Iranian Journal of Geophysics, Vol 16 No 4, 2023, Page 101– 112 (Research Article)
DOI: 10.30499/ijg.2022.340751.1422

Recognition of patterns and synoptic analysis of rainstorm in western Iran based on thermodynamic instability indices: A case study of Ahvaz

Bromand Salahi[1*] and Mahmoud Behrouzi[2]

[1] *Professor, Department of Physical Geography, University of Mohaghegh Ardabili, Ardabil, Iran*
[2] *Ph.D. in Climatology, Environmental Hazards, Marine Science Institute, Kish International Campus, University of Tehran, Tehran, Iran*

(Received: 9 May 2022, Accepted: 20 August 2020)

Abstract

In this research, patterning of rainstorm (more than 10 mm) was conducted by instability indices in Ahvaz. At first, rainfall data from 2000 to 2015 was extracted and statistically examined. Instability indices for rainy days were calculated by the Skew-T diagram. Then, patterning was done by using hierarchical clustering, Ward method, and Euclidean distance. As the sample, one day was selected from each cluster and was synoptically analyzed. The results revealed 60 rainstorms for the respective period. More rainstorms occurred in January and December. Autumn and winter had the most frequent days of rainstorm, while it did not occur in the summer. The results of classification divided rainstorms into 4 patterns and more days were in the fourth class, while the least was in the second class. In the second and fourth classes, instability indices were severe and could predict possible rainstorms, but the first and third classes couldn't predict because synoptic systems caused the occurrence of the rainstorm. In the second and fourth classes, rainstorms were convectional. The synoptic analysis showed that every time rainstorm occurred in Ahvaz, a deep trough at 500 hPa was formed in the East Mediterranean and the area was in front of it. Also, at sea level pressure, a low-pressure system formed in Iraq and winds got humid by passing through the Persian Gulf and entered into the atmosphere of Ahvaz. Due to the unstable atmosphere, the air would rise to heights causing rainstorm.

Keywords: Rainstorm, instability indices, clustering, synoptic analysis, Ahvaz

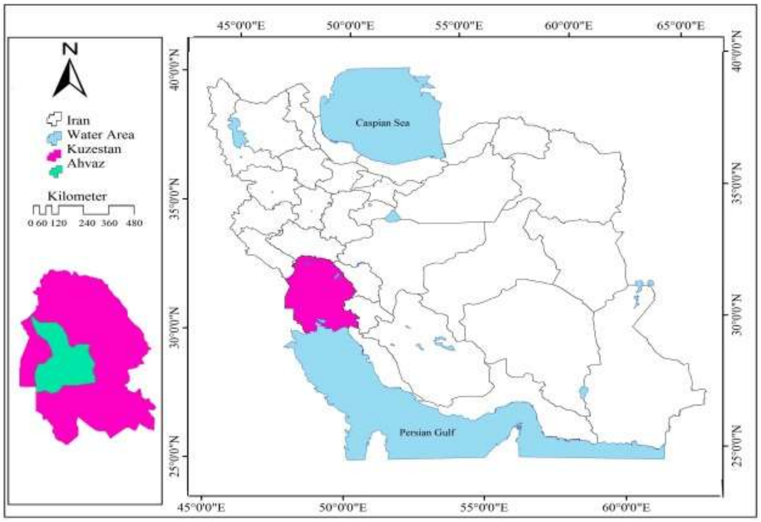
[*]Corresponding author salahi@uma.ac.ir

1 Introduction

Extreme precipitation events can lead to flooding and pose a threat to human lives and infrastructure (Dayan and Morin, 2006). Rainstorms are one of the main causes of extreme precipitation and have been discussed and examined from different perspectives. Studies have focused on their various aspects: spatial and temporal characteristics (Chen and Bradley, 2006; Qin et al., 2015), meteorological aspects (Jenamani et al., 2006; Zhao and Cui, 2010; Hansen et al., 1981), hydro-meteorological environment (Bradley and Smith, 1994), frequency (Changnon and Westcott, 2002), and their impacts (Changnon, 1999; Torri et al., 1999). But, most climatologists have studied the general characteristics of rainstorms and have focused more on the synoptic and thermodynamic aspects. Several atmospheric factors can lead to rainstorm. Cyclonic convergence is one of the main causes of rainstorm (Qingzhi et al., 2009). Also, a trough in the upper levels of the atmosphere with low pressure in surface creates a rainstorm (Kahana et al., 2002). The wind shear convergence at the level of 500 hPa is the main factor in rainstorm formation (Teng et al., 2007). The Mediterranean winter cyclones, Sudan and Red Sea troughs are known to be the main sources of rainstorm and flood in the southwest of Iran (Sabziparvar et al., 2010). But the importance of the large-scale ascent has always been small and little to provide the required lift in the convective events. In other words, for the process of the rainstorm, there should be a mesoscale process as well. The thermodynamic characteristics have an important role in rainstorm occurrence (Mahović et al, 2012). Instability is an important factor in the formation of the rainstorm. Rainstorm indices or instability indices such as Lift index, K Index, Showalter Index, Total index, the Severe Weather Threat Index (SWEAT), and Convective Available Potential Energy (CAPE) demonstrate the potential for convection (Hales, 1996). A vertical velocity larger than 10.5 m/s at 800 hPa and a relative humidity larger than 75% is suitable threshold values for rainstorm occurrence (Colquhoun, 1987). CAPE is an index of available energy for convection and an index for the possibility of convective events such as rainstorm, thunder, and hailstorm. In some studies, rainstorms have been individually studied and the amount of CAPE has been variable in those cases. It was equal to or greater than 750 J/kg in Taizhou during July 7-9, 2007 (Dong-Hong, 2009), while it was 517 J/kg on 19 January, 1996 during a severe wintertime rainstorm in the Appalachian Mountains (Barros and Kuligowski, 1998). CAPE values were 2500 to 3500 J/kg through southern portions of Northwestern Ontario, southeastern Manitoba, and northern Minnesota on June 8 to 11, 2002 (Cummine et al., 2002). Other indices of instability have been used in individual rainstorm occurrences (Li et al., 2007; Chantraketet al., 2015; Cao et al., 2011).

Rainstorms are also classified according to synoptic patterns. So far, several studies have examined the important role of synoptic patterns in rainstorms and extreme precipitations (Raveh-Rubin and Wernli, 2015; Sabziparvar et al., 2010; Kahana et al., 2002; Peleg and Morin, 2012). Other researchers include the characteristics of hailstorms (Punge and Kunz, 2016) and the role of synoptic systems and topography in the occurrence of hailstorms (Melcón et al., 2017; Trefalt et al., 2018; Salimi Sobhan et al.2019; Beal et al., 2020). Instability indicators, air rise, and divergence and convergence of atmospheric levels have also been studied by researchers (Yao et al., 2020; Beal et al., 2020; Lu et al., 2021; de Pablo Dávilaa et al, 2021; Toker et al., 2021).

Unstable atmosphere, the existence of orography, evolving cyclones, and synoptic patterns are the main causes leading to rainstorm. Although the occurrence of



Figureure 1. Geographic location of the study area

rainstorm is not always attributed directly to intense cyclones, in most cases, a surface cyclone is usually positioned in the rainstorm region (Dayan and Morin, 2006). Rainstorm over the west of Iran (Ahvaz) is patterned more often based on synoptic conditions. But in this study, it is patterned based on instability indices and by using hierarchical clusters.

2 Data and Methodology

With a height of 22.5 meters above the sea level (synoptic station) and an area of 16532 km^2, Ahvaz lies at 31º 20′ N and 48º 40′ E in the southwest of Iran and on the Ahvaz plain (Figureure. 1). With an average annual precipitation of 209.2 mm and the temperature of 25.4 C° during the sampled period of 1951-2015, it has a warm and dry climate (Movahedi et al., 2012). In this study, to extract the patterns of rainstorm formation, at first, rainstorm occurrence in an 11-year period (2000-2015) was taken from the synoptic stations in Ahvaz. By sorting the rainfall data, precipitations more than 10 mm were extracted, classified, and examined on monthly and seasonal bases. Then, data from radiosonde observations of Ahvaz was used. The advantage of this approach is that it is based on direct observations of the atmosphere. Archives of radiosonde data were obtained from the website of the University of Wyoming's department of atmospheric science. Then, using the RAOB software, the Skew-T diagram was plotted for the radiosonde data. The analyzed instability indices include: Showalter index (Showalter, 1953), lifted index (Galway, 1956), K index (George, 1960), Total index (Miller, 1972), Severe Weather Threat Index (SWEAT), Precipitation Water (PW), Convective Available Potential Energy (CAPE) (Moncrieff and Miller, 1976), Lifting Condensation Level (LCL), and the Level of Free Convection (LFC).

Different hierarchical clustering methods were tested to classify and extract the instability indices of the patterns. Finally, the Ward's clustering method with Euclidean distance was identified as the best method the results of which are reflected in the current research. In each step of clustering, the aim of the Ward's method was to find the least square error increases within the group in two clusters that were merged together. A total square error within groups V_T (K) at one point with the groups of K, and the variable j by having Ni and the elements in each of the groups are defined as follows (Hervada-Salaa and Jarauta-Bragulat, 2004).

$$V_T(K) = \sum_{K=1}^{K}(\sum_{j=1}^{J}(\sum_{i=1}^{N_i}\left(\left(X_{ijk} - \bar{X}_{jk}(i)\right)^2\right) \quad (1)$$

$$\bar{X}_{jk}(i) = \frac{1}{N_i}\sum_{i=1}^{N_i} X_{ijk} \quad (2)$$

$$\sum_{i=1}^{k_i} N_i = N \quad (3)$$

$$d_M^2(Z_i, Z_j) = (Z_i - Z_j)^T C^{-1}(Z_i - Z_j) \quad (4)$$

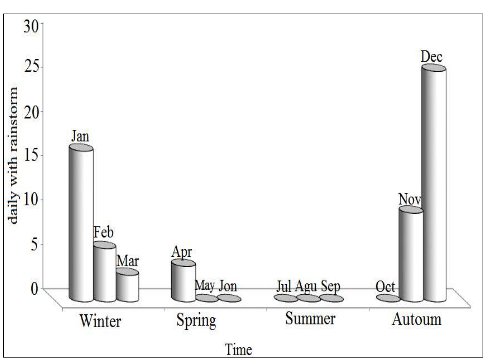
$$C = \frac{1}{N}\sum_{i=1}^{N}(Z_i - \bar{Z})(Z_i - \bar{Z})^T, i, j = 1,2,\dots,N \quad (5)$$

Where $\bar{Z}$ is the mean. In each stage, two clusters with the least number of variables are merged together. To synoptic analysis of the rainstorm in the study area, the geopotential height, circulation, sea level pressure, and humidity flow of the atmosphere provided by the National Oceanic and Atmospheric Administration (NOAA) were extracted, and one specific day as the index day having the highest correlation with the intragroup pattern was selected and examined. Also, GRADS software was used to draw the map of the patterns.

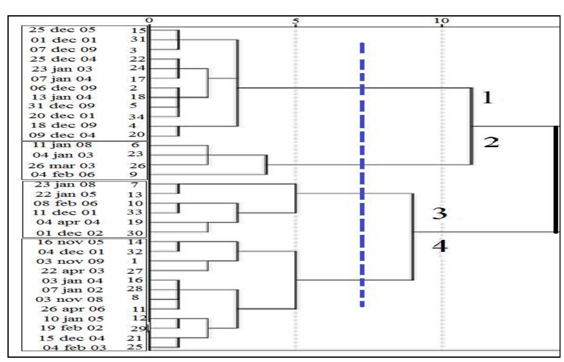
3 Results

Figureure 2 shows the seasonal rainstorm occurrences in Ahvaz station. Over the year, the maximum level of rainstorm has been in autumn and winter, respectively. Rainstorm has not been recorded in summer. Figureure 3 demonstrates the dendrogram of instability indices. Concerning the results from hierarchical clustering analysis and Ward's method, the days under study are divided into 4 clusters into one data type of instability indices. Extracted clusters could effectively justify the atmospheric patterns leading to rainstorm formation.

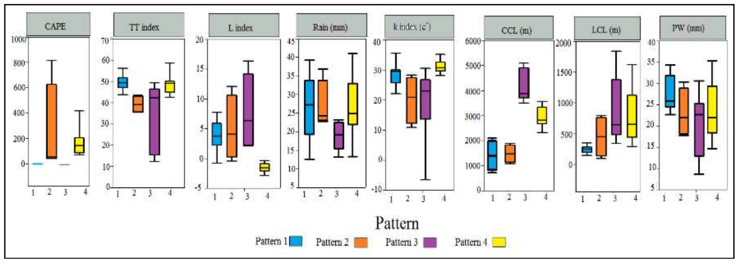
The difference between characteristics of rainstorm originated by various instability indices was analyzed (Figureure 4). Maximum CAPE was observed in the second and fourth patterns, while the minimum value was in the first and second patterns, respectively. Maximum TT index indicating a higher possibility of severe rainstorm was in the first and fourth patterns. The lift index was negative only in pattern four showing the intensity of the lifting of the air mass. Maximum K index, typically expected for severe rainstorms, was in patterns one and four. CCL was high in patterns one and two, while the highest value was observed in pattern three. The minimum of LCL commonly used to estimate the level of a cloud base from surface-based convection was in patterns one and two. Then, with regard to instability indices, the highest probability of the rainstorm was evaluated in the first and fourth patterns.



Figureure 2. Seasonal occurrence of storms in Ahvaz.



Figureure 3. Storms Dendrogram.



Figureure 4. Comparison of rainstorm properties (averaged for instability indices) of the four patterns: CAPE, Total Total index (TTI), Lift index (LI), rain, K index, Convective condensation index (CCL), Lifting Condensation Level (LCL), precipitation water (PW).

3.1 Pattern 1

Most rainstorms have occurred in this pattern. The CAPE value was just a little bit above zero in two rainfalls. It was zero in other rainstorms. LCL and CCL were low at heights indicating that the clouds were low and expected to be a type of convective rainfall. The LI index was positive which could not be expected to have a rainstorm (Table 1).

Table 1. The mean of characterizing of instability indices of rainstorm on pattern1.

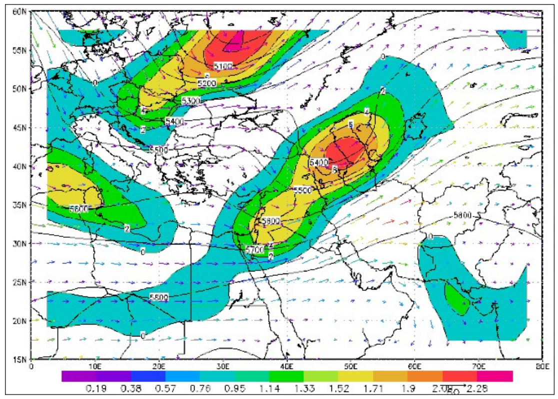
All events	CCL (m)	LCL (m)	CAPE (g/kg)	SWEAT	KI (c)	LI	TTI	PW
12	1767	205	0.16	125	28	3.6	47	2.6

At the level of 500 hPa (Figureure 5), a trough formed in the southwest Asia with its axis passing from the northwest of Iran to the Red Sea, while the west of Iran was in the front of the trough. Cold air coming from the south of Europe and the Mediterranean Sea to the north of Red Sea combining with warm air moved to the east. Air mass passing from the Red Sea received moisture and moved to the southwest of Iran. As the arrow of a flux of moisture on the map (Figureure 5) shows, the wind with humidity coming from the Mediterranean Sea and the Red Sea flowed to the southwest of Iran.

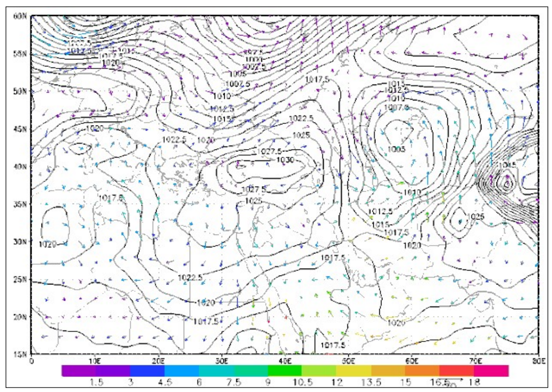
At the sea level pressure, severe high pressure with 1030 hPa formed in Turkey (Figureure 6). A low pressure with 1005 hPa formed on the Baikal Lake. Cool air moving from an anticyclone of Turkey to low pressure in the northeast of Iran and the Baikal Lake, also warm and humid winds from the Persian Gulf moved to the north coast of the Persian Gulf and these winds clashed with cool air coming from an anticyclone of Turkey and led this encounter to form a front over Ahvaz. The humidity being 11 g/kg was provided from the Persian Gulf and added to the atmosphere of the study area. These conditions led to rainstorm in Ahvaz.

3.2 Pattern 2

The least amount of rainstorm has occurred in this pattern. However, the value of CAPE is higher than zero in all rainstorms. The LCL and CCL have low altitudes indicating that the cloud is formed at a low level and is expected to be a convective storm. The LI index was positive as the first pattern (Table 2). For this pattern, March 26, 2003, with rainfall of 27 mm was selected. At the level of 500 hPa (Figureure 7), a deep trough formed over the Middle East the axis of which stretched from Turkey to the north of Saudi Arabia. Cold air came from the north of Africa over the Red Sea and the Mediterranean Sea to low altitudes and the arrow shows the direction of these winds.



Figureure 5. Geopotential height, wet wind (vector), and circulation in 500 hPa on 20 December 2001



Figureure 6. Sea level pressure and wet wind (vector) on 20 December 2001

Table 2. Characterizes of instability indices of rainstorm on pattern 2

All events	CCL (m)	LCL (m)	CAPE (g/kg)	SWEAT	KI (c)	LI	TTI	PW
5	1354	421	320	53.7	21	2.3	37.7	3.6

Southwest of Iran was in front of the trough and the circulation of the air mass was cyclonic causing divergences and moves to the northeast. Flux humidity (Figureure 7) showed that southwest humid winds moved from the Red Sea and the Persian Gulf to the study area and by passing from these sources of moisture brought humidity to the study area.

The map of sea level pressure (Figureure 8) indicated several systems most notable of which was low pressure by 1005 hPa over the west of Iran and Iraq. Two high pressure systems formed over the north of Africa and in Turkey. The wind blowing from those high pressures crossed from the Mediterranean Sea and took humidity to low pressure over Iran. Also, high pressure formed over the Indian Ocean, and humid winds blowing in the Persian Gulf and from there moved to the study area and injected humidity to atmosphere of Ahvaz. Therefore, 10 g/kg humidity was injected to Ahvaz. Low pressure formed over the west of Iran caused an unstable atmosphere and the flow of moisture from the Persian Gulf to the study area caused atmospheric convergence. These conditions led to rainstorm in Ahvaz. The Skew-T diagram (Figureure 9) also indicated a volatile atmosphere of this day at Ahvaz station which helped to easily predict thunderstorms and rainstorms.

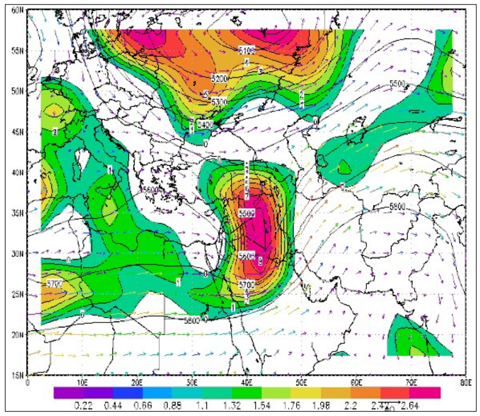


Figure 7. Geopotential height, wet wind (vector), and circulation in 500 hPa on 26 March 2003.

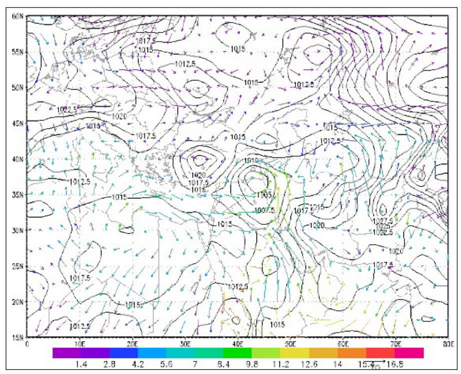


Figure 8. Sea level pressure and wet wind (vector) on 26 March 2003.

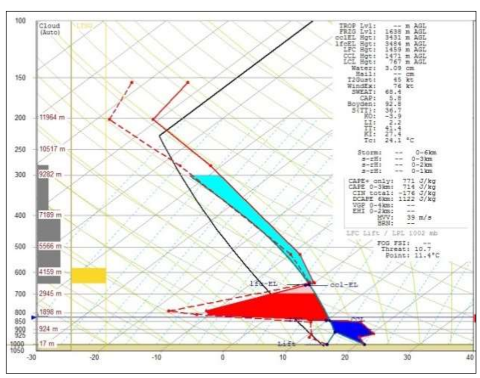


Figure 9. A sample of Skew-T diagram for Ahvaz.

3.3 Pattern 3

The least rainstorm occurred in the second and the third patterns. CAPE value was zero in all rainstorms. LCL and CCL were at a higher altitude than the other patterns. The mean of the Lift index was 7 (Table 2). According to the instability indices (Table 3), it can be said that the synoptic conditions caused the rainstorm occurrence in this pattern. April 4, 2004, when it rained 12 mm was selected for this pattern.

Table 3. Characterizes of instability indices of rainstorm on pattern 3

All events	CCL (m)	LCL (m)	CAPE (g/kg)	SWEAT	KI (c)	LI	TTI	PW
6	4071	918	0	66	19.9	7	33.2	1.9

The atmosphere of the southwest of Iran was warm and people were waiting for a dust storm, but a rainstorm occurred and it rained 12 mm. A trough formed over the east of the Mediterranean Sea at the 500 hPa level (Figureure 9) and its axis crossed from Russia to the Red Sea. Cold air came from the northern Europe to the Black Sea and the Mediterranean Sea and a cut-off low was created over the east of the Black Sea. Iran was in front of the trough and this condition caused its atmosphere to become divergent at the 500 hPa level helping convergence of the low levels of the atmosphere (Figure 10).

Sea level pressure map (Figureure 11) showed that a high pressure (anticyclone) with 1030 hPa formed at the sea level over the Balkan Peninsula (east of Europe) and cold air originating from it moved to Turkey, Iran, and Iraq. Also, a low pressure with 1005 hPa formed in Iraq, and the surrounding air moved toward this system. A high-pressure system over the center of Iran causing blowing warm and dry air toward the cyclone over Iraq. By toward

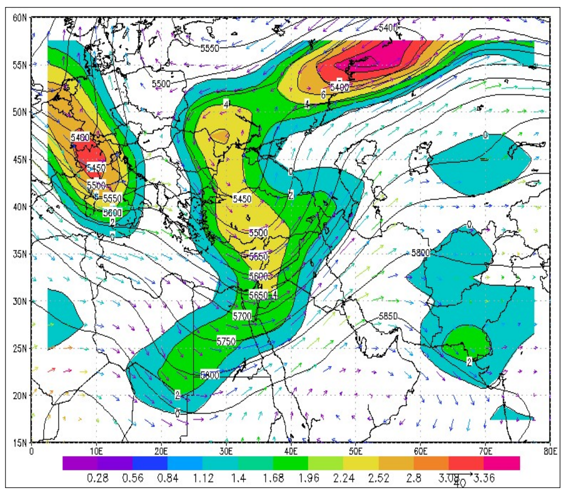


Figure 12. Geopotential height, wet wind (vector), and circulation in 500 hPa on 3 November 2009

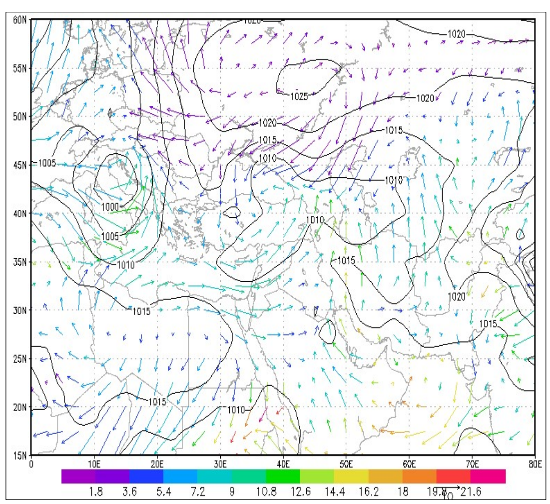


Figure 13. Sea level pressure and wet wind (vector) on 3 November 2009

Table 4. Characterizes of instability indices of rainstorm on pattern 4

All events	CCL (m)	LCL (m)	CAPE (g/kg)	SWEAT	KI (c)	LI	TTI	PW
11	2848	664	162	148	31	-1.5	46.5	2.44

crossing from the Persian Gulf, this wind earned enough humidity and moved low pressure over Iraq. Wind humidity map demonstrated that every moment 7 g/kg of humidity was added to the atmosphere of Ahvaz. These conditions led to rainstorms in Ahvaz.

3.4 Pattern 4

There were 11 rainstorms in this pattern. The CAPE value was above zero in all those rainstorms, with an average of 162 J/kg indicating that the convective energy was suitable for the air mass to climb and it could be expected to have rainstorm. The mean of LI was negative showing that the air was in an unstable state (Table 4). Based on the instability indices, it can be said that convection conditions caused the rainstorm to occur in this pattern.

For this pattern, November 3, 2009, was selected with a rainfall of 20 mm. A deep trough with the axis of Red Sea formed over the east of the Mediterranean Sea at the 500 hPa level (Figureure 12) stretching to the Red Sea caused warm and humid air to move from the Red Sea to Kuwait, south of Iraq, and Iran. It injected humidity to the atmosphere of the region and in turn led an unstable atmosphere. The arrow of humid winds shows that humidity from the Red Sea entered into the southwest of Iran and Ahvaz and humidity from the Mediterranean Sea did not play any role in the process. Iran and especially its southwest region were in front of the trough and humid air entered into its atmosphere. These conditions created a divergence in the atmosphere at 500 hPa level and in turn led to convergence and instability of the underlying atmosphere.

Sea level pressure map (Figureure 13) indicated a high pressure with 1025 hPa formed in the east of Europe blowing cold air toward low pressure with (1010 hPa) over the Caspian Sea and Turkey. Also, a high pressure formed in China moved winds toward Iran, which moved to the low pressure of Turkey. A high pressure of 1015 hPa was formed in the north of Africa and its warm winds crossing the Red Sea obtained humidity and were very humid and moved toward Iran. The arrow of humidity shows that south winds by crossing over the Persian Gulf and west winds by crossing over the Red Sea brought humidity toward the southwest of Iran. These two humid winds clashed in Ahvaz and due to the instability of the atmosphere, they converged and rose to the upper levels of the atmosphere. Finally, the atmospheric conditions caused the occurrence of a rainstorm and 20 mm of precipitation in Ahvaz.

4 Conclusion

The results of this study revealed that most rainstorms occur in Ahvaz in cold seasons. This finding is consistent with the results of a study by Dayan et al. (2015) which indicated that rainstorm is more probable in cold seasons in the east of the Mediterranean Sea. In the study area, the peak of rainstorm can be observed in autumn. According to the results of clustering, four patterns leading to rainstorm were detected based on instability indices. In the second and fourth patterns, instability indices showed remarkable conditions of instability and atmospheric convergence, but in the first and third patterns, these indicators were weak and high levels of atmospheric conditions led to rainstorm. Synoptic analysis revealed that every time rainstorm occurred in Ahvaz, a deep trough at 500 hPa level was formed in the eastern Mediterranean and the study area was in front of it. Also, at sea level, the low pressure center formed in Iraq caused winds to get humidity by passing through the Persian Gulf and enter into the atmosphere of Ahvaz. These conditions led to the instability and convergence of the atmosphere eventually resulting in rainstorm. A similar study was conducted by Bagheri (1993) in the north of the Iran. He found that anticyclones of the North Atlantic with high pressure spreading over the Caspian Sea led to rainstorm in the north of Iran. Sabziparvar et al. (2010) classified rainstorm-bearing systems into four different types in the south of Iran and Dalaki watershed river basin (south Iran). They found that the low pressure of Sudan and the humid air of the Indian Ocean and Mediterranean Sea resulted in rainstorm. Van Delden (2001) found that the principal synoptic features or processes causing the formation of heavy rainstorms were a high level of potential instability, convergence, cyclones. In addition, Siberian circulatory system was another cause of the convergence and instability of the atmosphere. But this study revealed that the formation of a deep trough at 500 hPa level in the east Mediterranean with low pressure in Iraq created rainstorms in Ahvaz.

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