

# Evaluating the Effect of Heat Waves on Early Melting of Snow Covers of Karkheh Catchment in Iran

Ghasem Keikhosravi (✉ [Gh\\_keikhosravi@sbu.ac.ir](mailto:Gh_keikhosravi@sbu.ac.ir))

Shahid Beheshti University <https://orcid.org/0000-0002-3668-9394>

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## Research Article

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# Abstract

The present study aims to evaluate the effect of heat waves on the early melting of snow cover in the Karkheh catchment of Iran. After collecting daily data on the maximum temperature of meteorological stations in the catchment during the statistical period (2000-2019), three indices of WSDI, Baldi, and ocular method were used to determine the threshold of days with heat wave. By extracting the hot waves and applying programming, the snow cover maps were drawn in the Google Earth Engine system and the area of snow cover zones was calculated in the Model Builder environment. Finally, the atmospheric data were received from the NCEP/NCAR site and their generating patterns were examined after drawing in Grads software environment after determining the atmospheric synoptic patterns. The results indicated that the slope trend of hot waves is increasing at the catchment level. The average annual frequency of heat waves extracted for the snow cover growth period (November to May) was equal to 24 days of hot waves during the year. Regarding the ground pressure conditions and synoptic conditions of high atmospheric levels, two dominant synoptic patterns of heat waves were identified in the region as follows: 1) The Siberian high-pressure synoptic pattern at the ground level and the Saudi-African high-pressure ridge at high atmospheric levels. This synoptic pattern reduces snow cover area by an average of 40% in the Karkheh catchment and the highest frequency of the occurrence of this synoptic pattern is in February and March. 2) Pakistan-Africa low-pressure synoptic pattern at ground level and Saudi-African high-pressure ridge at high atmospheric levels, the frequency of the occurrence of which is higher in April and May months and reduces the snow cover area in the Karkheh catchment by an average of more than 55%.

## 1 Introduction

The extent and variability of snow covers are important parameters in hydrological and meteorological systems (Udnaes et al., 2007; Brown and Armstrong, 2010). In mountainous and snow-covered basins, snowmelt and its runoff play an important role in changes in the flow regime and have a major share in the production of flow and water resources. Snow reserves of mountain basins are among the important and reliable sources of the country. Snow accumulation in high-altitude parts of the mountains controls the seasonal pattern of runoff in the lower parts. The gradual melting of snow is considered an important source of river flow for feeding groundwater aquifers, as well as a crucial source of fresh water for domestic, agricultural, and hydroelectric uses. However, rapid and early melting of snow covers can impose significant environmental hazards. Communities that live along rivers are forced to flee their homes, due to the sudden melting of snow covers and the possibility of flooding. In case of rapid melting of snow covers, the melted water reaches the downstream of the basin in a short amount of time, resulting in losing the opportunity for infiltration and feeding of groundwater aquifers. The rapid melting of snow covers leads to severe avalanches in mountainous areas and causes the transfer of huge volumes of snow masses to downstream areas, imposing destructive effects on downstream of the basin. Concerning the geographical position of Iran relative to the general atmospheric circulation, precipitation occurs in the cold half of the year in most parts of the country. The precipitation period starts from the middle of October and continues until the end of May. In the southern half of the country, this precipitation period is even shorter, and it does not coincide with the peak consumption period. Therefore, freezing rains in the cold period of the year are ideal phenomenon in arid and semi-arid countries such as Iran, as most of these precipitations are stored naturally behind mountain dams for the construction of dams with the lowest cost, in addition to supplying water to springs during the warm period of the year with gradual melting. Karkheh catchment is located in the west of Iran, in the middle and southern regions of Zagros Mountains. The area of Karkheh is equal to 50764 square kilometers. Karkheh River is formed by joining the main rivers of Gamasiab, Qarah Su, Seimare, and Kashkan, each of which, along with the lower part of Karkheh River, has catchments which form the main sub-catchments of Karkheh. The mountainous areas of the catchment with about 27645 square kilometers are mostly concentrated in the eastern and middle parts while the plains and foothills with about 23119 square kilometers generally cover the northern and southern parts of the catchment. In terms of longitudinal and transverse expansion, massive heights of the Zagros Mountains are located at the upstream of the catchment, where most of the rainfall falls in the form of snow and accumulates during the cold period of the year. This massive snow is the source of the springs that supply the water of the Karkheh River and the water needed by the extensive agricultural fields, towns, and villages downstream of the catchment during the spring and summer seasons. In some years, the arrival of early warm waves in the last months of the cold period of the year (March and early April) causes rapid and intense snowmelt in the upstream basin and therefore, significant amounts of valuable water reserves become unreachable. Consequently, this issue causes flood risks at the upstream of the dam and sometimes necessitates discharging water from dams due to their limited capacity. The results of previous research indicate that snow cover

decreased in most parts of the world in recent years. For example, Seluchi et al. (2006) analyzed the synoptic and thermodynamic nature of the 2003 heat wave in the South American subtropical region and introduced the existence of stable atmosphere and the advection of temperature and humidity as the main cause of the creation of the heat wave and its intensity. Stewart et al. (2004) predicted the flow time of snowmelt runoff in the northwestern United States under climate change conditions. By using climate models and considering temperature and precipitation changes in the 21st century in the affected areas, it was found that the snowmelt runoff flew about 30 to 40 days earlier. By evaluating the climate change in Michigan province of United States, winter rainfall changes from snow to rain due to increased temperatures. Further, it is expected that the number of snowy days by the end of this century decreases each year by 30 to 50% in optimistic scenarios and between 45 to 60% in pessimistic scenarios. By studying anomalies and changes in the dynamic structure of summer synoptic patterns in southwestern Iran based on the warm wave index, Jamalizadeh et al. (2019) concluded that temperature abnormalities in the region had a positive trend at all levels and this upward trend had sometimes reached up to one degree.

Bednorz (2009) prepared combined maps of sea surface pressure and 500 hPa level while examining the synoptic conditions of rapid melting of snow covers in Poland and Germany plains for days when the snow depth decreased by 5 cm. The results highlighted that low- and high-pressure systems caused rapid melting of snow cover in the North Atlantic and the Mediterranean Sea (NAO positive phase), respectively. MacDonald et al., (2012) studied a number of snow models to complement observations, evaluate important snow processes, and develop appropriate models for Chinook wind conditions. The results of modeling indicated that snowmelt occurs during Chinook winds and snow covers are heavily melted or destroyed completely. By using non-parametric tests, Changchun et al., (2008) investigated the annual temperature and precipitation of 19 meteorological stations over a period between 1958 and 2002, and examined the effects of climate change on the snow cover of the Tarom River catchment. The results showed that the altitudes between 2500 and 5000 meters were a sensitive area and affected by climate change. Hayhoe et al. (2010) predicted that Chicago temperatures would rise between 2 and 3.5 degrees Fahrenheit in the near future (2010-39) and 2.5 to 9 degrees Fahrenheit between 2040 and 2069, although summer temperature would rise between 5 and 19 degrees Fahrenheit by the end of this century. Yonggang et al. (2013) examined the effect of climate change on the snowmelt runoff of the Kaido catchment in northwest China, using the HADCM3 model output with different scenarios. The results revealed an increase in runoff in spring and a significant decrease in summer. Sharma et al. (2012) used MODIS sensor data from 2000 to 2011 to investigate snow trends in the sub-basins of the Jhelum River catchments in the northwestern Himalayas. Based on the findings, the decreasing trend of snow cover is observed in all sub-catchments, especially in Banihal sub-catchment.

In another study, Huang et al. (2017) measured the snow cover of the Tibetan Plateau, by using MODIS sensor daily images during the period 2001-14 and applying the non-parametric Mann-Kendall test. The results revealed a significant decrease in the level of snow cover at the plateau surface, especially at its high areas. Cohen and Saito (2003), and Dery et al. (2005) found the correlation with delay between meteorological signals with the level of snow covers. Falarz (2007) mentioned the positive correlation between the snow cover and the North Atlantic Oscillation (NAO) in October (winter). The lack of stability and dependence of snow cover on atmospheric circulation in the twentieth century are almost related to the circulations of local changes/European meridian. Mayr and Armi (2008) showed that the blowing of warm winds and increased temperature could be large enough to lead to more evaporation, as well as melting mountain snow. The occurrence of Foehn wind can be a challenge in mountainous areas with recreational centers and ski slopes, in addition to its effects on water resources. By examining the historical trend of early thermal waves, the present study seeks to analyze the conditions of thermal waves in terms of frequency and duration, aiming to inform relevant authorities to respond appropriately in the case of increasing trend of waves or their durations. On the other hand, the patterns and origin of these heat waves are identified by evaluating the synoptic of thermal waves. Ultimately, by monitoring the atmospheric synoptic conditions, the necessary warnings to the inhabitants of the river and its tributaries are given by the relevant organizations in case of the occurrence of patterns similar to heat waves.

## 2 Data And Method

To evaluate the effect of heat waves on the early melting of snow cover in Karkheh catchment of Iran, three indices were used to determine the threshold of days with heat waves after collecting daily data on the maximum temperature of meteorological stations in the catchment during the statistical period (2000–2000) (Fig. 1).

1. WSDI index: According to this index, the duration of heat period or the heat wave represents the number of days of the year, which at least six consecutive days have the maximum temperature of more than 90th percentile of the base period (Ahmadi et al., 2015).

Baldi index: Based on Eq. (1), this index attempts to determine heat waves (Baldi et al., 2004; Keikhosravi, 2019; Rahimi et al., 2017; Omidvar et al. 2016).

$$HV = (M + 1.5\delta)$$

where HV represents heat wave, M indicates average daily temperature, and  $\delta$  shows the deviation from the daily temperatures criteria. To define the heat wave, the above relationship was calculated for all stations in the catchment, and then, we identified the days with the heat wave occurred in the statistical period (2000–2000), as well as the persistence of each heat wave in the region. Concerning the Baldi index, the values of zero and more than zero degrees represent the occurrence of heat waves while values less than zero indicate the absence of heat waves.

3. In the third method, after examining the length of heat waves based on WSDI and Baldi indices, the case study samples were specified to identify synoptic patterns among the identified heat waves. A sudden increase in temperature at selected stations over a period of several days such that the temperature rises uniformly on the graph to a temperature peak, and then, returns to a normal state uniformly.

4. After extracting heat waves in the Google Earth Engine system, programming was applied to extract snow cover maps during the heat wave period a few days before occurring heat waves.

5. To convert raster maps to vector maps and calculate the area of snow cover, the maps obtained from the Google Earth engine system were transferred to the GIS environment and the area of cover zones was calculated in the Model Builder environment.

6. In the last step, to determine the atmospheric synoptic patterns, all the selected samples of heat waves, the cover zone area of which was prepared on the days of occurrence and before the occurrence of heat waves, as well as high atmospheric data including geo-potential altitude, sea level pressure, temperature, wind orbit, and meridian were received from NCEP/NCAR site and ultimately, their generating patterns were examined after drawing in Grads software environment.

### 3 Research Findings

The index (WSDI) shows the index variation trend in the 90th percentile of the maximum temperature for each year during the statistical period. By utilizing this index, it is possible to represent the behavior of hot extreme values. As shown in Figure (3), the trend of this index for the 90th percentile is different at the catchment level for different stations. The highest increasing slope of heat waves belongs to Pol-e Dokhtar stations with slope (0.751), followed by Kangavar (0.501), Ilam (0.428), and Malayer (0.383), respectively.

The average annual frequency of heat waves extracted in the studied statistical period (2019 – 2000) in Karkheh catchment is equal to 24 days of heat wave during the year for cold seasons of the year (November, December, January, February, March, April, May) based on the Baldi index. The frequency of the occurrence of heat waves during the year is 15.6% in January, 15% in February and March, 16.2% in April, 9.7% in May, 11.1% in November, and 17.5% in December. In general, the average incidence of heat waves in each month of the year is between 2 to 4 days. The highest occurrence of heat waves belongs to heat waves of 1, 2, 3, and 5 days with a total frequency of 117, 80, 61, and 50 days during the statistical period, respectively (Table 1).

Table 1  
Continuity of heat waves of 1 to 22 days in Karkheh catchment (2000–2019)

Year	Continuity of heat waves																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	22
2000	6	4	4	3	2		2	2		1	1									
2001	5	3	5	3	3		1	1		1	1									1
2002	8	2		7	1		3	2		1	1				1					
2003	9	9	3	2	1	1	1	1		2						1				
2004	4	6	4	1	4	3	1	1			1	1								
2005	2	4	3	2	4			1	1				1		1				1	
2006	9	4	3	3	2	6	3	1					1							
2007	6	5	3	2	1		3	1	1	1	1	1								
2008	5	4	3	3	2	2			2				1					1		
2009	9	2	1	1	1	2	2			1	1		1			1				
2010	5	3	3		1	1				2	1	1			1					1
2011	4	6	3	1	2	3	2		1					2						
2012	7	3	4	2	4		1		1				1	2						
2013	8		4	2	6		1	2		3										
2014	4	5	2	3	2		1		1	2	1		1							
2015	5	7	5		5	2	2		1		1		1							
2016	5	2		1	3		1			2	1			2					1	
2017	8	1	4	1		5	2	1	1		2									
2018	3	5	3	1	4	1	1		1				2		1					
2019	5	5	4	1	2	2	2	1	2						1					
Sum	117	80	61	39	50	28	29	14	12	16	12	7	9	4	3	2	1	2	1	1

To extract the synoptic patterns of heat waves and find their origin, the steps of the index waves were selected based on the results of WSDI and Baldi indices.

The temperature increase was coordinated in all stations.

The wavelength period should be lasted for at least 7 days as synoptic systems have a lifespan of 7 to 10 days (Alijani, 2013).

Based on these conditions, 38 heat waves were identified during the statistical period. Then, two dominant synoptic patterns of heat waves were identified in the region based on the ground surface pressure and the synoptic conditions of the high atmospheric levels.

### 3.1 Siberian high-pressure synoptic pattern at ground level and Saudi-African high-pressure ridge at high atmospheric levels

During the cold period of the year, the vast land of Central Asia, East, and especially Siberia lost a lot of energy through long wave radiation, due to the long distance from water sources and the lack of necessary moisture and clear skies. Therefore, the air near the earth cools down intensely and a high-pressure center is formed. The first sign of the formation of this high pressure is the

creation of a closed curve in September around Lake Baikal, which gradually increase in intensity with the continuation of the cold season (Alijani, 2008). By receiving properties from the ground, this high pressure is a thermal system and it does not have a deep depth. It enters Iran through two main routes: 1) After entering the Caspian Sea, it enters from the northwest Iran. 2. From the northeast and east of Iran. When this system enters Iran from the second route, if it is located in the mountainous areas, it usually stops behind the mountainous obstacles due to the shallow depth of the system. However, it climbs the mountainous obstacles if they are deep, accompanied by subsidence in the foothills of the mountains. This subsidence in the wind slope is accompanied by an increase in atmospheric temperature due to its adiabatic heat. These conditions are observed in Karkheh catchment because the presence of Zagros Mountains in the east of Karkheh catchment causes an increase in temperature in the study area because of the adiabatic heating. Table 2 and Fig. 4 provide the conditions of snow cover in the catchment at the time of occurrence of the heat wave and the times before the occurrence of the heat wave in this synoptic pattern. The occurrence of this pattern reduces the area of snow cover zone in the catchment by an average of 40%. For example, Sect. 3.1.1 presents a synoptic study of the sample of this model.

Table 2

Conditions of snow cover in the days of occurrence and absence of heat wave in the Siberian high-pressure pattern

Number	Heat wave	Time	Warm wave period by day	Snow cover area in km <sup>2</sup>	Ground surface conditions	High atmosphere conditions
1	Heat wave	25.2.2016-14.3.2016	18	677.8	Siberian high-pressure	Saudi Arabia anticyclone
	A few days before the heat wave	14.2.2016-25.2.2016	11	9874.4	-	-
2	Heat wave	1.3.2004-11.3.2004	11	777.3	Siberian high-pressure	Saudi Arabia anticyclone- Africa ridge
	A few days before the heat wave	22.2.2004-1.3.2004	7	1985.9	-	-
3	Heat wave	4.2.2018-15.2.2018	12	2105.1	Siberian high-pressure	Saudi Arabia anticyclone- Africa ridge
	A few days before the heat wave	27.1.2018-4.2.2018	7	7575.2	-	-
4	Heat wave	3.11.2013-10.11.2013	8	147.36	Siberian high-pressure	Saudi Arabia anticyclone- Africa ridge
	A few days before the heat wave	26.10.2013-3.11.2013	6	1221.45	-	-
5	Heat wave	7.3.2009-16.3.2009	10	881.84	Siberian high-pressure	Saudi Arabia anticyclone- Africa ridge
	A few days before the heat wave	1.3.2009-7.3.2009	6	1768.5	-	-
6	Heat wave	18.3.2008-31.3.2008	14	248.76	Siberian high-pressure	Africa ridge
	A few days before the heat wave	12.3.2008-18.3.2008	7	755.48	-	-
7	Heat wave	20.3.2018-3.4.2018	13	200.29	Siberian high-pressure	Africa ridge
	A few days before the heat wave	8.3.2018-20.3.2018	12	448.44	-	-
8	Heat wave	27.2.2015-28.2.2015	2	2932.68	Siberian high-pressure	Saudi Arabia ridge
	A few days before the heat wave	24.2.2015-27.2.2015	3	8201.4	-	-
9	Heat wave	1.11.2012-12.11.2012	12	32.88	Siberian high-pressure	Saudi Arabia anticyclone
	A few days before the heat wave	24.10.2012-1.11.2012	8	78.87	-	-
10	Heat wave	9.3.2008-11.3.2008	3	984.99	Siberian high-pressure	Africa ridge
	A few days before the heat wave	6.3.2008-9.3.2008	3	1512.71	-	-

Number	Heat wave	Time	Warm wave period by day	Snow cover area in km <sup>2</sup>	Ground surface conditions	High atmosphere conditions
11	Heat wave	17.4.2007-19.4.2007	3	384.32	Siberian high-pressure	Saudi Arabia anticyclone
	A few days before the heat wave	13.4.2007-17.4.2007	4	940.08	-	-
12	Heat wave	16.2.2005-28.2.2005	13	12802.8	Siberian high-pressure	Saudi Arabia anticyclone
	A few days before the heat wave	10.2.2005-16.2.2005	6	28537.2	-	-
13	Heat wave	20.2.2017-1.3.2017	10	10641.6	Siberian high-pressure	Saudi Arabia anticyclone
	A few days before the heat wave	13.2.2017-20.2.2017	8	16461.6	-	-
14	Heat wave	7.11.2002-13.11.2002	7	89.31	Siberian high-pressure	Africa ridge
	A few days before the heat wave	1.11.2002-7.11.2002	6	89.66	-	-
15	Heat wave	7.3.2010-18.3.2010	12	595.47	Siberian high-pressure	Saudi Arabia anticyclone
	A few days before the heat wave	1.3.2010-7.3.2010	6	4447.47	-	-
16	Heat wave	13.3.2013-17.3.2013	5	486.35	Siberian high-pressure	Africa ridge
	A few days before the heat wave	8.3.2013-13.3.2013	5	3313.3	-	-

### 3.1.1 Siberian high-pressure Hybrid Pattern and Saudi anticyclone (Sample, February 20 to March 1, 2017)

It is worth noting that the heat wave lasts for 10 days in this case study sample. During these 10 days, snow cover loses about 5820 square kilometers (64%) of its area compared to a few days ago (Fig. 5). Figure 6 shows the synoptic conditions prevailing in different atmospheric levels for the heat wave peak day, i.e. for February 28, 2017. As shown on the sea level maps, the anticyclonic center with a central pressure of 1029.6 hPa is located between Lake Baikal and Balkhash. A tongue of this anticyclone is in the east-west direction while the other tongue is in the northeast-southwest direction with the expansion of the west side, the northwestern and central part of Iran. The confrontation of these two pressure tongues has directed the currents of study area to the west, and thus, these currents are accompanied by subsidence after climbing on the roughness of the Zagros mountain range in the foothills of the mountains. This subsidence flow in the wind slope is accompanied by an increase in atmospheric temperature due to the resulted adiabatic heat. As shown in Figure (6A), the wind speed is very slow due to subsidence and increased temperature in the Karkheh catchment. Such synoptic conditions are observed up to the level of 850 hPa. In the middle layer of troposphere (levels of 700 and 500 hPa), Saudi Arabia anticyclone and its ridge replaces the Siberian high pressure in the lower layer. In this layer, Saudi Arabia anticyclone is located on the Arabian Peninsula. The ridge of this anticyclone in the southwest-northeast direction covers the whole area of Iran, except the eastern strip. The hot currents resulting from the anticyclone on the African desert, the transfer of these currents to the Saudi ridge, and the adiabatic descent of these currents in the ridge increase the temperature in the region.

### **3.2 Pakistan-Africa-Saudi Arabia low-pressure synoptic pattern at ground level and Saudi-African high-pressure synoptic pattern at high atmospheric levels**

Regarding the lack of vegetation and angle of radiation in the hot months of the year, the southeast of the country and the regions of Pakistan, Saudi Arabia, and Africa are considered as high-energy areas. The Pakistan low pressure is a thermal low pressure and usually starts to form in late April. With the availability of ground conditions, this system emerges with Persian Gulf low pressure on the Arabian Peninsula and generates heat in most regions of the west, southwest, south, and southeast of the country. In the case of occurrence, these synoptic conditions reduce the average snow cover area by more than 55% in the Karkheh catchment (Table 3, Fig. 7). For example, a synoptic analysis is conducted on two samples of this pattern in Sect. 3.2.1 and 3.2.2.

Table 3

Conditions of snow cover in the days of occurrence and absence of heat wave in the Pakistan - Saudi Arabia low- pressure and Saudi Arabia anticyclone

Number	Heat wave	Time	Warm wave period by day	Snow cover area in km <sup>2</sup>	Ground surface conditions	High atmosphere conditions
1	Heat wave	17.5.2012-21.5.2012	5	18.1	Pakistan low-pressure	Saudi Arabia anticyclone
	A few days before the heat wave	11.5.2012-17.5.2012	6	41.98		
2	Heat wave	18.5.2015-24.5.2015	7	4.74	Pakistan low-pressure	Saudi Arabia anticyclone
	A few days before the heat wave	14.5.2015-18.5.2015	4	7.9		
3	Heat wave	19.4.2005-26.4.2005	8	444.7	Saudi Arabia low-pressure	Saudi Arabia anticyclone
	A few days before the heat wave	16.4.2005-19.4.2005	3	624.6		
4	Heat wave	23.5.2019-31.5.2019	9	105.58	Pakistan low-pressure	Africa anticyclone
	A few days before the heat wave	19.5.2019-23.5.2019	4	119.34		
5	Heat wave	11.5.2011-13.5.2011	3	40.96	Pakistan low-pressure	Saudi Arabia anticyclone
	A few days before the heat wave	7.5.2011-11.5.2011	4	86.08		
6	Heat wave	13.5.2001-17.5.2001	5	38.08	Pakistan low-pressure	Saudi Arabia ridge
	A few days before the heat wave	5.5.2001-13.5.2001	8	112.6		
7	Heat wave	19.5.2011-24.5.2011	6	23.39	Pakistan low-pressure	Saudi Arabia anticyclone
	A few days before the heat wave	13.5.2011-19.5.2011	6	380.57		
8	Heat wave	22.5.2001-31.5.2001	10	20.2	Pakistan low-pressure	Saudi Arabia ridge
	A few days before the heat wave	12.5.2001-22.5.2001	10	32.38		
9	Heat wave	26.4.2010-30.4.2010	5	51.7	Pakistan low-pressure	Africa anticyclone
	A few days before the heat wave	19.4.2010-26.4.2010	7	69.18		
10	Heat wave	22.3.2006-28.3.2006	7	137	Africa, Pakistan low-pressure	Saudi Arabia anticyclone
	A few days before the heat wave	15.3.2006-22.3.2006	7	276.94		
11	Heat wave	28.3.2012-31.3.2012	4	734.64	Africa, Pakistan low-pressure	Saudi Arabia ridge
	A few days before the heat wave	23.3.2012-28.3.2012	5	802.85		

Number	Heat wave	Time	Warm wave period by day	Snow cover area in km <sup>2</sup>	Ground surface conditions	High atmosphere conditions
12	Heat wave	17.3.2011-23.3.2011	7	2458.5	Africa, Pakistan low- pressure	Saudi Arabia ridge
	A few days before the heat wave	11.3.2011-17.3.2011	6	6334.7		

### 3.2.1 Sudan low-pressure hybrid pattern and Saudi anticyclone (Sample, March 17 to 21, 2011)

This synoptic pattern is a combination of two Sudan low-pressure systems in the lower layer of the troposphere and the Saudi anticyclone in the middle layer of the troposphere and creates this heat wave. In this study sample, the heat wave lasts for 7 days. During this 7-day period, the snow cover loses about 3876 square kilometers (38%) of its area compared to the previous days (Fig. 8). Figure 9 shows the synoptic conditions and arrangement of systems at different atmospheric levels in the sample pattern of heat waves on the date (21/3/2011). In this pattern, a strong thermal low-pressure center with 1008.7 hPa is formed at sea level on Sudan and Saudi Arabia. After crossing the Red Sea and the west of Saudi Arabia, a tongue of this low pressure along the south north covers the entire area of western Iran to the eastern Mediterranean. In the lower level of troposphere, the geopotential height of 60 m is the same as the ground level. These conditions have strengthened the southern currents in the lower levels and caused the advection of warm air at the tropical latitudes over the study area. The air flow over the region is very slow and tends to be calm and relaxed. This relative stillness of the air in this layer and the lower layer has increased the heat intensification in the lower layer of troposphere. The heat core with a temperature above 37°C at the level of 1000 hPa is located in the center of this thermal anticyclone both in Pakistan and in the deserts of Saudi Arabia and Africa, which extends to the central half of the country and the study area so that the temperature in the studied region is above 27°C. With meridional motion, the currents cause the transfer of hot air from the southern latitudes to the study area (Fig. 9b). In the middle layer of troposphere (700 and 500 hPa levels), the Saudi Arabia anticyclone and the resulting ridge replace the thermal low pressure in the lower layer. In this layer, Saudi Arabia anticyclone is located in Sudan and southwestern Saudi Arabia. The ridge of this anticyclone in the southwest-northeast direction covers the whole area of Iran, except the northwest strip. As observed, the wind speed in the middle layers is very low and is almost slow and motionless. This vertical arrangement indicates the stability of the atmosphere in the middle layer, and these synoptic conditions prolong the heat wave continuation, by stabilizing and intensifying the heat advection on the catchment (Figs. 9c and d).

### 3.2.2 Low-pressure pattern of Pakistan, Sudan, and Saudi Arabia (Sample, April 19–26, 2005)

In this study sample, the heat wave lasts for 8 days, during which snow cover loses about 71% of its area, compared to the previous days (Fig. 10). Figure 11 shows the synoptic conditions and arrangement of systems at different atmospheric levels in the heat wave pattern in the date (2005/04/24). At sea level in this model, a strong thermal low-pressure center with a pressure of 1007.6 hPa is formed on northern Saudi Arabia and southern Iraq, which extends to the southwest and west of Iran. In the lower level of troposphere, the geopotential height of 75 meters is formed as the position of the ground level conditions. The hot core with a temperature above 37°C at the level of 1000 hPa is located in the center and the eastern side of this thermal anticyclone that extends to the central half of the country and the study area. Considering the meridional motion, currents transfer hot air from the southern latitudes to the study area. These synoptic conditions continue up to the level of 850 hPa. In the middle levels (700 and 500 hPa), the Saudi Arabia anticyclone center with a very wide ridge in the southwest-northeast direction covers the entire territory of Iran and extends in the same direction to the north of Iran. Regarding the location of the Karkheh catchment area adjacent to the anticyclonic central core, the air flow in the middle layer is very calm and indicates the stillness and subsidence of the air on this area. Thus, the air temperature at the levels of 500 and 700 hPa is – 9 and more than 16°C, respectively. As shown, the hot cell nucleus is located right on the Karkheh catchment and this temperature arrangement indicates a very strong dynamic temperature descend over the region. In this way, the heat intensity of the surface layer is intensified with the heating resulting from the adiabatic descent on the area.

## 4 Conclusion

So far, the results of some research have shown that a similar upward trend in heat wave frequency occurred in Europe, Australia, and most of Asia since the mid-twentieth century (Hartman et al., 2013; Pu et al., 2017). Despite the lack of agreed global definition for heat wave, such events include a period of several days or more with high temperatures which are above average, leading to human mortality and damage to vegetation, as well as the rapid melting of snow due to its stress. (Hunt, 2007). Heat waves can affect various sectors including water resources and consumption, agricultural products, food security, environment, and the like in such a way that heat waves with the rapid melting of snow cover in mountainous basins can provide significant amounts of valuable water reserves. The gradual melting of snow covers strengthens the groundwater aquifers and vegetation of the region and therefore, the arrival of a heat wave causes a huge volume of snow to melt, turns into runoff, and eventually evaporate due to the high temperature of the region. The present study aimed to investigate the frequency of heat waves and identify the synoptic patterns of heat waves on the Karkheh catchment. To identify heat waves, three indicators were used to measure the characteristics such as intensity, frequency, and durability of heat waves. The results indicated that the slope of the heat wave trend is increasing in the studied statistical period. Apart from 1-day heat waves, which cannot be called heat waves according to most geographers, the most frequent heat waves in the region belonged to 2-, 3-, and 5-day heat waves. The average annual frequency of heat waves extracted for the months (November, December, January, February, March, April, May) in Karkheh catchment is equal to 24 days of heat waves during the year, among which January, February, and March with the highest incidence rate of more than 15% had the highest frequency among the months. Based on the surface pressure conditions and the synoptic conditions of the upper atmospheric levels, two predominant synoptic patterns of heat waves were identified in the region, which include the Siberian high-pressure synoptic pattern in the ground surface and Saudi Arabia high pressure – Africa Ridge at high atmospheric levels. This synoptic pattern, if it occurs, reduces the snow cover in the Karkheh catchment by an average of 40%. The highest frequency of the occurrence of this synoptic pattern is in February and March. In this synoptic pattern at the ground level, Siberian high pressure is formed outside the territory of Iran (Siberian desert) with its penetration and expansion to the region. Specifically, the Karkheh catchment is forced to climb on this roughness due to colliding with the Zagros roughness. This current ascends and is accompanied by subsidence in the foothills of the mountains. The subsidence flow in the windward slope is accompanied by an increase in atmospheric temperature due to the resulting heat. At high altitudes (the middle layer of the troposphere), Saudi Arabia high-pressure, Africa, and in some cases, the Saudi Arabia ridge dominate the region. Under such conditions, the hot currents resulting from the vortex on the African desert and the transfer of these currents to the Saudi Arabia ridge, as well as the adiabatic descent of these hot air currents in the region, increase the surface temperature in the Karkheh catchment. 2) Pakistan-Africa low-pressure synoptic pattern and Saudi Arabia high-pressure at ground level and Saudi-African high pressure at high atmospheric levels. The frequency of occurrence of this synoptic pattern is higher in April and May. This synoptic pattern, on average, reduces snow cover by more than 55% in the Karkheh catchment. In warm seasons, southern latitudes (below 30° N), Pakistan, the Saudi Arabia desert, and Africa are considered in high-energy areas due to the lack of vegetation and more vertical radiation angle. The thermal low pressures formed at ground level in these areas, with a counterclockwise rotation in the hot, dry weather of the Saudi deserts, transport Iraq to the south and southwest of Iran. These conditions cause the Karkheh catchment to experience high temperatures with greater intensity and frequency due to its proximity to the above deserts. In the Middle troposphere (700 and 500 hPa levels), due to the high altitude expansion of Saudi Arabia, the adiabatic air descend occurs and simultaneously, with the formation of low thermal pressure centers in the lower troposphere, hot and dry air suction in the surrounding desert areas on the surface of Karkheh catchment causes heat waves to occur.

## Declarations

## Conflict of interest

The author declare no conflict of interest.

## References

1. Ahmadi M, Lashkari H, Keikhosravi Q, et al (2015) Analysis of temperature limit indices in detecting climate change in Greater Khorasan, *Journal of Geography*, Volume 13, Number 45, pp. 75-53.

2. Alijani B (2008) Iran's Weather; Eighth edition; Tehran; Payame Noor University Press.
3. Alijani B (2013) Synoptic climatology; Sixth edition; Tehran, Publication of Samt.
4. Baldi M, Giovanni D, Giampiero M, et al (2004) Heat Wave in the Mediterranean Region Analysis and Model Results. Institute of Biometeorology–Cnr.Rom, Italy (No, 10).
5. Brown R, Armstrong RL (2010) Snow-cover data measurement, products and sources in snow and climate. In Physical Processes, Surface Energy Exchange and Modeling, Armstrong RL, Brun E (eds). Cambridge University Press: Cambridge, UK
6. Bednorz E (2009) Synoptic conditions for rapid snowmelt in the Polish-German lowlands, Theor Appl Climatol 97:279–286, DOI 10.1007/s00704-008-0063-z.
7. Dery S J, Sheffield J, Wood E F (2005) Connectivity between Eurasian snow extent and Canadian snow mass and river discharge. Journal of Geophysical Research 110(023106). DOI: 10.1029/2005JD006173.
8. Changchun X, Yaning C, Weihong L, et al (2008) Potential impact of climate change on snow cover area in the Tarim River basin, Environ Geol 53:1465–1474, DOI 10.1007/s00254-007-0755-1.
9. Cohen J, Saito K (2003) Eurasian snow cover, more skillful in predicting U.S. winter climate than the NAO/AO, Geophysical Research Letters 30(23): CLM 3-1–3-4, <https://doi.org/10.1029/2003GL018053>.
10. Falarz M (2007) Snow cover variability in Poland in relation to the macro- and mesoscale atmospheric circulation in the twentieth century, Int.J. Climatol. 27:2069–2081, DOI:10.1002/joc.1505.
11. Huang X, Deng J, Wang W, et al (2017) Impact of climate and elevation on snow cover using integrated remote sensing snow products in Tibetan Plateau. Remote Sensing of Environment, 190, 274-288, <https://doi.org/10.1016/j.rse.2016.12.028>.
12. Hunt B.G (2007) A Climatology of Heat Waves from a Multimillennial Simulation. Journal of Climate 20(15):3802-3821, DOI: 10.1175/JCLI4224.1
13. Hayhoe K, VanDorn J, Croley T, et al (2010) Regional climate change projections for Chicago and the US Great Lakes. Journal of Great Lakes Research, Supplement 2, Vol. 36, 7-21, <https://doi.org/10.1016/j.jglr.2010.03.012>.
14. Hartman D L, Klein Tank A M G, Ruscicucci M, et al (2013) Observations: Atmosphere and Surface. In, Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (eds.) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, GB. Cambridge University Press, pp. 159-254.
15. Jamalizadeh N, Manizheh Z, Iashkari H, et al (2019) Anomalies Analysis and Changes in the Dynamic Structure of Summer Patterns in Khuzestan Province. Geography (Regional Planning), 9(4), 863-874.
16. Keikhosravi Q (2019) The effect of heat waves on the intensification of the heat island of Iran's metropolises (Tehran, Mashhad, Tabriz, Ahvaz). Urban Climate (28), 100453. <https://doi.org/10.1016/j.uclim>.
17. MacDonald M K, Essery R, Pomeroy J W (2012) Effects of Chinook winds (foehn) on snow cover in western Canada. EGU General Assembly 2012, held 22-27 April, 2012 in Vienna, Austria, p.13690, bibcode:2012GUGA..1413690M.
18. Mayr G, Armi L (2008). Foehn as a response to changing upstream and downstream air masses, Quart, J, Roy. Meteor, Soc, 134, 1357-1369, Doi: 10.1002/qj.295.
19. Omidvar K, Mohmoud Abadi M, Olfati S, et al (2016) Statistical survey of the occurrence of heat waves in the selected stations of Kermanshah province. J. Nat. Environ. Hazard. Year 5, 1–24 No. 10.
20. Pu X, Wang T J, Huang X, et al (2017) Enhanced surface ozone during the heat wave of 2013 in Yangtze River Delta region. China, Science of the Total Environment, 1-10, <https://doi.org/10.1016/j.scitotenv.2017.03.0506>.
21. Rahimi D, Mir Hashemi H, Alizadeh T (2017) Analysis of the structure of heat waves in the west and southwest of Iran. J. Geography Environ. Plan. 67 (3), 69–80 Year 28, Successive.
22. Stewart I T, Cayan D R, Dettinger M D (2004) Changes in snowmelt runoff timing in western north america under Business as usual climate change scenario, Climate change Journal 62, 217-232.
23. Sharma V, Mishra V, Joshi P (2012) Snow cover variation and stream flow simulation in a snow-fed river basin of the Northwest Himalaya; Journal of Mountain Science, Vol 9:853-868, <http://dx.doi.org/10.1007/s11629-012-2800-0>.

24. Seluchi M, Norte F, Gomes J, et al (2006) Synoptic and thermodynamic analysis of an extreme heat wave over subtropical South America, Proceedings of 8 ICSHMO Foz do Iguacu Brazil April 24-28 2006 INPE p 2009-2010.
25. Udnaes H, Alfnes C E, Andreassen L M (2007) Improving runoff modeling using satellitederived snow cover area. Nord. Hydrology Research 38 (1): 21–32. <https://doi.org/10.2166/nh.2007.032>.
26. Yonggang M A, Yue H, Xi C, et al (2013) Modelling Snowmelt Runoff under climate change scenarios in an ungauged Mountainous watershed, Northwest China. Mathematical problems in Engineering. Article ID 808565, 9 pages, <https://doi.org/10.1155/2013/808565>.