Calibration of TRMM Derived Rainfall Over Nepal During 1998-2007

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Abstract: In this study rainfall is calculated from Tropical Rainfall Measuring Mission (TRMM) Version 6 (V6) 3B42 datasets and calibrated with reference to the observed daily rainfall by rain-gauge collected at 15 locations over Nepal during 1998-2007. In monthly, seasonal and annual scales TRMM estimated rainfalls follow the similar distribution of historical patterns obtained from the rain-gauge data. Rainfall is large in the Southern parts of the country, especially in the Central Nepal. Day-to-day rainfall comparison shows that TRMM derived trend is very similar to the observed data but TRMM usually underestimates rainfall on many days with some exceptions of overestimation on some days. The correlation coefficient of rainfalls between TRMM and rain-gauge data is obtained about 0.71. TRMM can measure about 65.39% of surface rainfall in Nepal. After using calibration factors obtained through regression expression the TRMM estimated rainfall over Nepal becomes about 99.91% of observed data. TRMM detection of rainy days is poor over Nepal; it can approximately detect, under-detect and over-detect by 19%, 72% and 9% of stations respectively. False alarm rate, probability of detection, threat score and skill score are calculated as 0.30, 0.68, 0.53 and 0.55 respectively. Finally, TRMM data can be utilized in measuring mountainous rainfall over Nepal but exact amount of rainfall has to be calculated with the help of adjustment factors obtained through calibration procedure. This preliminary work is the preparation of utilization of Global Precipitation Measurement (GPM) data to be commencing in 2013.

Keywords: Rainfall, calibration, validation, TRMM, Nepal.

INTRODUCTION

One of the most interesting aspects of weather is rainfall, and its variance from one place to another. In the present work estimation of rainfall at upland region by Tropical Rainfall Measuring Mission (TRMM) data is focused on over Nepal as a pilot study. When mountains are nearby, the rainfall amounts can vary significantly within a small distance. There are two basic effects on precipitation caused by mountains. There is the "orographic" effect and the "rain shadow" effect. We are not interested in detailed information on exactly how the mountains affect the rainfall in different parts of this valley rather we are interested to calibrate TRMM measured rainfall with reference to the observed data for estimating mountainous rainfall over Nepal.

Reliable estimation of rainfall distribution in mountainous regions poses a great challenge not only due to highly undulating surface terrain and complex relationships between land elevation and precipitation, but also due to non-availability of abundant rainfall measurement points. Prediction of rainfall variability over mountainous regions is a logical step towards meaningful land use planning and water resources zoning [1]. Nepal is preponderantly a mountainous country. The altitude varies from 90 m above the mean sea level in south to 8848 m above the mean sea

level in north with an average rise of elevation of 45 meters for every one kilometer. Nepal has very pleasant climate. The country lies in the monsoon climatic regime. Nepal has four distinct seasons: (i) Spring (March-May), (ii) Summer (June-September), (iii) Autumn (October-November) and (iv) Winter (December-February). Weather and climate condition in Nepal vary from region to region. The mean annual precipitation ranges from more than 6000 mm along the southern slopes of the Annapurna range in central Nepal to less than the 250 mm in the north central portion near the Tibetan plateau. Amounts varying between 1500 and 2500mm predominate over most parts of the country. On an average, about 80% of the total precipitation of 1982 mm occurs [2] in the summer monsoon period. The other months (October-May) have little or no rain. There is a great disparity in rainfall distribution in the country. The northern side of the Himalayas receives scanty or as low as 174 mm of precipitation for the whole year and therefore is known as 'rain shadow region'. Most of the rain occurs on the southern slope of the mountains. These temporal and spatial variations of rainfall have various implications such as land degradations, waterbased energy output, agricultural activities, conveyance of goods and people, and so on. Thus, natural hazards including landslides, soil erosion and flooding occur as an inherent phenomenon in the Nepalese mountain region. However, the occurrence of landslides is controlled by various physical factors, such as elevation, slope, drainage density, geology, land use/land cover, etc., but rainfall is one of the key components responsible for above disastrous situations. The orographic effect on rainfall distribution during a storm event in mountainous regions is discussed by Oki *et al.* [3]. Kim and Barros [4] analyzed METEOSAT-5 IR imagery to obtain the contributions of the

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convective weather systems to rainfall during the monsoon 2000 in a mountainous region in Central Nepal and assessed rainfall using data from rain-gauges. Emmanuel *et al.* [5] used daily rainfall data and defined a relationship between monsoonal rainfall and the triggering of landslides in the Annapurna region of Nepal. There is little work on the utilization of long-term satellite data in estimation of rainfall over Nepal; especially calibration of TRMM derived rainfall with observed data is absent. The present work has two-fold objectives: first, to calibrate the amounts of rainfall obtained from TRMM 3B42 datasets with reference to the observed rain-gauges amounts based on data between 1998-2007 and secondly, to find the statistical scores of false detection by TRMM satellite in detecting rainy days over Nepal as a pilot study. These results are important for the coming GPM satellite measured rainfall.

DATA AND METHODOLOGY

Data Used

The Tropical Rainfall Measuring Mission (TRMM) is a joint U.S.-Japan satellite mission to monitor tropical and subtropical precipitation and to estimate its associated latent heating. TRMM was successfully launched on 27 November 1997 from the Tanegashima Space Center in Japan (http://gcmd.nasa.gov/records/GCMD_GES_DISC_TRMM_3B42_daily_V6.html). The rainfall measuring instruments on the TRMM satellite include the Precipitation Radar (PR), electronically scanning radar operating at 13.8 GHz; TRMM Microwave Image (TMI), a nine-channel passive microwave radiometer; and Visible and Infrared Scanner (VIRS), a five-channel visible/infrared radiometer. The purpose of the 3B42 algorithm [6] is to produce TRMM-adjusted merged-infrared (IR) precipitation and root-mean-square (RMS) precipitation-error estimates. The algorithm consists of two separate steps. The first step uses the TRMM VIRS and TMI orbit data (TRMM products 1B01 and 2A12) and the

monthly TMI/TRMM Combined Instrument (TCI) calibration parameters (from TRMM product 3B31) to produce monthly IR calibration parameters. The second step uses these derived monthly IR calibration parameters to adjust the merged-IR precipitation data, which consists of GMS, GOES-E, GOES-W, Meteosat-7, Meteosat-5, and NOAA-12 data. The final gridded, adjusted merged-IR precipitation (mm/hr) and RMS precipitation-error estimates have a daily temporal resolution and a 0.25° by 0.25° spatial resolution products. Details of the algorithm can be found at http://trmm.gsfc.nasa.gov/3b42.html. Spatial coverage extends from 50° south to 50° north latitude. In this work TRMM 3B42 datasets are utilized.

Daily rainfall collected by the Department of Hydrology and Meteorology (DHM) at 15 locations over Nepal is utilized in this work. Rain-gauge station names with altitude (m) and annual rainfall amount (mm) during 1971-2007 is presented in Table **1**.

Analysis Procedure

The major objective of this study is to calibrate rainfall obtained from TRMM 3B42 datasets with reference to the observed data over Nepal during 1998-2007. In this connection rain-gauge daily rainfall collected by the DHM at 15 locations over Nepal available at SMRC is utilized. Among the interpolation methods described in the literature, ordinary kriging and modified residual kriging are attractive by reason of their simplicity and ease of use [7]. But in case of only 15 stations over high topographic variation of Nepal, none of them are useful in gridding rain-gauges rainfall. This is the reason that rainfall obtained from TRMM 3B42 datasets in a 25 km grid box (Fig. **1**) are compared with the same from rain-gauge. The rain-gauge situated in a grid box represents the observed amount corresponding to the TRMM measured rainfall in that grid. The comparison of TRMM

Table 1.   Station Names with Altitude. Serial of Stations are Used Later On

SL No.	Station Name	Latitude (Degree)	Longitude (Degree)	Altitude (m)	Annual Rainfall (mm)
1	Biratnagar	26.48	87.27	72	1881.1
2	Bhairahawa	27.52	83.43	109	1673.1
3	Simara	27.17	84.98	130	1815.8
4	Nepalgonj	28.07	81.67	144	1416.4
5	Dhankuta	26.98	87.35	148	995.7
6	Dhangadhi	28.8	80.55	187	1799.7
7	Ghorai	28.05	82.5	634	1395
8	Dipayal	29.23	80.93	720	1145.2
9	Surkhet	28.6	81.62	720	1602.8
10	Pokhara	28.22	84	827	3951.5
11	Kathmandu	27.7	85.37	1337	1439.7
12	Okhaldhunga	27.32	86.5	1720	1745.6
13	Taplejung	27.35	87.67	1732	1993.2
14	Dadeldhura	29.3	80.58	1848	1376.4
15	Jumla	29.28	82.17	2300	828.2

3B42 day-to-day rainfall with rain-gauge data for each observation site is carried out. Then monthly, seasonal, annual and long-term amounts obtained from both analyses are compared. Regression analysis is performed using TRMM and observed data at every day. Regression slopes and constants are useful in validation purpose. Pearson correlation coefficient is also obtained for rainfall estimated by TRMM and rain-gauge. Performance of TRMM 3B42 algorithms was characterized into three basic categories [8]: underestimation, overestimation and approximately equal (within ±10%). To understand the TRMM performance the following performance-indices are also calculated for all stations mentioned in Table **1**:

1.   the false alarm rate FR = FA / (H + FA)

2.   the probability of detection PD = H / (H + M)

3.   the threat score TS = H / (H + FA + M) and

4.   the skill score SS = (Z*H - FA*M) / (Z + FA)*(M + H)

where FA is the number of false alarm, H is the number of hits, M is the number of misses and Z is the number of zeros [9]. The trace in observed data is not considered as rainy days and rainfall <0.1 mm/d measured by TRMM are excluded because rain-gauge data are used ≥0.1 mm/d.
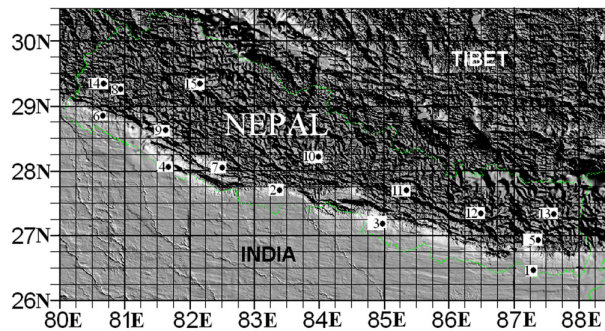
Fig. (1). Topography of Nepal with the locations of stations in number. Station numbers are according to serial in Table **1**.

RESULTS AND DISCUSSION

This section describes the rainfall in different scales such as daily, monthly, seasonal, annual and long-term. The year is chosen randomly as example out of analyzed 10 years.

Monthly Rainfall Distribution Over Nepal as Observed from TRMM

As mentioned earlier, measurement of spatial distribution of rainfall over a mountainous region like Nepal is very difficult, because of many limitations including set-up and maintaining dense rain-gauge network. The TRMM data can provide a better distribution of rainfall in mountainous region because it observes from upper side and covers wide area. TRMM 3B42 monthly rainfall averages during 1998-2007 for the month of January (left panel) and July (right panel) are presented in Fig. (**2**). Usually very light rainfall is observed over Nepal during January to May and October. Rainfall is hardly observed in November and December. Major part of annual rainfall comes during June to September. This is the usual rainfall characteristics of this

region. Heavy rainfall occurs in the Southern belt of the country. These results are consistent with Devkota *et al.* [10] who analyzed monthly observed rainfall during 1971-2004.
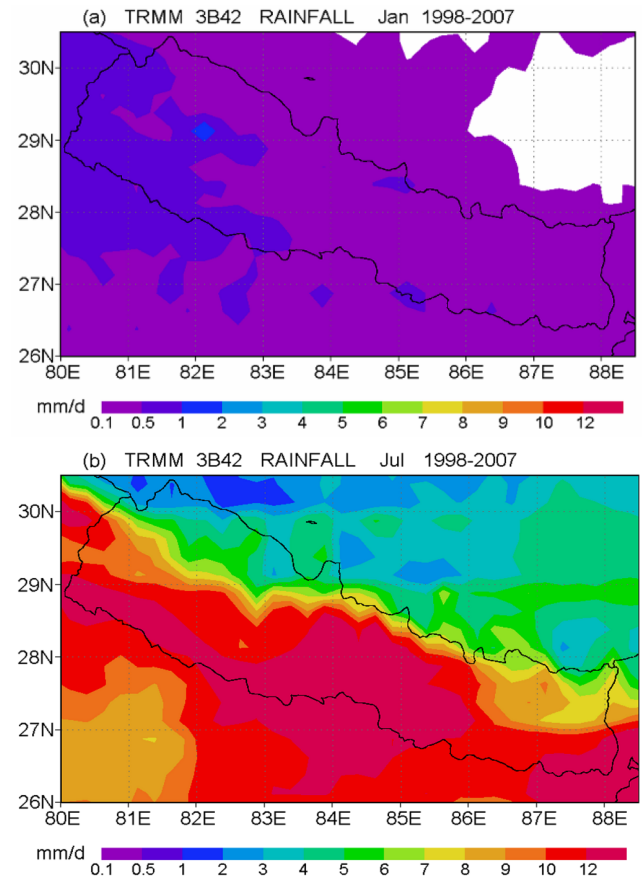

Fig. (2). TRMM 3B42 monthly rainfall for (**a**) January and (**b**) July averaged from 1998-2007.

Seasonal Rainfall Distribution Over Nepal as Observed from TRMM

As mentioned in pervious subsection, major part of the annual rainfall comes during monsoon months from June to September (JJAS), therefore, rainfall averages for the monsoon period is presented for 2003, 2004, 2006 and 2007, as examples (Fig. **3**). Rainfall is again large in the Southern parts of the country. Almost in every year, large amount of rainfall is observed in the Central parts and in some years it is large in southeastern and southwestern parts of Nepal. From the averages of monsoon (JJAS) rainfall during 1998-2007 over Nepal it is concluded that heavy rainfall occurs in the Terai (Southern slopes) and Central parts of the country.

Annual Rainfall Distribution Over Nepal as Observed from TRMM

Annual rainfall distribution averages for 1998-2007 (Fig. **4**) shows that rainfall over Nepal is large in the Southern sides and especially it is large in the Central Nepal. This result is very similar to the same obtained from 314 rain-gauges and averages for 1971-2004 [10]. The advantages of using TRMM data is that it covers large area, therefore, small pockets of rainfalls are not seen here which are
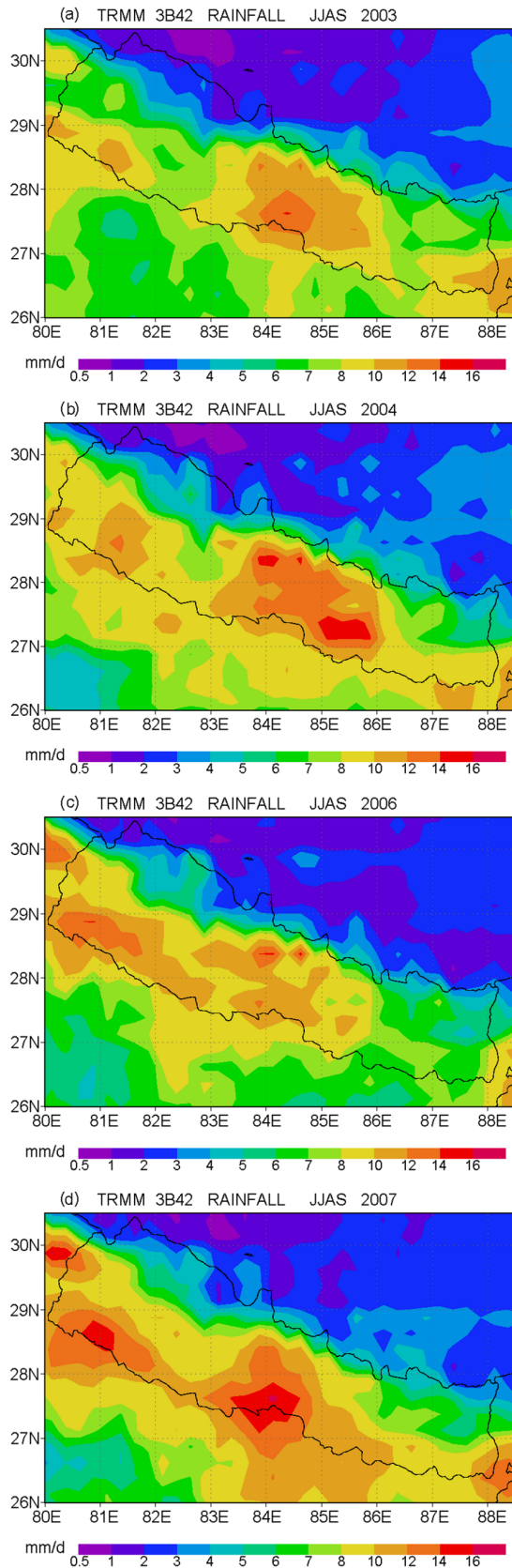
Fig. (3). Monsoon rainfall distribution over Nepal as observed from TRMM 3B42 data in different years (**a**) 2003, (**b**) 2004, (**c**) 2006 and (**d**) 2007.

common for rain-gauge data analysis [10] due to extrapolation and interpolation in data gridding from point values.
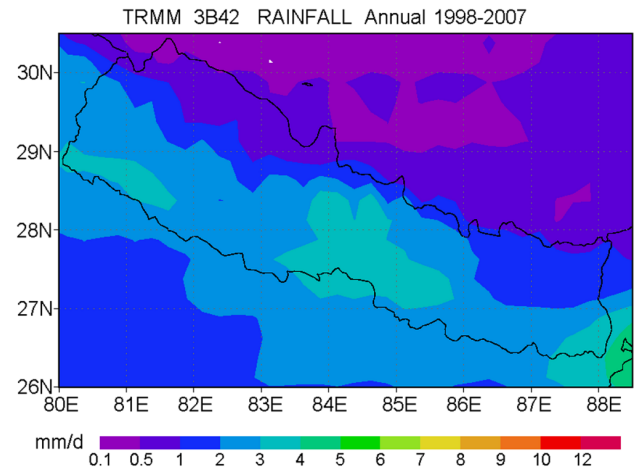

Fig. (4). Distribution of annual rainfall derived from TRMM over Nepal averages for 1998-2007.

Comparison of Day-to-Day Rainfall

To obtain day-to-day rainfall comparison obtained from TRMM and rain-gauge at individual stations, three pairs of stations are considered: i) Dadeldhura and Dhangadhi in the Western Nepal, ii) Pokhara and Bhairawa in the Central Nepal and iii) Taplejung and Biratnagar in the Eastern Nepal. In each pair one station is located at high elevation compared to another.

First Pair: Dadeldhura is a high elevated (1848 m) station compared to Dhangadhi (187 m). Day-to-day rainfall obtained from TRMM 3B42 and observed data in some years at Dadeldhura and Dhangadhi stations are shown in Fig. (**5**). At Dadeldhura, TRMM underestimated rainfall in daily scale for most of the rainy days in 2000 and overestimated in many days in 2004 (Fig. **5a**). It is found that TRMM underestimated on some days in 1998, 2002, 2003 and 2007 and overestimated rainfall in 1999, 2001, 2005 and 2006 (not shown). Overall, TRMM can detect most of the rainy days with reference to the observed data including a few missing and false detection. In most of the rainy days, rainfall magnitudes vary for both measurements. At Dhangadhi, TRMM underestimated rainfall on many days in 1999 and overestimated on some days in 2004 (Fig. **5b**). In this station TRMM underestimated rainfall in 1998, 2002, 2003 and 2007, whereas overestimated on many days in 2000, 2001, 2005 and 2006 (not shown). This indicates that in the same year 1999, TRMM overestimated rainfall at Dadeldhura and underestimated at Dhangadhi. However, this did not occur in all years; say in 2004 the patterns are almost same for both stations.

Second Pair: At high elevated Pokhara (827 m) TRMM underestimated rainfall almost all events in 1998 (Fig. **6a**). On the other hand, at low elevated Bhairawa (109 m) TRMM overestimated rainfall in many days, especially in 2005 (Fig. **6b**). It is found that at Pokhara TRMM underestimated rainfall in almost all years, and, at Bhairawa it overestimated rainfall on many days in 2000, 2002, 2003,
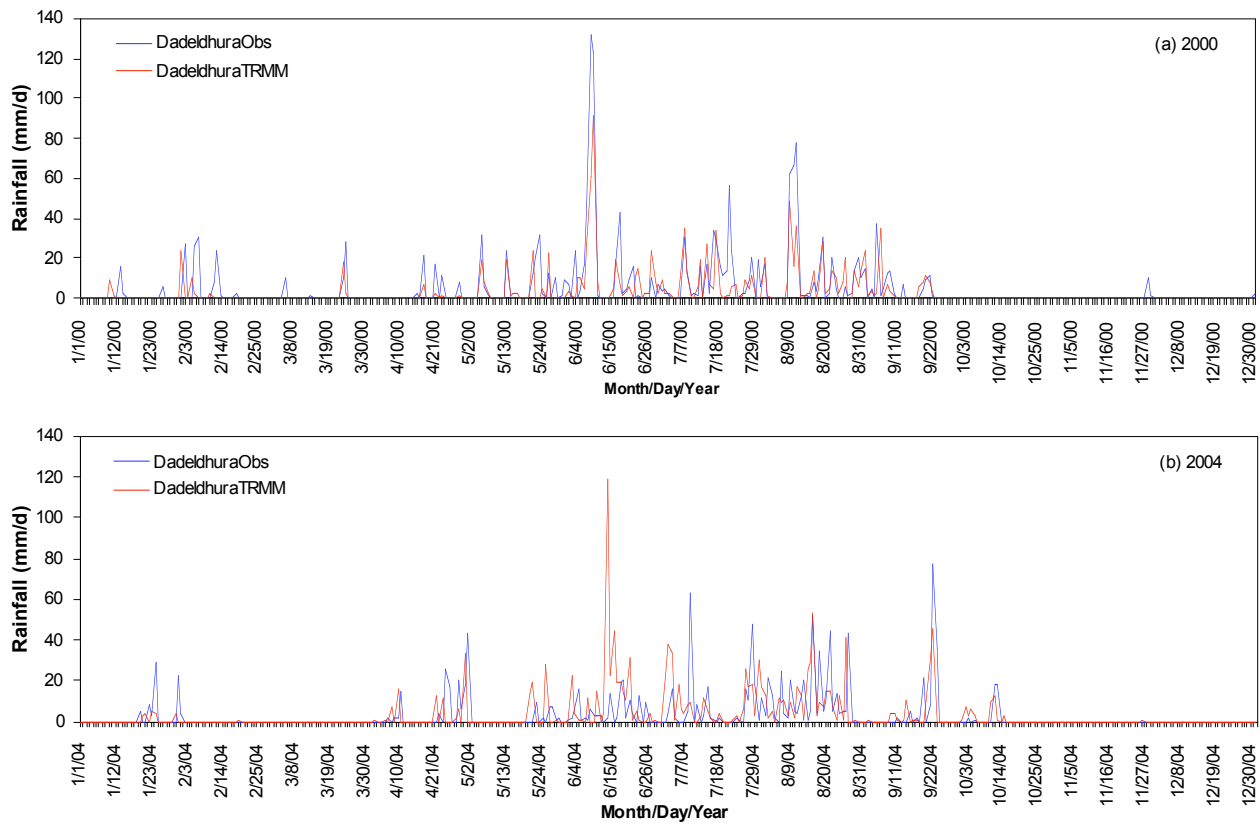
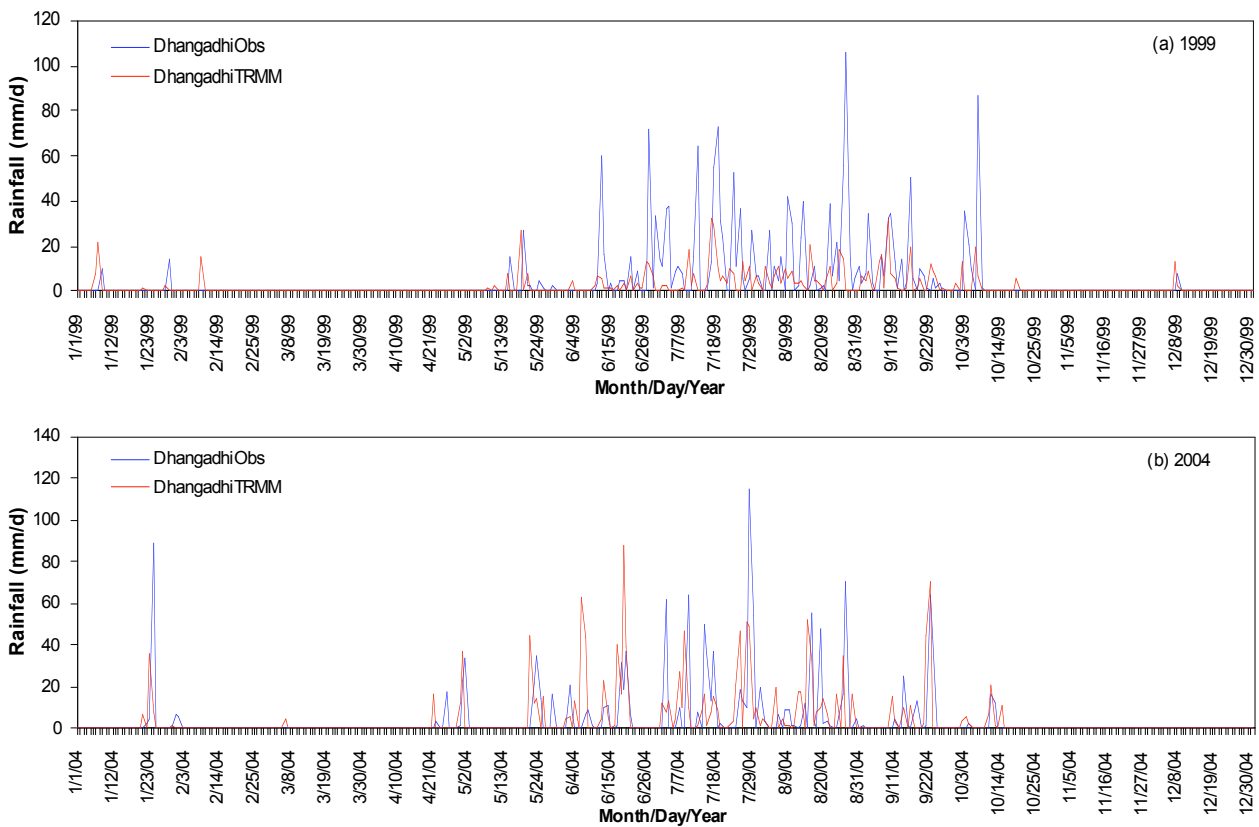**Fig. (5a).** Day-to-day rainfall (mm/d) obtained from TRMM 3B42 and observed data at Dadeldhura station in 2000 and 2004.

Fig. (5b). Day-to-day rainfall (mm/d) obtained from TRMM 3B42 and observed data at Dhangadhi station in 1999 and 2004.
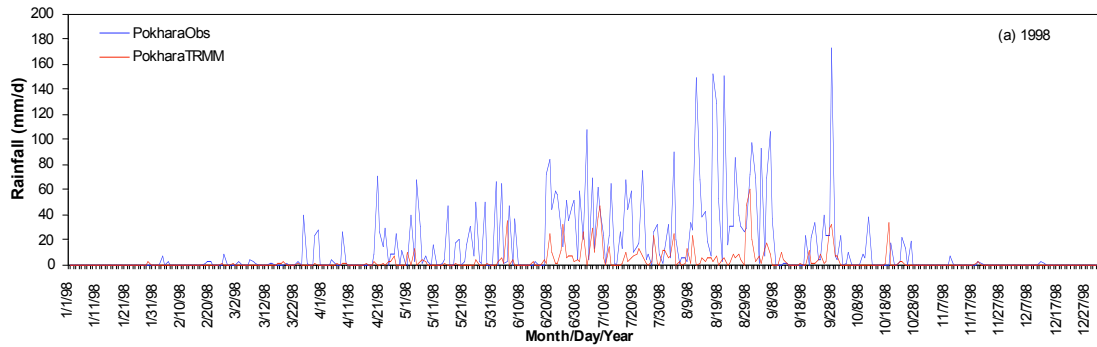
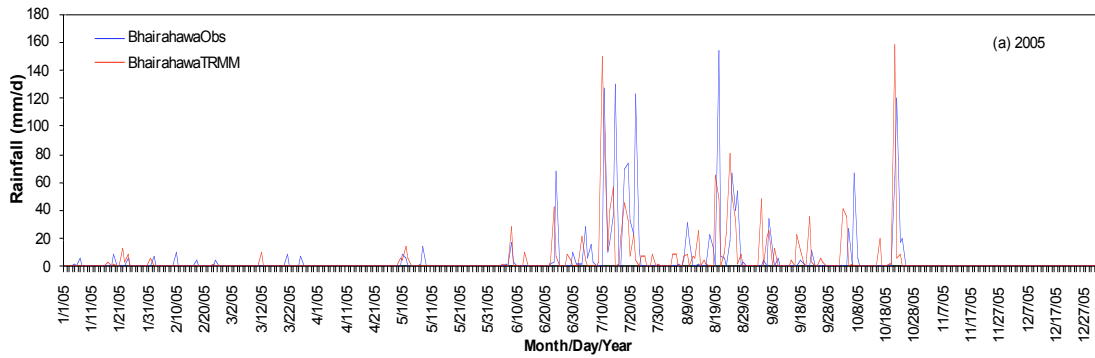**Fig. (6a).** Day-to-day rainfall (mm/d) obtained from TRMM 3B42 and observed data at Pokhara station in 1998.

Fig. (6b). Day-to-day rainfall (mm/d) obtained from TRMM 3B42 and observed data at Bhairahawa station in 2005.

2004, 2006 and 2007 (not shown). These clearly indicate that in the heavy rainfall region of Central Nepal, TRMM underestimates during maximum events at high elevation and overestimates many days at low elevation.
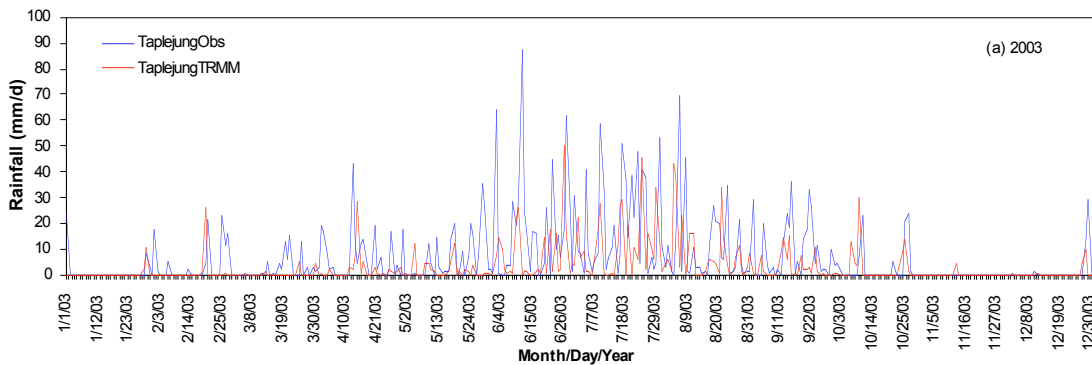

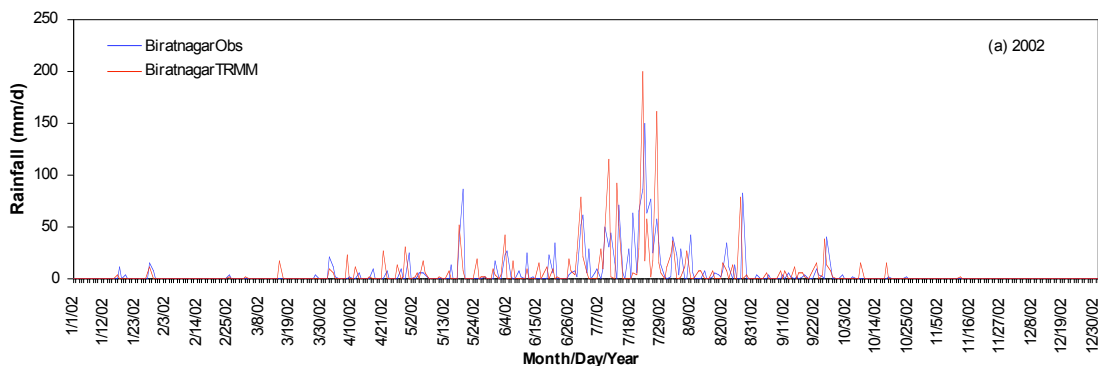**Fig. (7a).** Day-to-day rainfall (mm/d) obtained from TRMM 3B42 and observed data at Tapeljung station in 2003.

Fig. (7b). Day-to-day rainfall (mm/d) obtained from TRMM 3B42 and observed data at Biratnagar station in 2002.

Third Pair: At high elevated Tapeljung (1732 m) TRMM underestimates in most of the rainy days in 2003 (Fig. **7a**). At low elevated Biratnagar (72 m), TRMM measurement is very comparable and it overestimates in some days in 2002 (Fig. **7b**). The similar trends are found in both stations for other years (not shown). Hence it is observed that TRMM can detect most of the rainy days with reference to the observed data.

There is no particular underestimation or overestimation trend of rainfall with station altitude in Nepal. Detail is discussed later.

As discussed above, rainfall obtained from TRMM 3B42 at a particular location may detect most of the rainy days but magnitudes vary from observed data. Usually, TRMM underestimated rainfall in most of days and on some days it overestimated. Rainfall averages from all 15 stations in 2000 is shown in Fig. (**8a**), as example. TRMM underestimated rainfall with reference to the observed data almost all days. The similar trends are found in all analyzed years (not shown). Overall, trends of day-to-day variation match very much for both analyses. Performance of TRMM is obtained through detection of false alarm and missing cases discussed later. From averages of all years (1998-2007) it is clear that

TRMM estimated rainfall underestimated with reference to the observed data and underestimation is large during monsoon months (Fig. **8b**).

Annual cycle of rainfall averages from 15 stations and for 10 years (1998-2007) is shown in Fig. (**9**). TRMM followed well the annual cycle with an underestimation and the underestimation is large during monsoon months. In annual scale TRMM measured about 3.26 mm/d whereas rain-gauge value is about 4.98 mm/d.

The correlation coefficient (r) between daily rainfalls obtained from TRMM and rain-gauge data at each month is shown in Fig. (**10**). Correlation coefficient is significant (> 0.4) for all months except in July (r=0.23); it lies between 0.50 to 0.96 and in annual scale it is about 0.71. This indicates that there is a good relationship among the two measurements even though TRMM underestimates the amount of rainfall.

The scattered plot in Fig. (**11**) shows the linear relationship between rainfalls obtained from TRMM and rain-gauge data. Statistically, regression procedure is utilized to calibrate one unknown parameter in reference to the known one. The general regression equation has the form $y = c + mx$, where the m and c represent for slope and constant
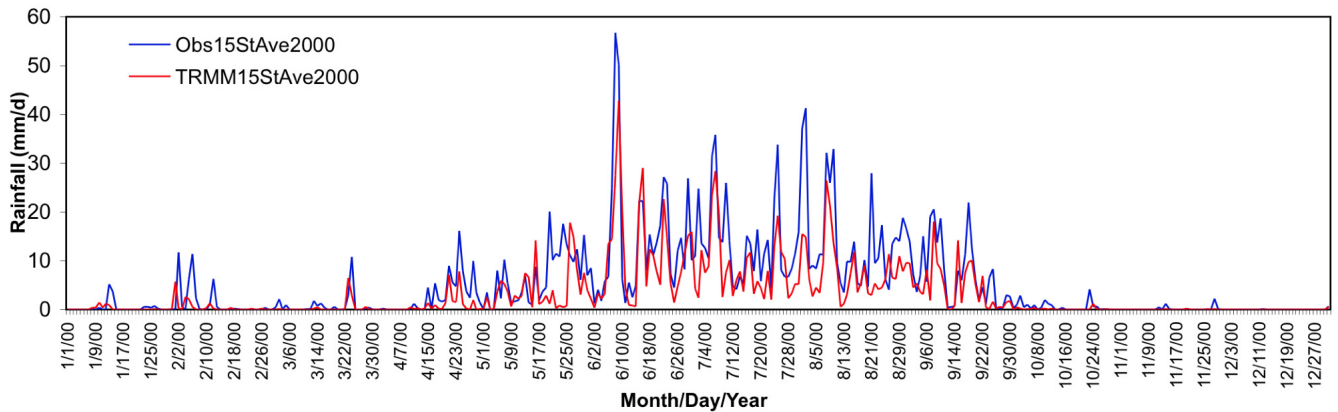

Fig. (8a). Comparison of daily rainfall obtained from TRMM 3B42 and observed data in 2000. Rainfall is averages from all analyzed 15 stations over Nepal.
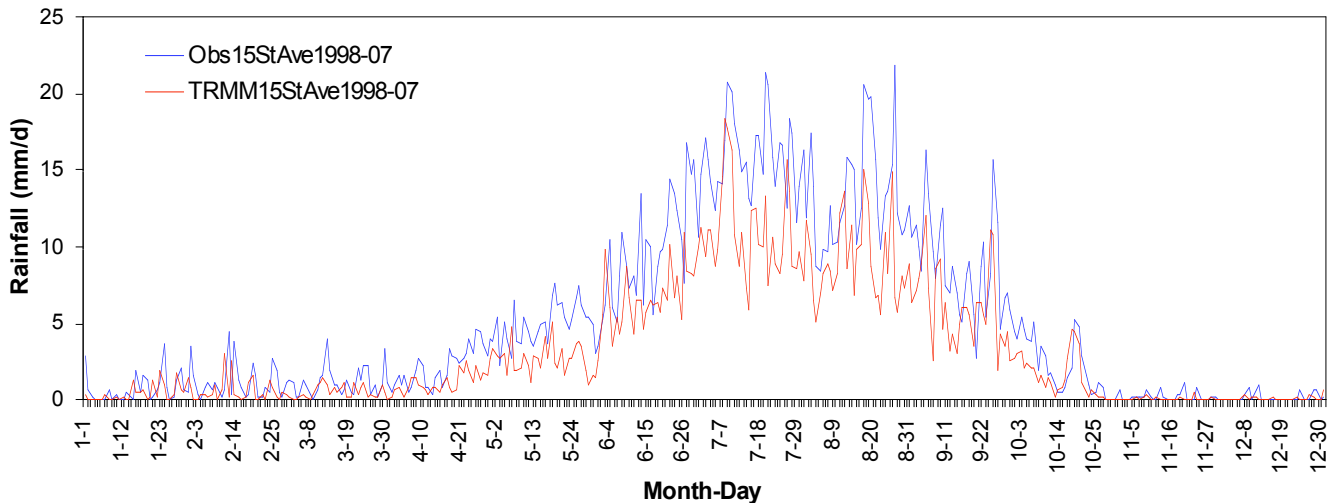

Fig. (8b). The same as in Fig. (**8a**) except averages for 1998-2007.

respectively. For the estimation of rainfall from TRMM, the regression equation is proposed below:

$$Estimated_{RF} = c_{RF} + m_{RF} (TRMM_{RF}) \qquad (1)$$

where $Estimated_{RF}$ is the rainfall to estimate, m_{RF} is the slope, c_{RF} is a constant and $TRMM_{RF}$ is the TRMM measured rainfall. Regression expression shown in each plot of Fig. (**11**) indicates the slope and constant. Consider all 3653 days (=365×10+3) from 10 years during 1998-2007, the slope m_{RF} is about 0.47 and constant c_{RF} is about 0.97. If rainfall is averaged for individual days (365 days in a year) from 10 years, then m_{RF} and c_{RF} are 0.64 and 0.05 respectively. These indicate that averages for 10 years in a particular day enhance the relationship of rainfall between TRMM and rain-gauge data. Alternatively, average data from many years reduces the difference from the two measurements.
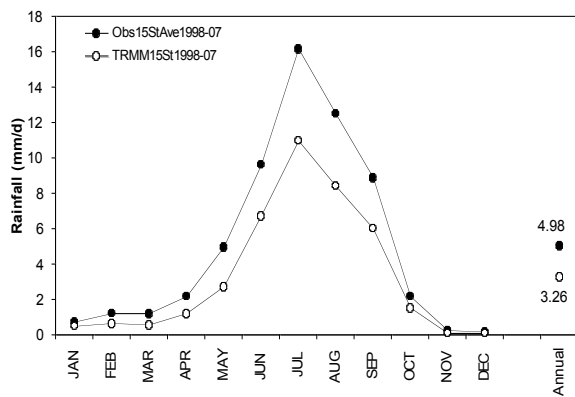

Fig. (9). Annual cycle of rainfall obtained from TRMM and observation. Rainfalls are averages from 15 stations and for 10 years (1998-2007).
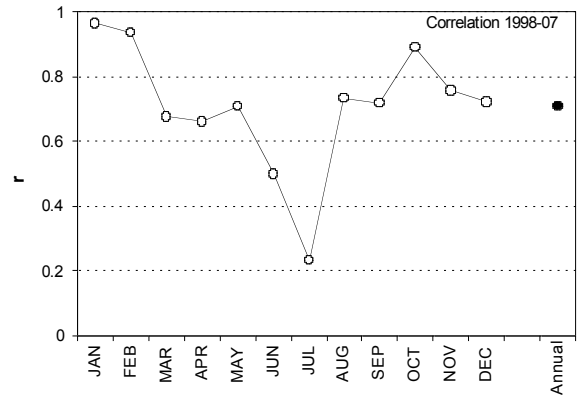

Fig. (10). The correlation coefficient (r) between daily rainfalls obtained from TRMM and rain-gauge in different months.

The slopes and constants obtained through equation (1) at different months are presented in Table **2**. These values are used to estimate the amount of rainfall from TRMM 3B42 datasets over Nepal as discussed in next section.

Comparison of Annual Rainfall

Annual rainfalls obtained from TRMM and rain-gauge data are shown in Fig. (**12**). Rainfall is averaged for 15 stations and Bias is defined as TRMM amount minus rain-gauge value divided by rain-gauge value in percentage. Bias is large for 1998 and 1999 whereas it is small in 2004, 2005 and 2006. In annual scale the Bias is about -34.61 i. e., TRMM rain rates are 34.61% lower than the rain-gauge rates. This underestimation (estimation) is too large (small) compared to about 4% (96%) obtained for Bangladesh by Islam and Uyeda [11]. The topography of Bangladesh and Nepal are different; topography of Nepal is hilly and high elevated compared to almost flat Bangladesh. In Nepal,
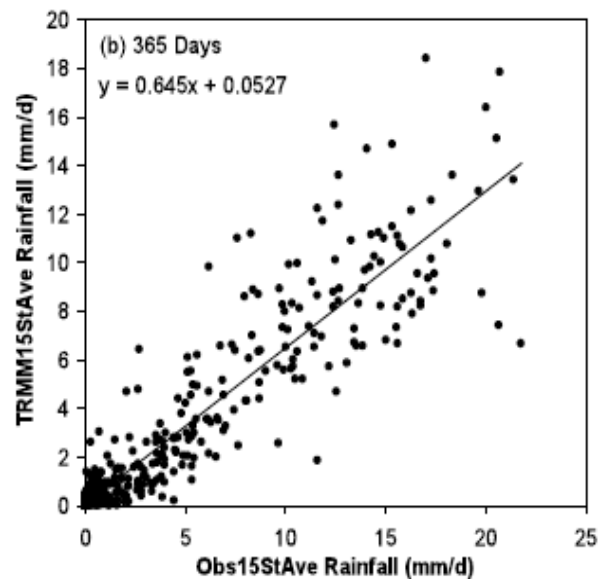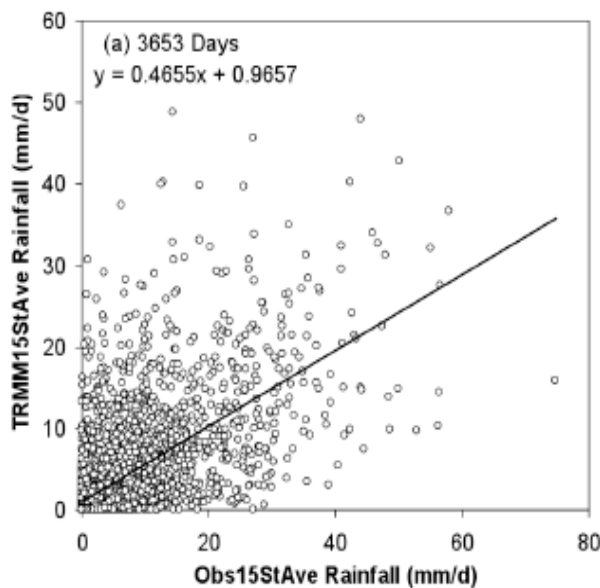

Fig. (11). Scattered plots of rainfall obtained from rain-gauge and TRMM 3B42 data. Rainfall averages for all 15 station **a**) 3653 days for 10 years during 1998-2007 and **b**) 365 days for each day in a year averages from 1998-2007.

Table 2.   Slopes and Constants at Different Months Averages from 1998-2007

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
m_{RF}	1.37	1.53	1.74	0.91	0.93	0.54	0.30	1.61	0.99	1.06	1.86	1.56
c_{RF}	0.09	0.30	0.22	1.10	2.46	6.00	12.82	-1.04	2.88	0.60	0.06	0.02

orographic and rain shadow effects are there. On an average, TRMM and observed data measured 3.26 and 4.98 mm/d respectively. After using calibration factors from equation (1) the TRMM estimated rainfall is 4.97 mm/d that is about 99.91% of the observed data. This indicates that almost the exact amount of observed rainfall is possible from TRMM data with the help of calibration factors discussed in Table **2**.
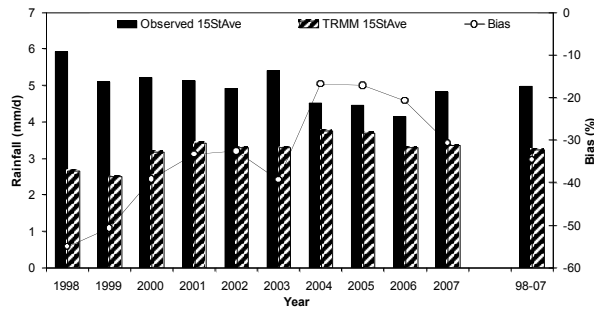

Fig. (12). Annual rainfall and bias obtained from TRMM and rain-gauge data. Rainfall and bias are averages for 15 stations.

VARIATION OF RAINFALL WITH ALTITUDE

Variation of rainfall with altitude is examined in this section because Nepal is a high elevated country where huge topographic variation is very common.

Fig. (**13**) shows the historical rainfall (Observed) amount (mm/d) at different stations with altitude (m). Rainfall is averaged during 1971 to 2007. It is difficult to conclude that large amount of rainfall occurred either at low or high altitude. There is no particular trend of rainfall amount observed with altitude. As an example, elevation of Jumla (2300 m) is highest among all stations but rainfall at this station is smallest (about 2.14 mm/d). The rain shadow effect may reduce the amount of rainfall in this location for its leeward side of a mountain. Pokhara received highest rainfall (11.55 mm/d) but its elevation is about 827 m. As the windward side, the orographic effect may cause this large amount of rainfall at Pokhara. TRMM measured rainfalls are averages during 1998-2007. It is clear that TRMM 3B42 underestimated rainfall almost at all stations except Dipayal and Dhankuta. TRMM estimated rainfall at Pokhara is only about 36.66% of observed value that is about 65.39% for all stations average.

The trend of variation of rainfall with altitude is shown in Fig. (**14**). Rainfall decreases with the increase of altitude. Decrease rate is slightly higher for TRMM rainfall (0.096) compared to observed data (0.046). Hence, it is clear that in Nepal rainfall at higher elevation is small compared to low elevation that reflects with small amount of rainfall in the Northern parts of the country (Fig. **4**).
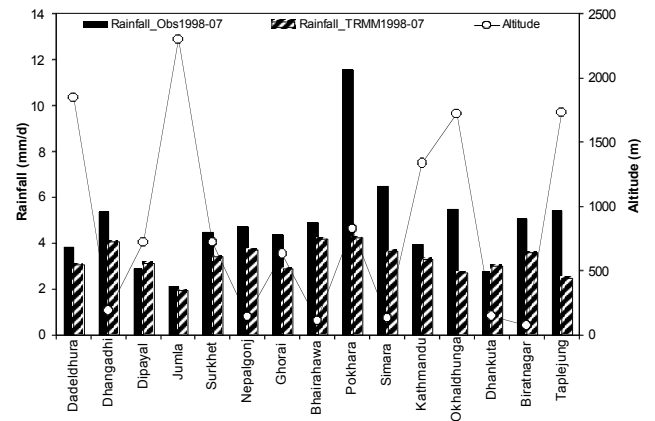

Fig. (13). Variation of annual rainfall (mm/d) with altitude at different stations over Nepal. Observed rainfall is averaged for 1998-2007 and TRMM rainfall is averaged for 1998-2007.

TRMM PERFORMANCE IN DETECTION OF RAINY DAYS

In this section TRMM performance in detection of rainy days are examined.

Approximately-, Under- and Over-Detection of Rainfall by TRMM

The performance of the TRMM 3B42 is summarized in Table **3** for the year 1998-2007. To find the distribution of analyzed 15 stations in 10 years, 150 (=15×10) individual stations are to be considered in Nepal. The values in each row under year in Table **3** show the number of stations either under-detected, over-detected, or approximately equal of the stations observed values for rainfall by TRMM 3B42 in different years. The TRMM V6 3B42 product was accurate to within 10% of the analyzed stations only about 19% of the time. By expanding definition of acceptable accuracy to be ±25% of observed precipitation [8], the TRMM V6 3B42 product was accurate for 57% of station locations. These results differ for Bangladesh which are 38% and 72% for ±10% and ±25% respectively [11]. The topography of Bangladesh is very flat compared to mountainous Nepal and may be the cause of this difference. For TRMM 3B42 under-detection was 72% and over-detection 9%. Hence, it is clear that the TRMM 3B42 underestimated rainfall over Nepal. However, for the estimation of daily rainfall, TRMM 3B42 data products are essential, especially for flood monitoring and measurement of rainfall in mountainous regions. Therefore, the TRMM 3B42 data products are further studied to settle on TRMM performance in estimating rainfall in Nepal and discussed later.
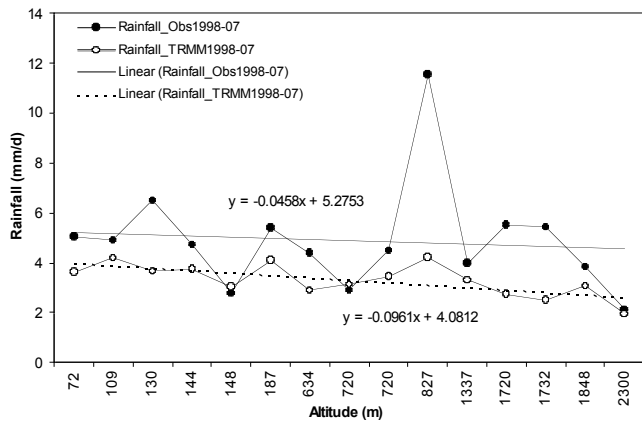
Fig. (14). Variation of rainfall with altitude in Nepal. Rainfalls are averages for 1998-2007.

respectively. There is no particular trend of performance-indices related with altitude in Nepal.

CONCLUSIONS

In this study TRMM V6 3B42 data are analyzed to calibrate TRMM derived rainfall with reference to the rain-gauge data over Nepal. Daily rainfall collected at 15 stations over Nepal by the Department of Hydrology and Meteorology (DHM) are utilized in calibration of TRMM rainfall during 1998-2007. TRMM obtained rainfall in monthly, seasonal and annual scales are found very similar to historical trends (1971-2004). Usually rainfall is large in the Southern belt and especially at the Central Nepal. In Nepal, rainfall amount is large in low elevation as well as in high elevation. It depends on station location that is windward or leeward. Overall, there is a decreasing trend of rainfall with altitude in Nepal.

Table 3.   False Estimation of Rainfall by TRMM 3B42 During 1998-2007

	Year	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	Total
Approx. Equal (±10%)		*0*	*0*	*3*	*2*	*2*	*0*	*6*	*5*	*7*	*3*	*28*
	11-20%	1	0	1	3	2	1	2	1	2	4	17
	21-30%	0	2	1	3	3	4	2	1	1	3	20
Underestimation	31-40%	1	2	5	3	4	5	0	1	0	0	21
	>40%	13	10	5	3	3	4	2	3	3	4	50
	Subtotal	*15*	*14*	*12*	*12*	*12*	*14*	*6*	*6*	*6*	*11*	*108*
	11-20%	0	0	0	0	0	1	2	2	0	0	5
	21-30%	0	1	0	0	0	0	1	1	1	1	5
Overestimation	31-40%	0	0	0	0	1	0	0	1	1	0	3
	>40%	0	0		1	0	0	0	0	0	0	1
	Subtotal	*0*	*1*	*0*	*1*	*1*	*1*	*3*	*4*	*2*	*1*	*14*
Total Stations		15	15	15	15	15	15	15	15	15	15	150

False-, Missing- and Exact-Detection of Rainy Days by TRMM

As discussed above the measurement of rainfall by TRMM 3B42 was mostly under-detection (72%) while over-detection was 9% and approximately equal was 19%. In this situation detection of false alarm and missing days out of exact rainy days determined by observed data is carried out to see the performance of TRMM sensors. Performance-indices are calculated and presented in Fig. (**15**).

Fig. (**15a**) shows the exact rainy days (Obs Rainy), TRMM detected rainy days, TRMM detected missing rainy days and TRMM detected false alarm at different stations. Fig. (**15b**) shows the False Alarm Rate (FR), Probability of Detection (PD), Threat Score (TS) and Skill Score (SS). It is seen that FR is lowest at Bhairahwa (altitude 109 m) and highest at Dipayal (altitude 720 m). The PD is almost good for all high and low altitude stations. Similarly, TS and SS are varying in between 0.45-0.61 and 0.47-0.63 respectively. On an average for 15 stations, TS and SS are 0.53 and 0.55

Correlation coefficient of rainfall between TRMM and rain-gauge is found significant (> 0.4) for all months except in July ($r=0.23$); it lies between 0.50 to 0.96 and in annual scale it is about 0.71. This indicates that there is a good relationship among the two measurements even though TRMM underestimates the rainfall amount compared to observed data. The Bias (TRMM amount minus rain-gauge value divided by rain-gauge value in percentage) in calculation of rainfall from TRMM lies in between -16.75 to 54.96 in different years during 1998-2007. On an average it is about -34.61. This indicates that TRMM underestimates (measures) rainfall by about 34.61% (65.39%) of the observed rain-gauge rainfall in Nepal. After calibration TRMM estimated rainfall is obtained about 99.91% of the observed data. The important fact is that how much accurately TRMM can detect the rainy days in mountainous Nepal. Obtaining hit score, false alarm, missing, false alarm rate, probability of detection, threat score and skill score, it may be concluded that TRMM performance in calculation of rainfall over mountainous region like Nepal is low compared to the same in flat region like Bangladesh [11]. Over Nepal,
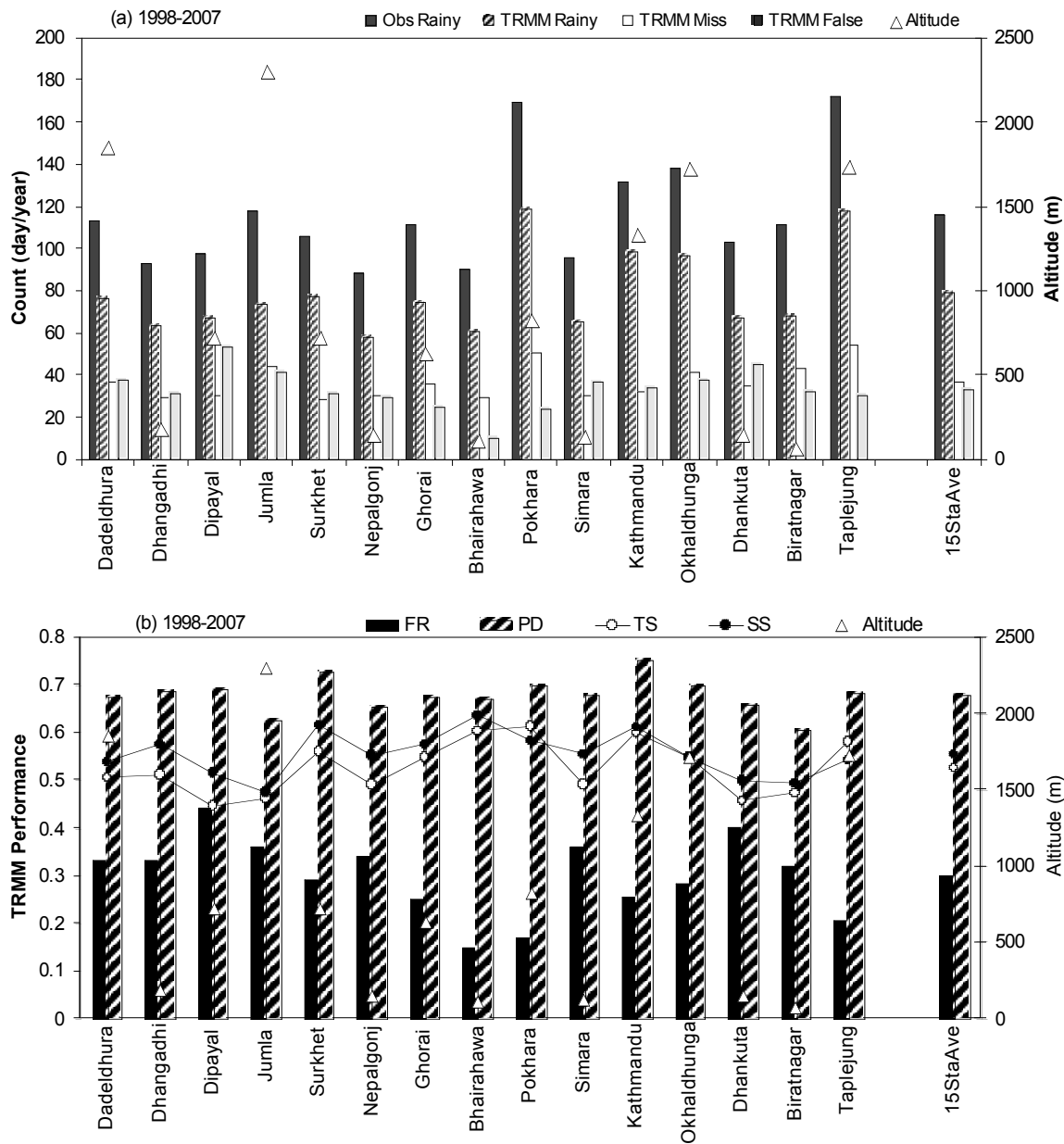
Fig. (15). Performance of TRMM in **a**) detecting rainy days and **b**) performance-indices.

false alarm rate, probability of detection, threat score and skill score are found 0.30, 0.68, 0.53 and 0.55 respectively. This analysis suggests that similar analysis may be carried out over the South Asian countries and involvement of large number of rain-gauge stations data including new analysis techniques for understanding TRMM performance over flat and mountainous regions. In particular, this is the back ground work for the preparation of GPM satellite data which will be available from 2013.

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