



# Synoptic aspects of two flash flood-inducing heavy rainfalls in southern Iran during 2019–2020

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## Abstract

This study investigates the synoptic aspects of two heavy rainfall events that occurred in the southern half of Iran during the period 2019–2020. To this end, daily precipitation data from 114 synoptic stations scattered over southern, southwestern, and southeastern Iran were used to characterize the 24-h total precipitation, while the general extreme value (GEV) distribution was used to estimate the associated return periods. The geopotential height,  $u$  and  $v$  wind components, sea-level pressure, and atmospheric relative humidity data relative to 100 to 250 hPA levels were also used to analyze the synoptic aspects of the considered heavy rainfall. The statistics showed the 155-mm 24-h total rainfall occurred in Izeh station in March 2019 ranked first during the study period, while the 142-mm 24-h rainfall of Poldokhtar station ranked second. The estimated return period of the heavy rainfall of late March and early April 2019 in western Iran varies between 7 and 200 years across the studied stations. The estimated chance of recurring 155-mm 24-h heavy rainfall at Izeh station is 96 years, but it is 56 years for the 142-mm rainfall in Poldokhtar station. In the case of January 2020 heavy rainfall that occurred in southern and southeastern Iran, the estimated return period of the 176-mm 24-h total rainfall measured in Qeshm and Minab stations of Hormozgan province was 115 years, whereas it was 10 years for the 107 mm of rainfall at Rask station in Sistan and Baluchestan province. The synoptic analysis of the consecutive downpour of late March and early April 2019 that occurred in the west and southwest of Iran and the successive heavy rainfall of January 2020 that occurred in the southern and southeastern Iran was related to the blocking synoptic systems and the associated atmospheric turbulences established in these areas. In the heavy rainfall of March 2019, the formation of a strong cut-off low centered over Iraq sank the higher-latitude cold air into the system that in turn intensified it that favors absorbing intensive moisture from the Mediterranean Sea. The penetration of the system's flanks into the Red Sea also aids the system to absorb hot and humid air from the low latitudes that fed consecutive days of heavy rainfall in southwestern Iran that lies in the forehead of the cut-off low. In the case of heavy rainfall of January 2020 that occurred in the south and southeast of Iran, a very deep trough was formed over the area due to the formation of an omega-shaped blocking system. The advection of cold air from the higher latitudes and the hot and moist air from the southern water bodies of Iran into the system causes intensive heavy rainfall in the area which is situated in front of the trough.

**Keywords** Vorticity · Blocking · Extreme rainfall · Flood · Return period

## 1 Introduction

Floods have always been considered as one of the main environmental hazards that have caused substantial financial damages and human losses in different parts of the world. For example, the devastating flood of July 1934 in Tabriz, northwestern Iran, that resulted from consecutive days of heavy rainfall events (Melville 1983), heavy floods of West Virginia (United States Signal Service 1889), the 1942 Pennsylvania floods (Eisenlohr 1952), September 1992 heavy floods of Vaison La Romaine, southeastern France (Senesi et al. 1996), heavy floods of November 2 to 4, 1994, in the Piedmont region of Italy (Lionetti 1996), the 1993 summer devastating flood of Brig city, Switzerland (Frei et al. 2000), the catastrophic flood of August 2001 in northern Iran (Sharifi et al. 2012), and the heavy flood of August 2016 in Louisiana, USA (Watson et al. 2017) are a few examples of floods with different intensities that occurred in different parts of the world. Due to the importance of studying different aspects of disastrous floods, researchers have always studied and analyzed the effective factors contributing to flood occurrences, more especially the human interferences in the natural environment, climate change, and the occurrences of heavy rainfall. Studies such as Bultot et al. (1990), Crooks and Davies (2001), Istomina et al. (2005), Brath et al. (2006), Mao and Cherkauer (2009), Sheng and Wilson (2009), Solin et al. (2011), Apollonio et al. (2016), Akter et al. (2018), and Jahanbakhsh et al. (2022) have considered the land-use changes as the main responsible factor for increasing flood occurrences in their studied areas. Several studies have also attributed the flood occurrences to the changes in land-use patterns and soil water infiltration reduction as a result of urban development and expansion (Campana and Tucci 2001; Liu et al. 2004; Nirupama and Simonovic 2007; Saghafian et al. 2008; Suriya and Mudgal 2012; Wang et al. 2020; Bayazit et al. 2020). In recent decades, in response to the anticipated changes in climate, the frequency of floods has increased in different parts of the world, largely due to increasing climate extremes including the occurrence of consecutive days of heavy rainfall (Pall et al. 2011; Wilby and Keenan 2012; Wang et al. 2020; Garner et al. 2017; Adnan et al. 2020).

Changes in climate and increases in climate extremes are more noticeable in countries like Iran that is characterized by very high climate variability. Due to the geographical location and complex topography, Iran has always been encountered various natural hazards such as droughts, dust storms, heavy rainfalls, and heavy floods. Precipitation is the most variable climate element in Iran both spatially and temporally. The very high spatial variability of precipitation in Iran is attributed to the country's wide latitudinal expansion from 25°N to 40°N and its complex topography (Miri et al. 2016; Raziei et al. 2013). On the other hand, due to diverse atmospheric circulation patterns and key climatic components that control the climate of Iran during a year, the climate variables of the Iranian plateau considerably vary throughout the year (Ziv et al. 2004). Therefore, the complex topography and wide latitudinal expansion of Iran with the associated diverse atmospheric circulation patterns, particularly in the cold season, have caused the precipitation amount and time in Iran to vary from a region to another (Masoudian and Kaviani 2012; Raziei et al. 2013). Heavy rainfall followed by a devastating flood is one of the climatic hazards that have frequently occurred in various regions of Iran in recent decades and left huge financial damages and losses. Heavy rainfall and flood of November 2015 in western Iran, the heavy flood of January 2016 in Sistan and Baluchestan province in southeastern Iran,

the flood of April 15, 2017, in northwestern Iran, the heavy rainfall and flooding of northern provinces of Iran on October 4, 2016, the heavy rainfalls of April 2016 with the associated destructive floods occurred in north, west, and southwest Iran, and the heavy rainfall and succeeding floods of January 2017 in the south and southeast of Iran are examples of heavy rainfalls leading to destructive floods in Iran during the last decade.

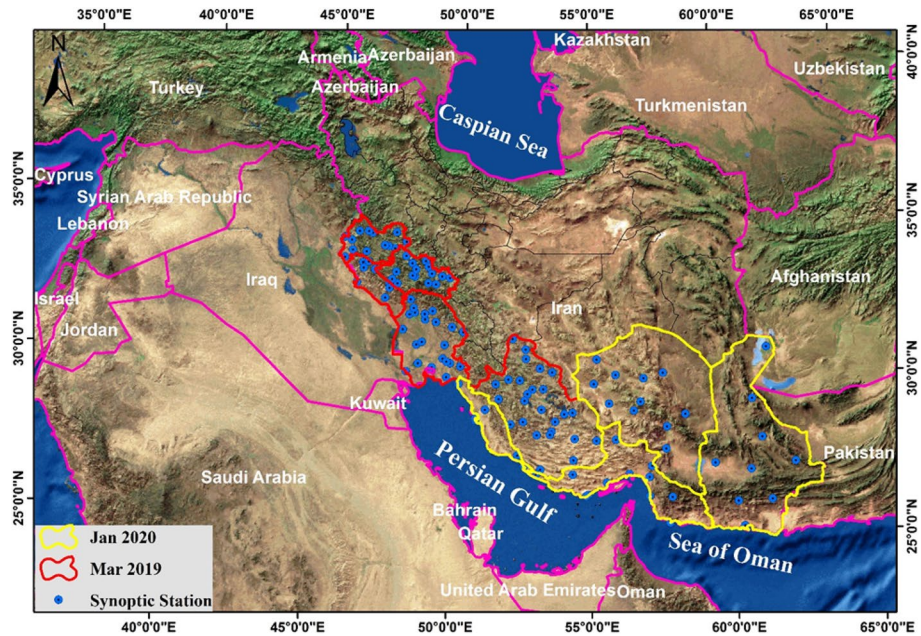
Because of their proximity to the water bodies of the Persian Gulf and Oman Sea, and being on the pathways of different air masses, western and southern Iran is prone to heavy rainfalls commonly succeeded by destructive floods. The western and southwestern parts of Iran faced heavy rainfalls in late March and early April 2019 that led to very large and devastating floods in the region that caused huge financial damages and human losses. In January 2020, another heavy rainfall event with relatively similar intensity and duration took place in southern and southeastern Iran and caused large damages and losses. According to the National Disaster Management Organization of Iran (NDMOI), 25 provinces of western and southwestern Iran including 200 cities and 4304 villages were affected by floods and river overflows. These floods destroyed more than 60,000 urban and rural units and more heavily damaged more than 75,000 urban and rural houses. According to NDMOI, 3285 people were injured and visited at site medical healthcare teams, from whom 1874 people were treated at the place, 1411 people were transferred to the medical centers, and 76 people were passed away at the beginning of the Iranians New year which coincides with 21 March each year. The Iranians New year is also considered as the initiation of the astronomical spring season in Iran and the surrounding countries such as Turkey, Afghanistan, Armenia, Azerbaijan, and Turkmenistan. Due to the large and pervasiveness damages imposed on the economical, agricultural, and natural resources infrastructures of the provinces of the west, southwest, south, and southeast of Iran, many experts attributed these extreme precipitations to the climate change phenomenon and claimed that such extraordinary rainfalls were unprecedented in this part of Iran.

Due to the changes in the world's climate and the increasing incidence of extreme climate events, very likely heavy rainfalls and consequent floods increase, causing significant damage to the environment and man-made infrastructures. Therefore, studying the return period and synoptic conditions of such precipitation events is necessary for environmental risk management. Considering that heavy rainfalls are the main responsible factor for floods, in this study, we identify the return periods and synoptic conditions of the two recent heavy rainfalls that occurred in the southern half of Iran. The results of this study can increase our understanding of the mechanisms responsible for the occurrence of heavy rainfall in the region and the possibility of timely forecasting such precipitation events as an essential prerequisite for flood control plans and reducing the associated damages.

## 2 Data and methods

### 2.1 Data

In the present study, the daily precipitation data of the GPM sensor and the synoptic stations distributed over the study area, and the atmospheric fields at different levels have been used. The daily precipitation data of 114 synoptic stations with suitable distribution over the west, south, southwest, and southeast of Iran (Fig. 1) were acquired from the Meteorological Organization of Iran, while the GPM data with  $0.10^\circ \times 0.10^\circ$  spatial resolution were obtained from the Giovanni Web site at <https://giovanni.sci.gsfc.nasa.gov>.



**Fig. 1** Geographical location of the studied areas and the synoptic stations selected for the analysis. In this figure, the borders of the provinces affected by the March 2019 rainfall are marked in red, and the borders of the provinces affected by the January 2020 rainfall are marked in yellow

According to the success of the TRMM sensor mission that ended in April 2015, a year before its fuel finish and the sensor fell to the earth, NASA and the Japan Space Agency launched the GPM sensor for Global Precipitation Measurement on February 27, 2014. It contains a network of various satellites such as TMPA, CMORPH, and PERSIANN, which provides more accurate measurements of rain and snow at a global scale by using dual-frequency radar and multi-channel microwave imaging. The products of this satellite with a time resolution of half an hour, as well as daily and monthly time scales, and a spatial resolution of  $0.10 \times 0.10$  degrees have been available to researchers and users since March 12, 2014 (Miri et al. 2019).

## 2.2 Methods

In the present study, GEV was used for determining the 24-h rainfall return periods of the mentioned stations. This distribution is often used to estimate extreme data values, especially for precipitation and flood frequency analysis. By fitting GEV to the historical observations of 24-h maximum precipitation values of March and January, the return periods of the March 2019 and January 2020 heavy precipitation events were identified for the examined stations. Then, by arranging the 24-h total precipitation values of each station in decreasing order, the rank of March 2019 and the January 2020 precipitation events were identified and compared to the other heavy rainfall events that occurred in the entire statistical period of that month and station. Comparing the return periods and the order of the heavy precipitation events considered for the analysis with other historical precipitation events at each station will allow us to figure out whether the resulting devastating floods



were due to the abnormal intensity and amount of these precipitation events or they have resulted from the land-use change, human encroachment to the riparian of the rivers, mismanagement of water resources, and/or not taking into consideration the early warnings of the Meteorological Organization, which had previously announced the very likely heavy rainfall and flood.

Finally, to determine the atmospheric circulation patterns responsible for the heavy rainfall events considered in this study, the geopotential height,  $u$  and  $v$  wind components, and the omega data of 1000 to 500 hPa levels, as well as the sea surface pressure of the events, were retrieved from the NCEP<sup>1</sup>/NCAR<sup>2</sup> Web site and used to map the considered atmospheric fields using the GrADS software environment.

### 3 Results

Since we have considered two heavy precipitation events that occurred in two different times and areas of Iran, the statistical characteristics of each event and the associated atmospheric circulation patterns are separately presented in the two following subsections.

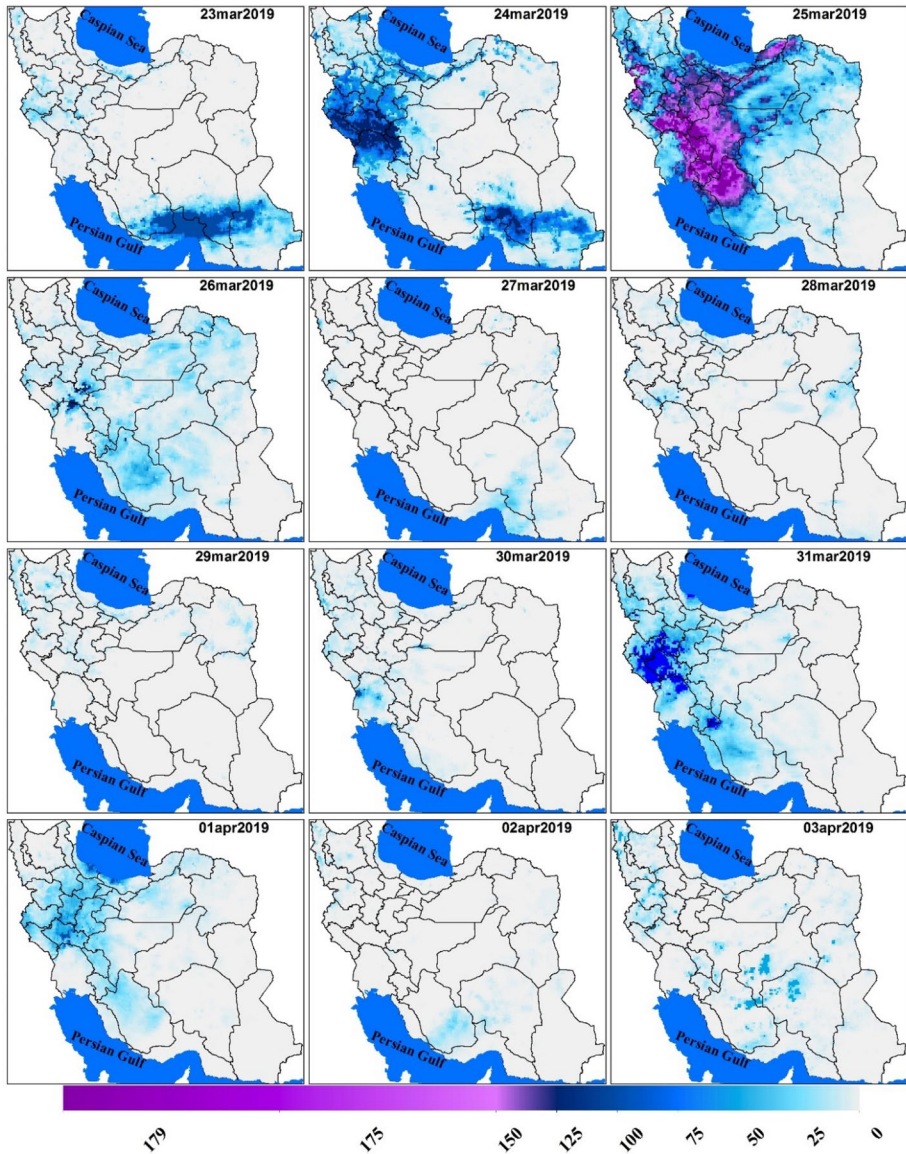
#### 3.1 Heavy rainfall and flood of western and southwestern Iran

Figure 2 shows the maps of the cumulative total amount of heavy rainfall events of March 24 to March 25 and March 31 to April 1, 2019, which occurred in western and southwestern Iran, measured by the GPM satellite. As shown in the figure, the occurrence of several consecutive days of heavy precipitation over western and southwestern Iran is the main features of this event as demonstrated by the GPM images. According to the satellite images, the mentioned precipitation system started on March 23, 2019, propagated over most parts of Iran on March 25 with a movement from northwest to southeast and west to east of the country. As is shown, the system has centered over Lorestan and Fars provinces in southwestern Iran, extending further to the east of Iran. It is worth noting that the total precipitation of this system has reached 180 mm in some areas of western and southwestern Iran as depicted by the GPM satellite images.

Figure 3 shows the return periods of 24-h maximum rainfall amounts of April at different stations of Lorestan, Kermanshah, Khuzestan, Fars, and Ilam provinces in western Iran, computed by fitting the GEV to the observed 24-h maximum rainfall data of that calendar month. During the consecutive days of the heavy rainfalls of late March and early April 2019, Ilam province located in western Iran received the lowest rainfall total in the region due to its geographical position from the entering air flows to the region. In Ilam province, the maximum 24-h rainfall of March 2019 with a value equal to 72.6 mm was recorded in Darreh Shahr station located in the south of the province. The estimated return period of a such precipitation amount for that location is 20 years. In Kermanshah province, the maximum rainfall of March 2019 with 109 mm was recorded in Kangavar station for which the estimated return period is more than 200 years. In this province, Kermanshah station has received 58.6 mm of precipitation during the 24-h consecutive rainfall occurrence of March 2019. For this month and station, this precipitation amount ranked first

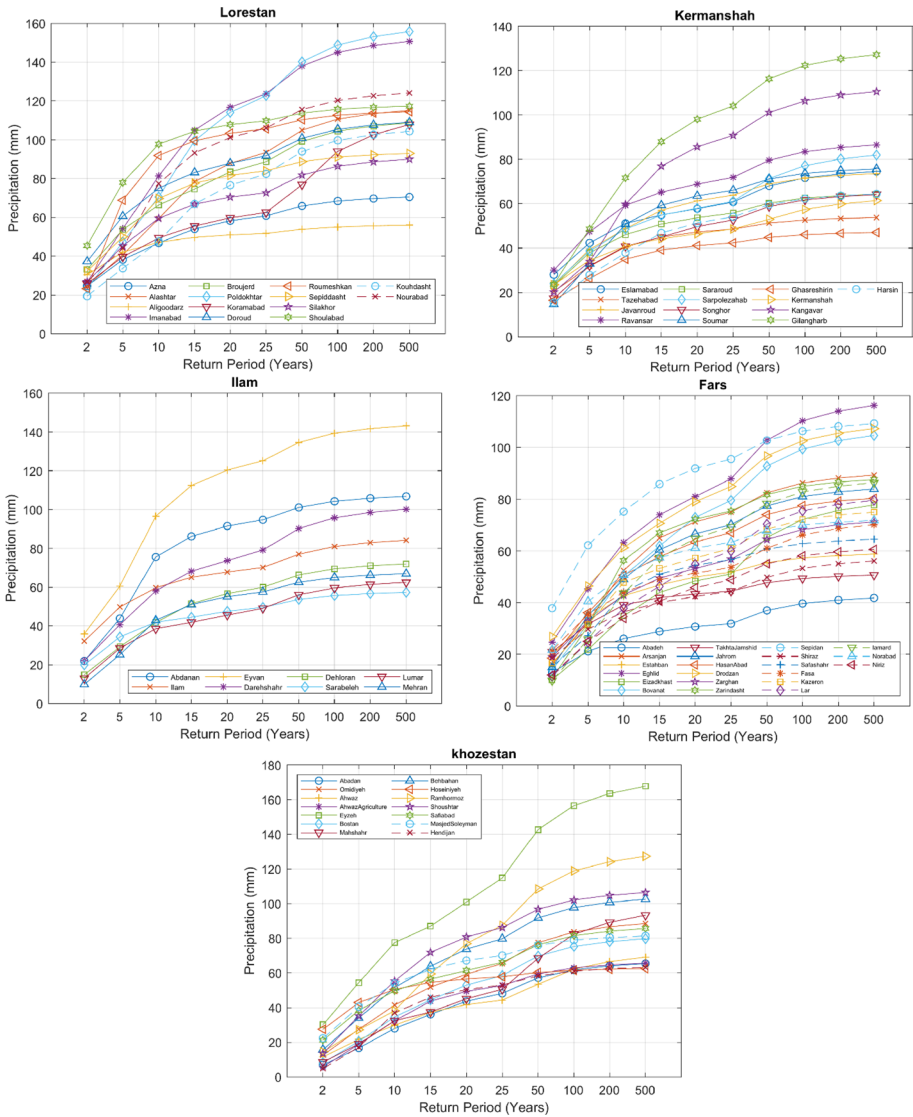
<sup>1</sup> National Center for Environmental Prediction.

<sup>2</sup> National Center for Atmospheric Research.



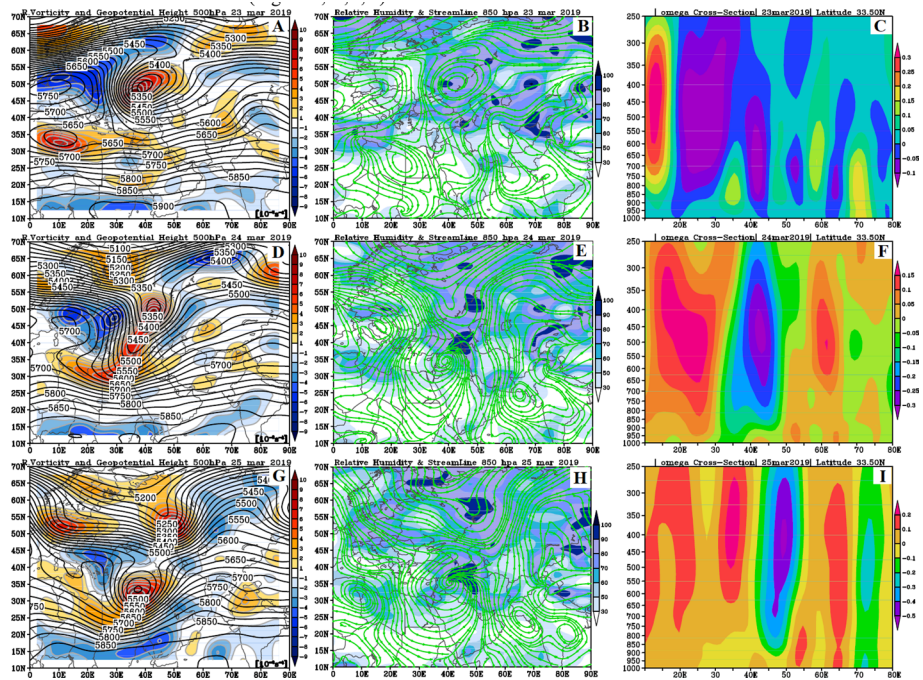
**Fig. 2** Total cumulative precipitation of March 24 to 25 and March 31 to April 1, 2019, measured by the GPM satellite

in the 1951–2019 period, with an estimated return period of 132 years. According to the March rainfall data records of Lorestan province shown in Fig. 3, the March 2019 rainfall observed in Poldokhtar station was equal to 142 mm, with an estimated return period of 56 years. The 106-mm 24-h rainfall of March 2019 in Khorramabad station ranked first in that station among the 24-h maximum rainfall records in the 1951–2019 period. Fars is another province that faced a very destructive flood in late March and early April 2019. Most synoptic stations of this province reported more than 50 mm of rainfall on March 26,



**Fig. 3** The estimated return periods of maximum 24-h rainfalls for March calendar month at some selected synoptic stations over the study area

2019. Sepidan station located in the north of this province recorded 102.6-mm total 24-h rainfall on March 26, with an estimated return period of 50 years that shows the possible occurrence of such rainfall every 50 years. Due to locating downstream of the rivers of the mentioned provinces and receiving substantial heavy rainfalls in late March and early April 2019, the northern areas of Khuzestan province faced also destructive floods. In this province, the maximum 24-h rainfall recorded in Izeh station during this period was 155.9 mm with an estimated return period of 96 years.

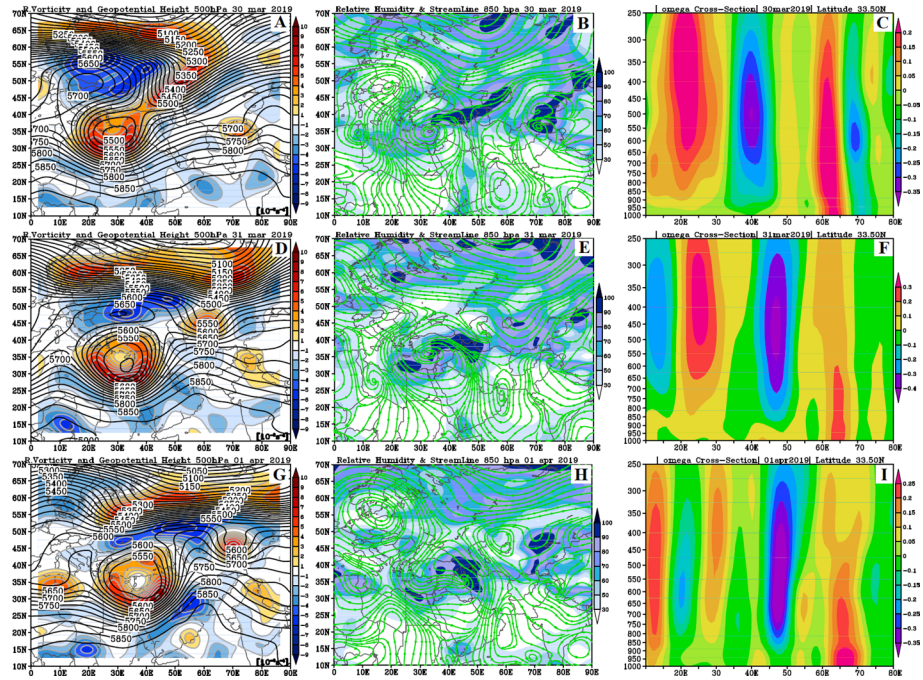


**Fig. 4** Average daily geopotential height (m) and relative vorticity of 500 hPa (s 5-10-1) (A, D, G), the airflow isopleths, and relative humidity at 850 hPa (B, E, H) and omega of 1000 to 250 hPa (C, F, I) of the heavy rainfall of March 23 to March 25, 2019, in western Iran

### 3.2 Synoptic aspects of the heavy rainfall occurred in western and southwestern Iran

As stated in “Method” section, the torrential heavy rainfalls of western and southwestern areas of Iran have occurred during a short period of March 23 to March 25, 2019, and March 31 to April 1, 2019. Figure 4 shows the synoptic condition of the heavy rainfall of March 24 to 25, 2019, at different atmospheric levels. During this period, the development of a mid-tropospheric ridge over Europe, with a southwest northeast tilted flank, that extended to sub-polar latitudes has intensified the meridional advection and has caused cutting a cold trough from the higher latitudes westerly air flows, that appeared as a northeast–southwest-oriented cut-off low with a 5325 geopotential meters closed center over the west of the Caspian Sea on March 23, 2019 (Fig. 4A). The ridges in the east and west of this system that caused cold advection from the higher latitudes into the area have substantially declined the eastward movement of the westerly waves and therefore have intensified the blocking system and increased its expansion areas and persistence in the next days, especially on March 25, 2019, when the blocking system has centered over Iraq (Fig. 4G). The expansion of the established cut-off low and the advection of the cold air from Europe in the back (west) of the cut-off low system, accompanied with the advection of hot air from the southern latitudes, have caused steep air geopotential gradients over southern Iraq and western Iran. Due to being under the upper air divergence and positive vorticity areas of the cut-off low system, the western and southwestern regions of Iran attain favorable





**Fig. 5** Average daily geopotential height (m) and relative vorticity of 500 hPa (s 5-10-1) (A, D, G), the airflow isopleths, and relative humidity at 850 hPa (B, E, H) and omega of 1000 to 250 hPa (C, F, I) of the heavy rainfall of March 30 to April 1, 2019, in western Iran

conditions for dynamical air rising and cloud formation. Due to the high intensity of the cut-off low center, its effects are continually observable from mid-troposphere to surface level as reflected by the steep geopotential contour gradients and uplift motion of cold air over Iraq and west of Iran. This is evident at 850 hPa level at which a low-pressure center is formed over eastern Iraq and western Iran, being accompanied by the positive vorticity area of 500 hPa level that is extended over the Red Sea and the Persian Gulf with closed cells. These conditions indicate the presence of atmospheric gradients and baroclinicity, causing air convergence at lower levels that subsequently led to rising air, condensation, and cloud formation. Because of intensive air rising over the study area, the advection of moist air from the Red and the Persian Gulf in the south and moisture fluxes from the Mediterranean and Black Seas in the northwest have provided favorable conditions for heavy precipitation over western and southwestern Iran (Fig. 4B, E, H).

Investigating the synoptic patterns responsible for the second wave of heavy precipitation on March 30 to April 1 in the studied region indicates the formation of another omega-shaped blocking system. On March 30, 2019, the ridge of this system was located over central Europe, while its associated trough with 5,500 geopotential meters closed center was centered over the Mediterranean Sea (Fig. 5A). The spatial extent of the blocking system is so wide that the contours of its eastern trough extend far southern over Africa from the south and the Red Sea and the Persian Gulf from the east. The location of the blocking system has caused very steep air and pressure gradients between the upper cold air of the higher latitudes and the hot and moist air of the lower latitudes. With the eastward

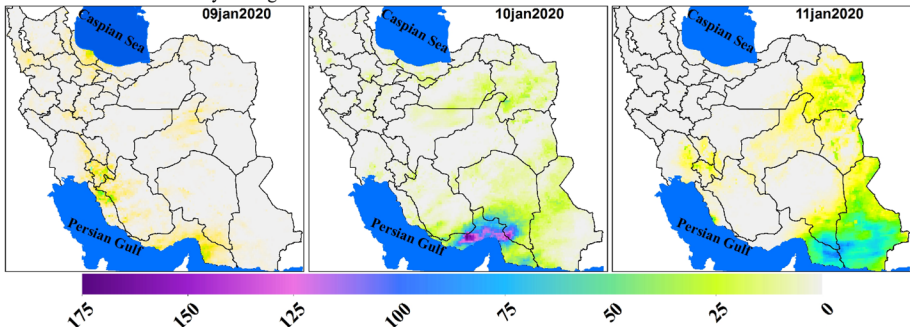


movement of the omega-shaped blocking system and strengthening the associated trough due to the cold air advection from the higher latitudes on March 31, 2019, the system's eastern trough has further expanded and intensified the contours of the eastern trough over the western and southwestern Iran (Fig. 5D). Due to the wide spatial extent of the system's eastern trough and intrusion of cold and moist air from the higher latitudes and the hot and moist air from the lower latitudes into the front of the system's trough, a strong temperature and pressure gradient has formed over eastern Iraq and western Iran. This condition has continued more intensively on April 1 when the rainfall occurrence was intensified. With the eastward movement of the blocking system, the divergence area of the eastern trough of the system has occupied the western and central regions of Iran on this day (Fig. 5G). The spatial extent of the trough on April 1, 2019, when the rainfall has maximized, is such that the contours of the system have extended further south up to the Red Sea. The formation of such a strong trough provides the necessary conditions for transferring moisture from the Red Sea and the Persian Gulf, as well as from the Mediterranean Sea into Iran, especially into the western region of Iran. The collision of two air masses with different thermodynamic conditions has caused the formation of air fronts and severe air baroclinicity over the studied area. The intensity of the mentioned trough is such that the omega values over the west and southwest of Iran are negative from 1000 to 250 hPa on the day that precipitation was maximized, which is an indication of intense activity of the trough and the existence of the ideal condition for intense air rising over the area (Fig. 5I). Accordingly, during this period, because of the existence of the trough axis with northeast to southwest direction over eastern Europe and positioning whole of Iran and its southern water bodies (the Red Sea and the Persian Gulf) in the eastern part of the blocking system (positive vorticity part), the condition necessary for severe air uplift and formation of widespread clouds over the western and southwestern Iran and occurrence of heavy rainfall have been provided. It should be noted that due to its high intensity, the presence of the system can be seen at the lower levels of the atmosphere as well. For example, as shown at the 850-hPa-level map, the omega-like blocking system was first formed over eastern Europe and subsequently moved eastward and located over Iraq and west of Iran in the subsequent days.

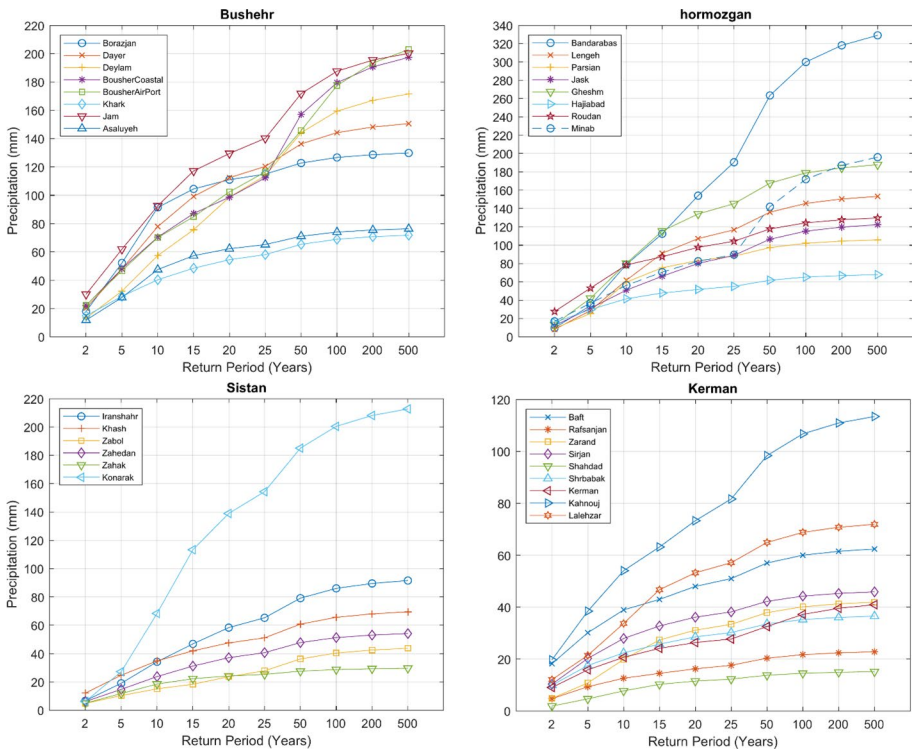
### 3.3 Heavy rainfall and flood of southern and southeastern Iran

Consecutive days of heavy rainfalls on January 9 to 11, 2020, over southern and southeastern Iran have overflowed the ephemeral rivers of the region and resulted in very intensive and devastating floods with extensive financial damages. As shown in Fig. 6, the occurrence of rainfall during a set of consecutive days over a wide spatial extent of the area is the main feature of this event. According to the GM satellite images, the considered precipitation bearing system appeared in the region on January 9, 2020, and has covered the whole of southeastern Iran in the subsequent days through an eastward propagation. According to the GM satellite images, the rainfall measured over the Persian Gulf water body during this event was more than 200 mm.

Based on the recorded rainfall amounts reported from different stations of southern and southeastern Iran during this period, the 176 mm of rainfall recorded in Qeshm and Minab coastal stations on January 11, 2020, was break recording 24-h total precipitation at these stations, as reported by the Meteorological Organization of Iran. The 24-h total precipitation of January 11, 2020, recorded at Minab station in Hormozgan province ranked first among all historical Januaries daily precipitation totals, with an estimation return period of 115 years (Fig. 7). The maximum amount of precipitation recorded during the period

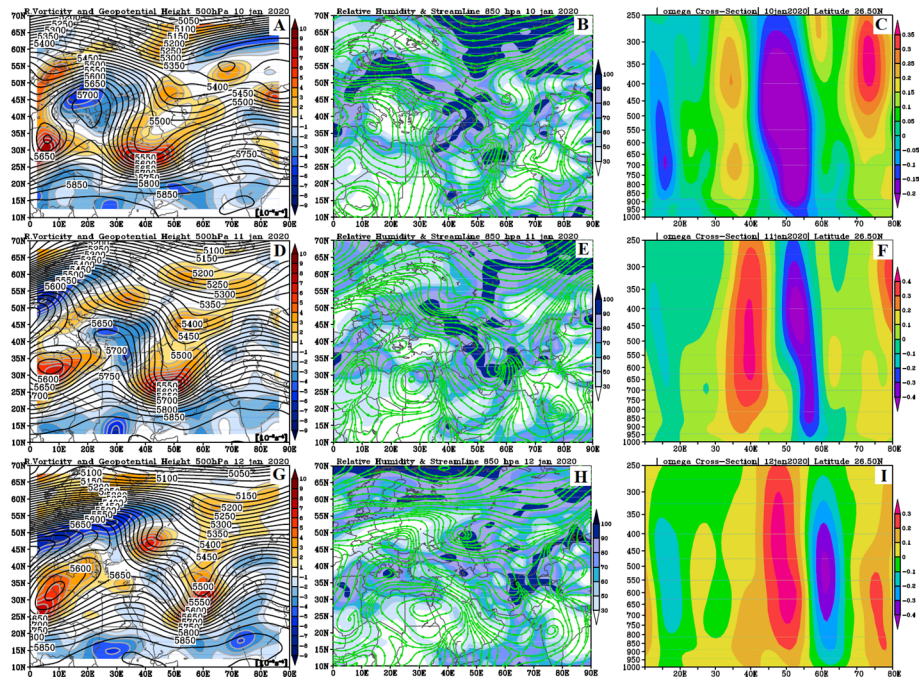


**Fig. 6** Total cumulative precipitation amounts from January 9 to 11, 2020, measured by GPM images



**Fig. 7** The estimated return periods of maximum 24-h rainfalls for January calendar month at some selected synoptic stations distributed over southern and southeastern Iran

in question in Sistan and Baluchestan province was 107 mm at Rusk station, followed by 76 mm at Chabahar station, with an estimated return period of 10 years for Rusk and 3 years for Chabahar station. In addition to the Hormozgan and Sistan and Baluchestan provinces, which received significant volumes of flood-induced rainfalls, parts of Kerman and Bushehr provinces have also been affected by this rain-bearing system. In Kerman province, the maximum rainfall amount recorded in March 2020 was 65 mm which



**Fig. 8** Average daily geopotential height (m) and relative vorticity of 500 hPa (s 5-10-1) (A, D, G), the airflow isopleths, and relative humidity at 850 hPa (B, E, H) and omega of 1000 to 250 hPa (C, F, I) of the heavy rainfall of January 10 to 12, 2020, in southern and southeastern Iran

occurred at Kahnooj station. This amount of rainfall has a return period of 17 years at this month. Such a rainfall that occurred for two consecutive days at most of the studied stations has destroyed a large part of the infrastructure of southern and southeastern regions of Iran and caused huge financial damages.

### 3.4 Synoptic aspects of the heavy rainfall occurred in southern and southeastern Iran

Examination of mid-tropospheric atmospheric-level synoptic maps relative to heavy rainfall event of January 10 to 12, 2020, indicates the formation of a large-scale omega-shaped blocking system over Eastern Europe (Fig. 8A, D, G). The spatial extent of this system is such that the associated ridge affects parts of northeastern Europe, north Asia, and parts of central Asia, while its forehead western trough influences western and southern Europe, and its second trough affects eastern Turkey and southwest Asia. Due to the considerable extent of this system, the eastern trough of this blocking system, with the northeast-southwest orientation, has affected a vast area from the Caspian Sea to the Persian Gulf and the Red Sea. The cold air advection from Europe in the western side of this system has provided an ideal condition for the formation of a strong trough and expansion and advancement of westerly winds further south up to the south of Saudi Arabia. Due to being situated under the positive vorticity of geopotential heights and air divergence area, the study area has a very suitable condition for dynamical uplift air motion and atmospheric

instability. Regarding the position of the blocking system and its eastern trough core cells over the Mediterranean Sea, the Red Sea, and the Persian Gulf, the counterclockwise air circulation of the system has advected moist air from the mentioned water bodies into the trough that further strengthens the system. The synoptic map of 850 hPa level is also consistent with the mid-troposphere atmospheric level, which indicates a vertical instability from the lower to mid-troposphere level and the domination of negative omega values over the study area (Fig. 5C, F, I). At the same time, with its northward displacement, a tongue from the sea-level low-pressure center formed over Saudi Arabia has merged with the dynamical low-pressure centers over Iran that resulted from the sharp divergence in the upper atmosphere. The creation of such a large extent low-pressure area over southwest Asia has caused extensive air convergence at surface level and subsequently air instability and uplift motion over the area. The surface-level air divergence in the high-pressure center formed over the Arabian Sea has caused moist air transportation into the low-pressure centers formed over Saudi Arabia through its clockwise rotation. The passage of the tongues of these low-pressure centers from the Persian Gulf has caused the passing air to absorb substantial amounts of moisture from this water body (Fig. 5B, E, H) and subsequently uplift and produce heavy rainfalls over the southern coast of Iran, as a result of the high moisture content of the surface-level air and extensive uplift air motion over the study area.

## 4 Discussion

In March 2019, most areas of Iran faced heavy rainfall events produced by the passages of several synoptic scales cold fronts. According to the IRIMO reports, the intensity, amount, and duration of these precipitation occurrences were much higher in northern, southwestern, and western Iran than in other areas of Iran. As an example, the heavy rainfall of late March and early April 2019 in northeastern Iran has caused severe floods in the Aq Qala district of the Golestan province. Also, from March 24 to April 2019, two waves of heavy rainfall hit western and southwestern Iran, especially the Lorestan province in mid-western Iran. Several consecutive days of these two heavy rainfall events have caused severe floods in Shiraz on March 22, 2020, as well as in different cities of Lorestan province on March 25, 26, 30, and 31, 2020, causing huge financial damages and human losses in these cities that are mostly located in the Kashkan watershed. Due to the extremely long period of times that these consecutive rainfall events occur over a high spatial extent of the study area, the volumes of the resulting floods were so high that most areas of the two cities of Poldokhtar and Mamolan in Lorestan province were submerged. The runoff induced by these heavy rainfalls has also created huge floods in the upstream rural areas and cities. Moreover, the continuous rainfalls for several consecutive days in southwestern Iran have also caused severe floods in other provinces, especially Khuzestan, Chaharmahal Bakhtiari, and Ilam located in the south and west of Lorestan province.

It is worth mentioning that the second precipitation event struck the western and southwestern regions of Iran only one day after the earlier event. The first system hit the Kashkan watershed area for six consecutive days from March 24 to 29, with 137-mm average rainfall over the whole watershed. The second system again struck the watershed from March 31 to April 2, 2019, with an average rainfall of 157 mm over the area. It is worth mentioning that the maximum 24-h rainfall of the studied stations in these three rainy days coincided with the most destructive floods of Lorestan province in recent years that occurred on April 1, 2019. In general, it can be concluded that the continuous rainfall occurrences

in nine consecutive days that maximized at the end of this rainy season are the main causes of the destructive floods of Lorestan province in March and April 2019, especially in the Kashkan and Karkheh basins, and thus, the assumption that very heavy and extraordinary rainfalls have induced such floods is not true. In other words, the role of continuous rainfalls has been much more influential than their intensities in producing the floods. Based on the computed return periods of the maximum 24 h of rainfalls, it can be concluded that the probability of such precipitation amounts is less than 100 and even 50 years in most of the studied stations. If the construction managers and policymakers of the western and southwestern regions of Iran have designed and constructed the infrastructures of the cities based on such valuable information, and if the municipalities and districts authorities of the region did not permit people to construct buildings and infrastructures on the rivers flood plains, very likely a large part of these damages could have been prevented.

Flood potential and flood inundation of an area are two important issues in flood control. Flood potential of an area is the degree of the proneness of the upstream of that area to produce floods, while flood inundation is more related to the downstream areas and the rivers banks where they are mostly occupied by buildings and residential areas. Increases in intensity and duration of precipitation events in conjunction with the reduction in the potential of flood degradation in an area (part of the precipitation that does not turn into floods) increase the potential of flooding in that area. At the same time, squatting the riparian zone and building obstacles on the river plains increase the river's flood inundations. Many studies have so far confirmed considerable land-use changes in Iran, especially in the upstream of the rivers (Khalighi and Ebrahimi 2010; Motevalli et al. 2012; Mohammadi et al. 2021; Jahanbakhsh et al. 2022). Nonetheless, many studies such as Miri et al. (2021) and Razinei (2017) have evidenced widespread climate change across Iran for the last decades that adversely affect many processes of the watersheds. For example, Modarres et al. (2016) showed that the number of drought events has significantly increased in Iran in recent decades. Increases in the frequency and severity of droughts reduce the capacity of watersheds in reducing flood losses and thus more sediments accumulate in the lower orders watercourses during the dry years. On the other hand, less vegetation cover caused by drought occurrences reduces the runoff losses and provides more sediment to the runoffs. Contrarily, due to the increased runoff volumes in the wet periods, the sediments transferred into the low-ordered streams do transfer into the outlets of the basin (higher-order streams) and increase the destructive power of the floods. As a result, if there appear more obstacles over the river beds, they result in larger floods with more significant damages. Therefore, such situations provide more difficult conditions for managing flood-related crises, which should always be taken into consideration in flood management.

## 5 Conclusion

Many experts and water resources management authorities have considered the heavy rainfall events of April 2019 in western and southwestern Iran and heavy rainfall events of January 2020 in southern and southeastern Iran as extraordinary rainfall events with estimated return periods of 200 years or higher. However, frequency analysis of the historical records of maximum 24-h precipitation of the selected synoptic stations indicates that the estimated return period of the considered precipitation event was about 150 years at only some selected stations like Khorramabad, the capital of Lorestan province. In other stations such as Kuhdasht and Aleshtar in Lorestan province, these



precipitation events have a return period of more than 70 years, while in other stations they have a return period of 50 years or lower. Therefore, even though the considered precipitation events were extreme with a relatively high return period at most of the stations, their very high intensity has not been the main cause of extensive flooding in the region, but it was the length of the events, i.e., the continuous days of heavy rainfall occurrences, as the main responsible factor for the catastrophe floods of March and April 2019 in western and southwestern provinces of Iran. However, in creating effective rainfall that appears as surface runoff, antecedent soil moisture is one of the most important factors. As rainfall continues in these events, soil moisture content increases and produced more runoff. Therefore, successive days of precipitation occurrences have increased the volume of floods at the outlet of the basins.

Synoptically, the formation of strong blocking systems over central and eastern Europe that gently moved eastward, and the positioning of their associated troughs over Iraq and western Iran have led to heavy rainfall over western Iran in late March and early April 2019. According to the atmospheric circulation patterns at different atmospheric levels, especially at the mid-tropospheric level from March 23 to April 1, 2019, the formation of a strong cut-off low system with a very sharp pressure gradient over Iraq was the main responsible factor for the heavy rainfall occurrences over west and southwest of Iran on these dates. Because the moisture and energy can exchange between the stratosphere and troposphere in these systems, and since they are often associated with deep moisture convection, they can lead to significant precipitation (Singleton and Reason 2007). Examination of the mid-tropospheric geopotential maps of these events shows that the formation of a cut-off low has transported cold air from the higher latitudes and moist air from the Mediterranean Sea into the study area. Similarly, it also has advected moist and hot air from the Red Sea and the Persian Gulf into the Zagros highlands in western Iran. The sharp air pressure and temperature gradients between the cold-moist air came from the higher latitudes and the hot-moist air advected from the hotter water bodies of the Red Sea and the Persian Gulf have resulted in severe atmospheric instability and uplift air motion in the studied area. The hot-moist air advected from the lower latitudes and the cold-moist air transported from the higher latitudes into the studied area have, respectively, formed hot and cold fronts over the studied area. The temperature contrast between these two different air masses that have different thermodynamic conditions has caused heavy rainfall occurrences in western and southwestern Iran.

Due to the vicinity to large water bodies, the southern and southeastern of Iran are also prone to heavy rainfall and flood when a suitable condition is provided for the uplift motion of moist air in the area. These conditions are mostly attained in the cold period of the year when strong synoptic systems pass across this part of Iran. In January 2020, forming a strong blocking system over the west and south of Iran and positioning the southeastern regions of Iran under the positive phase area of the blocking system were recognized as the main responsible factor for the occurrence of heavy rainfalls and devastating floods of January 10 to 12, 2020, in the south and southeast of Iran. In these two days, the formation of an omega-shaped blocking system over west of Iran and the advancement of its closed contours into the lower latitudes have caused a cold air advection from the higher latitudes and also an intense uplift motion of the lower latitudes hot-moist air that pass from across the Persian Gulf and the Oman Sea into the southern and southeastern regions of Iran. Therefore, because of the strong uplift motion of moist and hot air over the south and southeast of Iran in early winter 2020, very heavy rainfalls and floods have occurred in the considered area and imposed significant damages to the human infrastructures and the natural environment of the region.

In general, based on the statistical and synoptic characteristics of the recent heavy rainfalls in the west, southwest, and south of Iran, it can be concluded that because of the shorter return periods estimated for these flood producing heavy rainfalls, and also because of the geographical position of this region of Iran over the pathways of the different air masses entering to Iran, IRIMO should take into consideration the local geographical and physiographical characteristics of different regions of Iran in climate modeling or down-scaling the forecast outputs of different climate models, to better predict the magnitude, duration and areal extent of heavy precipitation events and issue timely early warning to reduce the adverse impacts of the events. On the other hand, the very high probability of occurring such heavy rainfall events in short durations indicates the vital importance of finding the more appropriate places for establishing infrastructures and urban facilities, choosing the right type of materials for buildings and infrastructures, taking into consideration the principles of safety and retrofitting the buildings and infrastructures, taking into account the capacity of the natural environment, and adaptation with the environment and the associated natural hazards is of great importance in the development of plans for different regions of Iran. Not taking into consideration such important issues, it is very likely to face such heavy rainfalls and floodings with associated huge damages and losses in near future again.

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## Declarations

**Competing interests** The authors declare that they have no competing interests.

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