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ORIGINAL PAPER

Assessment of climate change and vulnerability in Indian state of Telangana for better agricultural planning

M. D. M. Kadiyala[1] · Sridhar Gummadi[2] · Mohammad A. Irshad[3] · Ramaraj Palanisamy[3] · Murali Krishna Gumma[3] · Anthony Whitbread[3]

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Abstract

Climate variability and change pose ever-growing challenges in the semiarid tropics, where majority of the population depend on climate-dependent activities such as agriculture. This has rendered these countries more vulnerable to climate change–induced variability. In spite of the uncertainties about anticipated magnitude of climate change on regional scale, an assessment of the possible changes in key climatic elements to identify most vulnerable locations becomes important for formulating adaptation strategies. This study compiles the existing knowledge about observed climate and projections of future change in Telangana state of India. The agriculture in this semiarid state has to adapt to changes in mean climate variables to increased variability with greater risk of extreme weather events, such as prolonged dry spells. Based on climatic vulnerability assessment, we found that the number of vulnerable mandals (currently 28%) will be increased to 45% during early century and to 59% by mid-century. As per the climate exposure index scores, Jogulamba-Gadwal district was found to be most sensitive. Overall, vulnerability index scores indicated that Adilabad, Nagarkurnool, Nalgonda, Peddapalli, Suryapet, Wanaparthy, and Yadadri are extremely vulnerable districts in the state. The ranking of vulnerable mandals in each district envisages the need for a holistic approach for each mandal or a group of mandals to reduce their sensitivity though implementation of site-specific adaptation strategies to minimize climate-related shocks not only in agriculture but also in other sectors.

Keywords Climate change · Vulnerability · Agriculture and adaptation

1 Introduction

Managing climate-related risks is a major concern in the context of climate change in semiarid tropics. Identification of proper location-specific adaptation strategies and targeted agricultural investments backed up by robust policies are needed for communities whose livelihoods are at risk due to climate-related shifts (Porter et al. 2014; Kelley et al. 2015; Wiebe et al. 2015). As the frequency and type of extreme events such as cyclones, floods, and droughts are expected to rise (Cruz et al. 2007; Meehl et al. 2007), the primary challenge for decision-makers is to identify most vulnerable regions and helping rural communities to earn a living and achieve food security. These location-specific climate-related problems necessitate the need for analyzing and understanding the nature of climate change not only at the global but also at regional levels to deal with and plan action for possible impacts.

Adapting to the climate change is a complex and ongoing process requiring integrated efforts from communities, governments, individuals, and international agencies. Policymakers need timely and useful information about the possible effects of climate change to make informed decisions (Beauchamp and Childress, 2001). The challenge is to provide location-specific tailored information at administrative division level. The assessments should highlight all possible opportunities for adaptation to reduce risk and to take advantage of the new opportunities created by such change. Keeping in view the uncertainties involved in future climate projections, mitigating strategies should be planned based on the present assessment of changes in the observed climate data.

✉ M. D. M. Kadiyala
dakshu2k@gmail.com

[1] Acharya NG Ranga Agricultural University, Guntur, India

[2] International Rice Research institute, Hà Nội, Vietnam

[3] International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh 502 324, India

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The first crucial step in planning and implementing adaptation strategies is identification of geographical areas that are more sensitive and vulnerable to climate change and associated variability. Telangana state in southern India is highly diverse in terms of its geographical and climatic features as well as in terms of the development of various regions and socio-economic conditions of people. Hence, the impact of climate change is not likely to be uniform across regions within Telangana. In the current study, we carried out a vulnerability analysis at mandal level (small administrative unit) and classify the mandals according to their vulnerability to climate change by constructing a climate exposure index. Such climate information has potential for understanding the climate vulnerability of areas and can assist in planning for improving resilience of agricultural to climate shocks.

2 Materials and methods

2.1 Study area

Telangana state is situated on the Deccan Plateau in the central stretch of the Indian Peninsula. Telangana is bordered by the states of Andhra Pradesh to the south and east, Maharashtra to the north and north-west, and Karnataka to the west and Chhattisgarh to the north-east (Fig. 1). This southern state of India is a semiarid area with a predominantly hot and dry climate. Telangana state occupies the 8th rank in India with respect to gross domestic product (GDP) with a per capita income of US$ 3200 as per the year 2019–2020 estimates. Agriculture contributes 16% to GDP and 55.6% people of the total 39 million population are dependent on agriculture for employment (Socio Economic Outlook 2020). According to the 2011 census, Telangana's literacy rate is 66.46% which was slightly lower than country's average.

Telangana state is divided into three agro-climatic zones, viz., Northern, Southern, and Central Telangana zones, based on the geographical characteristics such as precipitation, surface temperatures, soils, cropped area, and irrigation facilities. The mean annual precipitation in Telangana state ranges from 900 to 1150 mm with south-west monsoon contributing 82% of the annual rainfall. The major crops grown in the state are paddy rice, sugarcane, sorghum, pulses, maize, cotton, groundnut, turmeric, chilies, and others. The predominant soils in the state are red soils with about 48% area followed by black soils (25%) and laterite soils covering 7% of the area. The state has agro-climate conditions which are highly favorable for seed production of major field and vegetable crops. More than 45% of the country's seed requirement is met from the state providing income to the farmers.

Telangana is a riverine state with major, medium, and minor rivers flowing in the state. However, with more than half of the cropped area under rainfed, occurrence of frequent droughts, depletion of groundwater resources, reduced per capita agricultural land availability, and increased production costs result in decreased net income for farmers. With increased investments by the government in major and minor irrigation projects, efforts are made to bring more area under irrigation.

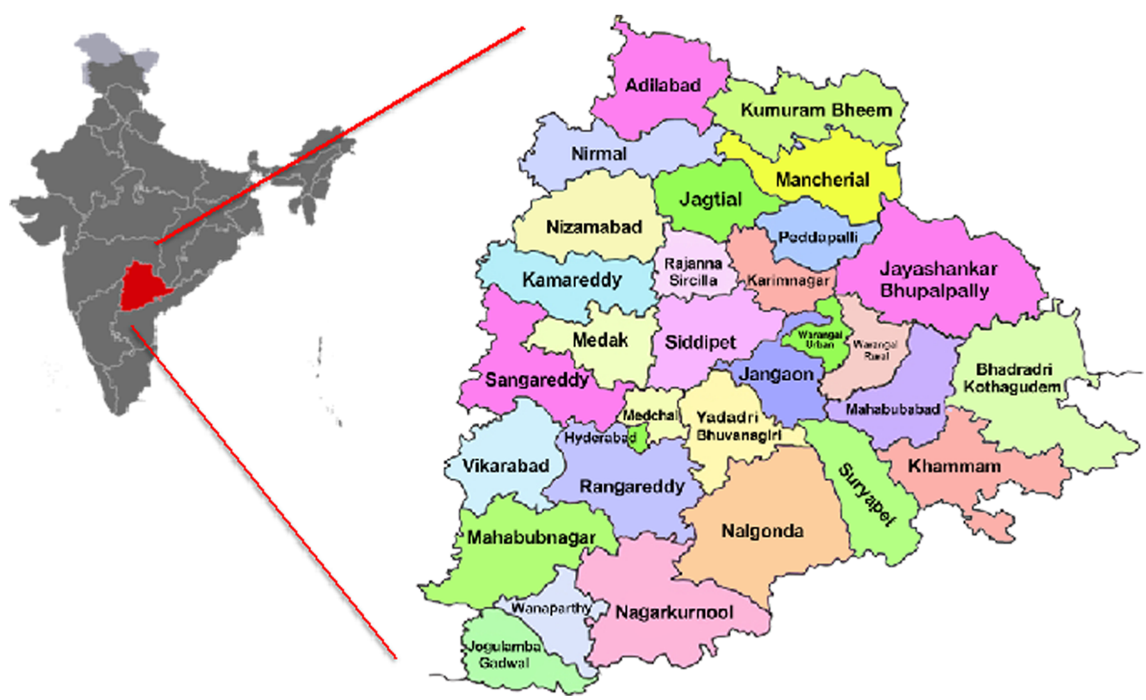


Fig. 1 Map showing the study area

2.2 Baseline climate data

Long-term precipitation and temperature data for Telangana was collated using India Meteorological Department (IMD) and AgMERRA Climate Forcing Dataset for Agricultural Modeling (AgMERRA). Reanalysis of datasets (Ruane et al., 2015) was performed at daily time steps. It serves as the current baseline climate for the time period 1980–2009 (30 years).

2.3 Future climate projection

Future climate projections were obtained from Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2012) and the Representative Concentration Pathways (RCPs) (Moss et al., 2010) for carbon emissions currently in use by the IPCC Fifth Assessment Report (AR5). Utilizing "mean and variability" approach as described in Villegas and Jarvis (2010), we have developed downscaled high-resolution future climate projections, in which the mean monthly changes as well as the magnitude of variability from baseline are perturbed to RCP 8.5 for near- and mid-century time slices. The climate scenarios developed using "mean and variability" approach are referred to as "mean and variability change scenarios". Future climate data were generated for 29 Global Climate Models (GCMs), two time slices, and all climate grids (350) of Telangana using the above approach.

The GCM-projected changes to monthly mean temperatures both maximum, minimum, and precipitation were perturbed into historical climate series. Furthermore, in addition to mean changes, changes in standard deviation of surface temperatures as well as the number of rainy days and the shape of the rainfall distribution were determined. The rational for incorporating mean and variability scenarios is to adjust the monthly distribution of climate variables, assuming a Gaussian fit (defined by mean and standard deviation) for surface temperatures and a gamma distribution (defined by mean precipitation, the number of rain events, and a shape parameter) for rainfall events when they do occur (Wilks 2011). The historical time series were stretched to mimic future projections to preserve observed patterns of temporal and spatial variability from the observations. Absolute monthly changes in temperatures are added, while multiplicative perturbations are used for rainfall to avoid potential sign problems. This facilitates generation of new scenario with mean and variability parameters adjusted according to the forced changes and essentially preserves the historical signature. Due to strong biases in GCM rainfall intensity, we presumed not to change the shape parameters for future scenarios.

In the current study to identify location-specific fundamental classes of projected climate change, we characterize an individual model projection of temperature and precipitation changes in terms of its deviation from the ensemble median. Accordingly, we identified four individual GCMs that capture a profile of the full ensemble of temperature and precipitation change with the annual and season to select the four climate models out of 29 GCMs. A scatter plot (Fig. 2) was developed as described by Ruane and McDermid (2017) to identify four different GCMs to represent cool/wet, cool/dry, hot/wet, and hot/dry scenarios. In the present study, we selected one GCM from each quadrat that is nearer to ensemble mean and the selected GCMs are presented in the Table 1. The main reason for following this approach is to identify four subsets of GCMs which can capture a profile of the full ensemble of temperature and precipitation change and also to avoid selection of extreme outliers that can skew the analysis.

2.4 Computation of climate exposure index

Climate exposure index (CEI) depends upon long-term changes in temperature,precipitation, and the frequency of extreme weather events in each ecological zone. The CEI was constructed by obtaining a weighted mean of the indicators (Table 2) identified and the weighting scheme followed in the computation of vulnerability index is given in Table 3. The determinants for climate exposure are derived from the previous studies conducted by O'Brien et al. (2004), Deressa et al. (2008), Ravindranath et al. (2011) and Rama Rao et al. (2013). Weights were assigned based on expert judgments (Adger and Vincent, 2005); even though this approach is often criticized for being too subjective, we ensured that all the subject matter specialist were made available and tried to create consensus among the experts themselves. Each climate index values were divided into four groups by using the following formula:

$$Zi = \frac{Xmax - Xmin}{4}$$

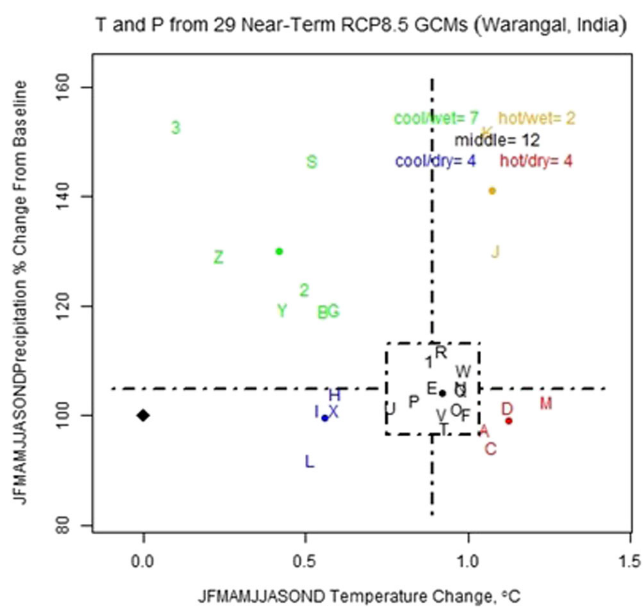


Fig. 2 Scatter plot for selection of GCMs for the study region using the precipitation and temperature change

Table 1 GCMs included in the five-member subset prioritized for climate analysis

Scenario	GCM and institution	Horizontal resolution
Cool-wet	bcc-csm1—Beijing Climate Center, China Meteorological Administration	~2.79° × 2.81°
Hot-dry	BNU-ESM—College of Global Change and Earth System Science, Beijing Normal University	2.79° × 2.81°
Cool-dry	GFDL-ESM2M—NOAA Geophysical Fluid Dynamics Laboratory, USA	2.02° × 2.5°
Hot-wet	HadGEM2-ES—Met Office, Hadley Centre, UK	1.25° × 1.87°

Z_i Normalized value of ith mandal w.r.t. the indicator.
X_{max} Maximum value of the indicator in original units.
X_{min} Minimum value of the indicator in original units.

By adding the Z for X_{min} we developed four classes for each parameter and assigned 1–4 values. Later climate exposure index was constricted by adding weighted means of each parameter to develop CEI for the respective grid. Higher values of CEI indicate higher vulnerability. This index is not an absolute measure of exposure due to climate change; it is only a relative measure of risk among various mandals (Table 2).

A database of all CEI described above for 350 grids was created and spatially connected to the mandals across Telangana state such that the respective CEI is available for the each mandal in the districts.

3 Results

The Climate Change Signals (CCSs) for each variable (maximum, minimum temperatures and rainfall) were calculated per season for RCP4.5, RCP8.5, and period (early and mid-century) over Telangana state to understand the observed changes and trends in current climatic variables over time and future occurrence of these events with respect to past and present trends.

3.1 Observed and anticipated climate of Telangana

The Climate Change Signals (CCSs) for each variable (maximum, minimum temperatures and rainfall) were calculated per season for RCP4.5, RCP8.5, and period (early and mid-century) over Telangana state to understand the observed

Table 2 Indicators considered in computation of climate exposure index

Indicator	Description
Annual maximum temperature	Mean 30-year annual maximum temperature in °C
Annual minimum temperature	Mean 30-year annual minimum temperature in °C
Heat wave occurrence (days)	No. of days when maximum temperature is > 45 °C
Cold wave occurrence (days)	No. of days when minimum temperature is < 10 °C
Severe heat wave occurrences (days)	No. of days when maximum temperature is > 47 °C
Severe cold wave occurrence (days)	No. of days when minimum temperature is < 8 °C
Annual precipitation	Mean 30-year annual rainfall (mm)
Monsoon rainfall	Total amount of rainfall (mm) received during June to September
Simple daily intensity index (mm/day)	Annual total precipitation divided by number of wet days (defined as RF >= 1.0 mm)
Heavy rainfall (days)	No. of days of daily rainfall events > 64.5
Very heavy rainfall (days)	No. of days of daily rainfall events > 124.5
Dry days duration	Number of consecutive dry days in monsoon period during a year
No. of times more than 14 days of dry days in monsoon (no/time slice)	Number of consecutive two weeks of dry days in monsoon period over 30-year slice in monsoon period during a year
Wet days duration	Number of consecutive wet days in monsoon period during a year
No. of times more than 14 days of wet in monsoon (no/time slice)	Number of consecutive two weeks of wet days in monsoon period over 30-year slice in monsoon period during a year
Number of annual rainy days	Annual count of days when RF >= 2.5 mm
95th percentile rainfall	Annual total precipitation when RF > 95th percentile
Hot day frequency	Number of consecutive days during summer period when maximum temperature > 45 °C

changes and trends in current climatic variables over time and future occurrence of these events with respect to past and present trends.

3.1.1 Surface temperatures

Firstly, the baseline surface temperatures were analyzed to assess the current climate variability and projected changes in future surface temperatures across Telangana state. The climatological normal of maximum and minimum temperature over Telangana was 33.7 °C and 22.1 °C, respectively. Similarly, the annual climatological normal was determined for all districts of Telangana. The district Jogulamba-Gadwal had the highest temperature of 34.5 °C followed by Suryapet 34.3 °C, Mancherial 34.2 °C, and Nalgonda 34.2 °C, while the lowest was in Medchal 32.9 °C (Table 4). Corresponding minimum temperature over districts of Telangana state varied from Khammam (23.6 °C), followed by Suryapet 23.4 °C and Nalgonda 23.2 °C, while the lowest was of 21.5 °C which was witnessed in both Medchal and Sangareddy districts.

Future projections of maximum and minimum temperatures of selected four climate models over Telangana indicate positive increase in temperature over all the districts in near and mid-century. All the four scenarios of future change considered projects an increase in maximum temperature with significant variation in magnitude. For the 4 climate scenarios, CSS of maximum and minimum temperatures features an increment of up to 2.5 °C and 3.2 °C during the mid-century (Table 5). In terms of annual cycle, the increase of minimum temperature by the end of the twenty-first century is apparently higher than maximum temperature.

In mid-century, surface temperatures maximum and minimum features lowest increment in cool-dry scenario and highest surge in hot-dry scenario across all the districts of Telangana state.

The cool-dry scenario in mid-century projects a highest increase in maximum temperature up to 2.2 °C over Medchal, while a low increment of 1.2 °C over Bhadradri-Kothagudem and Khammam districts. Similarly, minimum temperature exhibited highest increase of 2.0 °C over Adilabad, Bhadradri-Kothagudem, Jogulamba-Gadwal, Nagarkurnool, and Wanaparthy, while it predicted low increase of 1.8 °C over Hyderabad, Medak, Medchal, Nizamabad, Peddapalli, Rajanna Siricilla, Ranga Reddy, Vikarabad, Warangal (urban), and Yadadri districts. The hot-dry scenario on the other hand projects a highest increase of maximum temperature of 2.5 °C over Adilabad, Komurambheem Asifabad, Mancherial, Nirmal and Siddipet and a lowest increase of 2.0 °C over Wanaparthy. Projections of the other two scenario fall within the range of change projected by these scenarios. Minimum temperature unveiled similar results over different districts of the state under the hot-dry scenario, a highest increase of 3.2 °C over Adilabad, Jangaon, Kamareddy, Komurambheem Asifabad, and Medchal and a low increase of 2.5 °C over Khammam. Projections of the other two scenario fall within the range of change projected by these scenarios.

Table 3 Weighting scheme of the climate exposure index

Indicator	Weight (%)
Heat wave occurrence (days)	3
Cold wave occurrence (days)	3
Severe heat wave occurrences (days)	5
Severe cold wave occurrence (days)	**2**
CV of annual precipitation (%)	0
CV of June rainfall (%)	5
CV of July rainfall (%)	15
Annual precipitation	2
Monsoon rainfall	3
CV monsoon rainfall (%)	10
Simple daily intensity index (mm/day)	5
Heavy rainfall (days)	10
Very heavy rainfall (days)	10
Wet days duration	5
No. of times more than 14 days of wet in monsoon (no./time slice)	5
Number of annual rainy days	5
95th percentile rainfall	5
Hot day frequency	7

Table 4 Observed climate profile of Telangana

S. no.	Districts	Tmax (°C)	Tmin (°C)	Rainfall (mm)	RF CV (%)	Rainy days	SWM RF (mm)	SWM RD
1	Adilabad	33.9	21.5	1163	30	64	998	51.6
2	Bhadradri Kothagudem	33.6	22.9	1248	25	73	1012	55.9
3	Hyderabad	33.0	21.7	843	24	58	620	41.3
4	Jagtial	34.0	21.9	1094	29	59	908	47.0
5	Jangaon	33.7	22.3	869	29	56	674	42.2
6	Jayashankar-Bhupalpally	34.1	22.7	1293	26	70	1107	55.7
7	Jogulamba-Gadwal	34.5	22.7	683	26	48	476	33.7
8	Kamareddy	33.3	21.5	1006	29	60	815	46.9
9	Karimnagar	34.0	22.3	973	27	58	788	45.0
10	Khammam	34.2	23.6	1037	29	64	785	47.6
11	Komurambheem-Asifabad	34.0	21.8	1247	29	67	1091	55.1
12	Mahabubabad	33.6	22.5	1060	24	64	841	49.3
13	Mahabubnagar	33.7	22.1	729	25	53	544	39.2
14	Mancherial	34.2	22.2	1211	24	67	1036	54.2
15	Medak	33.0	21.6	907	27	59	721	45.2
16	Medchal	32.9	21.5	838	24	55	612	39.4
17	Nagarkurnool	33.2	21.8	697	27	49	492	34.7
18	Nalgonda	34.2	23.2	780	26	52	553	36.6
19	Nirmal	33.9	21.5	1114	32	63	945	50.5
20	Nizamabad	33.8	21.6	1027	32	59	850	47.3
21	Peddapalli	34.2	22.4	1105	27	64	928	50.2
22	Rajanna Siricilla	33.7	21.8	910	25	61	719	46.6
23	Ranga Reddy	33.1	21.7	790	22	55	569	39.3
24	Sangareddy	33.1	21.5	911	27	59	717	44.8
25	Siddipet	33.2	21.7	816	27	56	627	41.5
26	Suryapet	34.3	23.4	900	27	57	680	41.8
27	Vikarabad	33.3	21.7	846	27	59	664	44.9
28	Wanaparthy	34.1	22.4	705	24	51	509	36.8
29	Warangal (rural)	33.8	22.5	1069	22	65	882	50.5
30	Warangal (urban)	33.8	22.5	923	31	55	745	42.8
31	Yadadri	33.5	22.2	797	26	53	575	37.4

3.1.2 Rainfall and rainy days

The average annual rainfall received over Telangana state during 1980–2009 is 955 mm. The annual normal was calculated for all districts of Telangana state. The district Jayashankar-Bhupalpally had the highest rainfall of 1293 mm received in 70 rainy days followed by Bhadradri-Kothagudem (1248 mm in 73 days), Komurambheem Asifabad (1247 mm in 67 days), and Mancherial (1211 mm in 67 days). The lowest amount of rainfall received over Telangana is in Jogulamba-Gadwal (683 mm) received in 48 rainy days followed by Nagarkurnool (697 mm in 49 days). The amount of rainfall and their distribution indicate a longer growing period over the places receiving higher rainfall and shorter periods over the places with least rainfall and rainy days.

Future climate projections for mid-century period for Telangana indicate a wide range of variation in annual rainfall. All four possible scenarios of future change projects varying magnitudes of change in annual rainfall over all districts of Telangana. The future projected changes in annual rainfall over the Telangana state exhibited reduction in annual rainfall from − 11.1 to + 64.4% during the near-term and 0.0 to 67.1% increase during mid-century. Except hot-dry scenario, all other scenarios project an increase in rainfall across Telangana state. In case of distribution, the number of rainy days is projected to vary between − 8 and + 27% during mid-century period.

In mid-century, the hot-dry scenario projects a 12.9% increase in rainfall (4% increase in rainy days) over Wanaparthy, while model predicted no change over Bhadradri-Kothagudem and Khammam. The hot-wet scenario

Table 5 Future projected changes in surface temperatures during mid-century under RCP 8.5

District	Maximum temperature (°C)				Minimum temperature (°C)			
	Cool-dry MC	Hot-dry MC	Cool-wet MC	Hot-wet MC	Cool-dry MC	Hot-dry MC	Cool-wet MC	Hot-wet MC
Adilabad	1.6	2.5	1.6	2.5	2.1	2.8	2.0	3.2
Bhadradri-Kothagudem	1.2	2.2	1.4	2.1	2.0	2.2	2.0	2.6
Hyderabad	1.6	2.4	1.6	2.4	1.9	2.4	1.8	3.1
Jagtial	1.6	2.4	1.6	2.5	2.2	2.5	1.9	3.1
Jangaon	1.6	2.4	1.6	2.3	2.0	2.5	1.9	3.2
Jayashankar-Bhupalpally	1.6	2.3	1.5	2.2	2.0	2.3	1.9	2.8
Jogulamba-Gadwal	1.5	2.1	1.6	2.4	1.8	2.0	2.0	2.8
Kamareddy	1.6	2.4	1.6	2.5	2.1	2.5	1.9	3.2
Karimnagar	1.6	2.4	1.6	2.4	2.1	2.4	1.9	3.0
Khammam	1.2	2.2	1.5	2.1	1.9	2.2	1.9	2.5
Komurambheem-Asifabad	1.6	2.5	1.6	2.5	2.1	2.5	1.9	3.2
Mahabubabad	1.4	2.4	1.6	2.2	2.0	2.4	1.9	2.6
Mahabubnagar	1.6	2.3	1.6	2.4	1.9	2.3	1.9	2.9
Mancherial	1.7	2.5	1.6	2.4	2.1	2.4	1.9	3.0
Medak	1.6	2.4	1.6	2.4	1.9	2.4	1.8	3.1
Medchal	2.2	2.4	1.6	2.4	2.5	2.4	1.8	3.2
Nagarkurnool	1.6	2.1	1.6	2.3	2.0	2.1	2.0	2.9
Nalgonda	1.6	2.4	1.6	2.3	2.0	2.4	1.9	3.1
Nirmal	1.7	2.5	1.6	2.5	2.1	2.4	1.9	3.1
Nizamabad	1.6	2.4	1.6	2.5	2.1	2.4	1.8	3.0
Peddapalli	1.6	2.4	1.6	2.4	2.1	2.4	1.8	3.0
Rajanna Siricilla	1.6	2.4	1.6	2.4	2.1	2.4	1.8	3.0
Ranga Reddy	1.8	2.4	1.6	2.3	2.1	2.4	1.8	3.1
Sangareddy	1.5	2.4	1.5	2.3	1.9	2.4	1.9	3.1
Siddipet	1.6	2.5	1.6	2.4	2.0	2.4	1.9	3.1
Suryapet	1.5	2.4	1.6	2.2	2.0	2.5	1.9	2.9
Vikarabad	2.0	2.4	1.5	2.4	2.2	2.4	1.8	3.1
Wanaparthy	1.5	2.0	1.6	2.3	1.9	2.0	2.0	2.9
Warangal (rural)	1.5	2.4	1.6	2.3	2.0	2.5	1.9	2.9
Warangal (urban)	1.6	2.4	1.6	2.4	2.0	2.4	1.8	3.1
Yadadri	1.7	2.4	1.6	2.4	2.0	2.4	1.8	3.1

projected highest increase of 67.1% rainfall in Jogulamba-Gadwal with 27% increase in rainy days and lower limit of 35.6% increase in rainfall over Bhadradri-Kothagudem with 11% increase in rainy days. Spatial distribution of rainfall across Telangana state in baseline and future climate change scenarios are depicted in Fig. 3.

3.1.3 Monsoon rainfall

The climatological normal of southwest monsoon rainfall of Telangana is found to be 758 mm. The monsoon rainfall was determined for all districts of Telangana. The district Jayashankar-Bhupalpally received the highest rainfall of 1107 mm followed by Komurambheem Asifabad (1091 mm), Mancherial (1036 mm), and Bhadradri-Kothagudem (1012 mm). The lowest rainfall receiving location of Telangana is Jogulamba-Gadwal (476 mm) followed by Nagarkurnool (492 mm). The monsoon rainfall has similar spatial spread like that of annual rainfall.

Monsoon rainfall is also expected to vary widely under future climate projections during both near- and mid-century time slices. The four possible scenarios of future change project varying magnitudes of change in districts of Telangana state. Rainfall in Telangana is projected to increase 1.8 to 64.5% during mid-century. Spatial distribution of monsoon rainfall over Telangana in baseline and future climate change scenarios are depicted in Fig. 4.

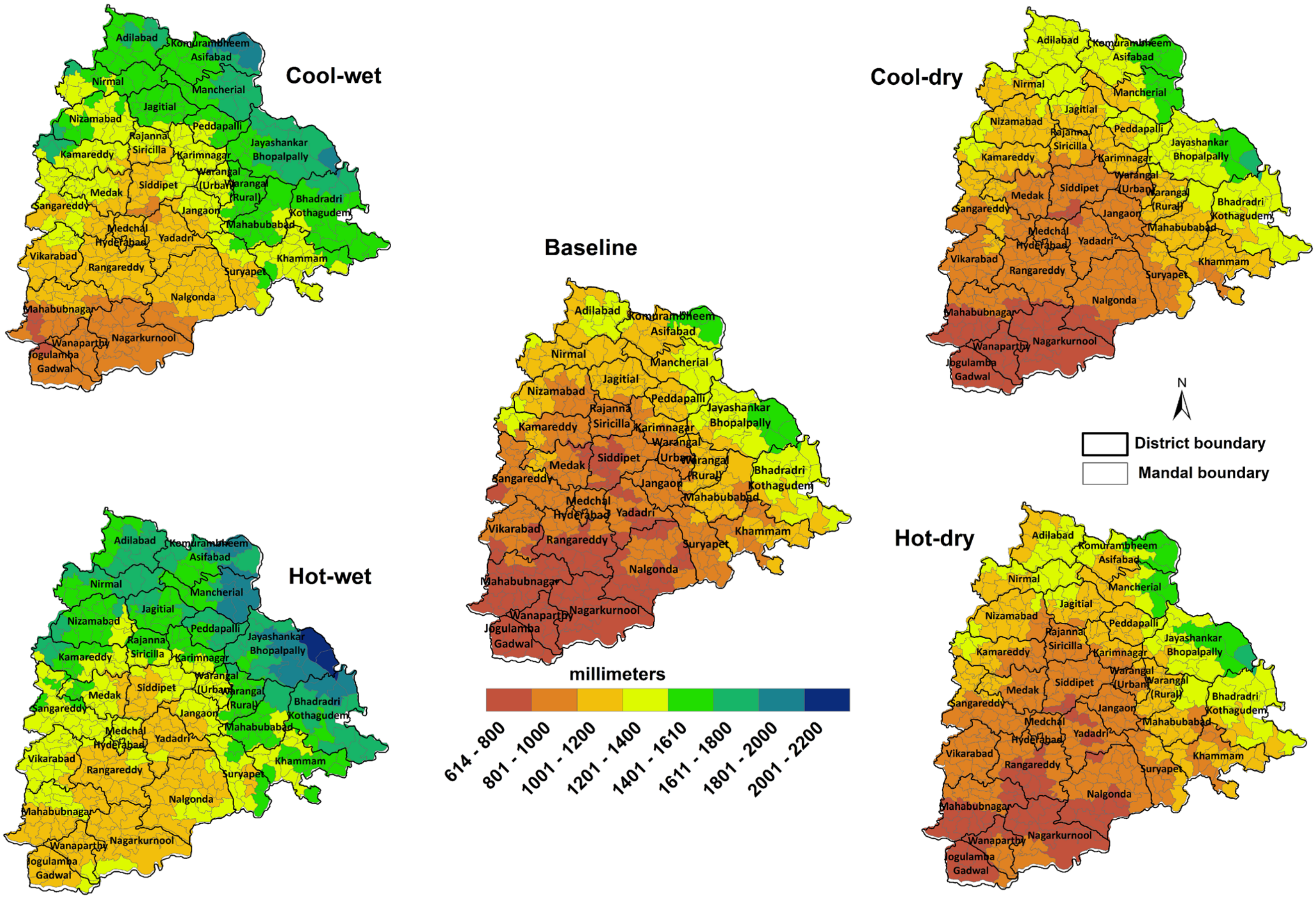


Fig. 3 Spatial distribution of annual rainfall over Telangana in baseline and future climate change scenarios in during mid-century period (RCP 8.5)

Southwest monsoon (during the months of June–September) is the major rainy season for Telangana contributing 67% of annual rainfall. Except hot-dry scenario, all other scenarios project an increase in rainfall over Telangana. During the mid-century, the hot-dry scenario projects increase in rainfall over Telangana, a lowest increase of 1.8% to a highest of 19.3% in Bhadradri-Kothagudem and Wanaparthy, respectively. The hot-wet scenario projects a highest increase of 64.5% rainfall in Jogulamba-Gadwal and a lowest of 29.9% increase over Adilabad.

3.2 Extreme weather events: observed and anticipated

3.2.1 High rainfall events

Extreme rainfall events are the major sources for flash floods across the globe. Therefore, understanding the changes in frequency and magnitude of such events are vital for agriculture operations, human society, and the natural environment. Historical rainfall analysis over Telangana displayed an average of 1 to 3 heavy rainfall events (based on 30 years of observed data) annually and particularly during southwest monsoon season. The districts Adilabad, Jayashankar-Bhupalpally, and Komurambheem-Asifabad had up to 3 heavy rainfall events, while all other districts had 1 or 2 such events (Fig. 5).

The frequency and magnitude of extreme rainfall events are expected to change as per future climate projections. Hot-wet scenario shows highest increase in such events; Komurambheem-Asifabad is anticipated to witness up to 5.2 heavy rainfall events followed by Adilabad (5), Jagtial (5), Mancherial (5), Jayashankar-Bhupalpally, and Nirmal (5). Very heavy rainfall events were also studied for current and future climate conditions. The districts Adilabad, Jayashankar-Bhupalpally, Komurambheem-Asifabad, and Nirmal have witnessed more number of very heavy rainfall events. In future climate conditions also, these districts are expected to witness further increase in very heavy rainfall events.

3.2.2 Heat wave

A heat wave is a period of excessively hot weather. The Indian Metrological Department defines heat wave conditions when maximum daily temperature at a location reaches at least 40 °C for Plains, 30 °C for Hilly regions and 37 °C or more for coastal region. The heat wave occurrence was examined for all districts of Telangana state. From the observed

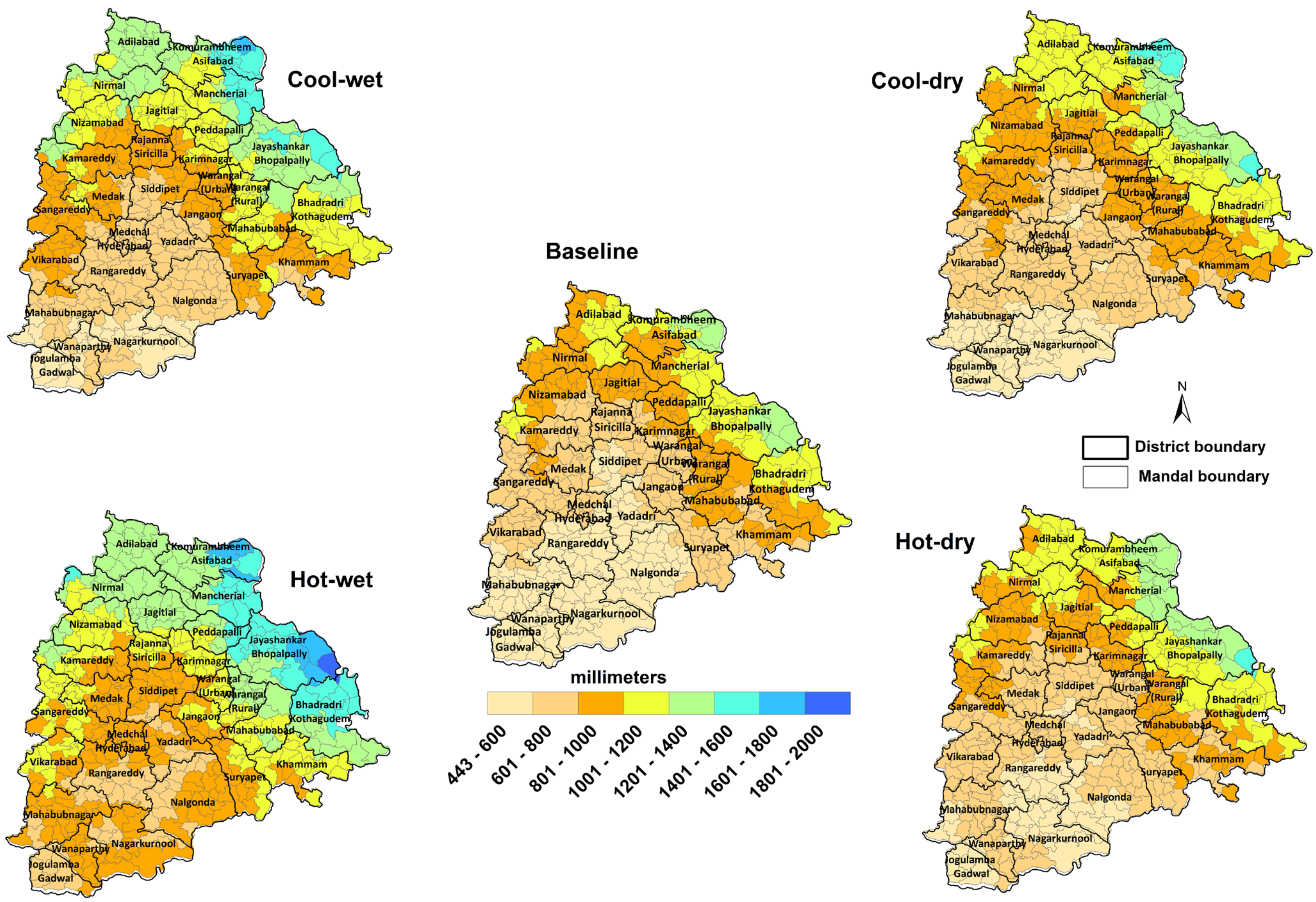


Fig. 4 Spatial distribution of monsoon rainfall over Telangana in baseline and future climate change scenarios in during mid-century period (RCP 8.5)

historical data, it is evident that this region experiences an average of 3 to 12 heat wave events annually (Fig. 6). The district Mancherial and Komurambheem-Asifabad experience the highest number of heat waves (12) followed by Peddapalli (11) and Jayashankar-Bhupalpally (10), while the least number (3) of such events were witnessed in the districts Sangareddy, Medak, and Medchal. Future climate projections indicate an increase in the number of heat wave days. In mid-century, a minimum of 11 to a maximum of 35 heat wave events were projected. It is interesting to note that all four scenarios project the highest number of heat waves over the Adilabad district during mid-century (Fig. 6).

3.2.3 Severe heat wave

When daily maximum temperature of a station is greater than or equal to 47 °C, then it is considered as severe heat wave. The observed data of severe heat waves over Telangana state displayed an average of 1 to 3 events annually. The district, Jayashankar-Bhupalpally, Khammam, Mancherial, and Komurambheem-Asifabad had the highest number of severe heat waves, while all the other districts had 1 to 2 severe heat wave events.

Future climate projection indicates an increase in the number of severe heat wave events in mid-century. In mid-century, a minimum of 3 to a maximum of 23 severe heat wave events were projected across districts in Telangana (Table 6).

3.2.4 Consecutive dry days

Monsoon rainfall amount and distribution are the most vital parameter in crop production; any break or dry spells during the monsoon (JJAS months) significantly affects the crop growth and establishment resulting in poor yields. Hence, the number of consecutive dry days was analyzed at mandal level for crop planning and management (Fig. 7). A minimum of 8 to a maximum of 11 consecutive dry days annually was observed across Telangana in the last 3 decades (1980–2009). The districts Nagarkurnool, Wanaparthy, and Yadadri have the longest stretch of dry days with about 11 consecutive days followed by Jangaon, Jogulamba-Gadwal, Kamareddy, Mahabubnagar, Medchal, Nalgonda, Ranga Reddy, and Siddipet with 10 consecutive dry days annually. Future climate projections indicate negligible or no change in the dry day's length in early and mid-century periods. All four scenarios project nearly similar range of consecutive dry days (Fig. 7).

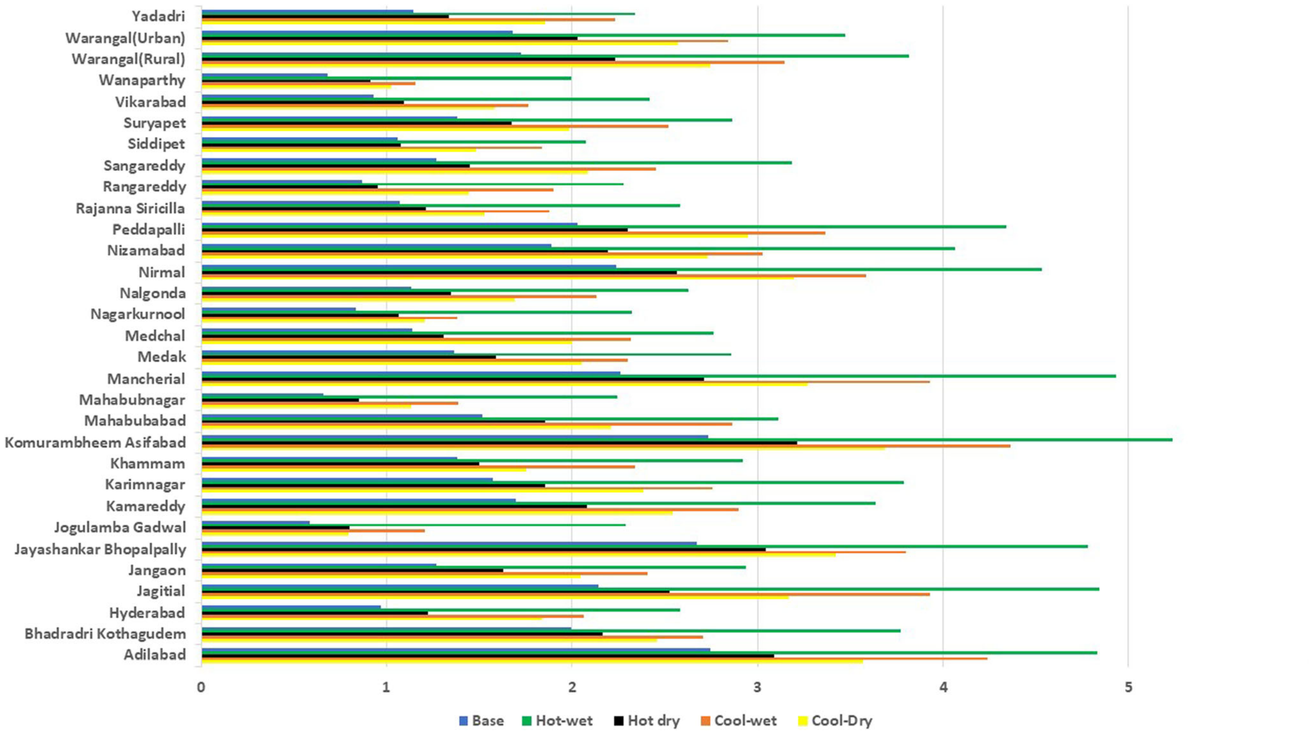


Fig. 5 Projected heavy rainfall events in a year over Telangana in baseline and future climate change scenarios in during mid-century period (RCP 8.5)

3.2.5 Long dry spells (> 14 consecutive dry days)

Dry period during the monsoon imparts moisture stress in plants. If the dry spells length is more than 2 weeks, it is more deleterious to crops survival. Thus, the number of such long dry spells during the monsoon season was examined in the 30 years' time slice of observed and future climate data. All districts of Telangana state have witnessed long dry spells in

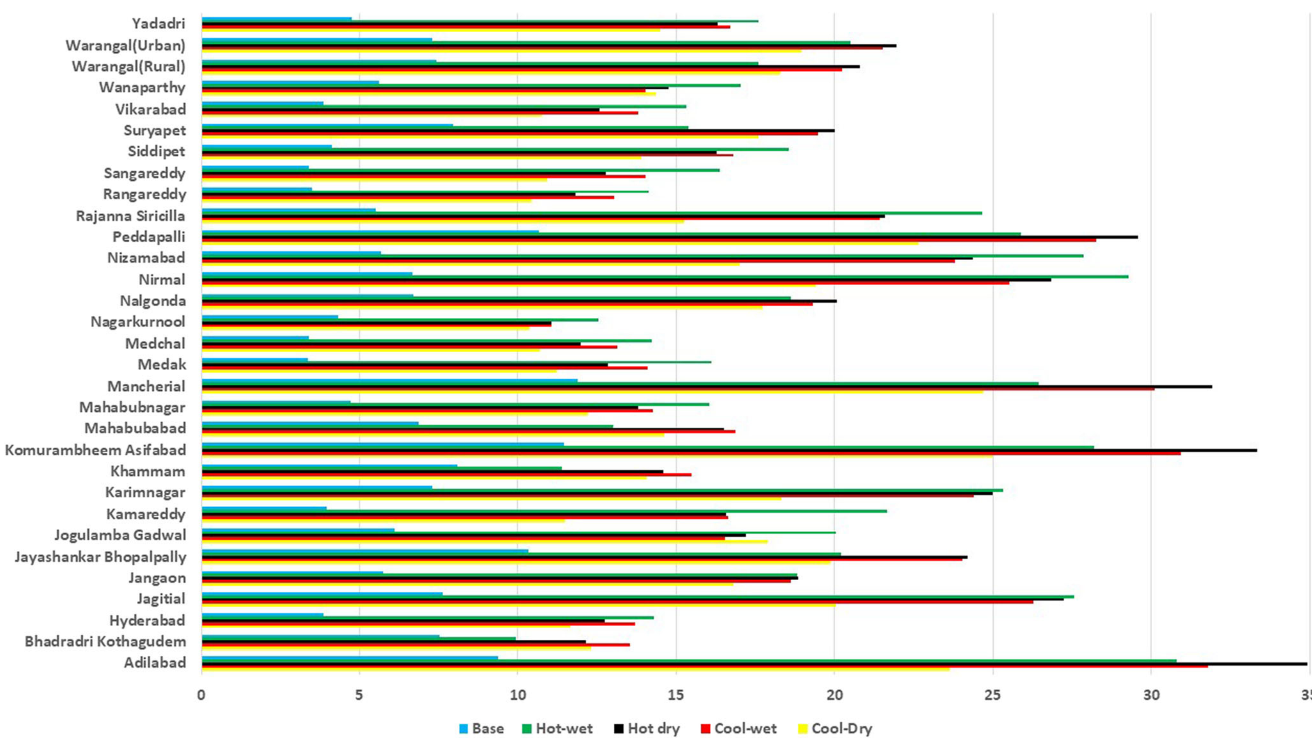


Fig. 6 Projected heat wave occurrence events in a year over Telangana in baseline and future climate change scenarios in during mid-century period (RCP 8.5)

Table 6 Projected severe heat wave occurrence days in a year over Telangana during the mid-century

S. no.	Districts	Base	Cool-dry	Hot-dry	Cool-wet	Hot-wet
1	Adilabad	1.9	7.5	12.5	13.0	21.2
2	Bhadradri-Kothagudem	2.5	0.7	5.2	7.3	8.5
3	Hyderabad	0.6	0.3	3.2	5.1	6.6
4	Jagtial	1.7	1.8	8.9	10.4	17.9
5	Jangaon	0.9	0.7	5.8	7.5	10.4
6	Jayashankar-Bhupalpally	2.7	1.3	10.3	12.3	16.6
7	Jogulamba-Gadwal	1.1	0.7	5.2	5.4	9.9
8	Kamareddy	0.7	1.5	4.0	5.1	9.4
9	Karimnagar	1.5	1.5	8.3	9.6	16.3
10	Khammam	3.1	0.7	6.5	8.0	9.8
11	Komurambheem-Asifabad	2.7	9.2	14.0	14.5	23.2
12	Mahabubabad	1.5	0.6	6.0	7.8	8.6
13	Mahabubnagar	0.7	0.4	3.8	5.2	7.2
14	Mancherial	2.8	9.7	13.7	14.6	22.6
15	Medak	0.4	0.8	3.0	4.1	6.1
16	Medchal	0.5	0.5	2.7	4.3	6.0
17	Nagarkurnool	0.7	0.4	2.9	3.6	5.9
18	Nalgonda	1.5	0.7	6.8	8.1	11.0
19	Nirmal	1.4	4.9	7.9	9.2	16.4
20	Nizamabad	1.1	1.9	6.7	8.1	14.6
21	Peddapalli	2.4	1.7	12.1	13.2	21.1
22	Rajanna Siricilla	1.0	1.5	6.0	7.6	13.4
23	Ranga Reddy	0.6	0.4	2.8	4.8	6.4
24	Sangareddy	0.5	0.6	2.9	4.0	6.2
25	Siddipet	0.7	0.9	4.0	5.5	8.5
26	Suryapet	2.1	0.7	7.9	9.2	11.1
27	Vikarabad	0.6	0.4	3.1	5.0	6.6
28	Wanaparthy	0.9	0.4	4.6	4.8	8.2
29	Warangal (rural)	1.5	1.0	7.7	8.7	11.2
30	Warangal (urban)	1.4	0.8	7.7	9.1	13.0
31	Yadadri	0.8	0.6	4.4	6.5	8.6

the past 30 years, with about 2 to 6 events annually (Fig. 8). A maximum of 6 long dry spells have occurred over Kamareddy, Nagarkurnool, Nalgonda, and Yadadri followed by Adilabad, Karimnagar, and Wanaparthy with 5 such occurrences. In the districts Bhadradri-Kothagudem, Hyderabad, Jayashankar-Bhupalpally, Mahabubabad, Mancherial, and Sangareddy least of 2 events were occurred. Future projections infer nearly similar number of events would occur in mid-century.

3.2.6 Consecutive wet days

The number of consecutive wet days is most important for good crop and bountiful yields. During monsoon period, the districts of Telangana experiences 10 to 21 consecutive wet days per year. Bhadradri-Kothagudem has the highest of 21 consecutive wet days followed by Jayashankar-Bhupalpally (20) and Komurambheem-Asifabad (20). The districts Nagarkurnool, Nalgonda, and Yadadri have the least consecutive wet days (10).

Future projections for the mid-century indicate an increase in the number of consecutive wet days. Overall, 8 to 37 consecutive wet events during mid-century were projected. The hot-wet scenario projects the highest number of such events in near term; 37 consecutive wet days were projected over Jayashankar-Bhupalpally and lowest of 13 such events over Yadadri (Fig. 9).

3.3 Assessment of climate vulnerability

Climate variability and climate change impose severe threat to agriculture of any region. Like the assessment of current

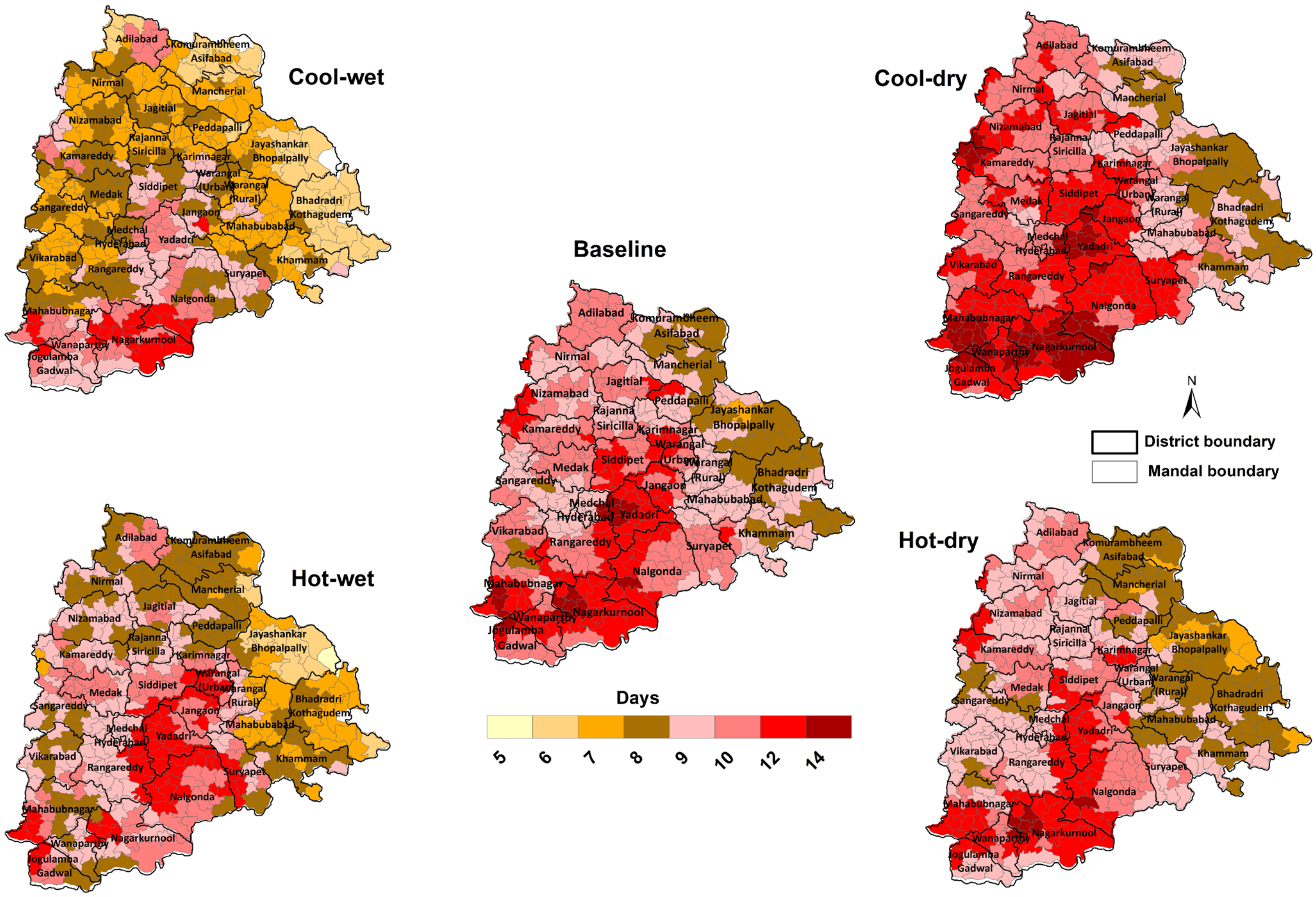


Fig. 7 Spatial distribution of average consecutive dry days over Telangana in baseline and future climate change scenarios in during mid-century period (RCP 8.5)

climate variability, it is imperative to assess the future climate vulnerability also. Based on climate analysis, representative parameter that affects agriculture was selected to construct the CEI. Based on the CEI, the mandals were categorized into vulnerability classes as very low, low, medium, high, and very high vulnerable mandals. Vulnerability assessment was done over Telangana for the present and future climate conditions and the high and very high categories were addressed here.

3.3.1 Current climate vulnerability over Telangana

The state of Telangana has 442 mandals. Presently, 28% of these mandals (123) were found to be vulnerable. In the future, 41 to 49% of the mandals were projected to become vulnerable to the changing climate in near term, while 37 to 84% of the mandals were projected to become vulnerable during the mid-century. In near term, cool-dry scenario projected 49% of mandals to become vulnerable, while in mid-century, hot-wet scenario projected 84% of mandals to become vulnerable (Fig. 10.). District-wise vulnerability accumulation of mandals was done to identify most vulnerable districts in Telangana state.

3.3.2 Future climate vulnerability of the districts

The district Jogulamba-Gadwal is found to be highly vulnerable in mid-century period as determined by all four scenarios that were studied. In contrast, the district Bhadradri-Kothagudem was found to be least vulnerable. After Jogulamba-Gadwal, the districts Adilabad, Nagarkurnool, Nalgonda, Peddapalli, Suryapet, Wanaparthy, and Yadadri were found to be more vulnerable than most of the districts with more 60% of mandals projected to be vulnerable by all scenarios. The districts Jangaon, Karimnagar, Komurambheem Asifabad, Mahabubnagar, and Mancherial are found to be vulnerable with more than 40% of mandals projected to be vulnerable. All other districts have less percent of mandals vulnerable to climate change than these districts mentioned above. Among the scenarios, hot-dry and hot-wet project more vulnerability over the districts. The trend of predicting district vulnerability is similar in all the four scenarios.

When mandal level climate vulnerability map was overlaid with crop land map of Telangana state (Fig. 11) along with irrigated command areas, it can assist the policymakers on land and agriculture planning and management. It also helps to figure out which places and crops are the most vulnerable, as well as the degree of vulnerability and helps in designing possible adaptation options. Smallholder farming is the most prevalent form of agriculture in Telangana, and hence, this kind of analysis is highly useful for planning adaptation options against possible climate change.

4 Discussion

In this study, we assessed the climate-related vulnerability of different mandals of Telangana state using various climate indicators. In our analysis, we observed increased spatial variability in temperature across the study area which could be due to elevation differences (Karmalkar et al., 2008), nearness to coast, and other geographical features. Similar pattern of increased warming also been reported by Rajalakshmi et al. (2013). These temperature projections were in agreement with range of change projected by Kothawale and Rupakumar (2005). Rupakumar et al. (2006), and Krishna kumar et al. (2011) over India. Rainfall analysis indicates broader variation across the state. The variations in the sign and magnitude of rainfall change throughout Telangana envisage the importance of careful location-specific crop planning (Rajiv kumar et al. 2012). This is the first of its kind exercise that aims to construct climate exposure index at finer administrative level which can help policymakers for better planning. We observed that one of the main barriers to scaling up climate-smart agriculture (CSA) practices in Telangana state is lack of information on current and future projected climate risk at mandal level. Several earlier researchers have taken up vulnerability studies in other states of India, but those studies mainly focused at district level (O'Brien et al. 2004, Kumar et.al 2016; Rama Rao et al., 2016). Research institutes and non-government organizations along with government agencies in Telangana state are working on scaling up climate-smart interventions; however, these practices are not implemented systematically or adequately due to lack of localized data/information. Furthermore, these organizations have little information on climate-related risks faced by each region, which affects trade-offs and undermines impacts of interventions at sub-district levels. In order to construct a unifying approach to implementing climate-smart agriculture policies and to produce an evidence-based framework for guiding investments and policymaking decisions in climate-smart

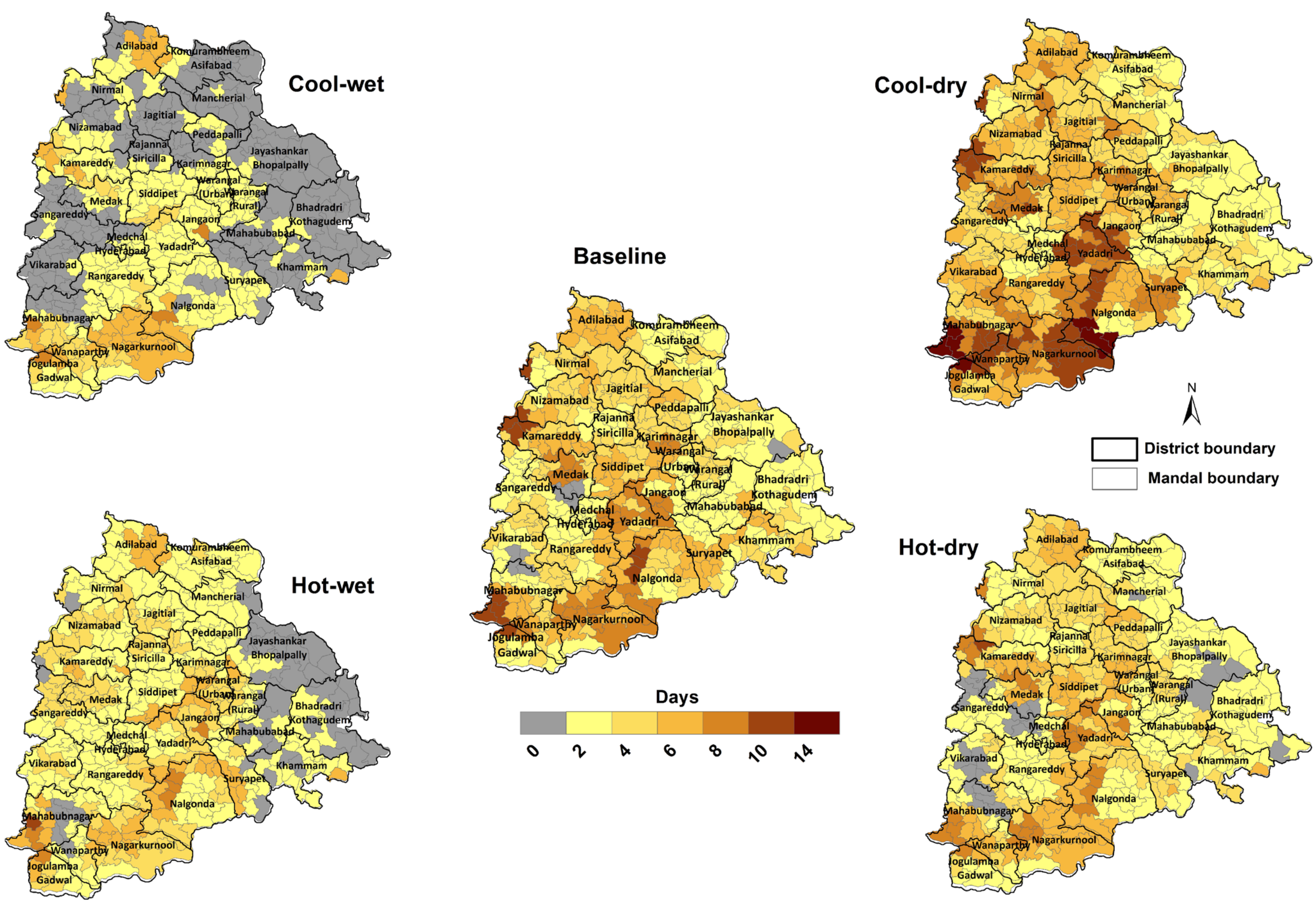


Fig. 8 Spatial distribution of number of consecutive dry days of more than 14 over Telangana in baseline and future climate change scenarios in during mid-century period (RCP 8.5)

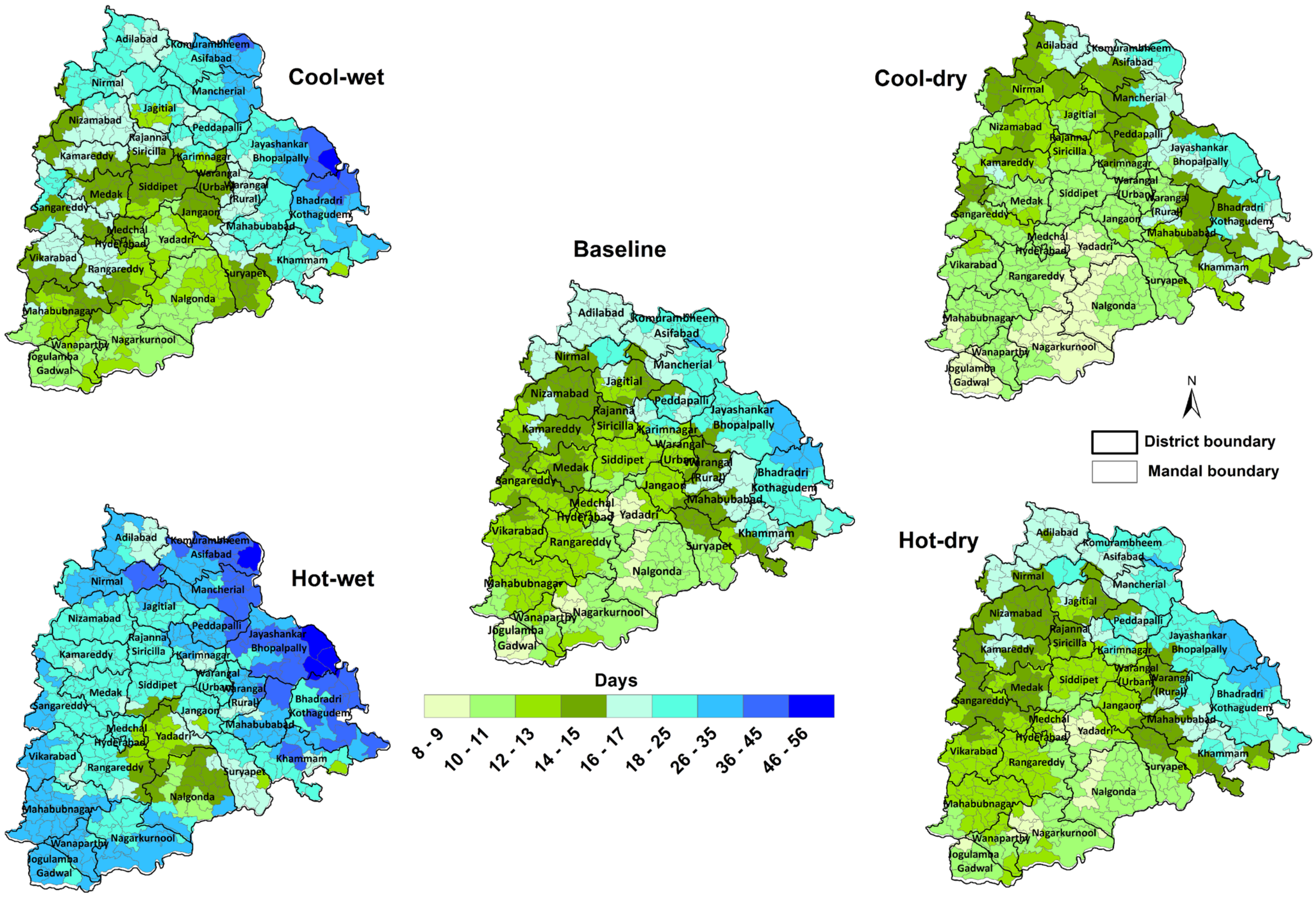
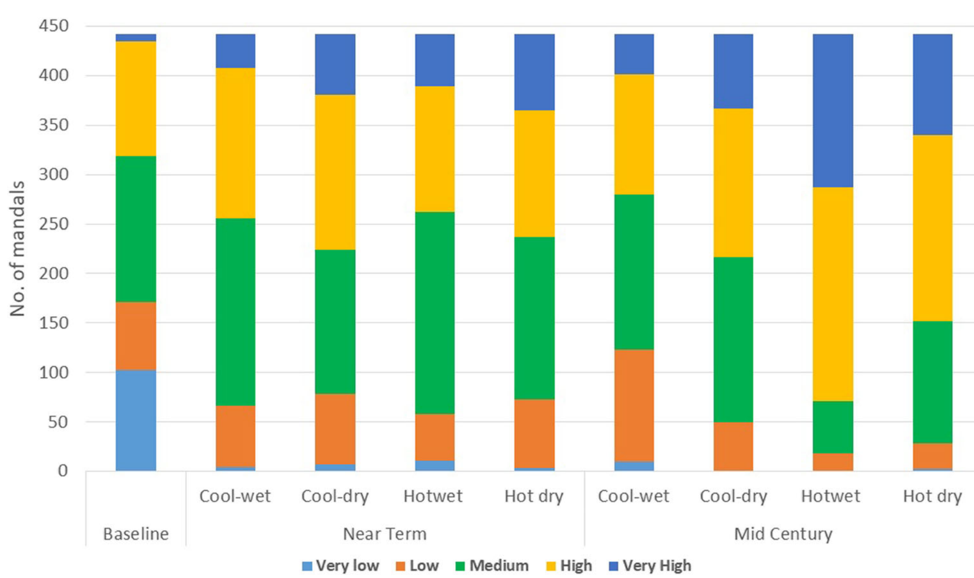


Fig. 9 Spatial distribution of average consecutive wet days over Telangana in baseline and future climate change scenarios in during mid-century period (RCP 8.5)

agriculture, the first step would be preparing climate exposure index at smaller administrative scales. This is the main motivation behind the current work.

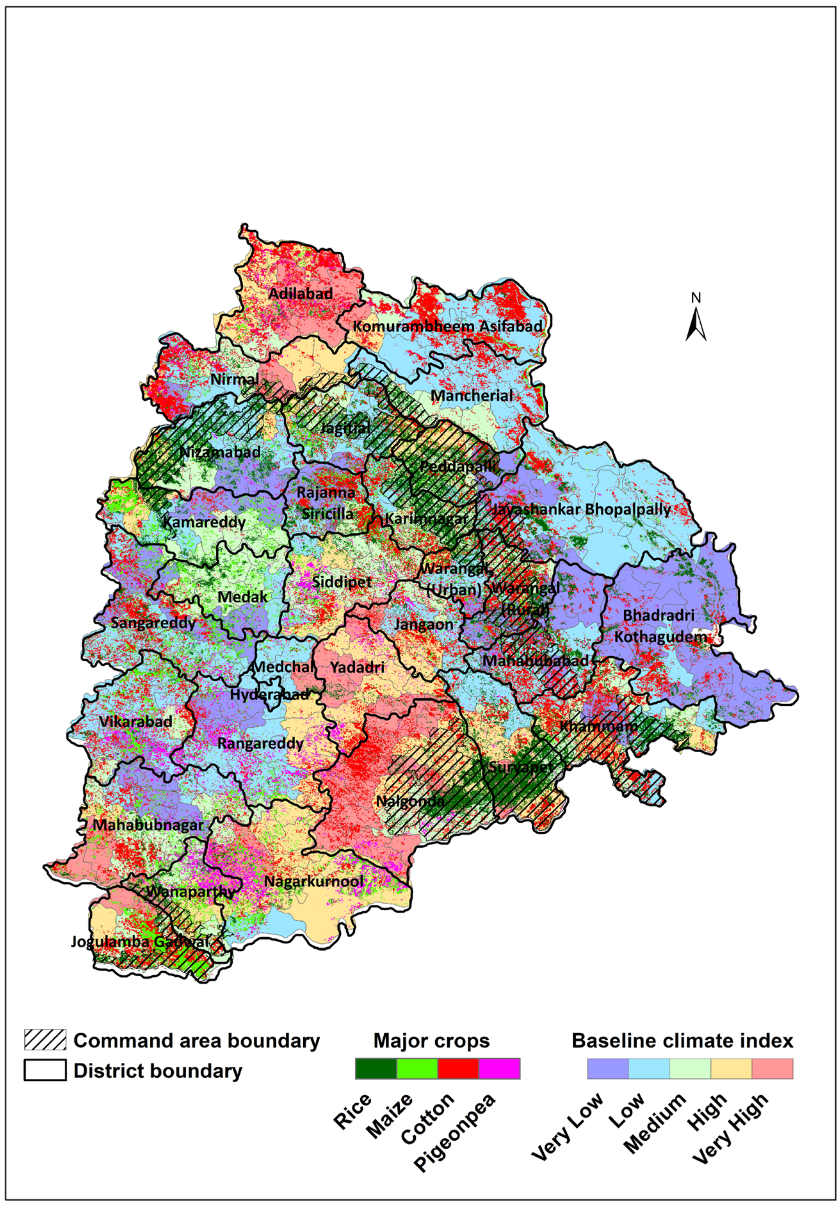
The results of this extensive analysis have shown that in Telangana state, specifically in southern Telangana zone, majority of mandals in districts were placed under "high to very

Fig. 10 Mandal-wise climate exposure index under various climate scenarios compared with baseline



high" level of climate vulnerability. In the baseline climate analysis, Nalgonda district has higher number of mandals (25) under climate vulnerability condition. This can be attributed mainly due to high coefficient of variation in both July and total monsoon rainfall. Further, the number of dry days during monsoon period and continuous dry days of more than 15 days also contributed to climate vulnerability. In semiarid tropics, unreliable rainfall along with higher growing season temperatures result in a high risk of water deficit at any stage of crop growth (Battisti and Naylor, 2009; Najmaddin et al. 2017). It was observed from several studies that high rainfall variability and dry spells during crop growth have a direct impact on crop yields especially under rainfed conditions (Gopika et al., 2014, Bewket, 2009, Haruhisa and Jun, 2009). The number of vulnerable mandals would substantially increase in the future as detected in the current study. The optimistic scenario (cool-wet) shows 47% of mandals while hot/dry scenario shows 66% mandals during mid-century period under high to very high category necessitating need of strategic interventions. The districts, Jogulamba-Gadwal, Adilabad, Nagarkurnool, Nalgonda, Peddapalli, Suryapet, Wanaparthy, and Yadadri were found to be highly vulnerable. Prolonged dry spells during monsoon period and heat wave conditions during summer are the major factors that contributed to high climate exposure index. Prolonged dry spells of more than 15 days are disastrous for plants especially after sowing, because they dry top soil layers and prevent germination, which may lead to total crop failure or yield reduction

Fig. 11 Mandal level climate exposure index overlaid with crop land mapping along with irrigation command areas in Telangana region



(Laux et al., 2008). In future climate projections, it was observed that temperature during the cropping season often exceeded the optimum conditions for physiological processes such as leaf area development, biomass partitioning, flowering, and grain filling. High air temperature during flowering can reduce pollen viability and grain set in major cereals of the tropics (rice, maize, sorghum, etc.). A study conducted by Lobell et al. (2008) highlighted that climate risks for crops in semiarid regions of Asia threatens food security with substantial increase in future surface temperatures and highly variable monsoon rainfall.

The factors that determine climate exposure index for a particular mandal are mainly due to high variability of monsoon rainfall, heavy rainfall events, and increase in minimum and maximum temperatures. These issues can be tackled to some extent by careful planning and technological interventions such as modifying the crop sowing windows, promoting drought, heat tolerance, and different crop maturity duration cultivars. Mandals where increased frequency of heavy rainfall events was observed/projected offer an opportunity to promote construction of farm ponds for rainwater harvesting which can be used for irrigation in periods of dry spells. The future climate projections in both near-term and mid-century periods showed increase in annual rainfall in majority of mandals in few districts. These positive aspects offer an untapped opportunity for improving agricultural productivity by promoting suitable crops and cropping systems for rainfed regions of Telangana state.

Finally, upon overlaying crop-type map with climate exposure index map of Telangana, we observed that crops such as cotton, pigeon pea, and maize are common in the mandals with highest climate risks. This clearly indicates the need to promote CSA practices that enhance resilience of these cropping systems in the short run and to assess alternative farming strategies for long run to make agriculture in Telangana state as climate resilient as possible.

5 Conclusion

The present study has identified climate change–related vulnerable areas in the Telangana state by computing climate exposure index using various climate parameters. This study helps in identifying the most vulnerable mandals to climate change that require intervention and support as investments must be strategic to areas that are most susceptible to climate variability and change. The paper is intended to inform decision-makers about the need for climate vulnerability analysis at sub-district level (mandal) for proper priority setting of government investments to mitigate the climate change impacts. It also presents an opportunity for better adaptation of agriculture sector to minimize risks due to climate change induced extreme events. Under the increasing vulnerability of Telangana state to climate change impacts, a holistic approach is needed for sustainable crop production.

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References

Adger WN, Vincent K (2005) Uncertainty in adaptive capacity. Compt Rendus Geosci 337(4):399–410

Battisti DS, Naylor RL (2009) Historical warnings of future food security with unprecedented seasonal heat. Science 323:240–244

Beauchamp TL, Childress JF (2001). Principles of biomedical ethics. Fifth Edition. Oxford, Oxford University Press

Bewket W (2009) Rainfall variability and crop production in Ethiopia case study in the Amhara region. In: Proceedings of the 16th international conference of Ethiopian studies, ed. by Svein Ege, Harald Aspen, Birhanu Teferra and Shiferaw Bekele, Trondheim 823-836

Cruz RV, Harasawa H, Lal M, Wu S, Anokhin Y, Punsalmaa B, Honda Y et al (2007) Asia. In Climate Change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, ML Parry, OF Canzian, JP Palutiko, PJ Linden, CE Hanson (eds). Cambridge University Press: Cambridge, UK, 469–506

Deressa T, Hassen R, Alemu T, Yesuf M, Ringler C (2008) 'Analyzing the determinants of farmers' choice of adaptation measures and perceptions of climate change in the Nile Basin of Ethiopia. International Food Policy Research Institute (IFPRI) Discussion Paper No. 00798, Washington

Gopika S, Lekshmi B, Chaidanya K, Varsha KM (2014) Rainfall variability and Rice productivity over Kerala. J Aqua Bio and Fish 2: 162–164

Government of Telangana, Planning Department (2020) Socio economic outlook: Reinventing Telangana. Author. 1–216. Accessed at https://www.telangana.gov.in/PDFDocuments/Telangana-Socio-Economic-Outlook-2020.pdf

Haruhisa A, Jun M (2009) Effects of rainfall variation on rice production in the Ganges-Brahmaputra basin. Clim Res 38:249–260

Karmalkar AV, Bradley RS, Diaz HF (2008) Climate change scenario for Costa Rican montane forests. Geophys Res Lett 35:L11702

Kelley CP, Mohtadi S, Cane MA, Seager R, Kushnir Y (2015) Climate change in the fertile crescent and implications of the recent Syrian drought. Proc Natl Acad Sci 112(11):3241–3246I

Kothawale DR, Rupa Kumar K (2005) On the recent changes in surface temperature trends over India. Geo- phys Res Lett 32:L18714

Krishna Kumar K, Patwardhan SK, Kulkarni A, Kamala K, Koteswara Rao K, Jones R (2011) Simulated projections for summer monsoon climate over India by a high -resolution regional climate model (PRECIS). Curr Sci 101:312–326

Kumar P, Geneletti D, Nagendra H (2016) Spatial assessment of climate change vulnerability at city scale: a study in Bangalore, India. Land Use Policy 58:514–532

Laux P, Kunstmann H, Bardossy A (2008) Predicting the regional onset of the rainy season in West Africa. Int J Climatol 28:329–342

Lobell DB, Burke MB, Tebaldi C, Mastrandrea MD, Falcon WP, Naylor RL (2008) Prioritizing climate change adaptation needs for food security in 2030. Science 319:607–610

Meehl GA, Stocker TF, Collins WD, Friedlingstein P, Gaye AT, Gregory JM, Kitoh A, Knutti R, Murphy JM, Noda A, Raper SCB, Watterson IG, Weaver AJ, Zhao ZC (2007) Global climate projections. In: Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M and Miller HL (eds)]. Cambridge University Press. Cambridge, United Kingdom and New York, NY, USA

Moss RH, Edmonds JA, Hibbard KA (2010) The next generation of scenarios for climate change research and assessment. Nature 463: 747–756

Najmaddin PM, Whelan MJ, Balzter H (2017) Estimating daily reference evapotranspiration in a semi-arid region using remote sensing data. Remote Sens 9:779

O'Brien K, Leichenko R, Kelkar U, Venema H, Aandahl G, Tompkins H, Javed A, Bhadwal S, Barg S, Nygaard L, West J (2004) Mapping vulnerability to multiple stressors: climate change and economic globalization in India. Glob Environ Chang 14(4):303–313

Porter JR, Xie L, Challinor A, Cochrane K, Howden M, Iqbal MM, Lobell D, Travasso MI (2014) Food security and food production systems. In: Climate change (2014): impacts, adaptation, and vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press

Rajalakshmi D, Jagannathan R, Geethalakshmi V, Ramaraj AP (2013) Assessing the impact of changing climate on water use index (WUI) and nitrogen use efficiency (NUE). J Agrometeorol Special Issue 2

Rajiv Kumar C, Joshi J, Jayaraman M, Bala G, Ravindranath NH (2012) Multi-model climate change projections for India under representative concentration pathways. Curr Sci 103:791–802

Rama Rao CA, Raju BMK, Subba Rao AVM, Rao KV, Rao VUM, Ramachandran K, Venkateswarlu B, Sikka AK (2013) Atlas on vulnerability of Indian agriculture to climate change. Central Research Institute for Dryland Agriculture, Hyderabad P 116

Rama Rao CA, Raju BMK, Subba Rao AVM, Rao KV, Rao VUM, Ramachandran K, Venkateswarlu B, Sikka AK, Srinivasa Rao M, Maheswari M, Srinivasa Rao CH (2016) A district level assessment of vulnerability of Indian agriculture to climate change. Curr Sci 110:1939–1946

Ravindranath NH, Rao S, Sharma N, Nair M, Gopalakrishnan R, Rao AS, Malaviya S, Tiwari R, Anitha S, Madhushree M, Niharika K, Bala G (2011) Climate change vulnerability profiles for north East India. Curr Sci 101(3):384–394

Ruane AC, Goldberg R, Chryssanthacopoulos J (2015) Climate forcing datasets for agricultural modeling: merged products for gap-filling and historical climate series estimation. Agric Forest Meteorol 200: 233–248

Ruane AC, McDermid SP (2017) Selection of a representative subset of global climate models that captures the profile of regional changes for integrated climate impacts assessment. Earth Perspectives 4(1): 1–20

Rupa Kumar K, Sahai AK, Krishna Kumar K, Patwardhan SK, Mishra PK, Revadekar JV, Kamala K, Pant GB (2006) High- resolution climate change scenarios for India for the 21[st] century. Curr Sci 90:334–345

Taylor IH, Burke E, McColl L, Falloon P, Harris GR, McNeall D (2012) Contributions to uncertainty in projections of future drought under climate change scenarios. Hydrol Earth Syst Sci Discuss 9:12613–12653

Villegas JR, Jarvis A (2010) Downscaling global circulation model outputs: the delta method decision and policy analysis working paper no. 1. International centre for tropical agriculture

Wiebe H, Lotze-Campen R, Sands A, Tabeau D, vander Mensbrugghe A, Biewald B, Bodirsky S, Islam A, Kavallari D, Mason-D'Croz C, Müller (2015) Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios. Environ Res Lett 10(8):085010

Wilks DS (2011) Statistical methods in the atmospheric sciences, 3rd ed. Academic Press, San Diego

The state of Andhra Pradesh was reorganized into states of Telangana and Andhra Pradesh on 2 June 2014, and 21 new districts were created on 11 October 2016, which lead to 31 districts in Telangana. On 17 February 2019, two more districts were formed taking the total number of districts to 33. This latest change was not accounted for present analysis and we used 31 districts only.

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