ORIGINAL PAPER

Analysis of temperature variability and extremes with respect to crop threshold temperature for Maharashtra, India

Deepika Swami[1] · Prashant Dave[1] · Devanathan Parthasarathy[1,2]

Abstract

Temperature is one of the prime factors affecting crop yield and thereby, in changing climate, it is imperative to investigate the co-variability of crop yield and temperature change. Temperature change can manifest itself in multiple factors such as deviation from long-period average, daily scale variability and frequency/intensity of extreme temperature events. To add to the complexity, each of these factors can affect the crop yield differently which necessitates understanding their effect on crop yield individually as well as collectively. Concerning this, we evaluated their distinct and combined impact with respect to threshold temperature of three major crops, i.e. sorghum, sugarcane and millet sown across the Maharashtra State of India. Further, the temperature parameters were conflated using confirmatory factor analysis to formulate a temperature variability index (TVI) that helped in identifying the collective impact of these multiple factors on each crop. Results show that the TVI and sugarcane yield for Nagpur and Bhandara districts of the Vidarbha region exhibited negative co-variability (-0.30/year), implying the negative impact of temperature change on sugarcane. For sorghum, Wardha and Bhandara of Vidarbha region, Solapur of Pune region and Ratnagiri of Konkan region exhibited negative co-variability with TVI (~ -0.2 to -0.4/year). Contrary to sugarcane and sorghum, for millets, Akola, Amravati and Chandarpur districts in Vidarbha region; Hingoli, Parbhani, Nanded and Osmanabad in Marathwada region; Satara and Sangli in Pune region; Jalgaon in Nashik region and Ratnagiri; and Sindhudurg in Konkan region exhibited positive co-variability (0.50/year), signifying the favourable temperature conditions for sowing millet. Overall, due to the high exposure of districts to temperature change in Vidarbha and Pune regions, farmers in these districts are advised to refrain from sowing sorghum and sugarcane; instead, farmers can moderate the adverse effects of climate change by sowing millet due to the existence of conducive temperature for millet in Maharashtra. Further, analysis was used to suggest the region and climate-specific cropping pattern for other districts of Maharashtra that can be used by the policy makers to improve the situation of agriculture, farmers and economy of India.

1 Introduction

Indian agriculture, an employer of ~ 42% of the Indian population, occupies ~ 60% of the geographical area, contributes ~ 16% to GDP (World Bank 2016) and is majorly dependent on climate change (Kumar and Parikh 2001). Climate change manifesting as extreme events of temperature and precipitation has become one of the major threats for sustainable agricultural production in India (Aggarwal and Mall 2002; Barnwal and Kotani 2013) and consequently add a lot of pressure on water resources, crop yields, farmers, agricultural labours and livelihoods of people living in that region (Guiteras 2007; Pal and Al-Tabbaa 2010; Khajuria and Ravindranath 2012). Number of studies have identified that monsoon extremes are adversely affecting the crop yield across India (Ghosh et al. 2009, 2016; Singh and Ranade 2010; Singh et al. 2014). However, only limited studies have investigated the trend in temperature variability and extremes and their impact on crop yield over India's regional scale. Globally, the last three decades (1980 onwards) have witnessed an accelerated warming compared with the earlier period with a rise of 0.13 °C per decade (Jones et al. 2000; Houghton 2001),

✉ Deepika Swami
  dsdeepika782@gmail.com

  Prashant Dave
  prashantdave25@gmail.cm

  Devanathan Parthasarathy
  dp@hss.iitb.ac.in

[1] Interdisciplinary Program in Climate Studies, Mumbai, India

[2] Department of Humanities and Social Sciences, Indian Institute of Technology Bombay, Mumbai 400076, India

indicating the impact of globalization and urbanization on Earth's temperature. Lobell et al. (2011) identified that temperature change since 1980 has adversely impacted the wheat, maize and barley which resulted in an aggregated net loss of 40 million tonnes of crop yields per year. Lobell et al. (2012) found that a temperature above 30 °C can damage leaf photosynthetic apparatus resulting in reduced crop growth. Temperature change leads to the shortening of the growing period and reduces crop yield if no adaptation measures are followed (Minoli et al. 2019). India has also experienced an increase in surface air temperature by 0.57 °C from 1880 to 1990, which has critically affected the different phases of crop development leading to severe implications on food production (Srinivasan and Rathore 2006). Indian agricultural research institute (IARI 2019) indicated that 2 °C rise in temperature can reduce the yield of pearl millet by 10–15% per year and rice by 1 tonne/hectare (Sinha and Swaminathan 1991). Kumar et al. (2011) predicted that rice yield will decline 10% by 2030 in the Western Ghats and maize yield by 15–50% in coastal regions due to temperature change. Mahato (2011) projected that temperature change will decline the productivity of multiple crops by 10–40% towards the end of this century. Contrary to the adverse effects of temperature rise on crop yield, some studies have also identified the beneficial impact of temperature change on crop production. For example, Easterling et al. (2007) analysed that an increase in temperature by 1–3 °C associated with CO_2 increase will enhance the crop yields in mid to high latitude regions. These studies indicate that temperature change proved to be disastrous for crops in one region but benefitted the crops in other regions, emphasizing that orography, crop type and local environmental conditions also play an important role in determining the cropping pattern of a region. Considering this, a better understanding of the localised temperature change will help in taking the necessary actions to improve the crop productivity of a region. Thereby, the present work focuses on understanding the localised temperature change with respect to major crops sown in India.

Temperature is showing a significant change over the Indian subcontinent, particularly in the last few decades. For instance, a significant warming trend of 0.05 °C/10 years was observed from 1901 to 2003 with an accelerated rate of 0.22 °C/10 years in recent time from 1973 to 2003 (Kothawale and Rupa Kumar 2005). Arora et al. (2005) observed an increasing trend of maximum temperature over the Indian subcontinent and a rise in mean regional temperature over Southern and Western India. Although studies such as Arora et al. (2005), Kothawale et al. (2010) and Pal and Al-Tabbaa (2010) have shown the heterogeneous impacts of temperature over different regions of India; however, in these studies, the inter- and intra-regional heterogeneity existing at micro-scale, i.e. at district or block level, could not be captured. The exclusion of inter- and intra-regional heterogeneity leads to under-

representation of ground level problems from India's existing policies (Dubash et al. 2014; SANDRP 2014). For instance, Maharashtra did not incorporate local, i.e. district/block/village scale climate information while formulating its action plan on climate change (TERI 2014), which became one of the reasons for continuous declining crop productivity of Maharashtra state, India (Kalamkar 2011). The current study will address this gap by analysing the temperature change at localised scale, i.e. at the district level for Maharashtra state, India. The second most crucial issue that is being evaluated during the present work is whether the temperature change at the district scale is beneficial or harmful for the crops sown in the region which becomes another advancement of the current study over earlier studies.

Crop yield is primarily determined by its temperature threshold, i.e. optimum minimum and maximum temperature required by the respective crop (Wheeler et al. 2000; Luo 2011). Any temperature going beyond this range is considered the lethal temperature, resulting in detrimental effect on crop growth (Luo 2011). Direction and magnitude of crop damage are dependent on how often and how much temperature threshold is crossed in relation to the optimum temperature required for crop growth. For example, the temperature threshold for wheat lies in the range of (22–32.7 °C), maize (33–38 °C), rice (25–35 °C) and beans (24–32 °C) as observed by Kim et al. (1996), Maiti (1996), Wheeler et al. (2000), Brandner and Salvucci (2002), Porter and Semenov (2005) and Prasad et al. (2006). Temperature going beyond this range for the above mentioned crops leads to adverse impacts on their productivity. In line with this, Schlenker and Roberts (2009) also found that corn, soybean and cotton yield increased with increase in temperature up to 29 °C but afterward decreased sharply once crossing the threshold temperature (29 °C for corn, 30 °C for soybean and 32 °C for cotton). Deviation of temperature from the optimum crop temperature leads to smaller seed size, reduces the activity of rubisco enzyme, which acts as CO_2 assimilator in plants, ultimately leading to declining crop yield (Chowdhury and Wardlaw 1978; Holaday et al. 1992). This implies that understanding the crop threshold temperature would effectively help in the development of crop models and adaptation options. So far, none of the studies have identified the impact of temperature change by considering the crop threshold temperature of different crops across India.

Thereby, the current study addresses these research gaps by analyzing the temperature change parameters considering the optimum crop temperature for three crops, namely sorghum, sugarcane and millet, at district level for Maharashtra state, India. It will help in identifying whether temperature change is adversely or favourably impacting the crop yield of sorghum, sugarcane and millet in each district. On this basis, the present study proposes the district-specific cropping pattern concerning temperature change that can be effectively

utilised by policymakers while formulating agricultural policies for India.

In line of this, the current study aims (i) to analyse the district-level minimum and maximum temperature change parameters, i.e. deviation from long period average, frequency and intensity of temperature extremes, and daily scale variability by considering crop threshold temperature of three major crops, i.e. sorghum, sugarcane and millet and (ii) to suggest cropping pattern for each district by formulating the district-wise temperature variability index for Maharashtra, India.

2 Data and methodology

2.1 Study Area

The present study has focused on Maharashtra state (Fig. 1) as it is part of India's semi-arid belt and exhibits high agricultural and climate variability, which primarily manifests in monsoon and temperature variability (O'Brien et al. 2004; Swami et al. 2018). Maharashtra state is divided into five administrative boundaries by India's Central government. These five regions of Maharashtra (Fig. 1) are Marathwada (Aurangabad region) in South-East, Vidarbha region comprising Amravati and Nagpur divisions in the eastern side, Pune in West-Central

side, Nashik in North-West and Konkan in the west. Abbreviation for district names is mentioned under section A.1 of Supplementary Index.

Further, a description of the data, variables and crops used during analysis is provided in Section 2.2. All the temperature change parameters were estimated for the four principal monsoon months, i.e. June–September (JJAS).

2.2 Data description

2.2.1 Agriculture data

Crop yield data were sourced from International Crop Research Institute for Semi-Arid Tropics (ICRISAT) for 1966–2015 for each district of Maharashtra state, India. For the present analysis, district-wise data of three major crops sown in Maharashtra namely sorghum (*Sorghum bicolor*), sugarcane (*Saccharum officinarum*) and millet (*Pennisetum glaucum*) were obtained. Botanical name of the crops was obtained from US Department of Agriculture (2020) which follows the guidelines of International Association for Plant Taxonomy (2020) that provides scientific names to any plant/ crop type on the basis of its association to kingdom, subkingdom, super division, division, class, order, family, genus and
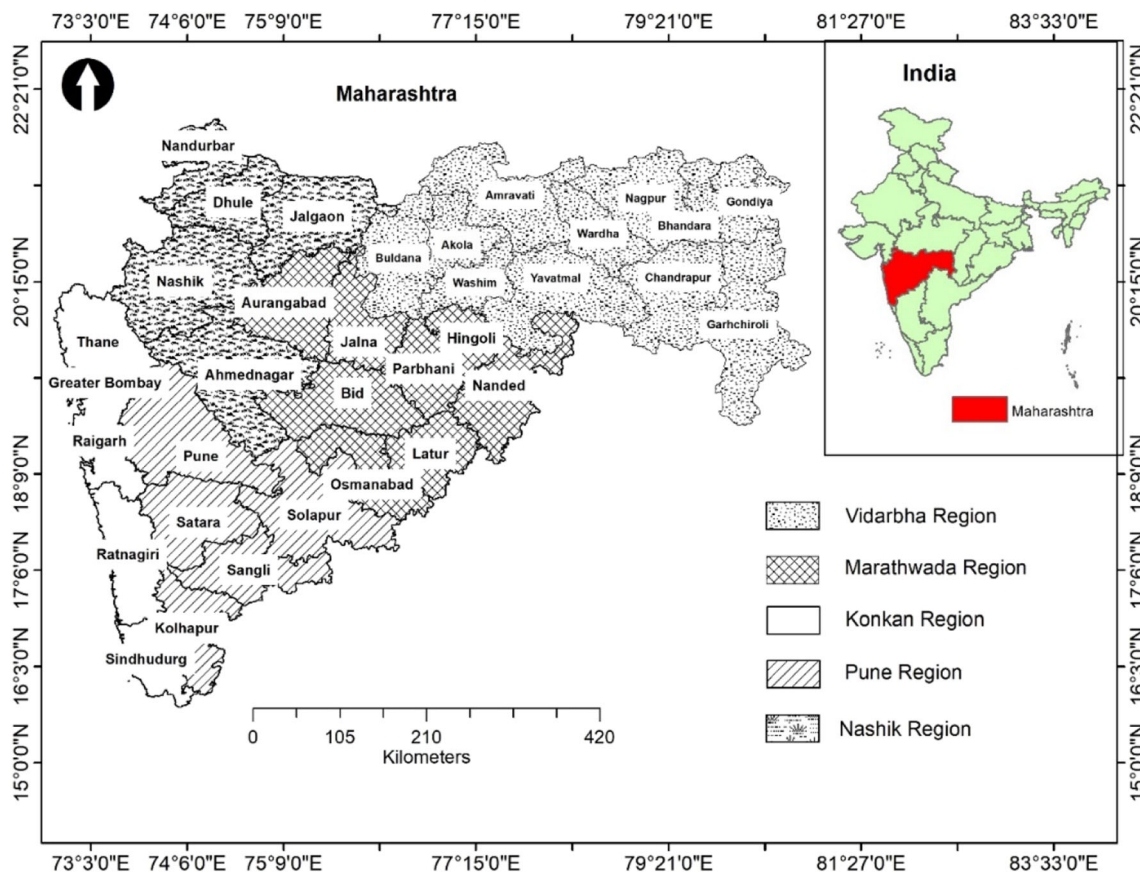

Fig. 1 Study region

species. Crops selected during present study are Kharif crops (Arthapedia 2015).

2.2.2 Temperature threshold for different crops

Daily temperature data were obtained from Indian Meteorological Department (IMD) which provides data at a resolution of 1° latitude × 1° longitude for the period of 1951–2018. The data belongs to the months of June, July, August and September (JJAS) as the crops considered during the present work are sown during JJAS. The data available at 1° × 1° grid resolution were interpolated at 0.25° × 0.25° using bilinear interpolation and have been used extensively for long-term temperature trend analysis (Kothawale et al. 2005; Pal and Al-Tabbaa 2009). The gridded data were averaged for each district using *ArcGIS version 10.1*. Optimum temperature requirement along with significance of each crop for Maharashtra and India is provided in Table 1.

These studies (Srivastava et al. 2010; DeFries et al. 2016; Verma et al. 2019; PriyamVandana et al. 2020) have considered multiple factors such as soil moisture, irrigation rate and evapotranspiration while estimating the threshold temperature values.

Temperature change parameters used during the present work are discussed in the subsequent section.

2.3 Temperature change parameters

It is noteworthy that the gridded temperature data were available from the year 1951–2018; however, district-scale crop data were available only from 1966 to 2015. Therefore, coinciding time period of 1966–2015, i.e. 49 years were used for analysing the different parameters of temperature change. Minimum (T^c_{min}) and maximum (T^c_{max}) temperature required by the crops (refer to Table 1) were considered as the threshold to

analyse the variations in different parameters of "temperature change" for both Tmin and Tmax. Temperature change parameters analysed during the present study include frequency/intensity, deviation from long period mean (DLPA) and daily-scale variability (DSV) for *minimum and maximum temperature*, calculated as follows.

2.3.1 Deviation from long-period average

The deviation from long-period average was calculated for both Tmin and Tmax by calculating the deviation of Tmin and Tmax from long-term average.

(a) X^{min}_{DLPA} for minimum temperature (Tmin):

For a given crop and a given year (y), the daily minimum temperature was averaged across days and subtracted from the minimum temperature required by the crop, as shown in equations (1)–(2).

$$\overline{X}_{.y} = \sum_{d=1}^{D} X_{dy}/D \qquad (1)$$

T^c_{Min} = minimum temperature required by each crop

$$X^{min}_{DLPA} = \overline{X}_{.y} - T^c_{Min} \qquad (2)$$

(b) X^{max}_{DLPA} for maximum temperature (Tmax):

Daily maximum temperature was averaged across days, which was subtracted from the maximum temperature required by each crop (check the value of maximum temperature from Table 1), as shown in the equations (3)–(4).

Table 1 Tmin and Tmax required by each crop

Crops	Significance of crop	Maximum temperature	Minimum temperature	References
Sorghum	Sorghum is considered as 5th most important crop over the globe and its production in India is around 7.4 million tonnes (FAO 2019). In India, around 85% of sorghum is cultivated in Maharashtra both during the monsoon as well as winter season.	32	27	Srivastava et al. (2010)
Sugarcane	India stands at 2nd position in the world in terms of sugarcane production with the largest contribution coming from UP, Maharashtra, Karnataka and Andhra Pradesh (FAO 2019).	32	28	Verma et al. (2019); PriyamVandana et al. (2020)
Millet	In India, millet occupies 3rd largest area after rice and wheat and is mainly grown in Maharashtra, Rajasthan, Gujarat, Haryana, Uttar Pradesh, Tamil Nadu and Karnataka (Yadav et al. 2012). Millet is resilient to climate variability with more drought resistant and higher temperature tolerance because of its shorter growing period of around 70–75 days (DeFries et al. 2016).	30	25	DeFries et al. (2016)

$$\overline{X}_{.y} = \sum_{d=1}^{D} X_{dy}/D \tag{3}$$

T^c_{Max} = maximum temperature required by each crop

$$X_{DLPA}^{max} = \overline{X}_{.y} - T^c_{Max} \tag{4}$$

where

d	day; D = total number of days; y = year;
X_{dy}	Daily temperature for each district;
$\overline{X}_{.y}$	Average daily temperature for each year;
X_{DLPA}^{min}	Deviation from long-period average for minimum temperature;
X_{DLPA}^{max}	Deviation from long-period average for maximum temperature

2.3.2 Daily-scale variability ($\sigma_.$)

Variability defined here is the daily scale variability (DSV) of temperature for JJAS. Change in seasonal variability for all the 49 years was calculated for maximum and minimum temperature, as shown in Equation (5).

$$\sigma_y^{Min} = \sum_{d=1}^{D}(X.y - T^c_{min})^2/(D)$$
$$\sigma_y^{Max} = \sum_{d=1}^{D}(X.y - T^c_{max})^2/(D) \tag{5}$$

where

σ_y^{Min}	Daily scale variability for minimum temperature;
σ_y^{Max}	Daily scale variability for maximum temperature;
T^c_{min}	Minimum temperature required by each crop;
T^c_{max}	Maximum temperature required by each crop

2.3.3 Intensity and frequency of extreme temperature events

In the present work, the definition of intensity and frequency is motivated by Krishnamurthy et al. (2009). As our objective was to identify the extreme events according to the crops, thereby, threshold value considers the minimum and maximum temperature required by the crops selected for analysis (shown in Table 1).

(a) Frequency for Tmin (f_{yj}^{min})

Frequency for Tmin is defined as the number of days with temperature less than the minimum temperature required by each crop. The minimum temperature required by the crops (T^c_{min}) is mentioned in Table 1. Equation (6) is used to calculate the frequency of Tmin over districts of Maharashtra for the period of 1966–2015.

$$f_{yj}^{min} = \sum_{d=1}^{D}\left(F_{\left(T_{dyj} < T^c_{min}\right)}\right) \tag{6}$$

(b) Frequency for Tmax (f_{yj}^{max})

Frequency of Tmax is defined as the number of days having temperature greater than the maximum temperature (T^c_{max}) required by each crop. The maximum temperature required by the crops is mentioned in Table 1. Equation 7 is used to calculate the frequency of Tmax over districts of Maharashtra, India.

$$f_{yj}^{max} = \sum_{d=1}^{D}\left(F_{\left(T_{dyj} > T^c_{max}\right)}\right) \tag{7}$$

(c) Intensity for Tmin (r_{yj}^{min})

Intensity for Tmin was calculated by averaging the minimum temperature for the days with minimum temperature less than the minimum temperature required by each crop (T^c_{min}) (Equation 8).

$$r_{yj}^{min} = \left\{\frac{\sum_{d=1}^{D}\left(F_{\left(T_{dyj} < T^c_{min}\right)}\right) \times T_{dyj}}{f_{yj}^{min}}\right\} \tag{8}$$

(d) Intensity for Tmax (r_{yj}^{max})

Intensity for Tmax was calculated by averaging the maximum temperature of the days with temperature greater than the maximum temperature (T^c_{max}) required by each crop (Equation 9).

$$r_{yj}^{max} = \left\{\frac{\sum_{d=1}^{D}\left(F_{\left(T_{dyj} > T^c_{max}\right)}\right) \times T_{dyj}}{f_{yj}^{max}}\right\} \tag{9}$$

where

T_{dyj}	temperature on day d in year y at district j;
f_{yj}^{min}	frequency of minimum temperature for year y at district j;
f_{yj}^{max}	frequency of maximum temperature for year y at district j;
r_{yj}^{min}	

intensity of minimum temperature for year y at district j;

$r_{yj}^{\max}$ intensity of maximum temperature for year y at district j;

F Indicator function, whose value is 1 when true otherwise 0.

2.3.4 Trend analysis

All the temperature change parameters were first normalised, followed by estimating the trend using non-parametric Mann-Kendall method, which is a widely used tool for trend analysis of climatological variables, such as temperature and precipitation (Kothawale et al. 2010; Rao et al. 2014). The statistical significance of trend was tested at $\alpha = 0.10$. For the sake of convenience, only significant results are shown in the paper.

2.4 Temperature variability index

Temperature variability index (*TVI*) was estimated using confirmatory factor analysis, assuming that temperature change manifests in the following factors: deviation from long-period average (*DLPA*), daily-basis temperature variability (*DSV*), frequency and intensity of extreme temperature events.

$$TVI = \Lambda_x X^T + \zeta \qquad (10)$$

Here, $TVI \in R^{n \times 1}$ is temperature variability index, $\Lambda_x \in R^{n \times m}$ is factor loading, $\zeta \in R^{n \times 1}$ is the measurement error, n is the number of observations and m are the number of factors. The problem statement of factor loading is that given a set of measurements $X \in R^{n \times m}$ (here comprised DLPA, DSV, frequency and intensity of extreme temperature), factor analysis estimates factor loadings Λ_x and *TVI*. Further, using the estimated factor score, the slope of *TVI* was calculated, where a negative slope represents a decrease in *TVI* and vice versa. It is to be noted that the positive value of *TVI* indicates a negative trend of frequency and DSV while a positive trend of DLPA and intensity. Significance testing of the estimated slope was performed at $\alpha = 0.1$. Additionally, a cropping pattern was proposed in the districts based on *TVI*, where high *TVI* refers to the positive impact, and low *TVI* refers to the negative impact on crop yield.

Flow of the work

The flow of the work can be understood with the following steps:

i) Calculate the temperature variability parameters using Equations (1)–(9).
ii) Calculate the TVI using factor analysis using Equation (10).
iii) Repeat steps (i) and (ii) for all the districts and crops.

3 Results and discussion

The trend of temperature parameters, i.e. frequency, intensity, DSV and DLPA for three major crops, i.e. sorghum, sugarcane and millet, are presented in Fig. 2. The study proposes the cropping pattern for each region of Maharashtra based on the manifestation of different temperature change parameters towards the temperature variability index (Fig. 3). Firstly, we present the Tmin change parameters for three major crops sown in Maharashtra, India.

3.1 Tmin change parameters with respect to crop threshold

(a) Frequency

Decrease in the frequency of Tmin has a positive impact on crop yield (Lobell and Field 2007; Lobell et al. 2011). Results for the frequency of Tmin for sorghum, sugarcane and millet are presented here.

Sorghum Osmanabad district of Marathwada region and Raigarh district of Konkan region displayed negative trend (~ -0.2 to -0.4 number of days/year) for the frequency of Tmin while Solapur district of Pune region showed a positive trend (~ 0.2–0.4 number of days/year) (Fig. 2a). Contrasting results observed between districts highlight the district level heterogeneity existing over Maharashtra, India. Decreasing trend for frequency indicates that the number of days away from the Tmin required by the sorghum are decreasing, signifying the favourable conditions to sow sorghum in those districts (Lobell and Field 2007).

Sugarcane Akola district of Vidarbha region, Jalgaon district of Nashik region, Raigarh district of Konkan region and Hingoli, Parbhani and Osmanabad districts of Marathwada regions exhibited a negative trend (~ -0.2 to -0.4 number of days/year) for the frequency of Tmin (Fig. 2b). Other districts of Vidarbha, Marathwada, Nashik, Pune and Konkan regions displayed an insignificant trend (Fig. 2b). Different Tmin frequency pattern of adjacent districts towards sugarcane yield indicates the different levels of exposure to temperature change in the districts of the same region, which supports our argument of district-level heterogeneity and highlights the need to formulate a District Action plan on Climate Change (DAPCC).

Millet Akola and Chandarpur districts showed a negative trend for frequency (> -0.5 number of days/year) in comparison with the Amravati district of Vidarbha region (~ -0.2 to -0.4 number of days/year) (Fig. 2(c)). Similarly, Hingoli, Osmanabad and Parbhani (~ -0.4 to -0.6 number of days/year) districts exhibited a large decreasing trend
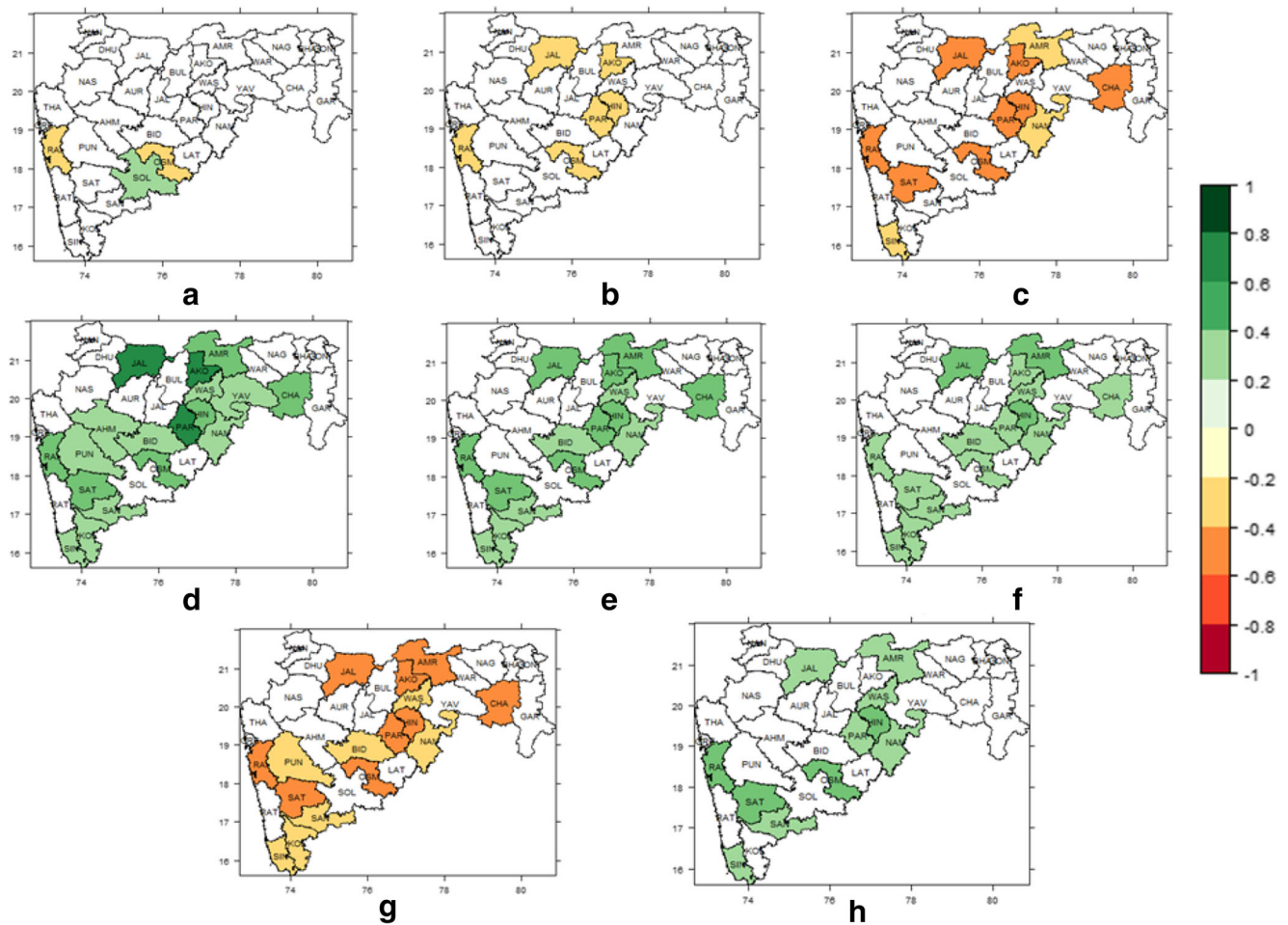
Fig. 2 Temperature change parameters with respect to crop threshold. **a–c** Frequency; **d–f** intensity; **g** DSV; **h** DLPA

compared with the Nanded district (− 0.25 number of days/year) of the Marathwada region. Similarly, Ratnagiri district (∼− 0.4 to − 0.6 number of days/year) showed decreasing trend in comparison to the Sindhudurg district (∼− 0.2 to − 0.4 number of days/year) of Konkan region (Fig. 2c). It warrants that each district should be studied individually a priori to formulating the policies at a macro scale as these are the regional level issues that lead to national and global scale problems.

Results support our argument for the existence of regional-scale heterogeneity of Tmin variability across Maharashtra, India. The results are not in accordance with Arora et al. (2005), Aggarwal et al. (2008) and Pal and Al-Tabbaa (2010), who have reported a non-significant trend for Tmin across Maharashtra, India. There could be two reasons for the observed differences in current findings from the earlier studies. First, the current study considers the crop specific threshold temperature for calculating Tmin variability parameters, which was not considered by earlier such studies. Second, previous studies (Arora et al. 2005; Aggarwal et al. 2008; Pal and Al-Tabbaa 2010 have carried out the analysis for Tmin at macro scale, i.e. by considering the whole Central

India, including Maharashtra as one unit, and not at the micro-scale, i.e. at the district level.

(b)   Intensity

Increase in intensity of Tmin has a positive impact on crop yield (Lobell and Field 2007), and the results with respect to sorghum, sugarcane and millet are presented in this section.

Sorghum Increasing trend for intensity of Tmin was observed across majority of the districts in Maharashtra ranging between (∼0.2–0.9 normalised Tmin/ year), indicating that Tmin in these regions is approaching the minimum temperature required by sorghum, signifying the favourable conditions to sow sorghum in these districts. Amravati, Washim, Yavatmal and Chandarpur districts showed a positive trend (∼0.4–0.8 normalised temperature/year) while Akola district which also belongs to the Vidarbha region, exhibited the higher rate of increase in Tmin (> 0.8 normalised temperature/year) (Fig. 2d). Similarly, Nanded and Bid districts (∼0.2–0.4 normalised Tmin/year) exhibited a lower rate of increase in minimum temperature as compared with
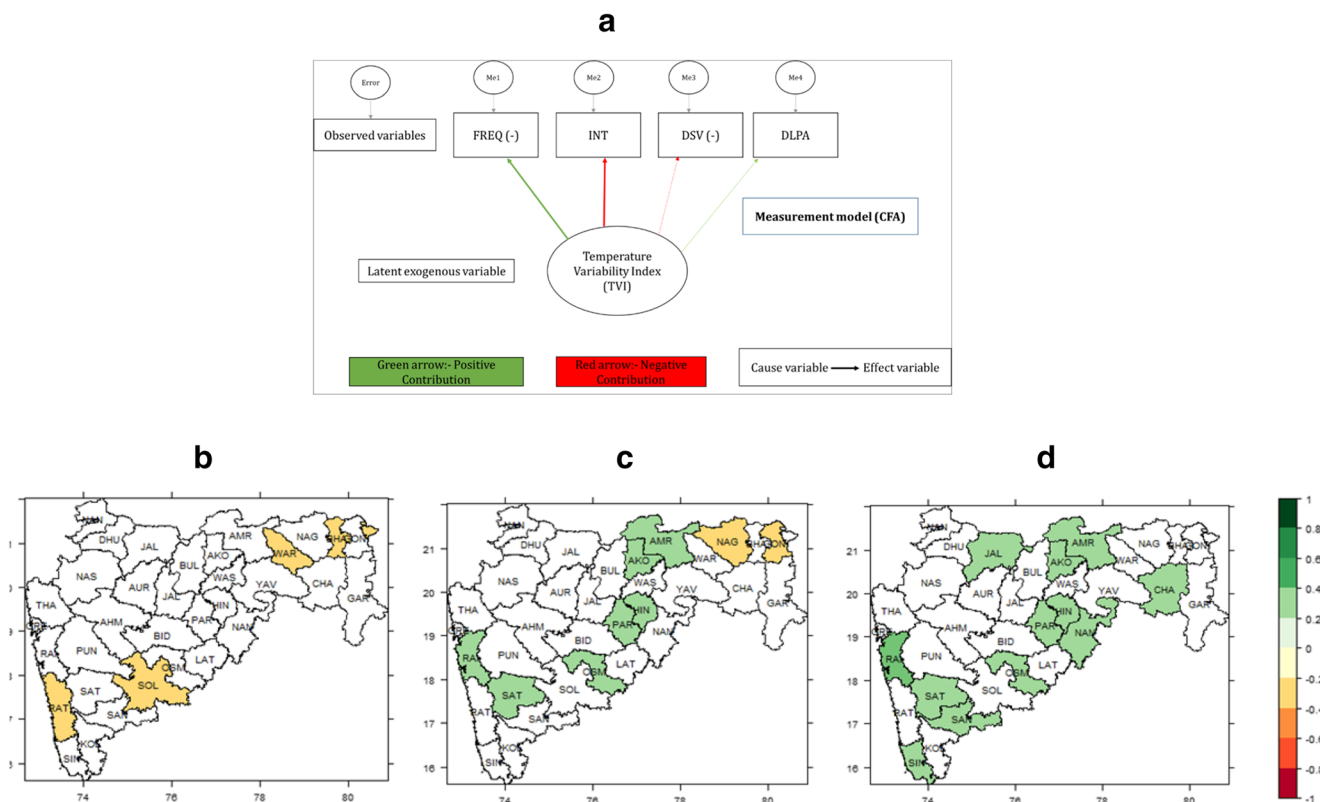
Fig. 3 Results for temperature variability index (TVI). **a** Model for TVI; TVI with respect to **b** sorghum, **c** sugarcane and **d** millet

Parbhani and Hingoli districts (~0.5–0.8 normalised Tmin/year) of the Marathwada region (Fig. 2d). Like Vidarbha and Marathwada region, in the Pune region, Sangli, Pune and Kolhapur districts (~0.2–0.4 Tmin normalised/year) exhibited a smaller increase in minimum temperature as compared with the Satara district (~0.4–0.5 Tmin normalised/year). Further, Nashik region's Jalgaon district exhibited the largest increase in the same region (Fig. 2d). Results strengthen our argument of intra-regional heterogeneity existing across different Maharashtra districts and warrant a district level analysis to understand the impact of different minimum temperature change parameters on crop yield.

Sugarcane Akola, Amravati and Chandarpur (~0.5 normalised Tmin/year) districts displayed a large increase in trend as compared with the Washim district (~0.30 normalised Tmin/year) of the Vidarbha region (Fig. 2e). Similarly, Parbhani, Hingoli and Osmanabad districts (~0.50 normalised Tmin/year) exhibited a positive trend in comparison with Bid and Nanded districts (~0.30 normalised Tmin/year) of the Marathwada region (Fig. 2e). Further, Satara district (~0.50 normalised Tmin/year) exhibited an increasing trend compared with the Sangli and Kolhapur districts (~0.30 normalised Tmin/year) of the Pune region. Jalgaon of the Nashik region and Ratnagiri of the Konkan region also exhibited the largest increasing trend for the intensity of Tmin.

Millet Amravati district displayed a positive trend (~0.3–0.5 normalised Tmin/year) for intensity in comparison with the Akola, Washim and Chandarpur districts (~0.2–0.4 normalised Tmin/year) of the Vidarbha region (Fig. 2f). Bid, Osmanabad, Parbhani and Nanded districts displayed a lesser increasing (~0.20 normalised Tmin/year) trend in comparison with the Hingoli district (~0.50 normalised Tmin/year) of the Marathwada region (Fig. 2f). Jalgaon district of Nashik region; Satara, Sangli, and Kolhapur districts of Pune region; and Raigarh and Sindhudurg districts of Konkan region displayed almost similar trend (~0.30 normalised Tmin/year) for the intensity of Tmin. Districts exhibited almost a similar trend across different Maharashtra regions, and district-scale heterogeneity was observed to a smaller extent for millet crop. Considering this, one should estimate the crop-wise trend of all temperature parameters at the district scale to understand how to improve the crop productivity of any district. Results do not corroborate to Rao et al. (2014), who have reported an insignificant trend across Maharashtra districts for Tmin. Similar to the results of frequency of Tmin, the observed contrasting results can be attributed to the consideration of crop threshold temperature for analyzing the different parameters of Tmin, i.e. frequency and intensity. This minimum threshold temperature consideration for sorghum, sugarcane and millet was missing in earlier studies.

(c)   Daily scale variability (DSV)

Sorghum High intra-regional heterogeneity at district scale was observed across Maharashtra, India. Akola, Amravati and Chandarpur districts displayed a large negative trend ($\sim$ $-$ 0.50/year) trend compared with the Washim ($\sim$$-$ 0.3/year) district in the Vidarbha region. On a similar note, Parbhani, Hingoli and Osmanabad districts of the Marathwada region exhibited a decrease in daily scale variability ($-$ 0.50/year) as compared with Bid and Nanded districts ($\sim$$-$ 0.30/year) of the same region (Fig. 2g). Daily-scale variability is decreasing at a higher rate in Satara of the Pune region and Raigarh of the Konkan region than the neighbouring districts of the same region (Fig. 2g). Results do not corroborate to Pal and Al-Tabbaa (2010), who has reported that the daily-scale variability of Tmin is insignificant over Maharashtra, which is mainly due to their analysis at the larger domain in comparison with the micro scale (district level) analysis performed by our study. The variability is expected to increase when we go further at the granular level.

Sugarcane and millet Results for daily-scale variability were found to be similar for sugarcane and millet crop as of sorghum, thereby, results of only sorghum crop are shown in Fig. 2g. Figures for sugarcane and millet are shown under *section A.2 in Supplementary Index.*

(d)   Deviation from long-period average (DLPA)

Increase in deviation of temperature from the optimal temperature required by the crops leads to a negative effect on crop yield (Lobell et al. 2011; Raju et al. 2013). Amravati and Washim district of Vidarbha region, Parbhani, Hingoli, Osmanabad and Nanded districts of Marathwada region, Satara and Sangli district of Pune region and Raigarh and Sindhudurg districts of Konkan region displayed an increasing trend for DLPA (Fig. 2h). DLPA is same for all the crops, i.e. sorghum, sugarcane and millet, and thereby, the result of only one crop is shown in Fig. 2h. This can become clear from Equation (4) where we can observe that with changing constant (T^c_{min}), the slope of DLPA would not change, and only the change in intercept would be observed. Figures for sugarcane and millet are shown under *section A.3 in Supplementary Index.*

Apart from these temperature factors, other factors such as rainfall, fertilizers, socio-economic, land-use factors and soil moisture also play a significant role towards crop yield (Mandal et al. 2001), which are not captured during the present analysis and are one of the limitations of the current work.

The next section explores the effects of Tmax variability on major crops sown in Maharashtra.

3.2 Tmax variability parameters with respect to crop threshold

Similar to Tmin, DLPA, DSV, frequency and intensity were also calculated for maximum temperature (Tmax) for each crop. We found that none of the districts displayed a significant trend for DLPA, DSV, frequency and intensity for Tmax. It entails that districts of Maharashtra are not affected due to change in maximum temperature. The findings corroborate to Pal and Al-Tabbaa (2010), who also observed an insignificant impact of Tmax for Kharif season across Maharashtra, India. Due to the insignificant trend found in Tmax variability, no further analysis was performed to formulate temperature variability index for maximum temperature.

3.3 Temperature variability index

Till now, we analysed the trend of temperature parameters for three major crops and observed the inter- and intra-regional heterogeneity across districts of Maharashtra, India. However, from the planning and developmental strategies perspective, considering the variability of each temperature parameter would complicate the temperature effect quantification in a wholesome manner. Therefore, formulation of a unified index can assist in identifying the crop response to the combined effect of all temperature change parameters. Policymakers can utilise this unified parameter to disburse the funding amount to the districts having the highest exposure to temperature change.

Considering this, we formulated a temperature variability index (TVI) using confirmatory factor analysis. The model followed for calculating *TVI* is shown in Fig. 3a, which depicts that *TVI* as a latent exogenous variable or factor that manifests in intensity, frequency, DLPA and DSV, which are the observed variables during the current analysis.

Parameters of temperature change are represented by a square, while a circle represents *TVI*. The influence of factor (*TVI*) on each parameter (DLPA, DSV, frequency and intensity) is represented by single headed arrow going from latent variable to observed variables (Fig. 3a). In this way, this measurement provides a more parsimonious understanding of the covariance among the observed variables. Formulation of *TVI* gives clarity about temperature change in a particular district, which will help in devising the planning and development strategies by the administration. Results of *TVI* are presented crop-wise in Fig. 3b–d. Negative and positive *TVI* values in Fig. 3b–d indicate the respective adverse and beneficial effects of temperature change on the crops sown in those particular districts. As the parameters related to Tmax did not show any statistically significant trend, thereby, only the parameters associated with Tmin were used to formulate TVI.

TVI and cropping pattern

The current study has proposed the cropping pattern by considering the combined effect of all temperature change parameters, i.e. by formulating temperature variability index (TVI) with respect to sorghum, sugarcane and millet for each district of Maharashtra.

Sorghum Wardha and Bhandara of Vidarbha region, Solapur of Pune region and Ratnagiri of Konkan region displayed a negative trend of *TVI* ranging from ($\sim - 0.2$ to $- 0.4$ [-]/year) (Fig. 3b), implying the negative impact of temperature change on sorghum yield. Thereby, our study suggests not sowing sorghum in Wardha, Bhandara, Solapur and Ratnagiri districts. Moreover, negative *TVI* was exhibited across some districts in Vidarbha, Pune and Konkan regions, but no significant impact in other districts of these regions. These regional disparities may result from local level factors, including land-use changes, urbanization, deforestation and the introduction of green revolution in Central and Northern parts of India (Pal and Al-Tabbaa 2009; Ghosh et al. 2011).

Sugarcane Amravati and Akola districts showed a positive trend for *TVI* (0.30/year) while Nagpur and Bhandara districts of the Vidarbha region exhibited negative trend ($- 0.30$/year) for *TVI*. Hingoli, Parbhani and Osmanabad districts of Marathwada region; Satara of Pune region and Raigarh of Konkan region displayed a positive trend (0.30/year) for *TVI* (Fig. 3c). Thereby, our study suggests not sowing sugarcane, especially in Nagpur and Bhandara districts of the Vidarbha region. However, as per our analysis, Tmin variability did not affect the sugarcane yield in Marathwada, Pune and Konkan region, implying the contribution from other climate and hydrological factors like monsoon, soil moisture, groundwater towards declining sugarcane yield in these regions (Swami et al. 2018). Additionally, sugarcane is a water-intensive crop and requires a massive amount of water for its different stages of growth, and due to the unavailability of irrigation and groundwater, the probability of failure of sugarcane increases more in comparison with other crops. Thereby, it is not recommended to sow sugarcane as it is adversely impacted due to climate variability in Maharashtra. The Maharashtra state government should provide irrigation facilities, water harvesting facilities and check-dams to increase sugarcane productivity in the state (Srivastava 2012).

Millet Almost all the districts in Maharashtra exhibited a positive trend for *TVI* with respect to millet at an approximate rate of 0.30/year. Akola, Amravati and Chandarpur districts in Vidarbha region; Hingoli, Parbhani, Nanded and Osmanabad in Marathwada region; Satara and Sangli in Pune region; Jalgaon in Nashik region; and

Ratnagiri (0.50/year) and Sindhudurg in Konkan region displayed a positive trend for *TVI* (Fig. 3d) signifying suitable conditions to grow millet considering the positive effect of temperature change in these districts.

4 Conclusion

The study analyses the response of each district to temperature variability and its extremes. Present work revealed that sorghum in Wardha and Bhandara districts of Vidarbha region and Solapur district of Pune region is more affected by the change in Tmin. Sugarcane yield in Nagpur and Bhandara districts of Vidarbha region is sensitive to Tmin change while sugarcane yield in other districts of Marathwada, Pune and Konkan regions gets benefitted by Tmin change. Tmin change does not lead to any negative impact on millet yield across districts of Maharashtra, India. Results show that temperature change has proved beneficial for a majority of the districts concerning crop yield of sugarcane and millet. Millet is found to be climate resilient crop, and therefore, farmers are advised to sow millet in Maharashtra in the absence of any adaptive strategy. Farmers can also sow sugarcane in Vidarbha and Pune regions, provided other resources and infrastructure such as water harvesting and irrigation facilitates are adequate in these regions. Contrary to the Tmin variability, no Tmax effect was found on the crop yield across Maharashtra. For policymakers, the present study recommends that Vidarbha and Pune regions should be given the highest priority while formulating policy for the state of Maharashtra as crop yield in the districts of these regions exhibits the largest impact due to temperature change.

The results highlight that districts of the same region displayed intra-regional heterogeneity, thereby strengthening the argument of having a district action plan on climate change (DAPCC). Government should evaluate the situation of each district separately before allocating funds and resources for development purposes so that amount of funds can be utilised according to the need of that particular region. Different levels of impacts on each district signify that one should also consider agro-ecological and other socio-economic parameters to gain deeper insight into the existing situation, which is beyond the scope of the current study and to be addressed in the future work. The framework developed during the current study can be utilised to build the model for cropping pattern with respect to climate change at national scale, i.e. for the entire Indian subcontinent.

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