B. TECH. PROJECT REPORT

On

Changes in the probability of concurrent droughts and heatwaves

By:
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DISCIPLINE OF CIVIL ENGINEERING
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Changes in the probability of concurrent droughts and heatwaves

A PROJECT REPORT

Submitted in partial fulfillment of the requirements for the award of the degree

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INDIAN INSTITUTE OF TECHNOLOGY INDORE
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Declaration of Authorship

I hereby declare that the project entitled **" Changes in the probability of concurrent droughts and heatwaves "** submitted in partial fulfillment for the award of the degree of Bachelor of Technology in 'Civil Engineering' completed under the supervision of **Dr. Munir Ahmad Nayak**, Assistant Professor, Discipline of Civil Engineering, IIT Indore is an authentic work.

Further, I declare that I have not submitted this work for the award of any other degree elsewhere.

Signature:

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Date:

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Certificate

This is to certify that the thesis entitled "Changes in the probability of concurrent droughts and heatwaves" submitted by Shalay Gupta, Roll No. 160004033 in partial fulfillment of the requirements for CE 493 B.Tech Project embodies the work done by him under my supervision. It is certified that the declaration made by the student is correct to the best of my knowledge.

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Abstract

Global warming has led to an increase in climate extremes such as droughts, floods, windstorms, and heatwaves. Most previous studies have focused on changes in the frequency, spatial extent and severity of individual extreme events. Recently, some studies on concurrent extreme events, defined as co-occurrence of multiple weather extremes, have received much attention because such events cause significant damage to society and ecosystem. This study focuses on changes in the probability of concurrent droughts and heatwaves over India from 1980 to 2018. Two heatwave indices the Excess Heat factor (EHF) and the Tmax97.5p are used for the quantification of heatwaves and Standardized Precipitation Index (SPI) is used for computation of droughts. The study area is divided into ten different cluster regions using a density-based clustering algorithm for analysis of concurrent extreme events. Most of the regions receive rainfall during monsoon season and experience heatwaves during months of March-June except north and northeastern states of India. The heatwaves of higher duration and low intensity occur in south and southeastern states of India, while heatwaves of lesser duration and varying intensity (low to high) occur in north and northeastern states of India. Higher frequency of concurrent drought and heatwave events are observed in north and northeastern states while northwestern and southeastern states have received lesser number of concurrent events during the period 1980 to 2018.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

The annual mean temperature over India has shown a warming trend of 0.6°C/100 years during the period 1901-2018[6] due to increase in anthropogenic activities. According to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), extreme events such as heatwaves and droughts are becoming more common across the world due to increase in the global warming over recent decades. Heatwaves are a period of anomalous high surface air temperatures. They cause huge damage to health, crop yield, ecosystem and eventually the global economy. A period of three or more consecutive days with maximum temperature higher than the threshold is defined as a heatwave[18]. The maximum and minimum temperature both should be used to define a heatwave as high nighttime temperature exacerbate the heatwave conditions[16]. Steadman (1984) developed apparent temperature[22,23] which takes into account humidity and temperature for accessing the heatwave conditions. Many indices have been developed to estimate the impacts of heatwave on different sectors (e.g. human beings, agriculture, wildlife, infrastructure, etc.). The predicted mean vote[4] (PMV) developed by Fanger (1970) and physiological equivalent temperature[10] (PET) developed by Mayer and Hoppe (1987) uses human energy balance to find the stress of heatwave on human beings. Due to the complexity involved in the calculation of the sector-based indices over the long period, the temperature based thresholds are generally used. The temperature-based thresholds are further divided into absolute thresholds (Summer days[1]: Annual number of days when Tmax>25°C, and percentile-based thresholds (TX95[1]: 95th percentile of daily maximum temperature of warm season). The increasing trends of heatwave characteristics, e.g., annual frequency, average duration, and maximum duration are observed in northwestern and southeastern parts of India during the period 1961-2013[20]. Many deadly heatwaves have been recently witnessed in India such as 2010 heatwave[2] that killed more than 1300 people in Ahmedabad, 2015 heatwave[8] that claimed more than 2500 lives in Andhra Pradesh and Telangana. The higher correlation is observed between income and health as compared to physical conditions and health in India[12]. The mortality rates due to heatwave will increase substantially even if summer mean temperature increases by only 0.5°C[12].

Drought is defined as a period with below-average water availability. Drought has different characteristics: duration, intensity, frequency, and spatial extent. The shortage of water due to drought can affect municipal water supply, agricultural fields, industries, etc. Severe droughts have huge impact on agriculture, industries, tourism and thus affect the lives of many people across the world. Various indices e.g. Standardized Precipitation Index[13] (SPI), Palmer Drought Severity Index[17] (PDSI), etc. are used for the computation of drought. The PDSI, developed by Palmer in 1965, measures the cumulative departure of atmospheric moisture supply and water demand at the surface. It uses precipitation, temperature and water balance model to identify drought. The SPI is a normalized index which indicates deviation of precipitation from climatological mean. SPI uses only precipitation data and can characterize drought of different timescales (1month-36month). Many previous studies have focused on the trends[15] of characteristics of drought, impacts[14,24] caused by drought over India. The study by Zhang[24] (2017) has evaluated the characteristics of four different types of drought (meteorological, hydrological, soil moisture and vegetation) and their effects on crop yield. The increasing trends[15] of drought frequency and severity is observed over India during 1972-2004. The study by Mishra[14] (2014) predicted increasing trends of frequency and spatial extent of soil moisture drought in the crop growing seasons during 2010-2039 and 2040-2069 over India.

Concurrent extremes are defined as co-occurrence of two or more extreme events (e.g., drought and heatwave), which may cause significant damage to nature and society as compared to individual extreme events. Despite knowing that precipitation and temperature are inter-connected, very little emphasis has been given to concurrent extreme drought and heatwaves. Omid (2015) study[11] has calculated the changes in the frequency of concurrent droughts and heatwaves over the United States during 1990–2010 relative to the baseline period 1960-1980. They used three different durations (3, 5, and 7 days) and three different thresholds (85th, 90th, and 95th) for the quantification of a heatwave and found that frequency of longer and more severe (7d-95th percentile) concurrent events has increased more than shorter and less severe (3d-85th percentile) concurrent events. A recent study[21] on concurrent droughts and heatwaves over India showed that there is an increase in the number of concurrent moderate droughts (SPI<-1.3) and 10-day 90th percentile heatwaves in Himachal Pradesh, Punjab, Gujarat, Central India, and Peninsular India while a decrease is observed in Rajasthan and

West Bengal during the period 1981-2010 relative to the baseline period 1951–1980. The increasing trend in spatial extent of concurrent droughts and heatwaves is observed over India[21].

Previous studies have focused on the frequency and spatial extent of concurrent droughts and heatwaves. The joint probability of characteristics of drought and heatwave (e.g., drought intensity, heatwave duration, heatwave intensity), future projection of concurrent droughts and heatwaves are the research areas that need to be studied.

Chapter 2

Methods

2.1 Study Area and Dataset Used

The fifth generation of ECMWF (The European Centre for Medium-Range Weather Forecasts) atmospheric reanalyses (ERA5)[3] high resolution (0.25°×0.25°) gridded dataset for the period 1980–2018 has been used in this study. The three variables namely (a) Hourly Maximum temperature (b) Hourly Minimum temperature (c) Monthly Precipitation are accessed over an area ranging between latitude 8°N to 38°N and longitude 68°W to 98°W for the study period. The data at 4722 grid cells lying inside India are obtained by masking the data at other grid cells using shape file[7] of India. The daily maximum (Tmax) and minimum (Tmin) temperature for each day (A day is considered from 0:00 UTC to 23:59 UTC) are obtained by taking the maximum value of hourly maximum and minimum temperature of that day respectively.

2.2 Heatwave

There does not exist any universally accepted definition of a heatwave. In broad terms, a heatwave is defined as a period of consecutive days with surface air temperature higher than normal (or some fixed threshold). According to the World Meteorological Organization[9], a heatwave is a period of five or more consecutive days with daily maximum temperature higher than average maximum temperature by 5°C or more. Many indices have been developed to quantify the impacts of heatwave on different sectors, for example, Predicted Mean Vote (PMV) based on human energy balance to find the heat stress on human beings, Absolute thresholds (30°C), Percentile based thresholds (TX95p: 95th percentile of daily maximum temperature). In India, many heatwave events have occurred in the past decade[8] which caused huge loss to human life. For this reason, a higher percentile-based threshold i.e. Tmax97.5p is used to estimate the risk due to extreme concurrent events (i.e. droughts and heatwaves) over India. However, to verify our results of heatwaves, another heatwave index EHF defined below is also used.

2.2.1 Heatwave indices

1.**Tmax97.5p**: 97.5th percentile of Tmax of warm-season (April to September) for the climatological period 1980–2018. There is only one threshold (non-time varying) for each grid cell. A heatwave is defined as a period of three or more consecutive days with Tmax>Tmax97.5p. It is also checked if two consecutive days are under heatwave and difference between third day maximum temperature and threshold is less than 0.5°C, then that day is also considered as heatwave day.

2.**Excess Heat Factor (EHF):** This index was given by Nairn[16] in 2009. It is based on two excessive heat indices, the significance index (EHI_{sig}) and the acclimatization index (EHI_{accl}).

$$EHI_{sig} = \left[\frac{T_i + T_{i-1} + T_{i-2}}{3}\right] - T_{95} \quad (1)$$

$$EHI_{accl} = \left[\frac{T_i + T_{i-1} + T_{i-2}}{3}\right] - \left[\frac{T_{i-3} + T_{i-4} + ---- + T_{i-32}}{30}\right] \quad (2)$$

$$EHF = EHI_{sig} \times \max(1, EHI_{accl}) \quad (3)$$

T_i is daily mean temperature (DMT) for day *i* and is calculated as the average of Tmax and Tmin. T_{95} is the 95th percentile of the DMT of the warm season (Apr to Sept) for the climatological period. T_{95} is a non-time varying threshold (one threshold for each grid cell). EHI_{sig} gives the anomaly of DMT averaged over three days with respect to T_{95}. The positive value of EHI_{sig} means the three days are warmer than the local long-term climate. EHI_{accl} gives the anomaly of DMT averaged over three days with respect to previous 30 days. The positive value of EHI_{accl} means three days are warmer than the recent past and people will face difficulty to acclimatize to a warmer climate. EHF, product of EHI_{sig} and max(1, EHI_{accl}), takes into account temperature anomaly with respect to long-term climate and recent past. Heatwave is defined as a period of three or more consecutive days with EHF >0.

The following climatological characteristics of heatwaves were then calculated

(a) Annual frequency of heatwave: It is calculated by dividing number of heatwaves with total number of years in the study period, i.e., 39.

(b) Average duration of heatwave: It is defined as the ratio of heatwave days to number of heatwaves.

(c) Annual maximum duration of heatwave: It is calculated by dividing summation of annual maximum duration with number of years in which heatwave occurred.

2.2.2 Concordance of heatwave

Concordance of a grid cell with a reference grid cell is defined as the percentage of heatwave days at reference grid cell occurring synchronously with the heatwave days at that grid cell. In other words, the fraction of heatwave days at reference grid cell occurring on the same dates of heatwave days at a grid cell. The concordant plot shows the concordance of each grid cell with respect to the reference grid cell.

2.3 Clustering

For analysis of concurrent extremes, grid cells having similar heatwave characteristics are grouped together to form homogeneous cluster regions. The clustering of regions is performed by density-based fast peak search method developed by Rodriquez and Laio[19]. This method is based on the fact that cluster centers are surrounded by data points of lower local density and their distance from any point of higher local density is relatively larger. To identify the cluster centers, two quantities local density and delta are computed for each grid cell. The local density (ρ_i) at a grid cell i is defined as the number of neighbouring grid cells with concordance greater than a predefined fixed concordance threshold. Delta (δ_i) at a grid cell i is defined as 1- maximum concordance between grid cell i and any other grid cell with higher density. The local density and delta are calculated for three different concordance thresholds 60, 70 and 80 percent. A scatter between local density and delta and a curve gamma (density × delta) = constant plotted on the scatter plot helps us to differentiate cluster centers from other grid cells. The grid cells lie above the gamma curve are identified as the cluster centers and remaining grid cells are assigned to the cluster centers with which its concordance is maximum.

2.4 Drought

Drought is generally defined as a period with below-average water availability. There are mainly three types of droughts: meteorological, agricultural and hydrological drought which occur due to large scale drying trends in precipitation, soil moisture, and streamflow, respectively. Various drought indices have been developed to monitor and quantify drought e.g., Palmer Drought Severity Index (PDSI), Standardized Precipitation Index (SPI) etc. In this study, SPI is used for the quantification of drought. SPI is a normalized index that indicates the deviation of precipitation from the climatological average. It uses monthly precipitation data to characterize drought of different timescales (1 month to 24 month). The 3-month SPI (SPI-3) gives rainfall conditions over a 3 month period as compared to its climatology, is related to soil moisture while the twelve-month SPI (SPI-12) indicates precipitation anomalies in groundwater and reservoir storage, since the twelve-month precipitation is compared with its climatology. In this study, we have defined drought as an event when SPI-12 falls below -1.

2.5 Concurrent climate extremes

According to the special report of IPCC[23], the concurrent extremes are defined in three ways: (a) two or more extreme events occurring simultaneously (b) combinations of multiple extreme events that can amplify the impacts (c) combinations of non-extreme events to form an extreme event. In this study, concurrent extremes are defined as the simultaneous occurrence of heatwave and SPI-12 < -1. The daily maximum temperature timeseries and monthly precipitation timeseries of each region are obtained by taking the average of daily maximum temperature and precipitation values of grid cells lying in the region. Heatwave characteristics (frequency, duration and intensity) and SPI-12 values are calculated for each region separately. The intensity of a heatwave is defined as the total temperature in excess of the threshold temperature divided by number of heatwave days.

Chapter 3

Results

Annual frequency of heatwave is higher in the north and northwestern states, Madhya Pradesh, West Bengal and Odisha based on EHF (Figure 1A). But the states with lesser annual frequency e.g. Chhattisgarh, Telangana and some parts of Andhra Pradesh receive heatwaves of higher average duration (Figure 1B). The annual maximum duration is also higher in states with higher average duration and lesser annual frequency (Figure 1C). The same spatial distribution of heatwave characteristics is observed based on Tmax97.5p. The magnitude of heatwave characteristics is lesser based on Tmax97.5p because of its higher threshold value as compared to EHF (Figure 1 D, E, F).

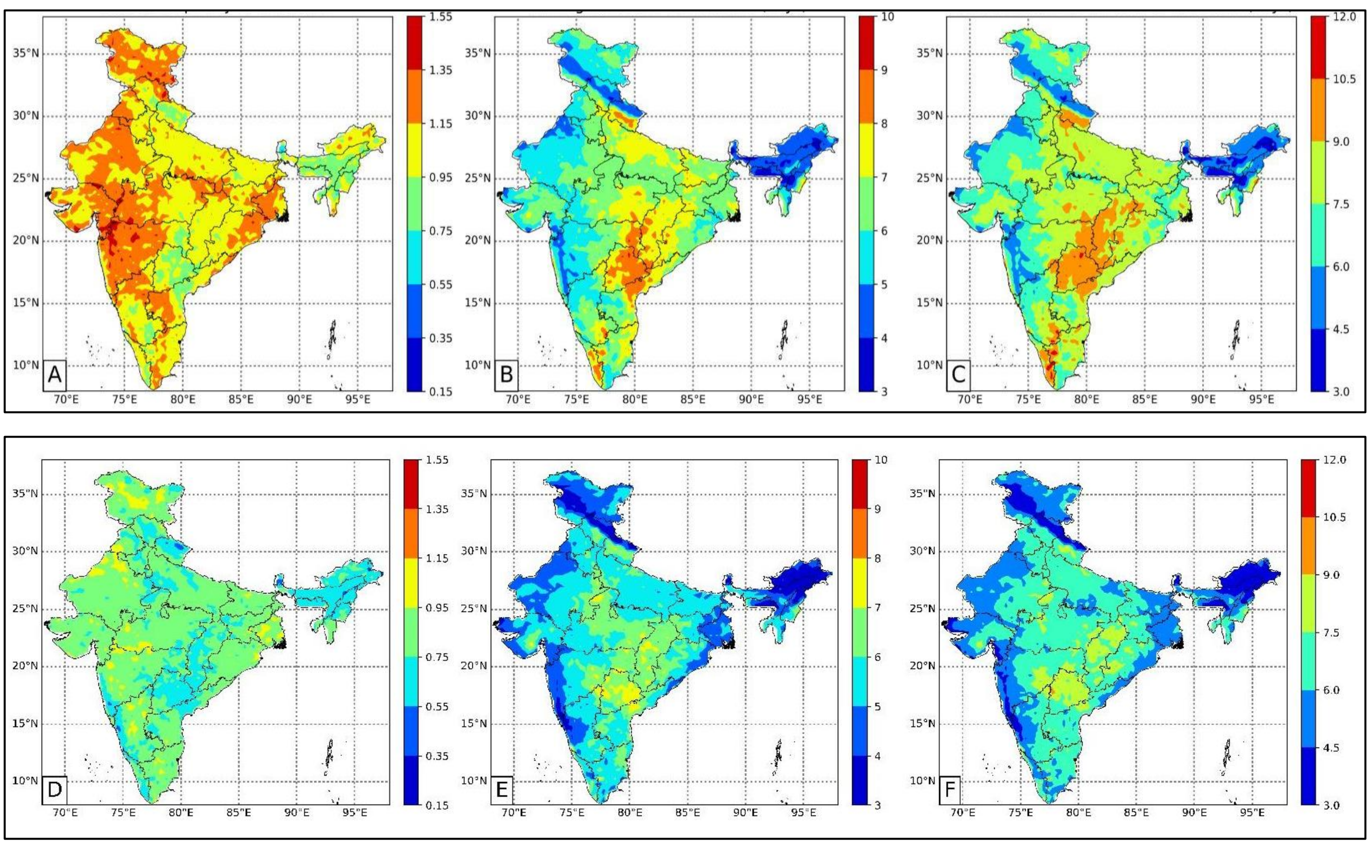

Figure 1. Climatological features of heatwaves (A, D) annual frequency (B, E) average duration (days) (C, F) maximum length of duration (days) over India based on (EHF, Tmax97.5p) during the period 1980-2018.

The concordancy plot (Figure 2) shows percentage of heatwave days at reference grid cell occurring synchronously with the heatwave days at other grid cells. The heatwave days of red, yellow, and green colored regions in concordancy figure occur simultaneously with the 90, 70 and 50 percentage of heatwave days at the reference grid cell respectively. It can be inferred from the concordancy figure that there exist regions with similar heatwave characteristics. Thus, for further analysis, grid points are grouped together based on the concordance of heatwave days using the density-based peak algorithm discussed in methods section

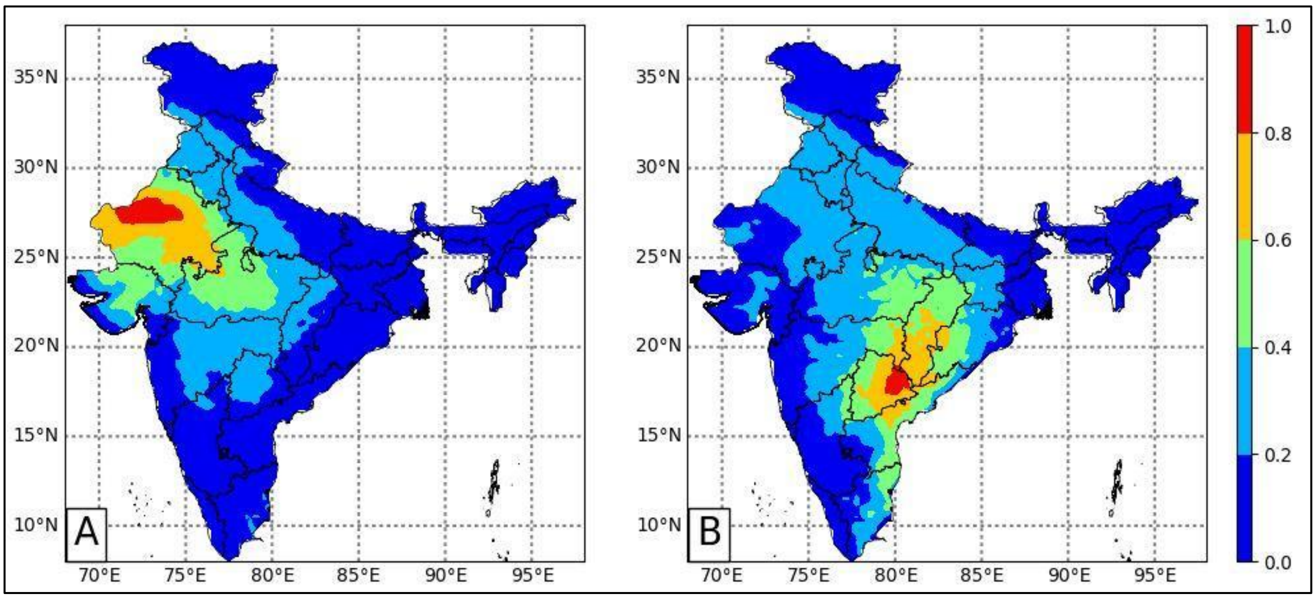

Figure 2. Concordance of heatwave days of reference grid point (A) Lat-27.5 Lon-73 (B) Lat-18 Lon-80

The density delta scatter plot for 60, 70 and 80 percent concordance threshold are used to identify the cluster centers. The grid cells marked with red and green colored dots are found to lie above gamma curve in density delta scatter plot for 70 percent concordance (Figure 3). But only red colored grid cells are taken as cluster centers because green colored grid cells lie in the neighbourhood of one of the red colored grid cells when plotted on the map of India. Figure 4(A) shows cluster centers marked with red colored dots obtained from density delta plot while figure 4(B) shows cluster regions with their ids.

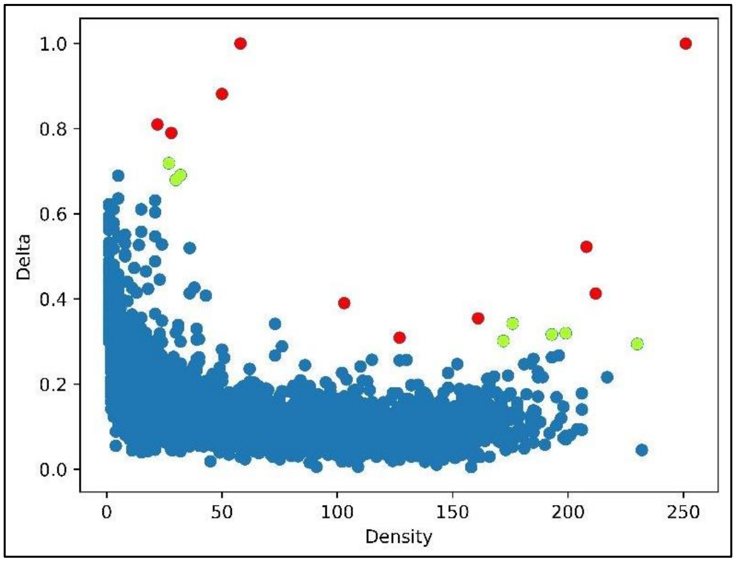

Figure 3. Density delta scatter plot for 70 percent concordance threshold. The grid points marked with red (cluster centers) and green colored lie above gamma curve

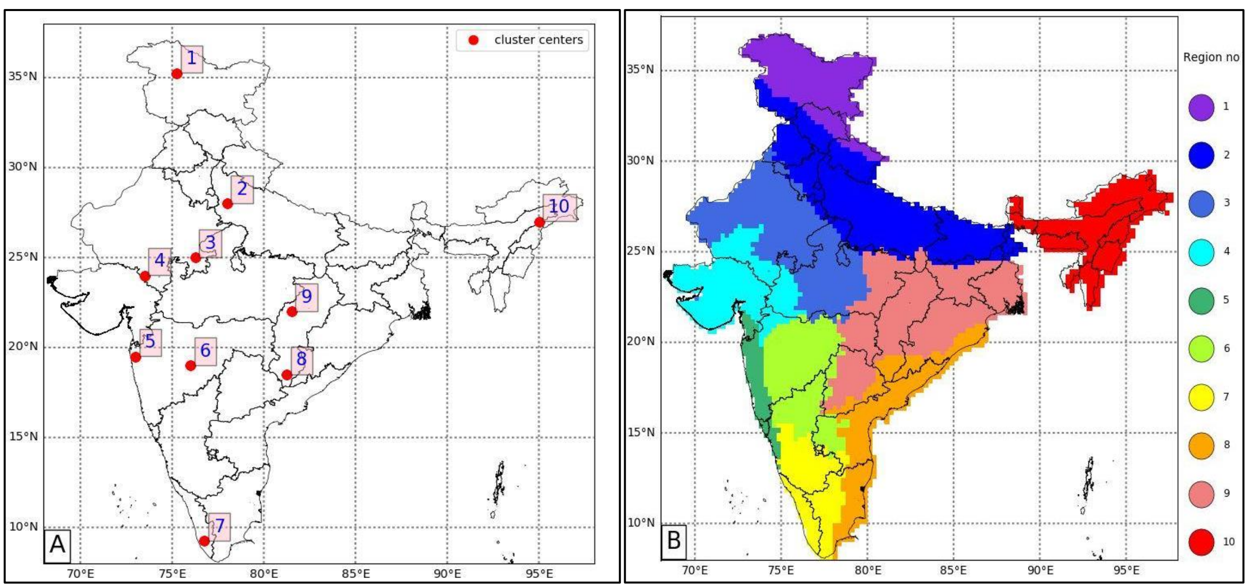

Figure 4. (A) Red colored dots (Cluster centers) are shown on map of India (B) Study area (India) divided into different cluster regions

The seasonal variation of heatwaves and precipitation for different cluster regions is shown in Figure 5. Heatwaves occur during months of March-June while precipitation occurs during months of June-October in all regions except northern states (region 1) and northeastern states (region 10) of India. The lesser duration (less than 10 days) and varying intensity (0 to 1.8°C/day) heatwaves occur in north and northeastern states of India while heatwaves of higher duration (10 to 25 days) and low intensity (0 to 1°C/day) occur in southeastern states of India (Figure 6). One can clearly see from Figure 5, precipitation is small during months of October to May in most of the regions. Therefore even if we take 1-month, 3-month, 6-month or 9- month SPI, precipitation values tending to zero will give large negative SPI (means severe drought) in some non-summer seasons, which is not true. For this reason, SPI-12 is used for the computation of longer-term droughts (precipitation deficiency in groundwater and reservoir storage).

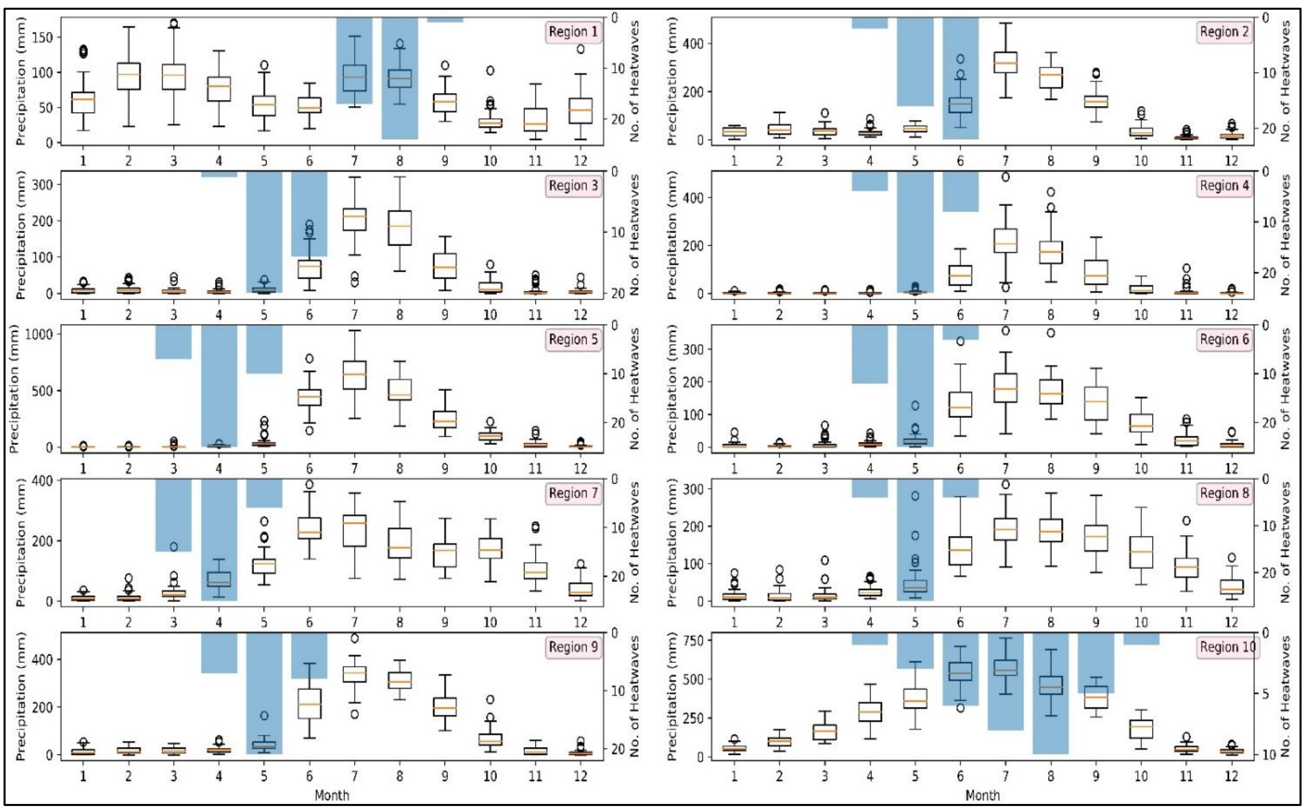

Figure 5. Seasonality of precipitation and heatwaves over the period 1980-2018 for different regions (region 1 to region 10). The x axes represent month and y axes on left side and right side represent precipitation in mm (down to up) and number of heatwaves (up to down), respectively.

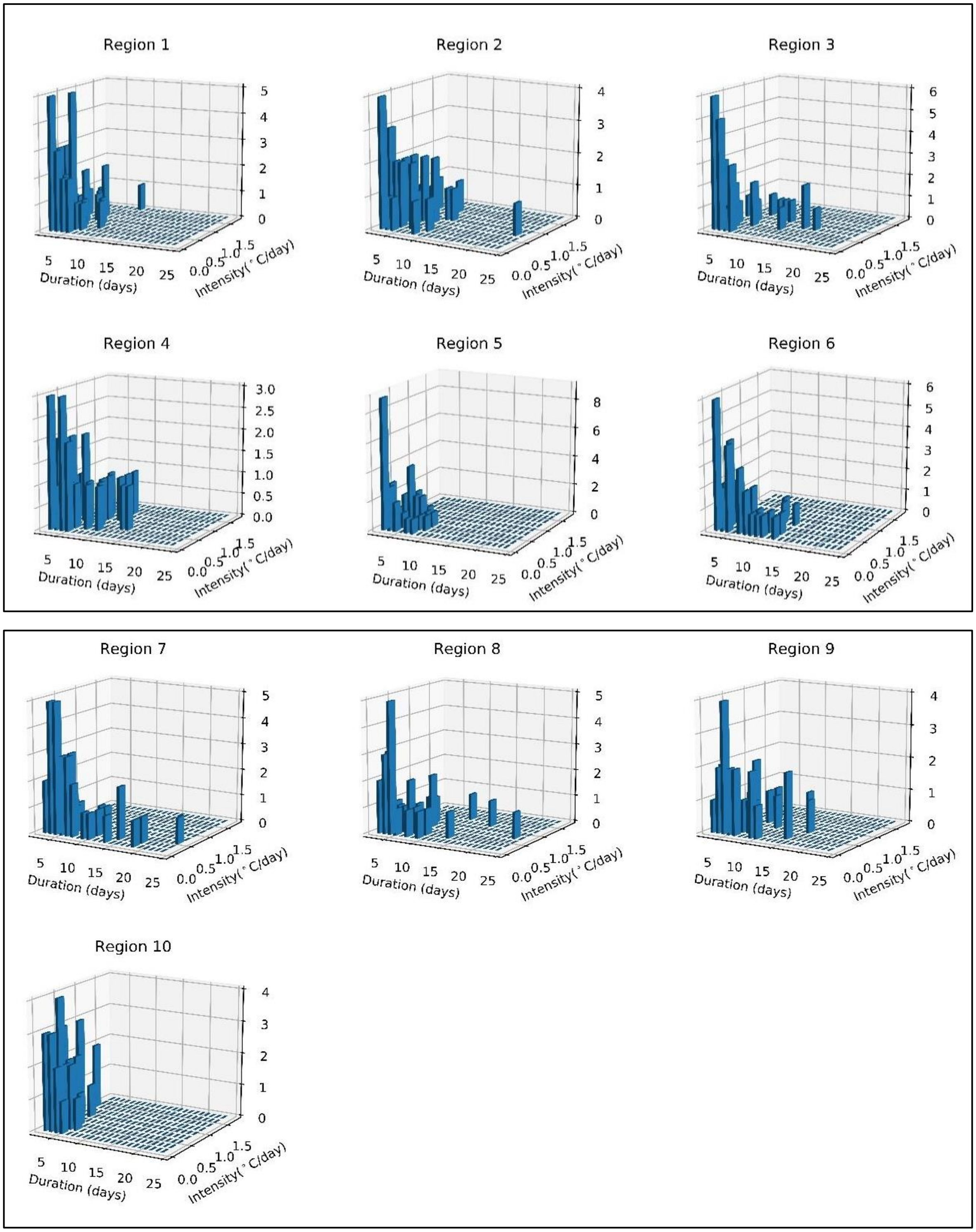

Figure 6. Variation of duration and intensity of heatwaves of different regions (region 1 to region 10) lying inside India

The duration of heatwaves and intensity of droughts (SPI-12) are plotted for each region to establish the relationship between these two variables (Figure 7). The deficiency in precipitation (SPI<0) is found during most of the heatwave events in southern states (region 6, 7), southeastern states (region 8, 9) and northeastern states (region 10) of India. The Pearson correlation coefficient between duration of heatwave and SPI-12, along with its p-value are shown in Table1 for each region. A significant correlation between heatwave duration and drought intensity is observed in Karnataka (region 6), Andhra Pradesh, parts of Tamil Nadu (region 8) and northeastern states (region 10) of India with p-values less than 10 percent

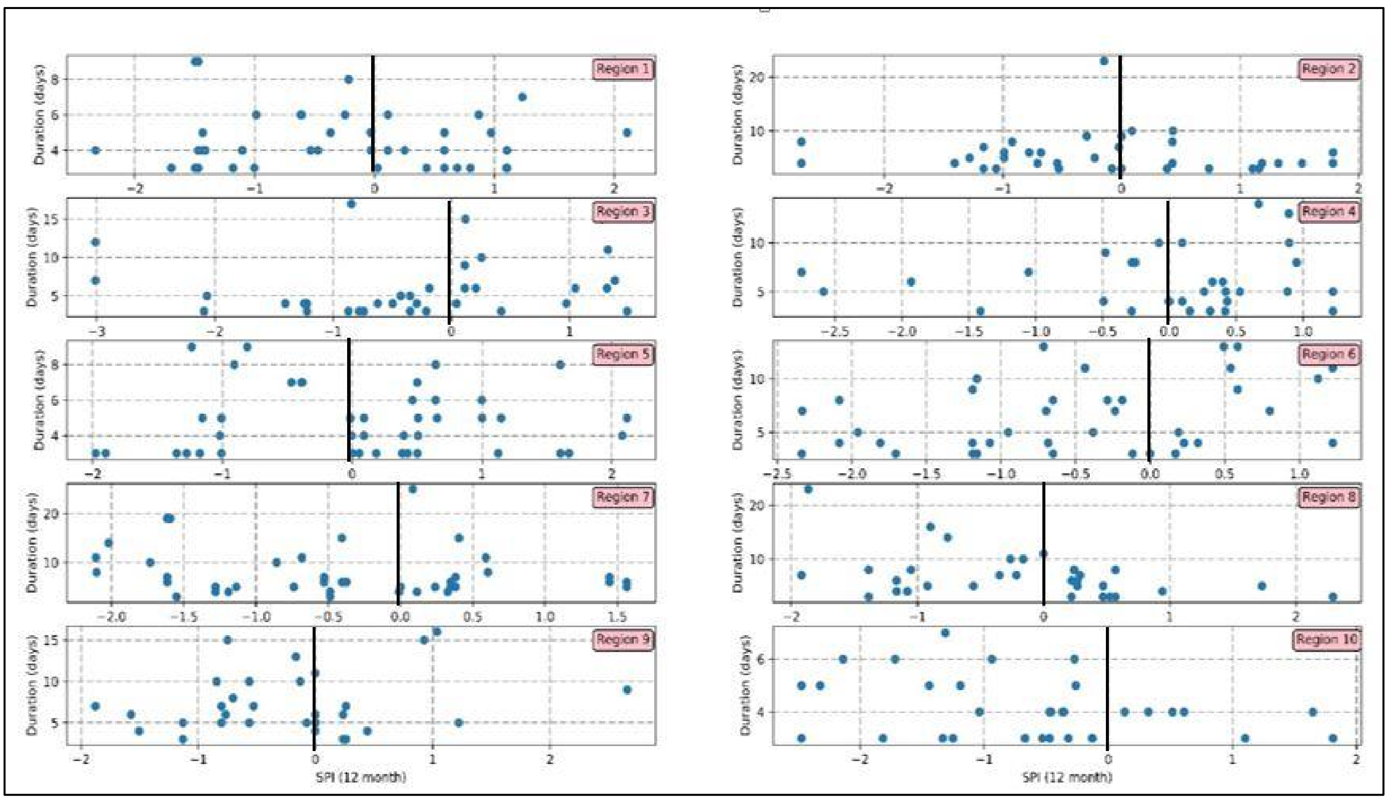

Figure 7. Duration of heatwaves and intensity of drought (SPI-12) for different regions (region 1 to region 10) lying inside India

Table 1. Pearson correlation coefficient between duration of heatwave and SPI-12 along with their p-values of different regions (region1 to region 10) lying inside India

Region no	1	2	3	4	5	6	7	8	9	10
Pearson correlation coefficient	-0.06	-0.08	0.12	0.14	0.01	0.35	-0.19	-0.43	0.22	-0.33
P-value	0.71	0.64	0.49	0.43	0.96	0.03	0.24	0.01	0.23	0.06

Chapter 4

Conclusion and Scope for Future Work

The spatial variation of heatwave characteristics is similar based on both heatwave indices Tmax97.5p and EHF. On an average, one heatwave of duration 5 days occurs every year in north and north western states, Madhya Pradesh, West Bengal and Odisha. States like Chhattisgarh, Telangana and some part of Andhra Pradesh receive lesser number of heatwaves with annual frequency of 0.75 but of higher average duration (around 10 days). For analysis of compound extremes, India is divided into 10 different climatologically homogeneous regions based on concordance of heatwaves. All regions receive rainfall during monsoon season (June-October) and heatwaves during the months of March-June except north and north eastern states of India. Most previous studies considered heatwaves in months of April-May-June only, but our study shows that there are some regions in which heatwaves occur in other months as well. The lesser duration (less than 10 days) and varying intensity (0 to 1.8°C/day) heatwaves occur in north and north eastern states of India while heatwaves of higher duration (10-25 days) and low intensity (0 to 1°C/day) occur in south eastern states of India. A significant correlation between heatwave duration and drought intensity is observed in three regions (region 6, 8, 10) with p-values less than 10 percent.

The joint probability of characteristics of drought and heatwave (e.g., drought intensity, heatwave duration, heatwave intensity), future projection of concurrent droughts and heatwaves, vulnerability of regions due to concurrent droughts and heatwaves are the research areas that need to be studied.

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