Investigating Role of Tropical-extratropical Interactions in Formation of Atmospheric Rivers and Supplying Extreme-widespread Precipitation Moisture in Iran: A Case Study on March 25, 2019

Helaleh Fahimi  
University of Zanjan

Abdollah Faraji (✉ abfaraji@znu.ac.ir )  
University of Zanjan

Buhloul Alijani  
Kharazmi university

Hossein Asakereh  
University of Zanjan

Koohzad Raispour  
University of Zanjan

Research Article

Keywords: Circulation patterns, interactions of circulation patterns, atmospheric river, extreme precipitation

Posted Date: January 5th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-2398107/v1

License: ☒ This work is licensed under a Creative Commons Attribution 4.0 International License. 
Read Full License
Abstract

This study aims to investigate the role of tropical-extratropical interactions in the formation of atmospheric rivers as an important source of moisture in extreme-widespread precipitation of Iran. Extreme precipitation events are extracted based on the 95th percentile index from 1989 to 2019 in Iran. Then, the threshold of widespread precipitation is determined. A day is defined as having extreme-widespread precipitation if one-third of the selected stations have mostly extreme precipitation. Finally, 9 days with the highest extreme precipitation and spatial continuity are selected. The upper air data of the 9 selected days are extracted and, accordingly, synoptic charts are plotted. The used data include ERA5, which are extracted from the lower (800 and 850 hPa) and middle (500, 600 and 700 hPa) levels. The results indicate an interaction with tropical circulation patterns by penetration of extratropical circulation patterns into tropical and subtropical regions. The interaction between patterns could lead to the formation of atmospheric rivers with tropical origin from ITCZ, their transport to subtropical and extratropical regions and their moisture supply along the path by different moisture sources in tropical, subtropical and extratropical regions. The formed atmospheric rivers are divided into two categories, namely continental and oceanic, based on their formation origin. The continental atmospheric river is formed at the lower level and, in some cases, at the middle level, while the oceanic atmospheric river is only formed at the middle level. With the emergence of atmospheric rivers in Iran, there have been extreme-widespread precipitation events due to unstable conditions and rising atmosphere.

Introduction

Identifying extreme environmental conditions and determining the relevant pressure patterns are among the important fields of synoptic climatology (Alijani 2013). Extreme atmospheric-climatic events are sometimes called social challenges. Sustainable economic development and vital conditions are referred to as the ability to manage extreme events (World Meteorological Organization, 2009). Extreme weather events are defined as rare and unusual weather events (Bartolini et al. 2008) that are placed in the frequency distribution sequence far from the center point of distribution (mean and median) (Asakere 2012). Extreme events are those events, the values of which exceed the threshold, i.e., the values of a specific variable are greater or lower than normal in a given period, so that different thresholds should be defined for that variable in different regions (Becker et al. 2007). Extreme events statistically include large or small values of elements in a set (Benstad 2006).

According to Intergovernmental Panel on Climate Change (IPCC) (2007), an extreme weather event is an event that is rare at a particular place and time of year. Studying extreme weather events has attracted the attention of researchers due to the heavy consequences of these phenomena on various socioeconomic and agricultural sectors of each country. Today, it has been proven that changes in the intensity and frequency of these events could have a more destructive effect on human health, social units and natural systems than changes in the moderate climate state (Erfanian 2017).
Precipitation, fluctuations, patterns and intensity are among the important weather elements, knowing which is required for understanding weather (Mozaffari et al. 2017). Extreme precipitation varies from one region to another (IPCC, 2007), and this difference depends on the mean precipitation of each region. Studies have indicated an increase in extreme precipitation in different parts of the world, e.g., increased extreme precipitation in Japan (Fujibe et al. 2006), Caspian coast in Iran (Oji and Ghafarian 2018), China (Shi et al. 2018), Singapore (Brown et al. 2010), northeast of the United States (Alexander et al. 2017), Australia (Klen and Konnen 2003) and an increase in the maximum annual and daily global precipitation (Asadieh and Krakauer 2015). However, its changes may not have the same pattern in different parts of the world (IPCC 2013). In the fourth assessment report (AR4), IPCC confirmed the increased number of extreme precipitation events during the last 50 years. The number of years with higher and lower extreme precipitations reached 9.64% and 33.7% in the last century (1901–2017), indicating the increased number of years with extreme precipitation. According to IPCC, warming was about 74% in 1906–2005. The increasing trend of extreme climatic elements is among the most important and worst effect of global warming.

It is assumed that an increase in air temperature increases atmospheric moisture content and evaporation from large water bodies, which accelerates water cycle and increases frequency and intensity of extreme precipitation (IPCC, 2007; Alleh and Ingram, 2002; Santos 2011; Dankers 2013; Wailate 2007), the impact of which is typically greater than that of moderate precipitation (Trenberth 2011). The occurrence of extreme precipitation is more sensitive to climate changes (Pen, quoted from Katz and Brown, 2020). The importance of studies conducted on extreme precipitation is due to direct and indirect impacts of this phenomenon on human life and activities, which justifies the necessity of paying attention to this climatic phenomenon (Ghayur et al. 2012). Synoptic identification of precipitation systems is an important point when investigating extreme precipitation events as it could be effective for forecasting extreme precipitation events and dealing with them (Mozaffari et al. 2017).

Tropical-extratropical interactions (TEIs) refer to interactions between circulation patterns of these two regions that occur in a wide range of processes at different scales. These interactions arise due to the penetration of high-level troughs into the tropical region at synoptic and planetary scales of Rossby waves at high and low latitudes and semi-permanent tropical-extratropical low-level convergence zones, which leads to the transfer of moisture from tropical to extratropical region (de Veries, et al., 2012, 2016; Kumar, et al., 2019; Almazroui, et al., 2016). Parts of the Middle East and several dry subtropical regions such as Northwest Africa, Southwestern North America, South Africa and South America are affected by extreme precipitation and floods. These events are often the result of tropical-extratropical interactions (de Veries et al. 2016; Al-Khalidi et al. 2017).

Formation of atmospheric rivers (ARs) is directly associated with tropical-extratropical interactions and occurrence of extreme precipitation. In extratropical regions, AR is responsible for transporting nearly 90% of atmospheric water vapor to higher latitudes (Ralph 2017). AR plays an important role in global water circulation and could lead to natural events such as floods and severe storms (Akbary et al. 2019; Salimi et.al. 2020). Kerr (2006) believes that only 20–40% of the AR water vapor reaches the earth’s surface and
could lead to storms and floods. The entry of Rossby waves into the subtropical region could transfer moisture from tropical to extratropical zone and cause AR formation. The horizontal circulation associated with mid-latitude cyclones may lead to the transfer of tropical moisture to poles as well as AR formation in the warm part of a cyclone (Sodemann et al. 2020). AR is a key factor in the study of water vapor in extratropical regions (Ejimenu 2014), which could lead to severe precipitation due to high water vapor and static stability, especially when it is directed towards topographic obstacles and forced to rise (Zhu and Newell 1998; Ralph et al. 2017, 2018; Dezfuli 2019).

There are seven important regions in the world, including western United States, western part of the southern cape of South America, northwestern Europe, route of northeastern Arabian Peninsula to Iran, Australia and distance between Japan and east coast of Russia, where AR has the greatest impact on the occurrence of precipitation. The southwest Asia is among the most important regions, where AR plays an important role in its precipitation. Approximately 90% of ARs that flow into oceans are longer than other ARs (Salimi et al. 2020). Subtropical jet stream is considered an important synoptic factor in the formation, path and direction of ARs (Salimi and Saligheh 2016; Lashkari and Esfandiar, 2020, 2021; Salimi, et al. 2020; Akbary et al. 2019). Moreover, the presence of high- and low-pressure centers, especially subtropical high-pressure (STHP) centers, are major factors (Salimi et al. 2020). Special attention should be paid to the role of Arabic anticyclone in the monthly pattern of AR axis displacement and severe precipitation, the westward and eastward displacement of which along the Mediterranean trough plays an important role in the path of AR entering Iran (Lashkari and Esfandiar 2021).

Although useful studies have been conducted on extreme precipitation events and their synoptic analyses in Iran, no comprehensive research has ever been done considering tropical-extratropical interactions for supplying extreme precipitation moisture. The present paper aims to investigate the role of tropical-extratropical interactions in AR formation as an important source of extreme-widespread precipitation moisture in Iran.

Study area

Iran is located at the latitude of 25–40° N and longitude of 44–64° E in the northern hemisphere and southwest Asia in the Middle East, a large part of which is situated in the subtropical region (Masoudian 2011). Due to its special geographical position, it is located in the transition zone based on large-scale general tropospheric circulation patterns, in which there are interactions between tropical, subtropical and extratropical circulation systems (Mofidi 2005; Mostafaei et al. 2015). These interactions could lead to temporal-spatial variation of precipitation in Iran (Alijani, 1995). In this regard, the interaction between Red Sea and mid-level troughs could be highlighted. If Red Sea trough is accompanied by establishment of a trough in the middle-level atmosphere, the possibility of deep rising and formation of clouds and rain will be provided (Lashkari 2003). Mediterranean systems in the extratropical region could not cause extreme precipitation in the southwestern and western Iran.

If the Mediterranean and Sudanese systems, known as Mediterranean-Sudanese pattern, merge in the eastern Mediterranean or Iraq and operate simultaneously, they could cause widespread precipitation
from the northwest to southwest of Iran (Lashkari 2005). Another example is dynamic interaction between the low-pressure monsoon trough in Iran and westerly wind flow systems in summer, which leads to summer rainfall in the southeast (Saligheh 2001).

This research was conducted to investigate the role of tropical-extratropical interactions in the formation of atmospheric rivers and supply of extreme precipitation moisture in Iran. The latitude of 0–60° N and longitude of 50° W-90° E were considered to cover both tropical and extratropical regions and identify their circulation patterns and interactions as well as moisture sources because based on previous synoptic studies, circulation patterns affecting Iran’s climate have more expansion and displacement in this area (Fig. 1).

Data And Method

To perform this research, the daily precipitation data of meteorological stations in 1989–2020 was received from the meteorological organization. The stations that did not have missing data in a 30-year statistical period were selected. Thus, 84 stations were included from the whole country (Fig. 2). The extreme precipitation threshold was obtained at each station in all days during 30 years based on the relative profile of the 95th percentile index. Based on the 95th percentile index, the extreme precipitation in 5% of the days is more than the threshold. Thus, this index was used to show the heaviest precipitation during the statistical period. In this research, extreme precipitation was equal to or greater than the 95th percentile. A day with precipitation equal to or greater than the threshold was defined as a day with extreme precipitation. The criterion of classifying extreme precipitation as widespread was defined. A day was defined as having widespread-extreme precipitation if one-third of the stations (28 stations) out of 84 selected stations had extreme precipitation. Based on the defined threshold, 450 days were obtained as days with extreme-widespread precipitation in 30 years. The isohyetal map of days with extreme-widespread precipitation was drawn to identify the spatial continuity of stations with extreme precipitation because days with extreme-widespread precipitation did not necessarily have spatial continuity. Finally, 9 days with the highest extreme precipitation and homogenous spatial distribution were selected (Table 1). Then, the upper air data of the selected days were extracted. The upper air data and geopotential height (HGT) (m) were used to investigate the expansion of circulation patterns and their interaction. V-component of wind (VWIND) and U-component of wind (UWIND) (m/sec) were employed to examine wind direction and speed. Subtropical and polar jet streams and specific humidity (SHUM) (g/kg) were used to investigate AR origin, path and direction. The selected data included ERA5 with the spatial resolution of 0.25°×0.25° and daily and hourly temporal resolution of 00.00, 06.00, 12.00 and 18.00, which were retrieved from https://www.ecmwf.int. In this research, the daily time scale was used in four observations: 00.00, 06.00, 12.00, 18.00. The data were drawn at lower levels of 800 and 850 hPa and middle levels of 500, 600 and 700 hPa in the study area (50° W-90° E and 0–70° N). The atmospheric data of the lower and middle levels were used to find the correlation between the extreme precipitation and circulation patterns at both levels. Selecting different levels could provide the possibility of identifying circulation patterns and moisture and examining their changes and unstable conditions in
the atmosphere. The subtropical and polar jet streams were drawn and examined from the level of 200 to 600 hPa.

Table 1

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993</td>
<td>February</td>
<td>3</td>
</tr>
<tr>
<td>1994</td>
<td>November</td>
<td>5</td>
</tr>
<tr>
<td>2003</td>
<td>March</td>
<td>26</td>
</tr>
<tr>
<td>2004</td>
<td>January</td>
<td>13</td>
</tr>
<tr>
<td>2013</td>
<td>January</td>
<td>29</td>
</tr>
<tr>
<td>2015</td>
<td>November</td>
<td>10</td>
</tr>
<tr>
<td>2017</td>
<td>February</td>
<td>13</td>
</tr>
<tr>
<td>2018</td>
<td>November</td>
<td>25</td>
</tr>
<tr>
<td>2019</td>
<td>March</td>
<td>25</td>
</tr>
</tbody>
</table>

**Discussion**

Considering that it was not possible to include all the maps and interpretations of the 9 selected days in this paper, the maps and interpretations related to March 25, 2019 were used as an example because among the 9 selected days, this day had the worst flood and damage, especially in the western and southern provinces of Iran. The precipitation map on March 25 showed most of the regions of Iran had precipitation (Fig. 3). Out of 84 stations, 58 stations had more than 1 mm of precipitation on March 25 of which had extreme precipitation. Koohrang station, with 153 mm, had the highest rainfall (Fahimi et al., 2021).

**Geopotential height and specific humidity of the lower level (800 and 850 hPa):**

Examining the specific humidity maps (Fig. 4.C, D) indicated interactions between extratropical Cut off low(COL) circulation systems and Arabic subtropical anticyclone at the lower level (Fig. 3) as well as Arabic anticyclone and western cyclone in the southern branch of the western winds at the middle level (Fig. 4), which has led to AR formation with a tropical origin. AR originates from the intertropical convergence zone (ITCZ) between 0 and 10° N. At two points of synoptic maps, the transfer of moisture from tropical to subtropical zone could be observed in the meridian direction (southwest-northeast) at high latitudes, at both of which extratropical COL has deeply penetrated into the tropical zone up to 15° N
This factor could be the reason for dynamic ascension of extratropical zone, which has led to the transfer of moisture from tropical to extratropical zone by entering the tropical zone. The first point is in the eastern Atlantic Ocean. The outer curve of a closed cyclone that is completely separated from its main current, i.e., deep Iceland cyclone, enters the Atlantic Ocean at 15° N. The North African anticyclone is formed in the east of cut-off low (COL), the divergence zone of which along the COL divergence transfers ITZC temperature and moisture of the Atlantic Ocean and western North Africa to subtropical latitudes up to 25° N over western North Africa. The second point is located in the west of the Middle East. COL in eastern Turkey reaches eastern North Africa, Red Sea and Arabian Peninsula up to 15° N and causes the suction and rise of ITZC moisture to the extratropical zone. This has expanded along the COL divergence zone and Arabic anticyclone up to 38° N over Iran. In the eastern Turkey’s Col, the Arabic subtropical anticyclone plays an important role in the transfer of atmospheric river. Moreover, it injects the moisture of several atmospheric sources in the tropical region into the atmospheric river by its anticyclonic circulation. Atmospheric rivers in East Africa are fed and strengthened by passing over the Red Sea and Persian Gulf. The Arabic anticyclone and Turkey’s COL systems transfer their moisture into the atmospheric river by passing over several atmospheric sources via cyclonic and anticyclonic circulations. The moisture sources that feed the atmospheric river are located in three regions: tropical, subtropical and subtropical. Moisture sources in the tropical region include the Arabian Sea and Indian Ocean. Moisture sources in the subtropical region include the Northern and Central Red Sea and Persian Gulf (Fig. 4.C,D).

The moisture of these sources is injected into the atmospheric river from the south, southeast and east through Arabic. The moisture of sources in extratropical (Black Sea and central and eastern Mediterranean Sea) and subtropical (northern and central Red Sea) zones enters the atmospheric river from the west and northwest by COL cyclonic circulation. Considering that the atmospheric river is fed by several moisture sources, its moisture content has not decreased along the path, even in the Arabian Peninsula (Fig. 4-B, C, D). Given that COL penetration depth into the tropical region is high, the two COL and Arabic anticyclone systems travel a longer path and are aligned for a long distance and, finally, reach the northwestern Iran. The Arabic anticyclone circulation in the west has a south-to-north direction. Also, the two systems are aligned in the same direction. This alignment is located on the southwestern, western and northwestern regions of Iran and corresponds to the regions with extreme precipitation (Fig. 4. C, D). The Arabic anticyclone with its south-north flow over the Persian Gulf and Oman Sea transfers their moisture to the southern, eastern, central, northeastern and northwestern regions of Iran (Fig. 4. C, D). The specific humidity map shows the highest moisture content of the atmospheric river belongs to the alignment zone of the two systems. The cores of maximum moisture convergence flux are located on the south of the Arabian Peninsula in the path of the atmospheric river, which could be considered an important source of moisture enhancement (Fig. 5.A, B). Moreover, the maximum moisture convergence flux over the Persian Gulf and its coasts as well as western Iran has enhanced moisture in the atmospheric river in Iran (Fig. 5.A, B).

**Geopotential height and specific humidity at the middle level (500, 600 and 700 hPa)**
Changes in the geopotential height at the middle level change atmospheric river transfer and path. The COL penetration depth into the tropical region decreases in the western cyclone and southern branch of westerly winds. The presence of COL and its anticyclone in the north over the Atlantic Ocean at levels greater than 700 hPa causes the westerly winds to split into two branches. The southern branch enters tropical and subtropical regions and the northern branch enters the subpolar regions (Fig. 6. A, B, C). ITCZ moisture decreases by going to higher levels, so that the atmospheric river moisture content and length decrease in the Eastern Africa (Fig. 6. D, E, F). At the level of 700 hPa, ITCZ specific humidity over the Atlantic Ocean, which rises to 25° over the west of North Africa in the subtropical region by COL and North African anticyclone, turns into an atmospheric river because it reaches the Red Sea by the southern branch of westerly winds in the orbital direction and, then, approaches Iran through Turkey’s COL divergence zone (Fig. 6.B, D). Although the moisture content decreases over North Africa, it increases by reaching the Red Sea and merging with the atmosphere river in the east of Central Africa and being fed by several moisture sources. Due to the greater penetration of southern branch of westerly winds into the lower latitudes, the atmospheric river in East Africa travels a more southerly path than the lower level upon reaching the Red Sea (Fig. 6. D, E, F). The maximum moisture content of the atmospheric river is 5–7 g in the Persian Gulf coast and southwestern and central Iran. The western, northwestern and southwestern regions of Iran are under COL divergence flow. The southeastern regions are under the influence of Arabic anticyclone, and there is an alignment between these two systems from the Persian Gulf coast to the northeastern Iran (Fig. 6.A, B, C), so that regions with maximum atmospheric river moisture correspond to this part of Iran (Fig. 6. D, E, F). The moisture of the Arabian Sea, Indian Ocean and southern Red Sea enters the atmospheric river through the Arabic anticyclone, and the atmospheric river absorbs moisture by passing through the Red Sea and Persian Gulf. The moisture is transported from the western Mediterranean Sea to the atmospheric river over North Africa via the western cyclone in the eastern part of the North Atlantic COL. Moreover, the moisture of the central and eastern parts of the Mediterranean Sea and northern Red Sea enters the atmospheric river on the Arabian Peninsula and northwestern and western regions of Iran through COL in the eastern Turkey (Fig. 6. D, E, F).

At the level of 600 hPa, the outer curve of the western cyclone reaches 18° N over the Red Sea and North Africa (Fig. 6. B). The poleward margin of atmospheric river in East Africa is merged with atmospheric river in the Atlantic Ocean. Distribution of atmospheric rivers has decreased in Iran, so that the eastern and southeastern regions of Iran do not have atmospheric rivers. Moreover, most of the atmospheric river moisture content is on the Persian Gulf coast and southwestern and western Iran. At the level of 500 hPa, the atmospheric river in East Africa becomes shorter and more southerly as the alignment zone of western cyclone in the southern branch and Arabic anticyclone becomes more southerly. With the emergence of western cyclone in Iran, the Arabic anticyclone no longer would have an effect on Iran, and the eastern Iran is placed under the cyclone of western circulations (Fig. 6. C). The starting point and origin of atmospheric river in East Africa tends more towards west and originates from 10° W on the west of Central Africa. Due to the southward alignment of Turkey’s COL and Arabic anticyclone systems, the atmospheric river in the east of North Africa does not enter Iran (Fig. 6. F). At this level, only the atmospheric river of the Atlantic Ocean reaches Iran. The atmospheric river moisture content increases on
the north of the Arabian Peninsula and reaches the northeastern regions of Iran after passing through the Persian Gulf by the cyclonic circulation of the western cyclone and Turkey's COL. The atmospheric river expansion decreases in Iran, and the eastern part and western border of Iran receive very little moisture from the atmospheric river. The atmospheric river of the Atlantic Ocean is fed by the Mediterranean Sea moisture via the North African cyclone, extratropical COL and COL of the northern Red Sea moisture as well as by passing through the Red Sea. At the level of 500 hPa, Arabic anticyclone is placed below 15° N on the Indian Ocean, and currents of the southern branch in the northern part flow by an orbital wind that prevents the Arabic anticyclone from entering the subtropical and extratropical latitudes. As a result, this system does not play a role in transferring the temperature and humidity of the tropical region to high latitudes (Fig. 6. C). At levels higher than 500 hPa, moisture is transferred to Iran only by the COL divergence zone and southern branch of western winds, which carries the Atlantic Ocean's atmospheric river over Iran.

The moisture convergence flux on the Persian Gulf and its coast occurs in the path of the atmospheric river, which leads to the atmospheric river moisture enhancement (Fig. 7. A, B, C).

**Tropical penetration of polar jet stream and interaction with extratropical COL and tropical anticyclone on March 25, 2019**

The level of 600 hPa is investigated to analyze the role of jet stream in the transfer of tropical to extratropical moisture and its tropical penetration (Fig. 8). The polar jet stream originates from the tropical region at the latitude of 20° N, which indicates the penetration of the polar jet stream into the tropical region. On March 25, a jet stream at the core speed of 35 m/sec is located on the north of the Arabian Peninsula, which starts from Sudan in North Africa and reaches the western Iran by crossing the Red Sea and Arabian Peninsula. A small part of the jet stream reaches the western and southwestern regions of Iran. The polar jet stream at 20–25° N in the meridian direction along the COL divergence zone and western cyclone of southern branch of western wind reaches 32° N in the western Iran. Considering the penetration of polar jet stream into tropical and subtropical regions and its origination from the level of 600 hPa, which is closer to the earth's surface, the extratropical COL divergence zone plays an important role in the suction and rising of moisture from tropical to extratropical region and formation of tropical atmospheric river. The instability and intensification of the rise of the earth's surface are increased by the interaction of jet stream and COL patterns (Fig. 8. A). At the level of 500 hPa, the polar jet stream starts at 20° E in North Africa and reaches Iran along the COL divergence zone up to 53° E (Fig. 8. B). The speed core with 40 m/sec is located in the north of the Arabian Peninsula. The front part of the jet stream reaches the western Iran. At the level of 400 hPa, the polar jet stream starts from the west of the Atlantic Ocean COL and is extended to the western part of Iran up to Alborz heights (Fig. 8. C). Its central core with 50 m/sec is located in the north of the Arabian Peninsula. The increased atmospheric river moisture content in the north of the Arabian Peninsula corresponds to the south of the central core of the jet stream and COL divergence. At the level of 300 hPa where the polar jet stream reaches its maximum speed and expansion, it starts from the branching point of the western currents and continues to the west of the map (Fig. 8. D). The central core of the jet stream with 60 m/sec at 10° E is located over
North Africa and Arabian Peninsula. At the level of 300 hPa, the jet stream is extended from 10° in the south of cyclone axis to 30° in the north, and its transfer to tropical regions leads to moisture transfer and rise. The subtropical jet stream is at the level of 200 hPa on the polar jet stream of the lower level (Fig. 8. E). It is widely expanded and covers the latitude of 10–35° N. The core of the jet stream is 65 m/sec, which is located over North Africa, Northern Red Sea and west of the Arabian Peninsula. The subtropical jet stream has covered all parts of Iran and is located in Bushehr and Fars provinces at the speed of 50 m/sec. The formation of polar jet stream at the levels of 500 and 600 hPa could increase instability and intensification of the ascent of air at the earth's surface and lower level.

Results

Atmospheric rivers are formed by interactions between extratropical COL of Turkey and Atlantic Ocean, southern branch of the westerly winds, subtropical anticyclone and polar jet stream. Interactions between the patterns of the two regions take place by the penetration of extratropical to tropical circulation patterns. With the transfer of moisture from moisture sources, the tropical and subtropical regions receive moisture by COL cyclonic circulations and anticyclonic circulations of the subtropical anticyclone and polar jet stream (Fig. 8). Moisture convergence flux maps showed moisture convergence zones are an important source of strengthening atmospheric rivers during their path. At two points of the specific humidity maps, there are atmospheric rivers, which enter Iran in the southwest-northeast direction.

Both points correspond to the place of penetration of extratropical COL at the lower level and western cyclone of the southern branch of the westerly winds at the middle level and accompany with the speed core of the polar jet stream, which aligns with subtropical anticyclones by its penetration into tropical regions. Turkey's COL reaches tropical latitudes in the Middle East. Moreover, the extratropical COL enters the tropical region over the Atlantic Ocean and western North Africa. Both COL are associated with the polar jet stream at the levels of 300 and 400 hPa and subtropical jet stream at the level of 200 hPa. The jet stream core speed coincides with COL divergence zone. This interaction could intensify rising of moisture. De Veries (2012), de Veries et al (2016), Almazouri et al (2016) and Kumar et al (2019) have considered the penetration of high-level troughs into the tropical region as an important factor in the transfer of moisture from tropical to extratropical region. Atmospheric rivers are divided into continental and oceanic based on the origin of their formation. The continental atmospheric river originates from the east of Central Africa, while the oceanic atmospheric river originates from the northern Atlantic Ocean. Polar jet streams at the levels of 300 and 400 hPa play a significant role in transferring moisture from tropical to extratropical regions. The largest tropical moisture content transferred corresponds to the alignment zone of extratropical COL and subtropical anticyclone systems, which are associated with the core speed of subtropical and polar jet streams.

Salimi and Saligheh (2016), Salimi et al. (2020), Akbari et al (2019) and Lashkari and Esfandiari (2020, 2021) considered the synoptic factor as an important criterion in the formation, path and direction of the atmospheric river of subtropical jet streams, this research highlighted the role of polar jet streams. Apart from transferring moisture to the extratropical region, the Arabic anticyclone plays an important role in
supplying the moisture of the originating point of atmospheric river in the eastern Central Africa, which was among the important findings of this research. The anticyclonic circulation in the east-west direction over the Indian Ocean in ITCZ leads to the transfer of moisture from the Indian Ocean to the east of Central Africa. At levels higher than 600 hPa, the atmospheric river in the eastern part of Central Africa is not often developed despite the tropical penetration of extratropical factors, which could be due to the absence of or a significant decrease in moisture in its place of origin. The atmospheric river in the eastern part of Central Africa enters Iran in the southwest-northeast direction after passing through the southern Red Sea, Arabian Peninsula and Persian Gulf. The maximum moisture of atmospheric rivers corresponds to the alignment zone of two tropical and extratropical systems. Atmospheric river is spread in Iran at the lower level, the reason for which could be attributed to the presence of two COL and anticyclone circulations in different directions, leading to the distribution and dispersion of the atmospheric river moisture in Iran. The alignment zone of the two systems brings a part of the atmospheric river to the western and northwestern Iran. The Arabic anticyclonic circulation leads to the spread of the atmospheric river in other regions of Iran in the southwest-northeast direction. The atmospheric river absorbs moisture along the way by passing through the Red Sea and Persian Gulf, which increases its moisture content. Its passage over the Red Sea corresponds to the maximum moisture of the Red Sea. Badin et al (2020) believed that the Red Sea provides moisture for large amounts of rainfall in the Middle East (parts of Syria, Iraq and Iran) from January to April. The maximum moisture is concentrated on the Red Sea at the place where northwest-southeast and southeast-northwest circulations meet and converge, which leads to water collision. Greater moisture content in the Red Sea leads to better feeding of the atmospheric river. Since the atmospheric river is transferred to the extratropical region along the Arabic anticyclone and COL divergence zone and convergence between these two patterns, its path changes at different levels of the troposphere due to the change in the position of these two systems relative to each other. The atmospheric river moisture is supplied by the COL and Arabic anticyclone systems. By passing through tropical, subtropical and extratropical water bodies, these two systems transfer their moisture into the atmospheric river and, thereby, enhance moisture content at different levels as follows:

A. At the lower level: The moisture of the tropical water bodies of the Arabian Sea and Indian Ocean enters the atmospheric river in the Arabian Peninsula from the south and east through the Arabic anticyclonic circulation and reaches Iran through the atmospheric river. The moisture of the subtropical water bodies of the Persian Gulf and Oman Sea enters the atmospheric river in Iran from the south and southwest through the Arabic anticyclone. The extratropical moisture of the Black Sea, eastern Mediterranean Sea and northern Red Sea enters the atmospheric river in Iran and Arabian Peninsula through COL from the northwest and west.

B. At the middle level: The Arabic anticyclone could only supply the atmospheric river moisture in the Arabian Peninsula due to displacement towards south. At the middle level, the continental atmospheric river in the eastern part of Central Africa travels a more southerly path compared to the lower level due to the greater penetration of southern branch of westerly winds into the tropical region and southward displacement of Arabic anticyclone, so that its path is in the south of the Persian Gulf and Oman Sea at the level of 500 hPa. Due to the lower penetration of Arabic anticyclone in Iran, the Oman Sea and Persian
Gulf moisture enters the atmospheric river only in the south and southeast of Iran, so that they supply the moisture of the southern coasts of Iran. The atmospheric river of the Atlantic Ocean, which is formed as a result of the entry of tropical COL of Atlantic Ocean and interaction with subtropical anticyclone in Africa, brings ITCZ moisture of the Atlantic Ocean to the latitudes of 25-30° in the southwest-northeast direction and flows eastward along the southern branch of westerly winds and polar and subtropical jet streams. Upon reaching the Red Sea, it merges with eastern Central Africa if there is an atmospheric river and enters Iran along the jet stream and divergence zone of the western cyclone by passing through the Arabian Peninsula and Persian Gulf. At levels higher than 600 hPa, in most cases, only the Atlantic Ocean jet stream is formed and enters Iran. The moisture of the Atlantic Ocean atmospheric river is supplied by the special moisture of ITCZ in Central Africa and transfer of the Mediterranean Sea moisture from the north by the anticyclone located over the Mediterranean Sea as well as moisture convergence flux over North Africa. The moisture is enhanced by crossing the Red Sea and merging with the eastern branch of Central Africa and crossing the Persian Gulf.

Conclusion

This study showed the role of tropical-extratropical interactions on atmospheric instability of Iran and formation of atmospheric rivers with tropical origin from ITCZ as the most important source of moisture in extreme-widespread precipitation of Iran. According to the previous studies, the most important sources of moisture in extreme precipitation in Iran include the Arabian Sea and Red Sea (Farajzadeh et al. 2009; Dadashi et al. 2018; Khoshhal et al., 2009; Heydarizad et al., 2018), Persian Gulf (Ahmadi and Alijani 2015; Karimian Kalki 2015; Masoudian, 2008; Masoudian and Jafari Shandi 2014) and Mediterranean Sea and Black Sea (Karimi and Farajzadeh 2011; Asakere et al., 2012; Ghayur et al. 2012; Hosseini and Qamsari 2016; Dustkamian et al. 2018; Heydarizad et al. 2018; Mirmusavii et al. 2020).

Atmospheric rivers, on their way to Iran, are supplied by different moisture sources in tropical, subtropical and extratropical regions due to the interactions of tropical and extratropical circulation patterns. According to the origin of formation, atmospheric rivers are divided into two categories: continental atmospheric river in the east of Central Africa and oceanic atmospheric river in the Atlantic Ocean. The continental atmospheric river is formed at the lower level and, in some cases, at the level of 700 hPa, while the oceanic atmospheric river is formed at the middle level. At the level of 700 hPa, in most cases, the oceanic atmospheric river merges with the continental atmospheric river upon reaching the Red Sea and, then, enters Iran. With the entry of atmospheric rivers into Iran, the extreme-widespread precipitation moisture has been supplied. Interactions between different tropical-extratropical circulation patterns, which lead to the formation of atmospheric rivers and their entry into Iran, could be divided into two categories:

A. Penetration of Turkey's extratropical COL and polar jet stream into tropical and subtropical latitudes and interaction with Arabian subtropical anticyclone: The interaction between the above systems has the greatest role in the extreme-widespread precipitation of Iran because it leads to atmospheric instability of Iran and formation of continental atmospheric rivers in the east of Central Africa at the lower level and, in some cases, at the levels of 600 and 700 hPa.
B. Penetration of the Atlantic Ocean COL, core speed of polar jet stream and interaction with subtropical anticyclone in the west of North Africa: Interaction between the above systems leads to the formation of the Atlantic Ocean atmospheric river and its transfer to Iran at the middle level, but they do not play a role in the atmospheric instability of Iran.

Declarations

- **Author's Contribution:** We, the authors, contributed to the research. Helaleh Fahimi. Abdullah Faraji . Buhloul Alijani . Hossein Asakereh . Koohzad raispour.

- **Conflict of Interest:** The authors declare that there is no conflict of interest while conducting this research.

- **Funding Statement:** The authors declare that no funds, grants, or other support were received during the preparation of this manuscript

- **Ethics approval:** The manuscript is original and is not submitted to another journal for simultaneous consideration neither have been published. Results are presented clearly, honestly, and without fabrication, falsification or inappropriate data manipulation. No data, text, or theories by others are presented as if we are the author's own.

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Helaleh Fahimi. The first draft of the manuscript was written by Helaleh Fahimi, Abdollah faraji and Buhloul Alijani, Hossein Asakereh and Koohzad Raispour and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

- **Consent to participate:** We, the authors, understand that any information we submit for this study will be treated as confidential, and that we have all contributed to the research.

- **Consent for publication:** We, the authors, provide our consent for this research to be published in Theoretical and Applied Climatology , which include maps and information within the text.

Abdulla Faraji(Responsible author)

References


23. IPCC (2013) Climate change, the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA:1535p.


46. Alijani b (1374) Climate of Iran, Payam Noor University Publications.


54. Karimian Kalaki R (2014) Investigating the mechanism of summer rainfall using the WRE model (case studied in southern Iran), Master's thesis, Yazd, Yazd University, Faculty of Physics, Department of Meteorology.


61. Masoudian, S.A, 2017, Identifying the simultaneous conditions associated with heavy rains in Iran, the third conference on resource management in Iran, Tabriz University, Faculty of Civil Engineering.


Figures
Figure 1

The studied area of tropical-extratropical circulation
Figure 2

geographical location of synoptic stations

Figure 3

the extreme and widespread precipitation map in Iran (in mm) March 25, 2019
Figure 4

Maps of A,B: continuous black lines of daily average geopotential height (geopotential meters), purple arrows of vector wind flow (meters per second), white circle of mid-Latitude col, blue circle of Arabia Anticyclone black line of convergence point of Arabia Anticyclone and mid-latitude col on March 25, 2019 in the lower level (850,800hpa).

Col(cut off low), AA(Arabic Anticyclone)

Maps D, E daily average maps of specific moisture (colored areas), geopotential height (black curves), wind flow (black arrows) at the lower level (800 and 850 hectopascals) on March 25, 2019. and the red circle show the country of Iran. The black line shows the convergence of the two patterns of cold and high Arabia and the AR path. The numbers show the moisture springs feeding AR. Tropical moisture springs: 1 Indian Ocean. 2 Arabian Sea. Extratropical moisture springs: 3 Black Sea. 4 Eastern and central Mediterranean Sea. Subtropical moisture springs: 5 North and Central Red Sea. 8 Sea of Oman. The red oval shows the geographical location of Iran.
Figure 5

Maps of A and B the daily mean of moisture convergence flux in the lower level (800 and 850 hpa) on March 25, 2019.
Figure 6

Maps of A,B,C: continuous black lines of daily average geopotential height (geopotential meters), purple arrows of vector wind flow (meters per second), white circle of extratropical Turkey's col, black line of the convergence of the southern branch of the western winds and the Arabia Anticyclone on March 25, 2019 in the lower level (700,600,500 hpa).

Col(cut off low), AA(Arabic Anticyclone), NAT col(Northern Atlantic cut off low)
maps of D, E, F daily average maps of specific moisture (colored areas), geopotential height (white curves), wind flow (black arrows) at the middle level (700,600,500 hpa) on March 25, 2019. The black line indicates the course of the East Central African Atmospheric River in maps D, E, the arrow of the red Atmospheric River of the Atlantic Ocean. The numbers indicate the feeding springs of the Atmospheric River. Tropical moisture springs: 1 Indian Ocean, 2 Arabian Sea. Extratropical moisture springs: 3 Black Sea. 4 Eastern and central Mediterranean Sea. Subtropical moisture springs: 5 Northern and Central Red Sea.

**Figure 7**

maps of C, D, F daily mean of moisture convergence flux in the middle level (700, 600 and 500 hpa) on March 25, 2019.
Figure 8

polar jet stream at levels of 500, 400, 300 hPa and subtropical jet stream of 200 hPa level on March 25, 2019. The red oval shows the geographical location of Iran.