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Research Article

EVALUATION OF THE TRMM PRODUCT FOR SPATIO–TEMPORAL CHARACTERISTICS OF PRECIPITATION OVER NEPAL (1998–2018)

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ABSTRACT

Precipitation is a fundamental component of the water cycle and integral to the society and the ecosystem. Further, continuous monitoring of precipitation is essential for predicting severe weather, monitoring droughts, and high-intensity related extremes. The present study evaluated the spatio-temporal distribution of precipitation and trends between 1998–2018 using Tropical Rainfall Measuring Mission (TRMM) (3B43-V7) with reference to 142-gauge observations over Nepal. TRMM moderately captured precipitation patterns' overall characteristics, although underestimated the mean annual precipitation during the study period. TRMM precipitation product well captured the seasonal variation of the observed precipitation with the highest correlation in the winter season. The decreasing seasonal and annual trend was found in both observed and TRMM products, with the highest (lowest) decreasing trend observed during the monsoon (winter) season. It was also noted that the TRMM product showed a smaller bias before 2007, while a large error was found after 2007, especially in the monsoon months. In general, the TRMM product is a good alternative to observe rain gauge measurement in Nepal. However, there is still space for further improvement in rainfall retrieval algorithms, especially in high-elevation areas during the winter season.

Keywords: Nepal, Precipitation, Satellite-based dataset, Spatial pattern, TRMM

INTRODUCTION

Nepal is a South Asian country situated in the steep terrain of the central Himalayan range, with more than 80% of the land covered by the mountains. Precipitation in the country immensely varies due to the complex topography, which leads to the high probability of floods, landslides, and debris flows, mainly during the monsoon season (Bhattarai, 2014). The mountains areas in the north are the source of rivers that flow towards the southern plains. When considerable precipitation occur in the upper stream areas, the large portion of bare southern areas experience devastating floods, impacting millions of people downstream in the southern plain areas. Thus, it is essential to monitor the spatio-temporal precipitation pattern to minimize the losses. Moreover, the availability of high-resolution near real-time rainfall datasets is a prerequisite for disaster risk reduction and management (Maharjan & Regmi, 2015).

Surface-based rain gauge measurement provides an accurate measurement of precipitation on the earth's surface (Petersen *et al.*, 2005; Sun *et al.*, 2018). However, these measurements are very sparse in the mountains and remote locations. Besides limited spatial coverage, a short length of the record and missing information further challenge the accurate rainfall data acquisition. Nevertheless, the observation by the Department of Hydrology and Meteorology (DHM) in Nepal was irregularly distributed (denser in lowlands while sparse in high mountain areas) (Barros & Lang, 2003; Diodato *et al.*, 2010). Such scarcity of rain gauge observation brings a significant challenge for precise hydro-meteorological studies and ample water and disaster management. Accurate and reliable precipitation records are crucial for studying weather and climatic trends, and variability and managing water resources, and hydro-meteorological forecasting (Jiang *et al.*, 2012; Larson & Peck, 1974; Liu *et al.*, 2017). To date, several high-resolution satellite-based precipitation products have been developed and are providing precipitation estimates on different temporal and spatial scales. However, these estimates are indirect measurements and must be verified and calibrated using gauge observations before further applications (Khairul *et al.*, 2018; Tian & Peters-Lidard, 2010).

Tropical Rainfall Measurement Mission (TRMM), a space mission jointly launched by NASA and the Japan

Aerospace Exploration Agency (JAXA) provides several products of rain estimates in near real-time to post real-time from a combination of passive microwave, visible/infrared, and rainfall radar data (Kummerow *et al.*, 1998). TRMM product is one of the high-resolution quasi-global multi-satellite rainfall products and is widely used in various applications. TRMM product combines the rainfall data derived from satellite sensors with punctual data measured by rain gauges that can significantly improve the accuracy of rainfall estimations globally, overcoming the challenges related to data availability (Hsu *et al.*, 1997; Huffman *et al.*, 2007; Joyce *et al.*, 2004; Miao *et al.*, 2015). Several studies have been conducted in Nepal for studying spatio-temporal variation of precipitation and related extreme events for different periods and regions. For example, Baidya *et al.* (2008) found the increasing trend of heavy precipitation events at a national scale. Karki *et al.* (2017) concluded that the spatial distribution of high-intensity precipitation extreme was different from annual and monsoonal distribution. Authors also mentioned that lowlands and mountainous areas were exposed to high–intensity precipitation extremes with a higher probability of floods and landslides. Besides these studies, a few other studies have evaluated the satellite-based precipitation product. Recently, Sharma *et al.* (2020d) found that TRMM product has similar performance as compared to new generation IMERG product across the country, while Duncan and Biggs (2012) found that TRMM product generally overestimated the precipitation values as compared to a gauge-based gridded product over Nepal.

The aforementioned studies in Nepal analyzed the spatio-temporal precipitation and its trends, focusing on river basin, topographic zones, different regions, or previous administrative zones. However, the focus was either on basin-scale or extreme precipitation using limited observed datasets. Thus, this study aims to fill this gap by analyzing the spatial distribution of annual, seasonal, and extreme precipitation events and their trends using TRMM product for 142 observed stations in the recent two-decade (1998–2018). Moreover, evaluating precipitation using TRMM products with observation will help understand the precipitation patterns and trends. Additionally, this study will provide new insights into the high-resolution satellite product with its applicability in the country for future studies. Therefore, understanding the spatial and temporal variability and recent precipitation trends over Nepal is essential for decision-makers and climate scientists, including hydrologists, agriculturalists, emergency managers, and industrialists.

MATERIALS AND METHODS

Study area

Nepal is a South Asian country located between 26.36 °N–30.45 °N and 80.06 °E–88.2 °E, encompassing 147,516 km^{2}, and an elevation range of 60–8848 m above sea level (masl). The country is divided into five standard geographic regions, i.e., Tarai, Siwalik, Middle Mountains, High Mountains, and High Himalaya (Kansakar *et al.*, 2004; Shrestha & Aryal, 2011), meanwhile Duncan and Biggs (2012) further categorized into three broader regions, namely, lowland, lid-mountains and high mountains (high Himalayas). Due to unique topographic distribution, the country features various climates within a short horizontal distance of less than 200 km (Karki *et al.*, 2016). There are four seasons in Nepal, namely, pre-monsoon (March-May), monsoon (June–September), post-monsoon (October–November), and winter (December–February). Two major weather systems receive precipitation over Nepal; the southwest monsoon significantly impacts the southeastern parts of the country during the monsoon season, while the western disturbances predominantly affect the northwestern high mountainous parts during the winter season (Hamal *et al.*, 2020a; Sharma *et al.*, 2020b). The Himalayas act as a barrier to the cold winds blowing from Central Asia in winter and form the northern boundary's monsoon wind patterns. A large portion of (~80 %) precipitation occurs during monsoon, while the remaining 20 % during the dry season (Hamal *et al.*, 2020b; Sharma *et al.*, 2020c).

Rain gauge datasets

The daily gauge observations used in this study were collected from 141 meteorological stations provided by the Department of Hydrology and Meteorology (DHM), Government of Nepal (https://dhm.gov.np) from 1998 to 2018. All the DHM data sets were chosen due to continuous precipitation data; however, some station data do not feature regular datasets. In addition to DHM observation, data from a high-elevation automatic weather station (AWS) located at the Everest region (27.95°N to 86.20°E, 5050 masl), pyramid was also used. The precipitation amounts observed from these stations were manually collected; therefore, subjected to personal and instrumental errors. In total, 142 daily gauge observations evaluate the TRMM product's accuracy was further subjected to quality control. For strict quality control, examination of erroneous values and discarded questionable data, amongst others, was applied to ensure a high quality of the rain gauge data. The data available at each station is presented in Table S1. The geographic location of the selected stations is presented in Fig. 1.

TRMM product

TRMM was the first space mission dedicated to the quantitative measurement of rainfall. It was jointly launched by the NASA and JAXA on 28 November 1997 (Huffman *et al.*, 2007) to monitor and estimate the tropical and subtropical precipitation and estimate its associated latent heating, respectively. The rainfall measuring instruments on the TRMM satellite include the

Precipitation Radar (PR), an 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 (Huffman *et al.*, 2007). The seventh version of the 3B42 algorithm (3B42 V7), available since 22 May 2012, incorporated several significant changes compared to its predecessor (3B42 V6). In addition to the previous version's data, the 3B42 V7 algorithm uses new data sources to enhance the rainfall estimations.

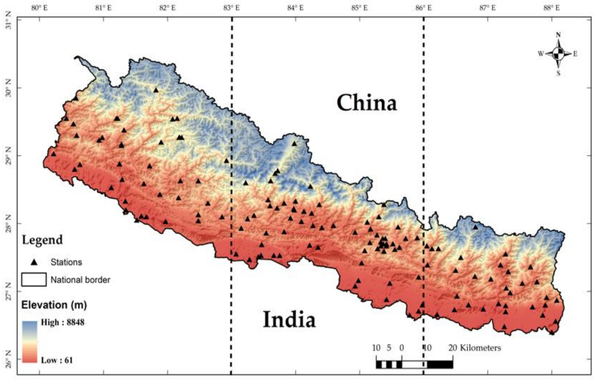

Fig. 1. The study area Nepal and distribution of 142 meteorological stations (black dotted line separates the western, central, and eastern regions)

This study used the daily TRMM 3B43-V7 precipitation product with a spatial resolution of 25 km, between January 1998 and December 2018. The TRMM–3B43 is a merged precipitation product based on a combination of microwave, infrared, and radar information from TRMM and other precipitation-relevant satellite sensors, infrared data from geostationary satellites (TRMM multi-satellite), and ground-observed data merged in the Global Precipitation Climatology Centre (GPCC) (Anjum *et al.*, 2016; Hence & Houze Jr, 2012; Jiang *et al.*, 2012).

Methodology

TRMM precipitation product is a 25x25 gridded dataset, and the observed datasets are at the point scale. To compare the point-based observed data with the gridded precipitation datasets, a point-to-pixel comparison method (Bai & Liu, 2018; Thiemig *et al.*, 2012) was used to avoid errors gridding the observed precipitation data. It is common practice in evaluation studies to compare the point-based observed precipitation data against the gridded satellite precipitation product. For this, the precipitation values from each rain gauge and the grid where the same gauge is located were extracted in pairs for evaluation. To compare the TRMM with the observed precipitation data set, it was also necessary to have the same temporal resolution.

Meanwhile, the precipitation rate from TRMM was multiplied by corresponding times to the obtained precipitation amount, which was on the same time scale as observed precipitation data sets. The monthly, seasonal, and annual precipitation data were obtained by accumulating the daily precipitation. Some of the station data do not feature regular data. Quality control was conducted for data consistency; if the observed daily data contain missing values, then the corresponding daily TRMM data was also considered a missing value. The monthly data were computed when the station has more than 25 days of precipitation data available in a month; otherwise, the precipitation in a particular month was considered a missing value. The monthly TRMM data were also considered a missing value for consistency if the corresponding monthly data were missing from the observed datasets.

Statistical analysis

Several statistical metrics (equations 1–5) were calculated to quantify the accuracy or discrepancy between observed and estimated precipitation from TRMM data sets daily, monthly, seasonal, and annual timescales. The correlation coefficient (R, Eqn. 1), measured the strength and direction of a linear association between datasets, root mean square error (RMSE, eqn. 2), depicted the mean, standard deviation of prediction from TRMM product as a reference to observation. The mean error (ME, eqn. 3) estimated the positive and negative errors of the TRMM. The bias provides the average tendency of the TRMM to be larger or smaller in percentage than their corresponding observed datasets (eqn. 4). Here, NSE is a normalized statistic used to define the residual variance's relative magnitude compared to measured data variance. The excellent and poor estimation ability was indicated by positive and negative values, respectively (eqn. 5). The formula of statistical metrics was defined using the following equations:

$$\mathrm{R} = \frac{\sum_{i=1}^{n}(O_i-\bar{O})(E_i-\bar{E})}{\sqrt{\sum_{i=1}^{n}(O_i-\bar{O})^2}\sqrt{\sum_{i=1}^{n}(E_i-\bar{E})^2}} \quad (1)$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(E_i-O_i)^2}{n}} \quad (2)$$

$$\mathrm{ME} = \frac{1}{n}\sum_{i=1}^{n}(E_i - O_i) \quad (3)$$

$$\mathrm{Bias} = \frac{\sum_{i=1}^{n}(E_i-O_i)}{\sum_{i=1}^{n}O_i} * 100 \quad (4)$$

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}(O_i-\bar{O})^2-\sum_{i=1}^{n}(E_i-O_i)^2}{\sum_{i=1}^{n}(O_i-\bar{O})^2} \quad (5)$$

Where, *O* is the observed data, *E* is the estimated precipitation by TRMM product, and *n* is the sample size.

RESULTS

Spatial distribution of precipitation

The spatial distribution of mean annual precipitation in observed and TRMM data sets was analyzed from 1998 to

2018 and presented in Fig. 2. The country's complex topographical setting with monsoon and westerly weather systems lead to high spatial precipitation heterogeneity. Meanwhile, the precipitation was mainly affected by two major systems: the monsoonal precipitation from the Bay of Bengal and Western disturbance. During the winter season, the western disturbances affect the country's western parts and snowfall in the high mountains and the Himalayas. In general, the country's eastern and central regions receive more precipitation than the western region due to the south Asian summer monsoonal system. The windward side of the mountains (Lumle) received the highest precipitation (>3000 mm/year), while the leeward side (Mustang) received the lowest precipitation (<500 mm/year) (Fig. 2a). The highest and lowest precipitation within the same Central region reflected precipitation contrast between mountain slopes and river valleys. The TRMM precipitation moderately captured the observed spatial pattern; however, it failed to capture the orographic effect of the south-north precipitation distribution, as shown in Fig. 2(b). Further, the TRMM product showed a high precipitation (~2200 mm/year) in the central region's low elevation areas, with the highest precipitation (~2800 mm/year) in the lower eastern range region. Interestingly, the TRMM product also showed a high precipitation in the Arun Valley and its surrounding areas, where only one DHM station is located. Generally, these valleys were considerably wetter than the surrounding slopes. The TRMM product showed less than 500 mm/year at high-elevation areas (leeward side) of the country, indicating that the TRMM precipitation product can capture the overall spatial distribution of mean annual precipitation in Nepal.

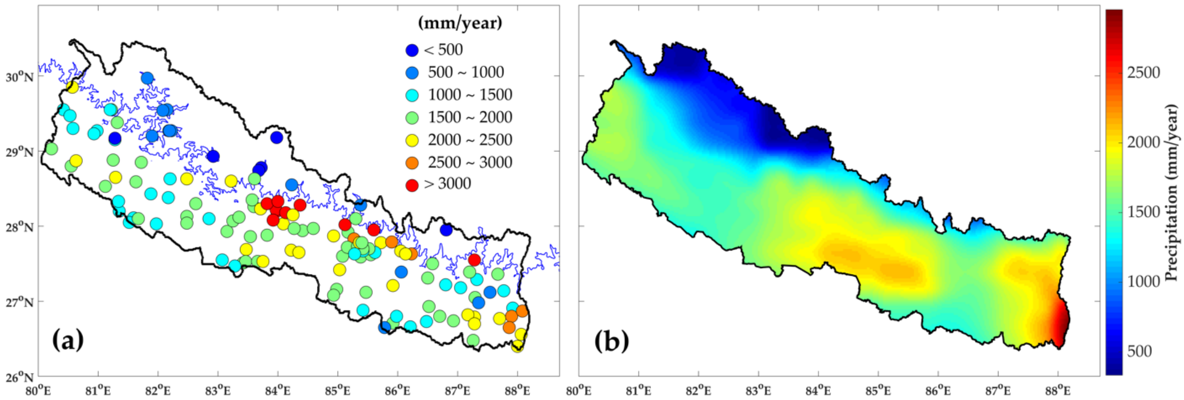

Fig. 2. Spatial distribution of mean annual precipitation (mm/year) in observation (a), and TRMM product (b) during 1998–2018 (color bar represents the precipitation in mm/year)

Temporal distribution of precipitation

The monthly cycle, bias, and interannual precipitation distribution over the study region between 1998 and 2018 are presented in Fig. 3. A considerable overestimation was observed during the pre-monsoon season, mainly in April and May. As the pre-monsoon end, precipitation initially increased with peak precipitation ~ 475 mm in June and later slightly decreased in July, August, and September, as depicted in Fig. 3(a). Further, the monsoon season contributed to the highest portion of annual precipitation, followed by the pre, post, and winter season. TRMM product also showed a similar monthly cycle as an observation; however, large underestimation was observed during the monsoon season compared to other seasons (Fig. 3a). Similarly, the bias map (Fig. 3b) also confirmed the large error in the TRMM product during the monsoon season. It is worth mentioning that the large bias was observed during the monsoon season and more pronounced after 2007.

Moreover, a distinct performance difference was observed in the interannual time series between observation and TRMM product with a smaller and larger error before and after 2007 (Fig. 3c). The highest negative and positive bias was observed in June 2016 and May 2011, with a value of -139.3 and +71.21, respectively (Fig. 3b). The TRMM product uses some of the gauge observations from DHM. A number of calibrated gauge stations were fluctuating during recent years, which might be the reason for apparent bias in the recent years. Overall, the TRMM product showed very consistent temporal characteristics with observation during the study period, indicating that the TRMM product can represent the monthly precipitation cycle and interannual variation of observed datasets in Nepal.

To analyze the seasonal performance of TRMM datasets, statistical metrics were calculated and presented in Table 1. Monsoon season is the wettest season since it contributes 80% of the annual precipitation. TRMM product showed a large ME of -19 mm/month and RMSE of 147 mm/month during monsoon season. However, overall underestimation was ~1 % and ~3 % smaller than the post and winter season, respectively. During the post and winter season, precipitation mostly occurs in the form of snow. TRMM products are less capable of capturing solid precipitation than the rainfall, as indicated by larger bias. Further, the TRMM product showed better overall performance during the winter season as indicated by smaller ME, RMSE, NSE, and higher CC values in Table 1; however, underestimation was higher. Most of the DHM gauge in high-elevation areas only record total precipitation (rainfall + snowfall), which might cause more considerable underestimation during the winter season. Overall, the TRMM product underestimated the observed precipitation (negative bias values in Table 1); however, it capture the overall seasonal and annual precipitation patterns during the study period.

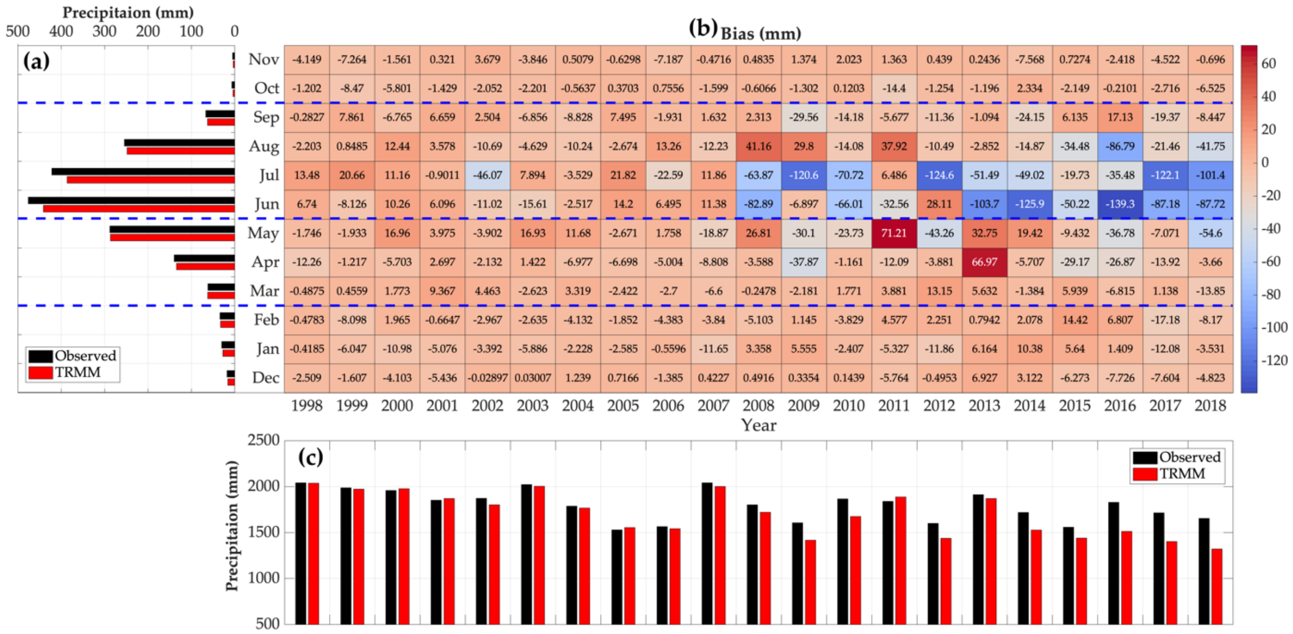

Fig. 3. (a) monthly precipitation cycle, (b) Bias (mm) in TRMM product at each month for the study period, and (c) interannual precipitation variation in TRMM and observed datasets average over the country (a blue dot line separates the different seasons)

Table 1. The spatial performance of TRMM products for different seasons averaged over the study region during the study period

Season	CC	ME (mm/month)	RMSE (mm/month)	Bias (%)	NSE	Mean (mm/month)
Pre-monsoon	0.67	-1.88	32.54	-2.35	-0.75	77.95
Monsoon	0.49	-19.25	147.43	-5.42	-3.05	335.98
Post-monsoon	0.44	-2.57	19.42	-6.53	-1.63	36.81
Winter	0.75	-1.23	4.97	-8.45	0.25	13.36
Annual	0.51	-7.99	61.25	-5.15	-2.55	147.14

The trends of mean annual and seasonal precipitation in observed and TRMM products for the period 1998–2018 are shown in Fig. 4. A significant decreasing trend was observed in pre-monsoon, monsoon, and post-monsoon precipitation series at different confidence intervals. The decreasing trend of precipitation was observed during the pre-monsoon season at the rate of -0.04 mm/day, as revealed by both gauge observation and TRMM data sets, as shown in Fig. 4(a). An apparent difference in trend rate was visible for observed and TRMM during the summer season with -0.012 mm/year, which indicated that TRMM showed a larger decreasing trend of precipitation in Nepal (Fig. 4b). The interannual variation of precipitation and decreasing trend values were almost similar for the post-monsoon season (Fig. 4c). The observed dataset showed a decreasing trend with -0.01 mm/day, whereas the TRMM has no trend for the winter precipitation; moreover, both the trends were not significant, as shown in Fig. 4(d). On an annual basis, the country's precipitation series showed a significant decreasing trend with a rate of -0.06 mm/day and -0.11 mm/day in gauge observation and TRMM product, significant at 99 % and 95 % confidence interval respectively, during the study period (Fig. 4e). Similar to Fig. 3(c), the large fluctuations between observed and TRMM products in seasonal and annual timescale occurred after 2007.

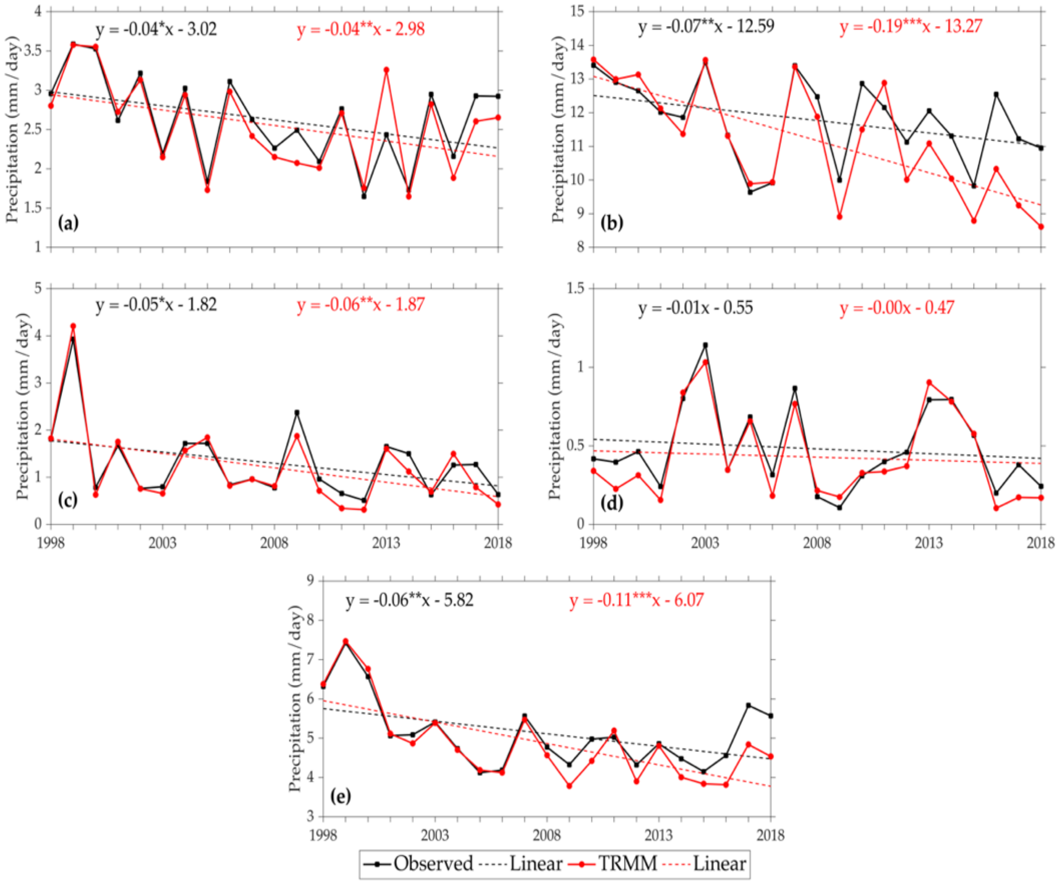

Fig. 4. Temporal distribution of precipitation and trend for (a) pre-monsoon, (b) summer monsoon, (c) post-monsoon, (d) winter, and (e) annual timescale (black and red dash line represents the linear trend during the study period; symbol *, ** and * denotes the statistical significance at 99 % (p<0.01), 95 % (p<0.05) and 90 % (p<0.1) confidence interval, respectively)**

DISCUSSION

Satellite-based precipitation products generally depend on cloud cover infrared observations, a combination of passive microwave and rainfall radar data (Kummerow *et al.*, 1998). Recent advancement in satellite-based rainfall estimates improved its performance at high spatial resolutions with homogeneous coverage (Huffman *et al.*, 2010, 2007). TRMM rainfall estimates were found to be inconsistent with the ground-based DHM rainfall measurements at some locations. Further, the TRMM product moderately captured the general characteristics of the observed spatial pattern of precipitation in Nepal. However, the study region's complex topographic nature significantly influenced the TRMM product's performance and showed a slight shift in high-rainfall hotspots (Cattani *et al.*, 2016; Dinku *et al.*, 2007; Wang *et al.*, 2019). Most of the high-elevation areas are snow-covered during the winter season and cold weather complicated the surface emissivity patterns, which may be falsely detected as precipitation by passive microwave sensors used in TRMM satellites (Sharma *et al.*, 2020d). The passive microwave sensors were also found inefficient in resolving the orographic enhancement in the liquid phase over highly uneven terrain (Dinku *et al.*, 2010; Shige *et al.*, 2013). Since the Himalayan area of the study region is characterized by all such climatic and topographic features, the inferior performance of satellite-based TRMM precipitation estimates over the study region may be attributed to the limited retrieval ability to exist passive microwave sensors and algorithms used to convert microwave signals into precipitation estimates.

With the influence of the Asian Summer Monsoon and westerly disturbances, precipitation varied seasonally over the country (Pokharel *et al.*, 2019). The monsoon season contributed 80 % of the annual precipitation, followed by the pre, post, and winter (Hamal *et al.*, 2020a; Sharma *et* *al.*, 2020b). Although the TRMM precipitation product generally underestimated observed precipitation, it showed a very consistent monthly precipitation cycle. Further, the underestimation was more prominent during the post-monsoon and winter season when precipitation occurs in the form of snow. TRMM precipitation products were less reliable to estimate solid precipitation, especially during the winter season. Moreover, the DHM rain gauge measurement was minimal over the country's mountainous region and was mostly located at the valley bottom (Barros *et al.*, 2000; Sharma *et al.*, 2020a), which may not represent the actual climatology of the Himalayan region. Further, these locations were significantly drier than high-elevation areas (Menegoz *et al.*, 2013). The inferior performance of TRMM over the regions with high snow content and complex terrain was discussed in many studies (Gebregiorgis & Hossain, 2012; Milewski *et al.*, 2015; Sakolnakhon, 2013). Additionally, scattering of microwave signals in snow-covered regions, the sensitivity of TRMM Microwave Imager to sub-freezing temperature, multiple scattering of microwave signals in mountainous terrain might be additional reasons for uncertainties in TRMM product. Such uncertainties in observation may lead to performance differences between observation and TRMM precipitation products. Furthermore, the underestimation of observed precipitation by TRMM precipitation product was evident in earlier studies and such underestimation might be related to the insufficient spatial coverage of the gauge station (Sharma *et al.*, 2020d). TRMM precipitation product was corrected using a gauge-based precipitation product (i.e., GPCC), and the performance was not uniform during the study period. From frequent update in rainfall retrieval algorithms and fluctuation in the number of calibrated gauge station, TRMM precipitation product showed distinct performance difference before and after 2007. TRMM product showed reliable performance before 2007, while error occured after 2007. Further, large scale local climatic variation might be another factor to characterize the uncertainty in TRMM precipitation product (Gebregiorgis & Hossain, 2013).

TRMM precipitation product was calibrated using gauge based monthly GPCC datasets (Becker *et al.*, 2011). However, these datasets were calibrated only for those areas where rain-gauge data were available. Hence, the TRMM product performances were also influenced by the quality and temporal range of the adjusted gauge-based GPCC product. Although the gauge density was minimal in the mid and high elevation areas, TRMM products performed very well in representing the monthly and seasonal precipitation patterns (Fig. 3 and Table 3). Additionally, a scatter plot was plotted, and statistics matrices compared the daily and monthly performance TRMM products (Fig. 5). As TRMM products were calibrated as monthly timescale, it showed slightly better performance (higher R) for monthly estimates than the daily timescale. Further, consistent performance on daily timescale reflected improved precipitation retrieval algorithms of the TRMM product.

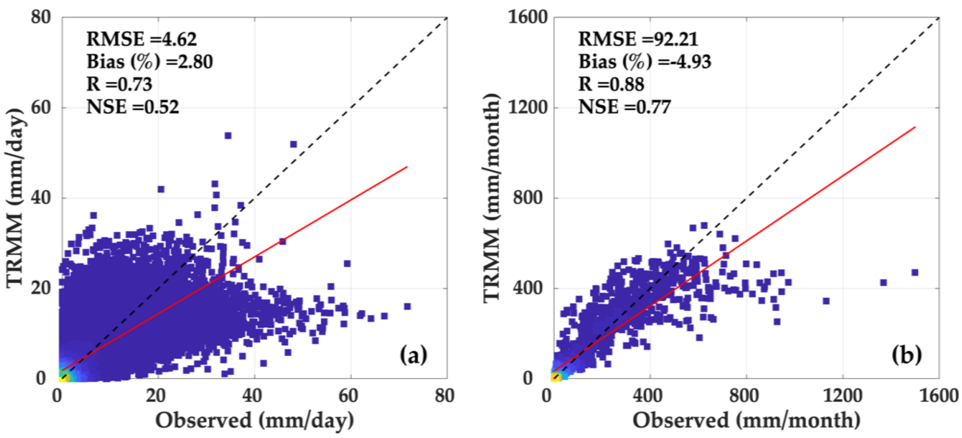

Fig. 5. Scatter plot between observed and TRMM based on (a) daily and (b) monthly timescale average over the study period. Statistical matrices summarized the performance on a daily and monthly scale (red and **black dotted line represents the regression and 1:1 line, respectively)**

SUMMARY

Remotely sensed rainfall estimation has proven to be a potential alternative to a ground-based rainfall measurement as satellite-based rainfall measurements have high spatial and temporal coverage. The present study evaluated the spatio-temporal characteristics and its trends using TRMM precipitation product (3B43-V7) against 142 rain gauge-based precipitation measurements over Nepal during the recent last two decades. Precipitation varied spatially and seasonally over the country, with the highest (lowest) precipitation observed in the windward (leeward) side of the central region.

TRMM product moderately captured the observed spatial pattern; however, it slightly underestimated the mean annual precipitation during the study period. It was also noted that TRMM product was less reliable to estimate precipitation amounts during the winter season, especially when precipitation occurred in the form of snow. TRMM precipitation product well captures the seasonal variation of observed precipitation with the highest correlation in winter season followed by a pre-monsoon, monsoon, and post-monsoon season. A decreasing seasonal and annual trend was found in both observed and TRMM product. The highest decreasing trend was observed during the monsoon season, with the lowest in the winter season. The discrepancy in precipitation estimates also varied spatially, whereas TRMM precipitation estimates' performance was relatively weaker during the dry season. Moreover, TRMM precipitation products can be good alternatives to DHM observation for Nepal's hydro-meteorological studies. Further, this study on the spatial and temporal variability of precipitation and its trend over Nepal will select TRMM products for future hydro-meteorological applications in the neighboring mountainous areas.

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CONFLICTS OF INTEREST

There is no conflict of interest among the authors.

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