Agricultural and Forest Meteorology 200 (2015) 192–202

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

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

B. Bapuji Rao*, P. Santhibhushan Chowdary, V.M. Sandeep, V.P. Pramod, V.U.M. Rao

Central Research Institute for Dryland Agriculture, Santoshnagar, Hyderabad - 500 059, India

ARTICLE INFO

Article history:
Received 22 June 2014
Received in revised form
23 September 2014
Accepted 27 September 2014

Keywords:
Wheat yields
India
Post-anthesis
Minimum temperatures
Heat stress

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).

---

* Corresponding author. Tel.: +91 9676333557.
E-mail address: bapujiraob2002@yahoo.com (B.B. Rao).

http://dx.doi.org/10.1016/j.agrformet.2014.09.023
0168-1923/© 2014 Elsevier B.V. All rights reserved.

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