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ORIGINAL PAPER

Study of the relationship between geopotential height anomaly over Europe and extreme abnormal weather over the Eastern Mediterranean and Middle East during December 2013

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Abstract The Eastern Mediterranean and the Middle East (EMME) is suffering from abnormal cooling of weather conditions and existence of an extreme weather phenomenon known as ice storm Alexa. The present paper investigates the weather conditions over Europe that causes this abnormal weather over the EMME through December of 2013. Daily data sets of several meteorological elements (temperature, precipitation, relative humidity, sea level pressure, and geopotential height at level 500 hPa, etc.) over the northern hemisphere, including Europe and EMME of December of 2013, have been used through the present work. In addition, to that, a time cross section analysis of the daily operational data for meteorological elements (mean surface temperature, temperature and geopotential height at level 500 hPa, relative humidity, precipitation rate, and sea surface pressure) was done over the EMME for December 2013. The methodology of anomaly and correlation coefficient techniques for the data sets has been used. The results uncovered that the EMME has abnormal and very cold weather conditions due to the inference of meridional blocking persisted over Europe and the existence of the extremely negative geopotential height anomaly aloft over Eastern Europe throughout this month.

Keywords Geopotential height · Extreme cooling · Abnormal weather · Alexa · Europe · EMME

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Introduction

The 2013 Middle East cold snap refers to the winter storm that hit the Middle East region in December 2013, affecting several countries in Eastern Mediterranean and Middle East (EMME). The storm caused mayhem to millions of poor and displaced people across the region. December of year 2013 is recognized as the coldest and extreme weather month of 2013/2014 winter season over the EMME region. It forced people to displace across the region. December 2013 has a mean surface air temperature of 7.79 °C for the EMME region. Meanwhile, surface air temperature is 8.27 °C for December 2012 for that region. The normal value of EMME surface air temperature is 8.36 °C through the period of 1981–2010. EMME suffered from a cold wave, heavy rainfall, and the existence of an extreme ice storm Alexa. The precise criterion for a cold wave is determined by the rate at which the temperature falls and the minimum to which it falls. This minimum temperature is dependent on atmospheric circulation and the geographical region (AMS, 2008). However, a rare winter storm, Alexa, struck the Middle East beginning on Monday, December 9, and lasted for 7 days. It produced heavy snow in areas that typically never see the white matter, like Cairo, Egypt. Jerusalem recorded an impressive 37–50 cm of snow with roads still blocked on Saturday, December 14. It was the most snow ever recorded in that region in the month of December for the last 60 years. Behind the surge of wintry precipitation, cold temperatures were widespread across the Middle East during the week of December 9–15, 2013. Snow and cold temperatures created difficult conditions, particularly across Syria, where refugees had to embrace the extreme conditions outside. The storm affected parts of Palestine, Jordan, Lebanon, Northern Syria, Iran, Turkey, and Egypt while bringing torrential rains and serious flooding in low-lying areas. Meanwhile, Cairo had a once-in-a-lifetime snowfall, the first recorded snowfall in that city in 100 years. The Mediterranean climate is under the influence of both tropical and midlatitude climate dynamics, being directly affected by continental and maritime air masses with significant origin differences (Barry and Chorley, 2003). In this region, most of the precipitation occurs from October to March (Xoplaki, 2002). The peak of precipitation of the winter season occurs between December and February, when the midlatitude cyclone belt has usually reached its southernmost position (e.g., H. M. S. O 1962). The climate of the northern EMME is mostly temperate with warm, dry summers, occasional droughts, and mild, relatively wet winters (Bolle 2003; Lionello et al. 2006). In the southern EMME, an arid, hot desert climate prevails, where precipitation is low and vegetation scanty (Issar and Zohar 2007). The temperature and precipitation gradients across the region are remarkable. In some areas, precipitation is among the highest in Europe, e.g., up to 2000 mm/year or more over the mountains of the Dinaric Alps, the Caucasus, and the Zagros Mountains, while several degrees latitude further south of this can be orders of magnitude less. The precipitation is most abundant in winter and largely associated with the southward propagation of the polar front jet, which directs cyclonic disturbances over the region (Krichak et al. 2000; Lelieveld et al. 2012). Precipitation patterns in the EMME depend not only upon the synoptic weather conditions but also on the pronounced topography; for example, the Taurus and Zagros Mountains through which the Euphrates and Tigris rivers supply the much needed water downstream (Barth and Steinkohl 2004; Evans 2009). Gradients and contrasts are characteristic for the EMME, not only in climatic conditions but also in social and economic aspects, access to natural resources, as well as cultural and religious traditions. This diversity is a regional attribute, but can also be associated with political tensions. Since the region is a primary climate change “hot spot”, there is atmospheric blocking that can influence near-surface temperatures via the circulation and radiative forcing Giorgi (2006). The relevance of blocking for co-located (sub-)daily temperature extremes, and the spatial variability of this relationship in the northern hemisphere was investigated by Pfahl and Wernli (2012) and Hafez (2012). Hafez and Almazroui (2015) found that there is a significant relationship between global radiative forcing and global annual climatic variability. The relationship between occurrences of extreme temperature events in central Europe and high pressure blocking situations during 2001–2011 was studied by Porebska and Zdunek (2013). They found a coincidence in the time between blocking situations and extreme temperature events. Cold and heat waves were often associated with occurrences of high pressure blocking situations over the Atlantic Ocean and Eastern Europe, respectively. Furthermore, blocking highs lasting for more than 5 days coincided more frequently with extreme temperature events than those that last shorter than 5 days. North Atlantic atmospheric blocking conditions explain part of the winter climate variability in Europe, being associated with anomalous cold winter temperatures (Sillmann et al. 2011). The EMME is likely to be greatly affected by climate change associated with increases in the frequency and intensity of droughts and hot weather conditions. Since the region is diverse and extreme climatic conditions are already common, the impacts will be disproportional (Lelieveld et al. 2012). Atmospheric blocking is an important source of low-frequency variability. A blocking detection and tracking method of ERA-40 data for the Atlantic-European region is applied to assess linkages to extreme events. The method is feature-oriented, identifies 500-hPa geopotential height maxima, and connects them with a next-neighborhood search in time. The analysis reveals a statistically significant decrease in number of blocking events over the period of ERA 40.Winters with an increased number of blocking events are associated with negative temperature anomalies over central to eastern Europe and dryer conditions (Buehler et al. 2011). Several seasonal and annual climate extreme indices have been calculated and their trends (over 1958 to 2000) analyzed to identify possible changes in temperature and precipitation-related climate extremes over the eastern Mediterranean region (Kostopoulou and Jones 2005). Many researchers investigated and discussed the climatological phenomenon, blocking high formation, persistence, behavior, and the role played in unusual weather and climate in the northern hemisphere (e.g., Rex 1950a, b, 1951; Namias 1964; Dickson and Namis 1976; Dole and Gordon 1983; Lejenas 1989; Liu 1994; Lupo 1997; Cohen et al. 2001; Wiedenmann et al. 2002; Hussain et al. 2007; Schalge et al. 2011; Lupo et al. 2012, Fujii et al. 2012; Cheung et al. 2012, 2013). However, there is a significant relationship between the 500-hPa geopotential height anomalies over Europe and the abnormal weather in the eastern Mediterranean during winter 2006 (Hafez, 2007). The teleconnection between the global mean surface air temperature and precipitation over Europe was discussed by Hafez (2008). In addition to that, it is found that the anomaly of global annual geopotential height was completely controlled by global warming and NAO, SOI, and El Nino 3.4. However, the trend of the global surface air temperature anomaly completely coincides with the trend of the 500-hPa geopotential height anomaly. This result uncovers the existence of abnormal weather phenomena through the last decades (Hafez and Almazroui 2014). There is a significant relationship between the global annual variability of weather and climatic elements and GHGs, global warming and climatic indices, NAO, SOI, El Nino 3.4, and SST (Hafez and Almazroui 2015). The present work aims to study the abnormal weather conditions over the EMME region and its relationship to weather conditions and geopotential height distribution at 500 hPa over Europe through December 2013.

Data and methodology

Data

The NCEP/NCAR Reanalysis project is using a state-of-the-art analysis/forecast system to perform data assimilation, within a resolution of 2.5 × 2.5 degrees lat/lon grid, using past data from 1948 to 2014. Daily data sets of several meteorological elements (temperature, precipitation rate, relative humidity, sea level pressure, and geopotential height at level 500 hPa etc.) over the northern hemisphere, including Europe and EMME of December 2013, have been used. This data is provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA and Kalnay et al. (1996). In addition to that, a time cross section analysis of the daily operational data for meteorological elements (maximum, minimum, mean surface temperature, geopotential height, relative humidity, precipitation, and sea surface pressure) was done over EMME from December 1 to 31, 2013. However, the NCEP data set domain considered in the present work are extended to 30° N–70° N, 0° W–70° E for Europe and 20° N−50° N, 15° W–55° E for EMME, whereas each grid point in the domain 16 × 28 degrees lat/lon grids of meteorological datasets for Europe and 12 × 16 degrees lat/lon grids of meteorological data sets for EMME. Satellite images during and after the Alexa ice storm have been obtained through the internet from the EURSAT website.

Methodology

A. Anomaly methodology

The anomaly in the mean meteorological element, e.g., daily surface air temperature, is A′ for each grid point in the domains through the period of study. This anomaly is calculated as the difference between the mean of daily surface air temperature (A) and its climatic mean value (Â) for each grid point. The climatic mean value of the surface air temperature has been taken through the period of 1981–2010. A linear correlation coefficient technique by Spiegel (1961) has been used. Statistical analysis of correlation coefficient using *t* test and the *P* test was obtained. The calculation of the *t* value and *P* values for the significance (both one-tailed (OTP) and two-tailed probability (TTP) values) with a Pearson correlation coefficient, given the correlation value *r*, and the sample size were used throughout the present work.

B. Blocking criteria

Blocking high episodes have great impact on the weather and climate of several areas because they are depicted by an abrupt change in the atmospheric flow, affecting the normal synoptic systems (e.g., Sinclair 1996; Wiedenmann et al. 2002; Renwinck 2005; and recently, Hafez and Almazroui 2013). There are several definitions of blocking high systems. The synoptic and numeric criteria of the formation of blocking systems are defined by Rex (1950a, b, 1951), Namias (1964), Dole (1986), and Dole and Gordon (1983). More recently, blocking high is defined using zonal index by Tibaldi and Molteni (1990), Pelly and Hoskins (2003), Barriopedro et al. (2006), Lupo et al. (2012), Fujii et al. (2012) and Cheung et al. (2012). There are three different types of blocking systems. First is Rex block which has high and low pressure systems approximately existing in the same longitude (diffluent block). Second is omega-shaped block (Ω-block).Third is the meridional block. For the first type of blocking, the Rossby wave is breaking. For the second one, Rossby wave has changes in its shape only as omega-shaped. For the third type, there is only an amplification of amplitude of Rossby wave. All characteristics of these blocking types must persist for a long time more than the synoptic scale time.

The definition of blocking using of zonal index has problems with omega-shaped block and particularly difficult with meridional block. The blocking definition by zonal index must be used for Rossby wave-breaking only. So, for the purpose of the present study, the blocking system was defined based on and according to Rex's (1950a, b) and Dole's (1986) definitions using synoptic charts and anomaly of geopotential height conditions at the 500-hPa level. These criteria have basic conditions such as the westerly air current aloft must split to two distinct branches. This splitting must be northern latitude of 30° N. For numeric, quantitatively, the anomalies in geopotential height values at 500 hPa level must be more than +100 m for blocking high pressure systems for several longitudes. Throughout the present study, these conditions must persist more than or equal to 5 days. However, through the course of the present work, the blocking criteria have been a combination of Rex (1950a) and Dole (1986), without the splitting of westerly air current condition. Meanwhile, the minimum duration chosen is 5 days.

Results

Study of blocking criteria over Europe on December 2013

The studying and applying of the above blocking criteria over Europe using the daily NCEP/NCAR 500-hPa geopotential height data over the northern hemisphere through the period of December 1 to 31, 2013 was done. The following is found:

1. All day, for the period from December 1 to 31, 2013, a maximum positive anomaly of geopotential height at

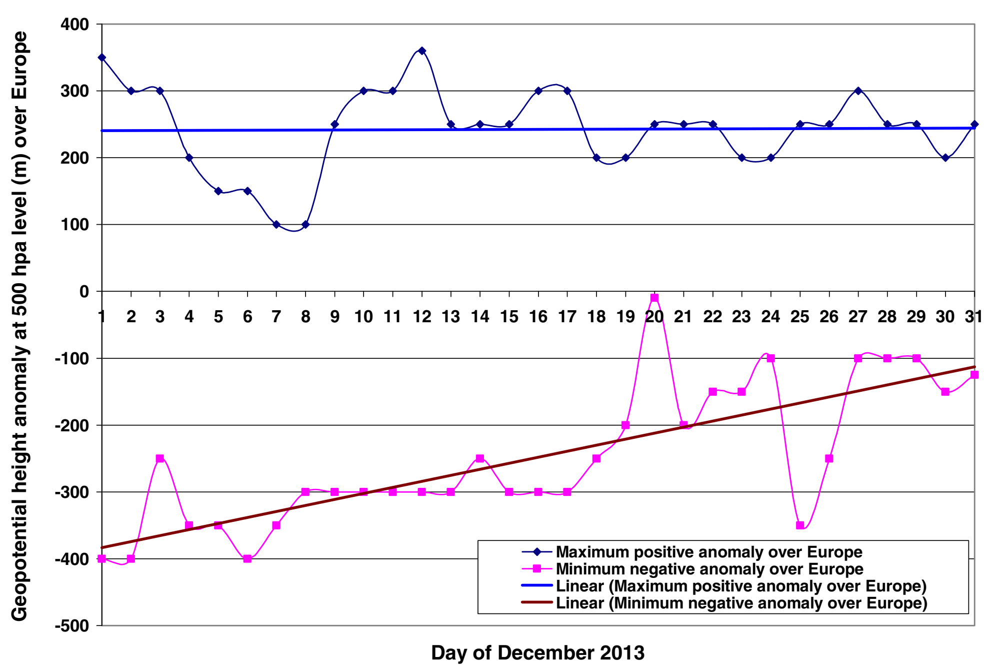
500 hPa existed over Europe. The linear trend of it is a constant trend around +240 gpm. The maximum positive anomaly of geopotential height is above +200 gpm from December 9 to 31 (see Fig. 1).
2. Through the month of December, the minimum negative anomaly of geopotential height has been less than or equal to −100 gpm, except on December 20 where it was equal zero. The linear trend of minimizing negative anomaly sharply increases during the study period as it can be seen clearly from Fig. 1.
3. From the analysis of the daily maximum positive and minimum negative anomalies of geopotential height, it becomes clear that a blocking high episode existed over Europe during December 9–19 and persists for a duration of 11 days.
4. Analysis of daily 5-day mean anomaly of geopotential height at level 500 hPa for December 2013 was done. It was found that for most of the period of study, the geopotential height reached extreme anomaly values over Europe. The positive and negative anomaly values reached ±300 m.
5. The Rossby wave oscillates and extends northward and southward to extreme extension of amplitude. The type of blocking system over Europe is a meridional type block. The meridional block is a blocking system characterized by an amplification of Rossby wave amplitude to extreme limits rather than the synoptic scale limits. The meridional block becomes clear of persistence over Europe with the extreme southward extension of the cut-off low pressure system over the EMME through December12–15, 2013 (see Fig. 2). Through this period, there is a main high pressure system, persisting over Western Europe, while the low pressure system persisted over Eastern Europe with a cut-off low over the EMME. This dipole pressure system over Europe invades the EMME by very cold air from the north and central Europe.

The variability of weather conditions over the EMME through December 2013

The NCEP/NCAR daily data sets of several meteorological elements (temperature, precipitation rate, relative humidity, sea level pressure, and geopotential height at level 500 hPa etc.) over EMME have been analyzed for December 1–31, 2013. The results revealed the following:

1. The positive anomaly of geopotential height at 500 hPa level over the EMME decreases with time through the first half of December 2013. Meanwhile, it increases rapidly through the next half of it. The trend of this positive anomaly is a constant trend (+60 m). The negative anomaly of geopotential height over EMME decreased sharply through the first half of this month, mainly from day 8 to day 15. For most of the second half of December, it increased. The trend is approximately constant (−100 m), as shown in Fig. 3a.
2. The positive precipitation rate anomaly reached +30 mm/day through the first half of December 2013. Furthermore, it is a normal value for most of the second half, with a negative trend. For negative precipitation rate anomaly, it

Fig. 1 The daily time series of maximum and minimum geopotential height anomaly at 500 hPa level (m) and its trend over Europe through the month of December 2013



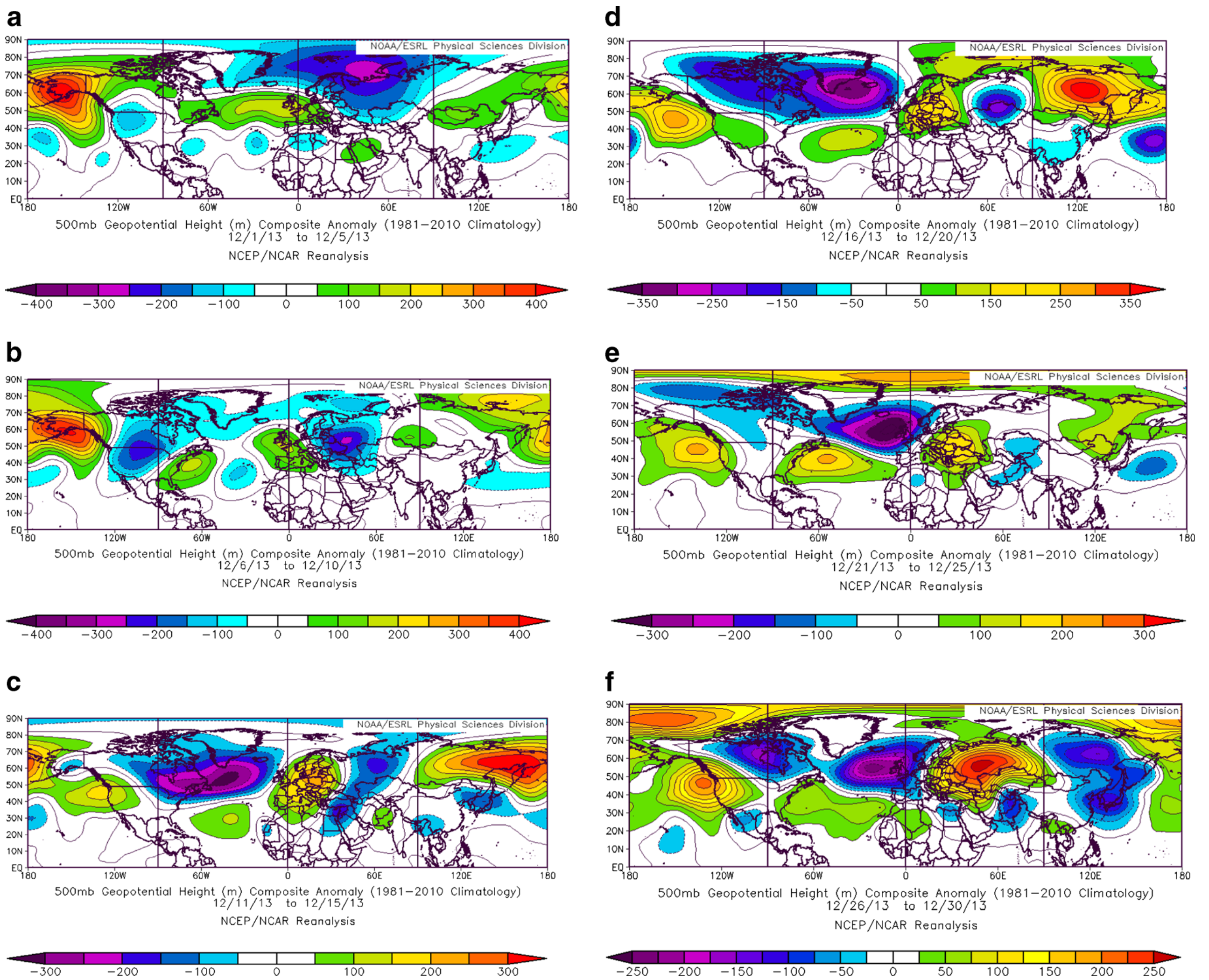


Fig. 2 **a**–**f** Distribution of 5 days—daily mean geopotential height composite anomaly over the northern hemisphere including Europe through the month of December 2013

is zero for the first half and less than zero for the second half with a negative trend, as can be clearly seen from Fig. 3b.

3. From the maximum positive surface air temperature anomaly analysis over the EMME, it becomes clear that the temperature was warm and was more than its normal value from December 1 to 8; afterward, it becomes a normal value until December 24 and increases again afterward until the end of the month. The linear trend is a negative trend. Meanwhile, it is found that minimum negative temperature remains normal from December 1 to 7. From December 8 to 27, there is a dramatic drop in surface temperature. It reached −12 °C below the normal on December 12. The linear trend is a negative trend, as illustrated in Fig. 3c.
4. Analysis of the maximum positive relative humidity over the EMME shows that for most of the first half of December, it was above its normal values and reached +40 % more than its normal value. Meanwhile, through the next half, it is approximately a normal value. The linear trend is a negative trend. For minimum negative relative humidity, it is clear that relative humidity is less than its normal value except from December 9 to 15, and it has been at its normal values. The linear trend is slightly a positive trend (see Fig. 3d).
5. Mean sea level pressure maximum anomaly is positive for most days of December and reached +18 hPa on December 25. Its linear trend is a positive trend. Minimum negative anomaly of mean sea level pressure has values less than its normal value for the first half of this month, whereas it has a normal value from December 15 to 26. It becomes clear that from December 10 to 15, pressure is sharply decreased. It reached −15 hPa on December 11 and 12. The linear trend is a positive trend, as it is clear on Fig. 3e.

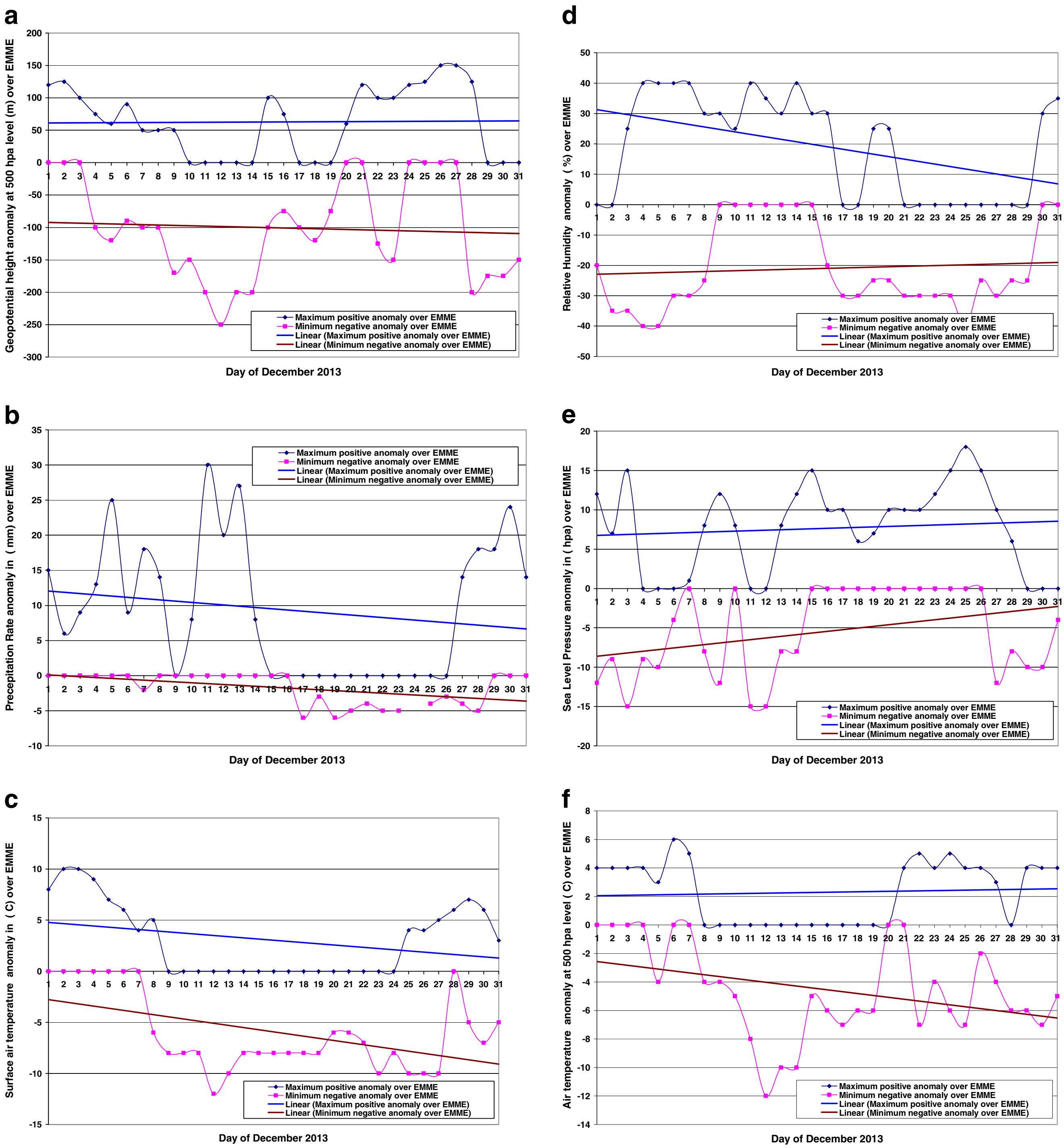


Fig. 3 Time series of maximum positive and minimum negative anomalies of meteorological elements and its linear trend over EMME in December of 2013. **a** Geopotential height at 500 hPa level, **b** daily precipitation rate, **c** surface air temperature, **d** relative humidity, **e** sea level pressure, and **f** air temperature at 500 hPa level

6. Air temperature anomaly at the 500 hPa level analysis leads to find that the maximum positive temperature anomaly is more than its normal value from December 1 to 7, and it is normal from 8 to 20, after that, it is more than its normal values in general. The linear trend is nearly a constant trend. The minimum negative anomaly of temperature is a negative value in general through this month. The negative values reached an extreme value (−12 °C) on December 12, 2013. However, the period from December 7 to 19 has a continual band of extreme negative temperatures (very cold period). The linear trend is a negative trend as it is clear from Fig. 3f.

Time-longitude cross section analysis of meteorological elements over the EMME on December 2013

Daily operational data for several meteorological elements over the EMME for December 2013 has been used. Through this section, analysis of time-longitude cross section of meteorological elements (geopotential height at 500 hPa level, precipitation rate, air temperature, relative humidity, sea level pressure) has been done. The results revealed the following:

1. Analysis of the geopotential height anomaly at 500 hPa over the EMME clearly showed that for the days from December 6 to 15, a wide band of negative anomaly exists. It reached −200 m on December 12. Meanwhile, the positive anomaly existed mainly from December 19 to 30 over this region and reached +180 m on December 22.
2. The precipitation rate over the EMME is more than its normal values mainly from December 5 to 15, 2013 over EMME.
3. Analysis of surface air temperature anomaly for EMME shows that surface cooling existed in December 9–18. The temperature is less than its normal values. However, on December 12, the surface air temperature is less than its normal value by 10 °C over most of the EMME.
4. Relative humidity over EMME becomes more than its normal values through December 6–15, while it becomes less than its normal on two periods (December 1–5 and December 18–31).
5. Sea level pressure of EMME was less than its normal values mainly from December 1 to 15. From December 16 to 27, the sea level pressure was more than its normal values.
6. Upper air temperature recorded significant cooling over EMME through days from December 7 to 15 and observed 10 °C less than its normal value on December 12. The temperature was above its normal through the second half of this month.

Severe ice storm Alexa over the EMME

Extreme weather conditions over the EMME

The EMME region suffered from abnormal cooling for most of the period of December 2013. The storm, named Alexa, brought snow, rain, and cold parts to Turkey, Syria, Lebanon, Jordan, Palestine, and Egypt. The EMME was hit with its heaviest snow storm in 60 years, exacerbating the humanitarian crisis in Syria and forcing Palestine to allow emergency aid into Gaza. On December 11, the Gaza Strip was lashed by torrential rain. The northern part of Gaza has been declared a disaster area by United Nations officials. Thousands of homes have been inundated or left without power, and the thousands of evacuees have been moved to emergency shelters and schools until the floodwaters receded. A winter storm, Alexa, has caused days of snow and heavy rain in the Middle East since December 12, and in Gaza, the storm resulted in flooding that forced the evacuation of over 5000 people. Snow in Nablus and Hebron ranged from 60 to145 cm, and in Bethlehem, it ranged from 20 to55 cm. Snow storms in the Middle East are not frequent but are not uncommon either. However, this one was unusually early in the winter and more intense than normal. The storm paralyzed parts of Palestine with 30 to 50 cm of snow, knocking out power for roughly 15,000 households. Amman and Jordan received about 45 cm of snow, and Lebanon and Syria also were unusually cold and snowy. This storm extended from Turkey to Egypt, with parts of Cairo reportedly experiencing their first recorded snowfall for a century. Several centimeters of snow fell in the Sinai Peninsula, usually an arid desert region, while authorities were forced to close the port in the coastal city of Alexandria (which saw relatively light snowfall) after a third consecutive day of bad weather and high winds. In Lebanon's Bekaa Valley (where there are an estimated 1 million Syrian refugees crowded into 250 camps), relief agencies handed out warm clothing, blankets, bedding, and heating equipment in refugee camps as snow fell relentlessly for the second day running. After a day of lesser snow, a heavy snowstorm on December 13, 2013 deposited 40–70 cm of snow in Jerusalem and 100 cm in the Kefar Etzionarea. In Cyprus, by December 14, the storm had covered the island's Troodos mountain range with snow. Four hundred men lost electricity, and several villages, including Armenohori, Farmakas, Kampi, and Sina Oros, completely lost power for extended periods of time. Egypt's capital, Cairo, witnessed extremely rare snowfall. The Kingdom of Saudi Arabia has recorded extreme cold temperatures and fall of snow over the northwestern part. In general, the EMME region suffered from extreme abnormal weather conditions with cooling (Fig. 4, satellite images shows areas where snow was falling on the ground on December 12, 2013). One swath covers Jerusalem and its surroundings. Patches in the West Bank, Jordan, Lebanon, Syria, and Egypt's Sinai Peninsula are also blanketed in white. There is just a sprinkling of clouds over the sunlit scene.

Impact of blocking over Europe on Alexa storm

Applying the abovementioned blocking criteria that were based on Rex (1950a) and Dole (1986) and taking in consideration that the minimum duration is 5 days over Europe in December 2013, it is found that there is only one blocking high episode that existed through the period of 9–19 of that month. This block is a meridional block shape. Through this period, a main high pressure system persisted over Western Europe, while the low pressure system persisted over Eastern

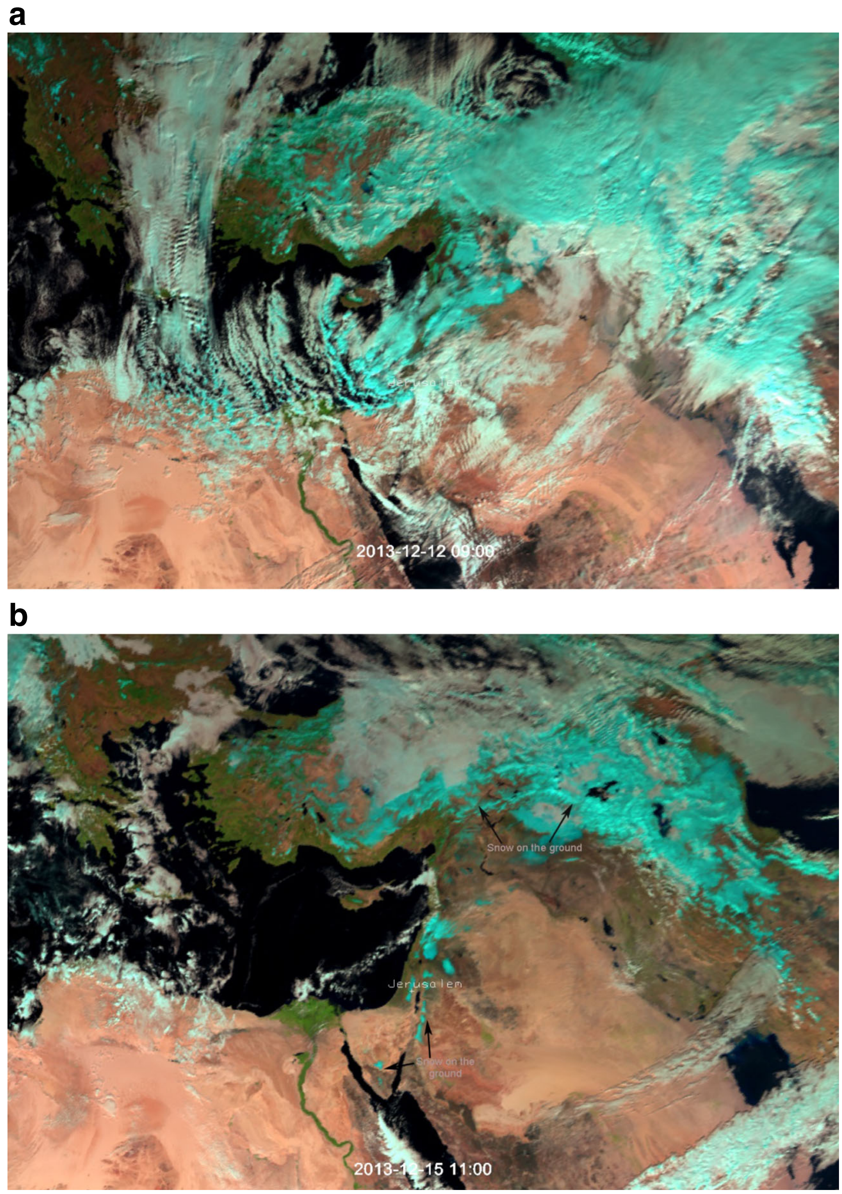


Fig. 4 Satellite images **a** during the ice storm Alexa and **b** after storm Alexa for the region of EMME. (Meteosat-10 Channels/Products, Natural Color RGB, EUMETSAT)

Europe with a cut-off low over EMME. This dipole pressure system invades the EMME by very cold air from the north and central Europe. Extreme upper air cooling existed over the EMME. The temperature anomaly reached −12 °C. Ice formation, rainfall, and extremely cold air over the EMME existed exactly on the period of blocking high persistence over Europe, whereas ice storm Alexa is accompanied to the EMME cut-off low of blocking over Europe as it is noticed from Fig. 5. Figure 5 shows the geopotential anomaly at a level of 500 hPa for December 9–15. It is completely clear that the dipole of pressure system over Europe and cut-off low pressure persisted over the EMME. It is also noticed that the meridional block has oscillated and shifts southward day by day to push down the low pressure to persist over the EMME and leads to the development of the Alexa storm.

Study of the relationship between geopotential height anomaly over Europe and abnormal weather over the EMME on December 2013

To ensure the role played by geopotential height anomaly and the blocking system over Europe on the abnormal weather conditions over the EMME through the days of December 2013, correlation coefficient techniques have been used. The correlation coefficient matrix between maximum positive and minimum negative geopotential height anomalies over Europe and several meteorological elements over the EMME has been studied and analyzed. *T* test and F-test of these correlation values were done. The correlation coefficient values between the abovementioned elements are tabulated in Table 1. The

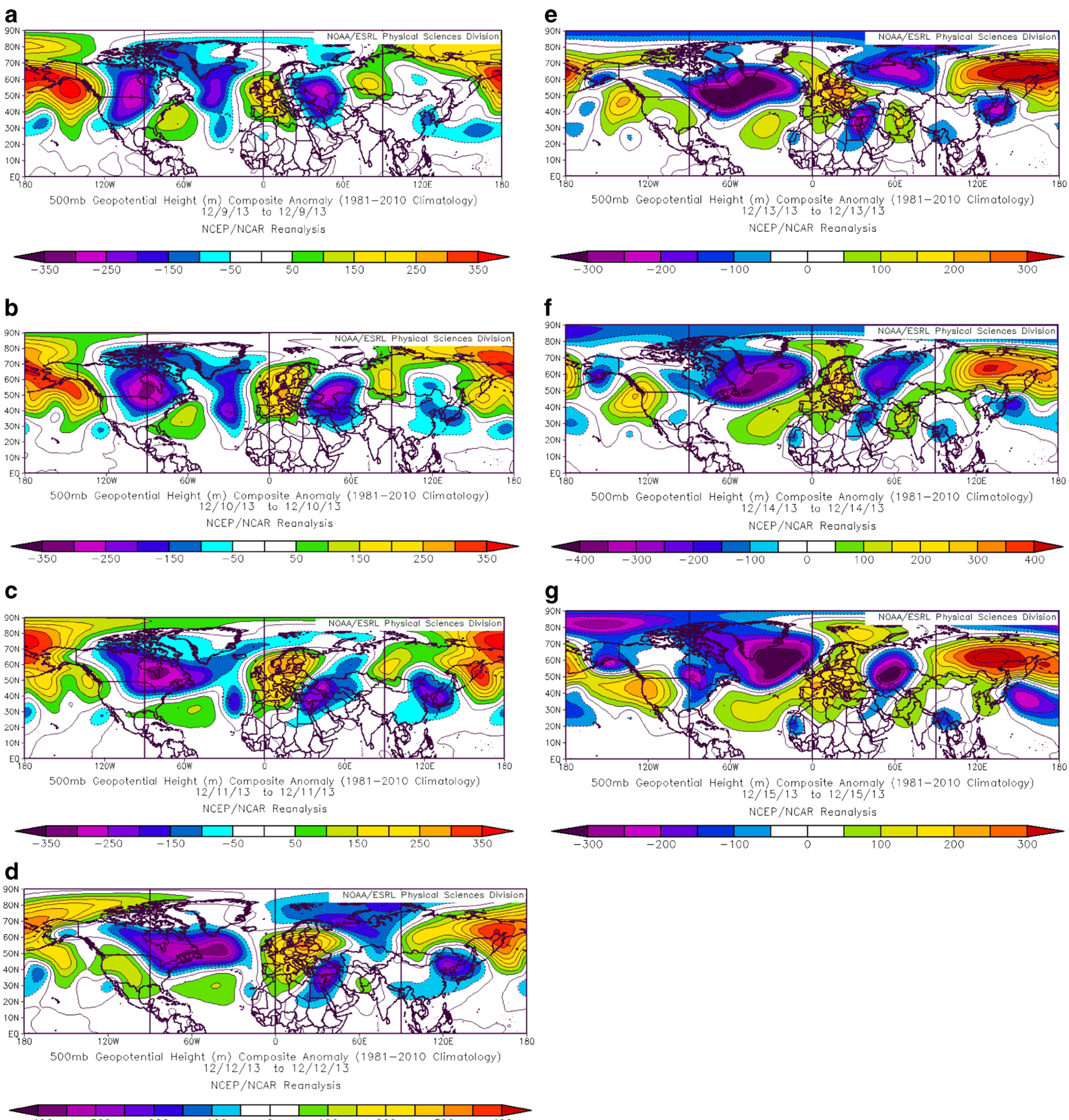


Fig. 5 Daily composite geopotential height at level 500 hPa anomaly during an Alexa storm over the northern hemisphere, including Europe through December 9–15, 2013

significant correlations obtained have been statistically analyzed and tabulated in Table 2. The results revealed the following:

1. The highest positive correlation coefficient value is +0.75, and it has been found between the maximum positive and minimum negative of geopotential height over the EMME.
2. There are notable negative correlations (−0.68 and −0.69) between the precipitation rates and the distribution of positive and negative mean sea level pressure values over the EMME.
3. There is a positive correlation of (+0.66) between the minimum negative surface temperature anomaly and minimum negative temperature at a level of 500 hPa over the EMME.

Table 1 Correlation coefficient matrix for geopotential height anomaly over Europe and several meteorological elements over EMME through the month of December 2013

CORR. COEF.	B	C	D	E	F	G	H	I	J	K	L	M	N	O
B	1.00	0.01	−0.04	0.04	−0.09	−0.26	−0.28	0.31	0.25	−0.30	−0.24	−0.23	0.05	0.03
C	0.01	1.00	−0.13	−0.48	−0.25	−0.28	−0.32	0.04	0.07	0.17	−0.01	−0.15	0.00	−0.02
D	−0.04	−0.13	1.00	0.50	0.36	0.26	0.59	0.30	−0.68	−0.69	−0.01	−0.22	−0.35	−0.51
E	0.04	−0.48	0.50	1.00	0.33	0.25	0.59	0.44	−0.34	−0.55	0.02	−0.01	−0.25	−0.28
F	−0.09	−0.25	0.36	0.33	1.00	0.75	−0.04	−0.45	−0.24	−0.49	0.52	0.53	0.35	0.29
G	−0.26	−0.28	0.26	0.25	0.75	1.00	0.16	−0.43	−0.34	−0.24	0.41	0.66	0.23	0.20
H	−0.28	−0.32	0.44	0.59	−0.04	0.16	1.00	0.45	−0.49	−0.28	−0.24	−0.09	−0.50	−0.43
I	0.31	0.04	0.30	0.44	−0.45	−0.43	0.45	1.00	−0.14	−0.24	−0.50	−0.53	−0.55	−0.62
J	0.25	0.07	−0.68	−0.34	−0.24	−0.34	−0.49	−0.14	1.00	0.34	−0.07	0.06	0.53	0.54
K	−0.30	0.17	−0.69	−0.55	−0.49	−0.24	−0.28	−0.24	0.34	1.00	0.06	0.10	0.12	0.30
L	−0.24	−0.01	−0.01	0.02	0.52	0.41	−0.24	−0.50	−0.07	0.06	1.00	0.50	0.49	0.42
M	−0.23	−0.15	−0.22	−0.01	0.53	0.66	−0.09	−0.53	0.06	0.10	0.50	1.00	0.54	0.67
N	0.05	0.00	−0.35	−0.25	0.35	0.23	−0.50	−0.55	0.53	0.12	0.49	0.54	1.00	0.69
O	0.03	−0.02	−0.51	−0.28	0.29	0.20	−0.43	−0.62	0.54	0.30	0.42	0.67	0.69	1.00

B maximum positive geopotential height at 500 hPa anomaly over Europe, *C* minimum negative geopotential height at 500 hPa anomaly over Europe, *D* maximum positive precipitation rate anomaly over EMME, *E* minimum negative precipitation rate anomaly over EMME, *F* maximum positive surface temperature anomaly over EMME, *G* minimum negative surface temperature anomaly over EMME, *H* maximum positive relative humidity at surface anomaly over EMME, *I* minimum negative relative humidity at surface anomaly over EMME, *J* maximum positive mean sea level pressure anomaly over EMME, *K* minimum negative mean sea level pressure anomaly over EMME, *L* maximum positive temperature at 500 hPa anomaly over EMME, *M* minimum negative temperature at 500 hPa anomaly over EMME, *N* maximum positive geopotential height at 500 hPa anomaly over EMME, *O* minimum negative geopotential height at 500 hPa anomaly over EMME

4. It is obvious that the minimum negative temperature at the 500 hPa level over the EMME region correlated positively with the geopotential height distribution at 500 hPa over the EMME.
5. The relative humidity negatively correlated with the minimum negative geopotential height over the EMME.

Discussion and conclusion

The present work aims to study the geopotential height distribution over Europe that leads to the extreme cold weather conditions over the EMME during December 2013. This month has an abnormal cooling weather and existence of the abnormal extreme weather phenomena, Alexa storm. The results of the present work revealed that December 2013 is a unique month with very cold and severe weather over the EMME. The meteorological elements (e.g., air temperature, precipitation, pressure, geopotential height, relative humidity, etc.) recorded extreme values throughout most of this month. Through the period of the Alexa storm, ice covered most of the northern part of EMME. It is noticed that during this month, Europe has an extremely positive geopotential height aloft mainly over western and central Europe. While, eastern Europe has a remarkable negative anomaly of geopotential height. In addition, blocking high episode persisted over Europe and extended southward with cut-off low over the EMME. Applying the abovementioned criterion of blocking high over Europe through December 2013, it becomes clear that a blocking high episode existed over Europe during December 9–19 and persists for duration of 11 days. It is found that the type of this block is a meridional block. This type of blocking is associated with extreme temperature conditions and invaded the EMME by strong cold air from the north of Europe. Through the persistence days of this block, the severe ice storm Alexa existed over the EMME. The ice storm Alexa is associated with the EMME cut-off low of blocking that persisted aloft over Europe. From the present study, it is clear that the dipole of pressure systems over

Table 2 *T* test and F-test of the high correlation coefficient values of the meteorological elements

Meteorological elements	Correlation coefficient	*t* value	F value	
			OTP	TTP
D Corr. With J	−0.68	−4.9943	0.00001288	0.00025770
D Corr. With K	−0.69	−5.1336	0.00000875	0.00017500
G Corr. With M	+0.66	4.7396	0.00002678	0.00005356
G Corr. With F	+0.75	6.1062	0.00000060	0.00000119
O Corr. With M	+0.67	4.8602	0.00001870	0.00003740
O Corr. With N	+0.69	5.1336	0.00000875	0.00001750
O Corr. With I	−0.62	4.2554	0.00009958	0.00019917

Europe and cut-off low pressure persisted over the EMME. Also, the meridional block is oscillated and shifts southward from day to day to push down to south the low pressure over EMME and leads to development of Alexa storm. This storm caused several disasters over several countries in the eastern Mediterranean region. However, thousands of homes have been inundated or left without power, and the thousands of evacuees have been moved to emergency shelters and schools until the flood waters receded.

The time-longitude cross section analysis of meteorological elements over EMME through the month of December 2013 uncover that EMME has the following weather condition characteristics:

1. All day, from December 1 to 31, 2013, maximum positive anomaly of geopotential height at 500 hPa existed over Europe.
2. The minimum negative anomaly of geopotential height has been less or equal to −100 gpm, except on December 20 where it was equal zero.
3. The positive anomaly of geopotential height at 500 hPa level over the EMME decreases with time for most of the first half of December 2013, while it increases rapidly through the next half of it. The negative anomaly of geopotential height over the EMME has decreased sharply through the first half of this month mainly from December 8 to 15. For most of the second half of December, it increased.
4. Over the EMME, a precipitation rate anomaly is more than zero and reached +30 mm/day through the first half of December 2013. Furthermore, it is a normal value for almost the second half with a negative trend.
5. From maximum positive surface air temperature analysis over the EMME, it becomes clear that the temperature was warm and more than its normal value from December 1 to 8, after that it becomes normal values until December 24, and increase after that until the end of the month. It is noticed that from December 8 to 27, there is a dramatic drop in temperature where it reached−12 °C below the normal on December 12.
6. Mean sea level pressure maximum anomaly is positive for most days of December 2013 and reached +18 hPa on December 25. It becomes clear that from December 10 to 15, it is sharply decreasing to reach −15 hPa on the 11th and 12th of this month.
7. Analysis of air temperature at 500 hPa level leads to find that the maximum positive temperature anomaly is more than its normal value from December 1 to 7, it is normal from December 8 to 20, and after that it is more than its normal values in general. The minimum negative anomaly of temperature is a negative value in general throughout this month. These negative values reached extreme negative values (−12 °C) on December 12, 2013. However, the period from December 7 to 19 has a continual band of extreme negative temperatures (very cold period) with a negative trend.
8. For geopotential height at 500 hPa over the EMME, it is clear that from December 6 to 15, there is a wide band of negative anomaly. It reached −200 m on December 12. Meanwhile, the positive anomaly existed mainly from December 19 to 30 over this region and reached +180 m on December 22.
9. The precipitation rate over the EMME was more than its normal values mainly from December 5 to 15, 2013.
10. Analysis of surface air temperature shows that there is a cooling trend that existed through December 9–18. The temperature is less than its normal by 10 °C on December 12 over most of the EMME.
11. Upper air temperature recorded strong cooling over the EMME throughout December 7 to 15. It is observed to be 10 °C less than its normal value on December 12.

Finally, statistical study to obtain the relationship between geopotential height anomaly over Europe and abnormal weather over the EMME on December 2013 was done. The significant correlation between geopotential height anomaly over Europe and abnormal weather over the EMME was detected. The highest positive correlation coefficient value of +0.75 was found between the maximum positive and minimum negative values of geopotential height over the EMME region. In addition to that, there are notable negative correlations (−0.68 and −0.69) between the precipitation rates and the distribution of positive and negative mean sea level pressure values over the EMME. It is becoming clear that there is a positive correlation (+0.66) between the minimum negative surface temperature anomaly and minimum negative temperature at a level of 500 hPa over EMME. It is found that the minimum negative temperature at the 500 hPa level over EMME correlated positively with the geopotential height distribution. One can conclude that the blocking high system that persist over Europe and the abnormal distribution of geopotential height over Europe have played a great role in the existence of severe cold weather conditions and the development of the ice storm Alexa over the EMME on December 2013. The present result shows teleconnection between geopotential height anomaly over Europe and extreme abnormal weather over EMME during December 2013 and encourages future studies of the relationship between the blocking high over Europe and existence of extreme weather events over EMME. Moreover, predictability of meridional blocking persistence over Europe will lead to forecasting of the extreme abnormal weather over EMME.

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References

AMS (2008) Cold Wave. Glossary of Meteorology. Retrieved 2008–09 - 25.

Barriopedro D, Garria-R LA, Hemandez E (2006) A climatology of northern hemisphere blocking. J Climate 19:1042–1063

Barry R, Chorley R (2003) Atmosphere, weather and climate. Routledge; 8 edition, pp 472

Barth HJ, Steinkohl F (2004) Origin of winter precipitation in the central coastal lowlands of Saudi Arabia. J Arid Environ 57: 101–115

Bolle HJ (ed) (2003) Mediterranean climate variability and trends. Springer, Berlin, p 372

Buehler T, Raible CC, Stocker TF (2011) The relationship of winter season North Atlantic blocking frequencies to extreme cold or dry spells in the ERA-40. Tellus 63A:212–222

Cheung H, Zhou NW, Mok HY, Wu MC (2012) Relationship between Ural-Siberian blocking and the East Asian winter monsoon in relation to the Arctic Oscillation and El Nino-Southern Oscillation. J Clim 25:4242–4257

Cheung HN, Zhou W, Shao Y, Chen W, Mok HY, Wu MC (2013) Observational climatology and characteristics of wintertime atmospheric blocking over Ural–Siberia. Clim Dyn 41:63–79

Cohen J, Saito K, Entekhabi D (2001) The role of the Siberian high in northern hemisphere climate variability. Geo Res Lett 28(2): 299–302

Dickson RR, Namis J (1976) North America influences on the circulation and climate of the North Atlantic sector. Mon Weather Rev 104: 1255–1265

Dole RM (1986) Persistent anomalies of the extratropical Northern Hemisphere wintertime circulation: structure. Mon Weather Rev 114:178–207

Dole RM, Gordon ND (1983) Persistent anomalies of the extratropical northern hemisphere wintertime circulation: geographical distribution and regional persistence characteristics. Mon Weather Rev 111(8):1567–1586

Evans JP (2009) 21st century climate change in the Middle East. Climate Change 92:417–432

Fujii A, Kuroda Y, Mukougawa H (2012) Mechanism and predictability of persistent Euro-Russian blocking in summer of 2010 examined by ensemble hindcast and forecast dataset. Geophys Res Abst 14: EGU2012–EGU3829

Giorgi F (2006) Climate change hot-spots. Geophys Res Lett 33:L08707. doi:10.1029/2006GL025734

Hafez YY (2008) The role played by blocking over the Northern Hemisphere on Hurricane Katrina. The J Amer Sci 4(2):10–25

Hafez Y Y (2012) Blocking systems persist over North Hemisphere and its role in extreme hot waves over Russia during summer 2010. Atmospheric Model Applications, I. Yucel, Ed., pp. 978–953, InTech, 2012

Hafez YY (2007) The connection between the 500 hpa geopotential height anomalies over Europe and the abnormal weather in eastern Mediterranean during winter 2006. I J Meteo U K 32(324): 335–348

Hafez YY, Almazroui M (2013) The role played by blocking systems over Europe in abnormal weather over Kingdom of Saudi Arabia in summer 2010. Adv Meteor Vol. 2013, Article ID 705406, 20 pages. http://dx.doi.org/10.1155/2013/705406

Hafez YY, Almazroui M (2014) Recent study of anomaly of global annual geopotential height and global warming. Atmos Clim Sci 4: 347–357, http://dx.doi.org/10.4236/acs.2014.43035

Hafez YY, Almazroui M (2015) A recent study on the relationship between global radiative forcing and global annual climatic variability. Atmos Clim Sci 5:23–55, http://dx.doi.org/10.4236/acs.2015.51003

H. M. S. O. (1962) Weather in the Mediterranean I: general meteorology. 2nd edition, London, pp 362

Hussain A, Lupo AR, Strong C, Dostoglou S (2007) A diagnostic study of atmospheric blocking using Lyapunov exponents over a 50 – year period. The 87th annual meeting of the American Meteorological Society, 19th conference on climate variability and change, San Antonio, TX

Issar AS, Zohar M (2007) Climate change, environment and civilization in the Middle East. Springer-Verlag Berlin Heidelberg. doi: 10.1007/978-3-540-69852-4

Kalnay E, Kanamitsu M, Kistler R et al (1996) The NCEP/NCAR 40-year reanalysis project. Bull Amer Meto Soc 77(3):437–471

Kostopoulou E, Jones PD (2005) Assessment of climate extremes in the East Mediterranean. Meteorol Atmos Phys 89:69–85. doi:10.1007/s00703-005-0122-2

Krichak SO, Tsidulko M, Alpert P (2000) Monthly synoptic patterns with wet/dry conditions in the eastern Mediterranean. Theor Appl Climatol 65:215–229

Lejenas H (1989) The severe winter in Europe 1941–1942: the large-scale circulation, cut-off lows, and blocking. Bull Am Meteorol Soc 70(3):271–281

Lelieveld J, Hadjinicolaou P, Kostopoulou E, Chenoweth J, El Maayar M, Giannakopoulos C, Hannides C, Lange MA, Tanarhte M, Tyrlis E, Xoplaki E (2012) Climate change and impacts in the Eastern Mediterranean and the Middle East. Clim Change 114:667–687. doi:10.1007/s10584-012-0418-4

Lionello P, Bhend J, Buzzi A, Della-Marta PM, Krichak S, Jansa A, Maheras P, Sanna A, Trigo IF, Trigo R (2006) Cyclones in the Mediterranean region: climatology and effects on the environment. In: Lionello P, Malanotte- Rizzoli P, Boscolo R (eds) Mediterranean climate variability. Elsevier, Amsterdam, pp 324–372

Liu Q (1994) On the definition and persistence of blocking. Tellus 46A: 286–298

Lupo AR (1997) A diagnosis of two blocking events that occurred simultaneously in the midlatitude Northern Hemisphere. Mon Wea Rev 125:1801–1823

Lupo AR, Mokhov II, Akperov MG, Chernokulsky AV, Athar H (2012) A dynamic analysis of the role of the planetary- and synoptic-scale in the summer of 2010 blocking episodes over the European Part of Russia. Adv Meteor 584257:11

Namias **J** (1964) Seasonal persistence and recurrence of European blocking during 1958–1960. Tellus 6:394–407, **J**

Pelly L, Hoskins BJ (2003) A new perspective on blocking. J Atmos Sci 60:743–755

Pfahl S, Wernli H (2012) Quantifying the relevance of atmospheric blocking for co-located temperature extremes in the Northern Hemisphere on (sub-)daily time scales. Geo Res Lett 39:L12807. doi:10.1029/2012GL052261

Porebska M, Zdunek M (2013) Analysis of extreme temperature events in central Europe related to high pressure blocking situations in 2001–2011. Meteorologische eitschrift 22(5):533–540. doi:10.1127/0941-2948/2013/0455

Rex DF (1950a) Blocking action in the middle troposphere and its effect on regional climate I: an aerological study of blocking action. Tellus 3:196–211

Rex DF (1950b) Blocking action in the middle troposphere and its effect on regional Climate II: the climatology of blocking action. Tellus 3: 275–301

Rex DF (1951) The effect of Atlantic blocking action upon European climate. Tellus 3:100–111
Schalge B, Blender R, Fraedrich K (2011) Blocking detection based on synoptic filters. Adv Meteor 717812:11. doi:10.1155/2011/717812
Sinclair MRA (1996) Climatology of anticyclones and blocking for the southern hemisphere. Mon Weather Rev 124:245–263
Sillmann J, Croci-Maspol M, Kallache M, Katz RW (2011) Extreme cold winter temperatures in Europe under the influence of north Atlantic atmospheric blocking. J Climate 24:5899–5913
Spiegel MR, (1961) Theory and problems of statistics, Schaum
Tibaldi S, Molteni F (1990) On the operational predictability of blocking. Tellus 42A:343–365
Wiedenmann JM et al (2002) The climatology of blocking anticyclones for the Northern and Southern Hemisphere block intensity as a diagnostic. J Climate 15:3459–3473
Renwinck JA (2005) Persistent positive anomalies in the Southern Hemisphere circulation. Mon Weather Rev 133:977–988
Xoplaki E (2002) Climate variability over the Mediterranean, PhD thesis, University of Bern, Switzerland, Available through: http://sinus.unibe.ch/ klimet/docs/phd_xoplaki.pdf.