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Rainfall over the Himalayan foot-hill region: Present and future

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Uttarakhand, one of the Himalayan foot-hill states of India, covers an area of 51,125 km^2. This region is enriched with bio-diversity and is one of the highly potential regions in the Central Himalayas for agro-climate, hydro power generation, food-processing, tourism, etc. Present study investigates the spatio-temporal rainfall distribution over the state during Indian summer monsoon period. Observational and modelled (under different Representative Concentration Pathways (RCPs) at radiative forcing 2.6, 4.5 and 8.5 W/m^2) rainfall distribution is studied to assess the present and future trends. Study uses standard observational rainfall estimates from APHRODITE, Tropical Rainfall Measuring Mission (TRMM 3B42) and India Meteorological Department (IMD) gridded rainfall datasets and inter-compare these products in order to find out orographic responses during the monsoon months and elevation dependent mean rainfall pattern changes. It is found that rainfall pattern breaks near 3100 m elevation. Comparative analysis reflects that with respect to IMD, TRMM 3B42 rainfall underestimates more than 3 mm/day rainfall whereas, APHRODITE overestimates rainfall below 4.5 mm/day. Future trends in modelled monsoon rainfall are examined and mixed results are found and discussed with possible explanation.

Keywords. Uttarakhand; rainfall; topography; trends.

1. Introduction

Understanding the rainfall processes and its spatio-temporal variability over the Indian sub-continent is very crucial for a wide range of applications viz., agriculture, water resource management, hydrological purpose etc. India gets about 80% of total annual rainfall during June–September (JJAS) summer monsoon season (Ghosh *et al.* 2009). The seasonal migration of the inter-tropical convergence zone (ITCZ), which is a manifestation of a wind reversal process in the monsoon region, plays an important role in the generation and development of the Indian Summer Monsoon (ISM) (Gadgil 2003). The strength of the summer monsoon rainfall decreases when it reaches the northern part of India specifically, the Western and Central Himalayas from east to west along its trajectory (Basistha *et al.* 2007).

The study region (figure 1) Uttarakhand is located at the foot-hills of the Central Himalayas encompassing geographic location from 28°N–31.5°N and 77.5°E–81.4°E. The total geographical area of the state is 51,125 km^2 and out of which 93% is mountainous, 65% is covered by forest and glaciers are found at the higher elevations. Geographically, the state can be divided into four regions: Terai and Bhabar (175–600 m), Shivalik

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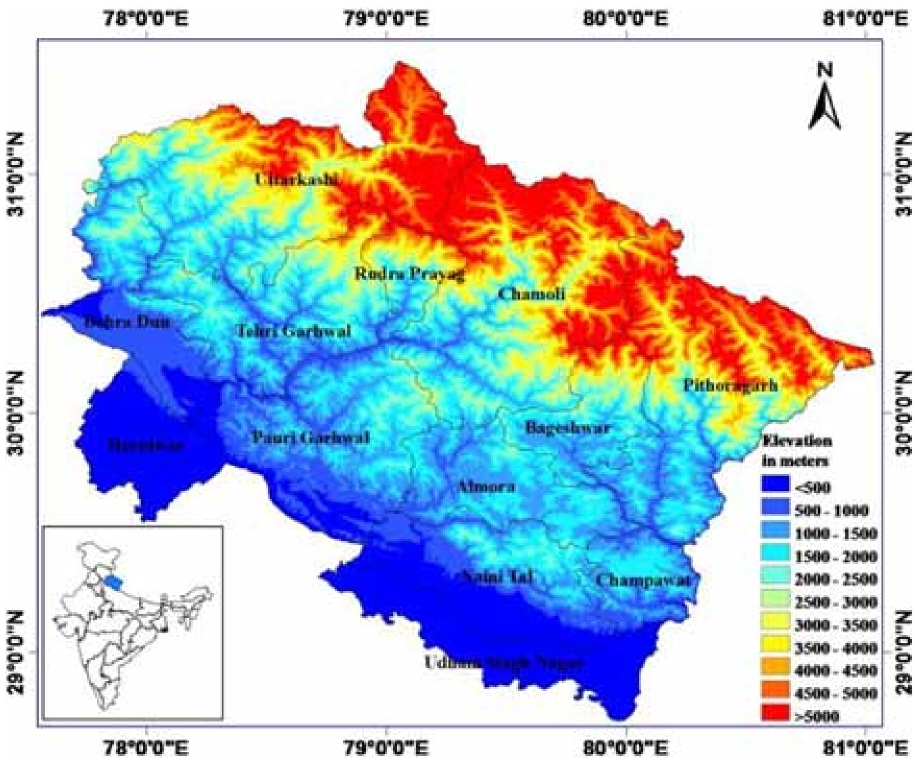

Figure 1. The topography (m) of Uttarakhand.

(600–1200 m), Lesser Himalaya (1200–3000 m) and Greater Himalaya (3000–7000 m). The climate of Uttarakhand can be distinguished into two divisions: the major hilly terrain and smaller lower plains. It receives 80% of annual rainfall during ISM (JJAS). The state receives an average rainfall of 1494.7 mm and is highly proned to extreme rainfall events during JJAS (Das *et al.* 2006).

Earlier studies attempt to remark on annual rainfall over entire country excluding the Himalayan region because of non-availability of data due to inadequate rain-gauge, weather observatory and Doppler radar over the mountainous terrain (Basistha *et al.* 2009; Kumar *et al.* 2010; Singh and Mal 2014). Understanding the rainfall variability at various scale and identifying the mechanism behind it is utmost important for climate research. Additionally, water resources in mountainous region are important, mainly for the Western and Central part of Himalayas. In such areas, characteristics of orographic precipitation on monthly scale is important for use in hydrological models for simulated precipitation by high resolution climate models.

Present study focuses on the Uttarakhand region to provide comprehension in changing rainfall patterns. This study is specifically cut out for the effort under National Mission on Himalayan Studies conceptualized under the Ministry of Environment, Forest and Climate Change, Govt. of India. Results will enable for policy–planners–governance to decide upon the extreme events (floods, cloudbursts, landslides, etc.) and adaptation.

1.1 *Rainfall pattern*

Sen Roy and Balling (2004) found increasing trend over different parts of the Western Himalayas (WH) and also some parts of Uttarakhand by using daily rainfall data for 1910–2000 period from 129 stations. Kumar *et al.* (2005) analysed rainfall data for the period 1901–1984 at 11 different locations of Himachal Pradesh and observed increasing trend in annual rainfall at eight locations. Ramesh and Goswami (2007) observed decreasing trend in early and late monsoon rainfall over India using daily rainfall data for the period 1951–2003. Study by Dash *et al.* (2007) indicated decreasing tendency in JJAS rainfall over India. Another study by Pattanaik (2007) found decreasing trend in JJAS rainfall over northwest India during 1941–2002. Analysing rainfall data of 80 yrs from 30 rain-gauge in Indian Himalayan region, Basistha *et al.* (2009)

observed an increasing trends between 1901 and 1964 and a decreasing trend between 1965 and 1980. Another study by Ghosh *et al.* (2009) found important spatio-temporal and inter-seasonal variation in the trends and rainfall variability in India. Naidu *et al.* (2009) observed notable negative trend of JJAS rainfall in northern India and increasing trend in southern India. Using daily gridded data for 1951–2003 period, Krishnamurthy *et al.* (2009) found significant increasing and decreasing trends in extremes of rainfall over different parts of India. Kumar *et al.* (2010) analysed rainfall data for 1871–2005 periods and identified no significant rainfall trends on all-India basis; whereas, Pal and Al-Tabbaa (2010) found decreasing trends in JJAS rainfall and increasing trend in DJF rainfall for the period 1954–2003 over India. Singh and Mal (2014) analysed ground based data from six stations of Uttarakhand for detection of trend and long term rainfall variability, and observed that different stations showed different trends. Previous studies depict decrease in rainfall pattern as one moves from southern Himalayan foothills to higher elevations northwards (Singh and Mal 2014).

With limited studies over the Indian Himalayan states, trend analysis of rainfall over mountainous states is felt urgent and need to pay attention due to significant implications on agriculture, food security, water management as well as economic activities and etc. (Dore 2005; Kumar *et al.* 2010).

1.2 *Elevation dependency*

The small scale rainfall patterns are most likely to be driven by local weather phenomena, orographic factors and physiographic conditions. Therefore, the micro-level rainfall statistics should be well known in view of the trends and variability of the large scale rainfall patterns.

Several previous studies reported that there is a linkage between elevation and meteorological variables, such as temperature and rainfall. Relationship between topography and rainfall are complex over the Himalayan region and better understanding on triggering mechanism by orography is thus of utmost important to understand rain-bearing processes over different sectors of the Himalayas. Rainfall usually increases with altitude only up to a certain elevation, and decreases thereafter (Singh and Kumar 1997; Shrestha *et al.* 2012). However, elevation alone is not the only factor for orographic rainfall, as the geometry of topography, i.e., slope, aspect, hill-shade, continentality etc. and orographic folds play crucial roles in orographic enhancement of rainfall (Smith 1979; Anders *et al.* 2006). No previous study is found over Himalayas that relates the elevation with rainfall.

1.3 *Satellite remote sensing of rainfall*

In Himalayas, there is undulating topography, and paucity of ground based observatory (rain-gauge and radar network) are very sparse to get accurate measurements of rainfall information. In particular, it is important to mention the deficit of observatories beyond 2000 m. The observations at higher Indian Himalayan region is very sparse and simultaneously influence from and to other neighbouring nations at large scale in the IMD observation is inhibited. Owing to understand large scale flow and associated manifestation over the bordering Indian Himalayan region is thus elusive. Present work and corresponding analysis, thus, corroborates these factors above 2000 m in segmentation manner using other observations viz., TRMM and APHRODITE and compare with the IMD observations. These findings in a way provide an added comprehension over the data sparse Himalayan foothill region. In addition, analysis on elevation dependent distribution as analyzed provide a kind of information which otherwise either is absent or elusive. Thus, advancements of meteorological satellite and improvements in algorithm for rainfall estimation techniques provide ample scope to study rainfall events (REs); which play crucial role in flood forecasting, weather monitoring, numerical weather models and etc. Tropical Rainfall Measuring Mission (TRMM) is a joint collaboration between NASA and JAXA that first dedicated a meteorological satellite to study rain structure and monitor precipitation distribution from tropical belt to the sub-tropical region (NASDA 2001). Since December 1997, it provides precipitation data (inter-calibrated) at fine spatio-temporal coverage. Latest release of version 7 (V7) data offers better rainfall estimates over previous versions with significantly lower bias over complex topography (Huffman *et al.* 2010; Zulkafli *et al.* 2014). Present study uses multi-satellite rainfall estimates from TRMM 3B42 algorithm to investigate it's strength and weakness in rainfall retrieval during summer monsoon period and inter-compare the result with APHRODITE and IMD rainfall estimates.

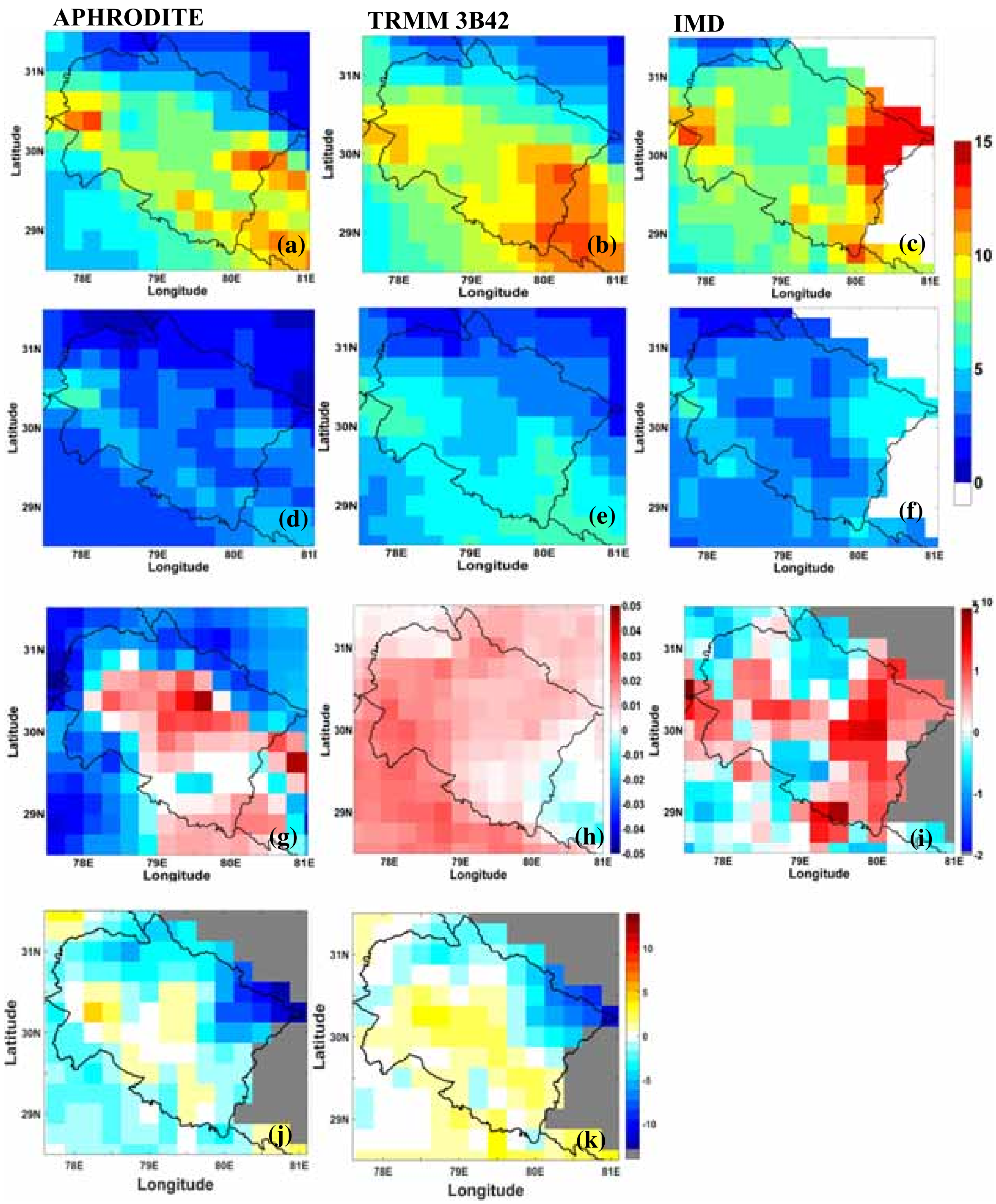

Figure 2. Monsoon rainfall from different estimates for Uttarakhand. **(a–c)** are mean rainfall estimates from APHRODITE (1970–2007), TRMM 3B42 (1998–2013) and IMD (1970–2010), respectively, where **(d–f)** are standard deviation for the same. Color bar indicates rainfall in mm/day. **(g–i)** are trends of rainfall estimates from APHRODITE, TRMM 3B42 and IMD for Uttarakhand for monsoon (JJAS) season. Color bar indicates trends in rainfall in mm/day/year. **(j, k)** shows bias in APHRODITE and TRMM 3B42 rainfall estimates with respect to IMD. Color bar indicates rainfall bias in mm/day and no data region corresponding to IMD are shown in grey color.

The motivation of the study is to examine present rainfall from three standard observational datasets and future rainfall scenarios from model simulation for the Himalayan foot-hill state of Uttarakhand. Specifically, study address the following research aims:

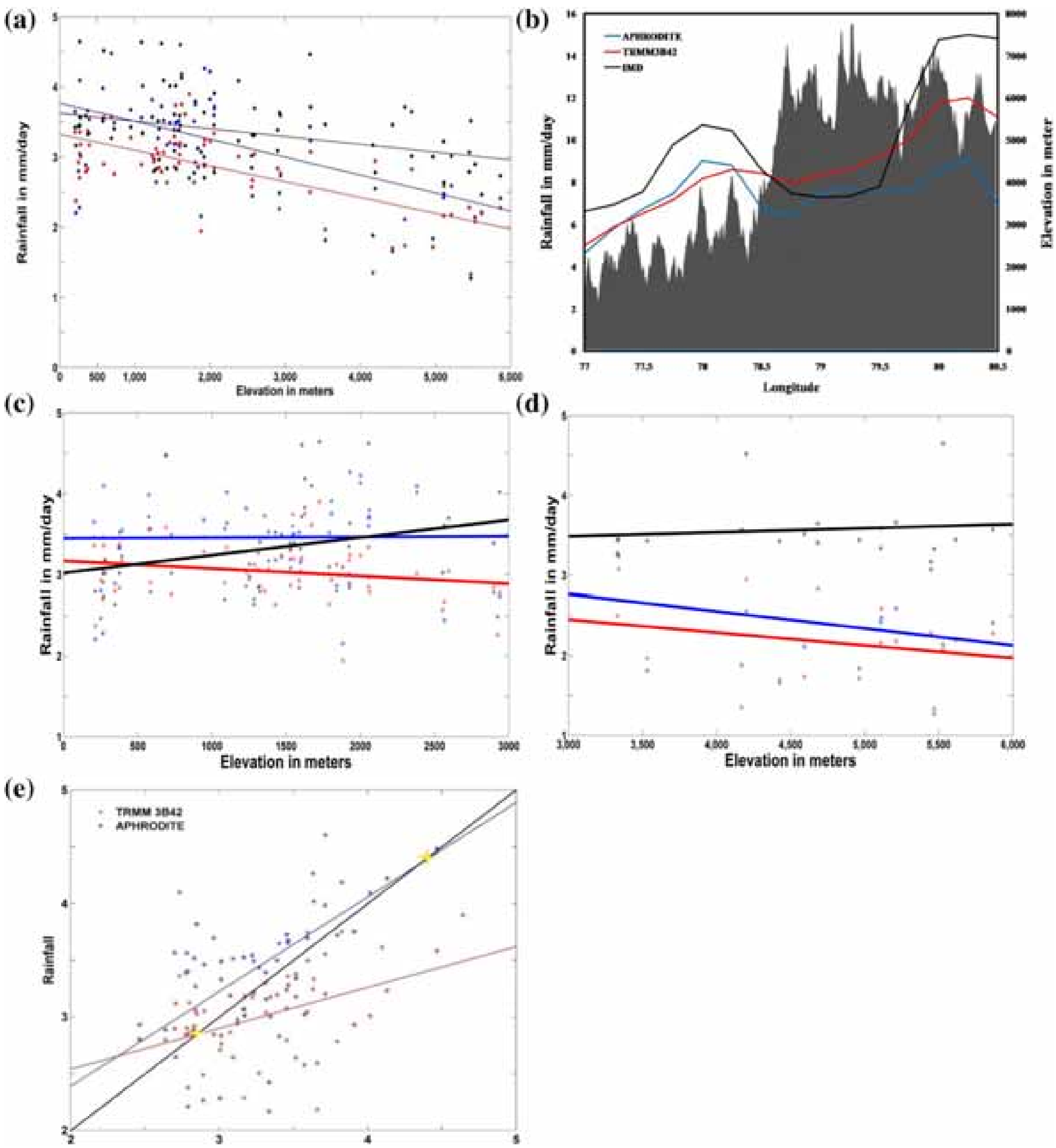

Figure 3. (**a**) Elevation *vs.* rainfall for Uttarakhand. Blue line indicates the trend of rainfall as estimated from APHRODITE, red line is for TRMM 3B42 and black line is for IMD. (**b**) Two-step topography of Uttarakhand. Blue line represents APHRODITE, red line represents TRMM 3B42 and black line for IMD rainfall estimates. (**c** and **d**) represents break-line near 3100 m. (**e**) IMD *vs.* others (TRMM 3B42 and APHRODITE) rainfall estimates over Uttarakhand for monsoon (JJAS) season. Blue line indicates the trend of rainfall for APHRODITE while red for TRMM 3B42. Black line is the diagonal. Yellow stars indicates TRMM 3B42 underestimates rainfall above 3 mm/day with respect to IMD estimation and APHRODITE overestimates rainfall below 4.5 mm/day with respect to IMD rainfall estimation.

- To investigate present climate over the state of Uttarakhand.
- To assess how rainfall is related to the orography of the state.
- To examine the extent to which future rainfall will change under different climate scenarios from model.

The paper is divided into 4 sections. Section 2 describes the datasets used and methodology adopted in this study. Section 3 presents the results with discussion and in section 4, we discuss these results and its impacts under future climate of the state.

2. Data and methodology

The different datasets and methodologies used in this study are discussed in this section precisely. For the present study, we have taken IMD as a benchmark data and inter-compare it with the other two observational datasets over the study region.

2.1 *Datasets*

Study uses different standard rainfall datasets that are discussed briefly here.

2.1.1 *APHRODITE data*

Present study uses APHRODITE (V1101R2) data of 0.25° spatial resolution at daily scale for 1970–2007 period over Uttarakhand and sub-regions. The datasets are prepared basically with data obtained from thousands of rain-gauge-observation network across Asia. The data was procured using the basic algorithm of Xie *et al.* (2007). This product interpolates the ratio of daily precipitation to daily climatology and provides better representation of the orographic precipitation pattern in the Himalayan region. The daily data set is available at http://www.chikyu.ac.jp/precip/. For details of the product and interpolation technique used in the procurement of this novel datasets, Yatagai *et al.* (2012) may be referred to. It is considered as one of the best research products for climate analysis over the Himalayan sub-regions.

2.1.2 *TRMM 3B42 data*

TRMM 3B42 is a multi-satellite based rainfall retrieval algorithm that provides rainfall estimates from geostationary infrared and microwave observations and is available from January 1998–2015 in gridded format from 50°S–50°N geographic location at 0.25° spatial resolution at 3-hourly, daily and monthly time scale. Present study utilizes 3-hourly and daily data from 3B42 algorithm, which provides rainfall estimates by merging high resolution IR precipitation and root-mean-square (RMS) precipitation error estimates (Huffman 2013 and references therein). The combine instrument rain calibration algorithm (3B42) uses an optimal combination of 2A12, 2B31, SSMI, AMSR and AMSU precipitation estimates to adjust IR estimates from geostationary IR observations. V7 data is considered as improvement over its previous versions specifically over the Himalayan foothill region and highly recommended for research work (Huffman and Bolvin 2014). The research quality data of TRMM 3B42 V7 are downloaded from the website link: http://disc2.nascom.nasa.gov/tovas/.

2.1.3 *IMD rainfall data*

IMD gridded rainfall product (0.25°×0.25°) is used in this study to validate the rainfall estimations over Uttarakhand. These quality dataset are procured by using 6995 rain-gauge stations in India for 1901–2013 (113 yrs). For the preparation of the high resolution gridded data at daily scale, on an average, about 3500 stations that varied between 1450 and 3900 were used. Different standard quality checking tests were applied on the datasets before the interpolation of the station-level rainfall data on to fixed spatial grid points. For the interpolation, the study used the Inverse Distance Weighting (IDW) interpolation scheme. The

Table 1. *Elevation vs. rainfall estimates over Uttarakhand.*

Rainfall products	Slope	Intercept	Correlation	RMSE
APHRODITE	−0.00026	3.8	0.28	0.666
TRMM 3B42	−0.00022	3.3	0.45	0.40
IMD	−0.00011	3.6	0.12	0.47

Table 2. *Break line analysis.*

Elevation break	Rainfall	Slope	Intercept	Sample size
Elevation < 3100 m	APHRODITE	0.0000082	3.4	55
	TRMM 3B42	−0.000094	3.2	55
	IMD	0.00022	3	55
Elevation > 3100 m	APHRODITE	−0.00021	3.4	17
	TRMM 3B42	−0.00016	2.9	17
	IMD	0.00005	3.3	17

spatial distribution and/or characteristics of rainfall in heavy rainfall areas and orographic regions is better represented using these dataset due to the higher spatial resolution and density of the network stations (Pai *et al.* 2013, 2014).

2.1.4 *REMO data*

The Regional Climate Model (REMO), a three-dimensional hydrostatic model of the atmosphere, is one of the Regional Climate Models (RCMs) used in Coordinated Regional Climate Downscaling Experiment – South Asia (CORDEX-SA). The model was developed at the Max Planck Institute under the advancement of German BALTIC Sea Experiment (BALTEX) as an atmospheric component of the coupled atmosphere-hydrology model system (Jacob *et al.* 2001; Engelhardt *et al.* 2017). Further details on REMO model is available at http://www.remo-rcm.de. Previous studies have shown comparatively better performance of CORDEX–REMO model over the Indian Himalayan Region (IHR) and reported with biases (Jacob *et al.* 2012; Dimri *et al.* 2013; Engelhardt *et al.* 2017). Present study used CORDEX–REMO data of 0.50° spatial resolution for historical period (1970–2005) and for future scenarios (2006–2100) using the three Representative Concentration

Table 3. *IMD vs. others (APHRODITE, TRMM 3B42) rainfall estimates.*

Rainfall with IMD	Slope	Intercept	Correlation	RMSE
APHRODITE	0.83	0.72	0.41	0.4725
TRMM 3B42	0.36	1.8	0.20	0.3404

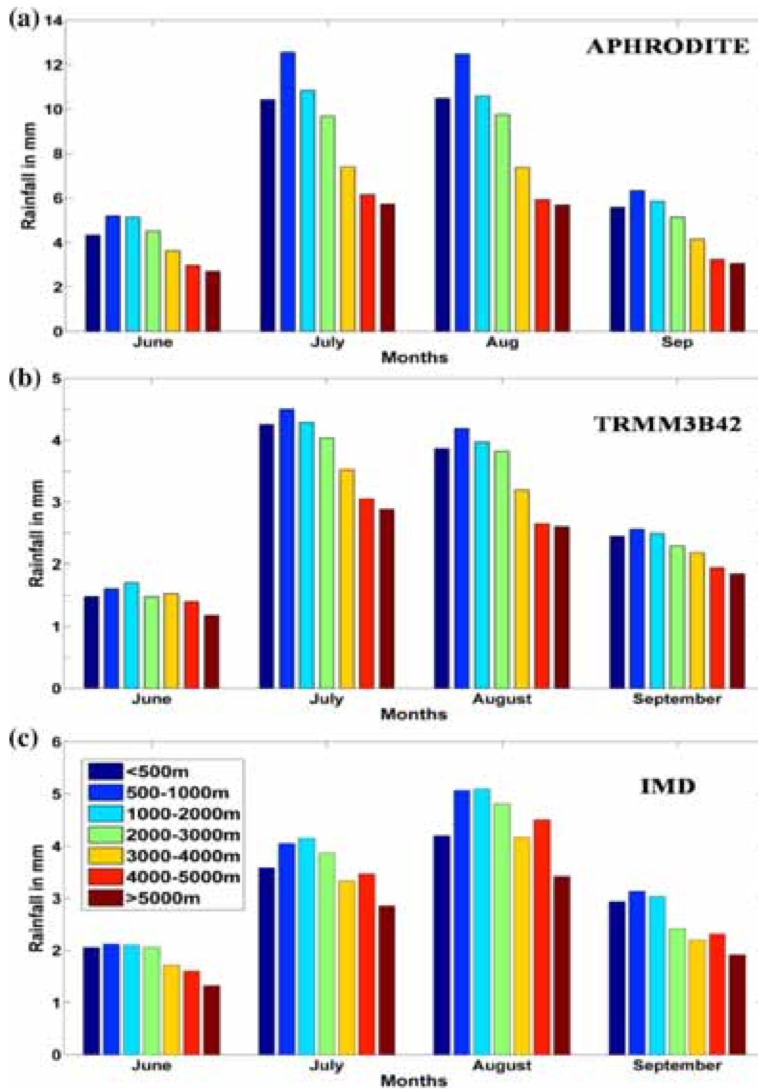

Figure 4. Mean monsoon rainfall for Uttarakhand from different estimates: (**a**) APHRODITE, (**b**) TRMM 3B42, and (**c**) IMD. Color bars indicate daily mean rainfall in mm along different elevation belts for the same period as in figure 2.

Pathways (RCPs) at radiative forcing 2.6 W/m^2 (RCP2.6), 4.5 W/m^2 (RCP4.5) and 8.5 W/m^2 (RCP8.5).

2.1.5 *SRTM data*

The present study uses Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) of spatial resolution ($\sim$90 m) to investigate the orographic relationship with rainfall over Uttarakhand. Geo-Tiff format data (version 4) are downloaded from the link: (http://www.cgiar-csi.org/). In terms of accuracy, quality and usability, SRTM provides more accurate measurements of elevation and other topographic derivatives as compared to coarser resolution digital elevation models (Jarvis *et al.* 2004).

2.2 *Methodology*

All the datasets used in this study are extracted for the geographic extent 77.5°E–81.5°E and 28.5°N–32°N. Elevation data of SRTM $\sim$90 m resolution pixels are re-sampled to 0.25° spatial resolution by using nearest-neighbour approach as other meteorological parameters used in this study are available at 0.25° spatial resolutions. Study region is divided into seven elevation belts (<500, 500–1000, 1000–2000, 2000–3000, 3000–4000, 4000–5000 and >5000 m) to investigate rainfall trend along the ranges.

2.2.1 *Trend analysis*

Trend analysis of time series data provides the magnitude of trend and statistical significance. Basically, the magnitude of trend in a time series is determined by either parametric test (regression analysis) or non-parametric test (Sen's estimator method). In this study, regression analysis is made with elevation as the independent variable and rainfall as the dependent variable. The linear trend represented by the slope of the simple least-square fit and regression line indicates the rate of rise/fall in the variable. Study estimates spatial linear trends of rainfall from all the three products and inter-compare the results.

2.2.2 *Rainfall analysis*

Study uses APHRODITE, TRMM 3B42 and IMD rainfall data to investigate the rainfall variability under present climate conditions. Rainfall data from these products are extracted for JJAS over

Table 4. *Contribution of seasonal rainfall from APHRODITE, TRMM 3B42 and IMD estimates for Uttarakhand along elevation belts.*

Elevation (m)	Rainfall source	June (%)	July (%)	August (%)	September (%)
<500	APHRODITE	14	34	34	18
	TRMM 3B42	13	35	32	20
	IMD	14	30	36	20
500–1000	APHRODITE	14	34	34	18
	TRMM 3B42	13	35	33	19
	IMD	13	30	38	19
1000–2000	APHRODITE	16	33	33	18
	TRMM 3B42	14	34	32	20
	IMD	15	30	36	19
2000–3000	APHRODITE	15	33	34	18
	TRMM 3B42	13	35	33	19
	IMD	16	29	37	18
3000–4000	APHRODITE	16	33	33	18
	TRMM 3B42	15	34	30	21
	IMD	15	29	35	21
4000–5000	APHRODITE	16	34	32	18
	TRMM 3B42	15	34	29	22
	IMD	15	28	35	22
>5000	APHRODITE	16	33	33	18
	TRMM 3B42	14	34	31	21
	IMD	16	28	33	23

the seven elevation ranges as mentioned earlier. Spatial analysis is performed using these datasets; and mean and standard deviation of rainfall estimates are evaluated for the study region. The study uses Pearson correlation coefficient (r), root mean square error (RMSE) to find out degree of association in rainfall estimates with elevation and inter-products. Pearson's Correlation coefficient evaluates the degree of linear association between the two datasets but do not determine the magnitude of errors (Ebert *et al.* 2007). The magnitude of errors is evaluated by the RMSE factor. Study also uses zonal statistics method in order to estimate which districts are more affected due to rainfall.

Using the 3-hourly rainfall estimates from TRMM 3B42 algorithm, mean rainfall structure are portrayed at 00, 03, 06, 09, 12, 15, 18 and 21 GMTs for Uttarakhand to locate how rainfall pattern changes and which region is needed to pay attention being highly prone to rainfall. Rainfall trends are calculated for observation based on TRMM 3B42 algorithm and IMD rainfall estimates in order to locate which region is drying/wetting under present climate scenarios. Study further uses precipitation data from CORDEX-SA REMO model for historical period (1970–2005) and future projection under RCP2.6, RCP4.5 and RCP8.5 scenarios for 2006–2100 period; and calculates the area average rainfall over Uttarakhand in order to find out percentage changes in near (2020–2050) and far future (2070–2100) under different climate scenarios for future prediction of rainfall.

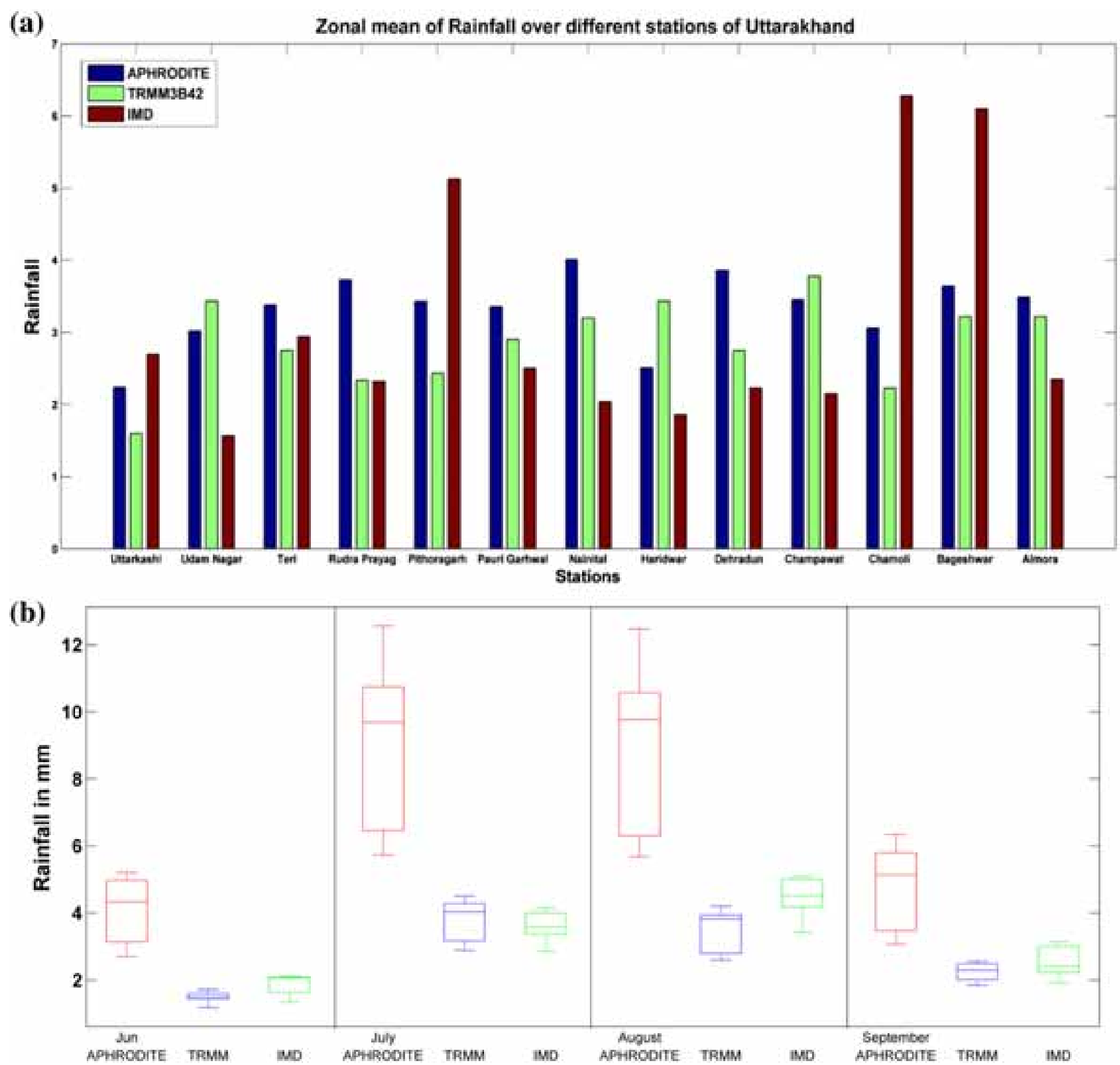

Figure 5. (**a**) Comparative analysis of monsoon rainfall estimates over different stations of Uttarakhand. Color bar indicates rainfall in mm/day. (**b**) Seasonal (JJAS) mean rainfall (mm/day) estimates from APHRODITE (red), TRMM 3B42 (blue) and IMD (green), respectively, over Uttarakhand for the same period as in figure 2.

3. Results and discussion

3.1 *Comparative analysis*

Firstly, mean and standard deviation of rainfall are estimated from the APHRODITE, TRMM 3B42 and IMD gridded rainfall datasets in order to locate which region is more wet or is relatively drier in monsoon periods, figure 2. It is found that Munsiyari of the state (eastern most region in Pithoragarh District) receives maximum contribution of mean JJAS rainfall (figure 2a–c); and Dehradun and adjacent region receives second highest mean rainfall. Standard deviation of rainfall, figure (2d–f), depicts about 5 mm/day maximum deviation from mean over Dehradun, as estimated from APHRODITE estimates. While TRMM 3B42 and IMD estimates show Dehradun, some parts of Champawat and Munsiyari to get maximum about 6 mm/day standard deviation from mean JJAS rainfall estimations. Study also evaluates rainfall trends during JJAS period. Trend analysis of APHRODITE estimate (figure 2g) shows Chamoli and Rudraprayag of the state to receive higher rainfall with trends of 0.045 and 0.038 mm/day/year, respectively; whereas, TRMM 3B42 rainfall estimate (figure 2h) shows western part of the state to depict maximum positive rainfall trends. Dehradun and Haridwar show highest rainfall trend of 0.02 and 0.015 mm/day/year, respectively, and relatively lower positive trend observed over the eastern part of the state, where trend analysis of IMD estimates (figure 2i) indicates that Munsiyari of the region has highest rainfall trends by 0.0002 mm/day/year during JJAS. Study further investigates zonal bias present

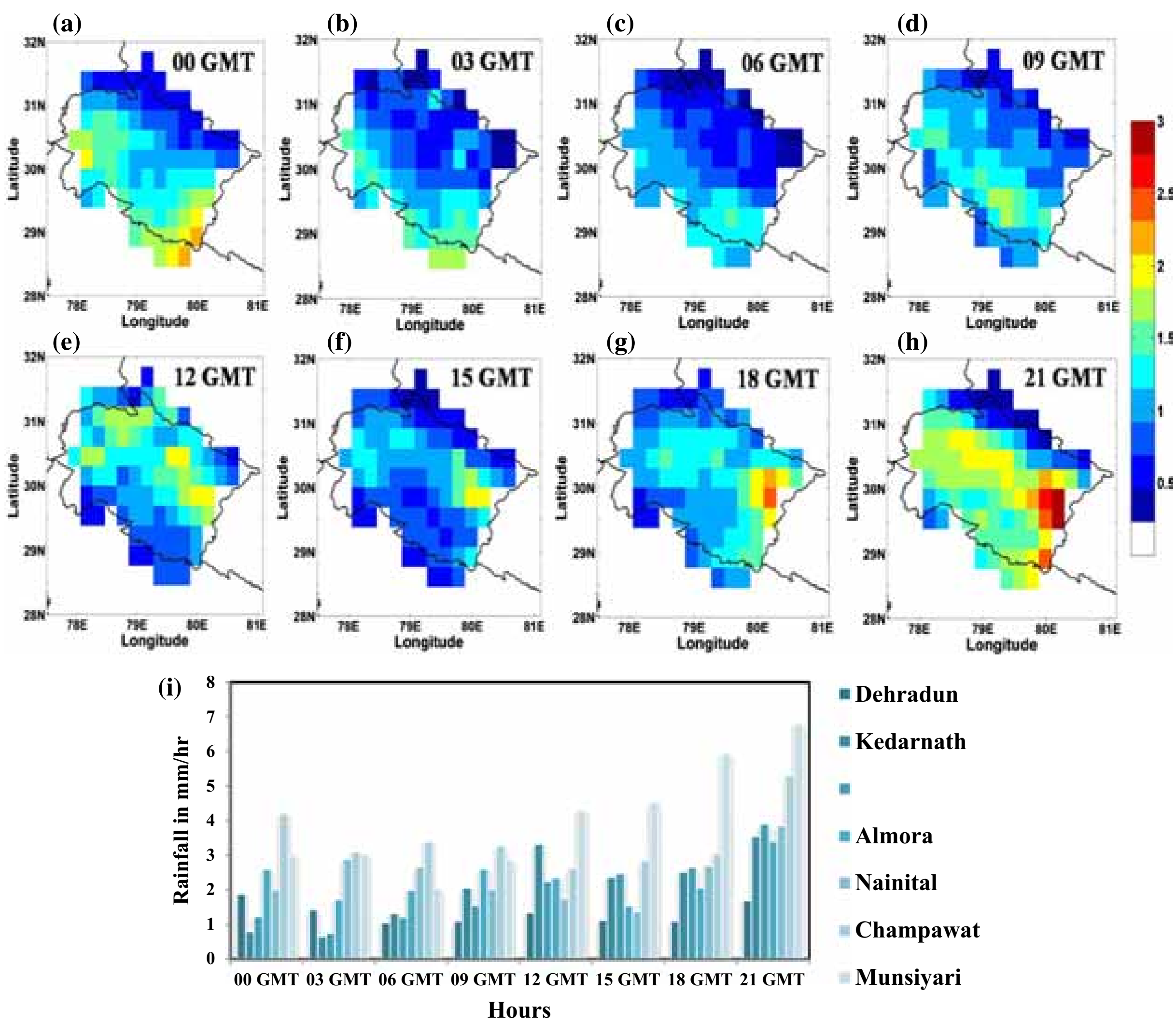

Figure 6. (**a–h**) 3-hourly rainfall estimates from TRMM 3B42 for Uttarakhand for monsoon (JJAS) season. Color scheme indicates rainfall in mm/hr. (**i**) Estimation of monsoon (JJAS) rainfall intensity from TRMM 3B42 estimates over different stations of Uttarakhand. Color bar indicates rainfall intensity in mm/hr.

in APHRODITE and TRMM 3B42 datasets with respect to benchmark rainfall estimates from IMD. Prominent deviations are observed in APHRODITE (figure 2j) and TRMM 3B42 (figure 2k) rainfall estimates which shows eastern part of the state (some parts of Bageshwar and Pithoragarh) to have negative rainfall bias whereas, central part (Tehri Garhwal, some parts of Chamoli and Pauri Garhwal) and south-eastern part of the state (Nainital, Almora, Champawat) to have positive rainfall bias. This bias may be due to the orographic factors associated with enhancement of rainfall over two-step topography of the state and as all three observational datasets are prepared using different methods to capture orographic rainfall.

Elevation dependent rainfall, figure 3(a), over two-step topography, figure 3(b), of Uttarakhand shows that rainfall decreases with increase in elevation ranges from all three products. Table 1 depicts relationship between elevation *vs.* rainfall estimates. TRMM 3B42 rainfall estimate shows higher correlation (0.45) with lower RMSE (0.40) as compared to APHRODITE and IMD rainfall estimations. Longitudinal variation in rainfall shows rainfall variability from the three different rainfall estimates. It is clear from the analysis that from western part of state to central region between (77°E–78.5°E) rainfall peaks near 78°E–78.25°E. Between 78.25°E–79.5°E rainfall estimates dips and is seen from all the three products. Up to this region, rainfall variability in these three products are closer. On further east (79.5°E–80.5°E), rainfall again increases within second topography step; however, rainfall variability is large. Study employs structural analysis based on Chow test (Zeileis *et al.* 2003) to investigate the optimal break-line in the linear regression between elevation and mean rainfall from all three observations. It basically determines the changes in linear regression model by minimizing the residual sum of squares of the linear regression model with a certain given confidence interval (Zeileis *et al.* 2003). It is found that 3100 m

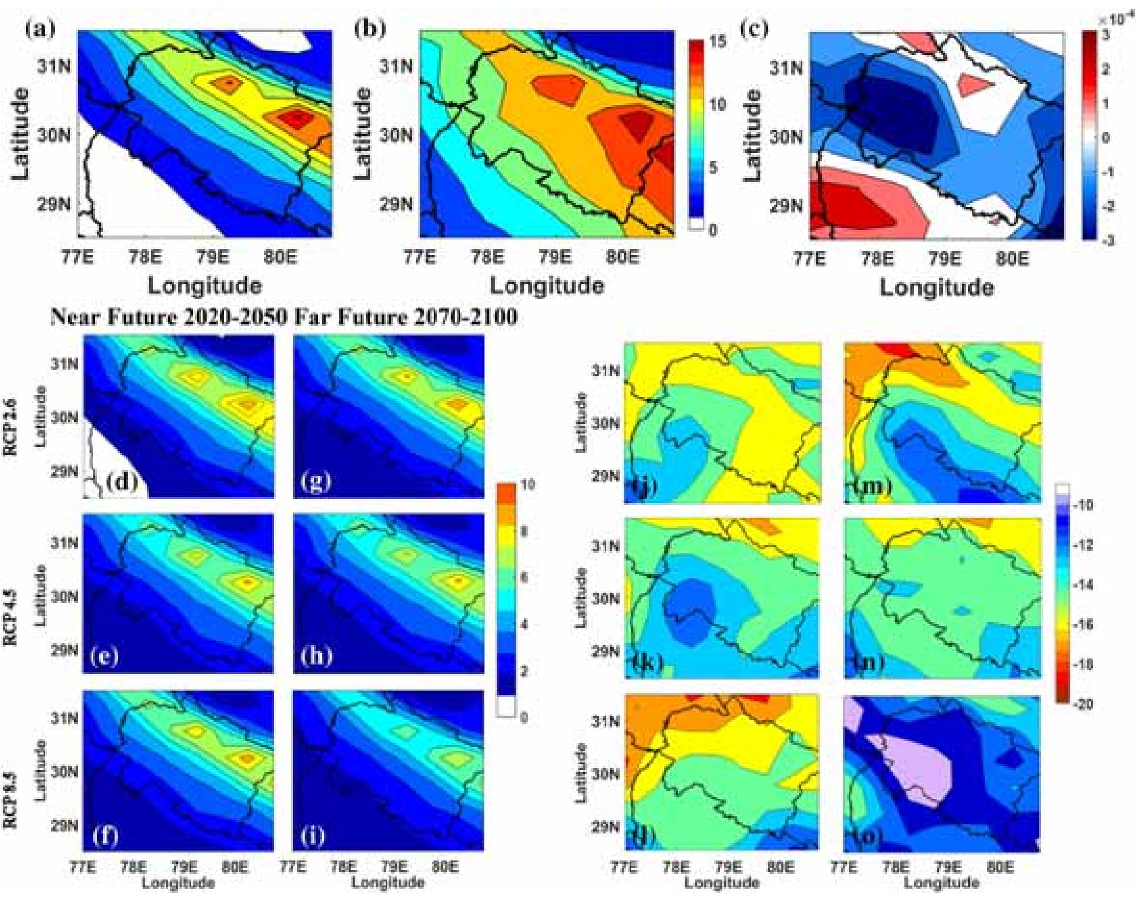

Figure 7. (**a–c**) shows mean, standard deviation and trends of historical mean rainfall for the period 1970–2005, respectively. (**d–i**) depicts future rainfall scenarios under RCP2.6, RCP4.5 and RCP8.5 and colours reflects rainfall in mm/day. (**j–o**) represents percentage changes in rainfall from historical mean rainfall. Color bar depicts % changes in rainfall and negative sign indicates decrease in future rainfall.

elevation acts as the optimal break-line over the study region. The connection between elevation and rainfall derived from satellite as well as APHRODITE and IMD observation changes very abruptly beyond this elevation. The mean rainfall values are evidently much higher up to around 3000 m elevation as observed in figure 3(c) and fall to much lower levels (figure 3d) after the break line. However, it is quite striking that IMD shows increasing trend (table 2) in both the areas; slope of the regression line found decreasing after 3100 m elevation from TRMM as well as APHRODITE observations but higher mean rainfall values by IMD estimate is observed beyond 5500 m elevation.

Further to this, comparative analysis among all the three rainfall products, figure 3(e), suggests that TRMM 3B42 estimates of rainfall underestimate rainfall more than 3 mm/day with respect to IMD; whereas, estimates from APHRODITE overestimate rainfall below 4.5 mm/day with respect to IMD estimates. Correlation and RMSE factor associated with their estimates is shown in table 3, which describes the correlation between estimates of IMD and APHRODITE is stronger than that between IMD and TRMM 3B42, whereas RMSE factor is high for APHRODITE estimates.

Distribution of mean rainfall estimates during JJAS over different elevation belts of Uttarakhand is shown in figure 4. It depicts all over similar rainfall pattern from the three products, though APHRODITE estimate of rainfall shows higher mean rainfall than TRMM 3B42 and IMD. It is also observed from IMD estimates that there is a sudden jump in rainfall near 4000–5000 m elevation belts, figure 4(c). In addition, monthly monsoonal contribution of rainfall estimates over different elevation belts show (table 4) close contribution in terms of percentage of mean rainfall estimates from all the three products. But it is also noteworthy that IMD shows maximum contribution of rainfall in August over the region.

3.2 *Zonal study*

Zonal statistics of rainfall is shown in figure 5(a). It shows maximum contribution of rainfall over Pithoragarh, Chamoli and Bageshwar from IMD estimate; whereas, TRMM 3B42 estimate shows maximum rainfall contribution over Udamsingh Nagar, Haridwar and Chamoli; and APHRODITE estimate over Tehri Garhwal, Rudraprayag, Nainital, Dehradun and Almora. Figure 5(b) represents statistics of these datasets. TRMM 3B42 and IMD rainfall estimates are close in terms of mean and standard deviation of rainfall distribution during JJAS, whereas there is higher mean values from APHRODITE estimates for JJAS.

In order to locate which region of the state is affected more during the JJAS period, study uses only available 3-hourly rainfall estimates from TRMM 3B42 algorithm and portrays rainfall pattern changes from western to eastern part of the state, figure 6(a–h). Munsiyari, Champawat, Pithoragarh, Bageshwar regions get maximum rainfall during JJAS. There is distinct pattern of rainfall distribution showing foot-hill region to receive higher amount. District averaged rainfall intensity as estimated from 3-hourly data is shown in figure 6(i) which shows that during 00–06 GMT (0530–1130 IST) mean rainfall intensity decreases

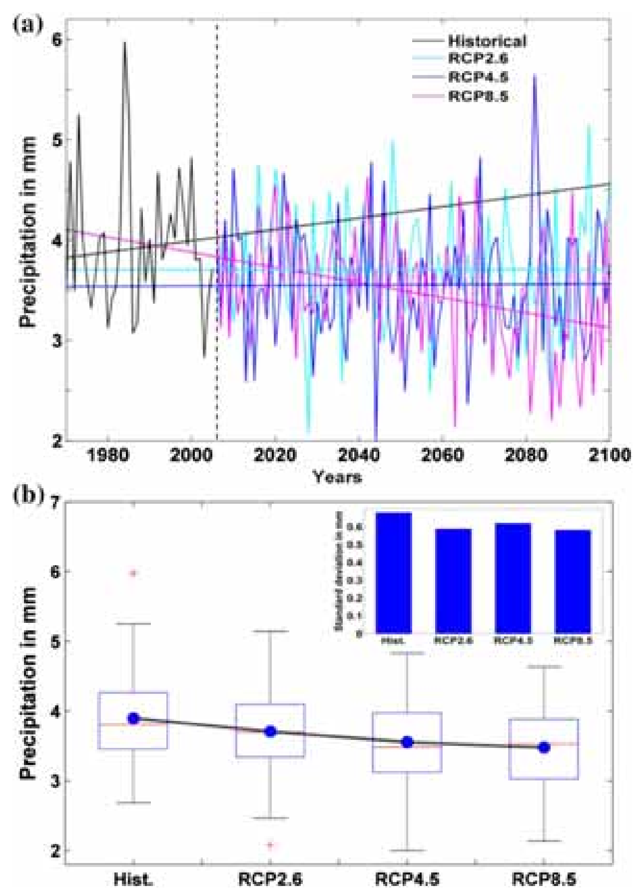

Figure 8. (**a**) Area average historical and future precipitation for Uttarakhand under different RCPs (RCP2.6, RCP4.5 and RCP8.5) and dotted lines represents their trends. (**b**) Represents mean (blue dots) and standard deviations (blue bars) of area average precipitation under historical period (1970–2005), RCP2.6, RCP4.5 and RCP8.5 scenarios for future climate projections over Uttarakhand.

Table 5. *Trends of historical and future precipitation over Uttarakhand from CORDEX–REMO model analysis.*

REMO rainfall	Slope	Intercept	Mean	Standard deviation	Remarks
Historical	0.005	3.767	3.89	0.6798	Increasing
RCP2.6	0.00001	3.706	3.70	0.5894	Stagnant
RCP4.5	0.0	3.544	3.55	0.6199	Stagnant
RCP8.5	−0.007	3.839	3.47	0.5813	Decreasing

from western part of the state to the central region of the state; and during 12–21 GMT (1730–0230 IST) rainfall intensity increases over Champawat and Munsiyari region. Over the hilly terrain of Uttarakhand rainfall intensity peaks particularly during night 18–21 GMT (2350–0230 IST) and early morning 00 GMT (0530 IST). This may attribute to lower level moisture convergence at lower altitude during the monsoon season and elevated topography acts as a heat source for mountainous flow at different altitude (Barros *et al.* 2000).

3.3 *Future trends*

In order to study the future trends of rainfall over Uttarakhand, study uses CORDEX–REMO model outputs. Figure 7(a–c) depicts the mean, standard deviation and trends of rainfall pattern for historical period 1970–2005 from model simulation. Eastern part of the state shows larger standard deviation in the model runs for historical period, which agrees with TRMM and IMD observations (figure 2e and f) as well. Western part of the state of Uttakhand shows negative rainfall trends for historical model runs and agrees with APHRODITE trends to some extent. Rainfall for near future (2020–2050) and far future (2070–2100) under RCP2.6, RCP4.5 and RCP8.5 are shown in figure 7(d–f) and figure 7(g–i), respectively, which show no significant changes in spatial distribution of precipitation under RCP2.6 and RCP4.5, but depict that future precipitation will decrease under RCP8.5 scenarios. Spatial analysis of percentage change in rainfall shows (figure 7j–o) future distribution of rainfall; negative sign indicates that under different RCPs future rainfall will decrease as compared to historical period. It is observed that Munsiyari of the state, which is highly prone to rainfall, will receive lesser rainfall under RCP8.5 forcing scenarios as compared to RCP2.6 and RCP4.5 scenarios. Similar signature is also observed over Rudraprayag and Uttarkashi districts of the state.

Area average precipitation over Uttarakhand for 1970–2100 is shown in figure 8(a). It illustrates trends of precipitation for historical period 1970–2005 as 0.005 mm/day and shows increasing trends (table 5), whereas RCP2.6 and RCP4.5 forcing shows stagnated precipitation trends over the region for future. Significant decreasing trends (–0.007 mm/day) is observed under RCP8.5 scenarios. Mean precipitation shows decreasing tendency (figure 8b) and standard deviation of precipitation shows fluctuations, under different RCPs, starting from historical period, within 0.58–0.68 mm/day.

4. Conclusions

Understanding of the spatio-temporal distribution of rainfall and its changing pattern is utmost important for the state of Uttarakhand, which is highly enriched with bio-diversity.

Mean rainfall estimates from all the three products suggest that eastern part of the state, especially Munsiayri region receives maximum mean monsoon rainfall, followed by Dehradun and adjacent part in the western side of the state. Further to this, trend analysis of JJAS rainfall estimates from all the three observational datasets suggest that Munsiyari of the region is highly prone to rainfall and needs to pay attention for the interests of agriculture, water management, food technology and etc. Prominent deviations are observed in all three standard rainfall estimates over the Western Himalayan foot-hill region.

Study finds that eastern part of the state shows larger rainfall variability than western and central region of the state from all the three standard rainfall estimates. Interestingly, it is observed that near 3100 m elevation there is an optimal break-line and it is probably due to the intersection of two-step topography at around 3100 m elevation. Rainfall pattern is different above and below the line.

Rainfall estimates from APHRODITE and TRMM 3B42 shows that 500–1000 m elevation belts get maximum rainfall during JJAS, while estimates from IMD shows that 1000–2000 m elevation received maximum contribution of monsoon rainfall. On the other hand, orographic contribution of rainfall shows how two-step topography controls the rainfall. It has been observed from the analysis that there is a sudden jump in rainfall in between 4000–5000 m elevation belt as estimated from IMD. Whereas there is a similarity in rainfall pattern as estimated from APHRODITE and TRMM 3B42, though APHRODITE estimates have shown higher mean rainfall as compared to TRMM 3B42 and IMD during JJAS. Study also finds that TRMM 3B42 rainfall underestimates rainfall above 3 mm/day with respect to IMD, whereas APHRODITE overestimates rainfall below 4.5 mm/day as compared to IMD estimations. This underestimation and overestimation may attribute to the non-availability of the satellite passes or may be in the algorithm used for the procurement of APHRODITE datasets. IMD gridded dataset is also not a true indicator of rainfall; as it is the station-interpolated dataset. 3-hourly rainfall estimates from TRMM 3B42 further depicts that eastern part of the state received maximum intensity of monsoon rainfall during 2350–0230 IST (18–21 GMT) and early morning at 0530 IST (00 GMT) and Munsiyari of the state received maximum contribution of monsoon rainfall during JJAS. It is important to mention that there is solid–liquid phase of precipitation and change of densification in precipitation type up to certain threshold as we move upslope in higher Himalayas. In the present study, upper reaches of the Himalayas definitely received precipitation in solid form which is not considered here. The study briefly portrays the efficiency of CORDEX–REMO model in capturing the future rainfall over the Himalayan foot-hill state, Uttarakhand. Rainfall pattern in the eastern part of the state is captured better in model simulation for historical period (1970–2005) as compared to benchmark IMD observation. Historical rainfall (1970–2005) from CORDEX–REMO model shows that rainfall trend increases as 0.005 mm/day but rainfall trends under future climate scenarios is quite alarming, as RCP2.6 and RCP4.5 scenarios show stagnated rainfall trends while RCP8.5 scenario shows significant decreasing trends in rainfall. Area average mean rainfall estimates from CORDEX–REMO also show decreasing trends in monsoon rainfall over the state.

All the datasets used in this study have their own limitations as different methods are involved to procure these datasets. TRMM 3B42 algorithm is a multi-source rainfall estimation approach by merging high resolution IR precipitation and root-mean-square (RMS) precipitation error estimates whereas, APHRODITE used interpolation technique over the Himalayan region. IMD gridded data is prepared by Pai *et al.* (2013) by using rain-gauge observations, followed by inverse distance weighted (IDW) interpolation method to procure all India based high resolution gridded rainfall datasets and it is considered as standard rainfall product over India. Though this dataset also has some issues over the hilly region due to sparse rain-gauge stations.

The present study analyzes the future changes in precipitation under various scenarios from regional climate simulation, which is part of CORDEX-SA experiment. Model simulated rainfall (figure 7a–c) captures the rainfall characteristics to some extent with standard observational products (figure 2a–c) in terms of climatological mean and standard deviations, but observational rainfall products reflect insignificant relationship amongst themselves in trend estimates and therefore, is incomparable with model trends. However, the uncertainty and biases in the simulations also needs to be considered while debating on the reliability of the future projections from the experiment. Observational datasets are at 25 km spatial resolution; whereas, model is simulated at spatial resolution 50 km, forced by three emission scenarios for future projection of precipitation over the Himalayan foot-hill region. In far future (2070–2100) under the intensified scenario RCP8.5, the changes seem to be more profound than that in near-future with less intensified scenarios.

Results presented here are only indicative of the range of expected changes in the magnitude of precipitation and its spatial pattern over the Himalayan foot-hill region. A detailed study will be made to further understand the physical reasons behind this and to address the relationship between precipitation and orographic modulation at more higher regional scale. High resolution topography is not introduced into the model simulation in this study and therefore, incorporation of this parameter will provide further scope to improve the result with higher regional scale over such varying mountainous topography. Vertical pressure level data is currently unavailable from CORDEX-SA and also beyond the scope of present study, which may attribute further on the future changes in precipitation pattern over such complex terrain. As regional climate model related uncertainty is large for projected changes in precipitation, improving the regional process and feedbacks to the model are crucial for narrowing this uncertainty and for providing more realistic regional climate projection over the Himalayan foot-hill region. Improvement in model physics, bias adjustment of model data, assessment of uncertainty in different set of models are therefore utmost important for further improvement of the result in this research area.

Present study concludes that due to the climate change impact, the future climate conditions of Uttarakhand is going to experience decrease in rainfall and this projected scenarios may significantly impact further on the regional hydrology, bio-diversity and eco-systems. Effect of rainfall on regional hydrology is a crucial factor, as it determines the availability of water level and soil moisture. Present study focuses on climatology, variability, and long term trends of rainfall over a regional scale, which provides very valuable information for water resource planners, hydrologist and water resource management.

It is important to mention that there is solid–liquid phase of precipitation and change of densification in precipitation type up to certain threshold as we move upslope in higher Himalayas. In view of this, as we suggested earlier also, that a separate future study will be carried out considering the snow fields available from other observational field and/or reanalysis fields over the study region.

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