

Observations of rainfall in Garhwal Himalaya, India during 2008–2013 and its correlation with TRMM data

D. D. Khandelwal^{1,*}, Anil K. Gupta^{1,2} and Vishal Chauhan¹

¹Wadia Institute of Himalayan Geology, 33 G.M.S. Road, Dehradun 248 001, India

²Department of Geology and Geophysics, Indian Institute of Technology, Kharagpur 721 302, India

Rainfall variations in the Garhwal Himalaya, Uttarakhand were studied for a period of six years from 2008 to 2013. The rainfall data were obtained through a dense network of rain gauges installed by India Meteorological Department (IMD), New Delhi, are spreaded over seven districts of Uttarakhand, combined with the data from Wadia Institute of Himalayan Geology (WIHG) rain gauge located at Ghuttu, Garhwal Himalaya. The rainfall data of WIHG have a sampling interval of 15 min, while IMD provides district-wise rainfall measurements with monthly temporal resolution. Therefore, extreme events of rainfall which occurred in a short duration of time were observed using the rainfall data of WIHG. Similarly, daily diurnal variations of rainfall were also observed in these data. The seasonal variations and distribution of rainfall in different districts of the Garhwal region were seen in both WIHG and IMD datasets. An increasing trend of rainfall activity was seen from 2008 to 2013. Meteorological observations suggest that the isohyet has shifted towards end-September in recent years. Two events of extreme rainfall in the Garhwal Himalaya in 2012 and 2013 caused a major loss of life and property in the region. The rain gauge of WIHG recorded heavy rainfall during both the events. In 2012, ~70 mm rainfall was recorded in 1 h and in 2013 the rain gauge data showed about 250 mm rainfall in 52 h. The daily diurnal records of rainfall show a minimum between 0700 and 1300 h local time (local time = UT + 5.30 h) and diurnal maximum between 2200 and 0300 h local time for all the years. The seasonal variation of rainfall reveals that the peak season of monsoon ranges from June to September in the Garhwal region, which contributes about 50–90% to the annual rainfall. We also compared the observed results of rain gauges with TRMM-derived rainfall data and found a good correlation ranging from 0.6 to 0.9.

Keywords: Extreme rainfall events, rain gauge, monsoon season, seasonal and diurnal variations.

THE summer monsoon precipitation holds the key in controlling agrarian economies of India. Rainfall observations play a crucial role in adequate agricultural planning and management, effective utilization of water resources

for drinking and irrigation, conservation planning of soil and water, and validation of weather prediction models. In addition to these applications, the detailed study of rainfall records significantly contributes to the understanding of the possible causes of natural calamities like flash floods, landslides, soil erosion and avalanches, etc. Considering the importance of rainfall measurements, a large number of rain gauges have been deployed around the globe to monitor rainfall behaviour for the benefit of mankind^{1–6}. Recently, Mishra *et al.*⁴ used a long record of rainfall observations for short-term rainfall forecast to increase irrigation efficiency of rice cultivation in North East India. Likewise, Hossain *et al.*⁵ used rainfall observational data to investigate water resource vulnerability for Dhaka, Bangladesh. Rozalis *et al.*¹ used radar rainfall data and uncalibrated hydrological model for the purpose of flash flood prediction in Israel.

Changes in precipitation are closely related to climate variability on decadal to centennial timescales. Extreme events of rainfall may have far-reaching consequences to the human societies, leaving them vulnerable to miseries. Model and observational studies suggest increasing frequency of extreme rain events over India in a greenhouse world⁷. The frequency and intensity of such events have also increased in the Himalayan region⁶. More recently, an extreme event of very heavy rainfall swept the Kedar-nath valley and adjoining areas of Uttarakhand Himalaya on 16 and 17 June 2013 that triggered widespread flash floods affecting a large section of human population in the region. Dobhal *et al.*⁶ presented some important facts regarding possible causes of the tragic event using rainfall observations recorded in the region.

Although a considerable number of rainfall monitoring stations has been installed at all possible locations around the world, there are still many remote locations where such facilities are yet to reach due to lack of logistic support. Therefore, most workers are using remote sensing satellite data. The Tropical Rainfall Measuring Mission (TRMM) is one of these remote sensing techniques and it is being accessed excessively for the study of rainfall distribution in different parts of the world^{2,3,8}. Nesbitt and Zipser⁸ studied diurnal cycles of rainfall activity using three years of TRMM satellite data over land and ocean areas. They found small amplitude of diurnal rainfall cycles over the ocean in comparison to the land areas. Almazroui² analysed a short-term rainfall climatology regime over Saudi Arabia through the TRMM data for the period of 11 years from 1998 to 2009 and calibrated results based on TRMM data with the observed rainfall data obtained through a network of rain gauges in Saudi Arabia. He found a good correlation (about 0.90) between TRMM results and observed rain gauge data. Varikoden *et al.*³ studied diurnal variations in rainfall across peninsular Malaysia using TRMM satellite data. These authors investigated rainfall characteristics in different intensity ranges for different seasons, and observed changed

*For correspondence. (e-mail: ddkhandelwal@rediffmail.com)

diurnal variations in coastal and inland regions. They also classified regions of high-intensity rainfall causing a number of flash flood events.

India Meteorological Department (IMD) has generated a large rainfall dataset in India for more than a century. IMD has deployed a vast array of rain gauges across the country; however, some locations are at remote places where gauge observations are not available. In the case of non-availability of gauge records, the outputs from numerical weather prediction (NWP) models and estimates inferred from satellite observations are used^{9,10}. In the Garhwal Himalaya of India, IMD has deployed numerous rain gauge stations; the Wadia Institute of Himalayan Geology (WIHG), Dehradun also has gauge observations in this region. One of the rain gauges of WIHG is installed at its Multi-Parametric Geophysical Observatory (MPGO) at Kopardhar near Ghuttu (30.53°N, 78.74°E; 1836 m amsl). The monsoon season in Garhwal region ranges from June to September every year.

In this communication, we present results of rainfall observations recorded at MPGO, Ghuttu for the period ranging from 2008 to 2013 and at seven districts of Garhwal by IMD for the period ranging from 2008 to 2012. We correlated these results with TRMM data to understand spatial variation in rainfall. We found evidence of two extreme rainfall events in the rain gauge at MPGO, Ghuttu. The first event of heavy rainfall was observed at midnight on 3 August 2012, when the MPGO rain gauge recorded ~70 mm rain in 1 h. The second event of heavy rainfall occurred between 16 and 17 June 2013 and during this period the rain gauge at MPGO recorded nearly 250 mm rainfall in about 52 h. A common diurnal feature was also observed every year at MPGO, Ghuttu with a maximum between 2200 and 0300 h local time and minimum between 0700 and 1300 h local time. The comparative study of monthly rain gauge observations and TRMM data reveals a good correlation (≥ 0.6) between the two datasets.

As mentioned earlier, the rainfall data used in this study were obtained for a period of five years between 2008 and 2012 from IMD gauge stations located in seven districts of Garhwal and from one station of WIHG located at Ghuttu, Garhwal Himalaya for a period of six years between 2008 and 2013. IMD provides district-wise rainfall data for all the states in India under District-wise Rainfall Monitoring Scheme (DRMS) through its website <http://www.imd.gov.in/section/hydro/distrainfall/district-rain.html>. Since IMD has several rain gauge stations in every district, it provides arithmetic averages of rainfall at all the stations under any district with monthly temporal resolution. In this study, we used data from seven districts of Garhwal region, namely Chamoli (CHM), Dehradun (DDN), Haridwar (HRD), Pauri Garhwal (PAU), Rudraprayag (RUDR), Tehri Garhwal (TER) and Uttarkashi (UTTR). The locations of all the stations of IMD under DRMS are shown in Figure 1.

At MPGO, Ghuttu, some meteorological and hydrological parameters were also monitored besides geophysical parameters, including rainfall measurements, atmospheric temperature, atmospheric pressure, temperatures at different depths within 68 m deep borehole and water-level change in the borehole¹¹⁻¹³. The meteorological data and changes in water level were recorded using Campbell (10×) data logger. These all parameters were recorded simultaneously at predefined 15 min intervals, the values were also integrated for 24 h period in the same data logger for observing the trend on a daily basis. The rain gauge has been installed at the roof of a hut which houses the borehole site. The water table in the borehole was monitored using a water-level probe installed at 30 m depth below the earth's surface.

To compare the rain gauge rainfall data recorded at MPGO, Ghuttu and IMD with the TRMM-derived rainfall, we used TRMM Multi-Satellite Precipitation Analysis (TMPA) dataset. The TMPA estimates are produced in four stages: (i) the microwave precipitation estimates are calibrated and combined, (ii) infrared precipitation estimates are created using the calibrated microwave precipitation, (iii) the microwave and IR estimates are combined, and (iv) rain gauge data are incorporated. For microwave precipitation related passive microwave data are collected by a variety of low earth orbit (LEO) satellites, including the Microwave Imager (TMI) on TRMM, Special Sensor Microwave Imager (SSM/I) on Defense Meteorological Satellite Program (DMSP) satellites,

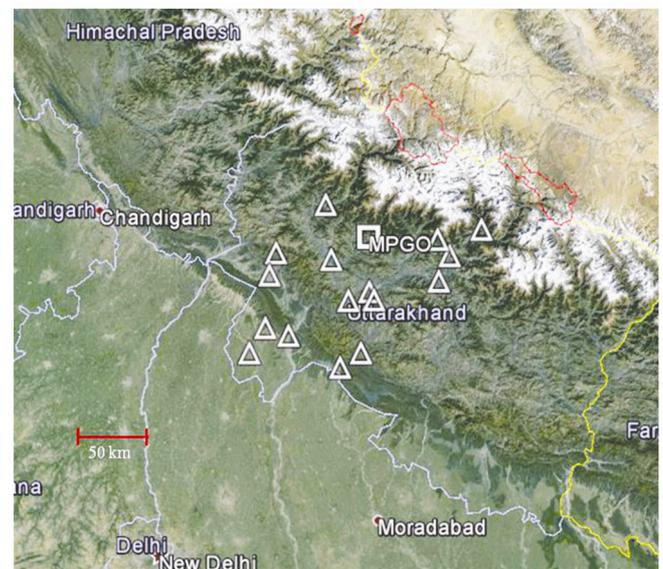


Figure 1. Location of rain gauge stations of IMD in the Garhwal region of Uttarakhand, India under District-Wise Rainfall Monitoring Scheme, the location of rain gauge of the Wadia Institute of Himalayan Geology (WIHG). The IMD stations are represented by triangles and WIHG's Multi-Parametric Geophysical Observatory (MPGO) is shown by a rectangle. The locations of the stations are plotted using Google Earth.

Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E) on Aqua, and the Advanced Microwave Sounding Unit-B (AMSU-B) on the National Oceanic and Atmospheric Administration (NOAA) satellite series. The infrared (IR) data are being collected by the international constellation of geosynchronous earth orbit (GEO) satellites. The TRMM-TMPA dataset contains two products, three-hourly estimates (TRMM 3B42 v7) and monthly estimates of precipitation (TRMM 3B43 v7). Both these products provide precipitation estimates at spatial resolution of $0.25^\circ \times 0.25^\circ$ (ref. 15). In this study we analysed monthly TRMM-TMPA data using TRMM 3B43 v7. The rain gauge data from IMD is also provided with monthly temporal resolution. As mentioned earlier, at MPGO, Ghuttu, the meteorological data were recorded at an interval of 15 min. Therefore, we calculated monthly accumulated rainfall for the purpose of comparison.

The rainfall variations, changes in water level, variations in atmospheric temperature and pressure measured at MPGO, Ghuttu are plotted in Figure 2 *a-d* respectively. The seasonal variation of rainfall in each year and inter-dependence of other parameters are clearly visible from the Figure 2. It can be seen from Figure 2 *a* that minimum rainfall was recorded during 2009, while high

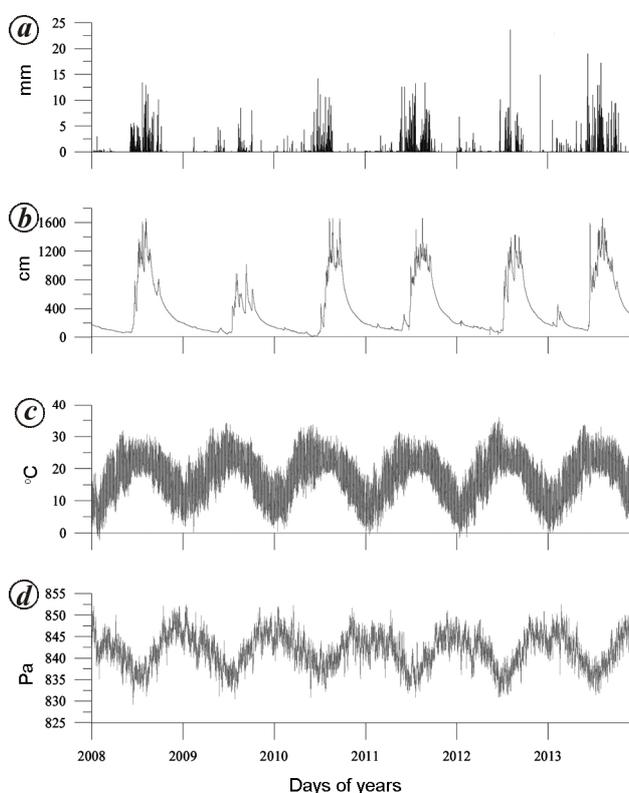


Figure 2. General variation of (a) rainfall, (b) water level, (c) atmospheric temperature and (d) atmospheric pressure measured at MPGO, Ghuttu at a sampling interval of 15 min for the duration of six years from 2008 to 2013.

intensity rainfall ($R > 15$ mm per 15 min) was recorded in 2012 and 2013. It is to be noted here that both 2012 and 2013 witnessed major natural devastations due to heavy rainfall within a short span of time. At midnight on 3 August 2012, flash floods and landslides were triggered due to heavy rainfall activity in the Garhwal region. Massive loss of life and property was reported during this event¹⁴. The MPGO rain gauge also recorded this heavy rainfall (23.6 mm in 15 min and 70.2 mm in 1 h) event at midnight on 3 August 2012. However, on 16 and 17 June 2013, the Kedarnath region of Garhwal Himalaya experienced an extreme event of flash flood due to continuous rainfall for about 52 h. This was a major natural calamity to affect India since the 2004 tsunami. Since the aerial distance of MPGO, Ghuttu from Kedarnath is about 38 km, the records of this extreme event of rainfall have been registered in the MPGO rain gauge also, which recorded 58 mm rainfall on 15 June 2013, 121 mm rainfall on 16 June 2013 and 93 mm on 17 June 2013 (ref. 6).

The effects of seasonal variations in rainfall are also visibly reflected in fluctuating groundwater levels (Figure 2 *b*). The result of low rainfall rate in 2009 is the shortage of groundwater during that year (Figure 2 *b*). On the other hand, early monsoon rainfall in 2013 caused a sudden rise in the groundwater level. Similarly, atmospheric temperature (Figure 2 *c*) and atmospheric pressure (Figure 2 *d*) are also related with rainfall activity. To identify rainy months and monsoon period in the Garhwal region, we also plotted the monthly average rainfall using the MPGO data for six years from 2008 to 2013 (Figure 3 *a*). The figure shows that maximum rainfall occurred during June–September, which represents the rainy season receiving ~80% of the total rainfall in India¹⁶.

We calculated cumulative annual rainfall and cumulative monsoon season rainfall for each year from 2008 to 2013. These results are presented in Figure 3 *b*. In the figure the white bars show values of annual rainfall and shaded bars represent values of cumulative rainfall in the monsoon season. It is clearly evident from the figure that every year the rainfall in the monsoon season is more than 70% of the annual rainfall. For instance, in 2008 the monsoon rainfall showed 96.14% contribution to the annual budget. Similarly, for rest of the years, the contribution of monsoon rainfall to the annual budget was – 2009: 51.24%, 2010: 84.58%, 2011: 90.30%, 2012: 76.41% and 2013: 78.62%. Krishan *et al.*¹⁷ also found a good contribution (>50%) of monsoon rainfall to the annual rainfall budget at Roorkee (Uttarakhand) using five years data from 2007 to 2011. Seasonal variations and extreme events of rainfall activity have also been studied by other workers^{3,9}.

The diurnal variation plots of rainfall at MPGO, Ghuttu for each year are obtained in three steps: (i) the hourly accumulated rainfall is calculated for each day of the rainy season (June–September) in a year; (ii) averages are measured for every hour using the calculated hourly

accumulated rainfall data of all the days of the rainy season in a year, and (iii) finally, the obtained diurnal curves are made smoother by applying a running average of 3 h. The results show a diurnal minimum between 0700 and 1300 h local time while a clearly visible diurnal peak is seen between 2200 and 0300 h almost every year (Figure 4). A second diurnal peak with low values of rainfall is

also seen between 1300 and 1900 h. Diurnal variations of rainfall have earlier been reported by numerous workers^{3,8,18,19}. Also, all the previous studies suggest that the amplitude of the diurnal cycle of rainfall over continents is larger than that over the oceanic regions^{8,20}. On the other hand, some studies show diurnal maximum of rainfall in the afternoon hours, while other studies show diurnal maxima between midnight and early morning^{21,22}. These different patterns of diurnal variation of rainfall are found to vary with geographical locations²³. Varikoden *et al.*²⁴ have also observed post-midnight diurnal peaks in the foothills of the Himalaya. Similarly, Barros and Lang²⁵ observed late morning minimum and post-midnight maximum diurnal features of rainfall in the Himalayan

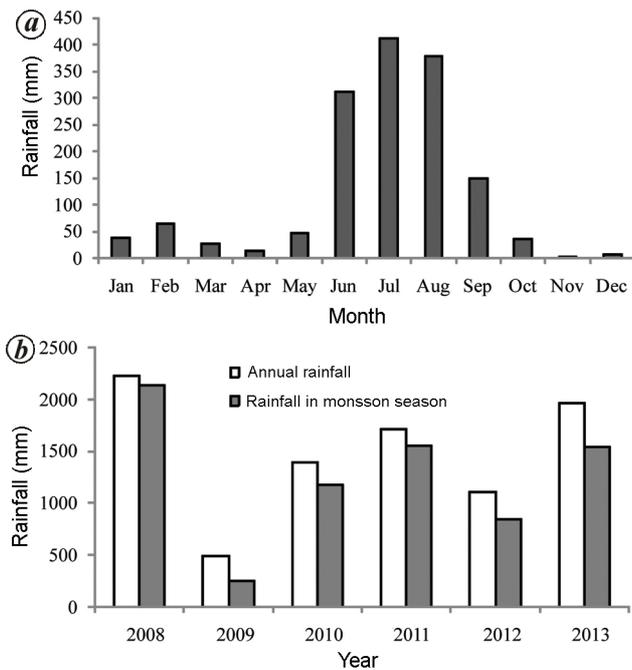


Figure 3. *a*, Variation in monthly average rainfall calculated from six years data of MPGO, Ghuttu between 2008 and 2013. *b*, Variation of annual rainfall (white bars) and rainfall during monsoon season (shaded bars) for each year from 2008 to 2013.

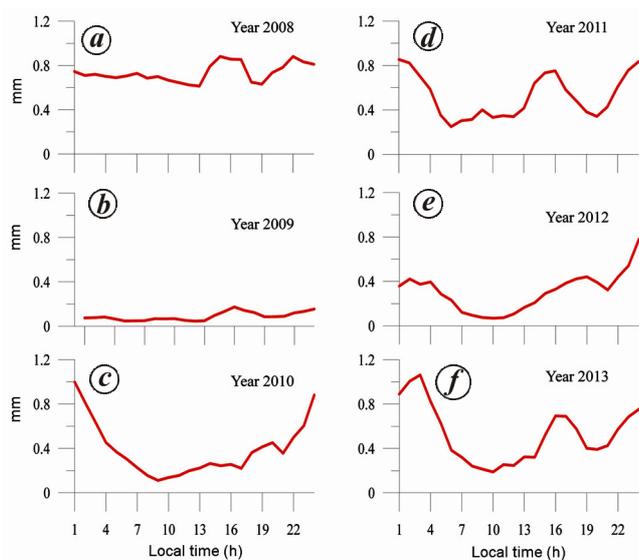


Figure 4. Diurnal variation of average rainfall in the monsoon season in (a) 2008, (b) 2009, (c) 2010, (d) 2011, (e) 2012 and (f) 2013.

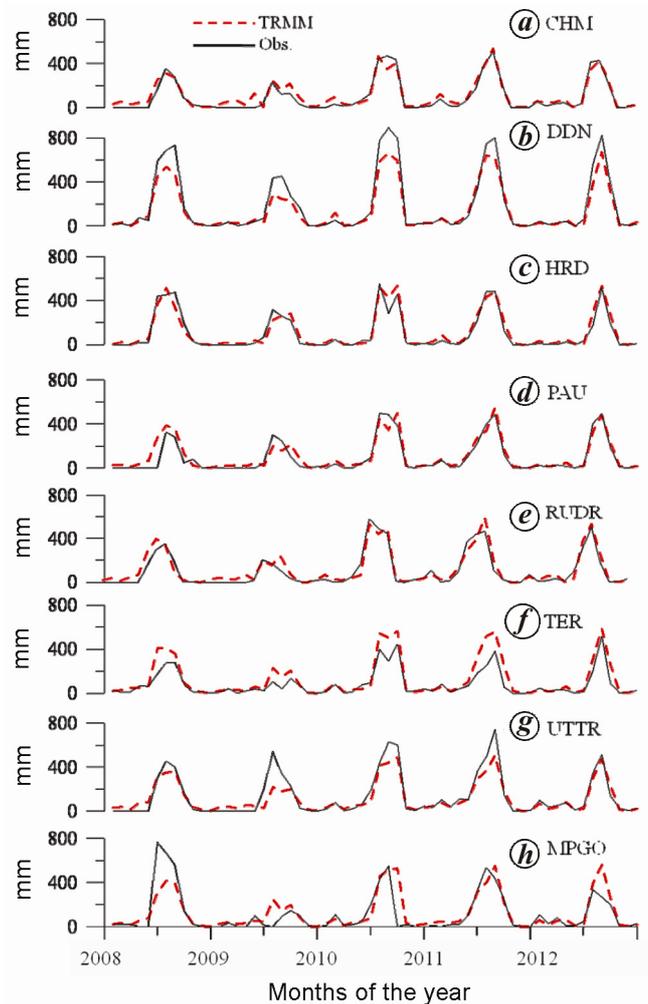


Figure 5. Monthly variations of rain gauge observations (continuous curves) and their corresponding TRMM data (dashed curves). These data are plotted for seven districts of Garhwal region, namely (a) Chamoli, (b) Dehradun, (c) Haridwar, (d) Pauri Garhwal, (e) Rudrapur, (f) Tehri Garhwal and (g) Uttarkashi and (h) for MPGO, Ghuttu. Other than MPGO, Ghuttu, the district-wise rainfall data are collected from the website of IMD (<http://www.imd.gov.in/section/hydro/districtfall/districttrain.html>), while the TRMM data are obtained through NASA's Giovanni on-line data system (<http://disc.sci.gsfc.nasa.gov/giovanni>).

region showing gradual build-up of convective instability during the day which releases after midnight causing the nocturnal diurnal peak of rainfall. These authors also found that at high altitudes total column moisture level is high during post-midnight hours, while temperature is found to be slightly cooler, which produce high instability and precipitate water.

As mentioned earlier, IMD provides arithmetic averages of rainfall data of all the stations under any district with monthly cumulative values. We obtained these data points for five years from 2008 to 2012 from seven districts of Garhwal region and MPGO, Ghuttu. The results are plotted in Figure 5 a–h with solid continuous curves. The diurnal variations as obtained in the MPGO data could not be calculated with IMD data owing to monthly temporal resolution. However, the features of seasonal variations in the rainfall data of all the districts are found to be similar to those obtained in the MPGO observations.

For the validity of TRMM data in the context of the Garhwal Himalaya region, we compared the above results of monthly rainfall variations in Garhwal with the

TRMM–TMPA estimates of precipitation. The monthly cumulative rainfall data obtained through TRMM corresponding to all the districts under consideration are plotted in each consequent panel of Figure 5 with dashed curves. The figure shows that almost similar variations are observed in TRMM data with those recorded through rain gauges at all the districts in Garhwal. The correlation between rain gauge and TRMM data for five years (2008–2012) for all the districts is positive and significant, with R^2 ranging from 0.6 to 0.9. These results of correlation between gauge and TRMM data for each district are plotted in Figure 6 a–h. The observed significant correlation between these two datasets for such a long duration shows that TRMM data may be a helpful tool of study when gauge observations are not available. Similar results of high correlation between gauge and TRMM data have been reported by other workers also^{2,26}. Ojo and Omotosho²⁶ studied the TRMM data and rain gauge observations for microwave applications in Nigeria. From quantitative comparison over different regions, they found positive correlations (>0.8) between these two datasets. Similarly, Almazroui² carried out comparisons between these two datasets and found considerable positive correlation (~ 0.9).

Study of the rainfall data of the Garhwal region for the period from 2008 to 2013 reveals important events of extreme rainfall, and seasonal and diurnal variations of rainfall. Two events of heavy rainfall in 2012 and 2013 were observed, in which the rain gauge recorded 70 mm rainfall in 1 h and 250 mm rainfall in 52 h respectively. The seasonal study of rainfall shows that the monsoon season in the Garhwal Himalaya spans from June to September every year and the monsoon rainfall contributes about 50–90% to the annual rainfall budget in the region. Every year a common diurnal change is also observed in the rainfall behaviour in the Garhwal region. A diurnal minimum in rainfall is observed between 0700 and 1300 h local time, while a maximum is seen between 2200 and 0300 h local time. The comparative study of rain gauge observations and TRMM data shows good correlation between the two with the correlation coefficients ranging from 0.6 to 0.9. This study significantly contributes to the existing knowledge on mountain meteorology of the Garhwal region and the data can be used in modelling and weather forecasting. The correlation results of TRMM data will be significant when the gauge observations are not available.

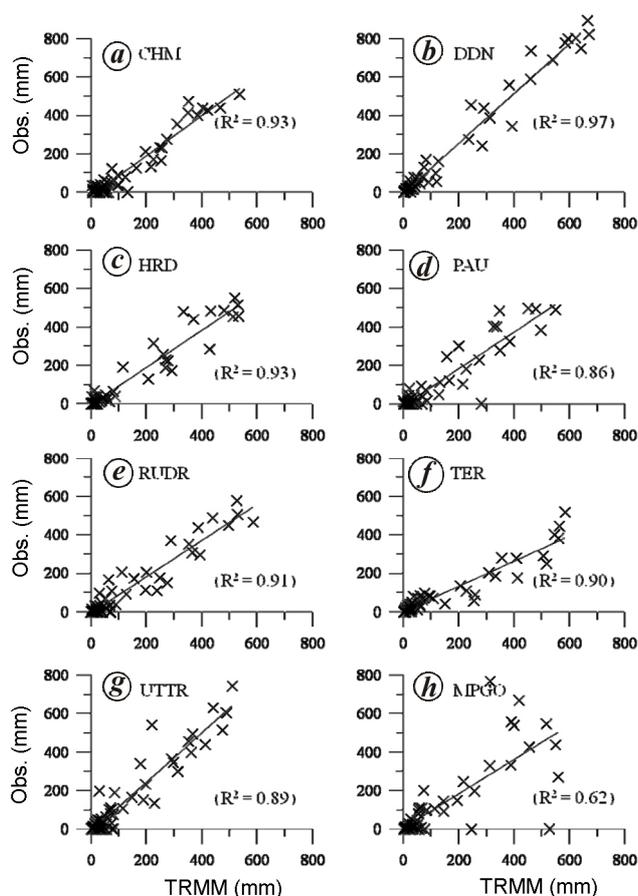


Figure 6. Correlation plots between TRMM rainfall data and rain gauge observations on monthly scale for the seven districts (a–g) of the Garhwal region as mentioned in Figure 5 and (h) for MPGO, Ghuttu.

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Drainage development in Achankovil Shear Zone, South India

V. Dhanya^{1,*} and G. Renoy

¹National Centre for Earth Science Studies (NCESS), Thiruvananthapuram 695 011, India

²Sannidhan Consultancy and Services, Kochi 682 021, India

The WNW–ESE trending Achankovil Shear Zone (ASZ) in southern India is a major crustal discontinuity of Proterozoic age which separates Kerala Khondalite Belt (KKB) in the south from the Charnockite massif in the north. The Achankovil river drains this structural valley. Although the river bears imprints of various geologic events, including neotectonic activities, it could maintain a straight course even in the lowland indicating its antecedent nature. The present communication is an attempt to study structural controls on drainage development and evolution within ASZ based mostly on geomorphological evidences and also on some geological indicators.

Keywords: Antecedent river, palaeo strand lines, shear zone, structural valley.

DRAINAGE development and valley configuration in a region largely depend on the topography, geology, structure

*e-mail: vdhanyageo@gmail.com