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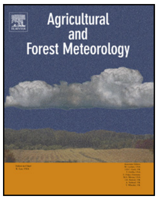

Spatial analysis of the sensitivity of wheat yields to temperature in India

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ABSTRACT

Over large wheat growing areas of India, a rise in minimum temperature (T_n) is occurring at a faster rate (@ 0.32 °C 10 yr^{-1}) than maximum temperature (T_x) (@ 0.28 °C 10 yr^{-1}). During February, coinciding with post-anthesis period of wheat, about 79.4% area showed significant warming in T_n (@ 0.37 °C 10 yr^{-1}) for 1970–2012 period. Indian wheat yields were observed to be prone to continual heat stress and especially to short-term temperature extremes. Wheat yields appear to be becoming more sensitive to T_n, especially during post-anthesis period. Mean wheat yields for the period 1980–2011 declined by 7% (204 kg ha^{-1}) for a 1 °C rise in T_n. Exposure to continual T_n exceeding 12 °C for 6 days and terminal heat stress with T_x exceeding 34 °C for 7 days during post-anthesis period are the other thermal constraints in achieving high productivity. Improved understanding from this study on the role of T_n during post-anthesis period may further reduce the uncertainties in anthropogenic climate change assessments on Indian wheat yields. There is a need to consider inclusion of early maturing, high yielding and heat tolerant wheat lines in the breeding program for Indian conditions. Thermally sensitive areas evolved from this study may guide the researchers to identify such wheat lines for their adaptability in to future climates.

1. Introduction

Wheat is the most important food crop of India during the post-rainy i.e., *rabi* (November–March) season grown over 30 million ha (58% of the net cropped area during *rabi*) with a production of 94 million tons and contributing about 43% to the country's granary. India is the second largest producer of wheat after China with about 12% share in global wheat production. With 91.3% of its area under assured irrigation in more than 200 districts (DACNET, 2013) that are largely (93.5%) confined to states like Uttar Pradesh, Madhya Pradesh, Punjab, Haryana, Rajasthan, Bihar, Maharashtra and Gujarat, wheat productivity had a quantum jump from 770 kg ha^{-1} in 1950–1951 to 3140 kg ha^{-1} in 2011–2012. In the very recent decade (2000–2009) its productivity oscillated in the range of 2590 and 3140 kg ha^{-1}, despite large area under irrigation. To maintain self-sufficiency, annual production of wheat and rice needs to increase by 2 million tons every year (Bhalla et al., 1999). Contrary to this requirement, Ray et al. (2013) in a recent study observed decreasing wheat yields in many areas of India and on a national basis the yield growth rate is 1.1% per year only, which is less than the required rate to double production by 2050.

The recent report of the IPCC and a few other global studies indicate a probability of 10–40% loss in Indian food grain production with an increase in temperature by 2080–2100 (Fischer et al., 2002; Parry et al., 2004; IPCC, 2007). The increase in temperatures and increased variability of rainfall would considerably affect food production despite the beneficial effects of higher CO_2 on several crops. These estimates generally assume business as usual scenario, no new technology development, and no or limited adaptation by all stakeholders. Many of the Indian studies on this theme generally confirm a similar trend of decline in wheat yields with climate change (Aggarwal and Sinha, 1993; Rao and Sinha, 1994; Lal et al., 1998; Aggarwal, 2003; Nagarajan, 2005; Aggarwal et al., 2010; Subash and Ram Mohan, 2012).

Studies suggesting the adverse impacts of temperature on wheat yields (Lobell and Field, 2007) stimulated interest to quantify the responses and to assess these effects in regulating the crop duration (Challinor and Wheeler, 2008) and productivity (You et al., 2009; Li et al., 2010). Recent studies carried out in India indicate the possible loss of 4–5 million tonnes in wheat production with every 1 °C rise in temperature, even after considering carbon fertilization but no other adaptation benefits and changes in irrigation water availability (Aggarwal, 2008).

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Notwithstanding the future temperature projections, temperature extremes in recent years were found to cause considerable yield declines. Samra et al. (2012) studied the role of temperature in regulating the wheat productivity in India and as an example, analyzed the yields of Ludhiana district, Indian Punjab. Cold wave conditions that prevailed during *rabi* 2010–2011 and 2011–2012 coincided with flowering and seed formation stage of wheat. Over a 12 year period, 8 years were normal, two each were with heat and cold waves. Their spectral density analysis indicated that temperature during wheat growing seasons of 2010–2011 and 2011–2012 were significantly lower than normal. They noticed an average yield loss of 217 kg ha^{-1} (4.5%) during a heat wave year and a gain of 356 kg ha^{-1} (7.4%) during a cold wave year. Between the two recent continuous cold wave years, productivity gain in the Punjab state, in the relatively colder year (2011–2012) was higher by 400 kg ha^{-1}.

Indian wheat yields were also observed to be more prone to short-term temperature extremes (Lobell et al., 2012). Senescence gets accelerated due to heat extremes, above and beyond the influence of increased average temperatures. For instance, a sudden rise in temperature during March 2010 caused significant wheat yield reductions over the Indo-Gangetic Plains (IGP) (Gupta et al., 2010). This calls for a better understanding of the impacts of increased mean seasonal temperatures, especially minimum or night temperature (Peng et al., 2004; Nagarajan et al., 2010; Welch et al., 2010) as well as impacts of short term extreme temperatures (Wheeler et al., 2000). Regional studies are also critical to determine the optimum and ceiling temperatures for yield formation and large scale varietal response to optimum and ceiling temperatures. Recent regional studies in China (You et al., 2009; Li et al., 2010) and Central Asia (Sommer et al., 2013) strengthened the necessity to understand the associations between regional temperature and wheat yield at different spatial scales, but this topic is still little researched for Indian climatic conditions. Northern part of Indian sub-continent that includes IGP has been placed under high risk zone for heat stress risk in future climates (Teixeira et al., 2013).

In this backdrop, we have examined the spatial variability and trends in temperature over major wheat growing districts in India and presented in Section 3.1 maximum temperature (T_x), 3.2 minimum temperature (T_n) and 3.3 diurnal temperature range (T_r). The correlation between wheat yield and temperature at the district level was analyzed in Section 3.4. We tried to detect the optimum and critical ranges in temperature variables during the sensitive crop growth stages which may ultimately help the planners and breeders to evolve suitable strategies. The response of wheat to the magnitude and duration of temperature extremes is shown in Section 3.4.1. Finally, we concluded with a summary and policy implications in Section 4.

2. Data and methodology

2.1. Temperature

All the previous studies on temperature trends in India (Hingane et al., 1985; Arora et al., 2005; Kothawale et al., 2010a,b) assumed that each station or a group of stations makes homogenous region and inferences were drawn accordingly. However, we opted in this study for a finer resolution data representing the entire country. In most of the earlier studies, region-wise trends in temperature were considered. However, we report here trends in temperature, district wise, which is an important administrative unit in India for implementing any strategy at field level.

Monthly surface temperature data of the Climate Research Unit (CRU), University of East Anglia, UK were sourced for 0.5 °C grid sizes for the period 1970–2012 (Harris et al., 2014). Data were downloaded and masked to our analysis domain (6.25 to 38.75°N and 66.75 to 100.75°E). We preferred this data source to the National Data Center (NDC), India Meteorological Department (IMD), Pune's 1° x 1° data because it is a flag product that several researchers (Rupa Kumar et al., 2006; Ravindranath et al., 2006) and government agencies (BCCI-K, 2011) used for climate change impact studies for Indian conditions and climate- wheat studies (You et al., 2009; Li et al., 2010) and it is available at finer resolution of 0.5°. Daily temperature data were sourced from NDC IMD which is available at 1° resolution. Area weighted temperature for each wheat growing district was computed considering the number of grids falling in that district. Influential area of a grid was computed using the Thiessen polygon method in a GIS environment. Area of different polygons falling in a district was derived in GIS environment. T_x, T_n and T_r of a district was computed by using a weighted average of temperature, with weights proportional to area of polygons falling in a district. Later these data at district level were segregated into means for individual months for the period November to March, and as a seasonal mean for November to March. In an earlier study, we observed that during October to March period, T_n is rising by 0.28 °C 10 yr^{-1} over 54.9% of the geographical area in India (Bapuji Rao et al., 2014). To detect warming in the wheat growing areas in the three temperature variables, Mann–Kendall's test, which is a widely used method for the analysis of trends in climatological (Mavromatis and Stathis, 2011) and hydrological time series (Yue and Wang, 2004) was used to detect any trend in the temperatures for each wheat growing district. The significance in the trend was detected by two tailed test at different probability levels (0.1, 0.05 and 0.01). Each district was classified as slightly warm, moderately warm and strongly warm based on the level of significance i.e., 0.1, 0.05 and 0.01, respectively, and placed in respective clusters. Values of temperature variables of different districts in each cluster were aggregated to arrive at the mean value of that cluster or region.

2.2. Crop data

Triticum aestivum occupies 95% of area, *T. durum* and *T. dicocum* have been grown over 4% and 1% of area, respectively. Uttar Pradesh, Madhya Pradesh, Punjab, Haryana, Rajasthan, Bihar, Maharashtra and Gujarat states contribute to 94.5% area of wheat grown in India. We considered the wheat growing districts from these states alone and thus our sample area represents 94% of the wheat growing region in India. We used historical wheat statistics to assess the association between wheat yields and temperature variations in the wheat growing districts. Data on district-wise wheat yields for the period 1980–2011 were sourced from Center for Monitoring Indian Economy (http://commodities.cmie.com). District-wise yields are generally estimated through several hundred crop cutting experiments conducted in each season and district within General Crop Estimation Surveys (GCESs). Since continuous yield data was not available for all wheat growing districts, 215 districts for which continuous data was available and where wheat is a major crop, were considered thus making our sampling area representing approximately 94% of the wheat growing region.

Time series yield data may feature strong trends that mask seasonal fluctuations likely to be associated with year on year variations in climate. Researchers have isolated these seasonal fluctuations by fitting and removing trends with polynomial and other parametric functions. For example, Parthasarathy et al. (1992) employed an exponential function to filter the All India Food Grain Production Statistics. To evaluate the relationship between the time series for yield and temperature, we opted for a commonly used approach (Nicholls, 1997; Lobell et al., 2005; Lobell et al., 2007; Li et al., 2010) which is based on the first-difference time series for yield and temperature (i.e. the difference in values from one year to the next). The use of first differences minimizes the influence of slowly changing factors such as crop management (Lobell and Field, 2007).

The information on the region specific growing season for wheat was obtained from http://farmer.gov.in/cropstaticswheat.html. Across the regions, wheat season starts from November 1st fortnight (normal sown) to December 1st fortnight (late sown). Growing season ends by March 2nd fortnight (normal sown) to April 1st fortnight (late sown). We considered November to March as the average growing season (sowing to maturity) for wheat for our analysis domain. Then, the growing season temperatures were worked out for different districts by averaging the monthly temperatures for the period 1980–2011 matching with crop yields' datum. Pearson's correlations were calculated for the detrended yield and temperature variables. Districts were segregated into respective clusters based on the level of significance (0.05%, one-tailed) test for correlation. Further, correlations were done between monthly temperatures and wheat yields to detect the most sensitive period to a change in temperature variables in the crop's life cycle. We then performed multiple linear regressions with 'first differences in yield' as the response variable, and the 'first differences of temperature variables' as predictor variables to determine the relative change in yield with a change in temperature variables in those clusters which are statistically significant.

3. Results and discussion:

3.1. Maximum temperature (T_x)

Mean growing season T_x ranged from 20.2 °C to 32.3 °C across the wheat growing areas. Among different months January experienced lowest T_x (24.0 °C) and we got highest T_x during March (32.3 °C). Time trend analysis showed that seasonal T_x increased significantly over 92.4% of the wheat growing area (183 districts) (Fig. 1a). The rate of increase in seasonal T_x in the slightly warm region ($p < 0.10$) spread over 8 districts, which constituted 2.4% of wheat growing area, was 0.19 °C 10 yr^{-1} (Tables 1a and 2a). The trend was significant at 5 and 1% levels over 6.7 and 83.3% of wheat area (18 and 157 districts), respectively. In the moderately warm and strongly warm regions, the rise in T_x was @ 0.22 and 0.33 °C 10 yr^{-1}, respectively (Table 2a). The trend was insignificant over the remaining 7.6% of the wheat area spread in 32 districts, mostly confined to Punjab, Haryana and western parts of Uttar Pradesh. During wheat growing season T_x increased over the entire area @ 0.28 °C 10 yr^{-1} (Table 2a). During November T_x rose @ 0.29 10 yr^{-1} over the domain area and about 53.6% area (112 districts) showed a rise 0.43 °C 10 yr^{-1} ($p < 0.01$) (Fig. 1b; Tables 1a and 2a). Mean monthly T_x over the wheat growing areas when subjected to trend detection, show that highest rise in T_x was significant at $p < 0.01$ during December over 65.0% of area (131 districts) (@ 0.38 °C 10 yr^{-1}) (Fig. 1c and Table 2a). A steep rise in T_x over different months was noticed during February (@ 0.53 °C 10 yr^{-1}). However, the extent of area under this warming category was 19.8% only. Warming was moderate during February and January over 48.4 and 5.9% area (85 and 13 districts) and proceeded @ 0.37 and 0.24 °C 10 yr^{-1}, respectively (Fig. 1d and e; Table 2a). A decrease in T_x is only noticed during January over 4.7% of the area (sum of 21 districts over three levels of significance) and in December over 0.12% area (one district). We tried to figure out the reason for the absence of any trends in temperature during the month of January. In India, western disturbances caused by meso-scale phenomena brings winter and pre-monsoon season rainfall across wheat growing regions and normally four—five western disturbances in a month cross over. They effect wheat growing environment through cloudy skies, higher night temperatures and, unusual rains. Over the Indo-Gangetic plains, they create cold wave conditions and occasionally dense fog and cold day conditions. No definite reason could be ascribed to the absence of any trend over considerable area during the month of January compared to other months, however it would be worth to study the changes in frequency of western disturbances crossing over India during post-monsoon season.

3.2. Minimum temperature (T_n)

Growing season mean T_n ranged from 6.8 to 19.2 °C across the wheat growing areas. Among the different months January experienced lowest T_n (9.5 °C) and highest T_n was during March (16.4 °C). Time trend analysis showed that seasonal T_n is increasing over 93.7% of wheat growing area (as the sum of three levels of significance) @ 0.32 °C 10 yr^{-1} (Fig. 2a and Table 2b). This rise is 0.04 °C 10 yr^{-1} greater than a rise in T_x. Strong warming ($p < 0.01$) was noticed in T_n @ 0.35 °C 10 yr^{-1} over 69.6% of the wheat growing area (157 districts). Moderate (0.25 °C 10 yr^{-1}) ($p < 0.05$) and slight (0.23 °C 10 yr^{-1}) ($p < 0.1$) rise in T_n was noticed over 18.1 and 6.0% of wheat area (39 and 12 districts), respectively (Fig. 2a; Table 1b and 2b). The trend was insignificant over 6.4% of area (seven districts) only. This implies that nighttime warming is occurring at a faster rate covering large areas than daytime warming. Over most of the wheat growing regions in India, wheat reaches anthesis stage by the end of January and crop duration after January is considered as post-anthesis period. Trend analysis of monthly T_n showed that the rise was strong ($p < 0.01$) @ 0.48 °C 10 yr^{-1} during February i.e., during post-anthesis period over 32.8% area (89 districts) (Fig. 2b–f) (Table 2b). During this month moderate (@ 0.35 °C) and slight warming (@ 0.29 °C) was noticed over 38.5 and 8.1% area (73 and 17 districts), respectively. Thus, the total area showing significant warming trend forms about 79.4% of entire wheat growing area. During March, 42.3% area (90 districts) showed strong warming. However, when all the classes were put together November ranked first with 88.3% area (192 districts) showing a rise in T_n (Fig. 2b–f and Table 2b). No area showed a decreasing trend in T_n.

3.3. Diurnal temperature range (T_r)

It is the difference between T_x and T_n and indicates the temperature extremes to which the crop is subjected on a daily basis during the growing season. Mean growing season T_r ranged from 10.8 °C to 17.6 °C across the wheat growing areas. Among the different months January experiences lowest T_r (15.3 °C) and highest T_r was during March (15.9 °C). Time trend analysis over the entire wheat growing region showed that changes in T_r on a seasonal basis is decreased @ 0.04 °C 10 yr^{-1}, which was not statistically significant (Table 2c). Among the different months, November alone showed a distinct decrease in T_r over an area of 18.1%. In about 9.5% and 8.6% of the area in 26 and 36 districts respectively, the decrease in T_r was slight to moderate ($p < 0.1$ and $p < 0.05$, respectively) (Table 1c). Historical observations revealed a substantial decreasing trend in the global mean T_r for 1950–1990 period, which was attributed to T_n rising faster than T_x (Easterling et al., 1997; Vose et al., 2005). Many climate models in the past have projected further significant changes in T_r (Stone and Weaver, 2003; Lobell et al., 2007). These projections seem to come close to reality in wheat growing areas of India with T_n rising faster than T_x resulting into a decrease in T_r. A shrinking in the cool period for wheat crop and increased threat of terminal heat stress has already been observed in major wheat growing areas in India (Rane et al., 2000; Sharma et al., 2002).

3.4. Sensitivity of wheat yields

Considerable experimental work exists on wheat response to extreme conditions and on the relationship of wheat growth and development with extreme temperatures (both high and low).

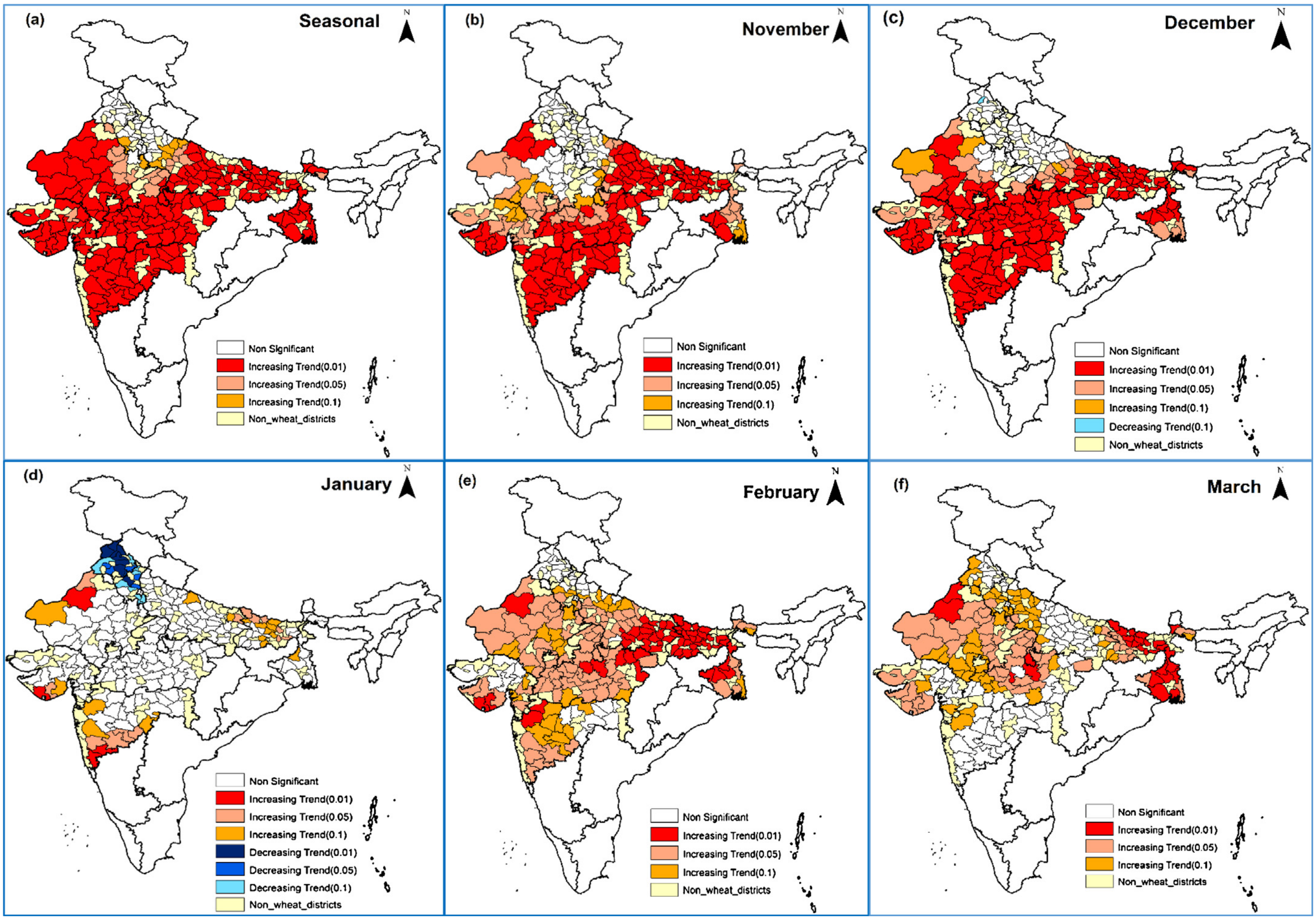

Fig. 1. Trends in seasonal (November–March) and monthly T_x in wheat growing districts (Un-shaded areas without district boundaries are not considered) (Shaded areas indicate either positive or negative trends at different significance levels and un-shaded with district boundaries indicate non-significant trends).

Table 1
Wheat growing area (per cent of total) and number of districts showing increasing/decreasing trends in (a) T_x (b) T_n and (c) T_r at different levels of significance.

(a) Maximum temperature						
Level of Significance	Seasonal *	November	December	January	February	March
1% (Increase)	83.3 (157)	53.6 (112)	65.0 (131)	4.0 (4)	19.8 (58)	11.0 (28)
5% (Increase)	6.7 (18)	19.6 (34)	14.9 (26)	5.9 (13)	48.4 (85)	31.9 (53)
10% (Increase)	2.4 (8)	6.7 (15)	4.6 (3)	9.4 (16)	15.6 (32)	19(50)
NS	7.6 (32)	20.1 (54)	15.5 (54)	76(161)	16.2 (40)	38.1 (84)
10% (Decrease)	0.0	0.0	0.0	2.2 (8)	0.0	0.0
5% (Decrease)	0.0	0.0	0.0	0.8 (5)	0.0	0.0
1% (Decrease)	0.0	0.0	0.12 (1)	1.7 (8)	0.0	0.0
(b) Minimum temperature						
Level of Significance	Seasonal *	November	December	January	February	March
1% (Increase)	69.6 (157)	37.9 (105)	50.0 (109)	3.4 (7)	32.8 (89)	42.3 (90)
5% (Increase)	18.1 (39)	32.1 (57)	26.7 (44)	8.1 (24)	38.5 (73)	24.3 (62)
10% (Increase)	6.0 (12)	18.3 (30)	9.7 (20)	4.0 (8)	8.1 (17)	7.9 (22)
NS	6.4 (7)	11.7 (23)	13.7 (42)	84.6(176)	20.7 (36)	25.6 (41)
(c) Diurnal temperature range						
Level of Significance	Seasonal *	November	December	January	February	March
10% (Increase)	0.0	0.0	0.0	0.0	1.5 (2)	0.0
1% (Decrease)	0.0	0.0	0.0	0.0	0.0	0.0
5% (Decrease)	0.8 (4)	8.6 (36)	1.0 (5)	0.7 (3)	0.0	0.0
10% (Decrease)	3.1 (7)	9.5 (26)	1.5 (7)	1.1 (5)	0.0	0.0
NS	96.2 (204)	81.9 (153)	97.5 (203)	98.2 (207)	98.5 (213)	100(215)

(*Seasonal – Mean of November to March period); (**Figures in the parenthesis are number of districts).

Table 2
Magnitude of change in temperature variables (°C yr^{-1}) at different levels of significance.

(a) Maximum temperature

Level of Significance	Seasonal [*]	November	December	January	February	March
1% (Increase)	0.33	0.43	0.38	0.25	0.53	0.42
5% (Increase)	0.22	0.27	0.26	0.24	0.37	0.37
10% (Increase)	0.19	0.21	0.26	0.21	0.30	0.32
10% (Decrease)	–	–	−0.13	−0.19	–	–
5% (Decrease)	–	–	–	−0.24	–	–
1% (Decrease)	–	–	–	−0.32	–	–
Mean of all districts	0.28	0.29	0.28	0.07	0.38	0.30

(b) Minimum temperature

Level of Significance	Seasonal [*]	November	December	January	February	March
1% (Increase)	0.35	0.45	0.40	0.25	0.48	0.46
5% (Increase)	0.25	0.28	0.31	0.24	0.35	0.34
10% (Increase)	0.23	0.27	0.26	0.09	0.29	0.28
Mean of all districts	0.32	0.36	0.31	0.08	0.37	0.35

(c) Diurnal temperature range

Level of Significance	Seasonal [*]	November	December	January	February	March
10% (Increase)	–	–	–	–	0.12	–
5% (Decrease)	−0.16	−0.03	−0.18	−0.21	–	–
10% (Decrease)	−0.15	−0.19	−0.17	−0.17	–	–
Mean of all districts	−0.04	−0.09	−0.03	−0.01	0.00	0.00

([*] Seasonal – Mean of November to March period).

Temperatures above 31 °C for 5 days prior to anthesis reduces grain yield by inducting pollen sterility, thus reducing grain numbers (Wheeler et al., 1996a,b). Similarly, Tashiro and Wardlaw (1990) found that temperatures of 36 °C during the day and 31 °C at night just before anthesis resulted in many sterile grains. Together, these results suggest 31 °C as T_x threshold value during the period immediately before anthesis. A few days later (after 50% anthesis), when half of the ears in a population have flowered, a temperature of 27 °C

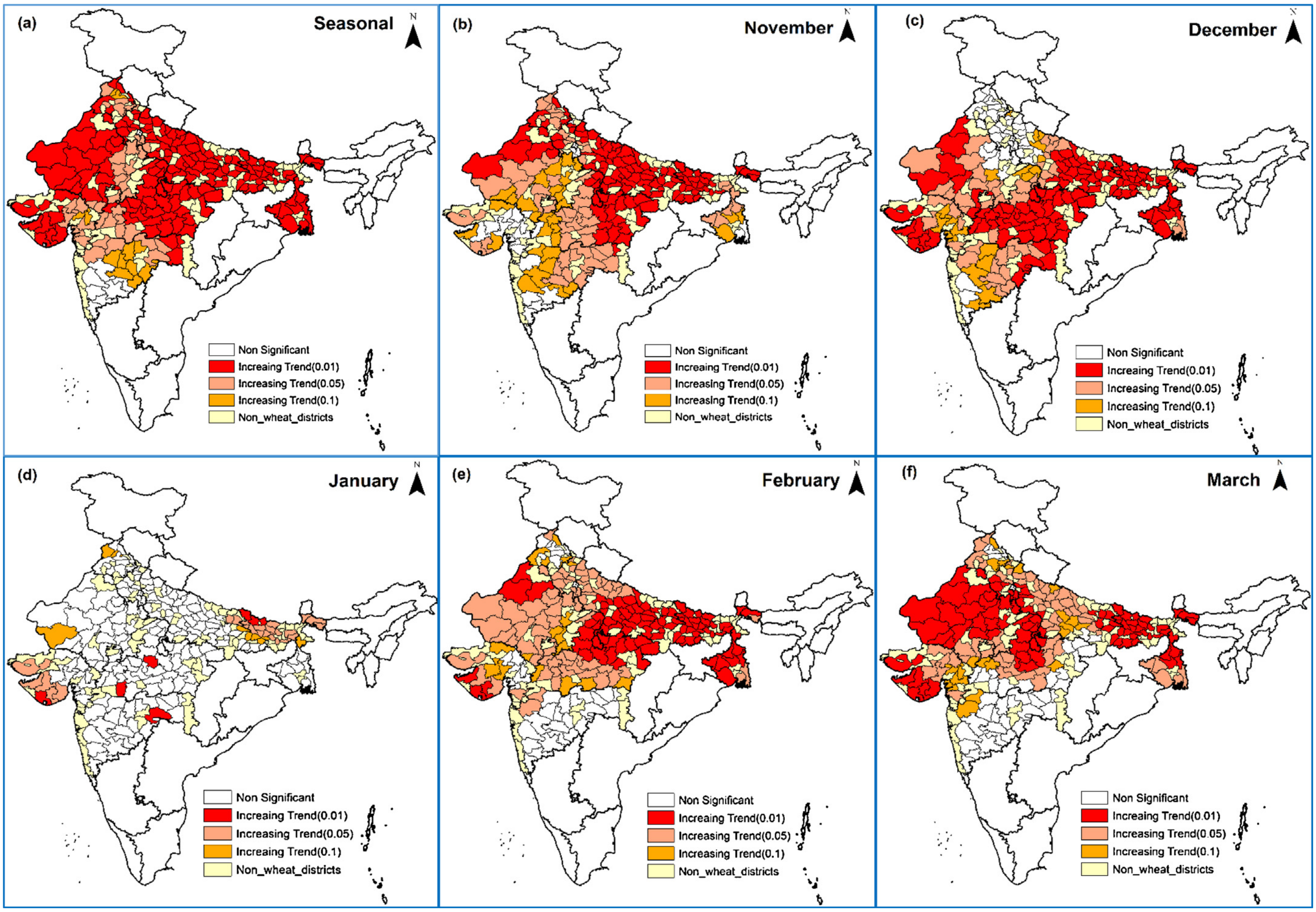

Fig. 2. Trends in seasonal (November–March) and monthly T_n in wheat growing districts (Un-shaded areas without district boundaries are not considered) (Shaded areas indicate either positive or negative trends at different significance levels and un-shaded with district boundaries indicate non-significant trends).

also results in a high proportion of sterile grains (Wheeler et al., 1996a,b). Exposure to sub- or super-optimal temperatures during anthesis may also reduce yields through the production of infertile florets (Russell and Wilson, 1994). MacDowell (1973), Russell and Wilson, 1994 considered T_n between 18 and 24 °C as optimum for the period around anthesis and temperatures higher than 31 °C or lower than 9 °C during anthesis were considered as the limits for successful anthesis. Stone et al. (1995) also showed that a short-but-early extreme heat treatment reduces grain growth to a greater extent than much longer periods of moderately high temperatures. The timing of heat event during grain-filling appears to be important, particularly exerting influence on grain quality via the accumulation of protein.

Majority of the above studies were carried out under regulated temperature conditions in growth chambers. Very few studies are available on temperature sensitiveness of Indian wheat varieties. Breeding efforts to overcome the continual and terminal high temperature stresses in South Asia, including India are of recent origin (Rane et al., 2002; Chatrath et al., 2007; Joshi et al., 2007; Mondal et al., 2013). Lobell et al. (2012) used satellite measurements of wheat growth in northern India to monitor rates of wheat senescence following exposure to temperatures exceeding 34 °C. They detected a statistically significant acceleration of senescence caused due to extreme heat and felt that warming presents greater challenge to wheat than applied by model simulations. Limited regional studies on the wheat response to temperature in Indian conditions have led us to examine the influence of rise in temperature at district level on the corresponding wheat yields. Correlations worked out between temperatures and wheat yields are shown in Fig. 3. Growing season T_x showed a negative association with yields over 162 districts (81.3% area) and of these wheat yields over 58 districts (35.5% area) showed a significant negative association with T_x (Fig. 3a). T_x of January and February had a significant negative association with 78 (43% area) and 54 (20% area) districts wheat yields, respectively. A significant and positive influence of seasonal T_x was noticed over a small area (7 districts and 2.6% area). This may be due to either cultivars being grown are less susceptible or prevalence of T_x lower than the cultivars' optimum. Of all the months, T_x of March showed a significant negative association over small area confined to western parts of the country, mainly in the state of Rajasthan, a region that experiences a relatively warm climate.

About 52% variance in year-to-year changes in wheat yields was explained by T_n. Significant negative association with T_n in 77 districts (42.7% of the area) was noticed compared to seasonal T_x (58 districts; 35.5% of the area) as seen in (Fig. 5a). Wheat yields over 7.2% more geographical area are influenced by T_n compared to T_x. Among different months, T_n during February has considerable area (79.2%) showing negative association with district wheat yields (Fig. 3d). January is another month, which has large area (86.7%) showing negative association. T_n of November and December could exert negative impact to a limited extent. Wheat yields from the more geographical area showing negative correlation with T_n in comparison with T_x is an indicator of role of nighttime warming. This has led us to regress district yields on temperature variables only for those districts where the correlations were negatively significant ($p < 0.05$) (Fig. 4). Best fitted models' statistics also provided most of the explanatory power with seasonal T_n (Table 4). We observed a mean yield decline of 204 kg ha^{-1} with 1 °C rise in T_n. This is approximately 7% of Indian wheat yields. You et al. (2009) found reduced wheat yields in the range of 3–10% with a 1 °C increase in wheat growing season temperature. The rising temperature from 1979 to 2000 reduced the wheat yield growth in China by 4.5%. However, they did not consider the individual effects of T_x, T_n or T_r. Lobell et al. (2005) observed a 10% yield reduction in wheat

Table 3a
Wheat growing area (%) that exhibited negative association with T_n and T_x of varying degrees.

Nature of association	T_n (°C) exceeding											T_x (°C) exceeding						
	6	7	8	9	10	11	12	13	14	15	16	30	31	32	33	34	35	36
Significantly negative	2.8	3.3	7.1	9	8.2	14.2	15.6	13.6	12.8	13.1	9.8	7.1	8	5.7	5	8.1	5.5	4.3
Negative but non-significant	30.2	28.5	42.6	48.9	52.4	44.8	48.5	45.6	45.6	46.8	50	46.4	41.9	44	47.4	47.7	35.1	27
Negative (Significant + Non-significant)	33	31.8	49.7	57.9	60.6	59	64.1	59.2	58.4	59.9	59.8	53.5	49.9	49.7	52.4	55.8	40.6	31.3

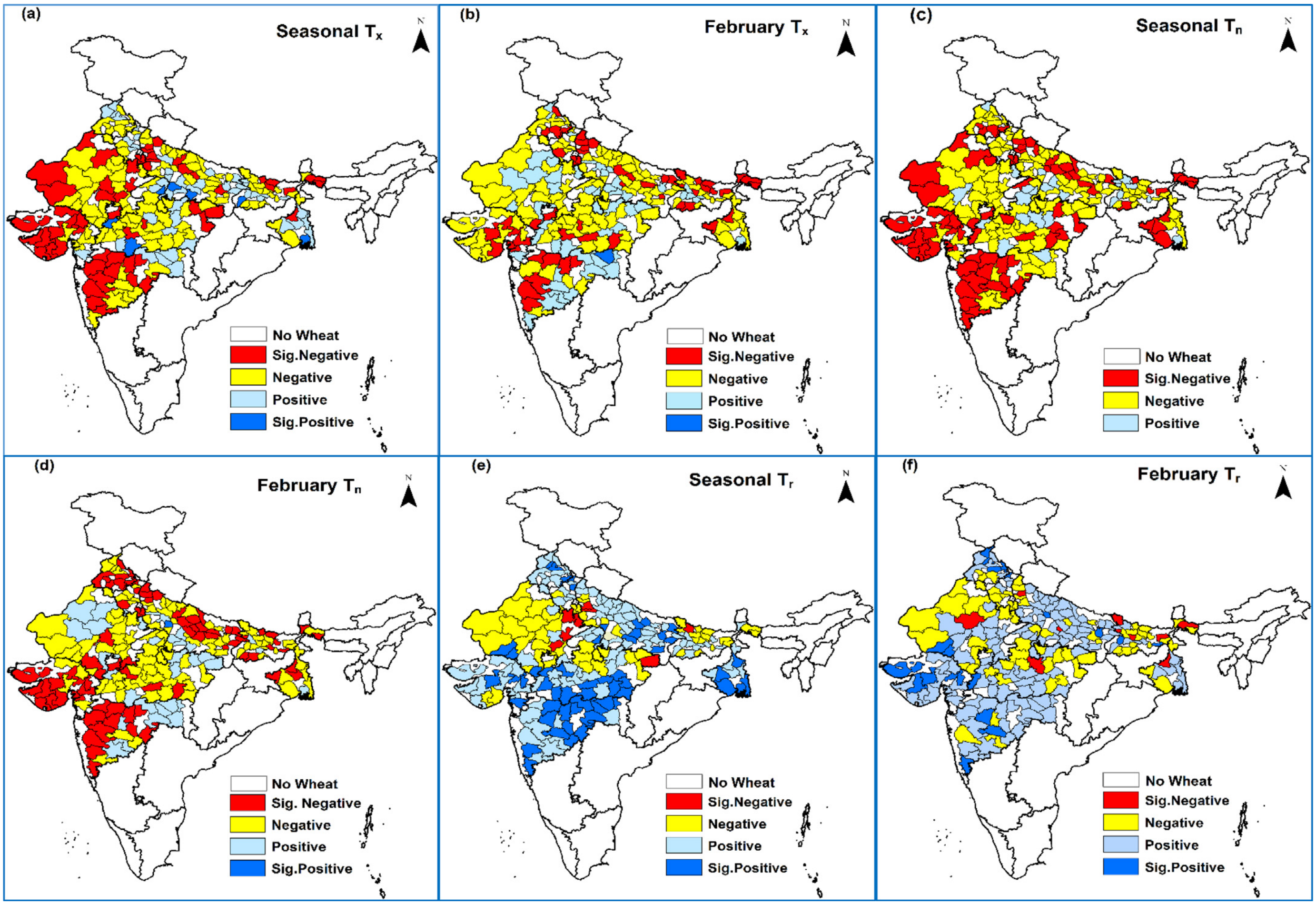

Fig. 3. Correlation between district wheat yields and (a) Seasonal (November–March) T_x;(b) February T_x; (c) Seasonal T_n; (d) February T_n; (e) Seasonal T_r; (f) February T_r (Un-shaded areas without district boundaries are not considered) (Shaded areas indicate either positive or negative association and un-shaded with district boundaries indicate non-significant association).

yields of Mexico with a 1 °C rise in T_n but a much smaller and statistically insignificant effect of T_x and solar radiation. An increase in T_r may benefit yields in crops where development or grain filling rates are more sensitive to T_n than T_x (Wilkens and Singh, 2001). A few studies indicate the negative impact of increased T_r on wheat yields (Rosenzweig and Tubiello, 1996; Dhakhwa and Campbell, 1998 Lobell et al., 2005; Lobell and Ortiz-Monsterio, 2007). But in our study, only 20% variance in year-to-year changes in wheat yields was explained by T_r.

3.4.1. Temperature extremes

Heat waves are likely to become more frequent with global warming (Tebaldi et al., 2006; IPCC, 2007). Peaks of high temperature, even when occurring for just a few hours, can reduce the production of important food crops drastically (Prasad et al., 2000; Teixeira et al., 2013). Heat stress damage is particularly severe in most crops when high temperatures occur concomitantly with critical crop development stages, particularly the reproductive period. At present there is a lack of understanding of the spatial distribution of extreme temperatures in India and intensity of damage to wheat caused by heat stress. Spatially, heat stress damage is expected to vary with region and the sensitivity of cultivars. Temporally, variations in crop calendars (i.e. time of sowing to harvesting) and the rate of crop development influence the exposure to extreme temperatures during critical phenological phases.

The optimum temperature range for wheat is generally considered as 17–23 °C over the entire growing season, with a threshold T_n of 0 °C and T_x of 37 °C, beyond which growth ceases (Porter and Gawith, 1999). However, cultivars differ in their tolerance to extreme temperatures (Pomeroy and Flower, 1973; Blum and Sinmena, 1994; Paldi et al., 1996). Mean growing season T_x under Indian conditions range from 20.2 to 32.0 °C. Though it is well below the upper threshold of 37 °C, on several days during March T_x exceeds 32 °C. The notable example of 2010 heat wave for several days during March, coinciding grain filling stage with T_x exceeding 40 °C causing an estimated yield decline of 6% over parts of IGP is an indicator of sensitivity of Indian wheat yields to T_x. Our analysis indicated that February T_n is also critical. More area showing significant negative influence to February T_x is confined to eastern parts of IGP. Exposure for a longer period to temperatures above optimum plays a crucial role in determining productivity as noticed in several studies (Wheeler et al., 1996a,b; Tashiro and Wardlaw, 1990). This has prompted us to analyze the impact of duration of days with T_n, T_x and T_r above threshold levels during post-anthesis period (through entire February). Frequency of heat stress events between 6 and 27 °C in the case of T_n and 30 to 43 °C in case of T_x with unit increment when correlated with district yields resulted in considerable area showing significant negative values with $T_n > 10$ °C and $T_x > 30$ °C (Table 3a). Along with this, the influence of the duration of T_n and T_x in the range mentioned with unit increment was also assessed. Areas (%) showing negative association of these two variables were worked out and presented in Table 3b. Yields over large area got affected with T_n exceeding 12 °C and T_x exceeding 34 °C thus indicating these values as critical during post-anthesis period

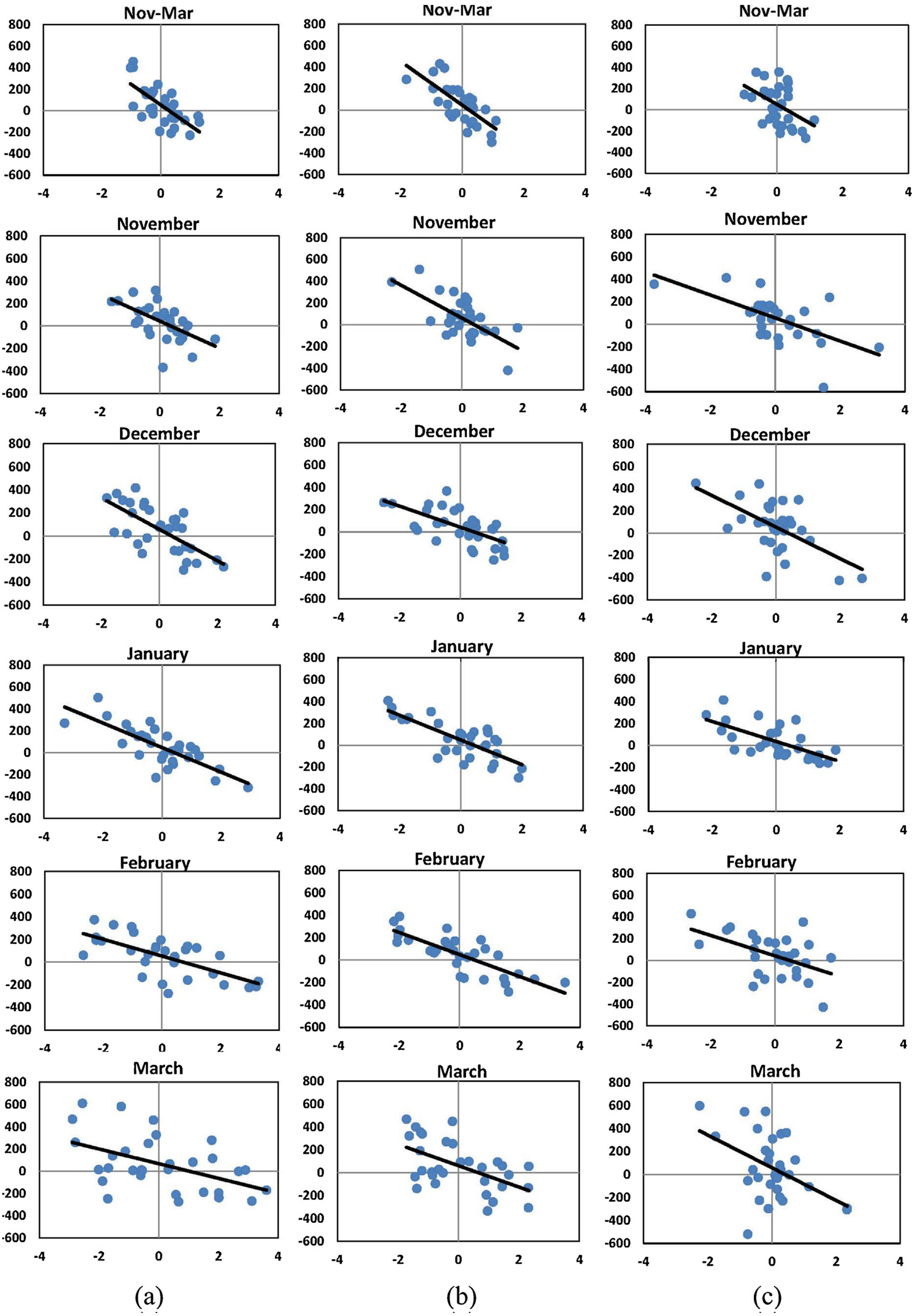

Fig. 4. Scatter plots showing association between first-difference time series for yield and (a) T_x (b) T_n and (c) T_r of different time scales. Solid line is the best fit linear regression.

Table 3b

Wheat growing area (%) that exhibited negative association with continual exposure to $T_n > 12\,^{\circ}\mathrm{C}$ and $T_x > 34\,^{\circ}\mathrm{C}$.

Nature of association	Number of days $T_n > 12\,^{\circ}\mathrm{C}$							Number of days $T_x > 34\,^{\circ}\mathrm{C}$									
	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8	9	10
Significantly negative	8.5	10.5	9.8	9.7	11.8	8.6	6.7	5.9	5.5	5.1	3.7	5.4	5.4	8.9	2.3	1.9	0.4
Negative but non-significant	50.8	45.1	46.1	40.1	44.9	38.4	42.1	43.4	39.6	30.4	29.6	28.9	26.8	29.3	17.6	11.6	1.7
Negative (Significant + Non-significant)	15.3	55.6	55.9	49.8	56.7	47	48.8	49.3	45.1	35.5	33.3	34.3	32.2	37.2	19.9	13.5	2.1

Table 4

Summary statistics of regression models between yield and temperature first differences of different time scales.

	Seasonal			November			December			January			February			March		
	T_x	T_n	T_r	T_x	T_n	T_r	T_x	T_n	T_r	T_x	T_n	T_r	T_x	T_n	T_r	T_x	T_n	T_r
Model R^2	0.47	0.52	0.20	0.33	0.43	0.37	0.48	0.41	0.35	0.60	0.60	0.43	0.47	0.63	0.25	0.24	0.31	0.25
Pearson's correlation coefficient	−0.68	−0.72	−0.45	−0.58	−0.66	−0.61	−0.69	−0.64	−0.59	−0.77	−0.78	−0.66	−0.69	−0.79	−0.51	−0.49	−0.56	−0.50
Change in yield (kg ha^{-1}) with 1 °C change	−190.6	−204.0	−177.5	−119.7	−150.8	−102.1	−136.1	−94.2	−142.2	−112.1	−113.0	−90.7	−74.0	−98.3	−93.6	−66.0	−93.7	−160.4
95% confidence limits	−268.0, −113.1	−278.1, −129.8	−312, −42.9	−183.8, −55.6	−216.3, −85.4	−152.9, −51.3	−190.5, −81.8	−137.3, −51.2	−216.5, −67.8	−146.9, −77.2	−147.9, −78.0	−131.6 −49.7	−103.7, −44.2	−126.8, −69.7	−154.7, −32.4	−110.7, −21.4	−146.8, −40.6	−266.2, −54.2

for the cultivars grown largely. Reductions were severe if T_n and T_x continued above these limits for 6 and 7 days, respectively. Indian wheat yields thus seem to be influenced by both extreme heat as well as prolonged exposure to $T_x > 34\,^\circ\mathrm{C}$ and T_n above $12\,^\circ\mathrm{C}$ during post-anthesis period.

4. Conclusions

In large wheat growing areas in India, nighttime warming is occurring at a faster rate than daytime warming. T_n is rising over the entire area @ $0.32\,^\circ\mathrm{C}\ 10\,\mathrm{yr}^{-1}$. Indian wheat yields appear to be more sensitive to night warming, especially during post-anthesis period (during February). Exposure to continual T_n exceeding $12\,^\circ\mathrm{C}$ for 6 days and heat stress with T_x exceeding $34\,^\circ\mathrm{C}$ continuously for 7 days during post-anthesis period could be environmental constraints both affecting normal productivity. Studies on wheat response to temperatures under Indian conditions using process based models such as DSSAT credited more decline in yield to increased T_x over T_n (Subash and Ram Mohan, 2012). There appears to be difference in this models' sensitivity to T_x and T_n. Under Indian conditions regional yield estimate studies using process based models are very few. Improved understanding from this study on the role of T_n during post-anthesis period using historical yield-temperature relationships may reduce the uncertainties in anthropogenic climate change projections further.

Ortiz et al. (2008) highlighted the need to develop adaptive measures for wheat production grown under warmer conditions. For Indian conditions, rice-wheat crop rotation is a common practice. Long duration varieties of rice are grown in this system and in most of the years, this practice leads to late sowing of wheat thereby exposing the crop to high temperatures (>35 °C) during grain filling (Tandon, 1994; Rane et al., 2000). Practicing of minimum-tillage in the rice-wheat system allows the wheat to emerge earlier and avoid exposure of the reproductive stage to extreme heat episodes thereby heat stress could be mitigated (Joshi et al., 2007; Biswas et al., 2008). Testing of adaptation strategies like adjusting the sowing dates and growing heat tolerant cultivars at the local level needs prioritisation. In fact, adaptive decisions ought to occur at the farm level in response to local conditions. Our results reinforce the need to consider inclusion of early maturing, high yielding and heat tolerant wheat lines in the breeding program augmenting production under Indian conditions. Reports on the dismal use of germplasm from gene banks in India is a matter of concern (Bonham et al., 2010) and therefore synergic approaches need to be adopted in the breeding programs. Agricultural practices per se, such as shifting sowing time, changing cultivars and minimum tillage, should also be explored as regional adaptation strategies to minimize the overall impact of rising and extreme temperatures on wheat productivity. Adjusting the crop calendar in turn depends on the length of growing period in a given environment (a function of precipitation and temperature) and timing and frequency of extreme temperature episodes. This calls for concerted research efforts at finer spatial scale. Any investments in understanding plant physiological responses to stress and in the development of adaptation options are vital to prepare current agricultural production systems for a warmer environment (Ainsworth and Ort, 2010; Challinor, 2011; Teixeira et al., 2013). Thermally sensitive areas evolved from this study may guide the researchers to evaluate such wheat lines for their adaptability for changing climates. Future work may include consideration of temperature extremes at a finer spatial scale, determining cultivar specific temperature thresholds, identifying from the existing germplasm or evolving cultivars that can adapt to warmer environments and tolerate temperature extremes of future climates with enhanced yields, promoting large scale adaption of management practices (growing genotypes with contrasting growing periods, adjusting sowing time) that minimize the thermal stress on wheat.

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