Role of Westerly Jet in Torrential Rainfall During Monsoon Over Northern Pakistan

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Abstract Pakistan experiences several torrential rainfall events for many years due to interactive role of midlatitude atmospheric and warm moist monsoon circulations. Deadly events such as flash flooding, runoff, and mudslides may trigger by torrential rainfall events which pose significant threat to human assets. This study was undertaken based on three severe weather events (1988, 2010, and 2013) by using percentage departure to identify wet and dry years during the period 1985–2016, which occurred over northern Pakistan. Rainfall data were obtained from 14 synoptic stations of Pakistan Meteorological Department, which were analyzed at daily, monthly, and annual bases. The data sets of Climate Research Unit, Global Precipitation Climatology Centre, and Pakistan Meteorological Department are used to justify the Weather Research and Forecasting model simulation and for analyzing the various atmospheric and diagnostic variables. Results showed teleconnection between large-scale circulation pattern and South Asian summer monsoon during the selected events. Detailed analysis revealed that during all three events, a westerly trough was moving in the north of Pakistan and well-marked monsoon circulations were present at the lower levels. It was observed that the interaction of two weather systems triggered heavy rainfall over area of interest. In addition, high vorticity at all levels and extension of westerly trough to the surface resulted in heavy rainfall and the penetration of upper-level circulations anomalies consists of blocking signature over Eurasia along with Tibetan anticyclone. Hence, the monsoon low-pressure system provides moisture convergence and upper-level westerly trough results in upper-level divergence to enhance the extreme rainfall events.

1. Introduction

Previously, Pakistan has experienced major meteorological disasters such as flash floods caused by torrential rainfall events due to monsoon depressions over the Bay of Bengal (BoB) and the Arabian Sea along with mesoscale convective systems during both winter and summer seasons (Fasullo & Webster, 2003; Ding & Wang, 2005; Ullah & Shouting, 2013). Country is characterized by a diverse land, unique topography, and wide-ranging coastlines which make this region versatile, complex, and unpredictable. Summer monsoon is a major source of rainfall in Pakistan, which generally approach Pakistan at the beginning of July (Faisal & Sadiq, 2012). It is critical for both the agriculture and economy of a country as indicated by Latif et al. (2017). Heavy rainfall events over various areas of Pakistan during monsoon have been observed due to the presence of low-pressure system originating from the Arabian Sea and BoB transport moisture flux toward low atmospheric levels (Cheema et al., 2012; Hunt et al., 2018a; Martius et al., 2013; Ullah & Gao, 2012). Inconsistency in monsoon seasonal rainfall is associated with torrential rain, flash flooding, and other severe weather conditions. Rainfall observations in Pakistan show increasing trends in extreme daily precipitation occurrences over northern Pakistan, and trends are more prominent during summer and spring as compared to winter between 1950 and 2010 (Hussain & Lee, 2013). Increase in extreme rainfall has been observed, and approximately 40% of the country’s population is affected by multiple disasters due to variation in rainfall patterns (Raju et al., 2005). Further, it is known that the onset of summer monsoon is due to different changes in rainfall patterns, surrounding water bodies and large-scale atmospheric circulations over Indian subcontinent. Summer precipitation over Pakistan and its adjacent regions is due to monsoon association with significant features of intraseasonal and interannual variability along with other dynamical processes that play an important role in precipitation including extratropical disturbances and upper-level forcing (Houze et al., 2013; Rahmatullah, 2002; Webster et al., 2011).
Forecasting of monsoon seasonal rainfall is very important for prediction and impact of heavy rainfall events by numerical weather prediction, but accuracy and intensity of these events are still a bigger challenge for complex terrain due to the interaction of synoptic and mesoscale processes (Dimri et al., 2017). Extensive work has been done on the interconnection of midlatitude dynamics and southwest monsoon (Lau & Kim, 2012). According to Afzal et al. (2013), western disturbances (westerlies) approach north Pakistan throughout the year whereas, easterlies prevail only during the summer season. Extreme precipitation events over north Pakistan and India are due to western disturbances although their location exhibits significant variation (Hunt et al., 2018b). The mesoscale convective phenomenon occurs because of low-level heating and monsoon circulation caused by the complex topography of region and southwest monsoon. Martius et al. (2013) suggested that upper-level forcing and the variability of monsoon on all spatial and temporal scales can play a significant role in the formation of precipitation.

According to recent studies, it has been reported that change in upper-level jet streams results in extreme events like floods and droughts (Francis & Vavrus, 2012; Schneider et al., 2013; Screen & Simmonds, 2013). The increased convective activity during the premonsoon trough phase agrees with the projected increase in the intensity of heavy rainfall events over northern Pakistan (Wang et al., 2011). Several previous studies (e.g., Ding & Wang, 2005; Kripalani et al., 1997; Lau & Kim, 2012; Martius et al., 2013) have shown the potential influence of upper-level circulation on southeast Asian summer monsoon; however, an upper-level circulations dynamics during extreme rainfall events over Pakistan is still warranted. For improvement of forecasting accuracy and mitigate flood hazards, the main objective is to study the dynamics of westerlies that play a key role in the enhancement of extreme rainfall over northern Pakistan during the summer monsoon. Keeping this view in mind, the interactive role of westerlies associated with large-scale monsoon circulations during the Pakistan major torrential rainfall events has been investigated. The aim of this study is to analyze and explore the interactive role of westerlies with monsoon circulations which modify convective rainfall. In addition, it provides better understanding of the atmospheric dynamics and forcing factors that control the formation, structure, and predictability of storms, which cause anomalous torrential rainfall events in northern Pakistan. Thus, the rest of paper is organized as follows. The description of the data, selection of extreme rainfall events, and model setup are presented in section 2. Section 3 discussed the results. Finally, summary and conclusions are provided in section 4.

### Table 1

| Stations Index | Elevation (m) | Latitude (°N) | Longitude (°E) |
|----------------|---------------|---------------|---------------|
| Balakot (BKT)  | 1             | 980           | 34.5          | 73.25         |
| Dir (Dir)      | 2             | 1,369         | 35.25         | 71.75         |
| Garhi dupatta (GRH) | 3     | 814           | 34            | 73.5          |
| Islamabad (ISL) | 4            | 507           | 33.75         | 73            |
| Rawalpindi (RWP) | 5            | —             | 33.5          | 73            |
| Jhelum (JLM)   | 6             | 232           | 33            | 73.75         |
| Kakul (KKL)    | 7             | 1,308         | 34.25         | 73.25         |
| Kotli (Kotli)  | 8             | 613           | 33.5          | 74            |
| Lahore (PBO) (LHR) | 9        | 214           | 31.5          | 74.5          |
| Murree (MRE)   | 10            | 2,291         | 33.75         | 73.5          |
| Muzaffarabad (MZF) | 11        | 701           | 34.25         | 74            |
| Parachinar (PCR) | 12           | 1725          | 33.75         | 70            |
| Saidu Sharif (SSF) | 13         | 961           | 34.75         | 72.25         |
| Sialkot (SKT)  | 14            | 251           | 32.5          | 74.5          |

### Table 2

| PD           | Classification       |
|--------------|---------------------|
| −10 to 10    | Near normal (N)     |
| +11 to +25   | Moderately wet (MW) |
| +26 to +50   | Severely wet (SW)   |
| +51 to +70   | Extremely wet (EW)  |
| −11 to −25   | Moderately dry (MD) |
| −26 to −50   | Severely dry (SD)   |
| −51 to −70   | Extremely dry (ED)  |

2. Data and Methodology

#### 2.1. Data Sets

The research work is based on Weather Research and Forecasting (WRF) model simulated data of precipitation and circulation products, to study the dynamics of westerlies associated with flood producing extreme
rainfall events over northern parts of Pakistan during the southwest monsoon rainy season. Pakistan Meteorological Department (PMD) observational data set was also used in this study for a period of 31 years (1985–2016) containing a record of rainfall of 14 meteorological stations as shown in Table 1 as well as in Figure S1. Moreover, CRU TS4.01 for the period 1985–2016 with 0.5° × 0.5° grid resolution (Harris et al., 2014) obtained from Climatic Research Unit and GPCC data from GPCC with grid resolution 0.25° × 0.25° (Schneider et al., 2013) was used to determine the similarity and suitability of different precipitation data sets as well as for the verification of model output.

Area factor for PMD station data was calculated by applying Thiessen’s (1911) polygon method commonly used in meteorology as suggested by Rhynsburger (1973). Area-weighted rainfall for PMD along with GPCC is also used to analyze the precipitation events. Time series normal rainfall and departure

| Table 3 | Classification of Wet Years Based on Standardized Precipitation Index (SPI) |
|----------|------------------|------------------|------------------|
| SPI      | Classification   | SPI              | Classification   |
| 0 to 0.99| Near normal (N)  | 0 to −0.99       | Near normal (ND) |
| 1 to 1.49| Moderately wet (MW) | −1 to −1.49    | Moderately dry (MD) |
| 1.5 to 1.99 | Severely wet (SW) | −1 to −1.99     | Severely dry (SD) |
| >2       | Extremely wet (EW) | <−2              | Extremely dry (ED) |

| Table 4 | Standardized Precipitation Index and Percentage Departure (1985–2016) |
|----------|-----------------|-----------------|-----------------|
| Year     | SPI             | PD              | Grades          |
|          | SPI grade       | PD grade        |
| 1985     | −0.37           | −9.19           |                  |
| 1986     | 0.39            | −9.91           |                  |
| 1987     | −2.19           | −35.58          |                  |
| 1988     | 2.17            | 35.18           |                  |
| 1989     | −0.93           | −0.47           |                  |
| 1990     | 0.36            | 10.86           |                  |
| 1991     | −0.23           | −5.62           |                  |
| 1992     | 0.32            | 9.53            |                  |
| 1993     | −1.11           | −20.16          |                  |
| 1994     | −0.05           | 22.03           |                  |
| 1995     | −0.67           | 8.64            |                  |
| 1996     | 0.09            | 3.32            |                  |
| 1997     | −0.73           | 22.38           |                  |
| 1998     | −0.73           | −14.85          |                  |
| 1999     | −0.06           | −2.01           |                  |
| 2000     | 0.50            | 5.64            |                  |
| 2001     | 0.08            | 4.64            |                  |
| 2002     | −0.63           | −19.18          |                  |
| 2003     | 0.24            | −3.75           |                  |
| 2004     | −0.47           | −14.03          |                  |
| 2005     | −1.44           | −30.45          |                  |
| 2006     | 0.89            | 26.56           |                  |
| 2007     | 0.83            | −0.32           |                  |
| 2008     | 0.60            | 7.62            |                  |
| 2009     | −2.11           | −38.57          |                  |
| 2010     | 1.49            | 27.44           |                  |
| 2011     | 0.63            | 1.53            |                  |
| 2012     | −0.77           | −7.87           |                  |
| 2013     | 1.79            | 37.46           |                  |
| 2014     | −0.27           | 1.90            |                  |
| 2015     | 0.39            | 0.38            |                  |
| 2016     | −0.71           | −13.17          |                  |
Figure 1. (a, b) Spatiotemporal analysis of ARW station rainfall and GPCC data of Pakistan.

Figure 2. (a) JJAS Percentage departure of PMD and GPCC data sets. (b) Standardized Precipitation Index (SPI).
from normal is calculated by using PMD station data over northern Pakistan. This helps to investigate the precipitation amount during extreme rainfall years.

2.2. Selection of Extreme Rainfall Events

Monthly and daily rainfall data have been collected for 14 meteorological observatories (Dir, Saidu Sharif, Balakot, Kakul, Sialkot, Lahore (PBO), Murree, Parachinar, Kotli, Muzaffarabad, Jhelum, Garhi dupatta, Islamabad airport (AP), and Islamabad zero point (ZP) from PMD for 31 years of June, July, August, and September (JJAS) from 1985–2016. Investigation of yearly precipitation information was done to identify the wet and dry years. Extreme rainfall events have been identified by analyzing daily rainfall data by using percentage departure, as it is a good tool to identify wet/flood and dry/drought years (Adnan et al., 2016). Positive percentage departure from long-term mean precipitation shows flood events, and negative shows drought years. From monthly rainfall data, seasonal total rainfall June, July, August, and September were obtained for each year under the study. Percentage departures of the rainfall for 31 years, as well as the departure for each month, were calculated to identify extreme precipitation years as well as months. The percentage of departure was calculated as follows:

\[
\text{%Departure} = \frac{\text{Annual rainfall} - \text{longterm mean}}{\text{longterm mean}} \times 100
\]  

The percentage departure is used to identify wet over period from 1985–2016 (Adnan et al., 2016) shown in (Table 2). The criteria for extreme wet cases were adopted when percentage departure was more than
Standardized Precipitation Index (SPI) is a tool used for historical floods/droughts analysis. SPI is used for extreme precipitation event over northern Pakistan using precipitation data from 1985–2016. The procedure used by McKee et al. (1993) for SPI calculation has been adopted. SPI is a standard deviation from longer mean (at least 30 years) used for wet/dry cases. In order to calculate SPI long-term precipitation, data are accumulated and transformed into normal distribution. Positive SPI values indicate above normal precipitation and negative below normal precipitation. Percentage classification of events based on SPI by McKee et al. (1993) is given in Table 3. Monthly values of rainfall data have been used for SPI calculation into time scale of 3 months. Flood/drought classification criteria are shown in Table 3. SPI values have been computed and used to analyze flood events (Table 4). Three wet years of extreme precipitation and flooding years as per reports (Annual Flood Report, 2013) 1988, 2010, and 2013 were chosen on the basis of seasonal and monthly analyses of percentage departure (Figures 2a and 3) and SPI (Figure 2b). For the detailed study of other meteorological parameters like wind vector, geopotential height contour along with a synoptic and diagnostic analysis of variables like vorticity and humidity WRF model output has been used. The spatiotemporal analysis of GPCC gridded data and area-weighted rainfall of synoptic stations in Pakistan are plotted (Figure 1). By analyzing observational data, it is found that precipitation was slightly higher than the GPCC precipitation in certain years during 1985–2016, but trend and variability were the same. Furthermore, the spatial analysis reveals that there is high correlation \((R = 0.7816)\) between the two data sets. A high correlation exists between GPCC and PMD data sets, and GPCC data can be used in the absence of station data in Pakistan as suggested by Adnan et al. (2016). Further, percentage departure was also calculated for both station data set and GPCC data set, and a strong correlation has been noted between both data sets (Figure 2). Extreme wet months were analyzed by calculating departure for 1988, 2010, and 2013 (Figure 3), respectively.

### 2.3. Model Setup

There are several studies that have been done to monitor the heavy rainfall events through mesoscale models like Chevuturi and Dimri (2016) described the heavy rainfall over Kedarnath (Uttarakhand) for 2013 flood event and Medina et al. (2010) over western Himalaya. Numerical simulations conducted in this study are based on WRF model version 3.7 (http://www.mmm.ucar.edu/wrf/users/) (Skamarock, 2008) and designed to have three nested domains with grid spacing 30, 10, and 3 km, which covers a region of most of inner northern Pakistan (Figure 4). High-resolution simulations of WRF model
have been used for better understanding of topography, land surface process, and Asian summer monsoon variations and showed better performance as compared to other global models (Gao et al., 2017; Adnan et al., 2016; Raju et al., 2015; Z. Wang et al., 2014). Simulations from numerical models are very sensitive to the representation of the physical processes. Therefore, it is important to incorporate suitable physical schemes into the model. High-resolution simulated data were used to analyze the westerly wind activity for all selected dates by using parameterization schemes by Kain and Fritsch (1993) and Planetary Boundary Layer by Hong et al. (2011) to study convective process suitable for selected region (Table 5). According to Wang and Seaman (1997), Kain Fritsch scheme is suitable for midlatitude convective environments. Likewise, this scheme predicted rainfall intensity and spread for flood events (Litta & Mohanty, 2008) and proved to be better than Betts-Miller-Janjic and Grell Devenyi.

Moreover, to investigate the environment owing to this unusual rainfall during 1988, 2010, and 2013, mean monthly climatology of July and August from 1985–2016 (mm/month) is plotted over an averaged area of northern Pakistan by using CRU and GPCC data sets (Figure 5). Monsoon become gradually advance over Pakistan in the month of July. To have a complete understanding of all heavy rainfall events over northern Pakistan, accumulated rainfall from WRF has been plotted for events (a) 22–24 July 1988, (b) 27–30 July 2010, and (c) 14 August 2013 (Figure 6).

3. Results and Discussion

3.1. Analysis of Extreme Rainfall and Wind Circulations

In 1988, rainfall was quite unusual at most of the meteorological stations except at Parachinar (Figure 3a). The percentage departure in 1988 showed that the rainfall was above mean during the month of July (Figure 3b). In July 2010, actual and normal rainfall was observed (Figure 3c). It is further noted that the rainfall was above normal at all meteorological observatories. Figure 3d shows
percentage departures from the normal. Figure 3e shows actual and normal rainfall during the month of August 2013, and it was above normal at all stations except Kotli station. Figure 3f shows percentage departure in 2013, which indicated that rainfall was above mean during the month of August except for Kotli station. Horizontal distribution of rainfall shows that Pakistan has received maximum rainfall during the above-mentioned events. In addition, to examine the meteorological conditions that occurred under these abnormal rainfall events, WRF model simulated rainfall and wind pattern have been plotted (Figure 6 left panel). The appropriately rainfall pattern shows that it is exceeded up to 120 mm/day responsible for flash floods. From the analysis, it can be revealed that due to strong convection, precipitation increased because of a continuous supply of moisture from the Arabian Sea with a maximum relative humidity of about 80% and negative vertical velocity (Figures 8 and 9) as demonstrated by.
Ullah and Gao (2012). Upper tropospheric wind patterns at 200 hPa (Figure 6 right panel) shows that the speed of wind increases ahead of westerlies prevailing over northern Pakistan which lead to velocity divergence. The magnitude of wind is greater than 30 knots (Figure 6 right panel). As we know upper-level divergence is favorable for low-level convergence which results in severe weather patterns. However, as the summer rainfall over Pakistan is of monsoon nature, these wind circulations are influenced by some global and midlatitude dynamics (Martius et al., 2013). As indicated by Adnan et al. (2019) approximately 47% rainfall of annual precipitation is from summer monsoon system in northern Pakistan. Pakistan is experiencing torrential rainfall events due to monsoon surges. Summer monsoon brings moisture from Arabian Sea and BoB which contributes in enhancing the convection over Pakistan leading to severe weather. Thus, the upper parts of Pakistan are attributed to the torrential rainfall during the months of July and August due to southwest summer monsoon.

3.2. Air Temperature

Air temperature gradient determines the velocity of jet streams. According to Molnos et al. (2017), if the temperature gradient is greater, stronger will be the jet stream. Therefore, to find the speed and location of jet air, temperature has been plotted at 200 hPa. Jet stream exists due to air temperature contrast of southern subtropical warm air and cold polar air of north, and it is controlled by several conditions like local weather and temperature of the ocean (Rana et al., 2016). The entrance part of upper-level jet can cause rainfall over Pakistan. Because of being embedded on left side of westerlies trough, the upper-level jet amplifies which result in affecting rainfall over Pakistan. Jet streams at hPa can be seen on all three selected events during 1985–2016 that might be the reason of heavy rainfall over northern Pakistan by that had caused

Figure 7. (a–h) Position of Jet stream at 200 hPa and air temperature analysis (shaded) from 22–24 July 1988, 27–30 July 2010, and 14 August 2013.
the advection of warm moist air from the Indian Ocean (Figure 7). According to Rasmussen et al. (2015), synoptic patterns along with easterly jet bring moisture advection from Arabian Sea and BoB into subcontinent. The moisture flux transported with monsoonal flow interacts with sinking cold air; it often results in torrential rainfall over northern Pakistan. Moreover, a cyclonic curve of the jet has also been observed over Afghanistan causing deep trough over the area of interest.

3.3. Relative Humidity

To find the deep convection, relative humidity and vertical velocity have also been plotted at 500 and 850 hPa which gives significant information about the rising and sinking of air over the study area. Figures 8 and 9 represent the vertical velocity (m/s) (dashed lines represent negative values) and relative humidity (%) at 500 and 850 hPa. It is clearly visible that high relative humidity existed over northern Pakistan (Figures 8 and 9), indicating that warm moist air is moving from the Arabian Sea and BoB toward
subcontinent and then approaching to north of Pakistan (Figures S3 and S2). Similarly, high-specific humidity anomalies were present over northeastern parts of Pakistan, which gives actual picture of moisture in air (Figure S2). This maximum relative humidity is the significant progenitor of the warm moist air from the Arabian Sea. It can be further seen from the analysis that the warm moist air is moving straight to the upper parts of Pakistan from the Arabian Sea during all selected events. Negative values of vertical velocity at 500 hPa have been observed over Afghanistan, India, and adjoining areas along with high values of relative humidity (Figure 8) which is a sign of uplifting of air and cause of convection leading to precipitation (Ahmed et al., 2019). In addition, it is also noted that topography is another triggering mechanism of convective rainfall over northern Pakistan.

3.4. Absolute Vorticity

Absolute vorticity has been analyzed because it plays a key role in the development of cyclonic circulations. As demonstrated by Wang and Wang (2018), the jet streams are linked with vorticity advection.

Figure 9. (a–h) WRF simulated data (domain 3 km), vertical velocity (negative values are dashed lines; positive values are solid lines) (m/s), as well as the horizontal distribution of relative humidity (%), shaded at 850 hPa, respectively.
For weather forecasting, analysis of absolute and relative vorticity is an excellent tool in midlatitude and tropics (Holton, 2004). Figures 10 and 11 are the WRF simulated data for domain 3 km, geopotential height contours and horizontal distribution of absolute vorticity at 500 and 850 hPa on all selected dates to analyze the interaction of midlatitude dynamics with monsoon circulations. At 500 hPa, an area of positive absolute vorticity lying over Pakistan and Afghanistan with lateral wind shear results in cyclonic circulation (Figure 10). Positive absolute vorticity value lies over Pakistan. Hence, the midlatitude atmosphere at tropospheric level is favorable for the maximum surface convergence over the selected region. However, geopotential height anomaly does not show a correlation with positive vorticity conditions. Similarly, absolute vorticity has been plotted at 850 hPa along with geopotential height as shown in Figure 11. Due to the topography of the region, the model could not capture the vorticity at 850 hPa in the upper parts of Pakistan. As above 30° latitude, absolute vorticity is positive and causes counterclockwise vorticity advection. Maximum values of absolute vorticity have been observed along 71°E to 73°E associated with deep depression in Figures 11b, 11e, and 11h. The westerly trough extending as depicted in model 30 km domain and high vorticity at all levels might be a critical reason of heavy rainfall. Indicatively, this may be the probable reason for the small-scale convergence that might have resulted in extreme convective development. Hence, the vorticity analysis suggests that abnormal rainfall over north of Pakistan was because of midlatitude dynamics as well as the monsoon circulation.

3.5. Potential Vorticity

To understand the dynamics of atmospheric flows on both synoptic and mesoscale, potential vorticity (PV) is an important variable for cyclogenesis and diagnosis of weather systems that contribute to heavy rainfall events (Egger & Chaudhry, 1942; Hoskins & Berrisford, 1988; Kawashima, 2007; Moore et al., 2008).
Positive PV values indicate the cyclonic circulation and can be used to identify the evolution of large-scale flow patterns during blocking. PV analysis along with wind vectors and geopotential height contours is given in Figure 12. Results showed that positive PV were prevailing in the north of Pakistan along with a linger trough during the event. Further, these positive values of PV are extended over northern Pakistan along with westerly trough at 300 hPa. As suggested by Moore et al. (2008), PV for midtroposphere triggers moist convection/cyclogenesis.

Vertical cross section of PV along with potential temperature was taken for detailed analysis of vertical structure at the upper and lower tropospheric levels at 1200 UTC interval as shown in Figure 13. Negative PV is an indication of potential instability at upper level and deep convergence at lower level which is linked with westerlies trough between pressure levels 750 hPa in upper troposphere as shown in Figures 13b, 13c, and 13f, respectively. It is also noted that some positive PV values between 600 hPa to upper troposphere in Figures 13 (c, f and h), which supports to cyclogenesis located at lower levels. High positive PV in upper troposphere shows that westerlies embedded in trough are baroclinic in nature. So stronger PV strengthens the low-level cyclonic circulations, which enhanced the heavy rainfall.

3.6. Analysis of Atmospheric Blocking

The National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis composite map of geopotential height and wind vectors daily anomalies for 31 years has been studied for deep insight of anomalous rainfall. Hill et al. (2014) analyzed three consecutive flooding years of Pakistan which revealed that a well-marked blocking signature was present at a midtropospheric level over Eurasian continent during the study period. Geopotential height anomalies at 200 and 500 hPa...
represent a strong convergence during all selected events as shown in Figures 14 and 15 as pointed out by Hunt et al. (2018a).

Daily composites at lower- and upper-level circulations are shown in Figures 14a and 15a, for 4 days prior to rainfall. Day 0 corresponds to the day of extreme rainfall over northern Pakistan. At 200 hPa Rossby wave train structure with positive cyclonic and anticyclonic gyres has been detected before heavy rainfall as shown in Figures 14a and 14b. The blocking signature over western Russia for 4 days prior to the heavy rainfall spell has been noted and that pattern has moved toward northern Pakistan 2 days before rainfall events agrees with study of Vellore et al. (2016). Blocking high diffused after 4 days is seen in Figures 14d and 15d. The excellent agreement has also been found in the geopotential height anomalies and surface temperatures as earlier studied by Lau and Kim (2012). The study of Hill et al. (2014) shows that the presence of positive geopotential height anomalies at 500 hPa over Tibetan Plateau (Figure 15) played a major role in attracting moisture advection from the BoB and the Arabian Sea over northern Pakistan, which supported mesoscale convective systems that led to heavy rainfall and flash floods in the country.

4. Summary and Conclusions

This research work provided deep insight into the dynamics of deepening of westerly jet stream pattern over the selected region. Results evidenced that the three selected extreme rainfall events during 1985–2016 are accompanied by interactions of moist monsoon circulations and penetration of midlatitude westerly troughs over northern Pakistan. The observations showed that a significant relationship that exists between the jet streams and Pakistan monsoon rainfall agreed with other past studies like (Martius et al., 2013; Vellore et al., 2016). While studying synoptic parameters of severe weather events in Pakistan, it was examined that
A westerly trough existed over north of Pakistan at 200 hPa. During the detailed analysis of all selected events, a westerly trough was moving over the northern parts of Pakistan and well-marked monsoon circulations were present at lower levels. The presence of this westerly trough along with jet stream played a key role in sucking up moisture which penetrate upper parts during these events. The positive value of absolute vorticity was observed which strongly supported cyclonic circulations. Due to the high value of positive vorticity, low-pressure systems become deep leading to extreme weather events. Maximum relative humidity and negative vertical velocity were noted over northern parts of Pakistan during the events. It has been observed that there was a 70–80% moisture that exists in the upper atmosphere during all the events. Clearly, dynamic depression overlying the thermal depression already established at the surface, and it appeared that the event might be well triggered because of the burst of the monsoon, allowing the vigorous inflow of moist air into northern Pakistan. Analysis of geopotential height and air temperature contours at 200 hPa indicated strong differential development which resulted in protraction of jet stream trough over northern Pakistan. In the presence of westerlies, a blocking signature was existed 4–2 days prior to rainfall events over northern Pakistan. It is an important element to forecast such events in the future. The high-resolution models like WRF are not being in practice for better assessment of daily forecast of upper-level circulation patterns which also considered as a vital element in triggering the extreme rainfall events over complex topography. This study will be helpful for understanding the processes that can be responsible for generating the heavy rainfall over northern Pakistan and its neighboring regions.

Figure 13. (a–h) Vertical cross section of diagnosed PV in shaded \((10^{-6} \text{ m}^2 \text{ Kkg}^{-1} \text{s}^{-1})\) superposed with potential temperature (contour interval 8 K) at 1200 UTC.
Figure 14. (a–d) A composite map of daily circulations (horizontal winds–vectors (m/s); and geopotential height (shaded; unit: m) at 200 hPa. Day 0 corresponds to the day of the extreme precipitation in the northern Pakistan by using NCEP/NCAR reanalysis data daily climatology derived from the period 1985–2016).
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Figure 15. (a–d) A composite map of daily circulations (horizontal winds–vectors (m/s); and geopotential height (shaded; unit: m) at 500 hPa. Day 0 corresponds to the day of the extreme precipitation in the northern Pakistan by using NCEP/NCAR reanalysis data daily climatology derived from the period 1985–2016).

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