

Future changes in growing degree days of wheat crop in Pakistan as simulated in CORDEX South Asia experiments

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ABSTRACT

Climate change has become a global phenomenon having severe ramifications on socio-economic sectors such as agriculture, water resources, environment and health. The effects of changing climate are much more prominent on developing economies as compared to the implications on well-developed industrial powers. Pakistan is one of the struggling agricultural economies confronting the issues of food insecurity as a consequence of profound climatic conditions. Notable changes in climatic factors such as temperature can have a direct effect on Growing Degree Days (GDD) and may alter the growing season length (GSL). Growing season length is an important factor in ensuring that each crop developmental stage has a sufficient period for the transition to the next developmental stage. Lengthening or shortening of GSL can have dire threats to crop development and ultimately, production. This study has been conducted to assess the changes in GSL in response to the variability in daily maximum and minimum temperatures with a base temperature of 5°C across Northern, Central and Southern Pakistan. RCP 4.5 and 8.5 have shown an increase of 2°C and 5.4°C in minimum and maximum temperatures, respectively.

1. INTRODUCTION

Temperature extremes are a global phenomenon having serious consequences, particularly in the agriculture sector, where it has considerably affected production in most of the developing countries (Elum, Modise, & Marr, 2017). This has created a highly vulnerable situation of food insecurity, especially in agrarian countries. In Pakistan, agriculture is one of the most important sectors that contributes about 18.5% to the GDP and provides occupation to more than 51% of the population. The principal crops include wheat, rice, sugarcane, cotton and maize. As in many other parts of the world, wheat is a popular cereal crop in Pakistan used as a staple food. Wheat, in Pakistan, holds high importance among all other cereal crops as it accounts for 8.9% value addition in agriculture and 1.6% in overall GDP with an area of 8.74 m ha under cultivation (Government of Pakistan, 2019). Despite being cultivated on such a large scale, wheat yields have undergone huge fluctuations since the year 2000 due to climatic uncertainties. Climate change, over time, has emerged as a key environmental concern. The cyclic pattern of weather has

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HIGHLIGHTS

- » Global warming in the coming years is expected to impact food security.
- » Growing Degree Days (GDD) is an important parameter determining the crop development.
- » Southeastern parts of Pakistan are likely to become unsuitable for wheat production due to temperature extremes over the mid-century.

changed principally as a result of a rise in temperature which is one of the impacts of elevated concentrations of greenhouse gases in the atmosphere (Ahsan et al., 2010). The projections given by the Intergovernmental Panel on Climate Change (2014) have estimated that if the greenhouse gas emission rates continue to accelerate, an increase of 1.5 to 4.5°C is expected by the year 2100. In contrast, Hansen, Sato, and Ruedy, (2012) have reported, based on their estimations, a 0.18°C increase in average surface temperature every decade during the 21st century. Production in the agriculture sector is under serious threat due to the change in climatic trends all over the globe (Hu, Weiss, Feng, & Baenziger, 2005; Ding et al., 2006; Tao, Yokozawa, Xu, Hayashi, & Zhang, 2006; Iqbal et al., 2009; Semenov, 2008; Liu et al., 2010; van Ogtrop, Ahmad, & Moeller, 2014; Ahmad & Hussain, 2017; Ahmad et al., 2017; Dettori, Cesaraccio, & Duce, 2017; Abbas et al., 2017; Liu et al., 2018).

Increased temperature can have dire effects on crop productivity, and particularly, winter crops which show highly sensitive behaviours towards temperature change. Wheat appears to be one of the crops showing a higher degree of susceptibility towards temperature changes (Singha, Bhowmick, & Chaudhuri, 2006; Hundal, 2007; Pandey, Patel, & Patel, 2007). Climate change can cause up to 17% decrease in cereal yield, which is a severe reduction in the harvest as a consequence of elevated temperatures (Lobell, Bänziger, Magorokosho, & Vivek, 2011). Crop productivity either directly or indirectly bears the negative consequences of climate change, and the situation becomes inevitably serious in agrarian countries like Pakistan. It has been demonstrated in the study conducted by Aslam et al. (2017) that 1°C may cause a decrease of 4.1 to 6.4% in wheat yields. Zhao et al. (2017), Iqbal and Arif (2010) and Hussain and Mudasser (2007) reported similar findings. High temperatures, above the thresholds, is one of the main reasons for the reduction in wheat yield. The optimum temperature ranges for the wheat crop during anthesis and grain filling stage is from 12 to 22°C. If wheat is exposed to temperatures higher than 30°C at the time of anthesis or grain filling, it can have adverse effects resulting in a massive reduction in wheat yields (Nuttall, Barlow, Delahunty, Christy, & O'Leary, 2018; Farooq, Bramley, Palta, & Siddique, 2011; Porter & Gawith, 1999).

The growing degree days (GDD) is considered an important parameter determining the crop growth and development under different temperature regimes (Kalra et al., 2008; Kingra & Kaur, 2012; Meena & Rao, 2013). It assumes a direct and linear relationship between growth and temperature (Nuttonson, 1955). The crops sown on the recommended time have a higher heat requirement

than those of later sown crops. This happens because of the lower temperatures during the early vegetative growth stages and comparatively higher temperatures at the time of reproductive stage (Khichar & Niwas, 2007).

This study is designed to assess the increasing daily maximum as well as minimum temperatures and to determine the impacts of rising daily mean temperature on heat requirements of wheat crop in wheat-growing zones all over Pakistan. The study applies RCP 4.5 and RCP 8.5 over two future time-slices, i.e. near-century and mid-century using the CORDEX datasets.

2. METHODOLOGY

2.1 Site selection

Pakistan is predominantly an arid country. The country area is divided into 10 Agro-Ecological Zones (AEZ) based on physiography, climate, land use and water availability. The main limitation for the development of agriculture in Pakistan is water shortage under high temperatures and aridity. Eighty out of the 131 districts (61%) in Pakistan encounters food insecurity and almost half (48.6%) of the population does not have access to sufficient food to have an active and healthy life.

Wheat is the first Rabi crop grown in the semi-arid, arid and rain-fed areas of Pakistan during the winter season. As the dietary staple of Pakistan, supplying 72% of caloric energy in the average diet, wheat ranks first among all the crops in the area under cultivation and production. This fact signifies its role in ascertaining food security at the national scale. In Pakistan, wheat sowing is usually carried out from mid-October to December and harvest from mid-March until mid-May. Figure 1 shows the selected case study sites in Pakistan.

The climate of central and southern Punjab is categorized as dry semi-arid agro-climate, a highly productive agricultural zone due to fertile soils and well-managed canal irrigation system. Wheat crop produced in the Punjab province contributes to almost 75% of the total production in Pakistan.

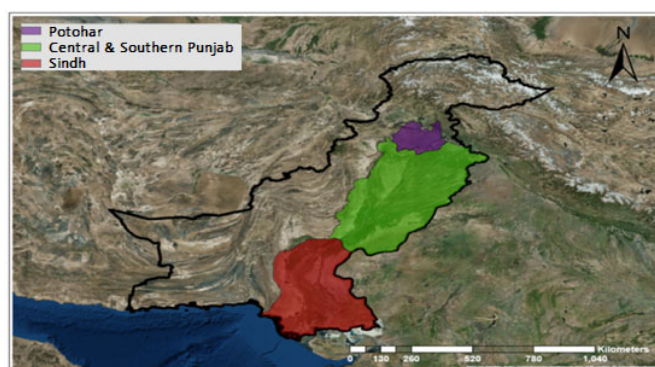


FIGURE 1. Case study sites of Pakistan.

The province of Sindh ranks second in wheat production. Wheat cultivated areas in lower Sindh are located in the irrigated plains which are fed by fertile alluvium soils deposited by the Indus River. Sindh has a hot and arid climate, with shorter growing season length and higher crop water demands as compared to the northern and central parts of the country. The growth duration of the wheat crop has a thermal dependency; short duration varieties are preferred for cultivation in the southeastern part, which matures in 100 to 120 days. Owing to climatic variations, crop periods range from November to March in lower parts and December to April in the upper plains.

The climate of Potohar region possesses semi-arid features in the southwest and sub-humid in the northeast. In a pluvial rain-fed region like Potohar, wheat cultivation depends on the available soil moisture at the time of sowing. Consequently, prolonged dry spell and late rain can drastically reduce crop yields. This region is considered to be the third-largest wheat contributor to national production.

2.2 Data

2.2.1 Baseline period and future scenarios

For the validation analysis, the baseline period was selected from 1981 to 2005 (25 years). Data of two climate change emission scenarios, Representative Concentration Pathways (RCPs) namely, Medium Controlled scenario RCP 4.5 and Business-as-usual scenario RCP 8.5 were evaluated for two future periods, near-century F1 (2006–2040) and mid-century F2 (2041–2070) periods.

2.2.2 Observed and reanalysis data set

Observed station data acquired from the Pakistan Meteorological Department (PMD) for the selected study sites were used to validate the selected reanalysis data.

Gridded data set (Harris, Jones, Osborn, & Lister, 2013) from the Climatic Research Unit (CRU), University of East Anglia, UK, was used as reference data to validate climate model data sets for observed climatology and model biases of monthly mean minimum and maximum temperatures over the historical period. Similarly, Reanalysis-gridded data, NASA-MERRA-II, was used for validation purpose for the period 1981 to 2005 for Tmin and Tmax over a daily time scale.

2.2.3 Model data

Six simulations using the Conformal Cubic Atmospheric Model (CCAM) (developed by the Commonwealth Scientific and Industrial Research Organization (CSIRO)) were driven using the lateral boundary conditions of six Global Climate Models were

validated against CRU over the historical period. These six simulations showed an almost comparable degree of biases over selected study sites over space and time. Subsequently, an ensemble approach was used, and all six CCAM simulations driven by six different GCMs were averaged using grid points of all dimensions for the selected variable. Ensemble approach was helpful to smooth the positive and negative biases and also to minimize errors.

2.3 Data analyses and techniques

Data analyses include plotting mean monthly biases of regional climate model data set with respect to reference data CRU for minimum and maximum temperature over Rabi season (Nov–May). Data is subset to a specified local region (Pakistan), and temporal and spatial interpolation was performed onto a common spatial grid using the bilinear interpolation scheme.

Growing Degree Day (GDD) bias was calculated for the historical period with reference to the MERRA data. Future projections of GDD were calculated. For calculating GDD, the first unit of the RCM data was converted from degree Fahrenheit to degree Centigrade. Later, the Rabi season was constructed which consisted of seven months, i.e. November to May. Seasonal aggregation was performed using Climate Data Operators (CDO) by first selecting November and December months from the year 1980/2004 and January, February, March, April, May from year 1981/2005. Both files were merged temporally, and resulting data were shifted ahead by two months in order to get 25-year data with all months of a season in every single year. In the next step, GDDs were accumulated in an individual season by first splitting all the years, each one containing daily values of GDD of the whole season (Nov–May), which were then added together to obtain the sum of a single season. Lastly, all seasons' calculations were merged to gather to get a single file of 25 years daily accumulated GDD during the Rabi season. Accumulated Growing Degree Days (GDD) were calculated using a base temperature of 5°C with the help of the following equation,

$$GDD_k = \sum_{n=1}^D \max \left\{ \left(\frac{TMAX_{nk} + TMIN_{nk}}{2} - B \right), 0 \right\}$$

where GDD_k is the growing degree days accumulated through the growing season for the k-th weather station, $TMAX_{nk}$ and $TMIN_{nk}$ are defined as the maximum and minimum temperatures, respectively, for the n-th day of the m-th month for the k-th weather station, B is a baseline temperature below which it is assumed that no growth occurs, and D represents the number of days in the growing season.

3. RESULTS AND DISCUSSION

3.1 Observed climatology and model biases (Minimum and maximum temperature)

One of the most straightforward approaches to evaluate models is to compare simulated quantities, including global distributions of temperature, precipitation and solar radiation, with corresponding observationally-based estimates (Gleckler, Taylor, & Doutriaux, 2008; Pincus, Batstone, Hofmann, Taylor, & Glecker, 2008; Reichler & Kim, 2008).

This study compares the simulated temperatures of CSIRO-CCAM-RCM ensemble with observed MERRA 2 data, for Pakistan. Model simulations for maximum temperature (Figure 2) in Rabi (November to May) season show that the model was able to reproduce agreeable skill scores with a general trend of minor bias ranging from 0 to 1°C over selected study sites. In the northern region, the ensemble depicts a bias of relatively wider range (>4.5°C). However, wheat cropping zones, i.e. Punjab simulations, show a positive bias of 0–1°C and in Sindh, there is a negative bias of -0–1°C. Overall, patterns of temperature bias are nearly similar for observed data as well as model simulations. A study carried out by Ahmad and Mahmood (2017) determined the observed, simulated and projected extreme climate indices in Pakistan using CSIRO-CCAM ensemble for a historical period of 35 years (1980 to 2004).

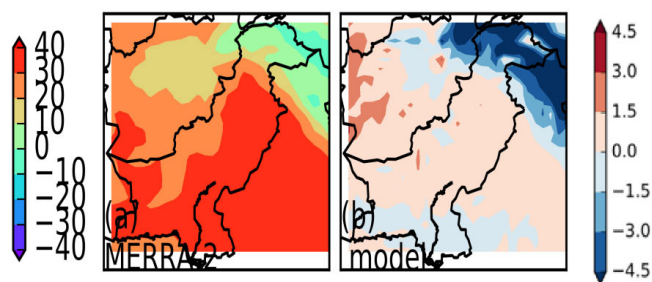


FIGURE 2. Bias estimation of Tmax using CCAM against MERRA-2.

Minimum temperature during early Rabi season is of utmost importance as the germination of the wheat seed depends on it (Ahmad & Shahzad, 2012). Seedling does not emerge if the required temperature conditions do not prevail. Figure 3 shows Tmin biases. CSIRO-CCAM has simulated minimum temperatures across the country with least bias of mixed nature in a greater portion of the country except for extreme northern parts where the largest values (>-4°C) of negative bias have been estimated. The findings of Ahmad and Mahmood (2017) also mark an increase of temperature by <1°C, which appears to be in strong agreement with our results. As Central Punjab estimations show a mixed trend

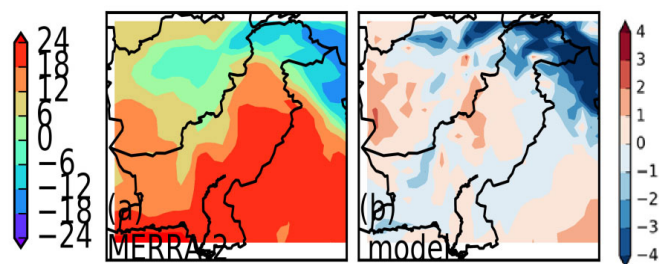


FIGURE 3. Bias estimation of Tmin using CCAM against MERRA-2.

with biases not higher than 1°C. Lower values of biases (Potohar <-1 °C, Sindh <+1°C and Central Punjab within 1°C) indicate that the results are reliable and model is recommended for simulations in the given area. A correlation of 0.99 and a standard deviation of 1.03°C were found between our selected model and observational data rendering the model as best pick for simulations of climatological parameters in Pakistan.

3.2 Observed climatology and model biases (Growing Degree Days)

Growing Degree Day (GDD) is a measurement of the heat accumulation above a specific base temperature. It relates plant growth, development and maturity (Parthasarathi, Velu, & Jeyakumar, 2013) in terms of specific GDD requirement of each phenological stage. On the whole, the growing season length and actual dry matter production critically depend on seasonal temperature conditions (Tsvetsinskaya et al., 2003). In the present study, the historical period consists of the growing season dating back from 1981 to 2005 for growing degree days of wheat crop during the winter season. For evaluation of CCAM model, MERRA-2 data has been used to collate bias estimation of CCAM for the historic period. The results generated by CCAM (Figure 4) are well-founded for GDD bias in wheat-growing zones of Pakistan. In areas of Potohar, Central Punjab and most of the Sindh territory, model estimation exactly overlaps the reference results showing no bias at all whereas in South-Western Sindh model estimates a bias of up to 100 GDD. Although the biases in the Hindu-Kush-Himalayan (HKH) region are conspicuous, yet they can be overlooked as the area of this study does not include the HKH region. The inferences drawn from the results for wheat-growing areas render the model as preferably recommended for bias estimation, specifically in the given area.

The reference figure showing results of MERRA-2 illustrates a wide range of heat requirement in wheat zones all over Pakistan. The magnitude of GDD goes on increasing linearly from Potohar to Sindh in a wide range of 3000 to 4500 heat units as determined by MERRA-2 data. The figure portrays that crop grown in Potohar requires the least heat units and stays in the

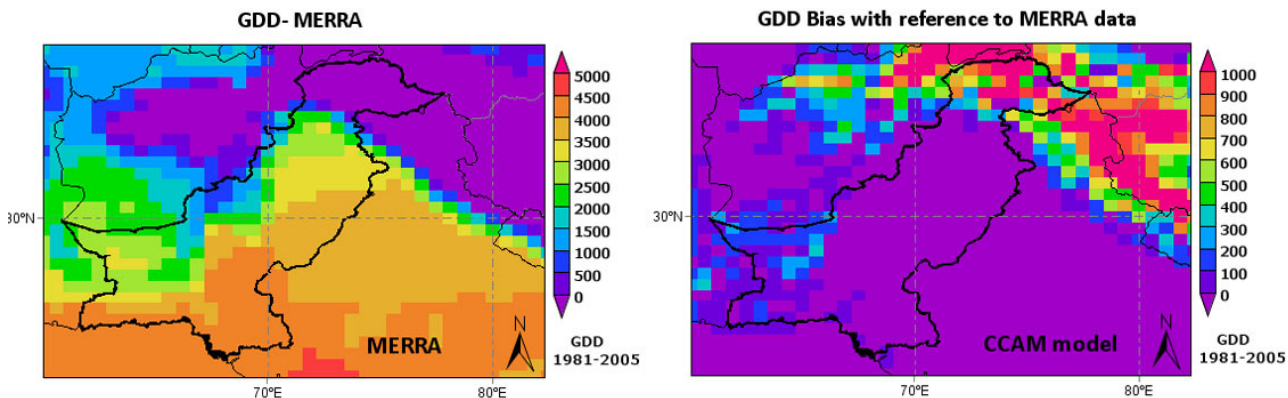


FIGURE 4. Differences (bias) between GDDs simulated by observed (MERRA) and model (CCAM) data during the historical period (1981-2005) in major wheat-growing zones of Pakistan. The figure on the left shows the average accumulated GDDs during the wheat-growing season as simulated by observed data; the figure on right shows the difference of average accumulated GDDs between observed and model data.

field for a longer duration (to accumulate the number of heat units required for maturity) than the crop grown in central Punjab and Sindh. The results of this study are in agreement with the findings of Ruiz Castillo and Gaitán Ospina (2016), where growing degree days for the historical period (1961 to 2004) ranged from 24,00 to above 3,500 GDD.

3.3 Future changes in growing degree days of wheat crop in Pakistan

Figure 5 delineates the spatial distribution of seasonal GDD's required by the wheat crop all over

Pakistan for three-time slots (near, mid and far century) under two RCPs (4.5 and 8.5). These maps aim to identify the areas with the greatest change in GDDs in the future over major wheat-producing areas in Pakistan.

The calculations for growing degree days are performed by obtaining the difference in daily mean temperature and base temperature. GDDs are accumulated by adding each day's GDDs.

The base temperature is the lower limit beyond which the plant cannot continue to grow and develop. In this experiment, the base temperature is assumed to be at 5°C (Gill, Babuta, Kaur, Kaur, & Sandhu, 2014). Base

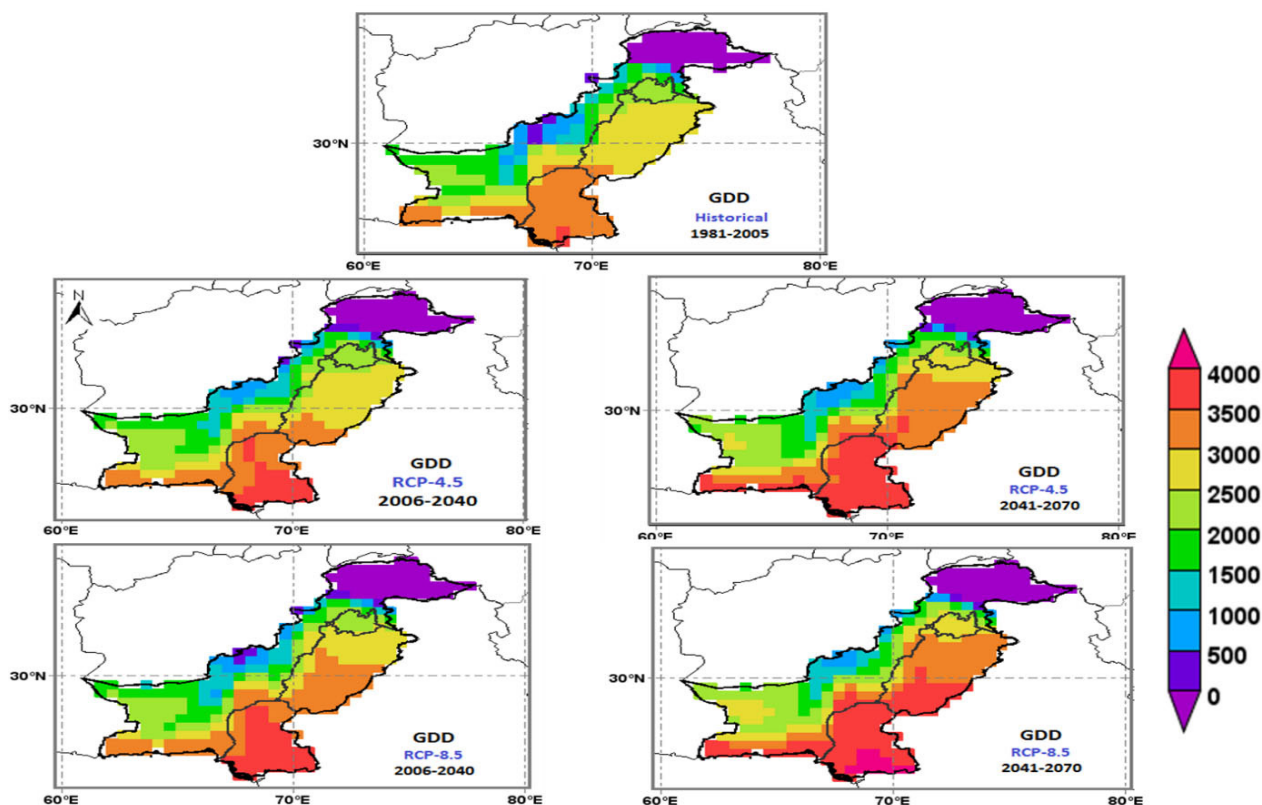


FIGURE 5. Spatial mapping of seasonal GDDs over Pakistan for control, F1 (near century) and F2 (mid-century) for RCP 4.5 and RCP 8.5 contribution during the season.

temperature can be different for each crop depending upon its genetic traits. An increase in the daily mean temperature indicates an accumulation of more degree days; shortening the crop duration accordingly which is very likely to be the reason for reduced crop yields (Ahmed & Fayyaz-ul-Hassan, 2015). Higher temperature together with reduced soil moisture decreases the season's length of crop growing which alters the plant growth stage and affects the partitioning and quality of biomass causing yield reduction (Hakim, Hossain, Silva, Zvolinsky, & Khan, 2012).

Figure 5 shows an increase in accumulated growing degree days in all major wheat producing zones of Pakistan including Sindh Central, Southern Punjab and Potohar region which is dominated by rain-fed wheat production under both RCP scenarios RCP 4.5 and RCP 8.5.

However, this increase is more intense in RCP 8.5 during mid-century. An overall increase of 1000 GDD between historical and late century extreme scenario in southeastern parts (lower Sindh province) of Pakistan has been observed. Results show the southeastern side of Pakistan, including wheat-producing districts of Sindh province (Thatta, Badin, Umerkot, Hyderabad and Sanghar) are likely to become unsuitable for wheat production due to temperature extremes during mid-century.

4. CONCLUSION

Daily mean temperature significantly affects phenology and grain yield of spring wheat. An increase in temperature is expected to shorten the crop lifecycle and lowering grain yields as a result of faster accumulation of GDDs in wheat crop. Studies indicate that temperatures in the southern part of Pakistan have shown to exceed the thresholds at the times of flowering and ripening. An overall increase of 1000 Growing Degree Days (GDDs) between past and mid-century extreme scenarios (RCP8.5) has been observed in case of wheat, implying that southeastern side of Pakistan is likely to become unsuitable for wheat production due to temperature extremes in future. An urgent response is required to help combat heat stress in cereal crops in order to ensure sustainability in food security. It requires high-quality research and policy planning for adopting to local scale, nationally oriented and forward-looking climate-smart practices and well-suited adaptation strategies, for resilient agriculture. Based on our study results, it is suggested that strategies like bringing more area under cultivation in North-Western and Mid-Western sides of Pakistan, considering multi-cropping and terracing options, early planting to avoid heat stress, and

developing drought tolerant and heat resistant varieties can be wise options to minimize climate change impacts on wheat crop in Pakistan.

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