



Investigation on dynamical structure and moisture sources of heavy precipitation in south and south-west of Iran

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Received: 4 March 2020 / Accepted: 6 October 2020 / Published online: 24 October 2020
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Abstract

The purpose of this research is to study the structure and mechanism of heavy precipitation systems on the Arabian Peninsula and Iran and what is role of hot seas on providing moisture to these systems. To this end, precipitation data from 45 stations in the region during the period 1982–2017 were extracted. Based on local indices, the rainfall threshold of 30 mm was selected as the heavy rainfall criterion. By this criterion, 92 single-day systems with heavy rainfall were identified. By visual inspection of different atmospheric levels maps, one sample that comprised more than 80% of the samples were selected as the dominant model. The vertical structure and the moisture flux of this pattern were plotted in three boxes (system motion path). The results of this study showed that high humidity systems are supplied from three regions. In the first box (Sudan), the highest moisture advection in the lower troposphere comes from Intertropical Convergence Zone (ITCZ), the Indian Ocean, and the Arabian Sea; at second box comes from the Red Sea, Arab, and Oman; and the at third box comes from the Persian Gulf. The new finding of this research is the identification of a front line. This front line is caused by cold advection of polar side latitudes by a deep trough in the eastern Mediterranean and warm and humid advection of the southern warm seas, while so far it is thought that convection phenomenon to be the main cause of heavy rainfall and flooding in this region.

Keywords Dynamical structure · Moisture sources · Heavy precipitation · South and south-west of Iran · Low-pressure system of Sudan

Introduction

The climate of north-east of Africa is generally influenced by a low-pressure system in Sudan region with special features of tropical regions and different surface factors (El-Fandy 1946, 1948, 1950a, b, Johnson 1965). Remarkable results obtained from the previous researches in this region include the formation of low-pressure systems in north-east of Africa and the Red Sea. Prior researches suggested that these low-pressure systems are isolated cells from the Intertropical Convergence Zone (Solot 1950; Johnson 1965). Regarding the low latitude and the absorption of high levels of radiant energy, in some other studies, they have been considered as thermal low-

pressure systems (Krichak et al. 1997). And other researchers believed that the convergent currents created in the region predisposes to the formation of surface low-pressure systems. Convergent currents are classified into two types: the first type includes the south-east, north–north-west convergent currents in the leeward of the Ethiopian plateau and its adjacent mountains, creating leeward low-pressure systems (El-Fandy 1946, 1948, 1950a, b; Krichak et al. 1997), and the second type includes the convergence of the two opposite currents from east-southeast and north–north-west within the Rift of the Red Sea, leading to the formation of low-pressure systems (Flohn 1965a, b, Pedgley 1966.).

El-Fandy (1950a, b) has described the annual changes by presenting the seasonal situation of Sudan low-pressure fluctuations. During the transitional seasons (April and October), this low-pressure system is located in the center of Sudan. Then, it moves to lower latitudes in January and locates in southern part of Ethiopia. The system expands early in the summer by moving to the higher latitudes up to the north-east of Sudan. Some studies have shown that under the usual winter conditions, its trough expands up to 20° in north

Responsible Editor: Zhihua Zhang

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latitude. This low-pressure and non-front trough is called the Red Sea Trough (RST) (Krichak et al. 1997; Alpert et al. 2004).

A number of studies have been conducted on the low-pressure systems of the north-east of Africa and the Red Sea over the past few decades, including the Sudan low-pressure system, which in general can be categorized into three periods regarding study type (Mofidi 2006). In the following, examples of these three periods are discussed.

- (A) The first period is started from the late 1930s to the early 1950s. In this period, researches were mostly carried out to identify primary mechanisms and factors influencing rainfall pattern in the Red Sea, Eastern Mediterranean, and north-east of Africa; herein, some of them are reviewed. In 1938, for the first time, Ashbell posed the phenomenon known as the Red Sea trough caused by low pressure that expands up to north-west as well as from the south of the Red Sea to the east of the Mediterranean. In 1940s and 1950s, Alfandi inspired by this idea studied the various features of the low-pressure systems in these regions and selected the low-pressure system of Sudan to study on the features of the low-pressure systems (El-Fandy 1946, 1948, 1950a, b, 1952; Soliman 1953), in his research, introduced this system as a non-front one that transmits warm currents from southeast to the east-southeast of the Mediterranean.
- (B) The second phase of the studies is started since 1960s, and they have been conducted focusing on the convergence in the Red Sea. Thus, the structure of local air circulation in the Red Sea region has been studied further (Johnson 1965, Pedgley and Symmons 1968), which led to the discovery of the Red Sea convergence zone (Flohn 1965a, b). Studying the temporal and spatial distribution of precipitation in the Red Sea zone, Flohn (1965a, b) concluded that the climate of north of Africa and the Red Sea zone is mainly controlled by high mountains and plateau, deep valleys.
- (C) The third period is started since 1990s following the advances in measuring equipment, numerical models, and the availability of observational techniques, satellite and climatic data. Several studies have been conducted since then on the relationship between dynamic, synoptic patterns of the upper troposphere and torrential rain in the Red Sea zone and the Middle East. Dayan et al. (2001) studied the heavy precipitations in the Middle East region in October 1997. Kahana et al. (2004) showed that southern winds in the middle troposphere of the Levent region play a key role in ARST and transfer of moisture from the tropical regions. Tsvieli and Zangvil (2005) showed that there are two main sources of moisture, one originating from the tropical regions of Africa or the Indian Ocean from

the south-western flows and the other one originating from the east of the Mediterranean that is supplied by west and north-west flows near the surface. Alpert et al. (1990) stated that the main cause for the rainfall in Eastern Mediterranean is the penetration of the warm and humid air masses from the Aden Gulf and the Arabian Peninsula through the Red Sea trough to the Eastern Mediterranean and the transfer of humidity to the Jordanian and Palestinian zones.

Almazroui and Awad (2016) studied the climatology of the Red Sea trough during the winter and stated that when the high-pressure systems of Azores and Siberia are strong and are formed as a high-pressure belt with high static stability on the north of the Red Sea, RST becomes weak. Many studies have studied on the Red Sea and Sudan low-pressure systems, including studies by Lashkari (2003), by studying 52 torrential systems, introduced low-pressure system of Sudan as the most important cause for creation of precipitation system in the southern regions of Iran. In his study, he identified five main routes for the entry of low-pressure system of Sudan in Iran. Three routes were related to independent low-pressure systems, and two other routes were related to hybrid low-pressure systems, including those crossing Iraq and the Eastern Mediterranean, and finally, he stated that the main cause for the diverse routes concerning the low-pressure system of Sudan is related to the trough axis state, the orientation of the subtropical jet axis, and its core speed (Lashkari and Mohammadi 2015). Regarding this subject, other studies have also been conducted including studies by Meshkati and Moradi (2004) and Mofidi (2006).

Data and methods

In this research, two datasets were used, one dataset included the data on daily precipitation of synoptic stations located in the south and south-west of Iran, which was obtained from the Meteorological Organization of Iran, and the other dataset included reanalyzed precipitation data such as ERA-interim, geopotential height, specific humidity, and zonal and meridional winds, which was obtained from European Center for Medium-Range Weather Forecasts (ECMWF) with spatial resolution of 1×1 degree in the range of $5\text{--}40^\circ\text{N}$ to $20\text{--}65^\circ\text{E}$. This location is shown in Fig. 1.

In the first stage of the study, the data on daily precipitation of 36 synoptic stations located in the south-west region of Iran were obtained from Meteorological Organization of Iran for the 36-year statistical period (1981–2017). Figure 1 shows the location of synoptic stations. According to the method used in the study by Borzoi and Azizi (2015), the criterion for selection of heavy precipitation samples was to select those samples reported to have more than 30-mm precipitation in half of

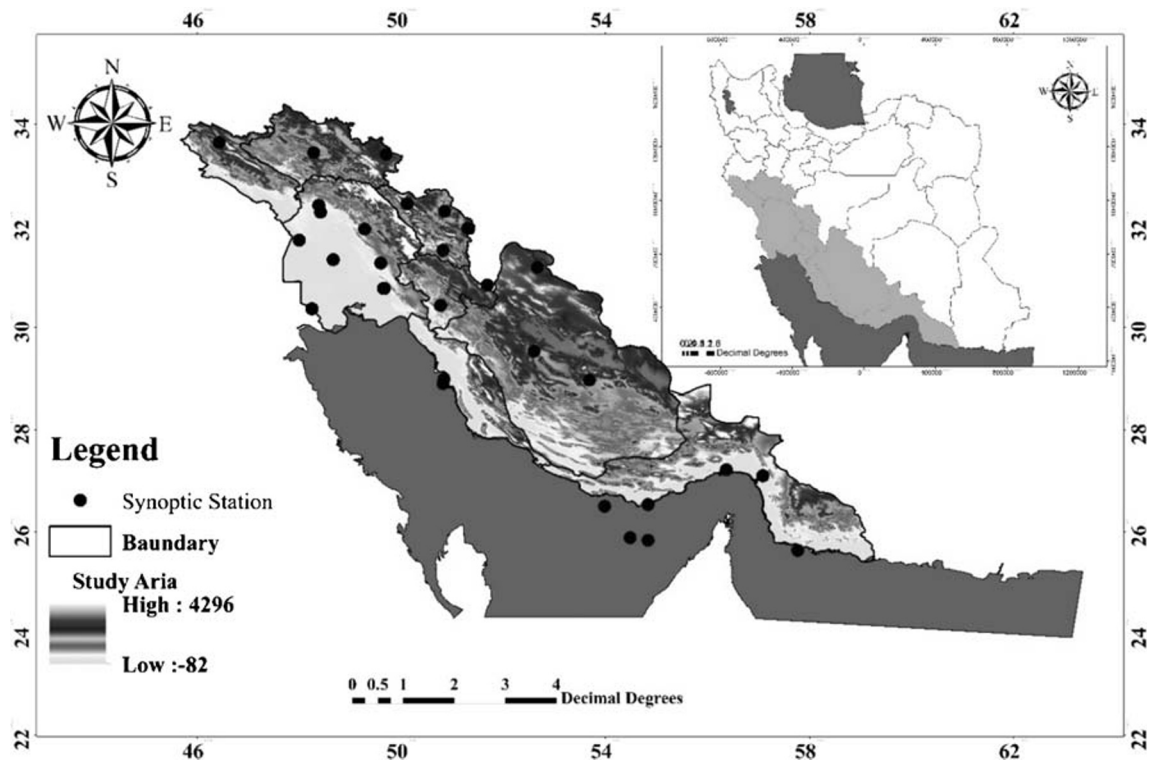


Fig. 1 The location of the synoptic systems

the selected stations. Table 1 illustrates the scattering of heavy precipitation systems for 36-year statistical period. The

Table 1 The most extreme sequences during different months and seasons over the statistical period of 1981–2017

	Days					
	1	2	3	4	5	6
Jan	32	32	7	2	0	0
Feb	25	24	7	3	0	1
Mar	35	26	8	2	1	0
Apr	35	15	4	1	1	1
May	11	1	0	1	0	0
Jun	5	0	0	0	0	0
Jul	2	0	0	0	0	0
Aug	13	1	0	0	0	0
Sep	3	0	0	0	0	0
Oct	3	1	0	0	0	0
Nov	14	7	1	0	0	0
Dec	37	12	3	1	1	0
Spring (MAM)	51	16	4	2	1	1
Summer (JJA)	18	1	0	0	0	0
Fall (SON)	54	20	4	1	1	0
Winter (DJF)	92	72	22	7	1	1
Annual	215	110	30	10	3	2

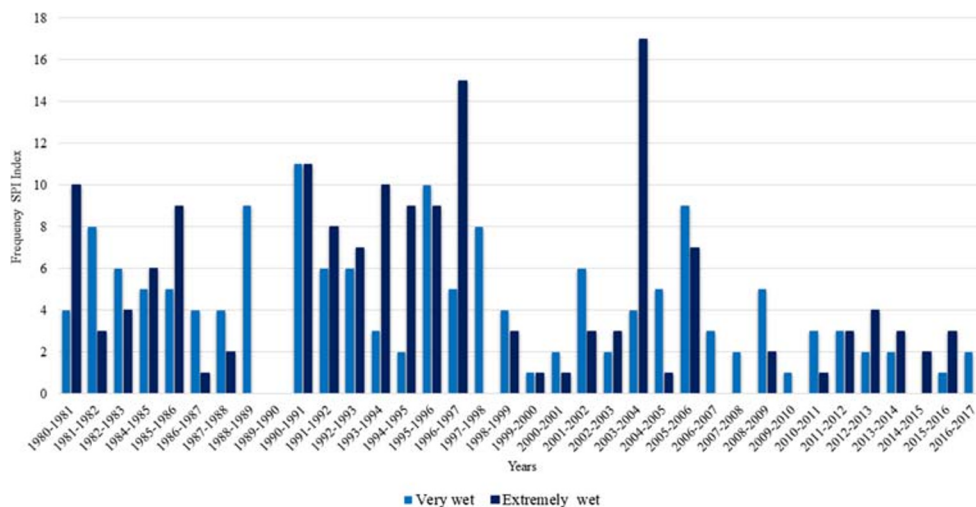
heaviest precipitation systems belonged to a 1-day system. Also, December, with 37 daily precipitation systems, showed the heaviest precipitation systems.

In the second stage, given that the purpose of the study is to investigate the moisture sources of heavy precipitation. Using the index (SPI) with the help of DIP software, the status of each station in a statistical period of 36 years in terms of dry and wet status was determined and then the years that showed at least half of the selected stations based on the extreme wet index as a more typical year. An intense year was chosen. Thus, 1996–1997 and 2003–2004 were selected as very wet years (Fig. 2).

Factor analysis using baseline component method (PCA) has been used to extract the circulating patterns causing heavy precipitation. To ensure the appropriateness of the data in order to perform factor analysis, KMO criterion and Bartlett test have been used. As shown in Table 2, the calculated value for KMO is 0.907. Considering that the closer the KMO criterion value is to 1, the more appropriate the data is for factor analysis (Mansourfar 2009; 374), the application of factor analysis was ensured. Also, the calculated value for Bartlett test was $p < 0.0000$. The study area was between 0 to 80° North and -60 to 100° East longitude and the number of days according to the resolution of spatial data which is 2.5×2.5° geographically, data in the matrix with dimensions of 67×2145 was formed.

S method and component-based analysis (PCA) with varimax period were used for grouping, so the period was used, which led to the proper distribution of factor loads, while the lack of rotation resulted in the lack of proper distribution of

Fig. 2 Status of selected years in the SPI index in the study period 1981–2017



factor loads. This method establishes a special relationship under a hypothetical pattern between a large set of changes and expresses them in a smaller number of dimensions or structures, which are called factors (Mohammadi and Lashkari 2018). According to the graph, the factors of 1 to 12° are more important than the other extracted factors (Fig. 3).

Justification of data diffraction according to eigenvalues, percentage of variance and cumulative variance for factor analysis was determined. Table 3 on the left of this table shows the variance explained by the initial analysis. Only 12 factors in the initial analysis have eigenvalues greater than 1. Factor analysis with baseline component method and varimax period showed that paying attention to the internal correlation of 12 factors justifies 89.18% of the behavior of the patterns.

In the third step, by preparing sea level atmospheric data, 1000 and 850 hPa from the site of the European Center for Medium-Term Forecasts (ECMWF) for 37 one-day precipitation systems by visual analysis of maps, the origin of these systems was identified. Systems of Sudanese origin were selected. Due to the general similarity of the origin of these systems, the precipitation system of December 15, 2004 was selected as the sample (Table 4). In the fourth stage, in order to analyze the synoptics of the selected systems, special flow and moisture pattern maps were drawn at the levels of 1000, 850, 700 and 500 hPa.

Table 2 KMO and Bartlett test to ensure that the data are suitable for factor analysis

KMO and Bartlett’s tests		
Kaiser–Meyer–Olkin measure of sampling adequacy.		.907
Bartlett’s test of sphericity	Approx. chi-square	324,252.152
	df	2211
	Sig.	.000

In the fifth stage, for performing the path analysis on the data of moisture sources in Iran, according to the synoptic circulation pattern of the region, three boxes were considered: Box 1 showed that a moisture source originated from the south-west of the Red Sea located between the two countries of Sudan and Ethiopia, Box 2 showed that a moisture source originated from the east of Red Sea and the Arabian Peninsula, and finally, Box 3 showed that a moisture source originated from the south of Iran. Subsequently, the total value for the omega divergence of the moisture flux was calculated in before precipitation and on peak days of precipitation for the selected precipitation system in three boxes and 5 layers of 1000 to 925, 925 to 850, 850 to 700, 700 to 600, and 600 to 500 hPa (Eq. 1). Finally, positive values for total vertical velocity divergence of the moisture flux in 1 × 1 grids of latitude and longitude on these levels were extracted and presented in the form of a diagram (Fig. 4). Perceptible water content above a point on the earth’s surface is expressed by the following relation (1)

$$\overline{W} = \frac{1}{g} \int_0^{p_0} \overline{q} dp$$

where q represents specific humidity, $\overline{W} = \frac{1}{g} \int_0^{p_0} \overline{q} dp$ represents perceptible water content on the Earth’s surface (total vapor column) (Peixoto 1973; Trenberth et al. 2011).

In the sixth stage, we also examined the origins and path transport of moisture for heavy rainfall event that occurred during the period Dec 15, 2004, into the southwestern Iran. We used the Hybrid Single Particle Lagrangian Integrated Trajectory model (HYSPLIT) (Draxler et al. 2014; Draxler and Hess 1997) developed by the National Oceanic and Atmospheric Administration Air Resources Laboratory to generate backward trajectories. For this study, we chose the REANALYSIS data set. The HYSPLIT model was run for one representative station in the southwest Iran (Fig. 4) and to calculate 72 h (3 days) backward air trajectories. The modeling period is from 00:06 UTC of Dec 12 to

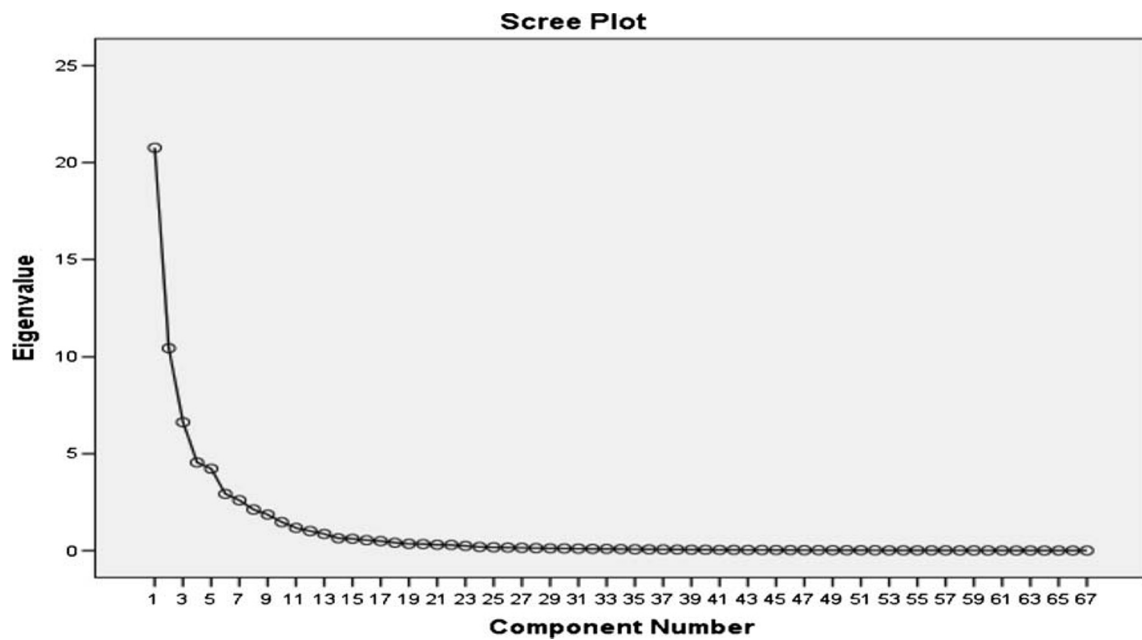


Fig. 3 Screen plot to show the eigenvalues of agents

00:18 UTC of Dec 15 for year 2004 with an integration time step of 6 h. Parcels are released at one level including 1500 m or approximately 850 hPa. This level is associated to main moisture transport paths for southwestern Iran.

In the final stage, vertical profiles of specific humidity, the flow pattern, and vertical velocity were plotted in three parts (lower, middle, and upper) for all three boxes and the results were interpreted.

Results

The current study was designed to identify the vertical structure of the atmosphere and the role of the seas located in the region in transfer of the systems. For this reason, the values of divergent flux, omega, and convective currents were investigated in three boxes. Box 1 showing the origin from southern part of Sudan and western part of Ethiopia was selected as the

Table 3 Display of eigenvalues, percentage of variance, and cumulative variance

Component	Initial eigenvalues			Extraction sums of squared loadings			Rotation sums of squared loadings		
	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %
1	20.756	30.979	30.979	20.756	30.979	30.979	14.893	22.229	22.229
2	10.445	15.589	46.569	10.445	15.589	46.569	7.932	11.839	34.068
3	6.625	9.888	56.456	6.625	9.888	56.456	5.788	8.639	42.707
4	4.550	6.791	63.247	4.550	6.791	63.247	5.779	8.625	51.332
5	4.227	6.309	69.557	4.227	6.309	69.557	4.767	7.115	58.447
6	2.925	4.366	73.922	2.925	4.366	73.922	3.946	5.889	64.336
7	2.597	3.877	77.799	2.597	3.877	77.799	3.482	5.196	69.533
8	2.120	3.164	80.963	2.120	3.164	80.963	3.330	4.971	74.503
9	1.857	2.771	83.734	1.857	2.771	83.734	2.899	4.326	78.830
10	1.471	2.195	85.929	1.471	2.195	85.929	2.578	3.848	82.677
11	1.173	1.751	87.680	1.173	1.751	87.680	2.356	3.516	86.193
12	1.008	1.505	89.185	1.008	1.505	89.185	2.005	2.992	89.185
13	.860	1.283	90.468						
14	.638	.953	91.421						

Extraction method: principal component analysis

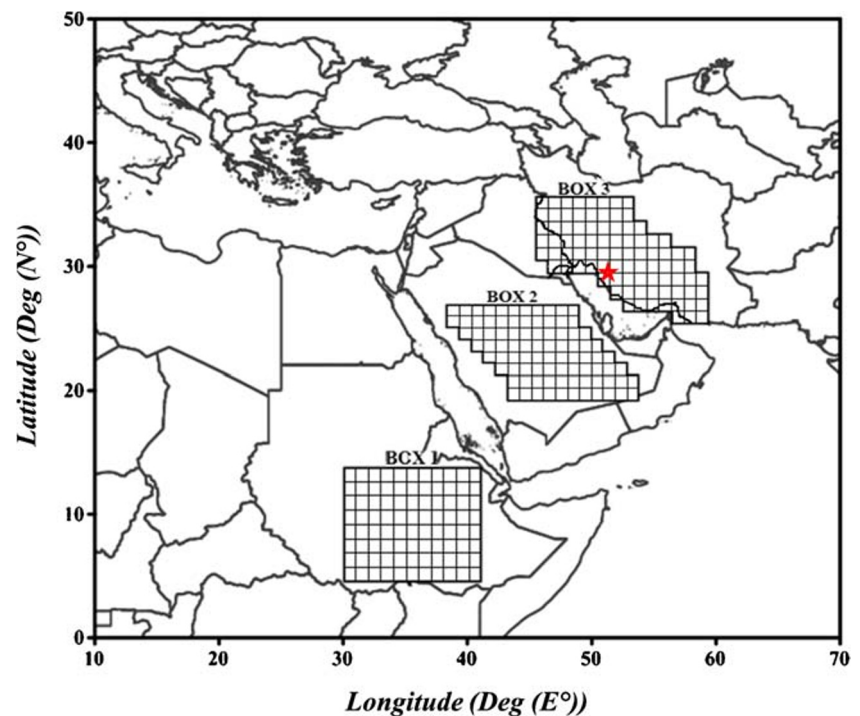
Table 4 The characteristics of the stations and the precipitation values of the selected system

Station name	Precipitation (mm)	Longitude	Latitude	Elevation
Ahvaz	30	48 40	31 20	22.5
Shahrekord	33.4	50 51	32 17	2048.9
Borujen	31	51 18	31 59	2260
Kuhrang	42	50 07	32 26	2365
Bandar-E- Mahshahr	30	49 09	30 33	6.2
Behbahan	53	50 14	30 36	313
Bushehr	63.01	50 49	28 58	9
Masjed Soleyman	36	49 17	31 56	3205
Ramhormoz	31	49 36	31 16	150.5
Safiabad (Dezful)	30	48 25	32 16	82.9
Abadan	30	48 15	30 22	6.6
Izeh	43	49 52	31 51	767
Omidiyeh(Aghajari)	39.4	49 40	30 46	27
Lordegan	50	50 49	31 31	1611
Bandar-E-Deylam	44	50 10	30 03	3.9
Bushehr (Coastal)	49.1	50 49	28 54	8.4
Emamzadeh Jafar	50	50 58	30 18	668
Dogonbadan	42	50 49	30 20	726
Omidiyeh (Air Base)	30	40 39	30 46	34.9
Hendijan	44	49 44	30 17	3
Saman	35	50 91	32 44	2075
Shiraz	57	52 36	29 32	1488
Yasuj	57	51 33	30 41	1816.3
Doroodzan	48	52 27	30 11	1642

source for the moisture flux of systems originating from Sudan, Box 2 showing the origin from middle part of the

Arabian Peninsula was selected as the second source for the moisture flux of the systems originating directly from the

Fig. 4 Coverage of grid points in the three boxes related to the origins of Sudan and Ethiopia, the Arabian Peninsula and Iran, used for extracting calculated values of moisture flux(The star icon indicates the sample station for routing)



Arabian and Oman Seas, and Box 3 showing the origin from south and south-west of Iran was selected as the third source for moisture flux and the effect range of the systems originating from Sudan. Prior studies carried out by Lashkari (2003), Lashkari et al. (2016a, b), Lashkari et al. (2017), Lashkari and Mohammadi (2018) showed that the systems originating from Sudan generally move from south-west to north-east and then entering Iran through three routes. Therefore, the selected three regions were selected in the same range.

Box 1

Figure 4 d shows the values of moisture flux in before and on peak days of precipitation in the five layers. In this region, the highest value of moisture flux in the layers of 925–1000 and 850–925 was in the second rank. In other words, the highest value of moisture fluxes occurred in the lower troposphere. Similarly, the value of moisture flux in the lower troposphere on the day before precipitation was higher than that on the peak day of precipitation. In the middle layer, the value of moisture flux on the peak day of participation was somewhat higher, and in the upper layer (600–500) the value of moisture flux on the day before the precipitation was higher than that of the peak day of precipitation.

The vertical profile for Box 1 in each of the different parts showed that in the southern part of the region (6°N), the dominant flow originated from east and descending in all layers between the sea level and 600-hPa level. But the dominant flow originated from east and ascending from 600 to 550 hPa (Fig. 5a). In the middle part of the region (10°N), the level of descending flow dropped a little. The dominant flow was descending below the level of 700 hPa, and the ascending flow occurred upper than this level (Fig. 5b). In these two parts, the input moisture of the system was supplied by moisture advection from the Indian Ocean (MAIO) and moisture advection from the Arabian Sea (MAAS) in the ITCZ region.

In the upper part of the region (13°N), the line between the descending and ascending flows did not change significantly compared with the middle part, and the 770-hPa level still was the line between descending and ascending flows. Figure 4 c shows that in the eastern part of this latitude, the south-west of the Red Sea (38°E), the vertical flows were upward in all levels of the atmosphere due to the dominance of the easterlies and the convergence of the flows in the Aden Gulf and the southern part of the Red Sea. The moisture of flows advected in the Arabian Sea and Aden Gulf (MAAG) (Fig. 5c).

The general pattern of this region showed that the southern part of the region (below 10°N), and especially below 700-hPa level, was located in the northern part of the Hadley cell. But above 10°latitude and above the 700-hPa level, the flows were ascending and northward due to the spread of the southward winds.

Box 2

In the middle box, which is the middle part of the Arabian Peninsula (the main route for systems originating from Sudan), the moisture flux and the pattern of the horizontal and vertical flows were found to be somewhat different.

The diagram about moisture flux values in before and on peak days of precipitation showed that in this region, the highest value of moisture flux occurred in the lower troposphere equal to 925–1000 hPa. The value of moisture flux in this layer was more than 3000 kg/m² per day and reached more than 600 kg compared with first box. In this area, the layer of 850–925 hPa was in the second rank regarding the moisture flux, and the layer of 700–850 hPa was in the third rank regarding the moisture flux with a slight difference. Therefore, firstly, compared with first box the values of moisture flux have become higher at all levels. Second, the value of moisture flux during the day before the precipitation was higher under the layer of 700 hp than that of the peak day of precipitation. Third, the value of moisture flux in the layer of 850–700 hPa has increased significantly. This phenomenon refers to the fundamental role of the Red Sea convergence zone on the moisture flux in transfer of systems, and addition of moisture advected in Arabian and Oman seas was considered as the main reason for the change in the values of moisture flux for the second box (Fig. 6d).

The vertical profiles of specific humidity, flow pattern, and vertical velocity in the different parts of the second box are presented in the following. In the southern part of the region (20°N latitude), which included the southern part of the Arabian Sea, the flows were ascending and upward in all layers of the troposphere. In southwestern part of the region, the flows originated from west and south-west, coincided with the convergence zone of the Red Sea, and vice versa. In southeastern part of the region, the flows originated from east and south-east. The same flows under the layer of 850 hPa showed well the moisture advection from the Red Sea (MARS) in the western part and moisture advection from the Arabian and Oman Seas (MAOS) in the eastern part of the region (Fig. 6a).

In the middle part of the region, the flows (24°N) in 46°W in the atmospheric lower layer (below 850 hPa) originated from west and zonal but flows were completely upward above the level of 850 hp, while there were ascending and upward flows in 46° east longitude from the sea level to 500-hPa level. The convective currents provided a suitable ground for moisture condensation advected from the Red Sea and the Arabian Sea, and consequently, convective clouds were formed and extended. In this part, the highest value of moisture advection was southward (Fig. 6b).

In the upper part of the region, there were descending flows, which included the northern part of Arabia (27°N latitude), in the atmospheric lower layer (below 750 hp) of the eastern shore of the Red Sea, with a slightly eastward gradient.

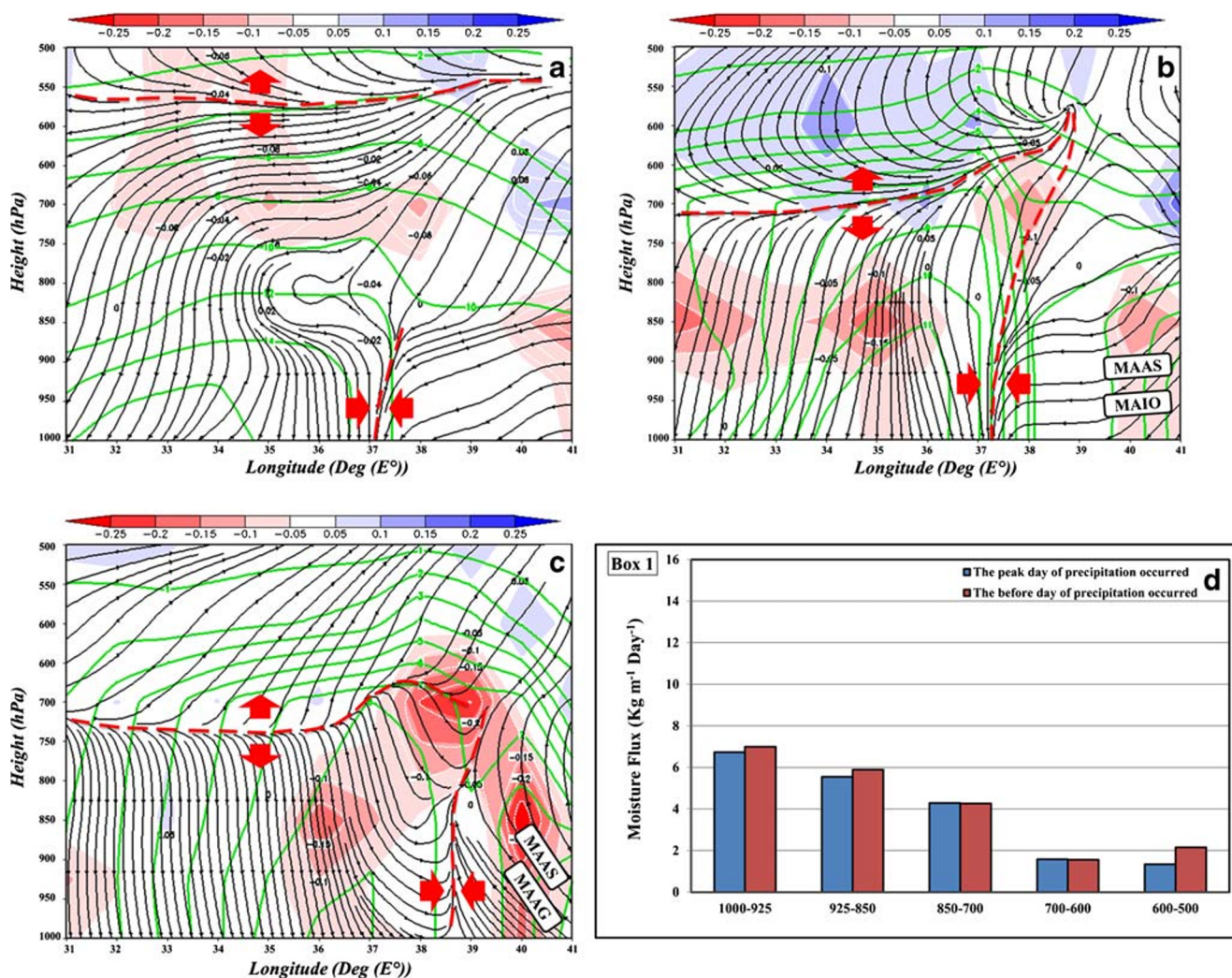


Fig. 5 Vertical profiles of specific humidity (g kg^{-1}), flow pattern (m s^{-1}) and vertical velocity (pa s^{-1}) in latitudes of 6 (a), 10 (b), and 13 (c) °N in the selected system and the graph related to average moisture flux ($\text{kg m}^{-1} \text{day}^{-1}$) in before and on peak day of precipitation (d) (Box 1)

It seems that the cold weather advection from the north latitudes in this part has provided an excellent opportunity for frontogenesis above the boundary layer while contacting with warm flow advection from the western side of Saudi Arabia anticyclone. Figure 5c shows that, following the flows originating from western side, the moisture advection from anticyclone was from the west, and the advection in the layer below 850 hPa had the highest contribution (Fig. 6c).

Box 3

The diagram about moisture flux values for third box showed significant changes for the moisture advection in the atmospheric layers and the moisture advection in before and on the peak days of precipitation. First, unlike the previous box, the highest value of moisture advection was in the layers from 700 to 850 hPa, which was more than 5000 kg/m^2 per day during the peak day of precipitation. The layer of 850–925

with 2800 kg/m^2 of moisture advection was placed in the second rank, and the layer of 700–600 hp. with 2200 kg/m^2 of moisture advection was in the third rank. In other words, in the third box, located on the west and south-west of Iran, the value of moisture advection was significant in the middle layers, indicating the vertical growth of convective clouds, especially in the southern strip of the country. Another remarkable phenomenon was that in all atmospheric layers, the value of moisture flux during the peak day of precipitation was much higher than the day before the precipitation. The difference in the value of moisture flux was very significant at the level of 850–800 hPa. It means that the main portion of moisture flux on the day of precipitation has changed into the precipitable water, and the process of cloud growth and precipitation occurred in a short time due to the dominance of strong convective processes (Fig. 7d).

The vertical profile in the southern strip of the country (28°N latitude) was ascending and upward in the atmospheric

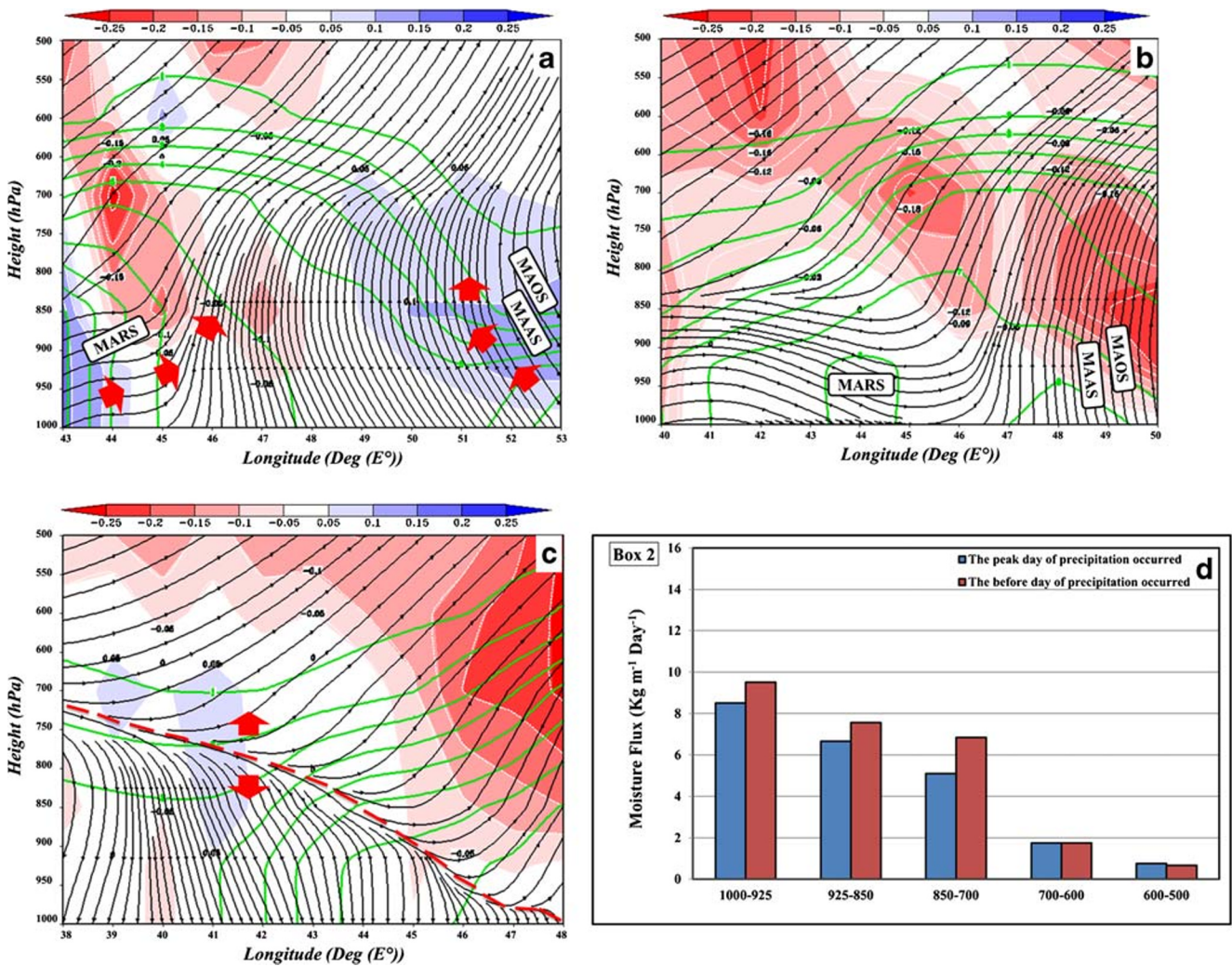


Fig. 6 Vertical profiles of specific humidity($g\ kg^{-1}$), flow pattern ($m\ s^{-1}$) and omega ($pa\ s^{-1}$) in latitudes of 20 (a), 24 (b), and 27 (c) °N in the selected system and the graph related to average moisture flux ($kg\ m^{-1}\ day^{-1}$) in before and on the peak day of precipitation (d) (Box 2)

lower and middle layers (sea level to 500 hPa). In this latitude, the highest moisture flux was southwestward, which in addition to the water levels contributing to the moisture advection in Boxes 1 and 2, moisture advection from Persian Gulf (MAPG) has also been added to this flow. On 31°N of latitude, which included the middle parts of Khuzestan and southern parts of Ilam and Yasuj, the flows were convective and upward in lower troposphere and middle troposphere except for a small part in the south-western part of this latitude. In this latitude, the highest value of moisture advection was in the range of 49–50°E and 52.5–55.5°E or the range between the provinces of Khuzestan and Bushehr. The moisture flux, unlike the lower regions, was also done in the atmospheric middle layer. On 34°N of latitude, there were upward flows in all atmospheric layers, and the moisture flux was still southward and south-eastern ward (Fig. 7a–c).

Moisture resource routing is the dominant and repetitive pattern

For a better understanding of what moisture resources were presented in the three boxes above, moisture routing of precipitation system was also the dominant pattern obtained from factor analysis. In this routing, only the first 20 routes that have the highest amount of moisture in the event of heavy rainfall are plotted.

Accordingly, on rainy days, two key paths of moisture transfer are observed. These two routes are one of the Arabian Sea and Oman and the Northeast Africa route (which originates from the ITCZ moisture and in which the Red Sea moisture participates). Also, it was found that almost all of the moisture transfer is done at lower altitudes (Fig. 8).

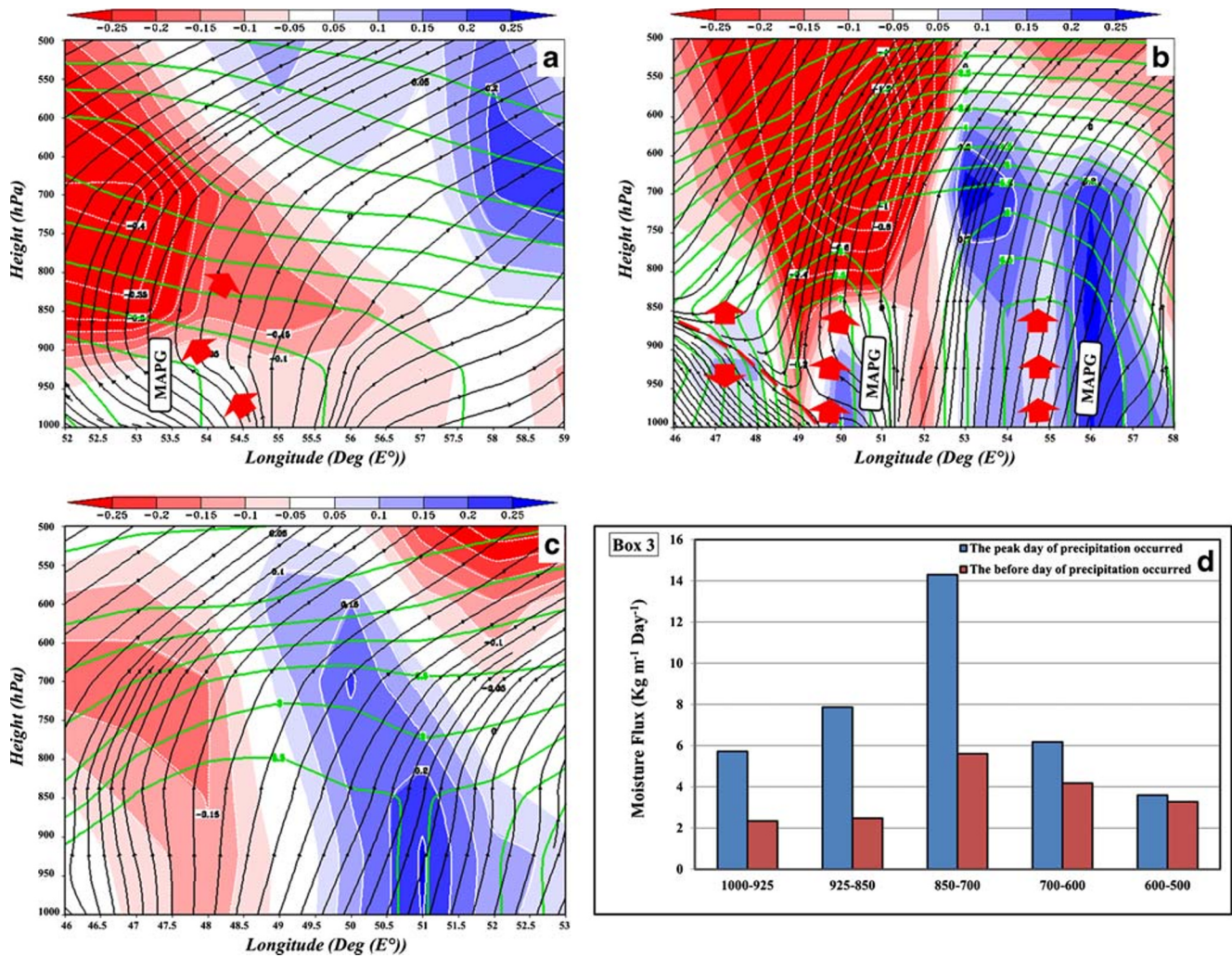


Fig. 7 Vertical profiles of specific humidity (g kg^{-1}), flow pattern (m s^{-1}) and omega (pa s^{-1}) in latitudes of 28 (a), 31 (b), and 34 (c) °N in the selected system and the graph related to average moisture flux ($\text{kg m}^{-1} \text{day}^{-1}$) in before and on the peak day of precipitation (d) (Box 3)

Synoptic analysis of the selected precipitation system

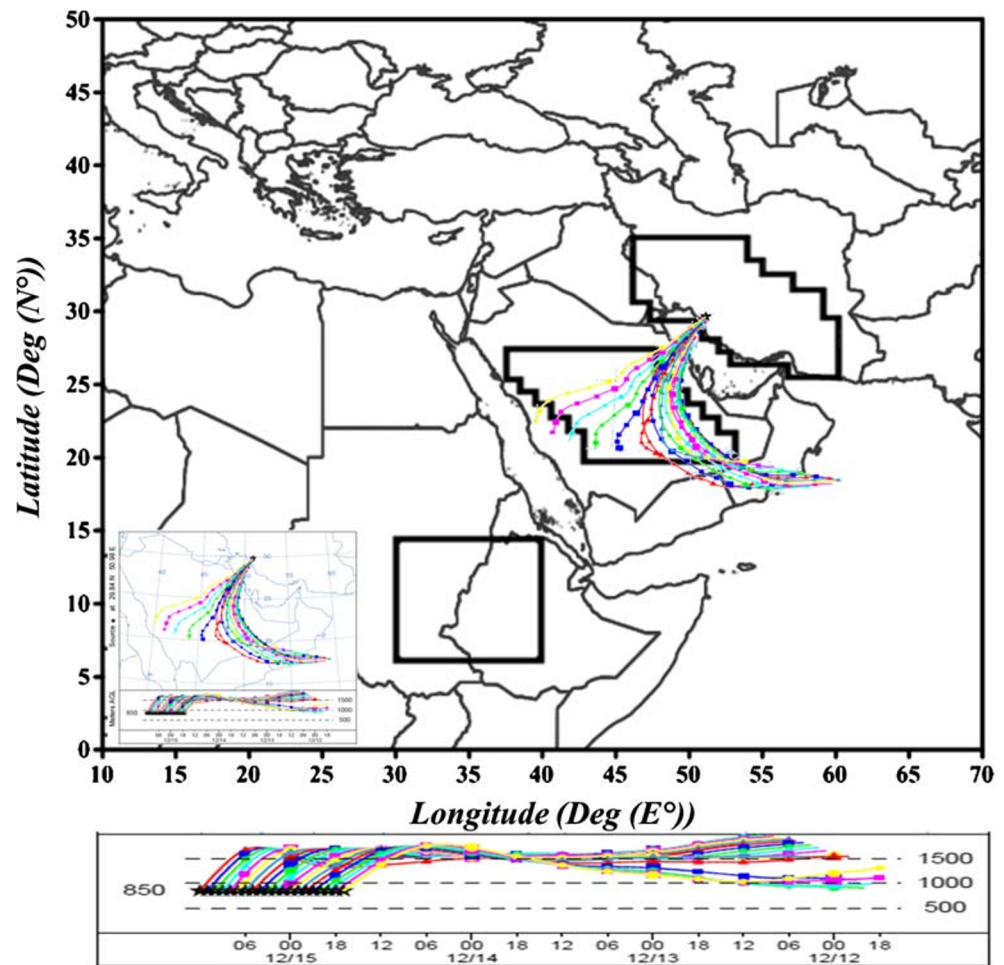
Figure 9 a–c shows the synoptic conditions related to one sample of the precipitation days at different levels. In the atmospheric lower layer (1000 hPa level); the northern currents caused cold advection. In Eastern Mediterranean, Egypt, and Sudan, some currents caused cold advection from north latitude to the east side in the first box. In warm Arabian and Oman Seas, windstorms coming from north-east and east caused warm and humid advection from these seas to the eastern side in the first box. The convergence of these two currents created a highly humid core in the south-west of the region. The opposite currents, channelized on the southern and northern sides of the Red Sea, led to the convergence of the current in the 15°N of latitude and created a highly humid core in this area. The same has happened in the center of the Persian Gulf and the central strip of the Arabian Peninsula. As a result, a current convergence line was observed from Sudan to the south-west of Iran with a southwest-northeast direction.

This current convergence line was in the same direction as for the trough of the low-pressure system of Sudan. At this level, the advection of moisture flux into unstable current occurred from four major regions Fig. 8a

- 1- Intertropical convergence zone (ITCZ)
- 2 Red Sea convergence zone
- 3 Arabian and Oman Seas through the easterlies and south-east currents of the Arabian Peninsula
- 4 Persian Gulf

At the 850-hPa level, which is the closest condition to the boundary layer, the synoptic and flow pattern was found to be more strikingly. The sharp cold advection from the northern latitudes to the back of the trough and the warm and humid advection from warm seas with a high potential of moisture advection to the front provided a suitable ground for the creation of a broad convergence line from southern Sudan to the

Fig. 8 The moisture path of the precipitation system is the predominant pattern obtained from factor analysis



south-west of Iran and led to the frontogenesis line mentioned in the analysis of the vertical profiles. There were also three highly humid cores on the south of Sudan, the Red Sea, and the Persian Gulf. At this level, the portion of moisture advection from the Red Sea was found to be more pronounced than in other two regions (Fig. 9b).

At 700-hPa level, although they were strong northern currents, the strong easterlies and south-east currents of the Arabian and Oman seas have extremely reduced. Unlike the two lower layers, the portion of moisture advection in Box 1 (Sudan) has become large in providing the system moisture. Therefore, at 700-hPa level, the portion of moisture advection by southern currents in front of the trough was much greater from the moisture source in intertropical convergence zone (ITCZ). The portion of moisture advection from the Arabian and Oman seas has significantly reduced (Fig. 9c).

At the level of 500 hPa, the portion of moisture advection in the surrounding seas has extremely reduced, and generally, the moisture advection was observed from lower layers in Iran. The convective moisture was from lower layers (Fig. 9d).

Conclusion

The Middle East is a climatically dry and water-poor region, which countries in many parts of it are also struggling to meet the needs of its population. At the same time, heavy rainfall and floods are causing irreparable damage to these countries every year. For example, in the autumn and winter of this year, severe floods occurred in the southern provinces of Iran and the southern Gulf countries, which caused extensive damage to farms and facilities and claimed the lives of several people. There have been many studies on the precipitation systems in the area so far. Most of these studies show that the main cause of heavy rainfall in this area is convective precipitations. In this study, new findings were found by study of 93 heavy and flooding systems, which are discussed below.

The low-pressure system originating from Sudan was identified as the most important precipitation system for the Arabian Peninsula countries and Iran. The moisture advected in Arabian Sea and the Indian Ocean by easterlies on the countries of Ethiopia and Sudan played an important role in providing the thermodynamic energy for the low-pressure system of Sudan. These conditions occurred in many days of the

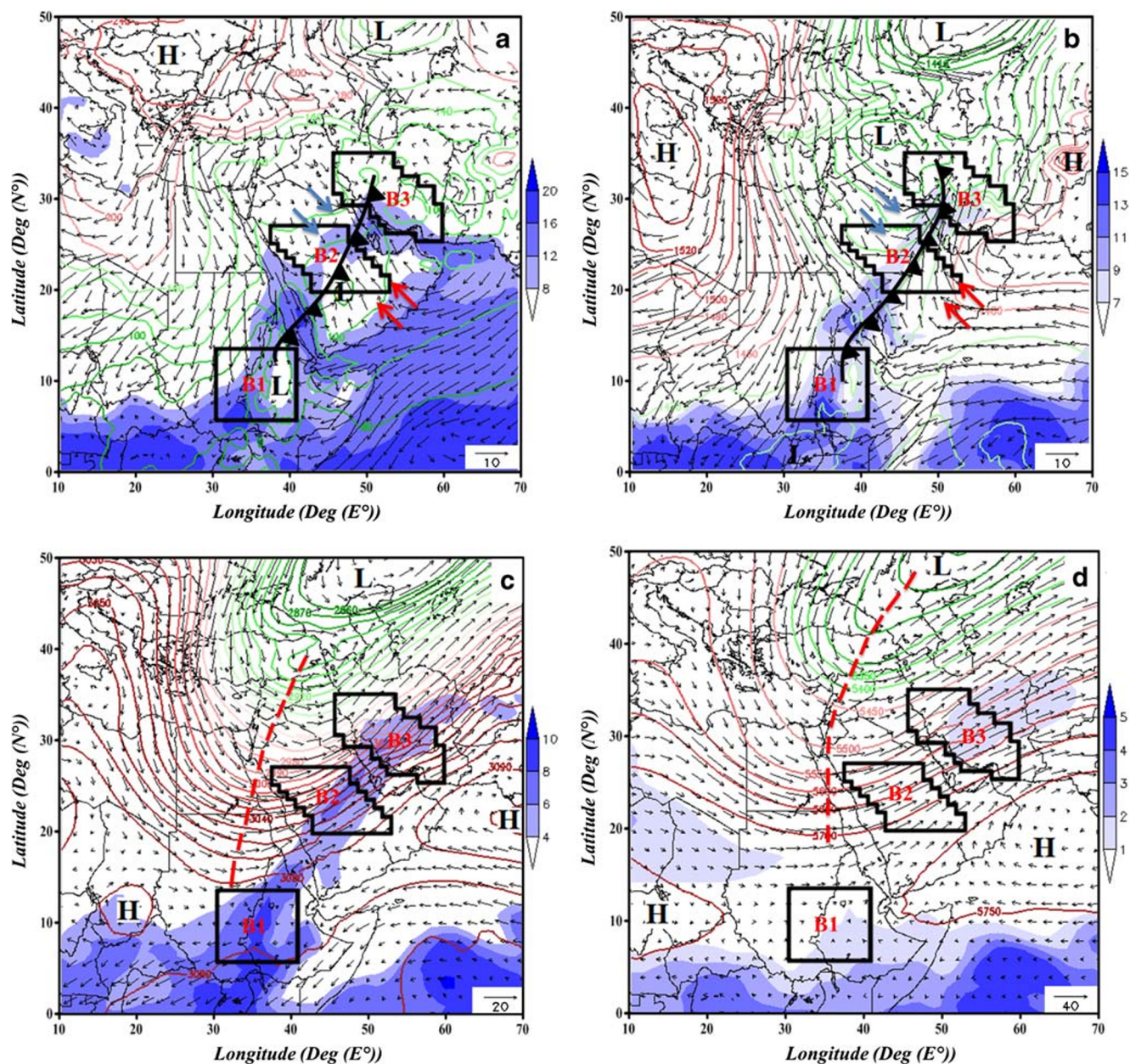
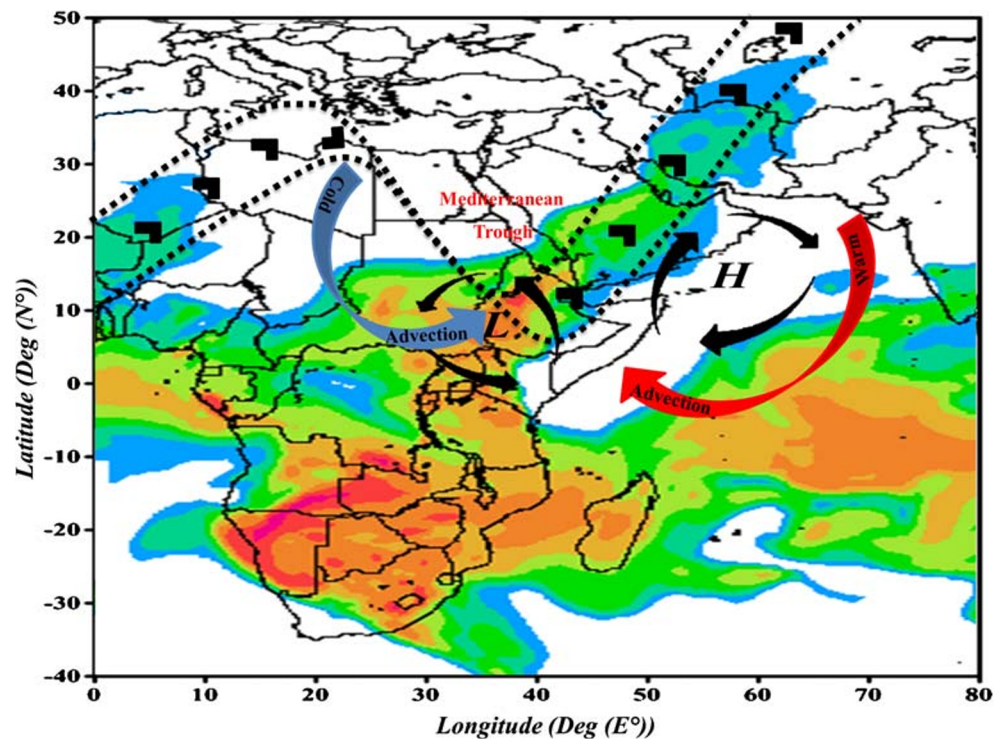


Fig. 9 Profiles of specific humidity (g kg^{-1}), flow pattern (m s^{-1}) and geopotential height (hPa) in December 15, 2004 in 1000- (a), 850- (b), 700- (c), and 500 (d)-hPa levels

year. It was found that there was a cold advection from the northern latitudes in the western side of low-pressure system of Sudan in the middle troposphere and lower troposphere which exacerbates and strengthens the low-pressure system of Sudan. These conditions usually occur with deep trough in the Eastern Mediterranean. The cold advection in the lower troposphere was done by northward ridge expansion over African anticyclone. Thus, the first formation zone of the precipitation system in this region was located between Sudan and Ethiopia and the initial moisture content of the system was provided by the intertropical convergence zone (ITCZ) (Box 1) (Fig. 10).

The second zone for the provision of moisture and strengthening of the system occurred in the second box or the west and the center of the Arabian Peninsula. In this area, both moisture sources from the Red Sea and the Arab and Oman seas were considered to be an important source of moisture supply for the system. In fact, the primary field of system reinforcement in this region occurred in Red Sea convergence zone. When Saudi Arabia's eastward anticyclone stayed on Oman and Arabian Sea, eastern streams isolated on the south side of anticyclone after entering the Gulf of Aden despite the northern and southern heights of the Gulf and extended to the Bab al-Mandeb Strait. This compressed

Fig. 10 Schematic pattern prevailing in the first box



flow continues north after crossing the Bab al-Mandeb Strait, encircling the heights on both sides of the Red Sea. These hot and humid flows continue along the route until meet with cold northern flows at the range of 18–22° latitude (Lashkari 2000) over the Red Sea and convergence formed. As a result, flows passing over the Red Sea reinforced by moisture injected through the Red Sea. After crossing the eastern highlands of the Red Sea in western Saudi Arabia, advected warm and humid eastern air through the Oman Sea converged with cold northern flows along the eastern shore of the Red Sea by Saudi Arabia anticyclone flows, providing the necessary setting for frontage.

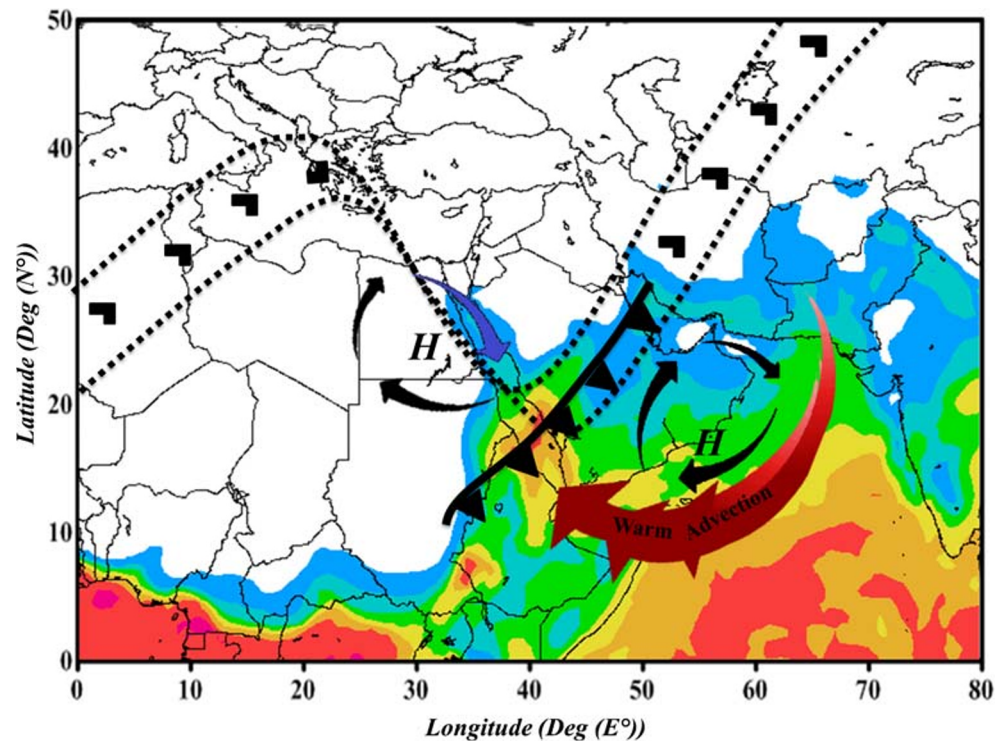
In this area, the warm and humid air of the east converged with the cold northern currents in the eastern shore of the Red Sea and predisposed to frontogenesis. A well-formed front, especially in the lower layer (up to 700 hPa), was evident in the synoptic analysis and vertical profiles. Suitable humidity infusion from the surrounding warm seas especially the Red Sea provided extreme front instability to Saudi Arabia and the southern coast countries of the Persian Gulf, which has led to the heavy precipitation. This pattern is the most important cause of heavy rainfall in Saudi Arabia and the southern margin of the Persian Gulf (Fig. 11).

The third box covers the south and southwest of Iran. The third box, which included the target zone of the study, was the entrance zone of low-pressure system of Sudan. In addition to moisture advection from two previous regions, the moisture content added from the Persian Gulf also played a vital role in provision of humidity in transfer of

systems, especially in the coastal areas and plain of Khuzestan. The results showed that the layer of 850–700 hPa had the highest moisture content in the zone. Also, the layer below 850 hPa had higher moisture content than the two previous boxes. This condition occurred due to the upward movement of air throughout the atmosphere of the region, caused the moisture to be transferred and accumulated from the lower layer to the middle and upper layers of the atmosphere. In other boxes, the existence of a divergence zone, especially at 850–700-hPa level, prevented the accumulation of moisture in this layer and led to its transfer to the lower and upper levels of the atmosphere through the descending and ascending air in this region. In this region, the height of Zagros Mountains (located in Iran) played an important role in exacerbating the unstable nature of highly humid systems of Sudan. Therefore, heavy precipitation systems do not necessarily result from convection phenomenon; rather the front structure of systems can also play a vital role in exacerbating instability and heavy precipitations. As in studies of convective systems, in some cases, the important role of dynamic factors in the occurrence of systems with high lifetime and span has been pointed out (Hejazizadeh et al. 2015).

In Boxes 1 and 2, the moisture content has increased during the day before the precipitation compared with the peak day of precipitation in all of the studied layers. This reflects the intensity of precipitation on the day of rainfall, with significant amounts of atmospheric moisture being discharged by rainfall

Fig. 11 Schematic pattern prevailing in Box II



and moisture sources were unable to supply the humidity that was charged due to being far from the precipitation area.

But in the Box 3, the opposite has occurred, and on the peak day of the precipitation, the moisture content not only was at maximum level in all layers but also it was twice higher in the lower troposphere. This situation illustrates the process of moisture transfer from nearby moisture source areas, especially the Persian Gulf to the system that has caused the system's moisture volume not to decrease despite heavy rainfall. Studies have been carried out in this case whose results indicate the major role and importance of the Persian Gulf in providing moisture to heavy rainfall systems in the south and southwest of Iran (Shadmani et al. 2018; Halabian and Hosseinalipour Jazi 2016).

Overall, in addition off this study results consistency with previous results regarding the important role of the Red Sea convergence zone in creation and intensification of precipitation in the eastern Mediterranean (Kahana et al. 2004; Tsvieli and Zangvil 2005, 2007; Alpert et al. 1990, 2004). It recognizes the consistence-related results of importance and impact of the surrounding hot seas such as Oman, Arab, and Red Seas in injecting moisture into the systems passing through the region, as well as the importance of the bottom layer of the atmosphere as the most appropriate layer for moisture advection from these seas into the rainfall inputs system to Iran with the results of Karimi (2007), Karimi and Farajzadeh (2011), Karimi et al. (2017), and Farajzadeh et al. (2007) studies. These study results also support the hypothesis of the impact and important role of the Intertropical Convergence Zone

(ITCZ) on intensifying and enhancing Sudanese systems and bolded an important factor in providing moisture to the system, especially at 700-hPa level through the ITCZ, as Lashkari et al. (2016a, b) hinted. As Hafez (2012) has pointed out, the unusual northeastward shift of the ITCZ in northern Sudan, Ethiopia, and the Red Sea is causing widespread flooding in the eastern Mediterranean.

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