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

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Abstract

Extreme precipitation events in the Mediterranean region during the cool season are strongly affected by the export of moist air from tropical and subtropical areas into the extratropics. The aim of this paper is to present a discussion of the major research efforts on this subject and to formulate a summary of our understanding of this phenomenon, along with its recent past trends from a climate change perspective. The issues addressed are: a discussion of several case studies; the origin of the air moisture and the important role of atmospheric rivers for fueling the events; the mechanism responsible for the intensity of precipitation during the events, and the possible role of global warming in recent past trends in extreme weather events over the Mediterranean region.

1 Introduction

The cool season (September–March) in the Mediterranean region (MR) is characterized by a substantial number of exceptionally intense cyclones with torrential rains and floods (extreme precipitation events, EPE, hereafter) and other features (Lionello et al., 2006) being comparable to those of hurricanes. The list of MR EPEs includes such cases as the "century" floods in Florence, Italy (4 November 1966, with up to 750 mm of rain in 24 h); floods in Gandía (eastern Spain, province of Valencia) on 3–4 November 1987, with 817 mm of rain in 24 h; heavy rains in Egypt, Israel and northern Italy during 1–6 November 1994 with more than 300 mm of rain in 36 h; a heavy precipitation event with greater than 260 mm of rain during 4 December 2001; a flood event in Antalya, Turkey on 4–6 December 2002 with more than 230 mm in 24 h, and many others.

The issue of the MR EPEs has been addressed in a large number of studies. A summary of the history of this research during the previous century may be found in Speranza (1975). The current analysis is focused on the discussion of more recent studies. Several international research projects have been devoted toward attaining a better understanding of the physical mechanisms responsible for the formation of the EPEs. Among these research efforts are, for instance, ALPEX (Devies and Pichler, 1990), the Mediterranean Experiment (MEDEX, Jansa et al., 2014), Climate Change and Impact Research: the Mediterranean Environment, (CIRCE FP6-EU, http://www.iddri.org/Iddri/Circe-Overview.pdf) project, the Mediterranean CLImate VARiability and Predictability (MedCLIVAR) network (e.g. Garcia-Herrera et al., 2014) and the HYdrological cycle in the Mediterranean EXperiment (HyMEX, Drobinski et al., 2014).

A number of cool season extremely intense and harmful storms, often characterized by huge economic losses, also occur in western and central Europe (e.g. Wernli et al., 2002; Fink et al., 2009; Liberato et al., 2013). During the last decade, the investigation of extreme storms in western and central Europe has been characterized by an increased understanding of the role of the export of moist (often tropical) air masses and, in particular, atmospheric rivers (ARs) in midlatitudes (e.g. Stohl et al., 2008; Knippertz and Wernli, 2010; Lavers et al., 2011; Lu et al., 2013; Liberato, 2014; Dacre et al., 2015). ARs are typically defined as being long (2000–3000 kilometers), narrow (a width of 400–1000 km) plumes with high values of precipitable water (PW, greater than 20 $\mathrm{kg\,m^{-2}}$) with strong (greater than 12.5 $\mathrm{m\,s^{-1}}$) southerly winds in the lower troposphere (2–3 km) (Zhu and Newell, 1998; Ralph et al., 2004; Lavers et al., 2011; Ralph and Dettinger, 2011). The AR plumes form within a broader region of generally poleward heat transport in the warm sector.

As in western Europe, the role of ARs in the formation of MR EPEs also appears to be important (Krichak et al., 2014b). As an example, Fig. 1, based on the data from the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis project (Kalnay et al., 1996), presents the patterns with PW (in cm) and sea level pressure in (gpdam) during the famous flood event in Italy on 4 November 1966. From this picture it appears evident that the process has indeed been characterized by an intense AR which is represented by an elongated area with exceptionally high PW values extending from Africa to Italy.

Another example of a possible contribution by an AR in the formation of a MR EPE appears to involve the "bomb" cyclone of 3–5 March 1982 in the Gulf of Genoa (e.g. Tsidulko and Alpert, 2001; Alpert et al., 1996). It may be speculated that the development has been a result of an AR intrusion into coastal areas of western Europe from the eastern North Atlantic and the processes involved (Zhu and Newell, 1994) on 00:00 UTC 3 March 1982 (not presented). Many other examples may be given.

It has been noted (Krichak et al., 2014b) that in many occasions the recent past MR EPEs have taken place during the same time period as intense Atlantic storms. The floods in Valencia, Spain of 3–4 November 1987 took place during the time period of a tropical depression (31 October–4 November 1987), the flood event in Egypt, Israel, and Italy from 1–5 November 1994 – occurred during the period of hurricane Florence (2–8 November 1994), the rainy event of 10 November 2001 in Algeria was possibly triggered by hurricane Noel (4–6 November 2001), the 3–4 December 2001 flood event in Israel overlapped with hurricane Olga (24 November–4 December 2001), and the flood event in Antalya, Turkey of 5 December 2002 took place during the period of the North Atlantic storm of 4–6 December 2002.

These are only a few examples that suggest a possible link between the occurrence of intense Atlantic tropical storms (and cyclones) and EPEs in the Mediterranean region. Although the exact effects of the Atlantic storms in each of the EPEs are not yet fully understood, the fact that they coincide with flood events appears to be important for an understanding of the role of extra-Mediterranean moisture exports in MR climate.

The paper is organized as follows. Section 2 focuses on the analysis of several important studies of specific EPEs. Section 3 focuses on the issue of the origin of air moisture fueling EPEs. The possible role of global warming for recent past trends in the frequency of the MR EPEs is discussed in Sect. 4. The summary and a final discussion are given in Sect. 5.

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2 Progress in understanding individual synoptic events

Apparently, the first discussion of the possible role of ARs in the formation of MR EPEs was presented for the event of 3–5 November 1966 (Berto et al., 2005; De Zolt et al., 2006; Malguzzi et al., 2006; Homar et al., 2007). Two additional EPEs (16–18 November 2000 and 24–26 November 2002) have been also investigated by Berto et al. (2005). A simplified conceptual model to visualize the traits of the moist airstreams inside Mediterranean cyclones has been also proposed. It appears worth noting here that the 1966 "century" flood in Florence coincided with hurricane Lois (4–11 November) (Sagg, 1967; Krichak et al., 2014b), which could be a primary cause for the formation of the AR.

Analyses of the MR EPEs (Krichak and Alpert, 1998; Ferraris et al., 2001; Reale et al., 2001; Turato et al., 2004) have allowed for the identification of a notable role for air moisture transported from extra-Mediterranean regions in the formation of the EPEevents. The study by Ferraris et al. (2001) focused on the analysis of a flood event that occurred over Friuli, Italy during 5–8 October 1998. The authors suggested that large scale dynamical processes played a major role, extracting moisture from various evaporative sources, followed by the advection of a significant amount of precipitable water, and a sub-synoptic scale process, which is able to concentrate the atmospheric moisture into a narrow column in the atmosphere, leading to the formation of the MR EPEs. It has been indicated that at least part of the moisture in the October 1998 floods in Friuli might have been provided by the remnants of three tropical storms ("Ivan", "Karl" and "Jeanne"). These storms decayed to non-tropical strength, but their anomalous trajectories caused significant advection of moisture towards western Europe between the end of September and the beginning of October. Once in the Mediterranean basin, an intense low-level moisture flux convergence concentrated the moisture over northeastern Italy (Ferraris et al., 2001).

The suggestion on the role of water vapor of extra-MR origin in formation of the MR EPEs has been further analyzed in the following studies. According to Turato et al. (2004), about 80 % of the moisture needed to produce extreme rainfall in the MR is of extra-Mediterranean origin. Specifically, more than 60 % of the evaporation contributing to the precipitation over the analyzed region comes from the North Atlantic. This conclusion has been confirmed by a number of inter-comparison studies based on different reanalysis datasets (e.g. Schmith et al., 1998; Ulbrich and Christoph, 1999; Sickmöller et al., 2000; Trigo, 2006; Wang et al., 2006; Raible et al., 2008; Ulbrich et al., 2009; Hodges et al., 2011). The analyses by De Zolt et al. (2006) and Malguzzi et al. (2006) have detected strong advection of moist air into the central Mediterranean Sea prior to a MR EPE (the disastrous storm of November 1966 in Italy).

Pinto et al. (2009) and Toreti et al. (2010) improved our understanding of the role of external sources of air moisture in the formation of several explosive “bomb” (Sanders and Gyakum, 1980; Zhu and Newell, 1994) cyclones in the Euro-Mediterranean region. According to these studies, air moisture originating in the storm track region over the North Atlantic has clearly played a key role in the intensification of the explosive cyclones. The authors also demonstrated a strong relationship between EPEs in the MR and the large scale atmospheric circulation at the upper, middle and lower troposphere (Toreti et al., 2010). In that analysis, a 2-step classification procedure allowed for the identification of several anomaly patterns both for the western-central and eastern Mediterranean basin. In the western Mediterranean, an anomalous southwesterly surface to mid-tropospheric flow is connected with enhanced moisture transport from the Atlantic. For the eastern Mediterranean EPEs, the anomaly patterns suggest warm air advection connected with anomalous ascent and an increase of the lower- to middle-tropospheric moisture. Furthermore, the jet stream position during more intense events is consistent with upper tropospheric divergence in the eastern Mediterranean basin, where ascending motions are favored.

The recent study of Krichak et al. (2014b) showed that the export of humid tropical air impacts the formation of cool season EPEs over the entire MR. They also examined the linkage between the export of humid tropical air and the multiyear trend in EPEs in this region. For this purpose, spatial distributions of a number of key atmospheric variables have been analyzed based on data for more than 50 MR EPEs. The results of this investigation show for both individual and composite events that ARs play an important role in the formation of the MR EPEs. The formation of MR EPEs is characterized by the poleward export of humid air of tropical origin into the midlatitude MR from the Atlantic and Arabian Sea.

A rather puzzling aspect of this finding is why and how typically unstable tropical air survives, without triggering a storm earlier, all the way to the Mediterranean area. Part of the reason could be a low level atmospheric river flow, which can transport air from a tropical source in a matter of several days. Further investigation on this issue is warranted.

3 The role of air-moisture advection from extra-Mediterranean areas

The issue of the origin of air moisture for precipitation events in the MR has been addressed in a large number of studies (e.g. Krichak and Alpert, 1998; Reale et al., 2001; Berto et al., 2004; Turato et al., 2004; Ziv et al., 2005; Sodemann and Zubler, 2010; Duffourg and Ducrocq, 2011; Krichak et al., 2012; Reale and Lionello, 2013). These analyses have demonstrated a notable role for moisture advection from extra-Mediterranean areas during MR EPEs. The relative contribution by evaporation from the Mediterranean Sea in the cool season MR flooding events significantly depends on their exact location and varies from case to case. For example, the Lagrangian-based moisture source climatology for Alpine precipitation by Sodemann and Zubler (2010) shows that moisture from the eastern North Atlantic contributes to southern Alpine precipitation with a fraction of 10.9 % for a climatology of the years 1995–2001 (fraction of the total North Atlantic: 33.3 %). Gimeno et al. (2010) have confirmed this conclusion by demonstrating that on average, about 9 out of 10 L of water evaporated from the oceans every year precipitates back onto the oceans with the remaining 10 % being transported to continents where it plays an irreplaceable role feeding the land branch of the hydrological cycle. The role of external sources of moisture clearly increased during the most intense flooding events in the MR. According to Turato et al. (2004) "more than 50 % of the evaporation contributing to the precipitation during a heavy precipitation event in Piedmont, Italy was coming from the Atlantic Ocean". This conclusion has been further confirmed in a study by Pinto et al. (2013) who performed an objective identification and cluster analysis ranking of extraordinary rainfall events for northwestern Italy using time series of annual precipitation maxima for 1938–2002 at over 200 stations. Based on the results, the two top clusters are characterized by strong and persistent upper air troughs inducing not only moisture advection from the North Atlantic into the western Mediterranean but also a strong northward flow towards the southern Alpine ranges. Humidity transports from the North Atlantic are less important for the weaker clusters.

By considering the 50 strongest precipitation events in the Alpine area during 1989–2009, Winschall et al. (2012, 2014) revealed the climatologically important role of evaporation hot spots over the eastern North Atlantic in establishing the conditions for EPEs in the MR. The results of this moisture source diagnostic analysis indicates that during precipitation extremes the Mediterranean Sea is only one of several source regions. Moisture from the North Atlantic dominates in autumn and winter, and land evapotranspiration in summer. The time of maximum moisture uptake varies between a few hours to more than one week before the precipitation event takes place. It is concluded that for the Mediterranean moisture contribution, convergence from the background moisture reservoir is essential, whereas for the remote sources anomalously intense surface evaporation is required to foster the moisture supply for Mediterranean EPEs.

Many Mediterranean storms are likely to develop at the synoptic scale baroclinically. In this case, tracing the potential vorticity anomaly (this also identifies the jet stream position objectively, cf., Sect. 2) would be more helpful. We should also remember that moisture does not automatically induce convection, but the air must become positively buoyant under appropriate circumstances. In the latter case, convective available potential energy (CAPE) would be a more appropriate quantity to evaluate. Unfortunately, an exclusive focus on the moisture budget could obscure this issue, because a high moisture anomaly is likely to be associated with a positive potential vorticity anomaly and CAPE. Further investigation appears necessary.

4 Climate change and processes leading to Mediterranean extreme precipitation events

Krichak et al. (2014b) have suggested a possible role for diminishing Arctic sea ice cover in determining the trend. Although the physical mechanisms involved are not fully understood, such a hypothesis appears plausible. This linkage between Arctic sea ice and precipitation in the MR may be manifested through the excitation of the North Atlantic Mode/Arctic Oscillation (NAM/AO) (and the very similar North Atlantic Oscillation (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. (2013) found statistically significant positive correlations between the NAM/AO and an increase in precipitation frequency in the southern Levant.

To test for the possible connection between declining Arctic sea ice and the trend in MR precipitation, we investigate the relationship between the frequency of intense precipitation events in the southern Levant and changes in Arctic sea ice. We focus on the southern Levant as it the part of the eastern Mediterranean that has been observed to undergo the strongest negative trend in the number of humid days (Krichak et al., 2014b). It is likely that this relationship for the southern Levant holds for much of the MR.

To examine this hypothesis, the monthly-averaged Arctic sea ice area and extent[1] are correlated with the monthly-mean frequency of intense precipitation events (referred to

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[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

as the intense precipitation frequency) in the southern Levant for the domain that covers six grid points; these grid points include two longitudes, 33.75 and 35.615° E, and three latitudes, 28.42, 30.33 and 32.24° N (Fig. 2). For this calculation, following Krichak et al. (2014a), the intense precipitation frequency is defined as the number of days in a given month, averaged over the six grid points, for which the precipitation exceeds a particular threshold value. This threshold value is determined separately for each grid point and for each month. We choose this threshold value to be the 90th percentile of the daily precipitation for that grid point and month for the years 1961–2000. For sea ice, we use data from the National Snow and Ice Data Center (http://nsidc.org). As can be seen statistically significant ($p < 0.05$) positive lagged correlations are found between the intense precipitation frequency in the southern Levant in December (Fig. 2a) and February (Fig. 2b) (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 southern Levant with a lead time of up to six months.

As discussed above, this linkage between Arctic sea ice and intense precipitation in the southern Levant 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).

Three recent studies (Peings and Magnusdottir, 2014; Feldstein and Lee, 2014; Kim et al., 2014), using both observational and model data, suggest that the following mechanism links a decline in Arctic sea ice during the late summer and early autumn to the

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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 exceeded (for more information, see http://nsidc.org/cryosphere/seaice/data/terminology.html).

negative NAM/AO/NAO in the winter season. Their results 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). This weakening in 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 two 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) showed that the opposite sequence of processes links an increase in Arctic sea ice to the positive NAM/AO in the troposphere.

A number of different explanations have been proposed to account for the recent warming of the Arctic and the decline in Arctic sea ice. The mechanisms suggested include (1) a sea ice albedo feedback (Budyko, 1969) whereby a reduction in sea ice coincides with increased absorption of solar radiation by the open ocean, followed by a warming of the ocean and further melting of sea ice, and vice versa, (2) a water vapor feedback, which involves increased evaporation over open parts of the Arctic Ocean, and leads to greater trapping of infrared radiation emitted by the Earth and the subsequent warming of the surface via increased down-welling infrared radiation (Screen and Simmonds, 2010), (3) an increase in the poleward heat and moisture flux (Graversen, 2006) triggered by the poleward propagating Rossby waves excited by enhanced warm pool tropical convection (Lee et al., 2011; Lee, 2014) and by the Asian summer monsoon, and Krishnamurti et al. 2015), and (4) a negative feedback due to the infrared radiative loss being more efficient at the warmer lower latitudes (Pithian and Mauritsen, 2014). Moreover, strong tropical cyclone activity in the North Atlantic basin seems to be linked to an Arctic sea ice reduction driven by an export of sea ice through

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the Fram Strait into the Nordic seas (Scoccimarro et al., 2012). No clear proofs for the validity of any of the explanations are yet available, however. After the mechanism that accounts for Arctic amplification and sea ice melting has been elucidated, it is likely that the inter-decadal relationship between Arctic sea ice and extreme precipitation, in the MR, will become more clear.

5 Summary and conclusion

This discussion presents our understanding of the main physical mechanisms responsible for the formation of EPEs in the MR. Research studies performed by a large group of researchers during the past 40 years consistently show that EPE periods in the region in many occasions are characterized by high values of precipitable water (also integrated water vapor) due to the exports of moisture of tropical and subtropical origin. Synoptic conditions during such events are often associated with AR-like narrow corridors of warm and moist air from subtropical and southern midlatitudes of the Atlantic Ocean and the Arabian Sea area.

In a majority of EPEs in the area of the analysis, the ARs persist for an extended period of time, often without being related to one particular cyclone (e.g. Sodemann and Stohl, 2013). The ARs mostly coincide with a southwest–northeast-oriented tropopause jet, pointing toward a leading role of the upper-level circulation for setting the moisture transport. A more meridionally oriented jet favored both stronger moisture advection from southern latitudes indicating a strong relationship between the poleward moisture (and energy) transport and the wave breaking pattern.

Evidence of a positive trend in the frequency of days with an extreme amount of water vapor over the North Atlantic (north of 50N) during 1979–2013, particularly during September–November, has been provided (Krichak et al., 2014b). This result is in agreement with data on recent past trends in precipitation (Zolina et al., 2010; Garcia-Herrera et al., 2014). Based on results from state of the art General Circulation Models (those involved in CMIP5), the intensity of heavy precipitation events over the Euro-

Mediterranean region is projected to increase more than the mean precipitation under a warmer climate. The increased availability of water in a warmer climate is also confirmed by a larger vertically-integrated water vapour content (Scoccimarro et al., 2014, 2015). Also the recent past and projected future trends in AR activity over the North Atlantic (Lavers et al., 2013) appear to be of a serious concern for the Mediterranean region. The higher frequency of the events with increased water vapor transport from tropical and subtropical area implies a greater risk of higher rainfall totals and therefore larger winter floods in the MR.

The increased pressure on limited water resources along with climate change demand improved scientific understanding of the role of tropical moisture exports and ARs in the Atlantic Ocean–African region. Providing those improvements appears to be a grand challenge for water cycle science in the MR with important implications for flooding and water supply.

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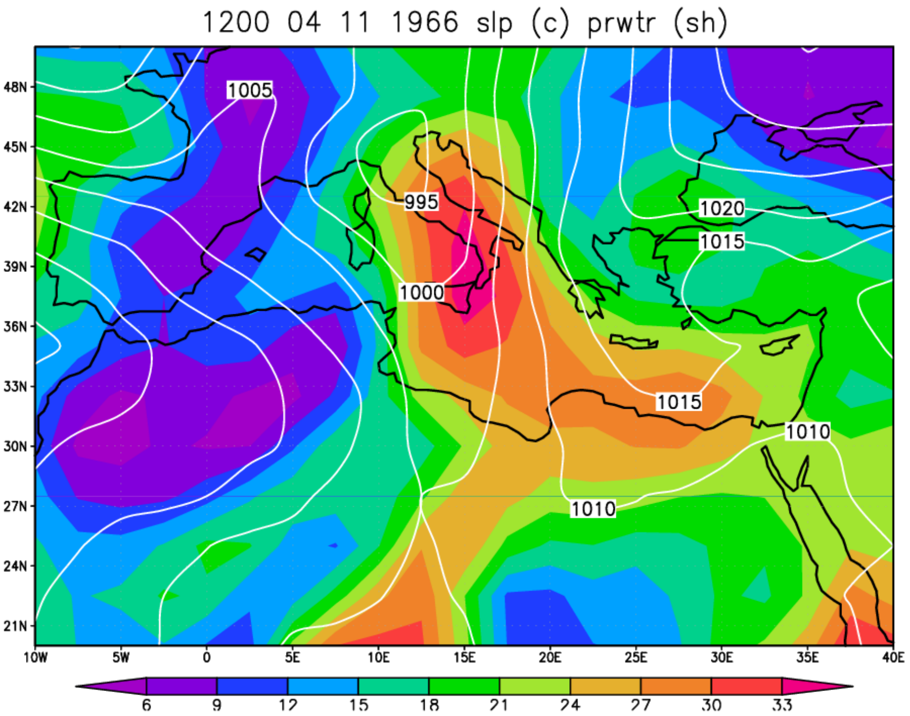

Figure 1. Precipitable water, shaded [cm] and sea level pressure [in gpdam (geopotential dekametres)] (contour interval 5 gpdam) at 12:00 UTC, 4 November 1966 (based on the data from the National Centers for Environmental Prediction (NCEP)-National Center for Atmospheric Research (NCAR) reanalysis project (referred to as NNRP) (Kalnay et al., 1996)).

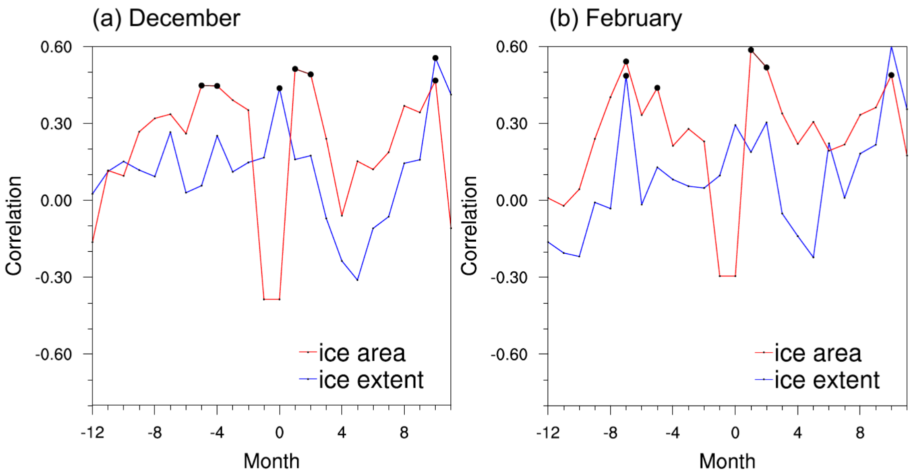

Figure 2. The results of the correlation between monthly-averaged Arctic sea ice area and extent with the monthly-mean frequency of extreme precipitation events in the southern Levant for the domain that covers six gridpoints; this includes two longitudinal gridpoints, 33.75 and 35.615° E, and three latitudinal gridpoints 28.42° N, 30.33 and 32.24° N **(a)** for December (*x* axis time lag (month), *y* axis correlation); **(b)** Same as in Fig. 2a but for February.