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ORIGINAL ARTICLE

Critical climate-stress moments for semi-arid farming systems in India

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Abstract

In the face of the increasing frequency of climate stresses, climate change projections can help in adaptation planning and resilience-building. However, typical climate change projections, such as annual average rainfall and temperature increases, are not helpful for farmers in understanding specific climate risks, like crop loss, and making adaptation decisions. Our study aims to identify and characterise context- and time-specific climate stresses in terms of climate conditions of concern to improve the understanding of future climate risks and enhance the climate resilience of semi-arid farming systems in India. Utilising the concept of critical climate-stress moments, we employ an innovative bottom-up methodology integrating insights from focus group discussions with farmers, key informant interviews, and an ensemble of downscaled and bias-corrected Coupled Model Intercomparison Project Phase 6 (CMIP-6) models. Our case studies include (i) a mixed crop-livestock farming system, (ii) a horticulture-based farming system, (iii) a cash crop–dominant farming system, and (iv) a cereal-dominant farming system. The specific climate conditions of concern identified were (i) increasing volume of late-monsoon rainfall, (ii) rising winter temperatures, (iii) increase in the number of days with temperatures exceeding 40 °C, (iv) increase in days with heavy rainfall (> 25 mm), and (v) increasing rainfall during the dry season. Identifying these critical moments improves understanding of both the temporal and spatial variations in climate risks, providing valuable inputs for targeted and implementable climate resilience–building actions. We recommend revising national and state action plans on climate change by utilising such region-specific assessments of critical climate-stress moments.

Keywords Climate resilience · Adaptation planning · Climate risk · Agricultural ecosystem · Regional climate scenarios · Communicated by Prajal Pradhan

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Introduction

India ranks amongst the most vulnerable countries to climate change, with continued exposure to climate stresses[1] such as heat waves, droughts, floods, and cyclones (Chen et al. 2015; Eckstein et al. 2021; Group 2021). Several studies have highlighted the increased vulnerability of India's dryland and semi-arid regions, which are easily influenced by changes in temperature and precipitation patterns, as well as anthropogenic land-use changes (Ramarao et al. 2019; Todmal 2021; Yaduvanshi et al. 2021). The increasing frequency of climate stresses threatens agricultural productivity, food security, and the overall well-being of rural communities (Pervez Bharucha et al. 2021; Singh and Chudasama 2021). The vulnerability of semi-arid regions to extreme weather events suggests the need for context-specific understanding of climate stresses and how these will evolve in the future. Efforts to downscale outputs from climate models to state or district level have been made to contextualise macro-scale climate change projections for specific regions in India (Todmal 2021, 2023; Yaduvanshi et al. 2021, 2019). Projections for western India show a significant increase in rainfall of 150–210 mm by the end of the century, whereas temperature is expected to rise by 1–2.5 °C by 2050 (Todmal 2021). India's state action plans on climate change (SAPCCs) were anticipated to be built upon context-specific climate change data, aiming to foster effective and decentralised actions for enhancing climate resilience (Jogesh and Dubash 2015). However, the suboptimal execution of the SAPCCs suggests the need to re-evaluate policy incentives and governance mechanisms to incorporate such context-specific climate change data in adaptation planning (Jogesh and Paul 2020; Kumar 2018).

Despite advances in downscaling climate change data from global and regional climate models, the use of such projections in local adaptation or resilience-building plans is not widespread (Lorenz et al. 2017; Nissan et al. 2019). Typical climate change projections, such as annual average rainfall and temperature increases, are not helpful for farmers in understanding specific climate risks, like crop loss, and making adaptation decisions. Groot et al. (2017) argue that focusing on context- and time-specific stresses may provide more valuable insights for decision-making. This focus on the timing of adaptation complements the typical questions of 'what' and by 'whom' that vulnerability and resilience assessments address, which can also aid decision-making for policymakers. Such moments, when 'households, communities, and the livelihood systems they depend on, are especially vulnerable to climate and weather-related risks and hazards', are defined by Groot et al. (2017) as critical climate-stress moments. This relatively new concept has seen limited application, such as in Pakistan's Indus basin by Shah et al. (2020) and in the Argentinian Pampas by Smolenaars et al. (2021). The former used only historical data, whereas the latter depended on rainfall data and limited stakeholder interactions. A lack of comprehensive application of critical climate-stress moments that includes the use of both historical and future climate data, temperature, rainfall, and the views of diverse stakeholders is the knowledge gap that our research aims to fill.

To better understand future climate risks and enhance the climate resilience of semi-arid farming systems in India, we aimed to identify and characterise context- and time-specific climate stresses in terms of specific climate conditions of concern. To address this aim, we used the concept of critical climate-stress moments and a bottom-up methodology based on the work of Groot et al. (2017) and Shah et al. (2021). We focused on four case studies in Maharashtra, India, covering both the Kharif and Rabi agricultural seasons. The four farming systems are different but typical to semi-arid Maharashtra. We relied on stakeholder engagement and key informant interviews (KIIs) to identify and characterise the local climate stresses in terms of specific climate conditions of concern. To understand how these climate conditions might evolve in future, we analysed climate data from an ensemble of downscaled and bias-corrected Coupled Model Intercomparison Project Phase 6 (CMIP-6) models.

In the context of agriculture and semi-arid farming systems, important agronomic decisions are taken by farmers based on their estimates for the season or even shorter time periods like the next week or next day. Enhancing the climate resilience of semi-arid farming systems requires building resilience to such context- and time-specific risks, apart from enhancing the general resilience attributes of a system (Srinidhi et al. 2023a, 2023b). Our study also helps bridge the gap between top-down quantitative outputs from climate models to bottom-up qualitative data, an issue considered key to effective decision-making and building future climate resilience (Lempert 2013; Wise et al. 2014). The application of this concept also fosters interdisciplinary collaboration and provides comparative insights across different regions within India, helping prioritise specific actions and specific geographies.

Methodology

Conceptual framework and approach

We used the concept of critical climate-stress moments to characterise the context- and time-specific climate stresses

[1] A climate stress is understood as a 'condition, trend, or event related to climate change and variability that can exacerbate hazards' (NOAA 2020).

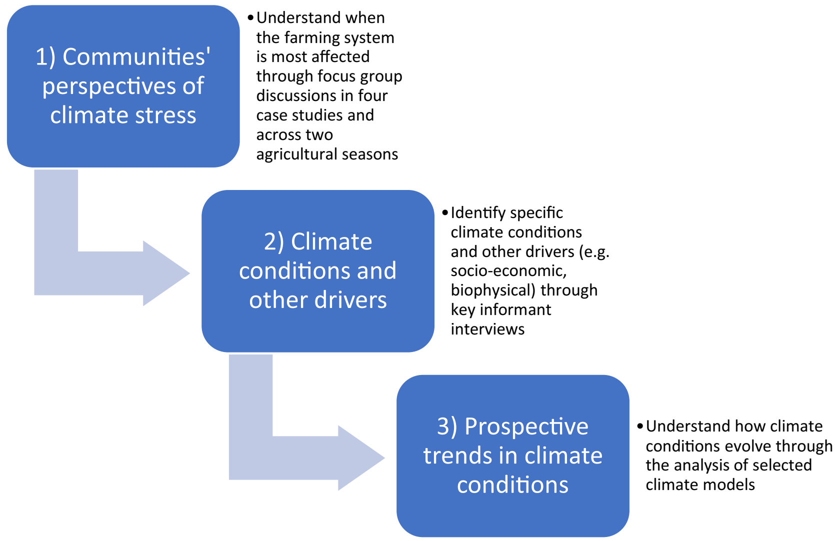

Fig. 1 Steps involved in identifying and characterising critical climate-stress moments

in terms of specific climate conditions, like temperature and rainfall levels. Within this framing, a range of events spanning diverse spatial and temporal scales are considered, such as heatwaves, cold spells, floods, droughts, and hail. The critical nature of these moments is due to the risks arising from the interaction of the context-specific conditions and the climate stresses that the households are exposed to.

To characterise critical climate-stress moments for semi-arid farming systems in India, we followed three steps based on the work of Groot et al. (2017): (1) communities' perspectives of when the farming system is most affected by climate stress; (2) climate conditions and other drivers of risk that cause periods of stress; and (3) expected evolution of climate conditions in the future (see Fig. 1). To bridge top-down and bottom-up information, we started with a bottom-up approach, where we began by understanding the climate stresses experienced by local communities through focus group discussions. We then carried out KIIs with experts to quantify the emerging critical moments in terms of specific climate conditions. Finally, we analysed global (top-down) climate data available from downscaled and bias-corrected CMIP-6 models to understand how the climate conditions (e.g. temperature and rainfall) will evolve in the future. Not all these steps took place at the same geographical scale. Step 1 was at the farming system level. Step 2 involved key informants, including agriculture and climate experts having regional-level insights. Step 3 involved the use of climate data from global climate models downscaled to a resolution of 0.25 degrees (1 degree ~ 110 km).

Communities' perspectives of climate stress

To address step 1 of our methodology, we followed a case study approach to qualitatively understand farmers' perceptions of climate stresses. Considering the context- and time-specific nature of climate stresses, different types of farming systems are expected to face different stresses at different times of the year. We therefore selected four different farming systems typical to semi-arid Maharashtra as our case studies. Other criteria included an interest to participate in the study and consent for data collection and documentation. The selected case study farming systems included the villages of Kalamkarwadi, Vaiju Babhulgaon, Mhaswandi, and Darewadi in the district of Ahmednagar in Maharashtra (for a map of the region, see Fig. A1 in Supplementary material).

Data were collected from the case study locations at the end of the Kharif and Rabi seasons (October 2022 and April 2023, respectively). In each village, we organised focus group discussions (FGDs) with farmers based on availability, with a particular focus on recruiting small and marginal[2] farmers and women to ensure a diverse range of experiences were represented in the discussions. We selected the most important crop and livestock asset of the local community for further discussions: (1) in Kalamkarwadi, a mixed crop-livestock dominant system with fodder crops to support hybrid cattle varieties for milk production; (2) in Vaiju Babhulgaon, a horticulture-dominant system focused on pomegranate plantations; (3) in Mhaswandi, a cash crop (onion, soybean, groundnut) dominant system; and (4) in Darewadi, a cereal (maize, wheat, millets) dominant system. We then developed a seasonal calendar and mapped all the key climate stresses related to the important crop and livestock assets of the community. We interacted with 29 people (18 men and 11 women) in the October 2022 FGDs

[2] Small and marginal farmers are those who own less than 2 ha of land as per land classification used by the Ministry of Agriculture in India (https://pib.gov.in/newsite/PrintRelease.aspx?relid=188051).

and 19 people (12 men and 7 women) in the April 2023 discussions (see Table A1 in Supplementary material for a breakup of participants from each case study). A checklist of questions used in the FGDs is provided in Supplementary material (Annexure 1). In the second round of field visits, we presented the findings from the first round for validation and also discussed any additional climate risks that could be added based on recent experiences.

Climate conditions and other drivers

To quantify critical moments in terms of specific climate conditions, we carried out KIIs with experts in the domains of agriculture, climate science, and development practice. The 14 key informants included agriculture officials, managers, climate scientists, and senior development practitioners from Watershed Organisation Trust (WOTR) (details in Supplementary material – Annexure 1) and cover all the four case studies. While the FGDs in step 1 helped identify the time of the year when significant losses occur, the KIIs provided quantitative insights in terms of the levels of rainfall and temperature related to the climate stresses. With the key informants, we also discussed other drivers of agrarian stress (e.g. socio-economic, biophysical) and available adaptation options to help discern their influence on climate stresses and quantification of climate conditions of concern. For instance, in the crop-livestock mixed farming case study, cattle are maintained in protected conditions, and the fodder crops grown to support livestock assets and milk production are generally less vulnerable to unseasonal rainfall. The key informants were identified based on suggestions during the earlier FGDs with farmers, as well as the experience of the researcher team.

Prospective trends in climate conditions

To understand how the climate conditions of concern will change in the future, we analysed climate projections available from a set of downscaled and bias-corrected CMIP-6 models. Our climate data analysis is based on the NEX-GDDP-CMIP6 dataset comprising global downscaled climate scenarios derived from General Circulation Model (GCM) runs conducted under CMIP-6 (see Thrasher et al. 2022). This dataset provides the outputs of 35 GCM models that are bias-corrected and downscaled to a spatial resolution of 0.25 degrees. We selected a period of 1950 to 2100 to provide us with roughly an equal spread of historical and future climate data. The outputs of GCMs have significant biases and pose difficulties in simulating the Indian monsoon conditions, warranting bias correction and model selection based on validation with observed data (Mishra et al. 2020; Rajendran et al. 2022). The NEX-GDDP-CMIP6 dataset already provides bias-corrected data, which we then compared with historical gridded data obtained from the India Meteorological Department (IMD) for validation and selection of models that best fit the historical observed data. The gridded dataset of the IMD is based on daily observational data from 6955 rain gauge stations in India and is available at a resolution of 0.25 degrees (Pai et al. 2014), while temperature data are available at a resolution of 1 degree (Srivastava et al. 2009). These IMD gridded datasets are a reliable proxy for actual observational data and are frequently used for validating other climatological datasets (Bhattacharyya et al. 2022). The historical gridded data from the IMD were accessed via a Python library (Nandi and Patel 2020).

The selection of GCM models is based on the correlation between the probability density function of the (mean-corrected) daily model outputs and the reference data (c.f. Lutz et al. 2016). Daily maximum temperature, daily minimum temperature, and daily precipitation data for the period of 1950–2014 from the IMD were used as the reference data. Of the 35 models, four had gaps in terms of daily maximum temperature, daily minimum temperature, or historical dataset and were excluded from further analysis. The results of the comparison of the remaining 31 models with historical IMD data for our case study sites are shown in Supplementary material Annexure 2. Based on the average model performance scores, the four climate models selected for generating projections are (1) ACCESS-ESM1-5, (2) NorESM2-LM, (3) MPI-ESM1-2-LR, and (4) CanESM5 (for details of models, see Thrasher et al. (2022)). The NEX-GDDP-CMIP6 dataset provides climate projections for four shared socio-economic pathway (SSP) scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) for the period from 2015 to 2100 (see IPCC (2021)). Based on our understanding of current global emission scenarios, we selected the moderate GHG emission scenario of SSP 2–4.5 and the very high GHG emission scenario of SSP 5–8.5 for estimating the critical moments of climate stress in our analysis.

To analyse the trends in climate conditions, we plotted the outputs from the climate models for each farming system. The "Climate stresses and climate conditions of concern" section provides a list of climate stresses affecting each farming system, while graphs showing trends in the climate conditions critical to each type of farming system are shown in the "Prospective trends in climate conditions" section. The graphs show a single line for the historical data up to 2014, which is an average of all the four model outputs. For data from 2015 onwards, the models provide a range of outputs for each of the selected future scenarios—SSP2-4.5 and SSP5-8.5. We plotted averages of the four model outputs for each of the SSPs. Climate conditions with a very clear trend are shown as line graphs (e.g. September and October precipitation, number of days with temperature > 40 °C). Climate conditions with a marginal change are shown as box plots with the mean and standard deviation of data (e.g.

monsoon onset date, number of dry or wet days). Where outputs from the climate models did not match the inputs from farmers, we also looked at trends in historical observed data from the IMD.

Results

Climate stresses and climate conditions of concern

The results of the data collection in steps 1 and 2 are provided in Table 1. We find that the cash crop–dominant farming system is exposed to the highest number of climate stresses (nine), whereas the crop-livestock mixed farming system is exposed to relatively fewer climate stresses (five). It must be noted that the crop-livestock system might be intuitively expected to be exposed to a larger number of stresses. However, our case study consisted of cattle in protected conditions and fodder crops (to support the livestock assets and milk production) that are generally less vulnerable to unseasonal rainfall. Moreover, while exposure to a climate stress is not the only factor that influences climate risk, it is certainly a contributing factor. We discuss this point in more detail in the "Discussion" section.

Prospective trends in climate conditions

The third step of our research involved understanding how climate conditions of concern evolve based on our analysis of locale-specific climate data from selected CMIP-6 climate models. As a reference, we also looked at annual trend lines with regard to historical temperature and precipitation based on gridded IMD data (see Fig. A2 in Supplementary material). The historical data indicate approximately 0.5 °C rise in mean temperature and an increase in annual precipitation by about 20% during the past 70 years.

Crop-livestock mixed farming system

The crop-livestock mixed farming system in Kalamkarwadi has primarily dairy cattle and fodder crops grown to support the livestock assets. Cattle are housed in semi-permanent sheds providing some insulation from weather variations. The fodder crops grown are hardy and less vulnerable to climate variability like unseasonal rain. Considering the higher water requirement of the hybrid cattle, climate conditions leading to an increase in water demand are the main causes of stress. Therefore, the climate conditions shown in Fig. 2 are (i) onset of monsoon, (ii) dry days in July and August, (iii) days with temperature > 40 °C, and (iv) frequency of drought years.

Climate conditions showing a very clear trend are depicted as line graphs (e.g. number of days with temperature > 40 °C). Climate conditions with a marginal change are shown as box plots with the mean and standard deviation of data (e.g. monsoon onset date, number of dry days). Frequency of drought years was assessed for a time-block of 25 years, with 1990–2015 as the reference period and projections made for two time-blocks: 2035–2060 and 2075–2100.

The onset date of monsoon (Fig. 2a), i.e. when there has been a cumulative rainfall of 70 mm after 1st June, appears to advance slightly by the end of the century. The number of dry days during July and August (Fig. 2b) is expected to decrease slightly, suggesting more rainy days. This is consistent with an overall increase in precipitation projected for the region (Fig. A2 in supplementary material) and a decrease in the drought frequency (Fig. 2d). While the trends in Fig. 2a and b show relatively small changes, the alarming increase in the number of days with temperatures going beyond 40 °C, from < 10 per year to 40 – 70 days per year by end-century suggests this is a critical climate-stress moment (Fig. 2c).

Horticulture-based farming system

The horticulture-based farming system in Vaiju Babhulgaon predominantly grows pomegranates, with some farmers opting for custard apple and citrus fruits. These crop choices are considered favourable for the dry climate of this region. Most farms have drip irrigation equipment and thus are not very vulnerable to dry spells. According to inputs from farmers and key informants, heavy, unseasonal rain, and days with > 40 °C are significant sources of climate stress—particularly for pomegranate. The trend for temperature is shown in Fig. 2c for the nearby village of Kalamkarwadi, and the trends for heavy rainfall days and dry season rainfall (January to March) are shown in Fig. 3. The projections by the climate models for both conditions show an increasing trend, matching with communities' perspectives, but the actual values did not match. Therefore, we also looked into historical observed data from the IMD (Fig. 3b and 3d) to check for trends based on actual values.

Graph 3 b and d show a rising trend in the number of days with extreme precipitation as well as the dry season precipitation. However, the recent trend of about 6 days of extreme precipitation and 10 to 15 mm of dry season precipitation, shown in these graphs, is much higher than the values indicated by the climate models of about 2 days of extreme precipitation and 0.10 mm of dry season precipitation (Fig. 3a and c). Going by the recent trends from observed data, the actual future values by end-century would be much higher than what the climate models estimate—perhaps a three to fourfold increase from the current value in the number of days with extreme rainfall and the volume of dry season precipitation (i.e. about 20 days of extreme rainfall per year and 40 mm of dry season precipitation).

Table 1 Climate stresses and climate conditions of concern

Communities' perspectives of climate stress	Farming systems perceived to be under stress[a]	Inputs from key informants on climate stresses	Climate condition of concern
Delayed rainfall at the start of the Kharif season leads to losses	Crop-livestock; cash crops; cereals	Delayed onset of monsoon results in a shorter growing season in the Kharif season. Farmers then tend to shift to shorter growing crops such as bajra (pearl millet) or moong (green gram), or they grow sorghum only as fodder	The effective onset of the monsoon is understood as the date by when there is sufficient rain for sowing, i.e. cumulative of 70 mm after 1st June
High rainfall late in the growing season or at harvest stage leads to severe crop loss	Cash crops; cereals	Increasing rainfall during September and October has multiple risks of (i) damaging Kharif crops and (ii) causing delayed sowing of Rabi crops, which would entail further knock-on or cascading effects of being exposed to a hotter period of the summer	Total rainfall during September and October
Days with heavy rainfall in a single day also damage crops	Horticulture; cash crops; cereals	Heavy rains lead to losses at the time of harvest but also during other critical stages such as sowing time or the nursery development stage (e.g. for horticultural crops, onions)	Number of days with rainfall > 25 mm throughout the Kharif season[b] Rainfall intensity—amount of rain per rainy day (days with > 2.5 mm rain)
Dry spells in July and August (after monsoon onset) lead to losses	Crop-livestock; cash crops; cereals	If a dry spell happens early in the season, it is managed by re-sowing. Later in the season, protective irrigation is required, especially if there is no rain for 20–25 days at a stretch. Such dry spells also lead to heat stress and a risk of disease in livestock	Number of dry days (< 2.5 mm/day) of rainfall in July and August Longest dry spell (consecutive days with rainfall < 2.5 mm) during July and August
Unreliable winter conditions affecting crops – too warm or affected by fog, hailstorms, etc	Horticulture; cash crops; cereals	Warmer winter temperatures lead to reduced yield, especially of wheat. Persistent fog-like conditions bring in increased risk of pest attacks. Sudden hail during winter is a big threat for all crops, particularly horticulture	Trends in winter temperatures—daily-min, daily-max, and daily-average Number of foggy days and number of hail days in the year[c]
Some rainfall during the Rabi (winter) season is good, but too much rain, especially at the time of harvest, is problematic	Horticulture; cash crops	Rainfall between January and March affects horticulture and cotton that is ready for picking	Rainfall between January and March
Rising summer temperatures are affecting livestock and making it difficult for people to work (migrant labourers in small towns)	Crop-livestock; horticulture; cash crops	Days with > 40 °C lead to heat stress in livestock, causing disease and miscarriage in large and small ruminants and death and disease in poultry. The yields of winter onions and horticultural crops ready for harvest are reduced	Days with > 40 °C
Frequency of drought years is increasing	Crop-livestock; horticulture; cash crops; cereals	Ground water used to be a very good buffer to deal with drought. However, with increased reliance on wells and deeper borewells, meteorological drought is increasingly correlated with hydrological drought	Years with rainfall < 75% of the long-term average

Table 1 (continued)

Communities' perspectives of climate stress	Farming systems perceived to be under stress[a]	Inputs from key informants on climate stresses	Climate condition of concern
Short spell of very heavy rainfall (e.g. 40–50 mm of rain in an hour) can be very damaging,	Crop-livestock; horticulture; cash crops; cereals	The generic understanding of a cloud burst is 100 mm or more rain in an hour. However, for this area, given its soil type and vegetation cover, even half of that can be damaging	Hours with rainfall > 40 mm[c]

[a]Crop-livestock system refers to dairy cattle and fodder crops grown to support the livestock assets in Kalamkarwadi. Horticulture system refers to pomegranate grown in Vaiju Babhulgaon. Cash crop system refers to onion, soybean, groundnut grown in Mhaswandi. Cereals system refers to maize, wheat, millets grown in Darewadi

[b]The standard threshold for heavy rainfall is 65 mm, which is a common threshold used by the IMD across India. However, in the semi-arid areas where our case studies are located, a day with 65 mm is extremely rare. Farmers consider anything more than 25 mm as a day with 'heavy rainfall', and this typically happens in about four to five times per year

[c]Fog and hail were difficult to characterise in terms of specific climate parameters and are left out of our analysis. Hourly data are also not available in most climate models and are hence excluded from the analysis

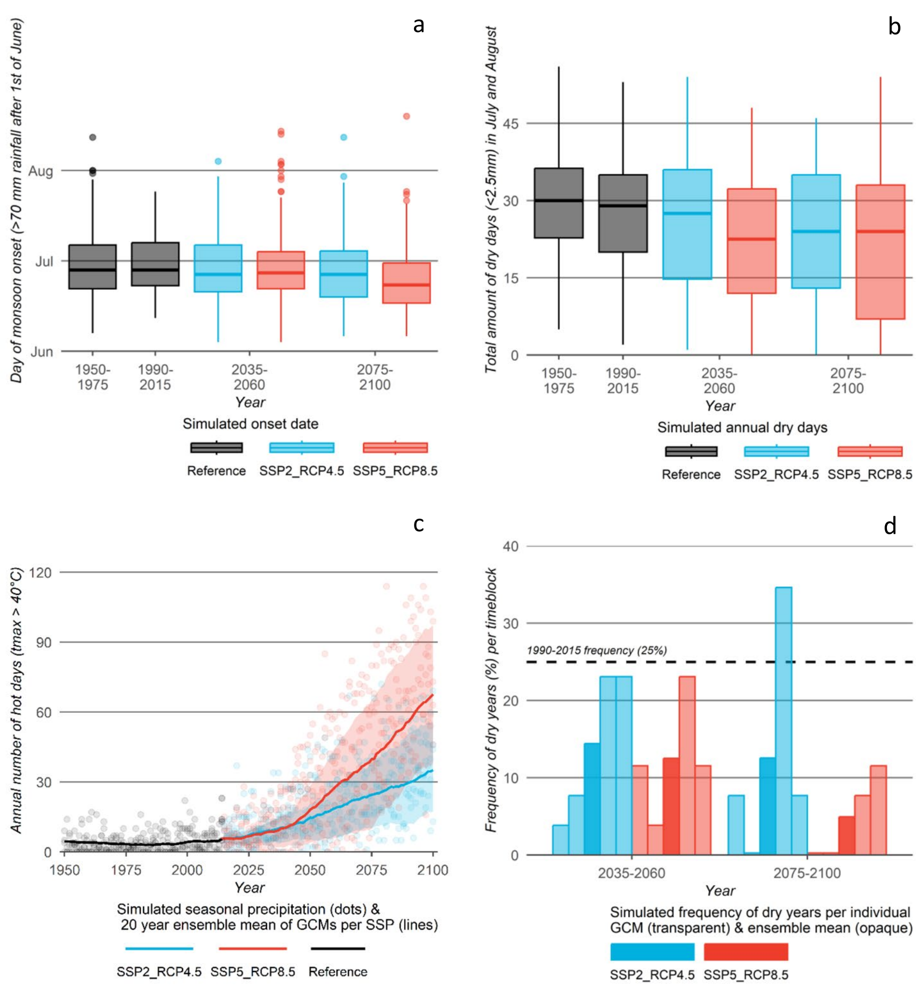

Fig. 2 Prospective trends in climate conditions for the crop-livestock system in Kalamkarwadi. Note: Red boxes, lines, and dots refer to the SSP5-8.5 scenario, while the blue boxes, lines, and dots refer to the SSP2-4.5 scenario. Black indicates historical data. The box plots show the mean and standard deviation of the data. In the line graphs, the dots represent the values for a year, while the lines represent a 20-year moving average. **a** Effective date of monsoon onset (> 70 mm of rain after 1st June). **b** Total number of dry days (< 2.5 mm/day of rain) in July and August. **c** Number of hot days (> 40 °C). **d** Frequency of drought years (years with < 75% of long-term average rainfall) for each of the four models, as well as the ensemble mean, for the time-blocks of 2035–2060 (short term) and 2075–2100 (long term), i.e. the percentage of years in the time-block of 25 years when there would be a drought

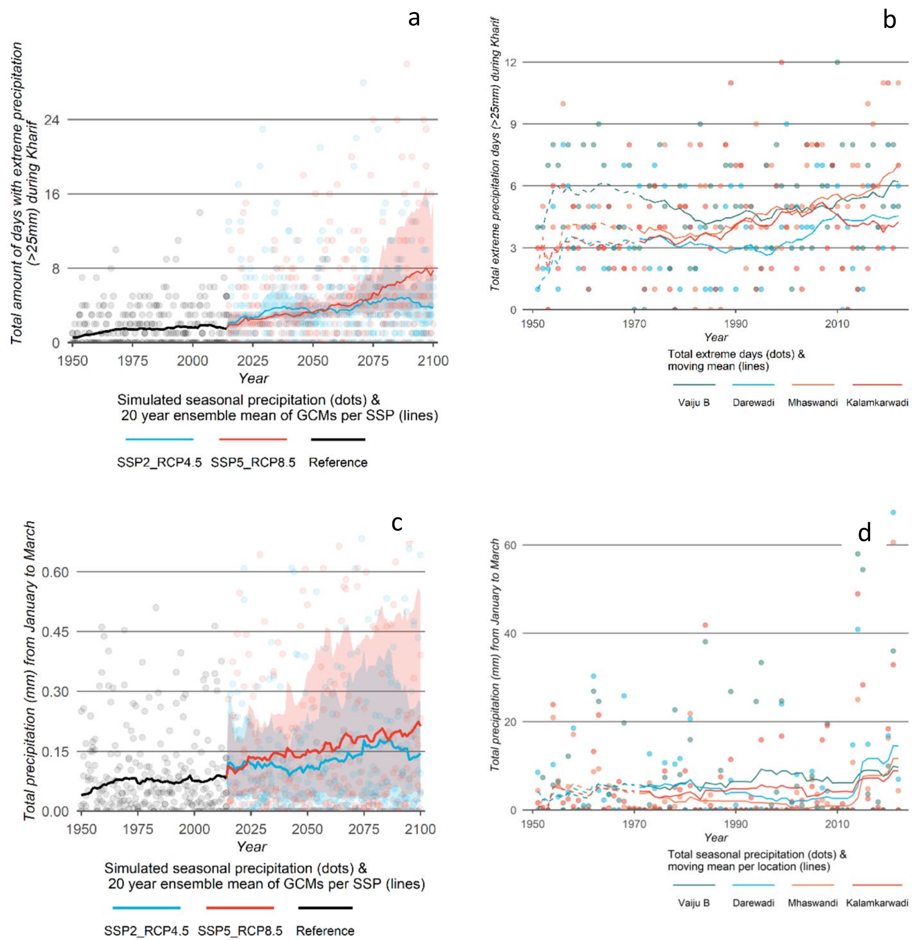

Fig. 3 Prospective trends in climate conditions for a horticulture-based system in Vaiju Babhulgaon Note: In the graphs, the dots indicate the individual value for a year, while the lines represent a 20-year moving average. The graphs on the left (**a** and **c**) are based on climate model outputs, while the graphs on the right (**b** and **d**) are based on historical IMD data for the four case study locations. **a** Days with high rainfall (> 25 mm/day) based on climate projections. **b** Trend in high rainfall based on historical IMD data. **c** Days with dry season precipitation (January–March) based on climate projections. **d** Trend in dry season precipitation (January–March) based on historical IMD data

Cash crop–based farming system

The cash crop–based farming system is exposed to the highest number of climate stresses (Table 1). Amongst these stresses, farmers and key informants are most concerned about (i) onset of monsoon, (ii) September and October rainfall, (iii) rising winter temperatures, and (iv) days with temperature > 40 °C. Trends in the onset of monsoon and days with temperature > 40 °C are shown in Fig. 2a and c for the nearby village of Kalamkarwadi, while the trends in September and October rainfall and rising winter temperatures are shown in Fig. 4.

Figure 4a shows an alarming increase in cumulative September and October rainfall. Irrespective of the future SSPs considered, the cumulative rainfall in these two months (currently ~ 200 mm) is expected to rise to over 300 mm in the coming 30 years. Being close to the time of the Kharif harvest season, this change will require important adaptation considerations. Minimum temperatures during winter are also expected to rise by 2–3 °C in the next 30 years (Fig. 4b), affecting the yield of Rabi season crops.

Cereal-based farming system

Typical cereals grown in Darewadi include maize, wheat, and millets. Communities' perspectives suggest that the climate stresses of most concern are (i) onset of monsoon, (ii) September and October rainfall, (iii) dry days in July and August, and (iv) rising winter temperatures. Trends for all these conditions are shown for the nearby case study villages in Figs. 2, 3, and 4. Graphs specific to Darewadi (Fig. 5) illustrate the extent to which the trends are comparable with the trends in nearby locations.

There is consistency between the trends in Darewadi (Fig. 5) and those of nearby villages (Figs. 2, 3, and 4) indicating robustness in the observations of critical climate moments. Figure 5a is comparable with Fig. 2a and shows only a small change with regard to the date of monsoon arrival. The total precipitation during September and October (Fig. 5b) shows a large increase, from 200 to 400 mm by end-century, and is consistent with the observations in Mhaswandi (Fig. 4a). The number of dry days during July

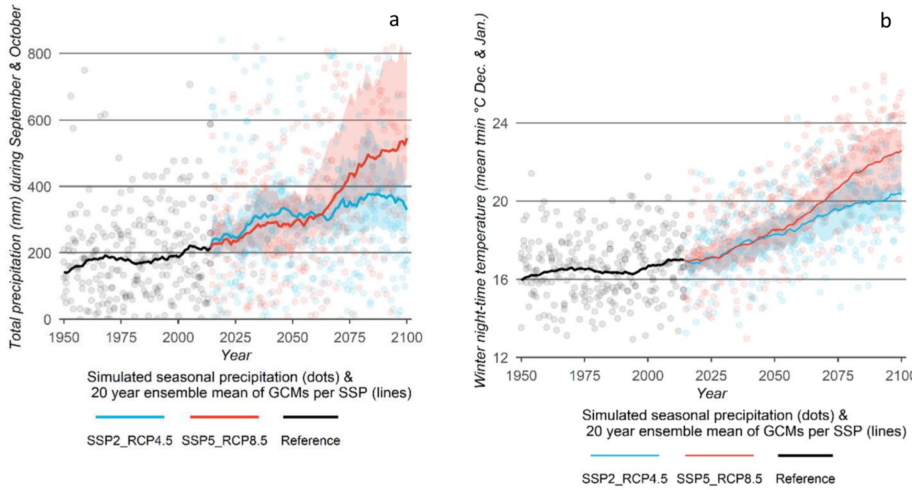

Fig. 4 Prospective trends in climate conditions for cash crop–based farming system in Mhaswandi. Note: In the graphs, the dots indicate the individual value for a year, while the lines represent a 20-year moving average. **a** Trend in cumulative September and October rainfall. **b** Trend in minimum temperatures during the winter months of December and January

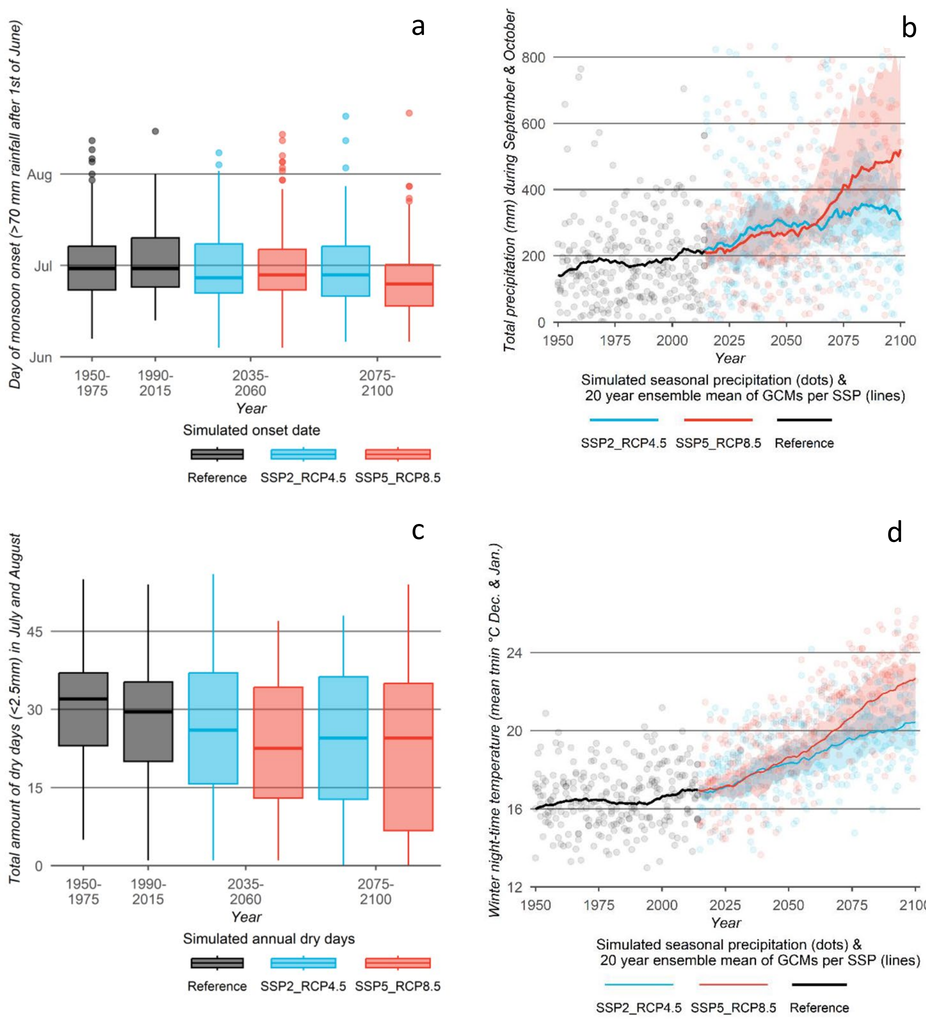

Fig. 5 Prospective trends in climate conditions for a cereal-based farming system in Darewadi. Note: **a** Effective date of monsoon onset (> 70 mm of rain after 1st June). **b** Cumulative September and October rainfall. **c** Number of dry days (< 2.5 mm/day of rain) in July and August. **d** Trend in minimum temperatures during the winter months of December and January

and August in Darewadi shows a slight decrease, from 30 to 25 days (Fig. 5c), and is consistent with the observations in Kalamkarwadi (Fig. 2b). And finally, the rising winter temperatures in Fig. 5d is similar to the trend seen in Fig. 4b.

Discussion

Nine climate stresses are listed in Table 1 based on engagement with primary stakeholders in each of our case studies. Further discussions with key informants helped us quantify and prioritise climate conditions of concern that were analysed using climate data from selected models ("Prospective trends in climate conditions" section). Based on the trends in climate conditions of concern that are expected to increase in frequency or intensity, we identify the following five critical climate-stress moments: (i) increasing volume of late-monsoon rainfall, (ii) rising winter temperatures, (iii) increase in the number of days with > 40 °C, (iv) increase in the number of days with heavy rainfall (> 25 mm), and (v) an increase in dry season (January–March) rainfall. Trends in the onset date of the monsoon, dry spells in July and August, or frequency of drought years did not show any cause for concern, while the lack of suitable data meant that we could not analyse climate stresses related to short spells (e.g. for an hour) of very heavy rain or increasing frequency of hailstorms.

Implications of the critical climate-stress moments and potential adaptation measures

Our finding of an increasing volume of late-monsoon rainfall is the most significant of the critical climate-stress moments. It coincides with the end of the Kharif season, when heavy rainfall can cause significant damage to crops ready for harvest (Preethi and Revadekar 2013). Delays in Kharif harvest further delays land preparation and subsequent sowing of Rabi crops (Prasanna 2014). Several researchers have been investigating recent changes in the pattern of the Indian monsoon (Maharana et al. 2021; Rajesh and Goswami 2023; Subrahmanyam et al. 2023). Rajesh and Goswami (2023) and Maharana et al. (2021) discuss a western shift in the monsoon, which might also be responsible for the increased rainfall projected in the semi-arid areas assessed in our study. According to Subrahmanyam et al. (2023), the Indian monsoon typically has four active spells between June and September, and the fourth spell, coinciding with September rainfall, has recently been showing an increasing trend of heavy rainfall events. Anecdotal evidence from discussions with stakeholders in our case studies and key informants also supports these observations around increased late-monsoon precipitation. While discussing potential adaptation measures, the communities and key informants suggested interventions such as increasing the use of mechanical harvesters to ensure a quick harvest and reduce the duration of climate stress exposure to the harvest-ready crop. They also suggested investing in storage facilities and forming farmer collectives, such as farmer producer organisations (FPOs), to protect their produce from climate risks and navigate market risks better. These adaptation or climate resilience–building interventions are also suggested by Srinidhi et al. (unpublished) in an upcoming article on climate-resilient development pathways for FPOs in semi-arid India.

Rising temperatures in winter are a compounding stress on Rabi crops. Delays in the sowing of Rabi crops would also result in a drop in yields due to subsequent delays in the harvest, which ends up being done under higher temperatures of late-March and April. While Kharif crops are rainfed, Rabi crops are largely dependent on irrigation and are sensitive to temperature (Bapuji Rao et al. 2014). Several studies show that the temperature increases are higher during the Rabi season than the Kharif season (Aggarwal 2008; Bapuji Rao et al. 2014) and suggest adaptation measures such as shifting to more heat-tolerant crops (DeFries et al. 2023). However, the relatively lower yields and lower market prices for heat-tolerant crops, such as sorghum, make them less attractive to farmers. Innovations in water and watershed management practices, such as through conservation agriculture, leveraging ecosystem-based watershed development practices, development of cheaper drip irrigation facilities, and diversifying production through mixed crop-livestock farming systems, are options for farmers to consider (Aggarwal et al. 2022; de Condappa et al. 2021; Jayaraman et al. 2020).

Rising summer temperatures, particularly the number of days with temperatures > 40 °C, cause heat stress to cattle (North et al. 2023), leading to miscarriage (Khan et al. 2023) and higher incidences of diseases in livestock (Bagath et al. 2019). Discussions with the key informants and communities from our case study locations also indicated that the typical hybrid breeds of cattle that they rely on for milk production are more sensitive to heat stress than indigenous breeds but provide much more milk on average. Many households in our case study locations also had some poultry assets to supplement their incomes. The poultry sector is also highly vulnerable to heat stress, with a significant drop in productivity around 38 °C and risk of mortality beyond 42 °C (Kumar; et al. 2012). Potential adaptation options discussed by key informants included adopting more stress-tolerant indigenous breeds and diversifying livestock assets with small ruminants. As with heat-tolerant crops and varieties, heat-tolerant livestock options also come with trade-offs in terms of revenue. Policy interventions to incentivise such transitions would help farmers negotiate such trade-offs (Aggarwal and Upadhyay 2013; Mahajan et al. 2015). Aggregating production and value addition from FPOs could also help improve the associated returns and contribute to other sustainable development goals, thereby improving the general resilience of the system (Mourya and Mehta 2021).

The remaining two critical climate-stress moments—days with heavy rainfall (> 25 mm) and an increase in dry season precipitation (January–March rainfall)—were identified based on inputs from communities and supported by trends in observed historical data. The projections from climate models showed an increasing trend, but the projected values are largely underestimated as compared to the observed values. There is a greater agreement between the perspectives of the local community and the trends in the observed data. This shows that with regard to extreme weather events, extrapolating historical trends may be a better indicator of future conditions than the outputs from global climate models. By design, global climate models are meant for estimating average climate conditions over large areas and not for simulating small-scale, individual extreme weather events (Alizadeh 2022; Roxy et al. 2017; Tebaldi et al. 2006). The models tend to compensate for the lack of extremes with a greater spread of precipitation events and number of low rainfall events (Alizadeh 2022).

The origin of the January–March rainfall is not related to the monsoons; instead, local pressure variations or western disturbances that arise in the Mediterranean region and central Asia may be the cause (Kulkarni et al. 2020). Such disturbances are also influenced by climate change, and there are some indications of its impacts in areas further to the north and west of India (Jangra and Prakriti 2023). Increased penetration of weather-based agro-advisories and the adoption of farming in protected polyhouse conditions are some potential adaptation measures to cope with the increased variability of rainfall (Aggarwal et al. 2022). Agricultural insurance can also serve as a risk mitigation strategy for coping with unseasonal and heavy rainfall events. However, evaluations of current agricultural insurance schemes reveal subpar performance and limited effectiveness in addressing these risks (Singh and Agrawal 2020). This calls for innovations in agricultural insurance, with improved access to context-specific data on losses, advances in remote sensing, bundling insurance with other sustainable agricultural practices, and creating a contingency for tail-end risks that are too expensive to insure (Kramer et al. 2022). Incentivising a transition to non-agrarian livelihoods to reduce exposure to climate stresses and improve resilient incomes also needs attention (Srinidhi et al. 2023a). From an equity and climate resilience point of view, investments in non-farm livelihoods might be an important strategy for dealing with multiple climate risks (NRAA 2022; Srinidhi et al. 2023a).

Limitations and future research potential

Our data analysis is limited to understanding how climate-related stresses will increase or decrease in the future. A more thorough understanding of climate risk will require a deeper assessment of all the dimensions of the underlying vulnerability of the farming systems. While socio-economic parameters, such as landholding size, prevalence of poverty, health and nutrition status of the communities with the farming system, access to government schemes, and prejudices of class and caste, are inherent to the case studies selected and the social dimensions of their climate vulnerability, we do not explicitly deal with these parameters in our research. Another important aspect of agrarian risk that our study does not categorically deal with is related to agricultural markets. The potential of better market prices and higher returns on investment motivates farmers to prefer cash crop and horticultural farming systems, despite their greater exposure to climate stresses compared to cereals and crop-livestock mixed farming systems. Although farmers complain of poor market prices for the more climate-resilient crop choices like millets, sorghum, and traditional rice varieties, value-added services such as grading, sorting, and packaging, especially at larger scales through FPOs, are promising options for building climate resilience (Srinidhi et al. unpublished).

Another limitation of our study is related to the different geographical scales of assessment in the different steps. We relied on farming system–level data in step 1, regional-level data from experts in step 2, and downscaled global climate data in step 3. The specific crops, geographical extent, and timing of potential climate risks from step 1 helped narrow down the discussions with key informants in step 2 to issues relevant to our study areas. Further, the climate data from the downscaled GCM, although available at a resolution of 0.25 degrees, is known to have biases and needs correction (Mishra et al. 2020). However, the step of model selection based on validation with observed local data makes the climate data from step 3 appropriate for use in conjunction with steps 1 and 2. Improving the reliability of climate models in simulating extreme weather events and rainfall events outside the main monsoon season (in the Indian context) are areas of research that can improve our understanding of emerging climate risks. The case studies analysed in our research were selected on the basis of the type of farming system they represented. The case study sites were located about 50–100 km away from each other—not far enough to have sufficient differences in actual trends (as can be observed in the similarities between the graphs 2a and 5a, 4a and 5b, 2b and 5c, and 4b and 5d). However, efforts to downscale the outputs from climate models to the state or even district level underscore the need for further analysis to understand their spatial and seasonal distribution (Todmal 2021, 2023; Yaduvanshi et al. 2021, 2019). Optimising the scale at which context-specific assessments of vulnerability or climate data analysis are carried out is an area for further research.

Policy recommendations

The disparities between average annual changes in rainfall and temperature, compared to the context- and time-specific variations revealed in our study, along with their implications for targeted climate resilience–building measures, underscore the need for policy initiatives. Accordingly, we recommend the inclusion of critical climate-stress moments in the drafting of national and state action plans on climate change. As noted earlier, India's state action plans on climate change (SAPCCs) were anticipated to be built upon context-specific climate change data, aiming to foster effective and decentralised actions for enhancing climate resilience (Jogesh and Dubash 2015). While the first round of formulating State Action Plans on Climate Change (SAPCCs) was not very effective (Jogesh and Paul 2020; Kumar 2018), their current revisions present a valuable opportunity (MOEFCC 2018). By re-evaluating policy incentives and governance mechanisms, we can integrate context-specific critical climate-stress moments into the SAPCCs. This will ensure they are more effective in adapting to the unique climate challenges faced by each region.

Another key policy imperative that arises from the findings is the need for increasing the density of weather stations across the country. Again, the differences between the average annual rainfall across the country and specific parts of central India highlight the importance of finer spatial resolution in weather data. For instance, the annual rainfall averaged over India shows a marginal declining trend between 1951 and 2015, although statistically insignificant (Kulkarni et al. 2020), in contrast to trends for parts of central and western India (Mohanty 2020; Mohanty and Wadhawan 2022). Mohanty and Wadhawan (2022) discuss an alarming observation of 42% of districts in hotspot states witnessing a shift from drought-prone to flood-prone areas and vice versa. The findings from our study—of critical climate-stress moments differing based on the type of farming system considered—further emphasise the need for greater specificity in terms of the availability of climate data and projections. As highlighted by Nagori and Chaudhari (2020), increasing the density of ground stations is an important way to increase the accuracy and resolution of the available gridded IMD data.

As noted earlier, the rising frequency and intensity of the critical climate-stress moments are also a call for (i) improving access to agriculture insurance in India, (ii) incentivising a transition to non-agrarian livelihoods, and (iii) incentivising a shift to climate-resilient crops and livestock varieties through aggregation, value addition and the improved economies of scale of FPOs. The last point in particular acquires significance in light of the Government of India's policy on promoting 10,000 FPOs across the country (GoI 2021), as well as ongoing efforts by the National Rainfed Area Authority and the Government of India to enhance farming systems' ability to cope with evolving challenges, including building resilience to climate change (Aggarwal et al. 2022).

Conclusion

To better understand future climate risks and enhance the climate resilience of semi-arid farming systems in India, our study aimed to identify and characterise context- and time-specific climate stresses. We integrated bottom-up insights from FGDs and KIIs with top-down analysis of regional climate data to arrive at a list of critical climate-stress moments for semi-arid farming systems in India. The five critical moments identified were (i) increasing volume of late-monsoon rainfall, (ii) rising winter temperatures, (iii) increase in the number of days with temperatures exceeding 40 °C, (iv) increase in the number of days with heavy rainfall (> 25 mm), and (v) an increase in dry season rainfall (January–March). These moments of stress occur at critical moments such as harvesting or flowering stages in the case of crops or gestation in the case of livestock, leading to losses.

The focus on specific, time-bound moments when communities are vulnerable to climate stresses can create a sense of urgency in decision-making. Quantitative outputs related to the frequency or intensity of climate stresses complement the insights from qualitative assessments of climate resilience or climate vulnerability. An important contribution of critical climate-stress moments is in strengthening the case for targeted climate resilience – building measures. Our results suggest that targeted climate resilience–building interventions, such as infrastructural improvements, promotion of farmer collectives, innovative watershed development, tailored agro-advisories, polyhouse farming, customised weather-based insurance products, adoption of mixed crop-livestock systems, and diverse non-farm livelihoods, go beyond the generic adaptation options proposed in response to climate change for farming systems in India (e.g. Aggarwal et al. (2022); Pathak (2022)). These targeted interventions include those designed for adapting to specific stresses and other strategies aimed at navigating variability in agrarian markets and other unforeseen challenges, thereby enhancing the overall resilience of the system. Accordingly, we make a number of policy recommendations including a key recommendation to consider critical climate-stress moments in the drafting of national and state action plans on climate change.

Critical climate-stress moments can also help define turning points or socio-political thresholds for decision-making (Smolenaars et al. 2021; Werners et al. 2015) to guide the development of climate-resilient development pathways

(Werners et al. 2018, 2021). In an upcoming publication, Srinidhi et al. (unpublished) rely on these critical climate-stress moments to discuss future climate resilience–building options and co-create climate-resilient development pathways with farmer collectives.

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Data Availability The authors declare that the data supporting the findings of this study are available within the paper and its supplementary material.

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