Evaluation of the Relationship between Blocking Patterns and Duration of Spring Frost Waves: The Case of Iran

Farzaneh JAFARI HOMBARI1, Gholamreza BARATI1,*, and Mohammad MORADI2

1 Department of Physical Geography, Faculty of Earth Sciences, University of Shahid Beheshti, Tehran 1983969411, Iran
2 Iran Meteorological Organization, Tehran 1387835811, Iran

(Received December 15, 2019; in final form March 10, 2020)

ABSTRACT

In order to evaluate the effects of blocking patterns on the duration of frost waves across Iran, the minimum daily temperatures of 60 weather stations were collected from 20 March 1968 to 21 June 2014. The findings, which were obtained based on the distribution tables of reported temperatures and their frequency variation graphs, resulted in identifying 114 frost waves. We obtained the daily weather maps at 500 hPa from NCEP/NCAR during the peak days of durable frosts, and it was revealed that the formation of low pressures over 20°–70°E and the dominant southwest–northeast troughs at 500 hPa facilitated the influx of cold air from both eastern Europe and central Siberia toward Iran, leading to the average frost duration of 12.4 days. Furthermore, low-pressure centers appeared in a dipole pattern in northern Iran over Caspian Sea and created durable frosts with an average duration of 15.4 days. The effect of omega shaped pattern of the geopotential height on durable frosts demonstrated a sharp difference with two recent patterns leading to the frost occurrence with a 13.3-day duration averagely. Additionally, the slow speed of cold western currents in the rex type of blocking from 30° to 50°N caused durable frosts of 14.3 days. Also, we found a specific reduction in the frequency of blocking patterns, which has occurred in the past four decades. Mostly, the blocking and non-blocking patterns cause long- and short-duration frosts over Iran, respectively.

Key words: blocking patterns, durable frosts, spring season, Iran

Citation: Jafari Hombari, F., G. Barati, and M. Moradi, 2020: Evaluation of the relationship between blocking patterns and duration of spring frost waves: The case of Iran. J. Meteor. Res., 34(3), 586–600, doi: 10.1007/s13351-020-9140-8.

1. Introduction

Frost is a weather phenomenon. A large number of studies reported that the atmospheric frosts occur when the air temperature is below 0°C (Snyder and de Melo-Abreu, 2005; Ruddell et al., 2013). For example, Kim and Byun (2016) indicated that the frost is associated with the fall of ground surface temperature to 0°C. Damages of atmospheric frosts have economic and social consequences (Simmonds and Rashid, 2001). They can destroy the fuel transfer (Lashkari and Keykhoosravi, 2010; Leviäkangas et al., 2011) and many economic activities. More importantly, the frost risks have always created some concerns in the agricultural sector, especially in spring (Snyder and de Melo-Abreu, 2005; Rahimi et al., 2007; Yue et al., 2016). Since winter is associated with the economic downturn, especially in agricultural sectors in Iran, while spring is considered as the beginning of economic outdoor activities. Accordingly, the occurrence of durable frosts in spring is considered as a major hazard due to an increase in inter-city trips, a boom in sales, nomadic relocations, and agricultural cultivation.

We find many farmlands on mountainous high-land and northern areas over Iran. These areas are more frost-prone in comparison with the low-land and southern areas. Also, the westerlies as well as their troughs and ridges are principal systems that cause warm and cold air flows. The location of Iran is in the south of midlatitudes. It means that, westerlies are dominating systems in northern Iran during autumn, winter, and spring, yet they are dominating ones in southern Iran only in winter. This means that the hazard of frosts is a serious danger to northern Iran than to southern Iran. Also, the weak easterlies are dominating systems during summer. The pro-
gressive westerlies toward South Iran occurs during autumn and regressive ones toward North Iran occurs during spring. This regression is periodic and irregular, which causes severe, moderate, long-, and short-duration frosts.

The atmospheric blocking is regarded as the major cause for spring frosts. Blocking is characterized as a high-pressure system, with also cut-off lows from the main-stream western winds (westerlies), and may settle for days or even weeks in a region (Croci-Maspoli et al., 2007). The occurrence of blocking is more frequent in the Northern Hemisphere in winter and spring (Barripedro et al., 2006).

Various terms have been suggested with regard to blocking and its consequences in the previous literature. These terms include the cold (Lejenäs, 1989; Hong and Li, 2009), cold wave (Porebska and Zdunek, 2013), cold period (Azizi et al., 2015), frost wave (Peterson et al., 2013), low temperature (Andrei and Roman, 2012), cold temperature in the middle latitudes (Cohen et al., 2014), wind anomalies along with significant cold advection and cold (Pezza and Ambrizzi, 2005), and northern currents (Kim and Byun, 2016).

The territory of Iran is located in the south of midlatitudes. Some studies related frosts in Iran to the large-scale atmospheric systems and remote factors (Yadav, 2016), especially the changes in positive and negative geopotential height anomalies (Yadav, 2017). Atmospheric movement such as polar air masses migrating southward (Katsafados et al., 2014) and temperature variations such as cold weather spells of several days' duration are considered as some of the most important blocking consequences. For example, frosts caused the damage to 400-hectare agricultural lands in central Alborz in 2002 (Rahimi et al., 2007). Further, Lashkari (2008) suggested the blocking pattern as a critical factor for the 6-day pervasive cold in winter over Iran in 2003. The pervasive frost is defined as the frost that covers 50% stations or more on its peak day in Iran.

By reviewing frost-related studies in association with atmospheric blocking, we find that most of the studies are case studies in Iran or the world. We think our study for Iran is different, which is to focus on the effect of atmospheric blocking on the duration of damaging frosts during spring. In other words, our purpose is to identify the synoptic patterns of westerly wind distribution at the 500-hPa level based on the occurrence time of durable frosts. For this aim, the minimum temperature daily data of 60 standard meteorological stations from 20 March 1968 to 21 June 2014 are collected from the Iran meteorological organization for all parts of Iran to identify durable frost waves and atmospheric patterns.

The question we would like to address in this investigation is the relations between harmful spring frosts in Iran and the atmospheric blocking patterns. In Iran, spring frosts are dangerous for orchards including apples and almonds over Northwest Iran, figs and pomegranates over central Iran, pears and cherries over northwestern Iran, and citruses over North Iran. Most of the frost damages by windy frosts happen during consecutive days. These frosts are not preventable and are controlled by the large-scale atmospheric systems. The results of the present investigation will help to highlight the synoptic dimensions of durable windy frosts and their mechanisms.

2. Data and methods

2.1 Data and study area

Our datasets are extracted from two sources:

1. In order to detect spring frosts, we extracted the daily minimum air temperatures from weather stations between the date of spring equinox (21 March) and summer solstice (21 June) for 93 days in Iranian Calendar; see Fig. 1) from the meteorology organization of Iran.

2. The daily weather map at 500 hPa from the NCEP/NCAR for frosty days from 1968 to 2014.

The data are collected from 60 standard weather stations across Iran to determine frost waves and analyze their durability relations with blocking patterns. In the present study, frost waves are defined as the occurrence of a minimum temperature of either 0°C or < 0°C at more than two meteorological stations within at least two geographical degrees (spatial criterion) and also for at least two consecutive days (temporal criterion). These criteria may look weak for frosts during March but it is deterministic for the frosts during April and May in Iran when frosts are rare but harmful dramatically. Previously, some researchers defined the “wave” and “frost period” as the frost occurrence lasting more than two consecutive days (Rousta et al., 2016), or at a number of stations simultaneously (Tomczyk et al., 2015).

Furthermore, the study area is determined from 0° to 80°N and from the middle of Atlantic Ocean in the Western Hemisphere to Alaska (40°W–100°E). This widespread coverage facilitates the detection of macro-scale blocking in the mid-level troposphere during frosts. Figure 2 displays locations of the selected stations throughout Iran and highlights the location of Iran across the synoptic study area.

2.2 Methods

In the present study, the frost wave is considered to
occur when certain weather stations show frost records (WFS). In the first phase, one frost wave illustrates the temporal distance on the day of the first frost record at two or more (at least two) stations toward the next day at one or two stations, or vice versa at one or more (at least one) station toward the next day at two or more stations. Maybe this threshold criterion (two stations) seems very low, but frost waves in Iran during the first month of spring are pervasive and with low damage, but during the second month we have small but very full-damage frosts. Both of the two months mentioned above have windy frosts.

The final frost waves were selected as the most pervasive ones in spring of every year, and no frosts caused by radiative cooling were considered. That is to say, all the selected frosts are windy, not radiation. Of course, we know that almost all windy frosts have more or less radiation aspects, but we took into account only the dominant synoptic aspect, based on our spatial and temporal criteria.

Figure 3 illustrates the fluctuation of WF frequency for every year from the first day of spring (21 March) to its last day (21 June). Actually, this figure is a grouped graph composed of 47 small graphs, which are under each other. Every small graph is related to one year and its Y-axis starts from 0 to 20. The Y-axis is related to the frequency/number of WFs. The X-axis is graded per day from 21 March to 21 June. We set the figure like this for convenience of comparison from one year to another.

We found one typical frost for some years, such as the year 1993; two frosts for some other years, like the year 2004; and even more frosts such as in 1997. We simply checked the two frosts in 2014 as an example (Fig. 3). The lines of A and B illustrate the start and end of two frosts. We find the increase and then decrease in the frequency of WFs respectively during the several consecutive days. This criterion has already been used by Fatahi and Salehi-Pak (2009) and Schoetter et al. (2015).

We could usually find more than one frost wave every year and we calculated all of them for 47 years. There were 114 frost waves detected throughout Iran. Figure 3 also depicts the daily frequency of WFs for the two samples in 2014. During this year, except for scattered frosts, two major frost waves occurred. In this phase, we used the data of daily minimum air temperatures from 60 weather stations.

It is obvious that many researchers have also used the daily weather maps and datasets including the maps of temperature and zonal winds (Nieto et al., 2005), data of the relative vorticity and wind speed (Nascimento and Ambrizzi, 2002), data of the sea level pressure and 2-m temperature above the ground level (Andrei and Roman, 2012), and maps of the air thickness (Rousta et al., 2016). They used the mentioned maps and data to de-
termine blocking patterns, but the priority of the present investigation is the “long datasets for spring frosts in Iran,” including the daily temperature for a period as long as 47 yr, as well as daily weather maps, in order to determine more durable frosts and identify their associated synoptic patterns.

Frosts include the radiation and frontal types. Our focus in this investigation is frontal ones. Since Iran is located in low midlatitudes, if we define our spatial criterion of “more than two meteorological stations,” we could miss some frosts. It seems that frosts with records at two or more (at least two) stations over at least two degrees in latitude and longitude (Fig. 3) and so, during at least two consecutive days, are trifle or worthless, but such frosts in Iran and especially during spring are dangerous for citruses, palms, apples, and other fruits in gardens.

You can find not only many containable and pervasive frosts from 1968 to 2014 but also some small-scale frosts in several years including 1977, 1985, 2001, 2002, and 2008 (Fig. 3). Specifically, when one frost occurs at two meteorological stations with at least two geographic degrees’ distance and for at least two consecutive days in Iran during spring, we can still find temperatures above 0°C at several stations. That is, two stations with frosts in Iran with different climates during spring are similar to the two small apparent peaks of one great iceberg above the sea level.

After identifying the frost waves, their peak days were evaluated. The peak day is a day between the lines of A and B for every enduring frost (Fig. 3). For example, among 113 and 114 there were two frost waves in 2014. Frost No. 114 was found to be more enduring with its peak day appearing on 2 April 2014. This frost was identified as the most durable wave of 2014, and its 13th day of spring corresponded to 3 April, which was taken as its peak day.

In addition, five characteristics were determined for each durable frost. The first two ones, which were regarded as its general characteristics, are the “wave duration (day)” and “occurrence date.” The other three characteristics comprises of “the frequency of WFs,” “their mean temperatures,” and “type of blocking patterns.” The last one was determined on the daily weather map, by which Iran was affected.

Accordingly, we identified four blocking patterns for spring frosts in Iran. Previous researchers (Nieto et al., 2005; Park et al., 2014; Müller et al., 2015; Woollings et al., 2018) have already found similar patterns for other regions of the world. The identified blocking patterns in-
clude the cut-off low, dipole, omega, and rex types based on the weather maps that we extracted from the NCEP/NCAR. In order to illustrate the four mentioned blocking patterns, the following factors were taken into consideration.

1. The patterns of cut-off low and dipole blocking were determined based on the difference per gpm between the height center of the cut-off low (blue circle in Figs. 4a, b) and the height of the contour that surrounds this center freely (heavy-black curve in Figs. 4a, b). We did not find scientific references for this visual comparison on weather maps about blocking except for determining the dominant location of blocking over the Northern Hemisphere (Tyrlis and Hoskins, 2008), and we had to apply this technique for sorting out our synoptic patterns. For instance, Fig. 4a indicates the center of cut-

Fig. 3. Daily fluctuations of the frequency/number of weather stations with frost records (WFs) during spring of 1968–2014 and examples of two enduring frost waves in 2014 (inlet). Every bar (highlighted with a blue circle) displays the representative day (peak day) of every enduring frost wave.
off low blocking with a height of 5450 gpm in the east of Aral Lake and its surrounding free contour with a height of 5600 gpm. The difference between these two contours is 150 gpm. All the differences for all patterns, including the cut-off low and dipole blocking, were between 15 and 200 gpm, and they were categorized into three classes including the low-depth blocking (less than 70 gpm), medium depth blocking (71–140 gpm), and high depth blocking (over 140 gpm). The three blue circles on the lower left corner of Fig. 4a with three different radii denoting the small, medium, and large depth of low were initiative for illustrating these three categories on synoptic patterns. In these patterns, the southern axis of every cut-off low was drawn in a continuous blue curve under each circle.

(2) In order to identify the omega blocking pattern, the first outward and free contour, whose shape was similar to omega, was drawn along its height. This free contour indicated the position of omega blocking in relation with the study area (Fig. 4c).

(3) For the rex pattern, the reverse S shape of the nearest contour to Iran was basically used for identifying the pattern, given that the cold airflow first occurs westward around the ridge axis and then eastward around the trough axis (Fig. 4d).

3. Results

Table 1 indicates the descriptive statistics of WFs in Iran during the peak days of 47 durable frosts. The highest frequency of frost records appeared at stations Zanjan, Saghez, Abali, Shahrkord, Sanandaj, and Urmia cities, respectively. Further, the cities located near southern coasts were identified as the free-frost ones.

Figure 5 depicts the frequency of WFs and type of impacting atmospheric patterns for all the 47 durable spring frosts during 1968–2014 over Iran. The color of the bars and their letters determine the diversity of patterns during the 47 years, while the height of the bars specifies the frequency of WFs for every durable frost on its peak day. In addition, the highest bar indicates the most extensive frost on 25 March 1968 with 43 WFs, and the shortest bar reveals the smallest durable frost on 29 March 1979 with 3 WFs.

The deceleration of westerly winds and corresponding formation of blockings (Huang et al., 2007) accompan-
ied with the durable frost waves during a few days or even up to a couple of weeks. Figure 5 demonstrates that the role of blocking patterns in incurring more durable frosts during the four decades (1968–2014) has weakened perceptibly from 2005 to 2014. In a similar way, some researchers highlighted some related issues. For example, Stillmann et al. (2011) emphasized the changed position of blockings and their reduced cooling effect on northeastern Europe. Further, Nascimento and Ambrizzi (2002) reported a decrease in the blocking frequency and their intensity in Japan. In another study, Ghavidel et al. (2016) indicated a reduction in the trough depth as one of the principal factor for frosts since 2005 in Iran.

We think that the decrease of blocking frequency is related to the climate change. Blocking patterns modify the surplus and deficit of energy between polar and tropical realms. The deforestation, desertification, drying swamps and lakes, over-grazing, increasing of green-house gases, and melting glaciers and polar caps, are human activities that can change the gentle and low speed westerlies (causing blocking patterns) to turbulent and high speed ones (causing non-blocking ones).

Table 2 shows the characteristics of 47 durable spring frosts. The first metric is frost duration per year and the other four metrics, depending on its peak day, include its occurrence date, frequency of WFs, mean temperature, and atmospheric pattern on the weather maps. Based on the results, it is confirmed that the frosts that were caused by blocking were pervasive. The pervasive frost refers to the frost that covers the half or more of weather stations in Iran. Also, it is revealed that the frosts that were caused by non-blocking atmospheric patterns including trough and zonal westerlies, were small and limited. The coldest day among all the studied frosts was on 21 March 1990, equivalent to the first day of spring in Iranian Calendar. The mean temperature for all WFs has been calculated to be \(-4.62°C\). Additionally, the dominant atmospheric pattern was cut-off low.

3.1 **Cut-off low blocking pattern**

According to Llasat et al. (2007), the cut-off low
blocking is considered as the pool of cold air originating from the circulating westerly over the midlatitudes in the middle troposphere. They are large-scale systems that lead air masses from both nearby and distant lands such as North Africa and Caspian Sea toward the territory of Iran and even more farther territories such as Northwest India (Yadav et al., 2009, 2018). Nieto et al. (2005) declared that the cut-off low blocking is formed under the deep trough of westerly winds. Based on the present study, 18 cases of the cut-off low blocking occurred in Iran and the thus induced frosts lasted 11.4 days during 1968–2014. Although the durability of frosts due to cut-off lows was less than the others, the most durable frost with a 24-day duration belonged to the one induced by a cut-off low. This frost event took place in March 1991.

Figure 6a illustrates the distribution of cut-off low blocking at the mid-level of the troposphere. The center of each low-pressure system was highlighted in the form of circular blue. The magnitude of each circle per unit indicates the depth of the low pressure, and the blue curve indicates the length of trough. The dominant direction of trough axis across Iran is northeast–southwest. Barati et al. (2012) found this direction for winter frosts in higher latitudes, over the Turan Plain (Kazakhstan), which would facilitate the entry and durability of the continental polar and continental Arctic air masses to Iran. Further, the southern trough of Caspian Sea is one of the major atmospheric factors (Yadav et al., 2010), which penetrates in the cold air masses toward Iran with interpretations of the cold weather entry from Russia (Omidvar and Ebrahimi, 2012). This mechanism is similar to the anti-clockwise airflow originated from higher latitudes (Hozhbarpour and Alijani, 2007; Nazari-Pour and Rigi, 2016). Some researchers considered it as cold air advection (Azizi et al., 2008; Montazeri and Masoudian, 2011).
masses originated from Siberia, southern Scandinavia, and southern England toward western Iran during 1983–1984 (Barati and Abrifam, 2007). The center of depressions is generally located at 20°–70°N and 40°–60°N over the Northern Hemisphere. In general, deepening the trough leads to a reduction in the duration of frosts.

As shown in Fig. 7a, the infiltration of cold air was observed from the Caucasus region in Northwest Iran on the peak day of frost waves on 29 March 1979, while the penetration of cold weather from Kazakhstan was located in Northeast Iran on the frost day of 21 March 1990 Fig. 7b.

3.2 Dipole blocking pattern

According to Antokhina et al. (2018), the dipole blocking caused the cold air advection toward western Siberia during 2004–2016. Based on previous study results, the dipole blocking caused frost waves across Iran with temperatures below −20°C in January (Azizi et al., 2008). Figure 8 illustrates the dominant location of five dipole blockings, and the frosts that have a 15.4-day duration. It is worth noting that the direction of usual trough axis is northwest–southeast. In the present study, the findings revealed that the closed depression of troughs is more concentrated over lower latitudes from the west of Black Sea to the north of Aral Lake. Further, the most durable frost, which lasted 23 days (April 1969), was related to the dipole blocking. Park et al. (2014) evaluated 332 frost waves in eastern Asia, where their atmospheric patterns were blocking and others. Some of them (nearly 59 or 17%) resulted from the dipole blocking as dominant atmospheric patterns. The percentage for spring frosts was 10.6% over Iran.

3.3 Omega blocking pattern

Four omega blocking types were determined as they occurred in the first two weeks of April with the resulting frost waves lasting 13.3 days. The pattern of omega blocking (Fig. 9) displays that the cold air flows toward Iran, spreading from Scotland to the west of Siberia. Further, as shown in Fig. 9, the nearest omega patterns in Iran led to more severe frosts. The most severe frost with an average temperature of −3.2°C had a relatively high duration (15 days). This coincidence can be related to the location of the omega pattern over eastern Atlantic Ocean compared with the other three blocking types (cut-off low, dipole, and rex). The Omega blockings are usually formed far from Iran but its eastern arm is wide-spread toward Iran. This implies that, while this system approaches Iran gradually, its eastern tall arm pushes the cold air ahead into Iran.

3.4 Rex blocking pattern

Kim and Byun (2016) observed the rex blocking shaped as letter S in the landscape orientation during the occurrence of late frosts in the Korean Peninsula. Based
on the current investigation, the rex pattern caused four spring frosts in Iran among a total of 47 durable frost waves. The average duration of frost waves due to the rex pattern was 14.3 days. Although the most durable frost is not in the rex blocking group, its average durability lasts longer than other identified blocking patterns. As shown in Fig. 10, three rex blocking patterns among the four identified ones are located over 35°–55°N. These three patterns can be observed as a type called the high latitude blocking (Berrisford et al., 2007; Davini et al., 2014). One of the four patterns is characterized by the 5650-contour gpm, and the cold air flow has originated from more eastward (the northeast of Aral Lake) than others. Furthermore, the gray-dotted arrow confirms that the southern expansion of cold and dry air tongues is from the basin of Siberian High. It was drawn based on sea level charts. Park et al. (2014) identified the significance of these tongues in the cold air transmission. The fourth pattern has a more limited scale, which is formed in lower latitudes, and its frost wave lasted 12 days.

As shown in Fig. 11, the formation of zonal troughs, as well as low-velocity, cold air flow across the Middle–East Iran (including the central regions of Iran), is observed on the peak frost day of 25 March 1968.
Further, since the patterns related to the western trough and zonal flow pattern were not a part of blocking patterns, they were not discussed and covered in this study. However, it is worth noting that some researchers emphasized the role of the western trough pattern in incurring heavy precipitation (Yadav, 2017) and cold waves in the northwest and southeast of Iran (Khosravi et al., 2015; Ghavidel et al., 2016).

4. Summary and discussion

In Iran, the westerly winds (dominant midlatitude winds) start to blow from autumn. Many factors affect their speed and direction day to day, including the decrease and increase of their speed and direction (blowing from north, south, and west). These changes cause some atmospheric patterns that have been called the blocking patterns. The curvature of westerly winds on the upper air maps in the mid troposphere is manifested in the form of atmospheric blocking patterns including the cut-off-low, dipole, omega, and rex. By analyzing the data related to the minimum daily temperature during 47 years (1968–2014) from 60 weather stations in Iran and their daily weather maps for all the identified frost wave events, it was revealed that the usual durable spring frosts were strongly affected by two atmospheric patterns: the cut-off-low, and dipole. Other patterns, such as the rex and zonal trough, are with turbulent or gentle winds. The zonal pattern was related to energetic winds. These winds cause the frosts with duration of 6.5–11.7 days on average in Iran. Among the 47 durable frosts, 16
frosts had such conditions. The patterns related to the low-speed winds include the cut-off low, dipole, rex, and omega. These winds cause the frost with duration from 12.4 to 15.4 days on average in Iran.

In the midlatitudes of the Northern Hemisphere, large water bodies such as the Atlantic Ocean and Mediterranean Sea, play a moderating role for adjacent territories during winters, but the territory of Iran is far from
them and thus it is exposed to direct invasion of both turbulent and gentle westerly winds during spring. These invasions are recognized as the attacks of continental Arctic and continental Polar air masses. Thus, the frost hazard for Iran is serious, and it is more dangerous during the farming season such as spring. The origins of cold air masses are the northern regions of Iran, Europe, and Baikal Lake, respectively. The moderating role of Caspian Sea (Masoudian and Darand, 2013; Darand and Masoudian, 2015) and the barrier role of Alborz Mountain against northern winds is weakening from west to east and from north to south. Therefore, western, central, and eastern regions of Iran are not immune in comparison with northeast and northwest areas. The Zagros Mountain range is not extended enough to curb northwest cold winds. Further, it is not as integrated and wall-type as Alborz, although it has numerous piles and mid-range plains and basins, which contribute to the penetration of durable frost waves.

REFERENCES
Andrei, S., and I. Roman, 2012: Severe weather phenomena in southern Romania in association with blocking circulation over Euro-Atlantic area during the cold season. Rom. Rep.
Antokhina, O. Y., P. N. Antokhin, E. V. Devyatova, et al., 2018: 2004–2016 wintertime atmospheric blocking events over western Siberia and their effect on surface temperature anomalies. *Atmosphere, 9*, 72, doi: 10.3390/atmos9020072.

Azizi, G., T. Akbari, M. Davudi, et al., 2008: A synoptic analysis of January 2008 severe cold in Iran. *Phys. Geogr. Res. Quart., 41*, 316942. (in Persian)

Azizi, G., M. Miri, and M. Rahimi, 2015: Identification of synoptic patterns influencing formation of temperature anomalies in Iran and Europe. *Phys. Geogr. Res. Quart., 47*, 91–104, doi: 10.22059/jphgr.2015.53680. (in Persian)

Barati, G. H., and M. Abrifam, 2007: Kermashah Province and precipitable air masses. *Proc. Conference on Water Resources of Kermanshah Region, Kermanshah, 16 December, Ministry of Energy–Kermanshah Regional Water Authority*, 268–279. (in Persian)

Barati, G. H., B. Alijani, and A. Moradian, 2012: Mid-tropospheric trough and severe frosts in Iran. *J. Nat. Environ. Hazards, 1*, 63–78, doi: 10.22111/jenh.2013.2456. (in Persian)

Barriopedro, D., R. García-Herrera, A. R. Lupo, et al., 2006: A climatology of Northern Hemisphere blocking. *J. Climate, 19*, 1042–1063, doi: 10.1175/JCLI3678.1.

Berrisford, P., B. J. Hoskins, and E. Tylrlis, 2007: Blocking and Rossby wave breaking on the dynamical tropopause in the Southern Hemisphere. *J. Atmos. Sci., 64*, 2881–2898, doi: 10.1175/JAS3984.1.

Cohen, J., J. A. Screen, J. C. Furtado, et al., 2014: Recent Arctic amplification and extreme mid-latitude weather. *Nat. Geosci.*, 7, 627–637, doi: 10.1038/Ngeo2234.

Croci-Maspoli, M., C. Schwierz, and H. C. Davies, 2007: A multifaceted climatology of atmospheric blocking and its recent linear trend. *J. Climate, 20*, 633–649, doi: 10.1175/JCLI4029.1.

Darand, M., and S. A. Masoudian, 2015: Analysis and recognition of thickness anomaly patterns during extreme cold days in Iran. *Geogr. Res., 30*, 105–120. (in Persian)

Davini, P., C. Cagnazzo, P. G. Fogli, et al., 2014: European blocking and Atlantic jet stream variability in the NCEP/NCAR reanalysis and the CMCC-CMS climate model. *Climate Dyn., 43*, 71–85, doi: 10.1007/s00382-013-1873-y.

Fatahi, E., and T. Salehi-Pak, 2009: A synoptic patterns analysis of winter freezing in Iran. *Geogr. Dev., 13*, 127–136, doi: 10.22111/gdj.2009.1232. (in Persian)

Ghavidel, Y., M. Farajzadeh, and S. Motalebzad, 2016: Statistical and synoptic analysis of cold waves in North West of Iran. *Res. Geogr. Sci., 16*, 29–46. (in Persian)

Hong, C. C., and T. Li, 2009: The extreme cold anomaly over Southeast Asia in February 2008: Roles of ISO and ENSO. *J. Climate, 22*, 3786–3801, doi: 10.1175/2009JCLI2864.1.

Hozhbapour, P. G., and B. Alijani, 2007: Frost synoptic analysing of Ardabil Province. *Geogr. Dev., 10*, 89–106. (in Persian)

Huang, F., X. Y. Tang, S. Y. Lou, et al., 2007: Evolution of dipole-type blocking life cycles: Analytical diagnoses and observations. *J. Atmos. Sci., 64*, 52–73, doi: 10.1175/JAS3819.1.

Katsafados, P., A. Papadopoulos, G. Varlas, et al., 2014: Seasonal predictability of the 2010 Russian heat wave. *Nat. Hazards Earth Syst. Sci., 14*, 1531–1542, doi: 10.5194/nhess-14-1531-2014.

Khosravi, M., N. Safarzaie, and M. Armesh, 2015: Synoptic analysis of winter frosts in Sistan region (Case study: The Frost January 2008). *J. Geogr. Plan., 19*, 113–140. (in Persian)

Kim, J. A., and H. R. Byun, 2016: Spatiotemporal variability of the latest frosts in Korean Peninsula and causes of atmospheric circulation. *Meteor. Atmos. Phys., 128*, 663–675, doi: 10.1007/s00703-016-0439-z.

Lashkari, H., 2008: Synoptic analysis of surrounding cold wave 2003 in Iran. *Phys. Geogr. Res., 66*, 1–18.

Lashkari, H., and G. H. Keykhoosravi, 2010: Synoptic analysis of January 8th–15th 2006 cold wave in Iran. *Spat. Plan., 65*, 151–177. (in Persian)

Lejénäs, H., 1989: The severe winter in Europe 1941–42: The large-scale circulation, cut-off lows, and blocking. *Bull. Amer. Meteor. Soc., 70*, 271–281, doi: 10.1175/1520-0477(1989)070<0271:TSLCCO>2.0.CO;2.

Leviäkangas, P., A. Tuominen, R. Moliariu, et al., 2011: Extreme Weather Impacts on Transport Systems. VTT Working Papers 168, Technical Research Centre of Finland, Finland, 145 pp.

Llasat, M. C., F. Martin, and A. Barrera, 2007: From the concept of “Kaltlufttropfen” (cold air pool) to the cut-off low. The case of September 1971 in Spain as an example of their role in heavy rainfalls. *Meteor. Atmos. Phys., 96*, 43–60, doi: 10.1007/s00703-006-0220-9.

Masoudian, S. A., and M. Darand, 2013: Synoptic analysis of extensive and persistent frosts in Iran. *Geogr. Environ. Plan. J., 50*, 29–32. (in Persian)

Montazeri, M., and S. Masoudian, 2011: Temperature advection patterns analysis of Iran in cold years. *Phys. Geogr. Res., 42*, 79–94. (in Persian)

Müller, A., P. Névir, L. Schielicke, et al., 2015: Applications of point vortex equilibria: Blocking events and the stability of the polar vortex. *Tellus A: Dyn. Meteor. Oceanogr., 67*, 29184, doi: 10.3402/tellusa.v67.29184.

Nascimento, E. D. L., and T. Ambrizzi, 2002: The influence of atmospheric blocking on the Rossby wave propagation in Southern Hemisphere winter flows. *J. Meteor. Soc. Japan, 80*, 139–159, doi: 10.2151/jmsj.80.139.

Nazari-Pour, H., and A. B. Rigi, 2016: Interaction between Scandinavian Low Pressure with Siberian–European and North West of Iran High Pressure Systems (Aggregate high pressure system) associated with frost wave event in Iran: 11 to 15 January 2008. *Phys. Geogr. Res. Quart., 43*, 1–18. (in Persian)

Nieto, R., L. Gimeno, L. de la Torre, et al., 2005: Climatological features of cutoff low systems in the Northern Hemisphere. *J. Climate, 18*, 3085–3103, doi: 10.1175/JCLI3861.1.

Ömür, K., and A. Ebrahimi, 2012: The analysis of cold wave severity between 6 to 15 January 2008 in central provinces of Iran (Isfahan, Kerman and Yazd provinces). *Geogr. Environ. Plan. J., 23*, 81–98. (in Persian)

Park, T. W., C. H. Ho, and Y. Deng, 2014: A synoptic and dynamical characterization of wave-train and blocking cold surge over East Asia. *Climate Dyn., 43*, 753–770, doi: 10.1007/s00382-013-1817-6.

Peterson, T. C., R. R. Jr. Heim, R. Hirsch, et al., 2013: Monitoring
and understanding changes in heat waves, cold waves, floods, and droughts in the United States: State of knowledge. Bull. Amer. Meteor. Soc., 94, 821–834, doi: 10.1175/BAMS-D-12-00066.1.

Pezza, A. B., and T. Ambrizzi, 2005: Cold waves in South America and freezing temperatures in São Paulo: Historical background (1888–2003) and case studies of cyclone and anticyclone tracks. Rev. Bras. de Meteorol., 20, 141–158.

Porebska, M., and M. Zdunek, 2013: Analysis of extreme temperature events in Central Europe related to high pressure blocking situations in 2001–2011. Meteor. Z., 22, 533–540, doi: 10.1127/0941-2948/2013/0455.

Rahimi, M., S. Hajjami, A. Khalili, et al., 2007: Risk analysis of first and last frost occurrences in the Central Alborz Region, Iran. Int. J. Climatol., 27, 349–356, doi: 10.1002/joc.1405.

Rousta, I., M. Doostkamian, E. Haghighi, et al., 2016: Statistical–synoptic analysis of the atmosphere thickness pattern of Iran’s pervasive frosts. Climate, 4, 41, doi: 10.3390/cli4030041.

Ruddell, D., D. Hoffman, O. Ahmad, et al., 2013: Historical threshold temperatures for Phoenix (urban) and Gila Bend (desert), central Arizona, USA. Climate Res., 55, 201–215, doi: 10.3354/cr01130.

Schoetter, R., J. Cattiaux, and H. Douville, 2015: Changes of western European heat wave characteristics projected by the CMIP5 ensemble. Climate Dyn., 45, 1601–1616, doi: 10.1007/s00382-014-2434-8.

Sillmann, J., M. Croci-Maspoli, M. Kallache, et al., 2011: Extreme cold winter temperatures in Europe under the influence of North Atlantic atmospheric blocking. J. Climate, 24, 5899–5913, doi: 10.1175/2011JCLI4075.1.

Simmonds, I., and H. A. Rashid, 2001: An investigation of a dramatic cold outbreak over Southeast Australia. Aust. Meteor. Mag., 50, 249–261.

Snyder, R. L., and J. P. de Melo-Abreu, 2005: Frost Protection: Fundamentals, Practice, and Economics. Food and Agricultural Organization of the United Nations, Rome, 181 pp.

Tomczyk, A. M., K. Szyn-Pluta, and A. Majkowska, 2015: Frost periods and frost-free periods in Poland and neighbouring countries. Open Geosci., 7, 812–823, doi: 10.1515/geo-2015-0061.

Tyrlis, E., and B. J. Hoskins, 2008: Aspects of a Northern Hemisphere atmospheric blocking climatology. J. Atmos. Sci., 65, 1638–1652, doi: 10.1175/2007JAS2337.1.

Woollings, T., D. Barriopedro, J. Methven, et al., 2018: Blocking and its response to climate change. Curr. Climate Change Rep., 4, 287–300, doi: 10.1007/s40641-018-0108-z.

Yadav, R. K., 2016: On the relationship between Iran surface temperature and Northwest India summer monsoon rainfall. Int. J. Climatol., 36, 4425–4438, doi: 10.1002/joc.4648.

Yadav, R. K., 2017: Midlatitude Rossby wave modulation of the Indian summer monsoon. Quart. J. Roy. Meteor. Soc., 143, 2260–2271, doi: 10.1002/qj.3083.

Yadav, R. K., K. Rupa Kumar, and M. Rajeevan, 2009: Increasing influence of ENSO and decreasing influence of AO/NAO in the recent decades over Northwest India winter precipitation. J. Geophys. Res. Atmos., 114, D12112, doi: 10.1029/2008JD011318.

Yadav, R. K., J. H. Yoo, F. Kucharski, et al., 2010: Why is ENSO influencing Northwest India winter precipitation in recent decades? J. Climate, 23, 1979–1993, doi: 10.1175/2009JCLI3202.1.

Yadav, R. K., G. Srinivas, and J. S. Chowdary, 2018: Atlantic Niño modulation of the Indian summer monsoon through Asian jet. npj Clim. Atmos. Sci., 1, 23, doi: 10.1038/s41612-018-0029-5.

Yue, Y. J., Y. Zhou, J. A. Wang, et al., 2016: Assessing wheat frost risk with the support of GIS: An approach coupling a growing season meteorological index and a hybrid fuzzy neural network model. Sustainability, 8, 1308, doi: 10.3390/su8121308.