by a substantial number of exceptionally intense extreme precipitation events (EPEs) with precipitation rates being comparable to those of hurricanes (Clarke and Rendell, 2006; Lionello et al., 2006b; Pfahl and Wernli, 2012). These EPEs have been selected as the main focus of the current review. The cold season MR EPEs are almost exclusively associated with cyclones (e.g., Reale and Lionello, 2013). Heavy rains during the MR EPEs are often associated with suddenly occurring flash floods that represent significant threats to society, human lives and infrastructure (e.g., Lastoria et al., 2006; Lionello, et al., 2006a; Jansa et al., 2014; Trigo et al., 2016).

The formation of a cold season rainy event in the MR typically results from the interplay between two acting factors – high water vapor content that induces mesoscale moist convection and larger-scale baroclinic dynamics. Obviously, moisture does not automatically induce convection, as the air must become positively buoyant. In the MR, moist convec-

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tion is often associated with the effects of topography (Reale and Lionello, 2013).

Among the famous MR EPEs are such cases as the “century” floods in Florence, Italy, on 4 November 1966, with up to 750 mm of rain in 24 h (e.g., De Zolt et al., 2006); floods in Gandía (eastern Spain, province of Valencia) on 3–4 November 1987, with 817 mm of rain in 24 h (Romero et al., 2000); the event on 15 November 1985 with more than 200 mm of rain in 2 h in the Balearic Islands (Romero et al., 1998); the rainy day of 9 October 1994 with 450 mm in 24 h in the province of Valencia, Spain (Ramis et al., 1998); heavy rains in Egypt, Israel and northern Italy during 1–6 November 1994 with more than 300 mm of rain in 36 h (Buzzi et al., 1998; Krichak and Alpert, 1998; Jansa et al., 2000); a case with catastrophic floods (11 fatalities) in central Greece and in Athens with more than 140 mm of rain in 24 h on 21 October 1994 (Lagouvardos et al., 1996); a case with devastating floods in central and southern Greece with more than 300 mm of rain in 24 h during 11–12 January 1997 (Kotroni et al., 1999); a torrential rain event in the Valencia region in October 2007 that exceeded 400 mm of rain in 24 h (Pastor et al., 2010); a heavy precipitation event in Israel with over 260 mm in 24 h during 4 December 2001 (e.g., Krichak et al., 2004, 2007); a flood event in Antalya, Turkey, on 4–6 December 2002 with more than 230 mm in 24 h (Kotroni et al., 2006); and many others (e.g., Ramis and Llasat 1994; Doswell et al., 1998; Romero et al., 1999, 2000; Kahana et al., 2004; Homar et al., 2007; Ramis et al., 2009; de Vries et al., 2013).

A number of international research projects have been devoted to attaining a better understanding of the physical mechanisms responsible for the formation of EPEs. The list of research efforts includes ALPEX (Davies and Pichler, 1990; McGinley and Zhupanski, 1990; Alpert et al., 1996; Buzzi et al., 1998), the Mediterranean Experiment (MEDEX, Jansa et al., 2014), Climate Change and Impact Research: the Mediterranean Environment (CIRCE FP6-EU, Navarra and Tubiana, 2013) project, the Mediterranean CLImate VARiability and Predictability (MedCLIVAR) network (e.g., Lionello et al., 2012, 2014; Garcia-Herrera et al., 2014) and the HYdrological cycle in the Mediterranean EXperiment (HyMeX; Drobinski et al., 2014).

In this paper, we present a discussion of the investigations on very intense cold season high-impact EPEs in the MR performed mainly during the last 30 years. The review was prepared in accordance with the call for a special NHESS issue on “Climate change, extreme events and hazards in the Mediterranean region” (edited by P. Lionello, V. Artale, D. Gomis and H. Saaroni).

The paper is organized as follows: an extended summary of the research that focused on the physical mechanisms responsible for the formation of the MR EPEs is presented in Sect. 2. The results of investigations on the role of tropical moisture as well as the mechanisms for its transport to the MR are discussed in Sect. 3. A discussion of the research that addressed the role of global warming for recent EPEs and the expected future MR EPEs trends is presented in Sect. 4. An extended discussion of the major trends of MR EPEs including an analysis of the possible role of the melting of Arctic ice, and the summary and conclusions are given in Sect. 5.

2 Identification of acting mechanisms

The cold season cyclones associated with EPEs in the extratropics are often characterized by an extreme pressure fall (“explosive” or “bomb” cyclones) as well as strong surface winds (e.g., Roebber, 1984; Wernli et al., 2002; Fink et al., 2009; Liberato et al., 2011). Such events can be especially damaging. The earliest analyses of these cyclones focused on individual cases (e.g., Sanders and Gyakum, 1980; Zhu and Newell, 1994; Alpert et al., 1996; Schmith et al., 1998; Massacand et al., 1998; Tsidulko and Alpert, 2001). These studies demonstrated the importance of mountains, upper-level jets, low-level fronts as well as air–sea interaction. Later analyses (e.g., Krichak and Alpert, 1998; Ulbrich and Christoph, 1999; Sickmöller et al., 2000; Ferraris et al., 2001; Ulbrich et al., 2001) identified a notable role for moisture transported from extra-Mediterranean regions.

The arrival of moist air from the tropical Atlantic into the Mediterranean basin is typically followed by an intense low-level moisture flux convergence over the area of the EPE formation (Ferraris et al., 2001). This series of processes appears to characterize the majority of EPEs in the MR. In contrast to rainy events of ordinary intensity, the MR EPEs are more likely to originate from a specific atmospheric process (or a group of processes) associated with the formation of hurricanes or intense cyclones over the Atlantic Ocean. Such synoptic developments are characterized by intense convergence of moist air from the tropics (serving as an unlimited moisture reservoir; Ralph and Dettinger, 2011) which is followed by a fast intrusion of moist air into the midlatitudes and eventually to the MR without significant mixing with the surrounding air.

The possibility of identifying moisture sources in the subtropics or tropics has stimulated the application of a Lagrangian approach for trajectory calculations. Reale et al. (2001) applied this method to investigate a series of 1998 flood events in the Mediterranean. Their analysis revealed a notable role for the advection of moisture from the North Atlantic in the formation of the EPEs. Further evaluations (Berto et al., 2004; Turato et al., 2004; Rudari et al., 2005; Ziv et al., 2005; De Zolt et al., 2006; Malguzzi et al., 2006) have supported this conclusion. In particular, by studying a precipitation event in the Trentino region (northern Italy), Berto et al. (2004) found contributions of moisture not only from the Mediterranean but also from North Africa and the eastern and central Atlantic. Turato et al. (2004) studied a heavy precipitation event in Piedmont in 2000. They identified a variety of moisture sources that contribute to the EPE, including those in the North Atlantic. Specifically, more than

50 % of the evaporation contributing to the precipitation during the event comes from the Atlantic Ocean. Rudari et al. (2005), De Zolt et al. (2006) and Malguzzi, et al. (2006) also arrived at the conclusion on the importance of strong advection of moist air into the central Mediterranean Sea prior to the formation of MR EPEs.

A number of intercomparison studies based on different reanalysis data sets (e.g., Trigo, 2006; Wang et al., 2006; Raible et al., 2008; Ulbrich et al., 2009; Hodges et al., 2011) have further addressed this issue. In particular, Pinto et al. (2009) have significantly improved our understanding of the role of external sources of moisture in the formation of several intense cyclones in the Euro-Mediterranean region. According to this study, moisture originating from the storm track region over the North Atlantic plays a notable role in the intensification of explosive cyclones.

A strong relationship between EPEs in the MR and the large-scale atmospheric circulation at the upper, middle and lower troposphere has been also demonstrated by Toreti et al. (2010). Here, a two-step classification procedure has been applied for the identification of anomaly patterns over the western–central and eastern Mediterranean Basin. Over the western Mediterranean, an anomalous surface to mid-tropospheric southwesterly flow induces enhanced moisture transport from the Atlantic. For the eastern Mediterranean EPEs, the anomaly patterns suggest warm and moist air advection into the region induced by anomalously intense moist air ascent.

The issue of the origin of the moisture affecting the Mediterranean during and prior to the formation of EPEs has been addressed in a series of studies (Gimeno et al., 2010a, b, 2012; Nieto et al., 2010). North Atlantic moisture sources were found to be dominant during winter. While the northern slope of the Alps is dominated by moisture from the North Atlantic and Central Europe, both with a clear seasonality and limited variability, the EPEs in the southern Alps have a stronger influence from the highly variable Mediterranean and extra-Mediterranean moisture sources. These evaluations were based on the methodology of Stohl and James (2004) who used a Lagrangian particle dispersion model. The atmosphere was divided homogeneously into a large number of particles, which have a constant mass. These particles were advected numerically. The evaluations using the Lagrangian tracking confirmed the earlier detected remote moisture sources for the EPEs. An area extending from the Gulf of Mexico to Africa has been found to be especially important for the EPEs in the western and central MR (Stohl and James, 2004; Stohl et al., 2008; Lionello et al., 2006a). Analyses by Duffourg and Ducrocq (2011) and Liberato et al. (2011) have additionally identified a notable contribution from moisture sources in the subtropical Atlantic for EPEs over southeastern France and Portugal, respectively.

A comprehensive analysis of tropical moisture exports based on the calculation of 7-day forward trajectories starting daily from the tropical lower troposphere (Knippertz and Wernli, 2010; also Knippertz et al., 2013) has allowed the identification of the existence of four distinct activity maxima with different seasonal behavior over the Northern Hemisphere. One of the maxima is located over the North Atlantic (mainly western, but in some cases reaching the MR) showing a small amplitude annual cycle with a maximum in winter and autumn. The result explains a link between tropical moisture sources and the climatology of precipitation and occasionally explosive cyclogenesis over the MR (e.g., Sodemann and Zubler, 2010; Pfahl and Wernli, 2012)

Application of a water vapor tagging approach into a limited-area numerical weather prediction model (Sodemann et al., 2009; Winschall et al., 2012) has complemented these studies. The method consists of labeling water vapor originating from different regions along its atmospheric pathway, including transport, phase changes and eventual precipitation. By keeping tag of water vapor origin, it is thus possible to gain quantitative information on the contribution of specific predefined water sources to a precipitation event. Using this method over the Atlantic Ocean, Winschall et al. (2012) simulated moisture transport and moisture source contributions to precipitation at high resolution, including all relevant parameterized processes, such as cloud microphysics. This diagnosis has demonstrated the importance of the coupling between surface evaporation and moisture advection for the EPEs. Pinto et al. (2013) confirmed this conclusion by performing an objective identification and cluster ranking of extraordinary rainfall events over northwestern Italy using time series of annual precipitation maxima for 1938–2002 at over 200 MR stations. The two top clusters are characterized by strong and persistent upper air troughs that induce not only moisture advection from the North Atlantic into the western Mediterranean but also a strong northward flow towards the southern Alpine ranges. Moisture transport from the North Atlantic was found to be less important for the weaker clusters.

By considering the 50 strongest precipitation events in the Alpine area during 1989–2009, Winschall et al. (2014) revealed the importance of evaporative hot spots over the eastern North Atlantic. Their results indicate that for MR EPEs in autumn and winter the Mediterranean Sea surface is only one of several source regions and is typically matched by moisture from the eastern North Atlantic.

The duration for the maximum moisture uptake varies between a few hours to more than 1 week before a precipitation event takes place. Whereas moisture uptakes that occur only a few hours or days prior to the EPE can be regarded as causally related to the dynamics of the EPE itself, the much earlier uptakes over the subtropical Atlantic were found not to be linked dynamically to the triggering of the MR EPEs (Winschall et al., 2014).

Additional analyses (e.g., Fiori et al., 2014; Dacre et al., 2015) have revealed a high sensitivity of the modeling results to the accuracy in the representation of the timing of the acting mesoscale processes. In particular, Dacre et al. (2015)

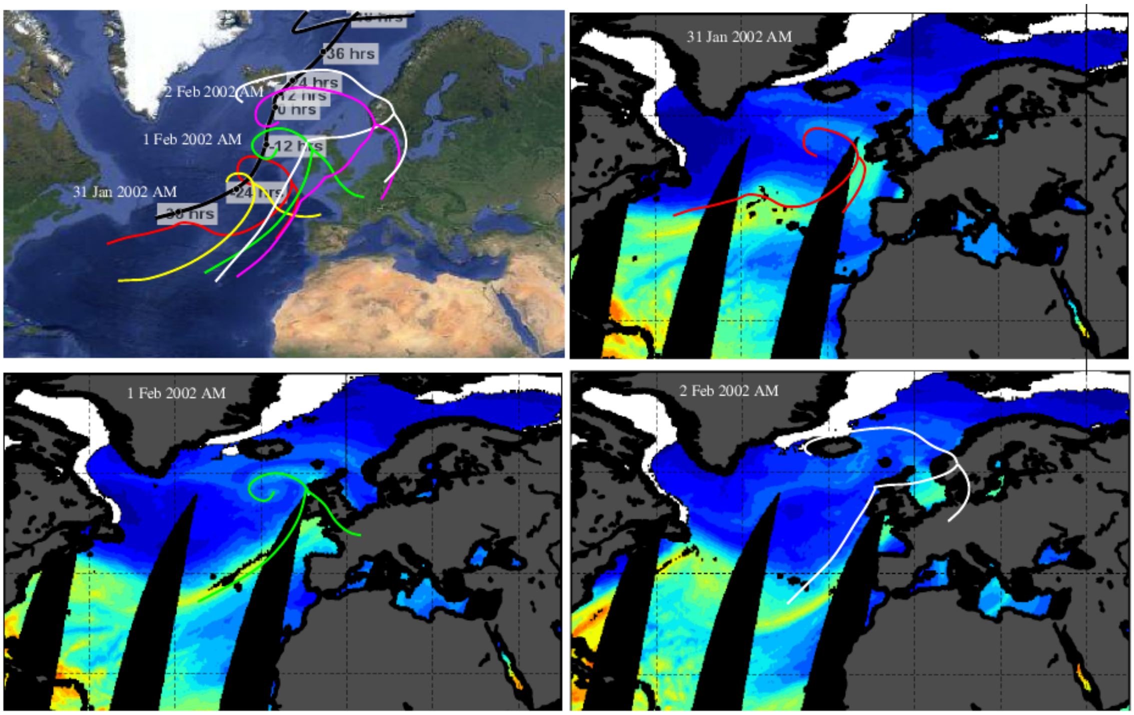

Figure 1. (a) Schematic showing positions of surface fronts at successive 12-hourly intervals, starting at 06:00 UTC on 31 January 2002, and Special Sensor Microwave Imager (SSM/I F13) integrated water vapor on **(b)** 31 January 2002 overlaid with 06:00 UTC on 31 January 2002 frontal positions, **(c)** on 1 February 2002 overlaid with 06:00 UTC on 1 February 2002 frontal positions and **(d)** on 2 February 2002 overlaid with 06:00 UTC on 2 February 2002 frontal positions (Fig. 8 in Dacre et al., 2015; used with permission © American Meteorological Society).

demonstrated the importance of tropical moisture transport in the climatology of extratropical cyclones by investigating the spatial distribution of the 200 most intense extratropical cyclones during 1979–2009 (identified and tracked in the ERA-Interim reanalysis using 850 hPa relative vorticity). The individual terms in the water vapor budget equation were calculated for each of the 200 cyclones. Their results showed that evaporation from the sea surface, occurring mostly behind the cold front, contributes significantly to the total cyclone water vapor throughout the entire cyclone life cycle. The total cyclone integrated water vapor decreases throughout its movement as the water vapor lost from the atmosphere by precipitation exceeds that gained via evaporation or water vapor convergence. In this study, water vapor convergence into and out of the system was found to be negligible and even negative during the most rapidly intensifying stage of the cyclone evolution, showing that water vapor is actually exported from the system, leaving a water vapor footprint behind the cyclone as it travels polewards. It was also concluded that, as the cold front catches up with the warm front causing the warm sector to narrow, local convergence of water vapor occurs along the cold front and is thus responsible for creating the band of high total column water vapor (TCWV). Figure 1 shows the relative positions of the surface fronts and regions of high TCWV in the cyclone case study of Dacre et al. (2015, their Fig. 8). The band of high integrated water vapor narrows as the cold front catches up with the warm front, sweeping up water vapor as it travels. The location of the band of high water vapor travels farther from the cyclone center as the cyclone evolves due to frontal fracture. By the decaying stage of the cyclone evolution, the band is found within 1000 km distance from the cyclone center. The filaments of high water vapor content seen in the special sensor microwave imager (SSM/I) satellite imagery represent the footprints left behind as the cyclone channels atmospheric moisture into a narrow band when it travels poleward from its origin in the subtropics.

In summary, a large number of scientific publications suggest a crucial role of anomalously intense transport of moist air from the tropical and subtropical Atlantic in the occurrence of MR EPEs.

3 The role of atmospheric rivers (ARs)

The physical mechanism responsible for fast transport of tropical air into midlatitudes has also been actively addressed in the research performed. It has been discovered (Krichak et al., 2015) that a significant number of the MR EPEs appear to take place during (or immediately after) Atlantic hurricanes or storms (Krichak et al., 2015). The following is noteworthy: the 1966 "century" flood in Florence coincided with Hurricane Lois (4–11 November); the flood that occurred in Valencia on 3–4 November 1987 took place during a time period characterized by Tropical Depression 14 (duration of 31 October–4 November; peak intensity of 55 km h^{-1}) in the Atlantic; the flood events in Egypt, Israel and Italy occurred during the same period as Hurricane Florence (2–8 November 1994); the heavy rainy event of 10 November 2001 in Algeria occurred immediately after Hurricane Noel (4–6 November 2001); the 3–4 December 2001 flood event in Israel occurred nearly concomitantly with Hurricane Olga (24 November–4 December 2001); and the flood event in Antalya, Turkey, on 5 December 2002 took place during the development of a powerful North Atlantic storm south of the Canadian Maritime Provinces on 5–9 December. An important contribution of moist tropical and/or subtropical air mass transport by ARs during the formation of the synoptic developments of the type has been demonstrated (Gimeno, et al., 2014; Krichak et al., 2015; Ramos et al., 2015).

ARs are defined as narrow bands in the warm sector of extratropical cyclones, characterized by strong (greater than 12.5 m s^{-1}) wind speeds, high values (more than 20 mm) of vertically integrated water vapor (IWV) and values of vertically integrated vapor transport (IVT) in the layer from 300 to 1000 hPa of about (or greater than) 250 kg m^{-1} s^{-1} (Zhu and Newell, 1998; Ralph et al., 2004; Neiman et al., 2011; Ralph and Dettinger, 2011; Gimeno, et al., 2014). These transient filamentary regions often occur within the warm conveyor belt (WCB; Browning, 2004; Sodemann and Stohl, 2013) of extratropical cyclones. At any one time, there are approximately four or five narrow, elongated ARs across the midlatitudes (Fig. 2; Fig. 1 in Gimeno et al., 2014), which account for approximately 90 % of the total global poleward atmospheric water vapor transport (Zhu and Newell, 1998; Lavers et al., 2011).

A large amount of water vapor transported by ARs often leads to heavy precipitation and floods when an AR makes landfall, especially when the moisture-laden air is forced to rise over mountains (Dettinger, 2011; Lavers et al., 2011; Ralph and Dettinger, 2011; Gimeno et al., 2014). A strong link between ARs and extreme precipitation over a large part of western Europe has been established (e.g., Stohl et al., 2008; Knippertz and Wernli, 2010; Lavers et al., 2011; Liberato et al., 2012; Lu et al., 2013; Liberato, 2014; Dacre et al., 2015). It has been demonstrated that ARs are responsible for a majority of extreme precipitation (8 out of the 10 largest daily rainfall events) particularly in autumn and winter in Britain, France and Norway (e.g., Lavers and Vallarini, 2013). The regions experiencing major effects of ARs are characterized by hills and mountainous relief, which provide the necessary uplift leading to a significant rainfall.

A study undertaken by Sodemann and Stohl (2013) considered a monthly time period characterized by EPEs in Norway (December 2006). Here, the authors applied a water vapor tagging approach to gain new insight into the processes

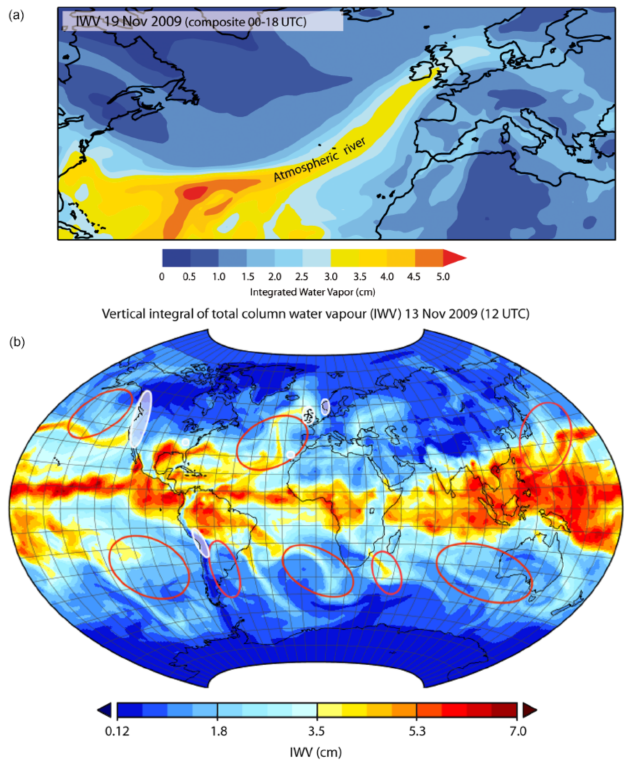

Figure 2. **(a)** Composite integrated total column of water vapor (IWV) between 00:00 and 18:00 UTC on 19 November 2009 showing an atmospheric river (AR) associated with extreme precipitation events that affected the United Kingdom. Data: ERA-Interim. **(b)** A general distribution of areas of occurrence of ARs (red contours) based on Zhu and Newell (1998). White contours showed the continental areas where there are reported cases of ARs linked with extreme precipitation and floods (Fig. 1 in Gimeno et al., 2014; used with permission from Frontiers in Earth Science Editorial Office).

leading to heavy precipitation in western Scandinavia and, more generally, of water vapor transport due to extratropical cyclones during winter. New process understanding has been obtained, which warrants corroboration on longer timescales and by a larger number of cases to attain a more general validity.

The results of the analysis are summarized schematically by Fig. 3 (Fig. 10 in Sodemann and Stohl, 2013). Here, the Thorncroft et al. (1993) classification of cyclone life cycles (LC1 and LC2) is adopted. The two life cycles, corresponding to "basic" and "anomalous" cases, illustrate two extreme and contrasting types of upper-air behavior ("anticyclonic" and "cyclonic"). Anticyclonic behavior dominates late stages of LC1 and is characterized by backward-tilted, thinning troughs being advected anticyclonically and equatorward. Cyclonic behavior dominates LC2 and is characterized by forward-tilted, broadening troughs wrapping themselves up cyclonically and poleward, producing major cut-off cyclones in high latitudes. When a pronounced wave pattern is present at upper levels, resembling the anticyclonic (LC1)

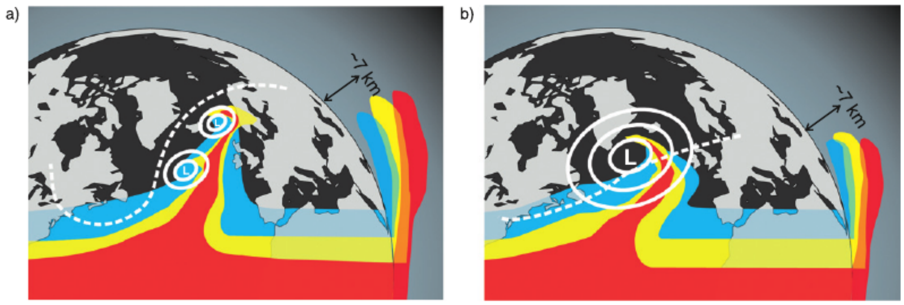

Figure 3. Schematic view of the two moisture transport configurations. **(a)** Anticyclonic (LC1-like) wave breaking with a meridional upper-level jet and **(b)** cyclonic (LC2-like) wave breaking with a zonal upper-level jet. Dashed white line shows the orientation of the upper-level jet, solid white lines show SLP, and shaded colors indicate oceanic moisture of different latitudes. On the right-hand side, quasi-vertical projections of the moisture tracers are shown. (Fig. 10 in Sodemann and Stohl, 2013; used with permission ©American Meteorological Society.)

life cycle (Fig. 3a, white dashed line), the meridional jet orientation enhances the poleward moisture advection throughout the troposphere, leading to the formation of sometimes irregular-shaped ARs (Fig. 3a, colored areas). Due to advection of the air masses along moist adiabats, a vertical stack of water vapor is thereby formed with water vapor originating from lower latitudes later residing at higher altitudes. At the western edge of the AR, small cyclones develop from frontal waves. Their cold fronts add moisture to the AR by zonal advection. At the same time, the cyclones tap the moisture available from the AR region for their WCB airstream, thus contributing to the AR at one end and feeding their spin-up and development at the other. Subsequent cyclones thus profit from the moisture transported poleward by previous cyclones, leading to a "handover" of moisture between subsequent short-lived cyclones.

A weak wave pattern at the tropopause, resembling the LC2 life cycle, leads to predominantly zonal flow throughout the troposphere (Fig. 3b, white dashed line). In this case a single, large, slow-moving cyclone develops, with more limited poleward advection of moisture to lower altitudes, as the AR is slowly advected eastward. As follows from Fig. 3, the LC1 regime is characterized by more intense intrusions of moist tropical and/or subtropical air in western Europe and, in some cases, the MR.

A role for ARs was also identified in the occurrence of many MR EPEs. The first to suggest a possible link between these events were Berto et al. (2005) and Malguzzi et al. (2006) in their analysis of the 3–5 November 1966 floods. Figure 4 confirms their findings: the AR is represented here by an elongated area with exceptionally high IWV extending from North Africa to Italy, high values of IVT and strong 850 hPa winds at 18:00 UTC, 4 November 1966. An IWV tongue connecting the AR with the air moisture reservoir in equatorial Africa may be also noted in the figure (see Krichak et al., 2015, for additional references).

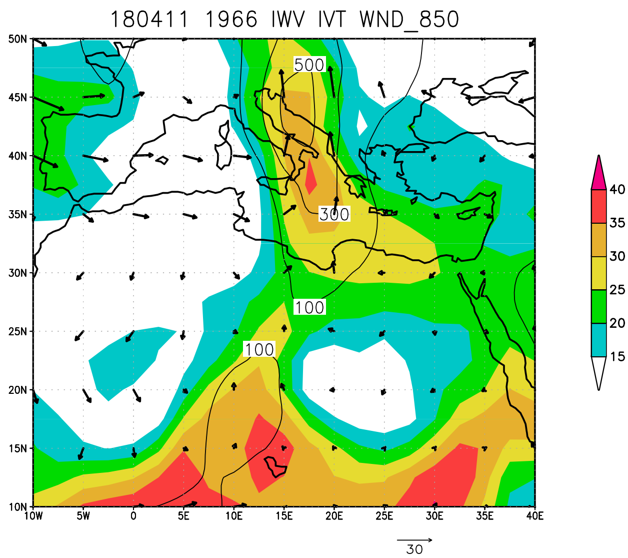

Figure 4. IWV (mm) starting from 15 mm shaded IVT ($kg\,m^{-1}\,s^{-1}$) and 850 hPa winds ($m\,s^{-1}$) at 18:00 UTC, 4 November 1966; based on the data from the National Centers for Environmental Prediction (NCEP) – National Center for Atmospheric Research (NCAR) reanalysis project (NNRP) (Kalnay et al., 1996).

Gimeno et al. (2010a, b), Krichak et al. (2012), Liberato et al. (2012), Winschall et al. (2012), Buzzi et al. (2014), Lu et al. (2013) and Liberato (2014) provided additional evidence of the important role for ARs in the formation of MR EPEs. The link between the export of moist tropical air and the multiyear trend in EPEs in this region has also been well documented.

Krichak et al. (2015) further addressed the role of ARs for MR EPEs by analyzing the data for 50 cold season MR EPEs. Their analysis identified a role for ARs during all the events considered. It was found that the location of ARs in the Atlantic controls that of specific EPEs in the MR. It was also found that the export of moist air of subtropical origin from the North Atlantic in the direction of Europe is more typical for the occurrence of EPEs in the western MR, whereas EPEs over the eastern MR are more strongly affected by the export of humid air over northeastern Africa.

An automated AR detection algorithm was adopted by Ramos et al. (2015) for the North Atlantic Ocean for the identification and a comprehensive characterization of the major AR events that affected the Iberian Peninsula over the 1948–2012 period. The extreme precipitation days in the Iberian Peninsula and their association with the occurrence of ARs was analyzed. The results of their evaluation demonstrated a noteworthy association between ARs and extreme precipitation days in the western part of the Peninsula, while for the eastern and southern parts of the Iberian Peninsula the impact of ARs was found to be reduced.

In summary, it may be concluded that, as was found earlier for western Europe, a majority of the most damaging cold season flood events in the MR are connected to ARs in the Atlantic along which the large flux of moisture is transported from the tropics to the midlatitudes.

4 Understanding climate trends

The recent past trends in climate extremes over different parts of the world, including Europe, have also been extensively investigated (e.g., Groisman et al., 2005; Zolina et al., 2010; Giorgi et al., 2011; van den Besselaar et al., 2013; Kunkel et al., 2013). The results have consistently demonstrated a rise in annual totals and in the frequency of cold season EPEs in western Europe and some parts of the MR. A change in western European precipitation, with longer wet periods and more abundant precipitation during the last decades, has also been highlighted (Zolina et al., 2010).

The situation appears to be more complex in the MR. Many climate change studies for the MR have been based on the results from reanalysis data sets and climate modeling (e.g., Xoplaki et al., 2012; Ulbrich et al., 2012; Gualdi et al., 2013; Kharin et al., 2013; Toreti et al., 2013; Mariotti et al., 2008, 2015; Saaroni et al., 2015). It should be noted, however, that the observation and climate modeling data, as well as methodologies used in these evaluations, were not necessarily optimal for a satisfactory assessment of EPEs. Discrepancies between observed and simulated trends in the MR and neighboring areas found in these studies are especially notable (Barkhordarian et al., 2013). They tend to vary on a regional basis and tend to be larger for seasonal means (Barkhordarian et al., 2013).

The result appears to be a consequence of the fact that general circulation models still cannot adequately capture the frequency, intensity, tendency and spatial distribution of observed precipitation extremes over large regions of the world (e.g., Toreti et al., 2012). Global warming implies an increase of atmospheric water vapor content at a rate of about $7\,\%\,K^{-1}$, through the Clausius–Clapeyron equation. Hence, a comparable increase in extreme precipitation would be expected over the next several decades (e.g., Kharin et al., 2013). Application of more sophisticated object-oriented methodologies focusing on extremes or frequencies of extreme events appears to be a helpful strategy for obtaining reliable estimates of the expected future changes in MR EPEs.

Progress in understanding the role of the export of moist air from the tropics and/or subtropics and that of ARs for cold season EPEs has motivated a number of additional climatological analyses addressing the issue of extreme precipitation in the MR. The recent past and expected future trends in synoptic developments have been investigated.

4.1 Evaluations based on the observation data

A number of studies evaluated the available observations on extreme precipitation in the MR during recent years (e.g., Vicente-Serrano et al., 2009; Gallego et al., 2011). In particular, Gallego et al. (2011) examined the trends in three indices designed to highlight changes in the frequency of precipitation at 27 stations covering the Iberian Peninsula for the period 1903–2003 (PT) and the two subperiods 1903–1953 (P1) and 1954–2003 (P2). Their analysis demonstrated a notable decrease in precipitation during the P2 subperiod. This trend is at least partially linked to a significant increase of the Arctic Oscillation (AO) and North Atlantic Oscillation (NAO) indices throughout the second half of the 20th century (Gallego et al., 2011).

Another recent study (Casanueva et al., 2014) focused on the variability of precipitation indices and their link to atmospheric processes over the western MR and Europe. This work, in particular, focused on the evaluation of the trend of three extreme precipitation indicators: the number of consecutive dry and wet days (CDD and CWD) and contribution of the very wet days to total precipitation R95pTOT. The authors noted that CWD and CDD are more related to the large-scale atmospheric circulation, while R95pTOT has a convective origin and depends more on local processes and moisture fluxes. The authors considered the roles of different acting factors in order to understand the extremes' variability by linking large-scale processes and precipitation extremes. Opposite associations with the NAO in winter and summer and the relationships with the Scandinavian Oscillation (SCAND) and East Atlantic patterns, as well as El Niño Southern Oscillation (ENSO) events in spring and autumn, have been found. The study also showed a significant correlation between the Atlantic Multidecadal Oscillation and R95pTOT during the entire year, apparently demonstrating the role of tropical moisture exports in the climatology of EPEs in the region.

It may be noted here that the results for the western MR are in agreement with other recent analyses that focus on the eastern MR (e.g., Givati and Rosenfeld, 2013; Krichak et al., 2014). Namely, in the eastern MR, four teleconnection regimes – AO, SCAND, East Atlantic/Western Russia

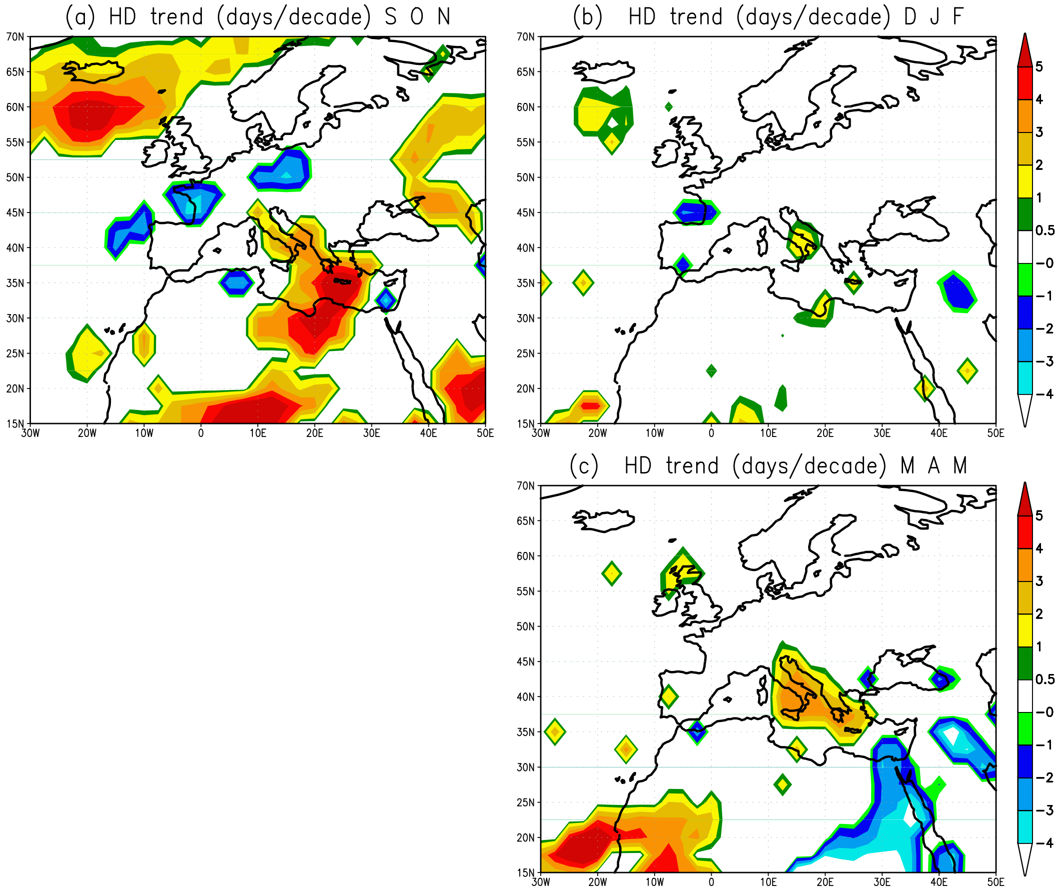

Figure 5. Linear trend in the frequency of occurrence of humid days (in days decade^{-1}) during 1979–2013 according to the NNRP data: **(a)** September–November; **(b)** December–February; **(c)** March–May (Fig. 13 in Krichak et al., 2015; used with permission from Springer).

Oscillation and ENSO – jointly influence the extreme precipitation.

These findings are also in agreement with that from Krichak et al. (2015), who detected a positive trend in the frequency of days exceeding 20 mm IWV values (frequency of humid days, HDs) over a large area in the Atlantic Ocean and western Europe during 1979–2013. The patterns showing the linear HD trends (Krichak et al., 2015) during 1979–2013 (for September–November, SON; December–February, DJF; and March–May, MAM) are presented in Fig. 5 (shaded values indicate statistical significance at $p < 0.05$; Fig. 13 in Krichak et al., 2015). The positive (negative) values of the trend indicate a rise (decline) in the frequency of days with HD conditions during the period. For SON (Fig. 5a), a region with a positive HD trend (up to $\sim$ 4 days decade^{-1}) for the North Atlantic Ocean west of the British Isles can be seen. Another two zones with positive trend values ($\sim$ 2–4 days decade^{-1}) are found from central Africa to the central MR and the southern Arabian Peninsula.

The positive trend zones are separated by areas with a negative HD trend over western Europe (−1–1.5 days decade^{-1}) and over the southeastern Mediterranean (−1.0 day decade^{-1}). For DJF (Fig. 5b), there are almost no statistically significant HD frequency trends for central and eastern Europe. A zone with positive trend values can be seen extending from central Africa to the central Mediterranean. Another region with positive statistically significant trend values (1 day decade^{-1}) is found for the North Atlantic.

During the MAM season (Fig. 5c), the tropical eastern Atlantic and west Africa are characterized by strong (up to 3–4 days decade^{-1}) HD frequency trends. Another zone with positive values of the trend (3.5 days decade^{-1}) occurs over the central MR. A zone with small positive trend values over the North Atlantic is also present. A large area from tropical east Africa to northeastern Africa and the Red Sea basin to the Middle East (Middle East–North Africa, MENA) is characterized by negative values of the HD trend (−1.0 to −4.0 days decade^{-1}). The existence of a dipole with mainly positive HD trend values over North Atlantic Ocean west of the British Isles (most notable during SON) and negative trend values over the MENA region (most notable during MAM) (Fig. 5a–c) appears to be of a special importance for EPE climatology over the MR. This is addressed in the following section.

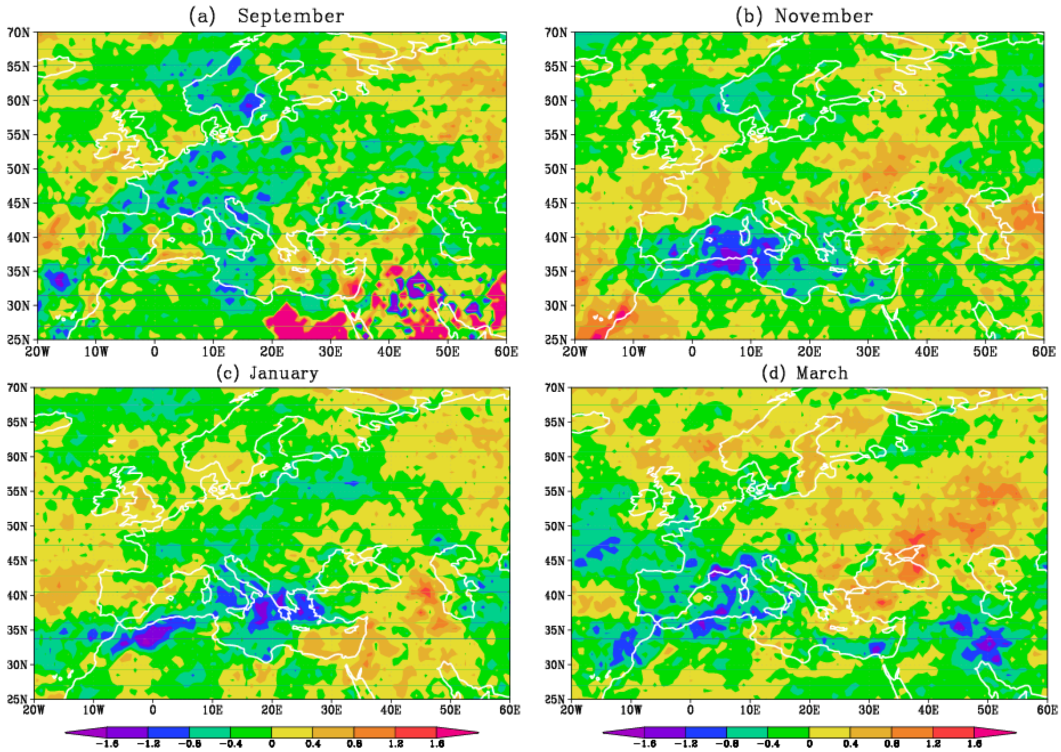

Figure 6. Climate change trend (2021–2050 minus 1961–1990) in frequency of days with extreme precipitation in **(a)** September, **(b)** November, **(c)** January and **(d)** March. The color bar presents values from -1.6 to $+1.6$ days month $^{-1}$ with 0.4 interval (Fig. 3.16 in Gualdi et al., 2012; used with permission from Springer).

4.2 Projections of future changes

Time periods characterized by frequent days with above-normal precipitation over some areas are quite typical for Europe. The intensity of such climate events is significantly affected by atmospheric dynamics. Climate change trends in the frequency of days with extreme precipitation in the MR have been investigated with gridded data from a climate simulation experiment performed for the EU CIRCE Project with an INGV climate model (Gualdi et al., 2012) according to a two time slice approaches for 1961–1990 (20C) and 2021–2050 (A1B) and A1B greenhouse gas (GHG) emission scenarios. Time series with the frequencies (number of days within each month) of extreme values of precipitation (ExtPrecF), dynamic tropopause pressure and IWV were constructed according to a recently suggested approach (Carril et al., 2008; Krichak et al., 2014). Climate change trends, calculated as the difference between 30-year mean ExtPrecF values (A1B $-$ 20C), are given in Fig. 6 (Fig. 3.16 in Gualdi et al., 2012) for September, November, January and March.

The results demonstrate a notable tendency toward an increase (up to 2 days month^{-1}) in the frequency of days with extreme precipitation over the MENA region during September (Fig. 6a). Taking into account the aridity of the area during September the modeling result indicates a tendency to a rise in the frequency of humid days. A rise in the frequency of days with extreme precipitation (0.8 days month^{-1}) is projected for the eastern Atlantic, northwestern Iberian Peninsula and southwestern Europe for November (Fig. 6b). A decrease in the frequency of extreme precipitation days (down to -1 day month^{-1}) is projected for the MENA region for March (Fig. 6d).

In another research effort (Hertig et al., 2013, 2014), model outputs from six "state of science" climate change simulation experiments for 1950–2100 (with A1B and B1 GHG emission scenarios for 2001–2000) were adopted for statistical downscaling of the hydrodynamic climate modeling results. The evaluation focused on above-normal precipitation intensity – exceeding the 95th percentile of daily precipitation from the reference period 1961–1990 (R95N). Hertig and colleagues also analyzed the changes in the total amount of precipitation from these events (R95AM) projected at the end of the 21st century for the considered scenarios. The analysis showed a decrease in the amount of extreme precipitation in autumn over many parts of the Iberian Peninsula with the strongest reductions over the eastern Mediterranean coast of Spain and parts of Mediterranean Algeria. Decreases are also projected for Tunisia, parts of Italy, the eastern coast of the Adriatic Sea and some eastern Mediterranean regions. In contrast, increases of R95AM have been found over the northern coast of the Ligurian Sea, Greece, and the southern coast of Turkey. In winter, increases of R95AM were projected in the study up until the end of the 21st century. Widespread decreases of R95AM have been projected in the MR for the spring season. The strongest declines were projected for the northwestern Iberian Peninsula, northwestern Africa, parts of Greece and Albania as well as over southeastern Turkey. At the same time, noticeable increases of R95AM in spring have been found for parts of northern and western Italy, southern France and southern Greece (Hertig et al., 2014). The conclusions are consistent in major details with the results by Gualdi et al. (2013).

It has to be noted, however, that the above presented projections of the climate change estimates have been only indirectly focusing on the effects of ARs. Only a limited number of studies have addressed the role of climate change in future trends of tropical and subtropical moisture sources and ARs in the Atlantic. Although the analyses have focused on western Europe, due to the geographic position of the region as well as predominant cyclone tracks, their results allow an interpretation relevant for the MR.

Lavers et al. (2013) examined future changes of ARs and their implications for winter floods over all of western Europe including the MR. A new set of CMIP model simulations (Taylor et al., 2012) was performed using state-of-the-art climate models and new GHG concentration scenarios (Representative Concentration Pathways or RCPs) under the CMIP Phase 5 (CMIP5) modeling framework (e.g., Taylor et al., 2012). Lavers et al. (2013) evaluated the results of the CMIP5 simulations (according to the RCP4.5 and RCP8.5 emission scenarios). Gridded reanalysis data were adopted for identification of the ARs. For each of the ARs identified in the historical (1980–2005) and the RCP4.5 and RCP8.5 projections (2074–2099), the maximum values of IVT between 1000 and 300 hPa (averaged over the lifetime of the AR) were calculated.

A sensitivity analysis was performed to determine the thermodynamic contribution to future AR changes. With this purpose for the historical and scenario (RCP) runs of each model, the average winter surface temperature (October to March over 1980–2005 and 2074–2099, respectively) over the North Atlantic Ocean (20–60° N; 60° W–0°) was calculated. The change in the regional temperature from the historical to the RCPs was then used to artificially scale up the specific humidity accordingly in the historical runs. This experiment allows testing how many additional ARs would be detected over the model dependent threshold if the historical circulation pattern were combined with the increased water vapor expected from the increased temperature in the RCP simulations.

The analysis leads to the conclusion that under the climate change scenarios used (RCP4.5, RCP8.5), the strongest ARs directed to western Europe and also the MR are projected to become more intense and – for any given intensity threshold – more frequent, indicating an increase of EPEs. A large part of these changes is thermodynamic in origin, suggesting that they are a relatively robust response to anthropogenic climate forcing. Consequently, the peak multi-day precipitation totals associated with extratropical cyclones are likely to be intensified over western Europe and the western MR, with more frequent and larger winter flood episodes under climate change.

The changes in the frequency and intensity of ARs and their potential contribution to an enhanced flood risk from ARs were also investigated by Baatsen et al. (2015). This analysis showed that baroclinic instability did not decrease significantly in future storms. The inflow of moisture increased greatly, however, resulting in more intense storms that carry more moisture. There are also additional changes in the future climate. Tropical cyclones become stronger under warmer climate conditions. The general tendency for extratropical cyclones to form in the western North Atlantic favors the development of LC1 type storms (Thorncroft et al., 1993) typically associated with a stronger influx of tropical air into Europe (see Sect. 3 for reference) has also been noted. This implies that not only the frequency of AR associated storms over the eastern Atlantic but also their intensity and the affected area may increase. In fact, these storms are more likely to reach Europe and the MR, because the transit region between the tropics and the baroclinic zone becomes smaller. Especially in the latter part of the 21st century, the expansion and eastward shift of the intense storm genesis region would result in more storms curving towards Europe and the MR and impacting a larger region (including the MR).

Baatsen et al. (2015) have also concluded that, in general, tropical air would have a greater impact on future European weather through more severe autumn storms. The projection for an increased availability of water in a warmer climate has also been supported by a larger vertically integrated water vapor content in climate change projections (Scoccimarro et al., 2015).

The results presented indicate a rise in the potential contribution of ARs to an enhanced flood risk in some parts of the mainly western MR associated with global warming.

5 Discussion and conclusion

The above review shows that research studies performed during the last several decades have revealed the notable role of tropical and subtropical moist air transport for MR EPEs. As in the case of the EPEs in western Europe, a significant part of extreme cyclonic events with heavy floods in the MR is associated with the effects of ARs. Atlantic ARs play a major role in the advection of tropical moisture which fuels the EPEs in the western MR. The situation is more complex for EPEs in the central and eastern MR. Moisture for these events also originates from the Atlantic or Indian oceans but ARs transport the moisture not to the MR directly but to other neighboring areas (mainly in North Africa), sometimes becoming a temporary moisture reservoir for future EPEs.

The identification (as demonstrated in Fig. 5) of a dipole with positive (over the northwest Atlantic Ocean, being most intense during SON) and negative (over the MENA region, most intense during MAM) trends in the frequency of HDs appears to be important for understanding the recent changes in the climatology of above-normal precipitation in the MR. A contribution arising from the reduction in the area of Arctic sea ice (Barnes, 2013) during the time period (1979–2013) could be among the factors influencing these trends.

To test for the possible connection between declining Arctic sea ice and the climatology of extreme precipitation in the MR, we have investigated the relationship between the frequency of EPEs in the MENA region and changes in Arctic sea ice. We focus on the MENA area as it is this part of the eastern Mediterranean that has been observed to undergo the strongest negative trend in the number of humid days during MAM (Krichak et al., 2015).

In this evaluation, monthly averaged data for Arctic sea ice area and extent[1] from the National Snow and Ice Data Center (http://nsidc.org) have been correlated with the monthly mean frequency (Krichak et al., 2014) of EPEs (referred to as the intense precipitation frequency) in the MENA region. In accordance with Carril et al., 2008) the data on the frequencies of days with above-normal precipitation amount have been determined (Krichak et al., 2014). The analysis was focused on daily precipitation amounts that exceed a particular threshold value (a 90 % threshold was used). With this purpose, at all grid points in the NNRP reanalysis data within the Euro-Mediterranean region, the total number of days within each month that the daily precipitation was found to exceed a particular threshold value (90 %) has been counted and the time series of the frequency of days per month with precipitation events of above-normal intensity in the region have been calculated.

The analysis of the relationship between Arctic ice extent and the frequency of days with above-normal precipitation has been performed for a target subregion represented by six locations (grid points) with longitudes 33.75° E and 35.615° E and latitudes 28.42° N, 30.33° N and 32.24° N.

The results of the evaluation are presented in Fig. 7. Here, the data for frequencies of days (per month) with above-normal precipitation are those that were previously calculated (Krichak et al., 2014). As can be seen from the figure, statistically significant ($p < 0.05$) positive lagged correlations are found between the intense precipitation frequency

[1]Sea ice area is defined as the area of the ocean surface that is covered by sea ice. The contribution to the sea ice area from each grid cell comes from the portion of the grid cell that is covered in sea ice. For sea ice extent, the grid cell is defined to be either ice covered or ice free, depending upon whether a threshold of 15 % ice concentration is exceeded (for more information, see https://support.nsidc.org/forums).

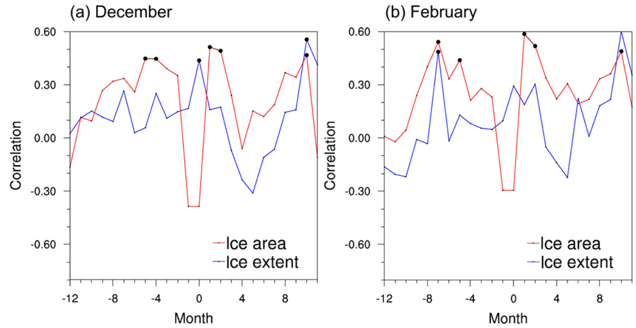

Figure 7. Correlation between monthly averaged Arctic sea ice area and extent with the monthly mean frequency of extreme precipitation events in the MENA region for **(a)** December (x axis time lag (month), y axis correlation) and **(b)** February.

in the region of analysis in December (Fig. 7a) and February (Fig. 7b) (although not significant in November and January) and Arctic sea ice area at lags −4 and −5 months for December and lags −7 and −5 months for February. This result supports the suggestion that Arctic sea ice may be seen as an important factor causing changes in the frequency of intense precipitation events in the MENA with a lead time of up to 6 months.

Indeed, this linkage between Arctic sea ice and intense precipitation in the MENA may be manifested through the excitation of the NAM/AO (and the very similar NAO). Many studies have shown that an increase (decrease) in Arctic sea ice area during the late summer and early autumn is followed 2 to 3 months later by the establishment of the positive (negative) phase of the NAM/AO (and the very similar NAO) (Deser et al., 2007; Francis et al., 2009; Francis and Vavrus, 2012; Honda et al., 2009; Smith et al., 2011; Liu et al., 2012). Furthermore, Krichak et al. (2014) found statistically significant positive correlations between the NAM/AO and precipitation frequency in the MENA area.

On the same line, three recent studies (Peings and Magnusdottir, 2014; Feldstein and Lee, 2014; Kim et al., 2014), using both observational and model data, show that a reduction in Arctic sea ice is followed by an increase in the vertical propagation of planetary-scale wave activity into the extratropical stratosphere and a deceleration of the stratospheric polar vortex. This enhancement in the vertical wave activity propagation was shown to arise from constructive interference (Garfinkel et al., 2010) between transient planetary waves excited by the loss of sea ice and the climatological planetary-scale stationary wave field (see also Smith et al., 2011; Cohen et al., 2014).

The weakening of the strength of the stratospheric polar vortex coincides with the excitation of the negative phase of the stratospheric NAM (Baldwin and Dunkerton, 1999). This is followed 2 months later by the excitation of the negative NAM/AO throughout the troposphere, likely through downward control and a positive eddy feedback (e.g., Polvani and

Kushner, 2002; Kushner and Polvani, 2004; Song and Robinson 2004; Simpson et al., 2009). Feldstein and Lee (2014) have shown that the opposite sequence of processes links an increase in Arctic sea ice to the positive NAM/AO in the troposphere.

It must be noted here that the above analysis represents one of the first attempts to understand the processes responsible for the trends in extremes in the MR in the context of the global dynamics. The interplay between the Arctic ice and NAM/NAO/AO appears to be an important object for further systematic studies. It also appears possible that the extension of the Arctic ice cover may be just one of the factors responsible for the trends in the EPEs.

There are also a number of physical problems that remain to be resolved. As pointed out by Baatsen et al. (2015), not only the moisture export by ARs but also baroclinic instability is important for the (re-)intensification of the MR EPE storms. The latter is most important for extratropical development while the former provides heat and moisture that enhances the latent heat release in a newly forming warm core as well as in the warm conveyor belt, thus speeding up the intensification. Under appropriate conditions, many Mediterranean storms are likely to develop at the synoptic scale baroclinically.

Another issue for further analyses is to determine what part of the water that rains during an EPE originates from the tropics. Analysis by Dacre et al. (2015) of North Atlantic extratropical cyclones shows that ARs are formed by the cold front which sweeps up water vapor in the warm sector as it catches up with the warm front. This causes a narrow band of high water vapor content to form ahead of the cold front at the base of the warm conveyor belt. Thus, water vapor in the cyclone's warm sector, and not long-distance transport of water vapor from the subtropics, is responsible for the generation of filaments of high water vapor content in ARs reaching northwestern Europe. The ARs reaching the MR, however, may be characterized by different peculiarities.

Finally, we conclude that the last decade has been characterized by a growing understanding of the critical role played by the export of moisture from the tropics and subtropics in the formation of cold season MR EPEs. This progress is in line with that in the investigation of disastrous flooding events in western Europe and other regions of the world. The moisture exports are typically taking place in narrow elongated zones characterized by high water vapor content and strong winds in the lower troposphere referred to as "atmospheric rivers".

In the current review we addressed this issue by discussing the major trends found in the investigations performed during the last 3 decades. The studies show that in spite of significant differences between the different parts of the MR, the export of large amounts of subtropical and/or tropical moisture entering coastal areas during the landfall of ARs may be seen as a critical factor responsible for the exceptionally intense precipitation during EPEs over the MR. Progress in understanding the role of ARs in the MR EPEs also allows a new perspective for projecting future climate changes in the MR, which appears to be especially important since contemporary global climate models still cannot adequately capture the frequency, intensity, tendency and spatial distribution of observed precipitation extremes over large regions in the world. Only a limited number of such evaluations have so far been performed. Current climate change analyses as well as the modeling studies show that anthropogenic global warming may lead to stronger and more numerous Atlantic ARs in the next few decades. This implies a greater risk of higher rainfall totals and therefore larger winter floods in some parts of the MR accompanied by a greater risk of droughts in the other parts of the MR.

The authors believe that the above discussions and recommendations also have policy relevance. Additionally, it is suggested that monitoring and reporting changes in tropical and subtropical moisture exports and AR activity may allow for reducing the risk of extreme floods in the MR under current climate conditions.

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