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The Asian summer monsoon response to the La Niña event of 2010

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ABSTRACT: The 2010 summer monsoon was marked by a series of flood events over Pakistan and Northwest India and an intriguing aspect during this season was the strong westward shift of West Pacific Subtropical High (WPSH) by nearly 15° longitude relative to the climatology. This period also witnessed the evolution of an intense La Niña in the Pacific Ocean. La Niña episodes are generally characterized by wetter-than-normal monsoons over South Asia, although the situation was rather different in 2010. Large areas covering east-central India, the Bay of Bengal and extending eastward into the South China Sea and the Philippines received deficit monsoon rains during 2010, while rainfall activity was enhanced mostly over northern India and adjoining northwest Pakistan. By conducting a detailed diagnostic analysis of observed and reanalysis datasets, it is found that the anomalous westward shift of the WPSH and suppression of convection around the Bay of Bengal region were crucial in sustaining the rainfall activity over northwest India and Pakistan during 2010. The results suggest that the westward shift of the WPSH favoured the setting up of an anomalous trough extending over the sub-tropical areas near India and Pakistan, so that the anomalous transport of moisture from the Arabian Sea sustained the local rainfall activity. An analysis of SST records during the last 60+ years, shows a long-term background La Niña-like warming trend in the tropical Pacific. Based on the present results, it is suggested that generation of La Niña events in the backdrop of the SST warming trend have significant potential in influencing the rainfall activity over the South Asian monsoon-trough region.

KEY WORDS Asian summer monsoon; La Niña; trend in SST

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1. Introduction

The 2010 summer monsoon was marked by the century's worst flooding over Pakistan and Northwest India caused by a series of monsoonal deluges, (Hong *et al*., 2011; Houze *et al*., 2011; Webster *et al*., 2011). The flooding over the mountainous part of North Pakistan during 2010 created a devastating impact (http://en.wikipedia.org/wiki/2010_Pakistan_floods). Houze *et al*. (2011) attributed the July to August 2010 floods over Pakistan to the westward displacement of storms pertaining to great departure of synoptic scale circulation. Webster *et al*. (2011) addressed the issue as to whether the extreme flooding over Northern Pakistan could have been predicted well in advance, especially since the series of flood events resulted from frequent occurrence of heavy rainfall events over the region. By analyzing 15 day ensemble forecasts from the European Centre for Medium Range Weather Forecasts (ECMWF), they showed that the heavy rainfall pulses in Pakistan throughout July and early August 2010 were in fact predictable almost 6–8 days in advance.

Hong *et al*. (2011) have pointed out that the anomalous rainfall activity over the India-Pakistan region during 2010 was related to persistent activity of European blocking and co-occurrence of tropical monsoon surges. Saeed *et al*. (2011) have suggested that the intensification of summer monsoon (June to September, JJAS mean) convection over the heat-low region of Pakistan and northwest India can set up a circum-global wave-like pattern that can interact with the summer monsoonal winds and sustain the enhanced rainfall anomaly over the region. In fact, the role of the circum-global teleconnection (CGT) pattern on the intraseasonal variability of monsoon rainfall over northwest India and adjoining region was pointed out by Ding and Wang (2005, 2007).

Another major aspect of the 2010 summer monsoon season was the evolution of a strong La Niña in the Pacific Ocean as catalogued in http://www.cpc.ncep.noaa.gov It can be noted from Figure 1 that the rainfall was anomalously enhanced over the warm SST regions of the equatorial west Pacific and the eastern Indian Ocean, together with strong-than-normal easterly trade winds and an intensified Pacific sub-tropical high that dominated the summer of 2010 (see description of Figure 2(b) in Section 3). An important question that arises here is the role of the anomalous La Niña conditions on the summer monsoon of 2010. Was the La Niña instrumental in setting up large-scale circulation patterns that were conducive for the persistent synoptic activity of monsoon disturbances over the India-Pakistan region during 2010?

La Niña events are known generally to favour surplus summer monsoon rainfall over India (Rasmussen and Carpenter, 1983; Halpert and Ropelewski, 1992). However, it is interesting to note that the monsoon rainfall activity was abnormally low during JJAS 2010, particularly over central and eastern India, the Bay of Bengal and adjoining areas of the South China Sea and the Philippine Sea (Figure 1). On the other hand, regions around northwest India received above normal rains during the 2010 summer monsoon (http://www.imd.gov.in/) An important large-scale anomalous feature during 2010 was the significant

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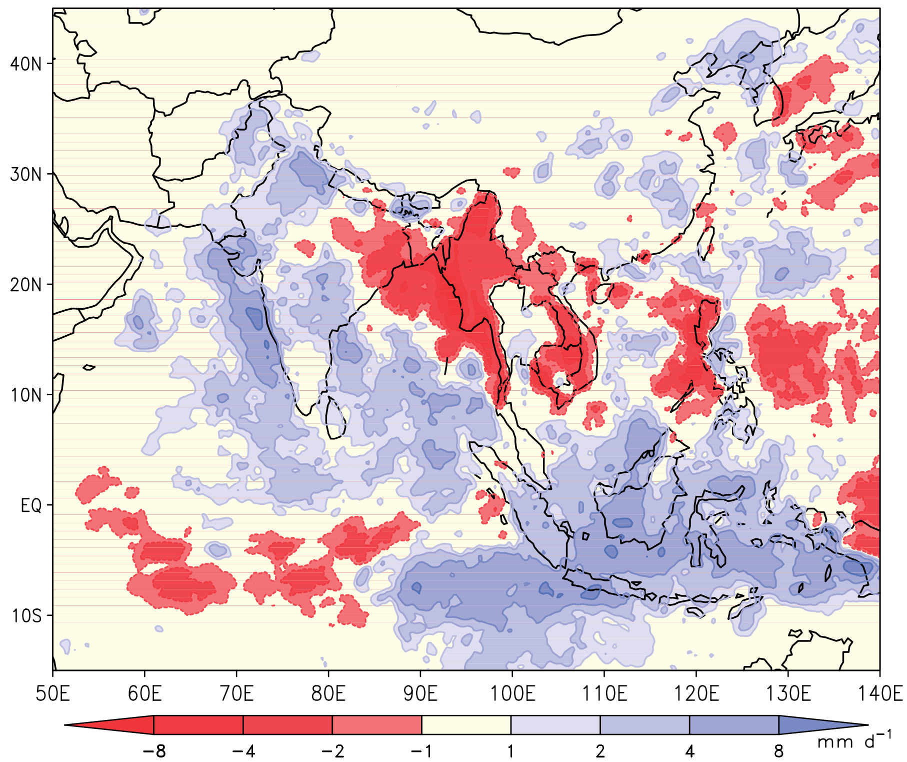

Figure 1. The spatial distribution of TRMM Rainfall anomalies (mm) for summer (JJAS) monsoon 2010. This figure is available in colour online at wileyonlinelibrary.com/journal/met

westward shift of the WPSH which was displaced by as much as 10–15° longitudes westward. The climatological mean position of western edge of WPSH was located at 133.5° E (Zhou *et al.*, 2009). It is not yet clear if this anomalous westward shift of the Pacific subtropical high influenced the large-scale monsoon circulation conducive for enhanced monsoonal synoptic systems and rainfall activity over Pakistan and northwest India during 2010. Have such large westward shifts of the Pacific subtropical high been observed during past La Niña episodes? Studies have pointed out that the spatial pattern of SST trends in the tropical Indo-Pacific basins during recent decades are associated with a La Niña type of condition (e.g., Cane *et al.*, 1997; Kumar *et al.*, 2004, 2010; Compo and Sardeshmukh, 2009). It is recognized that there is a debate about the phase of the SST trend in eastern tropical Pacific due to differences in some datasets, particularly when longer period data from the late nineteenth century are used (see Bunge and Clarke, 2009; DiNezio *et al.*, 2009; Deser *et al.*, 2010). Nevertheless, linear SST trends during the post-satellite era (1979–2010) seem to suggest a dominant La Niña type of SST pattern in the tropical Pacific (see Ashok *et al.*, 2012). Furthermore, this feature is consistently supported by the fact that the Western Pacific subtropical high has extended significantly westward since the late 1970s (see Zhou *et al.*, 2009). In the light of these studies, it would be interesting to contrast the La Niña and the anomalous monsoon during 2010 with the earlier events.

In this study, diagnostic analysis is carried out using observed data products to understand the interactions among La Niña induced large-scale circulation anomalies and their dynamical linkage with unusual summer monsoon rainfall activity over sub-tropical South Asia and tropical Indo-Pacific sector during 2010. The details of the observed data sets used in this study are given in next section. The results highlighting observed large-scale circulation features of unusual summer monsoon 2010 are presented in Section 3. An extended analysis covering the period (1948–2010) was also further carried out to understand how the La Niña induced monsoon teleconnections have varied in the past 60 years. Section 4 gives an overview of the extended analysis. The discussion and summary are presented in the last section.

2. Data

Datasets for the summer monsoon season (JJAS) from multiple sources have been employed in the present study. They include gridded rainfall data (0.25° × 0.25°) from Tropical Rainfall Measuring Mission (TRMM) 3B42-V6 from 1998 to 2010 (Huffman *et al.*, 2007) and the APHRODITE gridded (0.5° × 0.5°) daily rainfall dataset over Asia for the period 1951–2007 (Yatagai *et al.*, 2009). The National Center for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) reanalyses datasets (Kistler *et al.*, 2001) are used to represent the circulation field at standard pressure levels and mean sea level pressure, on a 2.5° × 2.5° grid resolution from 1948 to 2010. As a proxy of convection the National Oceanic and Atmospheric Administration (NOAA) interpolated outgoing long wave radiation (OLR) data (2.5° × 2.5°) for a period 1979–2010 (http://www.cdc.noaa.gov) have been used. The sea surface temperature (SST) data are based on monthly Hadley Centre Global Sea Surface Temperature (HadISST) data (Rayner *et al.*, 2003). In this study, an empirical orthogonal function (EOF) analysis (Bretherton *et al.*, 1992) has been used to decompose the dominant modes of the WPSH and Convection (OLR). The statistical significance of the various anomalies was estimated through the procedure in Noreen (1989), based on a permutation test with 9999 shuffles, following the Monte Carlo approach. More details about this statistical test are given in Terray *et al.* (2003).

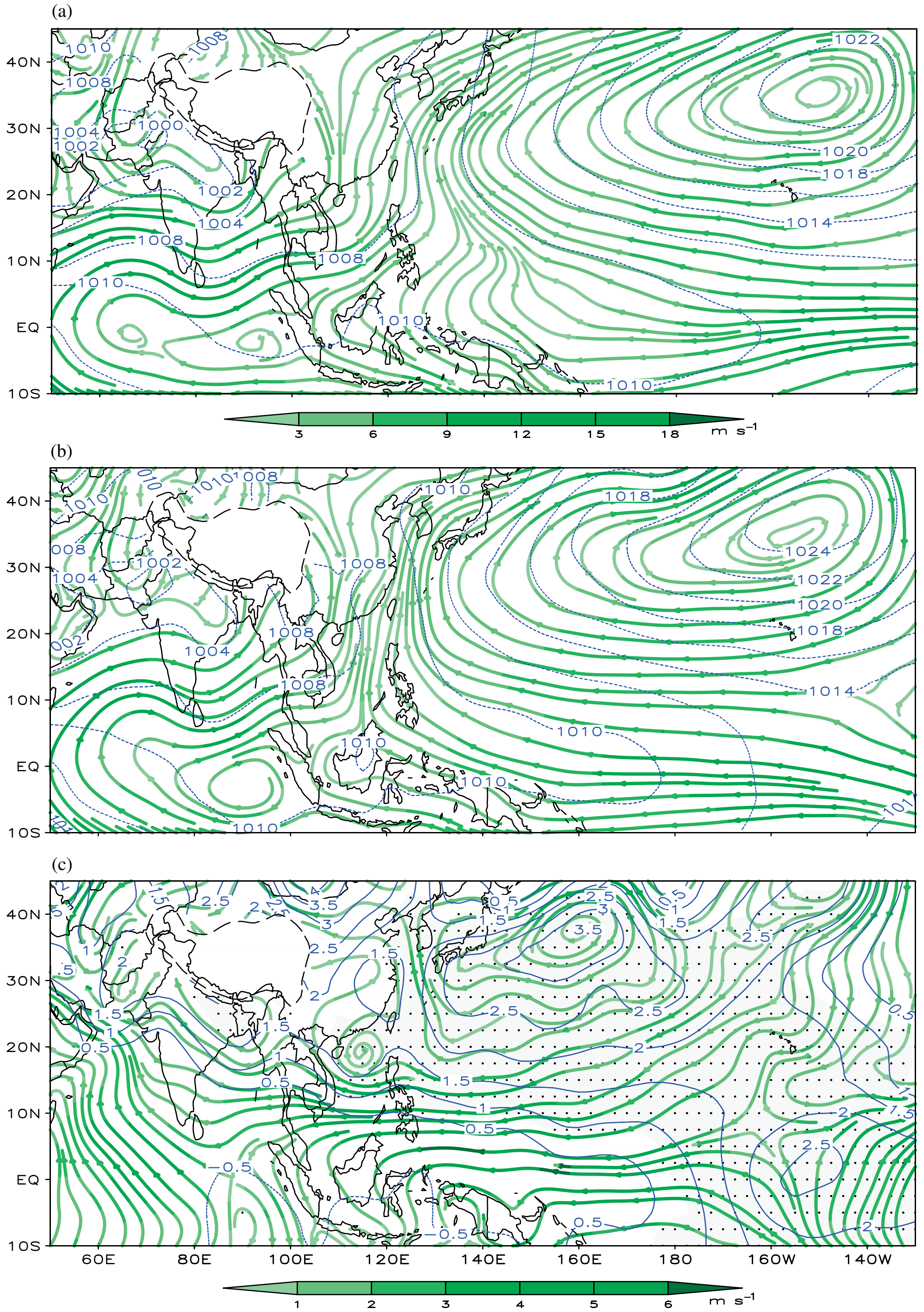

Figure 2. (a) The boreal summer (June to September, JJAS) monsoon climatology of lower tropospheric mean circulation features (from NCEP reanalysis dataset), sea level pressure (SLP) (hPa) (contours) and wind (m s^{-1}) at 850 hPa is shown with stream lines. The grey shades superimposed on streamlines depict the magnitudes of wind. The highly elevated (more than 1500 m) region of Tibetan Plateau is masked and marked by thick long dashed line. (b) Same as Figure 2(a) but for 2010 monsoon. (c) Same as Figure 2(a) except for JJAS 2010 anomalies. Also, the statistical significance (at 95%) of SLP anomalies for JJAS 2010 is shown in dot marks. This figure is available in colour online at wileyonlinelibrary.com/journal/met

3. Association of the 2010 Indian summer monsoon with the concurrent La Niña

Figure 2 shows the 850 hPa streamlines and mean sea level pressure (SLP) for the JJAS season. A comparison of the JJAS climatological low-level circulation (Figure 2(a)) and that of 2010 (Figure 2(b)) brings out two important points. Firstly, one can notice a prominent westward shift of the WPSH. Note that in the climatological SLP map (Figure 2(a)) the SLP contour of 1010 hPa, associated with the western rim of the subtropical high near 20°N, is located to the east of 140°E. On

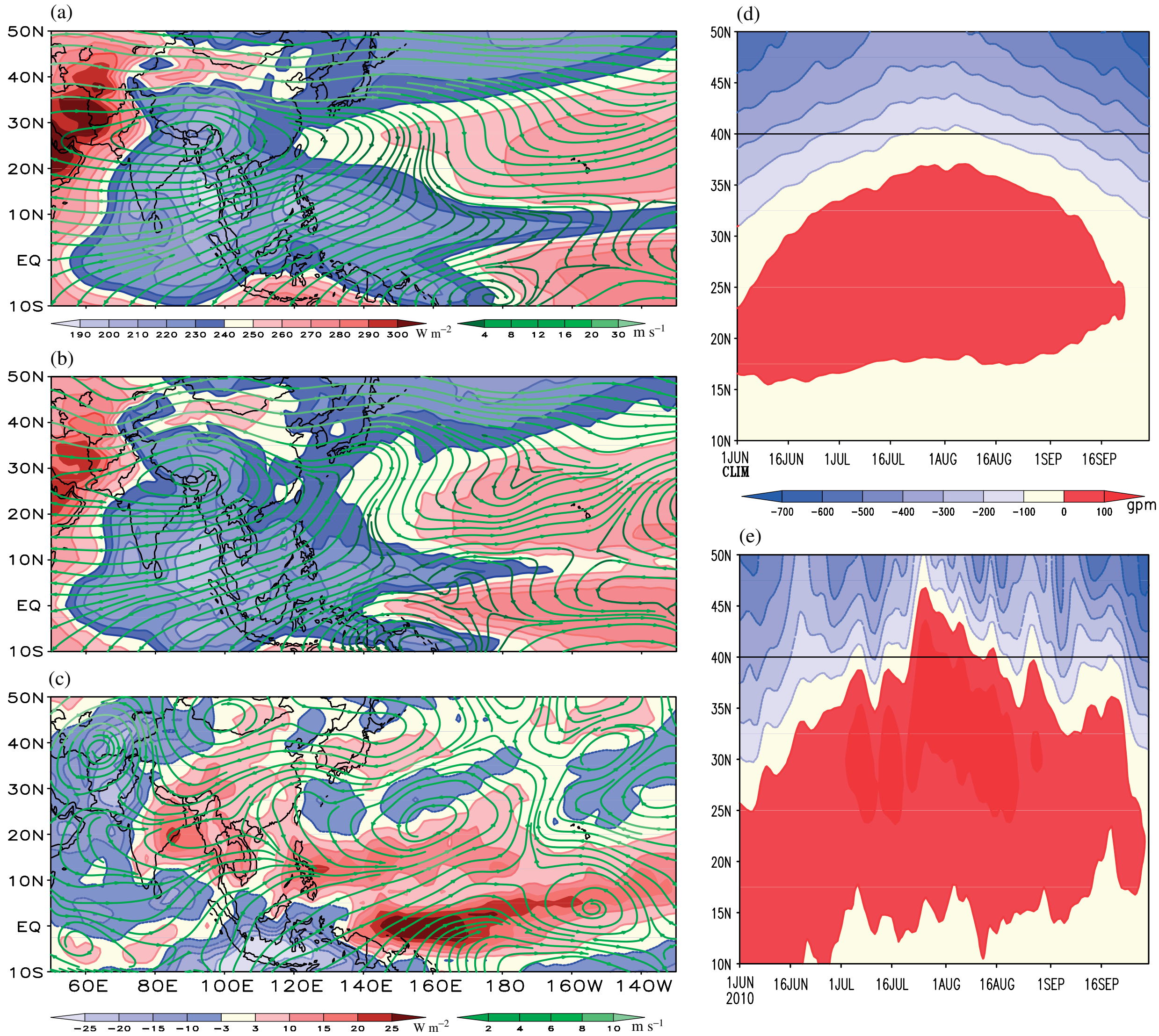

Figure 3. (a) The climatological winds (m s^{-1}, streamlines) at 200 hPa from NCEP reanalysis and outgoing long wave radiation (OLR) (W m^{-2}, shaded) from NOAA satellite for boreal summer (JJAS) monsoon. The shades superimposed on streamlines depict the magnitudes of wind. (b) Same as Figure 3(a)except for summer monsoon of 2010. (c) Same as Figure 3(a) except for the JJAS anomalies of 2010. (d) Latitudinal-time section of daily JJAS Climatology for 200 hPa Geopotential heights (+12 000 gpm, shaded) averaged over (70–90 °E), and (e) same as Figure 3(d) except for JJAS 2010. A line at 40°N has been drawn for better comparison. This figure is available in colour online at wileyonlinelibrary.com/journal/met

the other hand, the SLP contour of 1010 hPa during JJAS 2010 (Figure 2(b)) can be seen extending westward of 130 °E. This feature is referred to as the anomalous westward extension or shift of the WPSH. The positive SLP anomalies (Figure 2(c)), statistically significant at the 95% level, extending over the East Asian region, depict the anomalous westward extension of WPSH. Also, the anomalous anticyclonic easterly flow over the west Pacific and Bay of Bengal penetrate too deep into Indian sub-continent (Figure 2(c)). Due to the anomalous westward shift of the WPSH, one can note relatively weaker convergence of the easterly trades and the westerly mean monsoon winds in the off-equatorial west Pacific (125–135 °E, 10–35°N) during 2010 (Figure 2(b)) as compared to the climatology.

The second point is related to the heat low and monsoon trough which are important semi-permanent features of the South Asian monsoon (e.g. Sikka and Narasimha, 1995; Wang, 2004; Bollasina and Nigam, 2010; Ayantika and Krishnan, 2011). Studies have shown that cyclonic circulation associated with southward intrusion of mid-latitude westerly troughs over the western end of the monsoon trough together with moisture inflow from the Arabian Sea can favour increased convective activity locally (Ding and Wang, 2005, 2007; Saeed *et al*., 2010, 2011; Hong *et al*., 2011). The pronounced southerly component of monsoon flow from the Arabian Sea into northwest India during 2010 can be noted in Figure 2(b).

The aforementioned low-level circulation anomalies during 2010 are consistently supported by the variability of tropical convection and upper-level circulation. OLR from the NOAA satellite is a useful proxy for tropical convection wherein regions of low OLR are indicative of deep convection and low cloud top temperatures (Gruber and Krueger, 1984). It can be noticed from Figure 3(a) that the climatological mean OLR over the Bay of Bengal and adjoining areas has low values, ∼180–200 W m^{-2}, whereas during 2010 the OLR values (Figure 3(b)) exceeded 220 W m^{-2} depicting the positive OLR anomalies (Figure 3(c)) around + 20 W m^{-2} and is indicative of weakened convection over the region. The response of the upper tropospheric Tibetan high to changes in convection over the Bay of Bengal is consistently manifested in Figure 3. Upper tropospheric westerly anomalies over Bay of Bengal (Figure 3(c)) indicates weakening of the upper tropospheric easterlies and the Tibetan anticyclone during 2010 (Figure 3(b)) and this feature is accompanied by a meridional elongation of the Tibetan anticyclone at the centre (Figure 3(e)) when compared with the climatology (Figure 3(d)). On the other hand, it is interesting to note a clear southward intrusion of anomalous cyclonic troughs in the sub-tropical westerlies over Pakistan and adjoining areas during 2010 (Figure 3(c)). In particular, the OLR values were lower than 200 W m^{-2} (Figure 3(b)) with strong negative anomalies of -20 W m^{-2}

(Figure 3(c)) over the sub-tropical India-Pakistan and sub-Himalayan regions (around 70°E, 30°N). It is worth mentioning that the magnitude of OLR (SLP, Figure 2(c)) anomalies exceeds twice the standard deviation (figures not shown) over northwest India-Pakistan region (tropical Indo-Pacific sector). Consistent with the La Niña conditions, enhanced convection (mean OLR $<$ 180 W m^{-2} and negative anomaly exceeding -20 W m^{-2}) prevailed over the equatorial west Pacific, east Indian Ocean and adjacent Indonesian region (Figure 3(b) and (c)). The rainfall anomalies (Figure 1) are also consistent with the anomalous convection features in these equatorial regions.

4. Extended analysis over 1948–2010

Prompted by the anomalous convection and circulation response over the Asian monsoon sector during the summer monsoon 2010, we have extended our analysis over a longer period of 1948–2010 as well. The main objective of this extended analysis is to explore and understand past cases of anomalous monsoon response during La Niña events. Zhou *et al.* (2009) have reported that the boreal summer west Pacific subtropical high (WPSH) has undergone a westward extension since the late 1970s, which they attribute to the atmospheric response to the observed Indian Ocean-western Pacific (IWP) warming. Following Trenberth (1997) 12 summer monsoon seasons (1954, 1955, 1956, 1964, 1970, 1971, 1973, 1975, 1988, 1998, 1999, 2010) coinciding with La Niña events, during 1950–2010, are considered. Figure 4(a) shows the composite of JJAS sea level pressure (SLP) anomalies related to the above 12 La Niña events. This La Niña composite pattern of anomalous SLP, depicting the negative values over South Asian summer monsoon region, is associated with above normal monsoon rainfall episodes over the region (Krishna Kumar *et al.*, 2006). A comparison of the 2010 JJAS SLP anomalies (Figure 4(b)) with that of the La Niña composite (Figure 4(a)) also depict westward shift (statistically significant at the 95% confidence level) of WPSH (Figure 4(b)). A quantitative assessment of the Asian summer monsoon and WPSH variability can be obtained by performing a principal component (PC)/empirical orthogonal function (EOF) analysis of the seasonal (JJAS) mean SLP anomalies over the Pacific basin (100–270°E and 0–50°N) for the period 1948–2010. The analysis shows that the contribution of variance from the first EOF is about 28%, which is not small in view of the fact that it accounts for variations over a large domain (figure not shown). The other EOF components have been examined as well and it has been found that the second (third) EOF accounted for about 8% (7%) of the total variance, which were not as prominent as that of leading component. The time-series of the principal component (PC) associated with the EOF1 (Figure 4(c)) clearly brings out the peak (of WPSH, see Figure 2(b)) during boreal summer of 2010, indicating that an intensification of the Pacific pressure pattern could be influential in the evolution of distinctly different monsoon convection over Asia as in 2010.

A quantitative assessment of variability of the convective activities over the sub-tropical northwest India-Pakistan region and the tropical Indo-Pacific sector can be obtained by performing an EOF analysis of the daily OLR anomalies during the unusual La Niña phase of the summer monsoon of 2010. A series of monsoonal deluges over northwest India-Pakistan region was observed during July and August of 2010 (see Webster *et al.*, 2011). Since convective activities, associated with these monsoonal deluges, tend to be smoothed out in the seasonal mean OLR data, the daily OLR anomalies have been examined to highlight the importance of convective activities over the India-Pakistan region. The structure of the leading EOF in Figure 5 shows a pattern of negative anomalies over the northwest India-Pakistan sub-tropical region and widespread positive anomalies over north-central India, the Bay of Bengal and extending eastward into the South China Sea and the Philippines. This first EOF pattern explains about 18% of the total variance. It is important to note that the independent contribution from the first EOF is not small in view of the fact that it accounts for variations over a large region covering northwest Pakistan, the Indian region and west Pacific Ocean. The other EOF components have also been examined (figures not shown). However, the convective asymmetry over the northwest India-Pakistan region and tropical Indo-Pacific sector during the 2010 summer monsoon was mainly associated with the first EOF. The comparison of the first EOF pattern of the daily OLR anomalies for other La Niña cases (e.g.1988, 1998 and 1999; figures not shown) with that of the 2010 La Niña event, clearly illustrate prominent widespread positive anomalies over the Indo-Pacific sector during 2010.

Figure 4(c) also illustrates that the negative values are significantly dominant since late 1970s which is also indicative of long-term variation of WPSH. The time series of the first PC is also obtained for the seasonal (JJAS) mid-tropospheric geopotential height anomalies over the Pacific (figure not shown) and found to be significantly correlated (0.6) with the time series of the first PC of SLP anomalies (Figure 4(c)). The results discussed above confirm a peak during 2010 and long-term variation of WPSH as described by previous studies (e.g., He and Gong, 2002; Zhou and Yu, 2005; Zhou *et al.*, 2009). This unusual characteristic of WPSH (Figure 4(b)) during the La Niña Phase of boreal summer monsoon 2010 is a peak of long-term variation (Figure 4(c)).

Figure 6(a) shows the temporal regression of HadISST anomalies onto the first PC time series of the Pacific SLP anomalies (Figure 4(c)) for the period (1948–2010). The anomalous warming in the western Pacific, prominent over the south equatorial region, and the anomalous cooling in the central and eastern equatorial Pacific, depict a pattern similar to a La Niña. This east-west SST gradient in the equatorial Pacific region, associated with stronger easterlies over the central and west Pacific Ocean, seems to be induced by enhanced down welling in the equatorial western Pacific region. The convective asymmetry over the northwest India-Pakistan region and the tropical Indo-Pacific sector is also clearly depicted (Figure 6(b)) in the regression of OLR anomalies on to the PC1 time series shown in Figure 4(c) (for the period 1979–2010). This regressed OLR pattern (Figure 6(b))

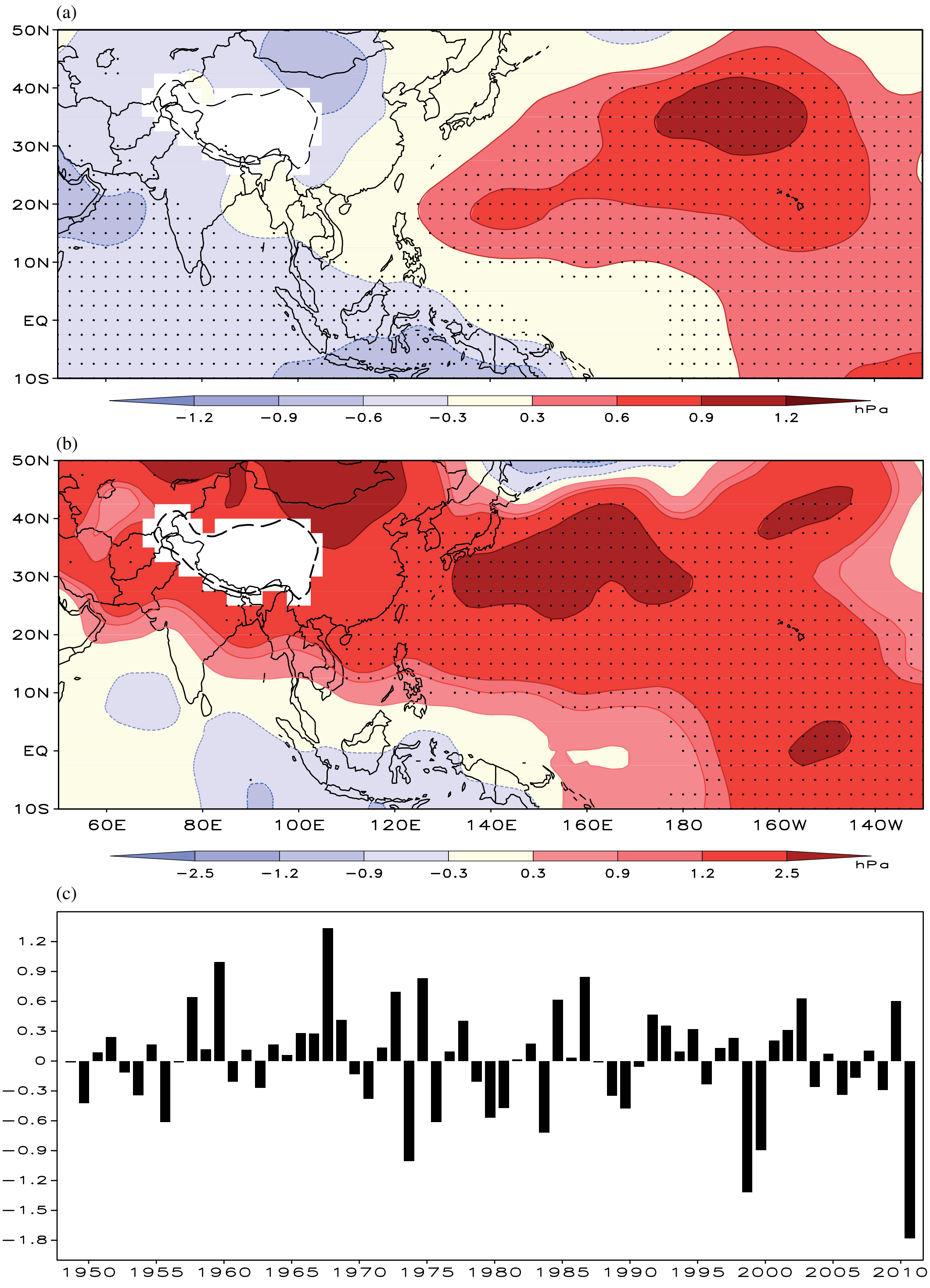

Figure 4. (a) Composite of summer (JJAS) monsoon sea level pressure (SLP) anomalies (shaded) for past La Niña events during 1948–2010. The statistical significance (at 95%) of SLP anomalies is shown in dot marks. (b) Same as Figure 4(a) except for 2010 La Niña case. (c) The time series of the first PC obtained from EOF analysis of boreal summer (JJAS) monsoon SLP anomalies over Pacific basin (100–270 °E and 0–50°N) during 1948–2010. The seasonal SLP during 2010 summer monsoon seems to be most remarkable. This figure is available in colour online at wileyonlinelibrary.com/journal/met

is consistent with the 2010 anomalous convective pattern over the region (Figure 3(c)). The suppressed convection over central and eastern India, north-central parts of the Bay of Bengal, South China Sea and Philippines region, and the enhanced convection over the Arabian Sea through the sub-tropical India-Pakistan region, could be interpreted as a westward shift in large-scale monsoon circulation. Further, intense convection over the southeast equatorial Indian Ocean and adjacent Indonesian region is consistent with the anomalous ocean warming over the region (Figure 6(a)).

The main feature depicted from the regression of the 850 hPa wind anomalies (1948–2010) on to the PC1 time series (Figure 4(c)) is a westward shift of WPSH (Figure 6(c)), with easterlies spanning the entire tropical Pacific and north Indian

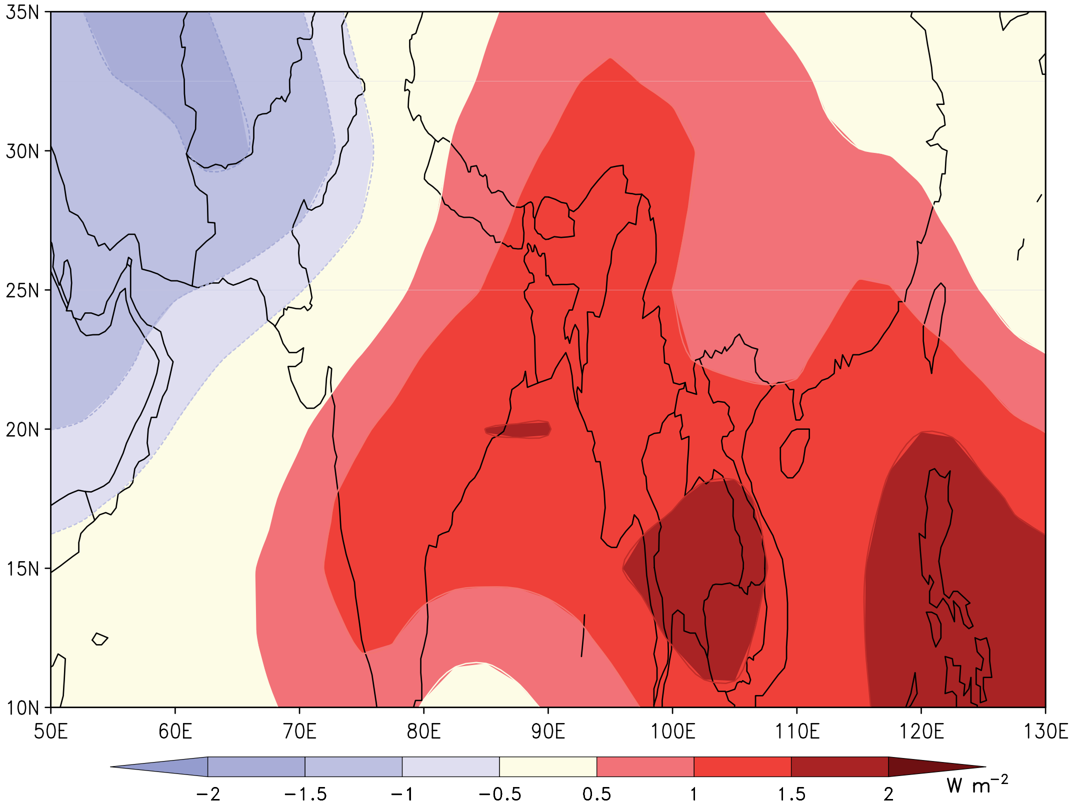

Figure 5. The spatial pattern (shaded) of the first EOF component of daily OLR dataset for JJAS 2010. The pattern of OLR anomaly depicts the opposite polarities over northwest India-Pakistan sector and south-central and east Asia. This figure is available in colour online at wileyonlinelibrary.com/journal/met

Ocean region, which is ultimately conducive for anomalous anticyclonic circulation over the region. The latter appears to fan out the convective activity over the Bay of Bengal, south China Sea and Philippines Sea, and is dynamically consistent with the large-scale negative rainfall anomalies over the regions. Thus, the westward shift of large-scale circulation over the Indo-Pacific sector seems to modulate the convective activities over the India-Pakistan monsoon trough region. It may be also noted that various recent studies (Goswami *et al.*, 2006; Guhathakurta and Rajeevan, 2008; Naidu *et al.*, 2009) have investigated the trend in Indian summer monsoon rainfall over a longer period (more than a century) and concluded that the various regions of India (e.g. Central India, west coast, northeast sector) depict a gradual increasing/decreasing trend. However, no significant trends could be noticed in monsoon as well as annual rainfall over All India domain. The association of westward shift of WPSH since the 1970s and the long-term changes in the large-scale summer monsoon circulation needs further investigation.

In addition to the flood events of 2010 (Webster *et al.*, 2011), there have been other summer monsoon seasons (e.g., 1956, 1973, 1983, 1988) when parts of Pakistan and northwest India received very heavy rain spells (>15 mm day^{-1}) leading to seasonal rainfall exceeding 300 mm (Figure 7). Incidentally, some of these years (e.g. 1956, 1973, and 1988) were associated with La Niña conditions in the Pacific. This suggests that convection changes during La Niña events have the potential to set up large-scale teleconnection patterns extending into the sub-tropical and mid-latitude regions of Eurasia, as in 2010 (Hong *et al.*, 2011). The generation of such large-scale teleconnection patterns with a cyclonic anomaly pattern over Pakistan and adjoining regions can in turn favour of increased rainfall and convective activity over the region.

5. Summary and discussion

Recent studies have discussed the persistent convective activities over the sub-tropical India-Pakistan region during the monsoon season of 2010 (Lau and Kim, 2011; Houze *et al.*, 2011; Webster *et al.*, 2011). An intriguing aspect of the 2010 summer monsoon circulation pertains to the strong westward shift of the West Pacific Subtropical High (WPSH) associated with La Niña conditions in the tropical Pacific. In this study, a diagnostic analysis of observed datasets has been undertaken to understand the linkage between the South Asian monsoon convective activity and the westward shift of unusually intense WPSH. In addition to the 2010 monsoon, an extended analysis is presented for the period 1948–2010 to comprehend whether similar westward shifts of the WPSH have occurred in the past and if they have influenced the monsoon convective activity over South Asia.

The results of the present study point to the role of La Niña conditions during JJAS 2010, in causing a significant westward shift (10–15° longitude) of the WPSH, thereby leading to a weakening of low level convergence and reduced convective activity over the off-equatorial regions of tropical west Pacific located near the Philippines and adjacent areas (Figure 2(b)). Furthermore, the anomalous low-level easterly winds associated with the westward shift of the WPSH favoured anticyclonic circulation and suppressed synoptic scale convective activities over the Bay of Bengal during the summer monsoon of 2010. The weaker monsoon circulation and large-scale suppression of

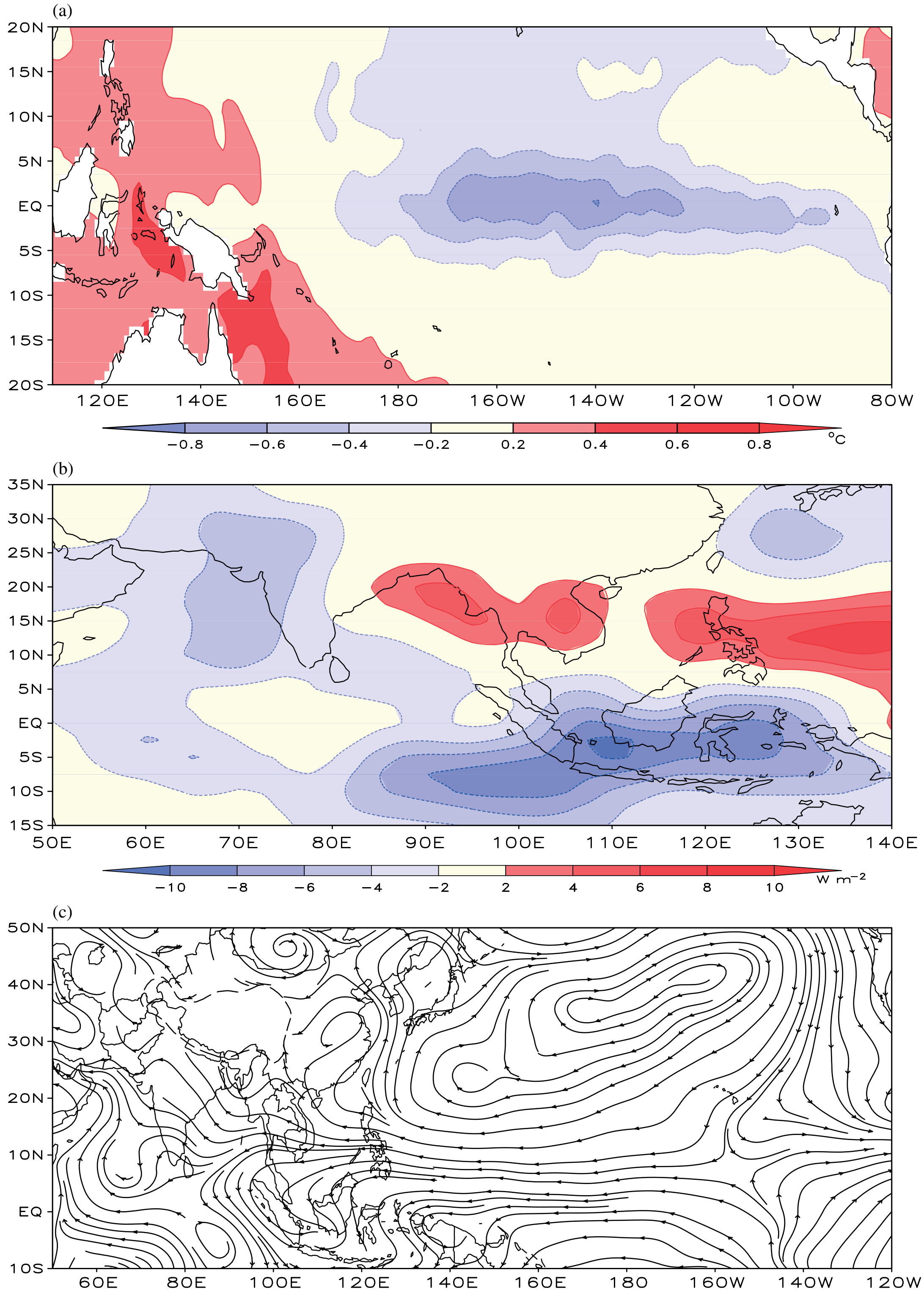

Figure 6. (a) Regression of Hadley Centre SST anomalies (shaded) on PC1 of boreal summer (JJAS) monsoon sea level pressure anomalies over Pacific basin during 1948–2010. (b) Same as Figure 6(a) except for NOAA OLR anomalies during 1979–2010. (c) Same as Figure 6(a) except for wind anomalies at 850 hPa (streamlines). This figure is available in colour online at wileyonlinelibrary.com/journal/met

convection over the Indo-Pacific sector also favours westward extension of WPSH and thereby endorses its interactions with the monsoon trough. The reduced summer monsoon convection over the Bay of Bengal and other adjoining areas is corroborated by a weakened Tibetan anticyclone during 2010 (Figure 3(b)). The direct comparison of Figure 3(d) with that of Figure 3(e) brings out meridional protrudment of the Tibetan anticyclone during the weaker monsoon conditions of 2010. The weaker Tibetan anticyclone and upper tropospheric easterlies, are characterized by meridional protrudment and weakened meridional potential vorticity (PV) gradients of the Tibetan High, which are conducive for the formation

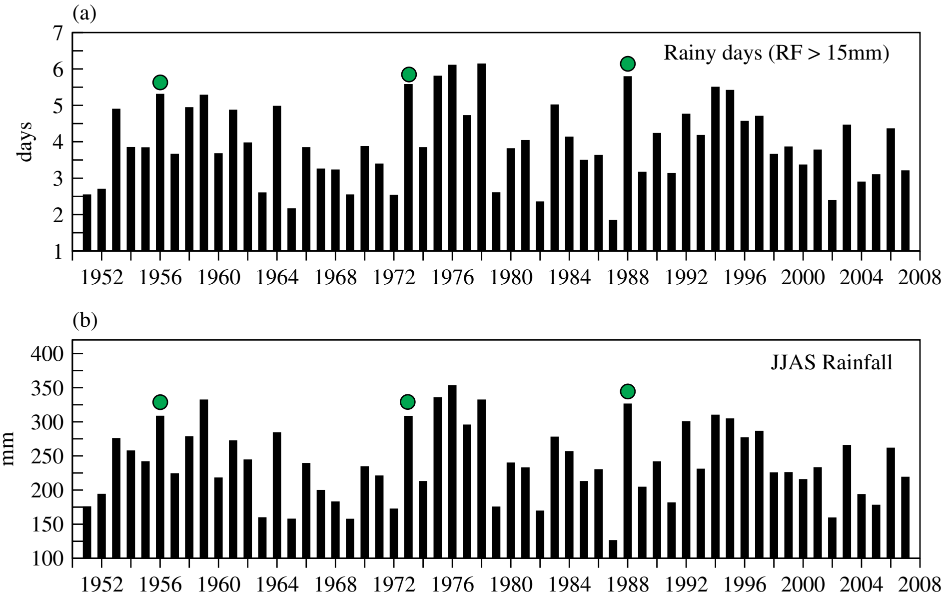

Figure 7. (a) Time series of number of intense rainfall events (>15 mm) over the India-Pakistan region (65–76 °E, 28–36°N) during JJAS (1951–2008). (b) Same as Figure 7(a) except for the accumulated JJAS rainfall over the region. The accumulated climatological summer (JJAS) monsoon rainfall is about 140 mm over the region. The La Niña events are marked by circle over the bars. This figure is available in colour online at wileyonlinelibrary.com/journal/met

of a north-south trough over the India-Pakistan region in the upper tropospheric mid-latitude westerlies. Hong *et al.* (2011) attributed the coupling of tropical monsoon surge and southward intrusion of the extra-tropical PV to the intense rainfall activities over north Pakistan and northwest India during 2010. Previous studies have shown that a weakening of the summer monsoon convective activity weakens the sub-tropical PV gradient in the middle of the Tibetan anticyclone and thereby reduces advection of sub-tropical low (high) PV around its western (eastern and southern) flanks (e.g., Hsu and Plumb, 2000; Liu *et al*., 2007). Further, the split of the single strong cell of Tibetan anticyclone (see Unninayar and Murakami, 1978) allows intrusion of the extratropical high PV into the western and eastern flanks of the upper level anticyclone. The occurrence of the north-south trough over the India-Pakistan region (Figure 2(b)) together with the southerly flow of moisture from the Arabian Sea can lead to intense moist convection over the region and is consistent with the results of previous studies (Saeed *et al*., 2010; Houze *et al*., 2011; Hong *et al*., 2011). Thus, the persistent rainfall activity over the northwest India-Pakistan region during 2010 involves complex interactions between the tropical and sub-tropical circulations.

An analysis of SST records during the last 60+ years shows a long term background La Niña-like warming trend since the late 1970s in the tropical Pacific. The maxima in the PC1 time series (Figure 4(c)) of seasonal mean SLP variations over the Pacific confirms the intensification of the Pacific pressure pattern during 2010. Also, the strong westward shift of the WPSH during 2010 seems to be prominent when the anomalous pressure patterns of La Niña composite (Figure 4(a)) are compared with those of the 2010 case (Figure 4(b)). It is interesting to note that the regression of the PC1 index on the OLR anomalies shows an asymmetric pattern of convective anomalies over the east Arabian Sea, subtropical northwest India-Pakistan region and tropical Indo-Pacific sector (Figure 6(b)). This evidence suggests that the westward shift of the WPSH during La Niña events can decrease convergence in the off-equatorial regions of the west Pacific near the Philippines, South China Sea and Bay of Bengal regions. The importance of ENSO in modulating the activity of tropical cyclones over the northwest Pacific and its influence on the Indian summer monsoon rainfall has been reported in earlier studies (Kumar and Krishnan, 2005; Mujumdar *et al*., 2007). In addition to 2010, there have been other years when heavy monsoon rainfall events over the India-Pakistan region have co-occurred with La Niña episodes (Figure 7). The sequence of flood events over Pakistan during 2010 was, however, among the strongest in the observed historical records. The presence of a long-term La Niña-like SST warming trend suggests that superposition of individual La Niña events in such a background can have major implications on extreme monsoon rainfall events over South Asia. A deeper understanding of the interactions among the WPSH, the monsoon convective activity and the stationary wave patterns over the Tibetan High and northwest India will be crucial for modelling and predicting these heavy flood events over South Asia.

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