Long term climatology and trends of heat and cold waves over southern Bihar, India

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The purpose of this paper is to analyse the trends and variability in extreme temperature indices. We examined climatological distribution of heat and cold waves of two important agro-climatic zones (South Bihar Alluvial Zone-IIIA and B), which is part of the middle Indo-Gangetic Basin and comprising 17 densely populated (1108 persons/km²) districts of Bihar state. We used series of daily maximum and minimum temperature data from 1969 to 2013 of seven stations to calculate temperature indices, from which the trend, occurrence, duration and severity of heat and cold waves were estimated. Results revealed that, in a period of 45 years, zone-IIIA and B has experienced 251/182 and 337/140 average number of heat and cold events, respectively. Although the zone-IIIA on average is experiencing ≥ 8 heat and cold wave days per season, both these high frequency temperature extremes are decreasing at the rate 0.15 and 0.17 per year, respectively, with significance at 95% confidence level. Zone-IIIB on average is experiencing ≤ 5 heat and cold days per season, but heat waves have been found increasing at the rate 0.11 per year, whereas, a non-significant decreasing rate of 0.04/year was observed in cold waves. The study also inferred that heat waves of the month of May in zone-IIIA and of June in zone-IIIB are more frequent, hotter and longer than other months of hot weather period under study, whereas, the cold waves of month January are more frequent and longer, in both zones.

1. Introduction

The amount of damage brought by weather-related natural disasters has skyrocketed in recent decades. Episodes of extreme heat and cold can have serious societal, agricultural, economic, and ecological impacts across the globe, with heat being the leading weather-related killers (National Weather Service 2014). According to the recent IPCC report (IPCC 2012), warm days/nights and their frequency and duration have increased since 1950s and it is projected that there will be more frequent hot temperature and fewer cold temperature extremes over most of the land areas of Asia.

Orlowsky and Seneviratne (2011), Clark *et al.* (2011) and Rajendran and Kitoh (2008) have also reported increases in the number of extremely hot days over East Asia and South Asia. However, the occurrence of cold nights/days are observed to be decreasing at the rate 2.82/2.93 days per decade, with significance at 99.9% confidence level (Kumar *et al.* 2013). Fine resolution projections (at 0.44°) over south Asia, obtained using PRECIS (Providing REgional Climates for Impacts Studies), indicate an increase in temperature extremes towards the end of the twenty-first century for A2 and B2 scenarios using CMIP3 projection (Revadekar *et al.* 2012).

Keywords. Extreme temperature; distribution; occurrence; duration; trend; climatology.

However, different regions are expected to experience differential change in the amount, magnitude and frequency of such extreme weather abnormalities and their impacts (IPCC 2007, 2012). Temperature extremes have profound impact on human society and natural environment (Easterling *et al.* 2000). Computer simulation and experimental studies have amply proved that temperature variability and its extremes increase the risks to crop yields (Porter and Semenov 2005; Chawade *et al.* 2013).

In India, heat wave and cold wave conditions are generally experienced during the period from March to July (hot weather period) and from December to February (cold weather period), respectively. In tune with the global warming trend, a warming trend in the range of 0.8–1°C per century has been observed in India (Kothawale *et al.* 2010, 2012), with an increasing number of hot days, defined as days with daily maximum temperature exceeding the 90th percentile of the time series from 1969 to 2005 (Dash and Mamgain 2011). Northern India shows high occurrence of heat waves, averaging between five and six per year (De *et al.* 2005).

Singh and Patwardhan (2012), while studying the spatio-temporal distribution of extreme weather events in India, for the period 1967–2006 (missing year 1977) found significantly increasing trends in heat and cold waves. Dash and Mamgain (2011), on the contrary, have reported significant decreasing trends in the frequency and spells of cold nights, for the period 1969–2005, in India as a whole and in all the regions in the north, except the western Himalaya. However, a significant increasing trend in the number of warm days in summer has been noticed only in the interior peninsula. In the entire country and on the east and west coasts, the maximum number of warm days in summer has been noticed only during the decade, 1996–2005. Pai *et al.* (2013), linking heat and severe heat waves with the ENSO phenomena, have inferred significant long term increasing trends in heat wave days over India during the analysis period (1961–2010). However, few stations have shown significant decreasing trends in heat waves (two stations from north India and three stations from the east coast) and severe heat waves (two stations from the east coast). In general, the frequency, persistency and area coverage of the heat wave and severe heat days were found to be more than average, during the years succeeding El Nino (El Nino +1) years.

Bihar state in India has been traditionally vulnerable to hydro-meteorological natural disasters, with north Bihar being highly flood-prone and south Bihar being highly drought-prone. The northern and southern regions of Bihar were assessed to be most vulnerable regions to climate changes in the Indo-Gangetic Plains (IGP), owing to high

exposure, high sensitivity and low adaptive capacity of people (Sehgal *et al.* 2013). Weather-related extremes (heat and cold waves, floods, droughts, cyclones) have been a recurrent phenomenon, that affect more than 45% of the geographical area of the state (Economic Survey 2014). Frequent disasters are often attributed to the state's ever increasing population (103.8 million), its growth rate (25.42%/decade) and density (1102 people per km²), which has made the region the second most populous state in India (Economic Survey 2014). The state's poverty headcount ratio (HCR) at 33.7% (highest in India) and the fact that nearly 92.5% of 16.4 million land holdings are of fragmented, small and marginal sizes, further aggravates the problem of environmental degradation (Anonymous 2012).

In this study, the main aim is to use local weather (temperature) information at the district level, of an over 45 years period (1969–2013) to examine the climatology and trends in the occurrence, frequency and duration of heat and cold waves to generate the information at a local level, in order to address the challenges of climate change and its extremes.

2. Data and methodology

Bihar lies in the eastern region of India extending between 25.09N latitude and 85.31E longitude, covering a total area of 94,163 km² and lying at an average altitude of 52.73 m above sea level. Based on soil characterisation, rainfall, temperature and terrain, four main agro-climatic zones in Bihar have been identified, viz., Zone-I (North Alluvial Plain), Zone-II (North East Alluvial Plain), Zone-IIIa (South East Alluvial Plain) and Zone-IIIb, (South West Alluvial Plain), each with its own unique prospects. In this study, we selected zone-IIIa and B, located in the south of river Ganga and comprising of 17 districts with total geographical area of 44875.5 km² (figure 1). Rice, wheat, maize and pulses are grown in these zones as principal agricultural crops. The data used in this study are the daily maximum and minimum temperatures of recent 45 years (1969–2013) of seven meteorological stations lying in agro-climatic zone IIIa and B of south Bihar (figure 1) obtained from the Meteorological Centre, Patna and India Meteorological Department, Pune, where all climatological data of India are processed, quality checked, and archived. At first, daily values of maximum and minimum temperature from all the meteorological station data (available for particular zone) were averaged to represent a particular agro-climatic zone, and in order to derive heat and cold wave information, daily climate normals

Figure 1. Location map of the study area and meteorological stations.

of the maximum and minimum temperatures for the hot weather (March–July) and cold weather (December–February) period were computed using the following equation:

$$\bar{\chi}_i = \frac{\sum_{j=1}^n \chi_{ij}}{n}$$

where $j = 1, 2, \dots, 45$; $i = 1, 2, \dots, 365$ and $n = 45$.

Using these daily climate normals of maximum and minimum temperature data, daily anomalies were computed and using the criteria given in the table 1, days that satisfied the heat wave (HW)/severe heat wave (SHW) and cold wave (CW)/severe cold wave (SCW) conditions were identified. This formed the basic information for examining various climatological features and trends

in the heat and cold event conditions over these two agro-climatic zones in this study. Quinquennial variation in all heat and cold events was examined. For this, the total number of HW/SHW and CW/SCW for each season was computed. The trend and the year-year-changes in the number of heat and cold events in each year during the entire data period (1969–2013) were also examined. For computing trends, simple linear regression method was used.

2.1 Heat wave/severe heat wave and cold wave/severe cold wave definition and features

There is no universal definition of a heat or cold wave, as both temperature extremes vary from region to region depending upon the climate

normals (average of 30 years) of maximum and minimum temperature. Here, we use the definition of heat wave/severe heat wave and cold wave/severe cold wave as per the criteria provided by the IMD (2002), based on maximum and minimum daily temperature thresholds.

2.1.1 Heat wave and severe heat wave

In case a climate normal maximum temperature of a station is $\leq 40^{\circ}\text{C}$, that day is defined as a heat wave day when (1) the day's maximum temperature is at least 5° to 6°C greater than the climate

Table 1. Criteria for HW/SHW and CW/SCW for plain region used in this study (IMD 2002).

Heat event	When the climate normal maximum temperature of a station is $< 40^{\circ}\text{C}$: HW: Departure from climate normal is $+5^{\circ}\text{C}$ to 6°C SHW: Departure from climate normal is $+7^{\circ}\text{C}$ or more When the climate normal maximum temperature of a station is $\geq 40^{\circ}\text{C}$: HW: Departure from climate normal is $+4^{\circ}\text{C}$ to 5°C SHW: Departure from normal is $+6^{\circ}\text{C}$ or more
Cold event	When climate normal minimum temperature is equal to 10°C or more: CW: Departure from climate normal is -5°C to -6°C . SCW: Departure from climate normal is -7°C or less When climate normal minimum temperature is $< 10^{\circ}\text{C}$: CW: Departure from climate normal is -4°C to -5°C . SCW: Departure from climate normal is -6°C or less

Figure 2. Quinquennial variation in heat and cold events over agro-climatic (a) Zone-IIIa and (b) B of Bihar.

normal temperature, and a severe heat day when (2) the day's maximum temperature is at least 7°C greater than the climate normal temperature.

If the climate normal maximum temperature of a station exceeds 40°C, that day is defined as a heat wave day when (1) the day's maximum temperature is at least 4° to 5°C greater than the climate normal temperature and a severe heat day when (2) the day's maximum temperature is at least 6°C greater than the climate normal temperature. If the maximum temperature of a day exceeds 45°C, irrespective of the climate normal maximum temperature of a region, that day is defined as a severe heat wave day.

2.1.2 Cold wave and severe cold wave

For declaring the cold wave situation, wind chill effective minimum temperature (WCTn) factor is taken into account which is defined as the effective minimum temperature due to wind flow. For example, when the minimum temperature is 15°C and the wind speed is 10 mph, WCTn will be 10.5°C.

In case when the climate normal minimum temperature of a station is equal to 10°C or more, that day is defined as a cold wave day when (1) the departure of minimum temperature from climate normal is -5° to -6°C and a severe cold day when (2) when the departure of minimum temperature from climate normal is -7°C or less.

If climate normal minimum temperature of a station is less than 10°C, that day is defined as a cold wave day when (1) the departure of minimum temperature from climate normal is -4° to -5°C and a severe cold day when (2) the departure of minimum temperature from climate normal is -6°C or less.

3. Results

3.1 Heat and cold events (quinquennial variation)

The quinquennial variation of total HW/SHW and CW/SCW days for the nine quinquennials during the period 1969–2013 in agro-climatic zone-IIIa and B of Bihar is shown in figure 2.

Figure 3. Frequency distribution of heat and cold events over agro-climatic (a) Zone-IIIa and (b) B of Bihar.

As seen in figure 2(a), zone-III A, in first three quinquennials (1969–1973, 1974–1978 and 1979–1983), has experienced 140 number of heat wave days, after which the number of heat events has decreased to 63 and 45 days in the middle three quinquennials (1984–1988, 1989–1993 and 1994–1998) and in last three quinquennials (1999–2003, 2004–2008 and 2009–2013), respectively. With respect to cold events, the zone has experienced 121 number of cold events during the first three quinquennials (1969–1973, 1974–1978 and 1979–1983), after which the number of cold events has decreased to 19 days in the middle three quinquennials (1984–1988, 1989–1993 and 1994–1998) and then increased to about 38 days in the last three quinquennials (1999–2003, 2004–2008 and 2009–2013).

Zone-IIIB, in the first three quinquennials (1969–1973, 1974–1978 and 1979–1983) has experienced 106 number of heat events after which the

number of heat episodes has decreased to 92 days in the middle three quinquennials (1984–1988, 1989–1993 and 1994–1998) and has then again increased to about 139 days in the last three quinquennials (1999–2003, 2004–2008 and 2009–2013). With respect to cold events, the zone in first three quinquennials (1969–1973, 1974–1978 and 1979–1983) has experienced 60 number of cold days, which has decreased to 35 days in the middle three quinquennials (1984–1988, 1989–1993 and 1994–1998) and then increased to about 45 days in the last three quinquennials (1999–2003, 2004–2008 and 2009–2013).

3.2 Frequency of heat and cold events

Data on the month-wise distribution of HW/SHW and CW/SCW events of agro-climatic zone-III A and B is shown in figure 3. The results revealed

Figure 4. Duration of heat and cold events over agro-climatic (a) Zone-III A and (b) B of Bihar.

that in zone-IIIA, the month of May is experiencing highest number of HW (92) and SHW (21) spells, followed by the month of June with 51 HW and 18 SHW spells. The months March, April, and July, on the other hand, have experienced lowest number of 17, 38 and 12 HW and 0, 2 and 0 SHW spells, respectively. With respect to the CW events, January and February months are experiencing the maximum number of 77 and 50 CW and 6 and 18 SCW spells, respectively; whereas, December month recorded lowest number of 30 CW and 1 SCW spells.

In zone-IIIB, the month of June is experiencing highest number of HW (96) and SHW (28) spells, followed by May with 100 HW and 10 SHW spells. The months April, March and July, contrastingly, have experienced lowest number of 35, 26 and 26 HW and 2, 10 and 4 SHW spells, respectively. With respect to the CW events, January and February months are experiencing maximum number of 53 and 19 CW and 18 and 22 SCW spells, respectively,

while December month recorded lowest number of 22 CW and 6 SCW spells.

We inferred that probability of maximum number of occurrence of HWs/SHWs remains in the month of May and June for zone-IIIA and B, respectively, than the other months of hot weather period. However, for CWs/SCWs the probability of maximum number of events remains in the months January and February, for both zones.

3.3 Duration and intensification of HW and CW events

Data on duration and intensification of HW and CW events for agro-climatic zone IIIA and B is presented in figures 4 and 5, respectively. In zone-IIIA, HW and CW events have registered an average duration of 4.06 and 3.34 days, whereas, for the characterisation of intensity of HW and CW events, the departure from climate normals of maximum and minimum temperature have been

Figure 5. Intensity of heat and cold events over agro-climatic (a) Zone-IIIA and (b) B of Bihar.

noticed within the range of $+5.0$ to $+9.61^{\circ}\text{C}$ and -4.01 to -9.37°C , respectively. HW events of months May and June were hotter, registering average departures of $+6.15^{\circ}\text{C}$ and $+6.31^{\circ}\text{C}$ from climate normals of maximum temperature and lasting longer with an average duration of 4.0 and 3.60 days, respectively, compared to the other months, viz., March, April, and July, which recorded average departures of $+5.88^{\circ}\text{C}$, $+5.63^{\circ}\text{C}$ and $+5.59^{\circ}\text{C}$ from climate normals of maximum temperature and duration of 4.5, 3.37 and 3 days respectively. The longest heat wave of 11 consecutive days and magnitude (average departure $+6.15^{\circ}\text{C}$ from climate normal maximum temperature) was observed in the month of May. Although heat waves of the month of March has registered a duration of 4.5 days on average, the event has occurred only in 2–3 times in 45 years of study period. We inferred from the study that heat waves of the month of May are more frequent, hotter and longer than the other months of hot weather period under study.

With regard to CW events, January and February months were identified to be more longer

recording an average duration of 3.98 and 3.5 days and colder registering average departure of -4.90°C and -5.63°C from climate normals of minimum temperature respectively, compared to month December which recorded an average duration of 3.0 consecutive days and departure of -4.75°C from climate normals of minimum temperature. The longest cold wave of 9.5 consecutive days with magnitude (average departure -5.18°C from climate normal of minimum temperature) was observed in the month of January.

In zone-IIIB, HW and CW events have registered the duration range of 2–13.5 and 2–15.5 consecutive days, respectively; whereas, for the characterisation of intensity of the HW and CW events, the departure from climate normals of maximum and minimum temperature have been noticed within the range of $+4.58$ to $+10.94^{\circ}\text{C}$ and -4.03 to -10.78°C , respectively.

HW events of the month June were identified to be longer, recording an average duration of 4.2 consecutive days, and hotter, registering an average departure of $+6.18^{\circ}\text{C}$ from climate normals of maximum temperature. This is followed by

Figure 6. Annual trend analysis of heat and cold events over agro-climatic zone-IIIA of Bihar. The trend is significant at 95% level of confidence (P -value 0.007).

Figure 7. Annual trend analysis of heat and cold events over agro-climatic zone-IIIB of Bihar.

the months May, July and April which recorded average durations of 3.1, 3.6 and 3.4 consecutive days and average departures of $+5.47^{\circ}\text{C}$, $+6.07^{\circ}\text{C}$ and $+5.38^{\circ}\text{C}$ from climate normals of maximum temperature. Although HW events of the month of March have registered average duration of 5.4 days and departure of $+6.76^{\circ}\text{C}$ from the climate normal of maximum temperature, the event has occurred less than five times in 45 years of the study period, compared to the months June and May, where HW episodes have occurred 24 times or more.

With respect to the CW events, the month January recorded longer and colder spells exhibiting an average duration of 4.4 consecutive days with an average departure of -5.23°C from climate normals of minimum temperature, followed by the months February and December, which recorded an average of duration of 5.9 and 2.3 consecutive days and registering an average departure of -6.74°C and -5.21°C .

3.4 Trend analysis of HW and CW events

Seasonal trend analysis of total HW and CW records over zone-IIIA is shown in figure 6. The

trend analysis exhibited quite good variation between two zones. Agro-climatic zone-IIIA, on an average, is experiencing ≥ 8 heat and cold wave days per season (hot and cold weather period), but both of these high frequency temperature extremes are decreasing at the rate of 0.15 and 0.17 per year respectively. The decreasing trend was significant at 95% level of confidence.

Whereas, agro-climatic zone-IIIB on an average, is experiencing ≤ 5 heat and coldwave days (hot and cold weather period), but, heat waves have been found increasing at the rate 0.11/year, whereas, non-significant decreasing rate of 0.04/year was observed in cold waves (figure 7).

4. Conclusion

During the period of 45 years (1969–2013), the results gave a well-founded insight into the trend, frequency of occurrence, duration and intensity of HW and CW events in the agro-climatic zone-IIIA and B of south Bihar, India. The zone-IIIA, on average, is experiencing ≥ 9 heat and cold wave days per season, but both these high

frequency temperature extremes are decreasing at the rate 0.15 and 0.17 per year, respectively, indicating decreases in warmer days during hot weather period but increases in warm days during cold weather period, which may cause yield loss in wheat crop of the region.

Zone-IIIB has experienced maximum number of 337 HW events compared to the amount of 248 HW events of zone-IIIA. Although, the region on average is experiencing ≤ 5 HW and CW days per season, HW events have shown increasing trend at the rate 0.11/year, whereas, a non-significant decreasing rate 0.04/year was observed in cold waves. Thus, the result indicates increases in warm days during hot and cold weather period, which may pose an additional threat to the yields under rice–wheat system of the region.

This study further concludes that HW events of May in zone-IIIA and June in zone-IIIB are more frequent, hotter and longer than other months of hot weather period under study, whereas, cold waves of the month of January are more frequent and longer in both zones.

At the same time, however, adaptation to climate extremes serves as a basis for reducing vulnerability to long term climate change and its associated risks. Some of the strategies developed to manage year-to-year climate variability can go a long way towards building resilience and managing the risks of climate. Some of the strategies which have been tasted under local conditions to mitigate the heat stress are (1) Adjustment of planting dates (early or late sowing) to avoid heat stress during flowering and maturity of crop. (2) Some of candidate genotypes like ‘Sabour Shrestha’, DWB107 and DWB14 in wheat (average yield potential of 4.0–4.3 tonnes per hectare) and ‘Sabour Ardhjal’, ‘BRR0006’ in rice crop (average yield potential of 5.0–5.3 tonnes per hectare) have been tested and were found best for resilience to heat and drought stress. (3) Application of potassium nitrate (KNO_3) at the rate 0.5% at boot-to-anthesis stage of wheat crop (sown under late conditions: 15–30 December) has been found effective in mitigating higher temperature stress. Using long term local weather data for identifying consequences of climate change like extreme weather events and its effects of local environment needs immediate attention for effective agricultural planning and its management.

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