Sadaf Nabeela (Orcid ID: 0000-0001-9527-9291)

Wet spells over the core monsoon domain of northern Pakistan during the summer season

Nabeela Sadaf[1], Yanluan Lin[1], Wenhao Dong[2]

[1] Ministry of Education Key Laboratory for Earth System Modeling, Department of Earth System Science, and Joint Center for Global Change Studies (JCGCS), Tsinghua University, Beijing 100084, China.

[2] Cooperative Programs for the Advancement of Earth System Science, University Corporation for Atmospheric Research, Boulder, Colorado, and NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey.

Corresponding author: Nabeela Sadaf (nh16@mails.tsinghua.edu.cn)

Abstract

Flooding events or wet spells have increased over Pakistan in recent years. However, a long-term classification of large-scale and synoptic-scale configuration for these events has been lacking. In this study, a total of 53 wet spells during the period of 1951-2015 over the core monsoon domain of northern Pakistan are identified using rainfall data. Based on daily geopotential height fields from NCEP/NCAR re-analysis, the dominant synoptic-scale systems, displaying distinct low-level circulation and moisture transport, are found during these wet spells over Pakistan. They are categorized as trough with low pressure system (LPS, 30 cases), trough without LPS (19 cases), and LPS only (4 cases) wet spells. Without the accompanying LPS over India, the trough tends to be deep and intrudes to southern Pakistan with moisture transport mainly from the Arabian Sea. In contrast, the trough is relatively shallow and interacts with presence of the LPS to steer moisture from the Bay of Bengal towards Pakistan. We found that subtropical trough is an essential ingredient of wet spells over

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Pakistan. This is different from wet spells over the core monsoon domain of India, which is mainly dominated by LPS. The ridge development over Siberia is a precursor to wet spells over Pakistan and provides guidance for prediction.

Key words: Floods, Trough, Wet spell, Low pressure system, Pakistan

1 Introduction

Located at the northwestern boundary of south Asian monsoon region, Pakistan receives 60-65% of its total annual rainfall during summer monsoon season (Asmat and Athar, 2017). The summer monsoon rainfall in Pakistan is mainly concentrated during July and August (Ding and Ke, 2013). Pre-monsoon season (May-June) is a very dry period with few localized convective rainfall events (Rasul *et al.*, 2015). The monsoon rainfall has key significance owing to the potential effects on agricultural activities as more than 25% of total agriculture area is considered as rain-fed (Baig *et al.*, 2013). Past studies have reported that water resources for agriculture are greatly affected by the extreme climatic conditions such as wet (dry) spells, causing floods (droughts) in July and August (Nabeel and Athar, 2018). Wet and dry spells are characterized by the day-to-day variability of rainfall in tropical monsoon climate (Singh and Ranade, 2009). Dry spells are prolonged periods of dry conditions and usually cause droughts. On the contrary, wet spells are extended periods of extreme heavy precipitating days and can trigger floods (Chaudhary *et al.*, 2017). These spells of rainfall are manifestation of synoptic-scale systems, which are considered to be a part of large-scale organization of convection (Ratan and Venugopal, 2013). A better understanding of wet and dry spells is extremely important to hydrologists, ecologists, agronomists and water-resource engineers for effective management of climate related risks (Singh *et al.*, 2014).

There are only a few studies focused on the wet spells and their contribution to summer rainfall over Pakistan. For instance, Nabeel and Athar (2018) used station wise monthly wet and dry spell characteristics to categorize the precipitation regimes in Pakistan. Syed *et al.* (2010a) made a composite of all active phases and found that before an active phase a tropospheric warm anticyclonic anomaly developed at the northwest of the core monsoon region. On the other hand, few studies used observed station precipitation data to check the extreme precipitation trends over Pakistan. For instance, Hussain and Lee (2012) reported an increasing trend of extreme precipitation over northeast Pakistan and a reducing tendency over southwest Pakistan from 1950 to 2010 in all seasons. In western Pakistan, the regimes are shifting towards drier conditions; while in the central part, the northwestern mountains, and in the southern part of country, the precipitation regimes are shifting towards humid conditions in terms of total rainfall (Hussain and Lee, 2014). It was reported that JJAS rainfall was vigorous and accounted for 82% of total rainfall during the active period of monsoon for the entire territory of Pakistan (Hussain and Lee, 2016a).

In contrast, there have been numerous studies on Indian monsoon extremes on various spatial domains. Different studies have identified and documented characteristics of wet and dry spells over India (Dhar and Nandargi, 1995; Dash *et al.*, 2009). Summer wet spells in India have been reported to constitute 30-50% of total seasonal rainfall (Rakhecha and Soman, 1994). Observational evidence indicates that active spells occur every year over the core monsoon domain of India. On the contrary, break spells are not frequent as 26% of years in the study period (1951-2007) did not show any break period (Rajeevan *et al.*, 2010). Conclusively, strong monsoon years are associated with wet spells or active conditions while weak monsoon years are associated with break conditions over India (Krishnamurthy and Shukla, 2000). Duration of an active spell is found to be shorter than that of a break spell, but in total causes more rainfall over India (Rao *et al.*, 2016). The main monsoon wet spell, which is a large-scale wet spell and covers the most portion of monsoon period, is found to contribute 70% of the main monsoon rainfall and 57% of annual rainfall (Ranade and Singh, 2014). As aforementioned studies show the importance of wet spells' rainfall over India, it is generally argued that many of these heavy rainfall events over India result from low pressure systems, which develop in the Bay of Bengal and move northwestward (Sagar *et al.*, 2017; Krishnamurthy and Ajayamohan, 2010). These aforecited systems have a time-scale of 3-6 days and occur with an average frequency of 13-15 storms per season (Godbole, 1977; Hurley and Boos, 2015). The frequency of these cyclonic disturbances from the Bay of Bengal, Arabian Sea and land area shows a positive correlation with extreme rainfall over India, yet the cyclonic disturbances from the Bay of Bengal play a dominant role in the precipitation extremes over India during the summer monsoon season (Pattanaik and Rajeevan, 2010). Interestingly in the recent decades, some observational studies have refuted the frequent cyclonic storms over India during the summer monsoon (Prajeesh *et al.*, 2013; Vishnu *et al.*, 2017). The decreasing trend in wet spell frequency over India is, therefore, consistent with the decreasing monsoon depressions generated in the Bay of Bengal (Dash, 2007). The decrease in wet spells frequency, however, is not statistically significant, and a significant increase in the intensity of wet spells due to increased convective available potential energy and enhanced low-level moisture convergence has also been reported (Singh *et al.*, 2014). Other studies argued that warming of the Arabian Sea has strengthened the monsoon westerlies, resulting in heavy rainfall over India (Roxy *et al.*, 2015; Goswami *et al.*, 2006). Some heavy precipitation events and flooding also occurred over parts of northern India and Nepal due to the interaction of these monsoon lows with extra-tropical disturbances and strong orographic forcing when these lows move northward towards the Himalayas (Vellore *et al.*, 2016; Joseph *et al.*, 2015).

Madden Julian Oscillation (MJO), characterized by the large scale convective anomalies over tropical Indian Ocean (Hendson and Salby, 1993), is one of the dominant modes of tropical intraseasonal variability and has significant effect on atmospheric circulation (Madden and Julian, 1972). It was found that during MJO, phase 1 and 2, enhanced convection in the western and central equatorial Indian Ocean causes break monsoon conditions in Indian sub-continent. Subsequently, as MJO moves eastward (phase 5 and 6), an anomalous subsidence over equatorial Indian Ocean and anomalous rising motion over monsoon trough caused stronger than normal monsoon conditions. Indian Ocean Dipole (IOD) was also believed to modulate Indian summer monsoon (Ashok *et al*., 2004). It was argued that IOD mainly impacts the mean position of the monsoon trough over the Indian sub-continent. The correlation between IOD and precipitation of Pakistan indicated a noteworthy impact over coastal and western regions of Pakistan (Hussain *et al.,* 2016b). Beyond the lower Indus plain and within Pakistan's mainland the coastal monsoons are weakened and moisture is reduced. The south Asian monsoon is associated with heating over the Tibetan plateau (Flohn, 1968, Yannai and Wu, 2006), but recent studies have challenged this view (Emanuel, 2007; Boos and Kuang, 2010). It was argued that such heating correlates with summer monsoon rainfall in early and late monsoon season. Correlations during main monsoon (15 June- 31 August) season are small and insignificant (Rajagopalan and Molnar, 2013). However, the Tibetan Plateau plays an important role in the large-scale circulation during summer. Dong *et al.* (2018) showed that the mid-tropospheric westerly flow over the Tibetan Plateau interacts with LPS over India to transport the moisture over the Himalayan mountains and extends the northern boundary of south Asian monsoon.

Despite the observed importance of wet spells and attribution of 40-80% of rainfall to low pressure systems over India (Hurley and Boos, 2015), the importance of wet spells' rainfall over Pakistan remains unexplored and heavy precipitation events have not been addressed systematically. Syed *et al.* (2010b) found that dynamics of active phases of Pakistan differ from the Indian mainland region because of the extratropical influence. Thus, there is a need to study the dynamics of heavy precipitation events separately. Pakistan is an area of high temperature and dry climate, so the impact of rainfall on agriculture is extremely important. Agricultural performance in Pakistan has been affected by high frequency extreme weather events including floods and droughts. It is therefore important that research should be conducted keeping in mind that agriculture is the backbone of Pakistan's economy (Hussain and Lee, 2012). Since most previous analyses are based on seasonal mean, they have neglected or overlooked critical synoptic signals. Therefore, the key features and synoptic systems that favor these extreme heavy events remain unclear. The sources of water vapor as well as configuration of lower to upper-level circulation needs to be clarified for these extreme precipitation events. The present study aims to bridge that gap. We have carried out this work with an objective to identify all the wet spells over the core monsoon domain of Pakistan for July-August during 1951-2015. For this purpose, we have followed the criterion for wet spell used by Rajeevan *et al.* (2010) and focused on the associated synoptic conditions during each wet spell. Additionally, we also have categorized those conditions according to their features to provide a complete picture of the dominant atmospheric circulations during wet spells over Pakistan.

2 Data and Methodology

2.1 Data

High resolution (0.25°×0.25°) daily gridded rainfall data from Asian Precipitation-Highly Resolved Observational Data Integration Toward Evaluation (APHRODITE, (Yatagai *et al.*, 2012)) product V1101 during 1951-2007 and APHRODITE-2 V1801R1 during 2008-2015 are used in this study. The fine resolution data was used to represent the complex topography of northern Pakistan, which has topographical barriers such as Margalla Hills, Murree hills and Pir Punjal range. This time period is selected for analysis because APHRODITE data is available from 1951 till 2015. The gridded APHRODITE data set is used because of its fine spatio-temporal resolution and better performance as compared to several other existing data sets over Pakistan (Ceglar *et al.*, 2017; Rana *et al.*, 2015). Winds, geopotential heights and precipitable water from National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR; daily with a 2.5°×2.5° horizontal resolution) during the period of 1951-2015 (Kalnay *et al.*, 1996) are used to investigate large-scale atmospheric circulation patterns as well as the associated moisture transport. To identify the monsoon low pressure systems (LPS), sea level pressure data from NCEP/NCAR reanalysis is used during 1951-2015. We also employed European center for medium-Range weather Forecast Re-analysis Interim (ERA-Interim; Dee *at al.*, 2011) with a resolution of 1°×1° during 1979-2015 to verify the identification of these LPS. The LPS in both datasets show good agreement (Table1).

2.2 Methodology

Our analyses focused on the extreme wet spells and associated synoptic conditions during peak monsoon months (July and August), when the monsoon is established over the entire sub-continent (Rajeevan *et al.*, 2010). The core monsoon region was the same as that of Latif and Syed (2016; represented in rectangle in Figure 1), that exhibits high seasonal mean precipitation (Figure 1a). Following Rajeevan *et al.* (2010), we used precipitation anomalies to define wet spells over the core monsoon region of Pakistan. Wet spells were identified as periods during which standardized rainfall anomaly (obtained by subtracting its long term daily mean during the period of 1976-2005 and then standardizing it by dividing its daily standard deviation) was greater than +0.8 for three consecutive days. Contrarily, dry spells were identified as periods during which standardized rainfall anomaly was less than -0.8 for three consecutive days. A total of 53 wet spells (189 days, Table 1) were identified during 1951-2015 based on this criterion. It is important to note that wet spells are characterized by a sequence of overlapping monsoon disturbances (Murakami, 1976). The average timespan of these synoptic systems is about 3-4 days. Most studies over India define wet spells as periods with standardized rainfall anomaly greater than 1. Here we use 0.8 rather than 1.0 to yield more samples to ensure a robust comparison.

Monsoon LPS is an important player over the Indian continent. These cyclonic systems form in the Bay of Bengal, Arabian Sea or over land in the monsoon trough region. LPSs are identified and classified based on sea level pressure around the center of the system following Ajayamohan *et al.* (2009), in which the system is called monsoon low with one closed isobar and associated maximum wind speed less than 8.5 m/s. While monsoon depression has two closed isobars at 2 hPa intervals with maximum wind speed between 8.5 and 13.4 m/s.

These heavy precipitation episodes generally occur under some favorable atmospheric conditions, such as the low-level convergence of moist air, ascending motion and upper-level divergence. Daily geopotential height at 500 hPa and 850 hPa during each wet spell was manually examined with attention on the 500 hPa trough and 850 hPa low pressure system over India. An upper-level trough is an elongated region of relatively lower heights and low atmospheric pressure, often associated with fronts. Typical synoptic features, including the presence of upper-level trough and LPS for each event are summarized in Table 1. The most obvious differences among these cases lie in the position and strength of the upper-level trough and the presence of LPS over India. Troughs are known to play a key role in triggering heavy precipitation episodes, e.g., for Pakistan's 2010 flood (Lau and Kim, 2012). 19 out of 53 wet spells showed a trough extending further southward to the core monsoon domain without the presence of contemporary LPS (hereafter named as trough without LPS). While for other 30 wet spells, the trough co-existed with an LPS over India (hereafter named as trough with LPS). Compared with the first group of wet spells, the trough in this category was relatively weak. The remaining four cases had only the presence of an LPS over India. Subsequent analyses will focus on the large-scale circulation patterns associated with these former two major types of wet spells.

3 Results

Prior to analyzing the characteristics of wet spells, it is useful to discuss the spatial patterns of mean summer and wet spell rainfall (Figure 1). Mean summer rainfall (Figure 1a) shows that the monsoon belt over Pakistan is very narrow in latitudinal position. Comparison between the geographic spread of mean summer and wet spell rainfall (Figure 1b) shows that the major part of north Pakistan receives significant amount of precipitation during the wet spell period. The spatially averaged precipitation in the core monsoon region during wet spells was 14 mm/day, more than three times of the mean precipitation (3.85 mm/day) during summer season. In addition, rainfall was also much larger along the foothills of the Himalayas and northeast India during the wet spell period (Figure 1). This indicates a close connection of the wet spells over Pakistan with monsoon activity over India.

The identified wet spells are summarized in Table 1 along with their synoptic conditions and mean precipitation during each wet spell. Out of the 53 wet spells identified during July-August, a majority (33) were observed in July. The frequency of wet spells showed a great interannual variability. Several years showed as much as 4 wet spells and few other years did not experience even a single wet spell. Large interannual variability was also observed in the intensity and duration of wet spells. The threshold criterion for a wet spell to occur in this study was at least 3 days, so the majority of wet spells had durations of 3 to 4 days. There were only 5 wet spells which lasted for 5 days and only one wet spell exceeded 6 days. Out of these 6 wet spells, 5 were trough with LPS type and only one belonged to the trough without LPS type. The minimum precipitation averaged over the core monsoon region during the wet spell was 7.94 mm/day; while the maximum was as large as 35 mm/day. No significant change was observed in the duration or frequency of wet spells on the interannual time scale. However, on the decadal scale, the occurrence frequency of wet spells showed a sharp increase during the last decade (i.e., 2006-2015). During this time period, the wet spells increased more than twice as compared to the last four decades (Table 1). There was also more severe flooding during the last decade, such as the 2010, 2013, 2014 and 2015 floods (Rehman *et al*., 2015). We explored the long-term trends of these two types of troughs, but no significant trend has been observed.

Mean precipitation and percentage contribution to the total wet spell rainfall by each type is shown in Figure 3. The core monsoon region of Pakistan receives copious amount of rainfall for all three types, but rainfall over the Indian subcontinent differs a lot. The features and associated synoptic scale conditions are discussed in more detail for each type in the following sections.

3.1 Trough with LPS

In general, the mid-latitude westerlies and subtropical jet stream remain north of India after the monsoon onset, but still could considerably influence Indian rainfall during the monsoon season via intruding troughs. Sometimes, western disturbances or trough move from west to east across Indian longitudes. These upper-level troughs affect Indian monsoon in four ways, i.e., i) triggering and intensifying the lower tropospheric lows, ii) enhancing rainfall in pre-existing synoptic scale system, iii) causing recurvature of LPS, and iv) leading to the onset of break monsoon conditions (Rao, 1976).

By analyzing the synoptic conditions during each wet spell, it was found that there are 30 cases (Table 1) when the trough co-occurred with an LPS. The two players during these wet spells were the troughs over north Pakistan and the LPS in the Bay of Bengal. In the course of these types of wet spells, the LPS usually propagated westward from the Bay of Bengal to central India and stayed there until dissipation (Figure 4b,d,f). The synoptic conditions at 500 hPa showed a ridge over mid-west Asia and an associated downstream trough over northern Pakistan (Figure 2a). The upper-level trough was relatively shallow and positioned over northwest of Pakistan. The low-level wind and moisture transport mainly steered from the Bay of Bengal along the orientation of the Himalayas by the presence of LPS over India (Figure 2b). The high pressure system over Iran and Arabia also moved southeastward due to the southward protrusion of upper-level trough. The ridge associated with blocking over mid-west Asia extended above 60°N. This upstream ridge was weak and manifested as a northward extension of the Iranian High. The upward motion induced by the approaching trough (Figure 6a), combined with the moisture supply via LPS from the Bay of Bengal, produced heavy precipitation over northern Pakistan (Figure 2b). Over central India, a mid-tropospheric cyclone (Figure 2a) was present during this kind of wet spells, which is one of the main synoptic scale systems causing rainfall in west and northwest Indian sub-continent. Consistent with this picture, rainfall in the foothills of the Himalayas is rather weak due to the along-mountain flow. 30-40% of total wet spell rainfall is contributed by these systems over the core monsoon domain of Pakistan (Figure 3a). In this type of wet spell, the trough generally moved eastward gradually. Sometimes (3 out of 30 cases) the trough moved southeastward toward southern Pakistan, where it merged with the westward-moving LPS to produce a significant amount of rainfall. Only two cases out of 30 have a rather stationary upper-level trough over western Pakistan.

3.2 Trough without LPS

Synoptic conditions showed that without the presence of an LPS, the trough was deeper and intruded further southward over southern Pakistan with a closed low north of Pakistan (Figure 2c). As a result, the upward motion over Pakistan was also stronger in this case (Figure 6b). The 500 hPa synoptic conditions during these wet spells showed two ridges over both sides of the trough (Figure 5a,c,e,g). The secondary ridge or east Asian blocking ridge appeared few days after the appearance of the primary or west Asian blocking ridge (Figure 5c,e,g). During these cases, the upper-level trough intensified and moved further southward. The high pressure system over Iran and Arabia was also stronger and the upstream ridge was an indication of a blocking high over western Siberia (Figure 2c). The southward protrusion of the upper-level trough was also accompanied by the intensified Iranian High and triggered heavy wet spells over the study region. The low-level wind was southwesterly and moisture was transported from the north Arabian Sea (Figure 2d). Advection of the cold and dry mid-latitude air towards the study region along with the northeastward advection of the moist and warm air from the Arabian Sea facilitated the onset and maintenance of this type of wet spells. The strong southwesterlies from the Arabian Sea impinged on the Himalayas and induced large orographic rainfall over the foothills there contributing 30-40% of total wet spell rainfall (Figure 3b). Rainfall over India also tends to be more confined in the northern part instead of concentrated in the mid-east region of India as in the trough with LPS type (Figure 3). The LPS only type was dominated by zonal flow north of Pakistan, but having a monsoon trough extending to the study region (Figure 2e). The Indian monsoonal flow was confined to south of 20°N. Rainfall distribution reflected a footprint indicating the westward movement of the LPS and contributes 30% of total wet spell rainfall (Figure 3c).

Since the trough was present for most (49 out of 53) wet spells, we composited the daily evolution of large-sale circulation five days before the wet spell onset date till the onset of the wet spell for a better understanding of the trough evolution (Figure 7). Five to four days before the wet spell (Figure 7a-b), a ridge started to develop over west Asia and the Iranian high was also observed. Three days (Figures 7c) before the event, as the ridge intensified, the Iranian high moved northeastward. The ridge further intensified two days before the events and the Iranian high was still present over Pakistan. One day prior to the event (Figure 7e), the ridge was well developed accompanied by two troughs on both sides. The downstream trough moved southward and the Iranian high moved westward. On the day of the event (Figure 7f), the Iranian high retreated completely from Pakistan and a trough developed over north of Pakistan. The lifting was observed over north of Pakistan and moisture towards Pakistan was transported from the Arabian Sea in deep trough cases and from the Bay of Bengal during trough with LPS cases. The evolution of the trough between two types of wet spells, i.e. trough with LPS and trough without LPS, was almost the same. The only difference was that after the onset of wet spells, the trough moved southward and intruded into south of Pakistan in trough without LPS case, while it remained over northwest of Pakistan without further penetrating in trough with LPS case. Different wet spell cases showed some variations in the position and movement of synoptic systems from each other, but generally the trough started to develop 3-4 days before the wet spell during deep trough cases. As the central Asian ridge moved between 30°E and 60°E, the trough developed and intruded southward.

Examination of upper-level features associated with trough without LPS cases indicated that the upper-level trough deepened when the Tibetan anticyclone at 200 hPa split into two parts. As it can be seen in the two example cases, 14-17 July 1964 and 22-25 July 1993 (Figure 8), two anticyclones were present on each side, i.e., west Asia and east Asia, with the trough protruded over Pakistan. The trough deepened, causing the formation of a jet streak downstream of the trough, which further resulted in strong jet accelerations and upward motion (Figure 8c-d and 8e-f). This upper-level mass divergence caused the pressure to fall over the study region. As a result, strong southerly from the north Arabian Sea occurred and caused moisture convergence in an unstable environment. The orientation of upper-level trough is controlled by the strength of anticyclonic pairs on both sides. Unninyar and Murakami (1978) noted the bifurcation of the Tibetan High under the influence of mid-latitude trough during weak Indian summer monsoon. It is also obvious from the figure that a second ridge is also present over east Asia during deep troughs between 90°E and 120°E (Figure 8c-d and 8f-h). As this east Asian ridge intensifies, it causes monsoon break conditions over India (Raman and Rao, 1981). It can also be seen that as the amplitude of the upper-level trough increases over Pakistan, the west Asian blocking ridge started to dissipate and the east Asian blocking ridge intensified (Figure 8g-h). This intensified east Asian blocking ridge causes further deepening of the upper-level trough, which in turn causes the break conditions of Indian monsoon by moving monsoon trough northward over the Himalayas.

3.3 Circulation anomalies during wet spells

To examine the large-scale circulation patterns during wet spells, a composite geopotential height anomaly on 200 hPa from day -5 till the day of wet spell was constructed. About 5 days prior to the onset of extreme precipitation, an anticyclonic anomaly formed over western Europe (Figure 9a). This anticyclonic anomaly intensified and further moved southward. Cyclonic anomaly split into two parts as the anticyclonic anomaly moved southward (Figure 9d). The cyclonic anomaly on the eastern side of the anticyclones merged with east Asian cyclonic anomaly and got intensified. With the approaching extreme event, the anticyclonic anomaly intensified and further moved southward (Figure 9e-f). Consequently, the cyclonic anomaly also intensified and deepened over Pakistan. The anticyclonic anomaly might be viewed as the blocking high considering its quasi-stationarity and persistence. Figure 10 shows the composite of the wave activity flux and geopotential height anomaly averaged over the period of 53 wet spells (i.e. from day 1 till day 3). The wave activity flux shows the maxima in location of two troughs (at 20°E and 70°E) and clear minima at the location of the ridge (at 50°E). The flux is strongly elongated in the zonal direction. A great part of the wave activity seems to be transported towards Pakistan, while another part of the wave activity seems to be transported eastward. In many of the investigated cases, the extreme event was associated with the meridionally elongated upper level trough (i.e., a breaking Rossby wave). Another distinct feature in this figure is that the anticyclone weakened over Eurasian region during wet spells. Tyrlis and Hoskins (2008) suggested that the decay of Eurasian blocking favored the eastward movement of cyclonic anomaly. Therefore, the eastward propagation of cyclonic anomalies downstream of the Eurasian anticyclonic anomaly played an essential role in the formation of trough over north of Pakistan. It was observed that anticyclonic anomaly was more intense and of large horizontal scale as compared to cyclonic anomalies.

4 Discussion

4.1 Factors favoring the incidence of wet spells

The composite analysis represents the synoptic features well during wet spells over Pakistan. Synoptic scale conditions showed that wet spells occurred over Pakistan when the upper-level trough was present either directly over Pakistan or north of Pakistan. Regions of positive vorticity advection occur ahead of approaching troughs and favor strong ascending motions at low-levels by increasing instability as dry upper-level air advects over warm and moist air in the lower troposphere (Hong *et al.*, 2011; Lau and Kim, 2012)). 34 wet spells also showed the existence of monsoon low pressure systems over Indo-Pak region. These low pressure systems provide abundant supply of moisture to Indian sub-continent. The onset of wet spells over Pakistan corresponded to these two synoptic conditions. Stagnation and increased amplitude of the upper-level trough was observed over Pakistan during the course of the wet spell. Previous studies also noted the stagnation and large amplitude of the upper-level trough due to blocking over central Asia (Ramaswamy, 1962, Raman and Rao, 1981). A study concluded that low pressure systems cause heavy precipitation over Pakistan during summer (Hunt *et al.*, 2018). However, our results indicate that only few wet spells occurred in the presence of low pressure systems alone. Even though the monsoon depression was present over India during many wet spells, the presence of a ridge over north of Pakistan caused the descending motion and inhibited heavy precipitation occurrence despite the presence of LPS. Our results are in agreement with synoptic patterns over north India observed by Vellore *et al.* (2016) and emphasize the importance of westerly systems in precipitation during summer monsoon. During the 2013 north Indian flood, the intrusion of an upper-level trough destabilized the atmosphere and caused heavy precipitation during 14-17 June (Joseph *et al*., 2015). Wang *et al.* (2011) concluded that Pakistan’s flood in 2010 occurred due to the interaction of tropical systems with extratropical disturbances downstream of the European blocking. Our results also support these studies and put an emphasis on westerly systems as important factors in causing summer wet spells over the core monsoon domain of Pakistan. In addition, a southward shift of the westerly jet has been observed over past several decades resulting in stronger upper-level troughs towards northern Indian sub-continent under warming climate (Wang *et al*., 2015). This implies an increased likelihood of the occurrence frequency of wet spells over Pakistan.

This study shows that during these 53 wet spells, the upper-level trough was present over Pakistan during 49 wet spells. Only 4 wet spells resulted from the LPS without the westerly trough intrusion. The connection illustrated here between the occurrence of wet spells and synoptic scale conditions points to a potential predictability of the wet spell risk to the extent that these synoptic systems can be predicted.

4.2 Extratropical systems and monsoon break over India

It was noted that protrusion of the upper-level trough to the south causes the incursion of moisture from the north Arabian Sea due to southerly flow. When the upper-level trough and low pressure system coexisted, the moisture was transported from the Bay of Bengal. This is different from the synoptic conditions causing wet spells over Indian core monsoon region. The intrusion of upper-level trough to southern latitudes is associated with the displacement of lower tropospheric monsoon trough into the Himalayas, a symptomatic of monsoon break over India (Raman and Rao, 1981). They also argued that a monsoon ridge over central Asia corresponded to weak monsoon conditions over India. It was observed that during normal monsoon over India, the upper-level trough moved eastward and did not grow in amplitude over Indo-Pak region. However, occasionally the upper-level trough stalled and grew in amplitude over this region replacing the easterlies with westerlies. It was in such situations that there were breaks in monsoon rain over India (Ramaswamy, 1962). On the other hand, 19 wet spells resulted from the sole presence of upper-level troughs over Pakistan. During these wet spells, the upper-level trough grew in amplitude over Pakistan. These troughs steered the cold air from north to the study region, where it interacted with warm and moist air from south. These patterns of convergence and deformation are favorable for frontogenesis (Chen *et al.*, 2007). Previous studies do not highlight this feature, as they focus on LPS as the triggering factor for heavy rainfall events. The occurrence of 19 wet spells in the presence of deep upper-level trough alone shows the importance of extratropical systems in triggering heavy rainfall events over Pakistan. While these conditions tend to cause a break of Indian summer monsoon.

Raman and Rao (1981) proposed that the development of an east Asian blocking ridge occurs a few days after the appearance of a west Asian blocking ridge, when the upper-level trough gets deeper. In deep trough cases, the east Asian ridge is more intensified. It suggests that the more pronounced of east Asian ridge, the deeper the trough. This will mark the onset of monsoon break over India, as it will shift the low tropospheric monsoon trough over the Himalayas. In this sense, when a wet spell starts over Pakistan due to an approaching deep trough, it also can be a short-term predictor of break monsoon conditions over India.

4.3 Anomalous large-scale circulation during wet spells

The anomalous circulation during wet spells showed that the 200 hPa cyclonic anomaly in geopotential height appeared over northwest of Pakistan. It was reported that the upper tropospheric cyclonic anomaly caused the intrusion of cold mid-latitude air into the tropics and resulted in dry spells over India (Singh *et al.*, 2014). The extremely active monsoon over northern India is preceded by the occurrence and strengthening of an upper-level tropospheric central Asian high and the anomalous low over this region preceded the strong monsoon break conditions (Ding and Wang, 2008). Krishnan *et al.* (2000) also observed a cyclonic anomaly over northwest of India during the weak phase of Indian summer monsoon. However, wet spells over Pakistan showed a tropospheric barotropic structure with cyclonic anomalies extending over northwest of the study region from the surface up to 200 hPa.

Hence, the analysis of wet spells over Pakistan showed distinct and opposite characteristics from that over India. The 200 hPa cyclonic anomaly over north of

Pakistan was an essential feature of wet spells, which was associated with dry spells over central India. So, the dynamics of wet spells over these two neighboring countries are different. Conditions causing wet spells over Pakistan do not cause significant precipitation over the core monsoon region of India (Figure 1b). This can be attributed to the different mechanisms of wet spells over India and Pakistan. We observed that more than 90% of wet spells over the core monsoon domain of Pakistan showed the presence of an upper-level trough over northern Pakistan. However, heavy rainfall in the core monsoon region of India in summer is mainly associated with monsoon depressions, and cold air intrusion from the mid-latitudes generally leads to dry spells.

In addition to the cyclonic anomaly over north Pakistan, another persistent feature is the presence of the significant anti-cyclonic anomaly over west Asia. This anticyclonic anomaly reaches its peak magnitude one day before the event. Previous studies associated this anticyclonic anomaly with a blocking high due to its persistence and believed to emit significant wave activity flux that drives the growth of cyclonic anomaly. Our results also show the persistent anticyclonic anomaly, which causes the downstream cyclonic anomaly over north Pakistan. These persistent cyclonic and anticyclonic anomalies indicate a Rossby wave train pattern. The wave activity flux shows maxima over Pakistan during the entire wet spells period.

The processes leading to the wet spells are as follows: Prior to the start of a wet spell, the main feature was a developing ridge over mid-west Asia. This ridge appeared over mid-west Asia 3 to 4 days prior to the occurrence of wet spell over Pakistan. In the next few days, the downstream trough developed and moved southward and deepened over north of Pakistan. On the day of wet spell, the trough got deeper over the study region. Ahead of this trough, the positive vorticity advection occurred to encourage strong vertical motion and enhanced instability. This strong uplifting controlled the initiation and strength of convection. During the trough without LPS wet spells, when the trough was deeper over Pakistan and reached southward, the moisture was mainly transported from the Arabian Sea. While in the case of trough with LPS systems, the trough was rather shallow over north of Pakistan and the moisture was steered from the

Bay of Bengal by an LPS. Though the low pressure systems helped in causing wet spells over Pakistan, but nearly one third of wet spells, showed the deepening of upper-level trough and associated moisture transport from the Arabian Sea. This confirms that low pressure systems are not the main contributors to these wet spells. Does heavy precipitation always occur during the presence of a mid-latitude trough? Among 53 wet spells identified, there are only four wet spells having no mid-latitude trough present. In this sense, we can say that the chances of a heavy rainfall event are very high when a mid-latitude trough develops and deepens over Pakistan.

5 Conclusions

The present study has focused on the large-scale and synoptic scale configurations causing wet spells in the core monsoon region of northern Pakistan. Using observation and reanalysis data, we have investigated the large-scale circulation patterns associated with these wet spells. Our analyses suggest that upper-level troughs over north of Pakistan and monsoon low pressure systems from the Bay of Bengal are the two dominant synoptic systems during heavy precipitation episodes over Pakistan. It is found that contemporaneous presence of LPS and trough causes the majority of wet spells with moisture incursion from the Bay of Bengal. The second leading system found is the large-amplitude trough protruding southern Pakistan that triggers the deep convection in the presence of moisture supply, particularly due to the southwesterly from the Arabian Sea. The composite analysis shows that synoptic conditions guide the atmospheric flow towards the study region and subsequently discharge the moisture due to synoptic forcing and orographic lifting. The confluence of the upper-level trough and monsoon low was found during 55% of wet spells. During 35% of wet spells, the low pressure system was not present. All wet spell episodes required a low-level convergence of humid air, vertical ascending motion and upper-level divergence over Pakistan.

One key finding of this study is the importance and prevalence of the upper-level trough for northern Pakistan wet spells. The development of the west Asian blocking ridge is generally a harbinger of the downstream trough development over

Pakistan. This is mainly related to the Rossby wave energy propagation. However, the trough needs to be steady or move slowly eastward to produce prolonged precipitation to cause a wet spell. In most circumstances, a downstream development of blocking or high is needed. As a result, the buildup of an upstream blocking and a subsequent development of a downstream high is an important signal for the prediction of wet spell over Pakistan, but what set up the blocking warrants further studies.

The presence of a blocking signal over west Asia before the heavy rainfall onset over Pakistan will give some guidance for its future behavior with climate change too. Nabezadah *et al.* 2019 reported that the area of blocking events in Northern Hemisphere will increase by as much as 17% due to anthropogenic climate change. In this sense, we can expect more catastrophic flooding events over Pakistan associated with increased atmospheric blocking in the future.

Acknowledgments

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Table Captions

Table 1. The wet spells over Pakistan during 1951-2015 showing the mean rainfall and presence of trough and LPS. P and A indicated the presence and absence of the upper level trough respectively.

Figure Captions

Figure 1 Spatial distribution of (a) mean summer rainfall during JAS and (b) averaged wet spell rainfall of the events shown in Table 1.

Figure 2 A composite map of (a) geopotential height (black contour with an interval of 30 gpm) and wind speed (shaded) at 200-hPa and (b) precipitable water (shaded) and low level winds (vectors) at 850-hPa level, during trough with LPS wet spells. (c), (d) same as (a), (b), but during trough without LPS wet spells. (e), (f) same as (a), (b), but during LPS only wet spells. The stippling shows geopotential height meets the 95% confidence level based on Student's t test.

Figure 3 Mean precipitation distribution for (a) Trough with LPS days, (b) Trough without LPS days, and (c) LPS only days. The contours show percentage (%) contribution by each system to total rainfall during wet spells.

Figure 4 The time evolution of 500 hPa geopotential height (contour interval 30 gpm) , 200 hPa zonal wind (a, c, e) and 850 hPa horizontal winds and sea level pressure (b, d, f) valid during 2-4 August 1953.

Figure 5 The time evolution of 500 hPa geopotential height (contour interval, 30 gpm), 200 hPa zonal wind (a, c, e, g) and 850 hPa horizontal winds and sea level presssure (b, d, f, h) valid during 14-17 July 1964.

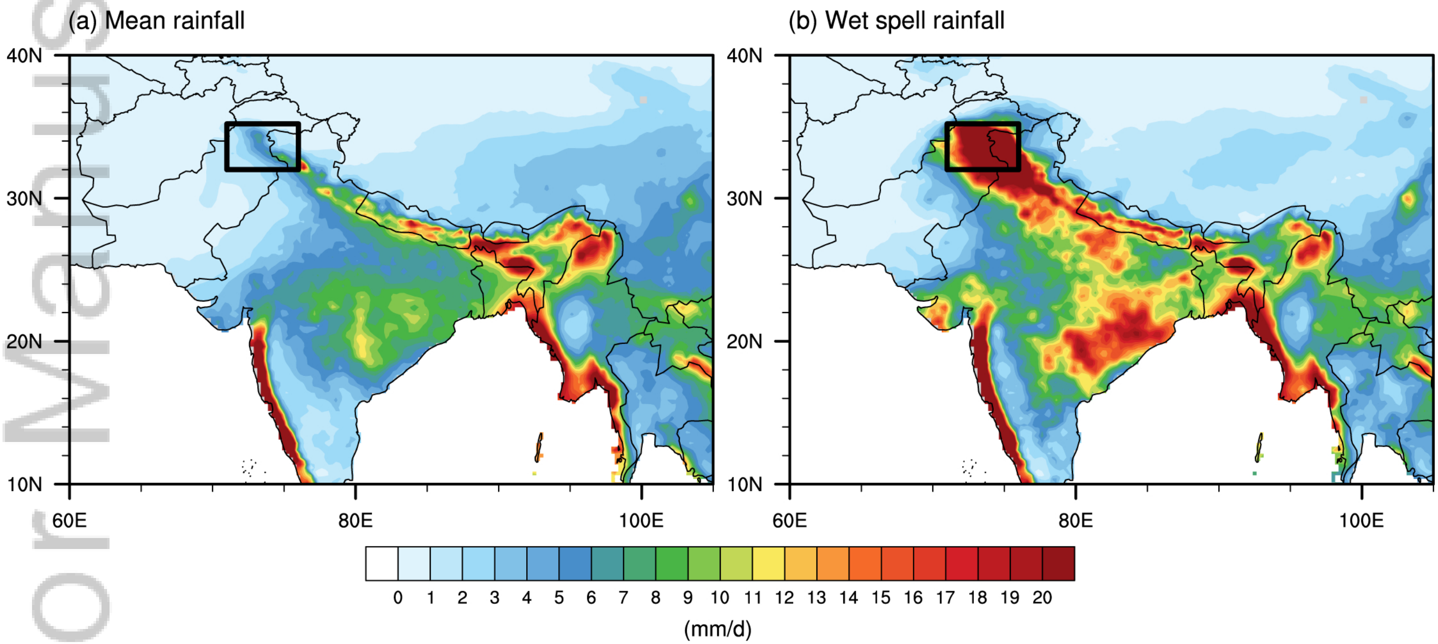
Figure 6 The composite of 500 hPa geopotential height and vertical velocity (omega) during (a) Trough with LPS, (b) Trough without LPS and (c) only LPS type of wet spells.

Figure 7 A composite map of 500 hPa trough (black contour) and 200 hPa zonal wind (shading). (a) 5 days, (b) 4 days, (c) 3 days, (d) 2 days, (e) 1 day prior to and (f) onset day of wet spells.

Figure 8 The time evolution of 200 hPa horizontal wind speed (shaded) and geopotential height (contours) during 14-17 July 1964 (a-d) and 22-25 July 1993 (e-h).

Figure 9 The time evolution of composite geopotential height anomalies (contours and shading) on 200 hPa surface from day -5 to day 0 (onset of wet spell) for 53 wet spells. The stippling indicates that results are significant at the 95% confidence level based on student's t test.

Figure 10 The geopotential height anomaly (contour and shading; units: gpm) and horizontal wave activity flux (vector; units: $m^2\ s^{-2}$) at 200 hPa averaged over 53 wet spells from day 0 to day +3.



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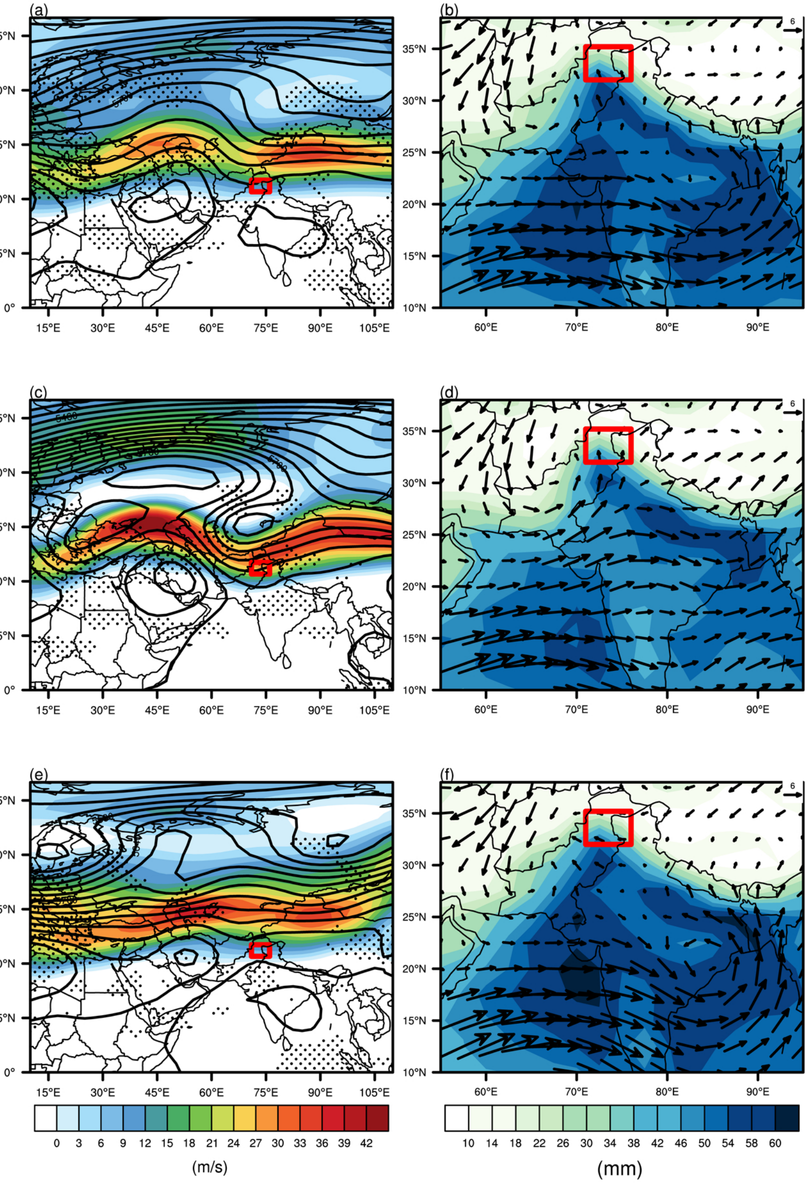

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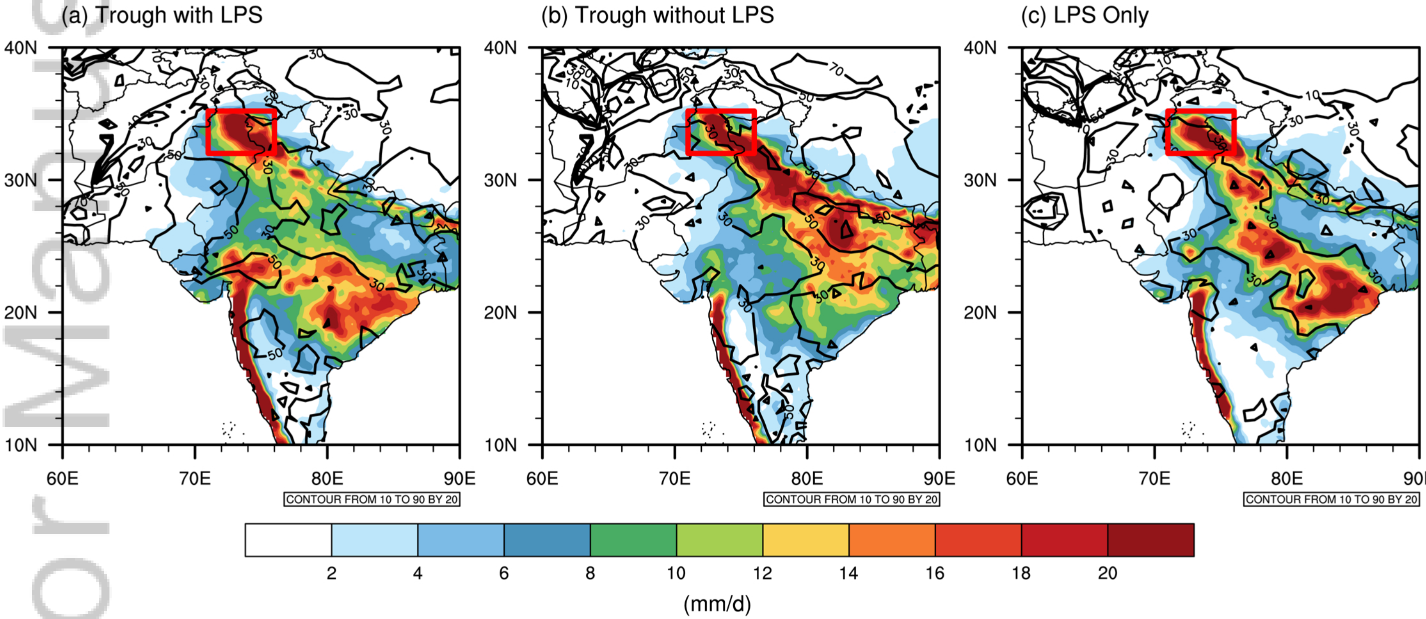

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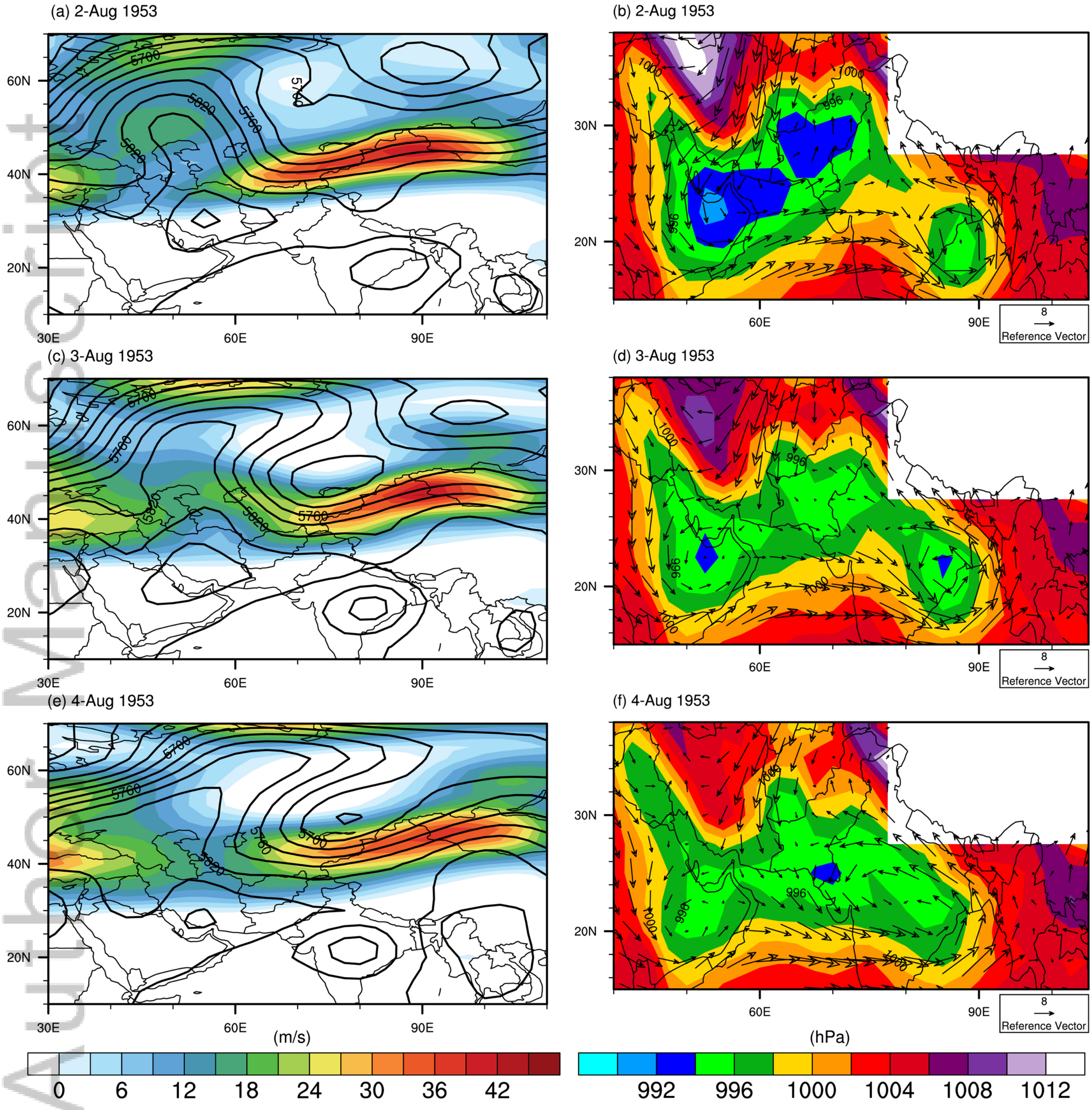

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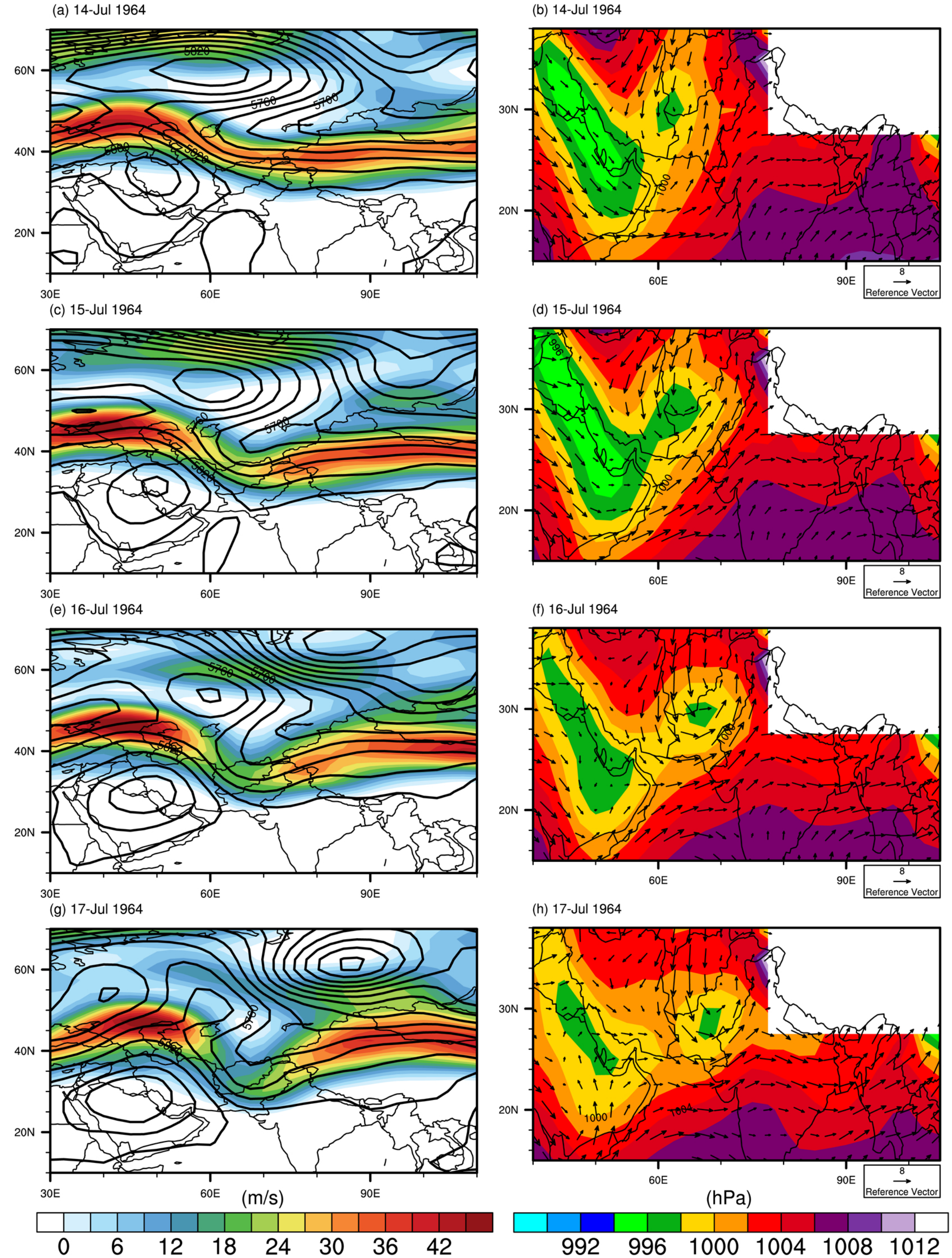

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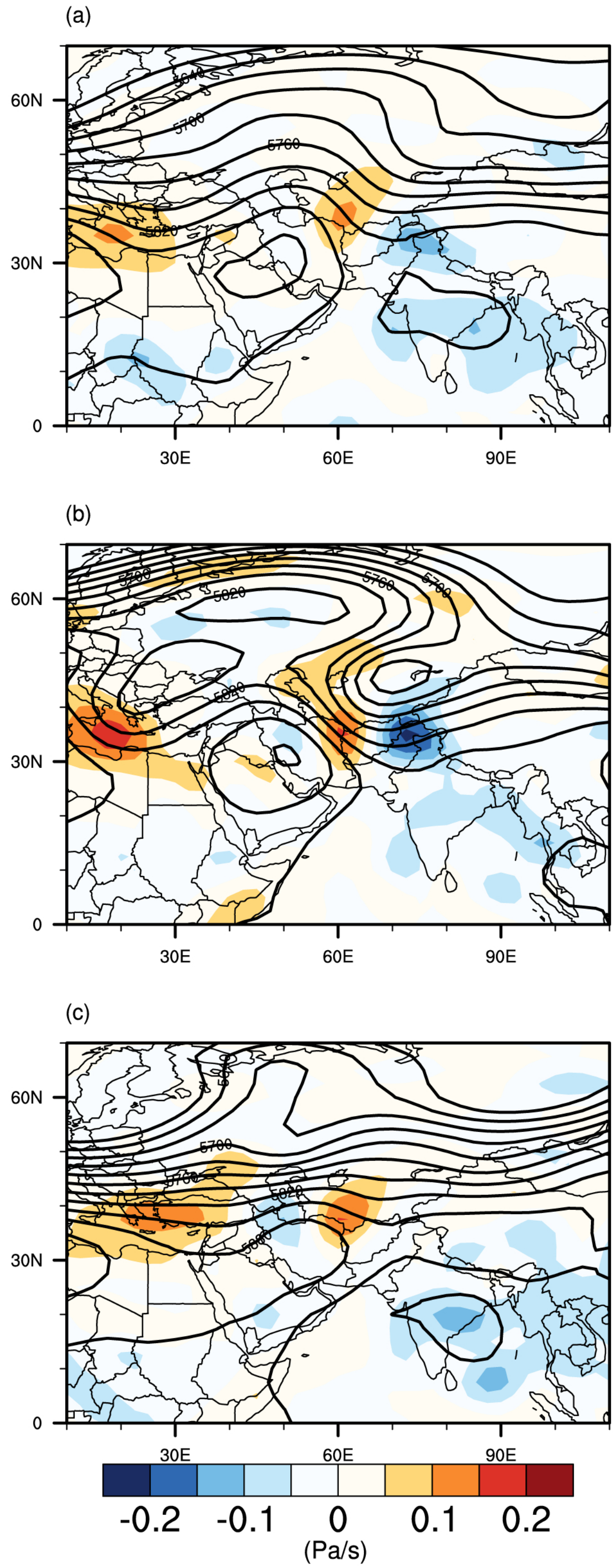

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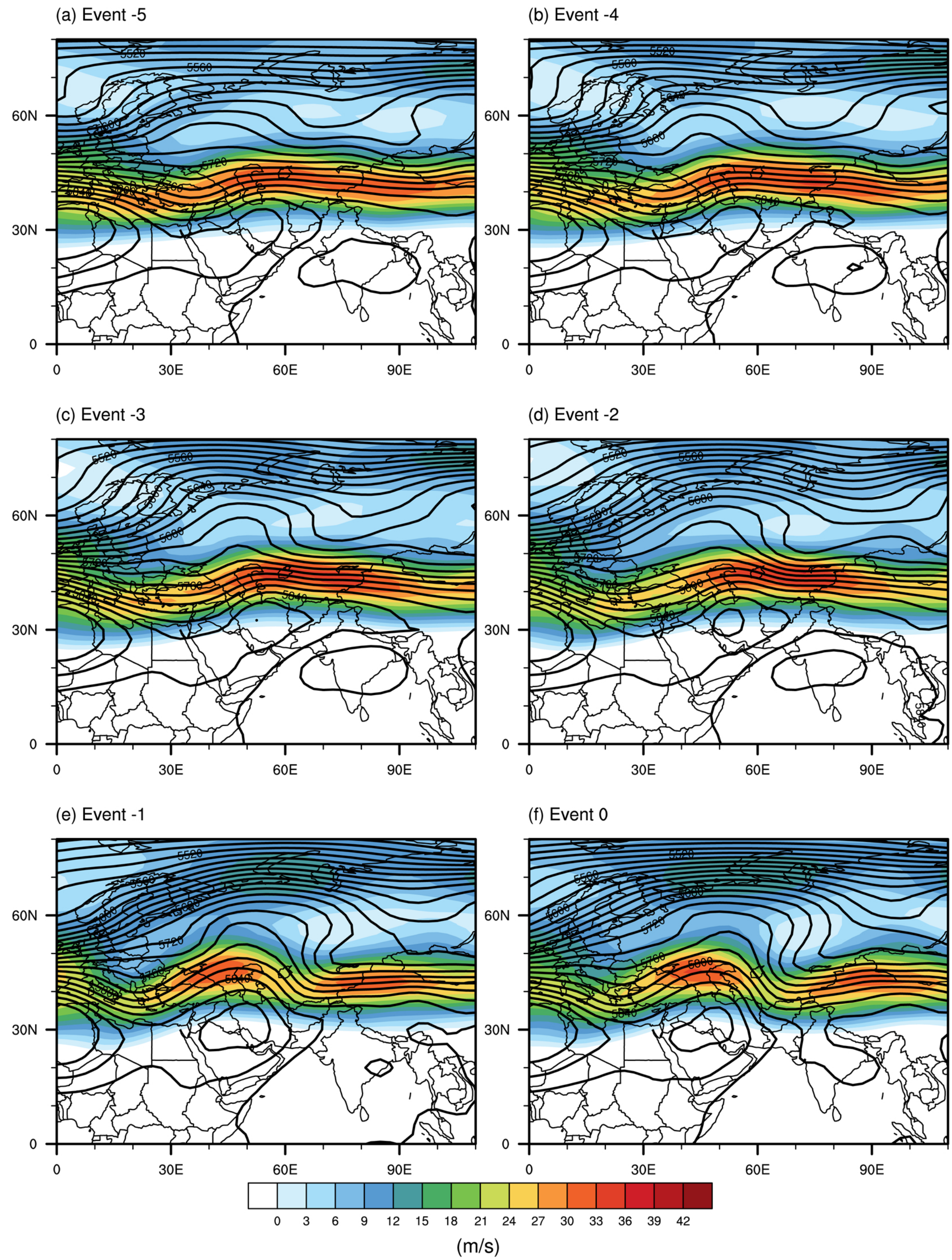

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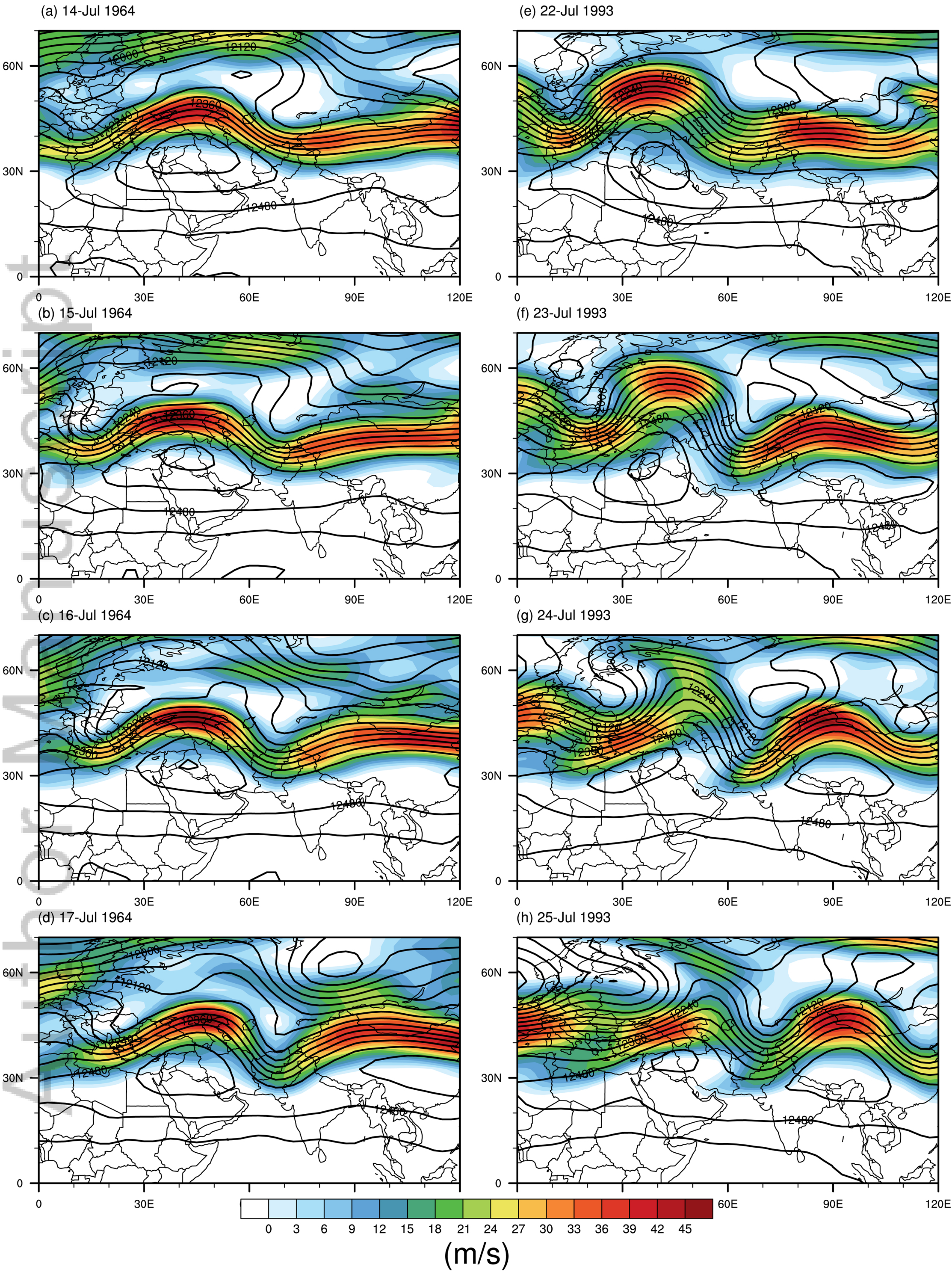

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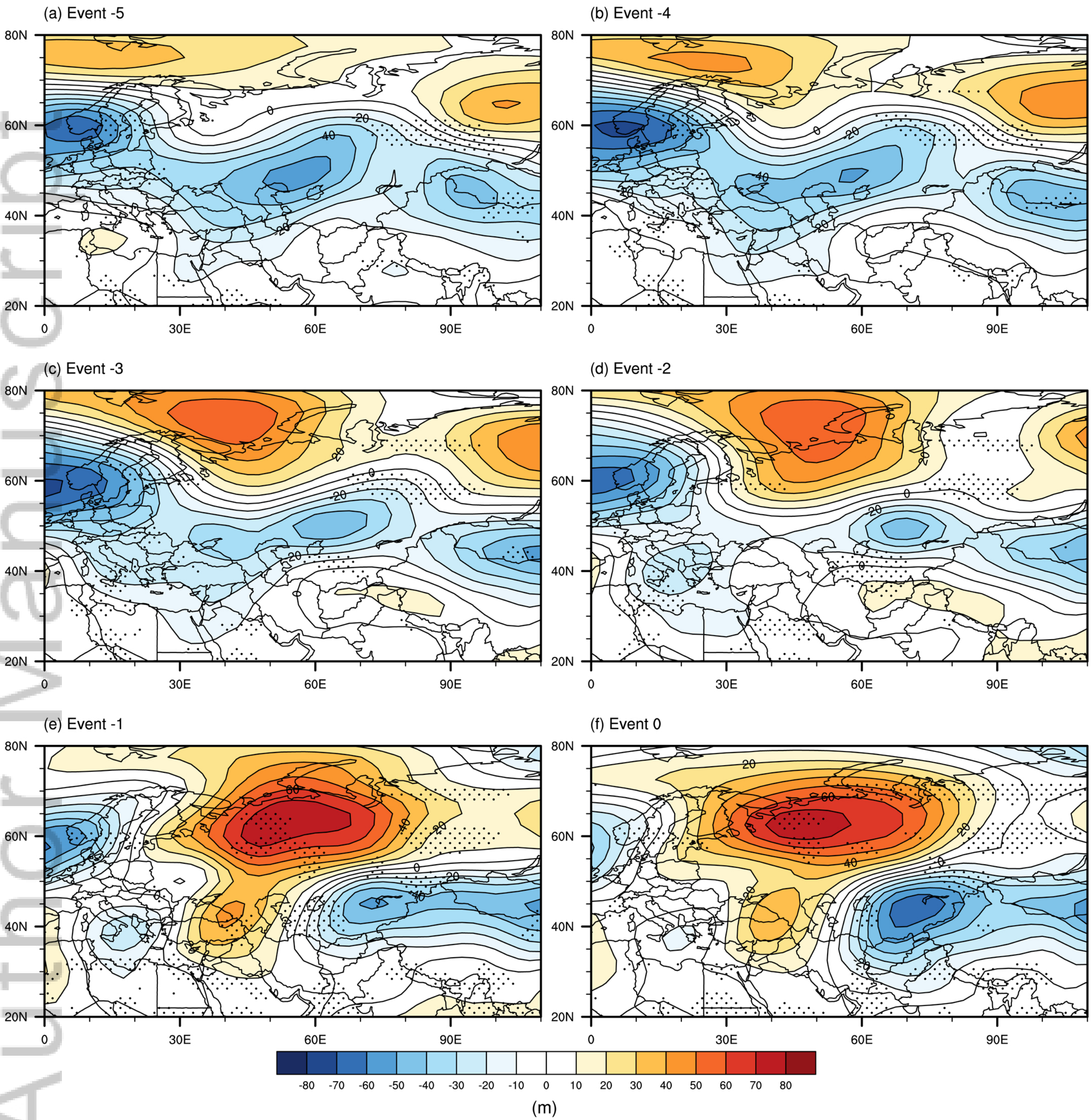

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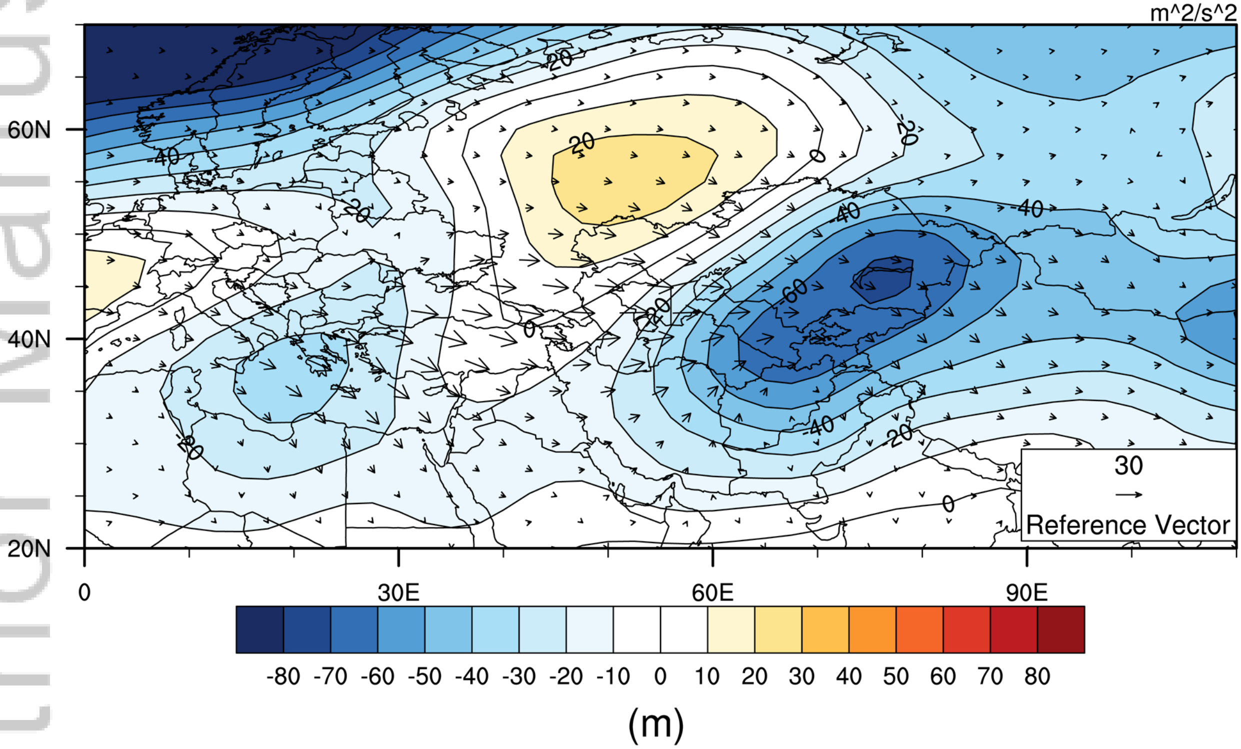

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Wet spells over the core monsoon domain of northern Pakistan during the summer season

Nabeela Sadaf[1*], Yanluan Lin[1], Wenhao Dong[2]

Key finding of this study is the importance and prevalence of the upper-level trough for northern Pakistan wet spells. The development of the west Asian blocking ridge is generally a harbinger of the downstream trough development over Pakistan. Sometimes these subtropical troughs are accompanied with low pressure system and cause moisture inflow from the Bay of Bengal. When amplitude of these troughs is high, the moisture incursion occurs form the Arabian Sea.

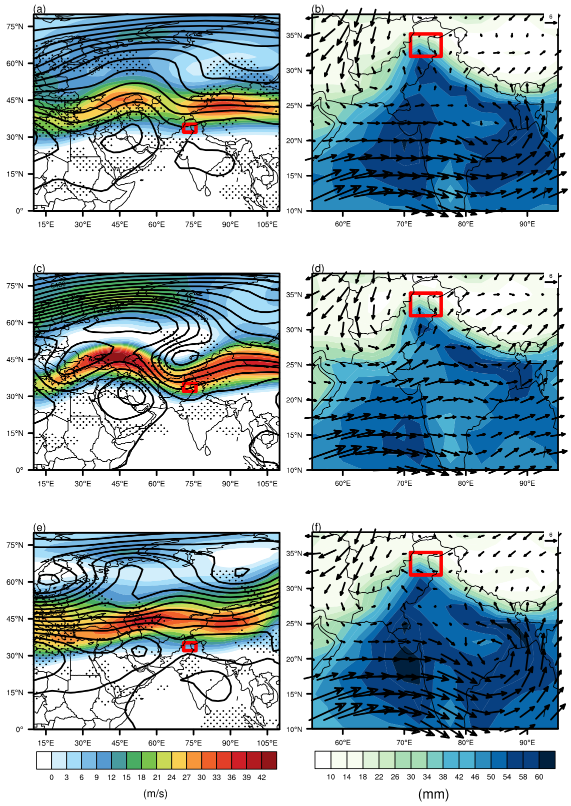

Table 1. The wet spells over Pakistan during 1951-2015 showing the mean rainfall and presence of trough and LPS. P and A indicated the presence and absence of the upper level trough respectively.

Case	**Year**	**Spell-period/P mm/day**	**Trough**	**LPS-status (NCEP)**	**LPS-status (ERA-Interim)**
1	1952	03-06Aug (7.94)	P	LPS	
2	1953	09-12 Jul (17.34)	P	No LPS	
3	1953	02 -04 Aug (12.30)	P	LPS	
4	1955	18-20 Jul (13.07)	P	No LPS	
5	1956	01-03 Jul (10.91)	P	LPS	
6	1956	01-03 Aug (19.31)	P	LPS	
7	1957	23-26 Jul (12.94)	P	No LPS	
8	1958	05-07Aug (15.84)	P	No LPS	
9	1959	02-06 Jul (25.85)	P	LPS	
10	1960	10-12 Jul (17.60)	P	LPS	
11	1962	19-21 Jul (12.87)	P	LPS	
12	1964	14-17 Jul (17.72)	P	No LPS	
13	1964	25-27 Jul (13.22)	P	No LPS	
14	1964	16-18 Aug (15.61)	A	LPS	
15	1969	23-25 Jul (9.74)	P	LPS	
16	1973	06-10 Aug (19.28)	P	LPS	
17	1974	04-06 Aug (10.21)	P	LPS	
18	1975	13-16 Jul (16.87)	P	No LPS	
19	1975	22-24 Jul (11)	P	No LPS	
20	1975	20-23 Aug (14.48)	P	LPS	
21	1976	01-03 Aug (35)	P	LPS	

22	1978	06-08 Jul (13.78)	P	LPS	
23	1978	22-25 Jul (11.7)	P	LPS	
24	1981	23-25 Jul (15.68)	P	No LPS	No LPS
25	1982	09-12 Aug (11.96)	A	LPS	LPS
26	1985	05-07 Aug (17.80)	P	LPS	LPS
27	1985	17-19 Jul (12.44)	P	LPS	LPS
28	1988	13-17 Jul (17.94)	P	No LPS	No LPS
29	1988	22-24 Jul (13.56)	P	No LPS	No LPS
30	1990	8-10 Aug (10.27)	A	LPS	LPS
31	1995	24-28 Jul (19.76)	P	LPS	LPS
32	1993	22-25 Jul (14.4)	A	LPS	LPS
33	1993	8-11 Jul (14.1)	P	LPS	LPS
34	1997	12-14 Aug (11.41)	P	LPS	LPS
35	1999	18-21 Jul (9.86)	P	No LPS	No LPS
36	2000	22-24 Jul (12.66)	P	LPS	LPS
37	2001	23-25 Jul (9.69)	P	No LPS	No LPS
38	2003	19-21 Aug (10.33)	P	LPS	LPS
39	2005	06-08 Aug (10.39)	P	LPS	LPS
40	2006	12-14 Jul (18.77)	P	No LPS	LPS
41	2006	03-07 Aug (15.07)	P	LPS	LPS
42	2010	19-22 Jul (16.96)	P	No LPS	No LPS
43	2010	27-29 Jul (27.46)	P	LPS	LPS
44	2010	05-07Aug (10.8)	P	LPS	LPS
45	2010	10-12 Aug (12.45)	P	LPS	LPS
46	2013	06-09 Jul (11.67)	P	No LPS	No LPS
47	2013	01-04 Aug (17.77)	P	LPS	LPS
48	2014	01-04 Jul (12.22)	P	No LPS	LPS
49	2014	16-18 Jul (27.5)	P	No LPS	LPS
50	2014	15-18 Aug (23.19)	P	No LPS	No LPS

51	2015	10-12 Jul (15.05)	P	LPS	LPS
52	2015	23-29 Jul (17.46)	P	LPS	LPS
53	2015	31Jul-04 Aug (25.30)	P	LPS	LPS