Multiscale Aspects of the Storm Producing the June 2013 Flooding in Uttarakhand, India

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ABSTRACT

Conditions producing disastrous flooding in Uttarakhand, India, in June 2013 differed from conditions that produced other notorious floods in the Himalayan region in recent years. During the week preceding the Uttarakhand flood, deep convection moistened the mountainsides, making them vulnerable to flooding. However, the precipitation producing the flood was not associated with a deep convective event. Rather, an eastward-propagating upper-level trough in the westerlies extended abnormally far southward, with the jet reaching the Himalayas. The south end of the trough merged with a monsoon low moving westward across India. The merged system produced persistent moist low-level flow oriented normal to the Himalayas that advected large amounts of water vapor into the Uttarakhand region. The flow was moist neutral when it passed over the Himalayan barrier, and orographic lifting produced heavy continuous rain over the region for 2–3 days. The precipitation was largely stratiform in nature although embedded convection of moderate depth occurred along the foothills, where some mild instability was being released. The Uttarakhand flood had characteristics in common with major 2013 floods in the Rocky Mountains in Colorado and Alberta, Canada.

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1. Introduction

The northern Indian state of Uttarakhand lies in hills at the base of the steep south slopes of the central Himalayan escarpment (Fig. 1). The northernmost part of the state consists of Himalayan peaks and glaciers. Deep valleys on the south-facing slopes are susceptible to landslides and flooding. Over a 3-day period in June 2013, approximately 500–1000 mm of rain fell over Uttarakhand and its river valleys as well as neighboring Nepal. The

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FIG. 1. (a) Geography of the region of study. Uttarakhand state (red) is indicated. (b) Uttarakhand state with locations of stations used to create Fig. 7.

extensive precipitation and runoff led to devastating floods and landslides throughout the region and resulted in much destruction and loss of life (over 4000 villages were affected, and the death toll exceeded 5000). Widespread blinding snow created hazardous conditions at higher elevations. The meteorological conditions leading to the Uttarakhand flood were unlike those of other major monsoon-season floods over and near the Himalayas in 2010–12 (Houze et al. 2011; Rasmussen and Houze 2012; Rasmussen et al. 2015). Those floods were produced by deep and intense mesoscale convective systems (MCSs) forming in a moist airstream sandwiched between a strong low pressure system extending across northern India and anomalously high pressure over the Tibetan Plateau.

All but one of the 2010–12 floods were slow-rising floods that lasted from a few days to over a month in the case of the 2010 Pakistan floods (Houze et al. 2011; Lau and Kim 2012; Galarneau et al. 2012). However, one notorious flash flood devastated Leh, India, in August 2010. The high-altitude city of Leh in the western portion of the Himalayas was struck by a strong, rapidly propagating MCS moving from the east off the Himalayan Plateau and over Leh. Anomalous easterly midlevel flow over the Tibetan Plateau formed a rear-inflow jet of the type described by Smull and Houze (1987) to organize convection, triggered earlier by daytime heating over the Tibetan Plateau, into a westward-propagating MCS (Rasmussen and Houze 2012; Kumar et al. 2014). Kotal et al. (2014) have likened the Leh event to the Uttarakhand flood. However, we will show that these two events arose from very different types of cloud systems.

On the synoptic scale, the Uttarakhand flood case was characterized by a *midlevel trough* in the *westerlies* that extended abnormally far south to the Himalayas, such that its region of upward air motion was located directly over Uttarakhand. This trough merged with a monsoon low over central India to produce the environment of the rainstorm that produced the Uttarakhand flood. In contrast, the Leh event was associated on the synoptic scale with strong *easterly flow* sandwiched between an anomalously strong *midlevel ridge* over the Tibetan Plateau and a very strong monsoonal low over northern India—very different synoptic conditions from the Uttarakhand event.

We are not the only investigators to have noticed that the synoptic environment was of a type that involved a southward-protruding trough on the synoptic scale. Both Vellore et al. (2015) and Ranalkar et al. (2016) have analyzed synoptic-scale aspects of the Uttarakhand flood and have reached conclusions that are consistent with those we present here. Vellore et al. (2015) identified 34 extreme rain events in the western Himalayas since 1979 and with a synoptic-scale composite approach showed that such events are often associated with a southward-protruding upper-level trough over the northern Himalayan region interacting with a moisture-laden monsoon circulation propagating toward the west over the Indo-Gangetic Plain. Using a convection-permitting model, Krishnamurti et al. (2017) simulated the Uttarakhand event and highlighted the role of moisture transport from the Bay of Bengal and the Arabian Sea over the Uttarakhand region, which resulted in a strong buildup of potential buoyancy. Priya et al. (2017) examined historical rainfall records and

showed that extreme precipitation events during the summer monsoon season have significantly increased over the western Himalayas since the 1950s. They attributed this increasing trend to the combined effects of a weakened southwest monsoon circulation, increased activity of transient upper-level westerly troughs over the western Himalayas, and increased southerly winds from the Arabian Sea into the region.

These previous studies have focused on the synoptic-scale aspects of cases involving troughs extending southward over the Himalayas. The Vellore et al. (2015) study employed a convection-permitting model to simulate some of the cases, with nested grid spacing down to 6 km. The results show where upward and downward motions were occurring in a general sense, but they do not show the cloud and precipitation field in the vertical in such a way that the convective versus stratiform nature of the precipitation can be determined. Nor are satellite analyses presented from which the nature of the clouds can be inferred.

Our paper examines the structure and dynamics of the Uttarakhand storm¹ in more detail, identifying the synoptic, mesoscale, convective, orographic, and land surface components of the storm. We include satellite observations, ground-based radar imagery, and convection-permitting model simulations down to 1-km grid resolution to show the three-dimensional character of the precipitating cloud systems in more detail than previous studies. Our premise is that a complete understanding of this flood event cannot be achieved without recognizing all the processes and scales contributing to the flood-producing cloud system. Analysis of other recent flood cases in this region (Houze et al. 2011; Rasmussen and Houze 2012; Rasmussen et al. 2015) has highlighted the importance of characterizing the detailed three-dimensional structure and multiscale aspects of the precipitating systems leading to flooding. The understanding gained from these multiscale studies has allowed for greater insight into the physical processes responsible for these other extreme flooding events.

All of the aforementioned previous studies of the Uttarakhand flood state that the weather event producing the flood was convective in nature, whereas we will demonstrate that the air flowing over the mountains was nearly moist neutral and that the precipitation was primarily stratiform in nature, with occasional embedded moderate convective elements, in contrast to other

recent floods associated with intense deep convection. A detailed analysis of the synoptic- to convective-scale processes responsible for the Uttarakhand flood also enables a more direct comparison to other recent major flood situations around the world. In this regard, our results will be seen to reinforce the position taken by Doswell et al. (1996) that local forecasting of flood situations is ideally based on identifying key meteorological and hydrologic “ingredients” and that a wide variety of synoptic and mesoscale situations can provide these ingredients.

2. Data

a. Synoptic data

The National Centers for Environmental Prediction–National Center for Atmospheric Research (NOAA/NCEP 1994; Kalnay et al. 1996) reanalysis data were used on a $2.5^\circ \times 2.5^\circ$ grid to investigate the large-scale synoptic features that define the environment in which the flood event occurred. Daily data were used to create mean composite and seasonal anomaly patterns from 10 to 18 June 2013 of geopotential height, winds, and precipitable water. In addition, quasigeostrophic $\mathbf{Q}$ vectors (Hoskins et al. 1978; Hoskins and Pedder 1980; Durran and Snellman 1987; Sanders and Hoskins 1990) and $\mathbf{Q}$ -vector divergence were calculated at 500 hPa for 15–17 June, the period before and during the flooding. These vectors are helpful in understanding the factors contributing to the forcing for quasigeostrophic vertical motion associated with the synoptic system that led to the flooding in Uttarakhand. As will be discussed below, the $\mathbf{Q}$ vectors help us to diagnostically separate synoptic-scale forcing factors from orographic, convective, and mesoscale factors at work in the Uttarakhand flooding event. We also use NCEP–NCAR reanalysis for comparing the Uttarakhand flooding event with the Leh flood case in section 8.

Backward air parcel trajectories were calculated using the National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory (ARL) Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT; Stein et al. 2015; Rolph et al. 2017). We chose the NCEP Global Data Assimilation System 1° grids (GDAS-1; Kanamitsu 1989; www.emc.ncep.noaa.gov/gmb/gdas) as the trajectory dataset instead of the NCEP–NCAR reanalysis grids described above, since the GDAS-1 grids have 23 vertical levels with a much finer resolution in the lower levels and produce more realistic trajectories than the NCEP–NCAR reanalysis grids (see the description of the archived GDAS-1 grids used by the HYSPLIT at <http://ready.arl.noaa.gov/gdas1.php>). Both

¹Throughout this paper we use the term *storm* to refer to a period of precipitation and its associated meteorological conditions. The nature of the clouds producing a storm's precipitation may be convective, stratiform, or some mixture of the two. At a given location, a storm can last from minutes to days.

the NCEP–NCAR reanalysis grids and the GDAS-1 grids are based on the NCEP Global Forecast System (GFS) model.

b. Satellite and radar data

The data used in this study are as follows:

- Version 7 of the Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) 2A25 data—Horizontal and vertical cross sections of the TRMM PR reflectivity data (Iguchi et al. 2000) are used to investigate the three-dimensional characteristics of the precipitating systems causing the floods.
- 3B42—TRMM-adjusted merged infrared precipitation estimates (3-hourly rainfall data; Huffman et al. 2007) are used to calculate accumulated rainfall over the Uttarakhand region. The use of the merged TRMM-adjusted dataset was necessary, because the TRMM satellite by itself has limited areal coverage of this region every day.
- Lightning data from the Lightning Imaging Sensor on board the TRMM satellite (available from https://lightning.nsstc.nasa.gov/data/data_lis.html) are used to investigate the number of lightning flashes that were associated with the storms that produced the Uttarakhand flood.
- Radar reflectivity data from the New Delhi Indira Gandhi International Airport (available in real time from http://imd.gov.in/pages/radar_main.php?adta=dlh) are used to show the orographic effects of the Himalayas on the precipitation at the time of the flood event.
- Meteosat-7 infrared satellite imagery (available from <https://eoportal.eumetsat.int>) is used to examine the evolution of the clouds during the flood event and to provide context for the radar analysis.

3. Models used in the study

a. Mesoscale simulations

The Advanced Research version of the Weather Research and Forecasting (WRF) Model (WRF-ARW), version 3.5 (Skamarock et al. 2008), was used in two simulation frameworks to examine the 1) mesoscale and 2) synoptic perspectives of the Uttarakhand flood event. The WRF Model is a compressible, nonhydrostatic, three-dimensional mesoscale model. Both simulation sets were initialized with GFS Final Operational Analysis data (GFS-FNL; available from <https://rda.ucar.edu/datasets/ds083.2/>) and were run for 48 h starting at 0000 UTC 16 June through 0000 UTC 18 June 2013. The simulation set 1 was run with a triple-nested domain at 9-, 3-, and 1-km grid spacing (Fig. 2a) and was used to

FIG. 2. WRF Model nested domains at (a) 9-, 3-, and 1-km grid spacing, and (b) 81- and 27-km grid spacing. Domain names d01, d02, and d03 are also shown. Uttarakhand (white circle) is indicated.

investigate the mesoscale aspects of the flood event. The second simulation was run with a double-nested domain at 81- and 27-km grid spacing (Fig. 2b; also see online supplemental material) and was used to produce the large-scale synoptic and $\mathbf{Q}$ -vector comparisons to reanalysis data. With both of these simulation sets, we are able to diagnose processes on scales ranging across synoptic, mesoscale, and convective scales. In addition, the Thompson et al. (2008) microphysics scheme was used for both sets of simulations because it has been shown to reproduce precipitating systems with both convective and stratiform precipitation in this part of the

TABLE 1. WRF Model setup for both simulation sets described in section 3a.

Physical process	Scheme	Reference
Microphysics	Thompson scheme; 6-class scheme with graupel, double moment for cloud ice	Thompson et al. (2008)
Longwave radiation	Rapid Radiative Transfer Model	Mlawer et al. (1997)
Shortwave radiation	Dudhia	Dudhia (1989)
Surface layer	Monin–Obukhov	
Land surface	Noah land surface model	Chen and Dudhia (2001)
PBL	Yonsei University (YSU) PBL	Hong et al. (2006)
Cumulus convection	Kain–Fritsch, none in d03 in Fig. 2a	Kain and Fritsch (1993)

world and elsewhere (Kumar et al. 2014; Rasmussen and Houze 2016). Simulated radar reflectivity was estimated from the WRF Model in simulation set 1 using the newly implemented Blahak (2007) methodology that utilizes direct microphysics assumptions and constants to calculate reflectivity. The specific physics options used in both simulation sets are summarized in Table 1.

b. Land Information System

Previous research on significant floods in this region has highlighted the role of soil moisture preconditioning and land surface interactions on these high-impact flood events (Kumar et al. 2014). To obtain soil moisture conditions for this study, we used the Land Information System (LIS), which is a land surface model developed at NASA Goddard Space Flight Center. The LIS uses a data assimilation framework developed to produce optimal fields of land surface states and fluxes (Kumar et al. 2006; Peters-Lidard et al. 2007; Mohr et al. 2013). We ran the LIS uncoupled (or offline) at 3-km spatial resolution over the Uttarakhand region [the same 3-km domain (d02) in simulation set 1 from Fig. 2a] and used the Noah land scheme (Ek et al. 2003) to reproduce soil moisture conditions in response to meteorological forcing fields obtained from GDAS. However, note that the LIS was not coupled to WRF in this analysis and was run only in the offline mode to investigate the long-term soil moisture characteristics in the Uttarakhand region. The LIS simulation was conducted from 1 January 2012 to 30 June 2013. This long offline simulation ensures that the land surface states simulated by the land surface model had adequate time to reach thermodynamic equilibrium with the forcing meteorology.

4. Characteristics of the synoptic conditions, clouds, precipitation, and soil moisture prior to the Uttarakhand flood

Before diagnosing the synoptic and mesoscale factors associated with the Uttarakhand flood, we first summarize the overall synoptic conditions and the nature of

the clouds and precipitation that occurred during the days leading up to the event. The 500-hPa geopotential height field on 10 June was characterized by a mid-tropospheric ridge centered over northern India and Tibet with the main westerly flow well north of the region (Fig. 3a). The midtropospheric flow at Uttarakhand (gold star) was thus easterly, and no large-scale trough was affecting the region. The 700-hPa wind over Uttarakhand was from the northwest and extremely dry air was being advected over the region from the highlands of the Hindu Kush of Afghanistan and Pakistan (Fig. 3b). At 850 hPa, the wind was also from the northwest, but it was transporting moist air originating from the Arabian Sea (Fig. 3c). The source of the moisture is confirmed by backward-calculated trajectories that end at the Uttarakhand region at 0000 UTC 11 June (Fig. 4). The trajectories ending at 2000 m above ground level (AGL) show strong rising motion into Uttarakhand and confirm that the low-level moisture source was the Arabian Sea (Fig. 4a). Trajectories that end at 5000 m AGL mostly originated from the highlands of Hindu Kush and were either flat or sinking into the Uttarakhand region (Fig. 4b). This layering of the flow patterns is similar to typical situations leading to intense convection over northwestern India and Pakistan in which low-level moist air from the Arabian Sea is capped by subsiding midlevel air from the Afghan Plateau (Sawyer 1947; Houze et al. 2007; Romatschke et al. 2010).

It is therefore no surprise that these synoptic conditions were associated with a massive convective event that produced a giant cold cloud shield and heavy rain over the Himalayas at 0000 UTC 11 June 2013 (Fig. 5a), which contrasts sharply with the generally lower cloud tops in the Uttarakhand flood case (Fig. 5b). The intense convection along the Himalayan escarpment on 11 June is typical of the type of synoptic situation in which flow over the complex terrain lifts the air mass and removes the convective inhibition maintained by the capping inversion. This event contributed several hundred millimeters of rainfall to the region of Uttarakhand. The

FIG. 3. Synoptic maps on 10 Jun 2013 showing (a) 500-hPa geopotential heights over Eurasia and Africa, (b) 700-hPa precipitable water anomalies (mm) and mean 700-hPa winds, and (c) 850-hPa geopotential height anomalies (m) and mean 850-hPa winds. Location of Uttarakhand (gold star) is indicated.

rain gauge network in the Himalayas is sparse; however, satellite remote sensing is used to show the rainfall for the period prior to the Uttarakhand flood. Figure 6a, based on the TRMM 3B42 merged satellite product, indicates the amount of precipitation that fell in the Uttarakhand region during 7–13 June, the period prior to the flooding and landslides. Several hundred millimeters of rain moistened the soil on the normally arid

Himalayan slopes during that period. The convective storm associated with the cloud shield shown in Fig. 5a was the main contributor to that rainfall.

The clouds and weather occurring during the 4 days immediately preceding and including the day of the flood (14–17 June) were very different from those of the earlier convective event shown in Figs. 5a and 6a. The relatively warm cloud-top pattern in the infrared imagery for the Uttarakhand flood period (Fig. 5b; see also the infrared satellite loop in the online supplemental material) indicates that vertical motions during the flood period were less intense than and not as deeply penetrating as in the 10–11 June event. Nevertheless, Fig. 6b shows that during 14–17 June, the accumulation of precipitation was even greater than that associated with the prior convective event—over 300 mm fell throughout the entire state of Uttarakhand, with approximately 600–900-mm accumulations in the central part of the region. This massive amount of rainwater flowed down the mountainsides moistened by the 10–11 June storm and was funneled into the intervening valleys to create the disastrous flooding and landslides.

The impact of the prior rainfall on the soil in the Uttarakhand region is indicated in Fig. 7, which shows the soil moisture and rainfall rate time series obtained by averaging results from the LIS model (section 3b) for the four locations shown in Fig. 1b for the period leading up to and including the time of the Uttarakhand flood. The soil moisture was very low in the first week of June, before multiple rainfall episodes. The LIS model results indicate that the rainfall on 10 and 11 June (Figs. 6a and 7b) caused the soil moisture over Uttarakhand to nearly double suddenly (Fig. 7a). After the first rain event, a succession of spikes in soil moisture occurred in response to subsequent rainfall episodes, and the soil moisture remained high. Thus, after 15 June, the soil moisture was greatly increased, and it is therefore not surprising that the mountainsides around Uttarakhand became susceptible to the landslide and mudslide conditions that occurred in connection with the Uttarakhand flood episode.

5. Synoptic setting of the Uttarakhand flood event of 17 June 2013

To understand the atmospheric events that led to the largely nonconvective storm that produced the extensive flooding in Uttarakhand, we first look at the large-scale flow pattern at 500 hPa over the European–Asian sector. On 13 June 2013 (Fig. 8a), a southwest–northeast-oriented short-wave trough in the westerlies (highlighted with the red dashed line in Fig. 8) was extending its influence southward to about 35°N between

FIG. 4. Air parcel trajectories calculated from the NOAA ARL HYSPLIT backward in time for 72 h ending at 0000 UTC 11 Jun 2013 and at nine locations (stars) in the Uttarakhand region for ending heights of (a) 2000 and (b) 5000 m AGL. Upper portion of each figure shows the origin and pathway for each trajectory, and lower portion shows the vertical motions experienced by each trajectory over the 72-h period where time increases from right to left along the x axis. Trajectories have different colors to aid in readability.

$\sim 60^\circ$ and 80°E . At the same time a closed cyclonic circulation (indicated by the red “L” in Fig. 8) was located along the eastern coast of India at about 20°N , 80°E . This low was of the type that frequently occurs over the Bay of Bengal during the monsoon and moves west to west-northwestward across the subcontinent (Shukla 1978). On 15 June 2013, the upper-level trough progressed to the southeast and was located to the immediate northwest of northernmost India (Fig. 8b). At the same time,

the lower-latitude closed cyclonic circulation migrated westward and was positioned over the Indian subcontinent, and the heights increased to the east of Uttarakhand over the Tibetan Plateau and eastward.

By 17 June 2013, when the Uttarakhand floods were occurring, the trough in the westerlies extended still farther south into India (Fig. 8c) and the ridging over the Tibetan Plateau amplified, creating southwesterly flow ahead of the trough directly over Uttarakhand. In

FIG. 5. Meteosat-7 infrared satellite imagery for (a) 0000 UTC 11 Jun and (b) 0700 UTC 17 Jun 2013. Location of Uttarakhand (white star) is indicated.

FIG. 6. Accumulated rainfall over Uttarakhand from TRMM 3B42 for the periods (a) 7–13 Jun and (b) 14–17 Jun 2013. Location of Uttarakhand (white star) is indicated.

addition, the trough in the westerlies had merged with the monsoonal low that had migrated westward so that the merged trough extended much further south to $\sim 10^{\circ}\text{N}$ over the Arabian Sea. This merger of the eastward-moving westerly trough and the lower-latitude westward-moving low produced the meridionally extensive southwesterly flow that contributed to orographic lifting of moisture over the Himalayas. Vellore et al. (2015) and Ranalkar et al. (2016) also noted that the upper-level trough combined with the westward-migrating monsoonal low and that this combination was important for synoptic-scale moisture transport into the region of the flood. Vellore et al. (2015) attributed the amplification of the trough in the midlatitude westerlies to Rossby wave breaking based on their composite analysis of the 34 heavy rain events in the Uttarakhand region.

The lower- and midlevel flow patterns in the days immediately leading up to the flood starkly contrast with the prior 10–11 June convective event (Fig. 3). Figures 9a–c show the 700-hPa wind and precipitable water anomaly evolution for the period 13–17 June 2013. The westward-migrating monsoonal low brought highly anomalous precipitable water westward so that by 17 June (Fig. 9c),

FIG. 7. NASA GSFC LIS output with 3-km spatial resolution over the Uttarakhand region for June 2013. (a) Average soil moisture (m^3 of water per m^3 of soil). Stations in the average are Joshimath (30.56°N , 79.57°E), Uttarkashi (30.72°N , 78.43°E), Kedarnath (30.73°N , 79.06°E), and Almora (29.81°N , 79.29°E). (b) Average rainfall rate (mm h^{-1}) is given; see Fig. 1b for locations. Period (shading) of the Uttarakhand flood is indicated.

the flow at Uttarakhand was perpendicular to the Himalayan escarpment and advecting highly anomalously moist air into the region. The mean precipitable water values at Uttarakhand were approximately 60 mm on 17 June 2013 (not shown). The sequence at 850 hPa (Figs. 9d–f) also highlights this westward migration of the monsoonal low. By 17 June, the 850-hPa flow had a southerly component perpendicular to the Himalayas that was advecting moisture toward the mountain barrier. The southerly direction of the wind at both 850 and 700 hPa on 17 June was dynamically consistent with Uttarakhand lying just to the east of the 500-hPa trough line seen in Fig. 8c. Backward-calculated trajectories shown in Fig. 10 show that the source region of the moist air was predominantly the Bay of Bengal and that the air underwent strong rising motion as it flowed into and over the Uttarakhand region. Two of the trajectories that ended at 3000 m AGL (Fig. 10b) originated from the northwest and also underwent some sinking motion.

Figure 11 shows the 500-hPa mean heights for 15–17 June 2013 and contours of the forcing term in the quasigeostrophic omega equation $-2\mathbf{\nabla} \cdot \mathbf{Q}$, where $\mathbf{Q}$ is the quasigeostrophic $\mathbf{Q}$ vector (e.g., Durran and Snellman

FIG. 8. Geopotential heights at 500 hPa (m) at (a) 13 Jun, (b) 15 Jun, and (c) 17 Jun 2013. Axis of the developing trough (dashed red line) is shown in all panels. Red “L” indicates the location of the monsoon depression as it moves westward across central India. Approximate location (star) of the Uttarakhand flood in all panels.

1987). Red contours in Fig. 11 indicate regions of positive forcing caused by $\mathbf{Q}$ -vector convergence. They show that $\mathbf{Q}$ -vector convergence east of the trough contributed to quasigeostrophic upward motion over the Uttarakhand flood area on all 3 days as the trough progressed eastward. According to quasigeostrophic reasoning (Holton and Hakim 2013, p. 200), the areas of converging $\mathbf{Q}$ vectors

indicate rising motion and areas of diverging $\mathbf{Q}$ vectors indicate subsiding motion owing to synoptic-scale forcing. The blue contours indicate areas of large-scale $\mathbf{Q}$ -vector divergence west of the trough line.

At these latitudes, quasigeostrophic balance may not be exact but authors such as Sanders (1984) and Nie et al. (2016) have provided evidence that quasigeostrophic

FIG. 9. Synoptic maps showing the 700-hPa precipitable water anomalies (mm) and mean 700-hPa winds (m s^{-1}) for (a) 13 Jun, (b) 15 Jun, and (c) 17 Jun 2013. (d)–(f) As in (a)–(c), but for synoptic maps of 850-hPa-height anomalies (m) and mean 850-hPa winds (m s^{-1}). Anomalies are departures from the monsoon seasonal mean (June–September).

FIG. 10. As in Fig. 4, but for trajectories ending at 0000 UTC 18 Jun 2013 at (a) 1000 and (b) 3000 m AGL.

balance at least partially applies in this region. The $\mathbf{Q}$ -vector divergence/convergence pattern in Fig. 11 indicates that the trough in the westerlies combined with the monsoonal low to the south was producing synoptic-scale upward forcing for ascent directly over Uttarakhand during the period of the flood. Figure 12 shows that the lower-resolution WRF simulation (d01 in Fig. 2b) also captured the $\mathbf{Q}$ -vector convergence and quasigeostrophic vertical motion over the flood zone at 0600 UTC 17 June 2013. The red and blue shading in Fig. 12 show the upward and downward motion, respectively, computed by inverting the $\mathbf{Q}$ -vector convergence to vertical motion, without orographic or boundary layer forcing [read–interpolate–plot (RIP) program; <http://www2.mmm.ucar.edu/wrf/users/docs/ripug.htm>]. This model result together with the NCEP reanalysis data (Fig. 11) indicates that upward air motion associated with the synoptic-scale pressure pattern was optimally positioned over Uttarakhand just before and during the time of the storm that produced the flooding. Thus, synoptic-scale lifting was a contributor to the storm producing the flood throughout the 3-day duration of the raining clouds over the region on 15–18 June. Vellore et al. (2015) also concluded that the synoptic-scale vertical motions at the jet entrance region positioned roughly over Uttarakhand and the associated ageostrophic thermally direct transverse circulations forced by quasigeostrophic dynamics were a strongly contributing factor to the development of the Uttarakhand flood event. Nie et al. (2016), however, find that the forced lifting over the Himalayan topography is a stronger effect.

A rough estimate of the vertical motion resulting from upslope motion over the Himalayan barrier can be made

using Eq. (5.2.88) of Bluestein (1992). Using an aspect ratio of 4:300 km and a horizontal wind speed of 20 m s^{-1} yields a vertical motion of $\sim 25 \text{ cm s}^{-1}$. This vertical velocity is an order of magnitude larger than those based on quasigeostrophic dynamics shown in Fig. 12. The evidence provided here thus shows that the two effects of quasigeostrophic forcing and orographic lifting coincided at the location of the Uttarakhand flood. However, the orographic vertical motion evidently dominated the condensation and precipitation. The importance of the synoptic-scale dynamics associated with the wave in the westerlies combined with the monsoon low over India was not the implied quasigeostrophic upward motions but rather to maintain a persistent horizontal flux of moist air into and over the Himalayan escarpment for a period of around 3 days.

6. Mesoscale vertical motion and thermodynamics on the day of the flood

Figure 13 shows the 1-km-resolution WRF Model (d03; Fig. 2a) vertical velocities at 500 and 700 hPa, where red shading denotes rising motion and the black vectors are horizontal winds at 0600 UTC 17 June. At both 500 and 700 hPa, the line of intermittent updraft motion was aligned with the approaching baroclinic trough seen in Fig. 11. The wind vectors in Fig. 13b show a weak lower-level cyclonic circulation center at about 30°N , 78°E behind the line of upward motion associated with the upper-level trough. The confluence of the wind pattern was a feature of the baroclinic wave and was important in concentrating the convection into a line. The winds veered from 700 to 500 hPa,

FIG. 11. Heights at 500 hPa (m; black contours) and calculated $\mathbf{Q}$ vectors (black vectors) from NCEP–NCAR reanalysis for (a) 15 Jun, (b) 16 Jun, and (c) 17 Jun 2013. Regions of $\mathbf{Q}$ -vector convergence (red contours, $10^{-17} \text{ m kg}^{-1} \text{ s}^{-1}$) and $\mathbf{Q}$ -vector divergence (blue contours, $10^{-17} \text{ m kg}^{-1} \text{ s}^{-1}$) indicate synoptic-scale areas of rising and sinking motion, respectively. Location (star) of the Uttarakhand flood is indicated.

becoming more directed into the Himalayas. Also notable in the 500-hPa vertical velocities is that where the warm, moist air originating from the Bay of Bengal reached the steep Himalayan terrain, the lifting occurred over a much broader region, corresponding to

where the air was forced up over the two-dimensional barrier. This broader region of orographic uplift was likely key to the massive condensation and accumulation of precipitation in the flood region. In addition, because this synoptic flow pattern was slow to evolve, the orographic component of lifting was persistent over a 2–3-day period. Persistence of lifting has been identified as a key ingredient in other notable floods around the world (see section 8).

An important question is, how stable or unstable was the air as it rose over the Himalayas? If the air impinging on the terrain is highly unstable, deep convection will erupt over the barrier. If the air impinging on the terrain is too stable, it will be blocked and turn parallel to the terrain, whereas if it is moist neutral, it will rise over the terrain unblocked (Rotunno and Ferretti 2001). Operational soundings are not available for the region directly upstream of the mountains in the area of interest to this study. However, we have obtained an indication of the stability from soundings reconstructed from the WRF output. Figure 14 shows model soundings from the 1-km-resolution WRF domain (Fig. 2a) at points A–C in Fig. 13, located upstream of the terrain and near Uttarakhand. Low-level veering of the wind up to 500 hPa (i.e., warm advection) is evident in all three panels. At point A, farther upstream, the temperature buoyancy of an undiluted parcel was $\sim 5^\circ\text{C}$ through most of the troposphere (Fig. 14a). That thermal profile was consistent with the line of intermittent cellular vertical motion upstream of the mountain range. Point B is in the lower foothills, and the sounding in Fig. 14b was closer to moist adiabatic. The air was probably more thoroughly mixed by prior convection. Farther north in the broader area of lifting over the windward slope, the sounding in Fig. 14c was saturated and moist neutral, implying that the air would have been rising over the barrier unblocked but without triggering deep convection.

Ranalkar et al. (2016) used the Lightning Imaging Sensor on the TRMM satellite to show that lightning existed in the region during the Uttarakhand flood. However, an independent analysis of the Lightning Imaging Sensor lightning flashes in a $2^\circ \times 2^\circ$ box over the Uttarakhand region from 16 to 18 June 2013 shows that only 14 lightning flashes were observed over these 3 days (Table 2). Thus, it appears that little convection was present, and it is well known that lightning can occur as long as certain conditions involving graupel, ice crystals, liquid water, and temperature are met in a cloud (Houze 2014, chapter 8). There is no requirement for environmental thermodynamic instability. The model soundings (Fig. 14) show that the thermodynamic profile of the air rising over the terrain was moist neutral, implying that the moderate embedded convection (and

FIG. 12. WRF Model 500-hPa $\mathbf{Q}$ vectors (black vectors). Upward motion (dPa s^{-1}) implied by $\mathbf{Q}$ -vector convergence (red). Downward motion implied by $\mathbf{Q}$ -vector divergence (blue shading). Fields shown are for 0600 UTC 17 Jun 2013. Location (star) of the Uttarakhand flood is indicated.

the sparse lightning) was mostly just upstream of the area of flooding. Thus, the presence of very few lightning flashes in the satellite data suggests that the precipitation was primarily stratiform in nature with some weak to moderate embedded convective cells along the Himalayan foothills. In a similar manner, low lightning flash rates during the Colorado Front Range flood in September 2013 were associated with embedded convective elements in the predominantly stratiform precipitation (Gochis et al. 2015).

7. Radar echoes and vertical structure

An analysis of the three-dimensional structure and dynamics of the precipitating systems that produced the Uttarakhand flood is helpful for understanding the nature of this high-impact event. Precipitation radar data from the TRMM PR have been especially useful for characterizing convective and stratiform precipitation in terms of the vertical and horizontal structures of radar echoes over low latitudes (Houze et al. 2007; Romatschke et al. 2010; Romatschke and Houze 2010; Rasmussen and Houze 2011; Houze et al. 2015). These

prior papers have identified three radar echo categories as defining the most extreme forms of convection over land: deep convective cores (DCCs; 40-dBZ echoes reaching >10-km height), wide convective cores (WCCs; 40-dBZ echoes exceeding 1000 km² in contiguous horizontal extent), and broad stratiform regions (BSRs; stratiform echoes extending contiguously >50 000 km²). An objective search of TRMM radar echoes for the period and region of the Uttarakhand flood showed no TRMM radar echoes that could be classified as either DCC, WCC, or BSR, whereas previous India/Pakistan floods that we have studied were all associated with these extreme forms of echo. Thus, we conclude that the convection in the case of the Uttarakhand flood was not extreme by these previously used standards.

The precipitation radar on the TRMM satellite shows only occasional and sporadically located snapshots of the three-dimensional radar reflectivity. The ground-based operational radar at the New Delhi Indira Gandhi International Airport continuously collected data during the period of the Uttarakhand storm. Figure 15 shows the reflectivity pattern detected by this radar at 0742 UTC 17 June 2013. This radar image is typical of

FIG. 13. WRF simulation of vertical velocities (cm s^{-1}) and horizontal winds (black vectors) for 0600 UTC 17 Jun 2013 for (a) 500 and (b) 700 hPa. Upward (red shading) and downward (blue shading) vertical velocities. The points A–C indicate the locations of soundings shown in Fig. 14. Location (blue line) of the cross section in Fig. 16c is indicated.

the echo pattern during the period of the flood; the meridional line of precipitation south of the Himalayas is consistent with the model vertical velocity and confluent low-level wind pattern shown in Fig. 13. Near the foothills and over the Himalayan escarpment, the

precipitation area was wider. The widening could have been partially a result of the increasing height of the radar beam with increasing range from the radar. However, the widening also corresponds well to the area where the lifting of nearly moist-neutral air (Fig. 14c)

FIG. 14. Soundings derived from the 1-km WRF output (D03 in Fig. 2a) for 0600 UTC 17 Jun 2013 for points (a) A, (b) B, and (c) C in Fig. 13. Temperature and dewpoint are displayed in skew T –log p format. Temperature of an undiluted parcel lifted from the surface (dashed red curves).

TABLE 2. Number of daily accumulated lightning flashes from the Lightning Imaging Sensor on board the TRMM satellite in a $2^{\circ} \times 2^{\circ}$ box centered over Uttarakhand (29° – 31° N, 78° – 80° E) (https://lightning.nsstc.nasa.gov/data/data_lis.html).

Date (2013)	No. of lightning flashes
15 Jun	4
16 Jun	8
17 Jun	6
18 Jun	0

ahead of the upper-level trough was being enhanced in a broad region by flow over the Himalayan terrain (Fig. 13).

The TRMM PR captured a snapshot of the vertical structure of the precipitating system over Uttarakhand on the day of the flood. Figure 16 shows *Meteosat-7* infrared imagery and TRMM PR data over Uttarakhand during a TRMM overpass at 0715 UTC 17 June. Figure 16b shows the TRMM PR echo in a cross section along the white line in Fig. 16a. The highly convective India and Pakistan flood events of 2010–12 described by Rasmussen et al. (2015, see their Fig. 8) had cloud-top temperatures mostly ~ 20 K colder than those associated with the Uttarakhand flood precipitating system (Fig. 16a). The vertical cross section of TRMM satellite radar data in Fig. 16b shows that the structure of the system over Uttarakhand was generally stratiform in nature with embedded convection along the mountainous

FIG. 15. Low-level radar reflectivity (dBZ) display from the operational radar at New Delhi Indira Gandhi International Airport (airplane icon) at 0743 UTC 17 Jun 2013, during the Uttarakhand flood event. Color bar and image were available on the Indian Meteorological Department website. Location (star) of the Uttarakhand flood is indicated.

FIG. 16. (a) *Meteosat*-7 satellite infrared brightness temperatures (K). Location (star) of flooding is indicated. (b) Vertical cross section of TRMM PR data (dBZ) taken left to right along the white line in (a). Height of the underlying topography (solid green region) is shown. (c) WRF radar reflectivity (dBZ) and vertical velocity (cm s^{-1}) (d03; Fig. 2a) computed along a similar cross section to (b) at 0700 UTC 17 Jun 2013. As in Fig. 13, upward vertical velocity (red contours) and downward vertical velocity (blue

foothills, where instability was still being released in the air moving over the terrain. The embedded convection was not penetrating to great heights, which is consistent with the general absence of very high cloud tops in Fig. 16a. In the highly convective cases described by Rasmussen et al. (2015), regions of deep convection with reflectivity values >35 dBZ reached at least 10 km, whereas in the Uttarakhand storm, the same reflectivities reached only ~ 7 km in height.

The reflectivity cross section computed from the 1-km-resolution WRF simulation with WRF-simulated vertical motions is shown in Fig. 16c. The simulated vertical motion field in this figure shows a broad area of upward motion greater than 0.5 m s^{-1} starting at the lowest elevations of the windward slopes of the Himalayas (from a 50–300-km distance along the cross section). Embedded in this broad region of upward motion, there are individual cores of stronger vertical motions greater than 1.5 m s^{-1} most likely associated with small individual convective cells embedded in the stratiform precipitation regions. These vertical motions are one to two orders of magnitude larger than those computed from quasigeostrophic (QG)-forcing alone ($1\text{--}2 \text{ cm s}^{-1}$, inferred from Fig. 12), consistent with the inference in section 5 that forced orographic lifting over the Himalayas was likely more important than quasigeostrophic forcing for producing the vertical motion responsible for the precipitation in the Uttarakhand event. The horizontal wind pattern of the synoptic-scale quasigeostrophic flow is nevertheless an important part of the multiscale aspects of the Uttarakhand case because it set up the pattern that made the strong and persistent orographic uplift possible.

The WRF-generated reflectivity field in Fig. 16c is consistent with the TRMM PR cross section in Fig. 16b. The TRMM cross section was truncated before it intersected the mountains because of problems with the radar data near the terrain. However, the cross section of model output shows the bright band sloping downward into the mountainside terrain (Fig. 16c). Such a downward sloping bright band is often seen in radar data in stratiform regions over mountains (e.g., Houze et al. 2017) and is probably due to a combination of these

← contours) are indicated. Shown are 150 cm s^{-1} (dotted red contour), 50 cm s^{-1} (solid red contour), and -50 cm s^{-1} (blue contour), and height of the underlying topography (solid white region). The blue bar under (c) indicates the approximate horizontal distance and location of the TRMM PR cross section in (b) relative to (c) for reference.

processes: cooling by the lifting over the terrain, latent cooling by melting precipitation, or melting distance of frozen hydrometeors (Minder et al. 2011). A feature notable in the Uttarakhand storm was the presence of widespread snowfall at higher altitudes in the Himalayas. Members of the Kailash pilgrimage in the higher terrain were blinded by continuous driving snow on 17 June 2013 (reported photographically to the authors by Professor David Battisti, who was on the pilgrimage; D. Battisti 2013, personal communication; see online supplemental material). The intersection of the bright band with the mountains indicates that the higher terrain was receiving snowfall consistent with the observations of the pilgrims.

8. Comparison with other recent flood events

The Uttarakhand flood is distinctly unlike other notorious floods in the Himalayan region in recent years. Rasmussen et al. (2015) described the large-scale conditions and mesoscale characteristics of the storms that produced several of the major floods of 2010–12. These storms were associated with a strong flow concentrated between abnormally high pressure over the Tibetan Plateau and a monsoon low extending anomalously far westward over northern India. That synoptic pattern contrasts sharply with the westerly trough dominating the Uttarakhand flood case.

In the 2010–12 cases examined by Rasmussen et al. (2015), strong flow between the high over Tibet and the low over India advected large amounts of moisture into the region just south of and over the Himalayas. This moist flow facilitated deep convective MCSs with trailing stratiform precipitation of the type described by Houze (2004). The floods in the 2010–12 cases were produced by these deep convective MCSs, in contrast to the more moderate clouds and precipitation of the Uttarakhand flood.

Another flood that differed from both the Uttarakhand flood and the slow-rise type of floods that occurred in Pakistan/India summarized above (Rasmussen et al. 2015) was the flood that occurred in Leh in 2010. That was a flash flood that occurred suddenly in the high-altitude terrain of the Indus River valley in Leh (Rasmussen and Houze 2012). This flash flood was caused by the passage of a deep convective MCS that formed over the Tibetan Plateau and moved rapidly westward over Leh. Figure 17a is an infrared satellite image showing the storm that produced the Leh flood. It had an extremely cold cloud top, similar to the 10 June 2013 Uttarakhand storm (Fig. 5a) and utterly unlike the clouds of the 17 June Uttarakhand flood case (Fig. 5b). Figure 17b shows the 500-hPa winds, which illustrate

FIG. 17. (a) *Meteosat-7* satellite infrared image (K) for 2000 UTC 5 Aug 2010 from *Meteosat-7* showing the MCS that resulted in the Leh flood. Location (circled cross) of Leh is indicated. (b) Winds at 500 hPa at 1200 UTC 5 Aug 2010. The 500-hPa-height deviation from the seasonal average (contours). Adapted from Rasmussen and Houze (2012).

how this case was associated with anomalously strong ridge over the Tibetan Plateau, with easterly flow directed toward and over Leh. Figure 17b also includes contours of the deviation of the 500-hPa height from its seasonal value, illustrating that the flow pattern in the Leh case was highly anomalous for the season. The Uttarakhand case was also unusual; however, its abnormality was in the form of the excursion of a synoptic-scale westerly trough into India, while the Leh case was abnormal for its ridging and easterly flow. The 500-hPa easterlies in the Leh case were directed into the trailing stratiform region of the MCS that caused the flooding in Leh. It formed a rear-inflow jet of the type associated with rapidly propagating leading-line/trailing stratiform squall lines (Smull and Houze 1987). This synoptic situation could hardly be more different from that of the

westerly trough associated with the Uttarakhand flood. Characterizing these two flood situations as similar (e.g., Kotal et al. 2014) is clearly incorrect. The only characteristic that we have found that these two flood cases had in common is the premoistening of the soil (described in section 4) by rain occurring in several days immediately preceding the flood. Yet, it is important to note that both flow situations were highly anomalous for the season in which they occurred, albeit in different ways.

Two flood situations that have more in common with the Uttarakhand flood are the Colorado and Alberta, Canada, floods of 2013, which have been investigated by Gochis et al. (2015), Milrad et al. (2015), and Friedrich et al. (2016). These authors point out that these floods were associated with low-level synoptic and mesoscale flow on the north sides of cyclonic circulations and that such circulation patterns are highly anomalous for the season in which they occurred. Further illustrating the anomalous character of the synoptic situation in the Colorado case, Gochis et al. (2015) found that the operational radar reflectivity–rain-rate (Z – R) relationship routinely used for this midlatitude location underestimated the rainfall by a factor of 2, but when the formula was changed to a tropical Z – R relationship, the radar-based rain estimates were much closer to the observed precipitation amounts. The North American cases, however, did not resemble the Uttarakhand case in all respects; Gochis et al. (2015) and Milrad et al. (2015) noted that the low-level cyclonic circulations in these cases were associated with a cutoff low at mid-levels, not an upper-level open-wave trough like that which propagated into and through the Uttarakhand region. However, the synoptic-scale flow patterns in the Colorado and Alberta cases concentrated moisture at low levels and produced persistent flow patterns toward the mountains for a sustained period, as was the case in Uttarakhand. Massive rain amounts occurred in Colorado and Alberta. However, the rain rates were not notably large nor were the airflows especially unstable, all similar to the Uttarakhand event. Milrad et al. (2015, p. 2839) found that the “QG and orographic ascent acted to release conditional instability in a moderate CAPE environment during the first part of the event (0000–0600 UTC 20 June), before a transition to moist-neutral stability.” This behavior of the low-level moist flow field is very similar to that which we have described for the Uttarakhand flood. In addition, the nature of the precipitation was similar. Friedrich et al. (2016) found moderate convective cells on the lower slopes of the Rockies, with warm coalescence processes dominating precipitation processes at lower levels and ice processes contributing above the melting level when the instability was moderate. These radar echo characteristics

resemble those seen in the Uttarakhand case. The Uttarakhand case is thus representative of a certain category of major flooding along major mountain barriers.

9. Conclusions

From 13 to 17 June 2013, a trough in the westerlies extended southward into northern India and accounted for the Uttarakhand flood of this period. The associated rainstorm had the following characteristics:

- The synoptic pattern produced confluence of the low-level wind so that it advected moisture into the barrier in a concentrated zone.
- The synoptic pattern maintained the moisture supply persistently for days.
- Orographic lifting converted the moisture to rain.
- Prior convection made the soil susceptible to runoff.
- The air passing over the terrain was nearly moist neutral.
- Convective cells of moderate intensity and depth formed upstream and over the foothills, but the layer of precipitation over the Himalayan slopes was primarily stratiform.

Storms associated with a trough extending southward over the Himalayas are a relatively rare event in this region and season. However, such events are known to be associated with major rainfall episodes over the Himalayas (Vellore et al. 2015; Ranalkar et al. 2016). In this case, the eastward-moving trough in the westerlies merged with a monsoonal low moving westward across India to produce low-level warm moist flow, which advected abnormally moist warm air directly toward the Himalayan escarpment into Uttarakhand for a long period. When the moist flow encountered the Himalayan escarpment, orographic forcing combined with upward motion associated with the wave in the westerlies to convert the moisture flux to heavy, continuous precipitation over the region. The orographic component of the upward motion was dominant compared to the synoptic-scale lifting ahead of the trough, consistent with the conclusions of Nie et al. (2016). The LIS showed that the mountainsides had been premoistened by deep convection in the week immediately preceding the flood and that the heavy rainfall running down the valleys of Uttarakhand led to the flooding and landslides. Being associated with a trough in the westerlies sharply distinguished this flood from the Leh flood of 2010. Previous studies asserting that the Leh and Uttarakhand floods were similar weather situations are incorrect.

Infrared satellite imagery showed the Uttarakhand floods were caused by a cloud system with relatively

warm cloud tops, unlike storms in more convective flood cases. TRMM PR observations on the day of the flood showed no extreme forms of convective echo of the types identified in other flood cases in India and Pakistan. Rather, it indicated that the precipitation was primarily stratiform with snow at high elevations, but that the storm nonetheless had embedded, though not especially deep, convection along the lower slopes of the Himalayas. In addition, analysis of lightning data from the TRMM satellite over Uttarakhand shows that there were very few lightning flashes in the region from 16 to 18 June 2013. The fact that this case was not dominated by deep convection distinguishes it not only from the Leh flood case but also from other recent major floods in Pakistan and northwest India, which have been caused by highly convective storm systems with very deep and intense convection, often in the form of MCSs (Rasmussen et al. 2015). It is thus clear that very different types of storms can produce flooding in northern India and Pakistan.

Recent major floods in Colorado and Alberta in 2013 had some features in common with the Uttarakhand flood. Both cases had low pressure systems that directed low-level moist flows into the Rocky Mountains for many hours, similar to the persistent low-level flow advecting moist air into the Himalayas in the Uttarakhand flood event. The Colorado and Alberta cases also took place under highly abnormal flow conditions like the Uttarakhand event. The storms leading to both the Uttarakhand and Colorado floods were composed of primarily stratiform precipitation with embedded convection and had minimal lightning activity. Other major floods in India and Pakistan, including both flash floods and slow-rise floods, have occurred in synoptic environments differing greatly from the Uttarakhand case, often with a ridge over the Tibetan Plateau and a pronounced monsoon low extending across northern India. Those floods were associated with extreme forms of convection seen in TRMM radar data; such extreme echo forms were wholly absent in the region and period of the Uttarakhand flood. These various synoptic situations and different forms of convection implicated in major floods in different mountainous regions of the world point to the essential approach for forecasters that was laid out by Doswell et al. (1996), namely, that one should focus on the specific meteorological ingredients constituting a flood situation, as opposed to broad synoptic categories such as “convection conditions” or “trough.” More specifically, forecasters should look for situations where, for whatever reason, air of high moisture content is subjected to vertical transport for a period that maximizes the output of rain on a given watershed. As pointed out by Doswell et al. (1996), such

ingredients can occur in diverse synoptic and mesoscale situations. The comparison of the Leh and Uttarakhand events illustrates the diversity of atmospheric environments in which severe flooding can occur in the Himalayas. Doswell et al. (1996) also list instability as an important ingredient. In the Uttarakhand flood, especially over the flood zone, the lapse rate was near-moist neutral and the storm persisted over a long time. In the Leh flood case, instability was great, the storm was transitory, and two storms manifested differently to produce destructive floods. Thus, all ingredients need not be present in the same way to produce a major flood. Our LIS calculations and the Leh case suggest further that soil moisture preconditioning by prior storms in the area in a vulnerable watershed is a hydrologic ingredient that should be taken into account along with the meteorological ingredients.

In addition, we suggest that the vigilance for ingredients on a day-to-day basis could be aided by continual monitoring for anomalous flow patterns. The India/Pakistan floods of 2010–2012 (Rasmussen et al. 2015), the Leh flood (Rasmussen and Houze 2012), and the Colorado and Alberta floods (Gochis et al. 2015; Milrad et al. 2015; Friedrich et al. 2016) all occurred in highly abnormal circulation patterns for their respective regions and seasons. The combination of abnormality of flow, meteorological ingredients, and premoistening of ordinarily dry soil in mountainous environments might be the best set of factors to consider when identifying a potentially damaging and dangerous flood situation.

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