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Different Characteristics and Drivers of the Extraordinary Pakistan Rainfall in July and August 2022

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Abstract: The unprecedented and long-lasting abnormal monsoon rainfall attacked Pakistan in the summer of 2022, causing severe flooding. This study investigated the sub-seasonal characteristics and mechanisms of this distinctively extreme precipitation event. The historical rainfall in July and August and extreme precipitation mainly occurred in northern Pakistan. Both the monthly rainfall in July and August 2022 and the extreme precipitation during the summer were far exceeding the historical record and involved unique spatial distribution. The rainfall in July 2022 is nationwide and mainly located in northern Pakistan, while the rainfall in August and extreme precipitation occurred in southern Pakistan. Different physical processes are responsible for the precipitation in July and August 2022. In July, the South Asian high (SAH) and Iranian high extended eastward. Meanwhile, the anticyclonic circulation anomalies occurred in northwestern Pakistan and the easterly winds enhanced in the south side of the Tibetan Plateau (TP), which strengthened water vapor transporting from the Bay of Bengal and cooperated with the cyclonic system over the Arabian Sea to enhance the precipitation over Pakistan. In August, the SAH further extended eastward and the Western Pacific Subtropical High extended westward to the TP. Meanwhile, the European blocking (EB) developed, and a deep trough appeared over northwestern Pakistan. This weakened the easterly flow along southern TP but enhanced the southerly flow accompanying the cyclone over the Bay of Bengal and the Arabian Sea, and thus guided the water vapor transporting to southern Pakistan and enhanced the precipitation. The extreme precipitation in July was mainly attributed to the unusually strong Indian monsoon, while the extreme precipitation in August was the result of a combination of the Indian monsoon and EB. The study provided important information about extreme precipitation in Pakistan, which will help policymakers take measures to deal with the effects of flooding.

Keywords: extreme precipitation; sub-seasonal characteristics; Pakistan; Indian monsoon; European blocking

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1. Introduction

Precipitation variability plays a critical role in sustaining livelihoods and economic development by affecting hydrological systems and agriculture production [1,2]. However, precipitation variability presents multiple space-time scales and involves very complex causes, leading to difficulty to predict precipitation accurately and hinder disaster prevention and mitigation. In particular, extreme wet/dry events and the corresponding

composite extreme events (e.g., floods and droughts) are closely related to drastic precipitation variability, which pose threats to the environment and society [3], such as reducing agricultural yields [4]. Because of the great devastation caused by extreme events, precipitation variability has been widely concerned and studied.

As the China–Pakistan Economic Corridor plays an increasingly important role in the Belt and Road Initiative [5,6], precipitation variabilities in Pakistan have a serious impact on the economy and have gradually attracted wide attention. Pakistan locates in the northwestern corner of the Indian subcontinent and is a typically arid and semi-arid country with diversified climate conditions. The spatial distribution of precipitation in Pakistan exhibits high spatial and temporal variability, and thus natural disasters related to precipitation seriously affect agriculture and economic benefits. In particular, floods have been reported in Pakistan every year from 2001 to 2015 and have killed more than 5700 people [7]. For example, the historically severe flood in 2010, in which heavy rains started in July and continued through August in Pakistan and the western Himalayan foothills, caused the flooding of one-fifth of the country, resulting in severe damage to the infrastructure and the deaths of 1700 people [8,9]. Compared to previous floods mainly caused by extreme precipitation [10,11], the Pakistan floods of 2022 are even more unprecedented in terms of scale and impact. The record-breaking events killed 1325 people, leaving more than 33 million homeless and submerging roughly a third part of Pakistan's land area. The economic loss could cost as much as $30 billion in Pakistan [12]. Thus, the characteristics and related mechanisms of such abnormal persistent extreme precipitation in Pakistan deserve more attention.

For the climatology, the annual precipitation in most parts was less than 400 mm and the monsoon season (June to September) is Pakistan's main rainy season, which could contribute nearly 60% of the total rainfall [13]. The observed monsoon rainfall gradually reduces from the northeast to the southwest and rainfall is most intense in northern Pakistan, with a maximum amount of >8 mm day^{-1} [14]. The precipitation increases over high latitudes and there are no significant trends over lower latitudes in Pakistan [13]. Bhatti, et al. [15] reported an increasing trend of extreme precipitation using different precipitation extreme indices over Pakistan. However, extreme precipitation in different regions exhibited distinct tendencies and the increasing trend of extreme precipitation is dominant in northeastern Pakistan, while the decreasing trend of extreme precipitation is generally observed in southwestern Pakistan [16,17].

Pakistan experiences an arid-to-humid climate with the most rainfall in summer due to monsoon phenomena and in winter due to western disturbances such as extratropical storms from the Mediterranean Sea [18]. Previous studies on precipitation in Pakistan have suggested that extratropical and monsoonal forcing factors could serve as the key factors [19], and considerable changes in extreme precipitation in Pakistan are influenced by more unstable monsoons [20]. Many factors, such as the Pacific Decadal Oscillation [21], Southern Oscillation [22], TP soil moisture [23] and high sea surface temperatures (SST) over the Indian Ocean [24], can affect monsoon precipitation variability. For extreme precipitation over Pakistan, a combined action of a mid-tropospheric trough bringing relatively dry and cold air from the mid-latitudes and the moisture advection from the Arabian Sea and the Bay of Bengal is the common circulation background. The statistically increasing trend of rainfall extremes in north Pakistan is because of the increase in water transported northward from the Arabian Sea and the Bay of Bengal in the context of climate change [25]. The extreme precipitation events in northern Pakistan could be attributed to the extratropical upper-level breaking waves [19] and the interaction between active monsoon flow and mid-latitude westerly trough [26]. In addition, atmospheric rivers can also influence extreme precipitation in Pakistan [27].

The extreme precipitation in Pakistan from mid-June 2022 lasted a very long time and occured throughout the country, particularly in south Pakistan [28]. Usually, floods occur primarily in northern Pakistan, whereas droughts are prevalent in the southern region [13]. Therefore, the extreme precipitation in 2022 differs greatly from previous heavy events.

Research has suggested that the occurrences of extreme flooding in Pakistan in 2022 could be attributed to the anomalous easterly flow over the subtropical TP [29], atmospheric rivers [27] and the impact of central and eastern China's extreme heat through mid-latitude teleconnections [30]. The long-lasting heavy precipitation also had significant sub-seasonal variability and it was urgent to study the causes of related events and improve the ability of sub-seasonal forecasting to reduce the losses caused by disasters [31,32]. However, related studies about extreme precipitation in Pakistan mostly focus on the weather scale or the seasonal scale.

The intra-seasonal evolution of extreme precipitation is often accompanied by changes in atmospheric circulation. For example, for the super-long record-breaking Meiyu in the Yangtze River Basin in 2020, the warm front-related rainfall from 11 to 25 June is caused by the interaction between the South Asia high (SAH) and the Western Pacific subtropical high (with the positive North Atlantic Oscillation (NAO)), but the cold front-related rainfall during 30 June to 13 July mainly attributed to the coupling of SAH with Mid-latitude Mongolian Cyclone (the negative NAO) [33]. In addition, the 2022 heatwave in central and eastern China is due to a relatively weak anticyclonic anomaly caused by the anomalous non-adiabatic heating forcing in northwestern South Asia in July, while it is due to strong anticyclonic conditions derived from the extreme Silk Road Pattern (SRP) in August [30]. Therefore, a study on the intra-seasonal evolution of extreme precipitation and related circulation in Pakistan in 2022 is needed to understand the different mechanisms behind it more clearly.

This study attempts to study the sub-seasonal characteristics and main drivers of the unprecedented and long-persisting heavy rainfall in Pakistan in 2022. The scientific issues are as follows: (1) What are the extreme and special features of precipitation in the summer of 2022 in Pakistan? (2) What is the key atmospheric circulation anomaly responsible for extreme precipitation? (3) What is the underlying mechanism connecting the anomalous atmospheric circulation with the extreme precipitation, as seen from the impact of the Indian monsoon and the European blocking (EB)? Scientific answers to these scientific issues will give a complete picture of the impacts of atmospheric processes on summer precipitation in Pakistan and shed new light on mechanisms behind new spatiotemporal patterns of extreme events in Pakistan. The datasets and methods used are described briefly in Section 2. Section 3 presents characteristics and trend of precipitation, and further explain how the Indian monsoon and the EB with NAO affect Pakistan monsoon rainfall. Finally, Section 4 gives a summary and further discussion.

2. Data and Methods

In this study, the gridded gauge datasets of daily rainfall from the National Oceanic and Atmospheric Administration's Climate Prediction Center (CPC) are used to describe the characteristics of the precipitation climatology and the extreme precipitation in Pakistan. The gauge-calibrated Global Satellite Mapping of Precipitation (GSMaP_Guage) from the Global Precipitation Measurement (GPM), whose spatial and temporal resolutions are 0.1×0.1 and 1 h, is also used. This satellite precipitation product is developed by the Japan Aerospace Exploration Agency (https://sharaku.eorc.jaxa.jp/GSMaP_CLM/index.htm, accessed on 21 April 2023) and is calibrated with CPC gauge-based precipitation and is one of the most popular algorithms in the era of GPM. To investigate the intensity and duration of heavy extreme precipitation in 2022, we further adopt the maximum 1-day (Rx1day) and the maximum 30-day (Rx30day) precipitation provided by the World Meteorological Organization Expert Team on Climate Change Detection and Indices (ETCCDI; http://etccdi.pacificclimate.org/list_27_indices.shtml, accessed on 21 April 2023). The European Centre for Medium-Range Weather Forecasts reanalysis (ERA5) dataset covering the period 1979–2022 with a horizontal resolution of $0.25^\circ \times 0.25^\circ$ is used to investigate the synoptic patterns during July to August in 2022, and the related variables are temperature, u-component of wind, u-component of wind, geopotential height, total column water

vapor, the vertical integral of water vapor flux and divergence of the vertical integration of water vapor.

The Indian monsoon index (IMI) monsoon is defined as U_{850} (5°–15°N, 40°–80°E)–U_{850} (20°–30°N, 70°–90°E) [34]. It reflects the tropical westerly monsoon intensity as well as the lower-tropospheric vorticity anomalies associated with the Indian summer monsoon trough [35]. The Eurasian teleconnection SRP index is defined as the principle component of the leading mode (PC1) of 200-hPa meridional wind over the domain of 0°–150°E, 20°–60°N [36]. The NAO Index, defined as the difference in the normalized monthly sea level pressure (SLP) regionally zonal-averaged over the North Atlantic sector from 80°W to 30°E between 35°N and 65°N, is obtained from the National Oceanic and Atmospheric Administration (https://ftp.cpc.ncep.noaa.gov/cwlinks/norm.daily.nao.cdas.z500.19500101_current.csv, accessed on 21 April 2023). The wave activity flux (WAF) defined by Takaya and Nakamura [37] is used to study the propagation of the Rossby wave train. The formula used is as follows:

$$W = \frac{1}{2|\overline{U}|}\begin{pmatrix} \overline{u}\left(\psi_x'^2 - \psi'\psi_{xx}\right) + \overline{v}\left(\psi_x\psi_y' - \psi'\psi_{xy}\right) \\ \overline{u}\left(\psi_x'\psi_y' - \psi'\psi_{xy}'\right) + \overline{v}\left(\psi_y'^2 - \psi'\psi_{yy}'\right) \end{pmatrix}$$

where the overbar and prime indicate the climatological mean and anomaly, respectively; ψ denotes the stream function; $U = (u, v)$ denotes horizontal wind; and W represents the two-dimensional WAFs of the Rossby wave.

3. Results

3.1. General Characteristics of Rainfall in Pakistan

Figure 1a illustrates the spatial distribution of the annual precipitation trend for the period of 1979–2021. A significant increase in precipitation occurs in northern and southeastern Pakistan with a trend of 0.3 and 0.1 mm decade^{-1}, respectively. However, in southwestern Pakistan (i.e., Balochistan province), an indistinctive decrease in precipitation appears. Overall, the precipitation in Pakistan mainly occurs in spring and summer (Figure 1b). Therefore, the precipitation peaks in July and August, accounting for nearly 18% and 17% of the annual precipitation, respectively, which is contributed by the summer monsoon precipitation. The following peak precipitation is in March, which only accounts for almost 10% of the annual precipitation.

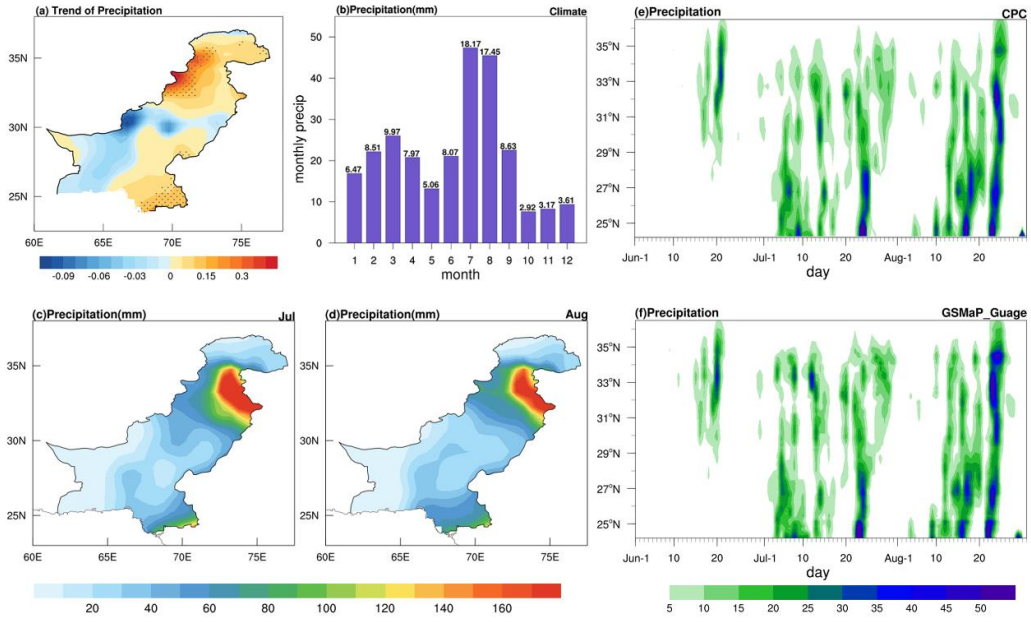

Figure 1. (**a**) Annual precipitation trend (mm decade^{-1}, shades) using CPC dataset during 1979–2021 and the dotted area is the region exceeding the 95% confidence level. (**b**) Monthly regional average

precipitation (bar chart) and its proportion (numbers, units: %) to the annual precipitation of Pakistan during 1991–2020. (**c**,**d**) Spatial distribution of monthly precipitation on (**c**) July and (**d**) August in Pakistan of 1991–2020. (**e**,**f**) Time–latitude distribution (mm day^{-1}, shades) of the precipitation in Pakistan in the summer of 2022 with (**e**) CPC and (**f**) GSMaP_Guage.

Further, the spatial distribution of precipitation in July and August in Pakistan is characterized in Figure 1c,d. Significantly, the rainfall gradually reduces from the northeast to the southwest, and the most intense of precipitation occurs in northern Pakistan (31°–35°N) with a maximum amount of 200 mm. The sub-center of monsoon rainfall locates in southeastern Pakistan (23°–25°N) with an amount of about 70 mm. However, in southwestern Pakistan, the rainfall amount is very small. This rainfall pattern is mainly induced by the westward transport of moisture flux along the Himalayas from the northern Bay of Bangle [38], in which more water vapor is accumulated in northern Pakistan than in southern Pakistan during the monsoon season due to the blocking effect of the surrounding terrain [39].

Figure 1e shows the time–latitude distribution of the precipitation in Pakistan in the summer of 2022. Pakistan suffers heavy precipitation from mid-June to August, and the precipitation process at the peak of the monsoon season (July and August) constituted the most significant abnormality (Figure 1e). Therefore, we mainly analyze the extreme rainfall in July and August. In addition, both the CPC and GSMaP_Guage consistently characterizes the temporal and spatial distribution of precipitation (Figure 1e,f). The spatial correlation coefficients of the two precipitation datasets in July and August both exceed 0.97 (above the 99% confidence level). As this, we mainly use the CPC data in the study due to it covers longer periods.

To investigate the characteristics of summer extreme rainfall in Pakistan, the climatology and trend of the maximum 1-day (Rx1day) and the maximum 30-day (Rx30day) precipitation are illustrated in Figure 2, respectively. Compared with monthly precipitation, the spatial patterns of the extreme precipitation with different duration are similar to that in July and August (Figure 2a,b vs. Figure 1c,d), in which the precipitation mainly occurs in the north (31°–35°N) and southeast of Pakistan. Similarly, the extreme rainfall also gradually reduces from the central and eastern parts to the southeast and northeast, with the largest rainfall amount in northern Pakistan. Moreover, the maximum Rx1day and Rx30day precipitation could reach 71.75 mm day^{-1} and 354.43 mm 30 days^{-1}, respectively. This strong rainfall could result in the increasing possibility of disastrous floods in northeastern Pakistan. The summer extreme precipitation in Pakistan shows annual variabilities during 1979–2022 (Figure 2c,d). The Rx1day precipitation reveals a significant increasing trend in the southern and central areas of Pakistan with a maximum value of 5.16 mm year^{-1}, but it is decreasing in north Pakistan (30°–35°N) with a maximum value of −4.50 mm year^{-1}. For the Rx30day precipitation, the trend is similar to that of the Rx1day precipitation, but the area with an increasing trend (maximum value: 4.55 mm year^{-1}) is much larger, indicating the increase in persistent extreme precipitation dominated the increase in precipitation in Pakistan.

3.2. Extremity and Particularity of the Precipitation in July and August 2022

Figure 3a,b show the spatial distribution of the monthly precipitation in July and August 2022. In July, the spatial pattern of precipitation is similar to that of the climatology, but the precipitation amount is much greater (Figure 3a). In particular, the extreme rainfall mainly occurring in northern Pakistan could produce a total amount of more than 500 mm. In addition, a sub-center of monsoon rainfall exists in southeastern Pakistan with a maximum total amount of 400 mm. However, the moisture source for this sub-center is from the northern Arabian Sea with a relatively much weaker intensity (more discussions can be found in Section 3.3), differing from that from the northern Bay of Bangle. In August, the spatial distribution of precipitation is obviously different from the climatology, in which

the precipitation primarily occurs in southeastern Pakistan with a maximum amount value of 500 mm. The source of water vapor is located over the northern Arabian Sea and the Bay of Bengal. The precipitation anomalies are mainly dominated by the positive anomalies in these two months in Pakistan. In July, there are two centers of positive precipitation anomalies (Figure 3c), where one locates in Islamabad (capital of Pakistan, 32°–34°N) and the other locates over the downstream Indus near the Arabian Sea. In August, the larger positive precipitation anomalies mainly occur over the lower Indus in southern Pakistan with a value of >500 mm. Further, the regional average precipitation anomalies in July and August are calculated (Figure 3e,f). The results show an increasing trend of precipitation, and the precipitation anomalies in 2022 can reach up to 5.04 mm day^{-1} and 4.94 mm day^{-1}, which both have broken the record since 1979.

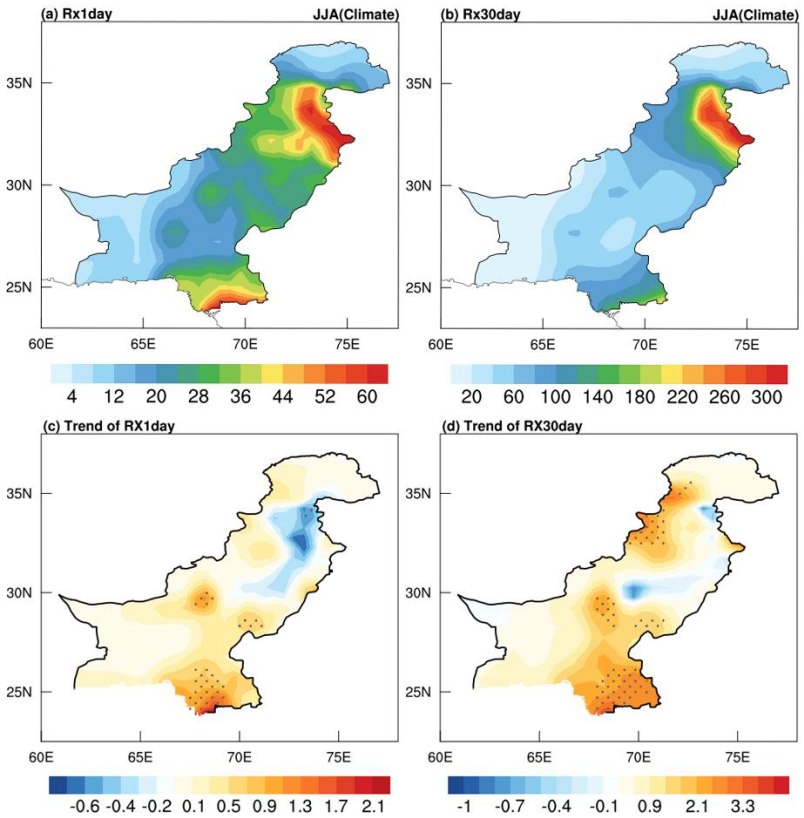

Figure 2. Spatial distribution of extreme precipitation with different durations during 1991–2020 in Pakistan. The maximum 1-day (Rx1day) (**a**) and the maximum 30-day (Rx30day) (**b**) precipitation during summer are used to represent the extreme precipitation. (**c**,**d**) Same as (**a**,**b**), but for the trend of Rx1day and Rx30day precipitation (mm year^{-1}, shades) in Pakistan during 1979–2022, and the dotted area is the region exceeding the 95% confidence level.

To characterize the extremity of precipitation in 2022, the maximum Rx1day and Rx30day precipitation are shown in Figure 4. Significantly, there are multiple centers with high values for the Rx1day precipitation, which is different from the climatology. Among them, the area with the most Rx1day precipitation (more than 150 mm day^{-1}) locates in southeastern Pakistan, followed by regions in the west-central and east-central borders of Pakistan (more than 120 mm day^{-1}). The Rx1day precipitation anomalies present positive anomalies in the same areas with a value of more than 100 mm day^{-1}. Differing from the Rx1day precipitation, the spatial distribution of Rx30day precipitation is similar to its climatology. In Figure 4b, the Rx30day precipitation in southeastern Pakistan (the sub-center of climatic precipitation) is apparently more than that in northeastern Pakistan (the main center of climatic precipitation), and the precipitation amount can reach 18.3 mm day^{-1} and 13.3 mm day^{-1}, respectively. For the anomalies of Rx30day precipitation, the

positive anomalies are mainly located in southeastern Pakistan with a maximum value of 18.3 mm day^{-1} (Figure 4d). These results indicate that both the short-term and long-term extreme precipitation in the summer of 2022 are widespread in Pakistan, especially in southeastern Pakistan, which is the immediate cause of the unprecedented flooding in Pakistan. Further, the interannual changes of the Rx1day and Rx30day precipitation in Pakistan are illustrated in Figure 4d,e. Both the Rx1day and Rx30day precipitation is gradually increasing in the last 40 years and the anomaly is the largest in 2022, which is up to 27.27 mm day^{-1} and 4.92 mm day^{-1}.

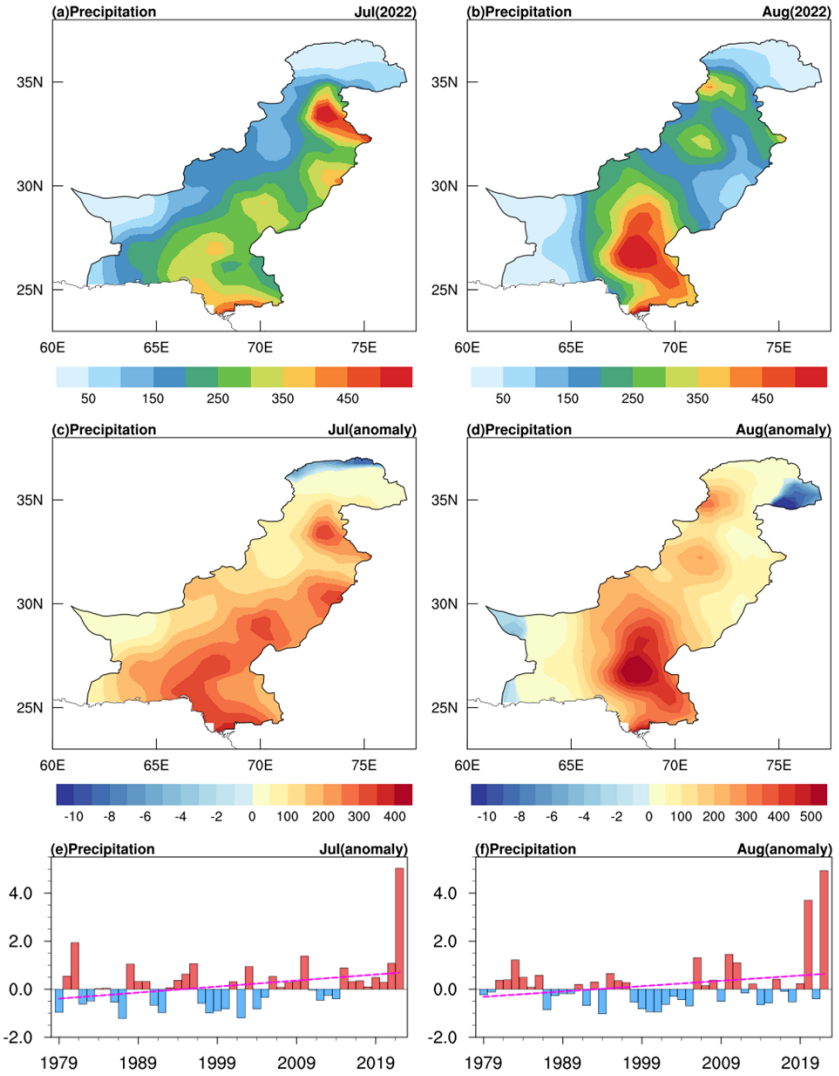

Figure 3. (**a**,**b**) Spatial distribution of the monthly precipitation in July and August 2022. (**c**,**d**) Same as (**a**,**b**), but for the monthly precipitation anomaly in July and August 2022. (**e**,**f**) Time series of the regional average precipitation anomaly (mm day^{-1}, bar) and the corresponding long-term trend (purple dotted line) in July and August in Pakistan.

Overall, the total precipitation and the Rx1day and Rx30day precipitation in Pakistan from July to August of 2022 are rated first in their histories. The accumulated rainfall, respectively, reaches 202.02 mm and 197.08 mm, which exceeds 311.42% (2.3 standard deviations) and 325.35% (2.3 standard deviations) of the local climatology. The Rx1day and Rx30day, respectively, reach 49.37 mm day^{-1} and 7.25 mm day^{-1}, exceeding 123.43% (3.5 times higher than the standard deviation) and 210.62% (4.3 times higher than the standard deviation) of the local climatology. This suggests that the precipitation during the peak monsoon season (July and August) in 2022 in Pakistan is extraordinarily extreme.

In addition, the spatial distribution of precipitation in July and August 2022 in Pakistan is unique and has obvious characteristics of intra-season transition. The precipitation in July is nationwide and mainly locates in northern Pakistan, while the large precipitation in August is concentrated in southern Pakistan, which is different from the climate spatial pattern that the precipitation mainly is in northern Pakistan. The Rx1day and Rx30day also mainly located in southeastern Pakistan. This indicates that the monsoon season in 2022 in Pakistan is distinctive and stands out among the several extreme precipitation events in history.

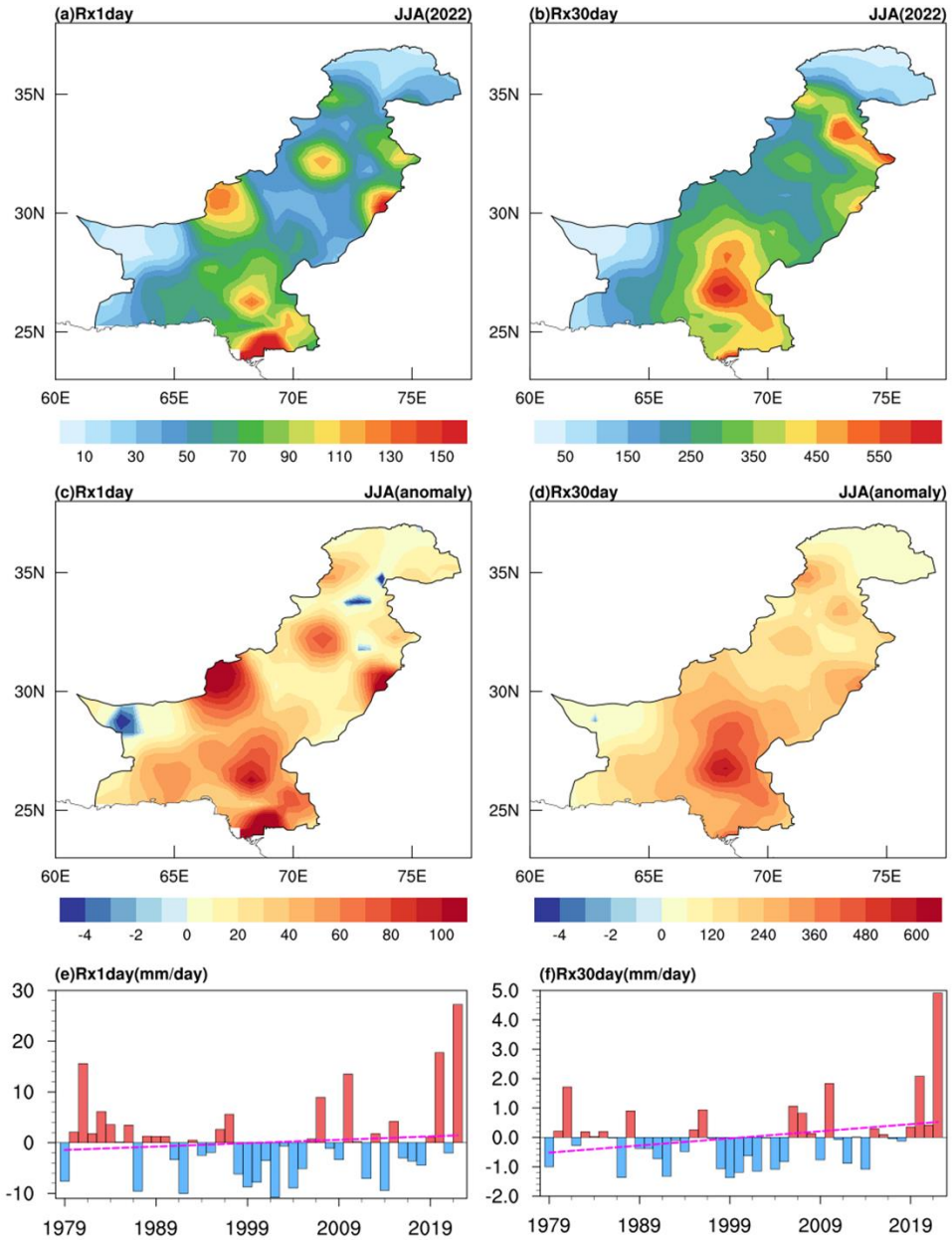

Figure 4. (**a**,**b**) Spatial distribution of the Rx1day and Rx30day precipitation in 2022. (**c**,**d**) Same as (**a**,**b**), but for the Rx1day and Rx30day precipitation anomaly in 2022. (**e**,**f**) Time series of the Rx1day and Rx30day precipitation anomaly (mm day^{-1}, bar) and the corresponding long-term trend (purple dotted line) during summer in Pakistan.

3.3. Favorable Large-Scale Atmospheric Circulations Associated with Extreme Precipitation in July and August 2022

Generally, atmospheric circulation anomalies can directly modulate the precipitation sub-seasonal variability. Therefore, the anomalies of large-scale atmospheric circulation are analyzed to understand the formation of 2022 extreme precipitation in Pakistan. Figure 5 demonstrates the anomalies of the tropospheric geopotential height and horizontal winds at different altitudes in July and August of 2022. In the upper troposphere, an anomalous anticyclone appears over Eastern Europe in July at high latitudes (Figure 5a). Meanwhile, an anomalous cyclone locates on the western side of the Lake of Baikal and an anomalous anticyclone locates over northeastern Asia. However, in August, the spatial pattern of circulation is characterized by a stronger anomalous anticyclone over Eastern Europe and a stronger anomalous cyclone over northern Asia (Figure 5b). The SAH presents a common feature of the eastward extension and northward lifting compared to its climatology in July and August, but with different intensities (much stronger in August) (Figure 5a,b), which enhances the divergence of the upper troposphere significantly and the convergence of the lower layer [40]. This circulation situation is very conducive to the occurrence and maintenance of precipitation.

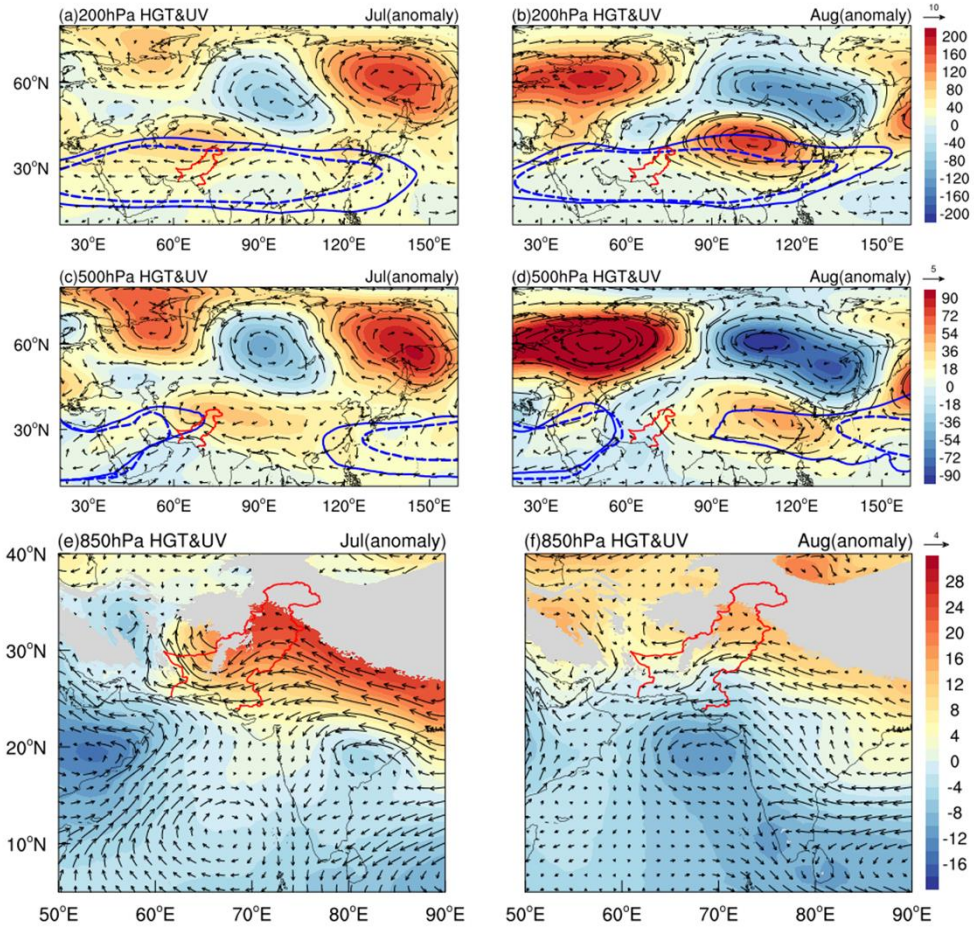

Figure 5. Spatial distribution of the horizontal wind anomalies (vectors; units: m s^{-1}) and geopotential height anomalies (shading; units: gpm) at (**a**,**b**) 200 hPa, (**c**,**d**) 500 hPa and (**e**,**f**) 850 hPa in July and August of 2022. Note that the blue solid (dashed) contour in (**a**,**b**) represents the 1250-gpm isopleth of the 200-hPa geopotential height in 2022 (climatology). The blue solid (dashed) contour in (**c**,**d**) represents the 5880-gpm isopleth of the 500-hPa geopotential height in 2022 (climatology). The grey shading in (**e**,**f**) delineates the topography higher than 1500 m. The climatology is based on the period 1981–2010.

In the middle troposphere, the spatial pattern of circulation at high latitudes is similar to that at 200 hPa, but the circulation anomaly is more intense. At mid-latitude, Pakistan is located on the central and the southern side of the anomalous anticyclone in July 2022 (Figure 5c). While the anomalous anticyclone covers China, Pakistan is located on the southwest side of the anomalous anticyclone in August of the same year (Figure 5d). Under the thermal heating action of the TP, the westerly wind jet on the north side of the SAH, the easterly jet on the south side of the SAH and the southwest monsoon are strengthened. Specifically, the deep trough of Eastern Europe extends southward along the western edge of the TP to Pakistan and the Northern Arabian Sea (Figure 5d). In July 2022, the Iranian high anomaly strengthens eastward and extended its eastern tip into Pakistan, facilitating the channeling of water vapor from the Bay of Bengal into Pakistan. At the same time, the western Pacific subtropical high (WPSH) extends to about 130°E (Figure 5c). Meanwhile, there is a low-pressure anomaly center in southern Pakistan. In August, the Iranian high retreats westward to the position of climatology, while the WPSH intensifies and shifts westward strongly to the west of the TP (Figure 5d) due to the synergistic effect of the anomalous Northwest Pacific anticyclonic and the eastward shift of the SAH in the upper troposphere [41]. In addition, a low-pressure anomaly center controls the northern Arabian Sea.

In the lower troposphere, a very strong easterly anomaly along the southern edge of the TP enters Pakistan and then changes to cyclonic circulation anomalies when collided with the lofty terrain in northwestern Pakistan and coordinated with the cyclonic circulation anomalies in the eastern part of the Arabian Peninsula in July (Figure 5e). In August, the abnormal easterly winds evidently weaken over the southern edge of the TP, and a monsoon low forms over the northern Arabian Sea (i.e., the southern side of Pakistan), resulting in unusually intense and widespread extreme precipitation over southern Pakistan (Figure 5f).

The abnormal summer wind and precipitation are often accompanied by abnormal monsoon water vapor transport. Figure 6a,b shows the anomalies of water vapor transport flux and the convergence and divergence from the ground to 100 hPa. In July, the water vapor from the Bay of Bengal reaches Pakistan with abnormal easterly winds along the southern edge of the TP and then divides into two branches. The northward reaches northern Pakistan and then forms precipitation. The southward one merges with moisture from the Arabian Sea which is related to the cyclonic anomalous circulation of the Arabian Peninsula and results in precipitation in southern Pakistan (Figure 6a). In August, the abnormal water vapor transport from the Bay of Bengal along the southern foot of the TP to Pakistan still exists, but the intensity is weaker. Water vapor from the Arabian Sea and the Bay of Bengal accompanies the cyclonic circulation over the northern Arabian Sea and transports to southern Pakistan (Figure 6b). The water vapor flux convergences over Pakistan and promotes the vertical transport of water vapor from the lower layer to the upper layer, improving the vertical upward motions of the atmosphere. This pattern, in which the divergence of water vapor flux in July and August was concentrated across Pakistan and in southern Pakistan, respectively, is very similar to the anomaly distribution of precipitation in Figure 4e,f, indicating that the extreme rainfall is accompanied by strong water vapor flux convergence.

Large-scale precipitation and convective precipitation may be associated with the outgoing longwave radiation (OLR) [42]. Generally, low OLR values correspond to strong convection, while high OLR values represent cloudless regions [43,44]. Figure 6c,d shows the OLR difference in July and August. In July, Pakistan showed unusually stronger convective activity over Pakistan (Figure 6c), but the intense convective activity in August is mainly located in southern Pakistan (Figure 6d).

In addition, the characteristics of the vertical profile circulation are presented to analyze the causes of abnormal extreme precipitation in Pakistan. Figure 7a,b shows the latitude-height section of meridional average zonal wind and vertical wind anomalies for July and August 2022. In July, the ascending motion areas are concentrated in the northern (about 33°–37°N) owing to the topography and southern (about 25°–30°N) parts

of Pakistan (Figure 7a). In addition, the very strong zonal easterly wind occurs above the 700 hPa (Figure 7b), which is conducive to the water vapor from the Bay of Bengal transporting along the Himalayan foothills to Pakistan. In August, the ascending motion area is concentrated in southern Pakistan (Figure 7c). Meanwhile, the southerly wind occurs in southern Pakistan, which would transport the water vapor from the Arabian Sea to Pakistan, while the easterly flow over Pakistan is weaker than that in July (Figure 7c,d), indicating less impact of the water vapor from the Bay of Bengal.

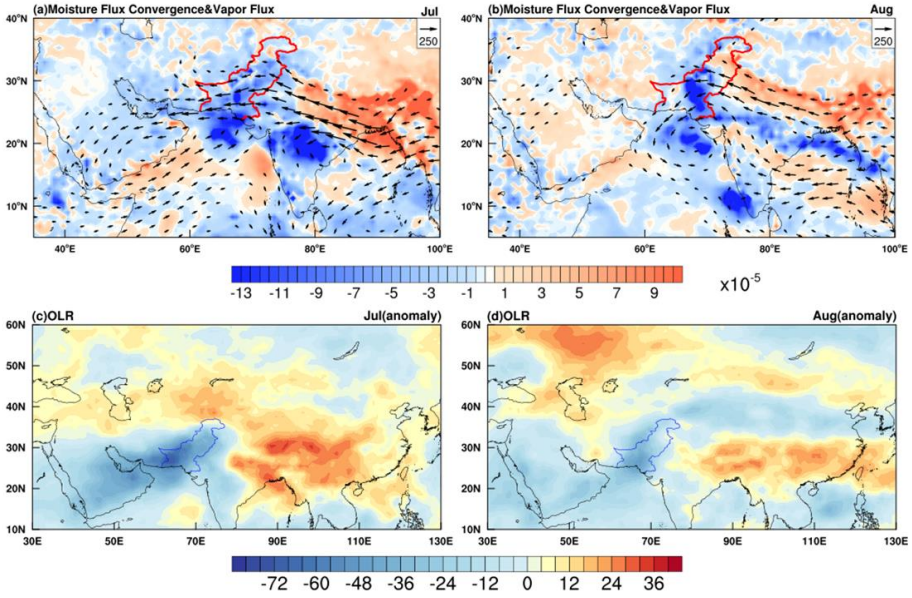

Figure 6. (**a**,**b**) Spatial distribution of the anomalies of the vertically integrated water vapor flux (from the ground to 100 hPa, vectors; units: kg $(m{\cdot}s)^{-1}$ and moisture flux convergence (shading, units: 10^{-5} kg $(m^2{\cdot}s{\cdot}hPa)^{-1}$) in (**a**) July and (**b**) August of 2022. (**c**,**d**) Same as (**a**,**b**), but for the anomalies of OLR in (**c**) July and (**d**) August of 2022. The climatology is based on the period 1981–2010.

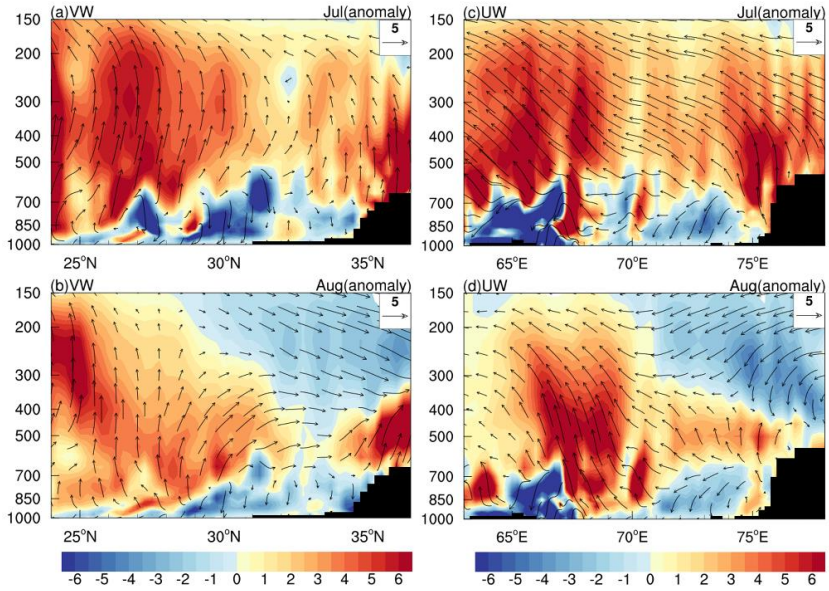

Figure 7. The latitude–height cross section of anomaly of the meridional vertical circulation averaged over Pakistan (vectors; units: m s^{-1} for the horizontal velocity and -10^{-2} hPa s^{-1} for the vertical velocity omega) and the vertical velocity (shading, -10^{-2} hPa s^{-1}) in (**a**) July and (**b**) August of 2022. (**c**,**d**) Same as (**a**,**b**), but for the zonal vertical circulation.

3.4. Possible Causes of the Anomalous Atmospheric Circulation in July and August 2022

The summer precipitation in Pakistan is strongly influenced by the Indian monsoon [45]. The correlation coefficients between the time series of daily precipitation in Pakistan and the IMI during 1979–2022 are 0.32 and 0.28 in July and August. Further, the time series of the standardized IMI indicates that the Indian monsoon in July and August 2022 are both stronger than the climatology (Figure 8a,b). The IMI in July is the highest since 1979 with a positive value of 3.5 and exceeds the climatology by two standard deviations. It ranks sixth in August with a positive value of 1.7.

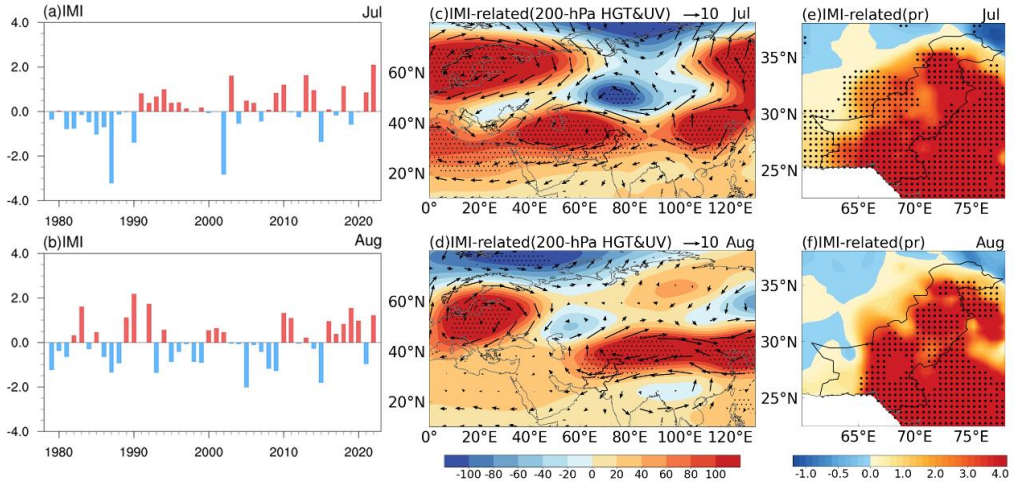

Figure 8. Time series of the standardized anomaly IMI in (**a**) July and (**b**) August in Pakistan. IMI-related components of 200-hPa geopotential height (shading; stippling for significant value above the 95% confidence level; units: gpm) and wind (vectors; units: m s^{-1}) in (**c**) July and (**d**) August 2022. IMI-related components of precipitation (shading; stippling for significant value above the 95% confidence level; units: mm day^{-1}) in (**e**) July and (**f**) August 2022.

Further, we calculate the regressed pattern of upper-level atmospheric circulation against the IMI in July and August of 1979–2022. Here, we define the IMI-related component as the product of the IMI index in 2022 and the linear regression coefficients at each grid point onto the IMI index during 1979–2022 to estimate the effect of the Indian monsoon on Pakistan's rainfall in 2022. The IMI-related components of 200-hPa geopotential height and wind shows that the Indian monsoon in July triggered anticyclonic anomalies in northwestern Pakistan (Figure 8c), which is more consistent with the raw anomalies presented in Figure 5a. The Indian monsoon in August induces a significant anticyclonic anomaly over Europe and western China and a cyclonic anomaly over northwestern Pakistan (Figure 8d), which is also corresponding well to the original anomalies in Figure 5b. In addition, there are significant abnormal easterly winds in the south side of the TP in these two months. Based on the linear regression equation (Figure 8e,f), the IMI anomaly in 2022 corresponds to a precipitation anomaly of about 125 mm and 121 mm in Pakistan in July and August, which accounts for about 80.0% and 79.1% of the observed anomaly of 156.1 mm and 153.1 mm, respectively. However, the observed precipitation in August mainly exists in southeastern Pakistan (Figure 3d), but the IMI-related precipitation in August is very heavy across the country, which is similar to that of July. Additionally, it should be noted that the IMI in August 2022 is not exceptionally strong to induce record-breaking rainfall. Therefore, it is reasonable to assume that there are other factors influencing Pakistan's extreme rainfall in August.

Moreover, the mid-latitude circulation has a potential influence on Indian monsoon precipitation [46,47]. The EB via the SRP teleconnection has a significant impact on extreme rainfall in Pakistan [48,49]. Downstream energy dispersion from the blocking region led to trough deepening over northwestern Pakistan and ridge building over the TP, thereby providing the linkage between the Russian heat wave and Pakistan flood events on the

large scale [47]. Lau and Kim [38] proposed that the Russian heatwave accompanied by atmospheric blocking over Europe-western Russia is closely associated with the 2010 extreme precipitation in Pakistan. The observations of circulation patterns (Figure 5b) in 2022 show an anticyclonic anomaly in Eurasia. Therefore, we speculate that in addition to the extreme IMI, other factors such as the EB may also play a role. To support our hypothesis, we further analyze the patterns of upper-level circulation and wave activity flux.

Consequently, a warm blocking high over Europe is observed, as evidenced by the height at 500 hPa and temperature anomalies at 850 hPa (Figure 9a,b). The blocking high in Europe in July and August 2022 resulted in unusually persistent dry and warm conditions. With the long-lived blocking high pressure, not only is the local weather affected but it also contacts the precipitation in Pakistan by the dynamics of extratropical atmospheric teleconnection pattern. Figure 9b shows that a very strong blocking high occurred in August in Europe and a cold-deep upper-level trough in the south of the anticyclone corresponding to the blocking high extends from western Asia to southern Pakistan in August, which is conducive to the development of the ascending region and convection [39]. This is similar to that in July 2010 [38]. The path of wave activity flux transport shows that there is a wave-like teleconnection pattern propagating zonally from Europe to northern Pakistan along the Asian jet stream in August (Figure 9d), as exhibited by the SRP-like pattern, which is a well-known teleconnection over the Eurasian continent in summer. The 200-hPa geopotential height averaged over Europe [50°–70°N, 0–40°E] presents a significant positive anomaly and is well correlated with precipitation in Pakistan in August (Figure 9e). Differently, the European geopotential height shows a negative anomaly on the whole (Figure 9e) in July, and there is no strong wave flux transporting from the high latitudes to Pakistan (Figure 9c). This indicates that the warm blocking high over Europe related to the severe heatwave may also play roles in the heavy precipitation in August in Pakistan.

According to the linked T-N flux, the wave energy originates in the North Atlantic westerly jet departure zone. Upstream disturbances can cause an anomalous high over Western Europe, which then causes a downstream wave to travel down the Asian jet (Figure 9d). Previous studies have revealed that the positive phase of NAO events is favorable for EB events to occur [50,51]. The NAO in August 2022 is observed as the third strongest since 1979 (https://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml, accessed on 21 April 2023). When the NAO enters its positive phase, the warm high of Europe gradually forms and positive precipitation anomalies occur in Pakistan [52,53].

To investigate how much of the blocking high contributes to precipitation in August, we analyze the SRP index and the SRP-related component of upper-level atmospheric circulation and precipitation. Negative SRP events existed in both July and August of 2022, but the SRP event is significantly stronger (the highest for the same period since 1979) in August (Figure 10a,b). Clearly, the SRP-related pattern of the 200-hPa geopotential height and wind exhibits a baroclinic structure over west-central Asia. In Figure 10d, the results clearly show that the SRP-related pattern is close to the raw anomalies presented in Figure 5b, indicating that the extreme SRP event contributes to the formation of the Eurasian teleconnection in August 2022. Nevertheless, it should be noted that the SRP-related pattern presents a cyclone and an anticyclone appeared zonally across the two sides of the TP in comparison (Figure 10d). The cyclone drastically amplified the lower-level cyclonic anomaly under the easterly vertical shear condition [54], favoring a stronger moisture convergence over Pakistan and allowing more moisture from the Arabian Sea to enter Pakistan, which is conducive to the generation of convective precipitation. The anticyclone favors the water vapor transport from the Bay of Bengal to Pakistan due to abnormal easterly winds on the south side of the TP and further enhancing the precipitation. The different contributions of negative SRP to the precipitation in the study area in July and August are also shown in Figure 10e,f. The contribution of negative SRP to the extreme precipitation in 2022 is mainly in southern Pakistan and the contribution is much larger in August. The linear regression of the SRP anomaly in 2022 corresponds to a

precipitation anomaly of 17.7 mm of about 153.1 mm in Pakistan in August, which accounts for about 11.6% of the observed anomaly and this value reaches 25.7% in southern Pakistan (23.75–29.25°N, 66.25°–71.25°E). This indicates that the historic extreme precipitation in the southern part of August 2022 is not only contributed to by the Indian monsoon but the downstream energy dispersion originating from the EB along the SRP is also involved. Therefore, the main influencing factor of the extreme precipitation in Pakistan in July and August 2022 is the Indian monsoon, but the precipitation in southern Pakistan in August is also affected by the blocking high.

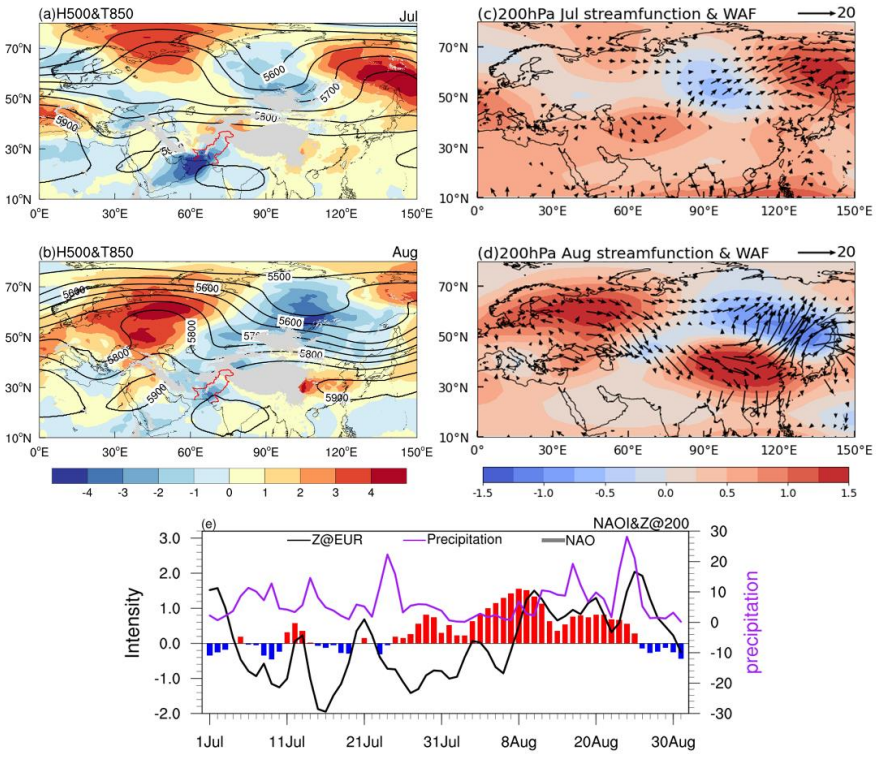

Figure 9. (**a**,**b**) 500-hPa geopotential height (interval 50 m) and 850 hPa temperature anomaly (shading, units: K) in July and August 2022. (**c**,**d**) 200 hPa stream function (shading, unit: $m^2\ s^{-1}$) and wave activity flux (unit: $m^2\ s^{-2}$). (**e**) Time series of sub-seasonal anomalies of the 200-hPa geopotential height averaged over Europe [50°–70°N, 0–40°E] (black line, gpm) and precipitation in Pakistan (purple line, mm day^{-1}) and the normalized daily NAO index (bars).

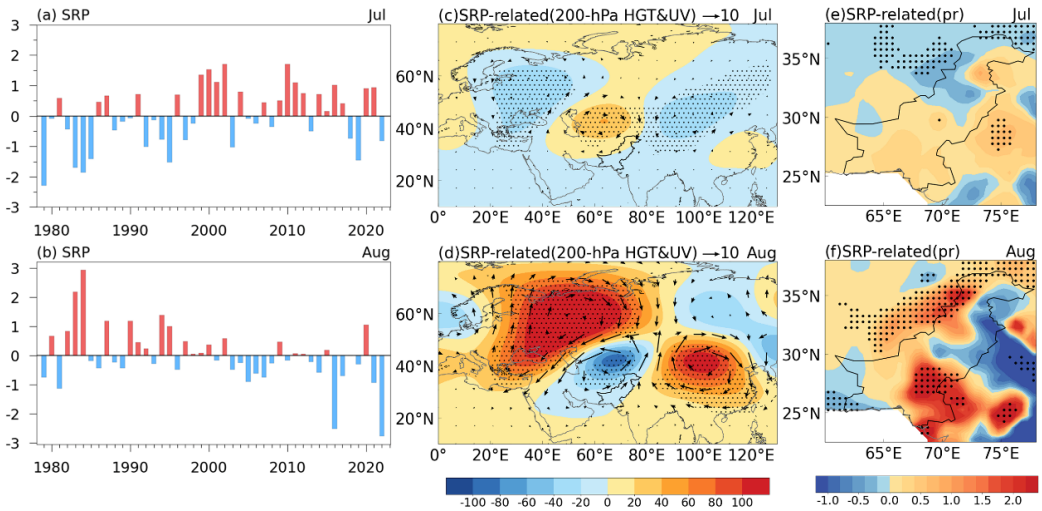

Figure 10. Time series of the SRP index in (**a**) July and (**b**) August. SRP-related components of 200-hPa geopotential height (shading; stippling for significant value above the 95% confidence level;

units: gpm) and wind (vectors; units: m s^{-1}) in (**c**) July and (**d**) August 2022. SRP-related components of precipitation (shading; stippling for significant value above the 95% confidence level; units: mm day^{-1}) in (**e**) July and (**f**) August 2022.

4. Conclusions

The unprecedented and long-lasting extreme precipitation attacked Pakistan in the summer of 2022. This study examines the sub-seasonal characteristics of precipitation in July and August and analyzed the atmospheric circulation and the role of the Indian monsoon and Europe blocking to understand the physical mechanism behind the special extreme precipitation event.

Generally, the arid climate dominates the whole region of Pakistan, and the main source of annual precipitation is the monsoon rainfall from July to August, accounting for ~35% of the annual rainfall. Historically, both the monthly rainfall in July and August mainly occurred in northern Pakistan, in which the Rx1day and Rx30day extreme precipitation presented an increased long-term trend. However, the spatial distribution of precipitation in July and August 2022 in Pakistan is unique. The rainfall in July 2022 is nationwide and mainly located in northern Pakistan, while the large precipitation in August is concentrated in southern Pakistan. The Rx1day and Rx30day extreme precipitation is mainly located in southeastern Pakistan. Meanwhile, both the rainfall in July and August 2022 and the extreme precipitation broke the record since 1979, exceeding 311% (July) and 325% (August) of the local climatology and 352% (433%) of Rx1day (Rx30day) rainfall climatology, respectively. This indicates that the rainfall in 2022 in Pakistan is especially distinctive and extreme.

Importantly, different physical processes are responsible for the formation of precipitation in July and August 2022. In July, the SAH extends to the east and an anticyclonic anomaly appears in northwest Pakistan (Figure 11a). The east extension of the middle Iranian high and the west extension of WPSH strengthen the easterly anomaly over TP, which guides and strengthens water vapor transport from the Bay of Bengal and cooperates with the cyclonic system over the Arabian Sea to enhance the precipitation over Pakistan. In August, the SAH continued to extend eastward and the WPSH further moves westward to the TP (Figure 11b). Meanwhile, the blocking situation over Europe develops and a deep trough appears over northwestern Pakistan. Influenced by the unusual atmospheric circulation, the easterly flow along the south side of the TP weakens and shifts southward, but the southerly flow is enhanced when it is accompanied by the cyclone over the Bay of Bengal and the Arabian Sea, which guides the water vapor transport to southern Pakistan and enhanced the precipitation.

The extreme Indian monsoon dominantly contributed to the 2022 anomalous precipitation in Pakistan. The Indian monsoon breaks the record since 1979 in July and ranked sixth in August, which triggers anticyclonic anomalies in northwestern Pakistan in July and induces a significant anticyclonic anomaly over Europe and a cyclonic anomaly over northwestern Pakistan in August. It enhances the abnormal easterly winds on the south side of the TP. Meanwhile, the SRP teleconnections over Eurasia induced by the extraordinarily powerful Europe blocking also play a role in precipitation. The SRP index in July is relatively low, which exerts a limited effect on the precipitation. However, an extreme SRP develops in August because of the rapidly intensified EB over Europe, which is conducive to the southeastward propagation of Rossby wave trains [38], thereby enhancing the precipitation by promoting and maintaining low pressure over Pakistan.

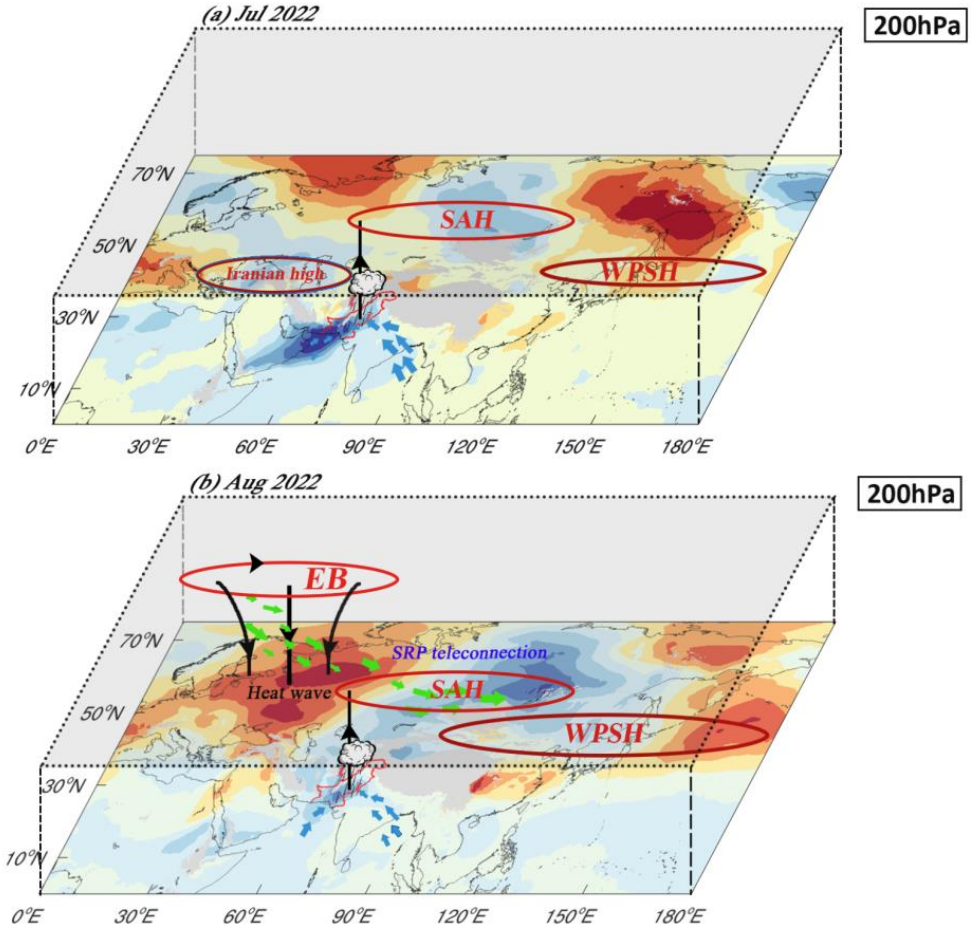

Figure 11. Schematic diagram illustrates the mechanism of the different circulation and influence mechanisms in Pakistan in (**a**) July and (**b**) August. The red curves indicate the European blocking, South Asian high, Western Pacific Subtropical High and Iranian High, respectively. The down (up) black arrows indicate descending (ascending) motion. The green and blue arrows represent the Silk Road Pattern (wave activity flux) and Indian monsoon (water vapor flux), respectively.

This study highlights that the long-lasting extreme precipitation in Pakistan in 2022 has unique spatial characteristics in July and August, which involved different physical mechanisms from the perspective of tropical–extratropical interaction. The Indian monsoon and Rossby wave activity originating from Europe blocking play an essential role in the occurrences of extreme rainfall events. However, the causes of the anomalous Indian monsoon and EB is still unclear. Previous studies recognized that the tropical Pacific SSTA is an important factor in anomalous atmospheric circulation [55,56]. As the third year of a rare triple La Niña, the cold SST anomaly in the Equatorial Eastern Pacific is developed in the summer of 2022. Meanwhile, the abnormally strong negative Indian Ocean Dipole modulates the rainfall by enhancing the northward propagation of the convective system across the Indian subcontinent [57]. The unusually positive NAO potential affects the EB over Europe. Further investigation adopting well-designed numerical experiments is needed to comprehensively explain the causes of the anomalous Indian monsoon and EB [58]. Global warming has increased the frequency and intensity of extreme precipitation and anthropogenic forcing intensified the similar heavy rainfall [59,60]. However, the attribution studies about the role of anthropogenic climate change on the extreme long-lasting rainfall in Pakistan have great challenges and uncertainties [61] and gained broad attention.

Author Contributions: Y.M. contributed to conceptualization, methodology and writing the original draft. X.H. performed the statistical analysis and visualization. Y.C., Z.H. and G.F. reviewed and edited the manuscript. T.F. contributed to conceptualization, investigation and supervision. Y.M. and G.F. performed the funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The CPC daily gridded precipitation data can be download from https://psl.noaa.gov/data/gridded/data.cpc.globalprecip.html. The gauge-calibrated Global Satellite Mapping of Precipitation from the Global Precipitation Measurement can be download from https://sharaku.eorc.jaxa.jp/GSMaP_CLM/index.htm. The ERA5 global gridded monthly reanalysis data can be download from https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels-monthly-means?tab=overview. The NAO Index is obtained from the National Oceanic and Atmospheric Administration (https://ftp.cpc.ncep.noaa.gov/cwlinks/norm.daily.nao.cdas.z500.19500101_current.csv).

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