



Dynamical and Synoptic Characteristics of Extreme Precipitation Events in Western Iran

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Article Info	ABSTRACT
Article type: Research Article	Extreme precipitation events pose a significant and growing threat to society, often leading to floods, landslides, and widespread socioeconomic damage. Daily precipitation data were collected from nine rain gauges from January 1, 1991, to December 31, 2023. To identify days associated with heavy precipitation, the 95th-percentile threshold was employed. Days on which the recorded precipitation exceeded the long-term mean of the 95th percentile at more than half of the stations were classified as heavy-precipitation days for Kurdistan Province. Based on this threshold and criterion, 210 days were selected. Two data arrays with an S-mode structure were constructed for sea-level pressure and 500-hPa geopotential height. Using Principal Component Analysis (PCA), components explaining more than one percent of the variance were retained as significant modes. For sea-level pressure, nine components were identified, and for the 500-hPa geopotential height, eight components were extracted. Together, these components explained over 92% of the variance in sea-level pressure and more than 95% of the variance in the 500-hPa geopotential height over the study domain. Cluster analysis (CA) performed on the score matrix of the 17 components was then used to identify the prevailing circulation patterns.
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Introduction

Due to global warming, extreme precipitation frequency and intensity have been increased significantly over globe (Zeder, J. & Fischer, 2020; Donat et al., 2019; Sun, et al., 2021; Westra et al., 2013; Kirchmeier-Young & Zhang, 2020; Chen et al., 2022). The Clausius-Clapeyron relationship indicates that atmospheric moisture-holding capacity increases by approximately 7% per degree Celsius of warming. This directly enhances the potential for extreme precipitation events. Human activities are responsible for an increase of 1.09 °C in the global mean temperature over the period 2011–2023 (IPCC, 2023), and this warming has raised the likelihood or intensity of heavy precipitation events by approximately 20 percent (Schiermeier, 2011). The increasing frequency of heavy precipitation events has led to serious challenges for soil erosion (Liu et al., 2020), extensive ecological damage (Mullan et al., 2012; Paerl et al., 2018), adverse economic and social consequences (Frame et al., 2020; Pastor-Paz et al., 2020), and human security (Zhang et al., 2018; Zhang & Zhou, 2020; Adhikari et al., 2025). According to previous study by Darand (2016; 2025) and Darand & Sohrabi (2018), the frequency and probability of heavy precipitation events occurrence in western part of Iran has been increasing. The province's topography and mountainous terrain significantly amplify the intensity of heavy rainfall and contribute to the rapid generation of flash floods. Therefore, understanding the atmospheric mechanisms and synoptic conditions associated with these events is essential—an objective that the present study seeks to address. A deep understanding of the atmospheric mechanisms that shape these events is crucial not only for improving the accuracy of weather forecasts but also for risk management, developing better early warning systems for the region, and climate change studies. The current study aims to conduct a comprehensive synoptic analysis to identify and characterize the dominant atmospheric circulation patterns associated with extreme precipitation events in western Iran. Through the use of cluster analysis and principle component analysis, this study will classify the key synoptic patterns responsible for these atmospheric high-impact events, providing crucial insights that can enhance the accuracy of extreme precipitation forecasts and inform effective risk management strategies. Several studies have investigated the synoptic characteristics of heavy precipitation events both in Iran and in other regions of the world. For example, Ghavidel and Jafari Hombari (2020) studied the atmospheric synoptic conditions leading to unexampled super heavy rainfall on April 1, 2019 in west of Iran. The results showed that the sea level pressure gradient caused by cold pressures in the east of the Caspian Sea and Europe combined with low dynamic/thermal pressures in the west of Iran and the north of Saudi Arabia led to front occurrence and extreme precipitation in the west of Iran. Also, cutoff low blocking in western Asia at the middle and upper levels of the troposphere led to deep trough and moisture advection from lower latitudes increased. Teixeira et al (2006) analyzed Dynamical and Synoptic Characteristics of Heavy Rainfall Episodes in Southern Brazil. They conclude that heavy rainfall in Southern Brazil is the result of a complex interplay between synoptic and dynamical factors which involves: An extratropical cyclone on the coast, An active South Atlantic Convergence Zone (SACZ), A strengthened low-level jet transporting moisture, and an upper-level trough providing lift and instability. Park et al (2021) identifies diverse synoptic weather patterns of warm-season daily heavy precipitation in South Korea. They found that daily heavy precipitation associated with a midlatitude cyclone from eastern China, the expanded North Pacific high, and strong southwesterly moisture transport in between. Sanuy et al (2024) analyzed the prevailing atmospheric conditions during heavy rainfall and storm waves in the Spanish NW

Mediterranean. To identify synoptic patterns associated with different event types, principal component analysis and k-means clustering with a Bayesian network have used. They identified SWPs associated with extreme compound events, which are often characterized by upper-level lows and trough structures in conjunction with Mediterranean cyclones, resulting in severe to extreme coastal storms combined with convective systems. Soltani et al (2023) identified the synoptic-scale systems which are responsible for the occurrence of the Sinai Peninsula extreme precipitation events. Their results showed that Mediterranean cyclones accompanied by the Red Sea and Persian troughs are responsible for the majority of extreme rainfall events year-round. Capozzi et al (2023) classified the atmospheric circulation patterns associated to daily heavy precipitation in the Campania Region (southern Italy). The heavy precipitation episodes are generally triggered by an upper level trough approaching the southern Italy from west and promoting a very moist southwesterly flow.

Although Darand (2015) conducted a synoptic analysis of heavy precipitation events in Kurdistan Province, the present study differs fundamentally in terms of both the dataset and the methodology used for identifying heavy rainfall events, as well as the synoptic analytical approach. In this research, heavy precipitation events were not categorized into wet and dry seasons. Instead, any day on which daily precipitation exceeded the long-term 95th percentile at a given station—and this threshold was simultaneously met at least in four out of nine stations—was defined as a province-wide, widespread heavy rainfall event. Another key distinction lies in the classification procedure. Cluster analysis was applied to the combined principal component scores derived from sea level pressure (SLP) and 500 hPa geopotential height (HGT) fields (17 component scores in total). This integrated approach enabled the simultaneous classification of surface and mid-tropospheric atmospheric conditions within the study domain, providing a more comprehensive synoptic perspective than separate clustering of each parameter. Furthermore, rather than examining moisture flux convergence (MFC) at individual pressure levels, this study analyzed vertically integrated moisture flux convergence (VIMFC) across atmospheric layers. In addition, anomalies of SLP and 500 hPa HGT, frontal structures, and patterns of divergence and convergence associated with each identified synoptic pattern were systematically investigated.

Material and Methods

The study area encompasses the approximately 29173 km² area in the Western Iran (Fig. 1). Topographically, the province is predominantly mountainous and forms part of the central Zagros Mountains system. Elevations generally range from about 700 m in the western plains to over 3,000 m in the central highlands. This complex terrain exerts a strong control on regional atmospheric circulation, enhancing orographic lifting and playing a crucial role in the spatial variability of precipitation.

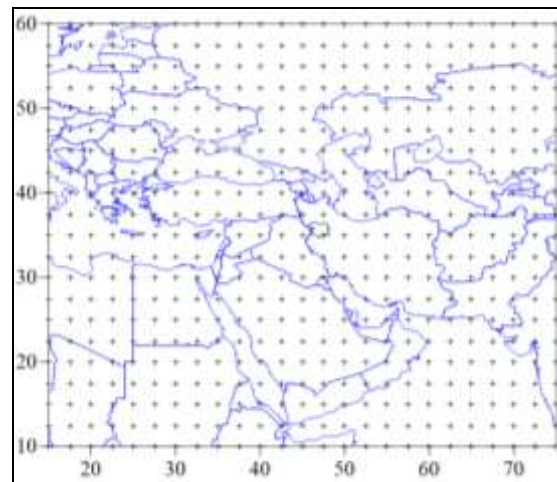


Figure 1. The kernel used for the analysis of synoptic systems.

For this research, two groups of data were employed. The first group include daily precipitation data, and the second group consisted of atmospheric circulation data. The daily precipitation data refer to station-based meteorological variables, specifically the daily precipitation amounts received from nine synoptic weather stations in Kurdistan province, from 1/1/1992 to 11/08/2023. These data were obtained from the Iranian Meteorological Organization.

The atmospheric circulation data included gridded data for the parameters of sea level pressure (SLP), zonal (uwnd) and meridional (vwnd) wind components, geopotential height (hgt), and specific humidity (shum). These were extracted from the American National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis. To identify the atmospheric conditions concurrent with heavy precipitation events in Kurdistan province (Figure 1). The NCEP/NCAR dataset, which combine observations with numerical weather prediction models, provide spatially and temporally consistent atmospheric data for synoptic studies (Kalnay et al., 1996; Dee et al., 2011).

To identify days with heavy precipitation, the 95th percentile threshold was utilized. Initially, for each individual day of the year at each station, the long-term 95th percentile average was calculated. The precipitation amount received on each day within the analyzed period was then compared with the long-term 95th percentile average for that specific day. Days on which the received precipitation exceeded the long-term 95th percentile average at more than four stations were selected as days with heavy precipitation in Kurdistan province (the areal extent and the intensity). Based on the aforementioned threshold and criterion, 210 days were selected. To identify the synoptic systems influencing the occurrence of heavy precipitation in Kurdistan province, two data arrays with an S-mode arrangement of 525 210 were created for sea level pressure and geopotential height at the 500 hPa level. In these arrays, rows represented days and columns represented the grid cells within the study kernel. Subsequently, Principal Component Analysis (PCA) was performed on the aforementioned matrices. Components explaining more than one percent of the variance were retained as significant components. Accordingly, nine significant components for sea level pressure and eight components for geopotential height at 500 hPa were identified. Together, these accounted for over 92% of the variance for sea level pressure and over 95% for the 500 hPa geopotential height across the study domain (Table 1). Since the sea level pressure pattern for each examined day is a combination of the aforementioned nine components for sea level pressure and the eight components for 500

hPa geopotential height, a cluster analysis with Euclidean distance and Ward method was performed on the matrix of scores for the 17 components to identify circulation patterns at sea level and the 500 hPa level.

The Vertically Integrated Moisture Flux Convergence (VIMFC) is used to calculate moisture transport (Eq. 1).

$$VIMFC = -\frac{1}{g} \cdot \int_{psurf}^{ptop} \left(\frac{\partial u q}{\partial x} + \frac{\partial v q}{\partial y} \right) dp \quad (1)$$

where q is the specific humidity, u and v are the x- and y-components of the wind, respectively, p is the pressure, $psurf$ is the surface pressure, $ptop$ is the pressure at the top of the atmospheric layer, and g is the acceleration due to gravity. VIMFC is calculated by summation of the horizontal moisture flux convergence over the intervals 1000–850, 850–600 and 600–400 hPa using finite centered differences on a lat/lon grid to approximate the term between brackets in Eq. (1). In the mentioned equation we will express values of VIMFC in units of $10^{-5} \cdot \text{Kg.m}^{-2}.\text{s}^{-1}$.

The location of a front is defined by how quickly the gradient of the magnitude of the potential temperature θ changes, as follow:

$$F = \frac{1}{|\nabla \theta|} \left\{ \left(-\frac{\partial \theta}{\partial x} \right) \left(\frac{\partial u}{\partial x} \frac{\partial \theta}{\partial x} + \frac{\partial v}{\partial x} \frac{\partial \theta}{\partial y} \right) - \left(\frac{\partial \theta}{\partial y} \right) \left(\frac{\partial u}{\partial y} \frac{\partial \theta}{\partial x} + \frac{\partial v}{\partial y} \frac{\partial \theta}{\partial y} \right) \right\} \quad (2)$$

where $\nabla \theta$ denotes horizontal potential temperature changes which is calculated by

$$|\nabla \theta| = \sqrt{\left(\frac{\partial \theta}{\partial x} \right)^2 + \left(\frac{\partial \theta}{\partial y} \right)^2} \quad (3)$$

All terms with $\partial u / \partial x$ or $\partial v / \partial y$ are confluence terms, all terms with $\partial v / \partial x$ or $\partial u / \partial y$ are sharing terms.

Divergence and convergence in units of s^{-1} during extreme precipitation calculated as follow:

$$\nabla \cdot \vec{v} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \quad (4)$$

Results and Discussion

Classified Synoptic Patterns

Figure 2 presents the dendrogram derived from hierarchical cluster analysis of the component scores of sea-level pressure and 500-hPa geopotential height. Based on these scores over the analyzed kernel, 210 days were classified into three distinct synoptic patterns, each representing different synoptic conditions. These results are consistent with pervious findings on classifications of synoptic patterns leading to extreme precipitation events (Darand, 2015) in the study area. The first synoptic pattern accounts for the largest contribution to heavy precipitation events in Kurdistan Province, with a frequency of 44.76%, followed by the second (28.09%) and third (27.14%) patterns (Table 2). Temporally, the first synoptic pattern predominantly occurs during the cold season, whereas the third pattern is mainly observed during the warm season. The second synoptic pattern is primarily associated with the transitional seasons (Figure 3). The interannual frequency of the identified synoptic patterns is shown in Figure 4. The highest occurrence

of heavy precipitation events was recorded in 2015, during which the third synoptic pattern occurred approximately eight times. In 2018, the second synoptic pattern exhibited its maximum frequency (seven events), while the highest occurrence of the first synoptic pattern was observed in 1993, with seven events.

The spatial distribution of mean daily precipitation associated with each synoptic pattern is illustrated in Figure 5. For the first pattern, the highest precipitation amounts are concentrated in the western and southwestern parts of the province, whereas the eastern regions receive the lowest amounts. Although precipitation intensity decreases under the second synoptic pattern, its spatial distribution remains broadly similar to that of the first pattern, with a west–east gradient. In contrast, the third synoptic pattern exhibits a distinct precipitation structure, with maximum mean daily precipitation occurring in the northern and northeastern regions of Kurdistan Province and decreasing toward the southern areas. Finally, Figure 6 depicts the mean annual precipitation of the provincial stations (mm) based on their spatial distribution.

Table 1. Principal component analysis results and the percentage of variance explained by individual components.

Component No.	Explained variance (Sea Level Pressure)	Accumulated explained variance	Explained variance (Geopotential Height)	Accumulated Explained variance
1	42.588	42.588	67.84	67.84
2	19.252	61.84	10.125	77.965
3	12.953	74.793	7.316	85.281
4	6.453	81.247	3.483	88.764
5	3.595	84.842	2.47	91.235
6	3.278	88.121	1.852	93.087
7	1.955	90.076	1.108	94.196
8	1.477	91.553	1.033	95.229
9	1.294	92.848	-	-

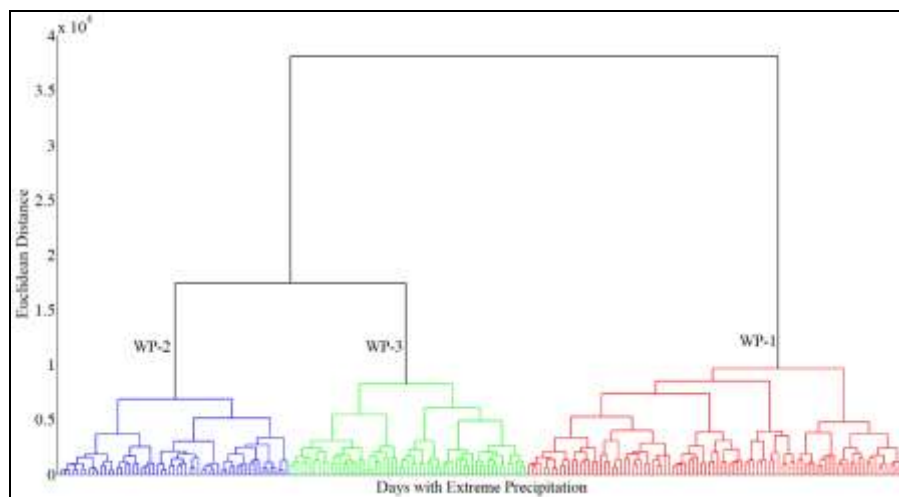


Figure 2. Dendrogram of cluster analysis of days associated with extreme precipitation.

Table 2. Absolute and relative frequency of synoptic patterns.

Patterns	Absolute Freq.	Relative Freq.
1	94	44.76
2	59	28.09
3	57	27.14
Total	210	100

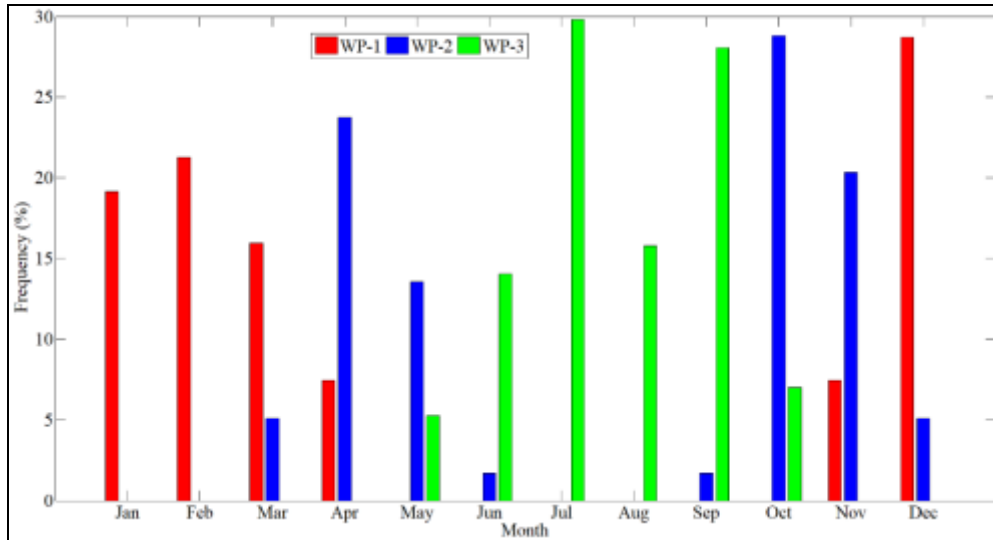


Figure 3. Monthly frequency of synoptic patterns.

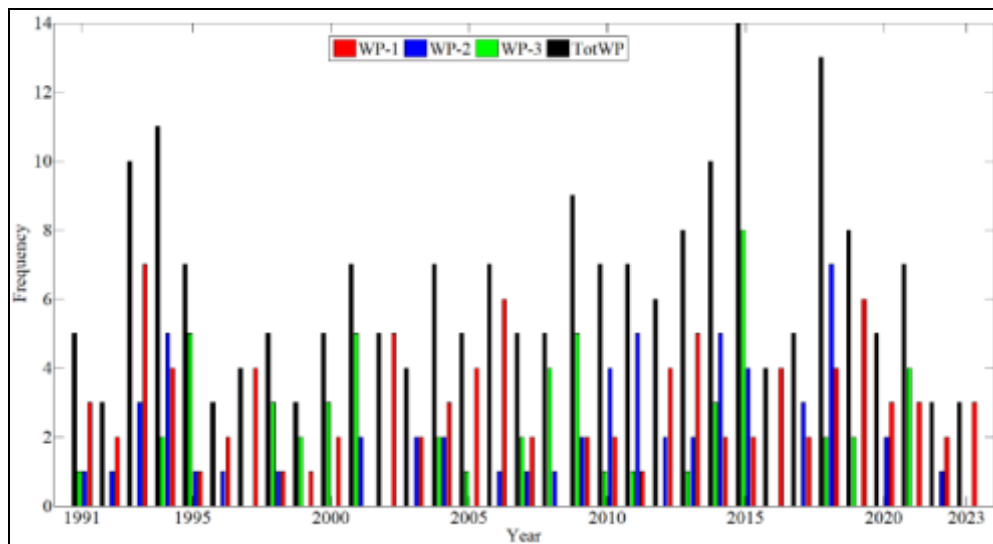


Figure 4. Yearly frequency of synoptic patterns.

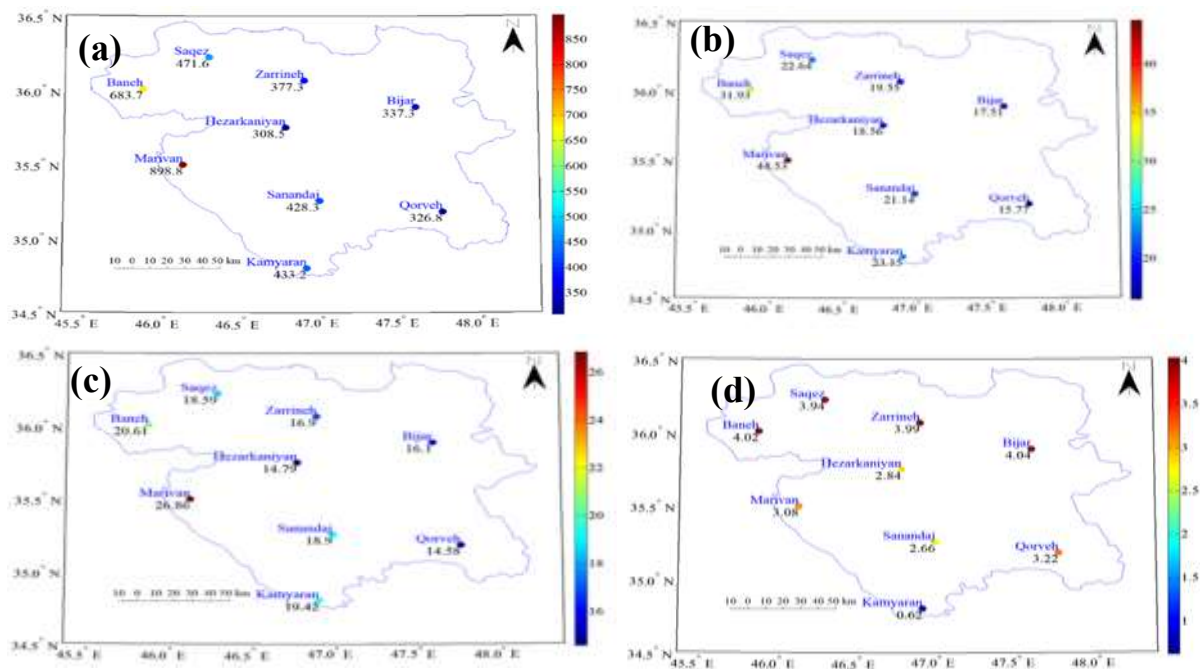


Figure 5. Spatial distribution of the long-term mean precipitation over Kurdistan Province (a) and during the occurrence of the first (b), second (c), and third (d) synoptic patterns.

Synoptic Patterns Characteristics

Based on the composite maps, the first synoptic pattern at sea level is characterized by the presence of the European High and the Siberian High. The Siberian High extends toward the Arabian Sea and southeastern Iran, while the European High expands southward to North Africa. Between these two high-pressure systems, the Sudan low pressure tongue penetrates northward from the Red Sea, crossing Saudi Arabia and Iraq, and extends into Iran, affecting the northwestern regions of the country. The clockwise circulation associated with the high-pressure systems enhances the counterclockwise rotation of the Sudan Low, reinforcing its cyclonic circulation and contributing to the persistence of atmospheric instability. At sea level, this configuration facilitates the northward advection of moisture from southern water bodies and adjacent seas. The southward displacement of the European High from higher to lower latitudes is primarily associated with the equatorward shift of the subpolar low pressure system, which drives and forces the European High pressure toward lower latitudes. Simultaneously, in the mid-troposphere, a deep trough is established, with its axis extending over Turkey, Syria, and the eastern Mediterranean, placing Kurdistan Province and Iraq within the eastern part of the trough. The interaction between the surface-level intrusion of the Sudan Low and the mid-level trough during the occurrence of the first synoptic pattern provides favorable dynamical conditions for the development of heavy precipitation over Kurdistan Province. Sea-level pressure anomalies indicate a pronounced negative anomaly core of up to -9.3 hPa relative to the long-term mean over northern Iraq, northwestern Iran, and Kurdistan Province, with Kurdistan located near the center of this anomaly. At the 500-hPa level, geopotential height anomalies reveal a negative core reaching -90 geopotential meters over western regions of Iraq, indicating a significant deepening of the mid-tropospheric trough relative to long term

climatology. Concurrently, a positive geopotential height anomaly of approximately +60 geopotential meters is observed over eastern Iran and western Afghanistan at 500 hPa (Figure 8).

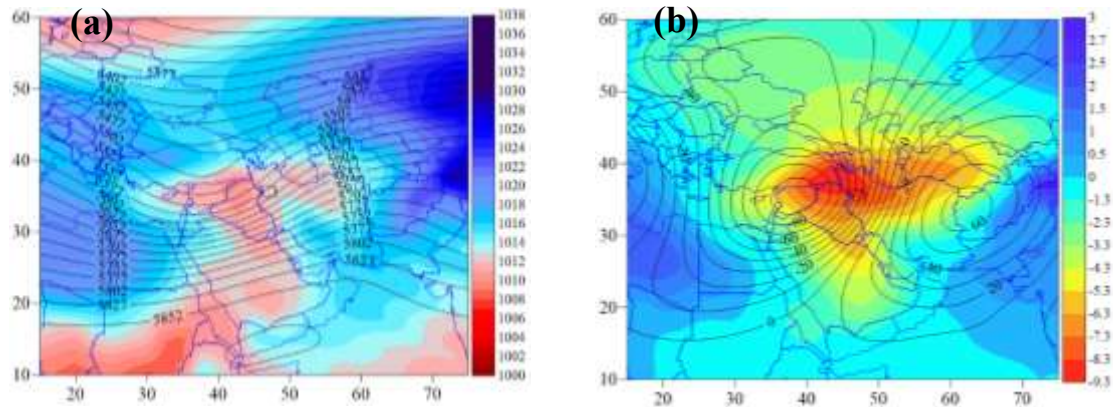


Figure 6. Synoptic circulation pattern at sea level and the 500-hPa level (a), and their associated anomalies in the first pattern (b).

The second synoptic pattern occurs during the transitional seasons (i.e., spring and autumn). During its occurrence, the sea-level pressure field shows the presence of two high-pressure systems: the Siberian High and the European High. However, compared to the first pattern, the Siberian High ridge extends less prominently toward lower latitudes, reaching only as far as Afghanistan (Figure 7). Meanwhile, the Sudan Low trough extends toward higher latitudes, covering Iraq and western Iran, though with less spatial extent compared to the first pattern. Under this configuration, the northwestern and western regions of Iran fall under the influence of the European High ridge. At the 500-hPa level, a relatively deep trough is evident over Iraq, with its axis extending across Syria, Turkey, and the eastern Mediterranean. The 500-hPa geopotential height over Kurdistan Province in the second pattern is higher than that observed in the first pattern, indicating a distinct dynamical mechanism compared to the first pattern. Negative sea-level pressure anomalies are observed in eastern Iraq and western Kurdistan Province, reaching -4.3 hPa. At the 500-hPa level, the most pronounced negative geopotential height anomalies—amounting to a decrease of 50 geopotential meters relative to the long-term mean—are located over parts of western Iraq, Syria, and Jordan.

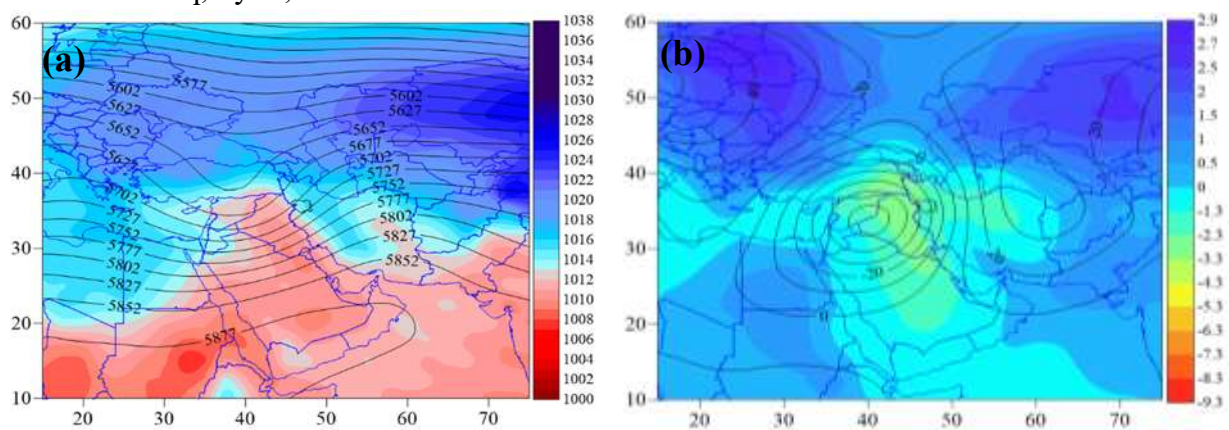


Figure 7. Synoptic circulation pattern at sea level and the 500-hPa level (a), and their associated anomalies in the second pattern (b).

In the third pattern, which occurs during the warm season, the atmospheric conditions differ from the other two patterns. With the onset of heat and the increase in solar radiation intensity, a monsoon low-pressure system forms over tropical and low-latitude regions, extending its ridge toward higher latitudes. The core of the monsoon low is observed over eastern Pakistan with a central pressure of 1000 hPa. Additionally, another strong low-pressure core with a central pressure of 1000 hPa is evident over the Persian Gulf, extending its ridge toward higher latitudes as far as northwestern Iran and northern Iraq. In contrast, the ridge of a high-pressure system over the northern Caspian Sea and Europe penetrates from the northwest of Iran and the Caspian Sea toward Iran and Kurdistan Province. The clockwise rotation of the incoming high-pressure ridge transports cold air from higher latitudes along with moisture from the Caspian Sea into Kurdistan Province from northern Iran. This converges with the warm, moist air advected from southern regions due to the counterclockwise motion of the monsoon and Persian Gulf low-pressure systems, forming a front. This interaction leads to the occurrence of heavy precipitation in Kurdistan Province during the warm months of the year. At the 500-hectopascal level in the third pattern, with the onset of the warm season, the Azores high extends from southern latitudes and from the direction of Arabia upward, reaching the southern and southwestern regions of Iran with a geopotential height of 5877 meters. Within the ridge of the Azores high, a relatively deep trough is observed over the western regions of Iraq. Given that Kurdistan Province is located east of this trough, it enhances atmospheric instability at the 500-hectopascal level over Kurdistan Province (Figure 8). The sea-level pressure anomaly during the occurrence of this pattern indicates an increase in positive sea-level pressure anomalies across Iran, particularly over the northern Caspian Sea and northern Iran, where a pressure increase of 2.9 hPa is observed compared to the long-term average. In contrast, negative sea-level pressure anomalies are evident over the eastern Mediterranean Sea and western Iraq. Regarding the 500-hectopascal level anomaly, the strengthening of a ridge over eastern Russia by 50 geopotential meters compared to the long-term average, along with a decrease in geopotential height by 20 geopotential meters over parts of Kurdistan Province and central regions of Iraq, indicates the injection of cold air from higher latitudes and the enhancement of instability over Kurdistan Province (Figure 12).

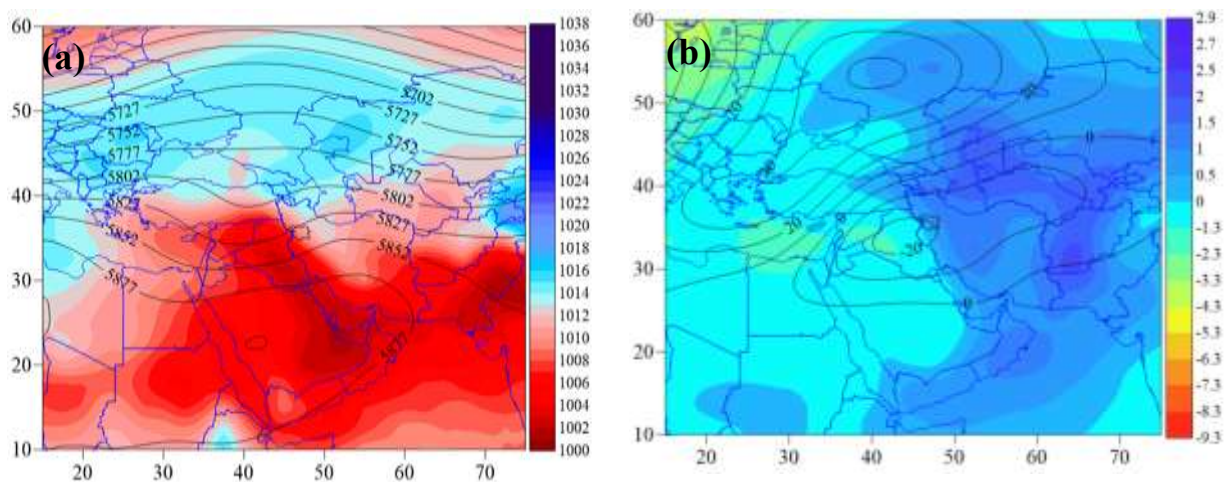


Figure 8. Synoptic circulation pattern at sea level and the 500-hPa level (a), and their associated anomalies in the third pattern (b).

For a better understanding of the moisture flux convergence along the vertical during heavy precipitation events, the atmosphere from the 1000 to 400 hPa levels was divided into three layers: 850–1000 hPa, 600–850 hPa, and 400–600 hPa. The reasoning behind this three-layer subdivision of the atmosphere is based on the findings of Darand and Pazhoh (2019). In their study of moisture advection toward Iran during persistent and dominant precipitation events, they concluded that moisture advection rates differ among atmospheric layers and can be categorized into the three aforementioned levels. In the first layer (850–1000 hPa) during the occurrence of the first pattern, the Siberian High's anticyclonic ridge, through its anticyclonic circulation, transports cold air from high latitudes toward the Arabian Sea and the Sea of Oman. Along a meridional direction from south to north, it advects moisture from these warm seas, together with the Sudanese Low, toward western Iran and Kurdistan province. Simultaneously, a closed low over Turkey is observed, which carries moisture from the Mediterranean Sea toward Kurdistan province. The resulting moisture flux convergence over Kurdistan province, due to the advection of moisture from the southern warm seas and the Mediterranean, ranges between 10 and $12.5 \times 10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$. In the second layer (600–850 hPa), the role of the Arabian anticyclone in advecting warm and moist air from the seas at southern latitudes toward Kurdistan province during the first pattern is quite evident and pronounced. The position of Kurdistan province east of a trough over Iraq and Syria in this layer establishes conditions conducive to atmospheric instability. In the second layer, the core of moisture flux over Kurdistan province appears with values of 7.5 to $10 \times 10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$. In the third layer (400–600 hPa), the Mediterranean Sea assumes the role of moisture supplier for the heavy precipitation events in Kurdistan province. The magnitude of moisture flux convergence resulting from the advection of moisture by the eastern Mediterranean trough in this layer is approximately $2.5 \times 10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$.

Generally, from the moisture advection maps across different layers during the occurrence of the first pattern, it can be inferred that the southern seas (Oman, Persian Gulf, Red Sea) supply moisture in the lower layers, while in the upper layer, the moisture sources for

heavy precipitation in Kurdistan province are the Mediterranean Sea and the northern Red Sea.

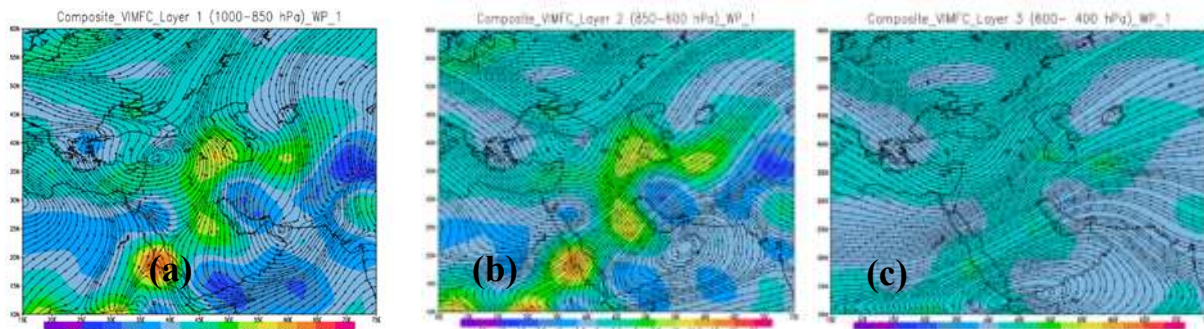


Figure 9. Vertically Integrated Moisture Flux Convergence ($10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$) during the occurrence of the first pattern in different layers: layer 1 (a), layer 2 (b), and layer 3 (c).

In the first layer, from 1000 to 850 millibars, similar to the first pattern, the flow is predominantly southerly. The anticyclonic circulation of the high-pressure system over the Arabian Sea advects moisture from the warm southern seas toward western Iran and Kurdistan Province, while the cyclonic circulation of the low-pressure system over Iraq transports moisture from the Mediterranean Sea toward Kurdistan Province. In the second layer, from 850 to 600 millibars, the role of the high-pressure ridge over the Arabian Sea and eastern Saudi Arabia is quite evident in advecting warm, moist air from the southern seas—particularly the Arabian Sea, the Red Sea, and the Persian Gulf—toward western Iran and Kurdistan Province. Additionally, in this same layer, the deep trough and low-pressure system over Iraq, Syria, and Turkey play a significant role in atmospheric destabilization and the transport of Mediterranean moisture toward western Iran. In the third layer, the trough over the eastern Mediterranean and Iraq plays an important role in transporting moisture from the Mediterranean Sea and the Red Sea, although the rate of advection is lower compared to the previous two layers.

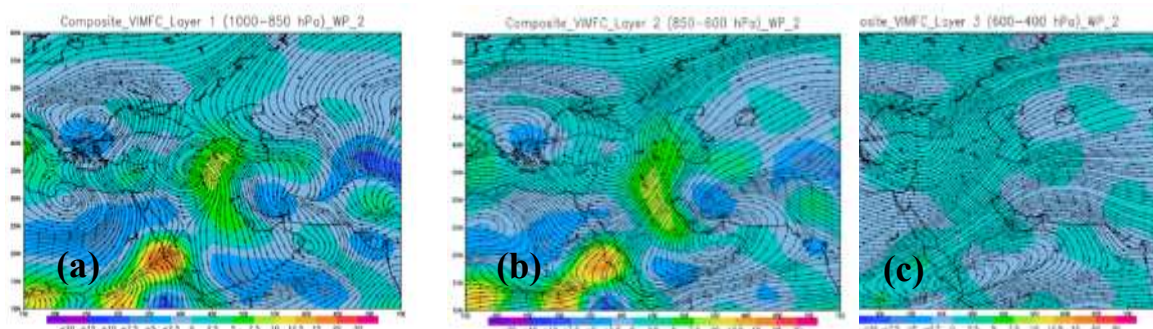


Figure 10. Vertically Integrated Moisture Flux Convergence ($10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$) during the occurrence of the second pattern in different layers: layer 1 (a), layer 2 (b), and layer 3 (c).

In the first layer (1000-850 hPa), the third pattern clearly exhibits moisture flux convergence values ranging from 7.5 to $10 \times 10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$ over Kurdistan province. This is driven by moisture advection from the Caspian Sea due to an anticyclonic system over the northern Caspian Sea, alongside moisture flux from the southern seas facilitated by the

cyclonic movement of the Persian Gulf low-pressure system. In the second layer (850-600 hPa), moisture convergence of approximately 10 to $12.5 \times 10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$ over Kurdistan province results from moisture advection originating from the northern Red Sea and the Mediterranean Sea, driven by a deep trough over Iraq. In the third layer (600-400 hPa), the atmospheric conditions resemble those observed in the first and the second patterns.

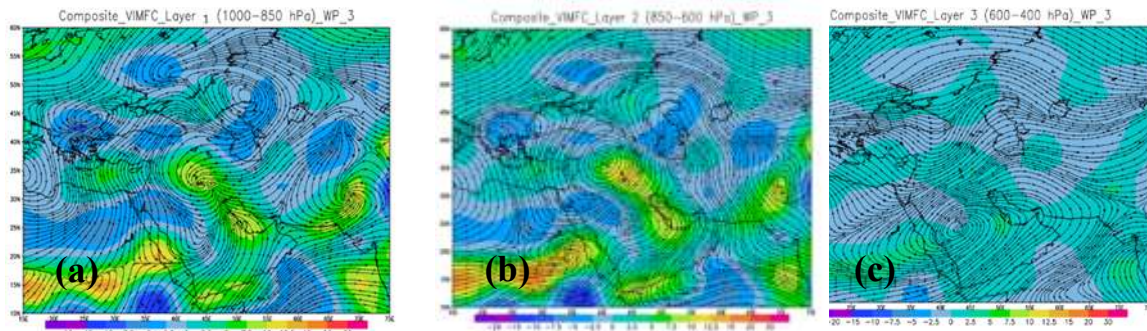


Figure 11. Vertically Integrated Moisture Flux Convergence ($10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$) during the occurrence of the third pattern in different layers: layer 1 (a), layer 2 (b), and layer 3 (c),

Front

Front is a boundary zone separating two different air masses with contrasting temperature, density, and humidity characteristics. Because these air masses don't easily mix, the front becomes the site where rising air, clouds, and precipitation are concentrated, making them the primary drivers of mid-latitude weather. The frequency of frontal occurrences for each pattern at the 1000, 925, and 850 hPa levels is presented in Figures 12 and 13. As shown, under Pattern 1, the frequency of frontal activity from 1000 to 850 hPa exceeds 20% along a southwest–northeast axis extending from the Red Sea to northwestern Iran and Turkmenistan. At the 1000 hPa level, three cores of maximum frontal occurrence are identified over southern Iraq, the Red Sea, and Turkmenistan, each exhibiting frequencies greater than 50% during Pattern 1 events. At 925 hPa, the maximum core over the Red Sea weakens relative to the other two cores; however, over southern Iraq and Turkmenistan, frontal frequencies still exceed 50%. At 850 hPa, the primary maximum shifts to central Saudi Arabia, where frontal occurrence reaches approximately 60%. For Pattern 2, the spatial configuration of frontal frequencies across the 1000–850 hPa levels is broadly similar to that of Pattern 1. However, the magnitude of frontal occurrence is generally lower. In particular, the maximum cores at 1000 and 925 hPa reach about 30%, indicating a weaker frontal signal compared with Pattern 1. In contrast to the first two patterns, Pattern 3 exhibits a distinctly different spatial organization of frontal activity during heavy precipitation events in Kurdistan Province. In this case, frontal structures are aligned along a northwest–southeast axis. At 1000 hPa, the principal maximum core is located over Kurdistan Province, with a frontal occurrence frequency of approximately 55%. Additional maxima are observed over southeastern Iran, where frequencies reach up to 65%, commonly associated with warm-season and summer monsoonal precipitation. At 925 hPa, a similar spatial pattern persists over Kurdistan Province, although the maximum frequency decreases to about 40%. At 850 hPa, frontal occurrence further weakens to

approximately 25%; nevertheless, the primary core remains centered over northwestern Iran and Kurdistan Province.

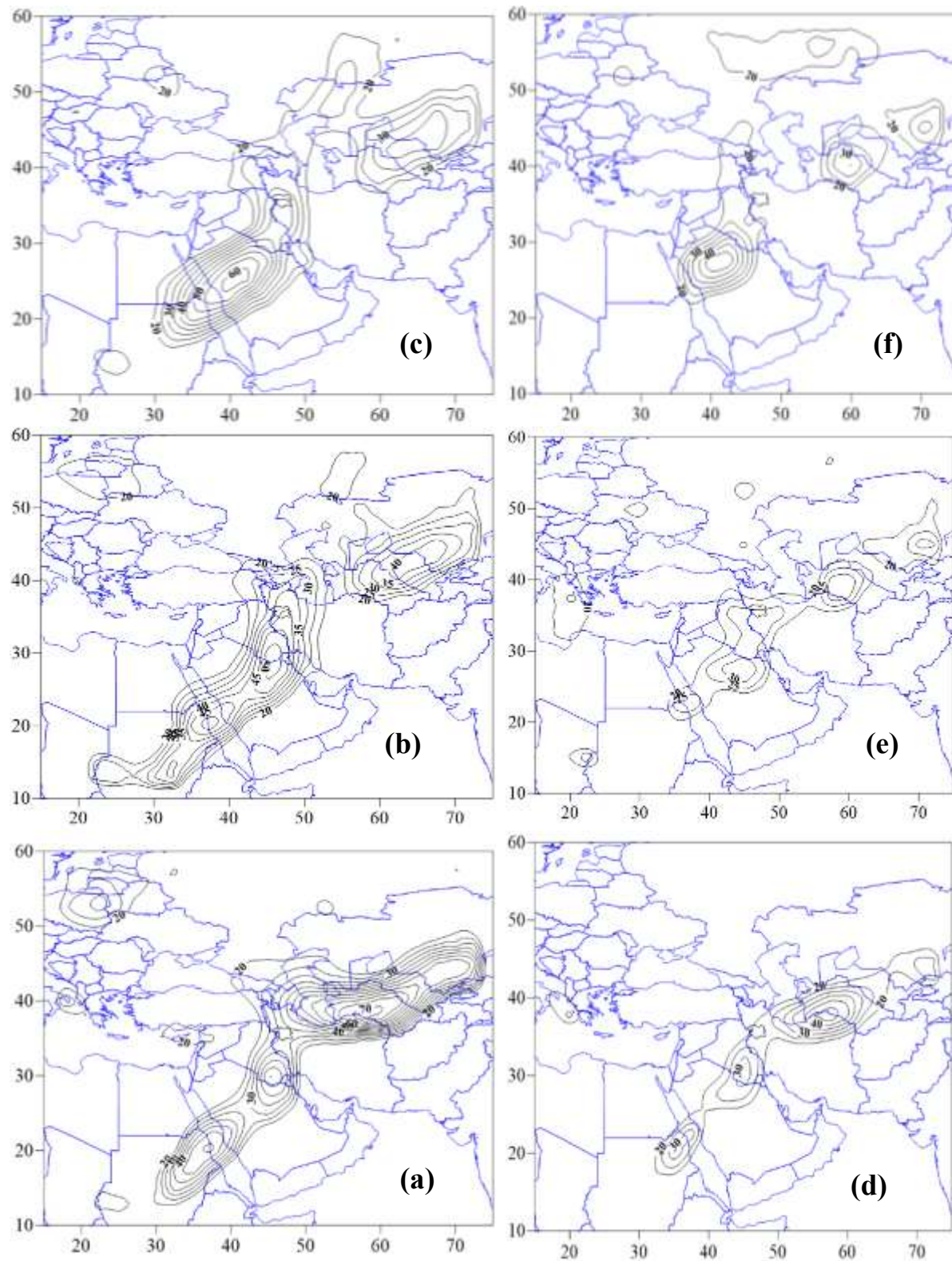


Figure 12. Frequency of front occurrence (%) during the occurrence of synoptic pattern 1 (1000 (a), 925 (b), and 850 (c) hPa) and pattern 2 (1000 (d), 925 (e), and 850 (f) hPa)

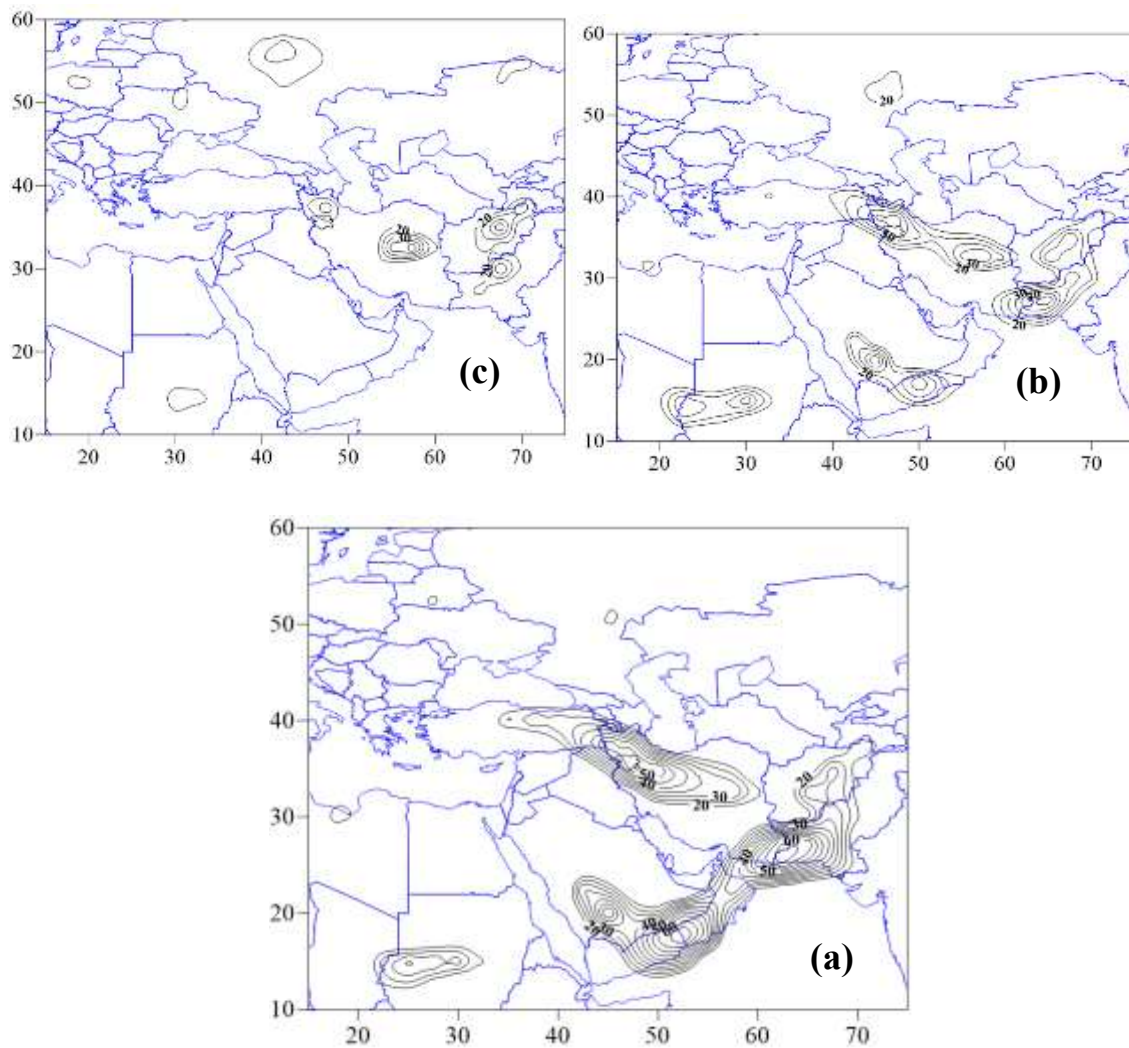


Figure 13. Frequency of front occurrence (%) during the occurrence of Synoptic Pattern 3 (1000 (a), 925 (b), and 850 (c) hPa).

Divergence and Convergence

To diagnose atmospheric instability during the occurrence of the different synoptic patterns, divergence (s^{-1}) was calculated at multiple pressure levels. Negative divergence values indicate convergence, whereas positive values represent divergence. The results show that, for all three patterns, divergence values are negative over Kurdistan Province and western Iran in the lower troposphere (from 1000 to 700 hPa), indicating pronounced low-level convergence. In contrast, at upper levels (500 and 400 hPa), divergence values become positive over the same region. The coexistence of low-level convergence and upper-level divergence promotes upward vertical motion and enhances atmospheric instability, thereby creating dynamically favorable conditions for the development of deep convection and the occurrence of heavy precipitation.

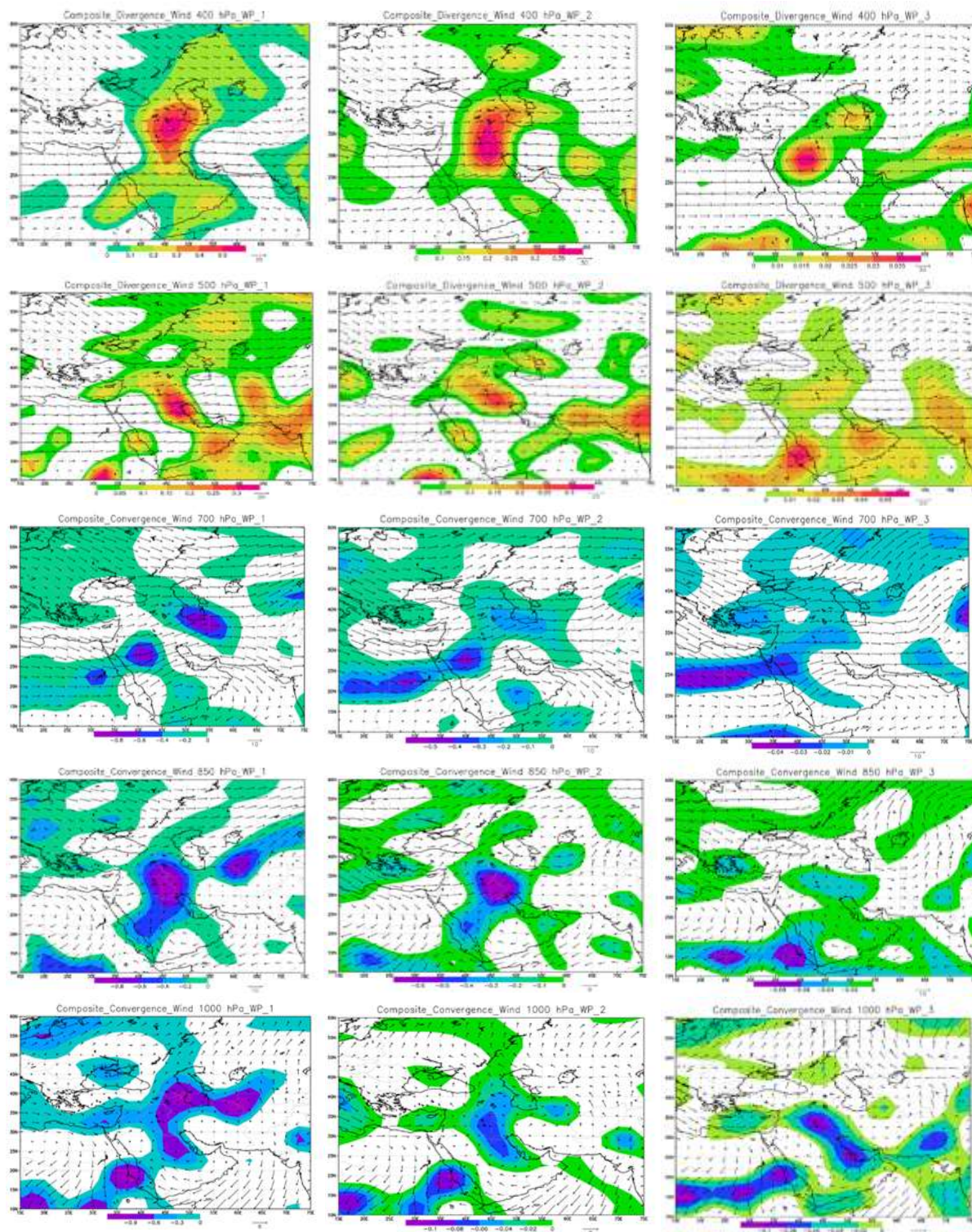


Figure 14. Atmospheric divergence (s^{-1}) at different pressure levels (1000-400 hPa) during the occurrence of Synoptic Patterns 1-3.

Conclusion

The results of this study indicate that heavy precipitation events in Kurdistan Province are associated with three distinct synoptic patterns. Seasonally, Pattern 1 predominates during the cold season, Pattern 2 occurs mainly in the transitional seasons (spring and autumn),

and Pattern 3 is characteristic of the warm season. The highest frequency of heavy precipitation events (44.8%) occurs during the cold season, while 27.1% and 28.1% of events are observed during the warm and transitional seasons, respectively. Under Pattern 1, the ridges of the Siberian and European thermal high-pressure systems extend southward to lower latitudes (reaching the Arabian Sea and the Gulf of Oman), while the Sudan thermal low penetrates northwestward toward Kurdistan Province and northwestern Iran. A pronounced negative sea-level pressure anomaly over western and northwestern Iran reflects the influence of the Sudan low. At 500 hPa, a strong negative geopotential height anomaly (approximately -100 gpm relative to the long-term mean) is centered over western Iraq, while a positive anomaly ($+60$ gpm) is located over eastern Iran. The positioning of Kurdistan Province along the eastern flank of the 500 hPa trough provides highly favorable conditions for atmospheric instability and heavy precipitation.

In Pattern 2, the Sudan thermal low similarly extends toward western Iran; however, its intensity and associated anomalies are substantially weaker than in Pattern 1. The southward extension of the Siberian high is also less pronounced, resulting in a weaker reinforcement of the cyclonic circulation linked to the Sudan low. In both patterns, the principal low-level moisture sources are the warm waters of the southern latitudes, including the Arabian Sea, the Red Sea, and the Persian Gulf.

Pattern 3 exhibits a fundamentally different synoptic mechanism. In this case, a high-pressure system over the northern Caspian Sea plays a dominant role in advecting cold air from higher latitudes toward Kurdistan Province. Concurrently, warm air transported northward by the Persian Gulf low converges over the region, leading to frontal formation, enhanced instability, and heavy warm-season precipitation.

Heavy precipitation events associated with Pattern 1 are, in most cases, accompanied by frontal systems. At 1000 hPa, three maxima of frontal occurrence are identified over southern Iraq, the Red Sea, and Turkmenistan, each exceeding 50%. At 925 hPa, frontal frequency remains above 50% over southern Iraq and Turkmenistan but decreases over the Red Sea. At 850 hPa, the primary maximum shifts to central Saudi Arabia, reaching 60%. In Pattern 2, frontal frequencies are generally lower, with maximum values of approximately 30% at 1000 and 925 hPa. In contrast, Pattern 3 displays a northwest–southeast alignment of frontal structures. At 1000 hPa, the maximum frontal occurrence (55%) is centered over Kurdistan Province; at 925 hPa, this maximum decreases to 40%, and at 850 hPa it further declines to 25%, while remaining focused over northwestern Iran. Dynamic analysis for all three patterns reveals a consistent vertical structure: during heavy precipitation events, a core of low-level convergence (1000–700 hPa) is situated over Kurdistan Province and western Iran, while at upper levels (500–400 hPa) a corresponding maximum of divergence is observed over the same region, providing favorable dynamical support for deep convection and intense rainfall.

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