Climatic analysis of effective jet streams frequency on extreme precipitations in west of Iran
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ABSTRACT
In this study, the frequency of effective jet streams was analyzed in extreme and widespread precipitations in the west of Iran. For this purpose, the daily precipitation of 69 synoptic and climatic stations over 18,624 days (1961–2010) were selected. Then, 119 days of extreme and widespread precipitation in the study area were chosen based on generalized distribution for conducting related reviews and analyses. The frequency of jet streams in the geographical location from 0° to 120° E and –10° to 80° N were reviewed at four levels (250, 300, 400 and 500 hPa). Due to the large volume of information, only the highest and lowest levels (250 and 500 hPa) in relation to the surface were considered. According to the results, the highest frequency of jet stream was observed at 250 hPa. The second quarter of the jet stream core lay over the west of Iran (which is associated with increasing positive vorticity as well as upper-level divergence and lower-level convergence of the atmosphere). In general, the extension of jet stream up to 500 hPa indicated an unstable layer thickness, which can cause extreme and widespread precipitation in the west of Iran. The results of selected days based on cluster analysis and Lund correlation revealed that on rainy days, the wind speed was more than 50 m/s and the subtropical jet stream speed was over 40 m/s, leading to extreme precipitation in the west of Iran.

Key words | atmospheric instability, extreme precipitation, jet stream, west of Iran

HIGHLIGHTS
• The role of subtropical jet stream in developing extreme precipitations is more than 70% in Western Iran.
• The spatial analysis of subtropical jet stream frequency in occurrence of widespread and extreme precipitations in Western Iran.
• The spatial analysis of jet streams frequency at the level of 250 hPa indicated that the highest frequency of jet streams belongs to the range from the south of the Red Sea to the south of the Mediterranean Sea.
• The synoptic analysis of jet streams of representative days of extreme precipitation.
• The results of the selected days obtained from cluster analysis and Lund correlation indicated that on precipitation days, the wind speed was more than 50 m/s and the speed of subtropical jet stream was over 40 m/s, making the atmosphere unstable and eventually causing extreme precipitation in the west of Iran.

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INTRODUCTION

The precipitation is mainly governed by various factors such as jet stream. As defined by the World Meteorological Organization (WMO), whenever the speed of these strips exceeds 30 m/s, the jet stream is created (Kaviani & Alijani 2010). On the other hand, according to the definition in the dictionary of weather and climate, jet streams are known as very severe horizontal winds with speeds over 50 knots, or about 26 m/s which are blowing above the planetary winds (Geer 2013). Indeed, jet stream refers to velocity of cores which move in the bed of long and short waves and has convergence and divergence zones like them (Alijani 2002). The speed of jet stream cores declines from its center to the outside where this reduction toward poles is cyclonic or positive, while it is anticyclonic or negative toward the equator. The speed cores are located in westerly winds of equatorial margins, and the other is over the polar front of tropical regions which moves more than in other areas. Consequently, they create two relatively distinct contexts called polar front jet stream and subtropical jet stream. Polar front jet stream occurs in the mid and higher latitudes in the polar front and at a height of 9–12 km, in the parallels of 20–30°, at the height of 12–14 km, and forms discontinuous circles around the earth (Masoodian & Mohammadi 2011).

The place of jet stream formation matches the belt of maximum gradient of the tropopause. It means that it is contingent upon the place where the temperature gradient, as well as the transfer of energy from the equator to the poles, has reached its peak (Halabian & Hosseinali 2014). The position of the jet stream, regulators and converters of atmospheric flows at all levels lies between the tropical and extratropical regions (Reiter 1965). This highlights the importance of studying this significant phenomenon.

To review the occurrence of jet stream events in the world, numerous studies have been conducted from various aspects. In this regard, considering the role of subtropical jet stream in upper-level cloud formation in the Middle East, Eltantawy (1960) concluded that there is an obvious and significant relationship between the subtropical jet stream position and the formation of clouds in this geographical region. Herron & Tolstoy (1969) found a correlation between the recorded pressures and wind direction and speed in jet streams. Weinert (1968) also tested the subtropical jet stream statistics in Australia and observed that the position of the jet stream in long-term average has been between the latitudes of 26° and 32° S. Dayan & Abramski (1985) attributed the heavy precipitation occurrence in the Middle East to unusual states of jet streams as well as their anticyclonic curvature. Johnson & Daniels (1954) concluded that the distribution of average precipitation in four stations of England is influenced by jet streams, where vorticity at the entrance region and anti-vorticity at the exit region of jet streams would receive different amounts of precipitation. Prezerakos et al. (2006) worked on the relationship between polar front jet streams and subtropical jet streams in East Mediterranean Cyclogenesis. They concluded that when the polar front jet stream is extended toward the south rather than toward its seasonal common position, it joins the subtropical jet streams which have expanded northward to their normal position, where the cyclogenesis process would be intensified. Degirmendžić & Wibig (2007) dealt with classifying jet stream patterns on Europe during the period of 1950–2001 as well as describing their basic statistics such as frequency, continuity and their structural daily changes. Among the four models identified in this study, they explained a pattern of extreme temperature changes in the western parts of Europe plus the other three patterns of considerable thermal advection in eastern and central Europe. Strong & Davis (2008) also examined the variability in the position and intensity of winter jet stream cores associated with teleconnection indicators in the Northern Hemisphere. In their view, there was an obvious relationship between the frequency as well as the position of the jet streams and the North Atlantic oscillation indicator. Farajzadeh et al. (2008) studied the relationship between the position of the jet stream and cyclones in the west of Iran during 1985–1999. The results revealed that during non- and low rainy days, the jet tracks were farther away from the area and the jet surges were scattered. However, during intensive rainy days, the tracks were close to the area and had a positive curvature. The upper flow pattern had developed a deep trough on the eastern coast of the Mediterranean Sea. Yuan et al. (2011) reviewed...
the relationship between the North Atlantic jet stream and tropical advection over India and the western Pacific Ocean. They found that over a time scale of decades, a major rise had emerged in the frequency of precipitation occurrence during the years 1958–1979 and 1980–2001 on the Western Pacific Ocean. Hoell et al. (2012) investigated the main pattern of precipitation in the Indian Ocean during the cold period of the year (from November to April, 1979–2008) in two time scales of seasonal and annual employing the analysis of empirical orthogonal functions and teleconnection index. They concluded that the precipitation pattern in the annual time scale is associated with the Madden–Julian Oscillation while in seasonal time scale, it is associated with the El Niño Southern Oscillation.

Also in native resources, Farajzadeh Asl & khorani (2007), while analyzing the position of jet streams regarding precipitation systems over the west of Iran, concluded that the cores of speed and the maximum precipitation are concentrated at two parts in prime days. Masoodian & Mohammadi (2011) analyzed the jet streams related to the occurrence of super-heavy precipitation of Iran. The results of their study suggested that although the jet stream in the Persian Gulf and south-west of Iran have significant frequencies, the northern parts of Saudi Arabia have been the main place of settlement and concentration of jet streams during the occurrence of super-heavy and major precipitation in Iran. Parvin (2013) studied the relationship between the location of jet streams associated with flooding at Orumieh lake basin by the clustering method and eventually detected seven patterns. According to their results, when widespread floods occurred, the axis of trough traveled deeper toward lower geographical latitudes and about 70% of jet streams in the south-western to north-eastern direction and have been stationed between the latitude of 25–35°N over the Mediterranean to the north-east of Iran. Asakereh et al. (2014) conducted a spatial analysis of subtropical jet streams in the desert areas of the Middle East and North Africa with an emphasis on Iran. They found the center of annual average of subtropical jet stream over North Africa, the Red Sea and northern Arabia at the level of 200 hPa. Halabian & Hosseinali (2014) analyzed the frequency of jet streams associated with extreme and widespread precipitations in western shores of the Caspian Sea. Their results suggested that over time, except at the level of 250 hPa where jet streams show a high frequency at 06:00, at levels of 300 and 400 hPa, they have mostly explicit representation in their study area at 18:00. Arvin et al. (2015) reviewed the effect of the subtropical jet streams on a daily precipitation greater than 10 mm in Zayandehrood’s basin. The dominant pattern in the occurrence of precipitation more than 10 mm and the position of the left exit region of subtropical jet stream on ascendancy slopes of westerly short-wave winds were tested. Rafati et al. (2016) revealed that in all studied months, most of the mesoscale convective systems were formed under conditions when low-level jet stream was present in the area, and warm and humid air of lower latitudes was injected into the area and intensified low-level convergence. Soltani et al. (2016) analyzed changes in the spatial and temporal pattern of climate extreme indices (at 50 meteorological stations) in Iran over the period 1975–2010. They used 16 indices of extreme temperature and 11 indices of extreme precipitation. The results revealed that there are no systematic regional trends over the study period in total precipitation or in the frequency and duration of extreme precipitation events. Statistically significant trends in extreme precipitation events are observed at less than 15% of all weather stations. Rousta et al. (2017b) investigated the spatial autocorrelation changes of Iran’s heavy and super-heavy rainfall over the past 40 years. They found that there is a negative spatial autocorrelation pattern of heavy rainfall in central Iran and parts of the east, particularly in Zabul. Finally, it is found that patterns of super-heavy rainfall are similar to those of heavy rainfall. Rousta et al. (2017a) investigated decadal variations of extreme precipitation thresholds within a 50-year period (1961–2010) for 250 stations of Iran’s north-west. The findings showed that the intensity of positive spatial autocorrelation pattern of extreme precipitation thresholds experienced a declining trend in recent decades. Azizzadeh & Javan (2017) studied the temporal and spatial distribution of extreme precipitation events in Lake Urmia basin in Iran from 1987 to 2014. In this study, 11 indices of precipitation were analyzed. Spatial distribution for precipitation extremes exhibited a declining trend in most regions in the Lake Urmia basin. Weiyye et al. (2019) investigated the long-term annual and daily extreme precipitation in China during 1960–2010 based on daily observations from 539 meteorological stations. They find an overall increasing trend in annual and daily extreme precipitation, particularly in the south-east and north-west of China. It is noted that the central urban area of one
metropolitan region may have significantly higher increasing trends of daily extreme precipitation than corresponding areas.

According to Zhang and Wang’s research (2019), the intensity and frequency of extreme precipitation have been increased to compare with the current level in most regions in China. The maximum consecutive 5-day precipitation over China is projected to increase by 16%, and the number of heavy precipitation days will increase as much as 20% in some areas. Rousta et al. (2020) studied synoptic-dynamic aspects of extreme precipitation in Karoun River Basin in Iran. The results showed that extreme precipitation of the study area is affected by the atmospheric pattern of the Caspian Sea low pressure–European migratory high pressure, Eastern Mediterranean low pressure–Central pressure-Central Iran low pressure, the Eastern Mediter-
nanean low pressure–Siberian-Tibetan high pressure and Sudanic low pressure-gigantic European high pressure. At 300 hPa level, the left side of the jet stream, the left exit of the subtropical jet stream and the right entrance of the polar front jet stream were located over the study area.

Since the geographic distribution pattern of rainfall and its intensity on a planetary scale are affected by the pressure system patterns, the location of Intertropical Convergence Zone (ITCZ), as well as the position and expansion of ocean currents, this study aims to identify another significant factor in the occurrence of extreme rainfall by the spatial analysis of the frequency of influential jet streams in the occurrence of extreme precipitation in the west of Iran. Specifically, the position and frequency of the jet streams are determined along with their mean velocities at the time of the occurrence of extreme precipitations.

The patterns of jet streams in the west of Iran were also analyzed by cluster analysis. The innovation of this research as compared with a similar study by Farajzadeh et al. (2008) is that the aforementioned study has only analyzed the consecutive rainy days with a length of 1–5 days, while in the present study, extreme indices of heavy precipitation have been investigated.

### MATERIALS AND METHODS

The type of this research is fundamentally experimental with an inductive approach. The geographic zone under study is western regions of Iran. The database of this research, which has an environmental to circulation approach, involves two groups of variables.

First, the daily precipitation data of 69 synoptic and climatologic stations of the west of Iran (provinces including Hamedan, Kordestan, Kermanshah, Lorestan and Ilam) were collected from 1961 to 2010, as an environmental event database from Iran Meteorological Organization via the website (www.weather.ir). The second group of variables including orbital wind components and wind meridional components data were obtained from the National Center for Environmental Prediction (NCEP)/National Center Atmospheric Research (NCAR) Reanalysis data from the National Oceanic and Atmospheric Administration (N.O.A.A) website (www.esrl.noaa.gov/psd/) in order to draw jet streams at levels of 250 and 500 hPa. Data extraction was done using Grads software.

According to the environmental event database, we used the Kriging interpolation method for daily precipitation of 18,624 days in the west of Iran. Here, we have presented only the levels of 250 and 500 hPa which are the highest and lowest values in relation to the surface given the large volume of information. For this purpose, upon interpolation of daily precipitation, we converted the study area with 1,367 pixels of 2.5 × 2.5 km resolution.

To determine the threshold of extreme precipitation, we used the distribution of generalized extreme values. So, we selected the days with precipitation equal to or more than 22 mm and covered 30% of pixels as widespread and extreme precipitation. During the study period, 119 extreme precipitations were selected. Figure 1 shows the study area and its pixels, plus the data used in the present study.

MATLAB software was employed for calculations, whose results were presented in the form of maps. We used Arc Map software for mapping. In spatial analysis, one of the most common parameters which is used regarding the distribution of points around the center of average is standard deviational ellipse. We have benefitted from the standard deviational ellipse since the situations of points may show directed deviations for the phenomena which occurred, and the standard ellipse can represent the directed deviations of probability distribution well, and finally to demonstrate the direction of deviation in the dispersion of points.
The standard ellipse was applied to the frequency of jet stream occurrence in each pixel. In the ellipse, the main axis represents the maximum dispersion of the center of gravity (the greatest displacement of the center of gravity), and the subordinate axis indicates the minimum displacement. The two axes in the Cartesian system are the same as $x$- and $y$-axes with clockwise direction. The stages of standard deviation ellipse determination are as follows (Asakereh et al. 2014):

(A) Calculating the coordinates of the center of the average of $x_{mc}$ and $y_{mc}$;

(B) Calculating the transition coordinates for each pt point in the distribution from the following equation:

$$
\begin{align*}
  x_i &= x_i - x_{cm} \\
  y_i &= y_i - y_{cm}
\end{align*}
$$

(C) Calculating the rotation angle $\theta$ according to the following equation:

$$
\tan \theta = \frac{(\sum_{i=1}^{n} x'_i\delta^2 - \sum_{i=1}^{n} y'_i\delta^2) + \sqrt{\left(\sum_{i=1}^{n} x'_i\delta^2 - \sum_{i=1}^{n} y'_i\delta^2\right)^2 + 4\left(\sum_{i=1}^{n} x'_i - \sum_{i=1}^{n} y'_i\right)^2}}{2\sum_{i=1}^{n} x'_i - \sum_{i=1}^{n} y'_i}
$$

Given the $\theta$ angle in the third stage, we can calculate deviation along $y_i$ and $x_i$ axes using the following formulas:

$$
\delta = \sqrt{\frac{\sum_{i=1}^{n} (x'_i \cos \theta - y'_i \sin \theta)^2}{n}}
$$

In the following, extreme precipitation days were classified based on the sea surface pressure and the Euclidean distance equation using hierarchical clustering techniques in the form of a tree graph. Cluster analysis is a statistical method for dividing a dataset into homogeneous and useful subsets or clusters which have the same features, while the dissimilar features would be placed in separate clusters (Gayoor & Montazarei 2004). Specifically, in the interval or clustering method, the classification of observations is performed based on the distance between them, signifying that observations or components with less distance from each other would be placed in a single group.

The main objective of the clustering method is reducing variation or variance within the group and increasing the variances between the groups (Alijani 2002). In order to select the representative days of the groups obtained from the classified maps of sea level pressure, we used the Lund method. This method is the same as Pearson’s correlation coefficient measures the linear correlation between two random variables and is used to classify meteorological maps and extract synoptic patterns. Thus, in selecting the representative day of each group, the day which is more similar to the dominant members of the group was chosen. Lund’s correlation coefficient indicated the degree of similarity in the patterns of two maps (Masoudian 2006). By selecting large thresholds such as 0.8 and 0.9, the number of map patterns increases and it becomes difficult to work with these map patterns. The permissive researcher accepted thresholds of 0.5 and 0.4. For this purpose, the
value of 0.5 was selected as the correlation coefficient threshold.

Then, the representative of each class with a correlation coefficient of 0.5 or more and with the greatest similarity to others in that class is qualified as being a representative of the group.

Figure 2 presents the tree diagram obtained from clustering extreme precipitation days with four derived clusters marked with dotted lines. Further, the representative days elected from Lund correlation are reported in Table 1. As can be seen in the table, the second group claimed 32.7% of precipitation days, while the fourth has the lowest share of 15.1% concerning extreme precipitation days. Finally, we analyzed the selected days at the levels of 250 and 500 hPa.

RESULTS AND DISCUSSION

In this section, the average speed and frequency of jet stream in 119 selected extreme precipitation days were analyzed using the generalized distribution of extreme values at two levels of 250 and 500 hPa. As mentioned earlier, we present only levels of 250 and 500 hPa which are the maximum and minimum values in relation to the surface given the large volume of information. In this regard, winds with a speed of greater than 30 m/s as defined by the WMO were considered as the jet streams. In addition, in order to further review and analyze the jet streams, maps of average speed of jet stream were also used.

Spatial analysis of frequency and average speed of jet streams on level of 250 hPa

The maps of the spatial analysis of jet streams frequency at a level of 250 hPa indicated that the largest frequency of jet streams belonged to the south of the Red Sea to the south of the Mediterranean Sea. In other words, more than 70% of place of formation as well as establishment of jet streams passage affecting extreme precipitation in the west of Iran were located in this area, whose main direction has been over the Red Sea. This, in turn, leads to injection of moisture over the Red Sea to the precipitation systems from the west of Iran. As displayed in Figure 3, the expanded area

| Table 1 | Representative days obtained from Lund correlation |
| Groups | Year | Month | Day | Percentage |
| The representative day of the first group | 1993 | 3 | 8 | 31.9 |
| The representative day of the second group | 1974 | 3 | 17 | 32.7 |
| The representative day of the third group | 1989 | 12 | 1 | 20.1 |
| The representative day of the fourth group | 1985 | 2 | 1 | 15.1 |
dominated by jet streams after crossing the Red Sea has the maximum occurrence in the west of Iran which passes over central Iran. Their main direction matches the west of Iran.

Figure 4 reveals the average speed of jet streams at the level of 250 hPa. Studying the average speed of jet streams at this atmospheric level also implied the establishment of speed cores on the studied area. Accordingly, the average speed of jet streams has been greater than 30 m/s. The maximum speed of jet streams happened from north of the Red Sea to the west of Iran, whose center was located in this area with a speed of more than 50 m/s.

Meanwhile, the average speed of jet streams decreased from the west of Iran toward the center reaching less than 50 m/s. Maps of average speed of jet streams, which match both the highest frequency of occurrence and the maximum speed of jet streams in the study area, indicated that the second quarter (with increasing positive vorticity as well as high-level divergence and low-level convergence in the atmosphere) has been located in the west of Iran. This can result in the expansion of the air mass at the high levels or vertical movement ascending. This can provide the basis for instability at the time of extreme precipitation occurrence within the geographical scope of the study.

At the level of 250 hPa, which can be seen in Figure 5, a relatively stretched standard ellipse is located in the west-east direction with the tendency of approximately 5° toward the south-east. This direction is a demonstration of the greatest displacement and alteration of places of the cores of jet streams at this level. This form of ellipse placement shows its noticeable displacement toward the west, and observed, the highest frequency of jet streams occurrence has occurred from the Red Sea to the west of Iran. Also, according to the subordinate axis of the standard ellipse, we can state that significant spatial variations of the core of jet streams along the north-south direction can also be seen. Iran’s western position in the standard ellipse at this level is located in the second half of the ellipse.
Spatial analysis of frequency and average speed of jet streams at 500 hPa

The spatial analysis of the jet streams frequency at 500 hPa indicated that during the study period, the highest frequency of jet streams covered a range from the north-eastern parts of the Red Sea to the west of Iran. In other words, the zones located in this range have been the place for formation and establishment of jet streams in more than 50% of the cases (Figure 6).

The spatial analysis of the average speed of jet streams at this atmospheric level also indicated that the average speed of jet stream was between 30 and 37 m/s, where the maximum speed of jet stream occurrence was in the north-eastern part of the Red Sea (Figure 7). The map of the average speed of jet stream at this level reveals that the second quarter (with elevation of positive vorticity as well as high-level divergence and low-level convergence in the atmosphere) is located in the north-east of the Red Sea.

At 500 hPa level (Figure 8), the main axis of the standard ellipse with deviation of greater than 10° has a north-eastern orientation which still shows a significant shift to the west. The jet stream core frequency at 500 hPa level is smaller than other levels. Nevertheless, as this level is the nearest studied level to the Earth’s surface, it will be more effective in extreme precipitation. This form of standard ellipse placement and even its deviation mode confirm shifting jet stream on the time scale.

Note that, during the cold season, the main axis of the jet stream is placed below 30°N, while in the warm season, it is above 40°N. This displacement in transitional seasons occurs at 30°–55°. Also, according to the subordinate axis of standard ellipse, the jet stream core has happened along the north-south at latitudes of 50–65°N. The subordinate diameter of the standard ellipse is smaller than at the level of 250 hPa, and reflects fewer meridional changes. The occurrence of jet stream core in the west of Iran, due to its position, represents the impact...
of the right entrance region of jet stream core (upper-convergence–lower-divergence) on this area.

**Synoptic analysis of jet streams of representative days**

In the tropopause, it is just above the Hadley cell, westerly wind speeds grow to a maximum of 345–385 km/h. Jet streams flow above the troposphere and beneath the stratosphere layers in the loop of westerly winds. Among them, the polar front jet stream, which is usually observed between 300 and 500 hPa, has a major effect on the climate of the Earth’s surface (Kaviani & Alijani 2010).

**March 8th, 1993, the first cluster representative**

According to Figure 9, we observe that at 00 o’clock on March 8th, 1993, the mid-latitudes with width of 15–21° to 61°N were affected by the intense flows of subtropical jet stream with a west-east direction. The wind speed in the study area was 50 m/s, which at 12 z (12 in G.M.T) on the mentioned day, had a more significant influence in Iran, and made the whole atmosphere of west, north-west and center regions unstable, eventually causing extreme precipitation in the west of Iran (Figure 9(a) and 9(b)).

On March 8th, 1993, at 500 hPa level, the subtropical jet stream with a speed of 35 m/s has also moved toward Iran in an east-west direction. It has been redirected in Saudi Arabia and entered west and north-west regions of Iran with its south-western to north-eastern direction, causing instability of atmosphere and precipitation in regions listed. At 12 z, this influence has been intensified and affected the Caspian shores (Figure 9(c) and 9(d)).

![Figure 9](http://iwaponline.com/jwcc/article-pdf/doi/10.2166/wcc.2020.284/820977/jwc2020284.pdf)
**March 17th, 1974, the second cluster representative**

As seen in Figure 12, at 00 z (24 in G.M.T) on March 17th, 1974, the middle latitude jet stream or subtropical jet stream has passed over northwestern and western regions of Iran with a speed of 40 m/s, intensifying heavy precipitation in these areas (Figure 10(a)).

The mentioned jet stream at 12 z (12 in G.M.T) has been intensified (Figure 10(b)) and covered the whole area with a speed of 50 m/s along the southwest-northeast direction. At these hours, at the level of 250 hPa along 30°N, the polar front and subtropical jet streams have joined together and moved eastward. The polar front jet stream helps formation of extratropical cyclones and directs them. It also creates instability in its underside atmosphere, resulting in rising ascending air and in the presence of warm and humid air, causing precipitation (Kaviani & Alijani 2010).

Thus, a high-speed wind tunnel has affected the north-west and west of Iran and created an unstable atmosphere engendering extreme precipitation on this day. Also, at the lower level 500 hPa, at 00 z, a tongue of subtropical jet stream core has extended to Iran’s west with a speed of 30 m/s, which at 12 z has covered the whole north-west and west of Iran (Figure 10(c) and 10(d)).

**December 1st, 1989, the third cluster representative**

As observed in Figure 11(a) and 11(b), at 00 z of December 1st, 1989, two polar and subtropical jet streams at a speed of 35 m/s have mutually moved along the south-western to north-eastern direction, causing intensification and instability for extreme precipitation in the north-west and west of Iran. At 12 z, these two jet streams have fully merged and crossed the entire region with a speed of 40 m/s. At the...
level of 500 hPa, only a tongue from the polar front jet stream along the north-east south-west has extended to lower latitudes, where at 12 z, this tongue has been completely redirected to the north-west of Iran while keeping its extension with a speed of 30 m/s (Figure 11(c) and 11(d)).

February 1st, 1985, the fourth cluster representative

Referring to Figure 12(a), at 00 z on February 1st, 1985 at 300 hPa level, the core of orbital jet stream with a speed of 65 m/s along the south-western axis has covered the north-east of Iran; the speed of jet stream in the study area was 30–45 m/s. This jet stream on the aforementioned day at 12 z (Figure 12(b)) with its almost horizontal axis has entered particularly to the south-west and south of Iran. The subtropical jet stream with such conditions, but a lower speed (30 m/s), has affected Iran's south-west part at 500 hPa level (Figure 12(c) and 12(d)).

Having compared the results of this study with related previously published works for the Iran region, it was found that the results of this study are similar to those of Arvin et al. (2015) who investigated the effect of jet streams on the daily precipitation which was more than 10 mm in the Zayandeh Rood basin. It has also been congruent with research by Masoodian & Mohammadi (2011) who investigated the relationship between jet stream frequencies and super-heavy rainfalls of Iran. The similarity of the aforementioned study with this study is related to the placement of jet streams during the occurrence of heavy precipitation confirming the results of this study.

CONCLUSION

The spatial analysis of jet stream frequency at the level of 250 hPa indicated that the highest frequency of jet streams
belongs to the range from the south of the Red Sea to the south of the Mediterranean Sea. In other words, more than 70% of place of formation, establishment and part of jet streams affected extreme precipitation in the west of Iran. So, this leads to injection of moisture from the Red Sea to the precipitation systems from the west of Iran.

The spatial analysis of the jet streams frequency at the level of 250 hPa revealed that during the study period, the largest frequency of the jet streams covered the range from the northern part of the Red Sea to western and central parts of Iran. In other words, zones located in this range, in more than 50% of the cases, have been the place for for-

mation and establishment of jet streams. This range corresponds to the maximum frequency of jet stream occurrence; from this range to the east, the frequency of jet streams has significantly decreased.

The values of jet stream frequencies at the level of 500 hPa are unexpected mainly due to less occurrence of jet stream at this atmospheric level. Review of the maps of jet streams average speed has been in accordance with the highest frequency of jet streams occurrence, coinciding with occurrence of maximum jet stream speed in the study area.

The results indicated that the second quarter of the jet stream (associated with increasing positive vorticity as well as upper-level divergence and lower-level convergence of the atmosphere) is located in the west of Iran across all levels. So, it seems that this can provide the basis for instability at the time of extreme rainfall precipitation in the discussed geographical domain due to the expansion of the air mass at a high level or vertical upward movement.

Figure 12 | Distribution of the polar front and subtropical jet streams at 00 z and 12 z, at levels of (a, b) 250 hPa and of (c, d) 500 hPa, on February 1st, 1985.
In general, the jet stream extension up to 500 hPa revealed an unstable layer thickness, which can cause extreme and widespread precipitation in the west of Iran. Also, the results of the selected days obtained from cluster analysis and Lund correlation indicated that on precipitation days, the wind speed was more than 50 m/s and the speed of subtropical jet stream was over 40 m/s, making the atmosphere unstable and eventually causing extreme precipitation in the west of Iran.

One of the main problems with this research is the lack of access to New Year’s data, which is generally available to researchers in Iran with delay. In future research, it is suggested to consider the possible effects of climate change on precipitation events using general climate models (GCMs).

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