



Evaluating the influence of Lake Jazmurian's extent on regional precipitation and associated atmospheric conditions using the WRF model

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Article Info	ABSTRACT
Article type: Research Article Article history: Received 2024/12/08 Received in revised 2025/04/19 Accepted 2025/05/14 Published 2025/05/15 Published online 2025/12/22 Keywords: Jazmurian Basin, precipitation variability, synoptic climatology, WRF model, lake extent.	Precipitation is one of the most complex and intermittent atmospheric processes, influenced by large-scale atmospheric circulation, weather-system characteristics, topography, land-atmosphere interactions, and moisture availability. This study evaluates the potential influence of changes in Lake Jazmurian extent on the spatial distribution and regional precipitation regime of its basin. Long-term precipitation records from 19 meteorological stations were analyzed using the Mann-Kendall test and Sen's slope estimator to characterize temporal variability and spatial differentiation in precipitation. The synoptic controls on precipitation were also assessed under representative wet- and dry-season conditions in February and July 2019, respectively. Three scenarios, namely NOW, NORMAL, and EXTEND, were simulated using the WRF model. Model performance was evaluated by comparing simulated and observed precipitation using Bias, RMSE, and MAE. The results revealed considerable spatial heterogeneity in precipitation trends across the basin, with no coherent and significant trend identified at the basin scale. Synoptic analysis indicated that winter precipitation is primarily associated with upper-level troughs, atmospheric ascent, and moisture transport from the Arabian Sea and Gulf of Oman. In summer, atmospheric conditions are generally dominated by the subtropical high-pressure system and associated subsidence, although limited monsoonal moisture occasionally affects the eastern part of the basin. The WRF model reproduced the timing and spatial distribution of major precipitation events with acceptable accuracy. Comparisons among the three lake-extent scenarios showed only minor changes in simulated precipitation. Precipitation anomalies generally remained within approximately $\pm 2 \text{ mm day}^{-1}$ in February and below $\pm 0.5 \text{ mm day}^{-1}$ in July. These anomalies exhibited fragmented spatial patterns, with no systematic increase in precipitation around the lake or along the prevailing wind direction. Overall, the findings indicate that changes in Lake Jazmurian extent have a negligible influence on regional precipitation under the simulated atmospheric conditions, which remains primarily controlled by large-scale atmospheric circulation and regional topographic conditions.

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1. Introduction

Previous studies demonstrated that inland lakes and wetlands influenced regional climate by modifying surface moisture availability, surface energy exchange, and boundary-layer processes. However, the magnitude and even the direction of these effects varied considerably among the geographical settings examined, depending on regional climatic conditions, lake characteristics, topography, and prevailing atmospheric circulation (Hostetler et al., 1993; Krinner, 2003; Laird et al., 2009; Thiery et al., 2015). For example, Dai et al. (2018) reported that Lake Nam Co enhanced downstream convective precipitation through increased evaporation and boundary-layer moisture, whereas He et al. (2021) showed that the desiccation of the Aral Sea exerted much stronger effects on temperature and surface energy fluxes than on precipitation. Similarly, Fazel et al. (2018) found that precipitation variability in the Lake Urmia Basin was governed primarily by regional topography and large-scale atmospheric circulation rather than by lake-induced processes. At a broader regional scale, Parker et al. (2019) demonstrated that long-term hydroclimatic variability in the Jazmurian Basin was closely associated with fluctuations in the Indian summer monsoon and the mid-latitude westerlies, while Dehghani et al. (2020) related precipitation variability across Iran to large-scale teleconnection patterns. Because of its ability to explicitly represent atmospheric dynamics and land-atmosphere interactions, the Weather Research and Forecasting (WRF) model has become one of the most widely used numerical models for investigating the climatic influences of inland water bodies (Skamarock et al., 2019). Previous studies showed that incorporating realistic lake characteristics into WRF improved the simulation of surface energy exchange, boundary-layer evolution, and regional atmospheric conditions (Gu et al., 2015; Rahimian et al., 2024). Nevertheless, accurately reproducing precipitation remains challenging in regions characterized by complex topography and heterogeneous land-surface conditions, where precipitation results from the interaction of large-scale atmospheric circulation and local physiographic controls (Solano-Farías et al., 2024). Therefore, integrating statistical trend analysis, synoptic analysis, and numerical atmospheric modeling provides a comprehensive framework for evaluating the respective influences of atmospheric circulation and Lake Jazmurian extent on regional precipitation variability.

Similarly, studies conducted in Iran demonstrated that precipitation was controlled primarily by large-scale atmospheric circulation, including Mediterranean troughs, the Sudan Low, upper-level troughs and disturbances, and moisture transport from the Persian Gulf, the Red Sea, and the Gulf of Oman, rather than by local land-surface processes (Alijani & Harman, 1985; Moradi, 2002; Mohammadi & Masoodian, 2010; Masoodian & Kaviani, 2013; Soltani et al., 2016; Roustaei et al., 2017). In addition, statistical analyses showed that precipitation trends across Iran were spatially heterogeneous and frequently lacked statistical significance despite widespread warming and increasing drought severity (Tabari et al., 2012). Other studies further emphasized the roles of sea-surface temperature, atmospheric instability, topography, climatic regionalization, and large-scale circulation patterns in shaping precipitation variability (Nouri et al., 2013; Razi, 2018; Ghaedi, 2021). Despite substantial progress in understanding precipitation variability over Iran, the relative importance of large-scale atmospheric circulation and changes in Lake Jazmurian extent in controlling regional precipitation remains unclear. Most previous studies focused either on precipitation variability, synoptic circulation characteristics, or numerical simulations, leaving the interactions among these contributing factors insufficiently evaluated for the Jazmurian Basin. To address this research gap, the

present study has combined statistical trend analysis, synoptic circulation analysis, and WRF simulations under three lake-extent scenarios: NOW, NORMAL, and EXTEND. This integrated approach has enabled the relative influences of atmospheric forcing and changes in lake extent on regional precipitation to be evaluated within a consistent analytical framework, thereby providing new insights into the hydroclimatic processes governing one of Iran's most environmentally sensitive closed basins.

2. Materials and Methods

The Jazmurian Basin is one of the largest endorheic drainage basins in southeastern Iran and extends across the provinces of Kerman and Sistan and Baluchestan. Owing to its distinctive geographical setting, the basin plays an important role in the region's hydrological and climatic systems. It lies approximately between 26°28'–29°30' N and 56°15'–61°23' E and covers an area of about 69,374 km². The basin is characterized by pronounced topographic heterogeneity, including high mountain ranges in its northern and western sectors, low-elevation central plains, and the Jazmurian wetland within the terminal depression. This complex terrain contributes to spatial variations in temperature, moisture, and precipitation across the basin. Climatically, the basin is influenced by Mediterranean disturbances and the Sudan Low during the cold season, whereas limited incursions of South Asian monsoon moisture may contribute to localized convective precipitation during the warm season. The interaction of these large-scale circulation systems with the basin's physiographic setting produces marked spatial and temporal differentiation in precipitation across the basin (Figure 1).

Analysis of precipitation records from the 19 selected stations across the Jazmurian Basin has indicated that the basin exhibits a predominantly winter precipitation regime. Most annual precipitation occurs between December and March, whereas the summer season is characterized by extremely dry conditions and negligible rainfall. The spatial distribution of precipitation has also revealed a distinct north-to-south gradient, with higher precipitation amounts recorded over the mountainous northern regions and progressively lower totals across the low-elevation southern plains. This spatial gradient highlights the combined influence of large-scale atmospheric circulation and regional physiography on the spatial and temporal variability of precipitation throughout the Jazmurian Basin. To characterize long-term precipitation variability, daily precipitation records from synoptic, climatological, rain-gauge, and evaporation stations located within and around the Jazmurian Basin have been used. Before the analysis, all datasets have undergone a comprehensive quality-control procedure, including the identification and removal of incomplete records, consistency checks, and homogeneity assessment of the time series. Only stations with sufficiently long and reliable observational records have been retained for subsequent analyses. The validated daily observations have then been aggregated into monthly and annual precipitation totals to establish the database used for trend assessment. Long-term precipitation trends have been evaluated using The non-parametric Mann–Kendall (MK) test, which is widely applied in hydroclimatological studies because it does not require normally distributed data and is relatively insensitive to outliers. The magnitude of the detected trends has been quantified using Sen's slope estimator, which provides an estimate of the annual rate of precipitation change over the study period. Statistical significance has been assessed at the 95% confidence level, and the results have been reported in terms of the Mann–Kendall test statistic, the corresponding p-value, and Sen's slope estimate.

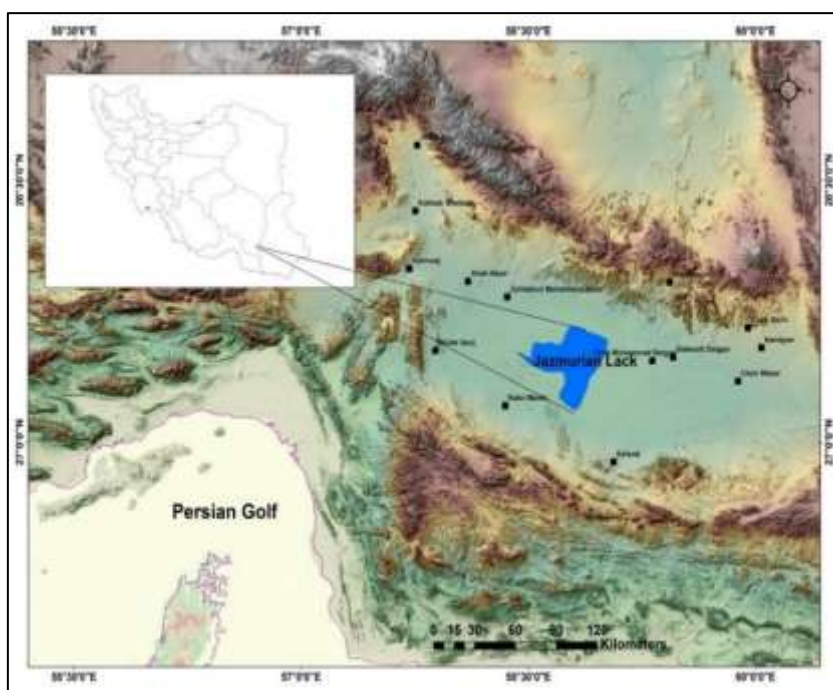


Figure 1. Topography of the study area, location, and type of the selected observation stations

To characterize the atmospheric conditions associated with precipitation over the basin, a synoptic assessment has been conducted for two representative periods: February, representing the cold season, and July, representing the warm season. These periods have been selected based on the spatial extent and intensity of precipitation during the simulation period to ensure that the dominant atmospheric conditions associated with the two distinct rainfall regimes are adequately represented. Atmospheric reanalysis datasets have been used to examine geopotential height fields, sea-level pressure, wind vectors, specific humidity, and pressure vertical velocity (ω) at multiple pressure levels. These variables have enabled the characterization of moisture-transport pathways, large-scale circulation patterns, and dynamical processes associated with precipitation development during the selected periods.

To assess the spatial sensitivity of regional precipitation to changes in the extent of Lake Jazmurian, numerical simulations have been performed using the Weather Research and Forecasting (WRF) model with the Advanced Research WRF (ARW) dynamical core, Version 4. Owing to its demonstrated capability to resolve mesoscale atmospheric processes and land-atmosphere interactions, WRF has become one of the most widely used regional atmospheric models. The simulations have employed three two-way nested domains with horizontal grid resolutions of 45, 15, and 5 km, respectively. The outer, intermediate, and innermost domains have consisted of 50×50 , 64×88 , and 70×106 grid cells, respectively, and the model domains have been centered at 27.40° N and 58.82° E. A time step of 225 s has been adopted, and each experiment has covered a 40-day simulation period. The first 10 days have been discarded as the spin-up period to minimize the influence of the initial conditions.

Three lake-extent scenarios have been designed to quantify the spatial precipitation response to changes in the surface extent of Lake Jazmurian. The first scenario, NOW, represents the current desiccated condition of the lake. The second scenario, NORMAL, approximates its historical

natural extent, whereas the third scenario, EXTEND, represents a hypothetical expansion of the lake to approximately twice its natural surface area. These scenarios have been implemented by modifying the relevant static geographical fields in WRF, specifically the LU_INDEX and LANDMASK variables. This procedure was designed to isolate the influence of lake-surface extent while maintaining identical atmospheric initial and boundary conditions across all simulations.

Model performance has been evaluated by comparing simulated and observed precipitation records at the selected meteorological stations. Three standard statistical metrics have been employed: Bias, Root Mean Square Error (RMSE), and Mean Absolute Error (MAE). Furthermore, to quantify the precipitation response to changes in lake extent, spatial differences in simulated precipitation have been calculated for the NOW-NORMAL and EXTEND-NORMAL scenario pairs. Difference maps have subsequently been generated to identify the spatial distribution and magnitude of precipitation differences associated with changes in lake extent and to determine the areas exhibiting the greatest simulated sensitivity to variations in Lake Jazmurian extent.

3. Results

3.1 Temporal Trends of Precipitation Based on the Mann–Kendall Test and Sen's Slope Estimator

The temporal evolution of precipitation across the Jazmurian Basin was evaluated using the non-parametric Mann–Kendall (MK) trend test together with Sen's slope estimator to identify long-term precipitation trends and to provide a statistical basis for subsequent synoptic and numerical analyses (Table 1). The results reveal pronounced spatial differentiation in precipitation trends across the basin, with no coherent basin-wide increasing or decreasing trend during the study period. At most stations, the Mann–Kendall test produced p-values greater than 0.05, indicating that no statistically significant monotonic precipitation trend was detected at the 95% confidence level. Accordingly, the observed interannual variability at most stations was not accompanied by a statistically significant long-term monotonic trend during the study period. The absence of statistically significant trends is particularly evident at stations such as Chah Shour, Jagard Khash, Qanat Marvan, Rahmanabad Irandegan, Daman, Chah Mohammad Delgan, and Kamal Golmoutori, where both Kendall's tau and Sen's slope remain close to zero. These stations exhibit no statistically significant monotonic precipitation trend during the observation period despite noticeable interannual variability. These results indicate that the observed year-to-year precipitation variability is not associated with a statistically significant long-term monotonic trend at these stations. In contrast, Ebrahimabad Dashtbard and Bidkardouyeh exhibit statistically significant positive precipitation trends ($p < 0.001$) and the highest positive Kendall's tau values among the analyzed stations. Sen's slope estimates of 4.20 and 6.90 mm year⁻¹, respectively, indicate statistically significant increasing trends in annual precipitation over the observation period. Among these, Bidkardouyeh exhibits the strongest positive precipitation trend among the analyzed stations. These localized trends may be associated with spatial differences in regional atmospheric circulation and physiographic conditions; however, the trend analysis alone cannot determine their underlying physical causes. Conversely, several stations, including Deh-Sard, Eslamabad-Kahnooj, Bolvard Sirjan, and Qaleh Askar, display negative Kendall's tau values and negative Sen's slopes, suggesting a tendency toward decreasing precipitation. However, because these trends are not statistically

significant, they cannot be interpreted as evidence of sustained drying conditions. Similarly, stations such as Rabor, Daman, and Rahmanabad Karvandar exhibit weak positive tendencies that also remain statistically insignificant. Overall, these findings indicate that both increasing and decreasing precipitation tendencies occur locally, while the basin as a whole lacks a consistent temporal trend. Spatially, significant positive trends are confined to limited parts of the basin, whereas most central, western, and southwestern stations show either negligible or statistically insignificant changes. This heterogeneous distribution indicates substantial spatial differentiation in precipitation trends across the basin, potentially reflecting differences in regional topography and atmospheric circulation. The absence of coherent spatial clustering indicates that the detected precipitation trends do not form a uniform basin-wide spatial pattern. Overall, the statistical analyses show that most stations exhibit no statistically significant monotonic precipitation trend during the study period, while significant increasing trends are confined to only a few locations. The predominance of statistically insignificant trends indicates that no systematic long-term monotonic change in precipitation can be identified across most of the basin during the study period. However, statistical trend analysis alone cannot identify the physical mechanisms responsible for the observed spatial differences because the Mann–Kendall test detects monotonic trends without explicitly accounting for the atmospheric processes associated with precipitation. Therefore, to provide a physical interpretation of the observed spatial differentiation, the following section investigates the synoptic circulation patterns associated with representative atmospheric conditions during the wet season (February) and dry season (July). This complementary synoptic analysis provides the physical context necessary for interpreting the statistical results and establishes the basis for evaluating precipitation responses to different Jazmurian Lake extent scenarios using the WRF model.

Table 1. Temporal trend analysis of precipitation at the selected monitoring stations using the Mann–Kendall test and Sen's slope estimator.

Station	Kendall's τ	p-value	Sen's Slope	Trend Classification
Chah Mohammad Delgan	-0.005	0.97	-0.07	No trend
Chah Kamal Golmoutouri	0.04	0.72	0.40	Non-significant increasing
Jagard Khash	0.01	0.92	0.15	No trend
Chah Shour	0.01	0.92	0.09	No trend
Daman	0.05	0.63	0.51	Non-significant increasing
Rahmanabad Karvandar	0.07	0.53	0.44	Non-significant increasing
Shamsabad	-0.005	0.97	-0.02	No trend
Rahmanabad Irandegan	0.009	0.95	0.07	No trend
Dadkan Khash	0.02	0.88	0.25	No trend
Rabor	0.06	0.61	1.25	Non-significant increasing
Oustor Sirjan	0.04	0.72	0.62	Non-significant increasing
Qaleh Askar	-0.05	0.67	-0.98	Non-significant decreasing
Qanat Marvan	0.01	0.90	0.32	No trend
Eslamabad Kahnootj	-0.11	0.32	-1.31	Non-significant decreasing

Ebrahimabad Dashtbard	0.38	<0.001	4.20	Significant increasing
Deh-Sard	-0.14	0.23	-2.20	Non-significant decreasing
Bidkardouyeh	0.41	<0.001	6.90	Significant increasing
Bolvard Sirjan	-0.08	0.47	-1.26	Non-significant decreasing

3.2 Synoptic Assessment of Representative Events

To complement the statistical trend analysis and provide a physical interpretation of precipitation variability across the Jazmurian Basin, representative synoptic events during February (wet season) and July (dry season) of 2019 were analyzed. The selected cases represent contrasting atmospheric conditions, including widespread winter precipitation, localized heavy rainfall, weak precipitation events, pronounced summer heating, and monsoon-related precipitation. These events were chosen based on the magnitude of observed precipitation, spatial differences among the Jiroft, Kahnooj, and Iranshahr stations, and their ability to represent the dominant atmospheric circulation patterns associated with regional precipitation. The synoptic analysis was conducted at regional and national scales using geopotential height, sea-level pressure, wind fields, moisture transport, and pressure vertical velocity (omega) to identify the large-scale and mesoscale atmospheric processes associated with precipitation development. This approach provides a spatially explicit physical context for interpreting observed precipitation variability and facilitates comparison with the WRF simulations under different Lake Jazmurian extent scenarios.

3.3 Synoptic Assessment of Selected February 2019 Precipitation Events over the Jazmurian Basin

To characterize the large-scale atmospheric controls associated with precipitation over southeastern Iran, three representative days (4, 12, and 20 February 2019) were selected for synoptic analysis at the regional and national scales. These dates were chosen based on precipitation intensity, spatial variability, and the contrasting dynamical characteristics of the associated weather systems. Specifically, 4 February represents a widespread winter precipitation event, 12 February corresponds to the most intense rainfall episode of the cold season, and 20 February illustrates a relatively weak transitional system. The analysis of geopotential height, moisture transport, wind fields, and omega provides insight into the synoptic conditions associated with precipitation events over the Jazmurian Basin. On 4 February 2019, the regional 500-hPa geopotential height field was characterized by a moderately deep trough extending from the eastern Mediterranean into western Asia, with its axis reaching southern Iran. Southeastern Iran was located ahead of the trough axis, within a region favorable for synoptic-scale ascent. At 850 hPa, southwesterly to southerly flow transported moisture from lower latitudes toward southern and southeastern Iran. Negative omega values indicated synoptic-scale upward motion and conditions favorable for cloud development. At the national scale, the trough extended across central and eastern Iran, placing southeastern Iran within an environment characterized by concurrent low-level moisture transport and synoptic-scale ascent. These atmospheric conditions were associated with widespread precipitation across much of the basin (Figure 2).

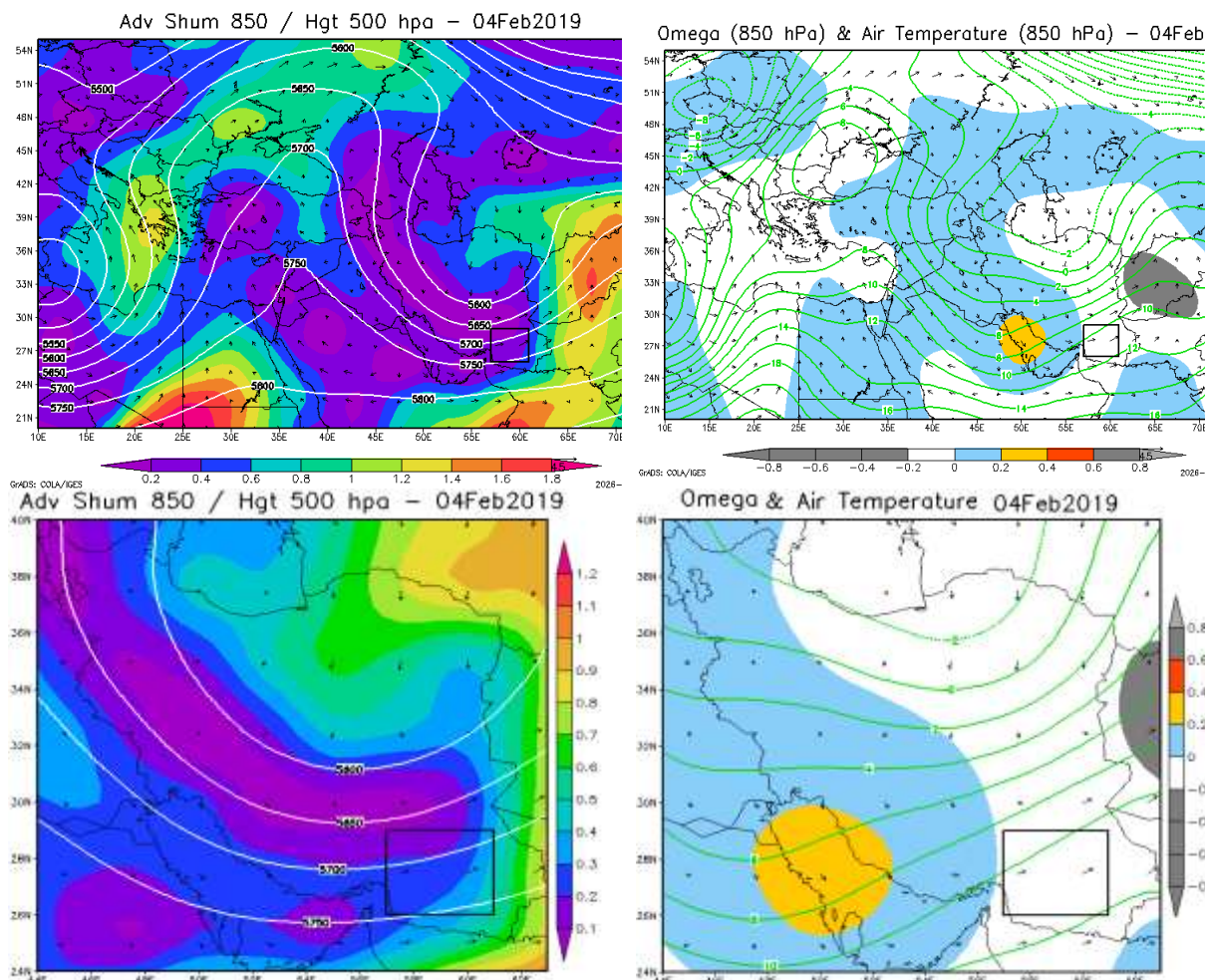


Figure 2. Regional- and Iran-scale synoptic fields on 4 February 2019, showing 850-hPa moisture transport, 500-hPa geopotential height, wind vectors, omega, and air temperature.

Among the selected events, 12 February 2019 represented the most intense precipitation episode. A deep 500-hPa trough developed over western Asia, positioning southern Iran ahead of the trough axis within a region favorable for enhanced synoptic-scale ascent. At the same time, strong southerly to southwesterly flow transported substantial moisture from the Arabian Sea and the Gulf of Oman toward southeastern Iran. Widespread negative omega values indicated strong synoptic-scale ascent and highly favorable conditions for heavy precipitation. At the national scale, strong low-level moisture transport was directed toward southeastern Iran, coinciding with enhanced synoptic-scale ascent over the region. Such synoptic configurations are characteristic of major winter precipitation events over the Jazmurian Basin (Figure 3).

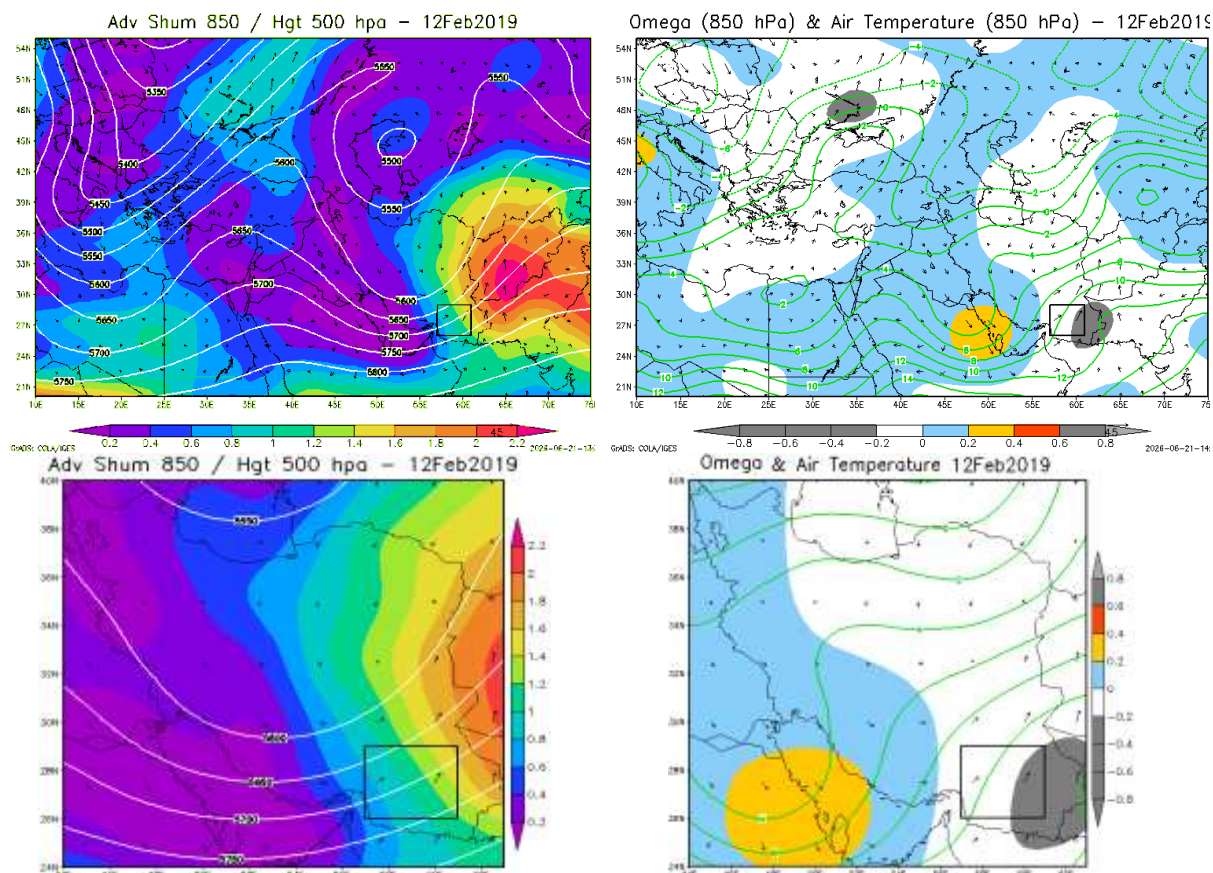


Figure 3. Regional- and Iran-scale synoptic fields on 12 February 2019: (left) moisture transport, 500-hPa geopotential height, and wind vectors; (right) omega (vertical velocity), air temperature, and wind vectors.

In contrast, 20 February 2019 represented the weakening phase of the synoptic disturbance. The mid-tropospheric trough shifted eastward and became less amplified, while low-level moisture transport weakened considerably over southern Iran. Wind speed decreased, and omega values indicated substantially weaker synoptic-scale ascent than during the previous events. At the national scale, weaker synoptic-scale ascent and reduced moisture transport were associated with substantially lower precipitation over southeastern Iran. Although light precipitation still occurred in some locations, the event was characterized by weak precipitation and limited spatial extent across the basin.

Overall, the comparison of the three representative February events indicates that winter precipitation over the Jazmurian Basin is closely associated with large-scale synoptic circulation, particularly Mediterranean troughs and related mid-latitude disturbances. Precipitation intensity appears to depend on the concurrent occurrence of synoptic-scale ascent, persistent moisture transport from the Arabian Sea and the Gulf of Oman, and favorable large-scale dynamical conditions. Among the analyzed events, 12 February provided the clearest example of these combined mechanisms, with strong moisture transport and pronounced synoptic-scale ascent producing favorable atmospheric conditions for widespread precipitation across the basin. These synoptic characteristics are consistent with the WRF simulations and

highlight the dominant role of large-scale atmospheric circulation in shaping precipitation variability over the Jazmurian Basin (Figure 4).

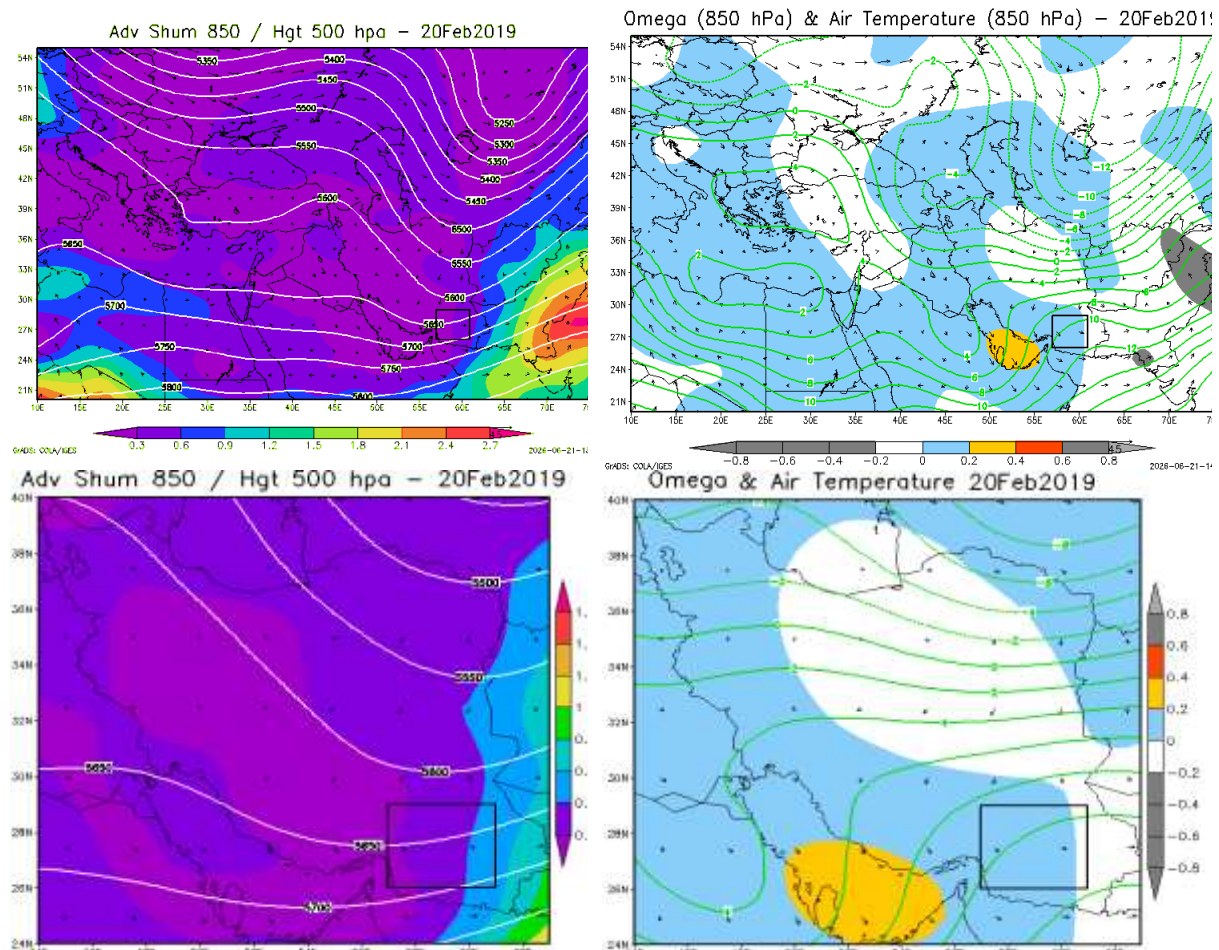


Figure 4. Moisture advection, geopotential height, and wind field (left panel), and omega, air temperature, and wind field (right panel) on 20 February 2019.

3.4. Synoptic Assessment of the Representative Days in July 2019

July 2019 was selected to represent the dry season and pronounced summer thermal conditions over the Jazmurian Basin. Unlike February, when Mediterranean disturbances and the Sudan Low are associated with widespread precipitation, July is generally characterized by the dominance of large-scale subsidence and limited moisture transport over southeastern Iran. During this period, the subtropical ridge extends across West Asia and is accompanied by widespread subsidence, which suppresses large-scale ascent and cloud development. Nevertheless, southeastern Iran can occasionally be affected by moisture associated with the South Asian summer monsoon. Accordingly, 5, 19, and 24 July 2019 were selected to represent contrasting summer atmospheric conditions. The 5 July event represents strong subtropical-ridge influence, 19 July corresponds to a temporary incursion of monsoonal moisture, and 24 July represents the subsequent weakening of moisture transport and re-establishment of predominantly dry conditions.

The analyzed meteorological fields indicate that 5 July 2019 represents a characteristic dry-season synoptic configuration over southeastern Iran. At the regional scale, the 500-hPa geopotential height field exhibits a strong subtropical ridge extending from North Africa and the Arabian Peninsula across Iran toward Pakistan and northern India. The pronounced ridge structure and relatively high geopotential heights indicate the strong influence of the subtropical circulation over the region and unfavorable conditions for the penetration of mid-latitude troughs into southern Iran. The omega field further supports this pattern, with widespread positive values over southern and southeastern Iran indicating large-scale subsidence. This descending motion suppresses cloud development and creates atmospheric conditions unfavorable for precipitation.

The 850-hPa moisture and wind fields indicate weak low-level moisture transport toward southeastern Iran. Low-level winds are predominantly southerly to southeasterly, while no substantial moisture transport from the Persian Gulf, Gulf of Oman, or Arabian Sea toward the interior of southeastern Iran is evident during this event. At the national scale, the 850-hPa temperature field shows high lower-tropospheric temperatures across Kerman, Sistan and Baluchestan, and Hormozgan provinces. The combination of strong subtropical-ridge influence, large-scale subsidence, weak moisture transport, and high lower-tropospheric temperatures produces atmospheric conditions unfavorable for cloud development and precipitation.

Overall, the synoptic configuration on 5 July 2019 illustrates the dominant dry-season circulation over southeastern Iran. The persistence of the subtropical ridge, together with strong subsidence and weak low-level moisture transport, is associated with suppressed precipitation across the region. This circulation pattern contrasts markedly with the winter regime, when Mediterranean troughs and enhanced moisture transport are associated with widespread precipitation over southeastern Iran (Figure 5).

Analysis of the synoptic charts for 19 July 2019 indicates that this day represents a notable summertime precipitation event over southeastern Iran. Despite the prevailing hot and dry summer conditions, rainfall over the eastern part of the region was associated with a temporary modification of the atmospheric circulation and an incursion of moisture related to the South Asian summer monsoon. At the regional scale, the 500-hPa geopotential height field shows that although the subtropical ridge remained dominant over the Arabian Peninsula, Iran, and southwestern Asia, it was weaker than during the earlier part of July. Meanwhile, a weak trough developed over eastern Iran and western Pakistan, favoring enhanced synoptic-scale ascent over southeastern Iran. In addition, the northward displacement of the ridge axis placed southeastern Iran near the transition between the subtropical ridge and the weak trough over eastern Iran and western Pakistan, creating more favorable conditions for localized convective development.

The 850-hPa moisture and wind fields further support this pattern. Southerly to southeasterly flow transported moisture from the Arabian Sea and the Gulf of Oman toward the Makran coast and eastern Iran, increasing low-level moisture availability over the region. This circulation pattern is consistent with the occasional extension of South Asian monsoon moisture into southeastern Iran during summer. Under favorable dynamical conditions, such moisture transport can contribute to localized precipitation over the region.

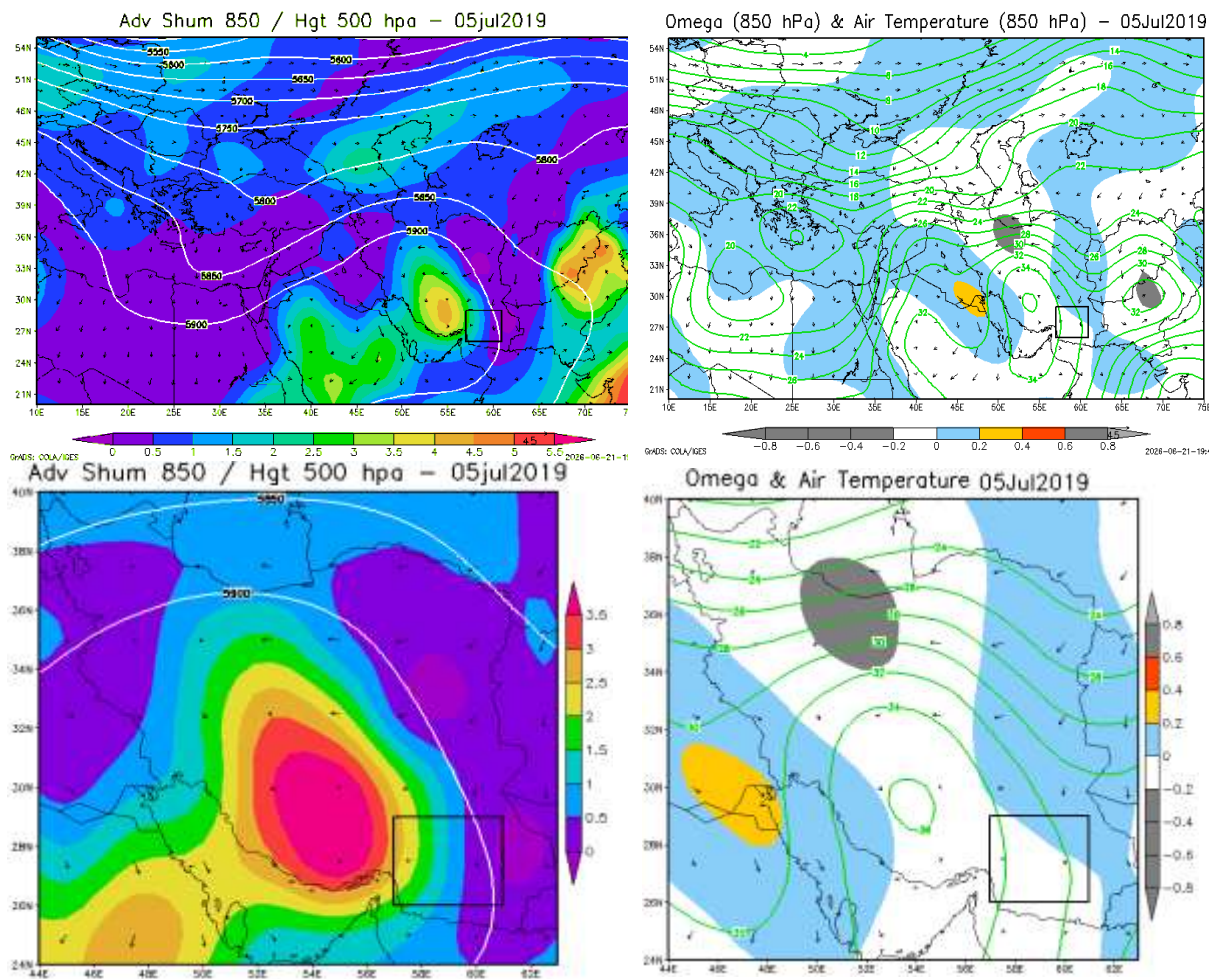


Figure 5. Moisture advection, geopotential height, and wind vectors (left panel), and omega, air temperature, and wind vectors (right panel) on 5 July 2019.

At the national scale, enhanced low-level moisture was evident over Sistan and Baluchestan Province and eastern Iran, whereas western parts of southeastern Iran remained comparatively drier. The omega field exhibited negative values over eastern Iran, indicating enhanced upward motion, while positive omega values persisted farther west, indicating continued subsidence. The spatial concurrence of enhanced low-level moisture transport and upward motion over eastern Iran provided favorable atmospheric conditions for localized precipitation on 19 July 2019 (Figure 6).

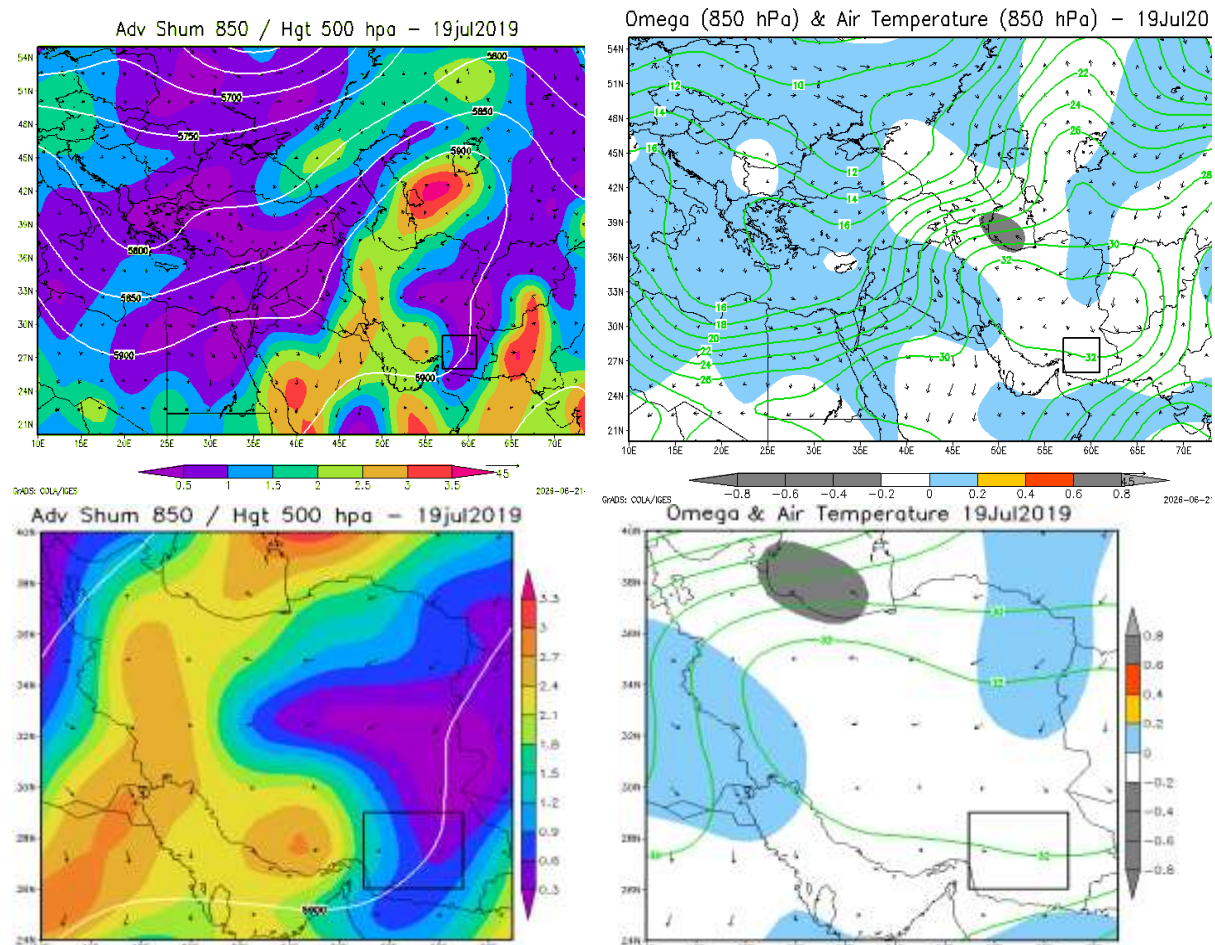


Figure 6. Moisture advection, 500 hPa geopotential height, and wind vectors (left panel), and 850 hPa omega, air temperature, and wind vectors (right panel) on 19 July 2019.

3.5 Synoptic Assessment of 24 July 2019

Analysis of the synoptic patterns on 24 July 2019 indicates that, following the enhanced moisture transport and precipitation conditions observed on 19 July, southeastern Iran returned toward the typical dry-season circulation regime. Although limited monsoonal moisture remained over the eastern parts of the region, the strengthening of the subtropical ridge and enhanced atmospheric subsidence reduced the potential for widespread cloud development and precipitation. Therefore, this day represents the weakening phase of the temporary monsoonal influence and the re-establishment of the dominant summer circulation pattern.

At the regional scale, the 500-hPa geopotential height field shows a strengthened subtropical ridge extending from the Arabian Peninsula across southern Iran into southwestern Asia. The increased geopotential heights indicate the persistence of the dominant subtropical circulation and unfavorable conditions for the development of widespread ascent. In contrast to 19 July, the weak trough previously located over eastern Iran shifted eastward toward Pakistan, reducing its influence on southeastern Iran. This synoptic configuration reflects the renewed dominance of the subtropical ridge over the region. The 850-hPa moisture and wind fields further support this

pattern. Although southerly and southeasterly winds originating from the Arabian Sea and the Gulf of Oman persisted, their intensity weakened compared with 19 July, resulting in reduced low-level moisture transport toward the interior of southeastern Iran. Consequently, moisture remained mainly concentrated near the Gulf of Oman coast and eastern Sistan and Baluchestan Province, with limited inland penetration. At the national scale, the omega field indicates weak upward motion confined mainly to the easternmost parts of southeastern Iran, whereas positive omega values associated with subsidence dominate much of southern and central Iran. This spatial distribution of vertical motion limited the development of widespread precipitation, with more favorable conditions restricted to localized areas. Meanwhile, the 850-hPa temperature field reveals persistently high lower-tropospheric temperatures across southern Iran, consistent with the influence of the strengthened subtropical ridge. Overall, the combination of enhanced subsidence, reduced moisture transport, and high lower-tropospheric temperatures maintained the prevailing dry conditions across the region (Figure 7).

3.6 Assessment of WRF Model Performance in Simulating Precipitation

Before assessing the influence of changes in Lake Jazmurian extent on regional precipitation patterns, the performance of the WRF model in reproducing precipitation events was evaluated. Daily observed and simulated precipitation time series from 14 meteorological stations, including synoptic, rain-gauge, and evaporation stations, were compared for February and July 2019 (Figure 8). In addition, three statistical performance metrics, including Bias, Mean Absolute Error (MAE), and Root Mean Square Error (RMSE), were employed to quantitatively evaluate model performance.

Comparison of the observed and simulated time series indicates that the WRF model successfully reproduced the timing of major precipitation events across most stations. Although differences in precipitation magnitude were evident on some days, the model generally captured the temporal evolution and occurrence of precipitation with satisfactory accuracy. This agreement was particularly pronounced during February, when precipitation was mainly associated with large-scale winter synoptic systems, suggesting that the model represented widespread precipitation events more effectively than localized convective precipitation events. The statistical assessment further supports these findings. During February, the mean bias was close to zero across all three simulation scenarios, indicating little systematic tendency toward overall overestimation or underestimation of precipitation. The mean RMSE ranged from 6.23 to 6.97 mm, while the mean MAE ranged from 2.26 to 2.41 mm, indicating differences between simulated and observed daily precipitation amounts during the month. In July, when precipitation was sparse and generally low, the absolute error metrics were substantially smaller, with mean RMSE values below 1 mm and mean bias values of approximately 0.1 mm. These lower error values should be interpreted in the context of the limited precipitation amounts and frequency during the dry season rather than as direct evidence of superior model performance. Furthermore, only minor differences in the statistical performance metrics were observed among the three lake-extent scenarios, indicating that changes in lake extent produced little variation in the overall precipitation simulation performance during the analyzed periods (Table 2).

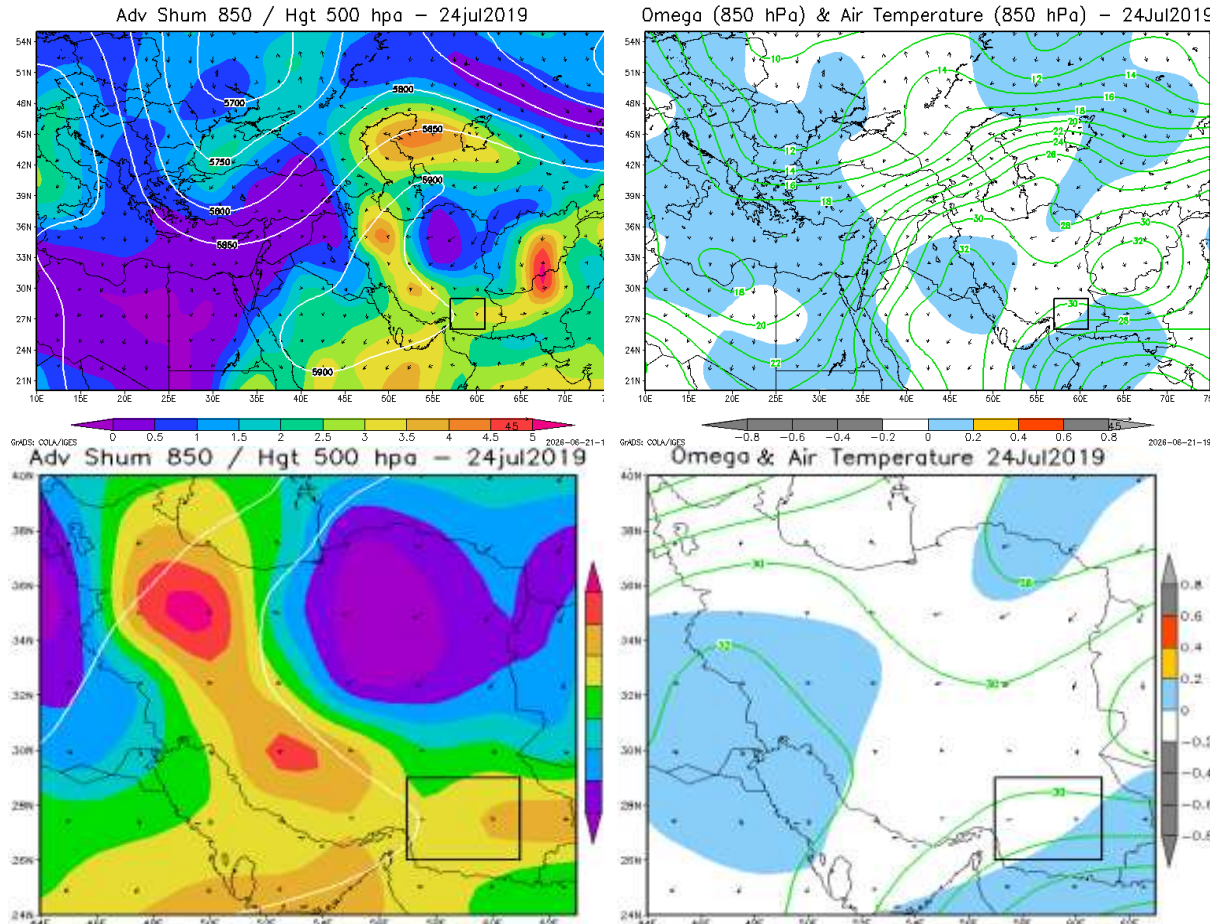


Figure 7. Moisture Advection, 500-hPa Geopotential Height, and Wind Field (left panel), and 850-hPa Omega, Air Temperature, and Wind Field (right panel) on 24 July 2019.

Table 2. Statistical evaluation of WRF model performance in precipitation simulation using Bias, RMSE, and MAE.

Month	Statistic	NOW	NORMAL	EXTEND	NOW	NORMAL	EXTEND	NOW	NORMAL	EXTEND
		Bias (mm)			RMSE (mm)			MAE (mm)		
February	Minimum	0.00	0.00	0.00	2.46	2.47	2.31	0.94	0.95	0.89
	Mean	0.00	0.00	0.00	6.23	6.97	6.73	2.26	2.41	2.40
	Maximum	0.00	0.01	0.01	11.72	15.13	14.06	3.96	4.22	4.10
July	Minimum	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00
	Mean	0.09	0.08	0.11	0.70	0.74	0.69	0.16	0.17	0.16
	Maximum	0.45	0.45	0.65	3.45	3.69	2.68	0.97	0.97	0.65

3.7. Spatial Response of Precipitation to Different Lake Jazmurian Extent Scenarios

To evaluate the sensitivity of regional precipitation to changes in the extent of Lake Jazmurian, precipitation differences between the EXTEND–NORMAL and NOW–NORMAL scenarios were calculated for February and July 2019 and presented as spatial difference maps (Figure 8). These maps provide a direct assessment of the simulated precipitation response to hypothetical lake expansion and contraction. During February, precipitation differences associated with changes in lake extent were generally confined to approximately $\pm 2 \text{ mm day}^{-1}$. Although both

positive and negative differences were detected, their spatial distribution was fragmented and lacked a coherent regional pattern. No systematic increase or decrease in precipitation was observed around the lake or in areas downwind of the lake. This lack of a consistent spatial response indicates that changes in lake extent did not produce a robust regional precipitation signal during the simulated February period.

In July, precipitation differences were even smaller, remaining below approximately ± 0.5 mm day⁻¹ across most of the study area. Similar to February, their spatial distribution was highly irregular and showed no coherent spatial pattern. The limited precipitation response coincided with the dominance of the subtropical ridge, widespread atmospheric subsidence, and weak large-scale ascent during the summer period. Under these synoptic conditions, changes in lake extent did not produce a systematic enhancement of precipitation over the basin. Overall, although the simulated precipitation differences were slightly larger in February than in July, neither lake expansion nor contraction produced a coherent spatial pattern or a substantial change in regional precipitation during the analyzed periods. These results, together with the synoptic analysis, suggest that precipitation variability over the Jazmurian Basin was more strongly associated with large-scale atmospheric circulation, moisture transport, and vertical motion than with changes in lake extent. Therefore, under the atmospheric conditions represented by the simulations, variations in Lake Jazmurian extent exerted only a limited influence on regional precipitation.

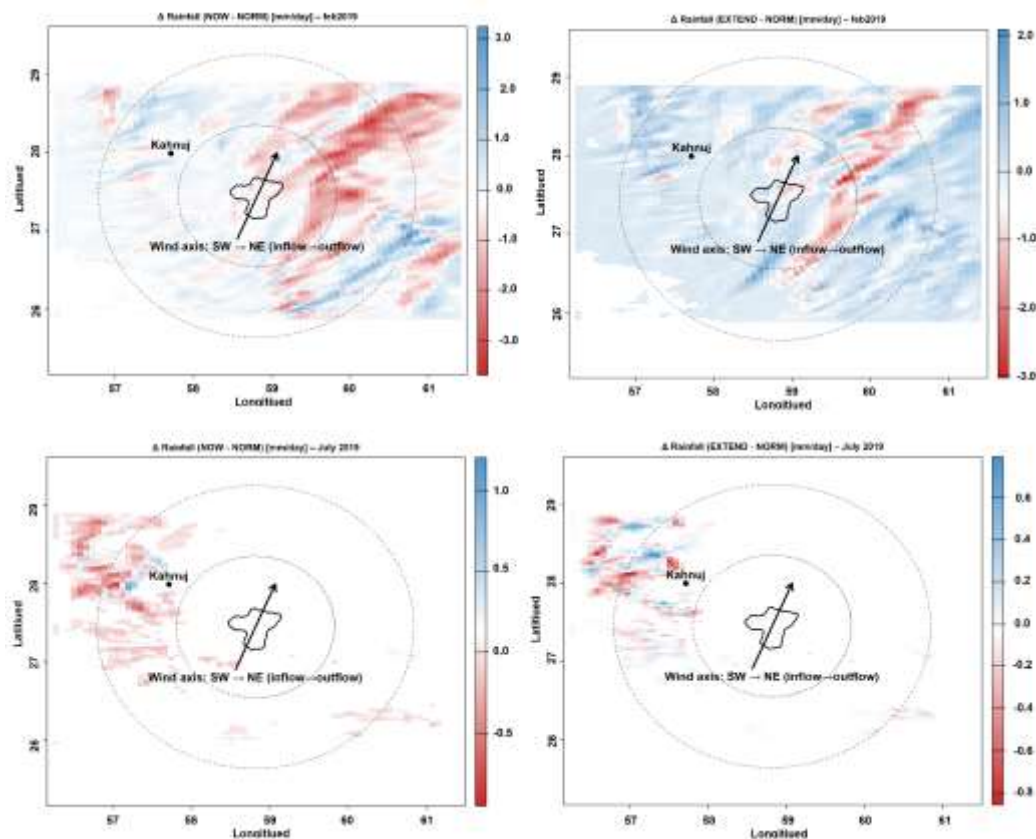


Figure 8.

Spatial distribution of precipitation differences between the EXTEND and NORMAL scenarios, and between the NOW and NORMAL scenarios, for February and July 2019.

4. Discussion

The present study adopted an integrated geographical approach combining long-term precipitation trend analysis, synoptic assessment of representative wet- and dry-season events, and numerical simulations using the WRF model to investigate the factors associated with precipitation variability in the Jazmurian Basin. Unlike most previous studies that have focused on individual components of the climate system, this study simultaneously evaluated statistical precipitation trends, atmospheric circulation characteristics, and the simulated precipitation response to different lake-extent scenarios. This integrated framework provides a basis for assessing the relative roles of large-scale atmospheric circulation and changes in lake extent in shaping the spatial variability of precipitation across the basin.

The statistical analyses revealed pronounced spatial heterogeneity in precipitation trends across the Jazmurian Basin, with no coherent basin-wide increasing or decreasing trend. Most observation stations exhibited statistically insignificant trends according to the Mann–Kendall test, indicating that no statistically significant long-term monotonic precipitation trend was detected across most of the basin during the study period. Only two stations, Ebrahimabad Dashtbard and Bidkardouyeh, showed statistically significant increasing trends. These findings are consistent with previous investigations conducted in Iran, which reported considerable spatial variability in precipitation trends and a predominance of statistically insignificant changes across arid and semi-arid regions (Tabari et al., 2012; Modarres & Ouarda, 2014; Rahimzadeh et al., 2020). Ghaedi (2021) similarly emphasized the important role of large-scale atmospheric circulation anomalies in precipitation variability across Iran. Therefore, the heterogeneous precipitation trends observed within the Jazmurian Basin may reflect spatial differences in regional topography and temporal variability in atmospheric circulation; however, the statistical trend analysis alone cannot determine the physical causes of the observed spatial differences.

The synoptic analyses provide a physical context for interpreting precipitation variability during the selected events. During February 2019, precipitation events were associated with Mediterranean troughs, enhanced moisture transport from the Arabian Sea and the Gulf of Oman, and synoptic-scale ascent indicated by negative omega values. Among the analyzed events, 12 February represented the most favorable atmospheric configuration, characterized by a deep upper-level trough, strong low-level moisture transport, and pronounced synoptic-scale ascent. These conditions were associated with widespread precipitation over southeastern Iran and the Jazmurian Basin. In contrast, 4 February represented a moderate synoptic event with more spatially widespread but less intense precipitation, whereas 20 February reflected a weakening synoptic disturbance accompanied by reduced moisture transport and weaker upward motion.

These results are consistent with previous synoptic climatology studies conducted over Iran. Alijani and Harman (1985), Mohammadi and Masoodian (2010), Masoodian and Kaviani (2013), Roustaei et al. (2017), and Soltani et al. (2016) emphasized the importance of Mediterranean troughs, the Sudan Low, upper-level disturbances, and moisture transport from southern water bodies in producing winter precipitation over southern and southeastern Iran. The present results further indicate that precipitation over the Jazmurian Basin is closely associated with large-scale atmospheric circulation and regional moisture transport, whereas changes in lake extent appear to exert a comparatively limited influence during the analyzed periods.

In contrast, the synoptic conditions during July 2019 were dominated by the subtropical ridge over Southwest Asia. On 5 July, widespread positive omega values indicated strong large-scale subsidence, while low-level moisture transport remained weak and lower-tropospheric temperatures were high, producing conditions unfavorable for cloud development and precipitation. On 19 July, a temporary weakening and northward displacement of the subtropical ridge, together with a weak trough over eastern Iran and western Pakistan, enhanced upward motion and allowed South Asian monsoon moisture to penetrate into southeastern Iran, where localized precipitation occurred. By 24 July, the subtropical ridge strengthened again, subsidence became more widespread, and low-level moisture transport weakened, resulting in the re-establishment of predominantly dry conditions. These findings agree with Parker et al. (2019), who suggested that long-term hydroclimatic variability in the Jazmurian region reflects fluctuations in both the South Asian summer monsoon and the mid-latitude westerlies. Similarly, Dehghani et al. (2020) demonstrated that seasonal precipitation variability over Iran is strongly associated with large-scale circulation anomalies and teleconnection patterns.

Evaluation of the WRF simulations showed that the model reproduced the timing and temporal evolution of the major precipitation events reasonably well during February and July. During February, mean bias values were close to zero, while mean RMSE values ranged from 6.23 to 6.97 mm and mean MAE values ranged from 2.26 to 2.41 mm. During July, absolute error metrics were substantially smaller, largely reflecting the limited amount and frequency of precipitation during the dry season rather than necessarily indicating superior model performance. Only minor differences in the statistical performance metrics were observed among the NOW, NORMAL, and EXTEND scenarios, indicating that changes in lake extent produced little variation in overall precipitation simulation performance during the analyzed periods.

The precipitation sensitivity experiments further showed that changes in Lake Jazmurian extent produced only small and spatially fragmented differences in simulated precipitation. During February, precipitation differences generally remained within approximately $\pm 2 \text{ mm day}^{-1}$ and lacked a coherent spatial pattern. During July, the differences were even smaller, remaining below approximately $\pm 0.5 \text{ mm day}^{-1}$ across most of the study area, with similarly fragmented spatial distributions. No systematic increase or decrease in precipitation was detected around the lake or in areas downwind of the lake. These findings indicate that neither lake expansion nor contraction produced a robust spatially coherent precipitation signal under the atmospheric conditions represented in the simulations.

The limited precipitation response identified in this study is consistent with several previous investigations. He et al. (2021), studying the desiccation of the Aral Sea, reported that changes in lake extent exerted stronger effects on surface temperature, energy fluxes, and boundary-layer characteristics than on regional precipitation. Likewise, Fazel et al. (2018) concluded that precipitation patterns within the Lake Urmia Basin are influenced primarily by regional topography and synoptic atmospheric circulation, while the climatic influence of the lake itself remains comparatively limited. Rahimian et al. (2024) further demonstrated that lake-related effects may become more evident under particular synoptic situations and during extreme precipitation events. Taken together, these studies support the interpretation that, in arid endorheic basins, regional precipitation is strongly influenced by large-scale atmospheric circulation, while changes in lake-surface extent may exert a secondary influence.

Nevertheless, the present results differ from studies conducted over larger lakes in humid or high-elevation environments. Dai et al. (2018) found that Lake Nam Co on the Tibetan Plateau enhanced downstream convective precipitation through increased evaporation and boundary-layer moisture under favorable atmospheric conditions. These contrasting responses may reflect differences in climatic setting, lake size, atmospheric moisture availability, physiography, and prevailing circulation regimes. In the Jazmurian Basin, particularly during summer, widespread subsidence and weak large-scale ascent limit the atmospheric conditions favorable for precipitation development. Therefore, even if lake expansion increases local moisture availability, additional moisture alone may not be sufficient to produce a substantial precipitation response in the absence of favorable upward motion and large-scale dynamical conditions. This interpretation is consistent with Nouri et al. (2013), who emphasized that increased moisture availability alone does not necessarily lead to enhanced precipitation unless it coincides with atmospheric conditions favorable for ascent and precipitation development.

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