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A study of the 1999 monsoon rainfall in a mountainous region in central Nepal using TRMM products and rain gauge observations.

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Abstract. Raingauge data from the 1999 monsoon were compared with precipitation derived from the precipitation radar (PR) and the microwave imager instruments on board the Tropical Rainfall Measuring Mission (TRMM) satellite. The raingauges are part of a new hydrometeorological network installed in the Marsyandi river basin, which extends from the edge of the Tibetan Plateau to the Gangetic basin. TRMM-derived precipitation showed better detection of rain at low altitude stations as compared with high elevation stations, with good scores for the PR product for rain rates > 0.5 mm/hr. The 3D PR rain rates suggest strong interaction between mesoscale convective systems and steep terrain at elevations of 1-2 km, which is consistent with the very high rainfall measured at those locations. Analysis of the raingauge data shows that even at altitudes as high as 4,000 m the cumulative monsoon rainfall is comparable to the highest amount recorded in the Indian subcontinent.

Introduction

Data to study the variability of precipitation and the dynamics of precipitation processes in the Middle and High Himalayas are very scarce. There are no operational weather radars or radiosonde networks and the existing raingauges are generally located along sheltered valley-bottoms. The Tropical Rainfall Measuring Mission (TRMM), which was launched in November 1997 to monitor and study precipitation in the tropics and subtropics provides, therefore, a unique research opportunity in this region.

Here, we report specifically on a study of the 1999 summer monsoon in the Marsyandi river basin in central Nepal. The objectives of the study were to : 1) describe the rainfall characteristics of the 1999 monsoon in the complex orography of central Nepal using raingauge data from a newly installed hydrometeorological network; 2) evaluate the skill of TRMM sensors in detecting rain-producing weather systems, and compare TRMM-derived precipitation with ground observations; and 3) use the 3D TRMM products to learn about the spatial structure of storm systems in the Middle Himalayas during the monsoon.

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The TRMM hydrometeorological network in central Nepal

In the spring of 1999, a network of sixteen meteorological stations was installed at elevations ranging from 500 m to 4400 m from the leading edge of the Himalayas to the accessible headwaters of the Marsyandi river basin in Central Nepal (Figure 1). The names corresponding to the station numbers are in Table 1. High-stand stations that were installed at locations above 2000 m consist of 10 m towers equipped with temperature and relative humidity probes, wind speed and wind direction sensors, a sonic ranger to make snow-depth measurements and a solar panel. Tipping bucket raingauges are on separate stands away from the towers. The low-stand stations consist of 1 m towers with temperature and relative humidity probes, and a tipping bucket raingauge. Both station types have autonomous data-logging systems. To our knowledge this is the first network covering a wide range of elevations and topographic settings in the Central Himalayas.

TRMM precipitation data

Three dimensional precipitation information is obtained from two instruments on board the TRMM satellite: the TRMM microwave radiometer (TMI) and the precipitation radar (PR). The TMI is a 9 channel passive microwave radiometer which records radiation at the 10.65, 19.35, 37.0, 85.5 (V and H) and 21.3 (V) GHz frequencies. The instrument scans along a conical swath with a width of 785 km. The footprints (IFOV's) of the channels range from 35.5 km x 59 km for the 10.65 GHz channel to 6.9 km x 4.2 km for the 85.5 GHz channel [*Kummerow et. al.*, 1998]. Surface rain and hydrometeor profiles are based on the Goddard Profiling algorithm for rainfall retrieval [*Kummerow et. al.*, 1996]. The PR operates at a frequency of 13.6 GHz. The antenna scans at a ±17 degree angle with a 215 km swath width. The range of vertical observation is surface to 15 km. The vertical resolution is 250 m and

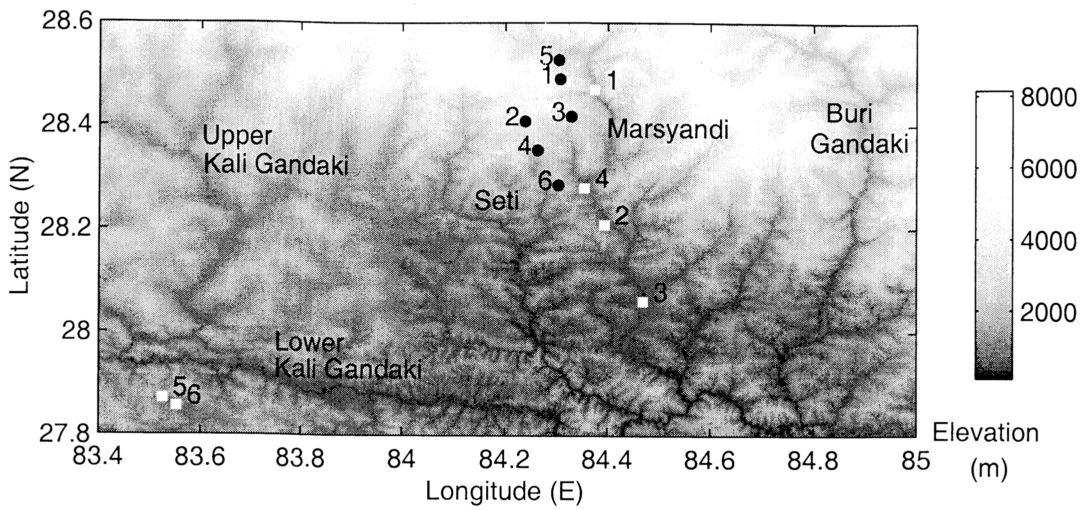

Figure 1. Locations of stations in the hydrometeorological network: high altitude stations are marked by circles and low altitude stations by squares. Major rivers in the area are also labeled.

horizontal resolution is 4.3 km (nadir values) [*Kummerow et. al.,* 1998]. A hybrid model - a combination of the Hitschfeld-Borden and surface reference method - is used to retrieve surface rainfall and hydrometeor profiles [*Iguchi et. al.,* 2000]. The TMI and PR precipitation data (Version 5) that are distributed by the Goddard Distributed Active Archive Center (DAAC) as products 2A12 and 2A25 were used in this study. (URL: http://lake.nascom.nasa.gov/data/dataset/TRMM/)

Analysis and comparison of raingauge and TRMM data for the 1999 monsoon season

Of the 16 stations on the hydrometeorological network we have processed four months of continuous data for 12 stations - 6 high altitude and 6 low altitude locations (Figure 1). The high altitude stations marked by solid circles range in altitude from 2100 m (Ganpokhara) to 4400 m (Rambrong). The low altitude stations marked by squares range in altitude from 510 m (Purkot) to 1500 m (Tansen). Other than Tansen and Bortung, which lie in the Terai plains, the rest of the stations lie in the Marsyandi river basin. The station data are summarized in Table 1. Listed are the mean and maximum observed rainfall intensities and the mean duration of rainfall events for the 4 months. This is the first instance of cumulative monsoon rainfall amounts on the order of 3 m being observed at such high elevation in the Himalayas. This is especially relevant because these values are comparable with the highest monsoon rainfall observed in the Indian subcontinent (http://grads.iges.org/india/partha.subdiv.html). The low elevation stations receive higher intensity rain over shorter durations than the high elevation stations. Locally, the mean diurnal rainfall shows distinct patterns for high and low elevations stations, which are seen in the 4-month (JJAS) mean diurnal rainfall intensities plotted for a typical low (Khudi) and high (Rambrong) altitude station in Figure 2. It is seen that the low altitude stations are characterized by heavier rain with a peak that occurs late in the night and early morning. This is consistent with the establishment (and superposition) of downslope and down-valley winds in the evening. The late night peak could also result from a low-level convergence zone at low elevations due to downslope flow, similar to a density current, driven by radiative and evaporative cooling and evapotranspiration from dense vegetation. The high altitude stations have a weaker peak at night and a stronger peak in the mid-afternoon, which may be linked to classical elevated heat sources leading to the establishment of relatively strong upslope flows during the day.

Table 1. raingauge network and basic statistics of rain events at the low and high elevation stations.

Station Name	Elev (m)	JJAS rain (m)	Max (mm/hr)	Mean (mm/hr)	Dur (hrs)
1. Danfedanda	4000	1.99	17.61	1.34	3.9
2. Rambrong	4400	2.89	17.40	2.24	3.0
3. Sundar	3800	2.88	51.47	2.44	2.7
4. Telbrung	3200	3.47	49.46	2.87	3.0
5. Temang+	2760	1.18	24.00	2.99	1.0
6. Ganpokhara	2100	3.76	92.20	6.08	1.6
1. Tal*	1400	1.27	21.52	3.58	1.0
2. Thalpant*	680	3.26	91.53	7.21	1.6
3. Purkot*	510	1.48	68.37	4.86	1.3
4. Khudi*	780	2.27	71.35	6.24	1.2
5. Tansen*	1500	1.66	62.22	3.32	2.1
6. Bortung*	1020	1.57	69.38	5.59	1.5

* Low Altitude Stations, + Rain shadow

The near surface rain rates from the PR and TMI for a pixel whose center latitude and longitude values were

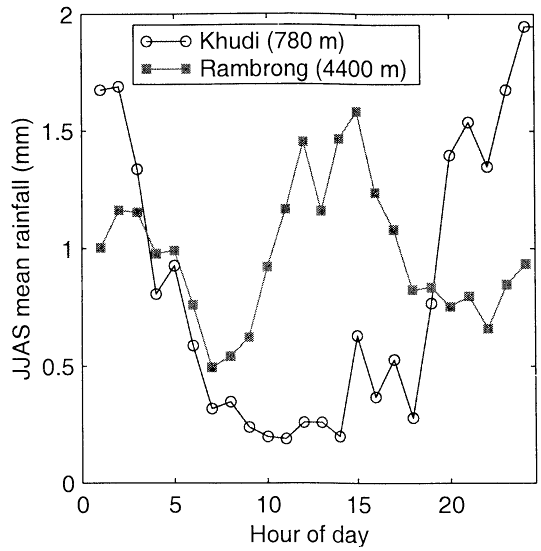

Figure 2. Mean (JJAS) diurnal cycle of rainfall intensity at Khudi and Rambrong.

within 0.02 degrees of the raingauge location were used to assess the skill of the satellite sensors in detecting rainfall and rain producing weather systems. Figure 3 (a and b) is a scatter plot of the raingauge data and the PR-derived rain rate. Since the PR is less sensitive to low intensity rain, which is often missed, only observations with rain rates >0.5 mm/hr are shown in

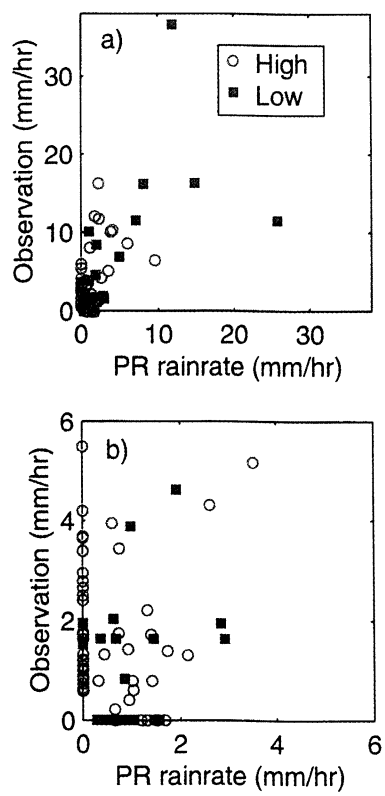

Figure 3. a) Scatter plot of raingauge observations (>0.5 mm/hr) vs. instantaneous PR near surface rain rate for low (filled squares) and high altitude (open circles) stations; b) a zoomed view of a) for low rain rates.

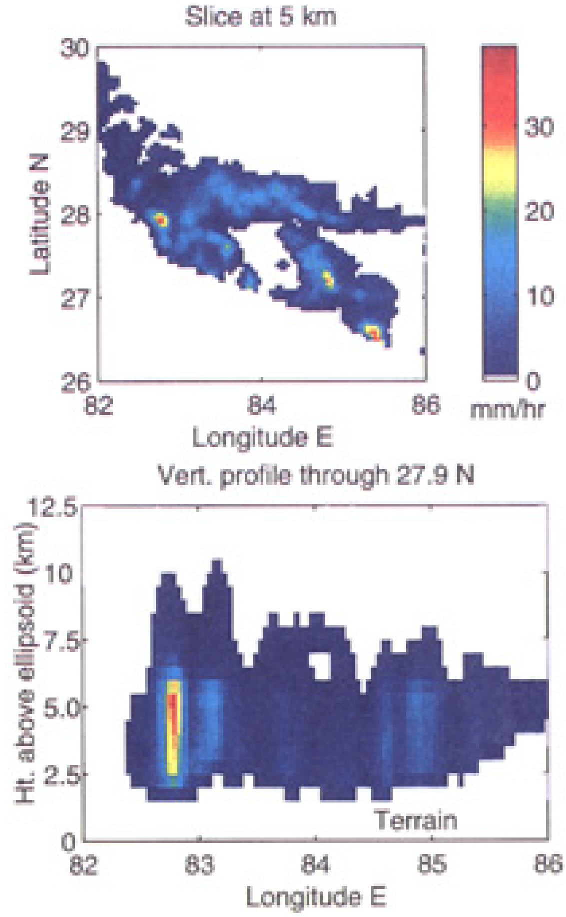

Figure 4. Rain rates along a horizontal (5 km above the reference ellipsoid) and a vertical (through 27.9 N) profile for a storm system on June 12 from PR product 2A25.

the figure (see Figure 3b). The comparison of PR/TMI rainfall with raingauge data was assessed by computing the following performance indices for the monsoon data for the high and low elevation stations (Table 2): the false alarm rate [FR = FA / (H + FA)], the probability of detection [PD = H / (H + M)], the threat score [TS = H / (H + FA + M)] and the skill score [SS = (Z*H - FA*M) / ((Z + FA)*(M + H))], where FA is the number of false alarms, H is the number of hits, M is the number of misses and Z is the number of zeros.

The scores were calculated for all observations, and also using only those with rainfall amounts > 0.5 mm/hr. Overall, the scores indicate that both the PR and TMI perform better at low altitude stations as compared with high altitude stations. This is consistent with the fact that stratiform rainfall is predominant at higher elevations, while convective rainfall is more frequent at lower elevations. The PR has better overall scores compared with the TMI at both high and low stations. Previously, *Adler, et. al.* [1993] reported an underestimation of shallow orographic rain based on passive microwave retrievals from the SSM/I over south Japan, and this study may present a similar situation.

Table 2. Performance of the PR and TMI-derived rain when compared with raingauge data for high and low altitude stations. Note: An observed rain rate of less than 0.5 mm/hr that is not detected by TRMM is counted as zero and not a miss.

Stn	#	Obs.>0.5mm/hr							All obs.						
	Samp	H	M	FA	FR	PD	TS	SS	H	M	FA	FR	PD	TS	SS
Low (PR)	294	17	2	11	0.39	0.90	0.57	0.85	17	6	11	0.39	0.74	0.5	0.70
High (PR)	276	26	37	5	0.16	0.41	0.38	0.39	26	63	5	0.16	0.29	0.28	0.26
Low (TMI)	458	31	28	14	0.31	0.53	0.42	0.49	31	35	14	0.31	0.47	0.39	0.43
High (TMI)	450	50	84	16	0.24	0.37	0.33	0.32	50	125	16	0.24	0.28	0.26	0.23

#Samp - number of samples, H - Hit, M - Miss, FA - False Alarm, FR - False Alarm Rate, PD - Probability of Detection, TS - Threat Score, SS - Skill Score

Although more conclusive results could be obtained if several years of data were available, a key finding of this study is that TRMM sensors, especially the PR, are capable of detecting heavy rainfall in regions of complex terrain with good consistency. This suggests that the 3D PR products can be used to characterize the structure of storm systems when such events are captured by an overpass. Horizontal and vertical profiles for one such system in the study region on June 12 (see Figure 4) show convective cells embedded in large areas of persistent stratiform rainfall up to elevations of 5000 m, and exhibit a leading-line-trailing stratiform mesoscale convective storm type structure. Although the instantaneous snapshots (one or two per day) provided by TRMM do not allow us to study the evolution of the kinematic and thermodynamic structure of mesoscale weather systems, the systematic study of the profiles suggests that heavy precipitation events during the monsoon are associated with organized convection at the foothills of the south-facing slopes and valleys. This analysis is especially relevant because there is no operational radar or radiosonde network in this region of the globe and this is a first look at the structure of storm systems in detail.

Conclusions

Based on the above evaluations the PR shows slightly better scores than the TMI at distinguishing between rain and no-rain events. The PR and TMI exhibit good skill in detecting rainfall at low elevation stations as compared with the high elevation stations that receive low intensity rain. These conclusions are, however, made keeping in mind the paucity of data as well as problems associated with comparing temporally averaged raingauge data with instantaneous, spatially averaged rainfall rates from satellite data.

Unexpected trends in the raingauge data, such as, rainfall amounts of almost 4 m (at 2 km elevation) and 3 m (at 4 km elevation) at locations well into the complex orography of central Nepal, and the recurrence of organized convective activity at the leading edge of the south facing slopes of the Himalayas, underscore the need for further research on the interaction between terrain and mesoscale convective activity during the monsoon. Data from other satellites, radiosonde and other hydrometeorological data are being examined to understand the relationship between weather patterns, storm structure and the TRMM and ground observations in the region.

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