Characteristics of the spatiotemporal pattern of Extreme Rainfall event over the state of Uttarakhand, India

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Abstract

Precipitation processes are perturbed by elevation, land use land cover change and land surface temperature. The fast expansion of road linkages has accelerated urban growth and tourism in previously inaccessible remote regions of the Himalayas. The state has been experiencing massive population influx, reduction in agriculture and forest cover and expeditious urbanization since the last decade. The increasing population and haphazard construction in this ecologically sensitive zone has also been regarded as one of the prime reasons behind huge death toll during recent catastrophic disasters initiated by heavy rainfall in Uttarakhand. The detection and understanding of rainfall extremes due to rapid urbanization in mountain areas is much required in climate and hazard studies. This paper attempts to analyze the spatiotemporal pattern of rainfall extremes in relation with elevation and later inspect the impact of land cover change and land surface temperature on the trends of rainfall through a case study for the city of Dehradun. It is a preliminary study which acts as a precursor for in-depth analysis of land-atmosphere interaction and its impact on rainfall extremes in future in the vulnerable Himalayan region.

1. Introduction

The landlocked Himalayan state of Uttarakhand is experiencing urbanization and economic growth at an unprecedented rate. Being a mountainous state with altitude ranging from 187 m to 7409 m (SRTM DEM v4) above mean sea level and average annual rainfall of approximately 1494.72 mm (IMD), it is highly prone to natural hazards such as cloudbursts, associated flash floods and landslides. However, the complex young folds and the fragile mountain eco-systems are being steadily agitated due to the increasing population and rapid haphazard urbanization. Consequently, the state witnesses colossal disasters initiated by heavy rainfall during monsoon season almost every year. The multi-date extreme rainfall event during June 15-17, 2013 resulting in devastating floods known as the Kedarnath Disaster was one such noteworthy disaster. This event is also termed as 'The Himalayan Tsunami' due to its sheer enormity and is widely acknowledged as India's worst natural disaster since 2004. It had resulted in thousands of fatalities and missing people, and the complete wipe-out of entire towns and several villages. Although Kedarnath already lies in a geographically vulnerable zone, researchers unanimously agree on rampant construction and mushrooming hotels in the area as one of the major causes behind huge death toll (Dobhal *et al.* 2013, Uniyal 2013).

It is well established that elevation has a profound impact on rainfall distribution (Duckstein *et al*. 1973, Shrestha *et al*. 2012). Moreover, speedy unplanned urban development in mountain valleys is creating massive change in land cover and causing high population density within small region. Past studies have shown its effects on atmospheric dynamics in terms of higher near surface air temperature, change in precipitation pattern, anthropogenic heat influx and introduction of harmful aerosol emission (Burian & Sheperd 2005, Han *et al*. 2014, Kharol *et al*. 2013, Williams & Kniveton 2011). Dehradun, the capital of the state, has been turning into a major commercial hub and had undergone extensive land cover change in the past decade. Besides, the changing climate and expanding cities are inducing changes in extreme precipitation pattern in this orographic regions.

Remote sensing is being used extensively in the study of atmosphere-land interaction especially in geographically complex regions. The major objectives of this paper are twofold: first, to examine the spatiotemporal pattern of rainfall extremes and its association with elevation over the state of Uttarakhand and secondly, the Land use land cover (LULC) change and land surface temperature (LST) in relation with rainfall as a separate case study of Dehradun district. In the present paper, it is proposed that any rainfall event above 98th, 99th and 99.99th percentiles can be classified as heavy and very heavy rainfall events respectively. The dearth of research papers on the climate extremes over the region with respect to increasing urbanization and the state's proclivity for disasters has been the principal driving force behind our research.

2. Study Area

The study area is confined to Uttarakhand state which extends from 28°43` to 31°27` N and 77° 34` to 81°02` E. Dehradun is situated in the Doon valley surrounded by the lesser Himalaya range known as Mussoorie hills. The elevation ranges from 290 m to 2800 m (SRTM DEM v4) above mean sea level within the district and average annual rainfall exceeds 2000 mm (IMD).

3. Datasets and methodology

The gridded dataset of TRMM (Tropical Rainfall Measuring Mission) 3B42 v7 3-hourly rainfall product with resolution 0.25° x 0.25° for the past 16 years from 1998 to 2013 has been used for the present analysis. The elevation has been derived from Shuttle Radar Topography Mission (SRTM) version 4 with a spatial resolution of 90 m. The state receives 86% of its annual rainfall during the Indian summer monsoon, hence our study exclusively focuses on monsoon months i.e. June to September. LST data has been acquired from MODIS Terra MOD11C3 product which gives monthly-mean daytime and night-time LST at 1° resolution. This data has been accessed through Giovanni (Geospatial Interactive Online Visualization ANd aNalysis Infrastructure) - Interactive Visualization and Analysis , a web- based application developed by NASA's Goddard Earth Sciences Data and Information Services Center (GES DISC). This data was available from March 2000 – April 2013. Thus, monthly analysis is performed for JJAS months from 2000-2012 but yearly analysis excludes the year 2000. LANDSAT 7 and LANDSAT 8 satellite images (spatial resolution – 30 m) have been acquired for the region for May 2000 and May 2013 respectively. The change analysis has been performed for the land use land cover (LULC) of the region post supervised classification scheme. Standard statistical methods, Karl Pearson's correlation coefficient, linear regression and student's t-test have been used for the analysis.

4. Results and Discussion

4.1 Analysis of rainfall extremes and its association with elevation over Uttarakhand

Firstly, the rainfall intensity associated with 98th, 99th and 99.99th percentile over the state has been calculated as 59, 74.7 and 179.9 mm/h for the past 16 years i.e. 1998-2013 and its distribution is visually analyzed. The spatial distribution of rainfall extremes is indicative of frequent heavy rainfall reception in lower elevated ranges of < 3000 m than higher ranges as seen in figure 1. It is observed that the South-East and North-West regions experience heavy rainfall as compared to other regions. Interestingly these are the regions undergoing rapid urbanization and industrialization including northwestern district of the state and the capital, Dehradun.

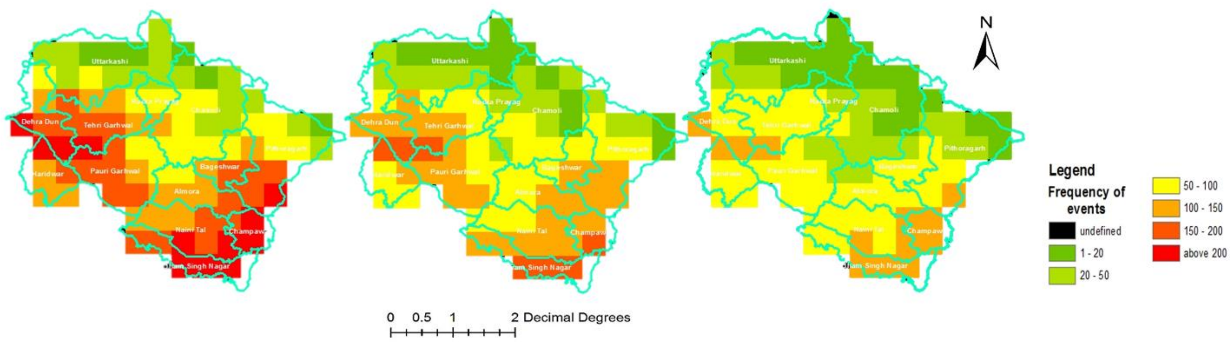

Fig 1: Spatial distribution of frequency of extreme rainfall events over Uttarakhand for (left) frequency of EREs with intensity >=98th percentile (center) same as (left) but for >=99th (right) same as (left) but for >=99.99th percentile

Further, the spatial map of intensity of rainfall extremes calculated for each grid point suggests that high intensity events are normally restricted to <3000 m elevated region. However, some exceptions have also been reported in the high altitude northern regions which usually have as low rainfall intensities as <60 mm/day associated with 98th and 99th percentiles but show sudden jump of >150 mm/day for 99.99th percentile. Remarkably, high altitude regions with >4000 m elevation also experience sudden local storms capable of producing rainfall extremes. As monsoon rainfall is of convective nature and is captured by the foothills and lower altitude regions predominantly, all of these results are indicative of the ability of moist monsoon flows to reach orographic interiors and produce significant rainfall.

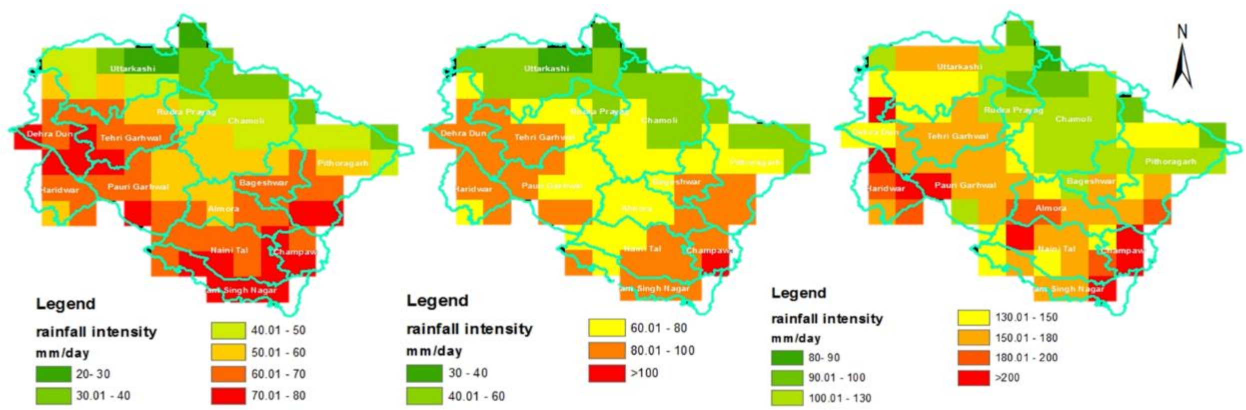

Fig 2: Rainfall intensities for each pixel/grid of Uttarakhand for (left) 98th percentile (center) 99th percentile (right) 99.99th percentiles during monsoon season of the period 1998 – 2013

The reported spatial variability of frequency and intensity of rainfall extremes seem to have an association with the elevation of this mountainous region. In order to understand the relation between both, spatial correlation was calculated between elevation and frequency and intensity of rainfall extremes. A strong negative correlation (~ -0.8) and negative slope of regression line was observed between intensity of extremes and elevation for all three percentiles indicating at decreasing intensity with increasing elevation. While a strong negative correlation (~ -0.8) was found between elevation and frequency of extremes above 98th and 99th percentiles, very poor negative correlation (~ -0.3) was seen for 99.99th percentiles. It implies that heavy rainfall events usually decrease with elevation but the same cannot be said for very heavy rainfall events.

4.2 Case study of Dehradun

4.2.1 Change in Land use land cover

The growth of urban settlement in the Himalaya Mountains has been transforming the land cover remarkably. Through this analysis, we attempt to estimate the increase in coverage of urban settle over Dehradun district in the past decade. The supervised classification has been performed on satellite images for May 2000 and May 2013 for four broad categories – vegetation (including all kinds of forest and shrubs), water, soil/rock (including crop land) and urban areas. The change analysis performed on these two images and corresponding statistics are shown in the figure 3 & 4. While a reduction of 9% can be observed in soil area, 9% increase in urban spread is reported simultaneously. Additionally, an overall decrease of 1% in vegetative areas is also observed.

Figure 4 also shows the change matrix indicating the % change in areas of different land covers. Roughly 5% of vegetation, 28% of water and 30% of soil areas converted to urban regions whereas 73% of urban regions were still intact. Although, seasonal effects cannot be ruled out as May month is the peak of summer season when water level are usually at the lowest resulting in drying of rivers and exposing river beds. However, an increase in urban spread as the major land transformation is clearly revealed. Urban surfaces like concrete trap more infrared radiation in day time which is slowly released in night time keeping the city warmer than its surroundings consistently. The increase in urban surface affects the surface temperature thus modifying the local circulation and precipitation processes (Han *et al*. 2014, Kug and Ahn 2013).

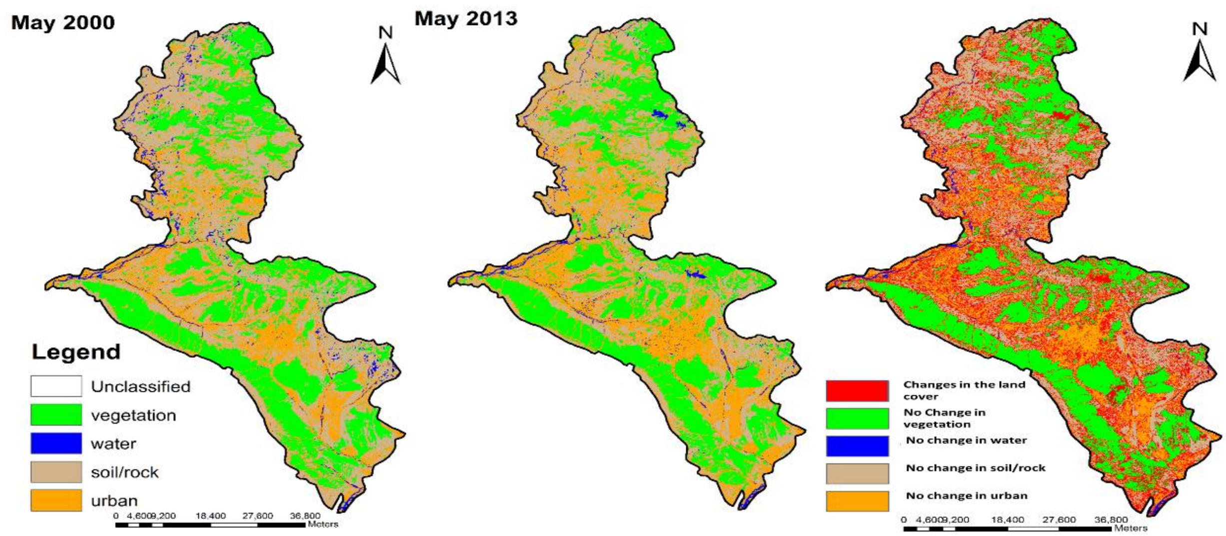

Fig 3: (left) LULC map for May 2000 (center) LULC map for May 2013 (right) Change detection map for May 2000 –May 2013 over Dehradun district

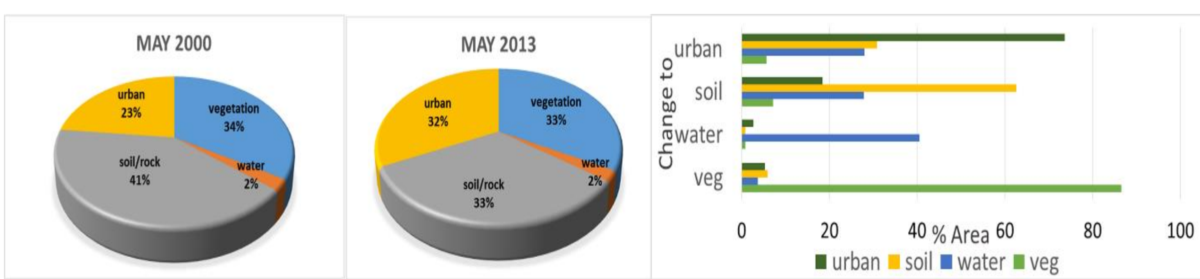

Fig 4: (left) Statistics for change analysis performed on LULC maps of May 2000 & May 2013 for Dehradun district; (right) Change matrix shows area converted to new classes in %

4.2.2 Land surface temperature (LST) and rainfall

Land surface temperature has been identified as the key parameter in land surface processes and affects precipitation variability. It is also linked with deeper boundary layer and latent heat flux (Li *et al*. 2013, Sun 2008). The trend analysis performed for JJAS months show increasing trend of LST for June and July months for both day and night whereas decreasing trend was seen for August month for both day and night. For September month decreasing trend was observed for day LST but night LST showed an increasing trend. However, decreasing trend of both day and night time LST is observed on yearly timescale. Other than June month, an increasing trend of average rainfall has also been observed over Dehradun. The increasing trend of rainfall intensity and frequency associated with 98th, 99th and 99.99th percentiles indicate heavier rainfall in near future, though frequency of events above 99.99th percentile do not show any concrete trend. Further, the relation between LST and rainfall was analyzed using correlation. The mean monsoonal rainfall intensity showed very weak negative correlation (~ -0.2) with annual day and night LST (significant at 1%). However, at monthly scale the correlation improves to a great extent. The table 1 shows the CC for day and night LST with rainfall at monthly scale.

Table 1: Correlation coefficients for monthly day and night LST with monthly rainfall

	With day LST	**With night LST**
June	-0.87	-0.66
July	-0.67	-0.45
August	-0.70	-0.75
September	-0.87	-0.71

It is found that on the monthly time scale, LST and rainfall have strong inverse relation ($p<1$). Previous study also show that due to urbanization precipitation can either increase or decrease depending on various factors including moisture supply (Han *et al*. 2014). Therefore, over Dehradun region with rapid urban sprawl precipitation seems to increase in intensity with time.

5. Conclusion

Urbanization can have severe implications on mountain weather system by inducing local climate modifications at regional level. Past studies have shown that increase in urban surface affects the convective activity causing changes in long term precipitation pattern. Through this study, we attempted to highlight the effect of increasing urbanization on rainfall and its extremes in mountainous region. As lower elevated regions are highly prone to extreme rainfall events in rainy season, this precipitation pattern can be affected in near future due to increasing industrialization and population in the Himalaya Mountains. The case study of Dehradun indicates increasing average precipitation intensity along with increasing frequency and intensity of rainfall extremes due to expanding urban sprawl. There are few limitations in the present study. Although we tried to obtain the largest sampling density available, still the number of observations is considerably less. Finer resolution precipitation data is required for regional analysis as well. Further efforts are needed to understand the effects of urban precipitation anomalies on mountain climate.

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