Study of the impact of orography on the amount of rainfall over North-West Himalayan region

Thesis submitted to the Andhra University, Visakhapatnam
in partial fulfilment of the requirement for the award of
Master of Technology in Remote Sensing and GIS

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CERTIFICATE

This is to certify that ***Mr. Abhisek Das*** has carried out the dissertation entitled ***"Study of the impact of orography on the amount of rainfall over North-West Himalayan region "*** in partial fulfilment of the requirements for the award of ***M. Tech in Remote Sensing and GIS Application for Natural Resource Management***. This work has been carried out under the supervision of ***Ms. Charu Singh,*** Scientist 'SD', Marine and Atmospheric Sciences Department, Indian Institute of Remote Sensing, ISRO, Dehradun, Uttarakhand, India.

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Declaration

I, ***Abhisek Das,*** hereby declare that this dissertation entitled "***Study of the impact of orography on the amount of rainfall over North-West Himalayan region*** " submitted to Andhra University, Visakhapatnam in partial fulfilment of the requirements for the award of ***M. Tech in Remote Sensing and GIS Application***, is my own work and that to the best of my knowledge and belief. It is a record of original research carried out by me under the guidance and supervision of **Ms. Charu Singh**, Scientist 'SD', MASD, Indian Institute of Remote Sensing, Dehradun. It contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of the university or other institute of higher learning, except where due acknowledgment has been made in the text.

Place: Dehradun Mr. Abhisek Das

Date: 16.06.15

ABSTRACT

This study explores the very high resolution (5x5 km) TRMM 2B31 data set of surface rainfall intensity, to resolve on the rainfall pattern and its spatial variability over the rugged terrain of the North-West Himalayan region. The high resolution 2B31 dataset has unveiled an intricate relationship between topography and spatial variability of rainfall over the study region.The data set has been processed for the time period from 1998-2013 and developed into a grid data for all the satellite passes. Further to this, the total mean rainfall intensity has been calculated to develop a fine scale spatial map based on the long term data of principal monsoon season of India over the topographically rich mountainous region. The map reveals a dual band structure of rainfall in Uttarakhand,characterized by two step topography and a single elongated band of high rainfall intensity in Himachal Pradesh characterized by one-step topography. For deriving promisingrelationship between rainfall and topographic features, SRTM DEM with high-vertical accuracy has been used in conjunction with the TRMM data set. The present work unfold the fact that two elongated band of rainfall peak has been found at the mean elevation of 1 km and 2km with a 100 km distance apart and a high rainfall peak appears over the region of 1-1.2 km elevation. Based on the percentile method, three thresholds corresponding to 98th, 99th and 99.99thpercentileshave been defined for the identification of the heavy and very heavy rainfall events. It has been observed that the heavy rainfall events in the category of 98 to 99thpercentile demonstrate a significant (at 1% significance level) increasing (decreasing) trend over the state of Uttarakhand (Himachal Pradesh). Based on the increasing tendency of the heavy rainfall events over Uttarakhand region, frequent occurrences of such events is anticipated in future. Locations of the extreme rainfall events have been identified in the present study which would be useful for the policy makers for the planof infrastructure activities and tourism. The information on the relationship between rainfall and topography may be further utilised for the modification of the rainfall retrieval algorithm. Results presented here are supported by the statistical robust significance tests. Nevertheless, to ascertain the robustness of the presented results, the use of the long term data set is suggested. Moreover, the precipitation processes, thus unveiled from the present study may also be verified with the aid of high resolution atmospheric models.

Dedicated to

my baba and ma

for their encouragement and inspiration
throughout my project work and
a swift enjoyment of life

Conference/symposium/workshop publications

- **Abhisek Das** and Charu Singh. ***Analysis of the atmospheric parameters during recent floods in Jammu and Kashmir using satellite data: A case study***. Oral presentataion in ISRS Proceeding Papers of Sort Interactive Session. ISPRS TC VIII International Symposium on Operational Remote Sensing Applications: Opportunities, Progress and Challenges. December 2014.

  (http://www.isrsindia.in/images/isprs_doc/Final%20list_ISRS.pdf)

- **Abhisek Das** and Charu Singh. ***Observation of heavy precipitation by TRMM and GPM(GMI) satellite during flood in J&K in 2014***. TROPMET 2015 National symposium on weather and climate extremes. February 2015. (Oral presentation)

  (http://www.tropmet2015.org/mausam/tropmet2015/images/Pre%20Proceedings.pdf)

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1. Introduction

1.1 Places of Orographic precipitation and Indian summer monsoon

North-western Himalaya region plays a significant role in governing climatic conditions of India.It hinders the access of dry,cold air coming from China.On the foothill of Himalayan region a rich and flourishing ecology has evolved. The Himalayan System has a distinctive climate; as a result climate of Indian Sub-continent probably gets impacted. Monsoon wind stops progressing farther North after getting deflected by the Himalayan barrier, this barrier along the West-East longitudinal expansewhich acts as a shield blocks the whole monsoon system from progressing northward. Across the northern edge of the Indian peninsula, the onset of the Indian summer monsoon [ISM] in early June marks the beginning of the principal rainy season for the Himalaya [e.g., Fasullo and Webster, 2003; Webster and Chou,1980]. Every year, the bulk of the annual rainfall occurs between June and September and thus monsoon rains have vital social and economic consequences [e.g.,Parthasarathy et al.,1992].Excessive rain over a particular region renders soil erosion and causes flooding owing to discharge of water in low-depth river. On the other hand, another type of flood which is most common in the state isflash-flood. The flash floods are extreme events that are sudden, severe and short-lived. It is a sudden and often destructive surge of water down a narrow channelor sloping ground, usually caused by heavy rain falls. Typical terrain of this Himalayan state provides a conducive environment to the cloudburst phenomena. The cloudbursts are the result ofcombination of different factors like deep valleys, steep gradient, vegetal coverand geology of area. Himalayan region receives huge amount of rainfall during the months from July to August when the south west monsoon is in progress and snow melts inthe higher reaches.Changing climatic conditions are having a direct effect on the amount of precipitation, pattern of rainfall. Over Indian Subcontinent the enhanced precipitation due to orography is observed prominently in southwest monsoon season. This moist-laden air undergoes modification owing to terrain behavior.Small scale flow interacts first with the mountains terrain and drives up the natural barrier.Amount of rainfall is determined by many factors like availability moisture,windvelocity,wind direction and orography of the region and in summer monsoon all these factors come into play in characterizing erosion of Himalayan region on long-short time scale[Bookhagen et al., 2005b; Burbank et al., 2003; Hodges et al., 2004].The profound effect of the Himalayan range on the climate of the Indian subcontinent and the Tibetan Plateau.Mountainous environment have a strong impact on spatial and temporal distribution of the precipitation compared with the impact of plane area.Following are the examples of areas which receive rainfall owing to topography, the Rocky Mountains are a major mountain range in western North America extended in north south direction. Moist air sustains from Northern Pacific ocean and strikes the Rockies mountain barrier to give heavy downpour [Smith & Evans, 2007]. Also the rainfall contrast has been noted at Washington and Oregon due to north south cascaded mountain range in North America [Moran & Morgan, 1997]. In South America, Andes is the north south mountain range proximity to the South Pacific Ocean. An asymmetric distribution of precipitation over Andes is found to be greatly dependent on altitude, latitude of mountains. Hawaii is the largest island at the south eastern most location in a chain of volcanic islands in the North Pacific Ocean. The effectively blocking of prevailing northeast trade wind reaching the eastern side of the island induces heavy precipitation to the eastern edge of island[Yang & Chen, 2008]. Also some studies on a small island in Caribbean Sea named Dominica observed high precipitation due to orographic lifting and rainfall on the east side of the mountain Waealeale in Hawaii is more than 20 times as much as the rainfall on the lee side of the mountain[Fig.1.1]. Western Ghats of India is the first topographic barrier monsoonal system strikes at the onset of monsoon in India and it causes frequent and heavy rain along its expanse parallel to western coast of India but the most air currents gets sapped of moisture after surmounting the barrier and progress over central India.

Precipitation that has been generated or modified by topography, typically through the forcing of vertical atmospheric motions is called orographic precipitation. Quantification of rainfall over mountainous regions has been a major issue for input to hydrological model and controlling soil erosion and flash flood over a river for atmospheric scientists therefore analyzing the impact of the static forcing due to natural mountain barrier on precipitation is necessary for better hazard management in future.

Normally in general amongst the non-linear processes thermodynamic process is the most causative fundamental. There are three primary lifting processes which cause air to rise and precipitate.

A. Convectional precipitation: vertical circulation of air parcels

B. Frontal precipitation: along the surface of warm/cold front

C. Orographic precipitation: forced ascent of air over mountain slope

The orographic influences on precipitation occur when air is forced upward by the topography of respective region. Rising and descending of atmospheric motion can be forced mechanically, as air encroaching on mountain is driven over it, or thermally, instability in air parcel due to heated mountain slope.

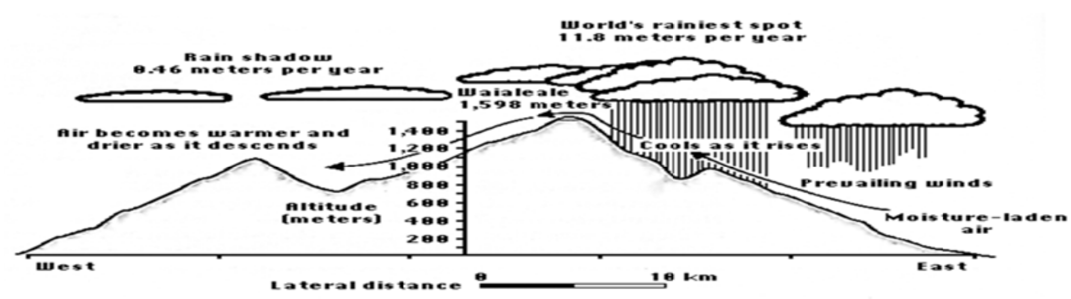


Fig.1.1: This shows the precipitation due to topographic effect on the wind-ward side and less rainfall on the rain shadow [lee side] area. Depending on the steepness of the slope of mountain precipitation decreases and increases[http://www.ldeo.columbia.edu/~martins/climate_water/case_studies/global_precip.html]

C.1 Stable ascent: Deep upliftment of moist air along windward slope of mountain isthe most common mechanism of orographic precipitation. If the air is moist and convection is sufficiently deep the precipitation cloud forms.

C.2 Seeder-feeder mechanism: Precipitation augments through rapid growth of crystals falling from upper stratiform clouds into the lower orographically induced convective clouds. While downfall ice crystals acts as a condensation nuclei to lower level super cooled water droplets and grow by accretion and aggregation.

C.3 Upslope release of potential instability: Shallow layers of potentially unstable air grow by convection over a mountain.

C.4 Day time convergence: In absence of strong winds, topographic boundary layer flow developed due to day time heating of mountain slopes. This leads to convergence at the top of the mountain.

C.5 Triggering of convergence at lee side: Stable air [Froude number <1], may be forced to travel around the lee ward side of the mountain and this lee ward convergence enhances precipitation on lee ward side of the mountain.

C.6 Enhancement of convergence at lee side: Lee side convergence develops warm convection of air mass at low levels. The mountain driven upper level cold air masses are many times separated from these warm air masses by thin stable layer. This generates extreme unstable condition and heightens convection.

Moist ascent over topography is inadequate to trigger precipitation, orographic effects mainly modify precipitation during preexisting storms [Browning et.al, 1974; Smith,2006]. Mountains influence the flow of air and disturb the vertical stratification of the atmosphere by acting as physical barriers and as sources or sinks of heat [e.g., Barros and Lettenmaier, 1994],depending on the parameter wind speed, winddirection, range width and Brunt vaisala frequency[static stability indicator]upslope wind gets blocked or passes over the top of the mountain. An orographically induced contrast in precipitation has been observed in many parts of the globe and has become an inquisitive research topic.Orography-caused rain has huge significance in mountainous terrain of different countries. The same happens over along the foothills of Himalaya and some part of the Himalaya is receiving more rain than other parts respective of its elevation, slope and relief. Topography itself has a profound effect on spatial patterns of precipitation both globally and regionally [e.g., Smith, 1979]. During Indian summer monsoon moisture-laden air in bulk amount strikes the upslope of rugged region of eastern Himalaya. The Himalayan ranges can be grouped into four parallel longitudinal mountain belts of varying width, each having distinct physiographic features and its own geologic history. They are designated, from south to north, as the Outer, or Sub-, Himalayas [also called the Siwalik Range]; the lesser, or Lower, Himalayas; the Great Himalaya Range [Great Himalayas]; and the Tethys, or Tibetan, Himalayas. Farther north lies the Trans-Himalayas in Tibet. From west to east the Himalayas are divided broadly into three mountainous regions: western, central, and eastern. Monsoonal season extends to the north-west side of Himalaya till the end September but monsoon starts over Easter side of Himalaya at the beginning of July. The Himalayan ranges form a barrier to the southwest monsoon [hereafter called “monsoon”]winds crossing over to Tibet, thereby causing heavy to very heavy rainfall in the foothills and the adjoining plains of India to its south [Dhar *et al*. 1975, DharandNandargi 1998]. In addition, the heavy rainfall does not occur in a continuous spell as seen overthe plain regions of India, but there can be sudden falls of heavy rain of short [3–4 h] to long [10–14 h]duration. In Ladakh, situated on the lee side of the western part of the Himalayas, monsoon activity is very weak, e.g. the mean annual precipitation of Leh station is hardly 93 mm, which is less than a quarter of what is received in Lhasa, the capital of Tibet [Dhar and Mulye 1987]. Whereas stations located in the PirPanjal range receive far greater rainfall because they are to the windward side of monsoon disturbances, the PirPanjal range holds captive most of the moisture from the monsoon currents as a result of orographic lifting. These monsoon currents accrue their moisture by the time they cross the 3000–4000-m-high PirPanjal range and stations located to the lee side receive much less rainfall [Dhar *et al*. 1982a].As shown in these studies, maximum rainfall is near the outer Himalayas, i.e. foothills and a second maximum occurs near the middle Himalayas at about 2400 m a.s.l. Thereafter, rainfalldecreases sharply as the system proceeds northwards to higher elevations till the Great Himalayan Range is reached. During the active phase of monsoon in central India there continues a break spell in Himalayan region so monsoon becomes strong in the middle of August. During Indian summer monsoon theHimalayan region receives 80% of total rainfall,the bulk of rainfall occurs during this season, therefore quantification of rainfall and identification of those regions which are susceptible to heavy rainfall would be easy to analyze.

Understanding the temporal and spatial distribution of precipitation is crucial in fathoming the global water cycle and energy budget scenario and as precipitation drives most hydrological,environmental and agricultural processes.Studies on orographic rainfall give evidences that rainfall gradient is always present across elevation gradient.Strong precipitation gradient over a short distance are difficult to capture with traditional point rain-gauge or weather stations because of the inaccessibility over hilly region , in hilly regions the density of monitoring network is usually low and insufficient for the use of spatial interpolation technique[Celleri,Willems,2007].Satellite rainfall products are the only resources which provides the information on rainfall over rain-gauge deprived regions with high spatial information .The one advantage of satellite-measured rainfall is its their uniformity and consistency in synthesizing temporal and spatial variability. But satellite rainfall has its own limitations in terms of its bias owing to sampling error or signal attenuation by different hydrometeors. Many projects, including the Tropical Rainfall Measuring Mission [TRMM] have focused on improving precipitation estimates in the tropics. Improving the accuracy precipitation estimates relies on a combination of understanding and improving deficiencies in the physical assumptions of the algorithms, and correcting for the sampling biases contained within the estimates. Validation and inter-comparison of the algorithms has been an important goal of the Precipitation Inter-comparison Projects [Adler et al. 2001] and TRMM. Over mountainous terrain, these precipitation estimates often digress. Here the high resolution 2B31 product of TRMM satellitehas been utilized to analyze the relation between rainfall and topographic aspect of North-West Himalayan region. Relationship between topography and rainfall remains poorly defined due to lack of reliable rainfall networks[Bookahgagen and Burbank,2005].The nature of topography changes every 5 km in greater Himalayan region therefore Himalayan region is very rugged which is an unsuitable factor for orography-induced rainfall.In the Himalayan forelandand at low to moderate elevations, precipitation is dominatedby rainfall during the Indian summer monsoon season[Anders et al., 2006; Bookhagen et al., 2005a; Bookhagenand Burbank, 2006].Finding relationship between precipitation and topographic features needs high resolution rainfall data but satellite gives rainfall estimation in mm/hr. So for realistic estimation of rainfall over a region throughout a particular period rainfall intensity undergoes conversion into mean rainfall.In this study TRMM 2B31 product has been used for its high resolution data set because TRMM's 3B42 product gives rainfall estimation but at lower spatial resolution.As there is interplay between rainfall and topography features over mountainous region, data from digital elevation model will be in use to find dependency of orographic characteristic on rainfall. Owing to TRMM's lower temporal resolution dataset data set has been integrated on daily basis and a climatological map will be developed to find spatial distribution of rainfall during monsoonal period.

The relationship between rainfall and the Himalayan topography remains poorly defined. The Himalayan System has a distinctive climate:this system has a strong impact on the spatial temporal variation of rainfall. The onset of the Indian summer monsoon [ISM] in early June marks the beginning of the principal rainy season for the Himalaya. Every year, the bulk of the annual rainfall occurs between June and September, and thus monsoon rains have vital social and economic consequences .In mountainous regions, orography provides necessary uplift to the air encountering mountains on windward slopes. Rising air cooled adiabatically results in increased relative humidity, which creates clouds & precipitation. This process is the main reason for increasing accumulated precipitation withaltitude. Owing to the inapproachability to the Himalaya region and lack of reliable rainfall networks,quantification of rainfall during ISM is poorly defined.With the help of high resolution satellite data of rainfall rate a climatological map of rainfall can be developed and an identification of regions receiving huge and scarce amount of rainfall.Information on the variation of precipitation with elevation helps in understanding the scenario of the Himalayan region receiving maximum and minimum precipitation ,determining the elevation up to which terrain is receiving precipitation over the Himalayan region and developing hydrological model.Topography is a static parameter where rainfall is a dynamic parameter, which is influenced by the elevation and relief factor of topographyof Himalayan region.The Himalayan region receives rainfall three times a year,where western Himalayan region receives substantial amount of rainfall during Indian summer monsoon.The relationship between rainfall and altitude is not linear and maximum rainfall falls at the foothills of an elevation of 2-2.4 km.[Bookhagen Burbank, et. al. 2005] .Previous studies have shown on an average rainfall amount increases with increase in altitude ,however precipitation decreases above a certain altitude over this western Himalayan region[Bookhagen Burbank, et.al. 2009].Therefore keeping all the aspects of the influences of the topographic featuresof Himalaya during ISM [Indian summer monsoon]which characterize the rainfall pattern and the distribution of rainfall, following are the problem statements which have been addressed in this present work.

1.3 Problem Statement

1. Whether the climatic condition has any substantial role to play in extreme and less rainfall over Himalayan region.

2. Which part of the north-western Himalayan region is receiving substantial amount of rainfall and whether topography has any influence on that region.

3. Identification of high spatial resolution data to capture the fine spatial structure of rainfall distribution throughout the monsoon.

4. During Indian Monsoon normally it precipitates considerably higher than all other non-monsoon months, quantifying the contribution of orographic-induced rain and the variation of rainfall amount with altitude.

1.4 Research Objective

1. Validation of TRMM 2B31 data with in-situ rain measurement data.
2. Processing of TRMM 2B31 daily data and monsoonal mean rainfall data.
3. Developing a high resolution [5 km] rainfall map for the monsoon season using long term data set [1998- 2013] over the North-West Himalayan region.
4. Finding regions receiving high rainfall and low rainfall and comparison of amount of rainfall as a function of topography.
5. Finding spatial temporal variability of rainfall owing to orography over the north-western Himalayan region.
6. Investigation of the trend of extreme rainfall events for 16 years using TRMM 2B31 data set.

1.5 Research questions

1. How accurately and efficiently does the satellite give the rainfall data in comparison to In-situ rain gauge records?
2. Do the topographic parameters enhance the precipitation during monsoon and if it does then can it be quantified and represented as a condition?
3. How does rainfall distribution change with time and region wise?
4. Can the findings related to orographic effect on rainfall be used to modify satellite rainfall algorithm?

2. Literature review

2.1 Indian summer monsoon over Himalayan region

Indian summer monsoon is a large-scale atmospheric phenomenon accompanied by reversal of seasonal wind during monsoon season and uneven heating of landsurface and sea. The south-west monsoon [or Indian summer monsoon]season amongst the other seasons such as a]pre-monsoon b]post-monsoon and winter occur from July through September and continuous high insolation over the Thar Desert and adjoining areas of the northern and central Indian subcontinent warms these regions[Ramage,1971].Every year, the immense of the annual rainfalloccurs between June and September, and thus monsoonrains have vital social and economic consequences[Parthasarathy et al., 1992].Low pressure regions cause moisture-laden air from Indian Ocean to blow over Indian landmass and bring rainfall over the country.Amongst other seasons, monsoon is the most significant and effective season in sustaining the ecology of the mountains in India. Across the northern edge of the Indian peninsula, theonset of the Indian summer monsoon [ISM] in early July marks the beginning of the principal rainy season for the Himalaya[Fasullo and Webster, 2003; Webster andChou, 1980].

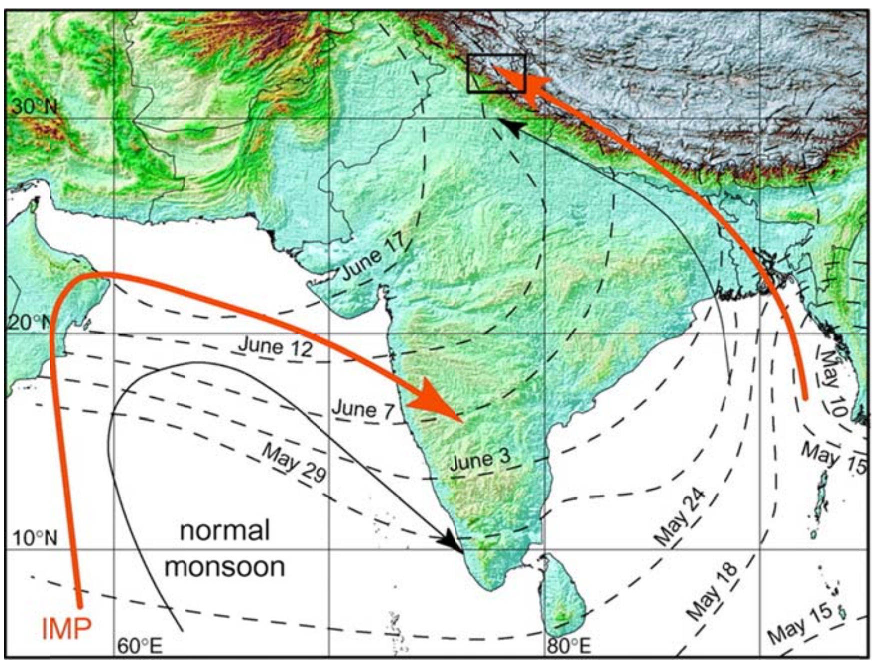


Fig.2.1: Onset of the Indian summer monsoon across India. Dashed lines indicate different branches of monsoonal winds strike coastal part of India on different date at the end of May and the beginning of June. Branches from Arabian Sea and Bay of Bengal together strike the North-West Himalayan region. The figure is adopted from http://geology.gsapubs.org/content/33/2/149/F1.expansion.html

The climate of the Himalayas is modified by the seasons characterized by the onset of monsoon [Das, 1968].Monsoon rainfall contributes the largest part of the annual rainfall for all the Himalayan ranges[Singh and Kumar, 1997]. The Himalaya plays a major role in maintenance and governing the monsoon system and climate of south-Asian region and rugged topography results in climate variability across Himalayan ranges [Pant and Kumar 1997]. The North-West Himalayan region mainly receives rainfall from the Bay of Bengal branch and with time it brings moisture laden air over the foot hills and the higher parts of Himalaya after ricocheting off the barrier of eastern Himalaya southern periphery. After deflection the monsoon low elongates over Gangetic plane and precipitation along the southern flank falls under the monsoon trough.[Hastenrath and yasunari,1985,1976] both have found that Southwest Monsoon circulation over India progressing over the Tibetan Plateau is closely related to the quasi-steady thermal anticyclone over Tibet called the “Tibetan High”. This emergence of high pressure zone over Tibetan platue causes disruption of Headly cell and attracts moist summer wind from Indian ocean [Hastenrath, 1985; Yasunari, 1976]. During the course of the Southwest Monsoon there are periods when the monsoon trough lies close to the Himalayan foothills and precipitation over much of Central India decreases, this is called a “Break in Monsoon” [Das, 1986].The interruption of the Southwest Monsoon has been related to a circulation cell in a meridional-vertical plane involving both the Indian lowlands and the Tibetan Plateau [Hastenrath, 1985; Pant, 1983]. Therefore, monsoonal precipitation over Himalayas may be related directly to the movement or variability of the Tibetan High and the influence of the monsoon trough [Das, 1986; Hastenrath, 1985; Nakajima et al., 1974; Yasunari, 1976]. The monsoon first reaches the Himalayan range over Bhutan, Sikkim, and eastern Nepal, where it arrives the earliest and stays the longest and then it enters into Uttarkhand, Himachal Pradesh and at the end Kashmir and remaining parts of the country. The eastern Himalaya receives above 2000 mm rainfall where the western part receives only 940 mm/yr[Stainton, 1972]. What all these studies lacked is detailed spatial and temporal information on rainfall pattern and characteristic over the Himalayan region during ISM. Even so, there are a handful of point-studies that have produced very detailed reports with respect to local climates in Nepal [Ageta, 1976; Inoue, 1976; Shrestha et al., 1974; Yasunari, 1976]. Yet, given the high degree of variability in local climatology, and the geographic concentration of those extant climate studies to central Himalayan region their applicability in characterizing Himalayan climate as a whole stand questionable[Nakajima et al., 1974; Schmidt-Vogt, 1990; Yasunari, 1976]. But later, studies on those regions using highly-dense rain gauges and TRMM data has brought out many revealing characteristic of rainfall during monsoon. A study by [Singh and Kumar,1995] shows that in outer Himalayan range spatial correlation of rainfall is higher than other ranges and rainfall increases with elevation in outer Himalayan and it exceptionally increases on the windward side but decreases on the leeward side of middle Himalaya . Mountainous environments inflict a strong robust impact on the spatial and temporal distribution of precipitation compared with the impact of plane areas so relationship between precipitation amount and elevation is an important factor [Shrestha et al, 2012].In addition, rainfall amounts ofup to several meters per year results in heavy erosion andflooding along the southern Himalayan front [Barnardet al., 2001; Bookhagen et al., 2005a; Gabet et al., 2004].

2.2 Orographic precipitation during Indian summer monsoon

During monsoon places on the windward side Western Ghats along the Indian south coast receive high amount of rainfall because of its barrier influence. The moisture-laden wind component of monsoon over Arabian sea strikes the long mountain barrier of western Ghats and getting an additional lift orographic precipitation takes place along the region at a distance 10-15 away from the crest of the mountain and at 25 km under weak monsoon conditions [Das, 1965]. Enhanced Rainfall influenced by orography is not only confined to regions along the foot hills of WesternGhats, the grand part of orographic precipitation unfolds in the Himalayan region during the mid-monsoon [Das, 1965].On striking a vertical obstacle an air mass is forced to ascend but it relies on the available energy inside to surmount obstacle, air parcels either shed all the moistures or fail to surmount the Himalayan barrier and Tibetan region gets deprived of rainfall. In mountainous region orography provides necessary uplift to the air encountering mountains on windward slopes [Shrestha,2012].This is the primary reason for increasing cumulated precipitation with altitude. Several studies have implied the importance of orographic precipitation to the realistic assessment of water resources, estimation of maximum precipitation and hydrological modeling of mountainous regions. [Dhar and Rakhecha,1981]have investigated using 50 rain-gauge stations the relationship of maximum elevation with increased rainfall and found no linear relationship between rainfall and altitude where [Singh,1995] has found the maximum rainfall zones fall near foothills at 2.0-2.4 km elevation.Previous studies of orographic precipitation were accomplished with rain-gauges and limited to basin scales [Shreshta, 2012]. But after the invention of TRMM satellite, a ground-breaking revealing information on the relationship between elevation and rainfall come out[e.g., Anderset al.,2006; Barros et al.,2004; Bhatt and Nakamura, 2005; Bookhagen and Burbank ,2006,2010; Houze et al.,2007;Twade & Singh,2014,Bharti,2015]. In addition, flash floods caused by extreme rain events over hilly region are major hydrological disaster in NEI [North East India] region owing to topographic feature and increased frequency of occurrences of such events [Goswami et.al 2010] . They have also observed that the frequency of extreme events increase in number during peak monsoon months in comparison to pre-monsoon months. So monsoon synoptic events add to the increasing number of intense rainfall event .The amount and pattern of rainfall have a hand in delineating the setting of mountain range [Roe, 2003]. So knowledge of spatiotemporal distribution of extreme events and factors influencing them would be fruitful in mitigating the damage from extremity of weather and in better hazard management. Topographic barrier saps upslope wind of moisture and few number of rainfall event on the lee side of the mountain [Barros 1994]. Hence space-time discretization [spatial resolution] is the crux of the quality understanding and study of rainfall over inhomogeneous elevated regions because of high spatial variability of orographic precipitation. [Biasuttiet.al,2011] has studied climatological rainfall intensity pattern over coast flanked by mountain using high resolution data. Francis and Gadgil [2005] have found that extreme rainfall occurs under the sway of orography. There are considerable numbers of studies which have been done over Himalayan region to find spatial distribution of rainfall over mountains region where rain-gauges network is sparse in number.

2.3 Orographic precipitation using satellite

Raingauge data from a particular year has been compared with precipitation derived from the precipitation radar [PR] and the microwave imager instruments on board Tropical Rainfall Measuring Mission [TRMM]satellite [Barros et.al,2000]. As elevation changes abruptly in Himalayan region, rainfall rate captured by satellite gets attenuated, a study by Barros,et.al,2000 has shown that TRMM shows better detection of rain rate at low altitude stations as compared with high elevation stations. A study by Bookhagen and Burbank,2006 &2010 using TRMM 2B31 data has resulted in a strong large-scale relationship among topography, relief and rainfall location and over high mountain barrier rainfall is caused by convection rather than by topography during monsoon[Romatschke and Houze,2011].They have found strong interaction between convective systems and steep terrain at elevations of 1-2 km.PR of TRMM is capable of detecting event of heavy rainfall in regions of complex terrain with a good consistency[Barros et.al,2000].The influence of monsoonal rainfall on the annual Himalayansediment flux is overwhelming, making the ISM thesingle most important factor in fathoming the reason of Himalayanerosion on long and short timescales [Bookhagen et al.,2005b; Burbank et al., 2003; Hodges et al., 2004; Thiede et.al., 2004; Wobus et al., 2003].Remote sensing offers an alternative method for studying orographic precipitation. Satellite methodsare particularly useful for remote, poorly instrumented regions. For example, the Tropical RainfallMeasuring Mission [TRMM] satellite operates by emitting pulses of microwave radiation, which arereflected by precipitation. Data from TRMM have been used to characterize the pattern of precipitationover the Himalayas at 10 km scales [Anders et al., 2006], revealing a broad double-band of maximumprecipitation along the southern slopes and local enhancements within windward valleys relative to the4 km-high flanking ridges where the moisture content is quite low [Anders et al., 2006] and other study by[Yatagai and Kawamot,2008] reveals that The Precipitation Radar [PR] data acquired by the Tropical Rainfall Measuring Mission [TRMM] over its10 years of observation can be used to show the monthly rainfall patterns over the Himalayas. Additionalremotely-sensed data come from ground-based radars, a great number of which are deployed forweather forecasting. These can be used to make detailed observations of precipitation, includingprecipitation phase, with high spatial and temporal resolution. In a classic study, Browning et al. [1974]used radar over the coastal hills of Wales to show that intense periods of mountain precipitation occurwhen rainfall cells from upwind of the mountains are advected over the mountains and enhanced asinstability is released and the seeder-feeder mechanism acts. Unfortunately, radar can be challenging touse in mountainous terrain where the beam is often blocked by topography.Both in situ and remote observations from aircraft have been a central component of several fieldprojects devoted to better understanding orographic precipitation. The most expansive of these effortsto date the Mesoscale Alpine Programe [MAP], focused on the southern slopes of the European Alps.Results from MAP revealed “that detailed knowledge of the orographically-modified flow is crucial forpredicting the intensity, location, and duration of orographic precipitation” [Houze and Rotunno, 2007], and that this flow is a strong function of the low level stability. Furthermore, under differentflow regimes contrasting microphysical growth mechanisms become important, influencing theenhancement and distribution of precipitation [Houze and Rotunno, 2007]. But to have knowledge of orographically modified flow, Indian summer monsoon is an important period to locate the regions of the mountains receiving highrainfall.

2.4 Use of TRMM 2B31

In Himalayan region hardly is there any ground-based radar which is to record rainfall over those rugged regions. TRMM satellite's PR [precipitation radar] data gives vertical profile of rainfall structure which functions well for moderate rainfall intensity but few study has reported it underperforms during extreme rainfall. Biasutti (2011) has mentioned that PR[precipitation radar] in TRMM does not detect light rain and drizzle in stratocumulus cloud.[Bookhagen and Burbank, 2005] has studied the contribution of the topography to orographic precipitation using 8 years composite high resolution TRMM 2B31 data set. Amongst all the studies done on the distribution of rainfall over hilly regions, fewer studies are there which performed using TRMM 2B31 product. [Shrestha et al, 2012] has used TRMM 2A25 product for the same study over Himalayan region. 2A25 is the level-2 product processed from level-1 PR product only whereas 2B31 is the merged product of PR and TMI [Thermal microwave imager] but 2A25 provides the vertical structure of convective system using reflectivity condition. Bookhagen and Burbank [2005, 2008, and 2010] calibrated the TRMM 2B31 rainfall intensity data with IMD rain-gauge data using linear fitting to compute more realistic rainfall data integrating all the 8 years data. Cumulative rainfall intensity of 2B31 for monsoon months from 2001-2004 has been compared with total IMD-station recorded rainfall for the same period by Bookhagen and Burbank [2005] to convert rainfall intensity into absolute rainfall. For climatorlogical purpose this dataset is of huge importance as compared to daily rainfall data usefulness. Model for prediction and understanding orographic precipitation has performed better than the data used from traditional rain-gauge networks but those model depends on rainfall data estimated from groud-based radar or in some cases rain-gauge network that is why TRMM's onboard precipitation radar is the only source which gives high-resolution rainfall data which to a great extent can be used to feed the models and modification to rainfall amount estimation over hilly regions. Using high resolution 2B31 dataset over entire Himalayan region [Bookhagen, 2005] has shown that there are two bands of rainfall respective of elevation in Uttarakhand state which is in concurrence with the study over Himalayan region by [Shrestha et.al,2012]and [Yatagai and Kamamoto, 2008].He has shown clear relationship between topographic features and zones where rainfall maxima occurs.It occurs in the frontal regions along the entire Himalaya at an average elevation of ~0.95 km or mean relief of ~ 1.2 km. But the study was done using 8 years of data set of TRMM.At present TRMM estimated rainfall becomes accurate with larger number of datasets and statistical relationship between every topographic feature and rainfall has to be developed for establishing a robust relationship which will reveal the influence of orography over rainfall.

2.4Study of SRTM DEM

High resolution of elevation data generated by digital elevation model (DEM) using different techniques and methods has brought a huge difference and outstanding quality in the analysis of long-standing relationship between rainfall and topography as compared to previous studies using topographic map before the invention of DEM. With the improvement of methods, technique DEMs are able to generated elevation information with higher spatial resolution but they trade off on vertical accuracy of elevation information over mountainous region. Several studies have investigated the vertical accuracy of elevation data sets comparing them to elevation data from different sources: stereo pairs [Nikolakopoulos et.al 2006] and national resources. The vertical accuracy of global elevation depends on the terrain, land cover and it decreases in mountain area characterized by complexities of ruggedness. [Gorokhovich and Vostianiouk, 2006]. Another study to evaluate vertical accuracy of Cartosat DEM [Indian satellite] over Drum mountain has revealed that SRTM DEM has more accurate DEM in terms of vertical accuracy [Evans, et.al, 2006]. SRTM DEM compromises on spatial resolution over North-West Himalayan region but for comparative analysis each pixel of 90 m resolution containing elevation information has been resampled to size of the area at which the spatial resolution of rainfall data is available.

3.Study area

3.1 Study area and data set

Many aspects of Indian climate are influenced by the Himalayas [Das, 1965].The massive barrier takes a shape of ellipse which elongate beyond thousand kilometers both along the east west and north-south direction. It boasts of some of the largest peaks and the deepest valleys of the world and some of the major rivers, Ganges,Brahmaputra and Indus, originate in the Himalayas. As the monsoon gradually progresses over North India, at the beginning of July Uttarakhand comes under the aegis of monsoon system and lots of regions over Himalayan foot hills start receiving huge rainfall and the system becomes weak in Jammu and Kashmir. Hilly areas in North-West Himalayan region are prone to cloudburst owing to extreme event and few places [for e.g.Dharamsala,Dehradun] in this whole region receive one of the highest amounts of rainfall during monsoon. Therefore the North western region of Himalaya has been selected for the study of contribution of orography to rainfall,this region is extending from Jammu and Kashmir to Himachal Pradesh to Uttarakhand[Fig-3.1]in terms of political boundary but geographically the Himalayan region is divided into three parts a] Left Himalaya b]Central Himalayan and c]East Himalaya.This study is focused on the western Himalayan region during JJAS[June,July,August,September,the principal monsoon season of ISM].Distinct topography patterns are preponderant in the Great Himalaya and the western Himalaya is characterized by one-step topography [Bookhagen and Burbank, 2006, 2010].The Himalayas extends from the Nanga Parbat [8125 m] in the west to the Tsangpo-Dibang bend around Namche Barwa [7755 m] in the east, forming an arc of 2400 km length and width 150–400 km north to south. The world’s highest mountains, MEverest [8848 m], K2 [8611 m] and Kanchenjunga [8586 m], are located within them. However the present study is limited within Indian region.The Himalayas comprise a complex chain of high mountains, elevated plateaus, deep gorges and extended valleys. There are three main ranges:

[a]Outer Siwalik range [Southern Himalayas] lying between the Lesser Himalayas and the Indo-Genetic plans, with average height 900–1200 m a.s.l. and width 1000–5000 m.

[b] Middle range or Lesser Himalayas [named differently in different sectors], which are a series of broken mountain ranges of mean elevation 3700–4500 m a.s.l. and width about 5000 meter. In northwest India, these are called the PirPanjal ranges and in Nepal the Mahabharat ranges.

[c] The Great Himalayan range is the innermost of the highest ranges with perpetual snow and ice whose average height varies from 6000 to 8800 m a.s.l., and which separates the Tibetan Plateau from the Indian sub-continent.

The loftiest mountain complex of the Himalayas contains 10 of the world's 14 peaks exceeding 8000 m [see Fig. 3.1 for illustration] and 31 peaks exceeding 7600 m in elevation. There are series of narrow chains of high mountains [crest-lines at 5000–5500 m] that are transverse by a number of trans-Himalayan rivers and their tributaries, which play an active role in eroding and shaping the high mountains, producing deep valleys and gorges. Every mountain is characterized by elevation, relief,slopeand aspect. To have quantified knowledge on the ruggedness of mountain, slope, aspect and relief are valuable aspect to consider. Slope of mountain controls many geologic processes, steep slope causes landslides and decent slope regulates the drainage of rainfall water and erosion of the basin and it also creates swamp.

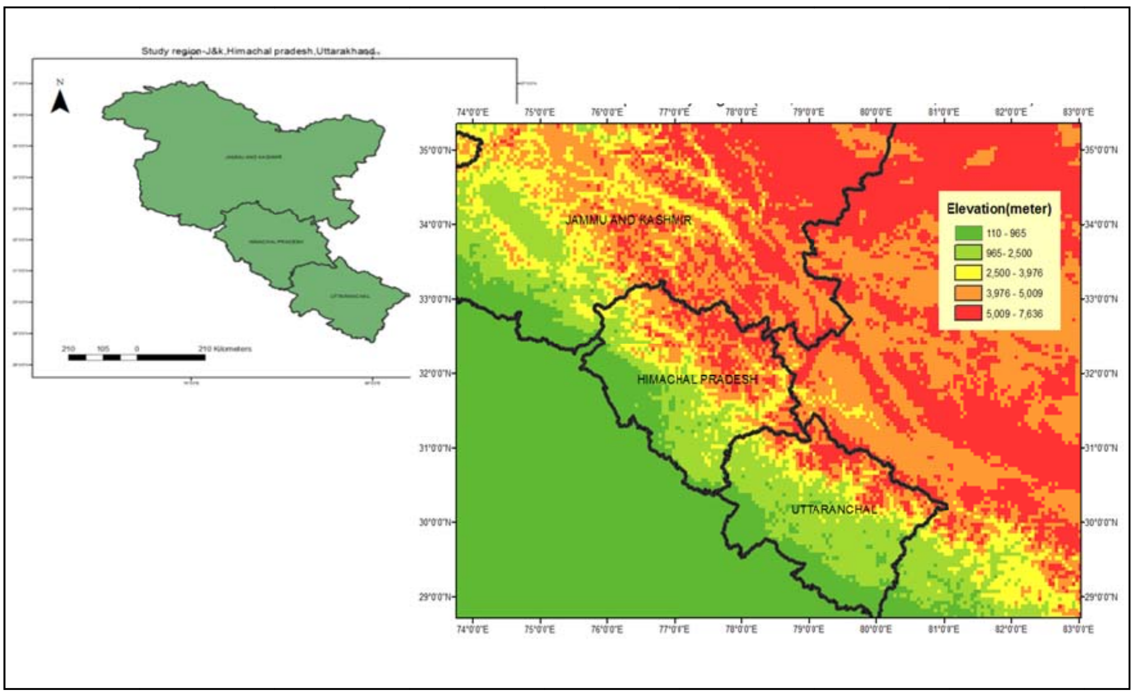


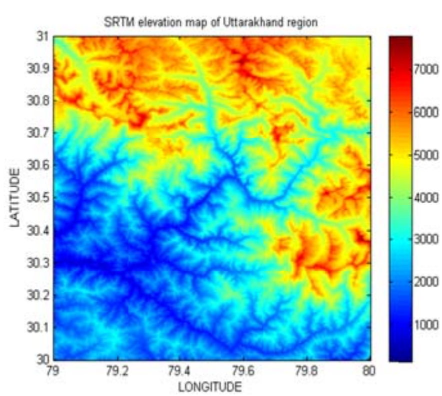
Fig.3.1: Resampled topography map at 5km spatial resolution, containing elevation information, from 90 meter SRTM DEM for comparative study of rainfall over the selected study regions.

For topographic-rainfall analysis the Shuttle Radar Topographic Mission [SRTM] Version 2 topographic data(http://srtm.csi.cgiar.org/) with a 90m grid cell size has been used [Farr et al., 2007] and SRTM DEM is an extremely accurate global model with accuracy of 6 meter and horizontal pixel spacing of 30 m developed using single pass radar interferometry [Jarvis et al.2004]As a result SRTM data has better vertical accuracy than CARTSAT DEM. After filling holes inthe SRTM data [using void-fill technique inbuilt in ENVI], the entire combined90 m data set was used to derive topographical features[aspect, slope, shaded relief].J&K extends beyond 36 degree North latitude but TRMM 2B31 data set remains confined between 36°S and 36°N.Regions above 36 degree North has been excluded from the spatial and temporal analysis.

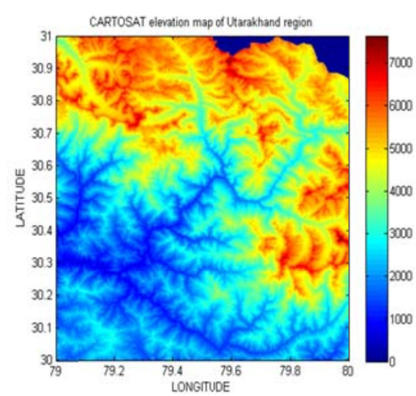
For computation of relief and aspect of rising slope of different regions of North-WestHimalaya, the SRTM DEM has been used. The SRTM data is available at 90 meter resolution with 1x1 degree tiles and its estimated accuracies for global product are 20 meter for vertical data and 30 meter for horizontal data.The version 4 product has been developed using new interpolation algorithm and better auxiliary DEMS.The data comes in its own .HGT format and available in tiles of 1x1 degree .This data is currently distributed free of cost by USGS and is available for download from the National Map Seamless Data Distribution System, or the USGS ftp site. The data currently being distributed by NASA/USGS [finished product] carries “no-data” holes where water or heavy shadow preempted the quantification of elevation. These are generally small holes, which nevertheless render the data less useful, especially in fields of topographic relationship with rainfall and hydrology because rainfall data is not available with that fine resolution SRTM DEM data is available with.

3.2Comparison of SRTM DEM and Cartosat DEM

Quite a few numbers of studies have been done on the evaluation of vertical accuracy of elevation information recorded by DEMs. Comparative analysis of DEMS over different regions by researchers manifest that SRTM has better vertical accuracy over mountainous regions as well as over planes than Cartosat and Aster Dem[for a detailed description of vertical resolution, please refer literature review]. It has better spatial resolution of 27 meter than SRTM DEM. For analyzing the vertical accuracy, the highest peak of India, Nanda Devi, has been selected because the elevation information of this peak is also available in Cartoset DEM. Using a tile covering distance 111.1 km both latitudinally and longitudinally, where the every pixel of Cartosat DEM has been resampled from 27 meter to 90 meter.



[a]



[b]

Fig.3.2: [a] SRTM DEM elevation map of a mountainous region and [b] is a resampled[bilinear interpolation] at 90 meter Cartosat DEM elevation map of the same mountainous region extending from 79° E-80° E and 30° N-31 °N. The color bar indicates elevation information.

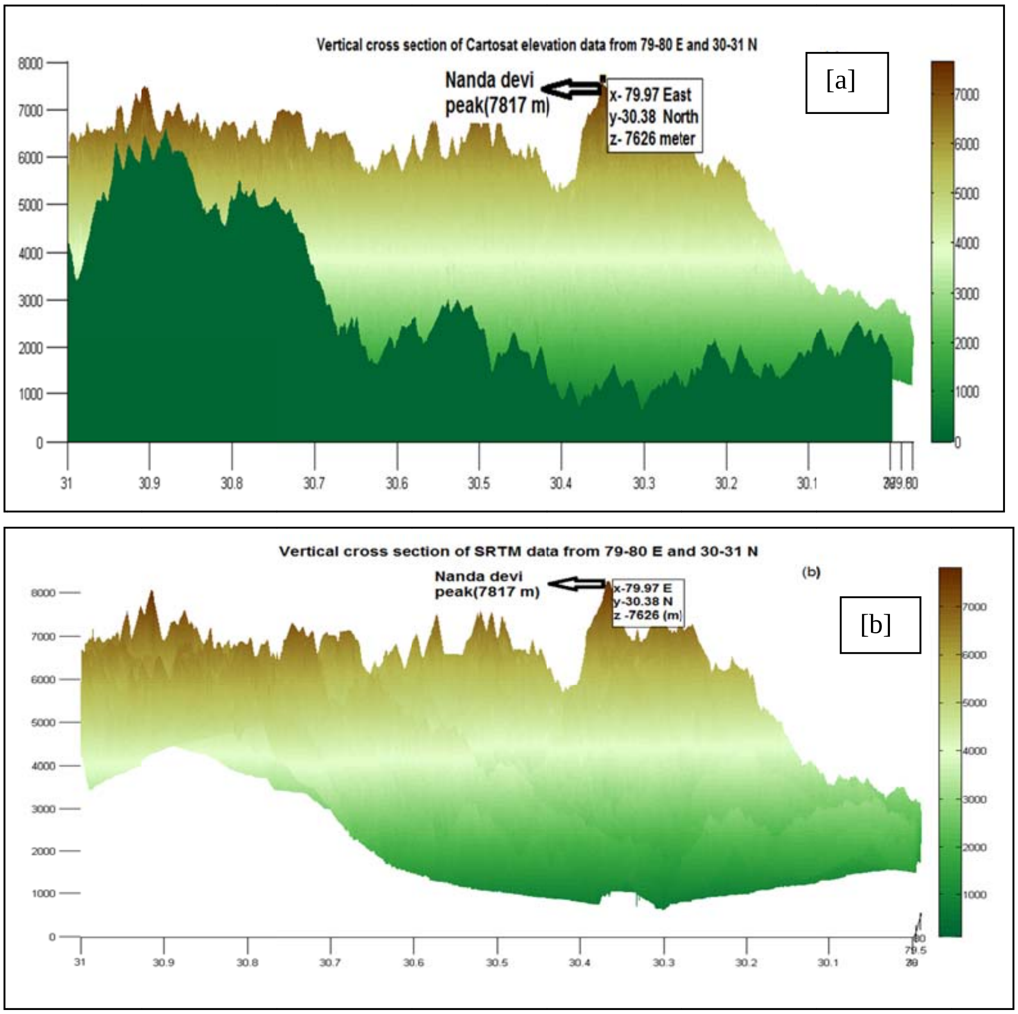


Fig.3.3:[a]represents the vertical cross-section of latitudinal extent of elevation of a region containing the highest peak Nanda Devi[7816 meter] of Cartosat DEM [b] same as[a] but for SRTM DEM.

These Fig. have beengenerated using Matlab and SRTM DEM has captured 7805 meter of the highest peak where Cartosat DEM .The recorded elevation information by Cartosat DEM is 7636 meter where the actual elevation is 7817 meter[Google Earth]. The more accurate information of Nand Devi peak is recorded by SRTM DEM which is 7626 meter.Therefore for topographic analysis SRTM DEM has been given preference to compute slope,aspect and relief map of the study region. Following are the maps of different aspects of North-West Himalayan region and central Himalayan region.

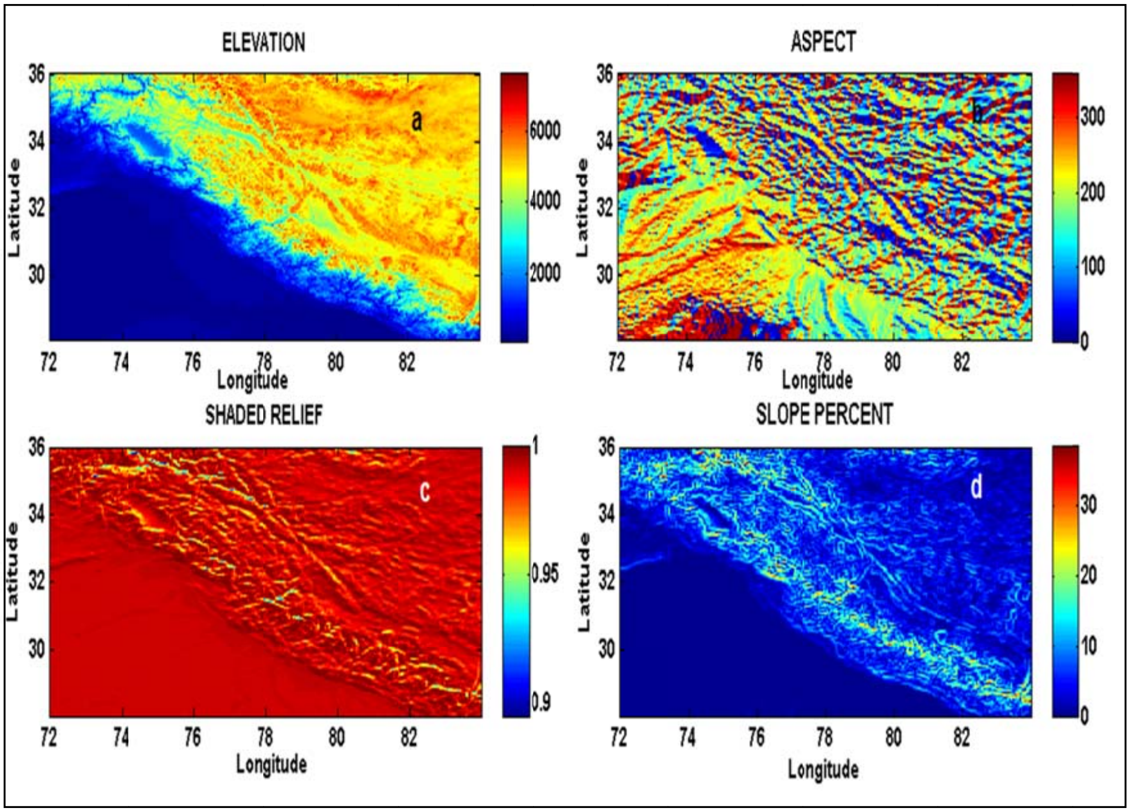


Fig.3.4:[a] is the 5 km resolution elevation map derived from 90 m resolution SRTM data, [b] is the aspect of the same region and [c],[d] are the shaded relief and slope map.The color bar of each Fig. indicates values of its characteristic [a]elevation [meter][b]aspect[0 degree from North direction],[c] shaded relief and [d] slope[in percentage].

Slope characterizes the steepness of a mountain and steepness between elevation points decides the suitability of upliftment of moisture-laden air. To analyse how rainfall gets influenced owing to the slope of a mountain slope map has been generated where the relief map is necessary to have an insightful understanding the distribution of elevation of Himalayan region and how the mountain ranges have extended itself over the study region. Shaded relief gives a real visual of the distribution,dirction of mountain ranges and the differene between gorges and peaks.

The study area[Fig.3.1] covers approximately 900 km area lengthwise from 74° E to 84 ° E and meriodinal 500 km stretch in Jammu and kashmir , about 200 km in Himachal pradesh and 150 km in uttarakhand from 28 °N to 36 ° N. Central Himalayan region is spreade over Uttarkhand and extend through Nepal[Out of study region] and west of 80 ° E is oriented in ESE-WNW direction [Shrestha,2012]. Elevation varies from 1000 meter to 3000 meter within 30 km in the one step topography over Himachal pradesh. Such abrupt variation in topography gives rise to wide range of climatic conditions and that conditions are omni-present over the Himalayan region.

4. Methodology

4.1 Dataset of rainfall and methods:

With the joint mission between Japan Aerospace Exploration[JAXA] and NASA launched TRMM [Tropical rainfall measuring mission]satellite to conduct research into precipitation and its affiliated phenomena in much more detailed and methodical way to the tune of first onboard-precipitation radar. TRMM was launched by the H-II rocket from NASDA/Tanegashima Space Center in November 1997 and it has taken a circular orbit of altitude 350 km with an inclination angle 35°and period 90 min. TRMM satellite is purported to observe rain structure, rain rate and its distribution over tropical and subtropical region. TRMM is the first space mission Precipitation radar was its unique invention in the realm of meteorological satellite. Ground-based radar detects rainfall over a limited area around its specified radius distance, depending upon the operating frequency. In India most of the ground-based radars installed near the shore line for better tracking any stormy phenomenon work well but it pales in comparison to high spatial and temporal variability of TRMM satellite because of its wide coverage of the Earth. Precipitation radar operates at 13.8 GHz frequency and it is a more direct method to detect hydrometeors in the atmosphere and has the ability to record information on rain rate above 0.5 mm per hour using very less electric power. It is also able to separate out rain echoes for vertical sample sizes and new methods have been developed to correct for rain attenuation effect at intense rain rate. PR has swath width of 215 km and horizontal resolution is much better than other satellite products. The horizontal resolution changes away from nadir. At nadir its resolution is 4.3 km and off nadir it becomes 5 km

Alongside PR , TRMM has TMI [Thermal microwave imager] working to give data related to rainfall rates which is operating at l0.65 GHz, 19.35 GHz, 21.3GHz, 37 GHz and 85.5 GHz microwave frequencies.More specifically TMI is a multi-channel dual polarized passive radiometer. It provides rainfall information over sea more accurately than on land surfaces because of its various emissivity. TMI is similar to SSM/I instrument onboard on Defense meteorological satellite program spacecraft. It has a spatial resolution of 6-50 km and swath is 760 km.

TRMM satellite generates rainfall products of various time periods. 2B31 is a merged product of level 1B of TMI and PR. 2B31 is called level 2B product. This product provides rainfall rate with high spatial resolution about 5 km but the temporal resolution is poor because it revisits a particular place after 46 days. Therefore TRMM is not successful in tracking a particular rainfall event or storm but on long term it provides huge quality information on rainfall characteristic if integrated over long time period. The satellite passes over the study region four times a day but not on the same places. Therefore the data of 2B31of monsoonalmonths from 1998-2013 have been processed to compute mean and cumulative rainfall rate. Satellite never gives rainfall data in an absolute amount rather it captures rainfall intensity in mm/hr .To analyze how this product has performed over foothills and mountainous region, computation oftotal mean rainfall intensity has been taken into consideration to compare intensity value of each pixel of study region with the rainfall data supplied by IMD but at 25 km spatial resolution.

4.1.1Preparation of TRMM 2B31 product

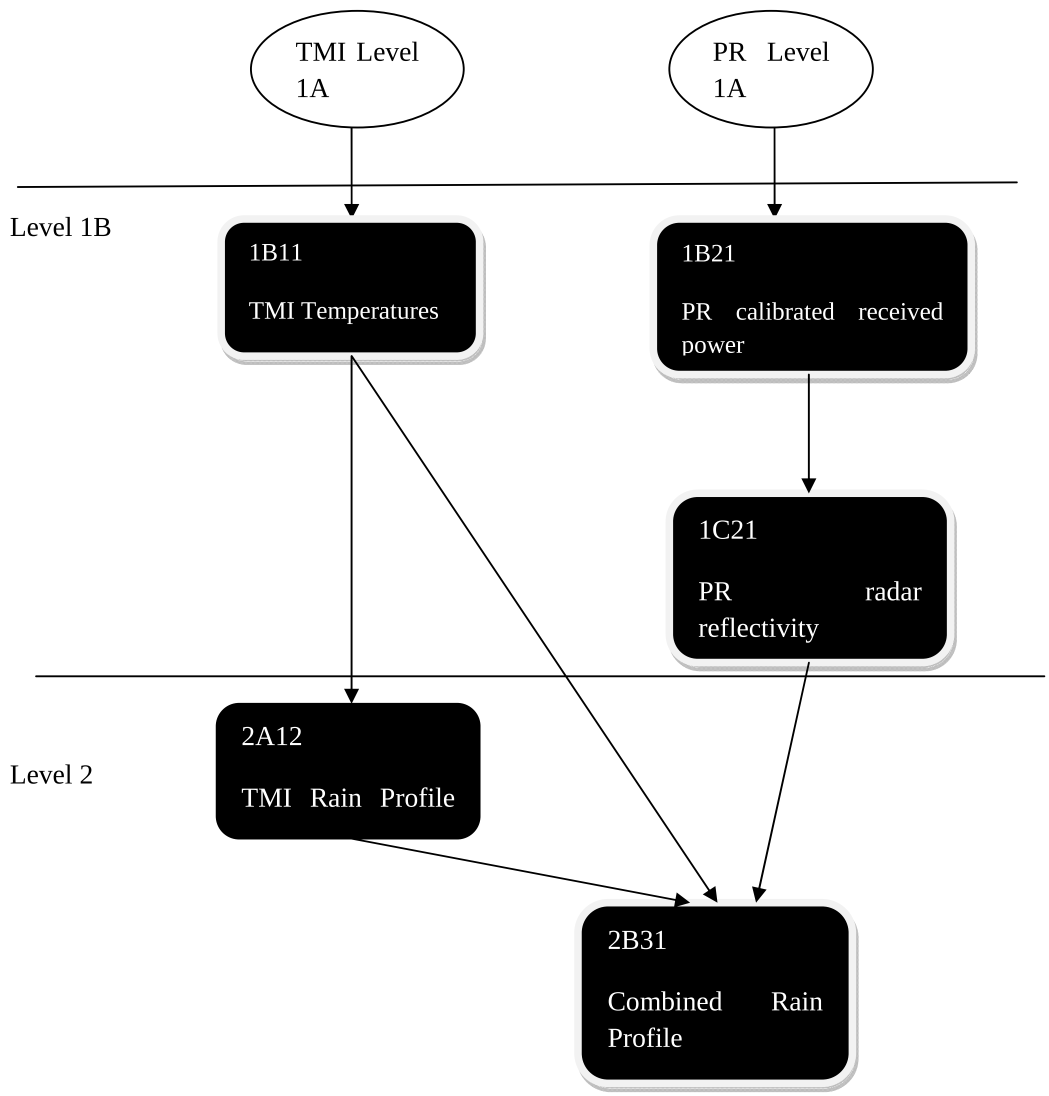


Fig.4.1:Flowchart algorithm for development of TRMM 2B31 data [adopted from TRMM handbook,www.eorc.jaxa.jp]

Table 4.1 : 2B31 data characteristics

TRMM 2B31 Data Characteristics		
	Pre-boost [before 2001-08-07]	**Post-boost [after 2001-0 8-24]**
Temporal Coverage	Start Date: 1997-12-08 Stop Date: 2001-08-07	Start Date: 2001-08-24 Stop Date: - at the end of December
Geographic Coverage	Latitude: 38°S - 38°N Longitude:180°W - 180°E	Latitude: 38°S - 38°N Longitude:180°W - 180°E
Temporal Resolution	About 91.5 minutes per orbit About 16 orbits per day	About 92.5 minutes per orbit About 16 orbits per day
Horizontal Resolution	4.3 km	5.0 km
Scan Characteristics	Swath Width: 215 km Rays/Scan: nray= 49 Scans/Second [SS]: 1/0.6 Seconds/Orbit [SO]: 5490 Average Scans/Orbit: nscan = SS*SO = 9150	Swath Width: 247 km Rays/Scan: nray = 49 Scans/Second [SS]: 1/0.6 Seconds/Orbit [SO]: 5550 Average Scans/Orbit: nscan = SS*SO = 9250
Average File Size	Compressed: ~11 MB	Compressed: ~11 MB
File Type	HDF	HDF

Validation data –High resolution daily gridded IMD data set[Pai et al,2014] from 1998-2013 has been used for validation and calibration of TRMM 2B31 data set for the same time period.

4.2 Softwaresused

ENVI:ENVI [Environment for Visualizing Images] is a software application used to process and analyze geospatial imagery. This software has been used to resample DEM data from 90 meter to 5 km using interpolation technique because [.HGT] file format is accessible in ENVIand land topographic features [elevation,slope,shaded relief, aspect] in ASCII format have been generated for future use on other platforms.

MATLAB:MATLAB [matrix laboratory] is a multi-paradigm numerical computing environment and 4th generation programming language. The huge complicated data set in [.HDF] file format has been visualized in MATLAB's inbuilt HDF viewer and conversion of orbital frame into uniform gridded frame, mathematical operation over huge data set, statistical analysis ,plot generation, all of this , have been carried out in MATLAB.

ArcGIS:ESRI's ArcGIS has been used to overlay geo-referenced image of rainfall over the topographic map to infer relationship, if any, visually with ease and most of the maps with detailed information have been generated using ArcGIS.

4.2.1TRMM 2B31 rrSurf

Orbital satellite data from the TropicalRainfall Measurement Mission [TRMM] has been used to estimate rainfallamounts [Kummerow et al., 1998, 2000]. The TRMM product2B31 provides rainfall estimates on a 4 × 6 km² pixelsize between 36°N and 36°S [TRMM product 2B31TRMM_2B31_readme.shtml]in rrSurf product. rrSurf represents surface precipitation rate[mm/hr] excluding snow and ice precipitation. The TRMM 2B31 data productis a combined rainfall profile product from the PrecipitationRadar [PR] and TRMM Microwave Imager [TMI].The data have been processed for 16 consecutive years from1998 to 2013 with a total of 8848 orbits [4-5 each day]and interpolated the orbital data onto an equally spaced 5 ×5 km² grid. Nearest neighbor interpolation technique has been used for interpolation at specific grid point and it has given almost similar rainfall rate captured by rrSurf generic data set. In August 2001, the orbital boost maneuver toextend the lifetime of the TRMM platform resulted in achange of the horizontal footprint resolution to5.0 km. The instantaneous rainfall amounts [mm/hr] wereconverted [or calibrated] to mean monsoonal withmonthly ground based IMD-interpolated data sets. The IMD interpolated data set is available at 25 km resolution, so rrSurf product of 2B31 has been resample at 25 km resolution from 5 km resolution then mean rainfall data has been calibrated with mean rainfall intensity of 2B31 using regression or linear fitting. The data fitting resulted in 60% similarity between both data sets after resampling. Every pixel of IMD data set represents 25x25 square kilometer area. Consequently, in that region there is a huge probability of different amount of rainfall at specific region. But this data set does not distinguish between those regions. Linear fitting has been done for pixels coming into study region. We have calculated mean monsoonal rainfall intensity and mean cumulative rainfall intensity for 16 years for calibration purpose. The calibration factor computed for cumulative rainfall intensity is in concurrence with the factor computed in similar study over Nepal region by [Bookahagen and Burban, 2005].

TRMM 2B31 has lower temporal resolution; hence it takes 46 days to revisit that particular place. It takes 4-5 snapshots every Himalayan region every day and upper part is captured more often than lower part above equatorial region because of satellite's ascending and descending passes, thus TRMM is incompatible tracking any continuous atmospheric phenomena. Rainfall intensity of every pass for particular day has been integrated for 16 years for more detailed information on rainfall distribution.Accordingly study of rainfall using this dataset needs monthly and seasonal dataset prepared after taking data set for several numbers of years.

There are two types of calibration technique used in previous cases for TRMM calibration;here we have used linear regression technique because unavailability of point rain gauges dataset. Because of the non-continuous satellitemeasurements, monthly or seasonal rainfall amounts aresignificantly lower than the true rainfall amounts. In order toderive more realistic rainfall amounts, we validated our dataagainstinterpolated gridded IMD datadiscussed in the later section [Fig.5.5 and Fig.5.8].

4.2.2Gridding of 2B31 rrSurf data

- TRMM satellite is a polar orbit satellite
- For estimation of total rainfall and analysis of spatial distribution of rainfall the path data has been represented on a equally-spaced grid of 5km resolution.
- There is an in-homogeneity in spatial resolution which has been countered using interpolation technique using Matlab.
- This product gives rrSurf product which contains the data of surface rainfall intensity[mm/hr].

4.2.3 Flowchart for gridding

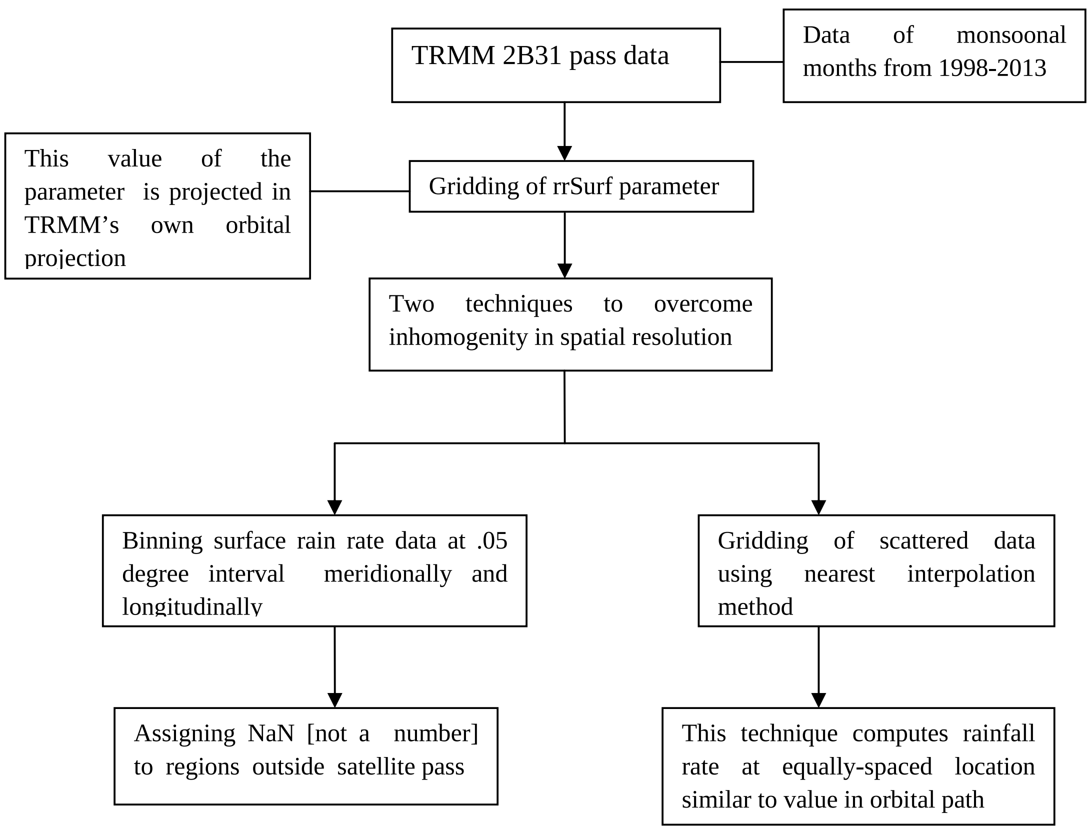


Fig.4.2 : Flowchart unfolding the stpes followed to convert the orbital path of satellite's data into gridded data using two methods.

4.2.4 Satellite pass data

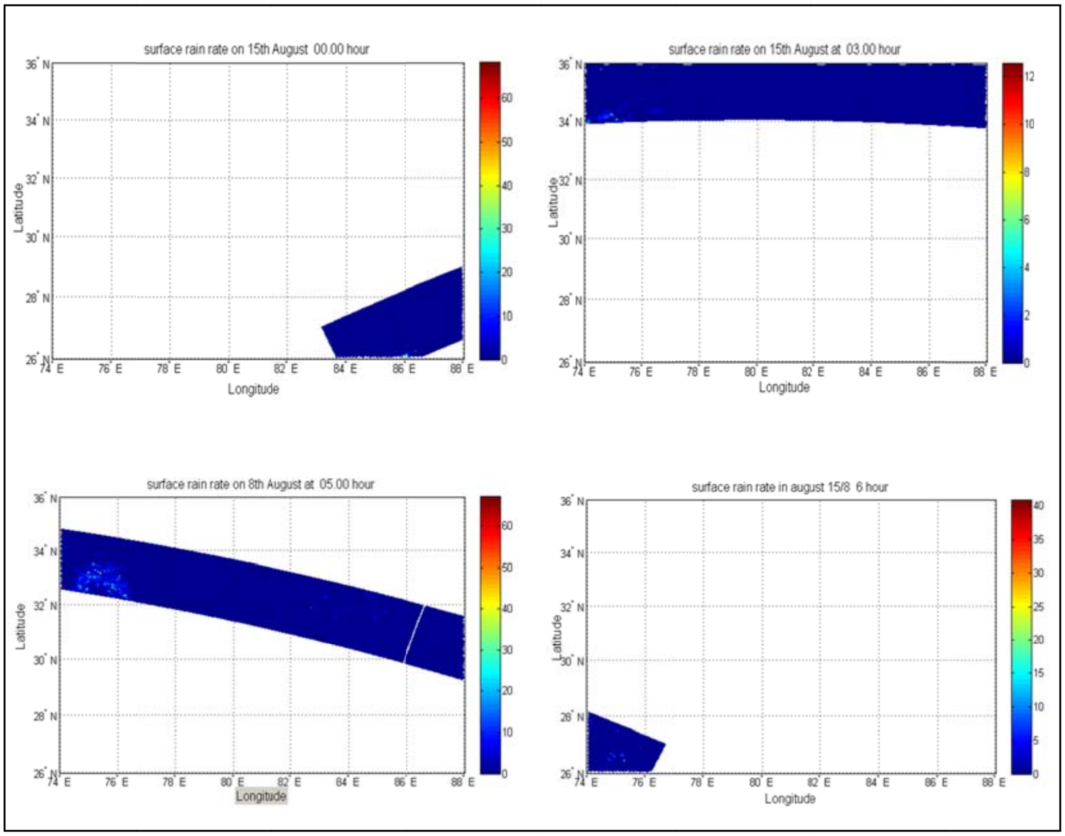


Fig.4.3:Interpolated Gridded data in terms of all the paths traveled by satellited over the study region on a specific day have been represented in a standard format for further operation for rainfall study.

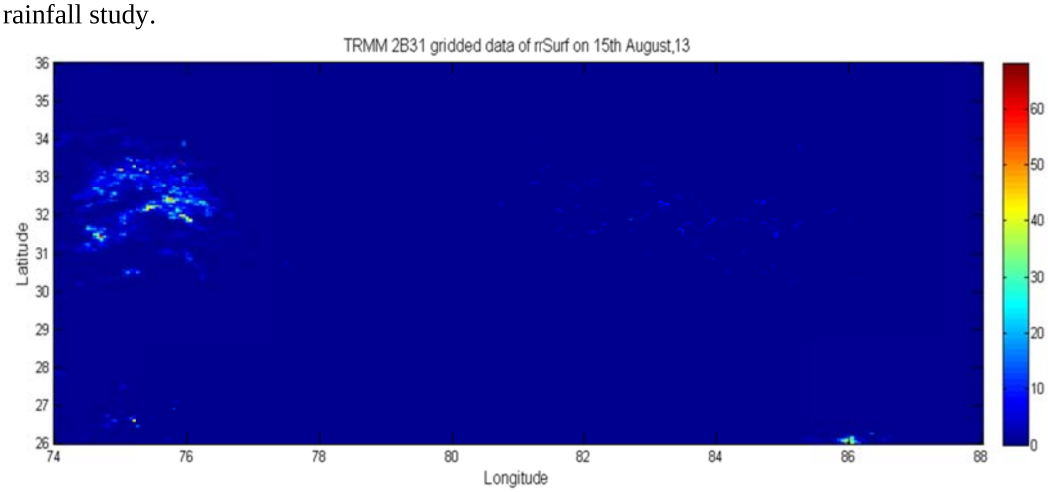


Fig.4.4 : Grided data genereated using Nearest-neighbour interpolation method on every satellite pass for a single day. In this Fig. all the satellite passes on 15th August,13 have beenconverted into standard projection and all the four gridded passes have been added

together to generate daily rainfall intensity data. The colorbar indicates rainfall intensity[mm/hour].

5. Results and discussion

After conversion of satellite path data into gridded data of every satellite pass, mean rainfall

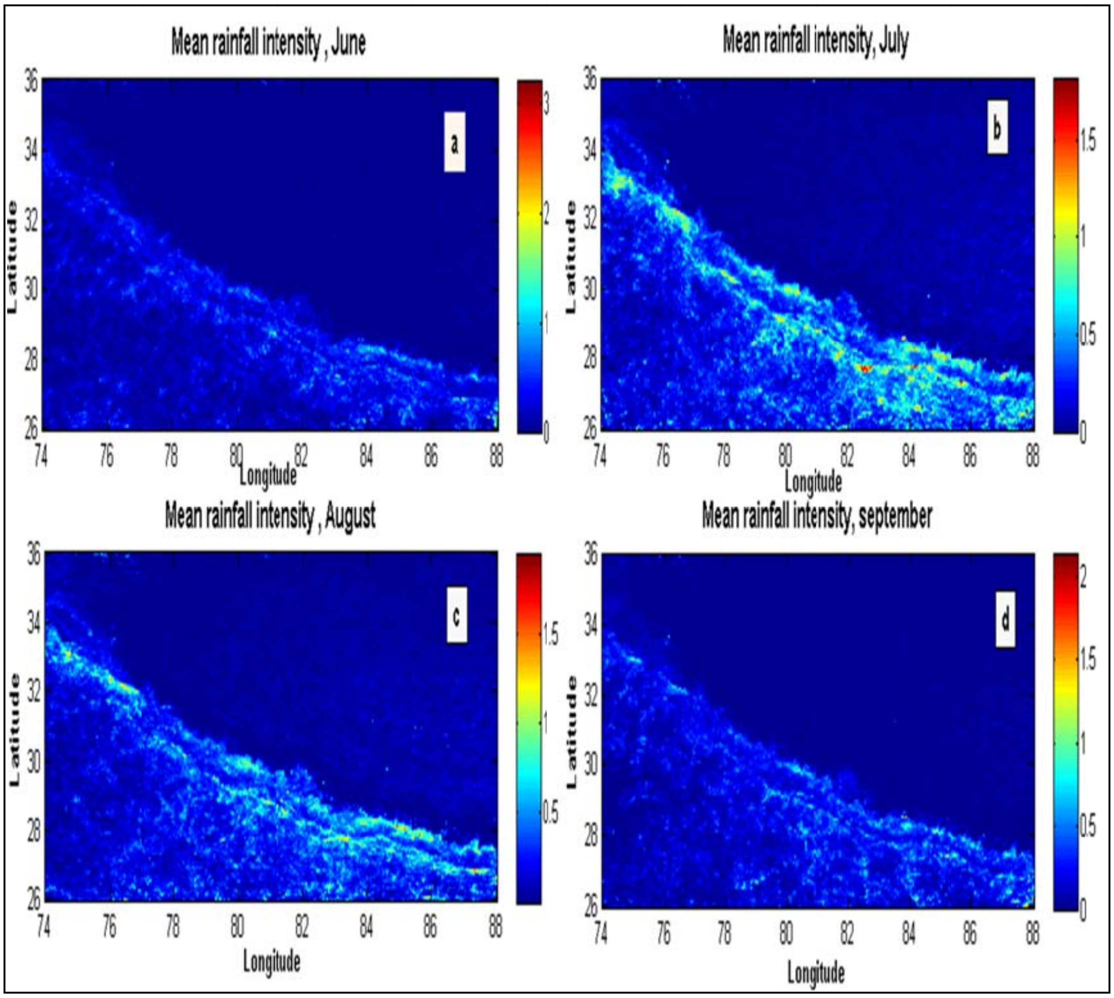


Fig.5.1:[a],[b],[c],[d] delineates the rainfall distribution over the North-West India using high spatial resolution data of TRMM 2B31 for the monsoonal months starting from June, July, August and September. As the monsoon gets active near the North-West Himalayan region, rainfall distribution is evenly scattered in [b] and [c], there are two parallel bands visible in [b] and [c] which are only resolved by this high resolution data set. In September,[d], rainfall intensity declines along the bands.

Intensitydata have been generated month wise for every year. The data gap owing to absence of satellite pass over specific regions has been accounted by taking integration of as many as satellite pass data having information on rainfall intensity from other years . After spatial synthesis using huge data sets and segregating dataset month wise a climatological map of mean rainfall intensity has been developed with finest resolution as well as rainfall distribution with no data gap.

5.1Climatological map of mean rainfall intensity

After applying the algorithm to convert satellite pass data into gridded data, normal mathematical operation has been performed each and every gridded data for the whole time period. The size of the gridded data for every pass is 201 by 281. Whereas the study region

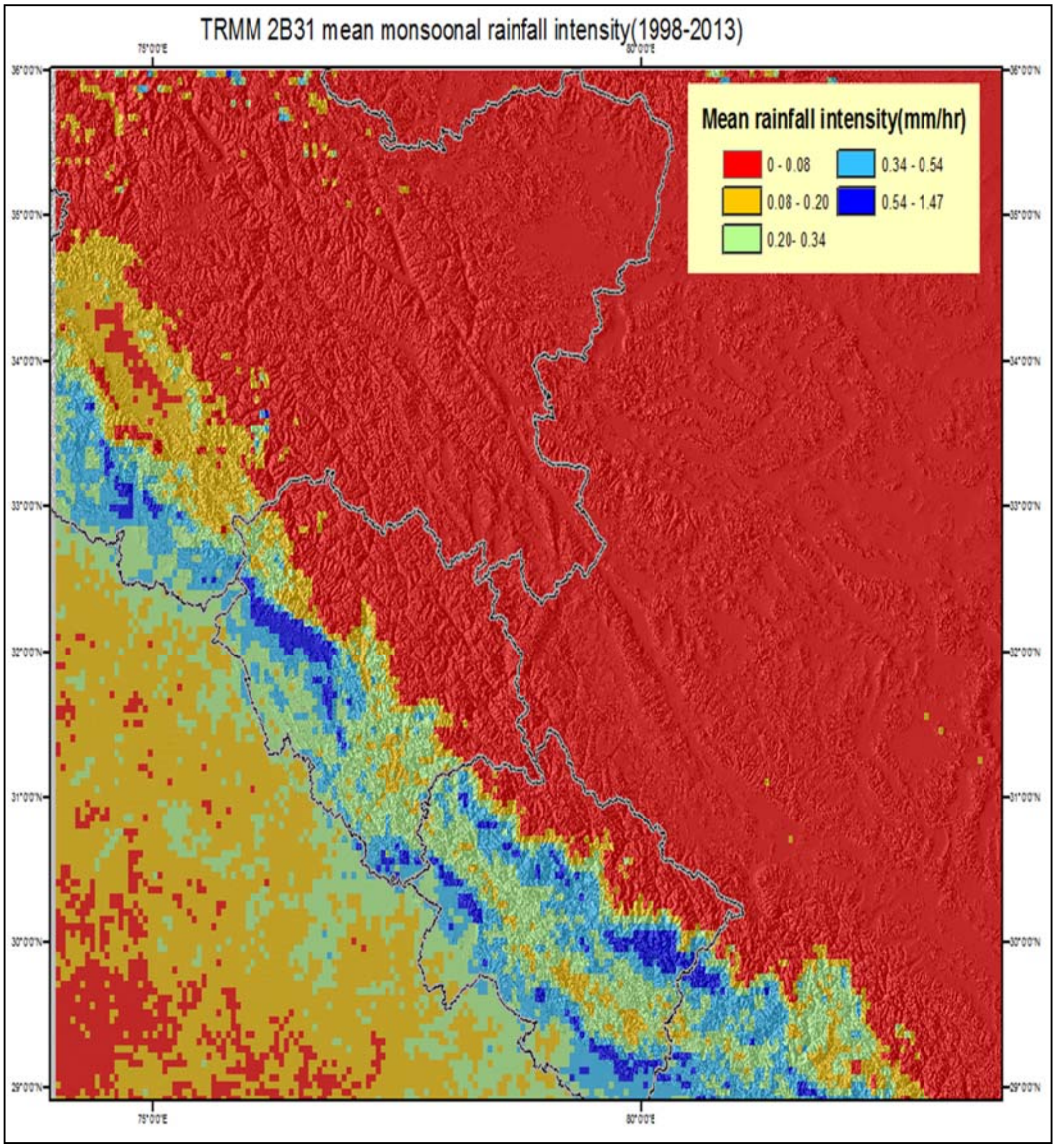


Fig.5.2: Callibrated TRMM 2B31 rrSurf parameter has been used to develop this climatological map.This is a high resolution map of 5 Km pixel.The rrSurf data has been integrated from 1998-2013 for computation of mean monsoonal intensity.There are an inner and outer bands of rainfall in Uttarakhand and a single band in Himachal Pradesh.Greater Himalayan regions has received less rainfall throughout the three states.

is enclosed between 28 °N-36 ° N and 74°E- 84°E. If a rectangular box is imagined to cover the region and every smallest pixel representing 5km area spatially, the size of the matrix containing all the rainfall information is fixed. For the preparation of mean rainfall data, matrices have been summed up for individual month from 1998 to 2013 then the average is taken over 16 years to develop seasonal mean rainfall intensity map.

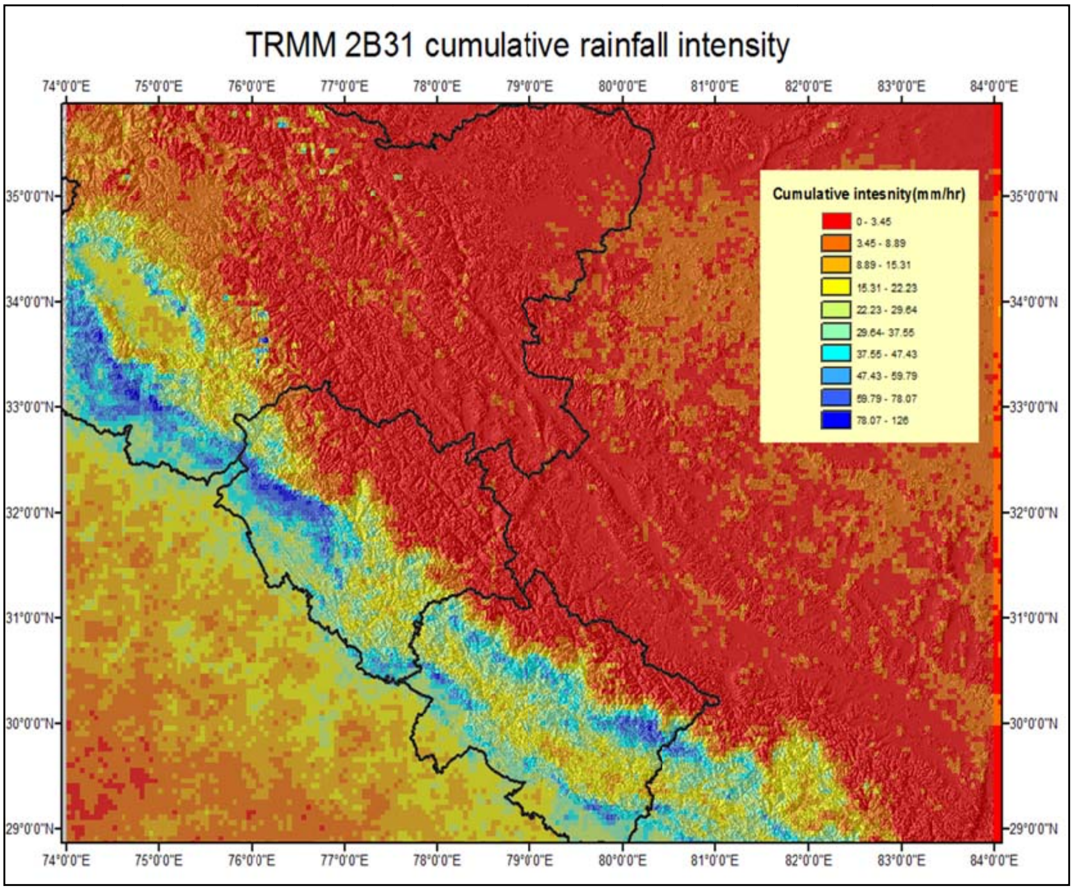


Fig.5.3: This Fig.delineates the cumulative rainfall intensity [mm/hr] over the study region. Cumulative rainfall intensity was used by Bookhagen and Barros to validate TRMM product with ground-rainfall data. Cumulative rainfall intensity is the added rainfall intensity throughout the monsoon. The highest value of cumulative rainfall intensity calculated using a 16 year long data set of TRMM 2B31.

Rainfall distribution over North-West Himalayan region using high resolution data set spanning 16 years has surfaced with huge detail in both ways. There are concentrated pixels of high rainfall data around Dharamsala in Himachal Pradesh and a dual band is evident in both the Fig.5.2 and 5.3, which is consistent with result of previous works over Himalayan region by [Bookhagen,Burbank,2006],[Shrestha,et.al,2012],[Anders et al 2006]. A high rainfall peak zone is conspicuous in the region 31-32 ° N and 76-77° E and it extends westwards through Jammu and Kashmir where Tibetan platue receive total rainfall of around

0.08 mm/hour intensity. The outer rainfall band in Uttarkhand [78-80° E,29-31° N] is thicker than the inner rainfall band along the southern flank of Himalaya. In western Himalaya high rainfall zone appears over high elevation area which is converse to the scenario in eastern Himalaya.

5.2 Validataion of TRMM 2B31 resampled at 25 km with IMD gridded interpolated data of 25 km resolution

Using nearest-neighbor interpolation technique inhomogeneity in the footprint of TRMM's satellite's passes has been handled and a climatological data set has been developed using data set of long period from 1998-2013. To convert rainfall rate [mm/hr] into absolute rainfall [mm], calculated mean rainfall intensity has been compared with the calculated mean absolute rainfall for the same time period. Please refer flowchart for the steps of the analysis [Fig.5.4].

After scaling down high resolution TRMM 2B31 mean rainfall intensity data from 5 km to 25 km every pixel, total 56481 number of pixels has stood down to 2337.To make the comparison more robust, accumulated mean of each month[June to September] has been taken for regression analysis. From regression analysis it can be shown that 63% of TRMM data agree with IMD data after scaling TRMM data to 25 km from 5 km each and every pixel. The linear fit has yielded decent agreeability between two two data sets while a calibration factor,674, has been applied to TRMM data set to estimate an absolute rainfall amount with 30 mm rainfall as an intercept, it means a pixel which has not registered any value of rainfall intensity according to TRMM after calibration those pixels have minimum 30 mm rainfall.

5.2.1 Flow chart for development of calilbration factor

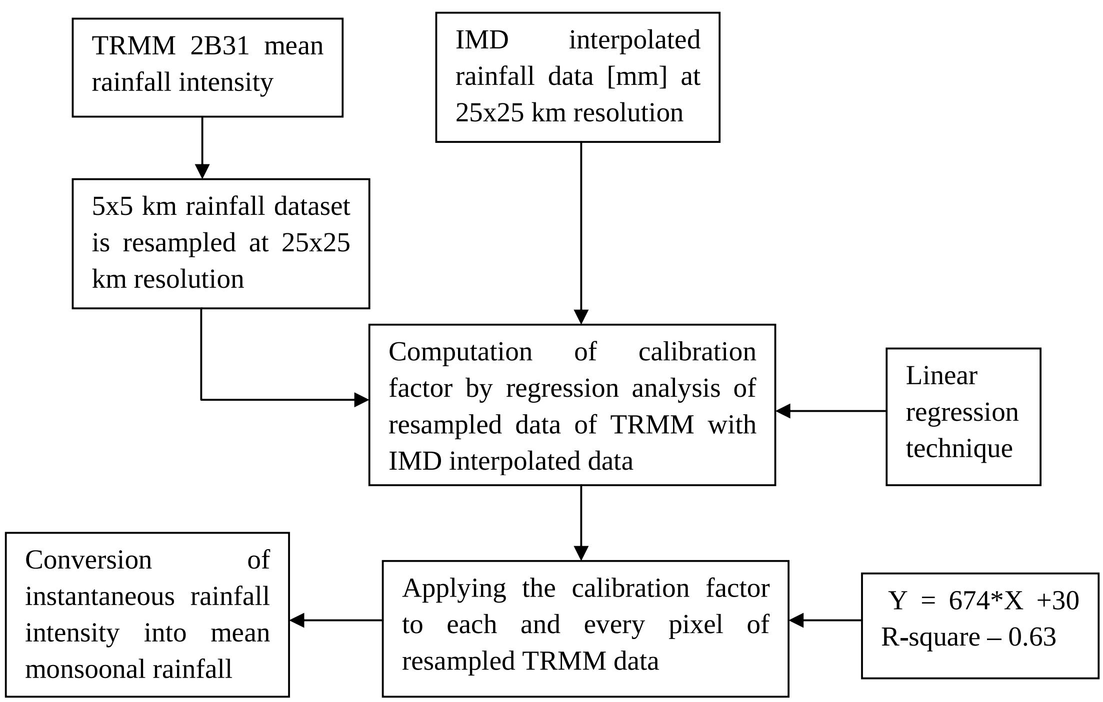


Fig.5.4: Flowchart for development of calibration factor to convert rainfall intensity into mean rainfall [mm].

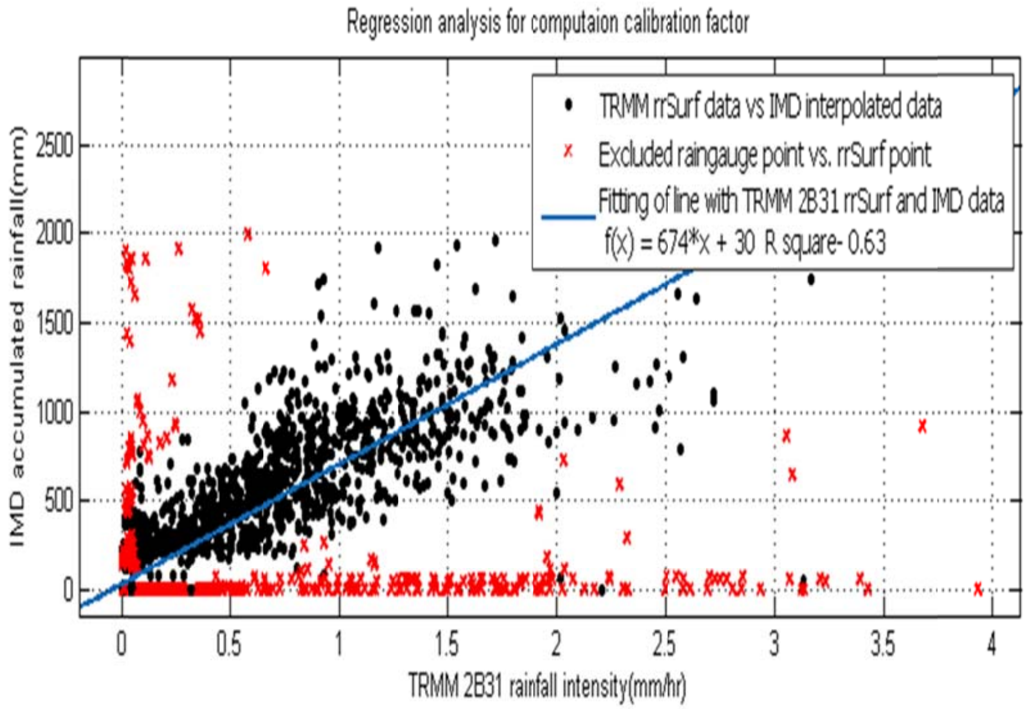


Fig.5.5: Calibration of TRMM data set with IMD interpolated data. Black points represents the accumulated value of mean rainfall intensity for individual month during summer monsoon and red cross points represent the excluded point which are not considered for linear fitting.

For regression analysis pixels having various elevations has been taken into consideration and excluded points in the Fig. marked in red color represent those regions having high elevation. Linear equation gives a factor of 674 which is to be multiplied with rainfall intensity and 30 mm common rainfall in terms of intercept has to be added with the previous term to get mean total monsoonal rainfall from 1998-2013.

Still this data lack veracity in high-elevated regions because there is a lack of rain gauge network and it has coarse resolution to resolve details of rainfall pattern where the terrain is so erratic in nature. To analyze the under and over estimation we have calculated bias of TRMM 2B31.

Underestimation [Bias]= IMD interpolated rainfall data **-** calibrated TRMM 2B31 rainfall data

Overestimation [Bias]= Calibrated TRMM 2B31 rainfall data – IMD interpolated rainfall data

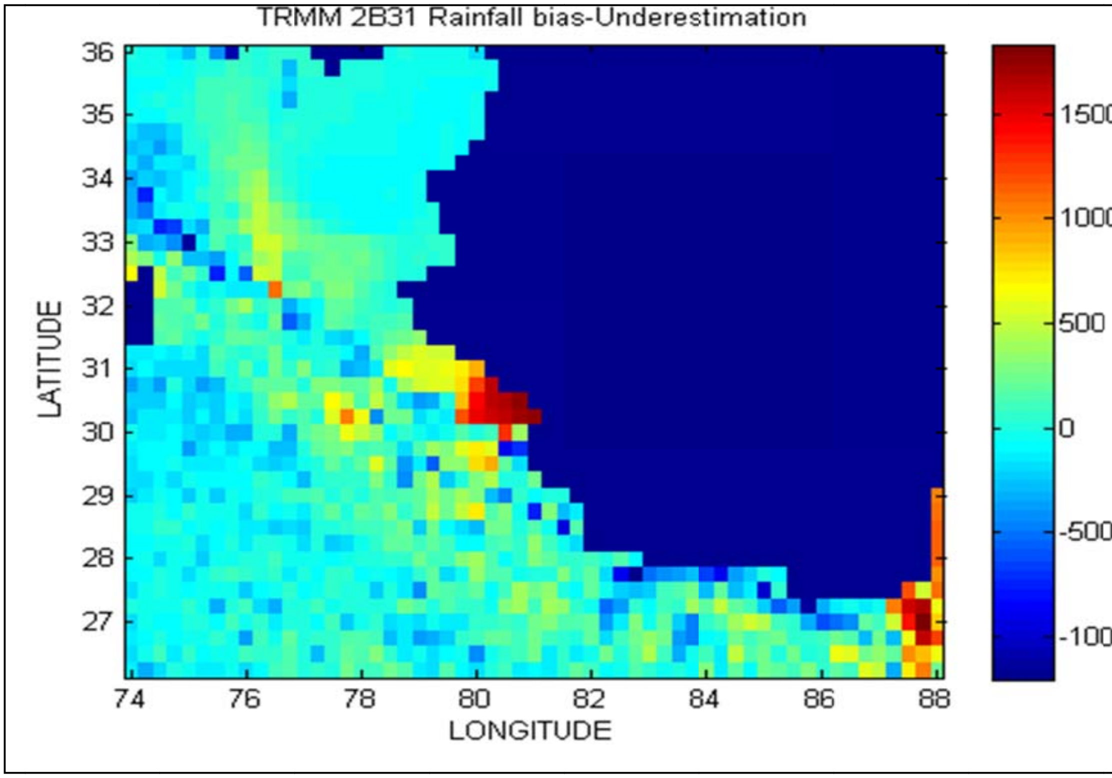


Fig.5.6: In Himachal pradesh and Uttarakhand greater Himalayan region resampled calibrated TRMM 2B31 data has underperformed as compared to IMD interpolated gridded data. Those regions has captured roundabout 1000 mm less rainfall during monsoon. The colorbar indicates the bias of the two dataset carrying the absolute rainfall amount during monsoon.

Bias has been calculated by subtracting both data sets from each other for better understanding the satellite bias over the hilly areas because from Fig.5.6 and Fig.5.7 it is evident that there is a bias of 1000 mm rainfall only over high elevated regions.Locations over which TRMM has underestimated in capturing actual rainfall really receives scanty amount of rainfall during monsoon.

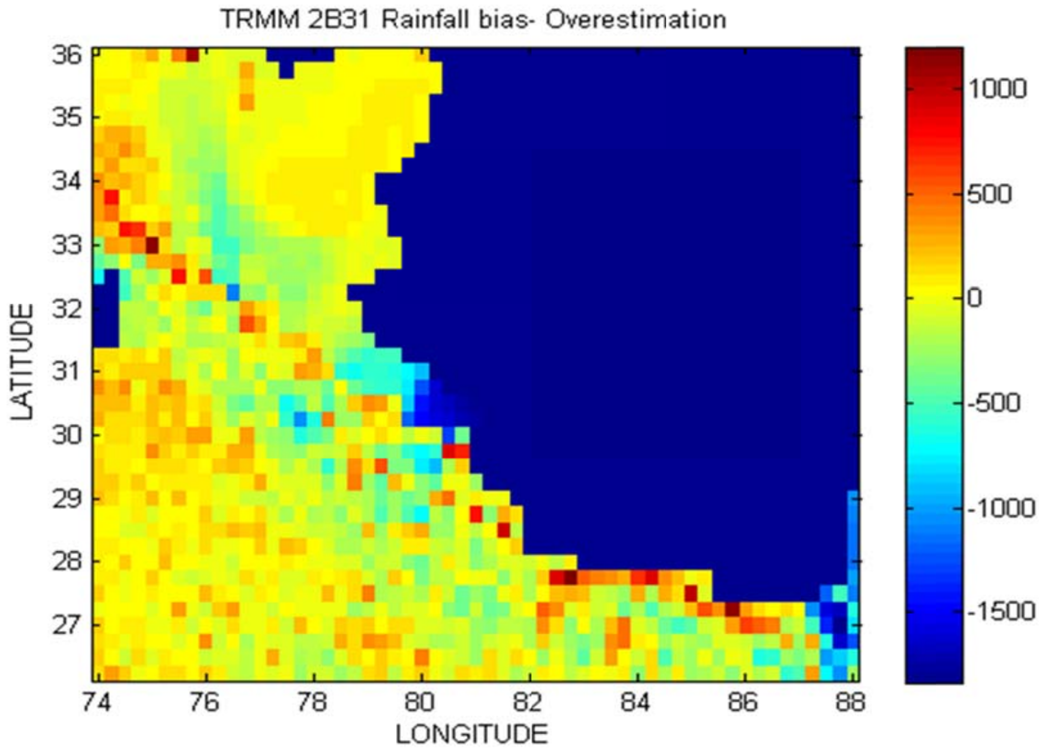
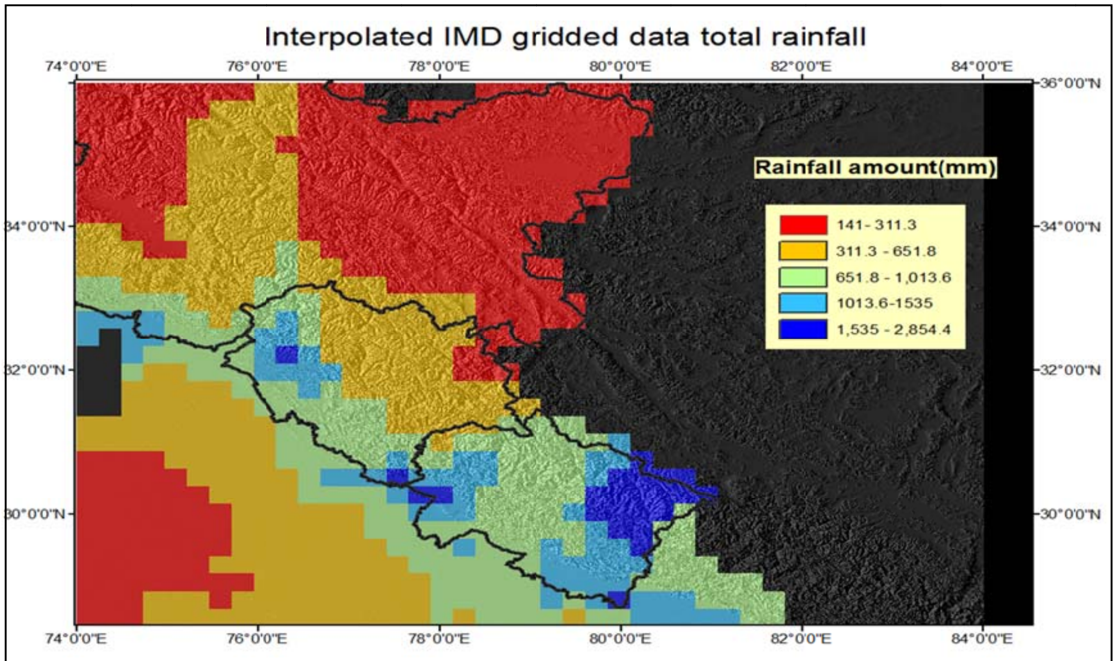
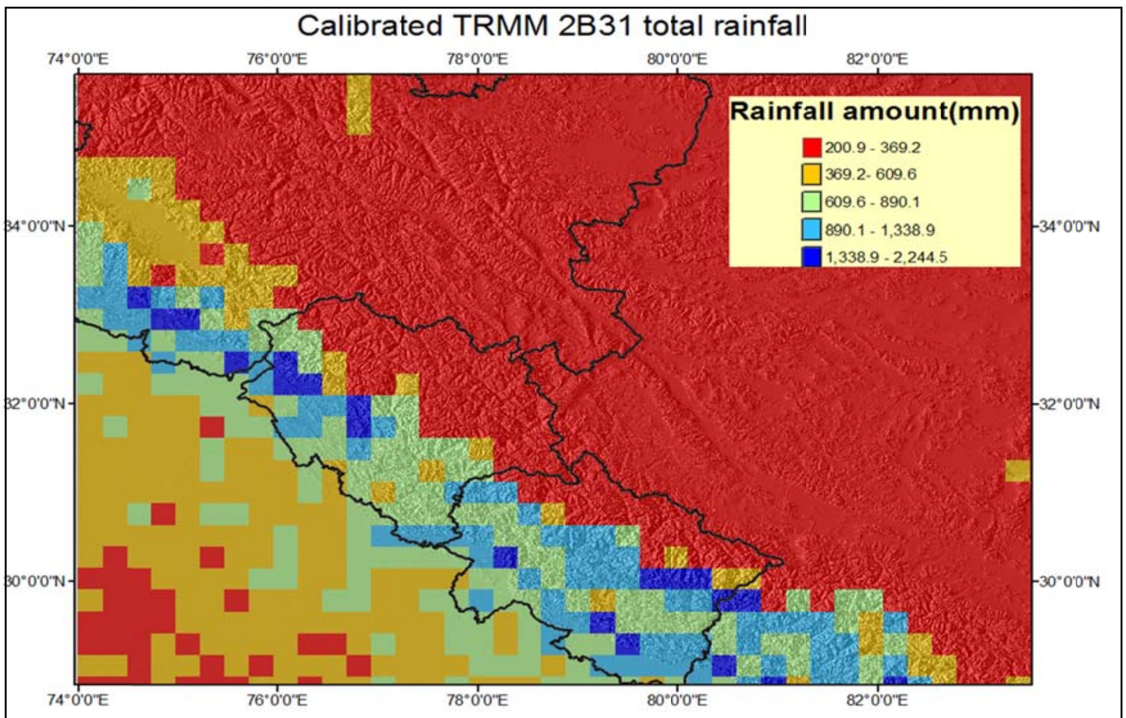


Fig.5.7: Previous Fig.delineates underestimation of satellite performance where it shows the satellite overestimation of rainfall during monsoon.

Few red pixels at 33 °N and 75° E indicates the instances of overestimation by around 1000 mm rainfall.Foothills of Himalayan belt come under the focus of satellite bias. Overall the validation of TRMM data set with IMD data at 60 % agreeability substantiates the little bias over the area considered for validation. Especially over plane regions satellite and IMD data corresponded well with each other that is evident from both the Fig.5.6 and Fig.5.7 of underestimation and overestimation case but in high mountainous region of LehLadak and regions extending northwards there is avoidable instances of satellite bias. Therefore TRMM has either underperformed or overperformed mountainous ridges of greater Himalaya passing through Himachal Pradesh and Uttarakhand. Dharamshala in Himachal Pradesh receives huge amount of rainfall during monsoon and the rainfall amount recorded by both the products for this place is near to the actual accurate rainfall. Bias of satellite data can be attributed to the interpolation technique [bilinear interpolation] used to resample original 5 km resolution data to 25 km resolution.



[a]



[b]

Fig.5.8:[a]Accumulated mean rainfall of each month[JJAS] derived from IMD gridded 25 km resolution data [b] resampled at 25 Km from 5 km calibrated TRMM 2B31 data for the same time period.

5.3 Methodology to study and analysis rainfallas a funtion of orography

Following flow chart illustrates the methodology adopted for the study of rainfall in association with the orographic parameters.

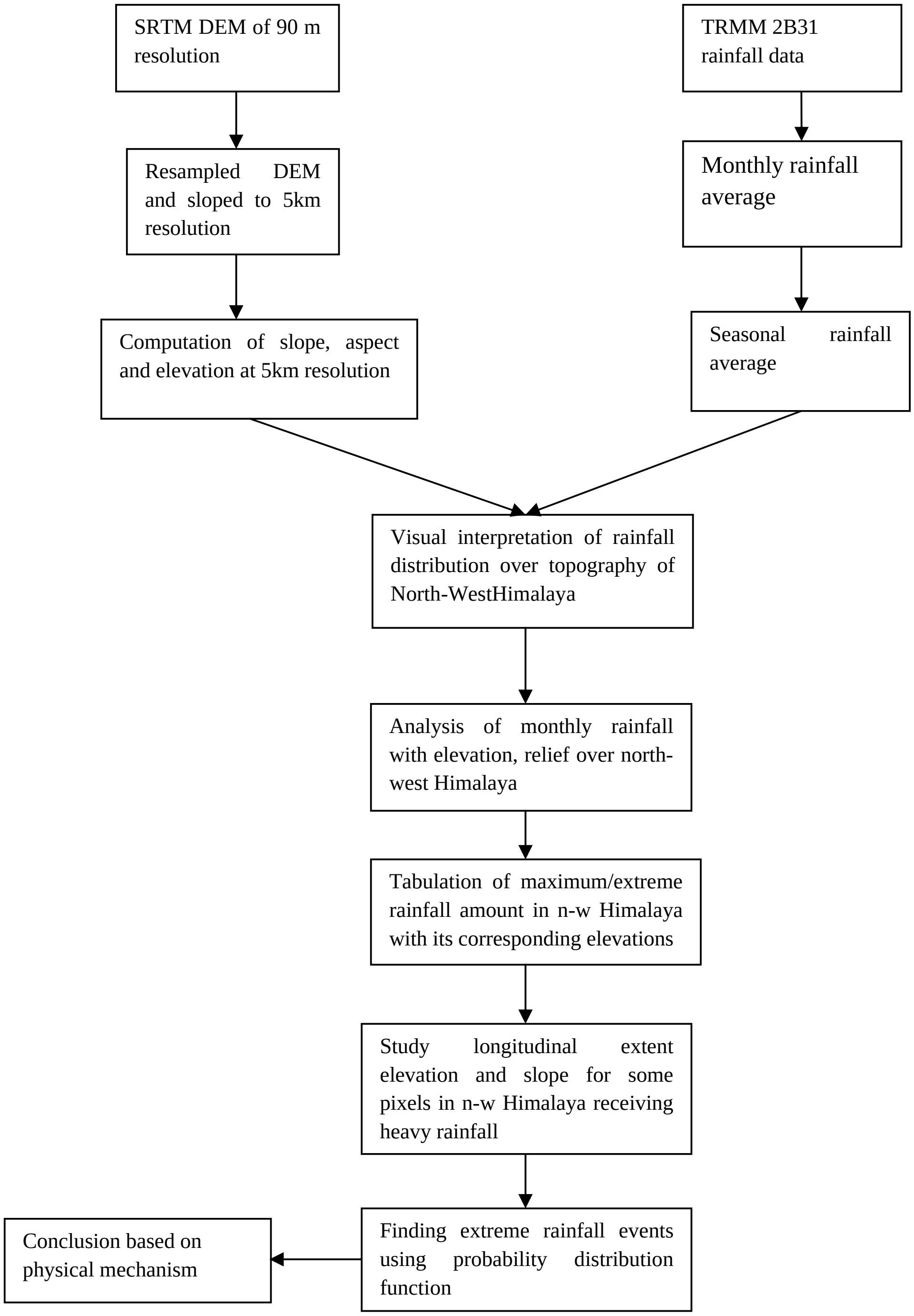


Fig.5.9: Flowchart depicting the 2B31 rain fall data analysis as function of orographic features.

5.3.1Extreme rainfall analysis in study region

Earlier Bookhagen [2005] has shown using 12 year TRMM 2B31 time series data that number of extreme events [>90th percentile] over mountainous settings is more than twice as many events occur in adjacent lower region and also rainfall in the 90th percentile has been previously associated with extreme rainfall events [e.g. Cayan et al. 1999, Grimm and Tedeschi 2009, Krishnamurthy et al. 2009]. Peak extreme naturally correlate with high rainfall region but few extreme event can occur in arid or semi-arid region .In the present study, using histogram statistical technique a better knowledge of the frequency of events of high and low amount of rainfall intensity during JJAS[June-July-August-Septemper] for 16 years has been gathered. Probability density plot of rainfall intensity has been generated for each state because there is huge variability in the rainfall intensity and localization of data on the basis of particular state provides strict revealing on the extremity of rainfall intensity in different regions.The histogram of the rainfall is shown in Fig.5.10to segregate rainfall events closer to extreme rainfall event ,percentile technique has been utilized percentile.

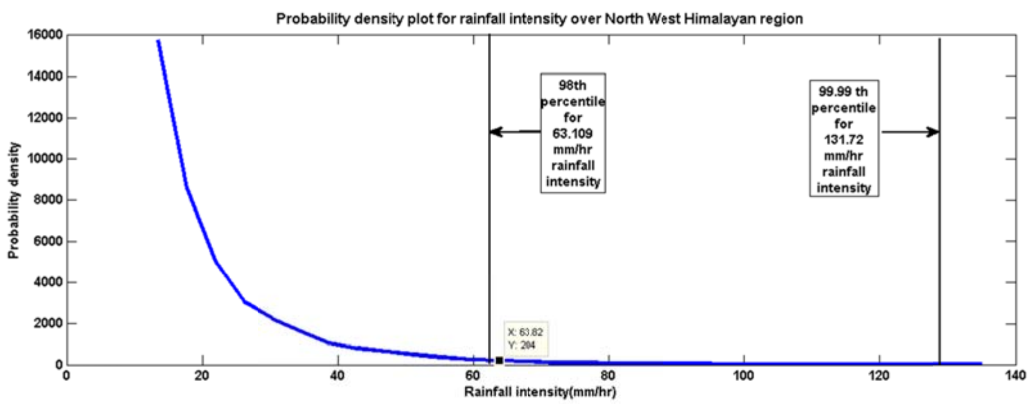


Fig.5.10: This panel represents probability density or number of occurrences with 4mm/hour width interval in NWH region using 16 years' time series.

Percentile thresholds have been selected at 98, 99 and 99.99thpercentile. The probability density plot gives information on the likelihood of particular rainfall event and the natural probability density plot shows exponential decrease in frequency of rainfall events with increase in rainfall intensity and it takes a form of skewed right distribution. Higher number of rainfall events usually have less than 25 mm/hour rain rate, which can be observed in the Fig.5.10.The threshold percentiles have been calculated for NWH and individual states respectively and tabulated in the Table 5.1. For the case of NWH, R.I [rainfall intensity]with width interval[bin size] of 4 mm/hr , the probability density plot gives 135.21 as the extreme rainfall intensity where the highest number of events comes out corresponding to R.I 22.51 mm/hour. 99.99th percentile indicates occurrence of cloudburst events and the interval between 98th and 99th percentile can be regarded as extreme rainfall event. The threshold value of rainfall intensity conducive to cloudburst event in NWH region is 132.76 [mm/hr]. In Himachal Pradesh there are two events of high rainfall intensity at 120.2 and 127.7 mm/hr

[Fig. 5.11]but the events of low R.I is lower than the events of same category in NWH. The cloudburst threshold for R.I is almost same as the value of threshold for NWH but the R.I values of percentile thresholds computed for events in Himachal Pradesh nearly mimics the values obtained for NWH. As the moisture-laden wind of monsoon almost sheds all its moisture while progressing over western side of the North-West Himalayan region, it enters

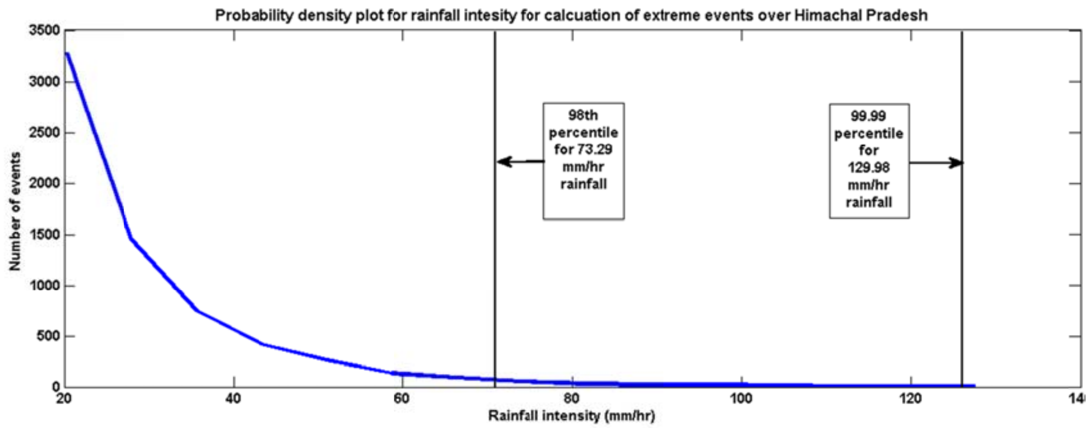


Fig.5.11: Probability density of rainfall rate in Himachal Pradesh where the rainfall value for 99.99th percentile is higher than the 99.99th percentile for J&K.

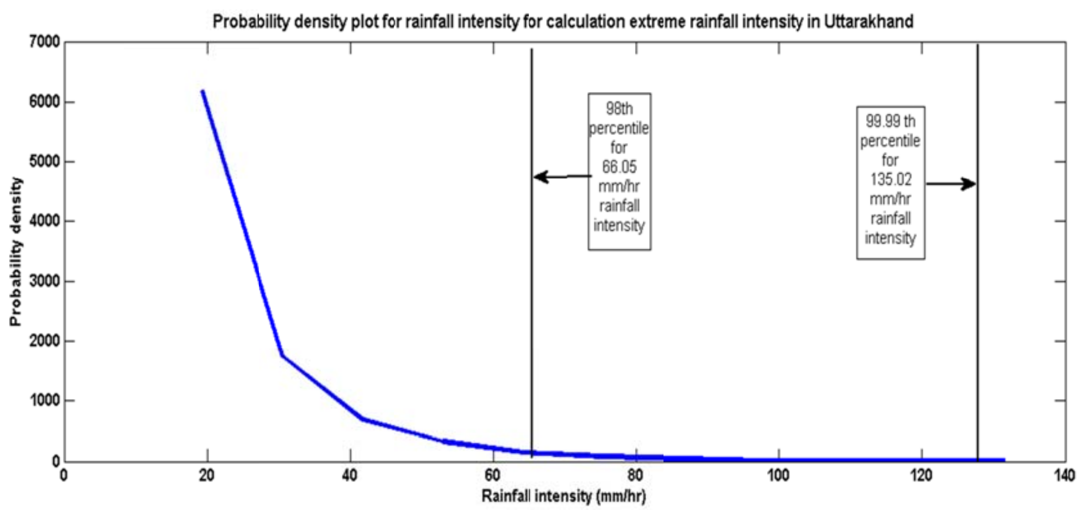


Fig.5.12: Probability density plot for rainfall intensity in Uttarakhand region. Percentile technique has been applied to compute the amount of extreme rainfall in 16 year period during monsoon. 98th percentile stands for 66.05 mm/hour rainfall intensity where 99.99 the percentile represents 135.02 mm/hour rainfall intensity.

into the Jammu and Kashmir as a feeble monsoonal wind ,making J& K a weak rainfall zone

Table 5.1: Rainfall intensities[mm/hour] associated with 98th,99th,99.99th percentiles for NWH, J&K ,Himachal Pradesh and Uttarakhand

Region	98th percentile[mm/hour]	99th percentile[mm/hour]	99.99th percentile[mm/hour]
NWH	63.10	74.68	131.72
J&K	52.77	63.2	121.8
Himachal Pradesh	73.29	86.10	129.8
Uttarakhand	66.05	76.69	135.02

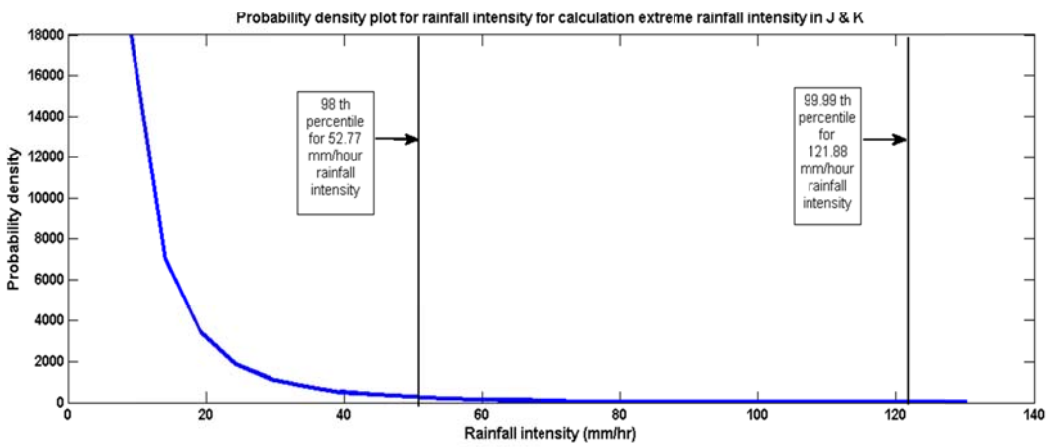


Fig.5.13: Probability density plot for rainfall intensity for Jammu and Kashmir.

area. It has been found that extreme event of rainfall intensity> 120 mm/hr in the months of August and July, where a study of extreme rainfall events over North-West Himalayan region for a long time period has revealed that extreme to extreme rainfall events over this region at the withdrawal time of monsoon [Nandagiri and Dhar, 1998]. In Himachal Pradesh two events greater than 120 mm/hr intensity have come out after analysis which has happened in 1998 and 2006 in Aug and July at different elevation where most of the extreme rainfall events over J&K [Jammu and Kashmir] have occurred at lower elevation from 300 meter to below 1 km elevation. During monsoon only 22% of its annual precipitation occurs in Jammu &Kashmir [IMD] and in Himachal Pradesh, Uttarakhand 70– 80 % of its total precipitation occurs in ISM. 99.99th percentile for rainfall intensity over Uttarakhand is 135.02 mm/hr which is higher than the other 99.99 the percentile thresholds, where higher number of rainfall intensity greater than 130 mm/hr has occurred throughout the monsoon season except in August. Highest number of events for rainfall intensity 13.71 mm/hr for Uttarakhand has been found from probability distribution function which is comparatively lower than the other highest number of event for R.I, 19.71 mm/hr, over Himachal Pradesh and a bit higher than the R.I, 6.63 mm/hr, for Jammu and Kashmir obtainedfrom 16 years longTRMM data set. The table calls attention to the fact there is a huge variation in R.I over the regions within NWH. It is more prominent that the extremity of rainfall event and higher frequency of high rainfall intensity are under the influence of monsoon system, which causes the occurrence of high amount of rainfall over Uttarakhand during ISM.

5.3.2 Trend analysis of extreme rainfall events

In the previous section, long time series of TRMM data set has been integrated to derive realistic climatological map. To the author's knowledge this is the first instance of utilizing the longest time series of TRMM 2B31 rainfall data sets for estimating the trend of extreme rainfall events. Calculating the trend of absolute frequency of events of high rainfall intensity

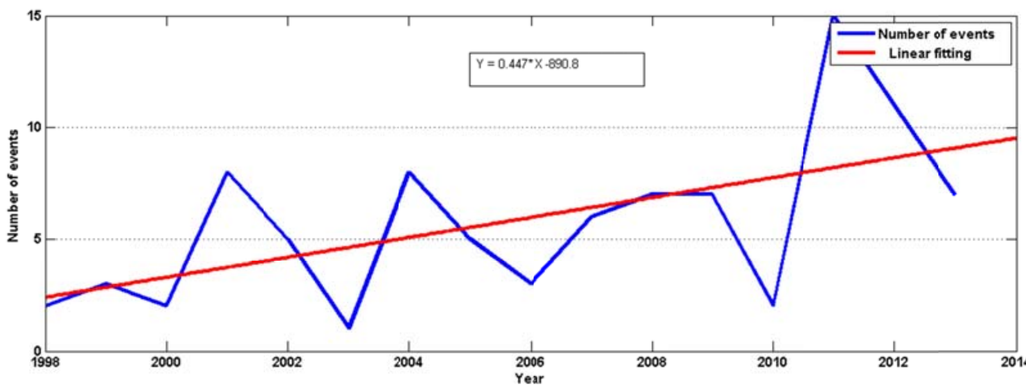


Fig.5.14: Inter-annual variation of frequency of extreme events conditioned by rainfall intensity >=98th&<99th over Uttarakhand

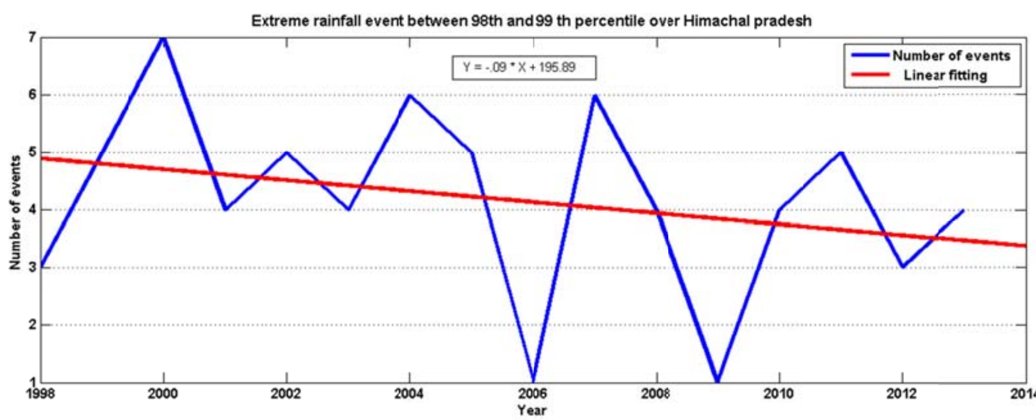


Fig.5.15: Inter-annual variation of frequency of extreme events conditioned by rainfall intensity >=98th&<99th over Himachal Pradesh

over a region depends on the length of the time period for which rainfall intensity data available. Here long data set of 16 years has been used to disclose the nature of trend of extreme events in individual states using 98th-99th percentile condition. In the Fig.5.14,5.15 and 5.16 number of events have been plotted against the event year from 1998-2013 . Student's t-test has been performed over the data set to indicate whether there is any trend present,ifpresent, then whether the trend is of increasing or decreasing nature. If the slope of regression line [basic fitting of data] is greater or less than zero given by t-test, then the null-hypothesis is rejected and there is a presence of trend.

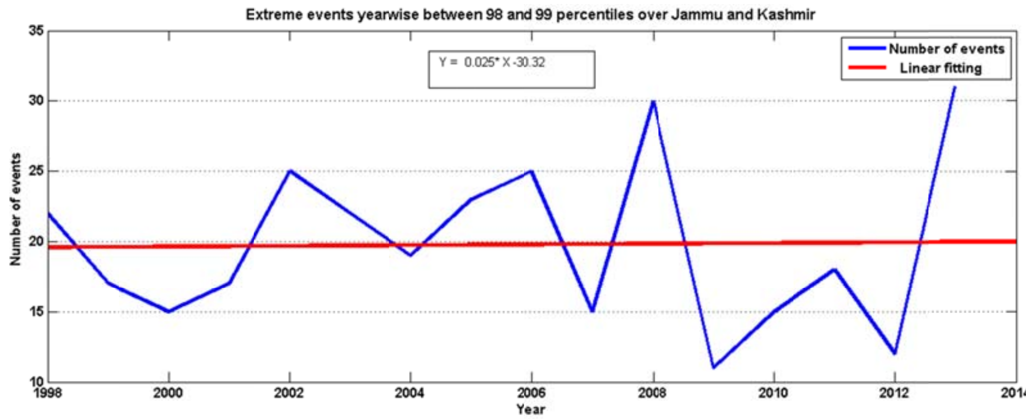


Fig.5.16: Inter-annual variation of frequency of extreme events conditioned by rainfall intensity >=98^{th}&<99^{th} over Jammu and Kashmir

From the previous section of computation of extreme event using probability density function, rainfall intensity falling under the condition [R.I>=98^{th}& R.I<99^{th}] has been considered for trend analysis during monsoon. R.I>= 66.05 and R.I<76.69 mm/hr condition has been applied to find trend over Uttarakhand and analysis reveals that there is a decent increasing trend of extreme rainfall events with a positive slope value of 0.4470 and p-value close to 0. Same as in Himachal Pradesh the trend computed implementing same percentile condition is of decreasing nature with higher negative slope of -0.13, this finding is in accordance with the finding by [Joshi, Rajeevan, 2006] for the region Shimla,Himachal Pradesh.Trend is of increasing nature with a positive slope value of 0.025 at 1 % significance level [p value close to 0] over J&K. Decreasing trend of extreme rainfall events are obtained from the student's t-test for Uttarakhand and Himachal Pradesh and a moderate increasing trend of extreme events is conspicuous in Jammu and Kashmir ,the increasing trend in J&K during monsoon is supported by the study of extreme events over NWH by NareshKumar,IMD. According to his study there is a 25 % increase in events during winter and summer monsoon. Rainfall intensity greater than 76 mm/hour has crowded over the Gangetic plane in Uttarakhand, these are the places Kotkendri,Sonanadi range,Tanda range,Mussorie,Katar village which receive considerable high amount of rainfall during monsoon. In Jammu and Kashmir Barwalpali, Sunderbani, Dhaloti are the places receiving extreme rainfall. Goswami et al, 2006 has reported that increase in heavy and very heavy rainfall events and decrease in low and moderate rainfall events in India. It can be said that rainfall of high intensity occurs over the places having elevation range 400-1000 meter during the onset of monsoon.

5.4 Rainfall distribution of rainfall intensity

To have a better insight into the rainfall distribution across Himalayan range, total mean rainfall intensity derived from TRMM 2B31 has been sectioned off based on the study regions[Uttarakhand,Himachal Pradesh and Jammu and Kashmir].There is a similarity between the distribution of rainfall over Uttarakhand and over Himachal Pradesh[Fig.5.18 and Fig.5.19]. The average monsoonal rainfall in Himachal Pradesh is around 700 mm and in

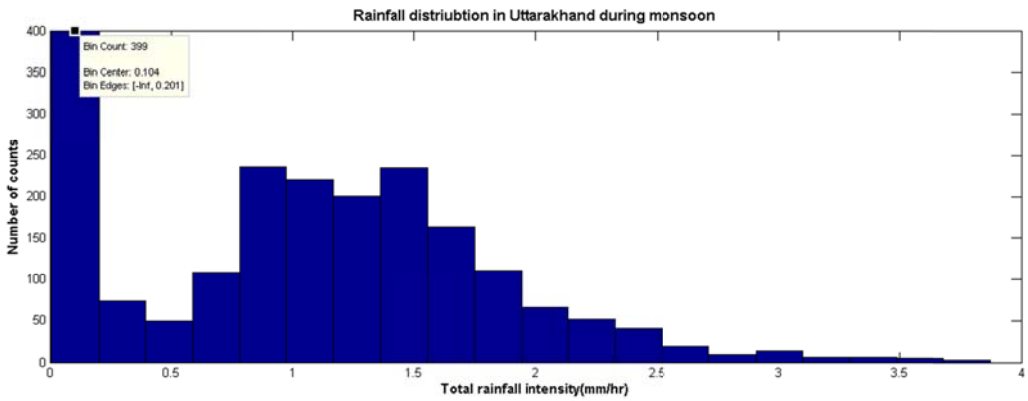


Fig.5.18: Total mean rainfall intensity distribution during monsoon over Uttarkahand.X axis represents the rainfall intensity with a fixed interval of rainfall intensity and Y axis represents the number of events for a particular bin.

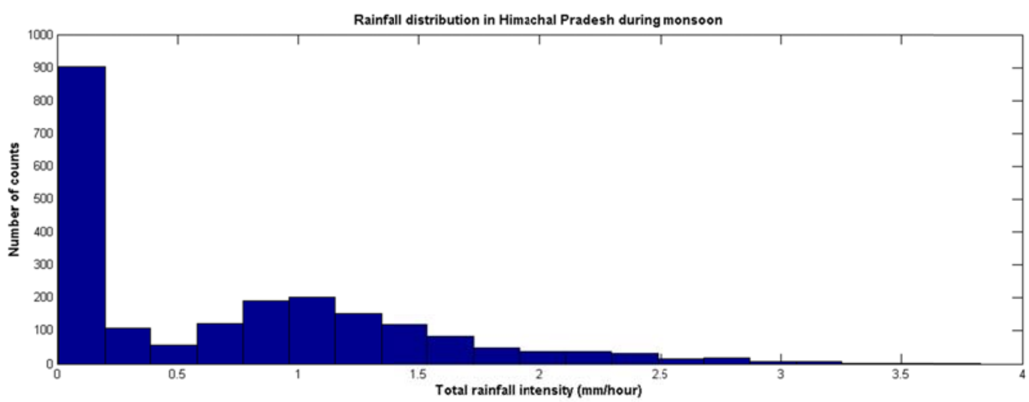


Fig.5.19: Total mean rainfall intensity distribution during monsoon over Himachal Pradesh.X axis represents the rainfall intensity with a fixed interval of rainfall intensity and Y axis represents the number of events for a particular bin.

Uttarakhand it is 1100 mm. This difference in average rainfall in both states can be vindicated from the histogram analysis of rainfall. From Fig.5.19 it is evident that there are 900 pixels each representing area of 25 km which receives very low amount of rainfall during monsoon because its total mean rainfall intensity is .102 mm/hr. To convert it into absolute rainfall this rainfall intensity can be multiplied by the total number of hours of a month. Where in Uttarakhand moderate rainfall intensity [not high or low] about 1-1.5 mm/hour is higher in density than the density of rainfall intensity in Himachal Pradesh. Topographic distribution can attribute to the rainfall amount in a particular region in the presence of monsoonal circulation. The highest total mean rainfall intensity is 3.73 mm/hr in Himachal Pradesh

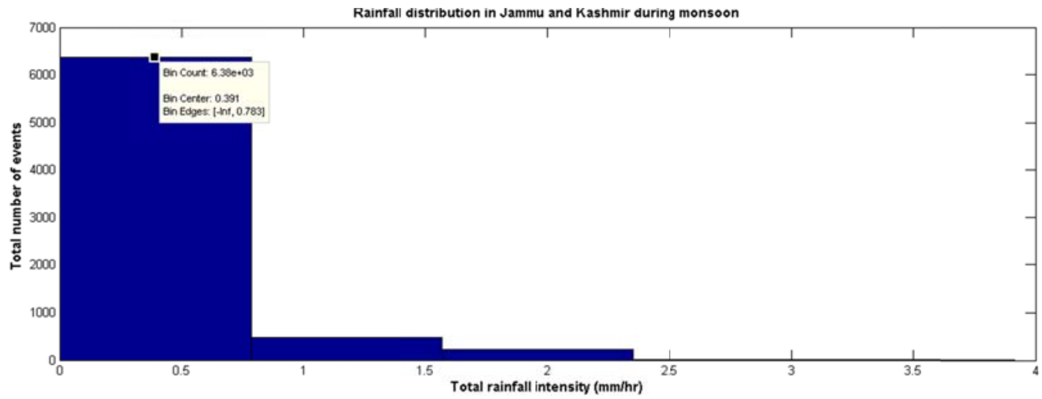


Fig.5.20: Total mean rainfall intensity distribution during monsoon over Jammu and Kashmir .X axis represents the rainfall intensity with a fixed interval of rainfall intensity and Y axis represents the number of events for a particular bin.

and whereas the highest rainfall intensity is about 3.78 mm/hour in Uttarakhand. As monsoonal wind enters into Jammu and Kashmir, rainfall occurs on the foothill of Lesser Himalayan region. Monsoon accounts for only the 28 % of its total rainfall because from January to March Srinagar and adjacent places receive precipitation owing to western disturbances. The difference between average rainfall in Uttarakhand and Himachal Pradesh can be accounted by topographic influence or the distribution of surface obstacles in orienting the moisture-laden wind vector and external forcing mechanically and thermally. This phenomenon is called orographic precipitation and due to this mechanism regions on the windward side of Western Ghats receive high amount of rainfall at the beginning of monsoon.The spatial pattern of the monsoon rainfall over the North-West Himalayan region is represented in Fig.5.1. It was observed that the greatest rainfall amount of rainfall during monsoon occurred in JJA over the eastern Himalaya region and CHR[central Himalayan region][Shasta et al 2012]. Bookhagen[2010] has noted that summer monsoon rainfall accounts for 80% of the annual moisture budget for the CHR. Local rugged topography plays important role in shaping cloud patterns [Anders et al, 2006]. Monsoonal wind undergoes additional upliftment and forced ascent, during ascent either it condenses into raindrops and sheds rainfall or the air may be blocked or diverted around the range [Simpos, 1987]. To find the impact of orography on rainfall in those states, spatial relationship between rainfall of a location and its topographic parameter has been derived in the later section.

5.5 Relationship between rainfall and topographic features

Visually it is difficult to extract any standard relationship between topography and rainfall. Rainfall data and topographic data has been put through for regression analysis. It has been observed the 2nd order polynomial provides the best fit.

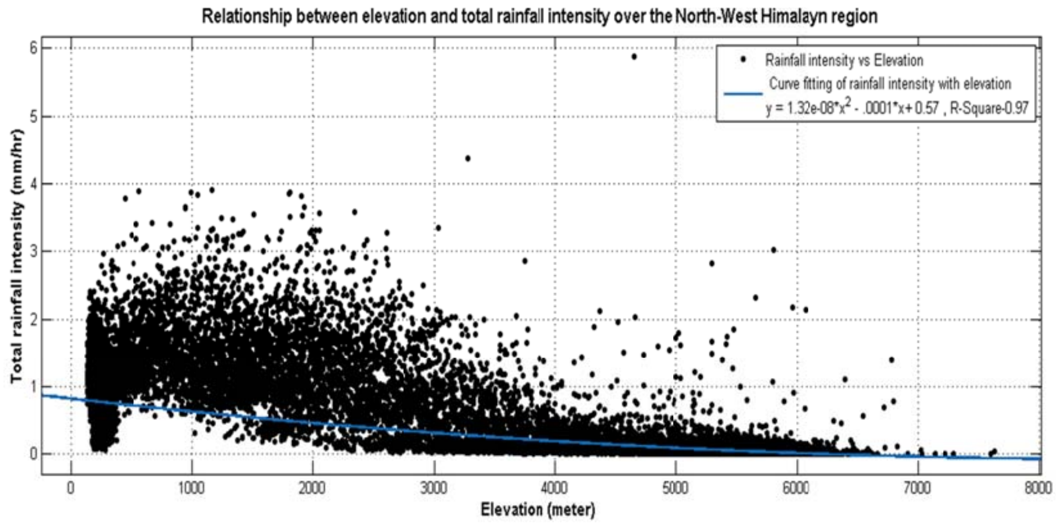


Fig.5.21: It represents the scatter plot of elevation and total rainfall intensity over the whole North-West Himalayan region. The density of rainfall intensity points decreases along the increasing value of elevation. It indicates the after certain elevation precipitation in the form liquid does not occur. X axis represents elevation in meter and Y axis total rainfall intensity[mm/hr].

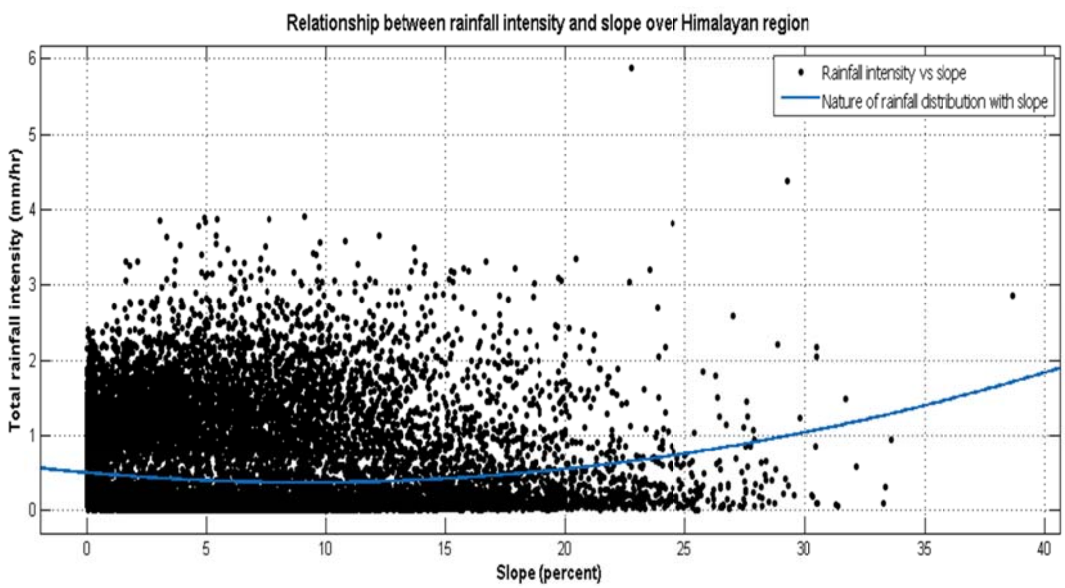


Fig.5.22: Relationship between slope and rainfall intensity is poor and inconclusive.

Bi-square robust fitting, 0.97 R-square value has emerged but this relationship clearly shows no robust linear relationship between elevation and rainfall. It is partly maintained for the places having elevation above 3 km. Wide range of rainfall intensity is distributed over surfaces having elevation ranging from 200 meter to 3000 meter [Fig.5.21].

5.5.1Elevational condition:

Elevation conditions[a] 0-1000 m[b] 1000-2000 m and above has been applied to procure an ideal segregation of rainfall zones relative to elevation. As North-West Himalayan region is of rugged nature, morelucidly, elevation ranges from 800 meter to 4000 meter above, it is better to analyze topographic effect on rainfall activity by considering locations received higher amount of rainfall. Values of higher amount of rainfall changes according to region what has been obtained using percentile concept. Previous studies over Himalayan region have shown a declinationin rainfall activity above 2 km elevation and almost no rainfall event above 4 km elevation. Based on that information the elevation condition of 1000-2000 meter has been implanted over data set to extract rainfall information distributed over this elevation range.

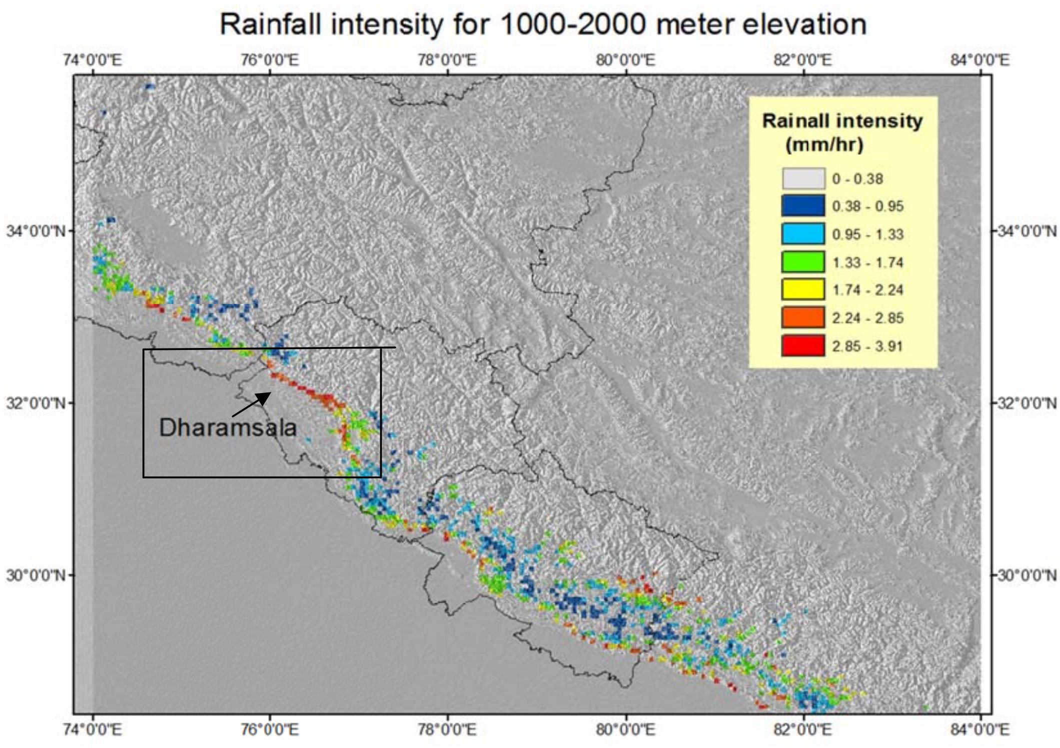


Fig.5.23: Rainfall intensity map for the elevation range 1000-2000 meter and in the image there is an inset around Dharma Sala[Pointed with an arrow].

Then to establish a pronounced relationship between rainfall and topographic parameter, a subset of a region incorporating the narrow rainfall band [indicated in a box in the

Fig.5.23]has been taken into consideration for regression analysis. This relationship produces a far better agreeability scenario of linearity between increasing elevation with decreasing rainfall intensity. This linear relationship proves that monsoonal wind undergoes a suitable condition which causes a cluster of high uniform rainfall intensity during July and August. Dharamsala [32.21° N, 76.32° E] is located along this narrow band of high rainfall intensity; it receives up to 2200 mm total rainfall during monsoon. Therefore the topographic features adjacent to it play a vital role in characterizing the high amount of rainfall during monsoon.

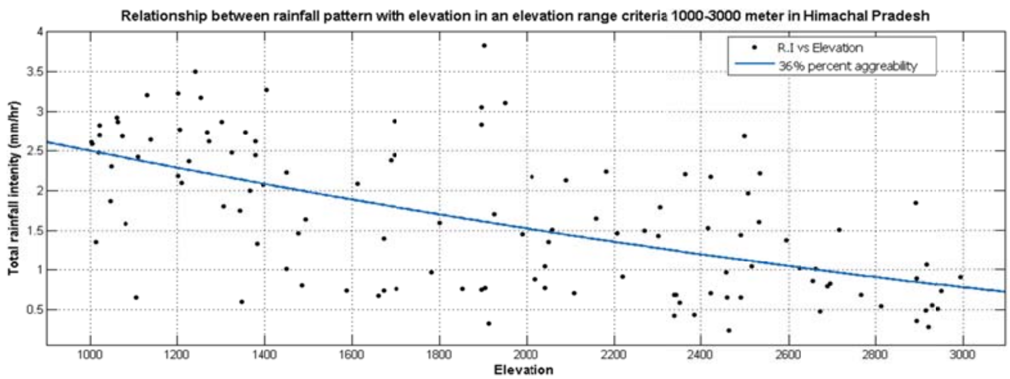


Fig.5.24:Correlation analysis between total rainfall intensity and elevation for a cluster located in Himachal Pradesh

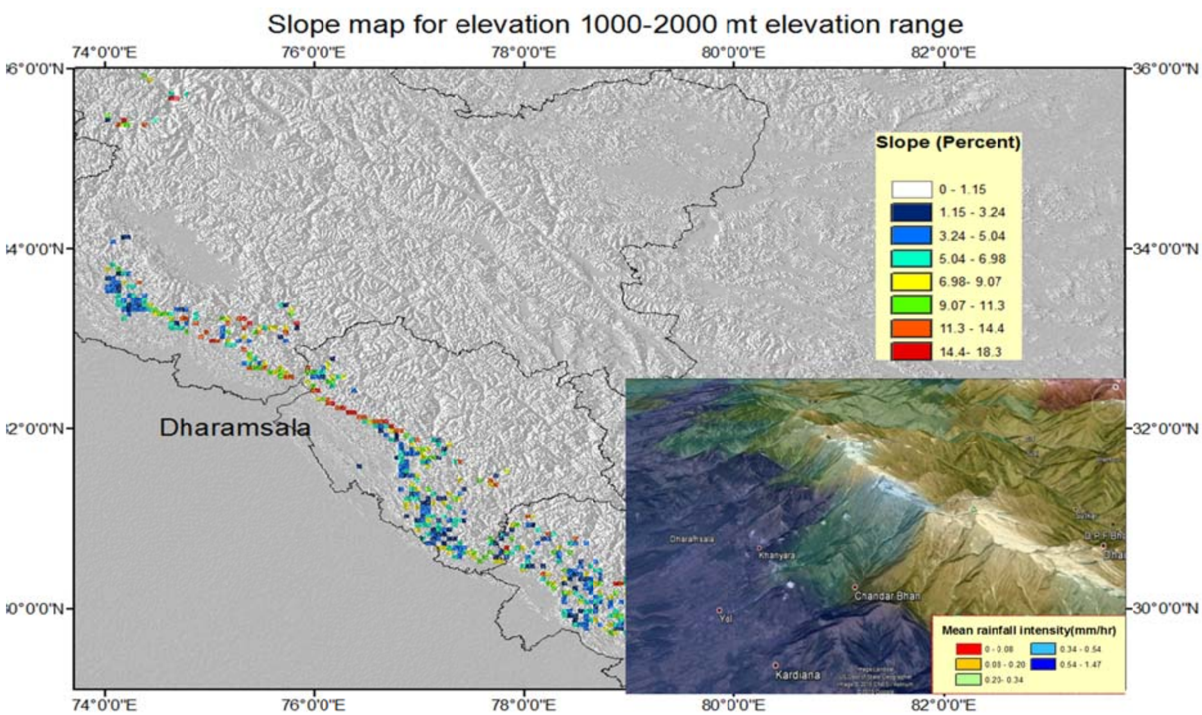


Fig.5.25: Locations of the narrow rainfall band passing through Dharamsala has uniform high values of slope. That is corresponding to elevation range 1063-1800 meter.

Insetfigurerepresents the topographic overview adjacent to Dharamasala and rainfall distribution.

Details of topographic features have been noted to find uniformity of increasing value of all the features for this narrow band of rainfall. High rainfall intensity has been distributed from the elevation range 1000-1800 m with the slope varying from 12 percent to 19 percent.

Table5.2: List of monsoonal total high mean rainfall intensity locations and its topographic information in individual state

[a]Uttarakhand

Longitude	**Latitude**	**Rainfall intensity [mm/hour]**	**Elevation [meter]**	**Slope [Percent]**	**Aspect [Degree]**
80.3	29.95	3.87	990	7.611	231
80	30	3.57	2051	9.74	1941
80.40	29.85	3.31	1990	16.68	204.2
79.85	29.1	3.776	447	4.689	191.8
79.7	29.2	3.19	936	13.56	212

[b]Himachal

Longitude	**Latitude**	**Rainfall intensity [mm/hour]**	**Elevation[meter]**	**Slope [Percent]**	**Aspect [Degree]**
76.4	32.2	3.82	1902	24.46	202.4
76.35	32.2	3.22	1202	17.86	199.7
76	32.35	3.19	1131	7.52	240.4
76.75	32.05	3.10	1905	19.74	207.1
76.6	32.1	3.26	1405	14.15	189.3

[c]Jammu and Kashmir

Longitude	**Latitude**	**Rainfall intensity [mm/hour]**	**Elevation[meter]**	**Slope [Percent]**	**Aspect [Degree]**
74.7	33.1	3.43	667	9.45	185.2
74.95	33	3.66	940	12.21	201.4
74.75	3.1	3.91	1163	9.10	158.9

Information on the topographic features has been collected with respect to places characterized by high rainfall intensity to find any topographic influence on rainfall,[Table 5.2]if present any. State wise high rainfall intensity greater than 3.00 mm/hr has been selected to find how the slope and aspect is related to elevation. In Uttarakhand high amount of rainfall is distributed over wide range of elevation and its corresponding aspect value implies that those locations are situated on the Himalayan region oriented towards south-west direction.

5.5.2 Spatial variablity of rainfall with topographic feautres

In Himachal Pradesh locations classified by substantial amount of rainfall intensity [greater than 2 mm/hr] are congregated along the flank of Lesser Himalayan range [Fig.5.26.A]. Across the Himalayan stretch over Himachal Pradesh a strong rainfall-gradient is present. Sudden increase of elevation behind the single band of rainfall maxima is evident from the Fig.5.26 [A] and 5.26 [B] over the same region. A sharp elevation gradient just adjacent those location acts as an impediment to the ascent of monsoonal wind over the barriers extending north-eastward direction.

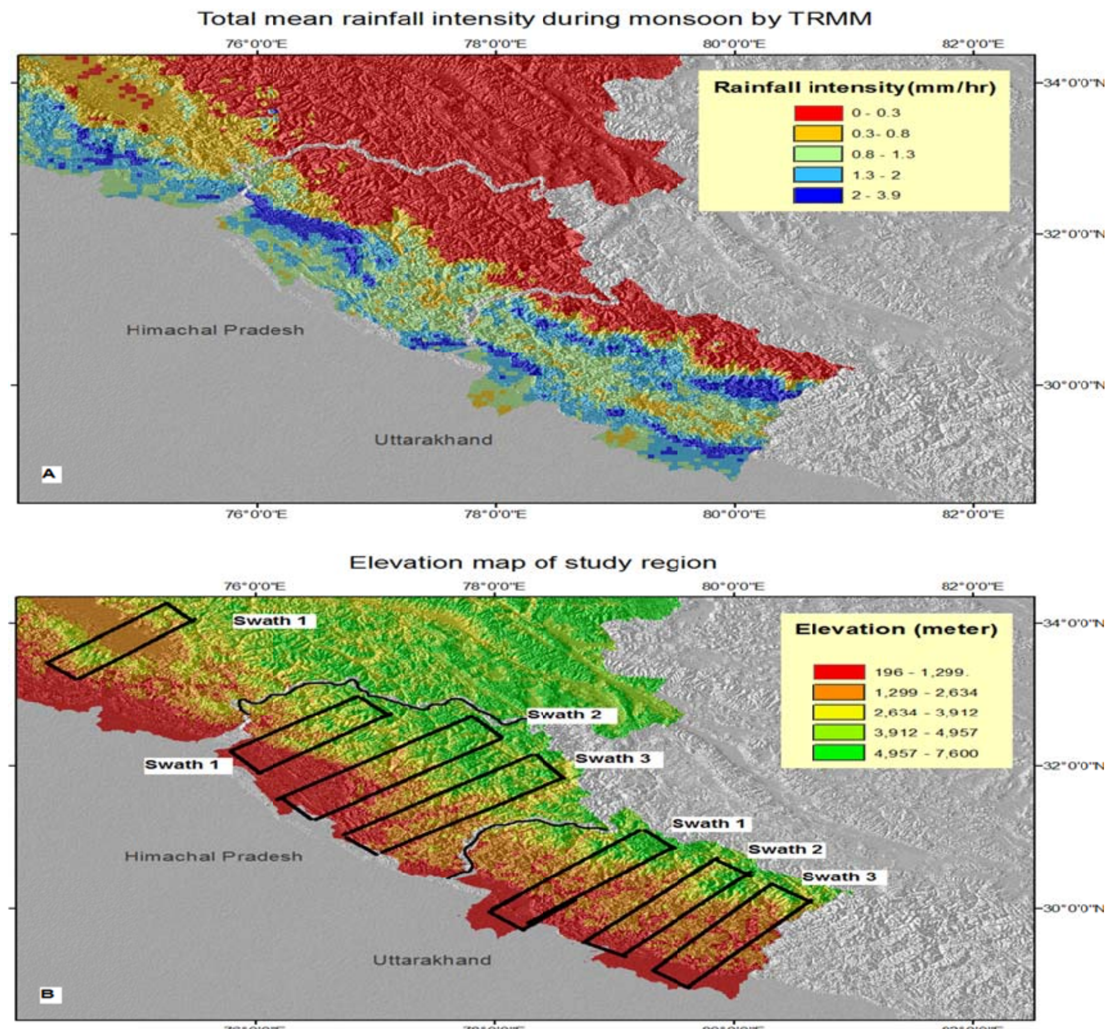


Fig.5.26: [A] is the total mean rainfall intensity map over Jammu and Kashmir, Himachal Pradesh and Uttarakhand during monsoon developed from processed high resolution [5x5 km] TRMM 2B31 data set by averaging from 1998-2013 for monsoonal months. There is a dual rainfall band over

Uttarakhand and a clustered region of high rainfall in Himachal Pradesh.[B] is the elevation map derived from SRTM DEMafter resampling it from 90 meter 5 km. Almost rectangular-shaped polygons represent the swaths in every state uniformly apart from each other for radial analysis of rainfall distribution.

5.5.3 Variation in rainfall pattern along the selected swaths over Uttarakhand

To derive more realistic relationship between rainfall intensity and elevation across the outer, lesser and greater Himalayan extent, study region comprising Uttarakhand, Himachal Pradesh and Jammu and Kashmir has been divided into sections or more technically into the swaths of elevation-gradient profile directed along the orientation of southern Himalayan flank[Fig.5.26.b].The swaths are more or less 20 km wide and 220 km long and average of rainfall, elevation and slope pixels within the swaths along east-west direction has been taken

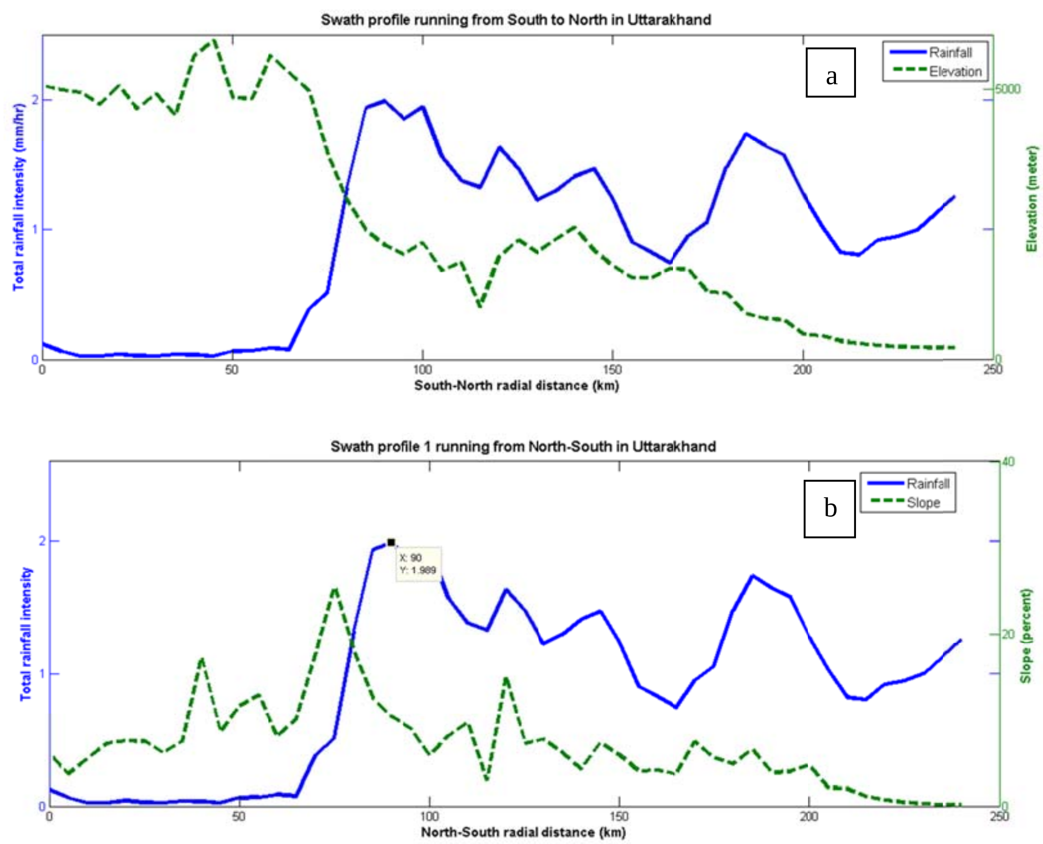


Fig.5.27:[a]vertical cross-section of elevation and rainfall intensity of swath-1 profile [b] is the same as [a] but instead of elevation slope is the varying parameter.

for all the pixels for deriving a single profile for each and every swath. Cross-section of Swath 1[Fig.5.27 a] reveals that there are two rainfall peaks of 1.73 mm/hr and 1.98 mm/hr 115 km apart from each other, these pattern of dual peak across the Himalayan range is identical to the findings by [A.M Anders et al] and [Bookhagen,Burbank,2006] where those same rainfall peaks modulated by different slopes of 3.9 percent and 8.4 percent[Fig.5.27 b] A sudden rise in slope and automated rise in elevation acts as a reason for the abrupt decreasing nature of rainfall farther beyond 200 km from the foothills of HimalayaSwath-2 profile also exhibits the dual rainfall maxima over the Himalayan region. Two rainfall peaks appear at the elevation of 1018 meter and the other peak at 2044 meter[Fig.5.28 a], almost an elevation gradient of 1 km over 80 km stretch along the orientation of Himalayan flank assist in the occurrence of 2nd rainfall peak. Elevation suddenly increases off the location of 2nd high rainfall peak. Abrupt increasing of topographic surface characterized by the slope

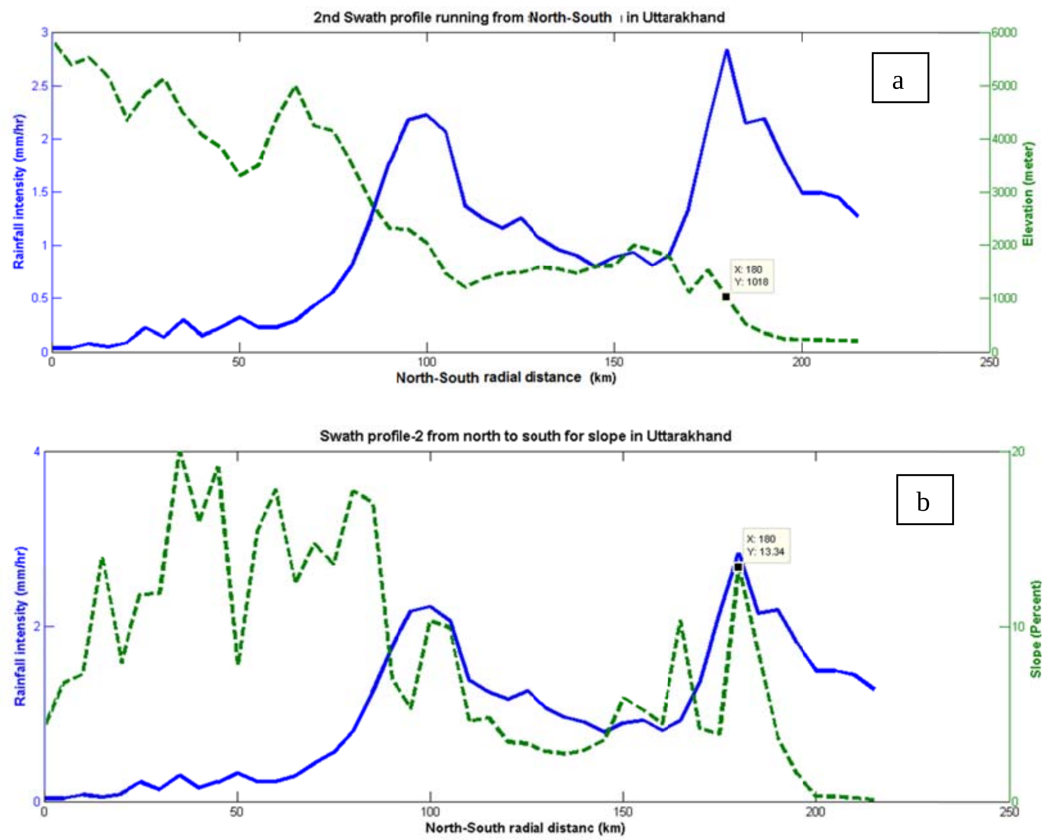


Fig.5.28: [a] vertical cross-section of rainfall intensity and elevation for swath-2 over Uttarkhand and [b] is the vertical cross-section of slope profile of Swath-2.

again explains the declining in the rainfall activity across greater Himalaya region[Fig.5.28.b]. Along swath-2 there is an elongated surface with little variation in elevation accounts for the high value of rainfall peak between the two peaks of rainfall maxima. Clearly heavy rainfall seems to be induced by the significant rise of topography that is encountered by the moisture laden wind spreading across the Himalaya.[Haselton,1998].

For swath-3 profile there are two peaks of rainfall intensity almost 100 km apart at the elevation of 919 meter and 1926 meter. The 2nd rainfall maximum has occurred over a location which is 1000 meter above than the first rainfall peak [Fig.5.29]. In Uttarakhand rainfall peaks are distributed along two elongated bands separated from each other by 100 km distance. The first rainfall peak occurs at 1 km elevation more and less and 2nd peak occurs at 2 km elevation more or less. This analysis using swaths substantiates the presence of dual band in Uttarkhand [Fig.5.26.A].

The above analysis of topographic relationship with rainfall and its pattern was confined in Uttarakhand regions whose topography is represented by two-step topography. Now the swaths selected across Himachal Pradesh have been used for finding more quantitative relationship between rainfall and orography.For swath-1 of Himachal Pradesh a single peak of 2.875 mm/hr rainfall intensity has been obtained at the elevation of 1279 meter 100 km away from

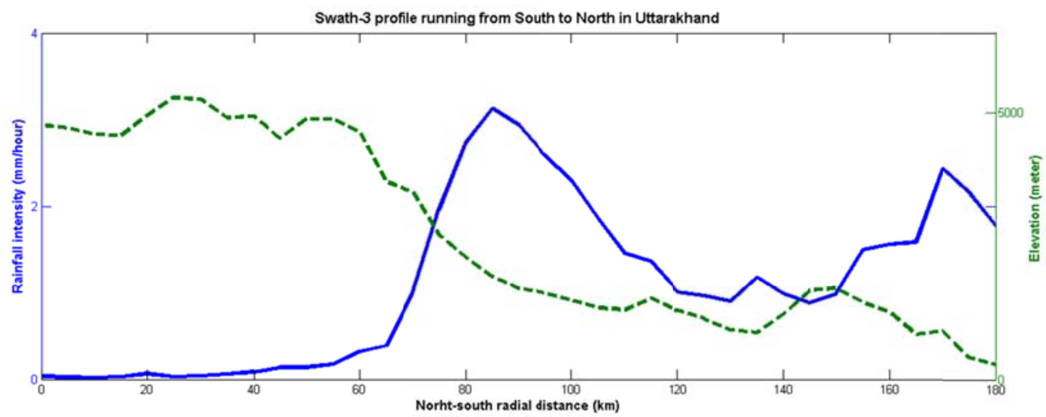


Fig.5.29: Vertical cross-section of rainfall intensity and elevation for the last swath-3.

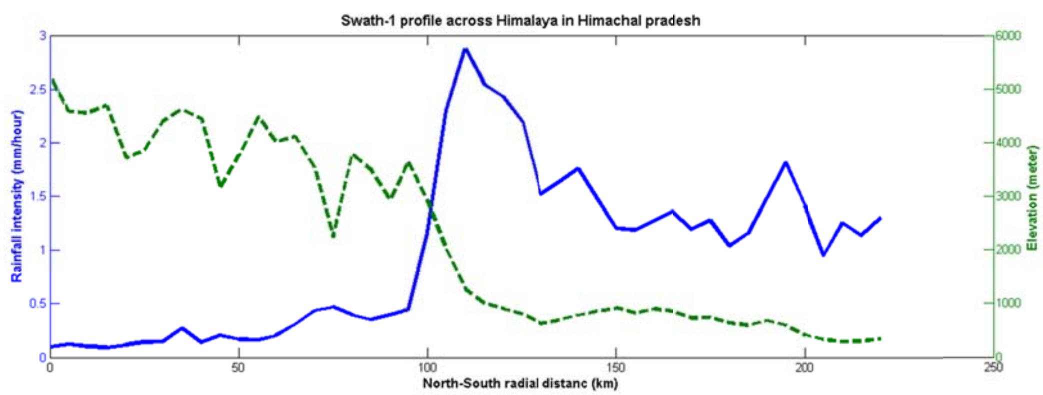


Fig.5.30: Vertical cross section of rainfall intensity and elevation for swath-1 over Himachal Pradesh

the Himachal Pradesh boundary . In swath-1 there is one pronounced rainfall peak registered total 2.875 mm/hour at an elevation 1279 meter and rainfall intensity sharply declines above 1279 meter elevation [Fig.5.30].From Fig.5.31, sharp declining of rainfall activity can be explained by the slope which is too much steep to carry moisture-laden air aloft rather due to this blockage moisture-laden gets deflected and progresses to the west of barriers. To find coherency in terms of the topographic and rainfall relationship amongst the swaths selected for Himachal Pradesh, the same way analysis of vertical-cross section of rainfall and topographic parameter has been performed. Analysis for swath-2 reveals that there is a strong single peak located 100 km away from the lower end of elevation along the path.

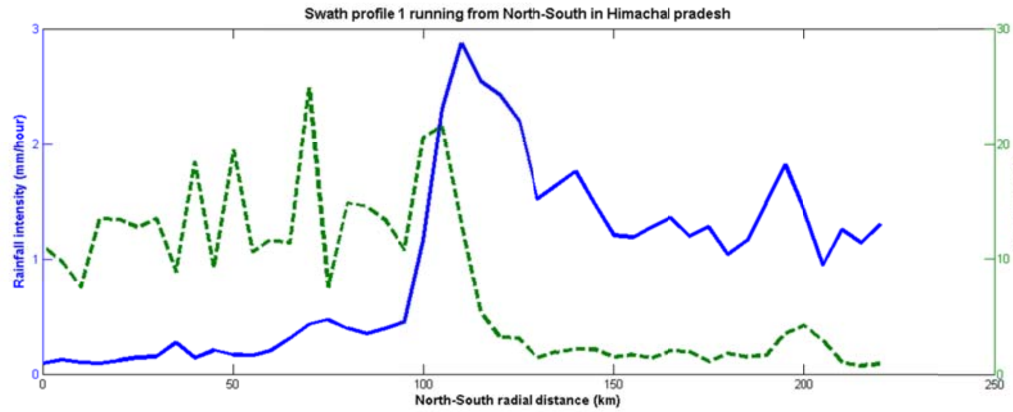


Fig.5.31: Vertical cross-section of rainfall intensity and slope for swath 1 over Himachal Pradesh.

Rainfall peak of 1.897 mm/hr at the elevation 1073 meter with a 5.53 percent slope value is obtained from the swath profile-2.[Fig.5.32.a and Fig.5.32.b].

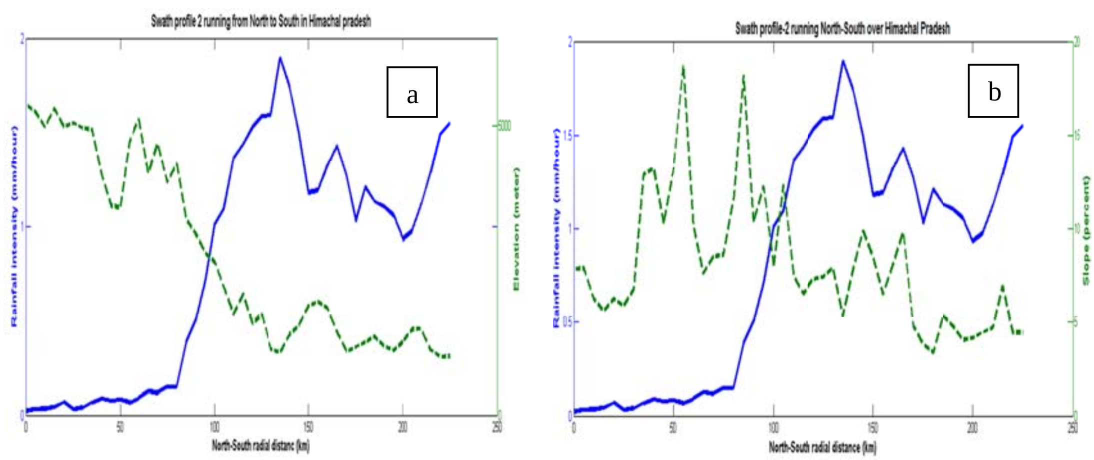


Fig.5.32: [a] represents the vertical cross-section of elevation and rainfall profile for swath 2 and [b] represents the vertical cross-section of slope along the same swath.

There is no sharp rising of slope on the decreasing side of the rainfall activity that is why rainfall intensity has not dropped abruptly after the high peak of rainfall intensity. The last swath profile-3 shows a relatively diminished rainfall activity along the swath during monsoon. In both swath-1 and swath-2 selected for Himachal Pradesh there is a pronounced peak of mean rainfall intensity at the elevation range of 1073-1279 meter but swath-3 profiles is characterized by high range of elevation of 1800 m to above 4000 meter [Fig.5.33.a and Fig.5.33.b].

In Himachal Pradesh high amount of rainfall distribution is confined to the elevation of up to

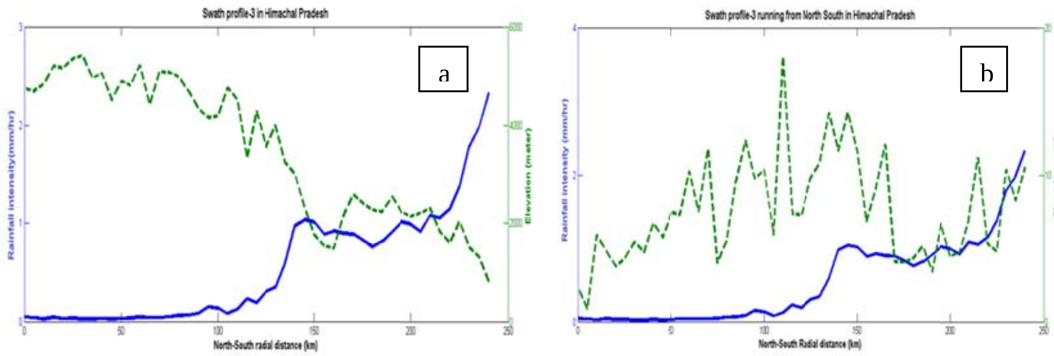


Fig.5.33: [a] represents the vertical cross-section of elevation and rainfall intensity [mm/hr] and [b] is the representation of vertical cross-section of slope.

1300 m but above this elevation there are no records of high rainfall intensity greater than 2 mm/hour throughout the monsoon. Monsoonal winds ,carrying bulk amount of moisture, coming from the eastern region of India after being deflected by the huge Himalayan barrier on the east strike the south-western oriented flanks of Himalaya in Uttarkhand causing an elongated band of high amount of rainfall and then this monsoonal

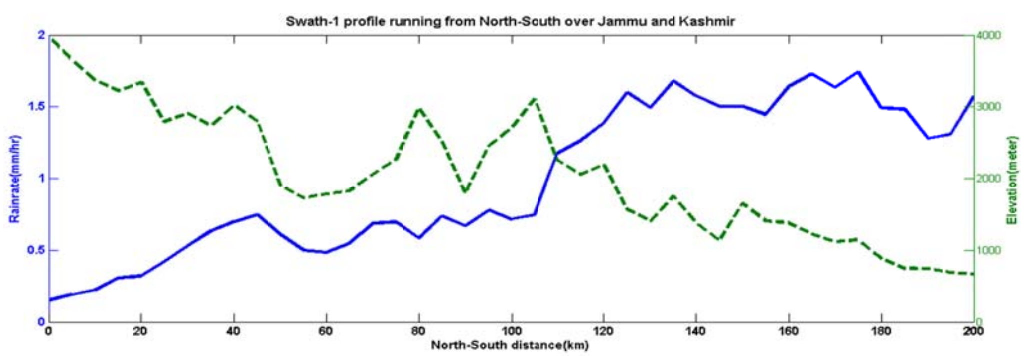


Fig.5.34: Vertical cross-section elevation and rainfall intensity for a single swath over Jammu and Kashmir.

system strikes the intersection of wide-stretched valley [elevation about 500 meter] and smooth topographic area of Shivalik[600-1200 meter]. Rainfall maxima is elongated along the 700-1200 m elevation distribution and this Shivalik zone is flanked by Inner Himalaya [1500- 4000 meter] along east-west direction over the upper side of Himachal Pradesh. Sudden topographic barrier being along the side of Shivalik region causes additional amount of rainfall owing to orographic effect over Dharamasala [which receives 70 % of its total rainfall during monsoon].In Jammu and Kashmir the vertical cross-section of rainfall and elevation almost reveals the same characteristics of rainfall distribution over a mountainous region but the amount of rainfall decreases because most of the moisture carried by monsoon system casts off over the eastern parts of North West Himalayan region[Fig.5.34].

6. Conclusions

Complexities of Himalayan region have given rise to wide variation of climate and rich bio-diversity along the foothills of Himalayan region and at the same time some region of the Himalaya experiences the impact of atmospheric activity and influences the climatic conditions every year. During monsoon, few places along the southern flanks of Himalaya receives additional amount of rainfall owing to orographic precipitation. As the mountains regions are poorly instrumented, dearth of information on rainfall puts constraints on the information on the variability rainfall pattern on the spatial scales of tens of kilometer. To reveal the exact detailed spatial pattern of rainfall with elevation TRMM 2B31 has been used, this long data set from 1998-2013 has been processed and developed in a common gird covering the NWH region to develop a high resolution climatological map of mean and cumulative rainfall intensity. The high resolution climatological map highlighted a unique characteristic of rainfall pattern over the study region. There are dual bands of rainfall existing all over Uttarakhand with a similar width of a band of moderate amount of rainfall and a discontinuous band of high rainfall to the North-West part of Himachal Pradesh. The discontinuous band extends into the state, Jammu and Kashmir because monsoon arrives over NWH with progression over Bay of Bengal branch of monsoon. For poor temporal resolution of TRMM 2B31, monthly mean of rainfall intensity has been calculated which gives presence of monsoonal rainfall over the North India during July and August and its distribution corresponds to timing of withdrawal of monsoon in September. Total mean rainfall intensity of TRMM has been calibrated against interpolated IMD rain-gauge data, with a decent agreeability between data sets the calibrated resampled TRMM data set gives the instances of underestimation over high-elevated regions but this underestimation can’t be justified by the sparse sampling of rainfall by gauge-networks the extrapolation technique used to calculate rainfall over mountainous regions using assumed topography-rainfall relationship. To find the impact of orography over rainfall elevation conditions have been applied and it is obtained from the result that in the range 1000-2000 m elevation comes the location of Dharamasala and its adjacent places that receive huge rainfall during monsoon. When the rainfall dataset compared with resampled -5 km digital topography, interesting results of effect of topography on rainfall have emerged. Lengthwise analysis of rainfall with elevation and slope for selected swaths reveal a strong relationship between these parameters and implies that abruptness and erratic characteristic of topographic features deprives the higher mountainous region of Himalaya of rainfall and turns it into arid region for a long time period. The study of the swaths has shown that rainfall peaks in Uttarakhand over two elevation zones characterized by 1 and 2 km where in Himachal Pradesh rainfall peaks are distributed within 700-1400 meter elevation zone. Slope of those regions has accounted for the sudden decrease of rainfall activity over 5 km spatial scale. Himachal Pradesh and Jammu and Kashmir do not show this dual band nature because of the topography does not elevate in a two-step pattern and a high slope appears close to the mountain front. So elevation connected with slope has characterized the orographic rainfall over particular places whose topographic conditions are the governing factor for additional rainfall as compared to other places which receive normal monsoon rainfall.

To the author's knowledge, the present work is the first of its kind effort by utilizing a long term time series (16 years) of fine scale (5x5 km) TRMM 2B31 rainfall data set over the topographically rich North-West Himalayan region. The present study unfolds the intricate relationship of the orographic variables and rainfall in detailed manner, therefore this work may be utilized further for the modification of the satellite derived rainfall retrieval algorithms. Based on the fine scale rainfall data sets, the trend of the heavy and very heavy rainfall events are also estimated in the present work, which are in concurrence with some of the previous studies, since the sample size used was very small, therefore the robustness of the trend may not be established. Nonetheless, Uttarakhand region indicate a secular increasing trend, and it is anticipated that there will be further increase in such extreme rainfall events in coming future.

The locations of the extreme rainfall events have also been identified in the present work, which would be useful for the policy makers to plan any infrastructure activity. Providing the physical mechanism of some of the finding is beyond the scope of the present work, nevertheless, for the better understanding of the orographic precipitation processes, an atmospheric mole study may also be carried out.

7.Recommendations

i] Calibration of instantaneous rainfall intensity with higher number of rain-gauge data located over the higher elevation as well as data of rain-gauges over plane.

ii] Conversion of the radar reflectivity factor Z to rain rate [mm/hr] is an important step in the hydrological radar measurements. Therefore, the modification to the constants of radar reflectivity-rain rate algorithm used by TRMM is necessary because the coefficients of the $Z = aR^{b}$ depend on the climatological character of a particular location or season and more specifically that of rainfall.

iii] The information on the relationship between rainfall intensity and topographic features can be used in modification of extrapolation and interpolation technique applied to derive ground-based rainfall data.

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