Pure Appl. Geophys. 178 (2021), 155–168

https://doi.org/10.1007/s00024-020-02642-6

Pure and Applied Geophysics

Future Climate Change Scenario over Maharashtra, Western India: Implications of the Regional Climate Model (REMO-2009) for the Understanding of Agricultural Vulnerability

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Abstract—The present investigation attempts to understand the near-term (up to 2050) and distant (up to 2100) future climatic changes over Maharashtra. Trend analysis of projected monsoon rainfall and temperature was carried out with the use of parametric and non-parametric statistical techniques. All the meteorological sub-divisions in Maharashtra reveal a significant increase in monsoon rainfall during 2015–2100 (by 150–210 mm), except Konkan. In a near-term future, parts of the Vidarbha Sub-division and Western Ghats exhibit a significant increase in rainfall by 82–225 mm. Almost the entire state is very likely to experience a rise in annual mean temperature (AMT) by 0.5–2.5 °C up to 2050. The state is very likely to experience considerably warmer conditions post-2033. In particular, parts of Konkan and Madhya Maharashtra Sub-divisions will register significant warming (by 1–2.5 °C). The estimations also signify a marginal increase in AMT during the post-2070 period. The annual maximum temperature (AMXT) does not show a considerable rise; however, the annual minimum temperature (AMNT) is expected to increase (by < 1.2 °C) significantly over about 80% of the districts in Maharashtra. These climatic changes are very likely to affect the productivity of principal crops in Maharashtra including sorghum, pearl millet, sugarcane, wheat, rice and cotton. Under the future climate change scenario, therefore, it will be a great challenge for agronomist and policymakers to formulate a judicial plan for sustainable agriculture.

Keywords: Maharashtra, climate change, rainfall, temperature, agricultural crops, trends.

1. Introduction

Scientific regional and global climate studies have confirmed that over the past 150 years, the Earth's surface temperature has increased by 0.74 °C (TERI 2014). As the climate predominantly determines agricultural production and productivity, adverse climatic changes and extreme events are a growing concern from an agro-economic standpoint (World Bank 2003). The annual mean temperature over India has increased significantly by 0.51–0.8 °C during 1901–2007 (Dash et al. 2007; Kothawale et al. 2010), and this warming was intensified (at the rate of 0.2 °C/decade) after 1971 (Jain and Kumar 2012). The Intergovernmental Panel on Climate Change (IPCC) (2007) has estimated a 10–40% reduction in agricultural production in India with a temperature increase by 2100. In this context, several studies (Saseendran et al. 2000; Garg et al. 2001; Mall and Aggarwal 2002; Aggarwal and Mall 2002; Krupa 2003; Aggarwal 2003; IPCC 2007; Kumar et al. 2011; Bapuji Rao et al. 2014; Jayaraman and Murari 2014; Rao et al. 2014; Jena and Acharya 2016) were carried out to understand the regional climatic changes and their impacts on agriculture in India.

With a global temperature rise, the state of Maharashtra clearly shows a comparable warming scenario during 1969–2006 (Dhorde et al. 2017). It is observed that the annual, winter and post-monsoon mean temperature increased significantly at a rate of 0.11–0.22 °C/decade (Dhorde et al. 2017). The annual maximum temperature (AMXT) temperature over the coastal cities in Maharashtra such as Mumbai and Ratnagiri has also registered a notable rise (Korade and Dhorde 2016). Under the climate change scenario, future rainfall and temperature over western India (including Maharashtra) are expected to alter significantly. Over the Indian Peninsula, widespread summer warming by 1–2.5 °C is projected (Niu et al. 2015). Jena et al. (2015) have estimated 10–20% changes in mean rainfall over the Madhya Maharashtra, Konkan and Marathwada regions by 2100.

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The estimates have also suggested a change in rainfall and evapotranspiration over the Krishna Basin by 20 and 5%, respectively (Gosain et al. 2006, 2011). By considering the regional climate models developed by the UK Met Office, The Energy and Resources Institute (TERI) (2014) has projected an increase in temperature (by 2–3 °C) and monsoon rainfall (by 21–25%) over Maharashtra up to 2070. In particular, the Vidarbha, Marathwada and the Nasik regions are very likely to experience intense warming (by 1.8–2.1 °C) as compared to the Konkan and Pune regions (by 1.5–1.8 °C) during the near-term future. The highest increase by 2.8–3 °C in mean temperature during 2000–2070 is projected over the Vidarbha region. Apart from this, the World Bank (2008) has conducted a study on the Godavari Basin where a rise in maximum temperature by 2.5–3.8 °C along with an increase in rainfall by 25–35 mm is estimated.

As the agriculture and allied sectors are the backbones of the Indian economy, it is a serious concern that climatic changes have the potential to adversely affect the agricultural yield in India. There are studies which have identified and predicted negative impacts of temperature rise on the agricultural crops such as sorghum (Boomiraj et al. 2011), sugarcane (World Bank 2003), rice (Singh et al. 2009), cotton (Hebbar et al. 2013), pearl millet (Ong and Monteith 1985) and wheat (TERI 2014). In the case of Maharashtra, sorghum, pearl millet and sugarcane are the crops most vulnerable to the adverse effects of climate change (World Bank 2003; TERI 2014). The future climate change impact study undertaken by Kelkar et al. (2020) has also concluded that the yield of sugarcane, rice and cotton in Maharashtra is very likely to decline by 2040. On account of temperature rise, the productivity of rice (INCCA 2010) and sorghum (TERI 2014) is expected to decline up to 35% and 6.3%, respectively, by 2050. TERI (2014) has also projected a 36% reduction in yield of soybean up to 2070. On the other hand, by considering the population growth in Maharashtra, a doubled food requirement is estimated by 2032 (GoM 1999). Furthermore, the cropping pattern in Maharashtra is rapidly shifting from food grain crops to cash crops (Kalamkar 2011; Todmal 2019), which may aggravate the food security challenge in the state.

On this background, the present study has attempted to estimate future (2015–2100) changes in rainfall and temperature over the state of Maharashtra. Concerning the magnitude of future change in temperature and by considering findings of experimental studies, probable effects on major agricultural crops in Maharashtra are discussed.

2. *Agro-Climatic Setting*

The climate of Maharashtra is predominantly determined by its geographical location and the physiography. The state receives 1363 mm of annual mean rainfall with an 8.7% coefficient of variability (Kelkar et al. 2020). About 85–90% of annual rainfall over the state is received during the monsoon period (June–October). Due to the orographic effect of the Western Ghats, there is an extraordinary variation in the distribution of monsoon rainfall over the Konkan, Madhya Maharashtra, Marathwada and Vidarbha Sub-divisions (2776, 727, 669 and 966 mm, respectively) (Gadgil 2002; Ratna 2012; data source: http://www.tropmet.res.in) which can be observed in Fig. 1a. Among these subdivisions, Madhya Maharashtra and Marathwada experienced higher rainfall variability ($>$ 23%). The Konkan and Vidarbha Sub-divisions display comparatively lower year-to-year variations ($<$ 19%) (Takle and Pai 2020). The number of rainy days has remarkable variation across the state (Gadgil 2002). It is observed that the Konkan and Vidarbha regions registered 80–100 and 50–60 rainy days, respectively (Ratna 2012), whereas the southern part of Madhya Maharashtra has the lowest number of rainy days (15–20). On account of this, the windward and leeward sides of the Western Ghats experience remarkable variation in monsoon rainfall. The sub-divisional data (1871–2015) obtained from Indian Institute of Tropical Meteorology (IITM) (http://www.tropmet.res.in) suggest that among all the sub-divisions in Maharashtra (see Fig. 1b), Vidarbha shows a non-significant declining trend in rainfall. The remaining sub-divisions reveal an increase in rainfall, among which only the Konkan Sub-division exhibits a significant increase in rainfall (by 8%) with respect to the long-term mean (1871–2015). The annual minimum temperature (AMNT) and AMXT (between 1985 and 2015) over Maharashtra are observed to be

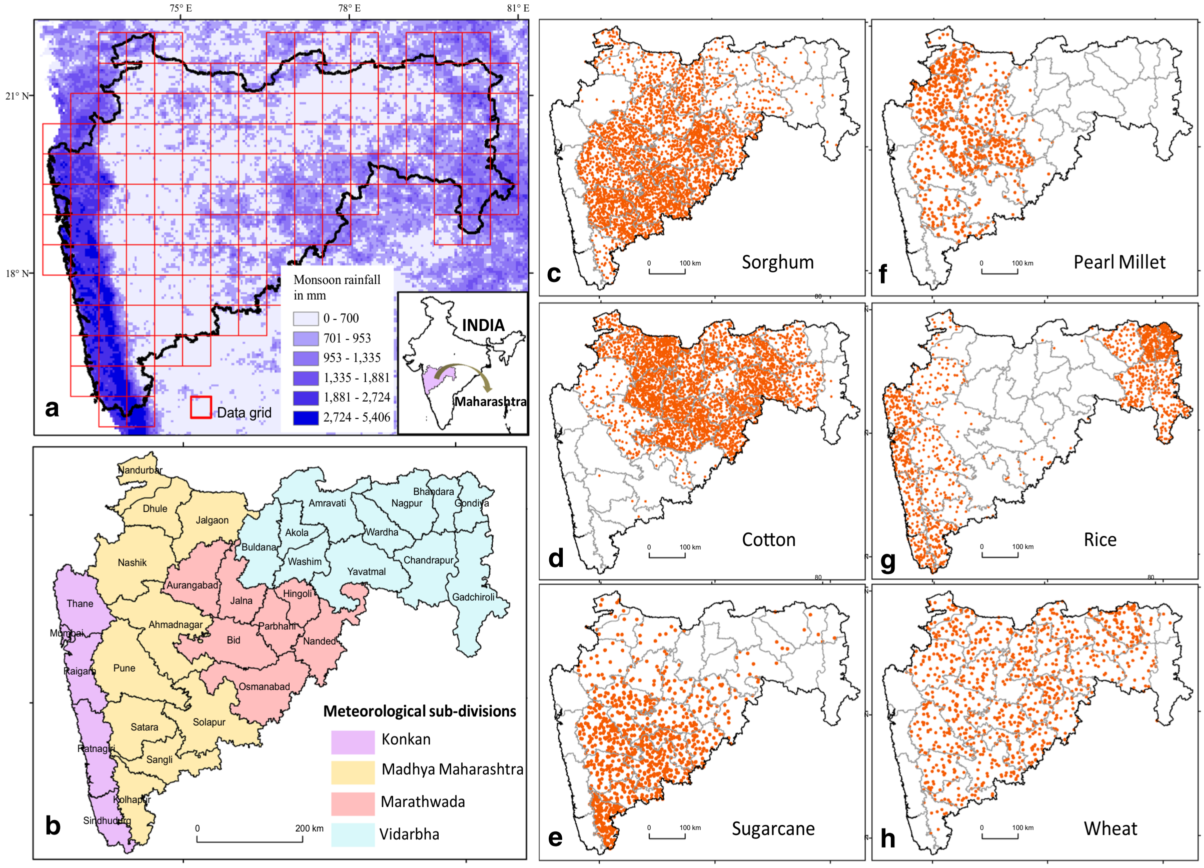

Figure 1

a Location map of Maharashtra State with average monsoon rainfall (June–October) distribution. Source of Tropical Rainfall Measuring Mission data: http://www.geog.ucsb.edu (average for 1998–2009 period). **b** Meteorological sub-divisions and districts. **c**–**h** Predominant cultivating areas of principal crops in Maharashtra. The Western Ghats (mountain region) is a boundary between the Konkan and Madhya Maharashtra Sub-divisions

15.05 and 30.3 °C, respectively (Kelkar et al. 2020). Generally, May is the hottest month when the mean maximum temperature ranges from 33 to 43 °C. The lowest mean minimum temperature (between 13 and 18 °C) is observed in December and January (IMD 2005). It is also well established that the variability in monsoon rainfall (Kulkarni et al. 2016) and temperature over Maharashtra plays a crucial role in determining agricultural yield.

The state of Maharashtra has a predominant agrarian economy. Sorghum, pearl millet, pulses and oilseeds are the principal rain-fed crops and collectively cover about 60% of the sown area, whereas sugarcane, rice, cotton and maize are the cash crops that account for about 27% of the cropped area (Kalamkar 2011). The sown areas of major crops are shown in Fig. 1. During the past few decades, the area used for irrigated crops in Maharashtra (sugarcane, wheat and onion) has increased, at the cost of cereal crops (sorghum and bajra) (Kalamkar 2003, 2011), particularly in the scarcity zone (Todmal and Kale 2016).

3. Data and Methods

The present investigation is based on the projected climatic data for the period between 2015 and 2100. The estimated rainfall and temperature data of the regional climate model (RCM) REMO (REgional MOdel) with 0.44° X 0.44° ($\sim$ 50 km) resolution were acquired from the Earth System Grid Federation

(ESGF), DKRZ, Germany (https://esgf-data.dkrz.de), and Indian Institute of Tropical Meteorology (IITM), Pune (http://cccr.tropmet.res.in). The REMO-2009 model is based on the Representative Concentration Pathway 4.5 scenario and recently considered in the Fifth Assessment Report of IPCC. The Coordinated Regional Climate Downscaling Experiment (CORDEX) project under World Climate Research Programme (WCRP) aims at producing an improved set of regional climate change projections for different domains across the globe. South Asia (SA) is one of such domains which includes Maharashtra. In the present work, future projections of the regional climate model REMO-2009 (Saeed et al. 2012; Kumar et al. 2013) under MPI-ESM-LR-REMO 2009 CORDEX SA simulation is used. It was developed by the Max Planck Institute for Meteorology, Germany, forced with the CMIP5 general circulation model (GCM) MPI-ESM-LR. The dynamical downscaling method using high-resolution limited-area RCMs utilizes the outputs provided by CMIP5 (AOGCMs) as lateral boundary condition (i.e. driving AOGCMs including winds, temperature, water vapour and surface pressure) to provide physically consistent spatiotemporal variations of climatic parameters at spatial scales much smaller than the AOGCMs' grid. In the present investigation, one ensemble member is considered. This investigation considered 1976–2015 as a base period.

It is pertinent to mention here that validation of the REMO model carried out by Saeed et al. (2012) concluded that this model is very well suited for the South Asia summer monsoon region. Additionally, in the present study, the simulated REMO-2009 model data for Maharashtra were validated. For this, the observed rainfall and temperature data (between 1976 and 2005) obtained from the India Meteorological Department (https://www.imdpune.gov.in) were compared with the historical simulated model data for the same period. Figure 2 shows that the simulated model data represent well the variations in the rainfall and annual mean temperature over Maharashtra, as obtained correlation coefficients are notably higher ($r^2 = 0.94$ and 0.96, respectively) and statistically significant at a 99% confidence level.

The Maharashtra State, excluding the Konkan Subdivision, receives rain from both branches of the monsoon, namely the Arabian Sea (during June–September) and the Bay of Bengal (majority in October) (Ratna, 2012). Broadly, about 85% of annual precipitation over the state of Maharashtra is received during the monsoon months (June–October). Therefore, the present investigation considered the total rainfall received during the monsoon period (June–October). In the case of temperature data, sub-division-wise annual mean temperature (AMT) values for the period between 2015 and 2100 were derived by averaging the pixel temperature values in the respective sub-divisions. For the detailed analysis, the obtained sub-divisional AMT data series were split into variable durations (2015–2050, 2015–2070 and 2015–2100). To understand the future changes in monsoon rainfall and temperature data, trend analysis was carried out by applying standard parametric and non-parametric statistical methods. Linear regression method was used to detect linear trends, and the obtained results were verified by non-parametric Mann–Kendall statistics. In the case of sub-divisional projected AMT, an attempt has also been made to understand the year of step change. For this, the cumulative sum (CUSUM), cumulative deviation and Worsley likelihood ratio tests were applied, as these tests detect point-of-step change in data series (Robson et al. 2000). The obtained results of the year of step change were verified by applying the rank-sum and Student *t* tests. With the use of the same tests, the sub-division-wise averages in the AMT before and after the step change were compared. In order to understand the recent cropping pattern (spatial) in Maharashtra, district-wise agricultural cropped area data were obtained from the Agriculture Department of Maharashtra State for the period between 2001 and 2016. Based on the district-wise average area under each major crop, the predominant regions were broadly identified (Fig. 1c–h) and used to relate crop zone-wise future temperature changes (in Table 2).

4. Discussion of Results

4.1. Trends in Future Monsoon Rainfall

Figure 3a shows an increasing trend in monsoon rainfall over the entire state by 2050, although the increase in rainfall has notable spatial variation. The

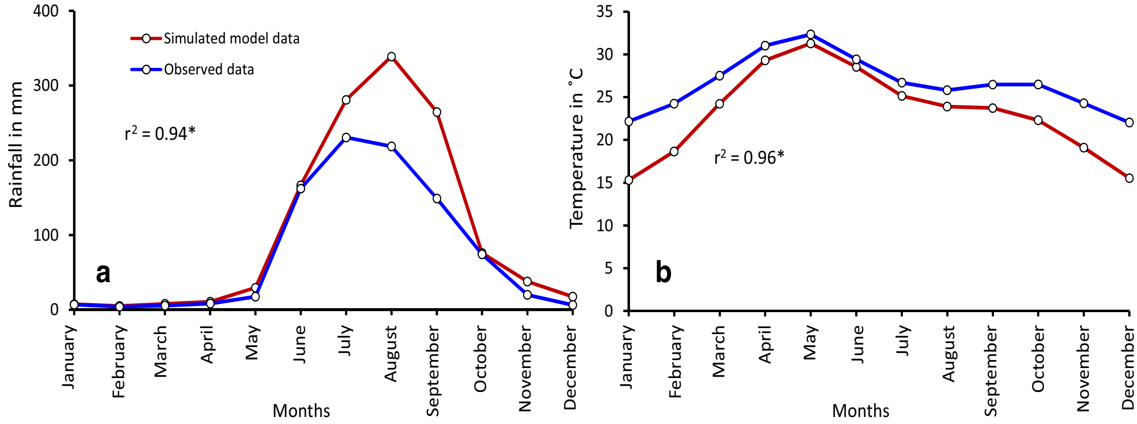

Figure 2
Average annual cycles of simulated model (REMO-2009) and observed **a** rainfall and **b** mean temperature data over Maharashtra for the period between 1976 and 2005. *Denotes significant correlation at a 99% confidence level

state of Maharashtra is likely to experience an increase in rainfall up to 225 mm. Broadly, by the end of this century, the increase in rainfall is projected to be about 18–22% with respect to long-term (1976–2015) sub-divisional average rainfall. Bal et al. (2016) and Kelkar et al. (2020) have reported a comparable increase in rainfall (∼ 23%) along with an increase in extreme events (TERI 2014). It is clear from the present investigation that around 40% of the state is expected to experience a significant increase in rainfall (Fig. 3a), most of which will fall in the Vidarbha Sub-divisions and Western Ghats region. The high-altitude domains in the Western Ghats which include the Pune, Satara and Kolhapur Districts show a distinctive pattern of a significant increase in monsoon rainfall (by 3–6 mm per year or 123–225 mm by 2050). It is important to mention here that Guhathakurta and Saji (2013) have observed increasing trends in rainfall (during 1901–2006) over the western districts of the state. Most of the districts in the Vidarbha Sub-division are expected to experience a significant increase in monsoon precipitation ranging between 53 and 225 mm. In particular, the rainfall over Nagpur and Wardha Districts is very likely to increase by 82–123 mm. The Bhandara, Gondia, Akola, Washim, Parbhani, Hingoli and Yawatmal Districts may register a significant rise in monsoon rainfall by 53–123 mm. Although the Madhya Maharashtra and the western part of the Konkan Sub-divisions exhibit an increase in rainfall (up to 82 mm), the trends are not significant. The pockets in Ahmednagar, Aurangabad and Jalgaon Districts are expected to undergo a notable increase in rainfall, without any spatial pattern.

It is reported that the amount of precipitation over Maharashtra will increase in the foreseeable future. However, TERI (2014) has estimated an increase in rainfall along with extreme events by 10–40% (with respect to 1970–2000 baseline data). In this context, the substantial increase in monsoon rainfall and extreme events over Maharashtra would result in flashy runoff which can cause catastrophic floods, particularly in the foothill zone of Madhya Maharashtra and Godavari Basin in Vidarbha. The extreme rainfall events (177–716 mm) between 1 and 8 August 2019 (The Hindu 2019) may have been responsible for the massive flooding in the Kolhapur, Sangli and Satara Districts. In addition, an appraisal of the present and required water impoundment structures needs to be undertaken by water resource management authorities to manage the additional water volume in the near-term future.

4.2. *Trends in Projected Annual Mean Temperature*

The future (up to 2050) annual mean temperature shows a significant rise across the state except in the Bhandara and Osmanabad Districts and surrounding

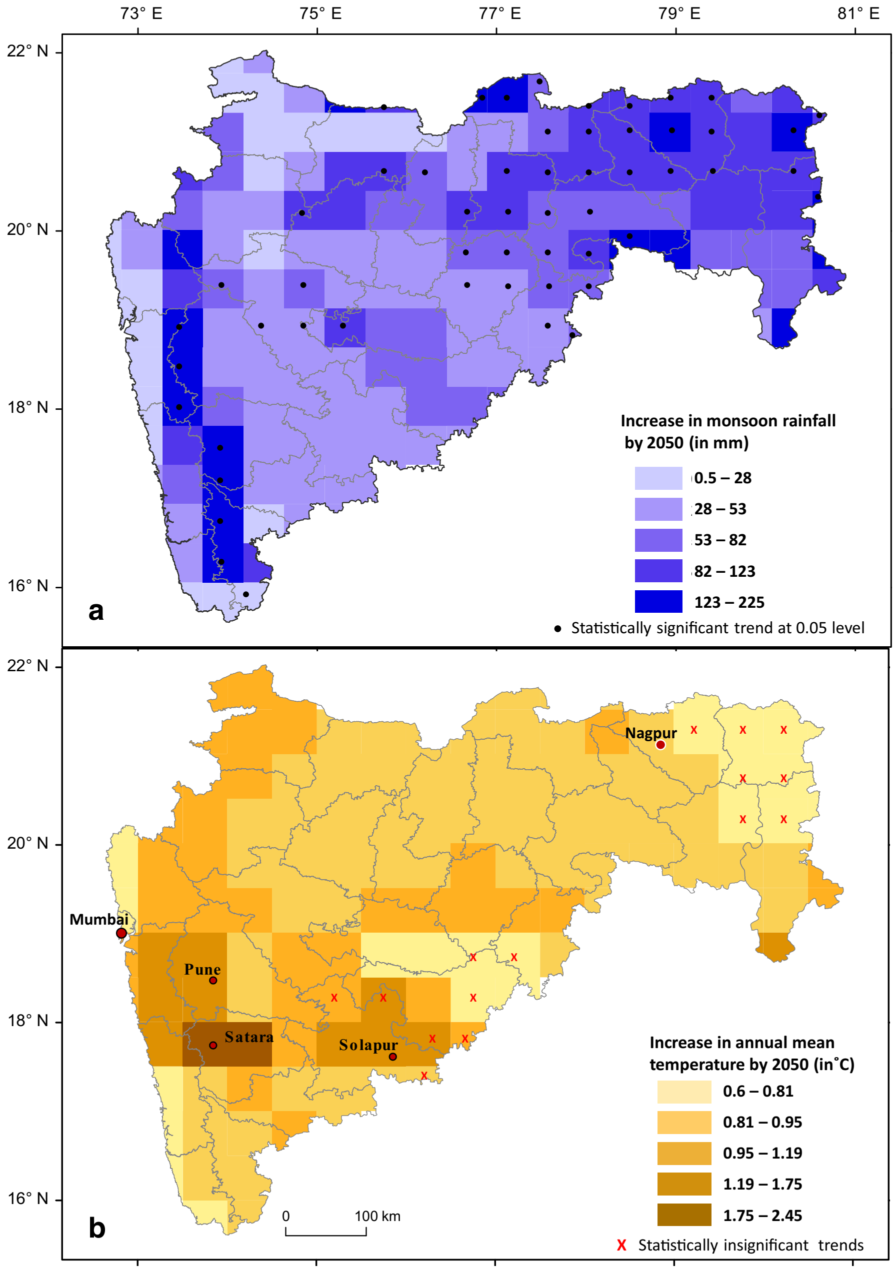

Figure 3
Projected change in **a** monsoon rainfall and **b** annual mean temperature over Maharashtra by 2050

areas (Fig. 3b). The obtained results of linear trend analysis suggest that the state of Maharashtra is very likely to experience warming by 0.6–2.5 °C up to 2050. This finding is corroborated by the study based on seven regional climatic models (Niu et al. 2015) that estimated the comparable rise in temperature over Maharashtra between 2040 and 2060. The IPCC (2013) has also reported comparable results of widespread summer warming (1–2.5 °C) over the Indian Peninsula. The present study indicates that the majority of districts may undergo a rise in temperature between 0.8 and 1.2 °C by 2050. It is interesting to note that the mountain regions (of the Western Ghats) in the Pune, Satara and Raigad Districts exhibit the highest increase (of 1–2.5 °C) in the annual mean temperature followed by the Solapur District (by 1.2–1.75 °C). However, the magnitude is comparatively lower (Fig. 3b). For the same pockets (except the Solapur District), a significant increase in monsoon rainfall is estimated. These results are in good agreement with estimates for the mountainous regions in America, Africa and Asia (Nogués-Bravo et al. 2007). In this connection, the climate change detection studies for the Tibetan Plateau (Liu and Chen 2000) and Northwestern Himalaya (Bhutiyani et al. 2007) regions have reported that temperature at higher altitudes has risen more rapidly than that at lower altitudes during the past century. The estimates from the present investigation highlight the same fact over Maharashtra up to 2050.

Figure 4 shows a significant increase in projected AMT over all sub-divisions in Maharashtra. Based on the obtained results, these sub-divisions are very likely to register AMT rise between 0.9 and 1.04 °C by 2050. Comparatively, the results based on the PRECIS (Providing REgional Climates for Impacts Studies) model suggested warmer conditions (AMT rise by up to 2 °C) over the state (Bal et al. 2016). Among all the sub-divisions, Marathwada and Madhya Maharashtra are expected to experience comparatively rapid warming (with $\sim$ 0.29 °C/decade). However, the study conducted by TERI (2014) has projected a greater increase in AMT of between 1.9 and 2.3 °C over the Vidarbha Sub-division. In addition, the significant results of the Student *t* test (by comparing sample means) and rank-sum test in the present investigation indicate that the AMT during the post-2033 period is considerably higher than the 2015–2033 period (Fig. 4).

4.3. Distant Future Climate Change Scenario

Table 1 summarizes the distant future (up to 2100) climatic trends over Maharashtra. All the meteorological sub-divisions show a considerable increase in monsoon rainfall by 2070 (except Konkan) and 2100, although the amount of the increase may vary spatially. The maximum increase in rainfall is estimated over the high-altitude domains in the Western Ghats, as the annual rate of change ($>$ 4 mm) is estimated to be highest. An almost comparable magnitude of increase ($\sim$ 2 mm/year) in rainfall is projected over the Madhya Maharashtra, Marathwada and Vidarbha Sub-divisions, which is statistically significant. By considering rates of increase, these sub-divisions will have additional rainfall between 150 and 210 mm by 2100. The study conducted by Kumar et al. (2006) has also reported a 10–50% increase in precipitation over Maharashtra by 2100, whereas Gosain et al. (2011) estimated about a 15% increase in precipitation over the Godawari Basin (Marathwada and Vidarbha Sub-divisions). The same study predicted a maximum increase in rainfall over the Marathwada and Madhya Maharashtra Sub-divisions. The results obtained from the present analysis show anomalously decreasing and increasing trends (during 2015–2070 and 2015–2100, respectively) for the Konkan region, although these are not statistically significant. Similarly, the Vidarbha Sub-division exhibits an non-significant increase in monsoon rainfall by the end of the twenty-first century.

It is a well-established fact that the Indian subcontinent has warmed during the past few decades. Predictions suggest that the annual mean temperature over India may rise by 2–5 °C (Rupa Kumar et al. 2006). In the case of AMT, all the sub-divisions and the Western Ghats region show a significant rise in temperature by 2070 and 2100. The AMT across the state shows a comparable rate of increase up to 2070 (0.23–0.26 °C/decade), which may result in warming by 1.3–1.5 °C. These results confirm the findings of the study conducted by TERI (2014). The climate model used in the present investigation indicates a significant increase in AMT by 2070 and 2100 over all the sub-divisions and Western Ghats as well. However, it should be noted that with the addition of succeeding 30 years (2070–2100), the magnitude of the increase in AMT declined notably (0.23–0.26 to 0.15–0.17 °C per year) (Table 1). This observation suggests that the period between 2070 and 2100 may contribute marginally ($<$ 0.1 °C per year) to the warming over Maharashtra.

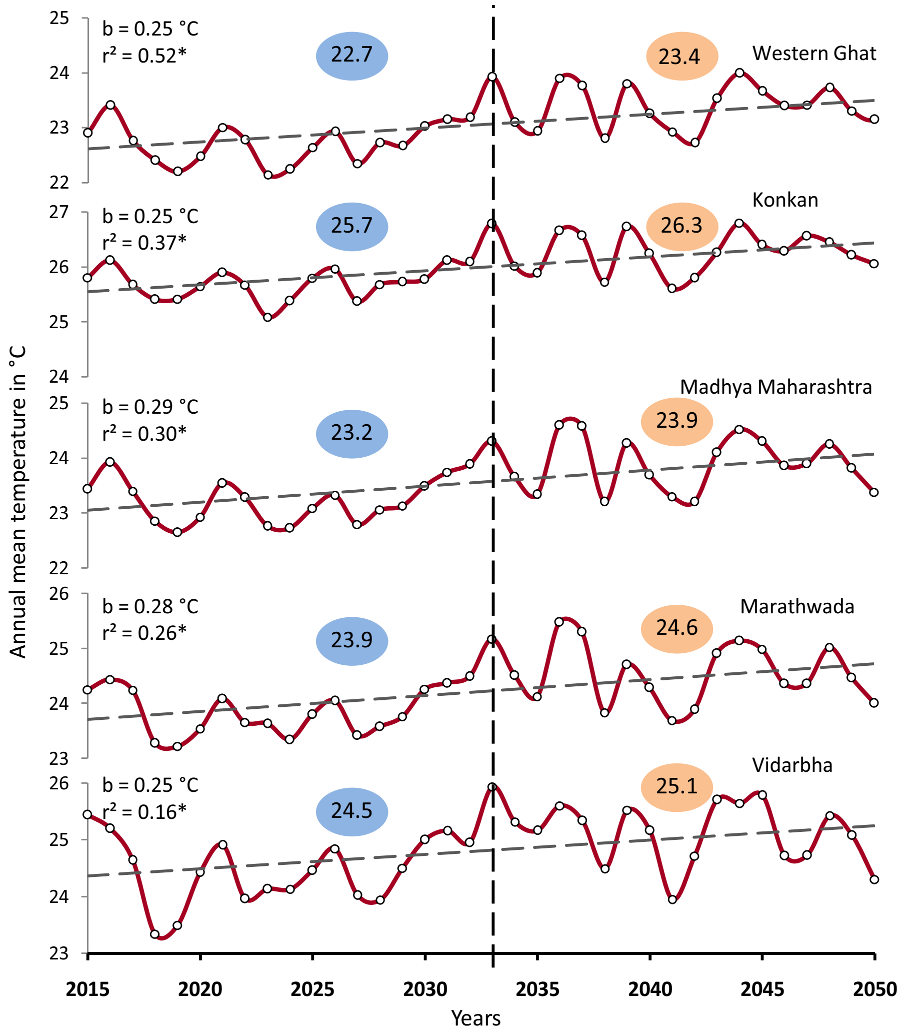

Figure 4

Sub-division-wise linear trends in projected annual mean temperature. *Denotes a significant trend at a 95% confidence level. *b* Decadal rate of change. Values in blue and brown ovals represent the average of AMT for the period 2015–2033 and 2033–2050, respectively. Western Ghats is not a sub-division. The dashed black vertical line divides data periods based on results obtained from CUSUM, cumulative deviation and Worsley likelihood ratio tests

4.4. Trends in Projected Annual Maximum and Minimum Temperature

Figure 5a shows a change in AMXT over Maharashtra. Although the results suggest an increase in AMXT by 2050, the trends are not statistically significant, except southern Kolhapur District. Buladhana, Amravati, Yavatmal, Akola and Washim of the Vidarbha Sub-division and Jalgaon, Dhule and Nasik of the Madhya Maharashtra Sub-division, as well as all the districts in the Marathwada Sub-division, may observe an increase (by 0.65–1.5 °C) in AMXT. These results are in contrast to the findings of the TERI (2014) study, which estimated the highest increase (between 1.8 and 2.2 °C) in AMXT over the districts of the Vidarbha Sub-division. Comparatively, the Konkan, western and eastern parts of Madhya Maharashtra and Vidarbha Sub-divisions,

Table 1

Sub-division-wise distant future change in rainfall and temperature

Period	Western Ghats#	Konkan	Madhya Maharashtra	Marathwada	Vidarbha
Projected change in monsoon rainfall (in mm)					
2015–2070	241 (4.3)*	–11	123 (2.2)*	101 (1.8)*	78
2015–2100	404 (4.7)*	129	163 (1.9)*	155 (1.8)*	206 (2.4)*
Projected rise in annual mean temperature (in °C)					
2015–2070	1.40 (0.25)*	1.29 (0.23)*	1.40 (0.25)*	1.29 (0.23)*	1.46 (0.26)*
2015–2100	1.38 (0.16)*	1.29 (0.15)*	1.46 (0.17)*	1.46 (0.17)*	1.55 (0.18)*

– Indicates a negative trend/change in monsoon rainfall. The statistically non-significant values of rate of change are avoided

*Denotes significant change at a 95% confidence level. Values in brackets are the annual and decadal rate of change in rainfall and temperature, respectively

#Represents high altitude domains in the Western Ghats (not a sub-division)

respectively, are expected to observe a moderate increase (< 0.6 °C) in AMXT. An increase in AMXT may adversely affect human health, as the hot climate leads to increased illness and mortality (Im et al. 2017; Mazdiyasni et al. 2017). It is also estimated that the frequently occurring heat waves in India due to climatic change may cause the death of about 66 people per million in the foreseeable future (Patz et al. 2005).

The rise in minimum temperature has a pronounced effect on wheat growth and yield (Asseng et al. 2011). On account of the 1.13 °C rise in minimum temperature, the productivity of rice crops has been reduced by about 10% (Peng et al. 2004). From the present investigation, a significant increase (by 0.1–1.2 °C) is estimated over about 80% of the state of Maharashtra. In particular, the pockets that can be observed (in Fig. 5b) in the Satara, Thane, Amravati, Nagpur and Gadchiroli Districts are very likely to register an increase in AMNT of 0.5–1.2 °C by 2050, whereas a temperature rise of < 0.58 °C is expected over the remaining areas in all four sub-divisions. Although Sindhudurg, Thane, Osmanabad and the surrounding areas exhibit an increase in AMNT, the estimated rise is not significant. Apart from this, it is found that the number of mosquitoes increases with the increase in minimum temperature, which may increase the incidence of malaria (Patz et al. 2005).

4.5. Future Climate Change and Agriculture in Maharashtra

As the climate is the chief determinant of agriculture, changes in rainfall and temperature may adversely affect agricultural yield (Mall et al. 2006). The impact of an increase in regional future rainfall is not prominently highlighted in the existing literature. However, the estimated significant increase in the monsoon rainfall, particularly over the Vidarbha Sub-division and Western Ghats region, may increase the rate of leaching (i.e. nitrates) in well-drained soil and adversely affect the decomposition of organic matter due to water saturation (Kelkar et al. 2020; Chauhan et al. 2014). Furthermore, the increased wet season (rainfall) along with temperature rise may result in development of fungal diseases and bacterial leaf blight (Chauhan et al. 2014), which ultimately affect agricultural yield in Maharashtra. The near-term future rise in AMT over Maharashtra is very likely to reduce the productivity of cereal as well as cash crops. Table 2 shows temperature rise (up to 2050) over the cultivating areas of principal crops in Maharashtra and its potential effects. Based on the findings obtained by Boomiraj et al. (2011), the yield of sorghum may decline by 6–18%, as the rise of 0.9–2.5 °C in AMT is projected over the existing crop region (names of districts are given in Table 2). Although a decline in sorghum productivity may be offset by increasing precipitation, it could not counter the adverse effects of warming by > 2 °C (Kumar et al. 2011). Similarly, it is documented that the

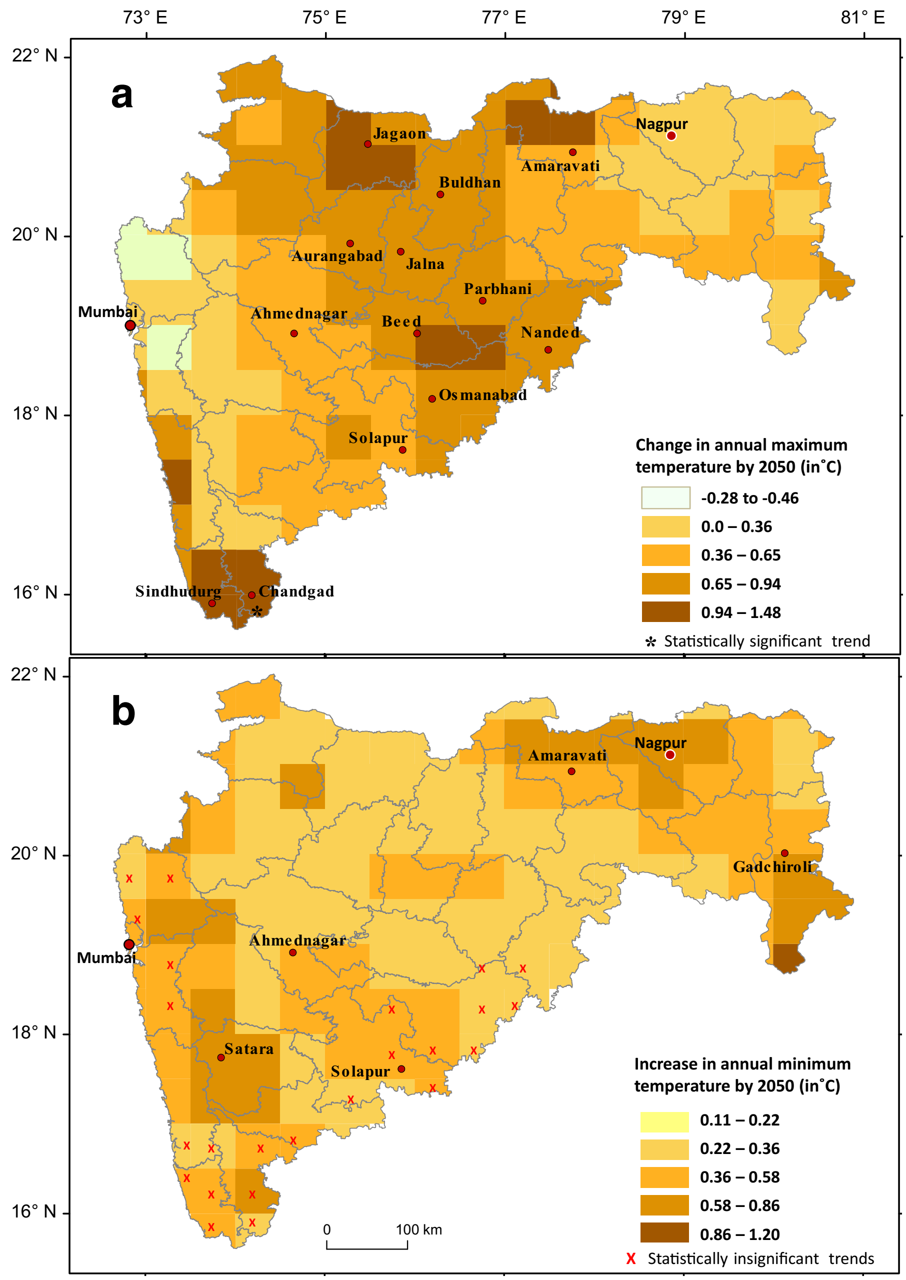

Figure 5
Projected change in **a** annual maximum temperature and **b** annual minimum temperature over Maharashtra by 2050

increase in temperature has a negative effect on the productivity of sugarcane (Kumar and Sharma 2014), as it is very climate-sensitive crop (Srivastava and Rai 2012). This investigation suggests near-term future warming by 0.9–1.6 °C over the sugarcane-cultivating region of Maharashtra, which may reduce the yield up to 22% (World Bank 2003). It is suggested that the selection of suitable varieties of cane, change in pattern and time of plantation and supply of sufficient nutrients may help to maintain

Table 2

Crop-wise potential impacts of AMT temperature rise by 2050

Climate risks	Crops	Temperature rise by 2050 (°C)	Crop-wise vulnerable area (districts)	Potential impacts on crops (up to 2050)
Increase in mean annual temperature	Jowar (sorghum)	1.5–2.5	North Satara Bhore Taluka (Pune)	6% and 18% decline in sorghum (jowar) yield (Boomiraj et al. 2011)
		1.15–1.6	Pune (Mulshi, Maval, Rajgurunagar), Northern Solapur, Eastern Osmanabad	
		0.9–1.15	Most of Madhya Maharashtra and Marathwada meteorological sub-divisions	
	Sugarcane	1.15–1.6	Osmanabad, Pune (Mulshi, Rajgurunagar, Maval) and Solapur	6–22% reduction in yield (World Bank 2003)
		0.9–1.15	A. Nagar, Pune (east) Sangli, Kolhapur, Aurangabad, Nasik, Parbhani, Hingoli	
	Rice	1.5–2.5	North Satara, Ratnagiri, Bhore Taluka (Pune)	Increase in temperature from 1 to 4 °C resulted in reduction in yield of rice from 0 to 49% (Singh et al. 2009; Bapuji Rao et al. 2014)
		1.15–1.6	Raigad, Pune (Mulshi, Maval, Rajgurunagar)	
	Cotton	0.9–1.15	Buldhana, Jalna, Parbhani, Nanded, Hingoli, Washim, Aurangabad, Jalgaon, Beed, Amaravati and Yavatmal	3.2 °C rise in temperature would lead to a 268-kg/ha decline in yield (Hebbar et al. 2013)
	Bajra (pearl millet)	1.15–1.6	Satara	Germination of bajra declined sharply for the temperature > 34 °C (Ong and Monteith 1985)
		0.9–1.15	Nandurbar, Dhule, Nasik, A. Nagar, Pune, Parbhani, Jalna, Aurangabad and Washim	
Increase in maximum temperature		0.9–1.48	Jalgaon, Northern Amravati, Eastern Beed, Sindhudurg, Southern Kolhapur, Central Ratnagiri	Sterility in rice pollen if during anthesis; decrease in pollen germination; 10% reduction in rice grain yield per °C temp rise beyond 1 °C (TERI 2014)
		0.7–0.94	Aurangabad, Jalna, Buldhana, Beed, Parbhani, Nanded, Osmanabad, Northern Nasik, Dhule, Nandurbar, Ratnagiri	
		0.4–0.65	A. Nagar, Solapur, Sangli, Eastern Satara, Akola, Yavatmal	
Increase in minimum temperature		0.9–1.2	Sindhudurg, Southern Kolhapur, Southern Thane	Negative impact of warmer nights on rice yield; negative impact on rabi wheat crop (TERI 2014)
		0.4–0.9	Thane, Raigad, Ratnagiri, Eastern Pune, Eastern Satara, Eastern Sangli, Northern Kolhapur, Eastern Nasik	
		0.1–0.4	Most of Madhya Maharashtra, Marathwada and Vidarbha	

the sugarcane yield even under the warmer environment (Srivastava and Rai 2012). Rice is another major crop in India which is vulnerable to climatic changes. The increment of temperature by < 4 °C reduces up to 50% productivity of rice (Singh et al. 2009). In the present context, the Konkan Sub-division and parts of Pune and Satara Districts are the rice-cultivating areas where the increase in AMT by 1.1–2.5 °C is projected. This warming will certainly have an adverse effect on rice productivity in Maharashtra by 2050. Moreover, a 0.7–1.5 °C rise in AMXT is also expected over the same region, which has the potential to accelerate a decline in rice productivity (TERI 2014). The results also reveal a 0.9–1.15 °C rise in AMT over the cotton-producing districts in the Marathwada and Vidarbha Sub-divisions (Table 2), whereas, the districts in Madhya Maharashtra and Marathwada (pearl millet-producing region) display near-term future warming by 0.9–1.6 °C (Table 2). This future warming is likely to negatively affect the profitability and overall growth of cotton (Hebbar et al. 2013) and pearl millet (Ong and Monteith 1985) crops. On the other hand, the AMNT is also expected to augment by up to 1.2 °C over Maharashtra. It is pertinent to mention here that the cold weather condition supports the growth and productivity of wheat crops. An increase in AMNT (estimated in the present study), therefore, could be hazardous for the wheat crop in Maharashtra (TERI 2014).

In summary, although the monsoon rainfall over Maharashtra is expected to increase, future warming is very likely to reduce the agricultural yield. Under such circumstances, it is advisable to change the sowing time and introduce new tolerant crop varieties to reduce the effects of future warming to some extent (Srivastava et al. 2010).

5. *Limitations of the Study*

Although the present study has incorporated various statistical techniques and the results have implications for agriculture and human health, it has limitations as follows:

- The present study has not conducted any experiment to understand the effects of warming on agricultural crops. For this, the findings of experimental studies (Table 2) undertaken in different parts of India were used. Therefore, their applicability for Maharashtra is in a broad sense.

6. *Conclusion*

The present investigation has confirmed the near-term and distant (up to 2100) future climatic changes over Maharashtra. The government agencies need to consider these environmental changes while formulating future policies regarding agricultural and water resources. Strategies should be decided to manage the additional volume of water in the regions where the substantial increase in the monsoon rainfall (by 2050) is very likely to occur. Prior to this, it is important to investigate whether the estimated additional rainfall is received through extreme rainfall events or is equally spread throughout the monsoon season. The future warming (up to 2.5 °C) and increased rainfall (atmospheric and surface moisture) over Maharashtra is inevitable and has the potential to negatively affect the productivity of agricultural food grains as well as cash crops. Moreover, a future increase in AMT in the areas where the rainfall remains unchanged may aggravate the water scarcity problem, particularly in the semi-arid region of the state. Under such circumstances, it will be a great challenge for agronomists and agricultural scientists to introduce drought-resistant crop varieties which can perform well under warmer conditions.

Acknowledgements

The author would like to express his sincere gratitude to Mr. Sudhir Sabade (Ret. Scientist), Mr. Sandip Ingle (Project Scientist C), Dr. Koteswara Rao (Project Scientist C) and the Director, IITM, for their valuable support and guidance to carry out the present work. The author thanks Mr. Nitin Atkare for his assistance in carrying out the statistical analysis. The author is also grateful to the anonymous reviewers for their comments and suggestions which helped in improving this manuscript. The World Climate Research Programme's Working Group on Regional Climate and the Working Group on Coupled Modelling former coordinating body of CORDEX and responsible panel for CMIP5 are gratefully acknowledged. The climate modelling groups are sincerely thanked for producing and making available their model output. The authors thank the Earth System Grid Federation (ESGF) infrastructure and the Climate Data Portal hosted at the Centre for Climate Change Research (CCCR), Indian Institute of Tropical Meteorology (IITM) and Indian Meteorology Department (IMD) for providing CORDEX South Asia data and observed data.

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(Received April 10, 2020, revised December 5, 2020, accepted December 9, 2020, Published online January 8, 2021)