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Impacts of 1.5 °C and 2 °C global warming on regional rainfall and temperature change across India

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Abstract

The participating member nations in Paris at the 2015 convention of the United Nations Framework Convention on Climate Change (UNFCCC) resolved to maintain the rise in global average temperature to a level much less than 2.0 °C compared to pre-industrial levels. It was also committed that the parties would continue with all-out endeavor to limit warming to 1.5 °C. For a country like India with a primarily agrarian economy this leads to two key questions. Firstly, what does the global rise of mean annual temperature (1.5 °C and 2.0 °C) mean at the regional scale? Secondly, what are the implications of keeping warming at or below 1.5 °C for different sectors and in particular on agriculture and water resources? To address these questions we have examined the annual and seasonal impacts of 1.5 °C and 2 °C global temperature rise (GTR) on temperature and rainfall change over all the states of India under two Representative concentration pathways, RCP 8.5 and RCP 4.5, using all Coupled Model Inter Comparison Project CMIP5 Models. Rainfall is projected to increase over all the states with very low change in the western part of the country and highest change in the North eastern and southern region of the country under RCP 8.5. 35% of the country is projected to witness a temperature change equal to or lesser than global mean temperature of 1.5 °C and 2.0 °C whereas 65% is expected to show a greater rise in temperature. The most severe temperature change is expected to be witnessed by the presently colder Northern most states of India such as Jammu and Kashmir, Himachal Pradesh and Uttaranchal (2.0 °C to 2.2 °C at 1.5 °C and 2.5 °C to 2.8 °C at 2.0 °C) in both RCPs. There are opportunities and threats due to climate change and it is imperative for researchers and policy makers to recognize these in the context of the scenarios of 1.5 °C and 2.0 °C global temperature changes. It is essential for the current national and state action plan on climate change and adaptation to be more sensitive in strategizing an efficient response to the different scenarios at the global level (3 °C, 2 °C and 1.5 °C) in order to take more informed policy decisions at global level in synergy with the regional analysis to be able to develop strategies that benefit the local populace.

1. Introduction

The increasing intensity and spread of anthropogenic activities is causing a swift accumulation of greenhouse gases in the atmosphere leading to a sustained greenhouse effect, which is resulting in worrying levels of global warming. The participating member nations in Paris at the 2015 convention of the United Nations Framework Convention on Climate Change (UNFCCC) resolved to maintain the rise in global average temperature to a level much less than 2.0 °C compared to pre-industrial levels. It was also committed that the parties would continue with all-out endeavor to limit warming to 1.5 °C. For a country like India with a primarily agrarian economy this leads to two key questions. Firstly, what does the global rise of temperature (1.5 °C and 2.0 °C) mean at the regional scale? Secondly, what are the implications of keeping warming at or below 1.5 °C for different sectors and in particular on agriculture and water resources? The IPCC (Intergovernmental Panel on Climate Change) first analyzed the possible climate risk corresponding to a 2 °C temperature rise with respect to pre-industrial era as a base in its Second Assessment Report (Houghton E 1996). All climatic projections involve an inevitable degree of uncertainty but still a considerably large number of scientific studies conclude that under representative concentration pathways RCP 8.5 global warming will overshoot 2 °C and may climb up to 6 °C by the year 2100 (Friedlingstein *et al* 2014 and Betts *et al* 2016). The Fifth Assessment Report (AR5) of the IPCC (2014) critically analyzes the expected severe impact of a warming of 1 °C–2 °C above pre-industrial levels on many facets of life. Several studies conclude with projections of a severe alteration in the hydrological cycle as a consequence of warmer climatic conditions (Rogelj *et al* (2012), Trenberth *et al* (2014), Alfieri *et al* 2015, Donat *et al* 2017). A constantly rising trend in global temperature and its expected outcome has made it imperative for the scientific community to understand and analyze the reasons of atmospheric warming and their causative correlation with natural hazards. An increase in temperature is seen to cause the moisture-holding capacity of the atmosphere to increase at a rate of about 7% per 1 °C rise in temperature (Clausius–Clapeyron equation). It is evident that higher air temperature is correlated to escalation of water vapour content in atmosphere, which subsequently may aggravate the possibility of more recurrent and extreme precipitation events (Stoffel *et al* 2014). Recent years have experienced a conspicuous impact of global warming in the form of natural hazards such as large scale floods (Hirabayashi *et al* 2013, Alfieri *et al* 2015), increased drought frequency (Dai *et al* 2011), and frequent heat wave (Meehl and Tebaldi 2004). In recent years, Extreme rain, heat waves are the prominent events occurring due to climate change across India. Weakening relationship between El Nino Southern Oscillation and Indian Monsoon Rainfall under current global warming is resulting in high rainfall variability, intense rain and severe dryness.

Regional level analysis can provide a more segregated picture than a global one based on combined metrics (Seneviratne *et al* 2016). Various studies have tried to project the impact of temperature rise in various parts of the world. O'Neill *et al* (2014) suggested that in the light of forecasts for urbanization and population growth in tropical parts of Africa and Southeast Asia, the risks constituted by extreme heat and potential crop yield reductions in these regions under a 2 °C warming scenario are conspicuously decisive. Tropical regions such as South-East Asia are expected to encounter substantial local yield reductions, especially for maize and wheat. In the China, the summer temperature is expected to increase by 1.2 to 9 °C by the end of the century (Luo *et al* 2005). Warming over land will be much higher as compared to ocean (Lambert (1995), Bengtsson *et al* 1996). The regional studies signal that as 3-σ events become the new norm under 2 °C warming scenario, the tropical parts of South-East Asia, Africa and South America are expected to face the most intense rise in land area covered by heat extremes relative to the regional natural variability (Hansen *et al* 2016). Even 1.5 °C rise in temperature will cause harsher droughts, more rises in global sea level and increase the frequency of storm surges which will inflate the cost of adaptation for millions.

The Indian scenario has also been explored in a number of studies (Auffhammer *et al* 2012, Jayaraman and Murari (2014), Sukumar *et al* 2016, Sharma and Pingali (2018) and Shafiq *et al* 2019). India was placed at the 10th position among highest climate risk countries in Asia based on extreme environment events (Global Sustainable Development Report 2015). A hub of diverse agro-climatic zones, India is highly susceptible to climate change. The report submitted to UNFCC second national communication by government of India predicted the rise of annual mean surface air temperature escalate from 3.5 °C to 4.3 °C. In particular, the variability of Indian rainfall under warming condition has been studied by many researchers (Menon *et al* 2013, Sharmila *et al* 2015, Yaduvanshi and Ranade (2017)). The North West India witnessed a lower monsoon rainfall with higher number of droughts (Jena *et al* 2016). The highest increase in annual summer monsoon, early onset of monsoon and higher inter annual variability were found to occur in North East and South West Coast of India (Duncan *et al* 2013). Southwest monsoon season in India is dominant one to bring rainfall for the most of the country. Other than monsoon, South East India mostly receives it's rainfall from North East monsoon (October-December) and North West region also get significant rainfall during winters (Rajeevan *et al* (2012)). Even though the impact of global warming have been analyzed at all India level (Bhowmick *et al* 2019), there is not much information regarding specific 2 °C and 1.5 °C temperature rise on the regional climate change of India at the state level. Most of the climate change and adaptation plans are prepared at the state level and it would be relevant to understand the impacts of 2 °C and 1.5 °C global warming across the different states in India. In this perspective, we analyze the mean annual and seasonal changes in temperature and rainfall across Indian states in the context of 1.5 °C and 2 °C global warming, using all CMIP5 model outputs.

2. Study area

India is an enormously geographic diverse place with a variety of climate regimes and local weather conditions. Barring hilly northern region and islands, entire India has been divided into 36 sub-divisions based on meteorological characteristics. There are 29 states and seven union territories present in India.

With its summer (South-west) and winter (North-east) periods, the Indian monsoon exerts its influence dominantly on the climate of the subcontinent. Variation in the beginning, departure and amount of rainfall during the monsoon season impacts the agriculture and allied activities, most of the industries and natural resources of the country.

3. Method and data sets

In this study the analysis was made to assess the regional rainfall and temperature changes at annual and seasonal scale under 1.5 °C and 2 °C global temperature rise (GTR). Convoluted shape of Indian land mass and dominance of tropical region brought large biases in projecting climate change over Indian regions climate simulations (Anand *et al* 2018). To avoid biases from individual model we have covered all possible CMIP-5 models to understand the range of temperature and rainfall changes. Total 81 members of RCP 8.5 and 108 members of RCP 4.5 were used which can be downloaded from KNMI Climate Explorer (https://climexp.knmi.nl). Annual and seasonal scale analysis has been done including four seasons such as Pre monsoon (March to May), Monsoon (June to September), Post monsoon (October to December) and winter (January and February). 78 CMIP-5 models under RCP 8.5 and 105 models under RCP 4.5 were used for rainfall change and for temperature change 81 (RCP 8.5) and 108 (RCP 4.5) models were used. To avoid the ensemble members from single model (model is operated multiple times) weighted statistic is used (Knutti *et al* 2017).

The timing of each global warming level (1.5 °C and 2.0 °C over preindustrial) in each model simulation was determined by calculating a 40-year preindustrial global mean temperature for the period 1861–1900 (Huang *et al* 2017); this period was chosen to incorporate the maximum number of models, as some models began with the year 1861. Then years were identified at which the 31-year running mean (1901–1931, 1902–1932) of global temperature exceeded 1.5 °C and 2.0 °C over the pre-industrial global mean temperature.

For each Indian state, an area-averaged temperature and rainfall changes relative to pre-industrial at the time of 1.5 °C and 2.0 °C global warming levels were then calculated using the 31-year mean centered. Consensus of minimum 75% members on the sign of change has been identified as one of the criteria of decision making (Pinto *et al* 2016).

To understand the normal behavior of different models for individual states descriptive statistics such as the measure of central tendency (mean, median, range, etc) and dispersion (SD) were used. Statistical significance of change based on the distributions of ensemble in their respective warming levels at 95% significance level is evaluated using Wilcoxon paired signed rank test (Silliman *et al* 2013). The spatial distribution of maximum and minimum temperature and rainfall change maps were generated at 1.5 °C and 2 °C global warming using ArcGIS version 10.3.1. The box plots were used to present the projected variability at each Indian state. Interquartile range which shows the distance between two percentiles (25th and 75th) represents the height of boxplot. The central line inside the box refers to the median value and the straight vertical lines above and below the box are the whiskers. The length of line indicates the minimum and maximum value.

4. Results and discussion

4.1. Rainfall change over different states

A regional distribution pattern shows that the maximum change is expected to occur over the North Eastern states of India under both 1.5 °C and 2.0 °C rise of global temperature under both RCP 4.5 and 8.5 scenarios, more so in the state of Arunachal Pradesh. Median value of rainfall change is considered to represent the quantitative change and the range of minimum and maximum rainfall change is presented in bracket for corresponding states. Under RCP 8.5, it was observed that the country shows an overall increase in rainfall which varies between a maximum of 44.00 mm (−188 to 416 mm) and 107.09 mm (−175 to 400 mm) in the state of Arunachal Pradesh to a minimum of 7.6 mm (−81 to 124 mm) and 20.01 mm (−69 mm to 91 mm) in Haryana (figure 1) for 1.5 °C and 2.0 °C rise of global temperatures respectively.

Under RCP 4.5 scenario, the rainfall changes in Arunachal Pradesh ranged from 39.7 mm and 92.3 mm. There is a large spread in range due to the variations in climate sensitivity of models across the region-particularly for rainfall (figure 2). It has been noted that spread provide important information about the change (McSweeney and Jones (2016)). Median/averaged mean of model compares better to observation than a single model.

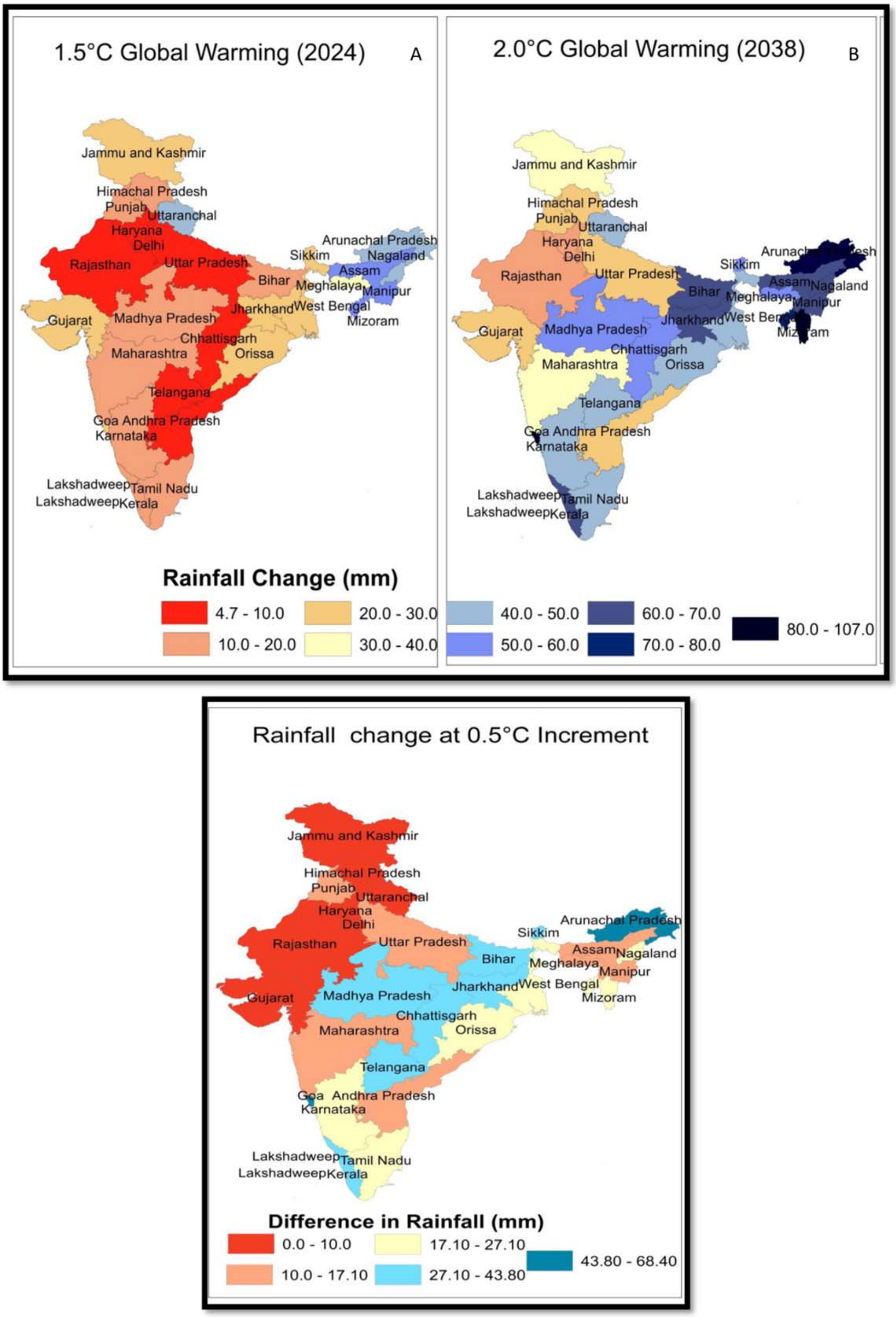

Figure 1. Indian states showing annual rainfall change using (Median) CMIP 5 models under RCP 8.5 scenario at 1.5 °C global warming by 2024 (A) and 2 °C (B) global warming by 2038, compared to pre-industrial level.78 models are used to calculate the changes in rainfall. Change in regional rainfall at 0.5 °C (Bottom map) difference in global temperature.

Since RCP 8.5 scenario projects extreme case, it is expected that the changes are larger as compared to RCP 4.5. It is noted that RCP 8.5 corresponds to the pathway that has highest greenhouse gas emission compared to other RCPs. In RCP 8.5 greenhouse gas emission grow by factor of 3 over the period (end of century) as resultant of high food demand, increasing population and high fossil intensity in energy sector (Riahi *et al* 2011).

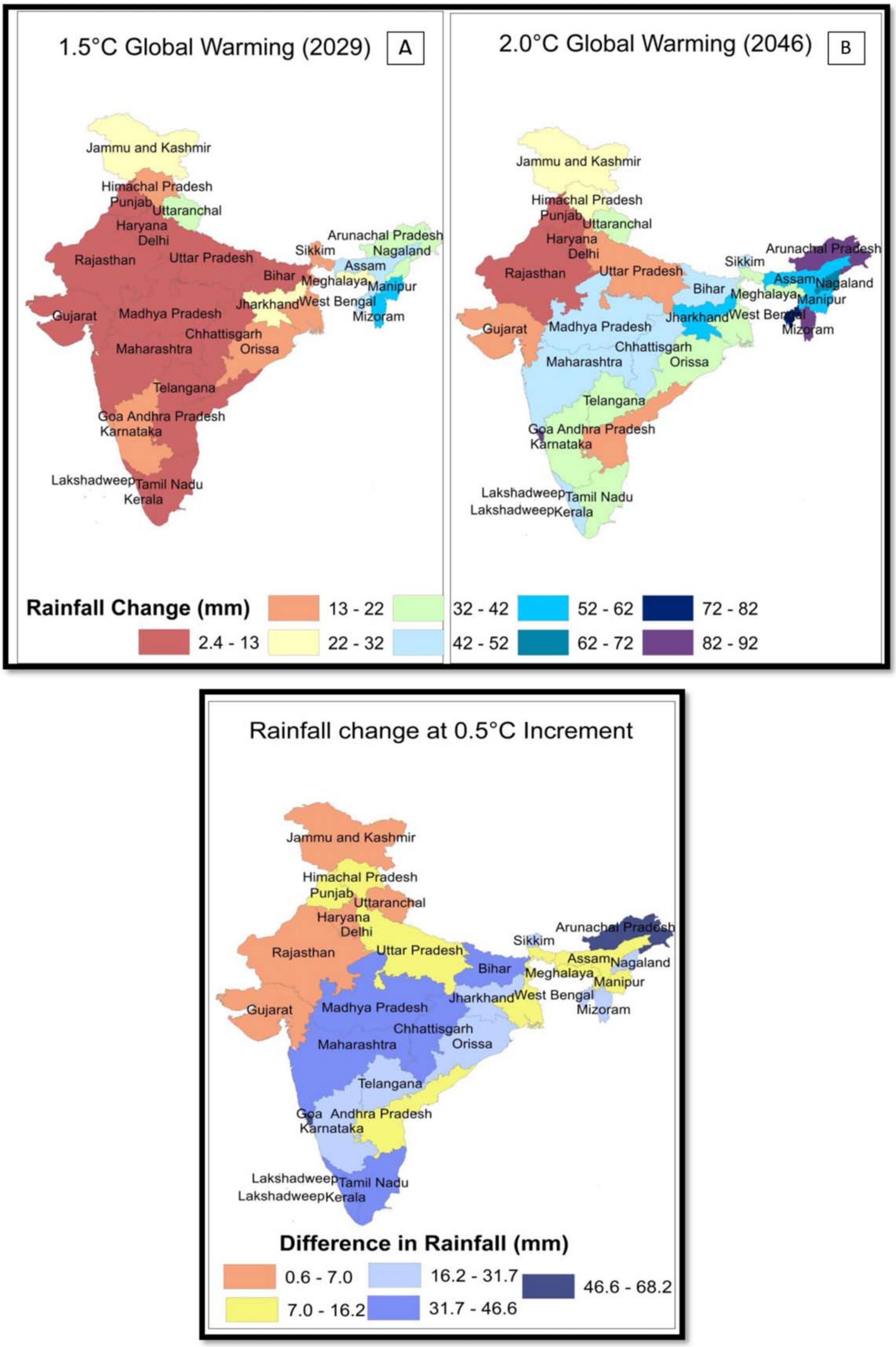

Figure 2. Indian states showing annual rainfall change using (Median) CMIP 5 models under RCP 4.5 scenario at 1.5 °C global warming by 2029 (A) and 2 °C (B) global warming by 2046, compared to pre-industrial level.105 models are used to calculate the changes in rainfall. Change in regional rainfall at 0.5 °C (Bottom map) difference in global temperature.

Seasonal changes in the regional rainfall pattern in RCP 8.5 are presented in figure 3. The state of Arunachal Pradesh showed higher rainfall in pre-monsoon season as compared to the monsoon period. This would certainly have implications on future crop planning in the state. Delhi, Karnataka, Orissa and Rajasthan states

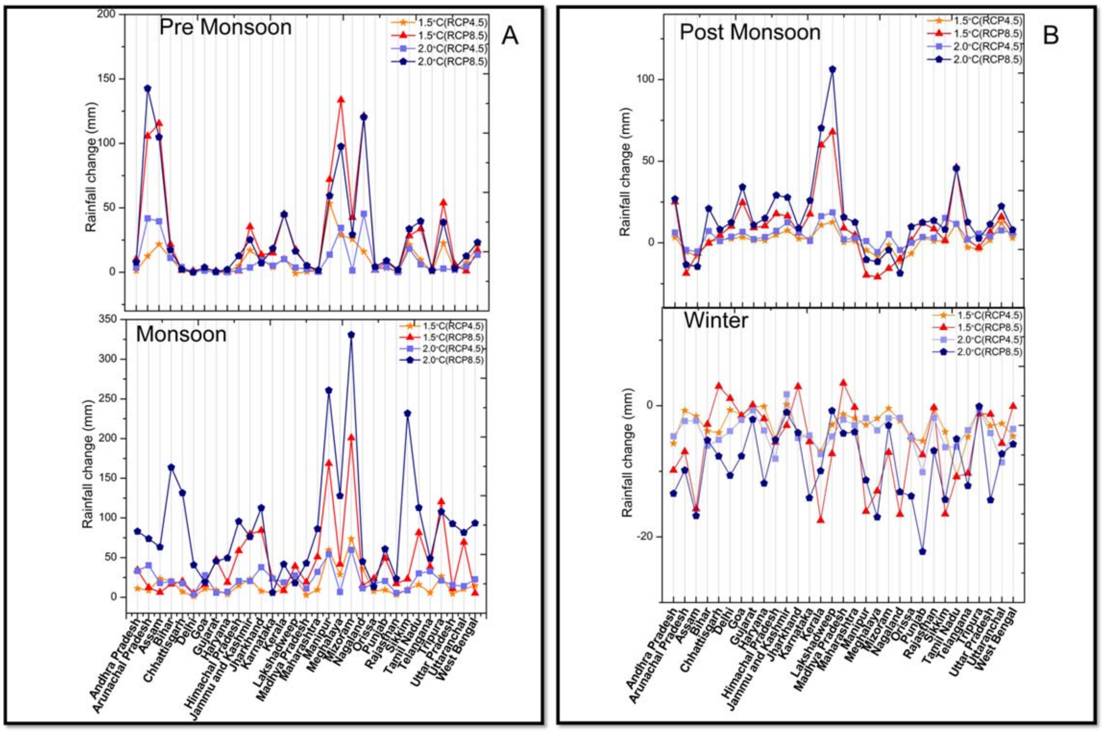

Figure 3. Seasonal changes in the rainfall at each Indian States using CMIP 5 models under RCP 8.5 and RCP 4.5 at 1.5 °C and 2 °C global mean temperature, (A) shows rainfall changes in Pre-Monsoon and Monsoon season and (B) shows rainfall changes in Post-Monsoon and Winter season.

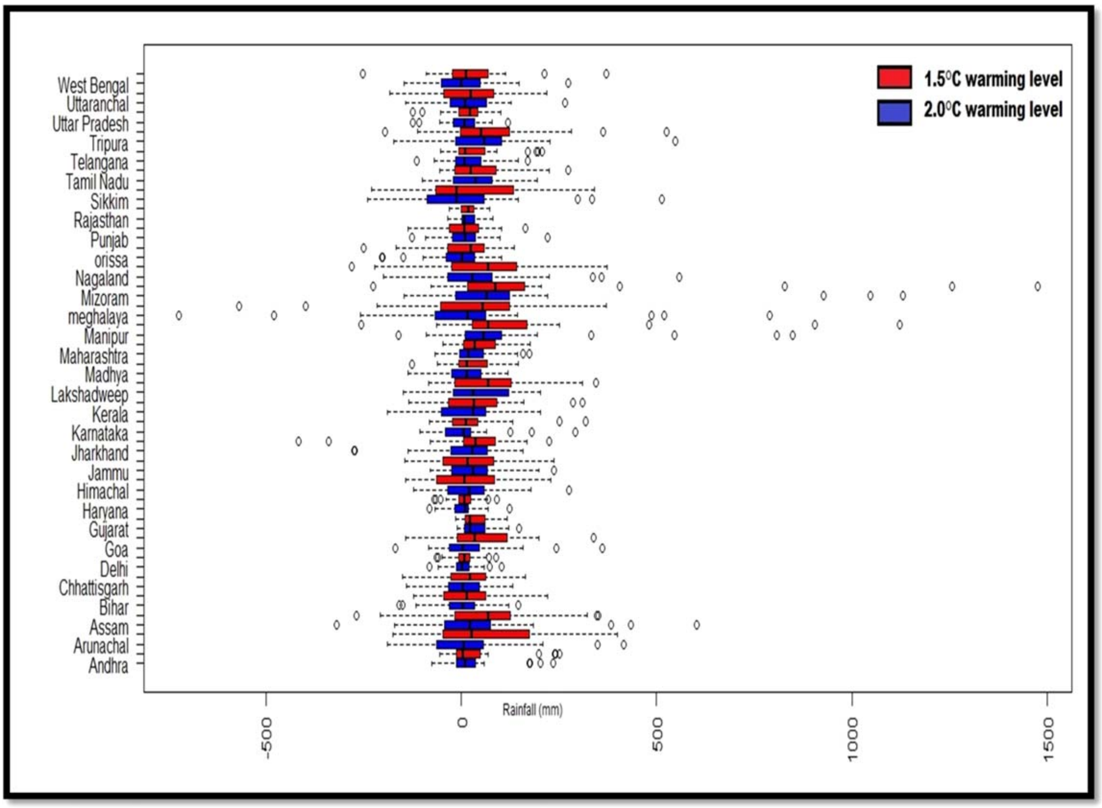

Figure 4. Box plot showing the range of annual rainfall change obtained using CMIP 5 models under RCP 8.5 (81 models) scenario at 1.5 °C and 2 °C global mean temperature compared to pre-industrial level for all Indian states.

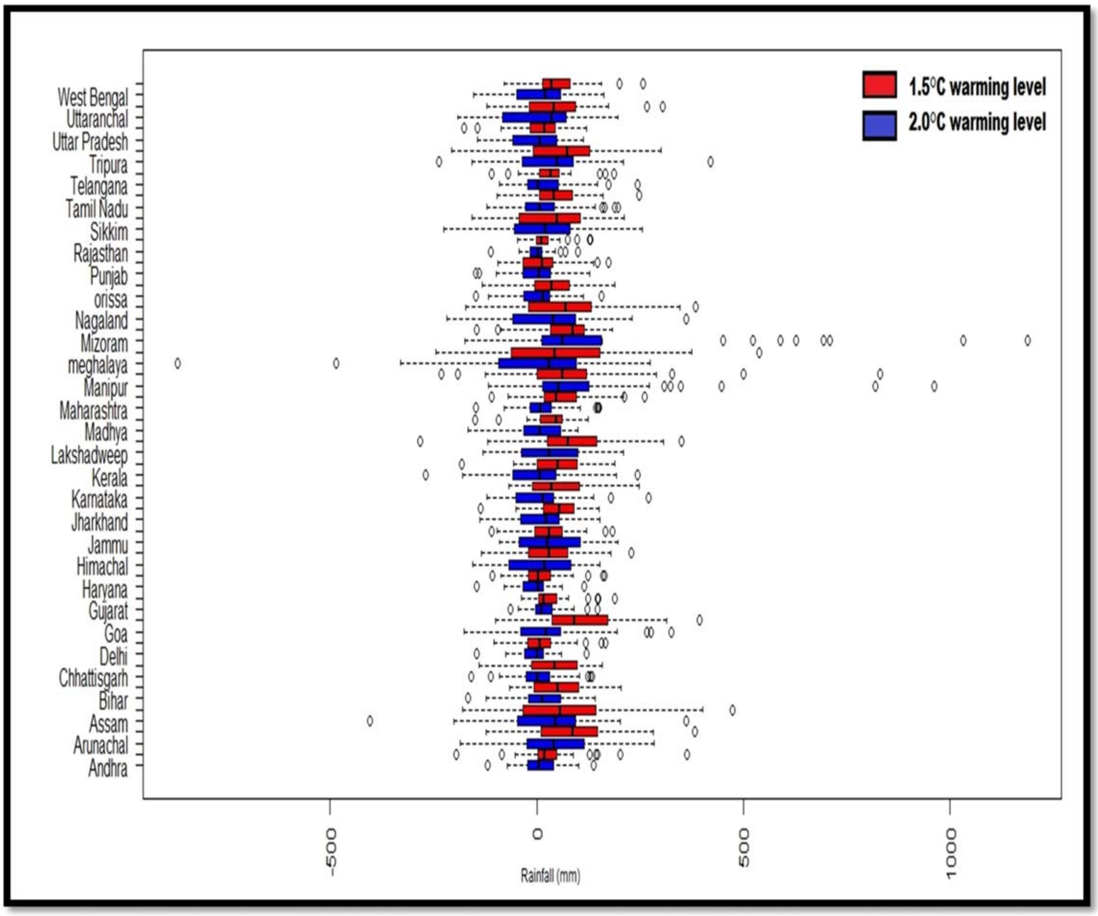

Figure 5. Box plot showing the range of annual rainfall change obtained using CMIP 5 models under RCP 4.5 (105 models) scenario at 1.5 °C and 2 °C global mean temperature compared to pre-industrial level for all Indian states.

show very small increase in the rainfall compared to pre-industrial period. In winter season, except for Jammu and Kashmir and Tripura States, in all other states there is a negative change in the regional rainfall compared to pre-industrial period. Similar seasonal pattern was seen in RCP 4.5 also.

The distribution of predicted values of the changes in regional annual rainfall for the 29 States of India obtained using the 78 GCM models (RCP 8.5) and 105 GCM models (RCP 4.5) are presented as a boxplot in figures 4 and 5 respectively. As shown in figure 1, maximum change in rainfall was observed in the northern eastern states of India but it is also observed that often the models are not converging to similar values, and so it becomes imperative to look at the whole range of predicted values. For example, in Arunachal Pradesh state, which showed highest change with a median value of 44.00 mm, the rainfall changes ranged from 416 mm to −188 mm with a few outliers among the 78 models in RCP 8.5. The standard deviation value of all models is quite high at 91.84 mm. Among the 78 models, eight models are suggesting an extreme value of rainfall change. Many other states such as Mizoram, Meghalaya and Manipur are facing similar pattern in RCP 4.5 as well. However, the states witnessing lower rainfall change such as Haryana, Rajasthan and Gujarat are showing a comparatively narrower range of rainfall change. For instance, in Rajasthan, the range is from −31.5 to 73.25 mm with 28.33 mm of standard deviation.

The median value observed was quite high for states like Nagaland, Meghalaya and Manipur in North-Eastern India and Kerala in Southern India, where total rainfall is very high, shown in a wide box plot (figures 4 and 5).

In the rainfall prediction, box plot shows high range of rainfall change in a few states of North East Region. Especially, in high rainfall receiving states like Nagaland and Meghalaya, the range of minimum to maximum rainfall change is highest among all other states of India. MIROC5 and MIROC-ESM predicted the highest change in rainfall with the value of 557.5 mm and 359.0 mm respectively. Sengupta and Rajeevan (2013) found that MIROC5 provide overestimated rainfall simulation over the western part of India, whereas Jena *et al* 2016 concluded good performance of MIROC5 and MIROC-ESM in order to estimate peak count of rainfall days and intensity of rainfall. In the arid and semi-arid zone of India the same models are showing the negative change. Capturing regional rainfall precisely is a difficult process due to the limitation of models. Models such as

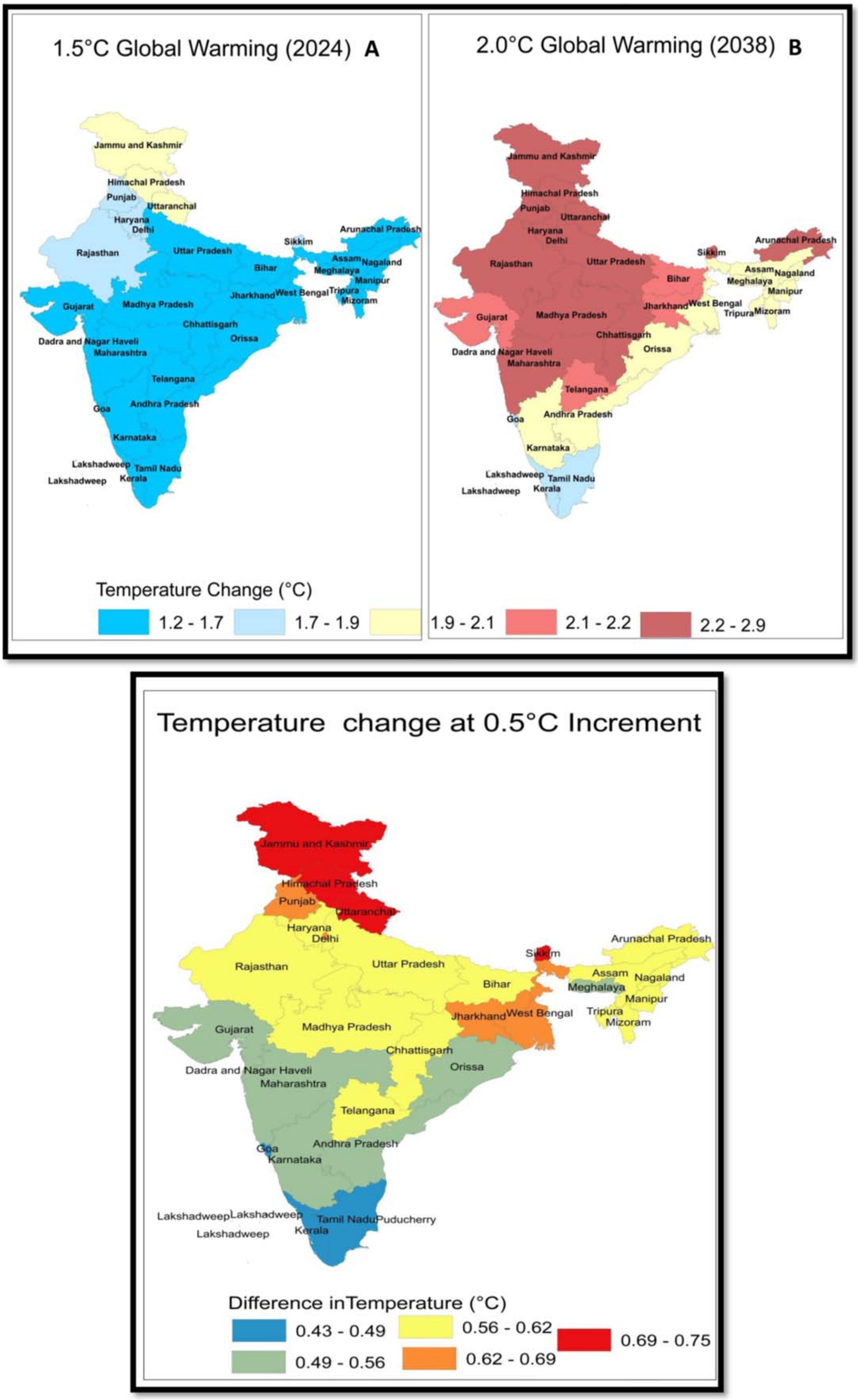

Figure 6. Indian states showing annual temperature change using (Median) CMIP 5 models under RCP 8.5 scenario at 1.5 °C global warming by 2024 (A) and 2 °C (B) global warming by 2038, compared to pre-industrial level.81 models are used to calculate the changes in rainfall. Change in regional rainfall at 0.5 °C (Bottom map) difference in global temperature.

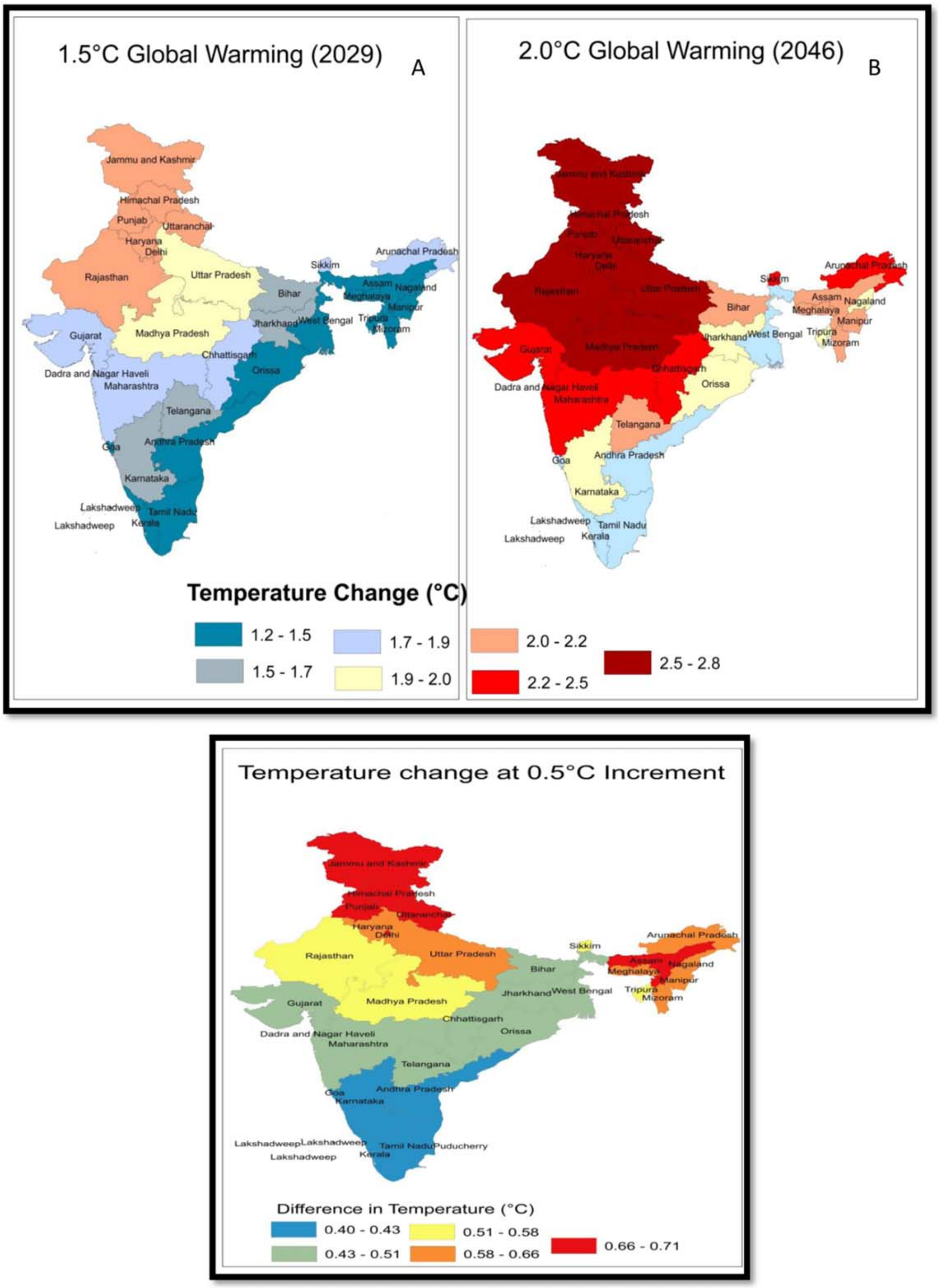

Figure 7. Indian states showing annual temperature change using (Median) CMIP 5 models under RCP 4.5 scenario at 1.5 °C global warming by 2029 (A) and 2 °C (B) global warming by 2046, compared to pre-industrial level.108 models are used to calculate the changes in rainfall. Change in regional rainfall at 0.5 °C (Bottom map) difference in global temperature.

HADGCM2-ES, GISS-E2R have shown negative rainfall change (−181.6 mm and −264.7 mm) in the highest rainfall receiving zones.

HADGCM2-ES is found to be capturing the low rainfall across India (Menon *et al* 2013). In the RCP scenario 8.5 the time difference of reaching from 1.5 °C and 2 °C is very short; reflects the instant need of adaptation in India as it will happen too fast. Results on precipitation should be interpreted with caution as rainfall values have larger inter-model spread and are more sensitive to interannual variability than the temperature response.

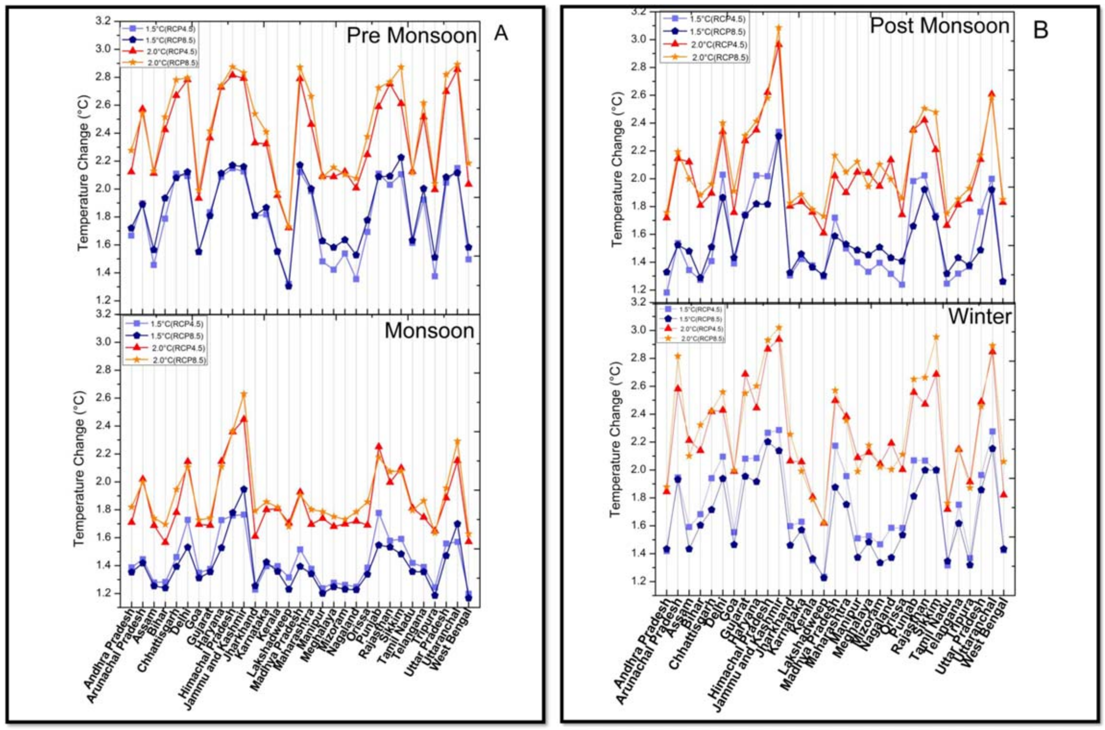

Figure 8. Seasonal changes in the temperature at each Indian States using CMIP 5 models under RCP 8.5 and RCP 4.5 at 1.5 °C and 2 °C global mean temperature, (A) shows temperature changes in Pre-Monsoon and Monsoon season and (B) shows temperature changes in Post-Monsoon and Winter season.

4.2. Temperature change over different states

Projected values of the change in global mean temperature for the 29 States of India are obtained using 81 GCMs for RCP 8.5 and 108 GCMs for RCP 4.5. Most states of Northern India (Jammu and Kashmir, Himachal Pradesh and Uttaranchal) are showing high increase in temperature under both RCPs (figures 6 and 7).

The median values of temperature changes for all the states are seen to be positive under both RCP 4.5 and RCP 8.5 (figure 7), and range from 1.4 °C and 1.9 °C for Kerala to 2.1 °C and 2.8 °C for Jammu and Kashmir at 1.5 °C and 2.0 °C GTR respectively. The lowest rise is observed over the South Eastern and North East part of India. In some states, models reflecting temperature changes under RCP 4.5 are higher than those under RCP 8.5 (figure 7). This is because, in RCP 4.5, year of reaching 1.5 °C difference is 2029, whereas in RCP 8.5 it is 2024. In similar way, timing of reaching 2 °C GTR under RCP 4.5 is 2046 and 2038 in the case of RCP 8.5. It is also noted that the year of showing 1.5 °C and 2 °C GTR is a median value chosen from among the 108 models under RCP 4.5 and 81 models under RCP 8.5. Worst case scenario, which is also known as RCP 8.5 is reaching 1.5 °C earlier as compared to RCP 4.5.

In all seasons, Jammu and Kashmir, Himachal Pradesh and Uttaranchal are projected to have higher temperature change. Many studies have shown similar findings in these zone with rise of 2.5 °C–4.5 °C by the end of century (Panday *et al* 2015), highest change in temperature recorded over western Himalaya (Joshi et al 2018). A slightest change in the climate over the Himalayas may lead to disastrous consequences for the people depending on various resources of Himalayas as well as for the people living in downstream areas (dimri *et al* 2018). For 2 °C of global warming, most land regions will be much warmer (Huntingford and Mercado (2016)). Winter and post monsoon season months are showing temperature rises that are greater than monsoon and pre-monsoon months. Other Indian states, such as Sikkim, Rajasthan and Haryana also showed significant increase in the winter season (figure 8). It has been showing in many literatures that winter temperature would rise significantly over the period (Mondal *et al* 2015 and Kundu *et al* 2017).

As shown in figures (9 and 10), models are converging to similar values in temperature as compared to rainfall, which is more than 75%. For example, in Himachal Pradesh, which showed highest change with a median value of 2.1 °C, the temperature change ranged from 1.2 °C to 2.7 °C among the 81 models under RCP 8.5. In spite of having wide range of the models, the standard deviation of all models is quite low.

In case of temperature range, the states such as Haryana, Rajasthan and Delhi have witnessed the widest range of temperature change (3.2 °C to 0.5 °C) with 0.54 °C standard deviation. GFDL-ESM-2M and CNRM-CM5 have given the highest change for the arid regions (3.3 °C) whereas CESM-1-CAM5 and CMCC-CM have

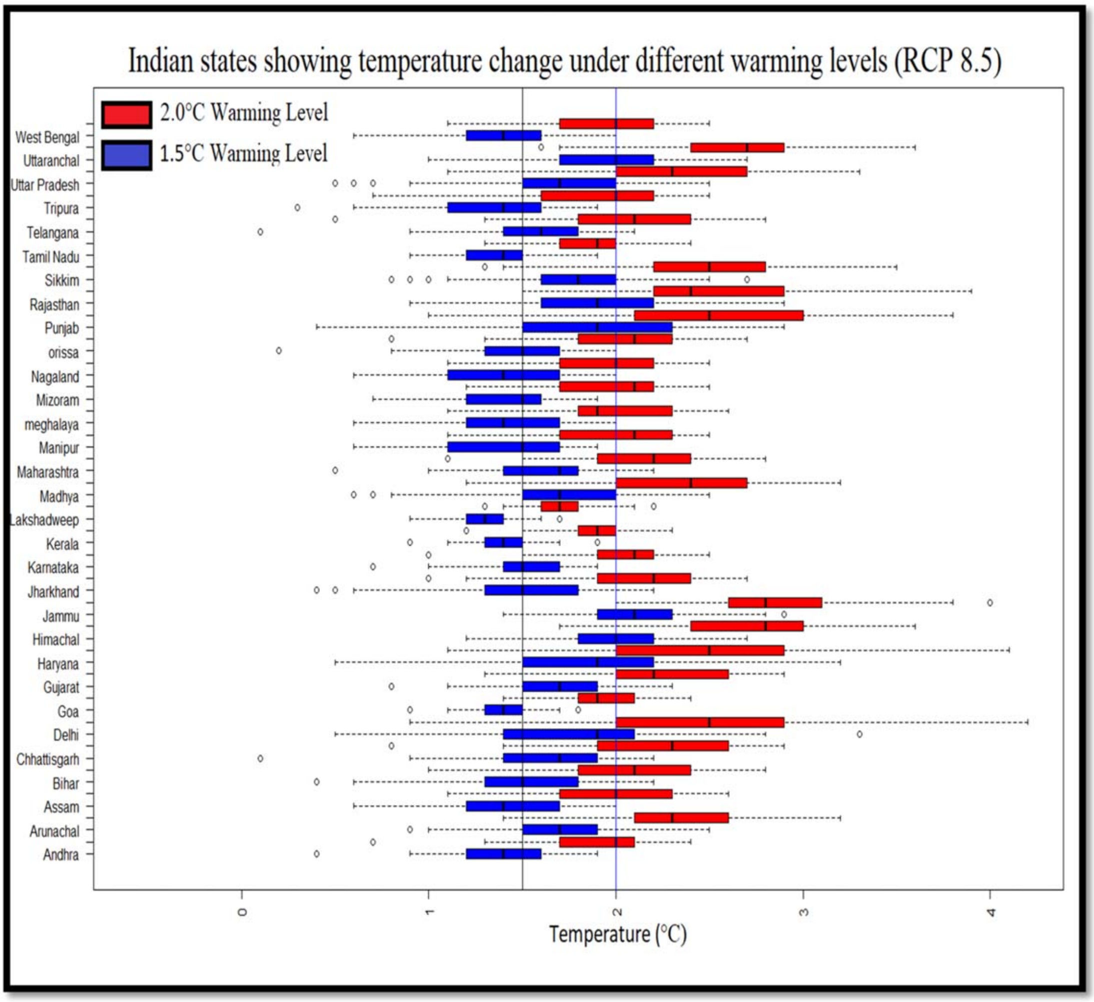

Figure 9. Box plot showing the range of annual temperature change obtained using CMIP 5 models under RCP 8.5 (81 models) scenario at 1.5 °C and 2 °C global mean temperature compared to pre-industrial level for all Indian states.

projected lowest rise in temperature (0.5 °C). Therefore, arid regions are difficult to capture in its real form from the GCM models. Apart from the temperature and rainfall change, CMIP5 models have also shown variability while reaching the 1.5 °C and 2 °C global warming. Models with high transient sensitivity to climate reach sooner than low climate transient sensitivity.

5. Discussion and conclusions

We comprehensively analyzed the temperature and precipitation changes using all CMIP-5 members across India in order to understand the implications of 1.5 °C and 2 °C temperature rise under RCP 4.5 and RCP 8.5. Relative to pre-industrial period, 65% of the country has shown the maximum increase in temperature of 2.1 °C and 2.8 °C under the threshold of 1.5 °C and 2 °C respectively. In addition, maximum increase in annual rainfall is expected in the North East region of country, especially during the pre-monsoon and monsoon seasons. Increase in rainfall projections in pre-monsoon season indicate a need for change in farm management practices such as early land preparation and sowing activities. On the other hand, in the monsoon period, quantum and intensity of rain would be the important causes of floods in the Brahmaputra valley which covers most states of northeastern region. For instance, Assam received close to 510 mm of rainfall between 1st June and 27th June 2017 (31% of excess rainfall as compared to normal rainfall of 388 mm during this period) resulting in the most devastating flood of a decade. The state action plan for climate change and adaptation needs to take into cognizance of increased frequency of such extreme events. States like Jammu Kashmir (now converted into union territories of Jammu and Kashmir and Ladakh), Himachal Pradesh and Uttaranchal are indicating temperature increases of 3 °C in winter and post-monsoon seasons under the 2 °C global warming and 2.4 °C under the 1.5 °C global warming in both scenarios. Rise in temperature would increase the climate variability

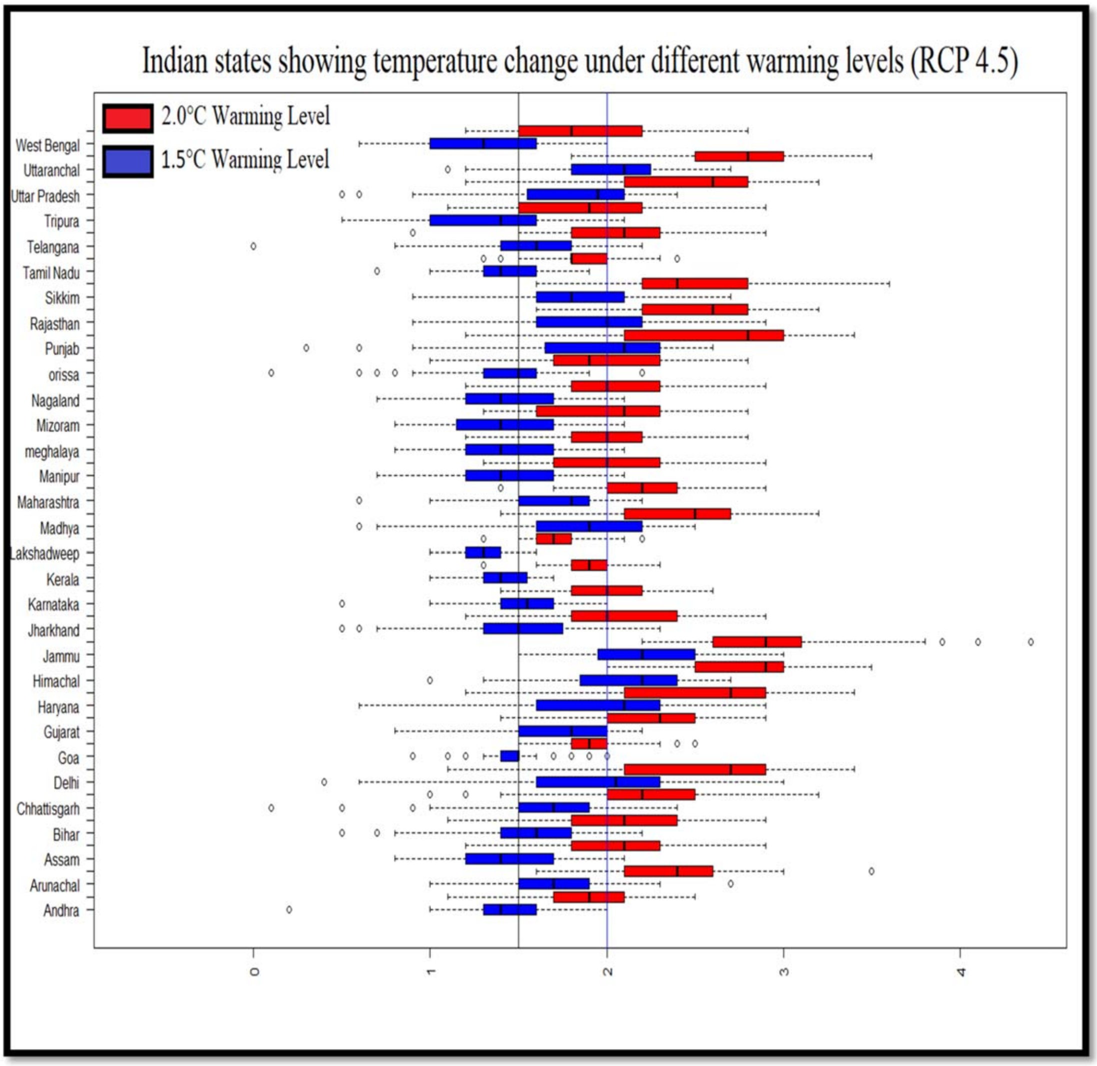

Figure 10. Box plot showing the range of annual temperature change obtained using CMIP 5 models under RCP 4.5 (108 models) scenario at 1.5 °C and 2 °C global mean temperature compared to pre-industrial level for all Indian states.

leading to extreme events affecting river discharge (Huntington 2006, Yaduvanshi *et al* 2018). Schleussner *et al* (2015) found that occurrence of extreme events could increase by 10 percent under the scenario of 2 °C global warming. Therefore, in both warming levels, there would be increased melting of snow and glaciers causing severe flooding in the lower plains of Ganges. The volumes of glaciers are changing in a negative manner from 3.6% to 97% with an average glacier degradation of 15% to 27% in the Himalayan range of Jammu and Kashmir (Koul and Ganjoo (2010)). Both these situations, viz. melting of glaciers due to temperature rise in Himalaya region and high rainfall in Northeastern states, will increase vulnerability of people residing in the deltaic regions of Ganga and Brahmaputra rivers by the year 2038. 11 CMIP5 GCMs show increase in flood frequency (under RCP 8.5) and increase in mean, high and low stream flows (under both RCP 8.5 and 4.5) in peninsular India (Hirabayashi *et al* 2013), which may worsen with projected increase in temperature and rainfall in future. This could potentially trigger widespread displacement and migration of millions of people into already highly populated inner lands resulting in increased pressure on local water and land resources.

Post monsoon and winter season are showing greater temperature rise compared to monsoon and pre-monsoon. The agriculture sector is particularly vulnerable to climate change and it would have to bear the maximum impact of increased climate variability and extremes. States in which agriculture could be potentially affected by increased temperature rise are Haryana, Punjab and Rajasthan (Northern part of India), which account for the highest wheat and paddy growing areas in the country. Yields of wheat, mustard, groundnut, soyabean and potato are expected to decline by 3–7% for every one degree increase in temperature. Erratic rainfalls and dry spells under the face of global warming cause reduction in paddy yields in India (Auffhammer *et al* 2012). Barlow *et al* (2015) found that excess heat initiated fall in grain numbers and reduced period of grain filling in paddy.

As shown by the study, the greatest repercussions of temperature rise are found over the northern and central Indian states where farmers are highly vulnerable and have low adaptive capacities despite various initiatives taken by the central and the state governments.

It is vital to establish robust assessment systems of climate change projections as well as impact assessment at the regional and local level. The problems of temperature rise need to be seen in totality as there is already an increased incidence of land use land cover changes, ground water decline, pests attack, frequently occurring heat waves etc and these are only expected to increase in future.

The implications of projected increases in rainfall and temperatures in the future could have potential risks at a larger biophysical level (ex. in terms of increased river flows and consequent floods) or at farm level production activities (ex. impact on crop productivity).

India, through its National Action Plan on Climate Change (NAPCC), has pledged to address the challenges of climate change. State governments are also working on the same line to address the objectives of NAPCC by formulating the state action plan on climate change (SAPCC). India has a number of climatic zones and response of each zone to climate change would be different (Khan *et al* 2009). More research with disaggregated data would provide insights into the differential impacts in the different agro climatic regions within a state, as each state has more than one agro climatic region.

It is important for the current national and respective state action plans on climate change and adaptation to be more sensitive as well as responsive to the different scenarios at the global level (4 °C, 2 °C and 1.5 °C) in order to take more informed policy decisions as well as develop strategies that benefit the regional or local populace.

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References

Alfieri L, Burek P, Feyen L and Forzieri G 2015 Global warming increases the frequency of river floods in Europe *Hydrol. Earth Syst. Sci.* **19** 2247–60

Anand A, Mishra S K, Sahany S, Bhowmick M, Rawat J S and Dash S K 2018 Indian summer monsoon simulations: usefulness of increasing horizontal resolution, manual tuning, and semi-automatic tuning in reducing present-day model biases *Sci. Rep.* **8** 3522

Auffhammer M, Ramanathan V and Vincent J R 2012 Climate change, the monsoon, and rice yield in India *Clim. Change* **111** 411–24

Barlow K M, Christy B P, O'leary G J, Riffkin P A and Nuttall J G 2015 Simulating the impact of extreme heat and frost events on wheat crop production: a review *Field Crops Research* **171** 109–19

Bengtsson L, Botzet M and Esch M 1996 Will greenhouse gas-induced warming over the next 50 years lead to higher frequency and greater intensity of hurricanes? *Tellus* A **48** 57–73

Betts R A, Jones C D, Knight J R, Keeling R F and Kennedy J J 2016 El Nino and a record CO_2 rise *Nat. Clim. Change* **6** 806–10

Bhowmick M, Sahany S and Mishra S K 2019 Projected precipitation changes over the south Asian region for every 0.5 °C increase in global warming *Environ. Res. Lett.* **14** 054005

Dai A 2011 Drought under global warming: a review *Wiley Interdiscip. Rev. Clim. Change* **2** 45–65

Dimri A P, Kumar D, Choudhary A and Maharana P 2018 Future changes over the Himalayas: mean temperature *Global Planet. Change* **162** 235–51

Donat M G, Lowry A L, Alexander L V, O'Gorman P A and Maher N 2017 More extreme precipitation in the world's dry and wet regions *Nat. Clim. Change* **6** 508–12

Duncan J M, Dash J and Atkinson P M 2013 Analysing temporal trends in the Indian Summer Monsoon and its variability at a fine spatial resolution *Clim. Change* **117** 119–31

Friedlingstein P *et al* 2014 Persistent growth of CO_2 emissions and implications for reaching climate targets *Nat. Geosci.* **7** 709–15

Hansen J, Sato M, Ruedy R, Schmidt G A and Lo K 2016 *Global Temperature in 2015.* (NY: GISS, NASA) *URL* http://data.giss.nasa.gov.

Hirabayashi Y, Mahendran R, Koirala S, Konoshima L, Yamazaki D, Watanabe S, Kim H and Kanae S 2013 Global flood risk under climate change *Nat. Clim. Change* **3** 816–21

Houghton J T (ed) 1996 *Climate Change 1995: The Science of Climate Change: Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press) 2

Huang J, Yu H, Dai A, Wei Y and Kang L 2017 Multi-scale dense convolutional networks for efficient prediction *Nature Climate Change* **7** 417

Huntingford C and Mercado L M 2016 High chance that current atmospheric greenhouse concentrations commit to warmings greater than 1.5 C over land *Sci. Rep.* **6** 30294

Huntington T G 2006 Evidence for intensification of the global water cycle: review and synthesis *J. Hydrol.* **319** 83–95

Intergovernmental Panel on Climate Change 2014 *Climate Change 2014–Impacts, Adaptation and Vulnerability: Regional Aspects* (Cambridge University Press)

Jayaraman T and Murari K 2014 Climate change and agriculture: current and future trends, and implications for India *Review of Agrarian Studies* **4** 1–49

Jena P, Azad S and Rajeevan M N 2016 CMIP5 projected changes in the annual cycle of indian monsoon rainfall *Climate* **4** 14

Joshi R, Sambhav K and Singh S P 2018 Near surface temperature lapse rate for treeline environment in western Himalaya and possible impacts on ecotone vegetation *Tropical Ecology.* **59** 197–209

Khan S A, Kumar S, Hussain M Z and Kalra N 2009 Climate change, climate variability and Indian agriculture: impacts vulnerability and adaptation strategies *Climate Change and Crops* pp 19–38

Koul M N and Ganjoo R K 2010 Impact of inter-and intra-annual variation in weather parameters on mass balance and equilibrium line altitude of Naradu Glacier (Himachal Pradesh), NW Himalaya, India *Clim. Change* **99** 119–39

Knutti R, Sedláček J, Sanderson B M, Lorenz R, Fischer E M and Eyring V 2017 A climate model projection weighting scheme accounting for performance and interdependence *Geophys. Res. Lett.* **44** 1909–18

Kundu S, Khare D and Mondal A 2017 Interrelationship of rainfall, temperature and reference evapotranspiration trends and their net response to the climate change in Central India *Theor. Appl. Climatol.* **130** 879–900

Lambert S J 1995 The effect of enhanced greenhouse warming on winter cyclone frequencies and strengths *J. Clim.* **8** 1447–52

Luo Y, Zongci Z, Xu Y, Xuejie G and Yihui D 2005 Projections of climate change over China for the 21st century *Acta Meteorol. Sin.* **19** 401

McSweeney C F and Jones R G 2016 How representative is the spread of climate projections from the 5 CMIP5 GCMs used in ISI-MIP? *Climate Services* **1** 24–9

Meehl G A and Tebaldi C 2004 More intense, more frequent, and longer lasting heat waves in the 21st century *Science* **305** 994–7

Menon A, Levermann A, Schewe J, Lehmann J and Frieler K 2013 Consistent increase in Indian monsoon rainfall and its variability across CMIP-5 models *Earth System Dynamics* **4** 287–300

Mondal A, Khare D and Kundu S 2015 Spatial and temporal analysis of rainfall and temperature trend of India *Theor. Appl. Climatol.* **122** 143–58

O'Neill B C, Kriegler E, Riahi K, Ebi K L, Hallegatte S, Carter T R, Mathur R and van Vuuren D P 2014 A new scenario framework for climate change research: the concept of shared socioeconomic pathways *Clim. Change* **122** 387–400

Panday P K, Thibeault J and Frey K E 2015 Changing temperature and precipitation extremes in the Hindu Kush-Himalayan region: an analysis of CMIP3 and CMIP5 simulations and projections *Int. J. Climatol.* **35** 3058–77

Pinto I, Lennard C, Tadross M, Hewitson B, Dosio A, Nikulin G and Shongwe M E 2016 Evaluation and projections of extreme precipitation over southern Africa from two CORDEX models *Clim. Change* **135** 655–68

Rajeevan M, Unnikrishnan C K, Bhate J, Niranjan K K and Sreekala P P 2012 Northeast monsoon over India: variability and prediction *Meteorol. Appl.* **19** 226–36

Riahi K, Rao S, Krey V, Cho C, Chirkov V, Fischer G, Kindermann G, Nakicenovic N and Rafaj P 2011 RCP 8.5—A scenario of comparatively high greenhouse gas emissions *Clim. Change* **109** 33

Rogelj J, Meinshausen M and Knutti R 2012 Global warming under old and new scenarios using IPCC climate sensitivity range estimates *Nat. Clim. Change* **2** 248–53

Schleussner C F, Lissner T K, Fischer E M, Wohland J, Perrette M, Golly A and Mengel M 2015 Differential climate impacts for policy-relevant limits to global warming: the case of 1.5 °C and 2 °C *Earth System Dynamics Discussions* **6**

Seneviratne S I, Donat M G, Pitman A J, Knutti R and Wilby R L 2016 Allowable CO_2 emissions based on regional and impact-related climate targets *Nature* **529** 477–83

Sengupta A and Rajeevan M 2013 Uncertainty quantification and reliability analysis of CMIP5 projections for the Indian summer monsoon *Curr. Sci.* 1692–703

Shafiq M, Ramzan S, Mahmood R and Dimri A P 2019 Assessment of present and future climate change over Kashmir Himalayas, India *Theoretical and Applied Climatology* **137** 3183–95

Sharma A N and Pingali P 2018 Looking beyond rice and wheat: climate change impacts on food systems and food security in India *World Food Policy* **4** 153–74

Sharmila S, Joseph S, Sahai A K, Abhilash S and Chattopadhyay R 2015 Future projection of Indian summer monsoon variability under climate change scenario: an assessment from CMIP5 climate models *Global Planet. Change* **124** 62–78

Sillmann J, Kharin V V, Zhang X, Zwiers F W and Bronaugh D 2013 Climate extremes indices in the CMIP5 multimodel ensemble: I. Model evaluation in the present climate *J. Geophys. Res. Atmos.* **118** 1716–33

Stoffel M, Tiranti D and Huggel C 2014 Climate change impacts on mass movements—case studies from the European Alps *Sci. Total Environ.* **493** 1255–66

Sukumar R, Sharma J K, Chaturvedi R K and Ravindranath N H 2016 the impacts of climate change on Biodiversity and Ecosystems in India *Tropical Conservation: Perspectives on Local and Global Priorities* 89

Trenberth K E, Dai A, Van Der Schrier G, Jones P D, Barichivich J, Briffa K R and Sheffield J 2014 Global warming and changes in drought *Nat. Clim. Change* **4** 17–22

Yaduvanshi A and Ranade A 2017 Long-term rainfall variability in the eastern gangetic plain in relation to global temperature change *Atmos. Ocean* **55** 94–109

Yaduvanshi A, Sharma R K, Kar S C and Sinha A K 2018 Rainfall–runoff simulations of extreme monsoon rainfall events in a tropical river basin of India *Nat. Hazards* **90** 843–61