# Anomalous Atmospheric Events Leading to the Summer 2010 Floods in Pakistan

BY R. A. HOUZE JR., K. L. RASMUSSEN, S. MEDINA, S. R. BRODZIK, AND U. ROMATSCHKE

**A MAJOR HUMANITARIAN DISASTER.** Addressing the United Nations General Assembly about the floods that affected the Indus Valley of Pakistan in July–August 2010, Secretary-General Ban Ki-moon stated, "Almost 20 million people need shelter, food, and emergency care. That is more than the entire population hit by the Indian Ocean tsunami, the Kashmir earthquake, Cyclone Nargis, and the earthquake in Haiti—combined." Such a profound humanitarian disaster deserves a close look at the conditions under which it occurred. Recent research based on data from the radar onboard the U.S.-Japanese Tropical Rainfall Measuring Mission (TRMM) satellite leads to an understanding of the anomalous character of this event and suggests how future disasters in this part of the world might be better anticipated through the use of such data to interpret atmospheric forecast models.

The July–August 2010 floods were the worst ever known to have occurred in this region. A recently obtained climatology of rainstorm structures compiled from the TRMM satellite indicates that the rainstorms responsible for the floods were of a type that does not normally occur in this region. Rather, this type of storm usually occurs and produces copious monsoon rain far to the east, over the mountains and wetlands of northeastern India and Bangladesh. In this event, catastrophic runoff and flooding resulted as these rainstorms were displaced to the west, an arid and mountainous region unaccustomed to such storms. Moreover, the potential of this devastating displacement of storms, far away from their usual location of occurrence, could be inferred from the synoptic-scale circulation that exhibited a great departure from its usual behavior during the South Asian monsoon season.

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**OROGRAPHIC RAINSTORMS SEEN BY TRMM.** Major rainstorms can occur in mountainous regions when air is lifted over the terrain. When the environment is especially unstable, storms may form that contain locally intense buoyant updrafts, heavy downpours of rain, and sometimes hail. High winds may occur where downdrafts, forming in raining regions, reach the ground and spread out. When a sequence of convective up- and downdrafts occurs, the precipitating cloud systems take the form of a "mesoscale convective system" (MCS; for a thorough description see Houze's 2004 article in *Reviews in Geophysics*), in which some "convective cells" die out while other new ones form, and the older dying storms morph into regions of wider-spread "stratiform rain." This process is described by Houze in a 1997 *Bulletin* article. The stratiform region features gentler rain but covers a much greater area and can last for long periods of time if the environment is favorable. Even if the instability is modest but the environment is humid enough to support the persistence of the stratiform regions of MCSs, or if the MCS stratiform region is enhanced by orographic or synoptic-scale upward motion, a great amount of rain can be produced by the MCS. As a result, if MCSs are the principal rain-producing cloud systems over a region such as the upslope side of the Himalayas, the mountains can affect the rainstorms in two important ways: 1) Airflow over rising terrain may trigger new intense convective cells, thus revitalizing and maintaining the vigorous convective region of the MCS for a longer period of time; and 2) the orographic upward air motions may sustain and broaden the stratiform region of the MCS so that the gentler (but nonetheless significant) rainfall that has formed from older convective cloud elements may last longer and cover a larger area. In the Pakistan flood cases, the broad stratiform rain area of the MCSs was widespread and persistent over a fixed and highly vulnerable regional watershed. The following discussion will illustrate the anomalous environmental factors leading to the occurrence of MCSs with large stratiform regions over the Himalayan watershed feeding the Indus River.

The satellite radar on TRMM provides a unique vision of storms in regions inaccessible to land-based surface observations—such as the mountains of Pakistan. The official TRMM data product 2A23 subdivides the radar echoes into three categories: convective, stratiform, and other. Recent work has used the TRMM data subdivided into these echo types to analyze the three-dimensional structure of the radar echoes producing major storms and rainfall throughout south Asia (Houze et al. 2007; Romatschke et al. 2010; Romatschke and Houze 2011). These studies are a timely and important backdrop for understanding what happened in the Pakistan floods because they show that extreme rainstorms in this part of the world are far from similar to each other, but rather subdivide into three characteristic types: storms with "deep convective" cells, where the buoyant updrafts produce extremely intense radar echoes at altitudes above 10 km MSL; storms containing "wide convective" rain areas, in which the extremely intense echoes extend contiguously over unusually large horizontal areas (> 1,000 km$^2$); and storms exhibiting "broad stratiform" rain areas, in which the spreading of old convective cells produces unusually large regions of stratiform radar echo (> 50,000 km$^2$ in area).

The TRMM studies show that in the region of the 2010 Pakistan floods, storms containing broad stratiform rain areas are extremely rare. Storms with deep convective cells, on the other hand, are common. Analyzing the TRMM radar data, Barros et al. (2004), Zipser et al. (2006), and Houze et al. (2007) have shown that some of the tallest, most intense, and most lightning-prone storms in the world occur in this region. The storms with extremely deep convective cells, however, do not account for much rain. They are generally local in nature, and the area near and including the mountains of Pakistan remains quite arid. These local but very deep storms occur characteristically near the boundary of dry air coming from the Afghan plateau and moist air currents at very low altitudes flowing into the region from the Arabian Sea, as documented very early by Sawyer (1947), and in the TRMM era by Houze et al. (2007) and Medina et al. (2010). This juxtaposition of airflows produces extremely buoyant cells within an otherwise dry environment, but it does not encourage the formation of broad stratiform rain areas.

In contrast, Houze et al. (2007) showed that mesoscale systems in the nonarid eastern Himalayan region (including the wetlands of West Bengal, Bangladesh, and environs) frequently develop broad stratiform rain areas. These mesoscale systems containing broad stratiform precipitation occur in the very humid confines of low-pressure systems over the Bay of Bengal. The airflow around the Bay of Bengal depressions often carries the cloud systems with broad stratiform rain areas into the eastern Himalayas, where they are strengthened and widened by upslope flow, as Medina et al. (2010) show in their study of terrain effects in the region. Rainfall events of this type do not normally occur outside of the eastern region; however, that is what happened in Pakistan in the summer of 2010.

**THE PAKISTAN STORMS.** To understand the events in Pakistan, we first present Fig. 1, which shows the 28 July 2010 deviation of the 500-mb height pattern in the midlevels of the troposphere from mean monsoonal (June–September) conditions. To appreciate how unusual this pattern was, we refer to recent work published in the *Journal of Hydrometeorology* by in which we (Romatschke and Houze) examined a database of radar echo types seen by the TRMM satellite and determined the mean large-scale flow anomalies associated with typical rainstorms in different parts of the region during the monsoon season. Figure 1b indicates two of these regions: the western Himalayan foothills (which include the Pakistan flood region) and the Bay of Bengal. Figure 1c shows the typical midlevel flow anomaly associated with rainstorms in the western Himalayan foothills. It brings dry air into the western Himalayan foothills region from the Afghan Plateau. When intense convective clouds form here, they are surrounded by this dry air and consequently cannot grow into wider-spread storms with large stratiform precipitation areas. This type of pattern rather supports rainstorms with deep convective cells, which are locally intense but overall do not produce much rainfall. Figure 1d shows the flow anomaly pattern when TRMM observed major rainstorms over the Bay of Bengal region. The rainstorms that account for the bulk of the rain in the Bay of Bengal and surrounding regions are of the type that

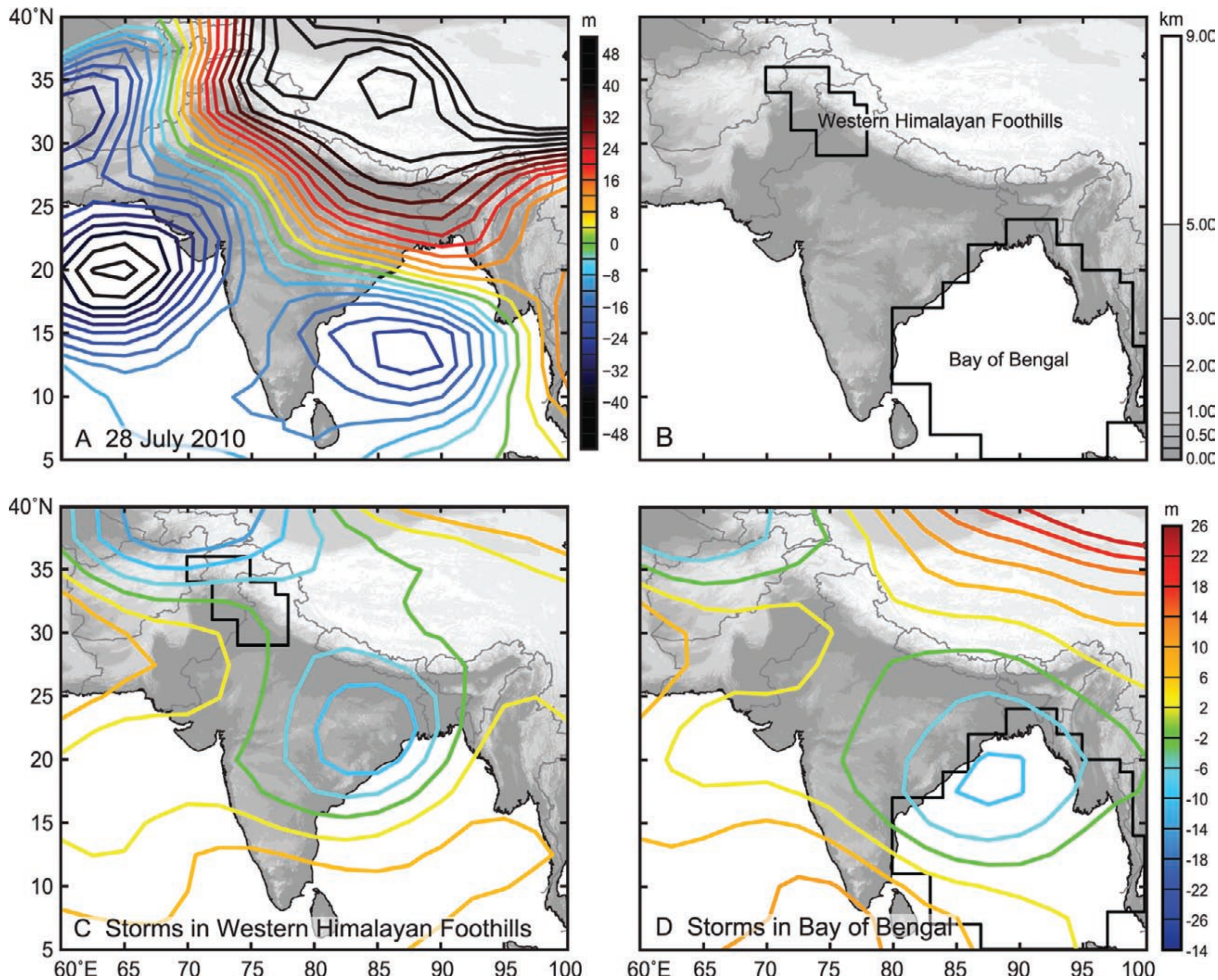


**Fig. 1. (a) One-day-average height anomalies (m) of the 500-mb surface on 28 Jul 2010. Panels (c) and (d) from Romatschke and Houze (2011) show the average anomalies associated with rainstorms detected by TRMM satellite in the Western Himalayan foothills and Bay of Bengal regions indicated in (b). The TRMM satellite data are for the 8-yr period of 1999–2006. These maps were derived from National Centers for Environmental Prediction (NCEP) 2.5° x 2.5° gridded reanalyses (Kalnay et al. 1996), as in Romatschke et al. (2010).**

contain broad stratiform rain areas. They are typically associated with a low-pressure system ("depression") centered over the bay. The mean flow anomaly in Fig. 1d reflects this fact by showing a mean low-pressure anomaly centered in the bay. The air in the depression is very humid, and the counter-clockwise winds on the northeast side of the depression bring a deep layer of moist air over land in the mountainous region to the northeast of the depression. These same winds bring the cloud systems with broad stratiform rain areas inland and over the mountains of the region north and east of the bay.

The wind and pressure anomalies of 28 July 2010 (Fig. 1a) were strikingly unlike either of these previously documented flow anomalies. Instead, an intense 500-mb geostrophic wind anomaly (height gradient) was located just equatorward of the Himalayas, between an intense high-pressure system over central Asia and the two 500-mb height negative-anomaly centers, which together extended across the middle of the subcontinent. This flow anomaly extended to lower levels, conveyed moisture into a region of Pakistan orthogonal to the Himalayan barrier, and was thus largely responsible for establishing the environment of the mesoscale rain systems that produced the flooding in the Indus region.

How the unusual and dramatic flow pattern seen in Fig. 1a developed is illustrated by Fig. 2, which

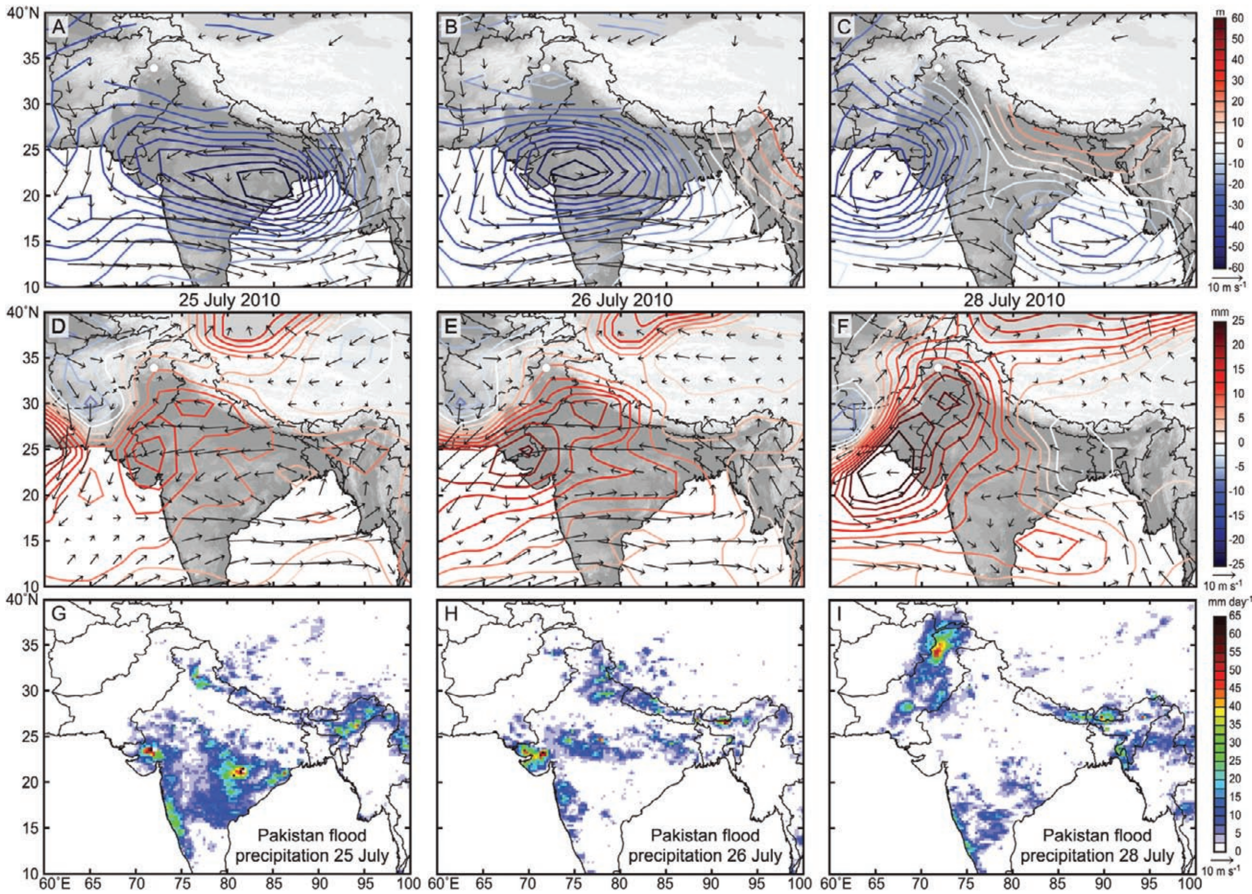


**Fig. 2. Sequence of maps showing the evolution of atmospheric structure prior to 28 Jul 2010 Pakistan rains. Top row: One-day-average height anomalies (m) of the 700-mb surface and the associated 700-mb actual wind vectors (not the wind anomaly). Middle row: Contours of vertically integrated precipitable water anomaly (mm) and 500-mb actual wind vectors (not the wind anomaly). Bottom row: Average rain rate from TRMM and other satellite observations (TRMM product 3B42). Data sources for top and middle rows are the same as in Fig. 1.**

displays a 3-day sequence of the winds, precipitable water, and rainfall beginning 25 July. The top row of Fig. 2 shows the height anomaly and actual (not anomaly) winds at the 700-mb level (~3 km altitude), which is well below the maximum height of the Himalayan barrier. The Bay of Bengal depression on 25 July was unusually intense and extended far westward across the subcontinent. Over the next 3 days, it propagated westward, far from its origin in the Bay of Bengal, and became centered over the northern Arabian Sea on 28 July. A lesser depression had by then formed over the Bay of Bengal, and the high-pressure anomaly over Asia had propagated over the Tibetan Plateau and extended into northern India, enhancing the height anomaly gradient. Together with the intense depressions to the south, this high-pressure system formed a very strong gradient of pressure producing southeasterly flow onto and over the face of the Himalayas in Pakistan on 28 July.

The middle row of panels in Fig. 2 shows the progression of the anomaly of precipitable water vapor together with the 500-mb actual winds. By 28 July, the water vapor anomaly and flow into the region of the floods had reached maximum proportions. The vapor anomaly was clearly associated with the earlier Bay of Bengal depression now located over the northern Arabian Sea and the stream of southeasterly flow from the northern Bay of Bengal. Note that although the Bay of Bengal region is a humid maritime environment, its anomaly of precipitable water was near zero, while the anomaly over Pakistan was enormous by virtue of the flow of Bay of Bengal air into the region. In other words, the humid air usually confined to and affecting the rainfall of the region north of the Bay of

Bengal had made its way westward all the way across to Pakistan in this unusual event and was driven into the mountains by the anomalous flow pattern. The bottom row of panels shows how the rainfall observed by TRMM and other satellites matched the moisture convergence over the Pakistani Himalayan slopes implied by the winds and water vapor patterns. Figure 3 zooms in on this region and shows the net rain accumulation for the period responsible for the floods.

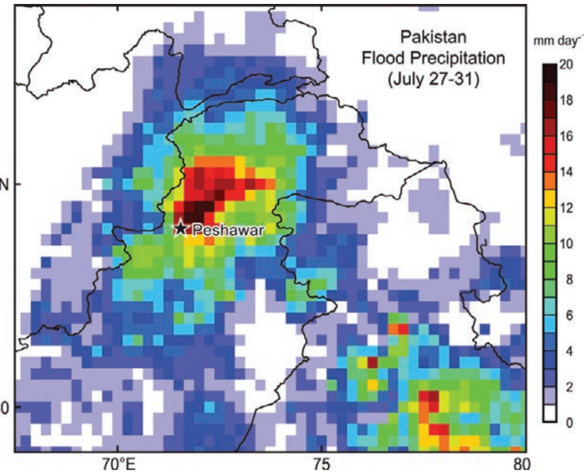


**Fig. 3. Average rainfall rate for 27–31 Jul 2010 from TRMM and other satellite observations (TRMM product 3B42).**

**THE NATURE OF THE PRECIPITATING CLOUD SYSTEMS.** The rainfall producing the Pakistan floods occurred in storms that were of a type commonly seen far to the east over the Bengal region but rarely over Pakistan. This fact illustrates how it is not enough to note that moist flow encounters mountains. Rather, a second question arises: what is the nature of the rain that falls as a result of this encounter? Figure 4 shows the relative humidity and temperature profiles observed on 27 July (solid gray line) upstream of the Pakistan flood storms and compares them to those in the environment of a typical severe rainstorm over the Pakistan region (dashed gray line). The humidity profile in the Pakistan flood storms was nearly saturated through the lowest 7 km, while the relative humidity in the environment of the more typical storm was ~50% at the same levels. The high humidity of the Pakistan flood storms was in fact similar to that found over the Bengal region in the presence of a Bay of Bengal depression (dotted black line). Also notable is that the temperature through most of the low-to-middle troposphere dropped off with height more slowly than in the more typical case. Parcels rising moist-adiabatically from lower levels would therefore have difficulty achieving large buoyancy through the middle troposphere and thus the convective cells in this environment would be expected to be less intense than in the more typical cases. Xu

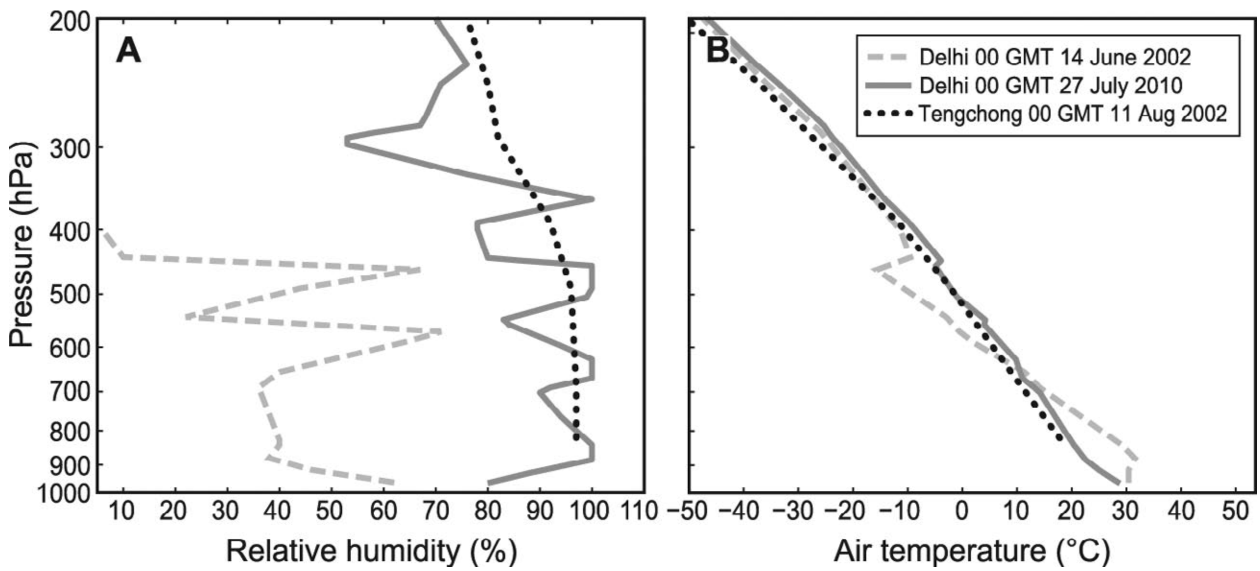


**Fig. 4. (a) Relative humidity (b) temperature profiles associated with: a typical Pakistan rainstorm (dashed gray line for Delhi sounding at 0000 UTC 14 Jun 2002); the 28 Jul 2010 Pakistan rainstorms (solid gray line for Delhi sounding at 0000 UTC 27 Jul 2010); and a typical Bay of Bengal storm (dotted black line for Tengchong sounding at 0000 UTC 11 Aug 2002).**

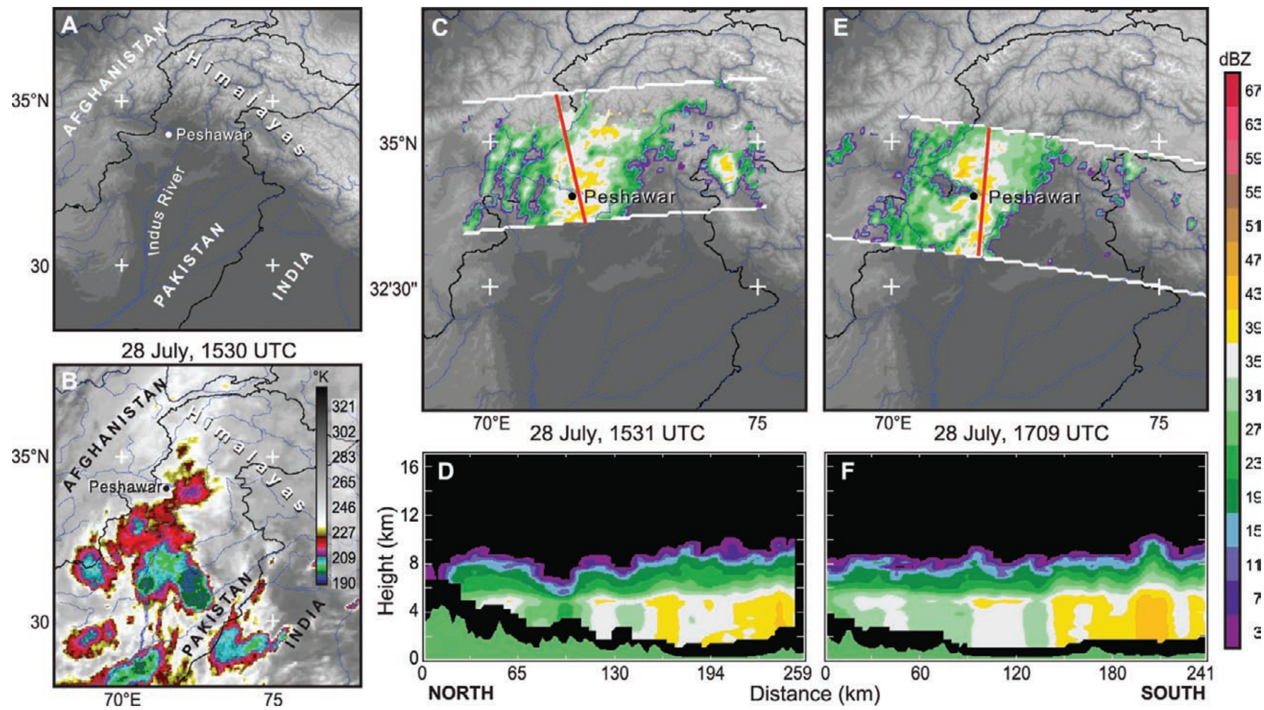


**Fig. 5. (a) Topography and (b)-(f) satellite data for 28 Jul 2010 Pakistan rainstorms; (b) infrared satellite image (K) from the METEOSAT 7 image for 1530 UTC 28 Jul; (c)-(f) reflectivity from the TRMM satellite radar in dBZ; (c)-(d) TRMM radar overpass at 1531 UTC 28 Jul; (e)-(f) TRMM radar overpass at 1709 UTC 28 Jul. Horizontal cross sections are at 5-km altitude. Red lines in (c) and (e) indicate the location of the vertical cross sections in (d) and (f), respectively.**

and Emanuel (in 1989) showed that soundings over tropical oceans tend to have lapse rates deviating only slightly from moist adiabatic, and as a result do not develop large buoyancy, even though the convection may be very deep. In two 1980 *Journal of the Atmospheric Sciences* papers, Zipser and LeMone and LeMone and Zipser showed that oceanic tropical convection contains updrafts of much less magnitude than occur over land. The sounding associated with the Pakistan flood storms (solid gray line in Fig. 4b), which was similar to those found over the Bay of Bengal in the presence of depressions (dotted black line), had a decidedly more tropical oceanic character than is normally associated with deep convection in the Pakistan region considered here (dashed gray line). The intense convection in that region is normally associated with dryline type convection where, as noted above, low-level moist flow from the Arabian Sea is capped by dry flow subsiding off the Afghan Plateau. This type of convection was absent in the summer 2010 flood cases and replaced by convection of a more oceanic character. The more oceanic type of convection flourishes in a high-humidity environment, which is favorable for storms to develop into wider, generally stratiform raining cloud systems, and as we will see, this oceanic type of storm occurred in the flood cases—in a decidedly nonmaritime environment!

Figure 5 shows the TRMM radar's view of the structure of the raining systems on 28 July. Figure 5a shows the Himalayan terrain and river valleys of the region that later flooded. Figure 5b is an infrared satellite image showing the extent of the cloud system that affected the region. Figures (c)–(f) show the TRMM radar data in horizontal and vertical cross sections. The rain areas were extensive—at least 200 km in horizontal dimension. Moreover, they were primarily stratiform. The maximum of echo intensity just below the 0°C level (~5-km) in the vertical cross sections was the radar "bright band." Produced by melting snow, it is a classic signature of primarily stratiform rain. This widespread stratiform rainfall, because it covered such large portions of the mountains, produced an extensive region of runoff into the rivers and the plains below. Houze et al. (2007) and Romatschke et al. (2010) showed that such large areas of stratiform rain are almost never seen in this arid mountainous region. Although the more typical rainstorms of this region consist of very intense convective clouds, they are highly localized, covering orders of magnitude less area than the storms seen in Fig. 5. In addition, Medina et al. (2010) show that the typically observed deep convective storms are usually triggered over lower terrain, so their rainfall does not accumulate over and run off from higher terrain.

**FORECAST IMPLICATIONS.** Previous studies have found that severe orographic rain events and flooding potential may be signaled by the arrangement of low and high pressure systems such that a channel of very moist airflow runs orthogonally into a mountain barrier (see Petersen et al. 1999 in the Rocky Mountains; Chen et al. 2010 in Taiwan). These previous studies further indicate the importance of identifying deep moist airflow directed toward a mountain barrier. However, they do not investigate the importance of the form taken by the convective cloud systems. The Pakistan flood case described here illustrates the importance of the particular form taken by the cloud systems producing the floods. The anomalous propagation of a Bay of Bengal depression and its moist environment across the subcontinent to the Arabian Sea together with the development of the high pressure over the Tibetan Plateau not only favored the occurrence of a synoptic-scale channel of anomalously moist flow toward the mountain barrier, but in addition it formed an environment in which the precipitating mesoscale cloud systems took on a form that included broad stratiform rain regions lying over the slopes of the Himalayas. The areal coverage of these wide raining systems contributed to the huge runoff and flooding event.

Webster et al. (in *Geophysical Research Letters*) show that weather forecast models can predict development and movement of such large-scale flow patterns that can produce strong flows of moist air toward the mountain barrier in the Pakistan region, but even the rapidly increasing number of models with horizontal resolution ~50 km do not yet have the precision to predict the exact *form* that the precipitating clouds will take. Satellite radar observations provided by TRMM, however, supply climatological knowledge of the different forms of convective precipitation systems that occur in certain large-scale flow patterns. Since the highly anomalous wind pattern was clearly one originating in the Bay of Bengal with great moisture content, it could be flagged as a situation that the TRMM radar has identified as producing raining cloud systems with broad stratiform structures. Given that storms of this type are exceedingly rare in the mountains of Pakistan, this situation could have perhaps been seen, in light of the TRMM radar data, as especially dangerous.

This case thus illustrates that the climatology of TRMM radar data and associated large-scale flow patterns that have been accumulated since 1997 for different regions of south Asia provide a background against which large-scale flows forecast by atmospheric models can be interpreted in terms of the form that a rainstorm might take. When synoptic-scale flow anomalies suggest that mesoscale storms forming in that environment are likely to have an unusually and particularly hazardous structure in relation to the terrain, such an interpretation could be extremely valuable in downscaling the synoptic-scale forecast flow pattern to predict patterns of flooding and thus helping to formulate advance warnings aimed at saving life and property in vulnerable regions such as the Indus Valley of Pakistan. We suggest that a methodology could be devised in which precipitable water and wind anomalies in the Pakistan region, predicted by global models, could be objectively scaled, for example using a method such as described by Junker et al. (in a 2009 *Bulletin* article) for California storms, to determine the environments in which flooding is probable. The method could be refined further using the climatology of storm structure derived from TRMM PR data to relate these synoptic conditions to specific Himalayan storm types to determine whether the storms would be of the type most likely to cause catastrophic flooding.

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