



# Dominant flood-inducing synoptic and dynamics mechanisms over western and southwestern Iran (case study: extreme rainfall on 11–14 April 2016)

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## Abstract

This study is aimed at investigating and identifying dominant flood-inducing mechanisms in western and southwestern Iran. For this purpose, the data of dynamic-synoptic components 11–14 April 2016, including total rainfall, sea level pressure, geopotential heights, the jet stream, potential vorticity at 250 hPa, the Omega index at 500 hPa, moisture flux convergence (MFC) at 1000 hPa, Convective Available Potential Energy (CAPE), were used for revealing the mechanisms of heavy rainfall events. On the other hand, Meteosat-7 satellite images were used to identify cloud type in the study area. The results showed that the main cause of the heavy rainfall was the formation of Mediterranean low and high pressure on the Aral Lake in the sea level and the presence of an upper-level cut-off low core over the northeastern Mediterranean and the study area. Moreover, analysis of MFC indicated that heavy rainfall moisture sources had been supplied from the Mediterranean, Red, and Arabian seas, respectively. Based on CAPE maps, the core of the maximum potential of convective energy is drawn as a line along the southwest-northeast from the Red Sea to the west of Iran. Meteosat-7 satellite images indicated that cumulonimbus clouds covered the study area during 11–14 April 2016. These results highlight that the intrusion of the southern polar vortex and its flux over the eastern Mediterranean and the Red Sea provides the conditions for cyclogenesis. The results of this study could serve as a guideline for monitoring and predicting heavy rainfall.

**Keywords** Flood · Red Sea Trough · Convective Available Potential Energy · Moisture flux convergence · Potential vorticity · Iran

## Introduction

Flooding is a primary natural hazard in the world (Cortès et al. 2018). Floods and flash floods are dangerous for people's health and safety and can have a major impact on various sectors of

society like economics, sociology, psychology, emergency management, agriculture, and other areas (Schumacher 2016; Engel et al. 2017; Er et al. 2017; Kumar et al. 2017; Gilabert and Llasat 2018). Flood characteristics, including magnitude, duration, timing, frequency, and flow variability, are affected by complex interactions between natural (climate and physiography) and human (land use and dams) factors (Rao 2017). Iran is among several countries in the world which has experienced frequent catastrophic flooding over the last few years (Parizi et al. 2022). Flash floods are common in Iran and strongly influence long-term economic development (Parizi et al. 2021). Each year, flash floods take many people's lives and cause millions of dollars in damage (Alijani et al. 2008). These floods are mainly due to extreme precipitation (Hadadi and Heydari 2012; Pourasghar et al. 2016).

The study of heavy precipitation in dry regions like Iran is difficult because of the poor spatial distribution and inadequate meteorological stations (Balyani et al. 2017).

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From a climatic perspective, Iran is identified as an arid and semi-arid country, and high spatial and temporal precipitation variability in Iran is one of its most important characteristics (Raziei et al. 2011). Most important synoptic systems which influence Iran's precipitation regime are systems from the west that mainly originate from Mediterranean and North Atlantic cyclones, as well as southwestern systems, which are called Sudan heat-low systems and Mediterranean frontal systems, and sometimes, these systems can merge and produce flooding precipitation in these areas (Sabziparvar et al. 2015). Asakereh (2012) examined annual precipitation in Iran from 1961 to 2003 and showed that the statistical characteristics of precipitation changed from 1986 to 2003.

Asakereh and Khani Temeliyeh (2022) analyzed the amount and frequency of daily precipitation in western and southwestern Iran during 1979–2016 affected by the Red Sea low pressure and concluded that during the activity of the Red Sea low pressure, the frequency of rainy days and the amount of precipitation increases. Lashkari et al. (2020) investigated the dynamic structure and moisture sources of heavy rainfall in the south and southwest of Iran and demonstrated that high humidity systems are supplied from different regions, including the Indian Ocean, Arabian Sea, Red Sea, Oman Sea, and the Persian Gulf. Shadmani et al. (2018) identified humidity sources and accurate trajectory of effective moist air mass on heavy rainfalls in the west and south of Iran and concluded that the Red Sea and the Indian Ocean participate equally in moisture supply for the studied flood in the western parts of Iran.

Many studies have been conducted in Iran on heavy precipitation events using various synoptic analysis techniques. Sabziparvar et al. (2010) analyzed the flood-generating meteorological systems in southwestern Iran using synoptic observations. According to their findings, the severe floods in the Dalaki River basin are mainly caused by a strengthening of the Sudan heat low and moisture advection from the Indian Ocean and the Red Sea. In another study, Halabian and Hossienalipour (2016) investigated the causes of heavy rainfall in the southwest of Iran using the environmental approach to circulation. They highlighted that a deep trough has formed over the eastern Mediterranean Sea and the Black Sea, which east of this trough is over the studied area and has caused severe dynamic instability and the creation of a baroclinic atmosphere in the region. Khansalari et al. (2021) analyzed a flash flood-inducing heavy rainfall event in arid and semi-arid central-northern Iran using the WRF model. They concluded that the low-level factors such as extensive moisture advection and mid-tropospheric diabatic processes such as the latent heat release, daytime deep convection, and topographical impact of Zagros Mountains were found as the key factors leading to this system.

Soltani and Rousta (2017) studied extreme precipitation events over the Central Plateau of Iran from a synoptic perspective. Their findings indicated that two patterns of deep troughs (76% of days with extreme precipitation occurred with this pattern, precipitating systems originated over the Persian Gulf, Oman Sea, Indian Ocean, and Red Sea), as well as large ridges over the eastern Mediterranean (including the Persian Gulf and Red Sea), were responsible for producing heavy precipitation events over the Central Plateau of Iran. Nouri (2013) showed that there are five sea-level pressure patterns for heavy precipitation days during the growth of visit viniferous. A combination of European and Siberian high-pressure systems, low-pressure systems over Iran and Black Sea high-pressure systems and low-pressure systems over western and southern Iran show an increasing trend in heavy precipitation days, but the other patterns show a decreasing trend or are without a trend in heavy precipitation days. Yarahmadi and Maryanji (2011) analyzed the dynamic and synoptic conditions of the heavy rainfall event on 4 November 2004 over the southwestern Caspian Sea and western Iran. Azizi et al. (2009) carried out a synoptic analysis of heavy rainfall on 7–15 March 2007 over western Iran. They suggested that Mediterranean low-pressure systems in conjunction with a tongue of moist air from Sudanic lows caused this rain event. Hamidian et al. (2010) identified the synoptic patterns of extreme precipitation events over northeastern Iran. Their results showed that the Sudanic low and the combined lows of the Sudanic-Mediterranean greatly influence the occurrence of extreme rainfall events over the area.

Gilabert and Llasat (2018) identified the synoptic circulation types associated with flooding events that occurred in Catalonia (Northeastern Spain) from 1900 to 2010. The results demonstrated that most synoptic situations were pure cyclonic structures in both extreme and catastrophic events. Curtis (2017) examined the synoptic and mesoscale mechanisms of heavy convective rainfall over Portland, Maine, on 13–14 August 2014. Their study identified changes to the low-level jet, and these changes made in the mesoscale beta convective element propagation vector were the primary causes of this event. Dobrir and Apostol (2019) analyzed the synoptic conditions generating the greatest precipitation amounts within 24 h in Romania. The results showed that large atmospheric instability, cold air advection associated with long-wave troughs propagating from the North Atlantic toward the center of the European continent, cut-off lows identified in the middle and upper troposphere in southeastern Europe, Mediterranean cyclones passing over the Romanian region, and Atlantic cyclonic activity produce extreme precipitation in Romania. Al-Nassar et al. (2020) studied extreme rainfall in Iraq and showed that cut-off lows displayed analogous synoptic characteristics when the surface waters of the Red Sea and Persian Gulf were warmer

than the air at the surface: upper-level divergence, upward vertical motions in the mid-levels, and low-level winds. This study is aimed at understanding the main mechanisms influencing the generation of large-scale floods in Iran to create tools for decision-making to reduce possible impacts on the community. In this study, we investigate the causes associated with the damaging extreme rainfall and severe flooding event that occurred from 11 to 14 April 2016 over western and southwestern Iran.

## Material and methods

### Location of the study area

The study area, western and southwestern Iran, is located from 30 to 36° North latitude and from 46 to 54° East longitude. Western Iran includes the Kurdistan, Kermanshah, Ilam, and Hamedan provinces, and southwestern Iran includes the Lorestan, Chaharmahal and Bakhtiari, Kohgiluyeh and Boyer-Ahmad, and Khuzestan Provinces (Fig. 1). The provinces in southwestern Iran are recognized as semi-arid and extreme arid climate zones and are located between high elevations of the Zagros Mountain Range, with altitudes between 1000 and 1600 m above sea level (ASL), and low elevations in the western boundaries, with altitudes lower than 200 m ASL in Khuzestan and Ilam. There are grasslands in the northern part of western Iran, and in the

central and southern parts, shrub lands, croplands, and barren islands are present (Kamal et al. 2020).

### Datasets used in this study

For the synoptic analyses to describe the regional structure of the atmosphere for the extreme precipitation event on 11–14 April 2016 over western and southwestern Iran, we will examine daily reanalysis data from the National Centers for Environmental Prediction (NCEP/NCAR), with a resolution of  $2.5^\circ \times 2.5^\circ$ , air temperature, sea level pressure (hPa), geopotential height (m), specific humidity (%),  $u$  and  $v$  wind components (m/s), and vertical velocity (Pa/s). Programming was accomplished in Grads software. In the next step, estimated TRMM rainfall data with an (NC) file format were used to analyze the spatial pattern of rainfall. The respective validation with observational data was achieved with precipitation data for eight provincial capital cities (Table 1) from IRIMO (Iran Meteorological Organization). A study of cloud patterns and coverage area will also be done using hourly Meteosat-7 weather satellite imagery from the Research Center of the University of Dundee, UK, for the Middle East region.

In mid-latitudes at the synoptic scale, the important dynamic properties are those which are related to rotation (Soltani et al. 2014). Precipitation analyses have been done worldwide focusing on the role of vorticity and the circulations within pressure systems that produce severe storms (Jenkinson and Collinson 1977; Rousta et al. 2018).

**Fig. 1** Location of the provinces considered in this study



**Table 1** Rainfall amount of 11–14 April 2016 for the eight provinces in western and southwestern Iran. *O* represents observed values and *R* represents reanalysis values

Province	11 Apr	11 Apr	12 Apr	12 Apr	13 Apr	13 Apr	14 Apr	14 Apr
	<i>O</i>	<i>R</i>	<i>O</i>	<i>R</i>	<i>O</i>	<i>R</i>	<i>O</i>	<i>R</i>
	(mm/day)							
Khuzestan	0.00	2.48	0.80	4.96	3.00	2.01	0.00	2.96
Hamedan	0.00	0.00	6.90	8.53	20.70	27.79	20.50	18.52
Ilam	5.80	6.09	41.20	32.18	1.50	0.67	28.30	22.60
Kermanshah	2.70	5.45	22.60	17.89	29.00	27.23	42.70	35.72
Lorestan	11.30	12.03	15.70	22.05	48.10	42.09	89.30	70.84
Kurdistan	0.00	0.00	22.60	15.24	3.60	6.58	1.20	4.73
Chaharmahal	0.00	0.00	0.00	0.00	11.60	8.10	0.20	0.82
Kohgiluyeh	0.00	0.00	9.40	7.08	23.40	17.25	4.90	7.08

Since convergence leads to upward movement, some studies have investigated vorticity advection, divergence, and vertical motions in association with upper-level jet streams as triggers for the development of surface low-pressure systems (Jones et al. 1993; Conway and Jones 1998; Trigo and Dacamara 2000). In addition, some studies showed that upper-level jet streams occur simultaneously with divergence aloft and positive relative vorticity advection (Nakamura 1993).

It is, therefore, imperative to analyze the following: moisture flux convergence (MFC) to assess moisture sources and advection, Convective Available Potential Energy (CAPE) to determine instability and the resulting potential for deep convection, and potential vorticity (PV) to assess the potential for strong cyclogenesis producing extreme rainfall events over the study area. A brief description of these terms is provided in the “Methodology” section.

### Methodology

#### MFC

In analyzing the moisture sources and advection that produced the 4 days of rainfall causing the flooding event over western and southwestern Iran, MFC is calculated using the following formula (Banacos 2004):

$$MFC = -\nabla \cdot (q\vec{V}_h) = -\vec{V}_h \cdot \nabla q - q\nabla \cdot \vec{V}_h, \tag{1}$$

$$MFC = -u\frac{\partial q}{\partial x} - v\frac{\partial q}{\partial y} - q\left(\frac{\partial q}{\partial x} + \frac{\partial q}{\partial y}\right) \tag{2}$$

Within Eq. 1,  $-\nabla \cdot (q\vec{V}_h)$  represents MFC,  $-\vec{V}_h \cdot \nabla q$  is the moisture advection,  $q\nabla \cdot \vec{V}_h$  is the moisture convergence, and  $q$  is the specific humidity. Within Eq. 2,  $x$  and  $y$  are independent spatial variables, and  $u$  and  $v$  are the zonal and meridional wind speed components.

#### CAPE

CAPE is a measure of the energy that can be released in the presence of free convection. CAPE is normally analyzed for undiluted parcel ascent, and we shall evaluate this using the approximate physics of the numerical model, that is, a model of CAPE (Persing and Montgomery 2005). The potential energy is assessed by integrating the difference between the virtual temperature of an idealized air parcel and its environment (Emanuel 1994). CAPE is calculated using the following formula:

$$CAPE = \int_{z_f}^{z_N} \frac{g}{T_{ve}} (T_v - T_{ve}) dz \tag{3}$$

Within Eq. 3,  $z_f$  is the level of free convection,  $z_N$  is the height of the equilibrium level,  $g$  is acceleration due to gravity,  $T_v$  is the virtual temperature of a parcel, and  $T_{ve}$  is the virtual temperature of the environment (Betts et al. 1976; Schefczyk and Heinemann 2017). CAPE is then obtained as the area enclosed by the moist adiabat through the cloud base, which corresponds to the lifting condensation level (LCL), and the environmental temperature profile. It is frequently observed that the level of free convection (LFC) lies above the LCL, as there is often an area of stable stratification or convective inhibition (CIN) near the cloud base (Bechtold 2009). The highest values of CAPE reached levels of extreme instability ( $CAPE > 2500$  J/kg), which is related to substantial updraft speeds (Chantraket et al. 2015).

#### PV

Cyclonic and anticyclonic behaviors play important roles in the synoptic scale within the mid-latitudes. Therefore, observational analysis, interpretation, and forecasting of these behaviors and the diagnosis of their dynamical aspects are important. One of



the approaches in assessing their dynamics is a PV framework (Davis and Emanuel 1991). This dynamic atmospheric parameter was presented by (Rossby 1940; Ertel 1942). The PV analysis assesses the impact of both vorticity and temperature advection and provides an estimation of the vertical motion. The analysis of isentropic potential vorticity (IPV) maps is an essential diagnostic tool to recognize the mechanisms responsible for atmospheric development (Hoskins et al. 1985).

### Results and discussion

As shown in the total daily precipitation maps (Fig. 2), heavy rainfall occurred over large parts of the study area. On 11 April (Fig. 2A), over all of western Iran, precipitation ranged from 10 to 66 mm. The next day, 12 April (Fig. 2B), the rainfall intensity decreased and precipitation of above 55 mm over western Iran. The maximum precipitation occurrence (> 80 mm) was on 13 April over western Iran (Fig. 2C). On 14 April (Fig. 2D), western

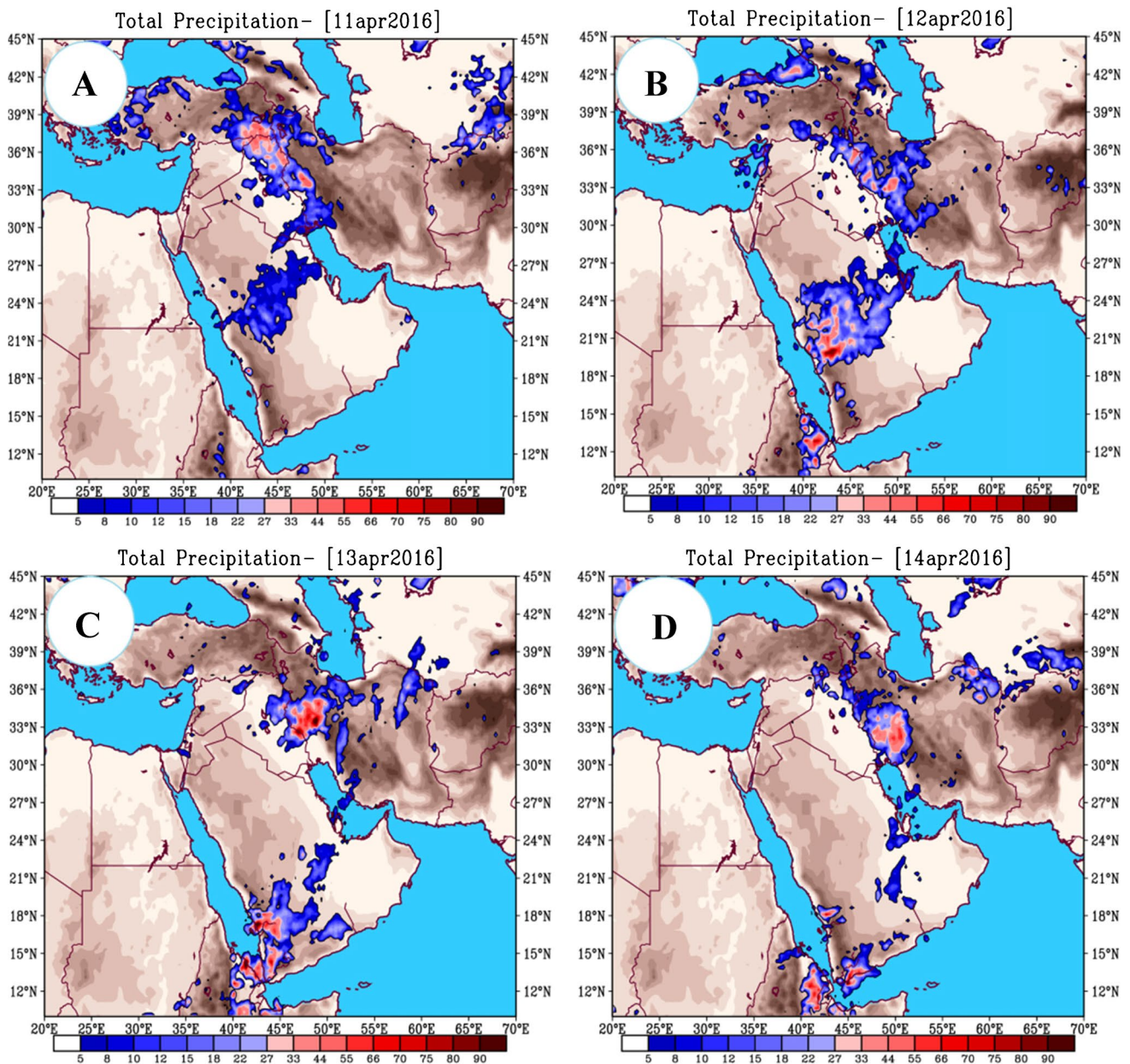


Fig. 2 Total daily rainfall for 11–14 April 2016



and southwestern Iran was greatly impacted by extreme precipitation.

### Sea level pressure and vorticity

Maps of sea level pressure and vorticity were plotted for 11–14 April to study these patterns (Fig. 3). Initially, a low-pressure system with a central pressure of 1004 hPa formed over western Turkey and the northeastern Mediterranean, with a strong positive vorticity, and additionally, a high-pressure system with a central pressure of 1024 hPa was situated over the Aral Sea (Fig. 3A). The study area

is located between these two Mediterranean lows and the Northern high that produced the surface front and the southerly flow, increasing the pressure gradient and wind speed, and eventually produced low-level convergence and upper-level divergence in the area. On 12 April, these pressure systems did not move, but they were weaker than over the previous day and the front remained at the surface (Fig. 3B), and on 13 April, the center of the high-pressure system moved to the northeast, and the low-pressure system moved to the southeast, which affected the study area, as well as Iraq and northern Arabian Peninsula (Fig. 3C, D). As a result, heavy rainfall was generated by to the

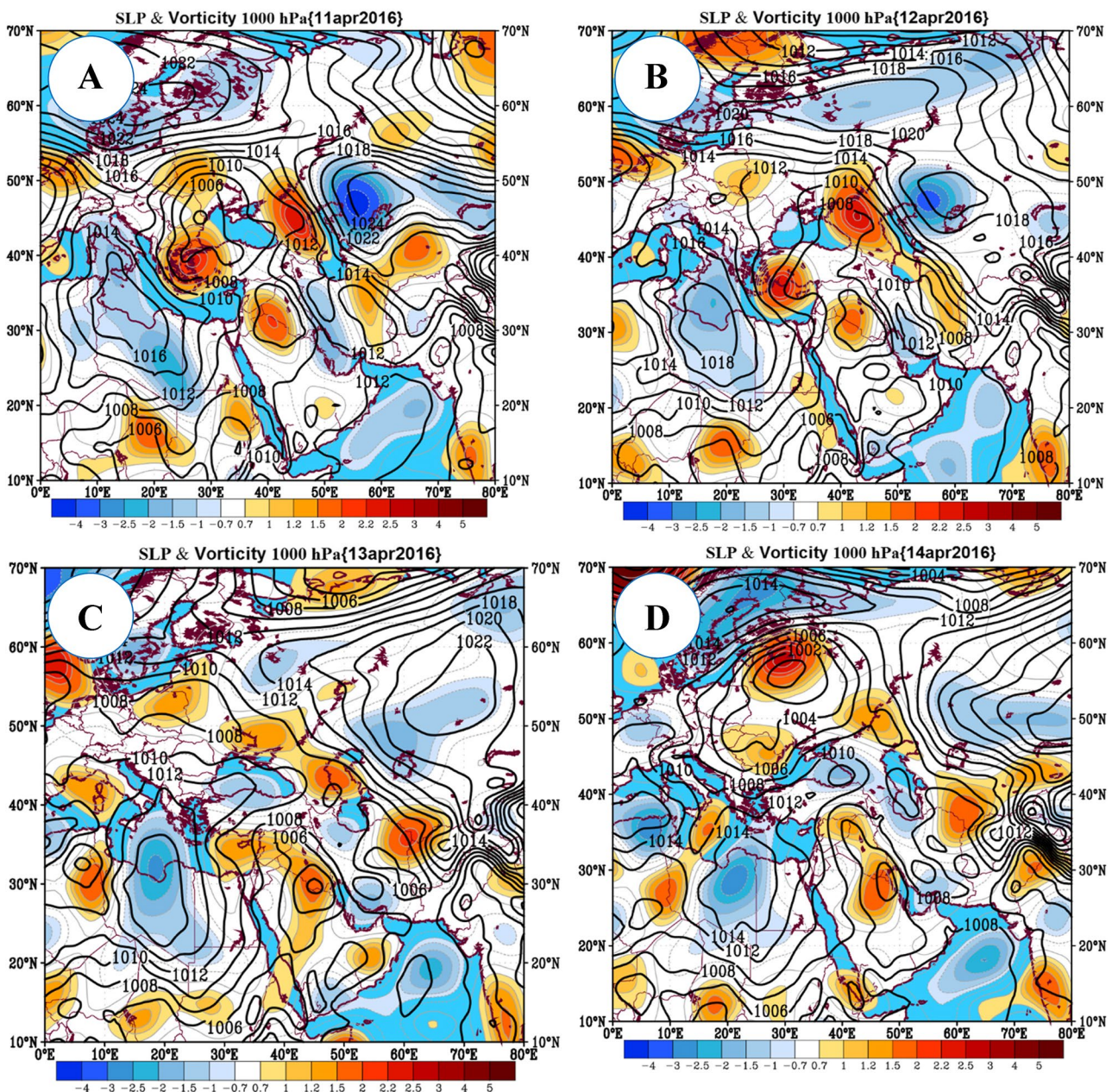


Fig. 3 Sea level pressure and 1000 hPa vorticity patterns for 11–14 April 2016



formation of the surface front and the close proximity of the two high-pressure systems to the low-pressure system.

### hPa geopotential height and vorticity

The cut-off low center with a maximum positive vorticity on 11 April is formed with a geopotential height of 5550 m over western Turkey and the northeastern Mediterranean Sea (Fig. 4A), in which motion was westerly. The study area is located under the eastern part of the cut-off low (the front part

of the trough), which is a place of air ascent and atmospheric instability. In the following days, this trough became deeper and the zonal flows changed to meridional ones toward the south, and the center of the system was over the Turkish Mediterranean coast (Fig. 4B), and its important feature was strong positive vorticity, which causes a rapid air ascent. On 13 and 14 April, the center of the cut-off low was reduced, and the flows became more southerly, allowing rapid air ascent (Fig. 4C, D). The study area was under the deep Mediterranean trough, which can be considered the main reason for the heavy rainfall.

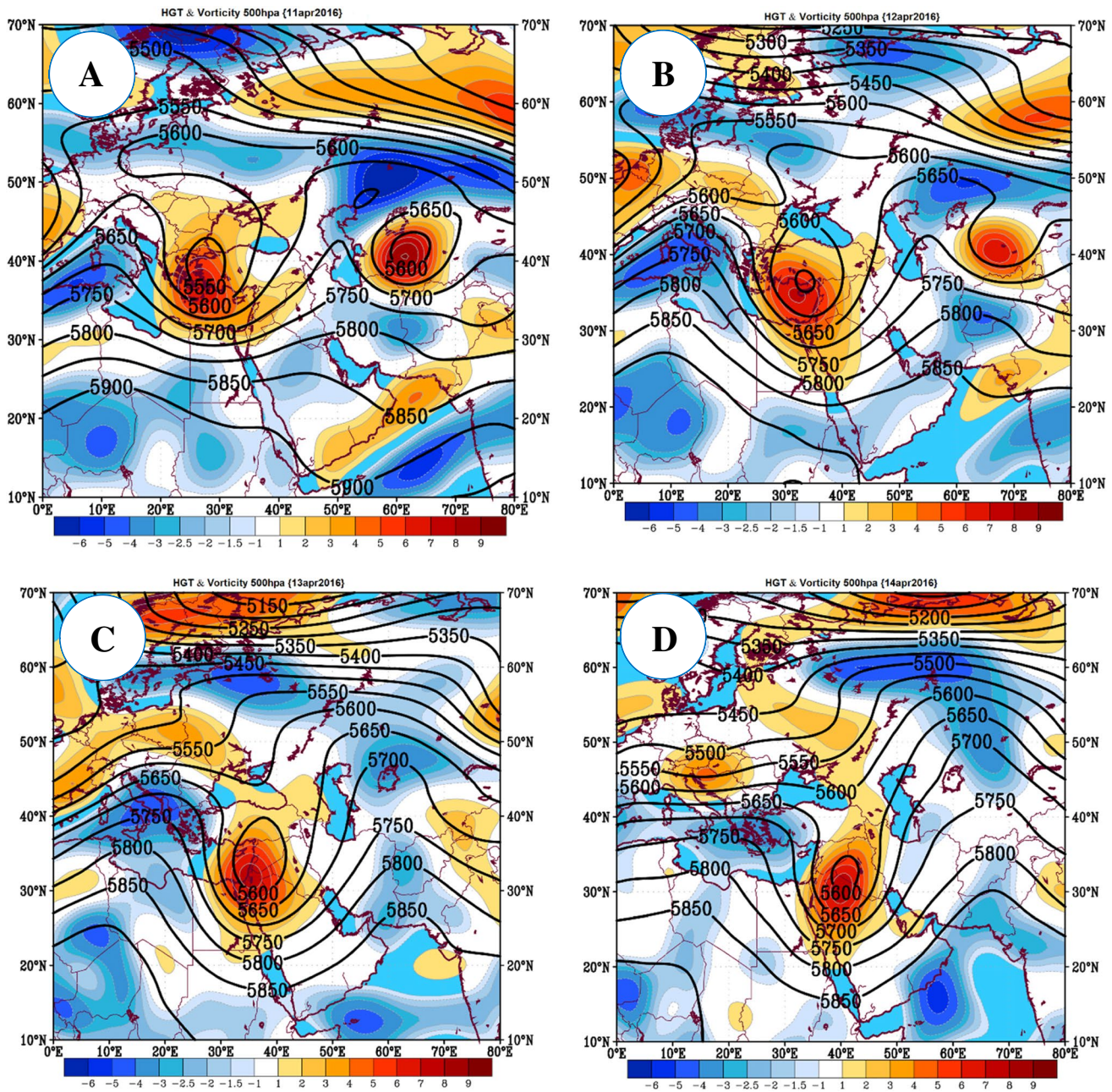


Fig. 4 Pattern of the geopotential height and vorticity at 500 hPa on 11–14 April 2016



## Jet stream

At the 250 hPa level on 12 and 13 April (Fig. 5B, C), the core of the subtropical jet stream, with an average speed of 40 to 42 m/s, was located over western Iran, with the maximum over North Africa and Saudi Arabia. The presence of the jet stream contributed to the atmospheric turbulence, which increased the intensity of instability and atmospheric turbulence and eventually caused heavy rainfall.

It is observed that from 11 to 13 April, the flows of the jet stream shifted from westerly to southerly on the third day of rainfall. The prevalence of the jet stream over Iran has controlled the low-level atmospheric circulation and intensified and reinforced the instability and atmospheric turbulence and, finally, cyclogenesis. The extreme divergence of the jet stream, associated with positive vorticity, caused strong air ascent and, as a result, has led to an intensification of rainfall over the study area.

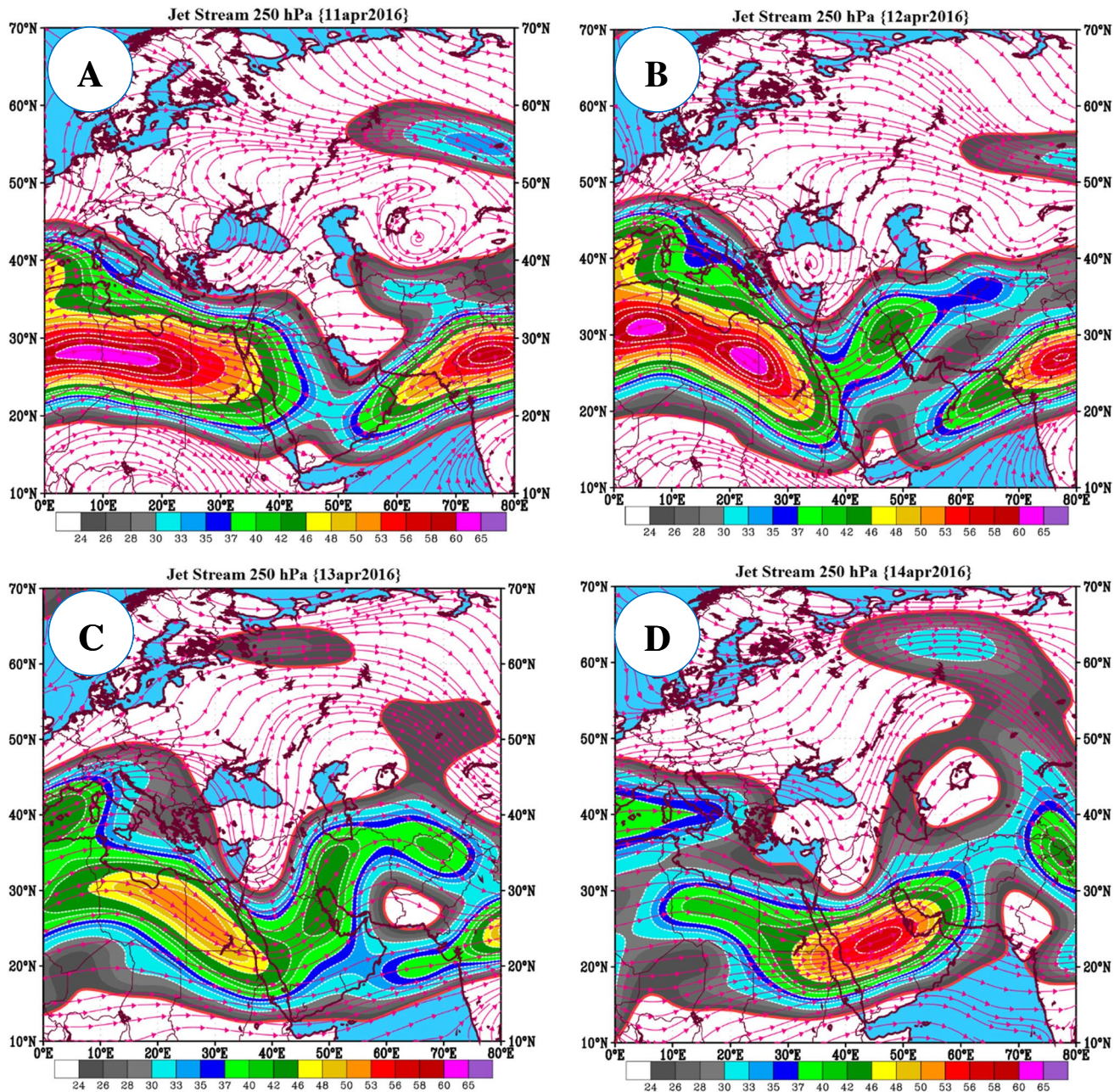


Fig. 5 250 hPa level jet stream on 11–14 April 2016



### hPa PV and geopotential height

In examining the 250 hPa map of 11 April (Fig. 6A), an atmospheric disturbance occurred in which the formation of a deep trough with a cut-off low between the Black Sea and the Mediterranean Sea caused an increase in the PV within the system. On 12 April (Fig. 6B), conditions for cold air advection into the trough were produced by the enhancement of the deep trough and the increase in the heights of the

ridge over North Africa. On 13 April (Fig. 6C), the trough deepened and extended to 15° North latitude. Under these conditions, the integration of the tropospheric and stratospheric PV in the study area provided conditions for substantial instability. On 14 April (Fig. 6D), an important factor in deepening the trough was the upper-level system over the eastern Middle East, which prevented the system from moving toward the east and by increasing the PV of the system strengthening it.

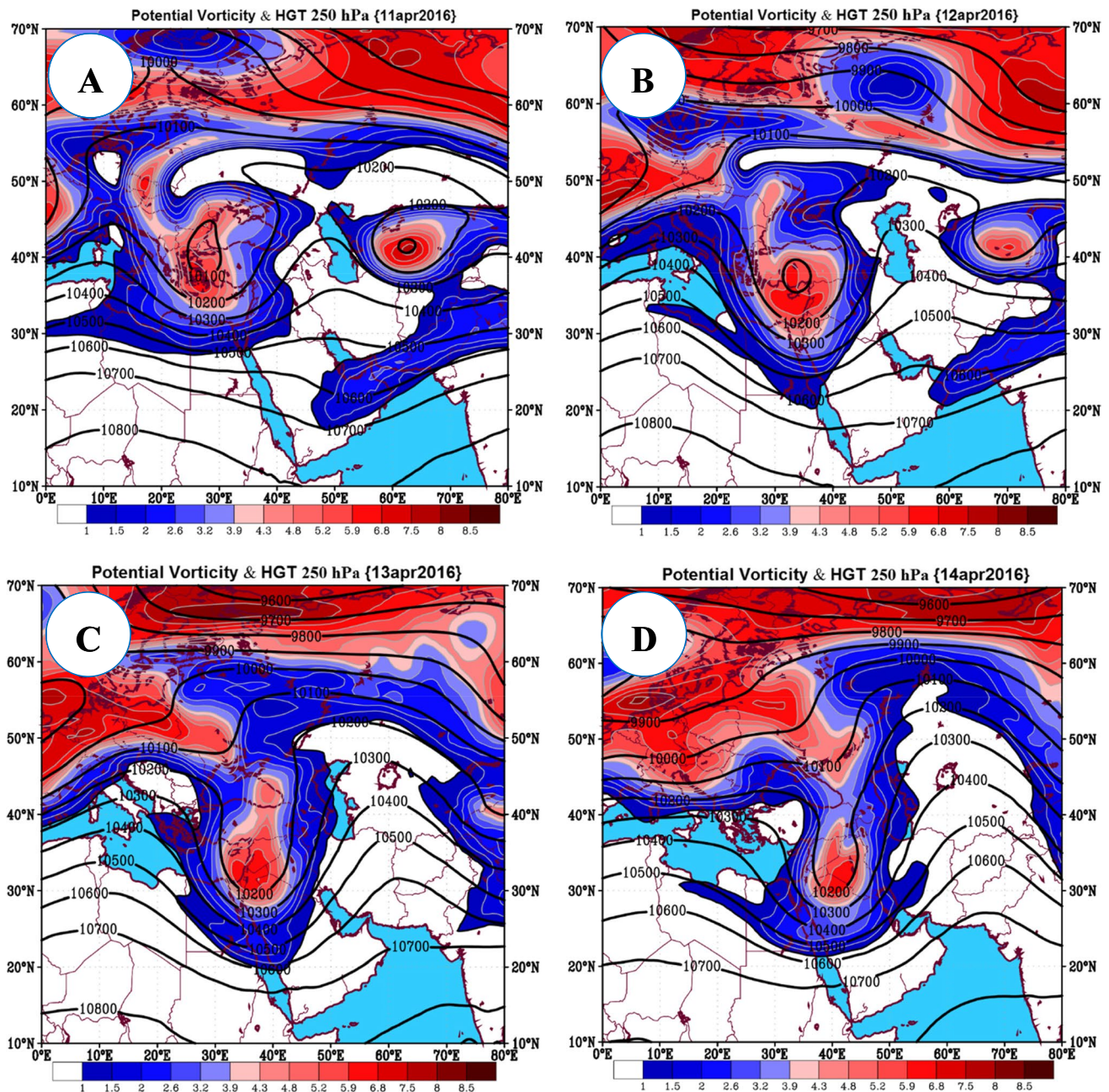


Fig. 6 Potential vorticity of the geopotential height at 250 hPa on 11–14 April 2016



## Anomalies of the 500 hPa geopotential height and Omega

In Fig. 7A, a negative anomaly of 500 hPa geopotential height was observed over western Turkey, moving southwards over the following days, with a maximum of  $-110$  m on 13 April (Fig. 7C) over Saudi Arabia, indicating a decrease in the geopotential height at 500 hPa and an increase in instability over the study area. Conversely, the two negative Omega centers were over western Turkey and over southern Iraq and northern Saudi Arabia with closed curves of  $-0.2$ , which moved over western Iran on 13 and 14 April (Fig. 7C, D), with a closed curve of  $-0.25$ , causing strong instability, atmospheric turbulence, and air ascent, resulting in heavy rainfall in the area.

## hPa MFC and streamlines

The 1000 hPa MFC maps indicate that on 11 April (Fig. 8A), a moist center was present from over southern Iraq to northern Saudi Arabia. In the days that followed, the moist center covered all of Iraq, and its trough was prevalent over the study area, and another strong center was observed over southern Saudi Arabia (Fig. 8B). Over the next two days, these two centers were reinforced (Fig. 8C, D), and the pattern of streamline vectors and the presence of these moist centers indicate substantial moisture advection from over the Mediterranean Sea, the Red Sea, and the Arabian Sea. These were the main sources of moisture for the heavy rainfall.

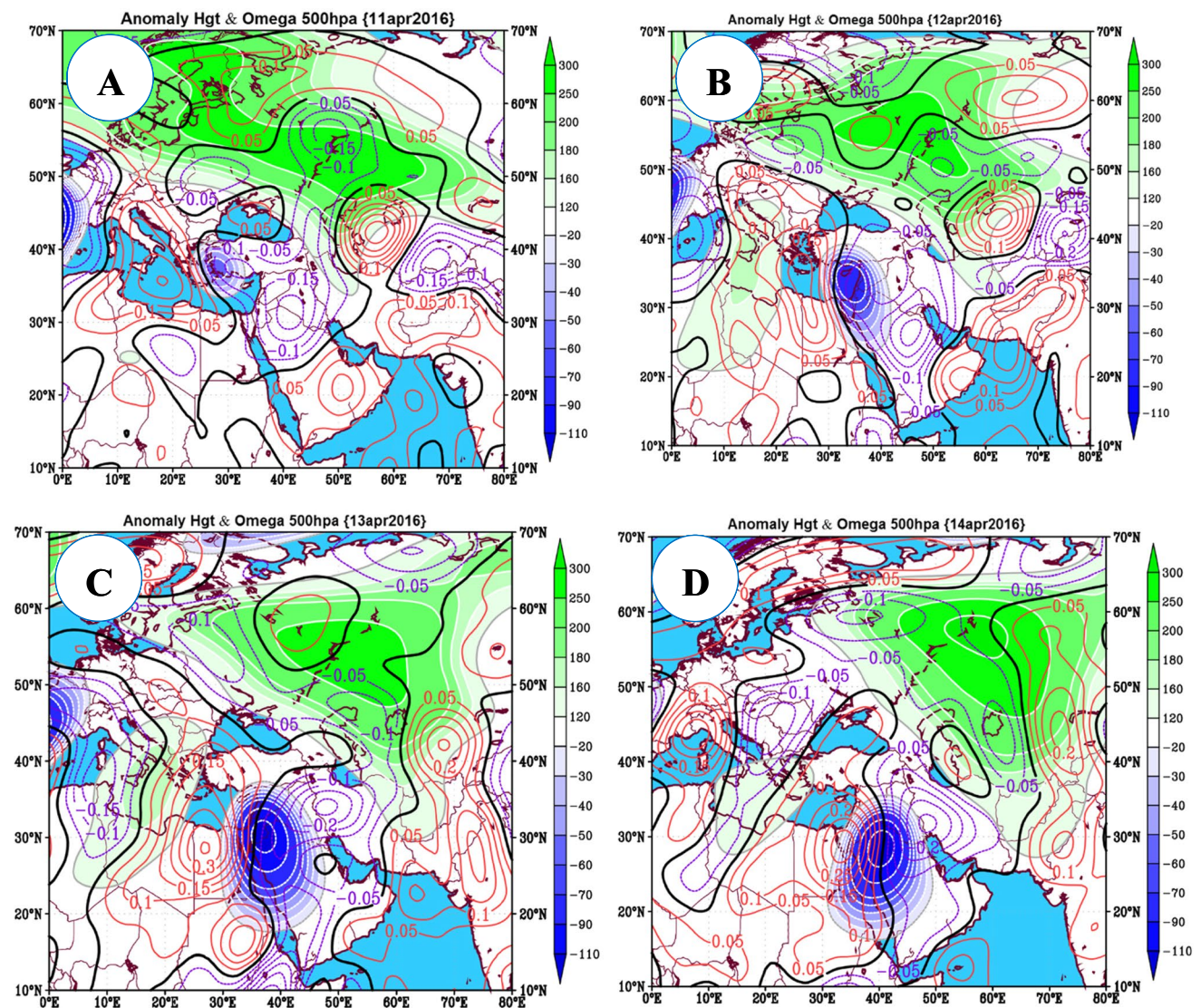
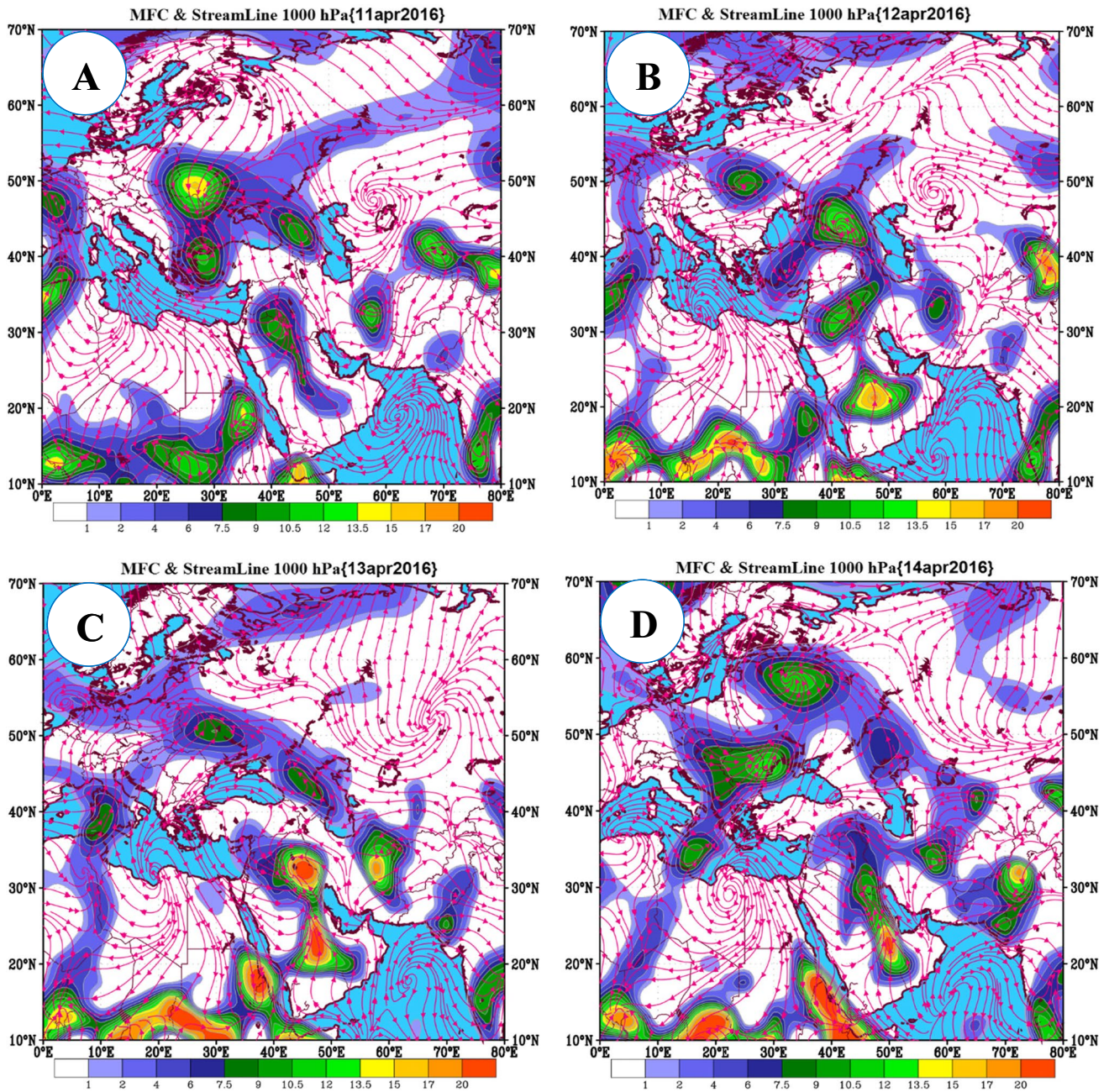


Fig. 7 Anomalies of 500 hPa geopotential height and Omega on 11–14 April 2016





**Fig. 8** 1000 hPa moisture flux convergence and streamlines on 11–14 April 2016

**CAPE**

In examining the CAPE map on 11 April (Fig. 9A), high amounts of CAPE were observed over the eastern Mediterranean and western Iran, but the main activity can be seen over the southern Red Sea. On 12 April (Fig. 9B), CAPE increased, over both the eastern Mediterranean and the southern Red Sea, indicating a baroclinic pattern. On 13

April (Fig. 9C), substantial instability from over the Red Sea to western and southeastern Iran was present, and mainly, tropical-like instability moved over the study area. These conditions were reinforced on 14 April (Fig. 9D), with two instability centers, one over western and southwestern Iran  $\geq 2000$  J/Kg and the other over the Persian Gulf  $\geq 2400$  J/Kg. These centers indicate the high favorability for occurrence of strong convective activity.



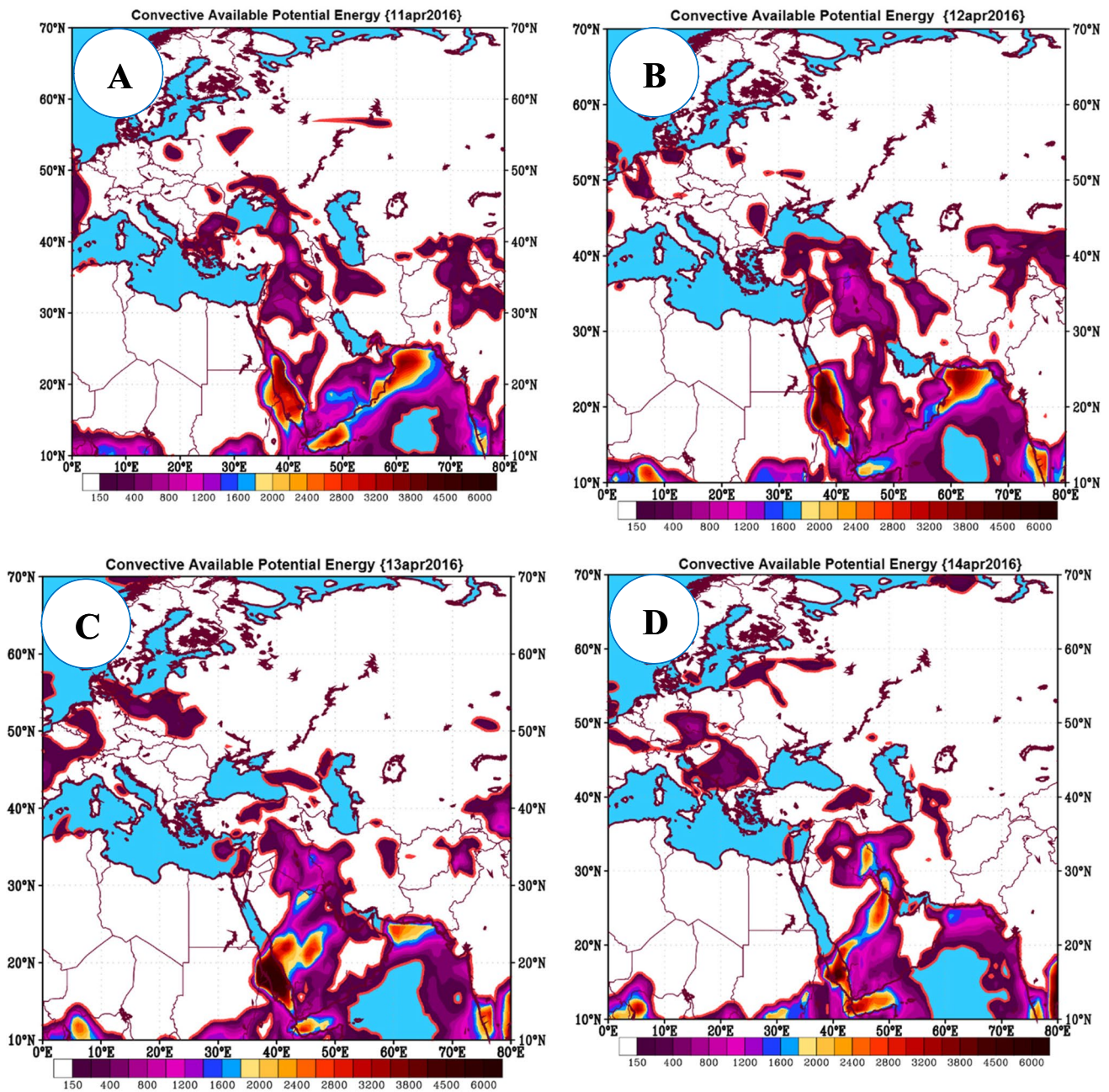


Fig. 9 CAPE on 11–14 April 2016

### Meteosat-7 satellite imagery

Meteosat-7 satellite imagery showed that on 11 April (Fig. 10A), the western half of Iran was covered by cumulonimbus clouds together with a series of clouds from over the Arabian Peninsula which came from the tropics.

On 12 April (Fig. 10B), the center of clouds over Saudi Arabia strengthened and merged with the center of clouds over western Iran. On 13 April (Fig. 10C), it is clear that a very strong flow that entered from the south toward the

region was the main origin of the clouds, and almost all regions of the country were under cloud cover. On 14 April (Fig. 10D), the clouds which were present from over the tropical regions moved over eastern and northeastern Iran, but a separate cloud segment was observed over the southwestern regions, resulting from local synoptic activity. However, the strip-like cloud pattern that passed over the study region from over the tropical areas was connected to the jet stream pattern, and due to the changing flow direction, the direction of the cloud pattern also changed. So, two types of



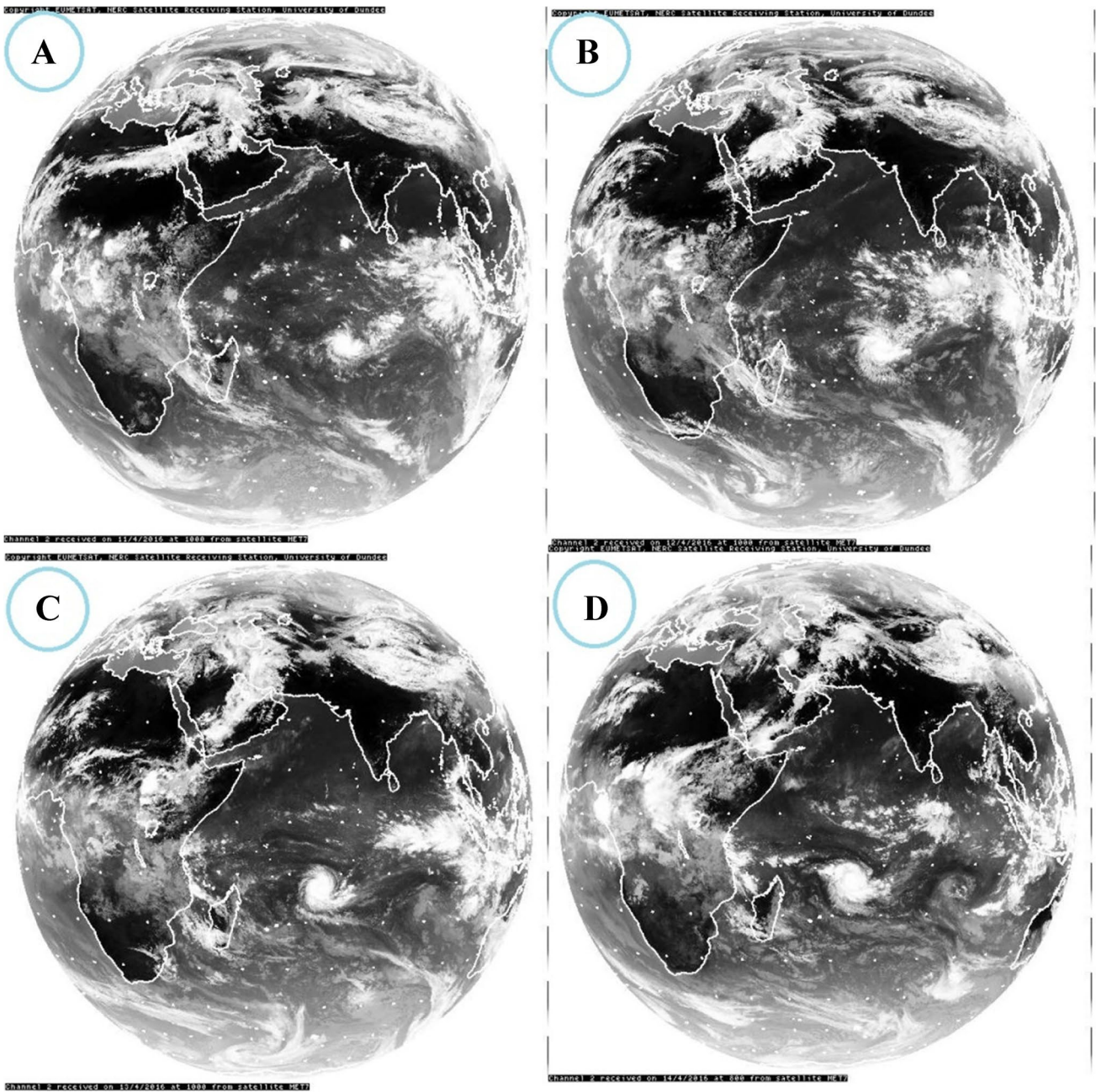


Fig. 10 Meteosat-7 satellite imagery on 11–14 April 2016

clouds were involved in the heavy rainfall over the region, one of which resulted from cyclonic activity and another due to the expansion and amplification of the tropical jet stream.

**Conclusion**

By studying the maps used in this study (total daily precipitation, sea level pressure, geopotential heights, jet stream, 250 hPa potential vorticity, 500 hPa Omega index, 1000 hPa

MFC, CAPE, and Meteosat-7 satellite imagery) for 11–14 April 2016, we conclude that the main causes of these heavy rainfall events were the formation of a low-pressure system over the northeastern Mediterranean and a high-pressure system over the Aral Lake, as well as the formation of a surface front and the interaction between these two pressure systems. At upper levels, the presence of a cut-off low center over the northeastern Mediterranean and the study area in front of the deep Mediterranean trough exacerbated the conditions which produced the heavy rainfall over the

study region. This was observed by high positive vorticity at both the surface and upper levels. The location of the jet stream from over northern Africa and Saudi Arabia to the study area led to an increase in atmospheric turbulence and instability, and a ridge present over the eastern Middle East blocked the eastern movement. The system has also been strengthened by increasing the potential vorticity. A negative anomaly of geopotential heights over western Turkey indicates a decrease in the height of the atmosphere, and the two negative Omega centers, one over western Turkey and the other over the northern Arabian Peninsula (both with closed curves of  $-0.2$ ) and its movement over the study area caused atmospheric instability and air parcel ascent. The examination of MFC indicates the moisture sources for the precipitation were the Mediterranean Sea, the Red Sea, and the Arabian Sea.

From the CAPE map, we observed substantial CAPE over the eastern Mediterranean, southern Red Sea, and western Iran, with the greatest instability from over the Red Sea to the studied area. Instability generated within the Red Sea Trough is the most important factor in generating extreme precipitation, floods, and severe societal impacts in the Middle East (Dayan et al. 2001; De Vries et al. 2013). The two instability centers, one over western and southwestern Iran  $\geq 2000$  J/kg and the other over the Persian Gulf  $\geq 2400$  J/kg, indicated a high favorability of occurrence of strong convective activity. Based on satellite imagery, the study area was covered by cumulonimbus clouds, a primary type of rainy cloud. The presence of this cloud type over the study area is due to cyclonic activity and is a result of the expansion and strengthening of the tropical jet stream that frequently contributes to heavy rainfall in the study area.

**Data Availability** The data that support the findings of this study are available from the corresponding author, (H.K), upon reasonable request.

## Declarations

**Conflict of interest** The authors declare that they have no competing interests.

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