Monsoon convection in the Himalayan region as seen by the TRMM Precipitation Radar

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ABSTRACT: Three-dimensional structure of summer monsoon convection in the Himalayan region and its overall variability are examined by analyzing data from the Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar over the June–September seasons of 2002 and 2003. Statistics are compiled for both convective and stratiform components of the observed radar echoes.

Deep intense convective echoes (40 dBZ echo reaching heights >10 km) occur primarily just upstream (south) of and over the lower elevations of the Himalayan barrier, especially in the northwestern concave indentation of the barrier. The deep intense convective echoes are vertically erect, consistent with the relatively weak environmental shear. They sometimes extend above 17 km, indicating that exceptionally strong updraughts loft graupel to high altitudes. Occasionally, scattered isolated deep intense convective echoes occur over the Tibetan Plateau.

Wide intense convective echoes (40 dBZ echo >1000 km² in horizontal dimension) also occur preferentially just upstream of and over the lower elevations of the Himalayas, most frequently in the northwestern indentation of the barrier. The wide intense echoes have an additional tendency to occur along the central portion of the Himalayas, and they seldom if ever occur over the Tibetan Plateau. The wide intense echoes exhibit three mesoscale structures: amorphous areas, lines parallel to the mountain barrier, and arc-shaped squall lines perpendicular to and propagating parallel to the steep Himalayan barrier. The latter are rare, generally weaker than those seen in other parts of the world, and occur when a midlevel jet is aligned with the Himalayan escarpment.

Deep and wide intense convective echoes over the northwestern subcontinent tend to occur where the low-level moist layer of monsoon air from the Arabian Sea meets dry downslope flow, in a manner reminiscent of severe convection leeward of the Rocky Mountains in the central USA. As the low-level layer of moist air from the sea moves over the hot and arid northwestern subcontinent, it is capped by an elevated layer of dry air advected off the Afghan or Tibetan Plateau. The capped low-level monsoonal airflow accumulates instability via surface heating until this instability is released by orographically induced lifting immediately adjacent to or directly over the foothills of the Himalayas.

Broad (>50 000 km² in area) stratiform echoes occur in the eastern and central portions of the Himalayan region in connection with Bay of Bengal depressions. Their centroids are most frequent just upstream of the Himalayas, in the region of the concave indentation of the barrier at the eastern end of the range. The steep topography apparently enhances the formation and longevity of the broad stratiform echoes. Monsoonal depressions provide a moist maritime environment for the convection, evidently allowing mesoscale systems to develop larger stratiform echoes than in the western Himalayan region. Copyright © 2007 Royal Meteorological Society

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1. Introduction

The South Asian monsoon provides an ideal setting to observe orographically influenced precipitation under very warm and highly unstable conditions. During the boreal summer, warm moisture-laden low-level winds bring air from the Bay of Bengal and the Arabian Sea over the hot South Asian continent (Figure 1(a); Rao, 1976; Krishnamurti, 1985; Webster, 1987a,b; Johnson and Houze, 1987; Das, 1995; Pant and Kumar, 1997; Webster et al., 1998). Upon making landfall, the low-level winds encounter the Himalayas, the world’s largest mountain barrier (Figure 2(a); Murakami, 1987). During the monsoon, large amounts of rain fall in this mountain-influenced regime over the northern Asian subcontinent, where the upper-level winds are weak, between strong easterlies to the south and westerlies to the north (Figure 1(b)). Most of the rain in this region falls during the monsoon season of June–September (Nayava, 1974; Shrestha, 2000). The physical interaction between the southwesterly monsoon flow and the South Asian topography affects the climatological distribution of precipitation in the region (Figure 2(b)). Studies dating back to the colonial period in India (Hill, 1881) have examined the distribution of surface rainfall in South Asia and its relation to orographic features.
Rather than surface rain mapping, the goal of our research is to gain insight into the physical mechanisms by which the heavy monsoon precipitation is produced. To gain this insight, we examine the three-dimensional structure of the storms producing intense monsoon precipitation. For this we turn to meteorological radar. Narayanan (1967) foresaw radars as providing ‘better insight into the intricacies of the hitherto hidden phenomena of monsoon clouds’...’ Specifically, we analyze data from the satellite-borne Precipitation Radar (PR) on the Tropical Rainfall Measuring Mission (TRMM) satellite (Kummerow et al., 1998; Kummerow et al., 2000). The satellite-borne radar is especially well suited for determining storm structure in mountainous regions since it points downwards from high altitude. It can detect precipitation (with a horizontal resolution of ~5 km) both over peaks of terrain and within valleys, which would be blocked from the view of a ground-based radar (Joss and Waldvogel, 1990). The TRMM satellite’s orbit (which is confined between 36° N and 36° S) results in multiple daily samples of the South Asian region, including the Himalayas. Since its launch in late 1997, the TRMM PR has accumulated a climatological sample of radar data over the monsoon region. Our objective is to use the TRMM PR data to assess the three-dimensional structures of the radar echoes in the Himalayan region in relation to the details of the topography and proximity to surrounding oceans.

2. Data acquisition, processing, and analysis

2.1. Acquisition of the PR dataset

The TRMM data products obtained for this study were the qualitative rain characteristics field (TRMM product 2A23) and the gridded, attenuation-corrected three-dimensional reflectivity field (product 2A25). Version 5 of the 2A23 and 2A25 products (Awaka et al., 1997; Iguchi et al., 2000a,b) was used. The rain-type field includes the categorization of the echo as convective or stratiform (see Section 2.3 below). We corrected the 2A23 version 5 data to eliminate the potential misclassification of shallow isolated precipitation, in a manner consistent with one of the updates.
Figure 2. (a) South Asian topography in kilometres of elevation. (b) Rain rate in millimetres per hour averaged over all time, including non-raining periods, for 0.1° × 0.1° grid squares derived from TRMM overpasses from 1998 to 2004.

2.2. Remapping the PR data

To analyze the precipitation processes in the monsoon convection documented in this study, we used software designed to easily display and assess the TRMM PR data. The primary visualization tool was MountainZebra (James et al., 2000), a specialized version of the NCAR Zebra software (Corbet et al., 1994), which permits visualization of the data overlaid on detailed topography.

MountainZebra requires a Cartesian grid structure as input, thus the non-Cartesian native PR data (Kummerow et al., 1998) required remapping to a regular latitude–longitude grid. The data were remapped to Cartesian grid points separated by 250 m in the vertical and 0.05° (approximately 5 km) in both latitude and longitude. Prior to remapping, small corrections were applied to the geolocation of upper-level data as follows. The PR has a beamwidth of 0.71° and a scan angle of ±17°, resulting in a swath width of 247.25 km and a horizontal ground resolution of 5 km at the orbital

employed in the current version 6 of this product, described at the Japanese Space Agency (NASA) TRMM website (http://www.eorc.nasda.go.jp/TRMM/document/pr_manual/pr_manual_v6.pdf). Since we applied this correction, updating to version 6 would have had no effect on the results of this study. The 2A23 and 2A25 data contain the orbital time and geolocation data (latitude and longitude coordinates) used in this study. For further discussion of these TRMM products, see Schumacher and Houze (2003a,b) and Houze et al. (2004).

The TRMM PR dataset is obtainable via the NASA Distributed Active Archive Center (DAAC) website (http://disc.gsfc.nasa.gov/). However, in order to reduce the volume of data, we obtained reprocessed subsets of the 2A23 and 2A25 data directly from NASA (Erich Stocker, personal communication) that included partial orbit files containing only the data from our region of study.
height of 402.5 km. (The TRMM altitude was boosted from 350 km to 402.5 km in August 2001.) The PR data were collected in 49 angle bins separated by 0.71° (Figure 3(a)). The observable vertical range of the PR extends from the surface (with surface clutter removed by the rain profiling algorithm) to a height of 19.75 km above the earth ellipsoid (surface of an idealized ocean-covered earth). Both the 2A23 and 2A25 algorithms assign the geolocation for each ray to the position of the range bin at the earth ellipsoid for that ray. Thus, all range bins of the reflectivity data in each angle ray are referenced to the same coordinate pair at the earth ellipsoid, despite the angular offset (Toshio Iguchi, personal communication). At nadir, there is no offset; however, the offset increases as the angle from nadir increases, with those bins at the highest altitude having the most significant offset. Our data processing involved shifting the nominal latitude and longitude coordinates of the bins above the earth ellipsoid to allow for this offset, such that the coordinates in space correspond to the surface coordinates vertically below the bin (Figure 3(b)). These corrected locations were the first step in remapping the data into a regularly spaced three-dimensional Cartesian grid for viewing in Zebra and for other calculations.

To complete the remapping, we emulated the three-dimensional interpolation method employed by REORDER, a method often used with airborne radar systems (Oye and Case, 1995). However, we also take advantage of the regularity in the retrieved data in terms of the distance from the satellite and the small along-beam sample depth (range bin). Our approach is an adaptation of the Cressman (1959) method, which employs a radius of influence $N$. However, we use a small radius of influence ($N = 4.25$ km), which is small enough to retain most of the detail of the recorded data, while minimizing gaps in the Cartesian-gridded field. The remapped value for radar reflectivity at a grid point at a given height incorporates the data within a horizontal radius of 4.25 km for height bins both at and immediately above and below the level in question. That is, data in a 0.75 km-deep layer centred on the height of the grid point are considered to determine the remapped value of reflectivity at the grid point. The echo features we examine in this study are of a sufficiently large scale that any slight smoothing that results from this remapping procedure has no effect on the conclusions we draw from the TRMM PR data. Details of our remapping method are in the Appendix.

2.3. Methods of analyzing the radar data

2.3.1. Using radar echoes to indicate precipitation processes

Houze (1997) has described the microphysical and dynamical differences between the convective and stratiform components of a precipitating tropical cloud system, and methodology exists for objectively separating radar echoes into convective and stratiform components (Churchill and Houze, 1984; Steiner et al., 1995; Awaka et al., 1997). The TRMM PR rain-type fields in product 2A23 have been subjected to a separation algorithm based on these methods, and we use the separation provided by this product as our first-order subdivision of the data. We further identify certain extreme degrees of convective and stratiform structure to select the best defined examples of these echo types in Himalayan monsoon convection.

2.3.2. Analysis of convective echoes: definition of intense convection

To analyze the characteristics of convective radar echoes, we examine only those echoes identified by TRMM product 2A23 as convective. An intense convective echo is defined as a subvolume of a convective echo consisting of an array of contiguous Cartesian bins with reflectivity

Figure 3. Approximate geometry of TRMM overpass. (a) TRMM satellite orbit altitude of approximately 400 km with 17° scan width (0.71° beam width) results in 49 angle bins and 80 height bins in the lowest 19.75 km, indicated by near-vertical lines at the bottom of the figure. (b) Exploded view of the inset square in (a), showing off-nadir bins. Arrows indicate the corrected reference position for the three outer beams at three different heights. Note that no correction is needed for the nadir position, and the amount of correction increases with angle from nadir and altitude.
≥40 dBZ. Defined in this way, intense convective echoes may comprise either single or multiple convective ‘cells’, as identified by discrete, vertically oriented reflectivity maxima occurring on the scale of individual buoyant convective updrafts. Often, the intense convective echo consisted of 40+ dBZ echo conjoined only at some level, usually at lower levels. Since stratiform echo was eliminated by the 2A23 algorithm, stratiform brightband returns did not affect the identification of intense convective echoes.

For purposes of analysis and discussion, two special categories of intense convective echoes are defined: deep and wide. Deep intense convective echoes are those for which the top heights of the 40+ dBZ echo volume exceed 10 km. Wide intense convective echoes are defined as those with horizontally contiguous regions of 40 dBZ echo exceeding 1000 km² in area at some altitude. The altitude of the areal maxima ranged from 1.0 km to 4.5 km amsl.

Echoes with intense convective components classified as deep or wide were further examined with the aid of MountainZebra. The 117 deepest and 121 widest intense convective echo cases were subjected to detailed analysis.

2.3.3. Analysis of stratiform echoes: definition of a broad stratiform area

The locations and sizes of stratiform areas were determined by finding contiguous grid areas that were classified as stratiform precipitation by the 2A23 algorithm. We applied no reflectivity thresholds to the data. However, the PR has a rather low sensitivity and can detect only reflectivities in excess of approximately 17 dBZ (Kummerow et al., 1998). A broad stratiform area in the PR data was defined as a stratiform echo region exceeding 50 000 km² in horizontal extent.

2.4. Ancillary datasets

Both intense convective echoes and broad stratiform areas were analyzed visually with the aid of MountainZebra to assess their vertical structures in relation to ancillary synoptic and satellite data. Climatological wind plots (Figure 1) were obtained though the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) global reanalysis dataset (Kalnay et al., 1996). Individual synoptic maps were generated for us by the Indian National Centre for Medium Range Weather Forecasting (NCM-RWF) from their global T80 model. These reanalyses incorporated regional data exclusive to the NCM-RWF (Rajagopal et al. 2001; Goswami and Rajagopal 2003). Sounding data were obtained through the University of Wyoming (http://weather.uwyo.edu/upperair/). Visible and infrared satellite imagery from Meteosat-5 were obtained from the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT, http://www.eumetsat.int/). Lightning flash data from the Lightning Imaging Sensor (LIS; Christian et al., 1999) on board the TRMM satellite were obtained via the Global Hydrology Resource Center (GHRC; http://ghrc.msfc.nasa.gov/ghrc.html).

3. Locations of extreme precipitation events relative to the Himalayas

Figure 4 shows the locations of deep and wide intense convective echoes and broad stratiform echoes over the two monsoon seasons of this study. The data are from all TRMM overpasses for which the PR swath included at least a portion of the three rectangles shown in the figure and referred to here as the western, central, and eastern subregions.

Figure 4. Regional distribution of (a) deep intense convective echoes (40 dBZ echo >10 km in height), (b) wide intense convective echoes (40 dBZ echo >1000 km² in area), and (c) large stratiform areas (>50 000 km² in area). The rectangles indicate locations of western, central, and eastern Himalayan subregions. The terrain height categories are: lowland 0–300 m, foothills 300–3000 m, mountain >3000 m.
3.1. Occurrence of intense convection as a function of distance from the barrier

The southwest monsoon undergoes intraseasonal variations known as active and break periods (Webster, 1987b; Webster et al., 1998; Lawrence and Webster, 2002; Wang et al., 2005; Webster, 2006). It also undergoes day-to-day fluctuations. However, the daily wind patterns throughout the season retain a persistent gross similarity to the climatological mean (Figure 1). When deep convection occurs during active periods in the regions shown in Figure 4, the low-level moist flow (Figure 1(a)) tends to underrun dry flow coming off the Afghan or Tibetan Plateau.

Carlson et al. (1983) described how ‘a particular configuration of topography and air flow can produce a low-level restraining inversion or “lid” which focuses the location and even enhances the intensity of severe local storms’. While capping inversions had ‘often been attributed to subsidence’, the Carlson et al. model ‘demonstrated that the lid may originate from differential advection of a hot, dry mixed layer from an elevated plateau over a cooler, moister layer’. Sawyer (1947) presented a similar interpretation of the environmental factors affecting monsoon convection occurring over northwestern India. He analyzed soundings from ten days (23 August–1 September) of the 1945 monsoon, and inferred that the low-level moist layer of air entering India from the southwest (Figure 1(a)) underran dry continental air advected off the Afghan or Tibetan Plateau (Figure 5(b)). According to this idea, the dry air flowing off the high plateau caps the moist layer and provides a lid, which allows the low-level southwesterly flow with high moisture content to build up extreme buoyancy via sensible heat fluxes as the air moves over the flat desert region of the northwestern subcontinent. The lid effectively delays the release of the deep convective instability. Sawyer and Carlson et al. pointed out that intense convection may occasionally break through the lid or break out along the lid edge (Figure 5(c)).

In the case of severe convection over the US High Plains, as analyzed by Carlson et al. (1983), deep convective updrafts are frequently triggered near a ‘dryline’, where the top of the moist layer intersects the sloping terrain (Bluestein 1993, pp. 282–290). By analogy, we might expect intense deep convection to break out just upstream of or over the lower portion of the mountain barrier, as seems to be the case in Figures 4(a) and (b), and as will be shown statistically in Section 7. Dryline-type convection, however, breaks out only when the stable lid is subjected to organized lifting (e.g. the upward motion ahead of a short-wave trough). By analogy, in the Himalayan region deep convection might thus be expected to erupt where the potentially unstable column defined by the previously capped moist monsoonal layer underrunning the warm dry layer is subjected to orographic lifting. Such lifting would be expected directly over the foothills (in connection with upslope flow) or immediately upstream of the mountain barrier towards which the moist layer is flowing, by diurnal processes interacting with the larger-scale flow, or as a result of blocking effects extending well upstream of the barrier (Grossman and Durrant, 1984).

3.2. West–east variability in the occurrence of intense convection

Figure 4(a) shows the locations of deep intense convective echoes. They occur occasionally over the extremely high terrain of the Tibetan Plateau, in the eastern and central subregions. However, both deep and wide intense convective echoes are most frequent in the western subregion, especially within the concave indentation at the northwestern end of the Himalayan range (Figures 4(a) and (b)). The occurrence of the most intense convection in the northwestern indentation of the Himalayas is consistent with the results of Barros et al. (2004), who showed a strong maximum of lightning frequency in that region (Figure 6). The concentration of the deep and wide intense convective echoes in the northwestern indentation of the Himalayan barrier suggests further that the complex shape of the mountain barrier may play a role in the distribution of intense convection. The concave indentation in the western subregion may be the natural preferred end point of trajectories of the Arabian Sea air heated by passage over the desert. Alternatively, the concave indentation in the barrier may affect the flow in a way that concentrates low-level convergence in the region of the indentation, as in the case of precipitation maxima in concave indentations on the Mediterranean side of the European Alps (Frei and Schär, 1998).

Figure 4(b) shows the locations of the wide intense convective echoes, which consist of groups of intense cells comprising portions of mesoscale convective systems (MCSs; Houze, 2004). Similar to deep intense convective echoes, the wide ones concentrate in the northwestern indentation (cf. Figures 4(a) and (b)). However, the wide intense convective echoes tend also to occur in the central subregion, in front of the central, convex, steep, wall-like Himalayan barrier.

3.3. Occurrence of broad stratiform events relative to terrain

Figure 4(c) shows that the broad stratiform precipitation events occur primarily in the eastern and central subregions, roughly at the terminus of the axis of mean southwestern low-level flow, in the zones of rapidly rising terrain immediately northeast and northwest of the Bay of Bengal (Figure 1(a)). They are clustered upstream of the mountain barrier and are grouped within a concave indentation in the mountain barrier. Compared to the western subregion, where low-level flow from the Arabian Sea experiences a long passage over the desert, the mountain barrier and the sharp indentation of lower terrain extending northwards from the Bay of Bengal between the Himalayan Barrier and the Arakan Mountains of Myanmar, are much closer to where the monsoon flow makes landfall. The preferential occurrence of well-defined stratiform regions in the northeastern subcontinent suggests...
Figure 5. Sawyer’s (1947) conceptual model of the monsoon environment over the northwestern subcontinent, as observed during 23 August–1 September 1945. (a) Synoptic and orographic context. The wide arrow indicates the general direction of the low-level monsoon flow. The cross-sections in (b), along AB, and in (c), along CD, are traced from the original paper.

Figure 6. TRMM Lightning Imaging Sensor (LIS) data (flashes per square kilometre per day) averaged for June–September 1998–2004. That convective cloud systems upstream of the mountains in this region retain a maritime character. Schumacher and Houze (2003a) showed that the stratiform component of tropical rain tends to be substantially greater over oceans than over land.

In addition, the convection in the eastern region occurs primarily in conjunction with synoptic-scale Bay of Bengal monsoon depressions (Ramage, 1971; Rao, 1976; Godbole, 1977; Sikka, 1977; Shukla, 1978; Sanders, 1984; Johnson and Houze, 1987; Douglas, 1992a,b). These depressions occur in conjunction with the advance of the active monsoon into the northernmost Bay of Bengal (Lawrence and Webster, 2002; Wang et al., 2005). The highly stratiform character of the clouds and precipitation in one such depression was documented by aircraft
radar and microphysical measurements in the Summer Monsoon Experiment of 1979 (Houze and Churchill, 1987).

4. Vertical dimensions of intense convective echoes

Altogether, 117 deep intense convective echoes (as defined in Section 2.3.2) were observed in our TRMM PR dataset (see Wilton, 2005, Appendix B, Table B.1, for details on the times and locations).

4.1. Example of a deep intense convective element over lower terrain

An example of a deep intense convective echo forming at the boundary of the low-level moist flow from the Arabian Sea and large-scale leeside downslope dry flow from the Afghan Plateau (Section 3.1) occurred in northwestern India at ~0900 UTC 14 June 2002. The flow resembled the climatological patterns in Figure 1 (Figures 7(a) and (b)). The low-level (10 m) winds show southwesterly flow entering northwestern India/Pakistan from the Arabian Sea, coming ashore and crossing the inland desert in a strong pulse. The deep intense convective echo occurred near the terminus of this moist low-level southwesterly jet (star in Figure 7), and at the southern edge of the midlatitude westerly jet (Figure 7(b)). The 10 m winds indicate that northwesterly flow (on a dry downslope trajectory from the Afghan Plateau) met the southwesterly moist monsoon flow near the deep intense convective echo. Since these maps are for the afternoon (1200 UTC = 1730 local standard time, LST), it is unlikely that the downslope flow was due to the diurnal heating cycle over the plateau (Murakami, 1987).

Soundings at 0000 and 1200 UTC (9 h prior to and 3 h after the TRMM overpass in which the deep intense convective echo was observed) were consistent with the observed convective development (Figure 8). The soundings in Figure 8 display the two-layered structure described in Section 3.1, as a low-level moist layer originating over the Arabian Sea underran dry warm air advected downstream from the Plateau, in the manner described by Sawyer (1947) and Carlson et al. (1983). The sounding at Patiala at 0000 UTC (Figure 8(a)) showed relatively large convective available potential energy (CAPE; Houze 1993, chapter 8) of 2700 J kg$^{-1}$.

Figure 9 shows the TRMM PR reflectivity associated with the deep intense convective cell at 0900 UTC (1430 LST) 14 June 2002. The vertical section shows that the cell was over 18 km in height, and that the 40 dBZ echo reached 16 km. Also notable is the vertical alignment (erect structure) of the deep intense convective echo, as opposed to the more tilted structure often associated with robust thunderstorms and squall lines (Houze, 1993, chapters 8 and 9). The erect cell structure in Figure 9(b) is consistent with the wind data showing little shear at the convective location well south of the core of the midlatitude westerly jet (Figure 7(b)). We have found this vertically upright structure of deep intense convective cells to be a ubiquitous aspect of TRMM PR data in northern India, consistent with the fact that the convection over and just upstream of the Himalayan barrier occurs generally in a region of weak shear, south of the upper-level westerly jet and north of the upper-level easterly jet (Figure 1(b)). The topography of the subtending terrain, shown in red at the bottom of Figure 9(b), further confirms that this convective event was clearly not triggered directly over the mountains.

4.2. A deep intense convective element over high terrain

While most monsoon convection occurs just upstream of or over the lower slopes of the Himalayas, deep intense convective echoes do occur occasionally over the high terrain of the Tibetan Plateau (Figure 4(a)). Wide intense convective echoes were generally not observed over the Plateau (Figure 4(b)), indicating that the convection over the Plateau tends to be unable to develop mesoscale organization, possibly because of insufficient moisture in the environment (generally <5 g kg$^{-1}$ of water vapour; Wang and Gaffen, 2001). We suggest that the semi-arid conditions over the southern portion of the Plateau (the part included in our study) are adequate to support...
the occurrence of occasional single deep intense isolated convective cells but inadequate to support a cloud system of greater breadth. Convection over the Plateau tends to be scattered cells, mostly isolated but sometimes aligned. An example of convective echoes over the Plateau (Figure 10(a)) shows that intense convective echoes (including deep ones, with 40 dBZ extending above 10 km) occur over the Plateau and look similar to the echoes over the lowlands and foothills except that their lower portions are truncated (Figures 10(b) and (c)).

4.3. Statistics of heights of intense convective echoes

Figure 11(a) shows the cumulative frequency distribution of the heights of all the identified intense convective echoes for the 2002 and 2003 monsoon seasons. The bulk of the intense convective echoes in all subregions...
are below the 0 °C level, which is generally located between 5.5 and 6.0 km over the study region. Since 40 dBZ is not the highest reflectivity found in the intense convective echoes, this result is consistent with the findings of Maheshwari and Mathur (1968) who found that the maximum reflectivity in Indian monsoon convective storms was generally at or below the 0 °C level. This figure also demonstrates that the eastern subregion has more frequent occurrence of 40 dBZ echo top below the 0 °C level. The occurrence of the echo maximum at low levels is a typical characteristic of convective precipitation in airmasses of maritime-tropical origin (Caracena et al., 1979; Szoke and Zipser, 1986; Szoke et al., 1986). The eastern subregion, being closer to the sea, evidently had convection resembling that over tropical oceans.

Although the intense convective echoes most frequently have tops below 5 or 6 km, a surprisingly large number of the 40 dBZ echo tops over northern India can reach extremely high levels. Seshadri (1963) and Ghosh (1967) studied echoes observed by ground-based radar at Delhi and found echoes occasionally reaching 17 km. To focus on the deeper echoes seen by the TRMM PR, Figure 11(b) shows only those 40 dBZ intense convective echoes with tops at or above 10 km. The occurrence of these high reflectivities in the upper-level ice region are likely explained by the presence of larger ice particles, which may be too large to be in the Rayleigh scattering regime for the 2 cm wavelength of the TRMM PR. Graupel particles of the order of 1 cm in diameter are evidently lofted to high altitudes by extremely strong updraughts in these cases. Rayleigh scattering requires the particle size to be much less than the radar wavelength. It is further evident from Figure 11(b) that the highest frequency of very deep 40 dBZ intense convective echoes occurs in the western subregion, with some intense convective echo-top heights extending to over 16 km! This region is far from the ocean, and the convection is of a more continental nature, with stronger updraughts. The convection
in this region is known for its intensity and high frequency of lightning, as noted by Barros et al. (2004) (Figure 6).

5. Horizontal dimensions of intense convective echoes

Altogether 121 of the intense convective echoes included in this study qualified as wide intense convective echoes (as defined in Section 2.3.2). Generally these echoes are complexes of interconnected echoes, which can be regarded as MCSs.

5.1. Example of a wide but amorphous intense convective element

A wide intense convective echo occurred in the concave indentation of the northwestern end of the Himalayas at ~1300 UTC 22 July 2002. Figure 12 shows the synoptic conditions on that day. Similar to the climatological patterns in Figure 1, a strong low-level southwesterly flow of moist air from the Arabian Sea was crossing the northwest coast of India and extended all the way to the foothills of the Himalayas (Figure 12(a)). The wide intense convective echo (star) occurred in the convergent region north of the terminus of the 10 m southwesterly flow, between the southwesterly flow and dry downslope flow from the north. Similar to the case described in Section 4(a), this convection occurred in the local afternoon, and dryline-type behaviour is suggested by the 10 m flow and its relation to the adjacent steeply sloped terrain. From the 200 mb winds (Figure 12(b)), it appears that the flow was again south of an upper-level westerly jet, and that the shear was not especially strong.

Soundings prior to the wide intense convective echo at Jodhpur resembled those of a classic severe storm situation over the Great Plains of the USA (Fawbush and Miller, 1954; Newton and Funkhauser, 1964; Palmén and Newton, 1969; Bluestein, 1993, pp. 448–451). These soundings indicated a strong capping inversion atop the moist boundary layer (Figure 13). The strength of the capping inversion lessened from 0000 to 1200 UTC and thus evolved towards a sounding where vigorous convection was more likely to break out. These soundings are consistent with upper-level warm dry flow from the Afghan Plateau overriding the low-level moist monsoonal flow and providing a cap that allows the low-level warm moist flow from the Arabian Sea to build up instability as it moves farther inland until being released by convergence directly over or just upstream of the Himalayas.

At 1300 UTC (1830 LST), the TRMM PR detected a wide intense convective echo over the plains of the northwestern subcontinent, within the concave indentation of the Himalayan barrier (Figure 14(a)). The 40 dBZ echo covered 3475 km² at an altitude of 3.5 km. It contained multiple more intense cells in its interior. However, it showed no elongation to form an echo band, nor was it part of an organized line of similar echo structures. In plan view, it was amorphous.

The vertical cross-section in Figure 14(b) shows about six vertically oriented cells (best identified by their protruding tops in the 30–35 dBZ contour range). These cells were vertically erect and packed close together to form a contiguous 40+ dBZ echo over a horizontal distance of ~90 km. The vertically erect structure of the cells seen in this case was typical of all the embedded cells of all the wide convective echoes that we have examined, consistent with the generally weak shear in this region during the monsoon. The cells could have been still growing or beginning to collapse. In either case they were likely headed toward formation of a stratiform region later in the lifetime of the complex of cells, in the manner normally expected as cells weaken in a MCS (Gupta et al., 1955; Houze, 1993, 1997, 2004).

Of the 121 wide intense convective echoes observed in this study, 20 (including the example above) were also classified as deep convective echoes. Fourteen of those doubly intense cases (i.e. both deep and wide) were located in the western subregion; only six were located in the central subregion, while no echoes in the eastern subregion were simultaneously classified as both deep and wide.
5.2. Examples of wide intense convective echoes with line organization

On some occasions, the wide intense convective echoes showed line organization. One recurring type is illustrated by Figure 15. A contiguous line of high-reflectivity echo roughly paralleled the steep Himalayan barrier. A cross-section along the convective line showed vertically erect cells (consistent with the weak shear) interconnected by strong (>40 dBZ) echo (Figure 15(c)). Stratiform echo is located along the northern red line in Figure 15(a). The vertical cross-section in Figure 15(b) shows bright-band echo surrounding a convective cell (at 85 km on the horizontal scale). The stratiform echo was likely formed as cells similar to the one at 85 km collapsed. The history of the echoes cannot actually be determined because the TRMM PR provides snapshot coverage only 2–3 times per day over the region of study.) The stratiform precipitation likely existed as the vertically erect cells collapsed. Collapse of convective echo cores is a well-known process of generating areas of stratiform precipitation in MCSs in low-shear environments (Houze, 1993, 1997) and had been noted in India by Gupta et al. (1955).

The central subregion is the only zone of our South Asian study area in which we have noted propagating arc-shaped leading-line/trailing-stratiform squall-line MCS structure. (Squall lines may be more common in the pre-monsoon season, when the westerly jet is positioned farther south, and the shear is greater; however, these early-season storms would be excluded from our study since we are considering only the monsoon months.) These squall lines are not as well developed as those over the central USA (Houze et al., 1989, 1990) or west Africa (Hamilton and Archbold, 1945; Fortune, 1980; Houze and Betts, 1981; Hodges and Thorncroft, 1997; Schumacher and Houze, 2006), where stronger shear prevails. An example in northern India is shown in Figure 16. It exhibits an arc-shaped line roughly perpendicular to the steep wall of the main Himalayan barrier. The bow of the line in Figure 16(a) was pointing generally to the southeast. Time-lapse looping of Meteosat-5 infrared satellite imagery shows that this system was propagating southeastwards, in the direction of the convex bow of the line. The PR data show that a stratiform echo was trailing behind, giving the echo a classic squall-line structure (Figure 16(b)). This day was unusual in that a strong midlevel jet lay over and parallel to the Himalayan barrier (Figure 17(b)). This jet lent the convection a sheared environment and apparently played a role in organizing a rear-inflow jet (Smull and Houze, 1987), in the way that the midlevel African Easterly Jet helps to organize squall lines in West Africa. The midlevel jet seen in

Figure 13. Rawinsonde data in skew $T$–$\log p$ format for Jodhpur, India, on 22 July 2002 at (a) 0000 UTC and (b) 1200 UTC, from the same source as Figure 8.

Figure 14. As Figure 9, but for 1309 UTC 14 June 2002.
Figure 15. TRMM PR reflectivity for 2208 UTC 3 September 2003. (a) Horizontal pattern at 4 km. (b) and (c) contain vertical cross-sections running left to right along northern and southern red lines in (a), respectively. Other details are as in Figure 9.

Figure 16. As Figure 9, but for 2017 UTC 5 June 2003.

Figure 17(b) persisted for three days, and squall lines occurred in the pre-Himalayan channel on each day. In our data sample, we found one additional instance of a similar squall line occurring along the Himalayas in an analogous synoptic regime, with a midlevel jet overlying the Himalayan escarpment. Apparently the convection favoured in the region just upstream of and over the foothills of the Himalayas can become organized into a propagating squall line in conjunction with these relatively rare synoptic events exhibiting strong shear.

5.3. Statistics of the horizontal dimensions of intense convective echoes

Figure 18(a) shows the cumulative distribution function of the horizontal area of 40+ dBZ intense convective echoes. This sample was extracted from the set of all intense convective echoes observed by the TRMM PR over the western, central, and eastern subregions during the 2002 and 2003 summer monsoon seasons. The average height at which the areal maximum was located was approximately 2.5 km. The highest altitude at which the areal maximum occurred was 4.5 km. These heights are below the melting level and consistent with the low-level echo centroid heights found by Szoke et al. (1986) and Szoke and Zipser (1986) in tropical maritime convection and with the results of the analysis of ground-based radar in India by Maheshwari and Mathur (1968). The wide areas of convection were all classified as convective precipitation by the 2A23 algorithm, thus eliminating the possibility that the horizontal scale of the echoes could have been determined by radar bright-band echoes. The portion of Figure 18(a) including echoes >1000 km² is replotted in Figure 18(b), which shows that widest areas of convection exhibited a higher frequency of occurrence in the western subregion, with a tendency to decrease eastwards. This same regional behaviour was noted for intense convective echo height (cf. Figure 11(b)).

6. Characteristics of stratiform echo regions in the monsoon

We have intensively investigated the 10 largest broad stratiform regions (as defined in Section 2.3.3) in our
dataset. Of these, six were associated with well-defined monsoon depressions. The remaining four were associated with what we would call quasi-depressions, which had all the characteristics of a Bay of Bengal depression except that the vortex in the low-level wind was not completely closed.

6.1. Example of a broad stratiform region in a Bay of Bengal depression

Figure 19 is a composite showing how the Bay of Bengal depression is connected with the monsoon intraseasonal oscillation (Webster, 2006). The four panels show the progression over a 13-day period. Day 0 is defined as the occurrence of 10 mm day$^{-1}$ of rain at 90$^\circ$E. The cyclonic gyre over the head of the Bay of Bengal on day 8 (Figure 19(d)) has propagated northeastwards into the Bay of Bengal as part of an equatorial Rossby wave. The arrival of the gyre in the northernmost portion of the Bay marks the onset of an active monsoon period.

On 11 August 2002, the PR detected a broad stratiform region in connection with such a Bay of Bengal depression. The large-scale flow (Figure 20) broadly resembles the climatological patterns in Figure 1. In the low-level winds (Figure 20(a)), the Bay of Bengal depression was centred at the head of the Bay (about 22$^\circ$N, 90$^\circ$E). The sounding for Tengchong (Figure 21, station location in Figure 20(a)) shows saturated moist adiabatic conditions through the troposphere. This sounding typifies the upper-air conditions in the depressions we have examined.

Figure 22(a) shows the radar echo sampled during a TRMM PR overpass of the Bay of Bengal depression. The PR echo (250 km $\times$ $\sim$500 km) represents only a small portion of the overall cloudy region associated with the depression. The areas of enhanced upper-level cloud and their associated radar echoes in the depressions never take on the synoptic-scale dimension of the depression. They appear to be MCSs embedded within and probably abetted by the parent Bay of Bengal depression. The widespread upward motion of the synoptic system evidently destabilizes the air and provides a moist environment favourable for MCSs. The distribution of MCS-like structures within the depression was reminiscent of the highly stratiform MCSs analyzed by Houze and Churchill (1987). The flow over the terrain likely enhances these mesoscale precipitation areas. Figure 22(b) exemplifies how the mesoscale precipitation features on the north side of the depression often tend to nestle into the eastern concave indentation of the Himalayan range, where large stratiform echoes occur most frequently (Figure 4(c)). The stratiform precipitation echo appears to have been composed of weakened convective cells (Figure 22(c)). This structure was typical of the mesoscale precipitation areas in all the depressions we have examined in
Figure 19. Evolution of the rainfall and 925 mb wind field of the monsoon intraseasonal oscillation. Rainfall is based on Microwave Sounding Unit data. Winds are based on NCEP reanalysis. Composite of 39 events from 1985 to 1995. (a)–(d) show composite distributions relative to day 0, defined as the occurrence of >8 mm day$^{-1}$ rainfall at 80–90°E/5°N–5°S persisting for three days. The numbers in the upper left of each panel indicate the number of days before (negative) and after day 0. The annual cycle has been removed. Adapted from Webster and Tomas (1997).

The PR data, whether the precipitation features were over the sea, the lowlands, or the foothills of the Himalayas. Occasionally they contained active, deep convective echo cells, which apparently later collapsed to form the broader background of stratiform precipitation (Houze, 1997), and active deep cells only occupy a small fraction of the rain areas at any given time. (The existence of ‘generating cells’ associated with a layer of convective overturning aloft, as is frequently seen in midlatitude cyclones, cannot be ruled out as an alternative explanation for the observed echo structure. In the tropical oceanic environment, where the convection in the depression takes the form of discrete MCSs, it seems more likely that the echo pattern is a manifestation of collapsed deep penetrative convective cells.)

Figure 19 shows how the cyclonic gyre within the overall low-level wind pattern of the Rossby wave structure that propagates into the Bay of Bengal typically induces strong southwesterly winds across the Myanmar coast. Zuidema (2003) showed that clouds tend to concentrate upstream of the coast, as they do upstream of the western Ghats and other mountain ranges of the region (Grossman and Durran, 1984; Xie et al., 2006).

A large number of the mesoscale patches of enhanced high cloudiness in Figure 22(a) are south of the depression centre within the low-level southwesterly regime upstream of the Myanmar coast. The strong upper-level easterlies prevailing at this comparatively low latitude are producing streamers of westward anvil blow-off from the precipitating cloud lines off Myanmar. A PR observation of some of these precipitation echoes over the northern Bay of Bengal is shown in Figures 23(a) and (b). A vertical cross-section shows convective echo cells of rather moderate depth, some of which have collapsed into stratiform echo (Figure 23(c)). Zuidema (2003) also found the clouds upstream of the Myanmar coast to be of small to moderate depth and width in comparison to the overall population of clouds seen in infrared imagery of the region.

6.2. Statistics of stratiform area sizes

Figure 4(c) showed that broad stratiform regions, i.e. the largest stratiform regions, preferentially occur in the eastern subregion. The cumulative distribution in Figure 24 further shows that stratiform areas of all sizes
tend to be more frequent in the eastern subregion, where synoptic forcing by Bay of Bengal depressions and proximity to the ocean should both favour the development of MCSs with larger stratiform precipitation areas.

7. Probability distributions of Himalayan region radar echoes

Figure 25 is a Contoured Frequency by Altitude Diagram (CFAD; Yuter and Houze, 1995) containing the non-interpolated TRMM PR 2A25 radar reflectivity values for the entirety of the 2002 and 2003 monsoon seasons and inclusive of all three subregions (west, central, and east). The contours represent the frequency of occurrence of a given reflectivity at a given height, \( f(\text{dBZ}, z) \). The entire distribution was normalized by dividing by the maximum absolute frequency of the samples within the region of analysis, \( f_{\text{max}}(\text{dBZ}, z) \). Thus, the contours are labelled in values of \( f/f_{\text{max}} \). This method permits the comparison of CFADs between regions despite the different absolute frequencies. The contours are truncated at lower reflectivity values as a result of the reduced sensitivity to low rain rates of the TRMM PR.

Figure 25 is characterized by three statistically distinct regimes, viz. those located above, at, and below the climatological 0 °C level (~5.5–6). Below the 0 °C level, the echoes are produced by raindrops and have a median reflectivity of ~25 dBZ (corresponding to a rain rate of about 1–2 mm h\(^{-1}\)). The wide spread of the distribution below the 0 °C level is consistent with rain falling from convection in various stages of development. Above the 0 °C level, in the ice region, the median reflectivity value is ~20 dBZ. At (or actually just below) the 0 °C level, the tendency for a melting-layer bright band to occur in the echoes is evident in the statistics in the form of a distinct rightward shift in the CFAD contours toward higher dBZ values at ~5 km. Subsequent CFADs add detail to the regional trends evident in Figure 4 by breaking down the CFAD statistics by subregion, rainfall type, and terrain height.

When the CFADs are further subdivided according to precipitation type (Figure 27), the regional differences become even more evident. The convective echoes (Figure 27(a) and (b)) showed a tendency to have both higher overall reflectivity values and higher reflectivities at upper levels in the western region. The CFAD contours indicate the occurrence of up to 40 dBZ echo at 12 km in the west, while 40 dBZ echoes are statistically evident only to about 9 km in the eastern subregion. The stratiform partitions (Figures 27(c) and (d)) show a more pronounced bright-band signature in the more maritime regime of the eastern subregion.

When the CFADs are stratified according to subtending terrain, they show that convection over the lowlands tended to be slightly deeper than that over the foothills in all three subregions (Figure 28(a)–(f)). Evidently, the net effect of the Himalayan range in triggering convection was most pronounced over the lowlands just upstream of...
Figure 22. TRMM PR reflectivity for 0252 UTC 11 August 2002. (a) Horizontal swath of PR reflectivity (green and yellow shades) at 4 km is superimposed on the Meteosat-5 infrared temperature field. Grey shades show the infrared temperature in K, with red and yellow shades highlighting the coldest cloud tops. (b) Zoomed-in view of the PR reflectivity in (a). (c) Vertical cross-section running left to right along the black line in (a) and (b). Meteosat-5 data were obtained from http://www.eumetsat.int. Other details are as in Figure 9.

Figure 23. TRMM PR reflectivity for 0455 UTC 11 August 2002. (a) Horizontal swath of PR reflectivity (green and yellow shades) at 2 km is superimposed on Meteosat-5 infrared temperature field. Other details are as in Figure 22.
the mountains. This result suggests that the formation of the most intense convection was focused at lower elevations immediately upstream of the mountains, i.e. near the leading edge of the warm, dry air advected downslope from the Tibetan Plateau, in a manner possibly similar to dryline convective triggering observed in the central USA (Section 3.1). Convection located directly over the foothills, though still strong, already has (on average) lost some buoyancy – conceivably because the near-surface moisture has been removed from the airstream flowing up the terrain. The availability of low-level moisture and ability to form deep convection is apparently nearly completely absent over the higher terrain. The echoes seen in the mountain CFADs (Figure 28(g)–(i)) were composed predominantly of stratiform echo, probably advected from the tops of the lowland and foothill convection.

8. Conclusions

The ability of the TRMM PR to provide vivid and detailed images of the vertical structure of convection in remote regions of complex terrain has given us fresh insight into two longstanding questions:

1. the behaviour of highly convective clouds in a moist flow impinging on a major mountain barrier, and
2. the particular structure and organization of summer monsoon convection over the subcontinent of South Asia.

The first question has general applicability to understanding the role of orography in affecting precipitation, while the second is vital to understanding and predicting monsoon clouds and precipitation. The schematic drawing in Figure 29 suggests some of the conclusions we have drawn from an extensive examination of the vertical structure of Himalayan region convection as seen in the three-dimensional TRMM PR data. The schematic does not depict every observed scenario but rather illustrates scenes typical of each of the subregions.
Figure 27. Contoured frequency by altitude diagram (CFAD) of TRMM PR reflectivity data for June–September 2002–2003 for (a) western subregion convective echoes, (b) eastern subregion convective echoes, (c) western subregion stratiform echoes, and (d) eastern subregion stratiform echoes. Contours and other details are as in Figure 25.

Figure 28. Contoured frequency by altitude diagram (CFAD) of TRMM PR reflectivity data for June–September 2002–2003 for categories of subregion and height of subtending terrain. Contours and other details are as in Figure 25. Terrain height categories are defined in Figure 4.

Our analysis of PR echoes identified by the TRMM 2A23 algorithm as being convective in nature shows that convective echoes >40 dBZ in intensity in the Himalayan region most commonly have tops below the 0°C level, consistent with early studies of radar reflectivity structure in the region (Maheshwari and
Mathur, 1968). Also consistent with early investigations (Seshadri, 1963; Ghosh, 1967), the TRMM PR data occasionally show much more extreme echo heights, and we term echoes of 40 dBZ or more extending above 10 km ‘deep intense convective echoes’. The Himalayan region of this study lies between the upper-level westerly jet to the north and the easterly jet to the south. In this setting of weak winds aloft and weak shear, the deep intense convective echoes usually exhibit no tilt. These vertically erect 40+ dBZ intense convective echoes sometimes extend above 17 km. Such high reflectivity values extending to such extreme altitudes suggests graupel particles of substantial size being lofted to great heights by intense convective updraughts.

The TRMM PR data further show the spatial distribution of extreme convective events. Deep intense convective echoes (40 dBZ echo tops >10 km) occur especially frequently in the western subregion, primarily within the concave indentation in the western end of the Himalayan range. The frequent occurrence of deep intense convective echoes lofting graupel to high altitude in the concave indentation of the Himalayan barrier in the western subregion is consistent with the frequent occurrence of lightning in this region (Barros et al., 2004).

The deepest intense convective echoes tend to be located just upwind of the Himalayas or over the foothills (Figures 4(a), 28). These extremely deep convective events appear to occur where the advance edge of the low-level moist southwesterly monsoon flow from the Arabian Sea meets dry air descending from the adjacent Afghan or Tibetan Plateau (Figure 29(a)). The location of the extremely deep convective outbreaks suggests a possible similarity to dryline convection. The moist southwesterly low-level flow coming from the Indian Ocean is capped by an associated inversion as it underruns dry air advected from the Afghan or Tibetan Plateau. Sawyer (1947) and Carlson et al. (1983) suggested that intense convection may occasionally penetrate this ‘capping inversion’ or (more frequently) break out near the leading edge of the warm, dry air advected in from the elevated plateau, where the lower moist layer is not capped. Our results are consistent with these earlier studies. This scenario is particularly applicable over the northwestern subcontinent, where the moist low-level flow from the Arabian Sea must traverse the hot arid plain of the northwestern subcontinent before reaching the vicinity of the Himalayan barrier. The similarity to some aspects of severe convective formation over the US Great Plains in the region east of the Rocky Mountains suggests a behaviour that is general and repeatable from one region to another.

The prevalent occurrence of the deepest and widest intense convective echoes just upstream of and over the lower elevations of the Himalayas – not over the higher terrain – has been seen in other precipitation regimes, e.g. the western Ghats (Grossman and Durran, 1984) and the European Alps (Houze et al., 2001). However, in the Himalayan region considered here, we also find that the most intense of the convection occurs upstream of and not over the higher terrain. The processes leading to this behaviour in the Himalayan region are likely at least partially different from the processes governing the precipitation in other regions. Volumetric statistical summaries (CFADs) compiled from all the TRMM PR overpasses of the study area show that the convective echoes tend to be slightly deeper and more intense over the lowlands than over the foothills of the Himalayas, indicating that the low-level conditions favouring deep convection are maximized just upstream (i.e. south) of the mountains. Apparently, the full complement of low-level moisture and heat content present over the plains is not present over the foothills and higher terrain, so that the greatest orographic effect on convective precipitation

Figure 29. Schematic illustrations of typical extreme precipitation events in each subregion of the study: (a) A deep intense convective echo in the western subregion, (b) a wide intense convective echo (mesoscale convective system) over the lower terrain of the central subregion and deep intense convective echoes over the plateau, and (c) a broad stratiform precipitation area over the lower terrain of the eastern subregion and a deep intense convective echo over the plateau.
is felt just upstream of the mountain barrier. The dry air off the Afghan or Tibetan Plateau overriding the leading portion of the low-level monsoon flow caps the convection in the region possessing this stratification, and a triggering mechanism is favoured immediately upstream of or over the lower foothills of the mountain range. The triggering might involve upstream lifting (Grossman and Durran, 1984). However, diurnal heating and cooling over the mountain barrier likely play a role in the triggering near the barrier. The exact triggering mechanism is a question to be resolved in future studies.

The intense convective echoes sometimes organize upscale to form wide convective elements in which several cells with vertically erect intense convective echoes become interconnected by weaker echo and cloud (Figure 29(b)). In extreme cases the interconnecting echo is of high intensity (>40 dBZ) and the embedded cells even more intense and very deep. We have called these extreme cases ‘intense convective echoes’, defined as areas of echo exceeding 40 dBZ over a horizontal area >1000 km². Such wide intense echoes are elements of mesoscale convective systems (MCSs; Houze, 2004). In several respects, the geographical pattern of occurrence of the wide intense convective echoes detected by the PR resembles that of the deep intense convective echoes: viz. the preferred location was in the western subregion, and their occurrences were most frequent in the concave indentation of the Himalayan barrier in that region. However, the pattern of occurrence of wide intense convective echoes differs in two respects from that of the deep intense convective echoes as defined in this study:

1. The wide intense convective echoes rarely, if ever, occur over the Tibetan Plateau, whereas isolated deep intense convective echoes do occasionally appear over the Plateau (Figures 29(b) and (c)). Wide MCSs contain large stratiform regions, which are favoured in more oceanic conditions (Schumacher and Houze, 2003a). We suggest that the arid conditions over the Plateau (Wang and Gaffen, 2001) make it difficult for convection to grow easily upscale to form MCSs.

2. The wide intense convective echoes have a tendency to appear in the central subregion, along the convex mid-portion of the steep Himalayan barrier. They most frequently occur along the foothills and just upstream of the steep terrain (Figure 29(b)).

The wide intense convective echoes in our dataset exhibit three repeatable types of structure:

1. Multiple intense, vertically erect cells amassed within a horizontally amorphous mesoscale echo;
2. Several intense, vertically erect cells grouped in a line parallel to the Himalayan barrier, either just upstream of the barrier or over the foothills. As the cells along these barrier-parallel lines weaken, they form stratiform regions within the wide contiguous precipitation feature; and
3. Arc-shaped lines quasi-perpendicular to the Himalayan barrier and propagating towards the southeast with a trailing region of older stratiform echo. These occur only rarely such as when anomalously strong midlevel flow and associated shear becomes aligned with the Himalayan escarpment.

Broad stratiform echoes occur primarily in the eastern and central subregions (Figure 29(c)). They occur primarily upstream of and over the lower mountainous terrain in association with Bay of Bengal depressions. Their centroids are most highly clustered within the concave indentation at the eastern end of the Himalayan barrier. This suggests that the tendency of the depression to promote convection is enhanced by moist flow over the topography of the Himalayas. Vertical cross-sections in MountainZebra show that the broad stratiform echoes in the depression have widespread well-defined bright bands. The appearance of embedded cellular echoes in the detailed cross-sections further suggests that broad stratiform echoes are, at least in part, the product of the weakening of earlier convective echoes, in the manner described by Houze (1997). This latter supposition is difficult to verify in this study since the TRMM PR provides only snapshots. As pointed out by Houze (1993), stratiform precipitation may form in response to convection, if either the convection is tilted by shear or if convective cells repeatedly die out and new cells form in the same mesoscale vicinity. In the latter case, the older, weakened cells coalesce to form a stratiform region in the vicinity of newer, active cells. Since the monsoon convection appears to have been predominantly non-tilted and occurring in a generally weakly sheared environment, it is likely that the stratiform regions were primarily conglomerations of older, weakened cells. Cross-sections such as Figures 22(c) and 23(c) are typical and qualitatively suggest that the bright band is the net result of dying cells.

CFADs show the bright-band signature to be much sharper and better defined in the eastern subregion than in the western subregion. This observation, together with the more frequent occurrence of large stratiform regions in the eastern subregion, suggests that the deep convection in the eastern subregion was of a more maritime character. By contrast, convection in the western subregion was of a distinctly continental nature. The large stratiform regions associated with Bay of Bengal depressions observed over land by the TRMM PR appear to be similar to those previously observed over the Bay (Houze and Churchill, 1987). Apparently these depressions continue to provide a moist maritime monsoonal environment supporting the convection as their parent circulations move over land. In the eastern subregion, the monsoonal flow associated with depressions traverses only rather moist land surfaces before encountering high terrain, in contrast to the low-level southwesterly flow entering northwestern India from the Arabian Sea which must first traverse the extremely hot and extensive desert region of the northwestern subcontinent.
The variations in cloud-system structure from west to east in the Himalayan region described in this study present a useful target for high-resolution numerical models. Model output will provide deeper insight into the orographic, convective, and microphysical precipitation processes of the region than can be determined from remote sensing from space or from the limited surface data in this rugged region. Ultimately, high-resolution models will be tasked with precise operational forecasting of severe monsoon precipitation events.

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Appendix

Algorithm for Remapping the TRMM Pr Data to a Cartesian Grid

The Cressman method, as we have applied it here, employs a first guess, for which we use the nearest neighbour. The correction for the reflectivity Z at a grid point \( i \) is

\[
C_{zi} = - (WE_{zi}).
\]

The subscript \( i \) indicates that this correction is based on the reflectivity values at each data point \( i \) within the 0.75 km layer centred on the grid point and within the horizontal radius of influence \( N = 4.25 \) km centred on the grid point. The variable \( W \) is the Cressman weighting factor, given by

\[
W = \frac{N^2 - d_i^2}{N^2 + d_i^2},
\]

and \( d_i \) is the distance of point \( i \) from the grid point. \( E_{zi} \) is the difference between the reflectivity value of the nearest neighbour, \( Z_{mn} \), and the reflectivity, \( Z_i \), at point \( i \). The interpolated value at the regular grid point is

\[
Z_{grid} = Z_{mn} - \sum_i C_{zi}.
\]

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