Identification of climate change induced heat stress sensitive environments and prediction for diverse representative concentration pathways – A novel approach for tracking hotspots

Sendhil R¹, Uttam Ghimire², Mamrutha HM²³, Rinki K⁴, Balaganesh G⁵ and GP Singh⁶

¹ Sendhil R
Scientist
ICAR-Indian Institute of Wheat and Barley Research
Karnal - 132 001 (Haryana), INDIA.
* Principal Correspondence to: r.sendhil@icar.gov.in
ORCID: https://orcid.org/0000-0002-5336-6415

² Uttam Ghimire
Researcher
Regional Integrated Multi hazard Early Warning Systems for Africa and Asia (RIMES)
Bangkok, THAILAND
(Currently affiliated with School of Engineering, University of Guelph, Ontario, CANADA, N1G2W1; and Stockholm Environment Institute Asia Center, Bangkok, THAILAND).
Email: ghimire.uttam92@gmail.com

³ Mamrutha HM
Scientist
ICAR-Indian Institute of Wheat and Barley Research
Karnal - 132 001 (Haryana), INDIA.
** Joint Correspondence to: mamrutha.m@icar.gov.in

⁴ Rinki K
Scientist
ICAR-Indian Institute of Wheat and Barley Research
Karnal - 132 001 (Haryana), INDIA.
Email: rinki@icar.gov.in

⁵ Balaganesh G
Scientist
Forest Research Institute, Dehradun, INDIA
Email: balaganesh.agri@gmail.com

⁶ GP Singh
Director
ICAR-Indian Institute of Wheat and Barley Research
Karnal - 132 001 (Haryana), INDIA.
Email: gp.singh@icar.gov.in

Acknowledgements: The author(s) thank the APEC Climate Center (APCC), Busan, South Korea for imparting training on statistical downscaling of climate information which laid the basis for initiation of the research concept. Our sincere thanks to the Indian Council of Agricultural Research (ICAR) for rendering financial support to execute the project (Code: CRSCIIWBRCL201500100182) and ADG (MR), National Climate Centre, India Meteorological Department (IMD), Pune, India for the climate data.

Preprints are preliminary reports that have not undergone peer review. They should not be considered conclusive, used to inform clinical practice, or referenced by the media as validated information.
Identification of climate change induced heat stress sensitive environments and prediction for diverse representative concentration pathways – A novel approach for tracking hotspots

Abstract

Climate change is unequivocal across economies and India owing to its distinct geography has been exposed to several climatic risks, especially in agriculture. Heat stress is a serious environmental problem posed by climate change, wherein mean temperature is expected to increase relatively more during wheat growing season affecting production and food security. In the milieu, the investigation is pioneered to predict heat stress sensitive wheat growing environments in India for research prioritization using a long term (30 years) historical daily data. The study has developed a methodological approach by integrating statistical downscaling of climate information and principal component analysis for computing heat stress intensity index (HSII) for 17 experiment locations across wheat growing environments. HSII were estimated for existing locations post testing for Levene’s homogeneity of variance, followed by prediction for three periods’ viz., early-future (2026-2050), mid-future (2051-2075) and far-future (2076-2100) under two emission scenarios namely RCP4.5 and RCP8.5. The results alarmed a radical shift in HSII of experiment locations from one period to another in both scenarios. Experiment locations with high index values for the existing environment has moved almost to lower category in the early future and subsequently shifted to higher position in the mid-future and far-future. The investigation also found that under projected RCP4.5, trial locations in peninsular zone need more emphasis, whereas in RCP8.5, peninsular zone coupled with central zone and north eastern plains zone have to be focused. Overall, the study develops a pragmatic approach in location prioritization across predicted periods which can be replicated to other regions. On policy front, rational allocation of research funds has been suggested to carry out field trials on climate change induced heat stress sensitive environments for sustaining the national wheat production apart from developing micro-level adaptation strategies to counter adverse effects of climate change.

Keywords: Heat stress, HSII, wheat, statistical downscaling, principal component analysis
**Introduction**

Intergovernmental Panel on Climate Change (IPCC, 2007) predicts an increase in temperature from 0.3°C to 0.7°C over the next two decades and an increase of 0.3°C to 4.8°C by the end of this century (Collins et al., 2013; Kirtman et al., 2013). Wheat is a cold adored cereal plant and temperature plays a detrimental role for its productivity. Despite the effects of climatic aberrations vary with location, some studies reported a yield reduction of 10% with only 1°C increase in temperature above normal (Brown, 2009), while some reports indicate 3–7% reduction in wheat yield for every 1°C increase in temperature in the range of 15°C-21°C (Wardlaw et al., 1989; Hatfield et al. 2008). The concern here is the future pattern of climate is much uncertain to plan the investment decisions for research. A galore of literature indicates that the crop is highly sensitive to the change in climatic variables in different growth stages (Sendhil et al., 2016). Relative higher temperature during the crop growth season generally accelerate the phenological progress, affecting the plant’s routine metabolic activities that impacts the yield (Lobell and Gourdji, 2012; Rezaei et al., 2015). Increase in the atmospheric demand for water has also been reported when the temperature is high, further causing reduction in the water-use efficiency of the crop (Ray et al., 2002).

Stress tolerance is a very complex trait and gets aggravated with the changing climate. It not only depends on the severity of the cause, but also on the sensitivity of developmental stage and duration of stress. Climate change induced heat stress reduces the plant growth and development by disrupting the process of photosynthesis, respiration, net assimilation rate as well as total plant dry weight (Wahid et al., 2007). Photosynthetic inhibition is a universal indicator of environmental stress. Temperature variations beyond a threshold level also causes growth inhibition occurred due to impaired stomatal activity, respiratory losses, bleaching of plant pigments etc. In general, change in plant architecture, coleoptiles elongation, stunted growth, scorching of leaves and stems and senescence are some well documented responses which have been observed under elevated temperatures leading to reduced productivity (Tian et al., 2009). During initial stage early vigor, coleoptiles length, canopy cover plays an important role in stabilization of a field crop. But,
reproductive phase is more critical as high temperature causes pollen sterility, grain loss in
susceptible wheat genotypes and up regulation of abscisic acid synthesis genes in the anthers
which support accumulation of abscisic acid in spikes (Ji et al., 2010). Reduced pollen quality,
altered morphology along with the reduced pollen tube growth rate is an example of heat stress
effect in wheat. High temperature during anthesis produces abnormal anthers in 80% wheat florets
(Hedhly et al., 2009). Abnormal ovary development in addition to accelerated stigma and ovule
development resulted in reduced pollen tube growth and seed set when heat stress coincided with
meiosis (Barnabas et al., 2008). Under severe heat stress a yield reduction up to 40% has been
reported by Wollenweber et al. (2003), and Hays et al. (2007). Impact of heat stress is not only
restricted to reduced crop yield but also detrimental to produce quality. Lower seed germination,
loss of seed vigor, altered starch-lipid ratio in grains, reduced starch accumulation, early
senescence, decreased grain weight because of grain shrivelling are some impacts of heat stress
(Balla et al., 2012). Terminal heat stress is one of the major limiting factors in wheat production
which affects the viability of pollens, flowering, availability and translocation of photosynthates to
the developing kernel, starch synthesis and its translocation to the kernel, causing lower grain
number and quality as well as test weight (Reynolds et al., 2012; Gonzalez-Navarro et al., 2015).
Climate change studies indicate that increasing temperature may be detrimental for the regions
where wheat productivity is high presently, like Indo-Gangetic Plains of India (Sendhil et al., 2015 &
2017a), but could improve the output from other wheat growing zones. Hence, it is not easy to
predict the impact of climate dynamics in a précised way as genotype – environment - climate
interaction plays a very critical role on crop productivity. Mamrutha et al. (2020) developed the
stress intensity indices for heat and drought using 11 years period but little is known on the real-
time effect of climate change that is captured by long-term trend usually 30-year period as well as
projections under diverse greenhouse gas emission scenarios. To equip with the climate dynamics
and to improve tolerance in wheat, prediction of intensity in heat stress across existing trial
locations is of utmost importance. Results of such prediction studies on a specific and highly
sensitive crop to the heat stress environments like wheat will guide the researchers and policy
makers to plan a visionary framework to address the environmental problems for sustainable
wheat production.
Data and Methodology

Study Region

The study is marshalled by the daily timeseries climate data (January 01, 1984 to December 31, 2013) obtained from the India Meteorological Department (IMD) for selected locations and tested for the homogeneity of variance following Levene's (1960) approach. In India, wheat is being cultivated across five diverse agro-climatic zones (Figure 1). The Indo-Gangetic plains (IGP) comprise north western plains zone (NWPZ) and north eastern plains zone (NEPZ) which is the major wheat tract covering around 21 million hectares, followed by central zone (CZ), peninsular zone (PZ) and northern hills zones (NHZ). The whole cropped area under wheat in India experiences heat stress under changing climatic scenario and production especially gets affected in high vulnerable central region of India (Sendhil et al., 2018 & 2017b). The CZ and PZ experiences heat stress all through the crop season and significant parts of NWPZ and NEPZ experiences terminal heat (Tiwari et al., 2017).

The ICAR-Indian Institute of Wheat and Barley Research being the nodal centre for wheat research in the country has been instrumental in screening large number of wheat genotypes at hotspot locations for heat stress under the All India Coordinated Research Project (AICRP) covering all four heat stress prone zones since 1996 (Rane et al., 2007). The major hotspots identified in the country for screening material for heat stress include Karnal, Hisar, Ludhiana, Pantnagar, Durgapura in the NWPZ; Faizabad, Malda, Kanpur, Kalyani and Ranchi in the NEPZ; Indore and Junagadh in the Central zone; and Dharwad, Niphad, Parbhani, Jabalpur and Pune in the Peninsular zone (ICAR-IIWBR, 2017). The present investigation on identifying the intensity of heat stress has been carried out for the aforesaid 17 experimental locations (Table 1) distributed in four major wheat growing zones (Figure 1).
Figure 1: Distribution of experimental locations on different wheat growing zones
Table 1: Heat stress experiment location details across wheat growing environments

| Location | Latitude  | Longitude  | State          | Wheat growing zone | Growing degree days* |
|----------|-----------|------------|----------------|--------------------|----------------------|
| Dharwad  | 15.26° N  | 75.07° E   | Karnataka      | PZ                 | 2066                 |
| Durgapura| 26.51° N  | 75.47° E   | Rajasthan      | NWPZ               | 1725                 |
| Faizabad | 26.47° N  | 82.80° E   | Uttar Pradesh  | NEPZ               | 1696                 |
| Hisar    | 29.10° N  | 75.46° E   | Haryana        | NWPZ               | 1829                 |
| Indore   | 22.37° N  | 75.50° E   | Madhya Pradesh | CZ                 | 2429                 |
| Durgapura| 22.37° N  | 75.50° E   | Madhya Pradesh | NWPZ               | 1725                 |
| Faizabad | 26.47° N  | 82.80° E   | Uttar Pradesh  | NEPZ               | 1696                 |
| Hisar    | 29.10° N  | 75.46° E   | Haryana        | NWPZ               | 1829                 |
| Indore   | 22.37° N  | 75.50° E   | Madhya Pradesh | CZ                 | 2429                 |
| Durgapura| 22.37° N  | 75.50° E   | Madhya Pradesh | NWPZ               | 1725                 |
| Faizabad | 26.47° N  | 82.80° E   | Uttar Pradesh  | NEPZ               | 1696                 |
| Hisar    | 29.10° N  | 75.46° E   | Haryana        | NWPZ               | 1829                 |
| Indore   | 22.37° N  | 75.50° E   | Madhya Pradesh | CZ                 | 2429                 |
| Durgapura| 22.37° N  | 75.50° E   | Madhya Pradesh | NWPZ               | 1725                 |
| Faizabad | 26.47° N  | 82.80° E   | Uttar Pradesh  | NEPZ               | 1696                 |
| Hisar    | 29.10° N  | 75.46° E   | Haryana        | NWPZ               | 1829                 |
| Indore   | 22.37° N  | 75.50° E   | Madhya Pradesh | CZ                 | 2429                 |
*Growing degree days (GDD) has been estimated till the crop maturity adopting the approach of Shaykewich (1995).

Testing the Homogeneity of Variance (Levene’s approach)

As a preliminary step, quality check was done for the collected daily data on maximum and minimum temperature as well as rainfall for 17 experiment locations. It was carried out by visual observation of time plot, climatology, outliers identification (if any) followed by computing the summary statistics and then tested for homogeneity of variance to proceed for further analysis. Levene’s approach was employed to check for the homogeneity in variance since the test is relatively less sensitive to departure of the time series from normal distribution. The test (Levene, 1960) was carried out with the following assumption:

Null Hypothesis (H_0) \( : \sigma_1^2 = \sigma_2^2 = \ldots = \sigma_k^2 \)

Alternate Hypothesis (H_a) \( : \sigma_1^2 \neq \sigma_2^2 \neq \ldots \neq \sigma_k^2 \)

Assume a climate time series data \((Y)\) with sample size ‘N’ that comprise ‘k’ sub-groups with \(N_i\) being the \(i^{th}\) sub-group’s sample size. The test statistic \((W)\) given by Levene is as follows:

\[
W = \frac{(N - k)}{(k - 1)} \sum_{i=1}^{k} N_i (\overline{Z}_i - \overline{Z})^2 - \sum_{i=1}^{k} N_i (Z_{ij} - \overline{Z}_i)^2
\]

where; \(Z_{ij}\) shall take the value of series mean, median or 10 per cent trimmed mean of the \(i^{th}\) sub-group; \(\overline{Z}_i\) are the values of group mean of the \(Z_{ij}\) and \(\overline{Z}\) is the overall mean of the \(Z_{ij}\).
**Statistical Downscaling and Projection of Climate Information**

Post testing the time series homogeneity of variance, the projections for future meteorological condition are done with the help of climate models that are capable of simulating large scale atmospheric processes (Fischer et al., 2005; Taylor et al., 2012). However, due to the spatial (hundreds of kilometers) and temporal resolution of such models, some intervention should be done before applying them to assess the impacts on different sectors at local level (Wilby et al., 2002; Christensen et al., 2008). Such interventions in the form of statistical techniques of downscaling and bias correction have been used in several researches throughout the globe to increase the reliability of assessment of impacts of climate change on multiple sectors (Teutschbein and Seibert, 2012).

One such technique of bias correction, quantile mapping has been used extensively in agriculture impact assessment studies owing to climate change (Fowler et al., 2007; Themeßl et al., 2011; Teutschbein and Seibert, 2012; Gudmundsson et al., 2012). Quantile mapping also known as cumulative distribution function was done to match and find a transformation (say h) of a model variable (say rainfall $P_m$) such that its new distribution equals to the distribution of observed variable (say rainfall $P_o$).

$$P_o = h(P_m)$$

If the distribution of variables is known, then the transformation h is defined as;

$$P_o = F_o^{-1}(F_m(P_m))$$

where $F_m$ is the cumulative distribution function (CDF) of $P_m$ and $F_o^{-1}$ is the inverse CDF (or quantile function) corresponding to $P_o$ (Gudmundsson et al, 2012).

Post statistical downscaling, the climate projections are done for three periods’ namely early future (2026-2050), mid future (2051-2075) and far future (2076-2100) under two representative concentration pathways (RCP) viz., 4.5 and 8.5 based on the greenhouse gas emissions as suggested by the IPCC. Figure 2 shows the illustration of the analytical approach used in the study.
Figure 2: Illustration of analytical approach used in the study
Trend Estimation: Mann-Kendall’s Approach

The trend in climate variables viz., maximum temperature, minimum temperature and rainfall was estimated using Mann-Kendall’s non-parametric test approach. It is a widely adopted method to identify the long-run trends in time series data (Ahmad et al., 2015) by comparing the relative magnitude of sample observations against the actual observations. It is a rank-based procedure with an assumption that only one data exists at a point of time, robustness to the influence of outliers as well as suitable for skewed time series possessing non-linear trend (Hamed, 2008; Helsel and Hirsch, 1992). The advantage of the technique is that it does not require any particular distribution. The null hypothesis (H₀) outlines that the deseasonalised data (x₁...xₙ) is a sample of ‘n’ independent and identically distributed random variables (Hirsch et al., 1982 and; Kahya and Kalayci, 2004). The alternative hypothesis (H₁) is that the distributions of xₖ and xⱼ are not identical for all k,j ≤ n with k ≠ j. The estimation procedure for the Mann Kendall’s trend coefficient is given in detail by Rathore et al. (2013). If the test statistic turns positive, it depicts an upward trend and vice-versa (Sendhil et al., 2015).

Normalisation of the Climate Data

The collected data on climate variables viz., rainfall, maximum and minimum temperature and rainfall were normalised – to make them unit and scale free – for comparison (Mahida and Sendhil, 2017). Variables having positive functional relationship with the heat stress (maximum & minimum temperature) were normalised as depicted in equation 1.

\[
\text{Normalisation} = \frac{(\text{Actual value} - \text{Minimum value})}{(\text{Maximum value} - \text{Minimum value})} \quad \text{...(1)}
\]

It is well known that rainfall reduces the heat stress. Owing to the negative association, the formula presented in Eq. 2 has been used for normalising the rainfall variable.

\[
\text{Normalisation} = \frac{(\text{Maximum value} - \text{Actual value})}{(\text{Maximum value} - \text{Minimum value})} \quad \text{...(2)}
\]

Assignment of Weights: Principal Components Analysis Approach

After normalising the data for the climatic variables, weight needs to be assigned for each variable to estimate the heat stress intensity index (HSII). Conventionally, three approaches have been used to assign the weights (Kumar et al., 2016): same weight for all variables, opinion of the experts and econometric approach like principal component analysis (PCA). Though each method
has its own merit and demerit (Sendhil et al., 2018), we used PCA owing to its advantage over other methods. Some studies have used only the factor loadings from first principal component as weights (Kumar et al., 2016). We followed the Kaiser (1960) criterion (selecting the principal components with Eigen value more than one) to capture maximum variation from the data to assign weights (Ayyoob et al., 2013; Rana et al., 2015; Kale et al., 2016). Eq. 3 shows the functional representation of the principal components.

\[ X_t = \Lambda_tF_t + e_t \]  

...(3)

where, \( X_t \) represents N-dimensional vector of variables influencing heat stress, \( \Lambda \) is \( r \times 1 \) common factor, \( F_t \) is the factor loading, and \( e_t \) is the associate d idiosyncratic error-term of order \( N \times 1 \)

The weight for each variable \( (W_i) \) is calculated as indicated by equation 4.

\[ W_i = \sum |L_{ij}| E_j \]  

...(4)

where, \( E_j \) represents the Eigen value of the \( j^{th} \) factor, and \( L_{ij} \) indicates the loading value of the \( i^{th} \) variable on \( j^{th} \) factor.

**Computation of Heat Stress Intensity Index (HSII)**

The weights for each variable for all the selected 17 trial locations were fitted in the following formula (Eq. 5) to arrive the composite heat stress intensity index (HSII) value for each location.

\[ HSII_{\text{Trial Location}} = \frac{\sum_{i=1}^{n} X_i W_i}{\sum_{i=1}^{n} W_i} \]  

...(5)

where, \( X_i \) is the normalized value of \( i^{th} \) variable and \( W_i \) is the weight of the \( i^{th} \) variable.

**Results and Discussion**

**Test for Homogeneity in Variance (Levene’s Approach)**

A mixed pattern in climate data (1984 to 2013) was evident across trial locations which supports for multi-location testing for heat stress in wheat (see supplementary files for summary statistics). For instance, the lower level of minimum temperature ranged from as low as -0.17°C in Ludhiana (Punjab: NWPZ) to as high as 10.52°C in Dharwad (Karnataka: PZ). Similarly, the quantum of rainfall (maximum in a day) hovered between 128.30 mm in Karnal (Haryana: NWPZ) and 345.90
mm in Malda (West Bengal: NEPZ). The climate data were then checked for the level of homogeneity in variance with the assumption of null hypothesis that equal variation exists. The Levene’s test results indicated that all variables turned to be significant (Table 2) rejecting the null hypothesis to establish the fact that there exists a significant difference in variance among observations. This led to proceed with the estimation of trend coefficient (Mann-Kendall’s test).

**Table 2: Estimates of Levene’s test statistic for homogeneity in variance**

| Climate variable            | Levene’s statistic | Degrees of freedom | Probability level |
|----------------------------|--------------------|--------------------|-------------------|
| Minimum Temperature (°C)   | 2916.197*          | 16                 | 186269            | .000              |
| Maximum Temperature (°C)   | 1702.041*          | 16                 | 186269            | .000              |
| Rainfall (mm)              | 337.114*           | 16                 | 186269            | .000              |

Note: Number of locations are 17 (so df₁=16) and number of observations are 186286 (so df₂=186269).

* denotes the statistical significance at one per cent level of probability.

### Level of Heat Stress Intensity in Wheat Producing Environments: Existing Scenario

Globally, wheat production is expected to fall by 6 per cent for each degree of temperature increase (Asseng et al., 2014), and testing the causal effect of temperature on wheat yield is more important owing to the prevailing uncertainty of the simulation models (Asseng et al., 2013). Long-term trend in climatic variables is a clear indicator for the level of heat stress intensity in different environments. A positive trend between 1984-2013 in minimum temperature (Min T), maximum temperature (Max T) and rainfall was noticed for a majority of the locations wherein experiment for heat stress in wheat is being conducted (Table 3). Lobell et al., (2011b) estimated wheat yield trend between -0.2 to -0.1 indicating the negative response to climate change (1980-2008). Projections indicate that it would lead to strong decline in wheat yields (Anonymous, 2011). Of the 17 trial locations across four major production zones; Dharwad, Durgapura, Kanpur, Malda, Faizabad, Kalyani, Parbhani and Patna exhibited a declining trend in one or other of the selected three climate variables as evident by the Mann-Kendall trend statistic. The highest positive trend has been noticed in Malda, Pune and Ludhiana, respectively for min T, max T and rainfall, corroborating the significant increasing trend identified for rainfall in Punjab (Kumar et al., 2010). On the contrary, the highest negative trend was observed in Dharwad, Malda and Kalyani, respectively. A similar kind of pattern has been observed for the index values derived from the
trend coefficients. Weights assigned from the principal component analysis (PCA) revealed more weight to min T (1.6358) and less weight to max T (1.3760). The composite heat stress intensity index (HSII) as furnished in Figure 3 for 17 locations indicated that in the existing scenario, considering 30 years observation, Ludhiana experienced high score (0.3123), followed by Pune (0.2901), Patna (0.2646) and Ranchi (0.2579). On the contrary Kanpur from the North Western Plains Zone registered the lowest index score (0.0266). High HSII score in Ludhiana is attributed to the highest positive trend coefficient from rainfall pattern over the past 30 years corroborating the findings of Kumar et al. (2010) wherein they estimated a significant and positive trend for rainfall in Punjab. Similarly, the lowest score in Kanpur is credited to the combined effect of all the three trend coefficients which are relatively lower in comparison to the highest trend statistic in each category. Surface temperature in India has increased over a period of time and is attributed to the greenhouse gases and land use (Basha et al., 2017). Overall the analysis on HSII for the existing scenario indicated that Ludhiana experiencing high heat stress intensity, whereas, Kanpur experience the lowest level of intensity among the selected trial locations.

Table 3: Climate trend (1984-2013) and indices for heat stress trial locations

| Station | Mann-Kendall’s Trend Statistic | Index values | HSII |
|---------|--------------------------------|--------------|------|
|         | Min T                          | Max T        | Rainfall | Min T                          | Max T        | Rainfall |
| Dharwad | -0.0023                        | 0.0204       | 0.0347   | 0.0000                         | 0.9496       | -0.3771  | 0.1246  |
| Durgapura | 0.0351                       | -0.0014      | 0.0246   | 0.8840                         | 0.4098       | -0.5209  | 0.1681  |
| Faizabad | 0.0240                        | 0.0116       | -0.0246  | 0.6210                         | 0.7325       | -1.2220  | 0.0286  |
| Hisar    | 0.0230                        | 0.0109       | 0.0239   | 0.5992                         | 0.7138       | -0.5304  | 0.1703  |
| Indore   | 0.0019                        | 0.0038       | 0.0324   | 0.1005                         | 0.5371       | -0.4093  | 0.0497  |
| Jabalpur | 0.0325                        | 0.0075       | 0.0084   | 0.8215                         | 0.6294       | -0.7521  | 0.1520  |
| Junagadh | 0.0360                        | 0.0143       | 0.0147   | 0.9058                         | 0.7983       | -0.6614  | 0.2268  |
| Kalyani  | 0.0482                        | 0.0034       | -0.0500  | 1.1934                         | 0.5284       | -1.5847  | 0.0298  |
| Kanpur   | 0.0210                        | -0.0017      | 0.0029   | 0.5512                         | 0.4013       | -0.8304  | 0.0266  |
| Karnal   | 0.0262                        | 0.0098       | 0.0123   | 0.6729                         | 0.6859       | -0.6956  | 0.1443  |
| Ludhiana | 0.0205                        | 0.0182       | 0.0611 H | 0.5394                         | 0.8960       | 0.0000 H | 0.3123 H |
| Malda    | 0.0669 H                      | -0.0179 L    | -0.0377  | 1.6358 H                       | 0.0000 L     | -1.4096  | 0.0492  |
| Niphad   | 0.0112                        | 0.0074       | 0.0062   | 0.3193                         | 0.6266       | -0.7837  | 0.0353  |
| Parbhani | 0.0046                        | 0.0244       | -0.0079  | 0.1637                         | 1.0504       | -0.9850  | 0.0498  |
| Patna    | 0.0433                        | 0.0244       | -0.0027  | 1.0771                         | 1.0491       | -0.9100  | 0.2646  |
| Pune     | 0.0187                        | 0.0376 H     | 0.0233   | 0.4962                         | 1.3760 H     | -0.5388  | 0.2901  |
| Ranchi   | 0.0401                        | 0.0237       | 0.0016   | 1.0031                         | 1.0316       | -0.8495  | 0.2579  |
| PCA Weights | 1.6358 H       | 1.3760 L     | 1.5847   |      |

Note: ‘H’ indicates the highest value and the ‘L’ indicates the lowest value.
Level of Heat Stress Intensity in Wheat Producing Environments: Future Scenario

The long-term trend in climatic variables as explained in Table 2 was computed for the future climatic predictions viz., early future (2026-2050), mid future (2051-2075) and far future (2076-2100) under two scenarios namely RCP 4.5 and RCP 8.5. The present analysis was carried out to know whether the heat stress intensity in trial locations will increase or decrease or remain constant over a period of time.

**A1. Early Future (RCP 4.5: 2026-2050):** The Mann-Kendall’s trend for the early future under RCP 4.5 scenario indicated that minimum temperature is expected to increase for all the trial locations, maximum temperature will increase in 16 locations with the exception of Junagadh, and, rainfall is expected to increase in 14 locations barring Durgapura, Hisar and Indore (Table 4). The highest positive trend is expected at Dharwad (+0.0777) for min T, Indore (+0.0467) for max T and Dharwad (+0.0168) for rainfall. In contrast, the lowest trend is expected to occur in Junagadh for min T (+0.0117) as well as max T (-0.0005), and in Durgapura for rainfall (-0.0119). Since the principal components analysis resulted only one PC with Eigen value more than one, a similar kind of pattern in maximum and minimum values was noticed with respect to the indices derived from the Mann-Kendall trend coefficients. Again, the weight assigned for index calculation was more to min T (1.9589) and less to max T (1.6820). The composite heat stress intensity index (HSII) for the early future under RCP 4.5 scenario indicated that Dharwad is expected to experience high...
intensity (0.5360), whereas, Junagadh shall have low HSII (-0.0140). High HSII score in Dharwad is attributed to the highest positive trend coefficient from minimum temperature and rainfall predicted for the early future, 2026-2050. A majority of the reports indicate a strong decline in wheat yield in the nearby decades (Anonymous, 2011).

A2. Early Future (RCP 8.5: 2026-2050): Under RCP 8.5, a considerable shift in the intensity of heat stress index across locations was noticed and a sharp increase in surface temperature has been projected by Basha et al. (2017). Junagadh a centre which registered the lowest HSII under RCP 4.5, surprisingly has shown a complete reverse trend in RCP 8.5 reaching the top slot of HSII (Table 5). Similar to RCP 4.5, the weight assigned for index calculation was more to min T (1.9813) and less to max T (1.7234) in the case of RCP 8.5. Minimum temperature and rainfall had shown an increasing trend statistic for all locations. However, the maximum temperature unlike RCP 4.5, has exhibited a declining trend for locations like Durgapura, Faizabad, Indore, Kanpur, Niphad and Parbhani. A symmetric pattern was noticed in the highest and lowest values for trend statistic as well as index values. On the whole, the index computation indicated that the HSII was highest in the case of Junagadh and lowest in the case of Parbhani.

Table 4: Climate trend and indices for early future scenario (RCP 4.5)

| Station     | Mann-Kendall’s Trend Statistic | Index values | HSII    |
|-------------|-------------------------------|--------------|---------|
|             | Min T                         | Max T        | Rainfall| Min T | Max T | Rainfall |         |
| Dharwad     | 0.0777 H                      | 0.0265       | 0.0168 H| 1.9589 H | 0.9610 | 0.0000 H | 0.5360 H |
| Durgapura   | 0.0301                        | 0.0358       | -0.0119 L | 0.5445 | 1.2947 | -1.8063 L | 0.0060 |
| Faizabad    | 0.0275                        | 0.0013       | 0.0125  | 0.4693 | 0.0616 | -0.2698  | 0.0479 |
| Hisar       | 0.0338                        | 0.0182       | -0.0029 | 0.6542 | 0.6659 | -1.2367  | 0.0153 |
| Indore      | 0.0525                        | 0.0467 H     | -0.0081 | 1.2112 | 1.6820 H | -1.5679 | 0.2433 |
| Jabalpur    | 0.0289                        | 0.0212       | 0.0018  | 0.5101 | 0.7746 | -0.9467  | 0.0621 |
| Junagadh    | 0.0117 L                      | -0.0005 L    | 0.0156  | 0.0000 L | 0.0000 L | -0.0763 | -0.0140 L |
| Kalyani     | 0.0273                        | 0.0219       | 0.0053  | 0.4616 | 0.7994 | -0.7274  | 0.0980 |
| Kanpur      | 0.0380                        | 0.0274       | 0.0073  | 0.7800 | 0.9565 | -0.5978  | 0.2162 |
| Karnal      | 0.0254                        | 0.0142       | 0.0040  | 0.4068 | 0.5249 | -0.8076  | 0.0228 |
| Ludhiana    | 0.0254                        | 0.0142       | 0.0040  | 0.4068 | 0.5250 | -0.8077  | 0.0228 |
| Malda       | 0.0393                        | 0.0302       | 0.0036  | 0.8180 | 1.0930 | -0.8319  | 0.1981 |
| Niphad      | 0.0464                        | 0.0314       | 0.0067  | 1.0290 | 1.1375 | -0.6359  | 0.2810 |
| Parbhani    | 0.0618                        | 0.0464       | 0.0072  | 1.4879 | 1.6729 | -0.6025  | 0.4696 |
| Patna       | 0.0291                        | 0.0053       | 0.0043  | 0.5162 | 0.2070 | -0.7872  | -0.0118 |
| Pune        | 0.0460                        | 0.0129       | 0.0117  | 1.0180 | 0.4783 | -0.3248  | 0.2151 |
| Ranchi      | 0.0273                        | 0.0289       | 0.0103  | 0.4622 | 1.0481 | -0.4078  | 0.2024 |

PCA Weights: 1.9589 H, 1.6820 L, 1.8063

Note: ‘H’ indicates the highest value and the ‘L’ indicates the lowest value.
B1. Mid Future (RCP 4.5: 2050-2075): In the mid future under RCP 4.5, rainfall has shown an increasing trend for all locations whereas, minimum temperature and maximum temperature exhibited declining trend for some locations (Table 6). In the case of minimum temperature, Durgapura, Hisar and Kanpur shown a declining trend and in maximum temperature, negative growth was observed in Durgapura, Faizabad, Hisar, Indore, Kanpur, Karnal, Ludhiana and Patna. The maximum and minimum values for trend statistic as well as indices for locations followed a similar pattern for the selected three climatic variables. Unlike early future (RCP 4.5 and 8.5) and existing scenario, the weight assigned by the PCA was more in minimum temperature (2.2869) and less in rainfall (1.8665). However, the composite HSII was highest in the case of Parbhani (0.5704) and lowest in Durgapura (-0.1391).

Table 5: Climate trend and indices for early future scenario (RCP 8.5)

| Station     | Mann-Kendall’s Trend Statistic | Index values | HSII  |
|-------------|--------------------------------|--------------|-------|
|             | Min T  | Max T  | Rainfall | Min T  | Max T  | Rainfall |       |
| Dharwad     | 0.0540  | 0.0144 | 0.0172   | 1.9813  | 1.0961 | -1.0091  | 0.3740 |
| Durgapura   | 0.0177  | -0.0162 | 0.0174   | 0.2330  | 0.0828 | -0.9948  | -0.1228|
| Faizabad    | 0.0129  | -0.0179 | 0.0218   | 0.0000  | 0.0239 | -0.7058  | -0.1233|
| Hisar       | 0.0176  | 0.0013  | 0.0192   | 0.2275  | 0.6620 | -0.8731  | 0.0030 |
| Indore      | 0.0222  | -0.0018 | 0.0236   | 0.4491  | 0.5579 | -0.5910  | 0.0752 |
| Jabalpur    | 0.0279  | 0.0018  | 0.0157   | 0.7240  | 0.6791 | -1.1034  | 0.0542 |
| Junagadh    | 0.0397  | 0.0070  | 0.0326   | 1.2935  | 0.8509 | 0.0000   | 0.3877  |
| Kalyani     | 0.0364  | 0.0236  | 0.0046   | 1.1326  | 1.4015 | -1.8257  | 0.1281 |
| Kanpur      | 0.0131  | -0.0186 | 0.0227   | 0.0097  | 0.0000 | -0.6476  | -0.1154|
| Karnal      | 0.0187  | 0.0012  | 0.0104   | 0.2799  | 0.6579 | -1.4493  | -0.0925|
| Ludhiana    | 0.0187  | 0.0012  | 0.0102   | 0.2799  | 0.6576 | -1.4599  | -0.0945|
| Malda       | 0.0460  | 0.0333  | 0.0059   | 1.5934  | 1.7234 | -1.7456  | 0.2841 |
| Niphad      | 0.0312  | -0.0173 | 0.0295   | 0.8809  | 0.0451 | -0.2067  | 0.1301 |
| Parbhani    | 0.0190  | -0.0157 | 0.0090   | 0.2951  | 0.0973 | -1.5412  | -0.2077 |
| Patna       | 0.0272  | 0.0027  | 0.0235   | 0.6887  | 0.7079 | -0.5933  | 0.1453 |
| Pune        | 0.0505  | 0.0008  | 0.0217   | 1.8128  | 0.6442 | -0.7158  | 0.3148 |
| Ranchi      | 0.0259  | 0.0122  | 0.0115   | 0.6269  | 1.0223 | -1.3756  | 0.0495 |

Note: 'H' indicates the highest value and the 'L' indicates the lowest value.
Table 6: Climate trend and indices for mid future scenario (RCP 4.5)

| Station   | Mann-Kendall’s Trend Statistic | Index values | HSII |
|-----------|--------------------------------|--------------|------|
|           | Min T | Max T | Rainfall | Min T | Max T | Rainfall |
| Dharwad   | 0.0407 H | 0.0216 | 0.0117 L | 2.2869 H | 1.7189 | -1.8665 L | 0.3336 |
| Durgapura | -0.0078 L | -0.0290 L | 0.0265 | 0.0000 L | 0.0000 L | -0.8918 | -0.1391 L |
| Faizabad  | 0.0105 | -0.0119 | 0.0401 H | 0.8642 | 0.5795 | 0.0000 H | 0.2251 |
| Hisar     | -0.0004 | -0.0105 | 0.0249 | 0.3479 | 0.6282 | 0.0000 | -0.9987 | -0.0035 |
| Indore    | 0.0054 | -0.0099 | 0.0237 | 0.6219 | 0.6502 | -1.0752 | 0.0307 |
| Jabalpur  | 0.0162 | 0.0098 | 0.0176 | 1.1300 | 1.3177 | -1.4787 | 0.1511 |
| Junagadh  | 0.0253 | 0.0044 | 0.0205 | 1.5603 | 1.1358 | -1.2866 | 0.2198 |
| Kalyani   | 0.0171 | 0.0053 | 0.0345 | 1.1749 | 1.1662 | -0.3665 | 0.3079 |
| Karnal    | -0.0023 | -0.0242 | 0.0361 | 0.2591 | 0.1643 | -0.2588 | 0.0257 |
| Ludhiana  | 0.0022 | -0.0071 | 0.0336 | 0.4732 | 0.7425 | -0.4266 | 0.1230 |
| Malda     | 0.0387 | 0.0279 | 0.0189 | 2.1948 | 1.9341 | -1.3942 | 0.4265 |
| Niphad    | 0.0276 | 0.0125 | 0.0215 | 1.6685 | 1.4116 | -1.2221 | 0.2897 |
| Parbhani  | 0.0392 | 0.0375 H | 0.0276 | 2.2150 | 2.2593 H | -0.8163 | 0.5704 H |
| Patna     | 0.0234 | -0.0030 | 0.0269 | 1.4725 | 0.8832 | -0.8668 | 0.2322 |
| Pune      | 0.0291 | 0.0188 | 0.0164 | 1.7403 | 1.6244 | -1.5563 | 0.2820 |
| Ranchi    | 0.0142 | 0.0050 | 0.0271 | 1.0379 | 1.1554 | -0.8545 | 0.2088 |

PCA Weights

|          | Min T | Max T | Rainfall |
|-----------|-------|-------|----------|
|           | 2.2869 H | 2.2593 | 1.8665 L |

Note: ‘H’ indicates the highest value and the ‘L’ indicates the lowest value

B2. Mid Future (RCP 8.5: 2050-2075): Unlike mid future RCP 4.5, minimum temperature and maximum temperature have shown a positive trend for all the trial locations under RCP 8.5 (Table 7). However, with respect to rainfall, Durgapura, Hisar, Indore, Niphad and Pune registered negative statistic. Low level of rainfall will lead to drought stress and affects the crop productivity (Lobell et al., 2011a). The maximum and minimum values for trend statistic as well as indices for locations followed a similar pattern for the selected three climatic variables. Similar to mid future (RCP 4.5), the weight assigned by the PCA was highest in the case of minimum temperature (1.9550) and lowest with respect to rainfall (0.2609). The composite HSII has shown a complete shift when the emission scenario changed from RCP 4.5 to 8.5. The computed index was highest in Dharwad (0.9111) and lowest in Indore (-0.0312). The top slot for Dharwad is attributed to the highest trend statistic in minimum as well as maximum temperature. Similarly, for Indore lowest trend statistic in minimum temperature and rainfall led the location to bottommost slot.
Table 7: Climate trend and indices for mid future scenario (RCP 8.5)

| Station | Mann-Kendall’s Trend Statistic | Index values | HSII |
|---------|--------------------------------|--------------|------|
|         | Min T                         | Max T        | Rainfall | Min T | Max T | Rainfall |
| Dharwad | 0.1013^H                      | 0.0565^H     | 0.0027   | 1.9550^H | 1.9539^H | -0.1099 | 0.9111^H |
| Durgapura | 0.0271                        | 0.0127       | -0.0090  | 0.1142 | 0.2542 | -0.2159 | 0.0366 |
| Faizabad | 0.0322                        | 0.0205       | 0.0077   | 0.2416 | 0.5557 | -0.0647 | 0.1757 |
| Hisar   | 0.0284                        | 0.0139       | -0.0085  | 0.1464 | 0.2999 | -0.2111 | 0.0564 |
| Indore  | 0.0225^L                      | 0.0095       | -0.0140^L | 0.0000^L | 0.1308 | -0.2609^L | -0.0312^L |
| Jabalpur | 0.0302                        | 0.0061^L     | 0.0103   | 0.1915 | 0.0000^L | -0.0416 | 0.0359 |
| Junagadh | 0.0577                        | 0.0349       | 0.0142   | 0.8745 | 1.1141 | -0.0067 | 0.4753 |
| Kalyani | 0.0442                        | 0.0278       | 0.0102   | 0.5396 | 0.8398 | -0.0428 | 0.3206 |
| Kanpur  | 0.0284                        | 0.0105       | 0.0088   | 0.1470 | 0.1694 | -0.0551 | 0.0627 |
| Karnal  | 0.0266                        | 0.0112       | 0.0068   | 0.1017 | 0.1949 | -0.0733 | 0.0536 |
| Ludhiana | 0.0266                        | 0.0112       | 0.0070   | 0.1017 | 0.1951 | -0.0716 | 0.0540 |
| Malda   | 0.0552                        | 0.0313       | 0.0083   | 0.8109 | 0.9771 | -0.0600 | 0.4144 |
| Niphad  | 0.0436                        | 0.0203       | -0.0124  | 0.5232 | 0.5493 | -0.2465 | 0.1981 |
| Parbhani | 0.0579                        | 0.0342       | 0.0040   | 0.8788 | 1.0901 | -0.0982 | 0.4486 |
| Patna   | 0.0390                        | 0.0143       | 0.0149^H | 0.4102 | 0.3180 | 0.0000^H | 0.1746 |
| Pune    | 0.0757                        | 0.0475       | -0.0043  | 1.3207 | 1.6028 | -0.1735 | 0.6595 |
| Ranchi  | 0.0373                        | 0.0229       | 0.0148   | 0.3669 | 0.6513 | -0.0013 | 0.2439 |

PCA Weights | 1.9550^H | 1.9539 | 0.2609^L |

Note: 'H' indicates the highest value and the 'L' indicates the lowest value.

C1. Far Future (RCP 4.5: 2076-2100): In the case of far future under emission scenario RCP 4.5, all the variables have shown a positive and negative trend in one or other locations. For instance, Durgapura exhibited negative trend in minimum as well as maximum temperature, and Hisar, Jabalpur, Kalyani, Malda, Patna and Ranchi are expected to have negative growth in the amount of rainfall received (Table 8). For minimum temperature, Durgapura and Indore have shown a declining trend, whereas in maximum temperature, apart from Durgapura negative growth was noticed in Indore, Junagadh, Kanpur and Niphad. A distinct change has been observed in the weights arrived by the PCA with respect to far future in comparison to previous discussed scenarios. The weight was more in the case of maximum temperature (2.2478) and less with respect to minimum temperature (1.9515). A similar pattern was observed in maximum and minimum values for the selected three climatic variables viz., minimum temperature, maximum temperature and rainfall as well their index values. The estimated composite heat stress index was more intensive in the case of Dharwad (0.4866) and less intensive in Indore.
C2. Far Future (RCP 8.5: 2076-2100): The far future scenario under RCP 8.5, followed a similar pattern to mid future scenario of RCP 8.5 with minimum temperature and maximum temperature exhibiting positive trend statistic for all locations (Table 9) corroborating the projections by Basha et al., (2017). Further, it is expected that heat stress events are likely to be more under RCP 8.5 scenario. Durgapura, Hisar, Indore, Karnal, and Ludhiana are expected to have a negative growth in quantum of rainfall received. The maximum and minimum values for trend statistic as well as their corresponding indices across locations found to have a similar pattern for the selected three climatic variables. Unlike earlier discussed scenarios, the weight allotted by the PCA showed a radical change. It was highest with respect to maximum temperature (2.0412) and lowest in the case of rainfall (1.7342). The composite HSII was found to be more in Dharwad (0.5474) which is attributed to the minimum as well as maximum temperature, and less in Kanpur (-0.1489) owing to lowest trend statistic in minimum and maximum temperature for the far future period.

Table 8: Climate trend and indices for far future scenario (RCP 4.5)

| Station | Mann-Kendall’s Trend Statistic | Index values | HSII |
|---------|--------------------------------|--------------|------|
|         | Min T | Max T | Rainfall | Min T | Max T | Rainfall |         |
| Dharwad | 0.0503 | 0.0271 | 0.0042 | 1.9515 | 1.7838 | -0.7143 | 0.4866 |
| Durgapura | -0.0004 | -0.0090 | 0.0131 | 0.1176 | 0.2889 | -0.0397 | 0.0591 |
| Faizabad | 0.0080 | 0.0009 | 0.0049 | 0.4204 | 0.6991 | -0.6613 | 0.0738 |
| Hisar | 0.0079 | 0.0039 | -0.0016 | 0.4164 | 0.8205 | -1.1529 | 0.0135 |
| Indore | 0.0036 | -0.0160 | 0.0136 | 0.0000 | 0.0000 | -0.6004 | 0.0155 |
| Jabalpur | 0.0099 | 0.0049 | -0.0012 | 0.4889 | 0.8625 | -1.1186 | 0.0375 |
| Junagadh | 0.0133 | -0.0140 | 0.0057 | 0.6129 | 0.0836 | -0.6004 | 0.0155 |
| Kalyani | 0.0253 | 0.0384 | -0.0129 | 1.0463 | 2.2478 | -2.0094 | 0.2069 |
| Kanpur | 0.0028 | -0.0082 | 0.0083 | 0.2315 | 0.3202 | -0.3992 | 0.0246 |
| Karnal | 0.0086 | 0.0071 | 0.0075 | 0.4440 | 0.9562 | -0.4585 | 0.1517 |
| Ludhiana | 0.0086 | 0.0071 | 0.0077 | 0.4439 | 0.9563 | -0.4472 | 0.1535 |
| Malda | 0.0248 | 0.0162 | -0.0029 | 1.0301 | 1.3310 | -1.2468 | 0.1795 |
| Niphad | 0.0132 | -0.0004 | 0.0062 | 0.6102 | 0.6439 | -0.5581 | 0.1121 |
| Parbhani | 0.0159 | 0.0118 | 0.0079 | 0.7055 | 1.1476 | -0.4336 | 0.2286 |
| Patna | 0.0259 | 0.0156 | -0.0018 | 1.0678 | 1.3071 | -1.1696 | 0.1941 |
| Pune | 0.0204 | 0.0014 | 0.0102 | 0.8703 | 0.7188 | -0.2545 | 0.2150 |
| Ranchi | 0.0217 | 0.0349 | -0.0068 | 0.9170 | 2.1057 | -1.5424 | 0.2384 |

PCA Weights | 1.9515 | 2.2478 | 2.0094 |

Note: 'H' indicates the highest value and the 'L' indicates the lowest value
Table 9: Climate trend and indices for far future scenario (RCP 8.5)

| Station | Mann-Kendall’s Trend Statistic | Index values | HSII |
|---------|--------------------------------|--------------|------|
|         | Min T | Max T | Rainfall | Min T | Max T | Rainfall |          |
| Dharwad | 0.0969^H | 0.0500^H | 0.0075 | 1.7948^H | 2.0412^H | -0.7868 | 0.5474^H |
| Durgapura | 0.0396 | 0.0293 | -0.0143 | 0.2409 | 1.0170 | -1.5894 | -0.0595 |
| Faizabad | 0.0394 | 0.0133 | 0.0150 | 0.2356 | 0.2196 | -0.5083 | -0.0095 |
| Hisar   | 0.0453 | 0.0412 | -0.0130 | 0.3961 | 1.6069 | -1.5390 | 0.0833 |
| Indore  | 0.0488 | 0.0312 | -0.0070 | 0.4912 | 1.1118 | -1.3187 | 0.0510 |
| Jabalpur | 0.0531 | 0.0242 | 0.0201 | 0.6072 | 0.7626 | -0.3230 | 0.1879 |
| Junagadh | 0.0739 | 0.0489 | 0.0077 | 1.1706 | 1.9888 | -0.7777 | 0.4276 |
| Kalyani | 0.0741 | 0.0483 | 0.0094 | 1.1757 | 1.9586 | -0.7166 | 0.4340 |
| Kanpur  | 0.0307^L | 0.0089^L | 0.0063 | 0.0000^L | 0.0000^L | -0.8293 | -0.1489^L |
| Karnal  | 0.0437 | 0.0433 | -0.0181 | 0.3521 | 1.7130 | -1.7272 | 0.0607 |
| Ludhiana | 0.0437 | 0.0434 | -0.0183^L | 0.3520 | 1.7132 | -1.7342^L | 0.0594 |
| Malda   | 0.0707 | 0.0312 | 0.0288^H | 1.0854 | 1.1071 | 0.0000^H | 0.3936 |
| Niphad  | 0.0619 | 0.0279 | 0.0155 | 0.8458 | 0.9452 | -0.4904 | 0.2335 |
| Parbhani | 0.0608 | 0.0349 | 0.0245 | 0.8147 | 1.2953 | -0.1587 | 0.3503 |
| Patna   | 0.0527 | 0.0224 | 0.0147 | 0.5963 | 0.6743 | -0.5209 | 0.1346 |
| Pune    | 0.0780 | 0.0297 | 0.0211 | 1.2819 | 1.0327 | -0.2852 | 0.3643 |
| Ranchi  | 0.0514 | 0.0165 | 0.0141 | 0.5623 | 0.3770 | -0.5433 | 0.0711 |

PCA Weights | 1.7948 | 2.0412^H | 1.7342^L |

Note: ‘H’ indicates the highest value and the ‘L’ indicates the lowest value

**Shift in Mann-Kendall’s Trend Statistic**

Perusal of Table 9 and 10 indicates that the trend in climatic variables is expected to undergo a major shift both in RCP 4.5 and 8.5 scenarios. Barring a few locations like Dharwad, Durgapura, Hisar, Indore and Kanpur, the rest found to have an increasing trend in minimum temperature for all the periods (Table 10). Dharwad, Jabalpur, Kalyani, Parbhani, Pune and Ranchi have shown a raising maximum temperature in all periods considered for the study. In the case of rainfall, Dharwad, Junagadh, Kanpur, Karnal, Ludhiana, Niphad and Pune had positive trend in the existing scenario and they are expected to have higher quantum of rainfall for the predicted period as well (Table 9). Barring Dharwad, all locations registered positive trend in minimum temperature all the periods under consideration (Table 11). Similarly, positive trend was noticed in Dharwad, Hisar, Jabalpur, Junagadh, Kalyani, Karnal, Patna, Pune and Ranchi for maximum temperature and with respect to rainfall, it was for Dharwad, Jabalpur, Junagadh, Kanpur and Ranchi. Interestingly, Pune in RCP 4.5 and Junagadh and Ranchi in RCP 8.5 registered positive trend statistic for all periods.
### Table 10: Shift in Mann-Kendall’s trend statistic under existing and RCP 4.5 scenario

| Station     | Min T | Max T | Rainfall |
|-------------|-------|-------|----------|
|             | ES    | EF    | MF | FF | ES | EF | MF | FF | ES | EF | MF | FF |
| Dharwad     | ↓     | ↑     | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ |
| Durgapura   | ↑     | ↑     | ↓ | ↓ | ↓ | ↑ | ↑ | ↓ | ↑ | ↓ | ↑ | ↑ |
| Faizabad    | ↑     | ↑     | ↑ | ↑ | ↑ | ↓ | ↑ | ↑ | ↓ | ↑ | ↑ | ↑ |
| Hisar       | ↑     | ↑     | ↓ | ↓ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ |
| Indore      | ↑     | ↑     | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ |
| Jabalpur    | ↑     | ↑     | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ |
| Junagadh    | ↑     | ↑     | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ |
| Kalyani     | ↑     | ↑     | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ |
| Kanpur      | ↑     | ↑     | ↓ | ↓ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ |
| Ludhiana    | ↑     | ↑     | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ |
| Malda       | ↑     | ↑     | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ |
| Niphad      | ↑     | ↑     | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ |
| Parbhani    | ↑     | ↑     | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ |
| Patna       | ↑     | ↑     | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ |
| Pune        | ↑     | ↑     | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ |
| Ranchi      | ↑     | ↑     | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ |

Note: ES: Existing Situation, EF: Early Future, MF: Mid Future, FF: Far Future, ↓: Decreasing and ↑: Increasing

### Table 11: Shift in Mann-Kendall’s trend statistic under existing and RCP 8.5 scenario

| Station     | Min T | Max T | Rainfall |
|-------------|-------|-------|----------|
|             | ES    | EF    | MF | FF | ES | EF | MF | FF | ES | EF | MF | FF |
| Dharwad     | ↓     | ↑     | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ |
| Durgapura   | ↑     | ↑     | ↓ | ↓ | ↓ | ↑ | ↑ | ↓ | ↑ | ↓ | ↑ | ↑ |
| Faizabad    | ↑     | ↑     | ↑ | ↑ | ↑ | ↓ | ↑ | ↑ | ↓ | ↑ | ↑ | ↑ |
| Hisar       | ↑     | ↑     | ↓ | ↓ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ |
| Indore      | ↑     | ↑     | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ |
| Jabalpur    | ↑     | ↑     | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ |
| Junagadh    | ↑     | ↑     | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ |
| Kalyani     | ↑     | ↑     | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ |
| Kanpur      | ↑     | ↑     | ↓ | ↓ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ |
| Karnal      | ↑     | ↑     | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ |
| Ludhiana    | ↑     | ↑     | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ |
| Malda       | ↑     | ↑     | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ |
| Niphad      | ↑     | ↑     | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ |
| Parbhani    | ↑     | ↑     | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ |
| Patna       | ↑     | ↑     | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ |
| Pune        | ↑     | ↑     | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ |
| Ranchi      | ↑     | ↑     | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ |

Note: ES: Existing Situation, EF: Early Future, MF: Mid Future, FF: Far Future, ↓: Decreasing and ↑: Increasing
**Heat Stress Intensity Index for Predicted RCP Scenarios**

Figure 4 and 5 shows the comparative depiction of heat stress intensity index (HSII) across locations for different predicted periods like early future (2026-2050), mid future (2051-2075) and far future (2076-2100). Under RCP 4.5, trial locations like Dharwad and Parbhani need more emphasis (Figure 4), whereas in RCP 8.5, Dharwad, Pune, Junagadh and Kalyani have to be focussed. Overall, a radical shift in the HSII pattern has been noticed for which prioritization of regions (Sendhil et al., 2018) as well as crop and/or region specific adaptation strategy (Hunt et al., 2019) assumes prominence.
Figure 5: Heat stress intensity indices for trial locations under RCP 8.5
Conclusions and Implications

Climate change is a serious issue threatening the performance of agriculture especially in developing countries. Among abiotic stresses posed by the climate change impact, heat stress tops the slot affecting the crop growth and development. The present study is a pioneer attempt to predict the heat stress sensitive environments in Indian wheat production for the existing scenario using timeseries climate data as well as for three future periods' namely early future (2026-2050), mid future (2051-2075) and far future (2076-2100) for two emission scenarios viz., RCP 4.5 and RCP 8.5. The study has developed a methodological approach for prediction by integrating statistical downscaling of climate information and principal component analysis for computing heat stress intensity index (HSII) in 17 selected locations where heat stress field experiments are being conducted presently. The study has ranked the 17 locations based on the composite HSII for all the four periods under consideration with weights assigned through principal component analysis.

A few salient research results are highlighted for better understanding and concluding annotations. As the emission scenario changes, a considerable shift was noticed in the trend statistic as well as their correspondent indices for the three climate variables across locations. Further, the results explicitly showed a radical change in the computed HSII of trial locations from one period to another in both the emission scenarios. Pune in RCP 4.5 and Junagadh and Ranchi in RCP 8.5 registered positive trend for all the four periods comprising present and future. The major outcome of the investigation on HSII prediction was locations like Dharwad and Parbhani need more emphasis under RCP 4.5, whereas Dharwad, Pune, Junagadh and Kalyani needs a special focus with respect to RCP 8.5 emission scenario. Overall, a pragmatic approach has been developed to identify and prioritize trial locations for the predicted periods under changing climate scenario using statistical downscaling integrated with the principal component analysis. Such approach can be replicated to other regions wherein crops like wheat are found to be sensitive to heat stress. The study concludes with a policy recommendation for rational allocation of research funds based on the HSII in carrying out field trials on heat stress under resource constraint to sustain the national wheat production. Additionally, region specific adaptation strategies have to be developed against heat stress to boost the wheat yield.
Declaration

Funding: Source of funding is given in the Authors page.

Conflicts of interest/Competing interests: The authors declare that they have no competing and/or conflict of interest.

Ethics approval: Approved by the Priority Setting, Monitoring and Evaluation Cell.

Consent to participate: Not Applicable.

Consent for publication: I, on behalf of all authors, give my consent for the publication of identifiable details, which can include photograph(s) and/or videos and/or case history and/or details within the text (“Material”) to be published.

Availability of data and material: Available as supplementary files

Code availability: Available on request (for IMD data extraction)
References

Ahmad I, Deshan T, Tian FW, Mei W, Bakhtawar W (2015) Precipitation trends over time using Mann–Kendall and Spearman’s rho tests in Swat River Basin, Pakistan. Adv Meteorol 2015:15. doi:10.1155/2015/431860.

Anonymous. (2011). Climate: Observations, projections and impacts: India. Met Office. pp. 1-157.

Asseng, S. et al. (2013). Uncertainty in simulating wheat yields under climate change. Nature Clim. Change 3, 827-832.

Asseng, S., et al., (2014). Rising temperatures reduce global wheat production. Nature Clim. Change. 1-5. DOI: 10.1038/NCLIMATE2470.

Balla, K., Karsai, I., Bencze, S. and Veisz, O. (2012). Germination ability and seedling vigour in the progeny of heat-stressed wheat plants. J Acta Agron Hung, 60(4): 299-308.

Barnabas, B., Jager, K. and Feher, A. (2008). The effect of drought and heat stress on reproductive processes in cereals. Plant Cell Environ, 31: 11–38.

Basha, G., Kishore, P., Ratnam, M.V. et al. (2017). Historical and projected surface temperature over India during the 20th and 21st century. Sci Rep 7, 2987. https://doi.org/10.1038/s41598-017-02130-3.

Brown, L. (2009). Plan B 4.0: mobilizing to save civilization. W.W. Norton & Company, New York.

Christensen, J.H., Boberg, F., Christensen, O.B. and Lucas-Picher, P. (2008). On the need for bias correction of regional climate change projections of temperature and precipitation. Geophysical Research Letters, 35(20).

Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, et al. (2013). Long-term climate change: projections, commitments and irreversibility. Pp. 1029–1136 in T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, et al., eds. Climate change 2013: the physical science basis. Contribution of Working Group I to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press, Cambridge, United Kingdom and New York, NY, USA.
Fischer, G., Shah, M., Tubiello, F.N. and Van Velhuizen, H. (2005). Socio-economic and climate change impacts on agriculture: an integrated assessment, 1990–2080. Philosophical Transactions of the Royal Society B: Biological Sciences, 360(1463), pp.2067-2083.

Fowler, H.J., Blenkinsop, S. and Tebaldi, C. (2007). Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling. International journal of climatology, 27(12), pp.1547-1578.

Gudmundsson, L., Bremnes, J.B., Haugen, J.E. and Engen-Skaugen, T. (2012). Downscaling RCM precipitation to the station scale using statistical transformations-a comparison of methods. Hydrology and Earth System Sciences, 16(9), p.3383.

Hamed, K.H. (2008). Trend detection in hydrologic data: the Mann–Kendall trend test under the scaling hypothesis. J Hydrol 349:350–363.

Hatfield, J. L., K. J. Boote, B. A. Kimball, D. W. Wolfe, D. R. Ort, C. Izaurralde, et al. (2008). Agriculture. Pp. 21–74 in P. Backlund, A. Janetos, D. Schimel and M. Walsh, ed. The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States. U.S. Climate Change Science Program and the Subcommittee on Global Change Resources, Washington, D.C.

Hays, D., Mason, E., Do J, Menz, M. and Reynolds, M. (2007). Expression quantitative trait loci mapping heat tolerance during reproductive development in wheat (T. aestivum). In: Buck HT, Nisi JE, Salomo’n N (eds.), Wheat production in stressed environments. Springer, Amsterdam, pp 373-382.

Hedhly, A., Hormaza, J.I. and Herrero, M. (2009). Global warming and sexual plant reproduction. Trends Plant Sci, 14: 30–36.

Helsel, D.R., Hirsch, R.M. (1992). Statistical methods in water resources. Elsevier, Amsterdam.

Hirsch, R.M., Slack, J.R., Smith, R.A. (1982). Techniques of trend analysis for monthly water quality data. Water Resour Res 18:107–121.

Hunt, R.J., et al. (2019). Early sowing systems can boost Australian wheat yields despite recent climate change. Nature Clim. Change. 1-5. DOI:10.1038/s41558-019-0417-9.
IPCC. (2007). Climate change 2007: Impacts, adaptation and vulnerability. In: Working Group II Contribution to the Intergovernmental Panel on Climate Change Fourth Assessment Report. Cambridge University Press, Cambridge.

Ji, X., Shiran, B., Wan, J., Lewis, D.C., Jenkins, C.L.D., Condon, A.G., Richard, R.A. and Dolferus, R. (2010). Importance of pre-anthesis anther sink strength for maintenance of grain number during reproductive stage water stress in wheat. Plant Cell Environ, 33(6): 926-942.

Kahya, E., Kalayci, S. (2004). Trend analysis of streamflow in Turkey. J. Hydrol. 289:128–144.

Kaiser, H.F. (1960). The application of electronic computers to factor analysis. Educational and Psychological Measurement, 20, 141-151.

Kale, R.B., Ponnusamy, K., Chakravarty, A.K., Sendhil, R., Mohammad, A. (2016). Assessing resource and infrastructure disparities to strengthen Indian dairy sector, Ind. J. of Ani. Sci. 86 (6), 720-725.

Kirtman, B., S. B. Power, J. A. Adedoyin, G. J. Boer , R. Bojariu , I. Camilloni , et al. (2013). Near-term climate change: projections and predictability. Pp. 953–1028 in T. F. Stocker, D. Qin, G. K. Plattner, M. Tignor , S. K. Allen , J. Boschung , et al., eds. Climate change 2013: the physical science basis. Contribution of Working Group I to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press, Cambridge, United Kingdom and New York, NY.

Kumar, S., Raizada, A., Biswas, H., Srinivas, S., Biswajit, M. (2016). Application of indicators for identifying climate change vulnerable areas in semi-arid regions of India. Ecol. Ind. 70: 507-517.

Kumar, V., Sharad, K.J., Singh, Y. (2010). Analysis of long-term rainfall trends in India, Hydrol. Sci. J., 55:4, 484-496, DOI: 10.1080/02626667.2010.481373

Levene, H. (1960). Contributions to Probability and Statistics: Essays in Honor of Harold Hotelling, I. Olkin, et. al., eds. Stanford University Press, Stanford, CA, pp. 278-292.

Lobell, D. B., Banziger, M., Magorokosho C., Vivek, B. (2011a) Nonlinear heat effects on African maize as evidenced by historical yield trials. Nature Clim. Change. 1, 142–145.

Lobell, D.B., and Gourdji, S.M. (2012). The influence of climate change on global crop productivity. Plant Physiol., 160: 1686 –1697. doi:10.1102/science.1204531.
Lobell, D.B., Schlenker, W., and Costa-Roberts, J. (2011b). Climate trends and global crop production since 1980. Sci., 333: 616-620.

Mahida, D., Sendhil, R. (2017). Principal Component Analysis (PCA) based Indexing. In ‘Data Analysis Tools and Approaches (DATA) in Agricultural Sciences’, ICAR-IIWBR. DOI: 10.13140/RG.2.2.28187.57125.

Mamrutha, H.M., Khobra, R., Sendhil, R., Munjal, M., Prasad, S.V.S., Biradar, S., Mavi, G.S., Dhar, T., Bahadur, R., Bhagwan, J.H., Prakash, S., Singh, H., Shukla, R.S., Srivastava, M., Singh, C., Gosavi, A.B., Salunke, V.D., Dhyani, V.C., and Singh, G.P. (2020). Developing stress intensity index and prioritizing hotspot locations for screening wheat genotypes under climate change scenario. Ecol. Ind. 118: 106714. DOI: 10.1016/j.ecolind.2020.106714.

Rana, V., Ram, S., Sendhil, R., Nehra, K., Sharma, I. (2015). Physiological, biochemical and morphological study in wheat (Triticum aestivum L.) RILs population for salinity tolerance. J. of Agril. Sci. 7: 119-128.

Rathore, L.S., Attri, S.D. and Jaiswal A.K. (2013). State Level Climate Change Trends in India, Indian Meteorological Department, Ministry of Earth Science, Government of India. pp 1-147.

Ray, J.D., Gesch, R.W., Sinclair, T.R., and Hartwell, A.L. (2002). The effect of vapor pressure deficit on maize transpiration response to a drying soil. Plant Soil, 239:113–21.

Reynolds, M., Foulkes, J., Furbank, R., Griffiths, S., King, J., Murchie, E., Parry, M. and Slafer, G. (2012). Achieving yield gains in wheat. Plant Cell Environ, 35: 1799–1823.

Sendhil, R., Jha, A., Kumar, A., Singh S. (2017a). Tracking Wheat Yield Sensitivity to Weather Variability across Indian Transect for Climate Smart Farming, Extramural Project Report, ICAR-Indian Institute of Wheat and Barley Research, Karnal. pp 1-40.

Sendhil, R., Jha, A., Kumar, A., Singh S. (2018). Extent of vulnerability in wheat producing agro-ecologies of India: Tracking from indicators of cross-section and multi-dimension data. Ecol. Ind. 89: 771-780. DOI: 10.1016/j.ecolind.2018.02.053.

Sendhil, R., Jha, A., Kumar, A., Singh S., Kharub, A.S. (2017b). Status of vulnerability in wheat and barley producing states of India. J. of Wheat Res. 9 (1): 60-63.
Sendhil, R., Meena, R.P., Thimmappa, K., Singh, R. and Sharma, I. (2015). Sensitivity of rice-wheat system yields to climate change: Evidence from Haryana. Kar. J. of Agril. Sci. 28(5): 797-802.

Sendhil, R., Ramasundaram, P., Meena, R. P., Thimmappa, K. and Sharma, I. (2016). Tracking the yield sensitivity of rice-wheat system to weather anomalies. Nat. Aca. Sci. Let. 39(6): 401-405 (doi:10.1007/s40009-016-0485-6)

Shaykewich, C. F. (1995). An appraisal of cereal crop phenology modelling. Can. J. Plt. Sci. 75, 329-341.

Taylor, K.E., Stouffer, R.J. and Meehl, G.A. (2012). An overview of CMIP5 and the experiment design. Bulletin of the American Meteorological Society, 93(4), pp.485-498.

Teutschbein, C. and Seibert, J. (2012). Bias correction of regional climate model simulations for hydrological climate-change impact studies: Review and evaluation of different methods. J. Hydrol., 456, pp.12-29.

Themeßl, J.M., Gobiet, A. and Leuprecht, A. (2011). Empirical-statistical downscaling and error correction of daily precipitation from regional climate models. International Journal of Climatology, 31(10), pp.1530-1544.

Tian, J., Belanger, F.C., and Huang, B. (2009). Identification of heat stress responsive genes in heat-adapted thermal Agrostis scabra by suppression subtractive hybridization. J. Plant Physiol., 166: 588–601.

Wahid, A., Gelani, S., Ashraf, M., Foolad, M. (2007). Heat tolerance in plants: an overview. Environ. Exp. Bot., 61: 199–223.

Wardlaw, I.F., Dawson, I.A., Munibi, P. (1989) The tolerance of wheat to high-temperatures during reproductive growth. 2. Grain development. Crop Pasture Sci., 40: 15–24.

Wilby, R.L., Dawson, C.W., Barrow, E.M. (2002). SDSM - A decision support tool for the assessment of regional climate change impacts. Environmental Modelling & Software, 17(2), pp.145-157.

Wollenweber, B., Porter, J.R., Schellberg, J. (2003). Lack of interaction between extreme high-temperature events at vegetative and reproductive growth stages in wheat. J Agron Crop Sci, 189: 142-150.
Author Contribution Statement: SR and MHM conceived the idea of research; BG compiled the daily weather data for the experiment locations; SR and UG analyzed the data; MHM, RK, UG and RS wrote the manuscript; GPS edited and approved the final version of the paper.