A Relationship Between Ural-Siberian Blocking and Himalayan Weather Anomalies

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Abstract Because of their distinctly high elevation, the Himalaya are directly influenced by upper-tropospheric jet stream winds and circulation anomalies that on many occasions have brought unusual weather patterns to the region. In this study, we establish the dynamical relationship between upper-tropospheric blocks formed over the Ural-Siberian region and anomalous weather patterns over the Himalaya using a combination of reanalysis data and mesoscale atmospheric model simulations. We identify two distinct blocks (an omega (Ω) block and a dipole (Rex) block) using an appropriate blocking index and computed the anomalous atmospheric fields associated with these types of blocks. In both cases, the low-pressure component of the block lies westward of the western Himalaya and the upper-level convergence/divergence of ageostrophic winds along the upstream/downstream portion of the trough creates anomalous positive/negative sea level pressure at the surface. The local sea level pressure is enhanced over the Arabian Peninsula and the Arabian Sea, while downwind over the Himalaya there is a negative pressure anomaly. There is entrainment of high potential vorticity air that descends and flows equatorward. During the Ω blocking event, the trough remains quasi-stationary over the Western Himalayan Notch and its circulation induces moisture transport from the Arabian Sea and the Bay of Bengal leading to strong precipitation events over the Western and Eastern Himalayan Notches. During the dipole blocking event, the trough gradually shifts southeastward and leads to widespread precipitation over the entire Himalayan arc.

1. Introduction

Atmospheric blocking events can bring anomalous and potentially extreme weather patterns to regions immediately around the blocks and to distant downstream regions. These patterns may last for a few days to a few weeks. They are formed by quasi-stationary high- and low-pressure systems in the upper troposphere that block the flow of the eastward moving jet stream, thereby inducing more meridional flow and more north-south exchanges of air masses and energy (Rex, 1950). Poleward advection of warm subtropical air typically occurs along the upstream edge of an anticyclonic midlatitude block and equatorward advection of cold polar air occurs along the downstream edge of the block. Together, these anomalous flows can result in such weather extremes as heat waves, cold waves, drought, and flooding. Documented examples of weather anomalies related to atmospheric blocking events are warm temperature anomalies in western Alaska (Carrera et al., 2004), cold anomalies over the western and southern United States (Casola & Wallace, 2007), cold spells in southeastern Europe (Brunner et al., 2017), cold anomalies over eastern Asia (Park & An, 2014), and enhanced precipitation over southeastern Australia (Pook et al., 2013).

The most common regions for the development of blocking events in the Northern Hemisphere are the Euro-Atlantic region, the Pacific Ocean, and the Ural-Siberian region over the Eurasian continent (Barriopedro et al., 2006; Cheung, Zhou, Mok, et al., 2013). In this paper, we focus on Ural-Siberian blocks and their associated weather events in South/Southeast Asia and the Himalaya. According to Takaya and Nakamura (2005), the upper-tropospheric blocking anticyclone over the Ural-Siberian region is associated with the eastward propagating component of a quasi-stationary Rossby wave train originating from the Euro-Atlantic sector. They further explained that the blocking ridge strengthens the amplitude of the Siberian high leading to cold air outbreaks along the downstream region for extended periods of time.

Blocking episodes over Eurasia are less persistent than over other regions (Tyrlis & Hoskins, 2008), although they are known to cause anomalous weather patterns over South/Southeast Asia. For example, severe
snowstorms across southern China in January 2008 and a Russian heat wave and Pakistan flooding during summer 2010 have been dynamically linked with an extended blocking episode over the Ural-Siberian region (Lau & Kim, 2012; Zhou et al., 2009).

The study of blocking events may lead to an improved predictive capability for anomalous Himalayan weather. The distinctly high elevations of the Himalayan Mountains control the atmospheric flows across and around them resulting in dynamical interactions between the orography and, for example, the summer monsoon circulation and westerly wind disturbances (Cannon et al., 2014; Medina et al., 2010). Furthermore, Vellore et al. (2016) established the relationship between extreme summer monsoon precipitation events and anomalous midlatitude upper-tropospheric circulation including atmospheric blocking events over Eurasia. However, their study is confined to a small region in the western Himalaya and does not explore how blocking influences the weather of the entire Himalayan region in other seasons.

The aim of this study is to ascertain the influence of atmospheric blocks on pan-Himalayan weather. We compute an appropriate blocking index to identify blocking events in the Ural-Siberian region and analyze the synoptic and mesoscale atmospheric conditions over Eurasia and the Himalaya during two typical but contrasting blocking events (an $\Omega$ block event and a dipole block event) that occurred in the spring and winter seasons. We use reanalysis data as well as simulated high-resolution atmospheric fields over the Himalaya using a mesoscale atmospheric model in order to ascertain the anomalies generated by these two different types of blocking events.

2. Materials and Methods

2.1. Data

The atmospheric variables used in the calculation of the blocking indices are from the ERA-Interim reanalysis data set (Dee et al., 2011). ERA-Interim data are available at 6-hourly temporal resolution, 0.75° × 0.75° default horizontal resolution (with different user selectable options), and 61 variably spaced vertical levels from the surface to 0.1 hPa. Thus, ERA-Interim geopotential height at 500-hPa pressure level and 2.5° × 2.5° horizontal resolution is used to calculate the blocking index. For all other calculations ERA-Interim data with default horizontal resolution are used. The ERA-Interim variables considered in this study are geopotential height, horizontal winds ($u$ and $v$ components), temperature, and surface evaporation.

Furthermore, the ERA-Interim reanalysis data set is used to initialize and force the atmospheric model at its lateral boundaries. The model output precipitation is compared with daily Tropical Rainfall Measuring Mission (TRMM) precipitation data at 0.25° × 0.25° horizontal resolution (Huffman et al., 2010). Likewise, the spatial extent of the simulated snow cover is compared with Moderate Resolution Imaging Spectroradiometer (MODIS)/Terra Snow Cover Daily L3 Global 500m Grid, Version 6 (http://modis.gsfc.nasa.gov).
Table 1

WRF Model Configuration

| Domain configuration         |            |
|------------------------------|------------|
| Horizontal grid spacing      | 18 and 6 km|
| Vertical levels              | 50         |
| Model top pressure           | 50 hPa     |

| Model physics                |            |
|------------------------------|------------|
| Radiation                    | Community Atmospheric Model |
| Microphysics                 | Thompson (Thompson et al., 2008) |
| Cumulus                      | Kain-Fritsch (Kain, 2004) |
| Planetary boundary layer     | MYNN level 2.5 (Nakanishi & Niino, 2006, 2009) |
| Atmospheric surface layer    | revised MM5 (Jiménez et al., 2012) |
| Land surface model           | NOAH-MP (Niu et al., 2011; Yang et al., 2011) |

| Dynamics                     |            |
|------------------------------|------------|
| Top boundary condition       | Rayleigh damping |
| Diffusion                    | Calculated in physical space |

| Lateral boundaries           |            |
|------------------------------|------------|
| Forcing                      | ERA-Interim 0.75° × 0.75°, 6 hourlies |

WRF = Weather Research and Forecasting.

2.2. Methods

The index used to detect atmospheric blocking events in this paper is derived from Lejenäs and Økland (1983) and Tibaldi and Molteni (1990). The blocking index includes two 500-hPa geopotential height gradients (GHGS and GHGN) computed daily for each longitude as given below:

\[
GHGN = \left[ \frac{Z(\lambda, \phi_n) - Z(\lambda, \phi_o)}{\phi_n - \phi_o} \right] 
\]

\[
GHGS = \left[ \frac{Z(\lambda, \phi_o) - Z(\lambda, \phi_s)}{\phi_o - \phi_s} \right] 
\]

where \(\phi_n = 80°N + \delta\), \(\phi_o = 60°N + \delta\), \(\phi_s = 40°N + \delta\), and \(\delta = -7.5, -5, -2.5, 0, 2.5, 5, \text{ and } 7.5\). The use of \(\delta\) values ranging from \(-7.5\) to \(7.5\) is due to the seasonal and spatial variations of the locations of blocks over the Ural-Siberian region. Furthermore, the selection of \(\delta\) at an interval of \(2.5\) is due to data resolution.

In the above expression \(Z(\lambda, \phi)\) is the 500-hPa geopotential height at longitude \(\lambda\) and latitude \(\phi\). A given longitude is considered to be blocked if the value of \(GHGS > 0\) and \(GHGN < -10\) per degree of latitude for at least one value of \(\delta\) (Barriopedro et al., 2006).

\[\text{Figure 2. (a) Average blocking frequency from 1985 to 2015 over 45°E to 75°E according to the season, and (b) number of blocking events per year from 1985 to 2015 centered between 55°E and 70°E.}\]
Figure 3. Daily 200-hPa geopotential height anomalies (shaded, m), geopotential height (contour, hectometer), and anomalous horizontal wind (vector, m/s) on (a) 10, (b) 11, (c) 12, and (d) 13 May 2014 (source: ERA-Interim reanalysis).

Figure 4. Daily mean sea level pressure anomalies (shaded, hPa), 850-hPa geopotential height (black contour, m), and 850-hPa anomalous wind (vector, m/s) on (a) 10, (b) 11, (c) 12, and (d) 13 May 2014 (source: ERA-Interim reanalysis).
A blocking frequency is defined as the percentage ratio of the number of blocked days to the total number of days over a study period. To be defined as a blocking event, the index must have at least five consecutive points of longitude (12.5° for the resolution of the data) blocked (Barriopedro et al., 2006) and the block must persist for at least four consecutive days (Pelly & Hoskins, 2003).

We compute GHGS and GHGN between 1985 and 2015 and identify blocking events upstream of the Himalaya. The blocking events are then classified according to the season and annual number of blocking events, and two unique cases of Ural-Siberian blocking events are selected, and the weather conditions over the Himalaya during those blocking events are analyzed. The two cases are selected based on the criteria given in section 3.1.

2.3. Regional Modeling of Atmospheric Conditions Over the Himalaya During the Blocking Events

The Weather Research and Forecasting (WRF) Model Version 3.8.1 is used to simulate the high-resolution atmospheric fields over the Himalaya during two different types of blocking events (an Ω and a dipole block). The WRF model is a nonhydrostatic and fully compressible mesoscale atmospheric model. It is configured with two nested domains of 18- and 6-km horizontal resolutions with both domains having 50 vertical levels. The model top is at 50 hPa and the lowest 11 model levels are below 1 km altitude. The geographical coordinates of the outer domain (D1) and the inner domain (D2) are shown in Figure 1. The locations of the Western Himalayan Notch (WHN) and the Eastern Himalayan Notch (EHN) are indicated in Figure 1b. The WHN is a notch formed by the Hindu Kush Mountains, the Karakoram, and the western Himalaya. Similarly, the EHN is a notch formed by the eastern Himalaya and the mountains along the Indo-Burma border. In this study we define the Nepal Himalaya as the central Himalaya. Thus, the region east of Nepal, we define as the eastern Himalaya, and the region west of Nepal, including the Karakoram and the Hindu Kush, we define as the western Himalaya.

D1 uses 5-arc min (~9.5 km) topography and D2 uses 2-arc min (~4 km) topography with U.S. Geological Survey 24-category land use classification. Due to the resolution of the input topography, the model.
Figure 6. (a) WRF rainfall (mm), (b) WRF snowfall (mm), and (c) TRMM precipitation (mm), accumulated over 9–17 May 2014; (d) MODIS snow cover difference between 16 and 9 May (blue shading indicates snow cover only). MODIS = Moderate Resolution Imaging Spectroradiometer; WRF = Weather Research and Forecasting; TRMM = Tropical Rainfall Measuring Mission.

3. Results
3.1. Blocking Frequency From ERA-Interim Data
The average blocking frequency over 45°E to 75°E (from 1985 to 2015) is calculated for spring (March to May), summer (June to August), autumn (September to November), and winter (December to February) seasons. In all seasons, peak blocking frequencies (in terms of percentage ratio of days blocked to the total number of days) are observed between ∼55°E and 70°E longitudes (Figure 2a), after a sharp drop in the blocking frequency through the Euro-Atlantic sector (peak values on far left corner of Figure 2a), which is the typical region for the formation of Ural-Siberian blocks (Cheung, Zhou, Mok, et al., 2013; Cheung, Zhou, Shao, et al., 2013). Thus, we focus on atmospheric blocks formed within these longitudes and on their associated downstream impacts on Himalayan weather as demonstrated by two unique cases.

Furthermore, the average number of blocking events in a year is 2.7 with the highest number of blocking events (six) observed in 1996, and zero blocking events in 1997 (Figure 2b). Atmospheric blocking events over the Ural-Siberian region have been shown to be associated with the Arctic Oscillation (AO) and the El Niño Southern Oscillation (ENSO), with fewer events when either AO or ENSO are in their positive phase (Cheung et al., 2012).

During the time period examined, the most commonly observed atmospheric blocks are the omega block and the dipole block. In this study, we selected two particular cases (one omega and one dipole) after 2000,
Figure 7. (a–e) Daily accumulated precipitation (shaded, mm), 500-hPa geopotential height (contour, hectometer), and 700-hPa wind (vector, m/s) from WRF simulations; (f–j) precipitable water (shaded, mm), vertically integrated moisture flux (vector indicating direction and contour indicating magnitude, kg m$^{-1}$ s$^{-1}$) computed from WRF simulations, and (k–o) ERA-Interim surface evaporation (meters of water) for 10–14 May, respectively. WRF = Weather Research and Forecasting.

which best represent these blocking events given their longevity over the Ural-Siberian region and the fact that the subtropical low-pressure trough(s) is(are) near the western Himalaya. We therefore identify the locations of low-pressure component(s) and select the cases where the low-pressure component(s) remain quasi-stationary westward of the western Himalayan for at least 50% of the blocking period. The reason behind the consideration of events after 2000 is the availability of TRMM and MODIS data, which provide better comparison with the high-resolution numerical simulations.

Based on the criteria set above, the omega block formed during 9–17 May 2014 is the most persistent block of its type with low-pressure troughs that remains quasi-stationary westward of the western Himalaya for $\sim$90% of the blocking period. Similarly, the dipole block formed during 1–11 February 2012 is the most persistent of its type and its low-pressure trough remains quasi-stationary westward of the western Himalaya for $\sim$83% of the blocking period.
3.2. Case I: Blocking Event (9–17 May 2014)

This section deals with an Ω block formed over the Ural-Siberian region during the spring season of 2014, which persisted for 9 days (9–17 May 2014). The synoptic conditions associated with this Ω block are determined using ERA-Interim reanalysis data, and a WRF simulation is used to analyze the anomalous weather conditions over the Himalaya and South Asia during this event.

3.2.1. Synoptic Conditions

The daily wind and height anomaly fields at the 200-hPa pressure level show the formation of an Ω block over Eurasia (Figure 3). This Ω block is characterized by a high-pressure ridge lying over Eurasia and subtropical troughs at its leading and trailing edges. The trough at the leading edge (western trough) lies over the Mediterranean region, and the trough at the trailing edge (eastern trough) extends from the Arabian Sea to the western Himalaya (lying over Pakistan, eastern Afghanistan, and northwestern India, Figure 3). Another prominent feature is the presence of upper-level anticyclonic wind anomalies over central Asia. The circulation anomalies associated with the eastern trough imply southward cold advection over the western Himalaya and northward warm advection over the central and eastern Himalaya.

The large-scale forcing associated with the upper atmospheric eastern trough resulted in negative mean sea level pressure (MSLP) anomalies over the Himalayan arc that extend up to southern China. Conversely, the MSLP anomalies over South Asia display positive values. Furthermore, the 850-hPa wind field shows

Figure 8. The 700-hPa average temperature advection (°C/hr), geopotential height (m), and wind (barbs, full barb = 10 m/s) for (a) 11 and (b) 12 May (source: Weather Research and Forecasting simulations).

Figure 9. Skew-T log-P diagram for Shreenagar station on (a) 00Z 12 May 2014 and (b) 00Z 13 May 2014 (source: University of Wyoming).
cyclonic flows over the Hindu Kush Mountains and anticyclonic flows over central India (Figure 4), which couple to generate convergent low-level winds over the WHN.

The isentropic potential vorticity (PV; on the 350 K surface) displays a reversal of the meridional PV gradient with high PV air circulating anticyclonically equatorward and low PV air moving poleward, an indicator of Rossby wave breaking in the region (Postel & Hitchman, 1999) and a feature that is often associated with blocking anticyclones in the midlatitudes (Pelly & Hoskins, 2003). Due to the entrainment of high PV air of stratospheric origin, the PV values over the western Himalaya are above 4 PV unit (Figures 5a and 5b). Furthermore, a tongue of high PV air descends to 4,000 m (Figure 5d), illustrating strong tropopause folding over the western Himalaya.

3.2.2. WRF Simulation of the Atmospheric Condition Over the Himalaya During an \( \Omega \) Blocking Event

WRF simulates high amounts of precipitation near the topographic notches in the western and the eastern Himalaya during this blocking event (Figure 6). There is a distinct variation in the type of precipitation along the topographic gradients. Lower elevations in both the western and eastern Himalaya receive rain, while the higher elevations receive snow (Figures 6a and 6b). For model validation, the spatial coverage and the quantity of precipitation simulated by WRF are compared with the TRMM precipitation data set. The spatial coverage of simulated precipitation is consistent with the TRMM data set. Simulated peak rainfall, however, is nearly double the magnitude of the observed peak over the higher elevation regions, although the quality of satellite observations is poor along the steep topographic gradients of the Himalaya, while

Figure 10. Skew-T log-P diagram for Dibrugarh station on (a) 00Z 12 May 2014 and (b) 00Z 13 May 2014 (source: University of Wyoming).

Figure 11. Cross section of daily accumulated precipitation (rain, snow, and mixed precipitation), average freezing level and elevation along the red lines ([a] CRS1 and [b] CRS2) shown in Figure 8b on 12 May 2014 (source: Weather Research and Forecasting simulations).
they are more accurate over flat terrain (Andermann et al., 2011). The TRMM data set has been shown to underestimate the precipitation magnitude above 3,100 m and overestimate it below, with relatively good performance between 1,000- and 2,000-m elevation over the Himalaya (Bharti & Singh, 2015). TRMM data underestimate solid precipitation, so we compare the model snowfall with the MODIS snow cover product, which provides validation to our simulation, as indicated by an increase in the extent of snow cover over the western Himalaya in the MODIS product during the study period (red boxes Figure 6).

Analysis of daily precipitation during this blocking event reveals strong precipitation over the WHN on 11–13 May (Figures 7b–7d), while the EHN receives precipitation throughout the blocking event. Strong precipitation over the western Himalaya is induced by winds converging onto the WHN (e.g., Figure 4). The topographic divide of the western Himalaya around 30.5°N and 77°E splits the moisture-laden westerly winds into two components, one of which converges toward the northwestern parts of the western Himalaya, while the other flows eastward along the southern margin of the Himalaya bringing precipitation to the EHN.
Figure 13. Daily mean sea level pressure anomalies (shaded, hPa), 850-hPa geopotential height (contour, m) and 850-hPa anomalous wind (vector, m/s) on (a) 3, (b) 4, (c) 5, (d) 6, (e) 7, and (f) 8 February 2012 (source: ERA-Interim reanalysis).

Higher values (greater than 45 mm) of precipitable water are observed over the region extending from the Bay of Bengal to the eastern Himalaya. Similarly, 30 to 40 mm of precipitable water is observed over the WHN on 10–13 May (Figures 7f–7i). To identify the sources of moisture during the blocking episode, the vertically integrated moisture flux (VIMF) is computed. The horizontal components of mean VIMF are defined as the horizontal moisture flux in the zonal ($Q_u$) and meridional ($Q_v$) directions integrated from the surface to 300-hPa pressure level, that is,

$$Q_u = \frac{1}{g} \int_{P_s}^{P_u} qu \, dp$$

(3)

$$Q_v = \frac{1}{g} \int_{P_s}^{P_u} qv \, dp$$

(4)

where $g$ is gravitational acceleration, $q$ is specific humidity, $u$ and $v$ are zonal and meridional components of wind, $P_s$ is the surface, and $P_u$ is 300 hPa. The magnitude of VIMF is computed as the vector magnitude of $Q_u$ and $Q_v$.
Figure 14. Daily PV unit (PVU) on 350 K isentropic surface on (a) 4, (b) 7, and (c) 8 February 2012, PV ≥ 1 PVU are contoured (source: ERA-Interim reanalysis); vertical cross section of simulated PV (shaded) and potential temperature (θ, green contour) on (d) 4 February, 12:00Z; (e) 7 February, 18:00Z; and (f) 8 February, 12:00Z, (d and e across 700°E longitude, and f across 800°E longitude; d–f are plotted from Weather Research and Forecasting simulations). PV = potential vorticity.

The VIMF displays strong moisture transport over the EHN from the Bay of Bengal and the Arabian Sea. Similarly, the western Himalaya receives moisture from the Arabian Sea and possible distal midlatitude sources (e.g., the Mediterranean and Caspian Seas) facilitated by the cyclonic circulation induced by the block. Thus, cyclones with strong flows across the topography and enough moisture flux lead to strong precipitation along the mountains' topographic gradient (Lang & Barros, 2004) as demonstrated by the intense simulated precipitation (~100 mm/day) over the western Himalaya on 12 May (Figures 7c and 7h).

The ERA-Interim evaporation data indicate strong evaporation over the tropical water bodies with higher values over the Arabian Sea and the Bay of Bengal (Figures 7k–7o). The spatial plots of moisture flux, evaporation and precipitable water and their comparison show the region extending from the Bay of Bengal to the EHN along the border of Bangladesh, India, and Myanmar exhibits intense evaporation, strong moisture flux, and high precipitable water (Figure 7). Thus, the accumulated precipitation over those regions during the blocking event is also very high.

The 700-hPa temperature advection during this blocking event displays cold advection over the central and western Himalaya (Figures 8a and 8b). Temperature advection over the Hindu Kush Mountains is, however, positive. The cold/warm advection associated with the block plays an important role in lowering/raising the freezing level. Thus, the cold advection associated with the block lowers the freezing level over the western
Himalaya as depicted by radiosonde profiles (Skew-T diagram) obtained from the Srinagar station, India (34.05°N and 74.5°E; Figure 9). The Skew-T diagram further displays the presence of a thick moist layer from the surface to 200 hPa (approximately the height of the tropopause) and indicates a convectively unstable layer with dry midtropospheric air lying between moist layers below and above.

Similarly, the Skew-T diagrams from the Dibrugarh station, Assam, India (27.48°N and 95.01°E) on 00Z 12 and 13 May exhibit a thick moist layer from the surface to 550 hPa (Figure 10). Wind barbs indicate the lower tropospheric air (950 to 850 hPa) as coming from the Bay of Bengal, while the winds above are westerly flowing along the southern margin of the Himalaya. The low-level air flowing from the Bay of Bengal is uplifted by the hills of east India and condenses its moisture in a band of precipitation extending from the Bay of Bengal to the EHN (cf. Figures 7a–7e).

The height of freezing level being associated with temperature advection plays an important role in determining the type of precipitation falling on the surface. Due to the lower freezing level, solid precipitation is present at an altitude below 2 km over the western Himalaya (Figure 11a). On the other hand, the eastern Himalaya experiencing warm temperature advection and thus higher freezing level display rainfall even at an elevation above 4 km (Figure 11b).

3.3. Case II: Blocking Event (1–11 February 2012)

Another typical blocking pattern (a dipole [Rex] block) formed over the Ural-Siberian region during the winter of 2012. It lasted for 11 days and produced widespread precipitation over the entire Himalaya.

3.3.1. Synoptic Conditions

The geopotential height anomaly at 200 hPa during this blocking event displays a strong ridge over Eurasia and a trough extending from Kazakhstan to the Arabian Sea, with its zonal extent from the Middle East to the Western Himalaya (Figure 12). Furthermore, the height field also shows the presence of weak ridges on either side of the trough. The anomalous wind field exhibits the transport of midlatitude air toward the tropics along the upstream portion of the trough and the transport of tropical air toward the midlatitudes along the downstream portion of the trough (Figures 12e and 12f).

The anomalous MSLP field during the blocking event exhibits positive anomalies over Eurasia with 850-hPa anticyclonic flow (Figures 13a–13d). A tongue of positive MSLP anomaly extends southward over the Middle East due to the large-scale sinking of cold air from midlatitudes along the upstream portion of the block.

Figure 15. (a) WRF rainfall (mm), (b) WRF snowfall (mm), and (c) TRMM precipitation (mm), accumulated over 1–9 February 2012; (d) MODIS snow cover difference between 10 and 1 February (blue shading indicates snow cover only). Location of Srinagar upper air station is represented by a black star enclosed within a black circle in (b). MODIS = Moderate Resolution Imaging Spectroradiometer; WRF = Weather Research and Forecasting; TRMM = Tropical Rainfall Measuring Mission.
There are two regions of negative MSLP anomalies on either side of this tongue: The western anomaly lies over the Mediterranean region, while the eastern anomaly lies over the western Himalaya and the Tian Shan Mountains. Thus, anomalous high pressure on the northwest side (west of Afghanistan) and low pressure on the southeast side (over the Indo-Pakistan border and the western Himalaya) forces the 850-hPa horizontal winds to converge over the WHN. Furthermore, due to anomalously low MSLP over the Himalaya on 7 and 8 February, the 850-hPa winds from both the Arabian Sea and the Bay of Bengal converge toward the central Himalaya (Figures 13e and 13f).

PV on the 350 K isentropic surface displays higher PV air circulating cyclonically toward the tropics (Figures 14a–14c). Similar to the anomalies associated with the $\Omega$ block, the vertical cross section of PV displays a strong tropopause fold with higher PV air descending to about 5000 m above MSL (Figures 14d–14f).
3.3.2. WRF Simulation of the Atmospheric Condition Over the Himalaya During the Dipole Blocking Event

The dipole blocking event is marked by strong precipitation over the entire Himalaya. WRF simulates the accumulation of both rain and snow over the southern slopes of the mountains in the Himalayan range (Figures 15a and 15b). In particular, the higher elevations in the Himalaya receive snowfall while lower elevations receive rainfall, and the magnitude of snowfall is twice the magnitude of rainfall. The spatial distribution of precipitation indicates that the model simulation is consistent with TRMM data (Figures 15a and 15c).

The MODIS Terra snow cover product over the Himalaya on 1 and 10 February displays a considerable increase in snow cover along the Himalayan arc during the simulated time period (Figure 15d). However, MODIS data do not show significant snow cover over the eastern Himalaya close to the border of India, Myanmar, and China. Reasons behind this discrepancy could be a thick cloud cover over that region or WRF simulating snowfall, though rainfall occurred in reality.

Analysis of daily WRF precipitation from 4 to 8 February indicates southward movement of the precipitating system from the western Himalaya toward the central and the eastern Himalaya (Figures 16a–16e). On 4 February, the downstream portion of the low-pressure component of the dipole block lies over the western
Figure 19. Cross section of daily accumulated precipitation (rain, snow, and mixed precipitation), average freezing level and elevation along the red lines ([a] CRS 3, 4 February 2012 and [b] CRS 4, 8 February 2012) shown in Figure 17b (source: Weather Research and Forecasting simulations).

Himalaya (close to the border of Afghanistan and Pakistan; cf. Figure 12b) and causes winds to converge on the WHN resulting in strong precipitation over the windward side of the western Himalaya. The topography of the Himalaya steers the movement of the precipitating low-pressure system southward along the Himalayan arc. On 7 February, the deep low-pressure trough spans 40°N to 25°N and causes strong moisture convergence over the Arabian Sea and directs the winds toward the central Himalaya (cf. Figure 12e), leading to strong precipitation over the Annapurna and Dhaulagiri Range in western Nepal. The slight eastward shift of the depression from 70°E to 75°E on 8 February causes strong precipitation over the entire central Himalaya.

The VIMF during the blocking event reveals the tropical water bodies (the Arabian Sea and the Indian Ocean) as the main sources of moisture for the precipitation along the Himalayan arc (Figures 16f–16j). The locations of higher values of total precipitable water and VIMF are consistent with the locations of strong precipitation. Thus, the cyclonic component of the dipole block promotes strong moisture transport from the tropical water bodies toward the Himalaya as evident from Era-Interim surface evaporation (Figures 16k–16o), which indicates high evaporation over the Arabian Sea during the blocking event. The Arabian Sea lies at the frontal boundary of the cold front formed by the southward advancing cold air. This cold front pushes warm-moist subtropical air toward the Himalaya (Figure 17).

The vertical temperature profile of the atmosphere during the blocking event shows the presence of a thick midtropospheric moist layer. The atmospheric sounding (Skew-T diagram) from the Srinagar station on 3 February 03Z shows a dry layer between the surface and 650 hPa and an overlying moist layer up to 350 hPa (Figure 18a). The absence of CAPE on 3 February implies topographic lifting as the only mechanism for the air parcel to precipitate. Furthermore, the surface temperature in the Skew-T diagram is below freezing level due to the cold advection associated with the block, so the Srinagar station (elevation 1,587 m amsl) and its surroundings receive solid precipitation (cf. Figures 15b).

There is widespread precipitation over the central Himalaya on 7 and 8 February. The Gorakhpur station lies in the simulated moisture transport route. Like the Srinagar station sounding, the Gorakhpur station sounding (Figure 18b) shows a thick midtropospheric moist layer with a dry layer below. The wind circulation in the lowest 100-hPa layer is from the southeast, while the blocking related southwesterlies flow above 900 hPa. The difference between the Srinagar and Gorakhpur soundings is that the surface temperature at Srinagar is below freezing, whereas at Gorakhpur the freezing level is at 660 hPa (∼3,000 m amsl). The higher freezing level at Gorakhpur is caused by the warm temperature advection associated with the block's wind circulation anomalies (cf. Figure 17).

A lower freezing level over the western Himalaya led to peak snow accumulation over the ridge with elevation below 4 km, with snow accumulation observed below 2 km (Figure 19a). On the other hand, due to the higher freezing level, liquid precipitation is still observed at an elevation close to 4 km (Figure 19b). The peak snow accumulation over the central Himalaya is observed at an elevation around 5 km, with a small amount of rainfall still observed at an elevation above 5 km.
4. Discussion and Conclusion

4.1. Discussion

The Ural-Siberian region is an important region for the formation of atmospheric blocks. We have presented two different, but characteristic, type of blocking events that form over the Ural-Siberian region, that is, an Ω blocking event and a dipole blocking event. Although the structure and the season of occurrence of both the blocking events chosen are different, they are both associated with strong precipitation and varied precipitation types over the Himalaya that are anomalous to that season.

A comparison of tropospheric height and wind field anomalies between the two blocking events displays troughs with axes parallel to the Hindu Kush Mountains, penetrating southward to the Arabian Sea in both cases. The combination of the midlatitude ridge and subtropical troughs enhance meridional wind flows. This generates southward advection of cold midlatitude air in both blocking events. The advected upper-tropospheric air subsides over the region from the Arabian Peninsula to South Asia, increasing the surface pressure.

Another feature associated with both blocking events is the equatorward protrusion of high PV air. The vertical cross sections of PV in both cases display high PV air descending to 5000 m asl showing strong tropopause folding. There is an air mass exchange between troposphere and stratosphere associated with tropopause folds, leading to high-ozone concentrations over the ridges of Himalayan Mountains (Bracci et al., 2012; Ojha et al., 2017). Furthermore, Bracci et al. (2012) performed back trajectory analysis associated with the high-ozone concentration measured at the Pyramid station near the Everest base camp and identified the high-ozone concentration trajectory as coming from the northern Eurasia (around the Ural-Siberian region).

During the Ω block, the upper-tropospheric trough induces convergence of ageostrophic winds upstream and divergence downstream. Thus, upper-level convergence occurs over the Arabian Peninsula, while divergence occurs over the Indo-Pakistan border extending all the way to the WHN. The convergence of ageostrophic winds over central Afghanistan and the Arabian Peninsula triggers the subsidence of cold midlatitude air (cf. section 3.2), while the divergence over the WHN drives the upward flow of air causing negative pressure anomalies and convergent, moisture-laden low-level westerly flow toward the WHN and precipitation over the mountains with a type determined by the local freezing level.

Similar to the Ω block, the dipole block initially induces convergence of ageostrophic winds in the upper troposphere over the Middle East and divergence over the Indo-Pakistan region. However, at the later stage, the upper-tropospheric convergence shifts over the region extending from the Middle East to northwestern India and the divergence shifts over the central and western Himalaya. Thus, subsidence of cold midlatitude air occurs over the Middle East and northwestern India, and the vertical ascent of warm-moist air occurs over the Gangetic Plain and the foothills of the central Himalaya.

Precipitation is mainly concentrated over the western and EHNs during the Ω blocking event, while the entire Himalayan arc receives precipitation during the dipole blocking event. The Ω blocking event is observed during the month of May (spring/premonsoon), which is close to the date of onset of the summer monsoon in South Asia. Strong convection near the Bay of Bengal is common in the premonsoon season (Virts & Houze, 2016) and the anomalous low-level westerlies associated with the block advect the moisture eastward and eventually produce precipitation over Bangladesh, Myanmar, and northeast India (cf. Figures 6a and 6c). The analysis of VIMF suggests the moist flow from the Arabian Sea is the main source of moisture for the precipitation around the WHN, while the EHN gets moisture from both the Arabian Sea and the Bay of Bengal. Moisture transport from the Arabian Sea to the EHN is anomalous and related to the dynamics of the subtropical trough portion of the block west of the Hindu Kush Mountains.

Likewise, the analysis of VIMF during the dipole block shows the moisture flux converging from the Arabian Sea to the WHN. However, as the trough deepens and extends southward over time, moisture transport concentrates over the central Himalaya generating strong widespread precipitation. Norris et al. (2015) simulated two winter precipitation events over the Himalaya, using the WRF model, and observed widespread precipitation over the entire Himalayan arc on one of their simulations (from 9 to 16 March 2006). Though their study is not related to the upper atmospheric blocks, their simulations also show the evolution of two cyclones over an 8-day period that triggered widespread precipitation over the entire Himalayan arc. Thus,
southward extension of the low-pressure trough is important to generate precipitation over the central and the eastern Himalaya.

The freezing level in both the blocking events drops/rises depending on cold/warm advection generated by the block and plays an important role in determining the type of precipitation at different elevations. For example, a lowered freezing level due to cold advection over the western Himalaya during the $\Omega$ block resulted in frozen precipitation at lower elevations, while an elevated freezing level due to warm advection over the central Himalaya during the dipole block resulted in liquid precipitation at higher elevations.

4.2. Conclusion

This study has presented the anomalous weather conditions over the Himalaya during two different blocking events (an $\Omega$ blocking event and a dipole blocking event) in the Ural-Siberian region using the simulated output from the WRF model. The analysis of synoptic conditions during both the blocking events reveal the cyclonic component of the block as a driver for the anomalous weather conditions over the Himalaya. The convergence and divergence of ageostrophic winds along the upstream and downstream portion of the upper-level trough cause subsidence of cold midlatitude air along the upstream portion and ascent of warm subtropical air along the downstream portion. This creates high surface pressure over the Arabian Peninsula and the Middle East, and local pressure deficit over South Asia. They also create tropopause folds characterized by equatorward protrusions of high PV stratospheric air that descend into tropospheric elevations.

Over high topographic elevations such as the Himalaya, the likelihood of such folding events, and hence stratospheric air, reaching the surface is significantly increased.

Simulated precipitation in both cases compares favorably with the TRMM data set and the MODIS snow cover product (as observations). The spatial distribution of precipitation during the $\Omega$ block is limited to the eastern and WHNs, while there is widespread precipitation during the dipole blocking event.

Our study shows that Ural-Siberian blocks are important perturbations in the upper atmosphere that generate strong precipitation events over the Himalaya, of both rain and snow, and hence are likely to play a role in the mass balance of Himalayan glaciers. Any change in frequency and intensity of blocks due to climate change, as well as changes in the freezing levels associated with these blocks, will therefore be a factor to consider in determining the future mass balance of Himalayan glaciers, and remains a subject for future research.

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References

Andermann, C., Bonnet, S., & Gloaguenn, R. (2011). Evaluation of precipitation data sets along the Himalayan front. Geochimica et Cosmochimica Acta, 75(20), 6261–6276. https://doi.org/10.1016/j.gca.2011.10.027

Bariopedro, D., García-Herrera, R., Lupo, A. R., & Hernández, E. (2006). A climatology of Northern Hemisphere blocking. Journal of Climate, 19(6), 1042–1063. https://doi.org/10.1175/JCLI3687.1

Bharti, V., & Singh, C. (2015). Evaluation of error in TRMM 3b42v7 precipitation estimates over the Himalayan region. Journal of Geophysical Research: Atmospheres, 120, 12,458–12,473. https://doi.org/10.1002/2015JD023779

Bracchi, A., Cristofanelli, P., Sprenger, M., Bonaf, U., Calzolari, F., Duchi, R., et al. (2012). Transport of stratospheric air masses to the Nepal Himalaya evaluated with MOZAIC. Quarterly Journal of the Royal Meteorological Society, 138(672), 1489–1507. https://doi.org/10.1002/qj.828

Cheung, H. N., Zhou, W., Mok, H. Y., & Wu, M. C. (2013). Observational climatology and characteristics of wintertime atmospheric blocking over Ural-Siberia. Climate Dynamics, 41(1), 63–79. https://doi.org/10.1007/s00382-012-1587-6

Cheung, H. N., Zhou, W., Mok, H. Y., & Wu, M. C. (2012). Relationship between Ural-Siberian Blocking and the East Asian winter monsoon in relation to the Arctic oscillation and the El Niño-Southern Oscillation. Journal of Climate, 25(12), 4242–4257. https://doi.org/10.1175/JCLI-D-11-00225.1

Cheung, H. N., Zhou, W., Mok, H. Y., & Wu, M. C. (2013). Revisiting the climatology of atmospheric blocking in the Northern Hemisphere. Advances in Atmospheric Sciences, 30(2), 397–410. https://doi.org/10.1007/s00376-012-1206-y

Carrera, M. L., Higgins, R. W., & Kousky, V. E. (2004). Downstream weather impacts associated with atmospheric blocking over the Americas. Journal of Geophysical Research, 109(D6), D06109. https://doi.org/10.1029/2003JD003867

Cannon, F., Carvalho, L. M., Jones, C., & Bookhagen, B. (2014). Multi-annual variations in winter westerly disturbance activity affecting the Himalaya. Climate Dynamics, 44(1-2), 441–455. https://doi.org/10.1007/s00382-014-2248-8

Casola, J. H., & Wallace, J. M. (2007). Identifying weather regimes in the wintertime 500-hPa geopotential height field for the Pacific-North American sector using a limited-contour clustering technique. Journal of Applied Meteorology and Climatology, 46(10), 1619–1630. https://doi.org/10.1175/JAM2564.1

Casanova, J. H., & Wallace, J. M. (2007). Identifying weather regimes in the wintertime 500-hPa geopotential height field for the Pacific-North American sector using a limited-contour clustering technique. Journal of Applied Meteorology and Climatology, 46(10), 1619–1630. https://doi.org/10.1175/JAM2564.1

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., et al. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. Quarterly Journal of the Royal Meteorological Society, 137(656), 553–597. https://doi.org/10.1002/qj.828
Huffman, G. J., Adler, R. F., Bolvin, D. T., & Nelkin, E. J. (2010). The TRMM Multi-satellite Precipitation Analysis (TMPA). In M. Gebremichael & F. Hossain (Eds.), Satellite rainfall applications for surface hydrology (pp. 3–22). Dordrecht, Netherlands: Springer. https://doi.org/10.1007/978-90-481-2915-7

Jiménez, P. A., Dudhia, J., Gonzalez-Rouco, J. F., Navarro, J., Montez, J. P., & Garca-Bustamante, E. (2012). A revised scheme for the WRF surface layer formulation. *Monthly Weather Review*, 140(3), 898–918. https://doi.org/10.1175/MWR-D-11-00056.1

Kain, J. S. (2004). The Kainfritch convective parameterization: An update. *Journal of Applied Meteorology*, 43(1), 170–181. https://doi.org/10.1175/1520-0450(2004)043<0170:TKCPA2.0.CO;2

Karki, R., ul Hasson, S., Gerlitz, L., Schickhoff, U., Scholten, T., & Böhner, J. (2017). Quantifying the added value of convection-permitting climate simulations in complex terrain: A systematic evaluation of WRF over the Himalayas. *Earth System Dynamics*, 8(3), 507–528. https://www.earth-syst-dynam.net/8/507/2017/

Lang, T. J., & Barros, A. P. (2004). Winter storms in the central Himalayas. *Journal of the Meteorological Society of Japan, 82*(3), 829–844. https://doi.org/10.2151/jmsj.2004.829

Lau, W. K. M., & Kim, K.-M. (2012). The 2010 Pakistan flood and Russian heat wave: Teleconnection of hydrometeorological extremes. *Journal of Hydrometeorology, 13*(1), 392–403. Retrieved from http://journals.ametsoc.org/ doi/abs/10.1175/JHM-D-11-016.1

Lejenäs, H., & Økland, H. (1983). Characteristics of northern hemisphere blocking as determined from a long time series of observational data. *Tellus A*, 35A(1), 140–165. https://doi.org/10.1111/j.1600-0870.1983.tb00210.x

Medina, S., Houze, R. A. Jr., Kumar, A., & Niyogi, D. (2010). Summer monsoon convection in the Himalayan region: Terrain and land cover effects. *Quarterly Journal of the Royal Meteorological Society, 136*(648), 593–616. Retrieved from https://mets.onlinelibrary.wiley.com/doi/abs/10.1002/qj.601

Nakanishi, M., & Niino, H. (2006). An improved Mellor–Yamada level-3 model: Its numerical stability and application to a regional prediction of advection fog. *Boundary-Layer Meteorology*, 119(2), 397–407. https://doi.org/10.1007/s10546-005-9030-8

Nakanishi, M., & Niino, H. (2009). Development of an improved turbulence closure model for the atmospheric boundary layer. *Journal of the Meteorological Society of Japan. Ser. II*, 87(5), 895–912. https://doi.org/10.2151/jmsj.87.895

Niu, G. Y., Yang, Z. L., Mitchell, K. E., Chen, F., Ek, M. B., Barlage, M., et al. (2011). The community Noah land surface model with multiparameterization options (Noah-MP): 1. Model description and evaluation with local-scale measurements. *Journal of Geophysical Research, 116*, D12109. https://doi.org/10.1029/2010JD015139

Norris, J., Carvalho, L. M., Jones, C., & Cannon, F. (2015). WRF simulations of two extreme snowfall events associated with contrasting extratropical cyclones over the western and central Himalaya. *Journal of Geophysical Research: Atmospheres, 120*, 3114–3138. https://doi.org/10.1002/2014JD022592

Ojha, N., Pozzer, A., Akrinitidis, D., & Lelieveld, J. (2017). Secondary ozone peaks in the troposphere over the Himalayas. *Atmospheric Chemistry and Physics, 17*(11), 6743–6757. https://doi.org/10.5194/acp-17-6743-2017

Park, Y.-J., & An, J.-B. (2014). Characteristics of atmospheric circulation over East Asia associated with summer blocking. *Journal of Geophysical Research: Atmospheres, 119*, 726–738. https://doi.org/10.1002/2013JD020688

Pelly, J. L., & Hoskins, B. J. (2003). A new perspective on blocking. *Journal of the Atmospheric Sciences, 60*(5), 743–755. https://doi.org/10.1175/1520-0469(2003)60<0743:ANPOBO>2.0.CO;2

Pook, M. J., Risby, J. S., McIntosh, P. C., Ummenhofer, C. C., Marshall, A. G., & Meyers, G. A. (2013). The seasonal cycle of blocking and associated physical mechanisms in the Australian region and relationship with rainfall. *Americal Meteorological Society, 141*(12), 4534–4553. https://doi.org/10.1175/MWR-D-13-0040.1

Postel, G. A., & Hitchman, M. H. (1999). A climatology of Rossby wave breaking along the subtropical tropopause. *Journal of the Atmospheric Sciences, 56*(3), 359–373. https://doi.org/10.1175/1520-0469(1999)056<0359:ACORWB>2.0.CO;2

Rex, D. F. (1950). Blocking action in the middle troposphere and its effect upon regional climate. *Tellus, 2*(3), 196–211. https://doi.org/10.1111/j.2153-3490.1950.tb00331.x

Takaya, K., & Nakamura, H. (2005). Geographical dependence of upper-level blocking formation associated with intraseasonal amplification of the Siberian high. *Journal of the Atmospheric Sciences, 62*, 4441–4449. https://doi.org/10.1175/JAS3628.1

Thompson, G., Field, P. R., Rasmussen, R. M., & Hall, W. D. (2008). Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. Part II: Implementation of a new snow parameterization. *Monthly Weather Review*, 136(12), 5095–5115. https://doi.org/10.1175/2008MWR2387.1

Vellore, R. K., Kaplan, M. L., Krishnan, R., Lewis, J. M., Sabade, S., Deshpande, N., et al. (2016). Monsoon-extratropical circulation interactions in Himalayan extreme rainfall. *Climate Dynamics, 46*(11-12), 3517–3546. https://doi.org/10.1007/s00382-015-2784-4

Virts, K. S., & Houze, R. A. (2016). Seasonal and intraseasonal variability of mesoscale convective systems over the South Asian monsoon region. *Journal of the Atmospheric Sciences, 73*(12), 4753–4774. https://doi.org/10.1175/JAS-D-16-0022.1

Yang, Z.-L., Niu, G.-Y., Mitchell, K. E., Chen, F., Ek, M. B., Barlage, M., et al. (2011). The community Noah land surface model with multiparameterization options (Noah-MP): 2. Evaluation over global river basins. *Journal of Geophysical Research, 116*, D12110. https://doi.org/10.1029/2010JD015140

Zhou, W., Chan, J. C. L., Chen, W., Ling, J., Pinto, J. G., & Shao, Y. (2009). Synoptic-scale controls of persistent low temperature and icy weather over Southern China in January 2008. *Monthly Weather Review, 137*(11), 3978–3991. https://doi.org/10.1175/2009MWR2952.1