The effect of atmospheric rivers on cold-season heavy precipitation events in Iran
Neda Esfandiari and Hassan Lashkari

ABSTRACT

Atmospheric rivers (ARs) as massive and concentrated water vapour paths can have a critical impact on extreme events in arid and semi-arid areas. This study investigated the effect of ARs on heavy precipitation events during the cold, rainy months (November–April) in Iran for 11 years. The results showed that 107 ARs had an influence on heavy precipitation, which providing partial moisture for Iran’s precipitation. On average, 11 heavy precipitation days were linked to the presence of ARs in the six cold months of each year. During the study period, ARs accounted for almost 20–50% of the country’s total heavy precipitation monthly. Although most ARs entered the country from the south through coastal areas, the western part of Iran, especially elevated stations along the western slope of the Zagros Mountains, received the highest heavy precipitation. Accordingly, about 66% of ARs directly originated from the Red Sea and the Gulf of Aden. Moreover, December experienced the highest frequency of ARs linked to heavy precipitation during the statistical period.

Key words | atmospheric rivers, cold season, heavy precipitation, Iran

INTRODUCTION

Iran is an arid and semi-arid country with limited water resources. Despite this limitation, water demand is growing every day due to the large waste of water for drinking and agricultural uses. Therefore, managing the use of such scarce water resources makes the issue even more important. The climate features and precipitation pattern in Iran are low annual rainfall with intense short-term fluctuations. Heavy precipitation events in most of the country’s basins cause out of reach precipitation in the form of flooding and cause huge damage which cannot be compensated for in the short term (Mostafaii et al. 2016). As an example, the heavy precipitation in late March 2019 affecting 25 provinces in the country for several consecutive days can be mentioned. Most of the precipitation was out of reach and a significant amount of runoff was also discharged in the downstream rivers to prevent possible damage to dams. The losses were estimated at 4.7 billion dollars (United Nations Office for the Coordination of Humanitarian Affairs 2019).

It should be noted that heavy precipitation occurs annually in different parts of the country, influencing many sectors including water resources, environment, agriculture, energy, health and financial security. Moreover, increasing climate variability and change has augmented the risk of such natural disasters (Van Aalst 2006), so that in recent years the number of these incidents has multiplied in Iran. Forecasting Iran’s climatic condition also shows a rising occurrence in flood events across the country, as reported by several studies (Abbaspour et al. 2009; Modarres et al. 2016; Keteklahijani et al. 2019; Vaghefi et al. 2019).

To meet these challenges, the government needs to be equipped with excellent operating infrastructure and warning systems. Flood alert for risk management is thus one of the most effective non-structural methods of flood management (Rezaee & Shakur 2009). Although it is possible to predict floods after the beginning of precipitation according to hydrological practices, there is not usually enough...
time for preparation operations and flood damage is in any case unavoidable. However, their occurrence can be predicted by means of flood patterns if effective mechanisms and circulation patterns of this event are identified (Taghvaei & Soleimani 2011).

The main purpose of this study was to identify the importance of the atmospheric phenomenon called ‘atmospheric river’ (AR) in the high-risk area of Iran. Numerous studies in this regard have revealed that the given phenomenon was potentially associated with heavy precipitation, floods and surface winds (Ralph et al. 2006; Stohl et al. 2008; Ruby Leung & Qian 2009; Knippertz et al. 2013).

ARs are relatively narrow and concentrated structures of water vapour in the lower troposphere moving from lower to higher latitudes in each hemisphere. They also play an important role in the hydrological cycle and account for 90% of water vapour transport over mid-latitudes (Zhu & Newell 1998). A bulk of water vapour transported by ARs can cause heavy rainfall or flooding in affected areas if accompanied with appropriate synoptic and thermodynamic conditions. Therefore, ARs play a crucial role in the global water cycle and weather extremes. Several researchers have studied the role of ARs in extreme weather events. Waliser & Guan (2017) showed that ‘ARs contributed to the distribution of half of the extreme winds and rainfall events, especially in mid-latitudes’. They attributed 40–75% of extreme events mentioned above in more than 40% of the world’s coastal regions to ARs. Lavers & Villarini (2013) studied the relationship between ARs and extreme precipitation in Europe and indicated that ARs were responsible for many extreme precipitation days. Gimeno et al. (2016) investigated the mechanisms of moisture transport and their role in extreme precipitation. Neiman et al. (2008) surveyed landfalling ARs along the west coast of North America for eight years. Their results showed that the north coast received more ARs than the south coast, and most of them occurred in north (south) coasts during warm (cool) seasons, respectively. Ramos et al. (2015) studied the association of ARs with daily extreme precipitation in the Iberian Peninsula. Some studies have also investigated the role of ARs in snow accumulation (Viale & Nuñez 2010; Gorodetskaya et al. 2014; Huning et al. 2019; Little et al. 2019). For example, on average, 30–56% of seasonal snow accumulation in Nevada (USA) has been attributed to ARs (Guan et al. 2010, 2015; Huning et al. 2017). Paltan et al. (2017) examined the effect of ARs on global floods and water availability. They found that ARs accounted for approximately 22% of the total runoff in more than 50% of the world. They also reported that ARs would increase the probability of flooding occurrence up to 80% in susceptible areas. Moreover, they showed that nearly 300 million people worldwide were affected by floods and droughts due to ARs. Skelly (2016) investigated the relationship between a flash flood and landfalling ARs over ten years in California and indicated that ARs were present during most cold-season days and caused floods. Matthews et al. (2018) demonstrated the association of ARs with ‘Super’ Storm Desmond in the British–Irish Isles. Papineau & Holloway (2012) studied ARs during the warm months in Alaska and concluded that not all ARs produced much rainfall despite having a large amount of moisture. The importance of research on ARs is also due to their relation with overall precipitation. Between 20 and 45% precipitation in central and northern California was linked to ARs (Dettinger et al. 2011; Dettinger 2013). Moreover, ARs are responsible for about 20–30% of the total precipitation in western Europe (Lavers & Villarini 2015).

Only two studies were carried out on ARs in Iran. Shademani (2016) investigated the impact of ARs on two heavy rainfall events, causing floods in the west and south of the country. She identified the characteristics of ARs for the selected events. In another study, Salimi & Saligheh (2016) identified ARs at different atmosphere levels for three years (2011–2013). They showed that south and southwest ARs had the highest amount of moisture, which, in some cases, led to floods and runoff in southern cities. However, they did not consider the total column water vapour flux in their study.

ARs may account for a proportion of heavy precipitation due to their geographical location. Identifying ARs leading to heavy rainfall events can help to create the necessary flood warnings and thus minimize the resulting damage.

This study examined whether ARs were associated with heavy precipitation in Iran during the cold months from November to April as the highest precipitation in more than three-quarters of the country occurs within the cold season (Masoudian & Ataei 2005). In the warm season, due to the dominance of the subtropical Saudi Arabia anticyclone in Iran, almost all its territory being affected by the tongues of this strong weather phenomenon (Alijani 2004).
As a result, rainfall is interrupted, except for a few areas in the north and the south-east of Iran.

This study aimed at fulfilling four basic goals: (1) identification and introduction of ARs associated with heavy precipitation; (2) investigation into their contribution to heavy precipitation within six cold months during 2007–2018; (3) study of their paths to Iran; and (4) reflection on the spatial distribution and affected zone of ARs associated with heavy precipitation.

DATA AND METHODS

Data sources

Generally, two major approaches are used in the determination of ARs (Gimeno et al. 2014). One method uses total integrated water vapour (IWV) data from satellites or reanalysed products (Ralph et al. 2004; Guan et al. 2010; Dettinger 2011). The other method is calculating integrated water vapour transport (IVT) data from reanalysed products or models (Nayak et al. 2014; Gao et al. 2015; Espinoza et al. 2018; Vitart et al. 2018). The first approach data refer only to the concentration of water vapour in the atmosphere (Blamey et al. 2018). Due to estimating zonal and meridional winds, as well as a direct relation to orographic precipitation (Neiman et al. 2008) or complex terrains (Junker et al. 2008), the flux data are more applicable. Therefore, this study has used the second approach. The 6-hourly data from the European Center for Medium-Range Weather Forecasts (ECMWF) ERA-Interim (ERAINT) Reanalysis were used to identify ARs. ‘One of the advantages of using reanalysis products, rather than satellite product, is that they use data assimilation of observations to produce the best available three-dimensional dynamical representation of the atmosphere. ERAINT is provided at high resolution and is an obvious choice given the fine filament structure of ARs’ (Blamey et al. 2018). Hence, eastward and northward vertically integrated water vapour transport parameters with 0.5° × 0.5° resolution were retrieved to calculate the IVT magnitude. Moreover, daily precipitation data of a total of 340 synoptic stations with their complete statistics were obtained from the Iran Meteorological Organization (IRIMO) and used to determine heavy precipitation.

Detection of ARs

In general, geometric characteristics and IWV/IVT are investigated in order to identify ARs. Moisture structures with a length of at least 2,000 km and a maximum width of 1,000 km while reaching above a certain threshold (IWV exceeding 20 mm) have been typically defined as ARs (Ralph et al. 2004; Neiman et al. 2008; Dettinger et al. 2011). These thresholds separate ARs from daily fluxes occurring in the atmosphere. Most previous works based on satellite-observed or reanalysed data have also used IWV thresholds to identify ARs (Ralph et al. 2004; Neiman et al. 2008; Guan et al. 2010; Rutz & Steenburgh 2012; Wick et al. 2013). With the emerging use of an IVT, some others have utilized the 250 kg m⁻¹ s⁻¹ absolute IVT threshold value for AR detection (Moore et al. 2011; Rivera et al. 2014; Rutz et al. 2014).

As moisture flux distribution differs in various regions of the world depending on geographical location, adjacency to water zones and topographic position, Lavers et al. (2012) established a varying IVT threshold value based on percentiles. An advantage of this is that it can be computed and set for other regions of the world and different reanalysed data. They correspondingly suggested the 85th percentile of IVT to identify ARs as used in many AR studies (Lavers & Villarini 2013b; Nayak et al. 2014; Guan & Waliser 2015; Eiras-Barca et al. 2018; Vitart et al. 2018; Espinoza et al. 2018). This threshold could reach 638 kg m⁻¹ s⁻¹ on the west coast of North America in the distribution of IVT for the winter and one-time step. A preliminary survey on Iran also revealed that the 250 kg m⁻¹ s⁻¹ IVT value was too high to detect ARs in arid and semi-arid areas. Therefore, the 85th percentile of IVT was used to detect ARs.

First, the IVT magnitude was calculated in the geographical domain of 33 to 69° E and 13–43° N (Figure 1(a)) using the eastward and northward IVT. The mentioned range was selected to locate the ARs in the threshold calculation domain as much as possible and to consider all potential humidity supply sources. The IVT is calculated from 1,000 to 300 hPa levels using a Eulerian framework as follows:

$$ IVT = \sqrt{\left( \frac{1}{g} \int_{1000\text{hPa}}^{300\text{hpa}} qv \, dp \right)^2 + \left( \frac{1}{g} \int_{1000\text{hPa}}^{300\text{hpa}} qv \, dp \right)^2} $$
where $q$ is the specific humidity (kg kg$^{-1}$), $u$ and $v$ denote the zonal and meridional components in (m s$^{-1}$), $g$ is the gravity acceleration and $dp$ is the pressure difference between the two adjacent levels (Lavers et al. 2012; Ramos et al. 2015). In general terms, a radicand represents the vertical integral of eastward–northward water vapour transport.

Then, the 85th percentile was obtained for 1,200 Coordinated Universal Time (UTC) of each day (Figure 1(b)) (Lavers & Villarini 2015; Eiras-Barca et al. 2018). IVT maps were plotted in 6-hourly steps to ensure the persistence of AR flow based on the 85th percentile for each month. In other words, the minimum observable IVT on the maps was the value of the 85th percentile for each month. In this study, the number of time steps marked as ARs was separated daily to be comparable with the sum of daily precipitation. The approach considers each day as an event with different rainfall characteristics, and the frequency and the sum of precipitation can also be monitored locally for each station. Eventually, the areas with a flux above the threshold and the mentioned geometric characteristics were recognized as ARs if they had entered into the land boundaries of Iran.

Different methods are usually used to check the geometric characteristics of ARs. In this line, Dettinger (2013) identified very moist, narrow and long structures as ARs by eye. Kim et al. (2017) also utilized the calculation of the maximum distance between two boundary grid cells. Others further employed the distance between the centres of each two neighbouring grid cells. In the present study, citing Guan & Waliser (2015), the axis of each AR was first obtained based on maximum IVT points (see Guan & Waliser 2015) or centres of AR gravity (for one time step as the representative), then, a line was drawn following these points. The axis of each river was also measured on the map with the km measuring instrument as AR length. For calculating the AR width, the length line was divided into four equal segments, and a line was drawn from these points perpendicular to flow direction. After measuring the distance of all segment lines, the mean width was obtained. Using this approach is simpler as it considers the ARs with a highly curved or unusual shape and works with any map projection (Guan & Waliser 2015). In this study, the axes were used to investigate the paths of rivers. To accurately measure the length of ARs and to determine the first location of their axes, the plotted coordinate was thus set in an extensive range between 0° and 50° N as well as 15° and 85° E.

In order to identify the paths of ARs, they were also classified according to the origin, location and time of entry into Iran. Thus, the axes of ARs were classified based on where they had started, as well as where they had entered into Iran, and when they had formed (monthly). All possible entry locations of ARs into Iran were also surveyed for classifying the entry paths; then, they were
classified into five regions based on provincial divisions in different geographical directions (Figure 2(a)). This approach could help to have a better insight from the spatial distribution and the frequency of ARs entering into Iran.

**Heavy precipitation determination**

There are different absolute thresholds to determine heavy precipitation that vary regionally. They have not been addressed in this work because the annual average precipitation was different in each region of Iran. For example, the average precipitation is 1,800 mm in the north of Iran, while it was nearly 70 mm in eastern parts. Thus, the occurrence of 20 mm precipitation is normal in the first region, but is destructive and causes flooding in the second one (Rousta et al. 2017). Accordingly, using an absolute threshold is not appropriate for all synoptic stations to determine heavy precipitation. Instead, using percentile indices is more applicable than threshold indices. The 95th and 90th percentile of precipitation are generally cited for heavy precipitation determination. Due to the arid and semi-arid nature of Iran and the low frequency of days with precipitation over the 95th percentile (Alijani 2011), we used the 90th percentile of precipitation as the threshold to determine heavy precipitation similar to Groisman et al. (2001), Haylock et al. (2006) and Li et al. (2010).

After testing the homogeneity of the precipitation data and fixing existing errors, the 90th percentile of precipitation in each station was separately calculated as the threshold of heavy precipitation events for that station. The 90th percentile of the precipitation zoning map over the cold months of the statistical period is demonstrated in Figure 2(b). In the next step, daily precipitation was extracted for dates associated with AR events (total 364 AR events), and the precipitation over the threshold was checked for each station. The number of stations with heavy precipitation was counted in the expanding AR domain, and each AR event was identified by the number of stations involved. The sum of heavy precipitation was calculated with and without the presence of ARs in order to recognize the monthly (November to April) contribution of ARs to the total heavy precipitation of the country during the 11 years. Finally, the frequency of ARs and the total value received for each station was mapped.

**RESULTS**

**Identifying ARs associated with heavy precipitation**

Among the 364 identified ARs, 107 were associated with heavy precipitation. Characteristics of ARs leading to heavy precipitation are depicted in Table 1. Investigating
| ARs event dates | All stations | ARs event dates | All stations | ARs event dates | All stations | ARs event dates | All stations | ARs event dates | All stations | ARs event dates | All stations | ARs event dates |
|-----------------|--------------|-----------------|--------------|-----------------|--------------|-----------------|--------------|-----------------|--------------|-----------------|--------------|-----------------|
| 1 12/2/2007    | 20           | 2 12/7/2007     | 57           | 3 12/8/2007     | 13           | 4 1/4/2008      | 12           | 5 1/4/2008      | 9            | 6 1/2/2009      | 8            | 7 2/11/2009     | 76           |
| 23 4/23/2010   | 53           | 52              | 12           | 26              | 25            | 19    | 28 2/1/2011     | 31            | 3 2/2/2011      | 11            | 3 2/2/2011      | 12            | 33 3/1/2011     |
| 10 67 3/30/2012| 26            | 22              | 17            | 4 53 11/8/2013  | 7            | 9    | 32 3/8/2011     | 17            | 5 3/14/2009     | 10            | 6 10 3/30/2009  | 26            |
| 10 67            | 13            | 10              | 10            | 13 5511/19/2013 | 13            | 12    | 34 3/12/2011   | 8             | 12 3/31/2009    | 77            | 7 34 3/13/2011  | 38            |
| 12 67 3/14/2014 | 10            | 5 3/6/2013      | 17            | 35 57 12/4/2013 | 49            | 48    | 36 4/2/2011    | 24            | 1411/7/2009     | 38            | 36 4/21/2011    |
| 8 67 2/12/2015  | 16            | 30 59 12/6/2013 | 19            | 57 58 12/5/2013 | 30            | 30    | 57 4/22/2011   | 30            | 1511/26/2009   | 5             | 37 4/24/2011    |
| 16 67 2/12/2015 | 16            | 28 60 12/12/2013| 28            | 23 38 11/16/2011| 21            | 18    | 28 12/12/2009  | 28            | 1611/28/2009   | 28            | 26 38 11/16/2011|
| 17 12/7/2009    | 20            | 39 11/17/2011   | 13            | 9 6112/13/2013  | 40            | 40    | 40 40 40       | 14            | 1812/8/2009     | 58            | 36 40 11/21/2011|
| 20 39 12/9/2009 | 10            | 6 41 1/12/2012  | 6             | 6 63 1/6/2014   | 23            | 13    | 63 12/12/2013  | 14            | 1912/9/2009     | 10            | 6 41 1/12/2012  |
| 20 1/25/2010    | 28            | 25 42 2/1/2012  | 35            | 32 64 1/11/2014 | 23            | 23    | 64 64 23       | 27            | 214/9/2010      | 27            | 27 43 2/2/2012  |
| 22 4/13/2010    | 11            | 11 44 2/26/2012 | 30            | 24 66 3/12/2014 | 31            | 31    | 31 31 31       | 88 12/2/2016  | 57            | 57            |

Table 1: The AR event dates and the number of stations with heavy precipitations.

Covered by ARs: 8, 10, 11, 13, 16, 19, 20, 24, 25, 26, 27, 30, 31, 32, 35, 40, 46, 53.
the statistics of stations with heavy precipitation showed that: (1) a maximum of 75 and minimum of 5 stations had heavy precipitation after the occurrence of ARs; (2) in 70 events, the total heavy precipitation recorded by 340 synoptic stations was related to ARs; (3) on average, 23 stations were exposed to heavy precipitation in each AR event; (4) 81 ARs covered between 10 and 30 heavy precipitation stations, while 26 ARs covered between 30 and 80 stations; and (5) 40 cases of ARs associated with heavy precipitation occurred on similar dates but in different years. A sample of such similarities is shown in Figure 3.

The role of ARs in heavy precipitation of Iran

The annual occurrence rate of ARs obtained from November 2007 to April 2018 with the sum of heavy precipitation associated with them is displayed in Figure 4(a). The highest number of ARs associated with heavy precipitation occurred from November 2013 to April 2014. Hence, of 107 cases, 16 ARs occurred in this time range with the sum of heavy precipitation being 10,829.3 mm, which accounted for 41% of the total heavy precipitation during this period. In contrast, the lowest number of ARs occurred during the study period from November 2007 to April 2008. Previous studies have shown that Iran experienced severe droughts during this period (Ghazanfarpar et al. 2008; Abounoori 2011; Hashemi & Hooshang 2012; Kavakebi et al. 2014; Salahi & Faridpour 2016; Alesheikh et al. 2018; Nouri et al. 2018). The number of ARs occurring each year was in full conformity with the sum of their heavy precipitation, as shown in Figure 4(a). On average, 11 days of AR events were linked to heavy precipitation, which accounted for about 3,000–11,000 mm of precipitation in the cold months.

The estimates of heavy precipitation linked to ARs compared to the total (November–April) heavy precipitation during 2007–2018 along with the monthly frequency of AR events is shown in Figure 4(b). On average, AR events accounted for about 30% of the total heavy precipitation during the statistical period. This contribution was variable from 17% in November to 51% in December. Moreover, the highest and lowest frequency of AR events occurred in December and April, respectively.

The paths and location formation of ARs associated with heavy precipitation

The paths and initial location of AR axes associated with heavy precipitation (Figure 5) indicated that the greatest

Figure 3 | The IVT magnitude (kg\(^{-1}\) s\(^{-1}\)) during two similar dates of AR events in 2015 (a) and 2016 (b). The date format is hour-day-month and year.
Figure 4  
(a) The column diagram shows the annual frequency of ARs during the cold season and the line diagram shows the sum of heavy precipitation associated with AR events. The left axis is the frequency and the right is the sum of precipitation. (b) The line plot shows the monthly frequency of AR events associated with heavy precipitation. The right axis is the number of ARs. The column plot depicts the estimation of heavy precipitation (mm) resulting from ARs compared to the total seasonal (November–April) heavy precipitation during 2007–2018. Moreover, it shows the percentage contribution of ARs to the monthly heavy precipitation. The left axis is the total heavy precipitation.

Figure 5  
(a) AR axes associated with heavy precipitation, occurring from November to April during the 11 years; (b)–(g) the paths in each month.
number of ARs generally formed from the Gulf of Aden and the Red Sea. Most of these ARs entered the Red Sea after crossing the Bab al Mandab Strait and left the Red Sea between 18 and 22°N. According to previous studies, this area corresponds to the Red Sea convergence zone (Lashkari 2000). ARs entered Iran after crossing the middle of the Arabian Peninsula, in a domain between the Strait of Hormuz and Western provinces, but influenced the whole country. The majority of them had a southwest-northeast direction and continued to the north and northeast of Iran.

The monthly distribution of AR axes is shown in Figure 5(b)–5(g). As shown, a total of 14 ARs occurred in November, of which most were terminated in the western lee of the Zagros Mountains and only a few were extended to the north and northeast of Iran. In December, most ARs entered the country from the southwest, and their regularity along this path indicated the frequency of a distinct system. In this month, the Sudanese system activity and the Red Sea convergence increased (Mohammadi & Lashkari 2019). Moreover, the extension range of ARs increased during this month compared to November, and most of the rivers were extended to the north and northeast of Iran as well as to Central Asia. In January, concurrent to decreased AR events, AR axes were sharply inclined southward and entered the country between the Strait of Hormuz and the southwest. Although most ARs originated from the Gulf of Aden and the Red Sea in the first three months, this pattern changed in February, and AR axes were initiated from Sudan and the Arabian Peninsula. ARs entered Iran in a wider area from the east of the Strait of Hormuz to the northwest, but the paths were irregular. In March, the majority of ARs again originated from the Gulf of Aden and entered in an extensive range from the Strait of Hormuz to the west and northwest. ARs entered Iran after passing through Saudi Arabia and then were distributed on various paths across the country. Moreover, in colder months, the paths were lengthened and expanded to Central Asia.

In April, we are approaching the last rainy month in the Arabian Peninsula and even Iran. During this month, the number of AR events significantly decreased and the westward displacement of them was totally evident. Most ARs pass through Central and Western Saudi Arabia and flow in a domain between the southwest and west regions of Iran with meridional tendency. These rivers are generally extended in the south-north direction and affect the western part of the country.

The pattern of atmospheric circulation in the Middle East and the displacement of the Arabian anticyclone corresponded with the location of the AR entry. Accordingly, the eastward displacement of the Arabian subtropical anticyclone in other months allowed entry of more landfalling systems from the south. In April, the westward shift of anticyclone was initiated, and, as a result, entrance landfalling systems moved westward (Lashkari et al. 2017). Thus, due to the location of the Arabian subtropical anticyclone on the east coast of the Red Sea, landfalling ceased and the summer pattern dominated the area.

Statistical information about the origin and entry location of ARs (based on the 85th percentile of IVT) is depicted in Table 2. Seventy-one ARs were formed from the Gulf of Aden and the Red Sea, which mostly entered

| AR origin                  | AR number | Southeast | South | Southwest | Northwest | West |
|----------------------------|-----------|-----------|-------|-----------|-----------|------|
| Gulf of Aden               | 33        | –         | 15    | 9         | 4         | 5    |
| Red Sea                    | 38        | –         | 17    | 14        | 2         | 5    |
| Sudan                      | 12        | –         | 5     | 2         | 1         | 4    |
| Arabian Peninsula          | 14        | –         | 9     | 4         | 1         | –    |
| Libya/Egypt/Niger          | 9         | –         | 2     | 3         | –         | 4    |
| Mediterranean              | 1         | –         | –     | –         | –         | 1    |
| Total                      | 107       | –         | 48    | 32        | 8         | 19   |
Iran from the south (32) and southwest (23). The Arabian Peninsula and Sudan were the next areas where ARs originated. As can be observed, the Mediterranean Sea did not play a significant role in the formation of ARs which led to heavy precipitation; however, its contribution to strengthening ARs should be studied. A total of 48 ARs from the south, 32 ARs from the southwest, 19 ARs from the west and 8 ARs from the northwest entered Iran, while no AR axis entered the country from the southeast.

Spatial impact of ARs on heavy precipitation

The frequency of heavy precipitation associated with ARs for the cold months is displayed in Figure 6. In November, heavy precipitation was highly concentrated in the southwest (including the two provinces of Chaharmahal and Bakhtiari and Kohgiluyeh and Boyer-Ahmad) west and northwest of Iran. Similarly, most of the AR axes were concentrated in these regions during this month. The main concentration of heavy precipitation on high-altitude provinces showed the key role of topography in intensifying rainfall in these geographical regions. In December, the affected zones were widened and covered the entire highlands of the Zagros Mountains, from the southwest to the northwest, and even to some extent to the western range of the Alborz Mountains. Also, ARs were extended to Lorestan, a high-altitude province. Further, the number of ARs increased so that ARs associated with heavy precipitation influenced these provinces for up to ten days. Previous studies also showed that December was one of the rainiest months in the south and southwest of Iran, that their landfalling systems were being formed from the Sudanese low-pressure system and the tropical convergence zone (Mohammadi & Lashkari 2019). In January, the impact zone of ARs was slightly more limited in the west and southwest, but increased in the south, and even in some parts of southeast Iran. According to Mohammadi & Lashkari (2018), by the eastward displacement of the central core of the Arabian subtropical high pressure, Sudanese systems can enter the country from the east. In addition, the most frequent heavy precipitation event was located in the highlands of the Zagros Mountains. In February, the impact range of ARs was at its highest point. Accordingly, except for the central arid part of Iran located in the leeward plains of the Alborz and the Zagros Mountains, other regions were affected by heavy precipitation for at least 2 days and more. Likewise, heavy precipitation cores were located in the highlands or foothills of the Zagros Mountains. However, the main core of precipitation was transferred to the southern part of Iran (Fars and Kerman provinces). The pattern in March was similar to that in February, with the main difference being that the most frequent precipitation cores moved from the southern slopes of the Zagros Mountains to the middle and western highlands of Zagros. In April, as can be observed in Figure 5, most of the AR axes entered the country from the west in a northward direction; as a result, they had a significant effect on heavy precipitation in the west and northwest areas, as displayed in Figure 6(g). The lowest number of ARs occurred in April, and the AR systems did not affect the southwest and south, unlike the other months. This result corresponds with the study of Lashkari & Mohammadi (2018). They also found that from this month onward, the number of precipitation systems imported into the southwest and middle-south regions of Iran decreased due to the westward movement of the Arabian subtropical high-pressure system.

The total frequency of heavy precipitation linked to ARs during the 11 years (November to April) is shown in Figure 6(g). The highest frequency was observed in the middle and west of the Zagros Mountains. In general, parts of western Fars, Kohgiluyeh and Boyer-Ahmad, Chaharmahal and Bakhtiari, Lorestan, Kermanshah, Kurdistan and parts of Hamadan provinces had the highest precipitation and experienced heavy precipitation up to 30 days associated with AR events. Moreover, Kohgiluyeh and Boyer-Ahmad, Chaharmahal and Bakhtiari, Lorestan, parts of Fars, Khuzestan and Kermanshah provinces received the highest amount of heavy precipitation, up to 1,700 mm in each of their stations (Figure 6(h)). Therefore, the potential for flooding in these provinces is higher than in other parts of Iran.

CONCLUSION

The arid and semi-arid nature of the Middle East and West Asia means that even light precipitation leads to devastating floods. This area has been highly prone to flooding due to improper use of soil and vegetation over many years,
imposing huge damage annually to infrastructure and natural resources, as a result. The effect of climate change on speeding up parts of the water cycle by increasing temperature, evaporation and precipitation has also provoked the spread of these events (Stagl et al. 2017). Studies on arid and semi-arid countries such as Iran do not indicate a promising future for the climate of these areas (Abbaspour et al. 2009; Rahimi et al. 2015; Modarres et al. 2016). Sequences of destructive floods in the years 2018, 2019 and 2020 in different regions of Iran are warnings of this climatic reality.
The results showed the major ARs originated from the few rivers had been formed from the Mediterranean Sea. It was observed that very southern systems were the most important factors affecting the access to moisture resources of the Arabian Sea, Gulf of Oman, the Red Sea, and the structural properties of the entry into Iran. The survey of the paths and location formed and initiation of ARs. It was observed that very important factors affecting the access to moisture resources of the Arabian Sea, Gulf of Oman, the Red Sea, and the structural properties of the entry into Iran. The survey of the paths and location for 41% of heavy precipitation in the country in 2013 associated with ARs. In the best situation, ARs accounted for 51% in December. In terms of annual distribution, not all months, varying from 17% in November to a maximum of 30 days of heavy precipitation during the statistical period. In other words, on average, ARs were associated with heavy precipitation for 11 days during each rainy period (November–April). Moreover, ARs were responsible for total heavy precipitation in the country of over 70 event days out of 107. In the remaining cases, part of the heavy precipitation was related to the AR expansion zone. This indicates that the formation mechanism of ARs alone plays an important role in the occurrence of heavy precipitation in the region.

After comparing heavy precipitation in the presence and absence of ARs, it was observed that the contribution of ARs in generating heavy precipitation was not the same in all months, varying from 17% in November to a maximum of 51% in December. In terms of annual distribution, not all years have had the same contribution of heavy precipitation associated with ARs. In the best situation, ARs accounted for 41% of heavy precipitation in the country in 2013–2014.

In this study, the paths of ARs were classified and analysed according to starting-place, position and time of entry into Iran. The survey of the paths and location formation of ARs based on applied threshold of IVT revealed that access to moisture resources of the Arabian Sea, Gulf of Oman, the Red Sea, and the structural properties of the southern systems were the most important factors affecting formation and initiation of ARs. It was observed that very few rivers had been formed from the Mediterranean Sea. The results showed the major ARs originated from the Gulf of Aden and the Red Sea. These ARs could have taken different paths after formation due to synoptic conditions. Therefore, their paths were divided into five geographical regions (from southeast to northwest), considering different directions in which ARs could enter into Iran. It has been recognized that most of the ARs’ departure from the Red Sea are in the range between 18° and 22° N, called the Red Sea Convergence Zone, as cited in the study by Lashkari (2000). These ARs had entered into Iran after crossing the middle of the Arabian Peninsula, in a domain between the Strait of Hormuz and the western provinces. Although more than 44% of ARs entered the country from the southern coast, most heavy precipitation occurred in the middle and western Zagros highlands. This indicates the role of topography in intensifying heavy precipitation.

The monthly pattern of displacement of AR axes and heavy precipitation linked to them conformed with the displacement pattern and positioning of the Arabian high-pressure system. Considering previous studies (Lashkari & Mohammadi 2018), it had been established that the zonal and meridional displacement of the Arabian anticyclone could play a decisive role in the movement of precipitation systems in south and southwestern Iran. As the rainfall season progresses, this anticyclone gradually shifts westward and is placed on the west of the Arabian Peninsula. At this time, precipitation that originated from the southern systems will be interrupted, but during the rainy season with the eastward displacement of this anticyclone, the precipitation systems increase in these areas. The results of the present study also showed that the number of ARs leading to heavy precipitation had amplified from the south and southwest during the colder months, especially from December. In addition, it was found that the rivers’ paths had lengthened in colder months and extended to Central Asia. On approaching the end of the rainy season in April, the entered ARs had shortened and shifted westward. As a result, heavy precipitation was focused on the west and the northwest of the country. In terms of temporal frequency, December and April had the highest and the lowest number of ARs associated with heavy precipitation, respectively.

In terms of spatial distribution, altogether, the mountainous and sub-mountainous provinces in the southwest and west of the country along the Zagros Mountains with a maximum of 30 days of heavy precipitation during the
rainfall period are more subject to the risk of flooding due to ARs. Also, according to the study by Vaghefi et al. (2019) on Iran’s climate forecast, the western slopes of the Zagros Mountains will be more prone to extreme phenomena such as floods during wet periods in the future. However, due to the topography of the area, basins are generally sloping to the south. Most of the floods in the area also flow down to the southern plains. Therefore, maintaining water balance and paying attention to watershed management and land use practices can help resilience in these areas.

Another important result of the study was the similarity of 40 AR event dates over different years, implying the sequence of repetitive systems in AR events occurring. These findings raise the possibility of predicting the occurrence of ARs and can be used to take preventive measures against flood hazards.

This study highlighted the potential of ARs for causing heavy precipitation in Iran, which had not been studied previously, and provided a better understanding of the paths and origins of these rivers. In addition, investigating the spatial and temporal distribution of heavy precipitation associated with ARs revealed the areas at risk of flooding as this phenomenon occurs.

With regard to ARs affecting many regions of Iran and making a contribution to water supply of these areas, analysing the effect of climate change on ARs using climate models to project their frequency and intensity in future conditions is suggested (e.g., Filipiu & Hu 2009; Moazenzadeh et al. 2018; Homsi et al. 2020). This work helped to partially improve the historical data on ARs associated with heavy precipitation events.

The results are also based on reanalysed data with records of synoptic stations. However, it has been found that selection of the type of data and the method can sometimes influence the results. Regarding the identification of ARs due to the high accuracy of the data used in this study and the magnitude of the occurrence scale of this phenomenon, it is unlikely that the present results are affected (Lavers et al. 2012). However, employing different threshold methods and criteria to identify ARs in future studies is recommended for better comparisons. In addition, the results revealed that not all identified ARs (364 cases) had caused heavy precipitation in Iran. Since the synoptic conditions of the river path could play a decisive role in converting this abundant moisture into heavy precipitation, it is suggested to reflect on effective synoptic patterns in heavy precipitation.

One of the main limitations of the study was no accessibility to station data from the Arabian Peninsula and other countries to investigate precipitation occurring along the AR paths. Therefore, it is suggested to examine the effects of ARs on heavy precipitation in the Arabian Peninsula in future studies to reveal the potential of ARs on this event. Further investigations into the persistence and sources of moisture enhancing ARs can also be undertaken.

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