Simulation of a Flash Flooding Storm at the Steep Edge of the Himalayas*

ANIL KUMAR

NASA Goddard Space Flight Center, Greenbelt, and Earth System Science Interdisciplinary Center, University of Maryland, College Park, College Park, Maryland

ROBERT A. HOUZE JR. AND KRISTEN L. RASMUSSEN

Department of Atmospheric Sciences, University of Washington, Seattle, Washington

CHRISTA PETERS-LIDARD

NASA Goddard Space Flight Center, Greenbelt, Maryland

(Manuscript received 25 October 2012, in final form 27 June 2013)

ABSTRACT

A flash flood and landslide in the Leh region of the Indus Valley in the Indian state of Jammu and Kashmir on 5–6 August 2010 resulted in hundreds of deaths and great property damage. Observations have led to the hypothesis that the storm, which formed over the Tibetan Plateau, was steered over the steep edge of the plateau by 500-hPa winds and then energized by the ingestion of lower-level moist air, which was approaching from the Arabian Sea and Bay of Bengal and rose up the Himalayan barrier. A coupled land surface and atmospheric model simulation validates this hypothesized storm scenario, with the model storm taking the form of a traveling mesoscale squall line with a leading convective line, trailing stratiform region, and midlevel inflow jet. In this region, the development of a mesoscale storm over high terrain is highly unusual, especially one in the form of a propagating squall line system. This unusual storm occurrence and behavior could serve as a warning sign in flash flood prediction. The coupled atmosphere and land surface model showed that the excessive runoff leading to the flood and landslide were favored by the occurrence of this unusual meteorological event coinciding temporally and spatially with favorable hydrologic conditions. Additionally, the model simulations showed that previous rainstorms had moistened the soil during the entire season and especially over the few days leading up to the Leh flood, so the normally arid mountainsides were likely not able to rapidly absorb the additional rainfall of the sudden 5 August squall line.

1. Introduction

Convective storms occurring at the steep edge of broad high topography, such as the Rocky Mountains and Himalayas, are notorious for producing surprising and lethal flash floods. Such a storm occurred over the

Himalayan range on 5 August 2010. It produced a devastating flash flood at the town of Leh in the high arid Indus Valley in northwest India (Fig. 1). Rasmussen and Houze (2012, hereafter RH) have recently described the meteorological setting and sequence of events for this storm. They arrived at a conceptual model of the storm in which cells generated by diurnal heating over the high terrain of the Tibetan Plateau gathered into a mesoscale convective system (MCS), which the 500-hPa winds then steered over the bank of the Plateau such that the storm could then draw upon low-level moisture arriving from the Arabian Sea and Bay of Bengal. They hypothesized that the ingestion of this moisture then energized the MCS just as it was passing over Leh and thus produced heavy convective and/or stratiform rain over Leh and
the surrounding mountainsides. The flash flood was a consequence of this heavy rain and runoff.¹

Although RH’s conceptual model based on observations is consistent with the available data for this storm, physical insight into the storm’s dynamics and precipitation-producing processes can best be derived from a numerical model given the remote nature of the region and limited observations of the flash flood. The purpose of this paper is, therefore, to provide such insight via a simulation with the Advanced Research Weather

¹ In India, sudden heavy rain events such as the one described in this paper are often referred to as “cloudbursts,” and many discussions online and elsewhere have referred to this event as the Leh cloudburst. For example, see the official description by the Indian Meteorological Department at http://www.imd.gov.in/doc/cloudburst-over-leh.pdf.
Figure 2 contains a flowchart of the LIS and WRF-LIS systems. The uncoupled LIS simulation was implemented with Tropical Rainfall Measuring Mission (TRMM) precipitation forcing from January 2008 through August 2010 to allow the model adequate spinup time for more realistic soil conditions to develop over a longer time. The TRMM precipitation forcing data are the 3B42 version 6 products from the TRMM Multisatellite Precipitation Analysis (TMPA) archive. The land surface fields generated were used as input to the coupled WRF-LIS to simulate the Leh flash flood event. We have conducted two simulations using the WRF-LIS coupled model: one with two-nested domains (27 and 9 km) at a coarser resolution that was conducted from 2 to 6 August 2010 and the other as a high-resolution simulation with four-nested domains that was conducted from 5 to 6 August 2010. The purpose of conducting two simulations is mainly because 1) the coarser simulation provides important information on larger-scale synoptic flows, moisture transport, and regional-scale precipitation patterns that occurred from 2 to 5 August 2010 and 2) the very high-resolution simulation provides important information about the storm structure that passed over Leh.

The boundary and initial conditions for the large-scale atmospheric fields, soil parameters (moisture and temperature), and sea surface temperature (SST) are given by the 1° × 1° 6-hourly National Centers for Environmental Prediction (NCEP) Final (FNL) Operational Global Analysis data (http://rda.ucar.edu/datasets/ds083.2/). These forcing data were interpolated to the respective NU-WRF grid using the WRF Preprocessing System (http://www.mmm.ucar.edu/wrf/users/wpsv3/wps.html). The two-way nested model domain is shown in Fig. 3: the outer domain has 27-km horizontal grid spacing with 190 × 190 grid points along the x and y axes, the second domain has 9-km horizontal grid spacing with 409 × 385 grid points, the third domain has 3-km horizontal grid spacing with 688 × 487 grid points, and the fourth domain has 1-km horizontal grid spacing and is zoomed in over Leh with 259 × 256 grid points. The model’s vertical layers are in terrain-following coordinates with 35 vertical layers from Earth’s surface to 10 hPa.

The high-resolution, four-nested domain simulation was initialized at 0000 UTC 5 August 2010 and was run until 0600 UTC 6 August 2010. The coupling of LIS to WRF enables integrated land–atmosphere modeling through both one- and two-way coupling, leading to a hydrometeorological modeling capability that can be used to evaluate the impact of land surface processes on hydrologic prediction. The modeled convective storms required 6–12 h of model spinup time for better prediction, so we initialized the model 15 h before the rain event in Leh. The coupled WRF-LIS run was done in two steps. First, the Noah land surface model initial conditions were generated by running a spinup integration using the offline LIS model with uniform initial conditions from 1 January 2008 to 30 August 2010. Second, the land conditions generated by LIS were used to initialize the WRF-LIS model. The LIS and WRF-LIS model and documentation are available on the LIS website (https://modelingguru.nasa.gov). For the backward trajectory analysis, which is used to track the air parcels to examine the synoptic-scale flow, we have used a separate set of model output using the same domain configuration and two-nested domains (27 and 9 km), and this experiment was run for 96 h (0000 UTC 2 August to 0000 UTC 6 August).

The model simulations were conducted using the following physics options and tools:

- cloud microphysics, using Milbrandt two-moment, seven-class microphysics, with separate graupel and hail species (Milbrandt and Yau 2005);
cumulus parameterization, using Kain–Fritsch cumulus
scheme for 27- and 9-km domains (Kain and Fritsch
1993; Kain 2004);
boundary layer, using the Yonsei University planetary
boundary layer (PBL) scheme of Hong and Pan (1996);
land surface, using the Noah land surface model (Chen
and Dudhia 2001);
radiation, using the Rapid Radiative Transfer Model
(RRTM; Mlawer et al. 1997) for longwave radiation
calculations and basing shortwave radiation calculations
on Dudhia (1989);
surface layer, using the Monin–Obukhov scheme; and
radar simulator, using the National Center for Atmo-
spheric Research (NCAR) Read/Interpolate/Plot, ver-
sion 4 (RIP4; http://www.mmm.ucar.edu/wrf/users/docs/
ripug.htm) program.

3. Meteorological setting

A meteorological observatory located in the valley
near Leh reported that a total rain amount of 12.8 mm
fell during the early morning hours of 5 August 2010
(http://blogs.wsj.com/indiarealtime/2010/08/06/lehs-flash-
floods-how-much-did-it-rain). This amount is abnor-
mally large for this desert valley, where 15.4 mm is the
monthly average rain accumulation for August. An addi-
tional important factor is that this rainfall was not
simply local to the town, but rather, fell over the sur-
rounding area on the valley’s bare mountainsides (see
photo on the title page of RH), where it ran off into
the town and flooded the Indus River. Figure 4a shows
the soil moisture gradient during 2–5 August in the LIS
simulation. The model indicates that a significant amount
of soil moisture was present prior to the landslide and
flash flood. Preexisting soil moisture saturation is one of
the key ingredients that, when combined with heavy rain,
can lead to landslides (Kirschbaum et al. 2012). Multiple
heavy rain episodes occurred during 3–5 August near
Leh, likely exacerbating the already wet soil conditions
and making the land surface especially conducive to
landslides when the flash flood occurred (Fig. 5). As
mentioned in RH, the Ladakh region is known for having
low-nutrient and poor soil conditions that are unsuitable
for agricultural purposes (Goodall 2004), which could
have contributed to the severity of the Leh flood and
related landslides. The results presented in RH and this
study based on satellite and model data show approxi-
mately 90–100-mm accumulation from 2 to 6 August. On
a longer time scale, the slow seasonal buildup of surface
water vapor mixing ratio in this normally arid region likely
preconditioned the area for a disaster when the period of
heavy rains occurred (Fig. 6).

Since the observed synoptic and satellite settings of
the Leh flood are described in RH, we summarize here
only a few key points. During the three days leading
up to the Leh flood, the 500-hPa winds were generally
easterly to northeasterly over Leh, coming across the
Himalayas after flowing around the south side of the
high-pressure system centered over the Tibetan Plateau
(Fig. 7). This anomalous wind formed a jet that helped to
organize MCSs and steer them over Leh. For three
successive days, well-organized MCSs traveled in the
downstream direction of the Indus River and passed
directly over Leh, which likely contributed to increasing
soil moisture in the entire region in addition to raising
the levels of the Indus River.2 At the same time, rela-
tively 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.
The vortex over northwest India (seen most strongly at
700 hPa; see RH) was a midlevel monsoon cyclone of the
type described by Krishnamurti and Hawkins (1970),

2 See the supplementary material for a Meteosat-7 loop showing
the three successive MCSs passing over Leh, India.
FIG. 5. The LIS resolved (a),(c),(e),(g) precipitation and (b),(d),(f),(h) soil moisture rate per day is shown from 2 to 5 Aug 2010. All panels are derived from the uncoupled LIS simulation.
Mak (1975), Carr (1977), Goswami et al. (1980), and Das et al. (2007). The lower row of panels of Fig. 7 show the progression of this low-pressure system weakening over the three-day period leading up to the Leh flood. However, it seems that the simulation conducted from 2 to 5 August 2010 did not adequately capture the strength, size, and location of the midlevel monsoon cyclone compared to the reanalysis data shown in RH. The midlevel monsoon cyclone is known as a stationary pattern as it typically grows and decays in place (Krishnamurti and Hawkins 1970; Mak 1975; Carr 1977; Goswami et al. 1980). However, during the numerical simulation, the cyclone propagates to the west and is located over Pakistan on 5 August 2010 (Fig. 7f), which likely altered the moisture flux into the lowlands of India and Pakistan by this feature. Additionally, the Bay of Bengal depression is deeper than the midlevel monsoon cyclone (Figs. 7d–f), which likely affected the dominant source of the lowland moisture in the simulation compared to the observations. Regardless of the shortcomings in the numerical simulation, the midlevel low from the Arabian Sea was instrumental in persistently driving low-to-midlevel moisture toward the Leh region from the south.

A Bay of Bengal depression was strengthening during this period, and flow around its north side paralleled the Himalayas and imported low-level moisture into the Leh region from the southeast. As mentioned above, the relative strength of the depression in the simulation is greater than the reanalysis data, but it is nonetheless an

![Fig. 6. The surface water vapor mixing ratio over Leh from 1 May to 30 Aug 2010. The surface moisture time series is constructed from NCEP reanalysis data.](image1)

![Fig. 7. (a)–(c) Model simulated geopotential height (m) contours and geostrophic wind vectors (m s$^{-1}$) at 500 hPa and (d)–(f) geopotential height contours at 700 hPa and terrain-following surface winds for 3–5 Aug 2010. Leh is indicated on each panel with a red circle. The model analysis presented is from the 9-km domain from the coarser resolution (27 and 9 km) nested simulation conducted from 2 to 5 Aug 2010.](image2)
important source of moisture. RH hypothesized that the moisture coming from the south and southeast, below the level of the Himalayan Plateau, rose up the steeply sloping terrain and strengthened convective systems past the edge of the Plateau. Although convection was able to form over the diurnally heated plateau, the moisture over the high terrain was in too short of a supply to maintain large mesoscale systems. The newly formed and growing mesoscale convective systems, however, could rapidly strengthen upon tapping the lower-level moisture, and mesoscale systems could then deposit a large amount of precipitation over the Leh valley. The conceptual model of RH reproduced in Fig. 8 illustrates this hypothesized sequence of events.

4. Model trajectory analysis

Figure 9 shows trajectories from the WRF model simulation of the storm producing the Leh flood on 5 August 2010. Two families of trajectories occurred. One family, arriving from the south-southwest, was associated with the flow around the monsoon vortex over northwestern India. The other family, arriving from the southeast, was associated with flow around the north side of the Bay of Bengal depression. These trajectories in the WRF simulation conform to the conceptual model in Fig. 8. Trajectory 1 (marked on Fig. 9) originates over the Bay of Bengal and brings plentiful moisture into the lowlands of India and Pakistan. Trajectory 2 begins over the Arabian Sea, picks up moisture from the Arabian Sea, and arrives near the India–Pakistan border, helping to increase the low-level moisture near the foothills of the Himalayas. Trajectory 1 also shows that the moist air present in the vicinity of Leh was brought up the steep slope of the Himalayas, importing moisture into the Leh valley region as indicated by the time series of variables along the model trajectories (Fig. 10b). The altitude and wind speed of the parcels along both trajectories are also shown in Figs. 10c and 10d. As suggested by RH, both the Bay of Bengal and the Arabian Sea were important sources of moisture that were necessary for the MCSs propagating along the Tibetan Plateau. Additionally, Medina et al. (2010) showed that surface fluxes of sensible heat can increase buoyancy and previous precipitation features can contribute to moisture fluxes from the Arabian Sea. Thus, in addition to the oceanic moisture sources, local moisture sources and surface fluxes likely

Fig. 8. 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 (from Rasmussen and Houze 2012).

Fig. 9. Model simulation backward trajectories of parcels from the final state to initial state to track the source of the moisture. The final state of all parcels is 1800 UTC 5 Aug and the initial state of the parcel is 0000 UTC 2 Aug 2010. The model analysis presented is from the 9-km domain from the coarser resolution (27 and 9 km) nested simulation conducted from 2 to 5 Aug 2010.
contributed to the enhanced moisture content in trajectory 2 while over the Indian continent.

Trajectory analysis demonstrated that moist air in the lowlands of India and Pakistan traveled up the steep slope of the Himalayas. The trajectories of warm, moist air flowing into the Leh region contributed to building an unstable stratification. Model-derived soundings over Leh are shown in Figs. 11a and 11b at 0000 and 1200 UTC 5 August 2010. The 0000 UTC sounding shows that the air was mostly humid up to 400 hPa, the precipitable water was about 2 cm, and the CAPE was 655 J kg$^{-1}$. After 12 h on the same day (1200 UTC) at the same place, the sounding showed that the CAPE had increased to 3819 J kg$^{-1}$, with precipitable water of about 3 cm.

5. Mesoscale storm organization

The initiation of convection over the Himalayan region is not well documented with surface-based observations. However, satellite data have established certain climatological relationships between cloud patterns, landforms, and orography in the Himalayan region (Houze et al. 2007; Barros et al. 2004; Romatschke et al. 2010; Romatschke and Houze 2011; Hirose and Nakamura 2002). Medina et al. (2010) used the WRF model to understand the synoptic events, mesoscale dynamics, and surface fluxes leading to the extreme forms of convection occurring in this region. In view of these previous studies, the heavy rain over Leh studied here was unusual; that is, it did not conform to the climatology and convective forms seen in these previous studies. The anomalous nature of the Leh event was twofold. First, the previous studies using satellite data show that convection over the Tibetan Plateau hardly ever forms mesoscale systems; the high-altitude arid conditions support primarily isolated
convective-scale showers, which may be locally intense but practically never grow upscale to form MCSs. Second, squall line systems with trailing stratiform regions are very rare in this region, probably because of the absence of a midlevel jet, which helps to organize convection into a squall line (Smull and Houze 1987). Houze et al. (2007) described one rare exception when a 500-hPa westerly jet was present during the monsoon and a squall line propagated along the Himalayan barrier.

In the Leh flood case, both of these general rules were broken. Convection grew upscale to form a mesoscale system over the Plateau, and the 500-hPa flow formed a jet that organized a propagating squall line system that moved over Leh. Analysis of the 30-min resolution Meteosat-7 infrared satellite data indicated that the MCS was in the vicinity of Leh for approximately 7 h (1700 UTC 5 August to 0000 UTC 6 August; shown in the supplementary materials). Figure 12 shows the simulated reflectivity development over a 6 h period leading up to the Leh flood. Convection over the Plateau was cellular and merged into a larger combined system that is consistent with the geosynchronous infrared satellite data presented in RH. By 2000 UTC 5 August, at about the time of the Leh flood, some of the convection had devolved into a stratiform region with a bright band while newer reflectivity cells were deep and intense (Fig. 13). The portion of the system shown in this figure was over the high terrain of the Tibetan Plateau, but other portions of the system were moving over the Leh Valley at this time. Figure 13 shows that the basic mesoscale structure of a squall line system had already taken shape over the Plateau. This structure was likely tapping lower-level moisture on the upslope side of the Himalayan barrier (Fig. 12), allowing the convection to become even more intense and capable of producing heavy rain. It should be mentioned that Barros and Lang (2003) described similar types of storms over Nepal, and their findings are consistent with the model obtained reflectivity.

A system of this type moving over a valley like that of Leh is a prescription for flash flooding, especially after the model-derived soil had likely become saturated as described in section 3. The Leh flood was unlike the slow-rising Pakistan flood of the lower Indus basin a week earlier (Houze et al. 2011). That flood occurred when the broad stratiform regions of mesoscale systems became locked into place over the Himalayan slopes surrounding the Indus River well downstream of Leh. The widespread and steady nature of the broad stratiform precipitation regions fed by moist airflow from the Bay of Bengal built up the rainwater runoff upstream, which slowly traveled downriver, where it affected a broad region of Pakistan. In contrast, the storm studied here contained both intense convective cells and a trailing stratiform region that was transitory over Leh. As will be shown below, the rain at Leh fell over a short period. However, the intensity of the downpour and the steepness of the slopes led to a sudden flood, somewhat similar to those that occur occasionally in the Front Range of the Rocky Mountains, such as the Big Thompson flood of 1976 (Caracena et al. 1979; Maddox et al. 1978). Although both the Leh and Big Thompson storms drew upon the upslope flow of moist, unstable, tropical air masses, they differed in that the Big Thompson storm was a quasi-stationary convective system, while the Leh flood was caused by a traveling squall line system, which had formed over the higher terrain but became energized when it moved over the escarpment and tapped the moisture at lower levels (Fig. 9). Another factor contributing to the Leh flood was undoubtedly that on two previous days, similar but smaller convective systems passed over Leh (see RH for the full description and the Meteosat-7 loop in the supplementary materials). The model results suggest that these prior storms likely contributed to the increasing saturation of the soil (Fig. 5), which exacerbated the rapid runoff of the heavy precipitation from the 5 August MCS.

6. Internal storm structure

Figure 14 shows horizontal and vertical cross sections through the storm when it was near the edge of the Plateau and passing over the Leh valley region. The storm was propagating as a squall line with leading convective and trailing stratiform precipitation, steered by the 500-hPa wind (Fig. 7c). At the time of the cross section, the leading convective line had reflectivity values exceeding 40 dBZ reaching up to 12-km altitude, with the echo top exceeding 16 km (Fig. 14c). Convective cells with these characteristics of maximum reflectivity and echo top height are among the most extreme seen in the South Asian monsoon region (Houze et al. 2007; Romatschke et al. 2010). The air motions in the modeled storm show the strong convective updraft over the Leh valley and a strong midlevel inflow into the stratiform region, which then sinks downslope toward the back edge of the leading convective line. The midlevel jet in the stratiform region is an extension of the environmental midlevel flow (about 500 hPa). It is well known that the midlevel rear-to-front flow in the stratiform region often is a continuation and an enhancement of the environmental midlevel flow (Smull and Houze 1987; Kingsmill and Houze 1999; Houze 2004). The air motions of this storm thus exhibit the typical properties of a squall line MCS with trailing stratiform precipitation and robust rear inflow. The 1-km resolution model simulation accumulated rainfall between 1500 and 2300 UTC on 5 August 2010 is shown
FIG. 12. Sequence of model reflectivity showing the initiation and evolution of convection on 5 Aug 2010. The red lines show the location of the vertical cross sections (see right), taken from west to east at (a),(b) 1400, (c),(d) 1600, (e),(f) 1800, and (g),(h) 2000 UTC. The wind barbs are surface winds that follow the terrain. The analysis presented is based on the 3-km resolution model output.
in Fig. 14b, and it seems that the model slightly missed the heaviest precipitation over Leh with upward of 50 mm of rain accumulations just south of Leh.

The simulated microphysical structure of the MCS producing the Leh flood is shown in Fig. 14d. For reference, note that the 0°C level is found at altitudes of 6–6.5 km above sea level. In the convective cell over the Leh region, graupel dominates the active region above the 0°C level, while high concentrations of rainwater dominate at lower levels. As suggested by Houze et al. (2007) for intense convective cells in this region, the graupel extends to very high levels. In this simulation, the 1.0 g kg⁻¹ graupel contour reaches 16-km height in the convective region, whereas in the stratiform region, little graupel occurs. Snow mixing ratio contours dominate the lower portions of the anvil, consistent with the cloud radar data analyzed by Cetrone and Houze (2009, 2011), Yuan et al. (2011), and Powell et al. (2012). The upper portions of the anvil, both leading and trailing, are dominated by cloud ice. The only precipitating anvil is in the trailing region, immediately following the deep convective region. At the time of the cross section, the stratiform rain and part of the convective rain is falling on the slopes of the mountainside above Leh, where it would quickly run off and contribute to the flooding at the base of the valley.

7. Precipitation and land surface moisture analysis

Spaceborne precipitation estimates from passive microwave sensors and the TRMM satellite have revolutionized the study of global precipitation and its distribution (Kucera et al. 2013). Despite known uncertainties in the satellite-derived precipitation estimates (e.g., Adler et al. 2012; Kidd and Levizzani 2011; Gao and Liu 2013; Rasmussen et al. 2013), the ability to examine precipitation in remote regions of the world has enabled an unprecedented view of the climatological occurrence, seasonal and diurnal variability, and individual extreme precipitation events that was not possible before this era. A recent study comparing precipitation gauge measurements over the complex terrain of the Tibetan Plateau to four merged precipitation datasets showed that the TMPA product had the lowest overall errors (Gao and Liu 2013). However, satellite datasets tended to underestimate the higher precipitation rates on average (Gao and Liu 2013; Rasmussen et al. 2013), so rain rates derived from merged satellite data for heavy precipitation events are likely a lower bound on the actual precipitation rates. An advantage of the satellite methods for studying flood cases is that they provide area-wide estimates so that the rain over a whole hydrologic basin can be seen. The areal rainfall is more useful than a point measurement, since the latter may not be representative of the region draining into the basin that floods. Regardless of the inherent and well-studied errors associated with satellite data, it is the best source of information for heavy precipitation events in remote regions with limited ground-based rain-measuring instruments and networks, and it provides both a spatial and temporal perspective that is crucial for studying events like the Leh flash flood.

The rainfall evolution for the Leh flood is well captured by the TRMM 3B42 product (which includes information from TRMM and other satellites). Gridded rainfall estimates are on a 3-h temporal resolution and a 0.25° x 0.25° spatial resolution in a global belt extending from 50°S to 50°N. At 1200 UTC 5 August, rainfall patterns (Fig. 15a) are scattered in small patches over the Himalayan belt, with rain accumulations of ~5–15 mm.
At 1500 UTC, rain is more concentrated and located over the Tibetan Plateau in an elongated region parallel to the Himalayas, with rain accumulations up to ~50 mm in the northwestern region close to Leh. By 1800 UTC, heavy rain is concentrated near Leh in a zone of 10–20 km in diameter with maximum accumulation of about 75 mm (Fig. 15c). To facilitate a reasonable comparison between the model and observational satellite precipitation data, the model data were resampled to the same resolution as the TRMM 3B42 data (0.25° or ~26 km), and the rain accumulation over Leh is presented in Fig. 16. Comparisons to the TRMM 3B42 data from around the same time (Fig. 15c) indicate that the model simulation produced a net accumulation of ~39 mm (Fig. 16), which gives greater confidence in the model simulated precipitation. A nearby Indian Air Force observatory recorded ~13 mm of precipitation (http://www.imd.gov.in/doc/cloud-burst-over-leh.pdf). These precipitation amounts do not, at first glance, seem excessive. So why did the flash flood and mudslide occur? First of all, station measurements of precipitation are not directly comparable to larger, gridded satellite estimates because of the difference in temporal and spatial scales. However, aside from this consideration, several factors must have combined. The storm maximized in intensity as it moved off the Plateau and tapped the moisture from the lowlands. Nearly all the rain fell over steeply sloping land. Unused to rain, the land was barren. Because of the buildup of soil moisture over the season (Fig. 6) and especially in the preceding several days (Fig. 5), the soil...
could have saturated. These factors, in addition to heavy precipitation from the final MCS, came together to produce the flood at Leh at about 1900–2000 UTC (0100–0200 local time).

Based on available observations over complex terrain, the atmospheric and hydrological processes must be accurately simulated (Warner 2011) in order to identify and develop a physical understanding of the Leh flash flood. We have tried to determine how well the model reproduced the actual rainfall leading to the Leh flood by comparing with standard sources of observational rainfall information. Total accumulations from the 24 h period that encompasses the Leh flood are presented in Fig. 17, which includes the TRMM 3B42 product as well as the Climate Prediction Center’s morphing technique (CMORPH) product that was bias corrected with precipitation gauge data (Joyce et al. 2004). The CMORPH and TRMM products show many of the same features but also have some inconsistencies, both qualitatively and quantitatively. The CMORPH product (Fig. 17a) shows overall less rain than the TRMM estimated rainfall (Fig. 17b), which likely results from the lack of rain gauge observations in the region. Despite the various inconsistencies, the overall rainfall patterns from TRMM and CMORPH are generally similar over Nepal, Tibet, and northwest India. The latter shows values of 40–50 mm of rainfall over the India–Pakistan border on 5 August, whereas TRMM estimated amounts similar to those observed over Leh and is consistent with the simulated rain accumulation from Fig. 16. The model-derived rainfall shows a basic qualitative agreement with both observational products, but is in somewhat closer agreement with the TRMM estimated rainfall given the spatial distribution and accumulated rain amounts. The model also captured the localized rainfall spots over Nepal and adjoining areas seen in both the TRMM and CMORPH products.

The atmospheric processes associated with flash floods that cause landslides over complex terrain have

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**Fig. 15.** TRMM 3-hourly accumulated precipitation (3B42) at (a) 1200, (b) 1500, (c) 1800, and (d) 2100 UTC on 5 Aug 2010. Leh is indicated on each panel with a black circle.

**Fig. 16.** Model simulated accumulated rainfall (mm) over Leh on 5 Aug 2010. The model resolved precipitation is based on the 1-km resolution inner domain, but was resampled to 26-km resolution to match the TRMM 3B42 pixel size.
been shown to have anomalous hydrometeorological characteristics, such as soil moisture, surface runoff, rainfall amount, and surface storage water (Kirschbaum et al. 2012). Land surface characteristics were not directly observed during the Leh flood event but have been hypothesized to play a role in the severity of the flood and media coverage–reported landslides in the region. The uncoupled LIS system provides improved estimates of land surface conditions such as soil moisture, evaporation, snowpack, and runoff, which were used as input conditions to the coupled LIS-WRF runs. In addition, this approach allows for further understanding of the hydrological aspects of features at much longer time scales, such as 3–6 months prior to the flash flood event. Using the uncoupled LIS system to investigate the Leh flash flooding event, analysis from May to September 2010 (Fig. 18) indicates that the soil moisture in the top layer was dry before July, but it increased in steps after multiple rain events. A sharp increase in soil moisture with a peak of approximately 0.42 m$^3$ m$^{-3}$ volumetric soil moisture occurred on 5 August 2010 during the Leh flash flood (Figs. 18a,b) and then gradually decreased through early September. Compared to the climatological volumetric soil moisture value of approximately 0.1 m$^3$ m$^{-3}$ over Leh derived from 62 years (1948–2010) of GLDAS, version 2 (GLDAS-2), 1°-resolution data from the Noah model (not shown; Rodell et al. 2004), the enhanced moisture preconditioning likely played a large role in the land surface impact on the flash flood. 
event. Anomalous surface runoff is also evident during the highly unusual flash flood over Leh, shown in Fig. 18c. High values of surface runoff are critical and particularly hazardous during such a short period of time because of the potential to trigger landslides. While the current LIS system lacks the potential influences and feedbacks between vegetation and geomorphic processes, such as landslides, debris flows, and channel evolution, using an integrated approach can lead to greater insight into hazardous conditions and natural disasters in remote regions, such as the Leh flash flood. As demonstrated in this study, both the land surface processes and the meteorological conditions contributed to the disaster in Leh, illuminating the potential benefit in implementing integrated land–atmosphere forecast models in vulnerable regions of the world (Kirschbaum et al. 2012).

8. Conclusions

The Leh flood was not only a tragedy worth understanding in its own right, but it is also representative of flash floods of the type that are prone to occur at the steep edge of a high plateau. The Himalayas are the mountainous edge of the Tibetan Plateau, somewhat like how the Front Range of the Rocky Mountains constitutes the steep boundary of the vast plateau of the western United States. The Big Thompson flood of 1976 is an example of such a flash flood over the Front Range. Like that flood, the Leh flood and its associated landslide killed several hundred people and did terrible damage. Both the Big Thompson and the Leh flood involved upslope flow of moist unstable tropical air masses; however, they were the result of very different types of convective storms. The Big Thompson storm was stationary over the Front Range, while the Leh Flood was due to a moving squall line with trailing stratiform rain forming over the Tibetan Plateau. It drew upon the warm moist air rising up the steep Himalayan barrier as it moved over the steep edge of the Plateau and was exacerbated by prior storms moistening the soil on the sides of the mountains surrounding Leh. As presented in Doswell et al. (1996), identifying similar ingredients that are present during a variety of flash flood–producing storms provides lessons for understanding and predicting flash floods and leads to insights into flash flood–producing scenarios in various regions of the world. The analysis in this study has investigated the physical mechanisms, storm structure, land surface characteristics, and precipitation of the MCS to provide a detailed analysis of the ingredients that combined to produce the flash flood in Leh.

RH examined synoptic and satellite data for the Leh case and constructed the conceptual model in Fig. 8 to explain the atmospheric aspects of the event. A key feature of the conceptual model was its suggestion that when the propagating MCS that formed over the Tibetan Plateau moved over Leh it was able to feed upon warm, moist air from both the Arabian Sea and Bay of Bengal. That moist air was thought to be flowing up the Himalayan slope in the Leh region as a consequence of low-pressure systems over the northwestern subcontinent and the Bay of Bengal. Trajectories in the model simulation presented here confirm this suggestion. The simulated storm approximately reproduced the rainfall pattern of the storm and total storm accumulations are consistent between the model and the TRMM satellite estimates (Figs. 15, 16). The model simulation further shows that the Leh storm’s mesoscale organization, internal air motions, and hydrometeor distributions were consistent with those of a typical traveling squall line with trailing stratiform precipitation. The convective region maximized over the Leh valley, and the stratiform region contributed rain there as well, as the system moved through the Leh region. The mesoscale proportions of the systems assured that the surrounding mountainsides, as well as Leh itself, received the heavy but short-lived downpour.

The hydrological aspects of the Leh flooding event were investigated with the coupled WRF-LIS modeling tool. In the vicinity of Leh, anomalously high values of soil and surface moisture were present just prior to the flash flooding event that likely preconditioned the soil for maximum immediate runoff and destabilized the ground, making it susceptible to landslides. The saturation of the soil in the model simulations was intensified by heavy rainfall from the succession of two MCSs propagating over the city of Leh on the two days before the flood. On 5 August 2010, when the third and most intense MCS propagated over Leh, all of the moisture parameters in the simulation were maximized both in the atmosphere and on the ground, indicating the hazardous nature of this flash flood event. Landslides and flash flooding occurred and were reported by local media. These events were indicated in the WRF-LIS simulation as high values of surface runoff during the event, as the barren land surface in this region could not absorb all of the water deposited in the short time of the 5 August storm. A coupled model like the WRF-LIS system or a similar coupled model is capable of providing hydrologic information and potentially dangerous scenarios that could be very useful in high landslide- and flood-prone regions.

Flash floods on the edges of major plateau regions are infrequent and devilishly hard to predict. Besides a model such as the WRF-LIS system, basic climatological awareness can be useful in forecasting events such as the
Leh flood, specifically awareness of what is usual in order to be able to recognize an outlier event. From recent satellite climatologies (Houze et al. 2007; Romatschke et al. 2010), we know that the Leh storm was highly unusual in two respects: 1) convection over the Tibetan Plateau seldom grows upscale into a mesoscale convective system and 2) traveling squall line systems are rare in the Himalayan region. RH demonstrated how the large-scale flow pattern and ordinary geosynchronous satellite imagery indicated that this highly unusual condition was occurring for several days. This fact suggests that, along with coupled atmospheric–land surface models, better use of real-time observations against the background of recent satellite climatologies of the region might also contribute to recognizing the warning signs for a flash flood like the Leh event.

Acknowledgments. This research was sponsored by NSF Grants ATM-0820586 and AGS-1144105 and NASA Grants NNX10AH70G and NNX11AL65H (Dr. Ramesh Kakar). This research was also supported by National Aeronautics and Space Administration grants from the NASA Modeling, Analysis and Prediction (MAP) Program (Dr. David Considine, MAP program manager). The NASA Center for Climate Simulation (NCCS) computing system provided resources for the model simulations. Thara Prabhakaran participated in an early phase of this study. Graphics art and manuscript editing were provided by Beth Tully. The authors thank Dr. Russ Schumacher and two anonymous reviewers for their comments and suggestions, which have greatly improved this manuscript.

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