A FLASH-FLOODING STORM AT THE STEEP EDGE OF HIGH TERRAIN

Disaster in the Himalayas

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A lethal flash flood inundated a town when moist airflow from the lowlands invigorated a mesoscale storm moving off the Tibetan Plateau.

THE DISASTER IN LEH. Less than 1 week after the catastrophic slow-rise flooding of the Indus River in Pakistan in late July 2010 (Houze et al. 2011), flooding of a different, more sudden type produced a disaster in the city of Leh, India, located 500 km to the east. The town of Leh, located in the Ladakh region of Jammu and Kashmir State in India, is a high-altitude cold desert valley, 3,500 m above sea level (Fig. 1a). It lies near the Indus River, which at this location flows northwestward through deep mountain valleys before it turns southwestward through Pakistan on its way to the Arabian Sea (Fig. 1b). The Ladakh region is known for having low-nutrient and poor soil conditions, leading to an unsuitable environment for agriculture (Goodall 2004), which could have contributed to the severity of the Leh flood. Torrential rains delivered to the region by a succession of mesoscale convective systems (MCSs; Houze 2004) moving over the region triggered extensive ▶

An aerial view of the Leh Valley in Jammu and Kashmir State, India in August 2010 preceding the flash flooding event. Image courtesy of Jennifer Spatz.

flash flooding and mudslides. Fatalities numbered 193, hundreds of persons were left missing, thousands were rendered homeless, and property and infrastructure experienced severe damage throughout the region. Local news reports from the region described the severe erosion of roads, failures of bridges, cave-ins, inundation by mud, and extensive flooding. The average August rainfall for the city of Leh is 15.4 mm with record rain accumulation in 24 h set in 1933 at 51.3 mm (Indian Meteorological Department 2010). During the Leh flood event, various sources reported a 1½-h rain accumulation of 12.8 mm[2] and 100 mm h^{-1} rain rates (see http://blogs.wsj.com/indiarealtime/2010/08/06/lehs-flash-floods-how-much-did-it-rain/). Given the arid nature of the region and the surrounding high mountains, the city of Leh was highly vulnerable to flash flooding. This brief article describes the meteorological conditions leading up to the event.

Flash-flooding disasters similar to that of Leh have been documented in other mountainous regions around the world. Perhaps the most notorious flash flood was the Big Thompson flood of 1976 in Colorado, which remains of intense interest in the United States. Limited surface and remote observations of the storm system have hindered studies of Big Thompson and similar flash floods in the United States. Caracena et al. (1979) and Nair et al. (1997) have documented the meteorological conditions leading to the Big Thompson flood and the 1972 Black Hills flood near Rapid City, South Dakota. Maddox et al. (1978) compared these two major flash-flood events and determined that there were numerous similarities in both the meteorological setup and character of the storms. In each case, a large thunderstorm complex developed on the eastern edge of the Rocky Mountains and was fed by warm and moist conditionally unstable upslope flow from the lowlands. An enormous amount of precipitation fell on the river valleys and the flash flooding that resulted claimed a total of 375 lives for both cases.

Flash floods result from a myriad of storm types with differing structures and synoptic conditions (Doswell 1985; Doswell et al. 1996; Maddox et al. 1978). Identifying similar ingredients that are present during a variety of flash-flood-producing storms in these two locations provide lessons for understanding and predicting flash floods over vulnerable regions, such as both the Himalayas and Front Range of the Rockies. The rarity of such flash-flooding events on the edges of steep plateaus not only makes them difficult to predict but also makes them difficult to study in a statistical way. It is therefore important to examine the Leh case for lessons that can be applied in future flash-flood occurrences.

Doswell (1985) identified a general principle—that flash floods may result when a stationary synoptic environment produces storms that regenerate over a steep watershed prone to flooding. Both the Big Thompson flood over the Front Range of the Rockies and the Leh flood in the Himalayas fall into this category; however, the storms that were regenerated over the slope were different in nature. The Leh flood was the result of a series of mobile mesoscale westward-propagating MCSs forming upstream over the high terrain of the Tibetan Plateau and then moving over the steep Himalayan face where they became invigorated by the moist flow. In contrast, the Big Thompson storm was nonpropagating and fixed in location over the steep terrain, where it was continuously regenerated. In the following, we provide the details of the storm scenario that produced the Leh flood.

TYPES OF RAINSTORMS THAT OCCUR DURING THE MONSOON. The summer monsoon season (June through September) in the Indian subcontinent is commonly known as the "wet season" and is recognized for having bounteous rainfall that can have large spatial and seasonal variations (Webster et al. 1998, 2006). These variations lead to significant socioeconomic impacts (see http://business.rediff.com/slide-show/2010/jun/02/slide-show-1-how-monsoon-impacts-indian-economy.htm; http://en.wikipedia.org/wiki/Monsoon_of_Indian_subcontinent); thus, forecasting periods of rain and drought within monsoon seasons is a high priority (Webster et al. 2010). During the monsoon, precipitable water values are at an extreme over the Bay of Bengal and the Arabian Sea, as latent heat fluxes act to increase moisture in the boundary layer through evaporation (Medina et al. 2010). This warm

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and moist air flows inland over the Indian subcontinent in the generally southwesterly low-level flow associated with the monsoon circulation. Xie et al. (2006), Hirose and Nakamura (2002), Romatschke and Houze (2011), and others have demonstrated that as this moist air approaches the foothills of west- or south-facing mountain ranges, such as the Western Ghats, Himalayas, Khasi Hills, or Arakan range of Burma, precipitation is maximized upstream of and over the lower windward slopes. Anders et al. (2006) show that this relationship between precipitation and topography is sufficiently robust to explain very small variations in measured precipitation. Thus, while the monsoon precipitation varies greatly from year to year and within a season, orographic influences over the Indian subcontinent greatly determine the character and location of precipitating cloud systems in this region.

Recent studies have taken advantage of the Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) observations to decipher the nature of precipitating systems over the monsoon region since the PR provides observations over regions inaccessible to other types of measurements. Barros et al. (2004), Zipser et al. (2006), and Houze et al. (2007) have shown that the northwest indentation of the Himalayan Mountains tends to have some of the most intense and tallest convective storms in the world. However, these deep and severe convective storms are typically local and highly intermittent so they do not produce widespread rainfall, and this region remains arid. In contrast, in the eastern Himalayas and over the Bay of Bengal and Ganges delta, convective systems tend to be mesoscale and contain large and persistent stratiform regions. These mesoscale systems dominate the rainfall climatology of the Indian subcontinent (Romatschke and Houze 2011; Medina et al. 2010; Romatschke et al. 2010).

TRMM PR climatologies show that while the monsoon rains tend to occur near the mountains, deep convection is nearly always based over the lower foothills or plains just upstream of the mountains (Hirose and Nakamura 2002; Xie et al. 2006; Houze et al. 2007; Romatschke et al. 2010). The upper slopes of the Himalayas have little rainfall, and the Tibetan Plateau is extremely dry. The TRMM PR storm-type climatologies further show that the sizes of radar echoes associated with what little rain does occur over the higher terrain are almost always isolated convective cells, which are minimal in horizontal extent. The occurrence of mesoscale convective systems (i.e. systems with complexes of convective cells and associated stratiform regions) over the Tibetan

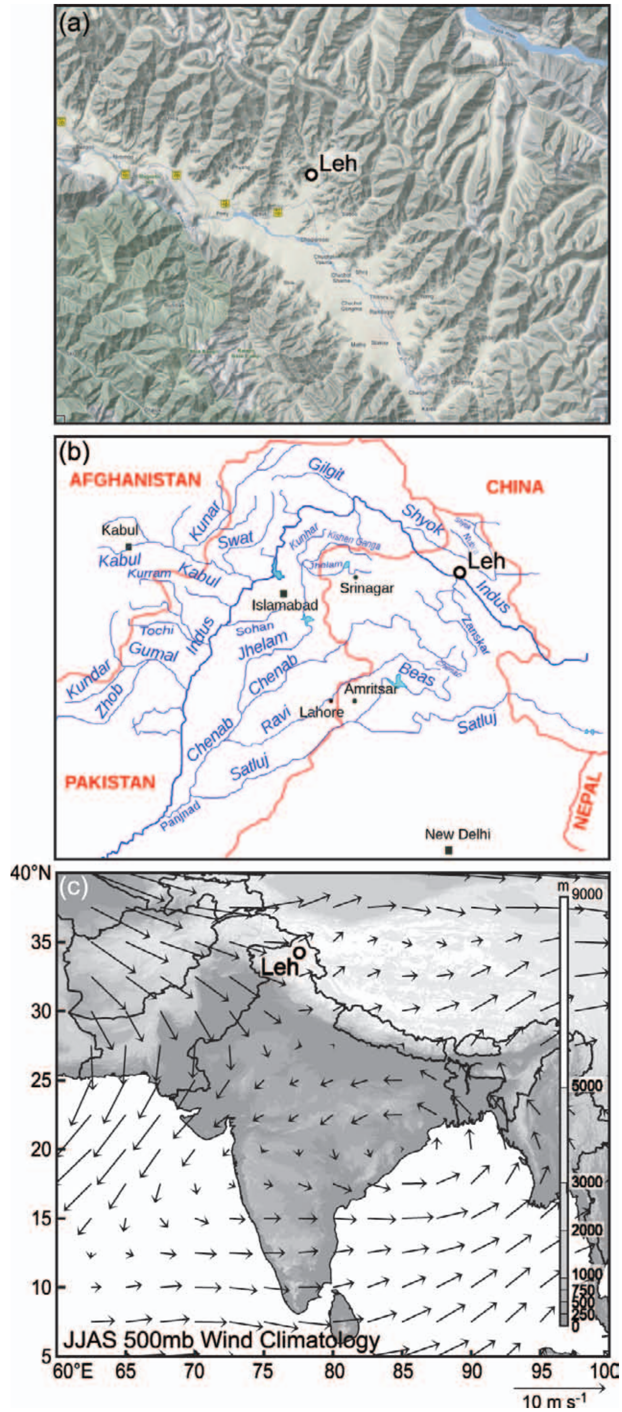

Fig. 1. (a) Topography near the city of Leh. The Indus River flows to the northwest and is just south of the city of Leh. [Source: Google Maps.] (b) The rivers of India and Pakistan. The Indus River originates in China and flows through India and Pakistan before reaching the Arabian Sea to the southwest. (c) Climatological 500-mb winds during the summer (monsoon) season. These maps were derived from National Centers for Environmental Prediction (NCEP) 2.5° × 2.5° gridded reanalyses (Kalnay et al. 1996), as in Romatschke et al. (2010) and Houze et al. (2011). In (a)–(c) the location of the city of Leh is indicated.

Plateau is extremely uncommon. In the rare instances that such larger rain-producing cloud systems do occur over the higher terrain, major floods are likely to occur. The 2010 Pakistan floods (Houze et al. 2011; Webster et al. 2011) and Leh flood discussed here were both occasions in which mesoscale precipitation systems anomalously occurred over the higher terrain. However, they were different types of mesoscale systems. In Pakistan, stationary systems with broad stratiform rain areas led to a slow-rise flood over a large area surrounding the Indus River that persisted for over a month. In Leh, propagating mesoscale systems produced a flash flood in a local area, much like the Big Thompson and Rapid City floods.

The occurrence of propagating squall-line-type systems was in itself somewhat unusual for this part of the world. In examining TRMM PR data for two monsoon seasons, Houze et al. (2007) found that mesoscale systems with the structure of leading line/trailing stratiform squall-line systems rarely occur near the Himalayas as they do in the United States (Houze et al. 1990; Smull and Houze 1987), West Africa (Fortune 1980), and subtropical South America (Rasmussen and Houze 2011). Such systems require shear with a midlevel jet, and such shear is generally absent near the Himalayas during the monsoon. Houze et al. (2007) found that during a 3-day period in which a westerly jet pushed anomalously far south, three squall lines of the eastward-moving type occurred. From these previous climatological studies of TRMM data, it is clear that while mesoscale systems are rare over the Tibetan Plateau, propagating mesoscale systems are even less expected.

Thus, in the case of the Leh flood, when a strong and persistent easterly jet on the Tibetan Plateau enabled precipitating systems to organize into well-defined MCSs that propagated from east to west, an extremely unusual and dangerous set of circumstances arose. We will show below that the precipitating systems that caused the flash flooding in Leh were indeed mesoscale and most likely line organized and propagating in a westward direction. The highly anomalous nature of this unusual flooding event in Leh deserves further investigation into the formation processes that led to such a devastating flash flood in this dry mountainous region. Because of similarity to flash floods along the Rocky Mountain Front Range, new insights into this type of event could be useful to forecasters in the United States, and possibly other regions of the world.

Was the Leh event technically a flash flood? There is no set definition, but according to Williams et al. (1972), flash flooding is confined to only one drainage basin or river valley. Maddox et al. (1978) conclude that intense convective storms typically cause flash flooding. Storms that result in flash flooding have been shown to vary in both type and organizational mode, but they tend to share similar basic ingredients (Doswell et al. 1996). Gruntfest and Handmer (2001) defines flash-flooding events based on specific characteristics, such as their sudden occurrence, high risk to life and property, occurrence in unexpected locations, small local scale, and short duration. Given that the affected area was confined to the Leh valley and the mesoscale convective systems leading to the flood were highly convective, it seems that flash flooding was likely the cause of the disaster. In this respect, the Leh floods differed from the Pakistan slow-rise flood, where the precipitating systems responsible for the widespread flooding of the Indus River primarily were due to the broad stratiform components of mesoscale systems becoming stationary over the arid slopes of the western Himalayas. This region is ordinarily impacted by deep convective cells without large stratiform rain areas, whereas, as we will note below, the storms that led to the Leh flood were likely both convective and stratiform in nature. Their rapid propagation over the region indicates that the rapidly falling convective rain rather than the more slowly falling stratiform rain was the primary culprit in the Leh case.

METEOROLOGICAL CONTEXT OF THE LEH FLOOD. During the summer monsoon season (June through September), the climatological 500-mb winds near Leh are generally westerly but weak in the northern branch of a split-flow pattern (Fig. 1c). However, during the 3 days leading up to the Leh flood, the 500-mb geopotential height field showed an easterly jet (Figs. 2a–c). The 500-mb flow pattern was relatively persistent over this period, constituting a quasi-stationary synoptic situation, which would be generally consistent with Doswell's (1985) principle. Winds above 500 mb also were generally easterly–northeasterly. By 5 August 2010, the 500-mb jet was pointed directly at Leh, helping to direct the MCSs toward Leh (Fig. 2c). At the same time, relatively stationary low pressure systems over north-central India were situated so that moist lower-level flow was directed into the Leh region from the south-southeast. A particularly important and interesting feature was the vortex over northwest India, which was seen most strongly at 700 mb (Figs. 2d,e). This vortex was part of the monsoon circulation. Such systems are referred to as midlevel monsoon troughs or cyclones. Transient vortices of this type have proved to be somewhat elusive, and have been treated only occasionally in the literature (Krishnamurti and Hawkins 1970; Mak 1975; Carr 1977; Goswami et al. 1980; Das et al. 2007). Krishnamurti et al. (1981) showed that strong barotropic shear was instrumental in the generation and maintenance of a midlevel vortex during the onset of the monsoon in this region. The Leh flooding event did not occur during the monsoon onset; however, the shear was strong, albeit in the easterly direction. The strong easterly shear suggests that the barotropic dynamics might have played a role in the generation and maintenance of the midlevel cyclone in this case. Regardless of its source energetics, and although it was weakening over the 3-day period of the Leh flood, this midlevel low was instrumental in driving additional moisture into the Leh region from the south.

Figures 2g–i show that during the days leading up to the Leh flood, midlevel southeasterly winds strongly advected moisture into the region of the northwest indentation of the Himalayan ranges. We suggest that this synoptic-scale moisture flux combined with diurnal upslope flow to feed and strengthen MCSs propagating along the edge of the Tibetan Plateau. As discussed earlier, mesoscale precipitation systems are very rare. For an MCS to survive on a dry and arid plateau, a large moisture source must be available for the system. Orographic lifting of moist air of tropical origin that feeds thunderstorm development over mountain barriers was shown to be the main meteorological reason for the Big Thompson flood and the Black Hills flood in the Rocky Mountains (Caracena et al. 1979; Nair et al. 1997; Maddox et al.

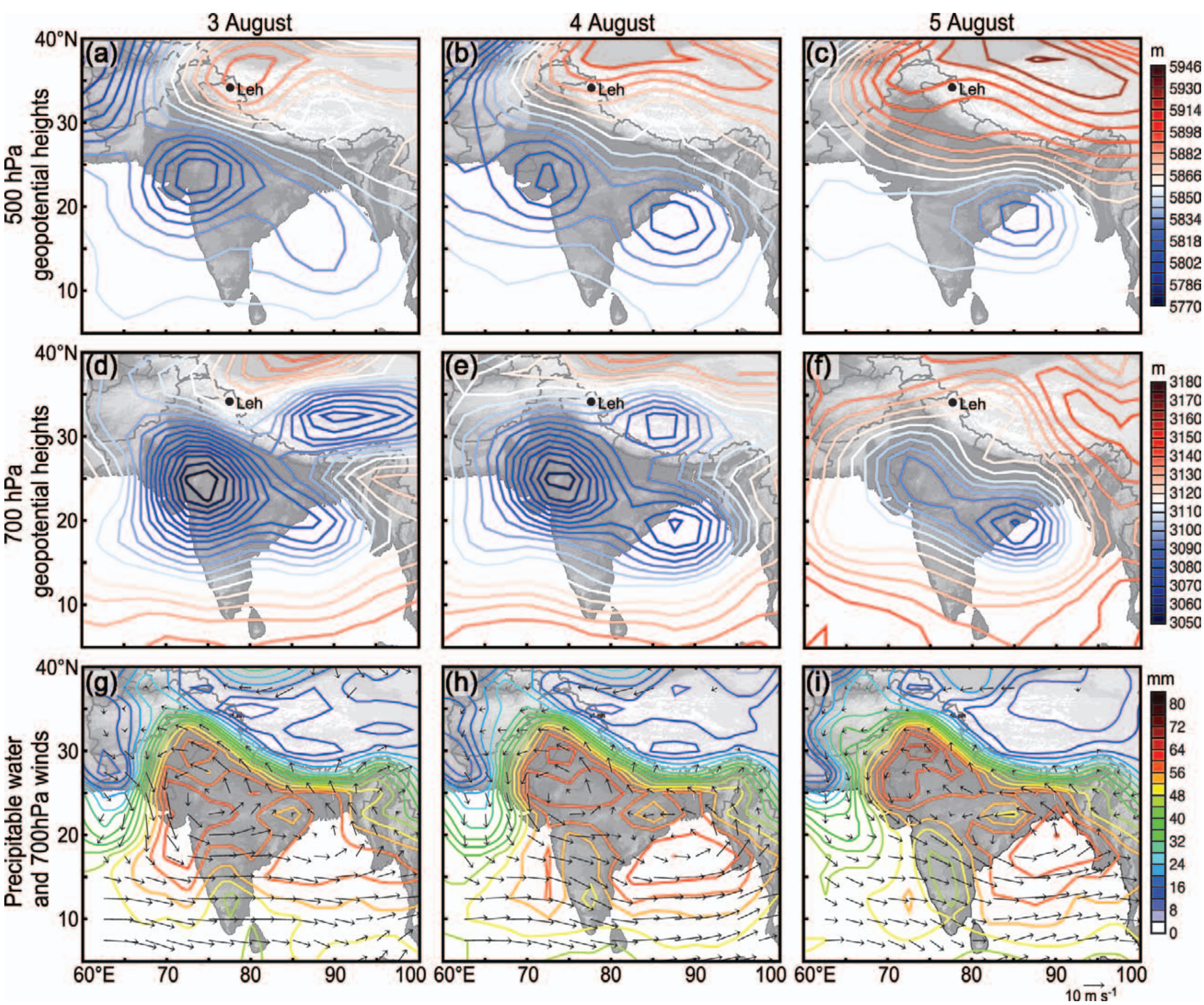

Fig. 2. Sequence of maps showing the evolution of atmospheric structure prior to the Leh flash-flooding event. One-day-average geopotential height field (m) of the (top) 500- and (middle) 700-mb surface. (bottom) Contours of vertically integrated precipitable water (mm) and 700-mb wind vectors. Note that the data source and topographic scale for (a)–(i) are the same as in Fig. 1c.

1978), as well as the Pakistan flood (Houze et al. 2011; Webster et al. 2011). In those cases, however, moist upslope flow fed quasi-stationary convection, whereas in the Leh case the moist upslope flow fed convection propagating into the region of upslope flow.

Surface heating on the Tibetan Plateau has a substantial impact on the regional circulation of the Himalayan region and its diurnal cycle during the premonsoon and monsoon seasons (Yanai and Li 1994). Figure 3 shows the diurnal cycle of the 500-mb and surface wind fields. The 500-mb-level diurnal cycle is pronounced because it is not far above the surface over the Tibetan Plateau. During the nighttime, the 500-mb flow over the Plateau becomes stronger and turns southwestward along the Himalayan ridge, thus forming a midlevel flow that can organize the mesoscale convective systems that have formed overnight into eastward-propagating squall-line systems of the type seen over sub-Saharan Africa and elsewhere in the tropics (Zipser 1977; Houze 1977; Fortune 1980; Schumacher and Houze 2006; Futyan and Del Genio 2007). The 500-mb maps for both 3 and 4 August show a similar diurnal signature in the midlevel flow over the Himalayas (not shown). The surface wind field exhibits a strong diurnal signature near the foothills of the Himalayas, with strong convergence over the Himalayas upstream of Leh (Fig. 3e). A sounding at New Delhi (Fig. 4a) shows that the entire layer of air below 600 mb (i.e., below the height of the Tibetan Plateau) was moist and flowing toward Leh. This moisture advection in conjunction with the strong low-level convergence and the persistent easterly flow at 500 mb provided the conditions conducive to MCS development over the high Himalayan and Tibetan terrain. Thus, it was possible for isolated convection breaking out over the Tibetan Plateau to organize into MCSs. One such MCS caused the devastating flash flooding in Leh during the nighttime hours of 5–6 August.

WESTWARD-PROPAGATING MCSS ON THE TIBETAN PLATEAU. The evolution of the storms producing the Leh flood is well shown by geosynchronous infrared satellite imagery over the Tibetan/Himalayan region. (The TRMM satellite did not pass over the region of interest at times that were useful to investigating the Leh flood.) It is clear from the images in Fig. 5 that strong diurnal forcing was responsible for generating three MCSs on successive days that all passed over Leh. This repetitive behavior satisfies Doswell's principle that the storms producing the Leh flood were of a regenerating type in a relatively stationary synoptic situation, although

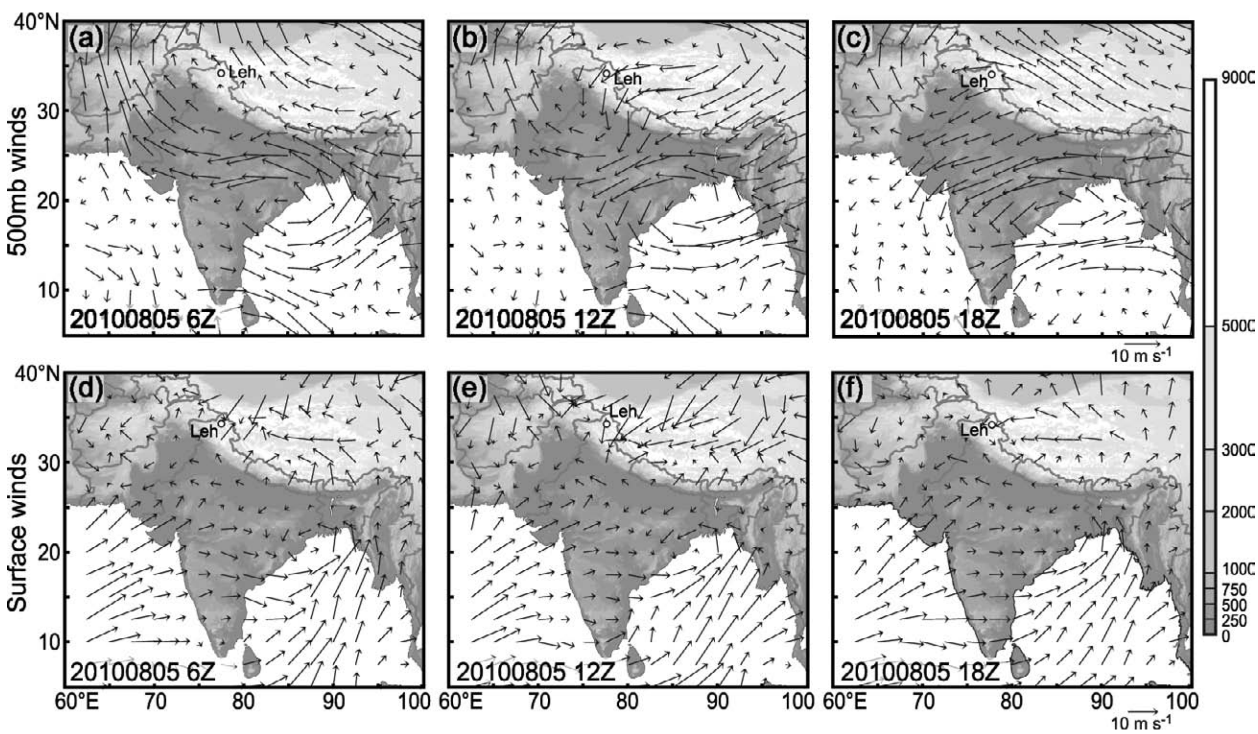

Fig. 3. Sequence of maps showing the diurnal wind patterns on 5 Aug, just preceeding the Leh flood. (top) 500-mb wind field and (bottom) surface winds at 0600, 1200, and 1800 UTC. The data source for both rows is the same as in Fig. 1c.

in this case it was the regeneration of a sequence of mobile mesoscale systems, each moving over the vulnerable slopes, rather than the regeneration of a cell or cells within a single stationary long-lived MCS located over the steep terrain.

Isolated convective cells formed over the Tibetan Plateau during the heat of the day (0600 UTC or local noon). During the afternoon, the convection grew upscale to form mesoscale cloud systems (1200 UTC or 1800 LT). Finally, some of these mesoscale systems continued to expand and become more organized in the evening. They moved west-northwestward, and at 2000 UTC (0200 LT) a large system was located over Leh on each day. The diurnal heating impact on the development of the succession of MCSs that resulted in flash flooding in Leh is evident from this storm evolution sequence. However, the diurnal timing of the rainfall over Leh was extremely unusual. Yanai and Li (1994) and Murakami (1983) found that the maximum of convective activity over the Tibetan Plateau normally occurs around 1200 UTC. That timing is consistent with the development of isolated cells of convection in Fig. 5. Houze et al. (2007) and Romatschke et al. (2010) show, however, that such cells rarely grow into mesoscale entities, which would have long enough lifetimes to exist into the night. In the Leh flood case, however, the unusual 500-mb easterly jet and diurnally pulsing moisture advection toward and up the slope of the Himalayas described above led to the development of MCSs that moved over Leh in the middle of the night, which is climatologically the time of minimum rainfall at this location. In the northwestern indentation of the Himalayas, the frequency of mesoscale systems is minimum around 0200 LT (Fig. 6). The three MCSs seen in Figs. 5c,f,i all passed over Leh around this time, demonstrating the highly anomalous nature of the precipitating systems that caused the flash flood. The fact that the flash-flooding storms occurring over Leh were climatologically unexpected precisely at a time when people are normally sleeping contributed to the tragedy.

While the exact internal structure of the MCSs that formed is not known from satellite data, we expect that because these systems organized upscale in the presence of a persistent jet and moisture inflow and were moving rapidly in the direction of the strong midlevel environmental flow, the storm had the character of a squall-line system and both the convective and stratiform precipitation contributed to the flash flood in Leh. The authors are aware of mesoscale modeling work that confirms this expectation (A. Kumar et al. 2012, manuscript submitted to

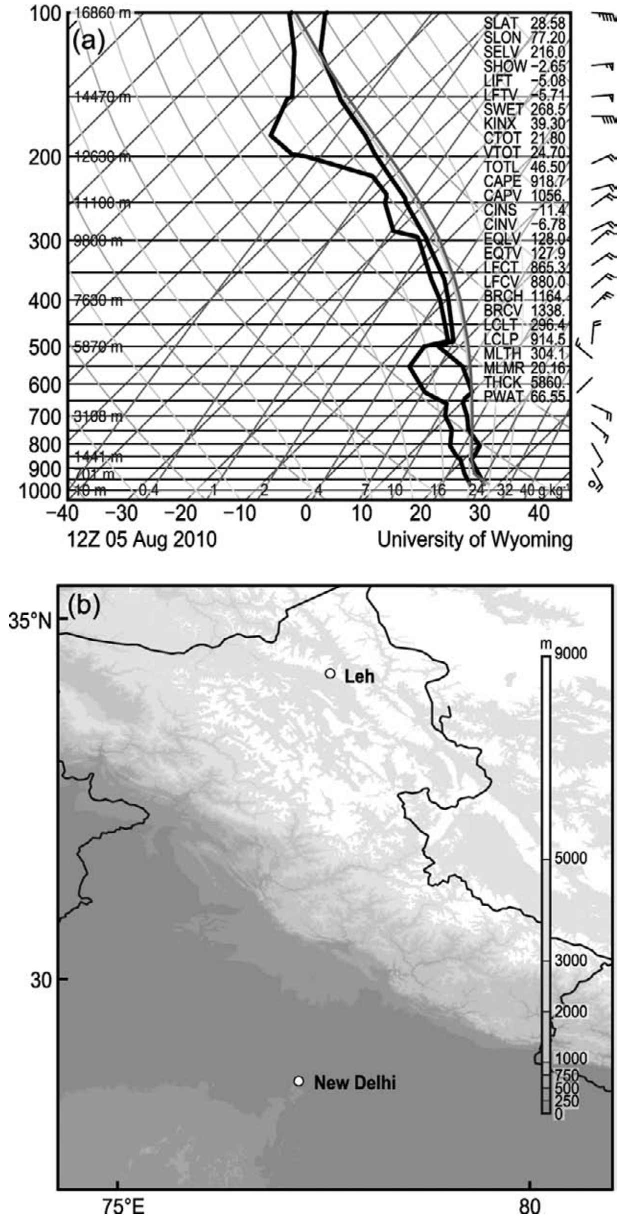

Fig. 4. (a) Rawinsonde data plotted on a skew *T*–log*p* graph from New Delhi at 1200 UTC 5 Aug 2010. (b) The location of the sounding from New Delhi relative to the city of Leh. Note that the sounding was downloaded from the archive at the University of Wyoming (http://weather.uwyo.edu/upperair/sounding.html).

J. Hydrometeor.). In addition, because of the amount of precipitation that fell during the short duration of the storm's passage and large size of the cloud shield observed in Fig. 5, it is reasonable to think that the MCSs contained deep and wide convective echoes, as defined in Houze et al. (2007), in addition to a trailing stratiform component. As noted above, the storm climatology of Houze et al. (2007) and Romatschke et al. (2010) shows that storms with deep and/or wide intense convective cells are extremely rare over the high terrain of Leh and other locations along the Himalayan barrier.

TRAJECTORIES. In order to more specifically identify the sources of the high precipitable water amounts observed in the northwest indentation of the Himalayan Mountains (Figs. 2g–i), the National Oceanic and Atmospheric Administration (NOAA)/Air Resources Laboratory (ARL) Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model (see www.arl.noaa.gov/HYSPLIT_info.php) was used to determine backward trajectories of low- to midlevel air. Figure 7 shows two prominent sources of moisture. Figure 7b shows that low- to midlevel air was brought into the region along the Himalayan foothills by the southeasterly flow shown in Fig. 2. The midlevel low pressure pattern set up the

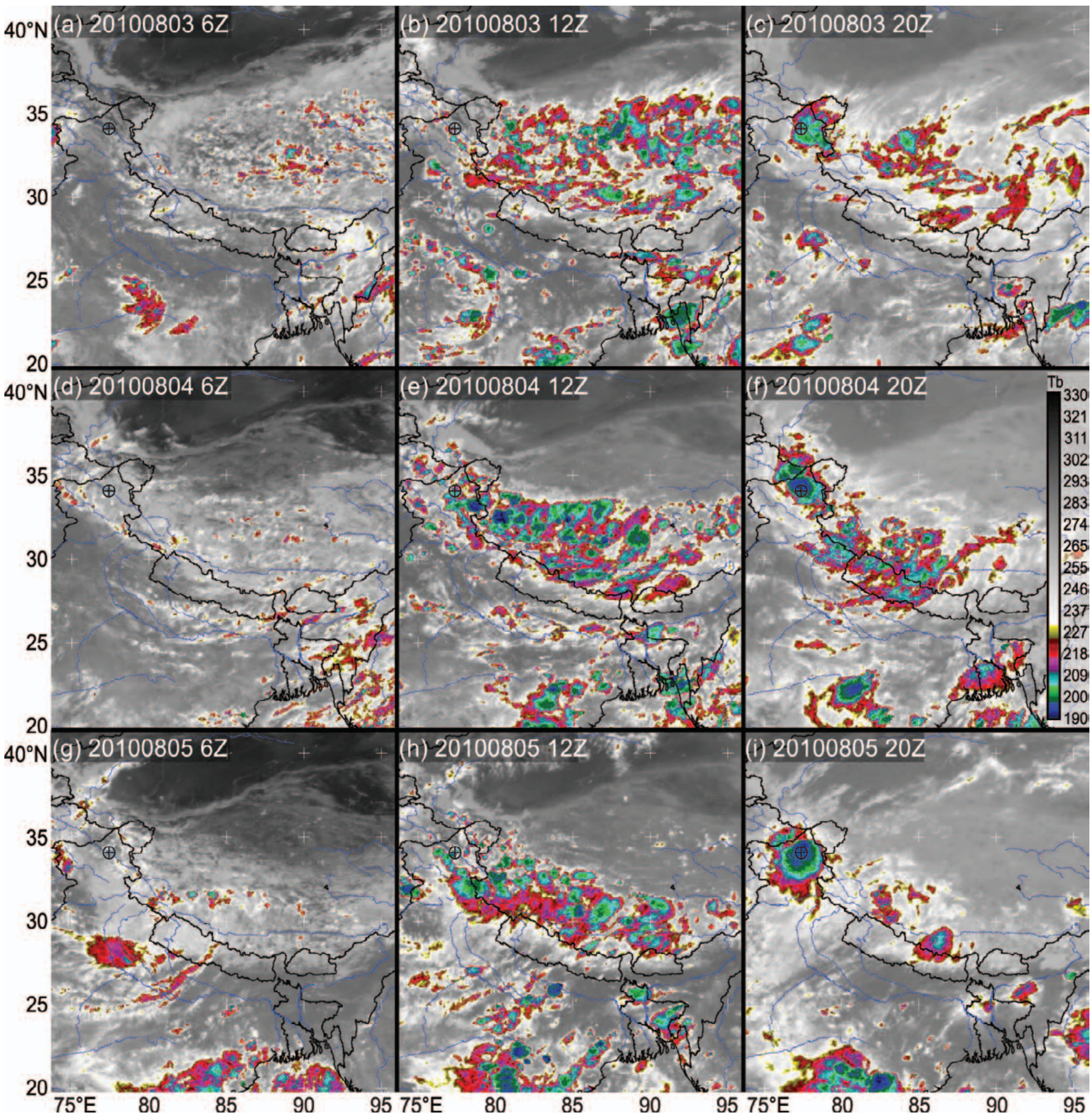

Fig. 5. Sequence of infrared satellite images (K) from *Meteosat-7* showing the diurnal evolution of the storm systems that resulted in the Leh flood. Each row shows data for a different sequential day leading up to the Leh flood (3–5 Aug) and each column shows a different time of day (0600, 1200, and 2000 UTC). The location of Leh is indicated (circled cross) on each map.

southeasterly jet that brought moisture into the region from the Bay of Bengal. Houze et al. (2011) found a similar pattern; however, they found that it was set up by westward-propagating low pressure centers, which brought moisture from the Bay of Bengal. In the Leh situation, the midlevel cyclone stays in place during the lead up to the flood, and moisture came into the region from both the Arabian Sea and Bay of Bengal (Fig. 7a). This pattern led to an uncharacteristically large amount of moisture being accessible to the MCSs as they propagated close to the edge of the Tibetan Plateau. Figure 7a also shows that the low-level moisture flowed up the slope of the Himalayas directly toward the city of Leh [similar to the Big Thompson Flood conceptual model in Caracena et al. (1979)]. Diurnal oscillations brought low-level moisture upslope onto the Himalayan Plateau most strongly during the afternoon. The confluence of these two sources allowed the MCSs to tap into the highly moisture-laden air as they propagated along the edge of the Tibetan Plateau, enabling them to be unusually (for this region) long lived.

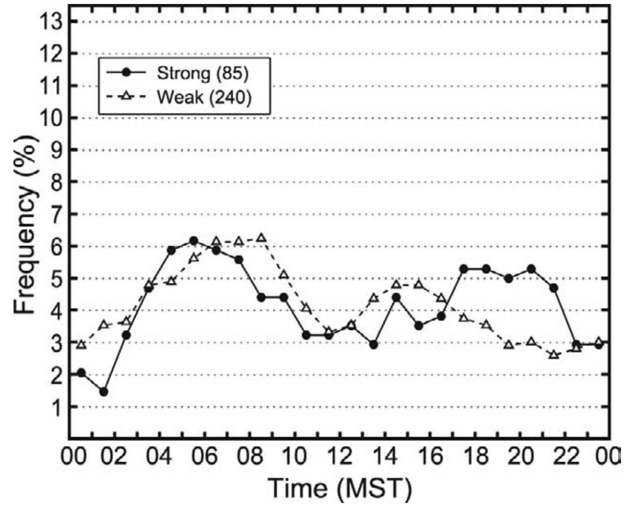

Fig. 6. The curves show the diurnal cycle of mesoscale convective systems in the region of Leh with rain areas in the size range 10,000–44,000 km² for 8 yr (1999–2006) of TRMM PR data. The systems designated as "strong" are the 85 systems that account for half the rain in this storm category in this region. The 240 "weak" systems account for the remaining half. Times are in mean solar time (MST). Note that 0200 MST, the time of the Leh flood storm, is the time of day when such systems are least expected. [From Romatschke and Houze (2011).]

PRECIPITATION. The succession of three organized MCSs moving in the downstream direction of the Indus River along the Tibetan Plateau likely inundated this dry and arid region with excess precipitation and saturated the watershed. By the time the third and most striking MCS seen in the satellite sequence moved over Leh in the early morning of 6 August (Fig. 5), flash flooding resulted in a catastrophic and deadly combination of mudslides and infrastructure damage that devastated the city of Leh and its inhabitants. The

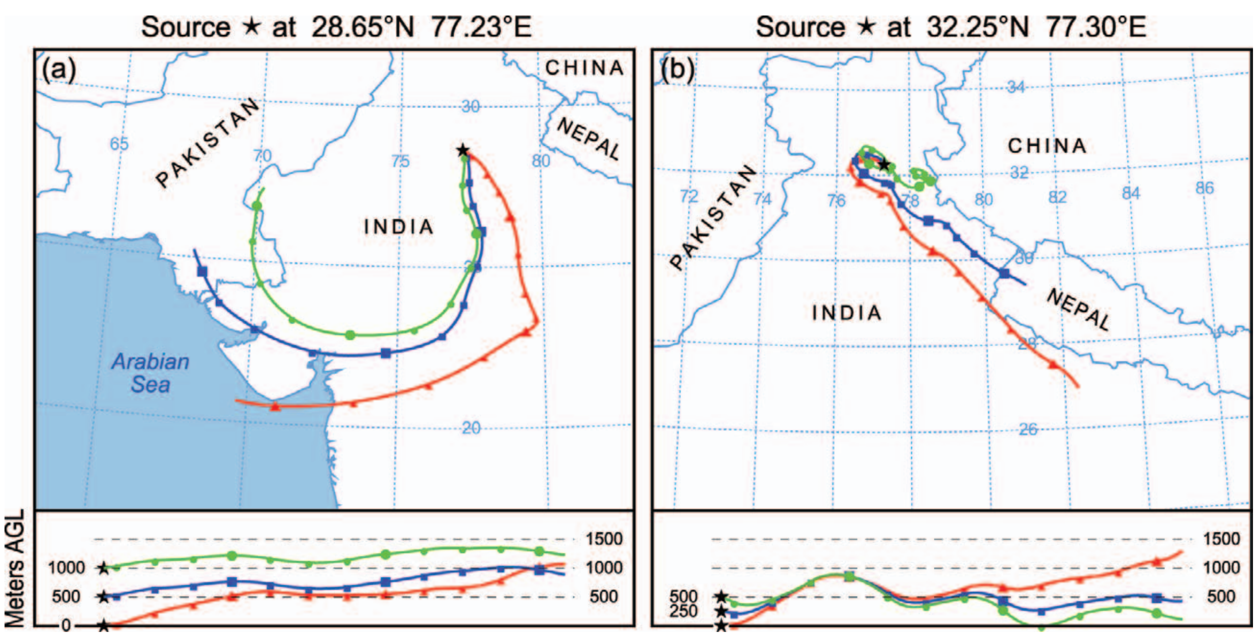

Fig. 7. Backward trajectories run for 72 h from the HYSPLIT model. Each 24-h increment is indicated (squares). (a) Backward trajectory ending in New Delhi. (b) Backward trajectory ending at 32.25°N, 77.30°E, which is located south of the city of Leh in the Himalayan foothills.

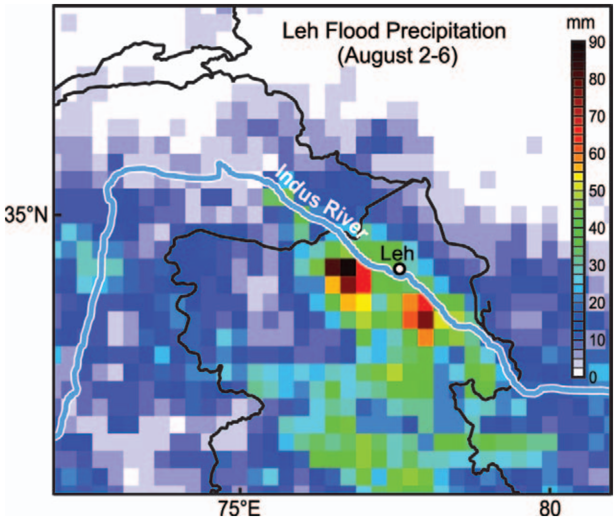

Fig. 8. Accumulated rainfall for 2–6 Aug 2010 from TRMM and other satellite observations (TRMM product 3B42). The Indus River location is indicated (blue line).

rain accumulation from the TRMM 3B42 product shows that the MCSs produced a maximum of rainfall along the Indus River upward of 90 mm, averaged over a 5-day period (Fig. 8). According to Maddox et al. (1978), both the Big Thompson flood and the Black Hills flood had 250–400 mm of precipitation on the day of the flash-flooding event. All of these locations are in relatively narrow valleys of streams or rivers. Comparing this to the 3-hourly TRMM 3B42 data around the time of the flash-flooding event in Leh, rain accumulations in the region were upward of 210 mm. This amount is both consistent with the reported rainfall in Leh as well as the idea that the flash flood in Leh was reminiscent of famous flash floods over the Rocky Mountains. Maddox et al. (1978) discussed various ways that have been documented to produce the amount of precipitation necessary for flash-flooding conditions: tropical disturbances interacting with extratropical disturbances or mesoscale topographic features, slow-moving thunderstorms, organized mesoscale systems, or orographic lifting triggering storms along mountain barriers. We hypothesize that the flash flooding in Leh was due to a combination of MCSs organized by a persistent easterly midlevel jet and fueled by the orographic lifting of conditionally unstable air along a mountain barrier. Even though they were propagating through the region, the MCSs had sufficiently intense rainfall for the necessary amount to fall and produce a flash flood in the valley.

CONCLUSIONS. Our investigation into the meteorological setting of the catastrophic flash flood in Leh, India, reveals that the event was related to the highly unusual development of mesoscale convective systems from diurnally generated convective cells forming over the Tibetan Plateau within the context of a persistent 500-mb flow pattern directing the MCSs over Leh and forcing moisture up the slope of the Himalayas in the Leh region. Figure 9 shows a conceptual model of this event as inferred from the results of this study. Diurnal heating of the Tibetan Plateau triggered isolated convective cells in the afternoon over the high terrain. The easterly 500-mb jet was diurnally enhanced, which helped the cells to organize upscale into MCSs moving west-southwestward toward Leh. The MCSs eventually passed near the edge of the Tibetan Plateau, where they tapped the moist layer over the Ganges Plain. Trajectories show that moisture arrived from both the Arabian Sea and Bay of Bengal, and that the moist flow was associated with circulation around a midlevel vortex and rose up over the Himalayan wall. This moist air energized the MCSs coming from the Plateau, deepened their convection, and enriched their precipitation-producing capability. Probably both convective and stratiform precipitation contributed to the rainfall over Leh. Being of mesoscale proportions, the energized MCS spread over the slopes of the surrounding valleys, so that the large rain accumulations from all the surrounding mountainsides drained at once into the Indus River and its valley near Leh. The resulting flash flood in Leh was devastating to both the people and property in the region. The juxtaposition of the midlevel monsoon vortex over northwestern India,

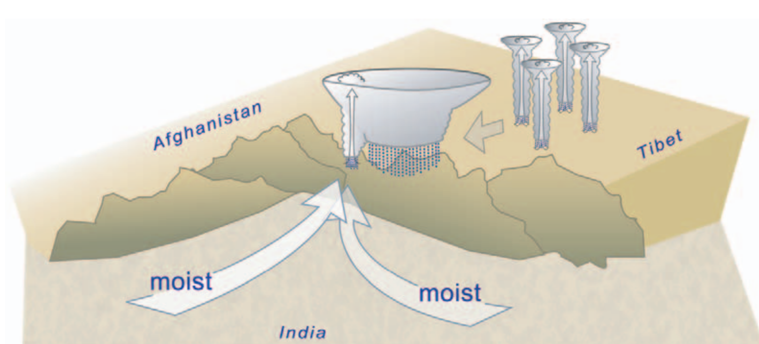

Fig. 9. Conceptual model demonstrating key meteorological elements that led to the anomalous flash-flooding case in Leh. Convective cells on the Tibetan Plateau organize upscale and propagate to the west. The MCS on the edge of the Himalayas taps into the upslope low-level moisture.

combined with high pressure to the north, allowed for the following departures from the typical storm climatology of the region:

1) Mesoscale convective systems are not commonly observed over the higher terrain of the Himalayas or the Tibetan Plateau (Houze et al. 2007; Romatschke and Houze 2011; Romatschke et al. 2010), although many occurred during the lead up to the Leh flood. A strong, moist flow from the lower elevations toward the Himalayas in the Leh region rose up to higher elevations to provide the developing systems with precipitable water and latent energy.
2) Propagating squall-line-type systems are rarely observed in the vicinity of the Himalayas during the monsoon unless a midlevel jet is present. In the Leh case the midlevel vortex over northwestern India and the high to the north provided for a midlevel jet that could organize the MCSs into propagating systems. The easterly jet drove the MCSs toward the edge of the Tibetan Plateau and Leh.

In this way, a region typically characterized as a high-altitude desert valley with only rare occurrences of intense convection suddenly received upward of 210 mm of precipitation in 3 h, resulting in a destructive flash flood that the local population will likely never forget.

Major flash-flooding events have been documented near other major mountain ranges around the world. The Leh flood shares certain characteristics with the synoptic setup for the Big Thompson flood and Black Hills flood near the Rocky Mountains. Comparing Fig. 9 to the conceptual model presented in Caracena et al. (1979), which detailed the Big Thompson flood, both flash floods occurred near the steep edge of a high plateau, with a moisture source from the lowlands below. Low-level moisture flowing upslope into the storm system was of particular importance for each flash-flooding event. Similar ingredients leading to flash flooding in both the Himalayas and Rocky Mountains gives us a better understanding of the indicators of this type of extreme natural disaster. The Leh case illustrates that flash flooding in these situations is not confined to MCSs continuously regenerating over a region of steep slope. In this case, MCSs were repeatedly generated by diurnal heating over the high terrain upstream of the flood zone and organized by the 500-mb flow to move over the steep slope and tap the moisture from lower levels. Identifying these common characteristics between flash-flooding events on the steep edges of major plateaus will not only give us a greater understanding of the meteorological aspects of flash-flooding storms, but can provide background for developing greater skill at forecasting these rare but extreme events. The present investigation, though compelling, has been limited by the lack of detailed surface and remote observations. However, this case is also being investigated using a high-resolution model simulation to identify common denominators of flash floods around the world. The present paper and the conceptual model presented in Fig. 9 provide an empirically based hypothesis to be tested by modeling. The results of these tests could be the basis for a step forward in the forecasting of flash floods at the edge of high terrain.

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