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Climatological Characteristics of Heavy Rainfall in Northern Pakistan and Atmospheric Blocking over Western Russia

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ABSTRACT

Pakistan and northwestern India have frequently experienced severe heavy rainfall events during the boreal summer over the last 50 years including an event in late July and early August 2010 due to a sequence of monsoon surges. This study identified five dominant atmospheric patterns by applying principal component analysis and *k*-means clustering to a long-term sea level pressure dataset from 1979 to 2014. Two of these five dominant atmospheric patterns corresponded with a high frequency of the persistent atmospheric blocking index and positive sea level pressure over western Russia as well as an adjacent meridional trough ahead of northern Pakistan. In these two groups, a negative sea surface temperature anomaly was apparent over the equatorial mid- to eastern Pacific Ocean. The heavy precipitation periods with high persistent blocking frequency in western Russia as in the 2010 heat wave tended to have 1.2 times larger precipitation intensity compared to the whole of the heavy precipitation periods during the 36 years.

1. Introduction

Pakistan and northwestern India experienced torrential rainfall between late July and early August 2010 due to a sequence of monsoon surges, along with the worst flooding in the last 100 years. The rainfall recorded during May–August 2010 was somewhat higher than during the period 1981–2010 (Webster et al. 2011). Houze et al. (2011) described the 2010 summer floods of Pakistan as the consequence of anomalous atmospheric events. Galarneau et al. (2012) described the 2010 historic floods over northern Pakistan using observations, model analyses, and ensemble forecasts of the extreme heat wave over Russia. According to the World Meteorological Organization (WMO), 20 million people

were affected by this record-breaking flood, and 1.8 million homes were lost with an economic loss estimated at more than \$40 billion (U.S. dollars; WMO 2011; Lau and Kim 2012; Syvitski and Brakenridge 2013). During the early summer of 2010, an exceptionally strong and prolonged extratropical atmospheric blocking event caused a heat wave and subsequent droughts and wild fires (e.g., Dole et al. 2011). Because of this heat wave, more than 5000 km² of forest in western Russia was severely damaged and the total economic loss exceeded \$15 billion (U.S. dollars).

A previous study proposed a meteorological connection between the heavy rainfall in Pakistan and the Russian heat wave (e.g., Lau and Kim 2012). They hypothesized that the Russian heat wave was caused by an atmospheric blocking event over Europe and western Russia that was also associated with the excitation of a large-scale atmospheric Rossby wave extending across western Russia to northwestern China–Tibetan Plateau. The southward penetration of upper-level vorticity perturbations in the leading trough of the Rossby wave was instrumental in triggering anomalously heavy rainfall events over northern Pakistan and the vicinity from mid- to late July 2010. Aon Benfield Inc. (2010) reported an abnormally active jet stream moving around the periphery of the omega block into western Pakistan.

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Furthermore, Arslan et al. (2013) reported that this 2010 flood was due to the “blocking event” in the jet stream, which caused intense rainfall and flash floods in northern Pakistan and riverine flooding in southern Pakistan. Hong et al. (2011) suggested that the key factor leading to the severe flooding in Pakistan was the interaction between the tropical monsoon surges and the extratropical disturbances downstream of the atmospheric blocking. Recently, Shaevitz et al. (2016) found that the extratropical influence was of a second order to the local advection of moisture and topographic initiation.

Webster et al. (2011) described the predictability of the 2010 Pakistan flood. A comprehensive multiscale examination of 3 years of anomalous flooding events, with a special emphasis on the 2010 flooding in Pakistan, and the importance of both large- and mesoscale meteorological environments, including precipitating systems, has been well documented by Rasmussen et al. (2015). Additionally, 2010 was a La Niña year, which contributed indirectly to the flooding by inducing a low-level easterly anomaly in South and Southeast Asia that weakened eastward moisture transport and enhanced moisture transport to, and convergence in, the northern Arabian Sea and Pakistan. Wang et al. (2011) suggested that the anomalous circulation in 2010 was not sporadic, but was rather part of a long-term trend that defies the typical linkage of strong monsoons with an anomalous anticyclone in the upper troposphere.

The climatological relationship between heavy rainfall in northern Pakistan and atmospheric blocking in eastern Europe and western Russia has not been closely investigated, and this is the purpose of this study. We analyzed meteorological variables during June–August (JJA) from 1979 to 2014, including the heavy rainfall year of 2010, to determine whether the occurrence of atmospheric blocking and the sea surface temperature (SST) anomalies over the both the Pacific Ocean and the Indian Ocean can help forecast heavy precipitation in northern Pakistan. Section 2 introduces the methodology, and results are provided in section 3. Finally, a discussion and conclusions are provided in section 4.

2. Methodology

a. Data

We investigated pentad (5-day average) precipitation data for northern Pakistan and its surrounding areas (30°–36°N, 69°–76°E) during JJA 1979–2014. We used the Global Precipitation Climatology Project, version 2.2 (GPCP), combined precipitation dataset, with 2.5° spatial resolution (Huffman et al. 1997; Adler et al. 2003). Atmospheric data for sea level pressure (SLP), wind velocity, air

temperature, geopotential height, and precipitable water (PW) were obtained from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalyses (Kalnay et al. 1996). In addition, outgoing longwave radiation (OLR) data from the National Oceanic and Atmospheric Administration (NOAA) were used (Liebmann and Smith 1996). El Niño and La Niña years were identified based on the oceanic Niño index (ONI) by using the running 3-month-mean SST anomaly for the Extended Reconstructed Sea Surface Temperature, version 3b (ERSST.v3b; Smith et al. 2008), over the Niño-3.4 region (i.e., 5°N–5°S, 120°–170°W; ONI details were obtained from http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml).

Figure 1a shows regionally averaged pentad mean precipitation data for JJA from 1979 to 2014. The green and red lines indicate the climatological mean (2.8 mm day^{−1}) and mean plus standard deviation (1σ, 5.2 mm day^{−1}) for the entire period, respectively. Of the 648 pentad periods between 1979 and 2014, 81 satisfied the definition of 1σ. Averaged daily precipitation over northern Pakistan among the 81 periods was 7.7 mm day^{−1}.

b. Principal component analysis and k-means cluster

Principal component analysis (PCA) is a data-reduction technique that is used extensively in meteorology and climatology (Baeriswyl and Rebetez 1997) without the loss of climate information. In PCA, the original variables were transformed into a smaller set of linear combinations. Spatial regionalization based on the principal components (eigenvectors) of climate variables is called S-mode PCA (Richman 1986). However, PCA was conducted based on an S-mode (grid points as variables and days as observations) data matrix (Yarnal 1993) after standardizing the SLP data. The S-mode PCA is a proven technique for climate regionalization (Knapp et al. 2002). In the regionalization of climate variables using S-mode PCA, the eigenvalues and eigenvectors of the correlation or covariance matrix of the time series and loading matrix are computed first. The loading matrix represents the correlation of the original variables with the principal components. The correlation matrix (Barry and Carleton 2001) is used to efficiently represent the patterns of spatial correlation without possible domination by the grid points with the largest variances (Jolliffe 1986). The loading matrix **C** can be obtained using the following:

$$\mathbf{C} = \mathbf{A} \times \boldsymbol{\lambda}^{1/2}, \quad (1)$$

where **A** is an orthogonal matrix of the eigenvector of the correlation matrix **R** and **λ** is the diagonal matrix of

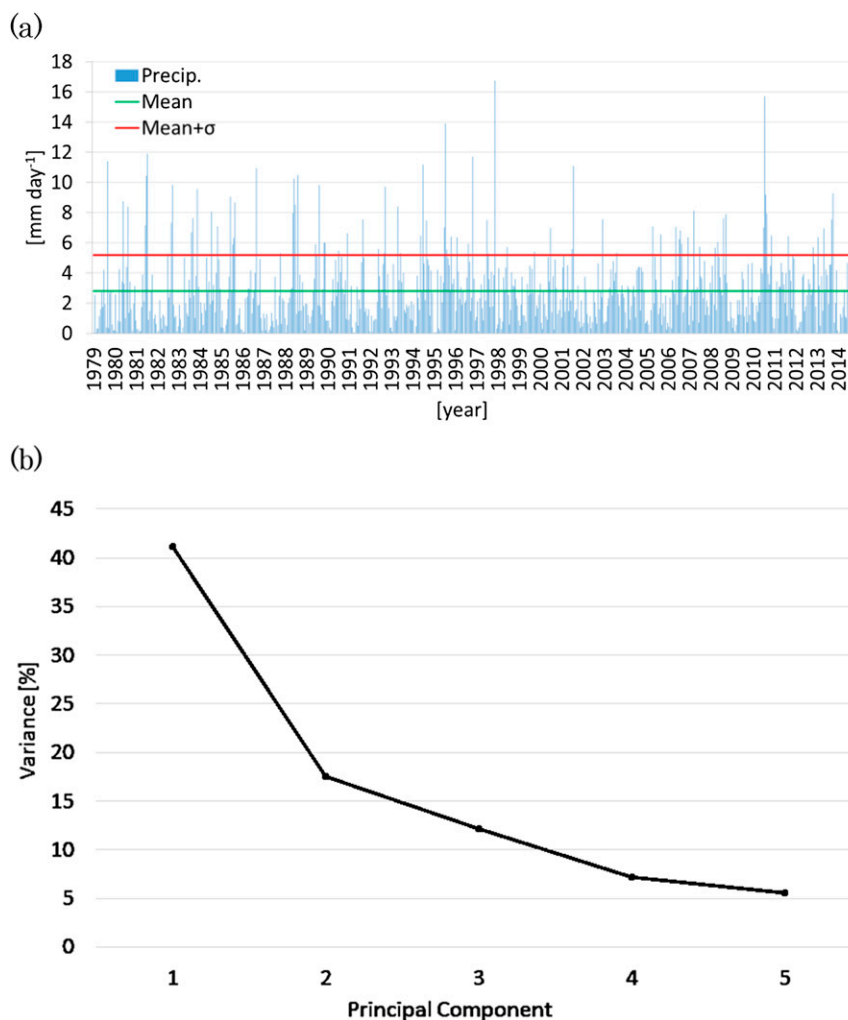


FIG. 1. (a) Pentad precipitation (m s^{-1}) over northern Pakistan (30° – 36°N , 66° – 76°E) during JJA 1979–2014. The green solid line indicates the climatological mean daily precipitation, and the red line indicates the total precipitation value of the climatological mean plus its standard deviation (1σ). Heavy precipitation periods are defined as rainfall events that fall above the green line (81 of 648 periods in JJA 1979–2014). (b) Eigenvalues of components. A scree test was used to select principal components to be retained for rotation.

eigenvalues of **R**. Based on the results of the loading matrix, the SLP values that were strongly correlated with the particular principal components could be identified. The number of components explaining a significant portion of the total variance (Barry and Carleton 2001) was determined by a scree test (Cattell 1966). The scree test determines the number of factors that will be retained in a PCA. The scree test involves plotting the eigenvalues in descending order of magnitude against their factor numbers. The transition from a steep slope to leveling off indicates the number of meaningful factors, which differs from the random error. Finally, the retained components were rotated using a varimax procedure (Yarnal 1993).

PCA was applied to SLP data for the 81 pentad periods with values greater than or equal to 1σ . PCA was performed on SLP data to derive the dominant patterns of variability from the raw fields by focusing on an area (7.5° – 40°N , 60° – 100°E) covering all of Pakistan, India, and Bangladesh. Finally, we used a clustering technique to classify the observations and merge the circulation pattern maps (Yarnal 1993).

The nonhierarchical k -means method was used to cluster the observations (Hair et al. 1998). This analysis is simply an objective identification method that can be applied to different atmospheric datasets (e.g., Gerstengarbe et al. 1999; Fovell and Fovell 1993; Martineu et al. 1999; Unal et al. 2003) to ensure the

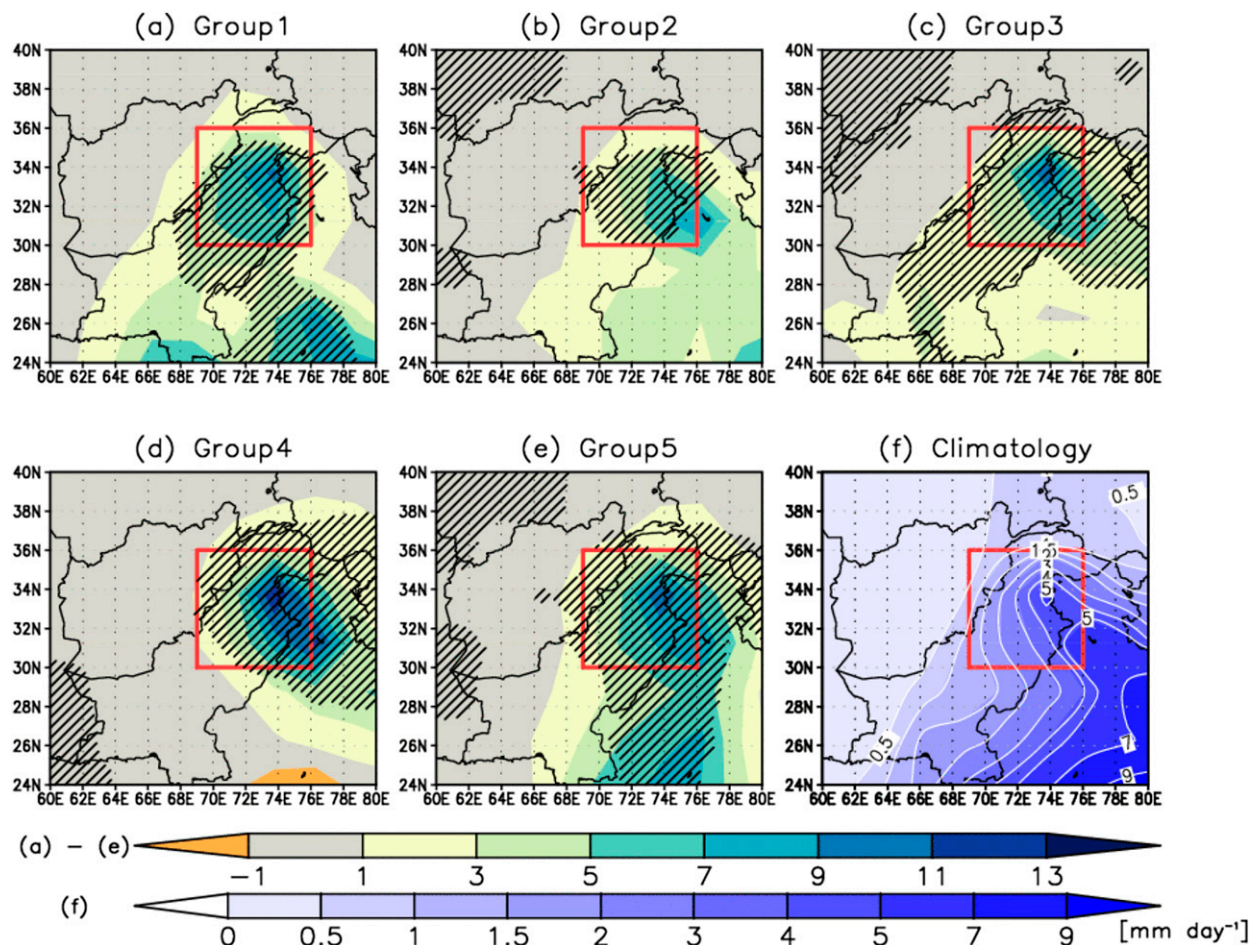


FIG. 2. (a)–(e) Geographical distribution of the precipitation anomaly (mm day^{-1}) for each group against (f) climatological mean precipitation in JJA 1979–2014. Northern Pakistan and its surrounding area is shown by the solid lines (30° – 36°N , 69° – 76°E). Areas with diagonal lines satisfy the 95% statistical significance level by the Student's t test.

comparability of the results for different climate scenarios. Additionally, this method allows for the processing of huge amounts of data, which was of the utmost importance for this study. The analysis permits the separation of elements based on the cluster structure dominated only by the analyzed data itself. To determine the

number of groups and centroids, we considered the spatial variation patterns established by the PCA. Centroids of the groups were made by following Birkeland et al. (2001) and the method of Tait and Fitzharris (1998). The k -means also produced the final classification of all observations (days) with a similar distribution of SLP fields.

TABLE 1. Number of pentad periods corresponding to the area-averaged daily precipitation and PW and their anomaly against climatological means over northern Pakistan. The rightmost column is the number of La Niña and El Niño years. Parentheses represent the anomaly relative to the climatological mean.

	No. of periods	Precipitation (mm day^{-1})	OLR (W m^{-2})	PW (mm)	Stability index	La Niña/El Niño years
Group 1	16	8.1 (5.3)	245.5 (−15.8)	31.6 (4.8)	34.3 (2.2)	1/1
Group 2	11	6.4 (3.6)	240.5 (−20.8)	32.0 (5.1)	35.3 (3.2)	0/1
Group 3	25	7.3 (4.5)	240.3 (−20.9)	32.1 (5.2)	33.7 (1.6)	4/4
Group 4	15	8.4 (5.6)	237.6 (−23.7)	33.2 (6.4)	36.6 (4.5)	4/0
Group 5	14	8.3 (5.5)	241.7 (−19.6)	31.4 (4.5)	34.4 (2.3)	3/2
Groups 1–5	81	7.7	241.1 (−20.2)	32.1 (5.2)	34.8 (2.7)	12/8
Climatological mean	648	2.8	261.3	26.8	32.1	—

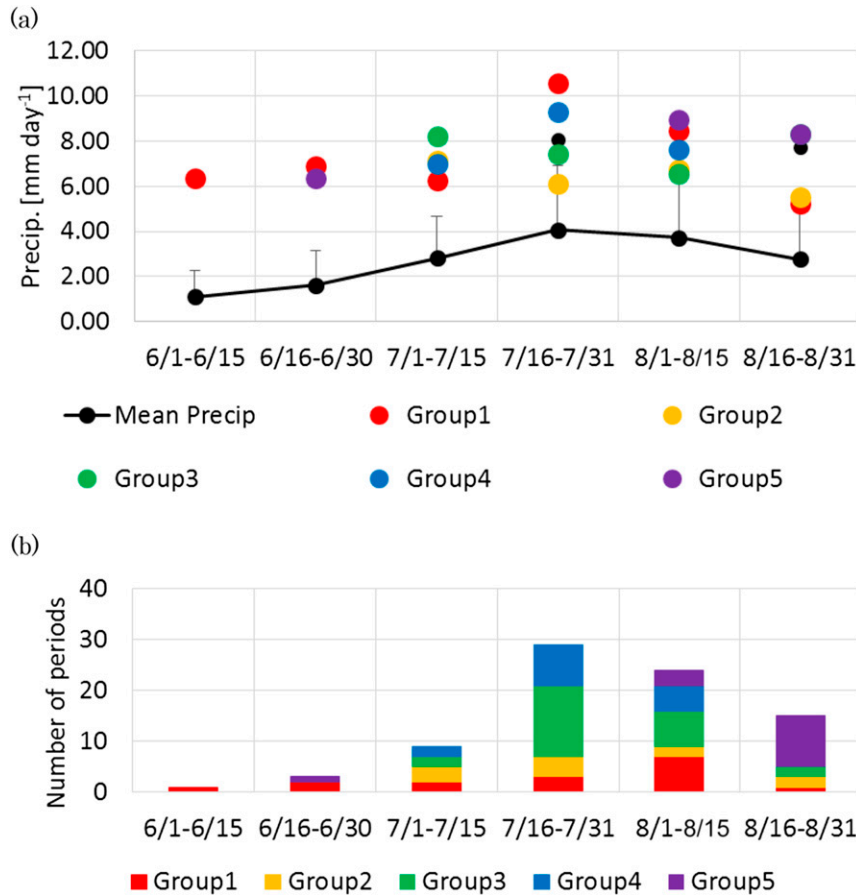


FIG. 3. (a) Daily average precipitation intensity (mm day^{-1}) of each group for the first and second halves of each month during JJA 1979–2014. Dashed black lines indicate the daily average precipitation intensity among all five groups (81 heavy precipitation periods) for the first and second halves of each month. Solid black lines indicate the daily climatological mean precipitation intensity and its std dev for 1–15 Jun, 16–30 Jun, 1–15 Jul, 16–31 Jul, 1–15 Aug, and 16–31 Aug. Circles indicate the average daily precipitation intensity for groups 1–5. (b) The number of heavy precipitation periods (among the top 81 recorded) for groups 1–5 between 1979 and 2014.

As the centroids were well established by the PCA grouping (reflecting the circulation pattern), noniteration of the k -means clustering was used. Synoptic maps of the atmospheric circulation groups were constructed for the SLP, 850-hPa moisture flux, horizontal wind field, and 500-hPa geopotential height.

c. Blocking frequency

We investigated the frequency of atmospheric blocking over Europe and western Russia by applying a two-dimensional blocking index from daily 500-hPa geopotential height data (Tibaldi and Molteni 1990; Scherrer et al. 2006). This field was evaluated on a $2.5^\circ \times 2.5^\circ$ regular latitude–longitude grid covering the Northern Hemisphere. Subsequently, the geopotential height gradient south (GHGS) and geopotential height gradient

north (GHGN) for mid- and high latitudes, respectively, were computed for all grids (λ, φ) in the region of interest between 35° and 75°N :

$$\begin{aligned} \text{GHGS} &= [Z500(\lambda, \varphi) - Z500(\lambda, \varphi - \Delta\varphi)]/\Delta\varphi \quad \text{and} \\ \text{GHGN} &= [Z500(\lambda, \varphi + \Delta\varphi) - Z500(\lambda, \varphi)]/\Delta\varphi, \end{aligned} \quad (2)$$

where $Z500$ indicates daily 500-hPa geopotential height and $\Delta\varphi = 15^\circ\text{lat}$. A given grid point was defined as “instantaneously blocked” in time and the instantaneous blocking (IB) index was 1 when the following two conditions were fulfilled: (i) $\text{GHGS} > 0$ and (ii) $\text{GHGN} < -10 \text{ m } (^\circ\text{lat})^{-1}$. Additionally, a 5-day persistence criterion was applied at every grid point. If the IB index was 1 for at least 5 days at a grid point, blocking

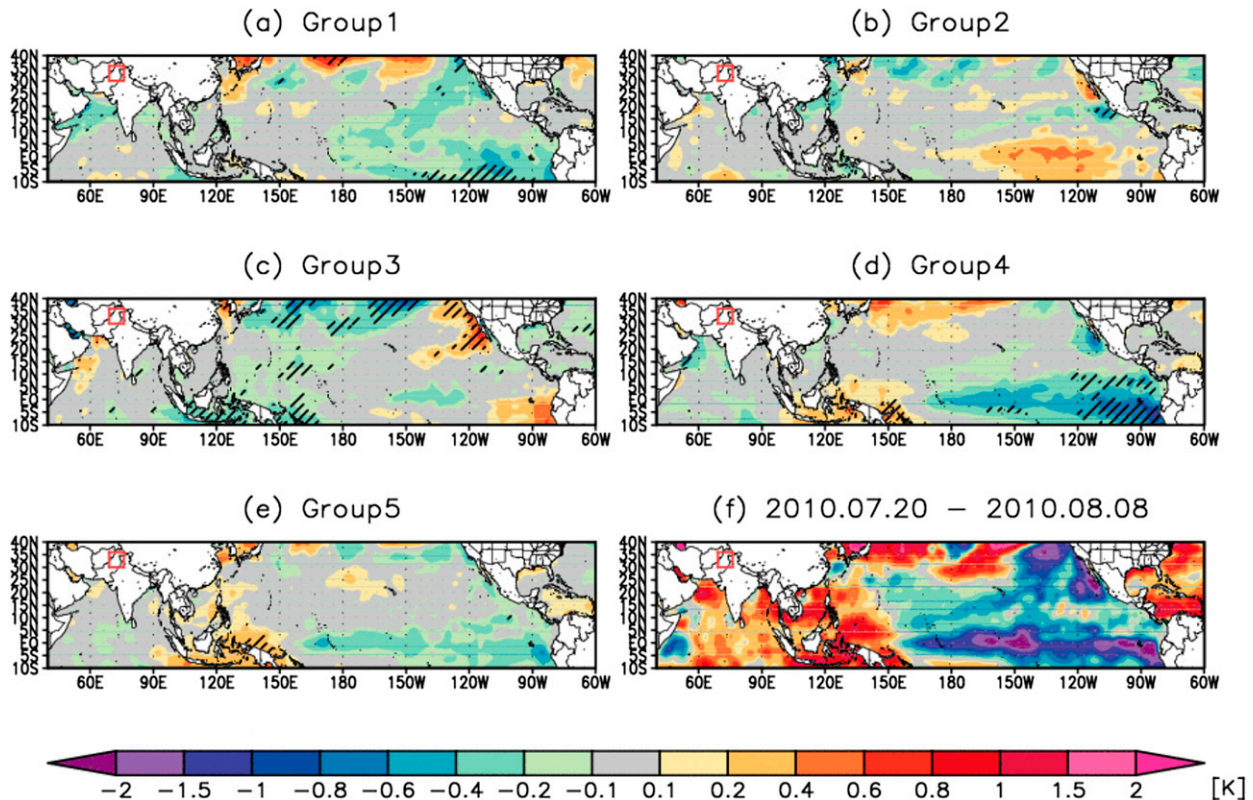


FIG. 4. (a)–(e) SST anomalies (K) of each group compared to climatological mean states. (f) SST anomaly of the 2010 heavy precipitation period (from 20 Jul to 8 Aug) against the climatological mean state. The rectangles show the target area in northern Pakistan. Areas with diagonal lines satisfy the 95% statistical significance level by the Student's t test.

was deemed to occur at this point during this period and the persistent blocking (PB) index was 1. The mean time of the PB index denotes the blocking frequency.

3. Results

The scree test procedure allowed us to select five principal components (Fig. 1b), which together explained 83.6% of the total variance. The dominant SLP values were classified into five groups (groups 1–5) representing the most relevant circulation patterns over northern Pakistan. Figures 2a–e show the geographical distribution of precipitation anomalies for the five groups against the climatology JJA for the period 1979–2014 (Fig. 2f). Areas with diagonal lines satisfy the 99% statistical significance level by the Student's t test. Table 1 lists the number of pentad periods for each group and the average precipitation, OLR, and PW and their anomalies for an area over northern Pakistan, shown by the area with solid lines in Figs. 2a–e.

Figure 2f shows a large amount of precipitation distributed from northern India to northern Pakistan to the south of the Himalaya Mountains. The area-averaged

precipitation over northern Pakistan for 1979–2014 was approximately 2.8 mm day^{-1} . All of the groups exhibited a positive precipitation anomaly, mainly over northern Pakistan and India. The anomaly against the climatological mean during JJA between 1979 and 2014 was particularly large for groups 4 and 5 (8.4 and 8.3 mm day^{-1} , respectively, see Table 1). A total of 15 and 14 heavy precipitation periods were observed for groups 4 and 5, respectively, compared to 16, 11, and 25 for groups 1, 2, and 3, respectively.

Figure 3a shows the daily average precipitation intensity for groups 1–5 in the first and second halves of each month in JJA between 1979 and 2014. The dashed black line indicates the average precipitation intensity among all five groups. The solid black line is the daily climatological mean precipitation intensity, with the standard deviation, for each 15- or 16-day period. Figure 3b shows the number of precipitation events in each group during the first and second halves of each month. As shown here, 63 of the 81 heavy precipitation periods occurred during the second half of July and the first half of August. For example, there were 13 precipitation events in group 4 during 16–31 July and 1–15 August. For group 5, 10 of 15 cases occurred during 16–31 August.

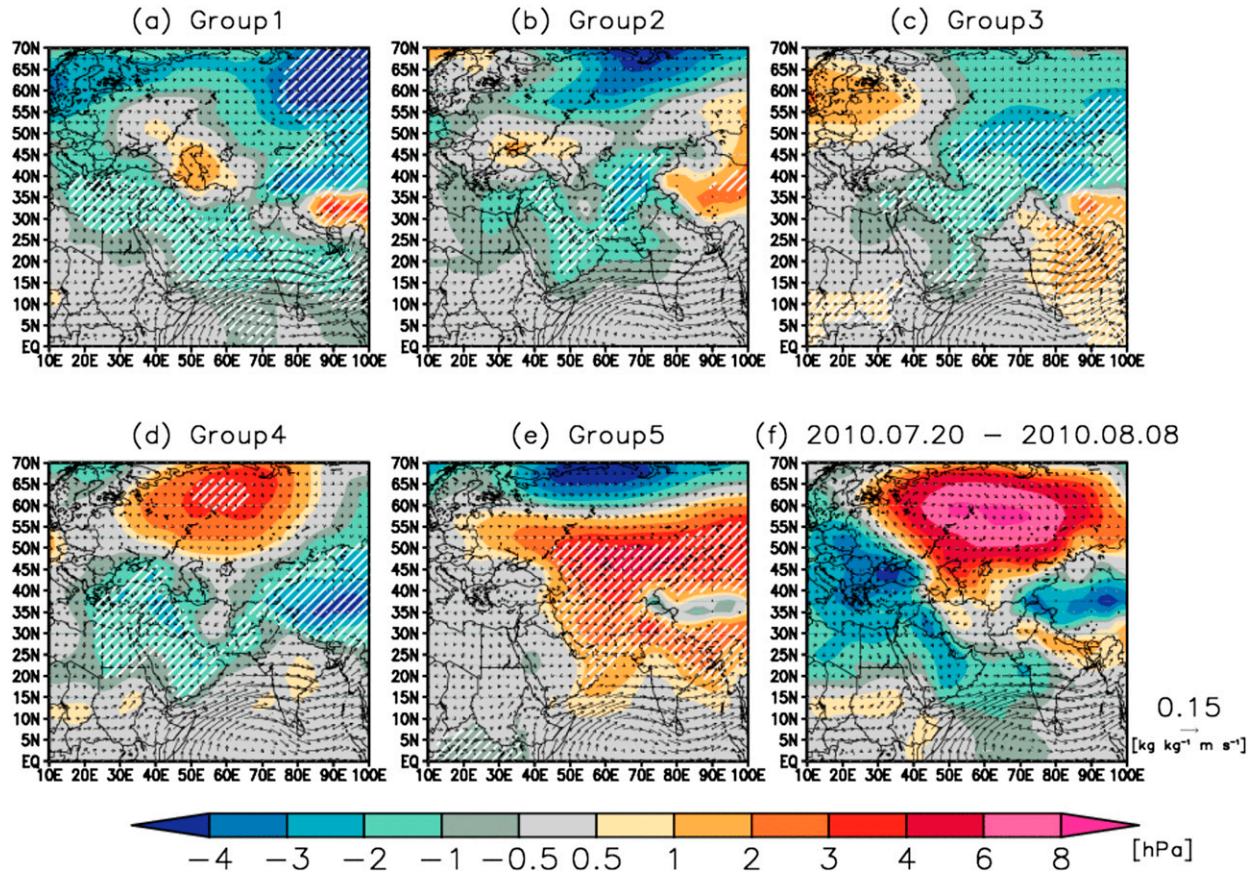


FIG. 5. (a)–(e) Geographical distribution of the SLP anomaly (hPa) for each group. (f) The similar figure for the 2010 Pakistan flooding. The horizontal moisture flux at the 850-hPa level is also plotted by vectors ($\text{kg kg}^{-1} \text{m s}^{-1}$). Areas with diagonal lines satisfy the 95% statistical significance level by the Student's t test.

Table 1 also lists the OLR and its anomaly against the climatological mean over northern Pakistan. Group 4 had a smaller OLR than the other groups, and this region received heavy convective and stratiform precipitation associated with an anomalous midlevel jet (Rasmussen et al. 2015). In addition to the OLR, group 4 also had the largest PW and stability index.

The rightmost part of Table 1 shows the number of heavy precipitation periods corresponding to each group for both La Niña and El Niño years. There were 12 heavy precipitation periods in La Niña years between 1979 and 2014, including 4 in 2010, and 11 of the 12 belonged to groups 3, 4, and 5, with group 4 having 4 of them. Figures 4a–e show the geographical distribution of the SST anomaly for groups 1–5 against the climatological mean state. To exclude seasonal characteristics between June and August, the anomaly was calculated for each 30 days and obtained its average for each group. Here, the NOAA Optimum Interpolation Sea Surface Temperature, version 2 (OISSTv2; weekly mean), for 33 years between 1982 and 2014 was

adopted [Reynolds et al. 2002; OISSTv2 data were provided by the NOAA/OAR/ESRL Physical Sciences Division (PSD), Boulder, CO, at <http://www.esrl.noaa.gov/psd/>]. The solid area indicates the target in northern Pakistan. Figure 4f shows the SST anomaly during the 2010 Pakistan flooding (from 20 July to 8 August) against the climatological mean state.

The heavy precipitation period in 2010 was associated with a negative SST anomaly over the equatorial mid- to eastern Pacific Ocean. On the other hand, a positive SST anomaly was distributed over the equatorial western Pacific Ocean and the mid- to eastern Indian Ocean. As shown in Figs. 4a, 4d, and 4e, groups 1, 4, and 5 had a negative SST anomaly over the equatorial eastern Pacific Ocean, similar to that during the heavy precipitation period in 2010 (Fig. 4f). The geographical distribution of the negative SST anomaly can be classified according to La Niña years. Group 2 had the opposite geographical distribution compared to these groups over the same region. The Indian Ocean region does not have large positive anomalies with wider

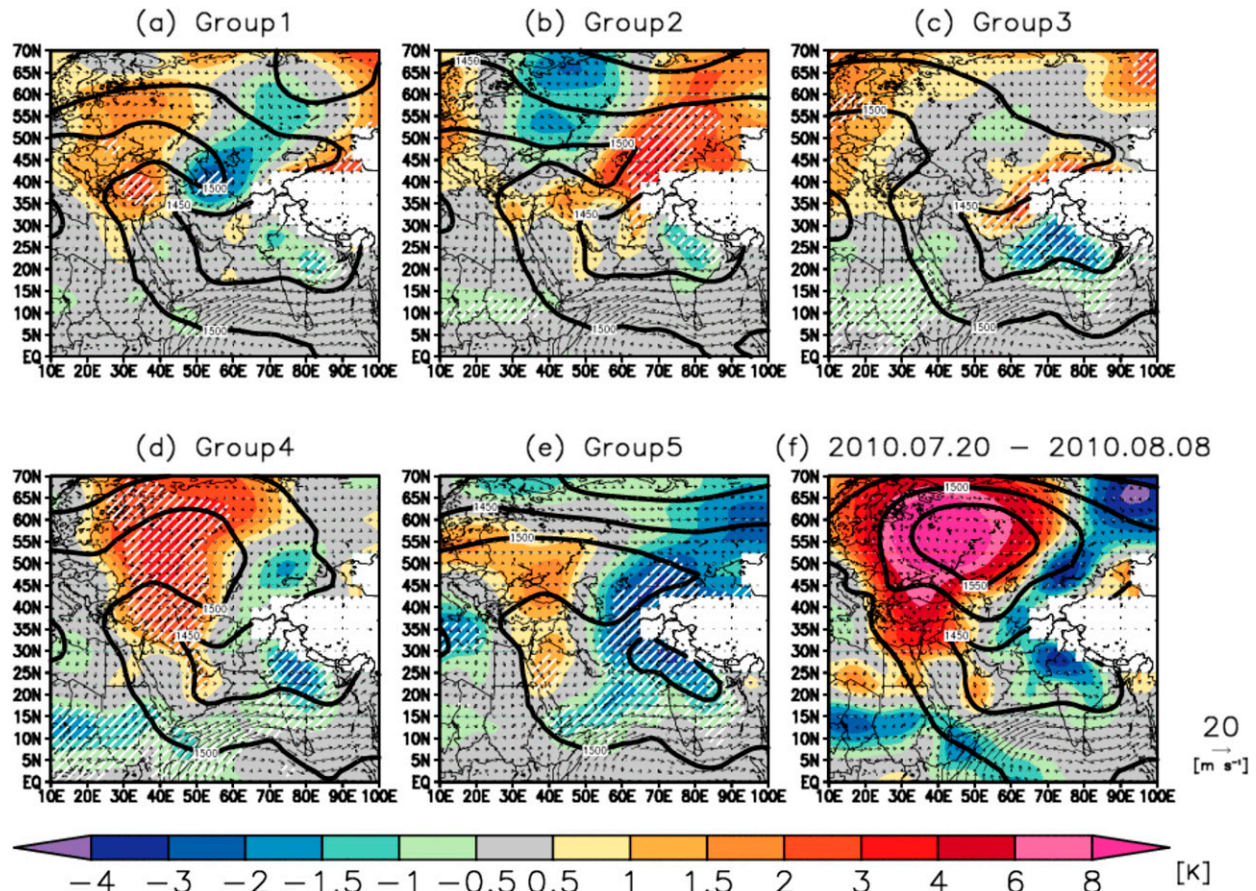


FIG. 6. As in Fig. 5, but for the temperature anomaly (K), wind vector (m s^{-1}), and geopotential height (m) at the 850-hPa level.

spatial coverage in the five groups even though the Pacific Ocean has both positive and negative anomalies with the wider coverage. This result could suggest that the anomaly of SST over the Pacific Ocean has a more important role in heavy precipitation over northern Pakistan than the climatology during the target years.

Figures 5a–e show the geographical distribution of the SLP anomaly and water vapor flux at the 850-hPa level for groups 1–5. Figure 5f shows the geographical distribution of SLP and water vapor flux during the 2010 Pakistan flooding. The figure shows an anomalously high SLP widely distributed across western Russia, which was associated with atmospheric blocking. A similar pattern was displayed in groups 4 and 5. The other three groups exhibited a positive SLP anomaly over some areas in western Russia and/or northern Europe, but with a smaller horizontal scale and intensity than groups 4 and 5.

Figures 6a–e show the geographical distribution of the temperature anomaly, horizontal wind vectors, and geopotential height at the 850-hPa level. Figure 6f shows similar results for the period of the 2010 Pakistan

flooding. Figures 6a–e show the geographical distribution of the temperature anomaly, horizontal wind vectors, and geopotential height at the 850-hPa level. Similar results for the period of the 2010 Pakistan flooding are shown in Fig. 6f. Figure 7 is as in Fig. 6, but for the 500-hPa level. During the flood, the temperature at the 850-hPa level showed a higher anomaly over all of western Russia associated with an omega-shaped atmospheric blocking at the 500-hPa level (Fig. 7f). The temperature anomaly at the 850-hPa level and the geopotential height at the 500-hPa level displayed a deep trough extending meridionally from the eastern part of the atmospheric blocking from Russia to South Asia, including Pakistan between 50° and 80°N . A similar negative temperature pattern at 850-hPa level was observed for groups 1, 4, and 5 (Figs. 6a,d,e). At both the 850- and 500-hPa levels, group 4 had a clear meridional trough and positive temperature anomaly over western Russia, similar to that observed during the 2010 Pakistan flooding (Figs. 6f and 7f). Group 1 shows the positive temperature anomaly over western Russia at the 500-hPa level (Fig. 7a), which was shifted westward compared to

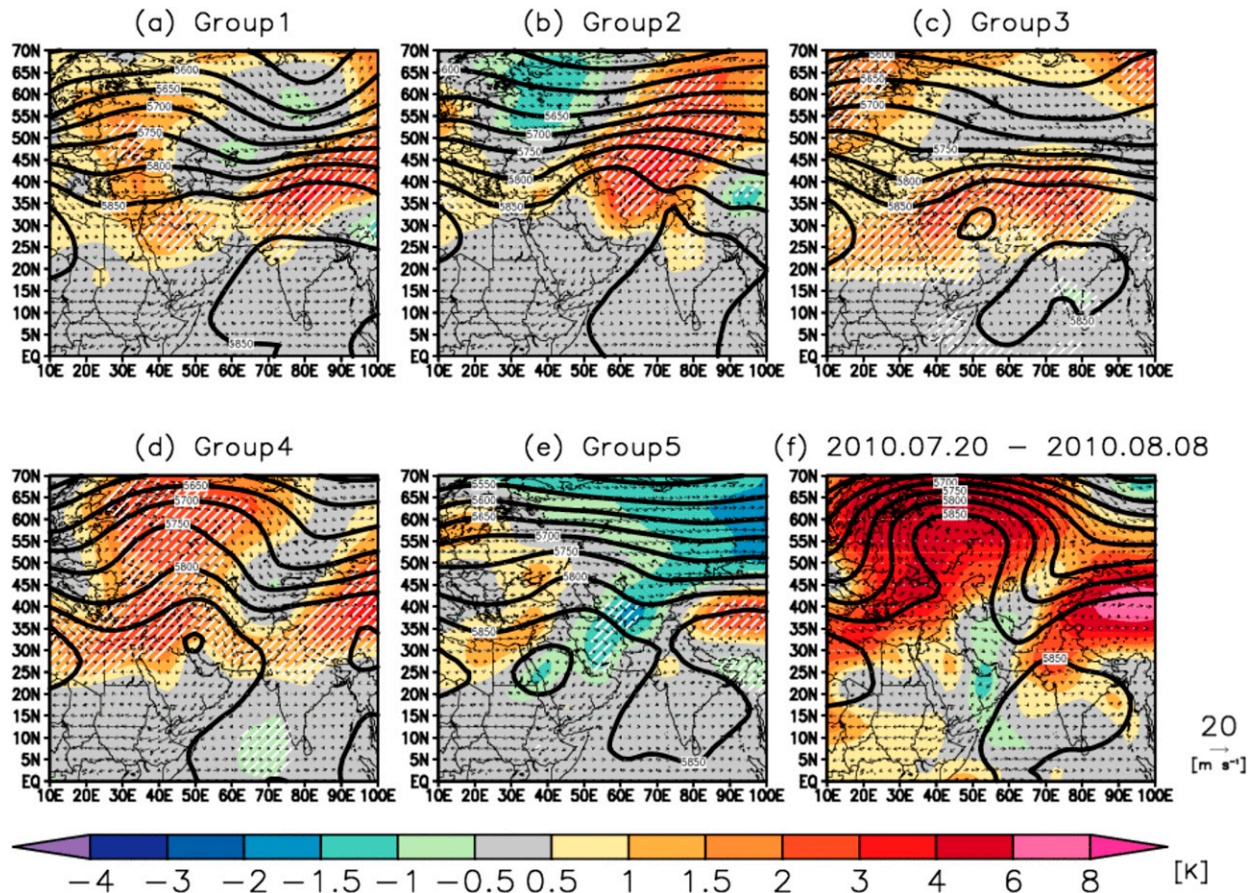


FIG. 7. As in Fig. 5, but for the temperature anomaly (K), wind vector (m s^{-1}), and geopotential height (m) at the 500-hPa level.

group 4 (Fig. 7d) and the 2010 Pakistan flooding (Fig. 7f). In addition, this group had a weaker meridional trough that did not reach northern Pakistan.

Contour lines in Fig. 8 show the geographical distribution of PB during the 2010 Pakistan flooding. The geographical distribution of the PB index (Tibaldi and Molteni 1990; Scherrer et al. 2006) is introduced in section 2c. Similar figures for groups 1–5 are plotted in Fig. 9. Colors in Figs. 8 and 9 represent the ratio of PB against the climatology that is shown in Fig. 8f. The rectangle shows the area significantly affected by the Russian heat wave in 2010 (Dole et al. 2011). In the climatological mean state, a large PB was centered over the area and was widely distributed from northeastern Europe to west-central Russia on 20 July and 8 August 2010. Over the rectangular area, PB was 0.46, which is 23 times larger than the climatology ($\text{PB} = 0.02$) in JJA between 1979 and 2014 (Fig. 9f). The area-averaged PB over the rectangular area among the 81 heavy precipitation periods is 0.03. Groups 4 and 5 exhibited PB over the rectangular area of approximately 0.05–0.07, which was more than 2.5–3.5-fold larger than the

climatological mean. Furthermore, in group 4, large PB is widely distributed over western Russia and northern Europe including high latitudes centered over the eastern part of the area with solid lines. In the meantime, group 5 has zonally larger PB areas around 55° and 60°N over western Russia. Group 3 also shows the widely distributed PB over Europe and western Russia, but the geographical distribution was shifted to the north compared to groups 4 and 5.

Seven heavy precipitation periods had a PB of more than 0.09 (more than 1σ of PB greater than the rectangular area between 1979 and 2014). The average precipitation intensity among the seven heavy precipitation periods was 9.1 mm day^{-1} , which is 1.2 times larger than the whole of the 81 heavy precipitation periods (7.7 mm day^{-1}). Three of the seven heavy precipitation periods occurred in 1996, 2003, and 2006. During the target periods in these three years, northwestern Pakistan and Kashmir were affected by floods (Brakenridge 2016). This indicates that the heavy precipitation over northern Pakistan occurred before 2010, when atmospheric blocking remained in a certain area in western

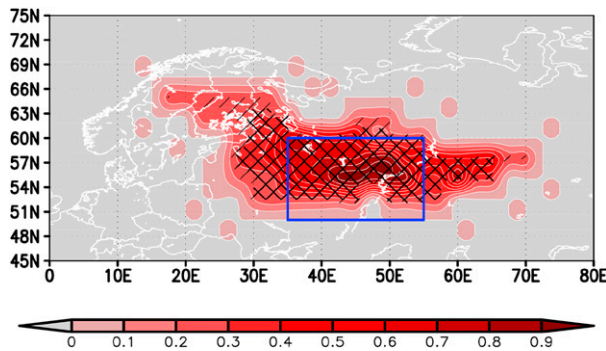


FIG. 8. Geographical distribution of the persistent atmospheric blocking on 20 Jul and 8 Aug 2010. The condition of persistent atmospheric blocking was adopted for this analysis. The area with solid blue lines indicates the location of atmospheric blocking, which was identified in 2010 (Dole et al. 2011). Areas with single and diagonal lines indicate 90% and 95% statistical significance level by the Monte Carlo method, respectively.

Russia. In addition, in 11 of the 81 heavy precipitation periods, precipitation intensity of more than 10 mm day^{-1} was recorded over northern Pakistan. Three periods (in 1996, 1997, and 2010) had large PB values (>0.06). In 1996 and 1997, atmospheric patterns were classified as group 5, which was the main pattern during the heavy precipitation periods in 2010.

4. Discussion and conclusions

Previous studies (e.g., Lau and Kim 2012) have suggested that the two extreme climatological events in the summer of 2010 (the Russian heat wave and the

Pakistan flood) were meteorologically connected. This study investigated a long-term dataset for a period of 36 years (1979–2014) to identify the meteorological connection between the two events from previously occurring similar events.

The dominant SLP patterns were classified into five groups with anomalously high precipitation (more than 1σ from the climatological mean) over northern Pakistan. Two of these five dominant atmospheric patterns (groups 4 and 5) were identified during late July and early August 2010, namely a high frequency of the atmospheric blocking index over western Russia and an adjacent meridional trough. These two dominant atmospheric patterns were responsible for the five heaviest rainfall events in JJA 1979–2014 including the 2010 heavy precipitation year.

Two of the groups (groups 4 and 5) showed persistent atmospheric blocking over western Russia and an adjacent meridional trough that brings cold air mass from mid- to high latitudes to northern Pakistan in addition to a positive SLP anomaly over western Russia. In these two groups, negative temperature anomalies at the 850-hPa level were found along the trough over South Asia including Pakistan. As shown in Table 1, precipitation in groups 4 and 5 tended to be greater than for the other three groups. In addition, in these groups, a negative SST anomaly was observed over the equatorial mid- to eastern Pacific Ocean, with geographical distributions that can be classified as La Niña year type. The Indian Ocean had an SST anomaly over some areas, but the geographical distribution is smaller than the Pacific Ocean even though 2010 was classified into groups 4 and

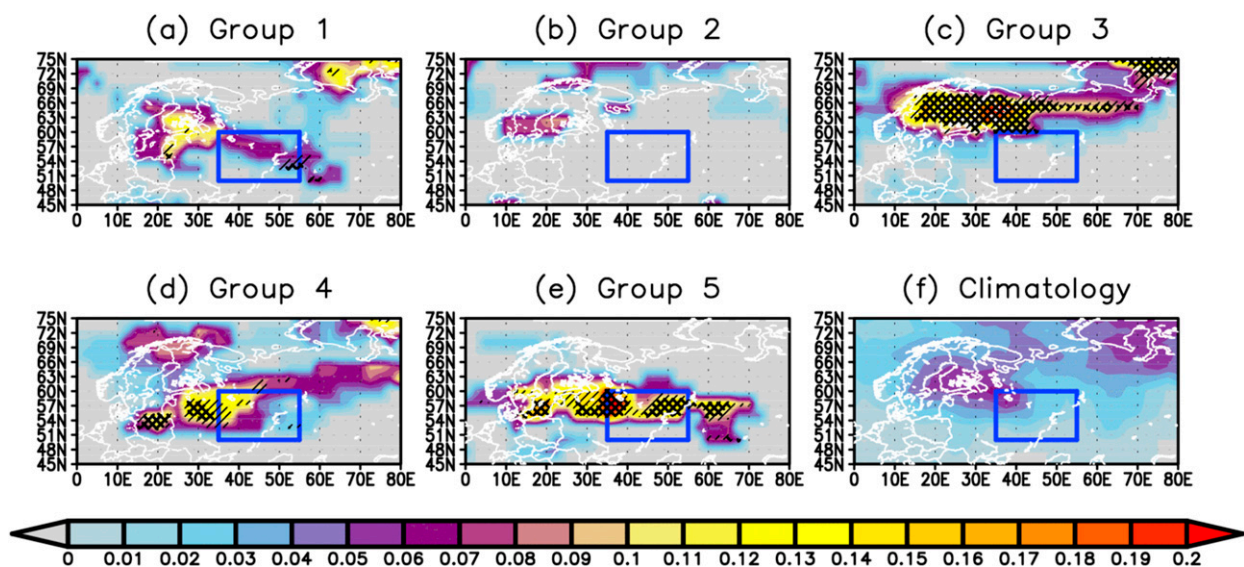


FIG. 9. (a)–(e) As in Fig. 8, but for groups 1–5 against (f) the climatological mean in JJA 1979–2014. Areas with single and diagonal lines indicate 90% and 95% statistical significance level by the Monte Carlo method, respectively.

5 with a large positive SST anomaly over the Indian Ocean. This result may suggest that the anomalous positive SST anomaly in 2010 enhanced precipitation over northern Pakistan in addition to the favorable SST anomaly over the equatorial mid- to eastern Pacific Ocean.

Groups 4 and 5 had widely distributed the large persistent blocking (PB) values over western Russia during the period of the 2010 Pakistan flooding, where the PB was large. During 1979–2014, seven pentad periods had larger PB over the area affected by the Russian heat wave in 2010. These seven pentad periods recorded a precipitation intensity of 9.1 mm day^{-1} , which is 1.2 times larger than the whole of the 81 heavy precipitation periods. In addition, five of the seven periods were classified into groups 4 and 5. Therefore, these groups tended to cause heavy precipitation over northern Pakistan in association with atmospheric blocking over western Russia and a negative SST anomaly over the equatorial mid- to eastern Pacific Ocean. These results may suggest that atmospheric patterns and the persistent blocking over the study area might be an import indicator of heavy precipitation, with a meteorological connection to the heat wave.

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