# Climate Change in Madhya Pradesh: Indicators, Impacts and Adaptation

**Vimal Mishra**
**Reepal Shah**
**Amit Garg**

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Vimal Mishra, Reepal Shah
Indian Institute of Technology (IIT) Gandhinagar

Amit Garg
Indian Institute of Management Ahmedabad

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Vimal Mishra, Reepal Shah
Civil Engineering, Indian Institute of Technology (IIT) Gandhinagar
vmishra@iitgn.ac.in, +919687944337

Amit Garg
Indian Institute of Management Ahmedabad
amitgarg@iima.ac.in, +91 79 6632 4952

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# Summary

Climate variability and climate change pose an enormous pressure on population, infrastructure, livelihood, and socio-economic conditions. Evidences of climate change are already visible on many sectors such as agriculture, water resources, infrastructure, ecology, and biodiversity. While the problem of climate change is at global scales, its detrimental impacts are often visible at local scales, which highlight the need of climate change impacts assessment and policy making at a local administrative levels. Using the observed and projected data for the future, climate change assessment was performed for the state of Madhya Pradesh. Results indicate that a majority of the state of MP experienced a significant decline in the monsoon season precipitation during the period of 1951-2013. Air temperature increased significantly in the post-monsoon (October- December) season. Results also indicated that the frequency of severe, extreme, and exceptional droughts has increased in Madhya Pradesh. Droughts in the recent years were severe and wide-spread. The number of hot days has increased significantly in the state. However, changes in hot nights, cool days, and cool nights were not found statistically significant during the period of 1951-2013. The number of heat waves became more frequent during the recent years in Madhya Pradesh. Projected changes under the future climate were estimated using the high resolution downscaled and bias corrected projections based on the five best models. The five best models were selected out of 40 CMIP5 models and 9 CORDEX South Asia models after a careful evaluation against the observed precipitation and air temperature. Results showed that for the majority of the state RCP 4.5 is the most representative while a few areas in the northern regions have experienced changes in air temperature that follow RCP 6.0 and 8.5. About 30% of the state is projected to experience more than 2°C warming by 2050 under the RCP 8.5 scenario. The monsoon season precipitation is projected to increase in most of the RCPs by 5-15% under the projected future climate. However, the monsoon season precipitation is projected to decline in the Near (2016-2045) term climate under the RCP 4.5 scenario. Extreme precipitation events are projected to become more frequent in most of the regions of the state under the projected future climate. Frequency of severe, extreme, exceptional droughts is projected to increase under the RCP 4.5 scenario. Moreover, increased warming under the projected future climate may lead to more frequent, severe, and wide-spread droughts during the monsoons season. Almost in all the RCPs, the frequency of hot days, hot nights, and heat waves is projected to increase in Madhya Pradesh. Most of the district of the state are projected to experience 1-1.2 °C increase in mean annual air temperature in Near term while 2-2.5 °C warming in the Mid (2046-2075) term climate. A significant increase in the number of hot days, hot nights, droughts, and extreme precipitation is likely under the future climate, which may pose enormous pressure on agriculture, water resources, infrastructure, tourism, and energy sectors. To effectively manage the detrimental impacts of climate change, local level policies will be required with a careful analysis of the natural resources and impacts of climate change on various sectors.

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# 1. Introduction

The impacts of climate variability and change are already visible on observed temperature and rainfall. For instance, global and regional air temperatures increased in the 20th century with the largest warming occurred during the last 30 years [*WMO*, 2005]. Moreover, the year 2014 was recorded as the warmest year in the entire record for which measurements are available. The difference between maximum and minimum temperature is narrowing, which could be detrimental for agriculture [*Easterling et al.*, 1997]. Significant changes have also been noticed in climate variables (i.e. precipitation and air temperature) across India during the period of 1950-2008 [*Mishra et al.*, 2014a, 2014b]. Declining trends in the observed precipitation during the monsoon season were noticed in *Mishra et al.* [2012], which were partially associated with the warming in the Indian Ocean [*Alory et al.*, 2007; *Brown and Funk*, 2008]. An increase in mean air temperature was reported globally [*Karl et al.*, 1996] which is consistent with the trends observed in India [*Kumar et al.*, 1994]. At the regional scale, *Mishra et al.* [2014] reported that precipitation declined while temperature increased over the majority of India in the last few decades, which caused increased frequency of droughts and reduction in soil moisture for crop growth.

Some of these trends in climate variables (e.g. precipitation and air temperature) are projected to remain same under the future climate [*Easterling et al.*, 2000; *Sheffield and Wood*, 2008; *Mishra et al.*, 2014b]. *Kumar et al.* [2011] reported that annual air temperatures are expected to increase under the projected future climate change scenarios even more than India has witnessed so far. *Rupa Kumar et al.* [2006] reported that both rainfall and air temperature are projected to increase across India under the projected future climate. Moreover, *Chaturvedi et al.* [2012] using the CMIP5 climate projections showed that there is a large uncertainty in precipitation projections, however, temperature is projected to increase 3-4ºC under the representative concentration pathways (RCP) 8.5 by the end of 21st century. *Mishra* [2015] reported that there is a large uncertainty in projections of the monsoon season precipitation under the projected future climate. Moreover, *Mishra et al.* [2014] argued that the selection of model is important to understand the projected changes in the future climate. Since the global climate models use coarser grids (150-200km), it may be appropriate to use the regional climate models at higher spatial (50km) resolution for the climate impact studies.

Decreases in rainfall and increases in air temperature could lead to persistent moisture deficit conditions that can hamper the crop production in India. Frequent droughts during the monsoon season under the current and projected future climate will pose enormous challenges for crop production in India [*Mishra et al.*, 2014]. Future climate with significant increases in temperature and heat waves, number of hot days and hot nights as well as decreases in precipitation might further enhance the likelihood of drought occurrences. The impacts of drought and climate variability and changes on agricultural production are well documented [*Lobell and Asner*, 2003; *Lobell and Field*, 2007; *Mishra and Cherkauer*, 2010; *Mishra et al.*, 2014]. Modelling studies showed that grain yield might decline by 2.5% to 16% for every increase of 1ºC in seasonal temperature in the sub-tropics and tropics [*Lobell et al.*, 2008; *Battisti and Naylor*, 2009]. Moreover, *Fischer et al.*, [2005] reported that in changing climate, the gap between crop production and consumption will increase especially in the developing countries. *Schmidhuber and Tubiello* [2007] argued that the impacts of climate change on food security could be even more than previously thought.

Food grain production in India increased significantly after the Green Revolution; however, still about 20-34% population in India is undernourished. Irrigation played a major role in food grain production especially after the Green Revolution. Our dependence on irrigation has substantially increased regardless of the monsoon rainfall variability mainly because of multi-cropping agricultural systems. Climate change can put severe pressure on water resources and agriculture in India due to the following reasons:

- Increased climate warming will lead to more losses through evaporation and evapotranspiration, which in turn will increase irrigation frequency for multiple crops and seasons[*Barnett et al.*, 2005; *Schlenker et al.*, 2007];
- During the recent years, climate has become somewhat more erratic leading to frequent droughts in India [*Ramanathan et al.*, 2005; *Mishra et al.*, 2010];
- Surface water storage in ponds and reservoirs may become short-lived under climate change and enhanced hydrologic cycle [*Barnett et al.*, 2005; *Tanaka et al.*, 2006] and;
- Indian population is growing while potential area that can be used for agriculture is shrinking [*Mishra et al.*, 2010].

## 2. Study Area: State of Madhya Pradesh

State of Madhya Pradesh (MP) is located in the central India. It has the states of Uttar Pradesh to the north-east, Chhattisgarh to the south-east, Maharashtra to the south, Gujarat to the west, and Rajasthan to the northwest. Madhya Pradesh has sub-tropical climate with hot-dry summer (April-June) followed by the monsoon (June-September) season. Winter in Madhya Pradesh is cool and dry. Average annual rainfall in Madhya Pradesh is about 1300 mm, which is more in the eastern part than the western part due to the movement of moisture from east to west. There is a high spatial variability in rainfall in MP. For instance, districts located in the south-west receives more rain (~2100 mm), while districts located in north-west regions receive only about 1000 mm. About 31% of the MP is covered with forests, which is about 12% of the total forest cover in India. Agriculture is one of the most important sectors in MP. About 75% of the total population is living in rural areas which is directly or indirectly engaged in agriculture related activities. Therefore, agriculture plays an important role in economy and socio-economic conditions of MP. The net sown area of MP is about 15,000 hectares, while the gross cropped area is 20,000 ha. About 5000 ha area is under double crops and about 5500 ha is irrigated. The major crops grown in MP are following: rice, wheat, Jwar, gram, soybean, sugarcane, and cotton. In MP sugarcane is grown in the largest area of about 4200 ha followed by Soybean, Wheat, and Jwar. Total population of MP is about 7.5 crore with population density of 236/km$^2$. About 21% of the total population of India resides in MP. There are many district of MP that have more than 50% of population as schedule tribes. Climate change and climate variability can pose tremendous threats to the population that is more vulnerable. Therefore, a climate change impacts assessment for the state level is desired to understand the potential implications under the projected future climate. Moreover, the problem of climate change and its interaction with human and earth systems is complex and it is vital to understand the linkages between climate change processes, impacts and vulnerability, and adaptation (Figure 1).

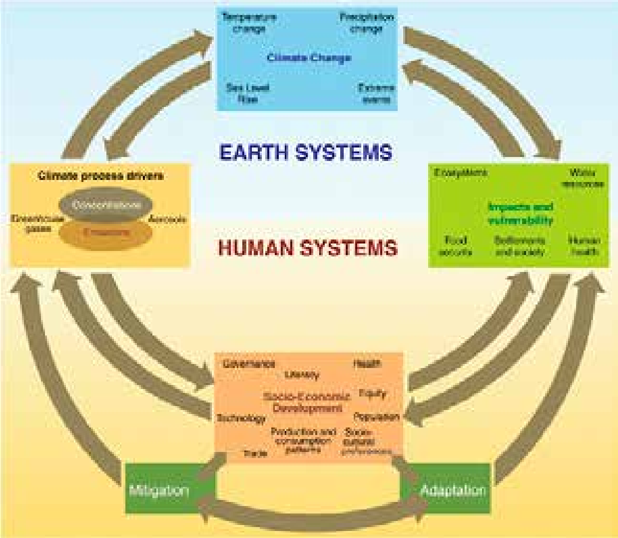


**Figure 1:** The complexity of climate change: drivers, impacts, adaptation, and mitigation (Image source: IPCC 2007).

### 2.1 Science Questions and Objectives

**The following science questions and objectives are aimed to address:**

1) *To what extent changes in mean and extreme climate occurred in the State of Madhya Pradesh during the period of 1951-2013?*

2) *What do climate change projections under the different Representative Concentration Pathways (RCPs) suggest for the State of Madhya Pradesh?*

**Objectives:**

1) To evaluate changes in the observed climate in the state of Madhya Pradesh for the period of 1951-2013

2) To develop bias corrected and downscaled climate projections for the state of Madhya Pradesh using the CMIP5 model output at 0.25 degree spatial and daily temporal resolution

3) To understand changes in mean and extreme climate variables using the high resolution climate change projections for the two periods: 2016-2045 and 2046- 2075

## 3. Data and Methods:

### 3.1 Observed Data:

Observed data for daily precipitation (rainfall) was obtained from the India Meteorological Department (IMD, *Pai et al.* [2014]) for the period of 1951-2013. The gridded daily precipitation data obtained from IMD were developed using 6995 stations [*Pai et al.*, 2014]. In the newly gridded precipitation product climatological features are well represented, which include orographic precipitation in the Western Ghats and Northeastern India. Further details on data can be obtained from *Pai et al.* [2014]. We obtained 1 degree gridded daily maximum and minimum temperatures data for the period of 1951-2013 from IMD. The dataset was developed by *Srivastava et al.* [2009]and are based on 395 observational stations across India. Daily maximum and minimum temperature were regridded to 0.25 degree (which is consistent to the resolution of precipitation) using lapse rate and Digital Elevation Model (DEM) as described by *Maurer et al.* [2002]. Using precipitation and temperature data, we developed daily meteorological dataset (precipitation, maximum and minimum temperatures) at 0.25 degree spatial and daily temporal resolutions for the period of 1951-2013.

### 3.2 Future Climate Projections:

#### 3.2.1 Model Selection

We developed high resolution climate change projections using the data from the CMIP5 models. The best performing models based on the representation of the Indian monsoon as well as air temperature were selected out of the 40 CMIP5 models that were evaluated. We used monthly data for the monsoon (June to September) season precipitation and air temperature from the 40 CMIP5 models (Table 1). Moreover, we obtained data from the CORDEX south Asia regional climate models (RCMs) for precipitation and air temperature (Table 2). Data from all the models (CMIP5 and CORDEX) were evaluated for the monsoon season precipitation and air temperature against the observed data from the IMD for the period of 1951-2005. We evaluated the performance of the models for the monsoon season using the bias, temporal and spatial correlations, and coefficient of variation in the model output and the observed data. We selected the five best models (Table 3) based on the selected performance measures. We noticed that none of the CORDEX south Asia regional climate models fell in the selected five best models, which indicate that the CORDEX models need further improvements before these can be used for the regional climate change impact assessment. These findings are consistent with the results reported in *Mishra et al.* [2014a].

**Box 1**

- CMIP5 models provide a valuable data resources for climate change impacts assessment
- The models need to be properly evaluated against the observed data for the study domain
- The best performing models can be selected for the statistical or dynamical downscaling
- Regional Climate projections such as CORDEX South Asia based on dynamical downscaling can be developed at higher resolution
- Ensemble based on the best performing models can be used for the impact assessment

**Table 1:** List of the CMIP5 models that were evaluated for the monsoon season precipitation and air temperature

| | | | |
|---|---|---|---|
| IPSL-CM5B-LR | IPSL-CM5A-LR | CanESM2 | CESM1-CAM5 |
| MRI-CGCM3 | FGOALS-g2 | MPI-ESM-LR | NorESM1-M |
| MRI-ESM1 | IPSL-CM5A-MR | MPI-ESM-MR | NorESM1-ME |
| GISS-E2-R-CC | bcc-csm1-1-m | ACCESS1-0 | CESM1-CAM5-1-FV2 |
| GISS-E2-R | HadGEM2-CC | CNRM-CM5 | GFDL-CM3 |
| GISS-E2-H-CC | HadGEM2-ES | inmcm4 | CESM1-BGC |
| CSIRO-Mk3-6-0 | CMCC-CM | CMCC-CESM | CESM1-FASTCHEM |
| GISS-E2-H | CMCC-CMS | FIO-ESM | CCSM4 |
| ACCESS1-3 | HadGEM2-AO | GFDL-ESM2M | MIROC5 |
| bcc-csm1-1 | MPI-ESM-P | GFDL-ESM2G | CESM1-WACCM |

**Table 2:** List of the CORDEX South Asia models that were evaluated for the monsoon season precipitation and air temperature

| | |
|---|---|
| MPI-ESM-LR_CSIRO-CCAM-1391M | NorESM1-M_CSIRO-CCAM-1391M |
| ACCESS1-0_CSIRO-CCAM-1391M | IITM-RegCM4_v411_LMDzOR |
| CNRM-CM5_CSIRO-CCAM-1391M | SMHI-RCA4_v2_ICHEC-EC-EARTH |
| IITM-RegCM4_v411_GFDL-ESM2M | MPI-M-MPI-ESM-LR_MPI-CSC-REMO2009_WAS-44 |
| MPI-M-MPI-ESM-LR_MPI-CSC-REMO2009_WAS-44i | |

**Table 3:** List of the five best CMIP5 models that were selected for the downscaling and bias correction

| |
|---|
| CCSM4 |
| GFDL-ESM2M |
| MIROC5 |
| NorESM1-M |
| NorESM1-ME |

**Box 2**

- The five best models that performed well for the monsoon season precipitation and air temperature were CCSM4, GFDL-ESM2M, MIROC5, NorESM1-M, and NorESM1-ME
- The selected CMIP5 models showed less than 1°C bias in temperature and less than 100mm bias in mean monsoon season precipitation.

### 3.2.2 Bias Correction and Statistical Downscaling

The bias correction and statistical downscaling was performed using the data from the best 5 CMIP5 models at 0.25 degree spatial and daily temporal resolutions. We selected 1950-2099 as the time period of bias correction and statistical downscaling. Bias corrected and spatially disaggregated (BCSD) data were used to evaluate changes under the projected future climate.

The BCSD approach was originally developed by *Wood et al.* [2002, 2004]. The modified BCSD approach [*Thrasher et al.*, 2013] was used to develop daily meteorological forcings using the daily precipitation, maximum and minimum temperatures and diurnal temperature range (DTR) outputs from the five best General Circulation Models (GCMs) for the period of 1950-2099.  Daily outputs of precipitation and air temperature were obtained from the five best GCMs (Table 1) that participated in the *Coupled Model Intercomparison Project Phase 5* (CMIP5). Daily data from the GCMs were obtained from ensemble member r1i1p1 (see *Taylor et al.* [2012] for details) for representative concentration pathways  2.6,4.5, 6.0, and 8.5 (RCP 2.6, 4.5, 6.0, and 8.5), which assumes an increase of  2.5, 4.5, 6.0, and 8.5 Watt/m$^2$ in radiative forcing by the end of 21st century [*Taylor et al.*, 2012]. The RCP 8.5 is the most pessimistic scenario while the RCP 2.6 is the most optimistic scenario. The RCP scenarios were developed based on the assumptions on the development, economy, and the mitigation effort [*Taylor et al.*, 2012]. For the climate change impact assessment, it is recommended to evaluate all the RCPs so that uncertainty associated with the scenarios can be well understood for the policy making. Because of uncertainty in the climate model projections that could vary regionally, data from the five best GCMs were used for the downscaling and bias correction. The modified BCSD approach [*Thrasher et al.*, 2013] is different from the original BCSD method [*Wood et al.*, 2002, 2004] as this uses daily projections of precipitation and maximum and minimum temperatures rather than monthly precipitation and average temperature. As the modified BCSD approach uses daily dataset, it essentially avoids daily data disaggregation from bias corrected monthly data using daily time series from a monthly historic climatology as used in the original BCSD approach. The BCSD approach has been widely used for the hydrologic impact assessments [*Hayhoe et al.*, 2004; *Cayan et al.*, 2008; *Mishra et al.*, 2010]. Moreover, the BCSD approach has been successfully compared to various statistical and dynamical downscaling techniques for both mean and extremes [*Wood et al.*, 2004; *Maurer and Hidalgo*, 2008; *Bürger et al.*, 2012]. Bias-corrected and spatially disaggregated daily dataset were developed for the best five GCMs at 0.25 degree spatial resolution and daily temporal resolution. Consistent with the historic climatology, gridded future climate projections included daily precipitation and maximum and minimum temperatures were developed for the period of 1950 to 2099. The observed climatological data for the bias correction and statistical downscaling were obtained from the IMD. *Mishra et al.* [2014b]used bias corrected and statistical downscaled data for the climate change impact assessment on soil moisture drought in India.

### 3.3 Analysis Approach

A range of indicators were selected to evaluate changes in the observed and projected future climate in the state of MP. For instance, the analysis was conducted to understand changes in monsoon (June to September), post-monsoon (October-December), winter (January-February), and pre-monsoon (March-May) periods for the observed record (1951-2013). However, for the projected future climate the analysis was done only for the monsoon season for precipitation and annual period for temperature to minimize uncertainty that could arise due to magnitude of precipitation and changes in seasons under the projected future climate. Similarly, changes in the mean air temperature for the monsoon, post-monsoon, winter, and pre-monsoon periods were estimated in the observed period (1951-2013). Apart from the changes in mean climate, changes in the extremes under the observed and projected future climate were estimated for the period of 1951-2013. Changes in the mean annual number of hot days and hot nights were estimated using the 95th percentile of maximum and minimum temperatures, respectively [*Mishra et al.*, 2015]. The number of heat waves was estimated using the daily maximum temperature and the 95th percentile threshold for the three warmest months in the year. More information about the extreme indices can be obtained from *Mishra et al.* [2015]. Moreover, changes in annual maximum precipitation and meteorological droughts for the monsoon season were estimated. For the drought assessment in the state of MP, standardized precipitation index (SPI, *McKee et al.* [1993]) was used and a 4-month SPI at the end of September was considered to estimate changes and variability in the droughts during the monsoon season.

Moreover, we also considered Standardized Precipitation Evapotranspiration Index (SPEI) to evaluate extreme droughts and wet periods under the projected future climate. Similar to SPI, 4-month SPEI at the end of September was considered for the drought evaluations. For drought assessment, frequency of severe, extreme and exceptional droughts was estimated. Changes in the observed climate were estimated using the non-parametric Mann-Kendall analysis. To estimate changes for the period 1951-2013, trend slope was multiplied with the period of record as described in *Mishra* [2015]. Statistical significance in the trend analysis was estimated at 5% significance level. Since hydroclimatic variables often show persistence, the effect of serial and spatial autocorrelations was removed using the method described in *Yue and Wang* [2002]. The Mann-Kendall method has been widely used for trend detection in hydroclimatic variables at regional and global scales [*Mishra and Lettenmaier*, 2011; *Mishra et al.*, 2015].

Changes in the mean and extreme climate indices under the projected future climate were estimated using the downscaled and bias corrected dataset, which was obtained for the five best GCMs from the CMIP5 models. Changes in the projected future climate in the selected indices were estimated for the two periods of 30 years each: 2016-2045 (Near), and 2046-2075 (Mid) term climate with respect to the reference period of 1971-2000. Changes were estimated for all the four RCPs (2.6, 4.5, 6.0, and 8.5) for the monsoon season and annual period. Moreover, changes in the selected variables were also estimated for each district using all the 0.25 degree grid-cells within the district boundaries.

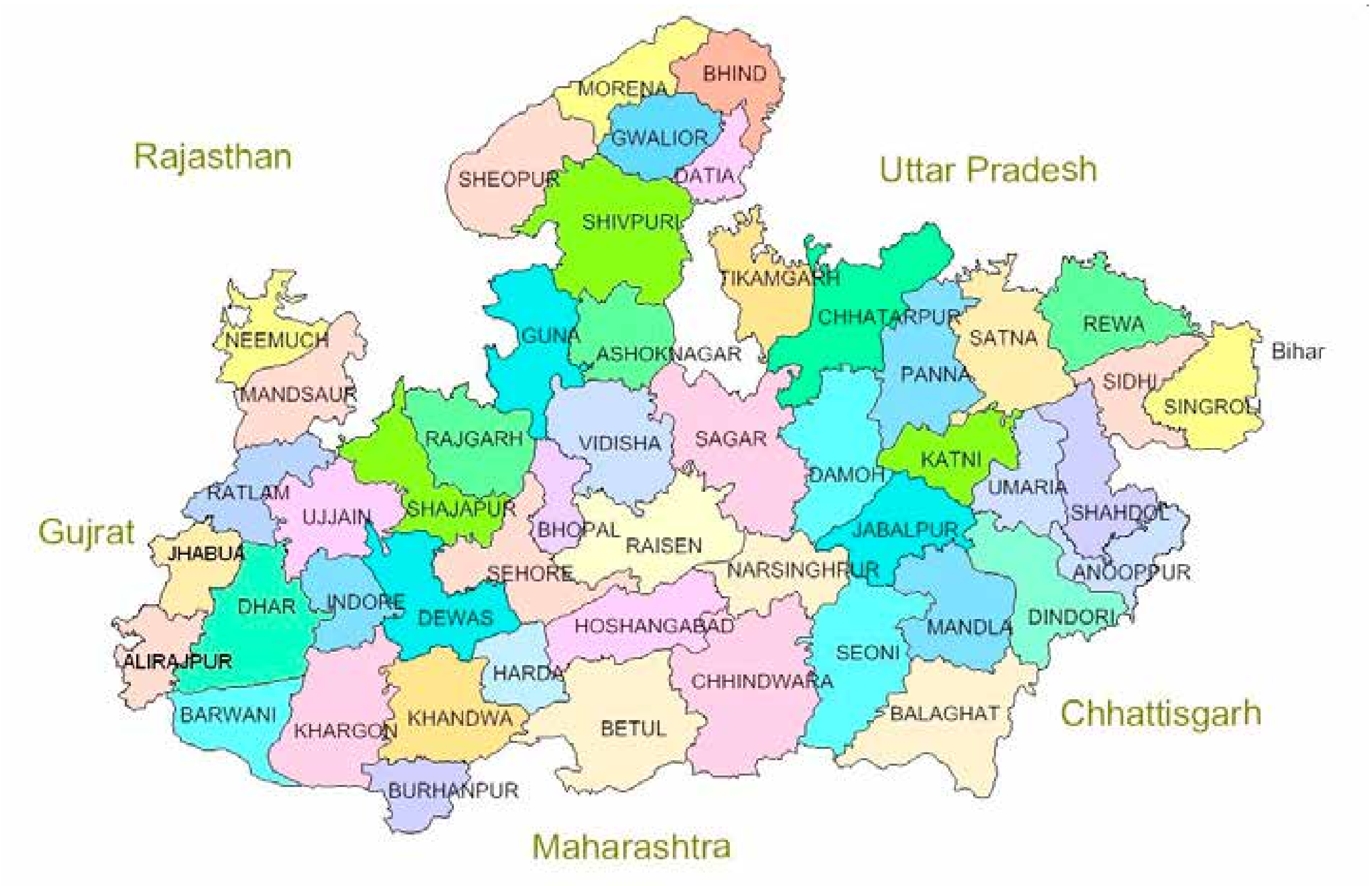


**Figure 2:** State of Madhya Pradesh and its districts (source: http://www.nchse.org)

# 4. Results

## 4.1 Changes in the Observed Period (1951-2013)

### 4.1.1 Precipitation

The precipitation data for the period of 1951-2013 was analysed for the state of MP to understand seasonal cycle and the monthly contribution in total annual precipitation (Figure 3). Results suggested that the long-term mean annual precipitation for the state was about 1043 mm. Mean monthly precipitation for the monsoon season months was 124, 315, 333, 177 mm for June, July, August, and September, respectively. Mean precipitation in the monsoon, post monsoon season, winter, and pre monsoon season was about 950, 50, 20, 18 mm, respectively (Figure 3). July and August months receive the 30 and 32% of the total rainfall while June and September receive about 12 and 17% of the total annual rainfall (Figure 2b). About 90% of the total annual rainfall occurs during the monsoon season in the state of MP.

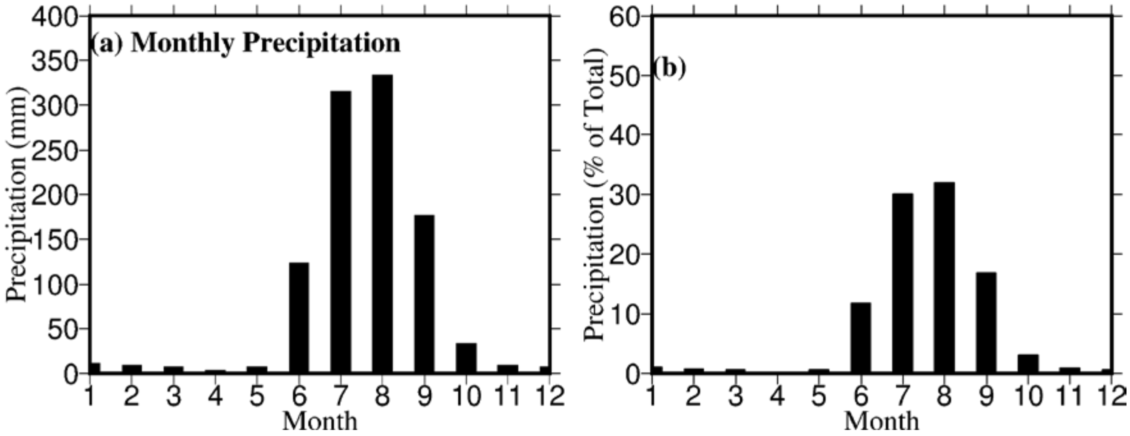


**Figure 3:** (a) Mean monthly precipitation for the period of 1951-2013, and (b) percentage of total precipitation in each month

Long term (1951-2013) data for mean precipitation for the monsoon, post monsoon, winter, and pre-monsoon seasons was analysed for the state of MP (Figure 4). It was observed that the long-term monsoon precipitation for the state of MP was stable for the period of 1951-2013 (Figure 5a). However, it can be noticed that monsoon season precipitation declined slightly during the recent decades. This decline is noticed in the previous works and mainly driven by the Indian ocean warming and the atmospheric aerosols [*Bollasina et al.*, 2011; *Mishra et al.*, 2012]. During the monsoon season, the five most deficit years occurred in 1979 (597 mm), 1965 (610 mm), 2007 (696 mm), 1966 (702 mm), and 2009 (725 mm). On the other hand, the five most surplus years during the monsoon season occurred in 1961 (1372 mm), 2013 (1307 mm), 1994 (1303 mm), 1973 (1243 mm), and 1990 (1167 mm). Precipitation during the post monsoon season in the state of MP is normally below 200 mm. It was also noticed that that precipitation in the monsoon season is relatively stable without any significant changes. Winter season precipitation normally ranges around 50-70 mm in MP (Figure 4). Winter period between 1970 and 1990 was relatively wetter; however, significant changes were not noticed during the recent period. Similar to winter precipitation, pre-monsoon season precipitation in MP is normally below 50 mm and there was no significant change was detected during the period of 1951-2013.

### Box 3

- Based on precipitation data from the Indian Meteorological Department (IMD), the long-term mean annual precipitation in Madhya Pradesh was around 1043 mm
- About 90% of the total annual rainfall in Madhya Pradesh occur during the monsoon (June to September) season
- About 62% of the total annual rainfall occurs in the months of July and August while 29% of total annual rainfall occur in June and September
- The five most deficit years during the monsoon season occurred in 1979, 1965, 2007, 1966, and 2009
- The five most monsoon season precipitation surplus years occurred in 1961, 2013, 1994, 1973, and 1990
- The lowest monsoon season rainfall occurred in 1979 (597 mm) and the highest in 1961 (1372mm) in Madhya Pradesh

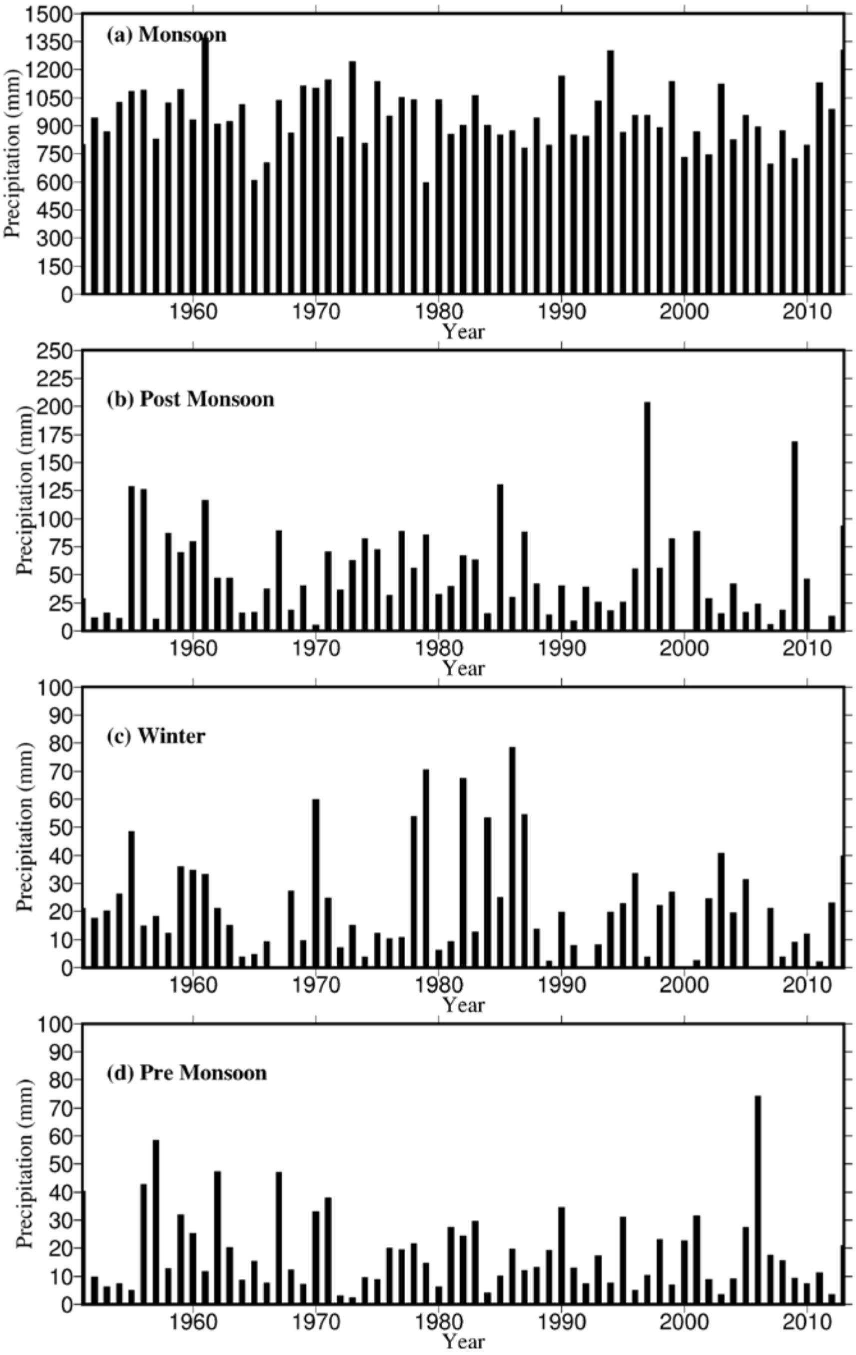
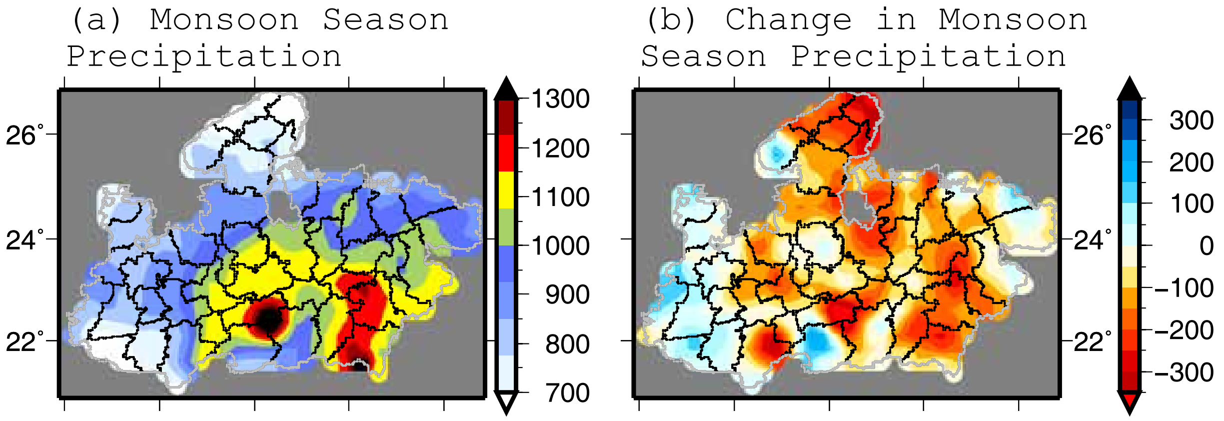


**Figure 4:** Areal averaged precipitation for the monsoon, post-monsoon, winter, and pre monsoon seasons for the state of MP for the period of 1951-2013.

Figure 5 shows mean monsoon season precipitation for the period of 1951-2013. It can be noticed that there is a large spatial variability in the monsoon season precipitation in the state of MP (Figure 5a). For instance, mean monsoon season precipitation varies between 700 to 1300 mm with higher precipitation in the southern MP and lower values in the northern MP. We estimated changes in the monsoon season precipitation using the non-parametric Mann-Kendall method for the period of 1951-2013. Results of trend analysis indicated that the monsoon season precipitation declined during the selected periods in the northern and central regions while a slight increase can be noticed in the western part of the state. The decline in precipitation in MP is associated with the large scale climate variability especially due to the warming of the Indian Ocean. Previous studies reported that warming in the Indian Ocean caused decline in precipitation in the Gangetic Plain and parts of the central India regions [*Mishra et al.*, 2012; *Roxy et al.*, 2015]. However, this decline in precipitation can also be associated with the increased black carbon aerosols as reported in *Bollasina et al.* [2011]. The number of extreme precipitation events was estimated using the 95th percentile threshold for the rainy days (precipitation more than 1 mm). For each year during the period of 1951-2013, number of events above the 95th percentile was estimated. It can be noticed that central and south-eastern regions receive on an average 3-5 extreme precipitation events each year (Figure 5). Analysis of the long-term data for the extreme precipitation events showed a mixed nature of trends in the state of MP (Figure 5). A few regions in the state have witnessed an increase in extreme precipitation events while other regions experienced declines. These results suggest that during the period of 1951-2013, the state of MP experienced decline in the monsoon season precipitation. However, mixed changes in the frequency of extreme precipitation were observed.



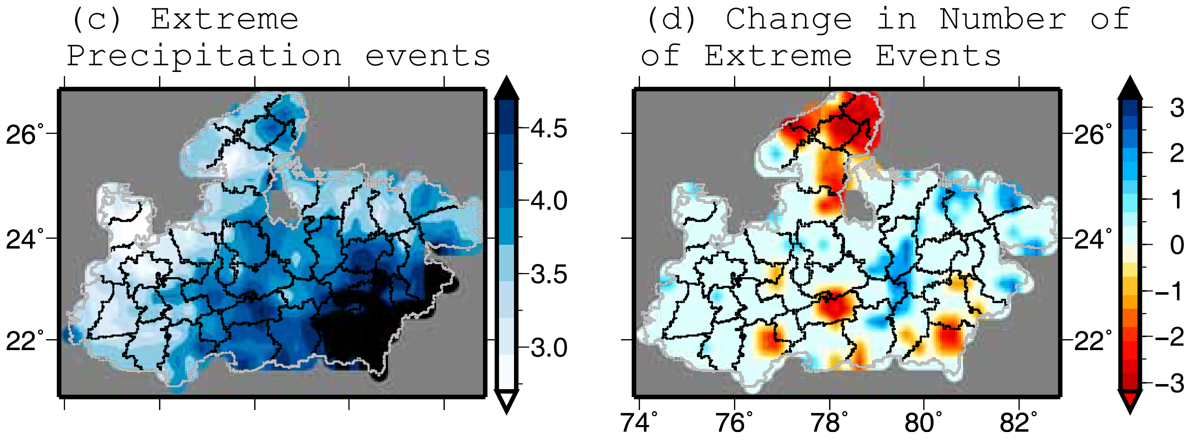


**Figure 5 :** (a) Observed mean monsoon season precipitation (b) change in observed monsoon season precipitation, (c) observed number of extreme precipitation events and (d) change in number of extreme precipitation events during the period 1951-2013.

**Box 4**

- The monsoon season precipitation declined (up to 200mm) in the majority of the state during the period of 1951-2013
- Changes in the frequency of extreme precipitation events showed increases in a few regions while declines in other regions of the state
- Changes in extreme precipitation events were not found significant in most of the regions of Madhya Pradesh

### 4.1.2 Drought and Wet Periods

Drought and wet periods in the observed climate (1951-2013) were estimated using the Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI). SPEI differs from SPI as it considers the effect of air temperature on drought by estimating evapotranspiration using the empirical methods such as Throntwaite method. Using the observed monthly precipitation and air temperature from the IMD, SPI and SPEI were estimated for the period of 1951-2013. The values below -1.3 for SPI and SPEI show droughts under severe, extreme, and exceptional category. Moderate droughts were not studied as they may have minimal impact on agriculture or water resources. On the other hand, SPI and SPEI values above 1.3 show severe, extreme, and exceptional wet spells. Four month SPI/SPEI at the end of September in each year was considered to evaluate severity, frequency, and areal extent of drought in the state. Figure 6 shows areal weighted 4-month SPI and SPEI at the end of the monsoon season for the state of MP for the period of 1951-2013. It can be noticed that both SPI and SPEI effectively captures all the drought and wet periods in the state. A few years in the observed record showed differences in SPI and SPEI highlighting the role of air temperature on droughts during the monsoon season. Considering just the monsoons season precipitation (SPI), the five most severe droughts in the state occurred in 1979, 1965, 2007, 1966, and 2009. All these droughts fell under severe, extreme, and exceptional category (Figure 6a). It was observed from the SPI data that the state experienced four severe droughts during the period of 2000-2010 highlighting that the drought frequency has increased during the recent years. Results obtained from the 4-month SPEI were similar to 4-month SPI for the period of 1951-2013. For instance, the five most severe drought considering SPEI occurred 1979, 1965, 2009, 1987, and 1966 (Figure 6b). From these results it can be inferred that air temperature might play a significant role during the monsoon season drought of 1987. The five most extreme wet monsoon seasons based on SPEI occurred in 1961, 2013, 1994, 1971, and 1973. On the other hand, based on SPI, the five most wet monsoon season in the state of MP was experienced in 1961, 2013, 1994, 1973, and 1990. Differences in the results obtained from SPI and SPEI showed that air temperature anomalies can play a significant role in drought and wet periods in the state.

Figure 7 shows areal extent (percentage area under drought) estimated using SPI and SPEI for the period of 1951-2013. Areal extents of droughts during the monsoon season were estimated using the -1.3 SPI/SPEI threshold that considers severe, extreme, and exceptional droughts in the state. It was noticed that the most wide spread droughts occurred in 1965 and 1979. However, areal extent of severe, extreme, exceptional droughts has increased during the recent decades, which is associated with the weakening monsoon season precipitation in the state of MP. The five most wide-spread droughts based on SPI occurred in 1965, 1979, 2007, 2009, and 2000 with areal extent of 65, 63, 46, 31, 30%, respectively (Figure 7a). On the other hand, the five most wide-spread droughts based on SPEI occurred in 1965, 1979, 2009, 1987, and 2007 with areal extents of 76, 72, 53, 48, 44%, respectively (Figure 7b). The difference in areal extents obtained from SPI and SPEI highlights the role of air temperature during the monsoon season drought. Higher temperatures led to increased atmospheric demands of water through evapotranspiration which in turn results in wide spread droughts in the state. These results highlighting the role of air temperature may have serious implications on droughts under the warming climate [*Mishra et al.*, 2014b].

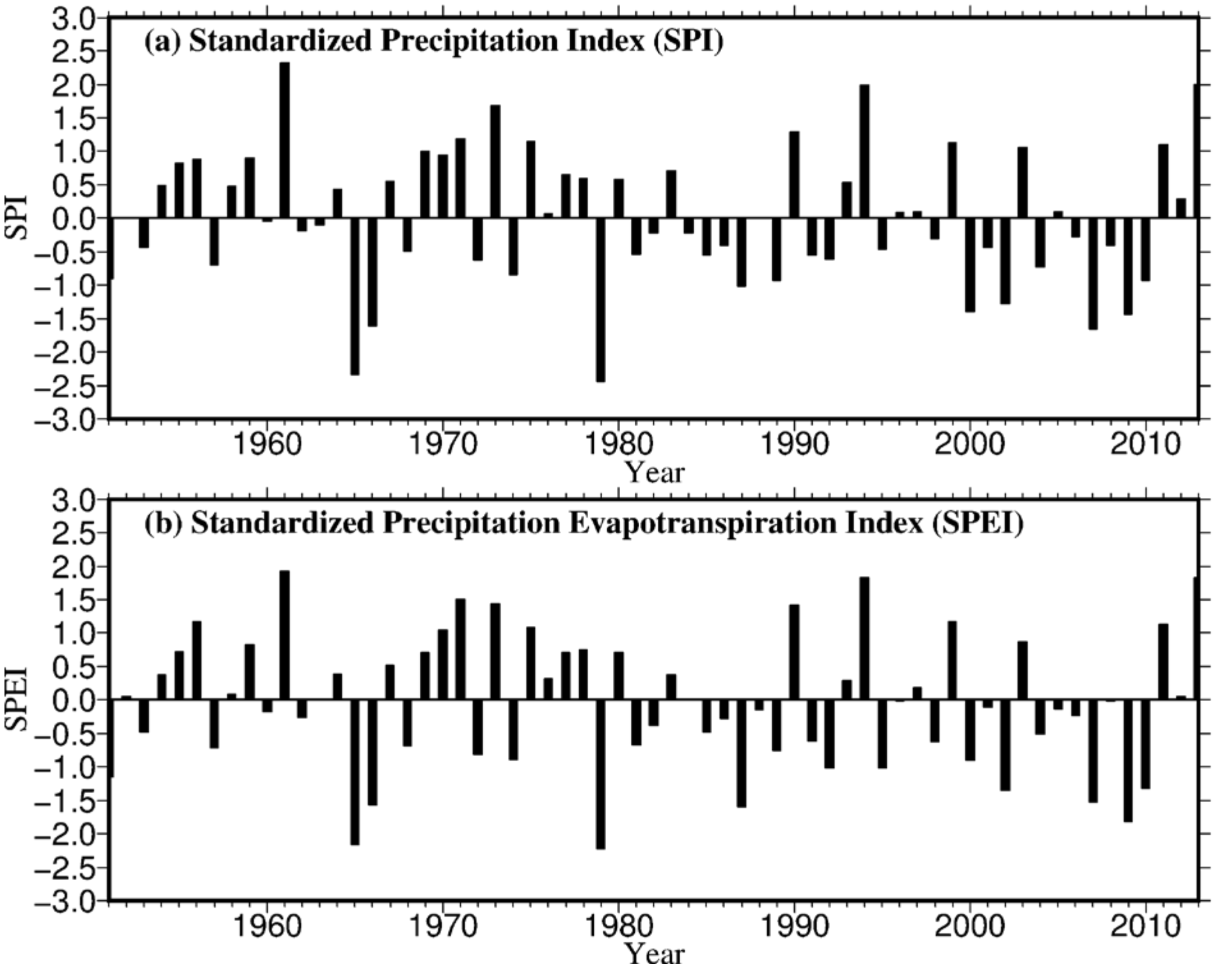


**Figure 6:** (a) Areal averaged Standardized precipitation Index (SPI) and (b) Standardized Precipitation Evapotranspiration Index (SPEI) for the period of 1951-2013.

As severity and areal extent of droughts were different estimated using SPI and SPEI, we compared spatial pattern of 1987 drought using the 4 month SPI and SPEI at the end of the monsoon season (Figure 8). It was observed that a positive temperature anomaly in the state during the 1987 increased the severity of drought in the northern, central, and southern parts of the state (Figure 8a, b).

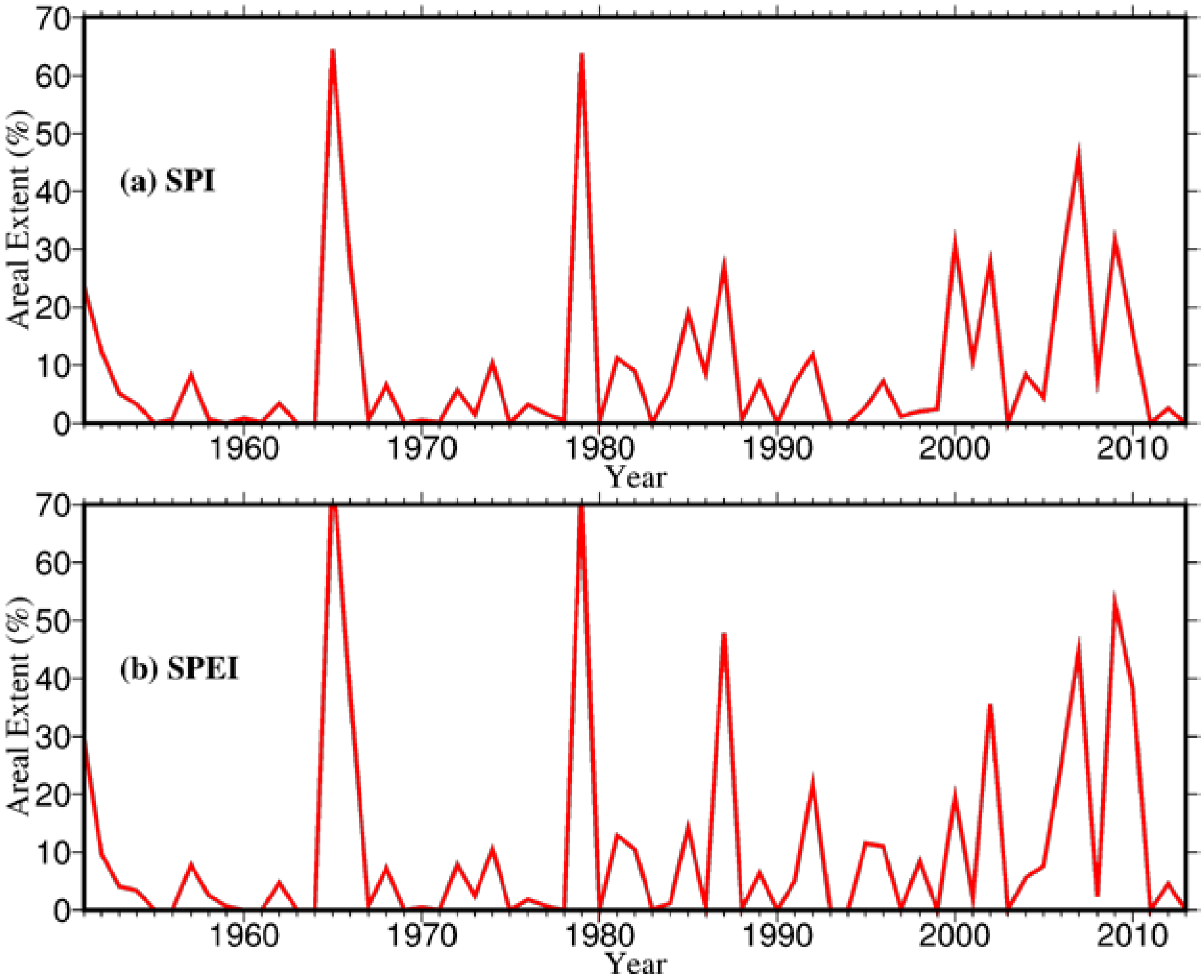


**Figure 7:** Areal extent of observed severe, extreme, and exceptional droughts in the state of Madhya Pradesh estimated using SPI (a) and SPEI (b) for the period of 1951-2013.

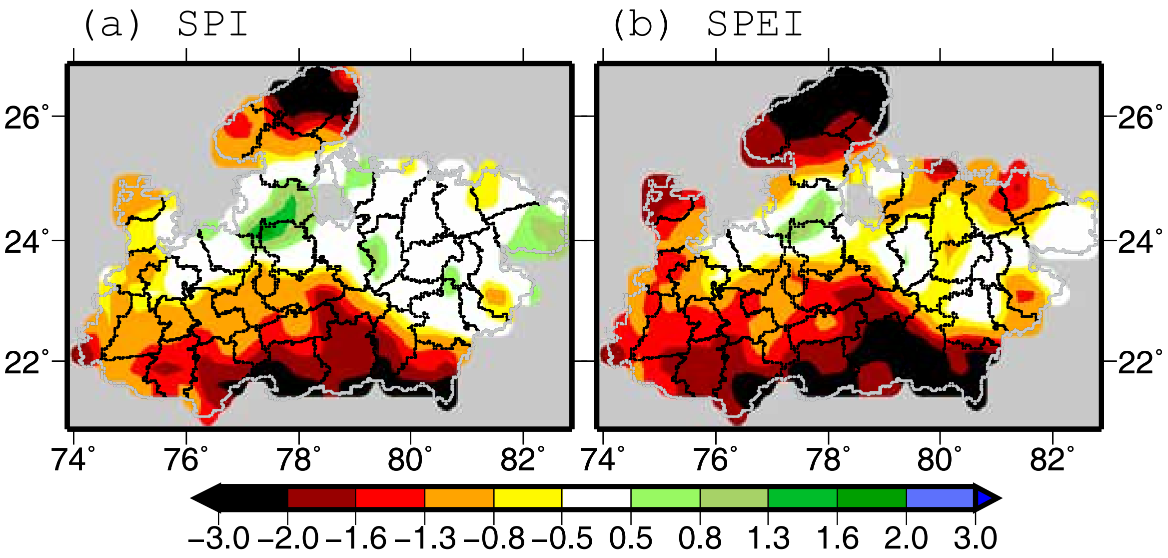


**Figure 8:** Observed drought during the monsoon season of 1987 based on (a) SPI and (b) SPEI.

**Box 5**

- The frequency of the severe, extreme, and exceptional droughts has increased during the recent decades in Madhya Pradesh
- Droughts during the monsoon season were estimated using 4-month Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI)
- The five most wide-spread droughts based on SPI occurred in 1965, 1979, 2007, 2009, and 2000 with areal extent of 65, 63, 46, 31, 30%, respectively
- The five most wide-spread droughts based on SPEI occurred in 1965, 1979, 2009, 1987, and 2007 with areal extents of 76, 72, 53, 48, 44%, respectively

### 4.1.3 Air Temperature

Mean monthly air temperature for the state of MP was estimated using the 0.25 degree daily data from the IMD for the period of 1951-2013 (Figure 9). Mean monthly air temperature in the state varied between 17.5 and 33.5°C (Figure 9a) for the period of 1951-2013. Moreover, the variation in minimum and maximum temperatures was recorded between 9.5 and 26°C and 25 and 41°C, respectively (Figure 9a). January and December are the coldest months while April and May are the hottest months in the state of MP. Long term mean minimum temperature for the monsoon, post monsoon, winter, and pre monsoon seasons was 26.5, 19.0, 16.5, and 27.5°C. On the other hand, mean maximum temperature in the state of MP based on the long-term observations was 30.3, 24.5, 22.0, and 32.0 °C for the monsoon, post monsoon, winter, and pre monsoon seasons, respectively. The seasonal mean temperature for the monsoon, post-monsoon, winter, and pre monsoon seasons was 28.5, 22, 19, and 30°C, respectively during the period of 1951-2013 (Figure 9b).

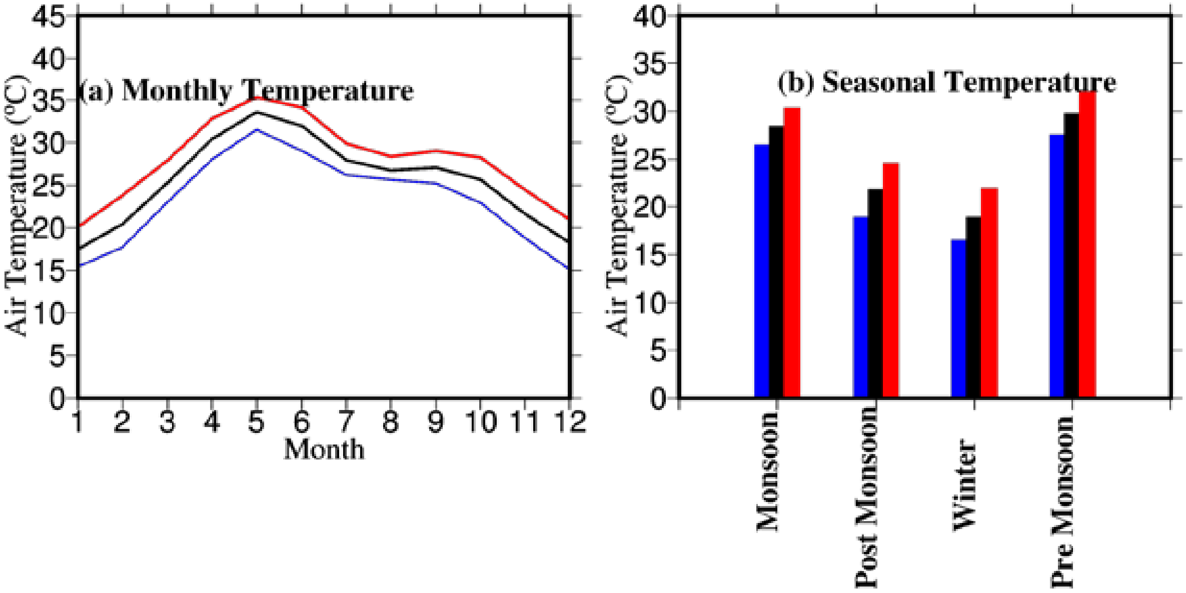


**Figure 9:** (a) State averaged mean (black), minimum (blue), and maximum (red) monthly air temperature for the period of 1951-2013, (b) state averaged mean, minimum, and maximum temperature for the monsoon, post monsoon, winter, and pre monsoon seasons.

Figure 10 shows long-term time series of the state wide air temperature during the period of 1951-2013 for the monsoon, post-monsoon, winter, and pre-monsoon seasons. State average mean air temperature during the monsoon season did not change significantly as only a moderate warming of 0.03ºC was observed during the period of 1951-2013. However, mean air temperature increased significantly (0.8ºC) during the post-monsoon season in the state of MP (Figure 10b). Moreover, a non-significant warming of 0.4ºC was observed during the pre-monsoon season in the 1951-2013 period. Results indicated that there is no significant increase in mean air temperature during the winter season in the state of MP. The five warmest years during the monsoon season were 1987, 2009, 1995, 2010, and 1979. These results highlight that deficit in the monsoon season precipitation is highly correlated with the air temperature during the monsoon season. Majority of the drought years led to above normal temperature in the monsoon season. The five warmest years in the post monsoon seasons were 1979, 1976, 2008, 2002, and 2006. On the other hand, in the winter season, the five warmest years occurred in 2006, 2009, 1952, 1966, and 1988. As the pre-monsoon season is the hottest season in the state of MP, the five warmest years were recorded in 2010, 2004, 1980, 1973, and 2002 (Figure 10). Here, it is important to note that most of the warmest years in the monsoon, post-monsoon, winter, and pre-monsoon seasons occurred during the post-1980 period.

Figure 11 shows mean annual average, maximum, and minimum temperature and changes during the period of 1951-2013. Changes in air temperature were estimated using the non-parametric Mann-Kendall method. It was noticed that there is a large spatial variability in mean, maximum, and minimum annual air temperature in the state of MP. Moreover, the south-west region has higher air temperatures than the rest of the state (Figure 11). Central belt of the state experienced a warming of about 0.5-0.8ºC during the period of 1951-2013 (Figure 11b). Moreover, districts located in the northwest region experienced substantial warming in annual mean air temperatures while regions in the north-east and south-west did not experience increases in annual mean air temperatures. Results showed that the districts located in the eastern and western regions experienced a prominent warming in mean maximum annual air temperatures (Figure 11d). On the other hand, central MP experienced warming in mean minimum annual air temperatures. The implications of the warming and spatial variability in the state of MP can profound. For instance, warming in maximum temperatures will lead to an increased frequency of the number of hot days. While warming in minimum temperatures can be associated with the decline in frequency of cool nights and increased in the frequency of hot nights as explained in *Mishra et al.* [2015]. Moreover, increased warming in maximum and minimum air temperatures can pose detrimental impacts of crop production in the state of MP.

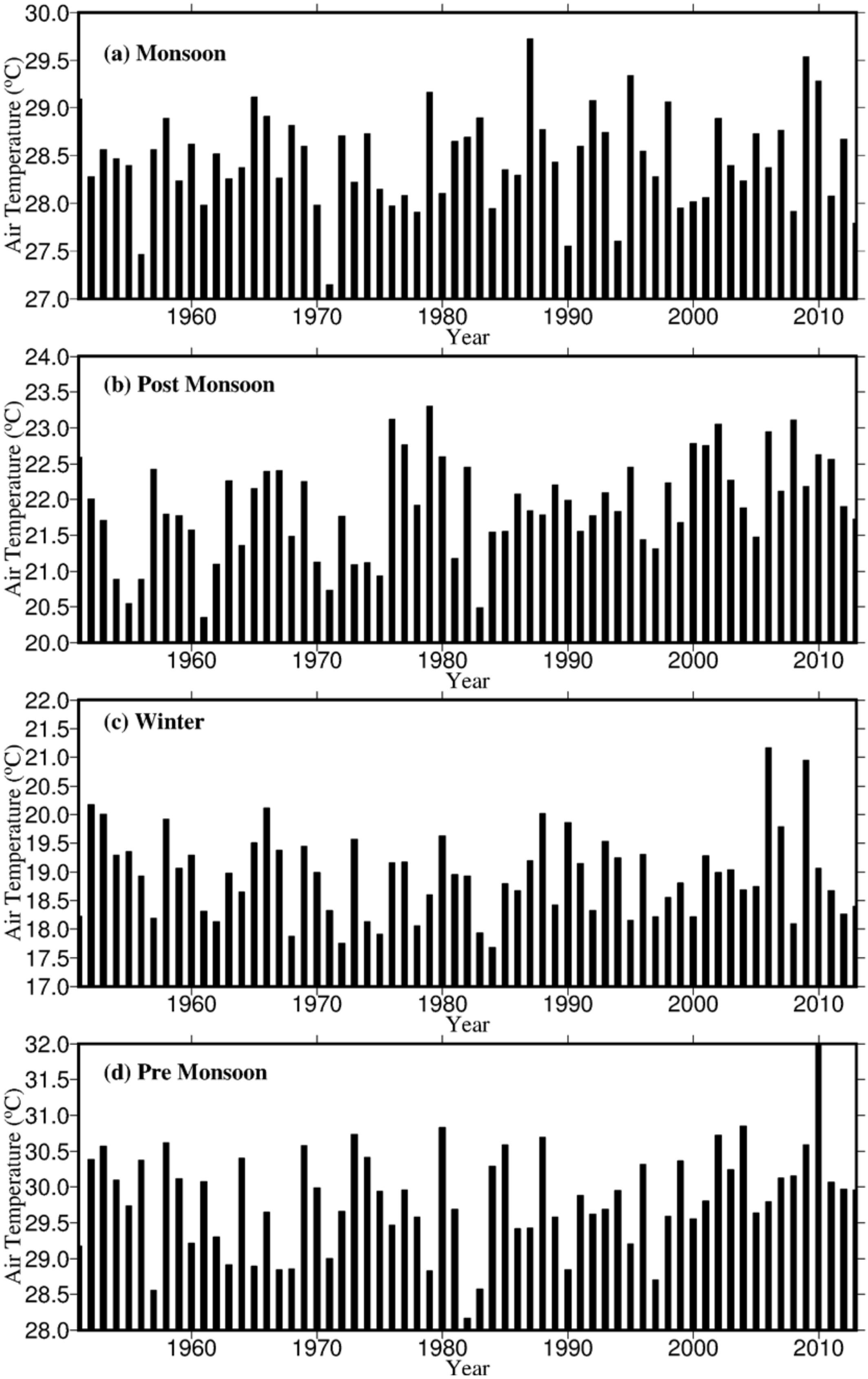


**Figure 10:** State averaged observed air temperature for the period of 1951-2013 for (a) monsoon, (b) post-monsoon, (c) winter, and (d) pre-monsoon seasons.

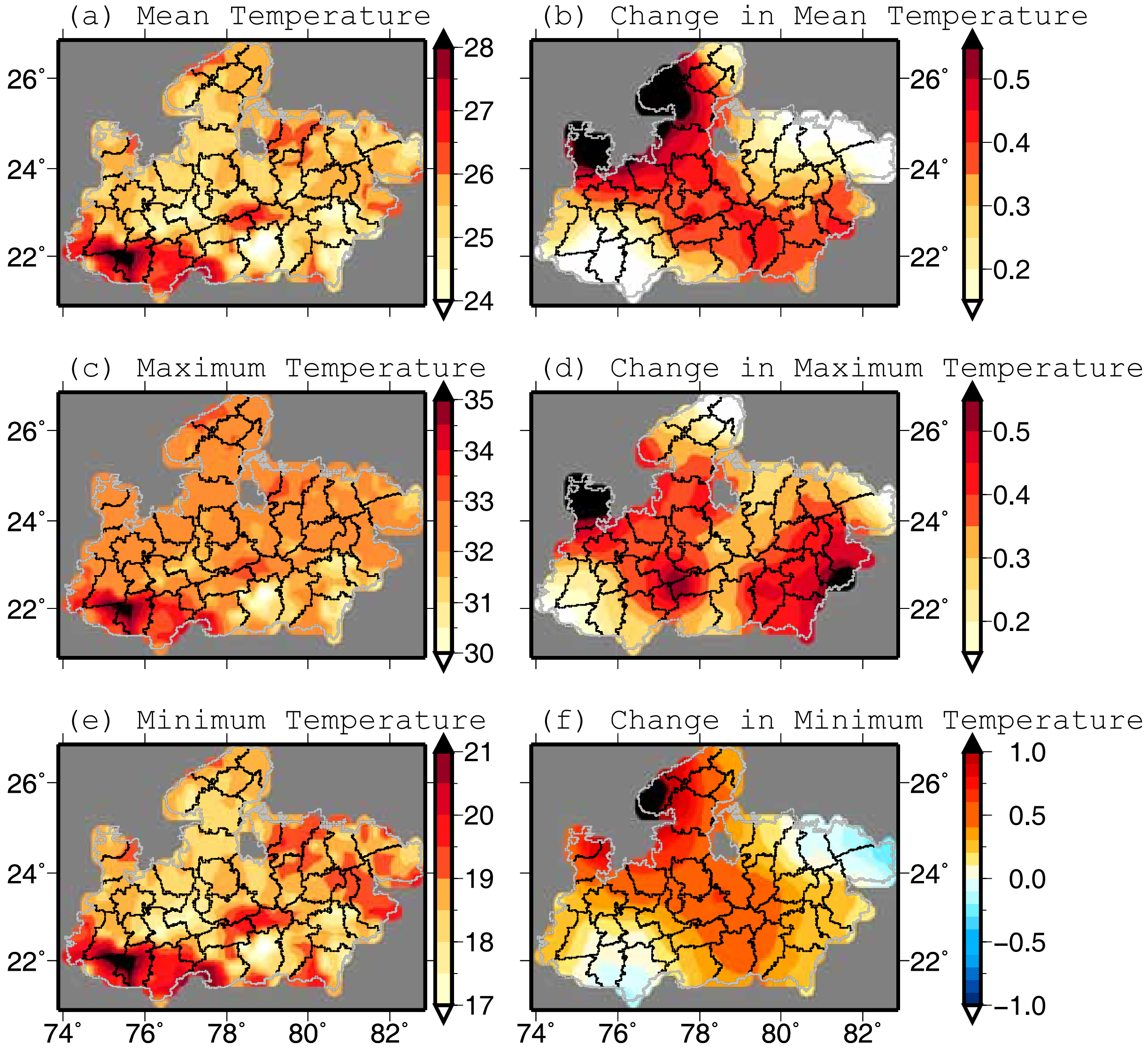


**Figure 11:** (a,c,e) Observed mean (1951-2013) annual of daily mean, maximum and minimum temperatures (b,d,f) change in mean, maximum and minimum temperature during the period.

**Box 6**

- State averaged mean air temperature during the monsoon season did not change significantly as only a moderate warming of 0.03ºC was observed during the period of 1951-2013
- Mean air temperature increased significantly (0.8ºC) during the post-monsoon season in the state of MP
- Non-significant increases in the pre-monsoon and winter seasons.

### 4.1.4 Temperature Extremes

Under the climate warming, temperature extremes have increased across the globe [*Mishra et al.*, 2015]. The observed daily temperature data from the IMD was analysed to evaluate changes in hot days, hot nights, cool days, and cool nights during the period of 1951-2013. The number of hot days and hot nights were estimated using the 95th percentile of daily maximum and minimum air temperatures for the three warmest months (April-June) in the state of MP. For each year, the number of days above the 95th percentile threshold was estimated. On the other hand, the number of cool days and cool nights was estimated using the 5th percentile threshold of daily maximum and minimum air temperatures for January and February months for the period of 1951-2013. The frequency of cool days and cool nights was estimated using the counts that have lesser temperature than the defined threshold. Since we used percentile based thresholds rather than fix thresholds as followed by the IMD, extremes were studied for six consecutive days. For more details, please refer to *Mishra et al.* [2015]. Results showed a sharp increase in the frequency of the number of hot days during the period of 1951-2013 (Figure 12a). The number of hot days has greatly increased after 1990 in the state of MP. The five years with the most number of hot days were 2010, 1993, 1988, 1973, and 1998. Results indicated no significant trends in the frequency of hot nights in the state of MP (Figure 12b). For instance, the period between 1951 and 2000 experienced more number of hot nights than the most recent period. Moreover, the five years with the most number of hot nights were 1953, 1958, 1952, 1998, and 2010. Non-significant trends were noticed in the number of cool days during the period of 1951-2013 (Figure 12c) with the five years with the most number of cool days were 1997, 1961, 1995, 1981, and 1998. A decline in the number of cool nights in the state of MP was observed till 2005; however, the number has increased during the recent period (Figure 12d).

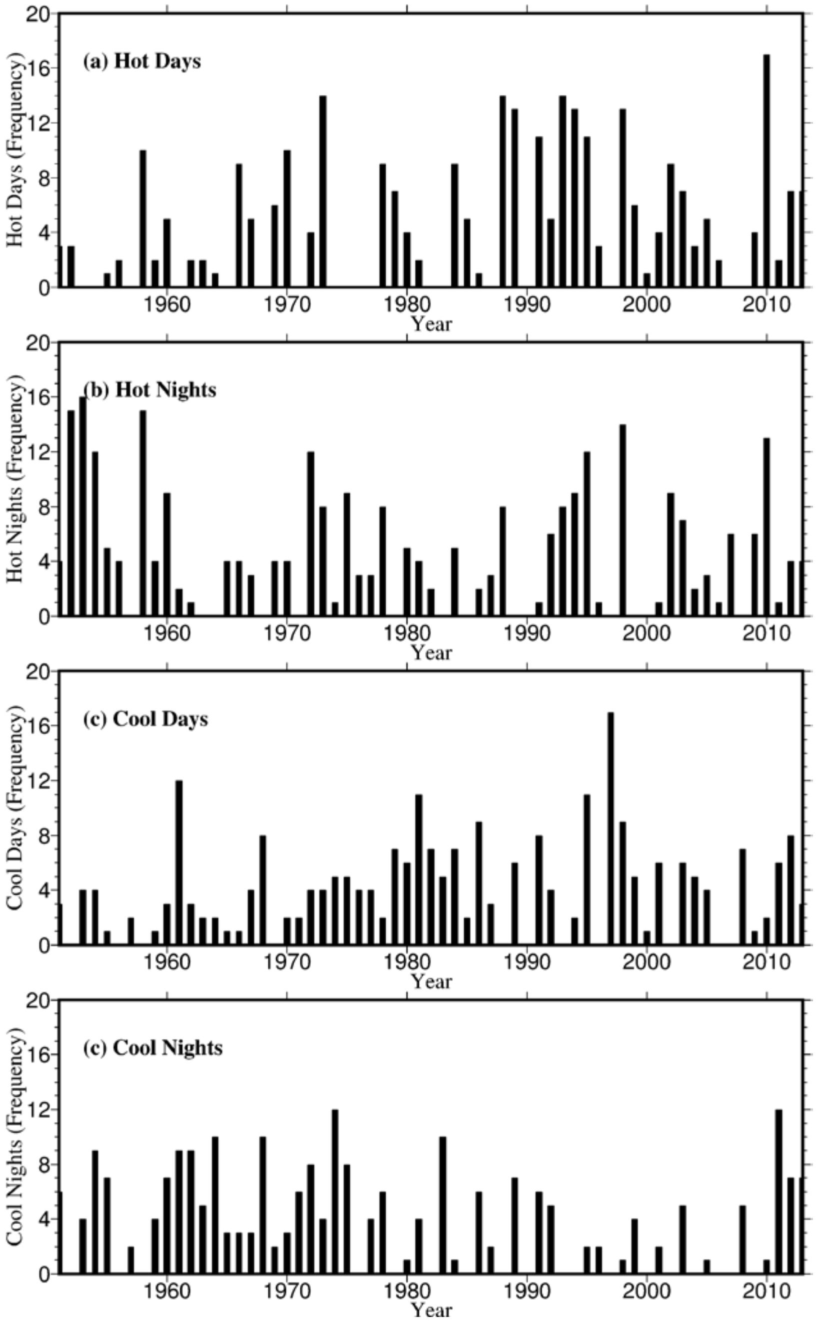


**Figure 12:** Observed frequency of hot days (a), hot nights (b), cool days (c), and cool nights (d) during the period of 1951-2013 for the state of Madhya Pradesh.

Figure 13 shows occurrence of heat waves during the period of 1951-2013. The number of heat waves was estimated for each year using the 95th percentile of daily maximum temperature for the three hottest months (April-June) in the state of MP. The number of heat waves in each year was counted if the daily temperature exceeds above the threshold in consecutive manner for more than six days. The method to estimate the number of heat waves in the observed period is similar to described in *Mishra et al.* [2015]. *Mishra et al.* [2015] estimate the number of heat waves in the global urban areas and reported that the frequency of heat waves has increased significantly during the period of 1972-2012 in the major urban areas across the globe. Results for the observed period in the state of MP showed that the frequency of heat waves has increased after the 1980 in the state of MP. Moreover, the year of 1988 experienced the most number of heat waves during the period of 1951-2013. The central India region experienced an extreme drought during the monsoon season in 1988[*Mishra et al.*, 2014b], which could be associated with the increased number of heat waves in the state.

The spatial patterns in the mean number of hot days and hot nights showed a high variability in the state (Figure 14). It can be noticed that the number of hot days has increased across the state during the period of 1951-2013. On the other hand, the number of hot nights declined mostly in the eastern part of the Madhya Pradesh (Figure 14d).

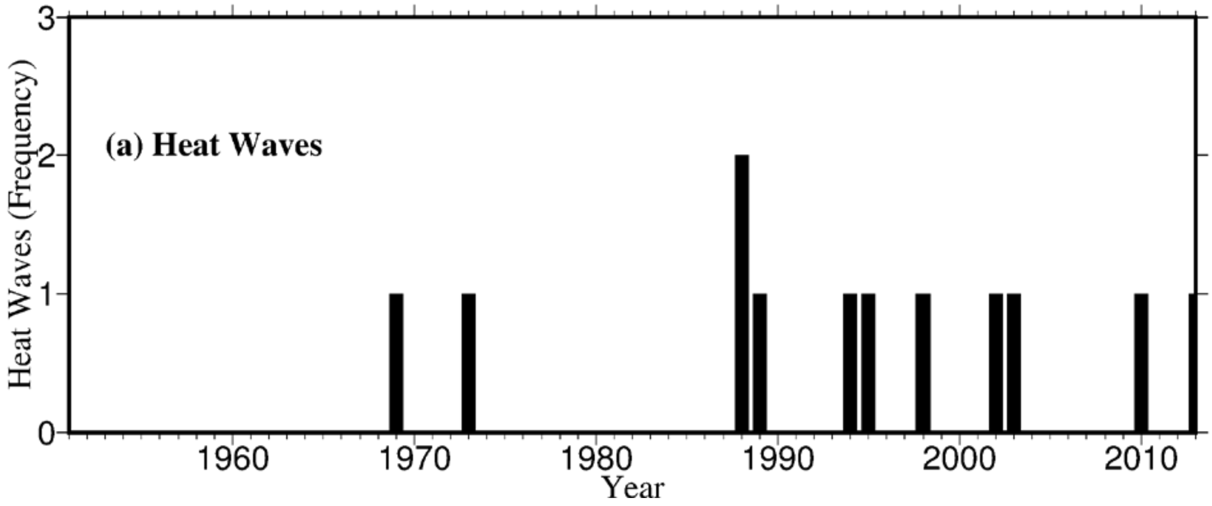


**Figure 13:** Observed frequency of heat waves during the period of 1951-2013 in the state of Madhya Pradesh

**Box 7**

- A significant increase in the number of hot days in Madhya Pradesh during the period of 1951-2013
- The five years with the highest number of hot days were 2010, 1993, 1988, 1973, and 1998
- The period between 1951 and 2000 experienced more number of hot nights than the most recent period
- The five years with the most number of hot nights were 1953, 1958, 1952, 1998, and 2010.
- A decline in the number of cool nights in the state of MP was observed till 2005, however, the number has increased during the recent period
- The frequency of heat waves has increased after the 1980 in the Madhya Pradesh

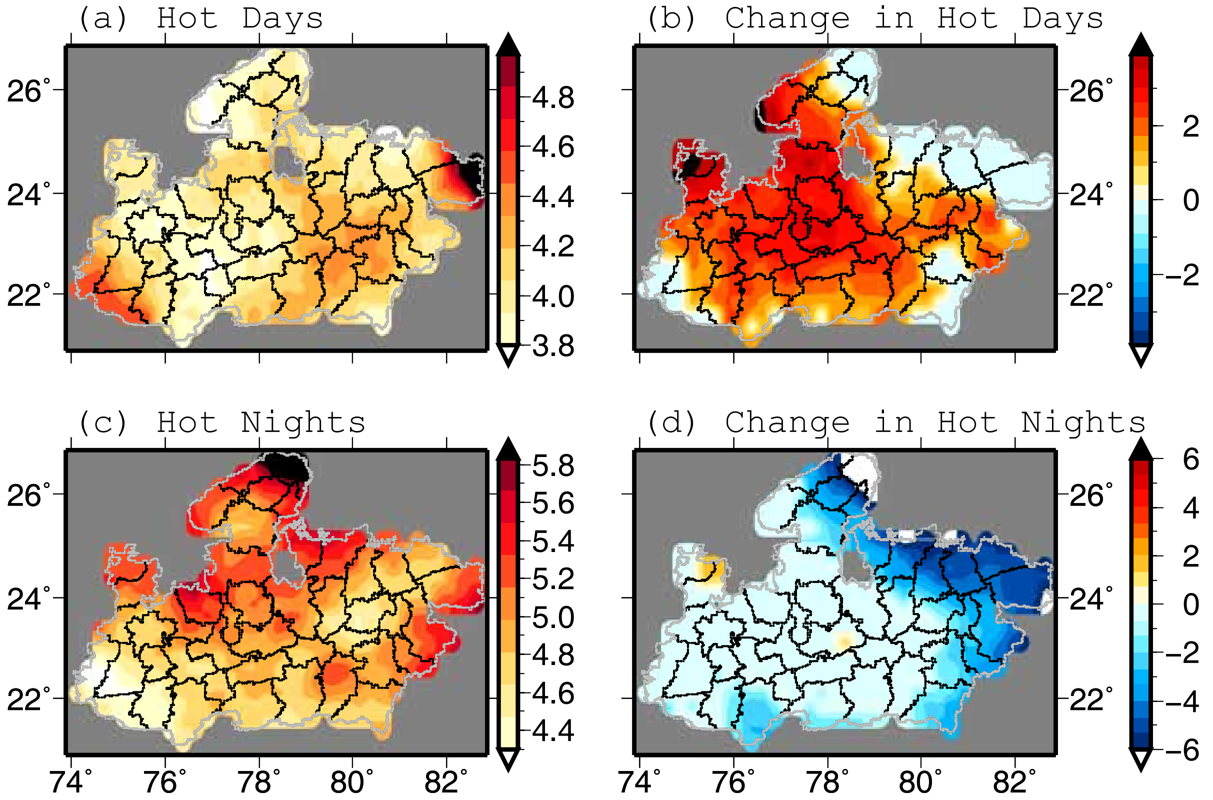


**Figure 14:** (a, c) Mean number of hot days and hot nights and (b,d) changes in the number of hot days and hot nights for the period of 1951-2013. Changes were estimated using the Mann-Kendall method. Statistical significance was tested at 5% significance level.

## 4.2 Climate Change Projections

Climate change projections for daily precipitation and air temperature were developed using the five best CMIP5 model output. The bias correction and spatial disaggregation (BCSD) method was used for statistical downscaling as described in the methods section. The downscaled and bias corrected data at 0.25 degree spatial resolution and daily temporal resolution were developed for the historic (1950-20005) and projected future (2016-2075) periods. The changes under the projected climate were estimated for each model for the Near (2016-2045) and Mid (2046-2075) century periods against the historic reference period of 1971-2000. The multimodel ensemble mean change was estimated using the change from the individual models and taking the average of that. To represent the uncertainty in the five CMIP5 models, inter model variation was estimated. Changes under the projected future climate were estimated for the four (2.6, 4.5, 6.0, and 8.5) representative concentration pathways (RCPs).

Since there is uncertainty based on the emission scenarios (RCPs 2.6, 4.5, 6.0, and 8.5), we estimated the potential RCPs that the state of MP following using the observed temperature data for the period of 2006-2013 and mean air temperature from the down scaled and bias corrected data (Figure 15). It was observed that air temperature increased between 0.4 to 0.7°C during the period of 2006-2013 (Figure 15a). These results suggest the prominent warming that the state has been experiencing during the recent period. The observed change in air temperature estimated using the IMD data was then compared with the multimodel ensemble mean change under all the selected RCPs for each 0.25 degree grid-cell. Based on the comparison between observed and ensemble mean change, the closed RCP was identified for each grid cell (Figure 15b). It can be noticed that the majority of the MP state follows the RCP 4.5. However, a few regions in the northern part of the state that experienced prominent warming are following RCP 6.0 and 8.5 (Figure 15b). Here, it is worth mentioning that RCP 8.5 is the most pessimistic emission scenario. Results also indicated that none of the regions in the state follows the RCP 2.6, which is the most optimistic scenario.

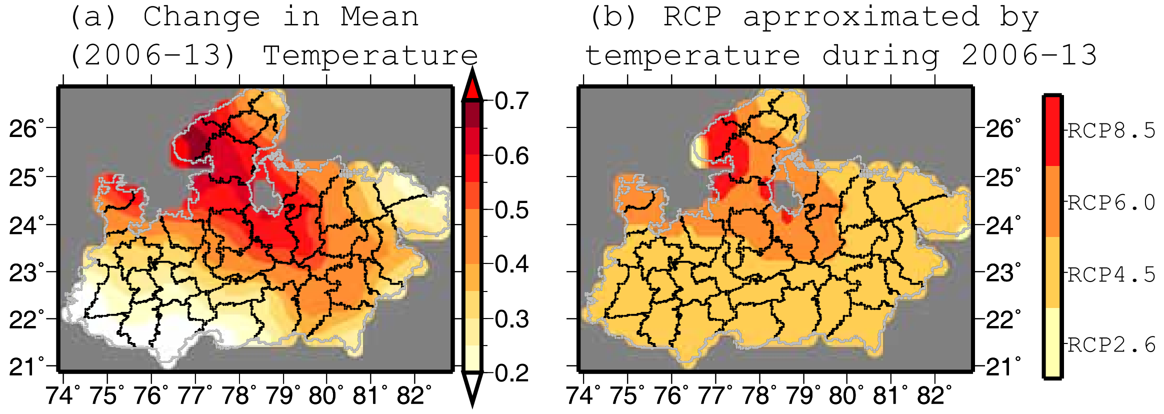


**Figure 15:** (a) Change in mean (2006-13) annual temperature as compared to historic (1951-2005) period and (b) Representative Concentration Pathway approximated during 2006-2013 based on change in mean annual temperature for each grid cell.

**Box 8**

- Multimodel climate change projections for Madhya Pradesh were developed suing bias corrected and downscaled data for the best five CMIP5 models for the period of 2016-2045 (Near) and 2046-2075 (Mid) for the Representation Concentration Pathways (RCPs) 2.6, 4.5, 6.0, and 8.5
- Multimodel ensemble mean changes and associated intermodel variations were estimated for the projected climate against the reference period of 1971-2000
- Based on changes in mean air temperature during the period of 2006-2013, the most representative RCP for Madhya Pradesh is RCP 4.5
- North-central regions of Madhya Pradesh can be represented with RCP 6.0 and 8.5
- Based on RCP 4.5, about 10% of the state is projected to witness more than 2ºC warming by 2035
- Based on RCP 8.5, about 30% of Madhya Pradesh is projected to experience more than 2ºC increase by 2050.

Using the air temperature data for the projected future climate, the percentage area in the state of MP that is projected to experience above 2ºC change between 2016 and 2099 was estimated for all the RCPs (Figure 16a). There is a large intermodel variation in the estimates of the area of MP that is projected to witness more than 2 º C rises in air temperature. However, results indicated that under the RCP4.5 scenario, which is the most representative scenario for the state, about 10 % of the state is projected to witness more than 2ºC increase in air temperature by 2035 (Figure 16a). Moreover, under the RCP 8.5 scenario, the 30% of the state is projected to experience rise in more than 2 degree air temperature. More than 2ºC increases in air temperature may have profound implications on agriculture, water resources, and many other sectors. It is therefore desirable to evaluate the impacts of 2ºC increase in air temperature on the various sectors for the state of MP. Our results of the empirical probability distribution of air temperature for the Near and Mid periods of the 21st century showed a significant increases in both mean and extreme temperature in the state under the selected RCPs.

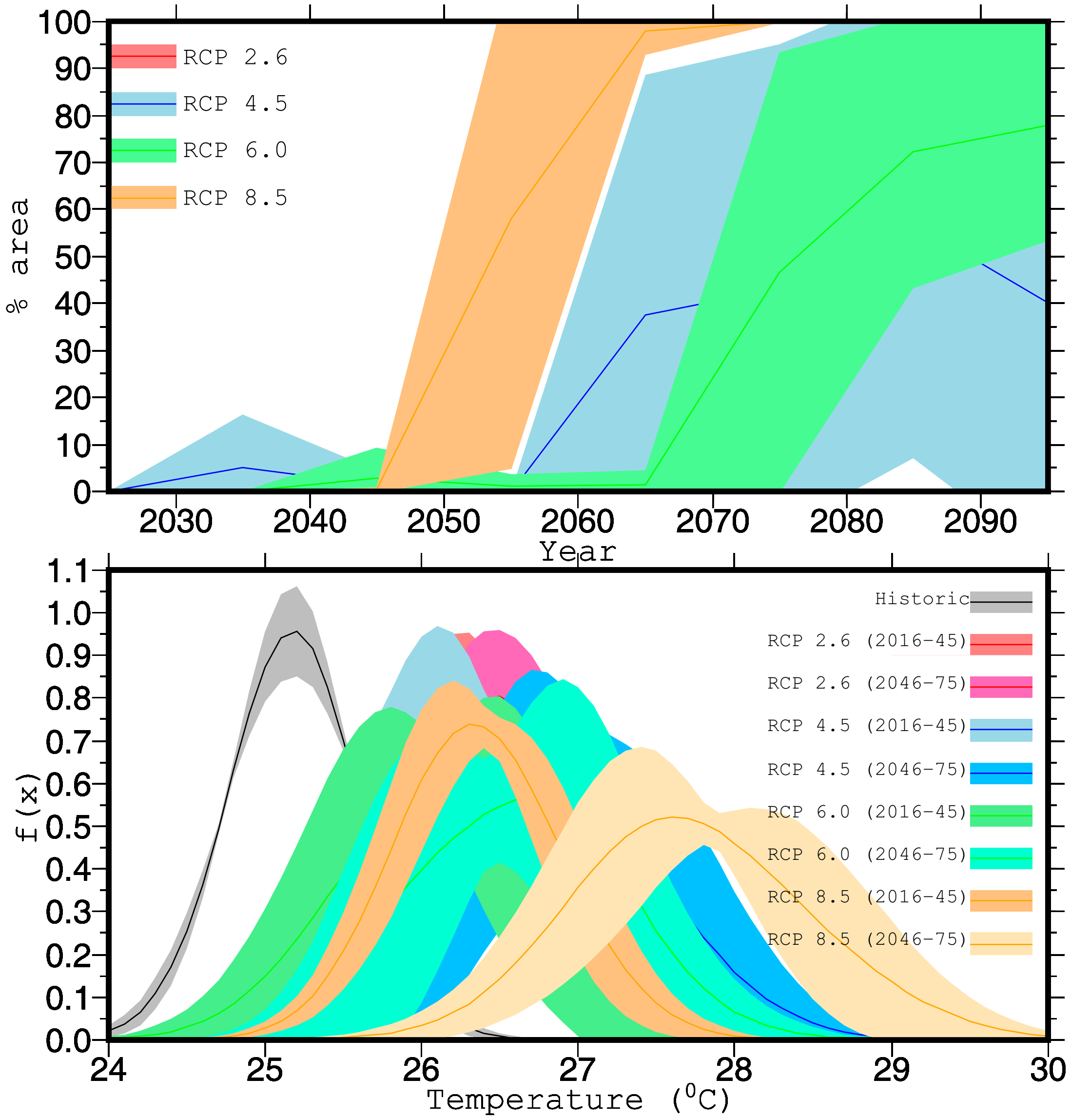


**Figure 16:** (a) Projections of percentage of grid cells going to face temperature more than 2 degree Celsius during each decade (represented by central value in figure) under different scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) as compared to base period. (b) Ensemble probability distribution function of mean annual temperature for historical period (1951-2005) and different RCP scenarios (for the periods 2016-45 and 2046-75).

### 4.2.1. Precipitation

Figure 17 shows changes in mean monthly precipitation in the state of MP under the projected future climate for the Near (2016-2045) and Mid (2046-2075) periods for RCP 2.6, 4.5, 6.0, and 8.5. Results showed that in the monsoon season precipitation is projected to increase in the RCP 2.6 scenario for both Near and Mid periods (Figure 17a, e). However, in the Near term period, the monsoon season precipitation in the state of MP is projected to decline under the RCP 4.5 scenario, which is the most representative scenario for the state of MP (Figure 17b). The monsoon season precipitation is projected to remain about the same in the Mid 21st century under the RCP 4.5 scenario (Figure 17f). Larger increases in the monsoon season precipitation are projected in the state under the RCP 6.0 while relatively smaller increase in likely under the RCP 8.5 scenario (Figure 17d, h). These results highlight the uncertainty associated with the precipitation under different RCPs. Moreover, it is worth to note that in the most representative scenario (RCP 4.5), the monsoon season precipitation is projected to decline in the state of MP. Decline in the monsoon season precipitation with the increased warming could have far reaching implications for the agriculture and water resources sectors in the state. It was also observed that the RCP 4.5 scenario is in agreement of the observed changes in the precipitation in the state of MP. Changes in mean monthly precipitation for the Near and Mid term climate are presented in Table 4 and Table 5, which highlight reduction in precipitation in July and August months during the period of 2016-2045.

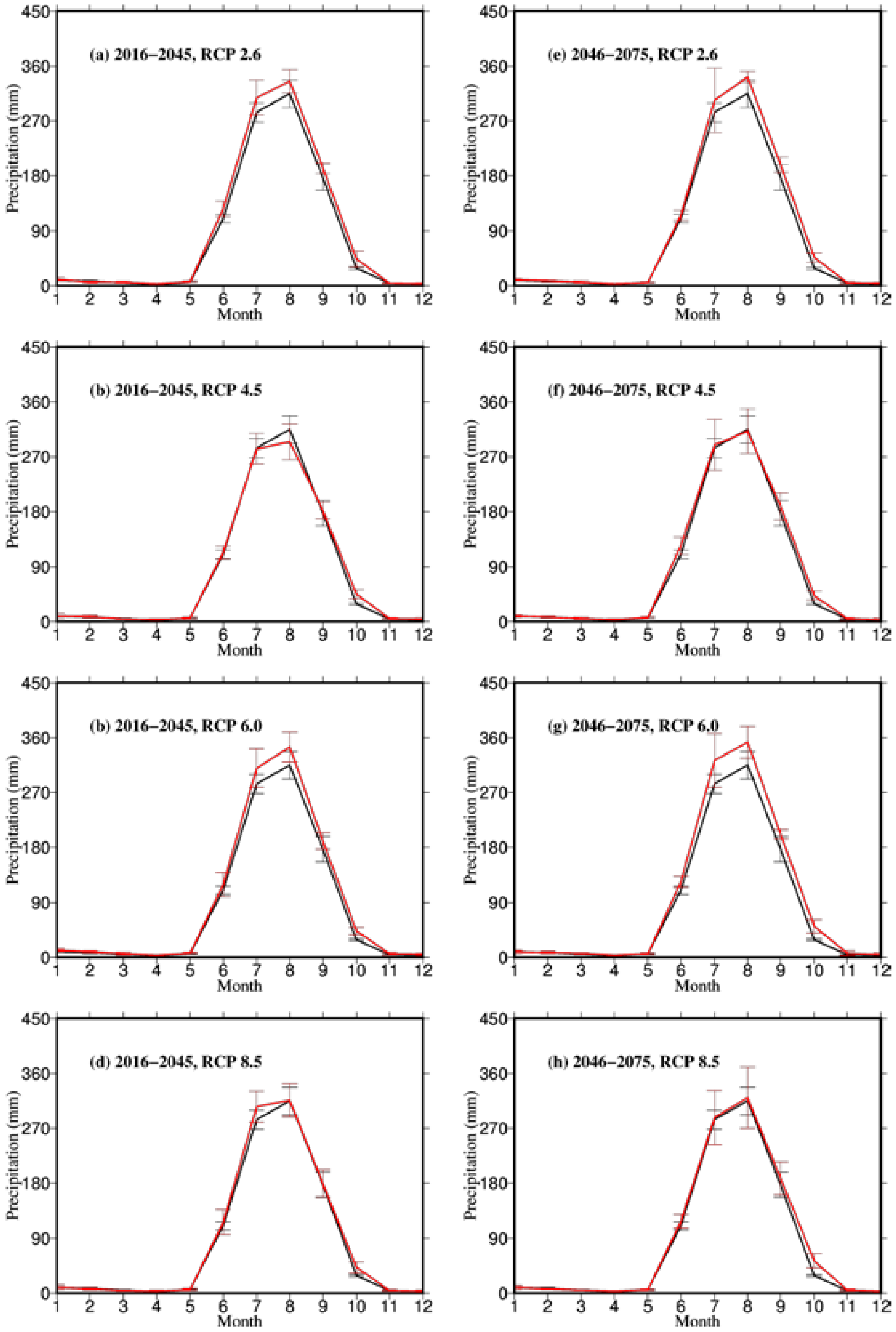


**Figure 17:** Multimodel ensemble mean projected changes (red) under the projected future climate in the mean monthly precipitation for the Near and Mid term climate for the selected RCPs. Changes were estimated with respect to historic mean monthly precipitation for the reference (1971-2000) period (black). Error bars show intermodel variation in the five best CMIP5 models.

**Table 4.** Multimodel ensemble mean and inter model variation (std.) in monthly precipitation in the state of Madhya Pradesh for the Historic (1971-2000) and projected future climate for the period of 2016-2045.

| Month | Historic | | RCP 2.6 | | RCP 4.5 | | RCP 6.0 | | RCP 8.5 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | Std. | Mean | Std. | Mean | Std. | Mean | Std. | Mean | Std. |
| January | 9.1 | 0.9 | 11.2 | 2.8 | 9.4 | 4.0 | 12.0 | 2.6 | 9.6 | 4.1 |
| February | 7.4 | 1.5 | 6.0 | 1.8 | 8.8 | 1.9 | 9.4 | 1.3 | 6.7 | 1.7 |
| March | 5.1 | 1.0 | 5.8 | 1.4 | 4.1 | 1.0 | 5.9 | 2.3 | 4.3 | 0.6 |
| April | 2.7 | 0.8 | 3.3 | 0.6 | 3.3 | 1.7 | 3.5 | 1.1 | 3.2 | 2.0 |
| May | 5.6 | 0.8 | 6.6 | 1.7 | 5.8 | 2.1 | 7.1 | 1.0 | 6.2 | 1.7 |
| June | 109.9 | 6.6 | 126.4 | 12.8 | 113.2 | 10.7 | 119.0 | 19.6 | 116.2 | 20.6 |
| July | 284.1 | 16.0 | 308.6 | 28.5 | 283.0 | 25.0 | 310.3 | 31.9 | 305.5 | 25.2 |
| August | 314.7 | 22.3 | 334.9 | 18.7 | 294.3 | 29.3 | 344.5 | 24.4 | 315.6 | 27.1 |
| September | 177.4 | 21.0 | 193.0 | 8.5 | 181.9 | 13.3 | 190.2 | 13.7 | 179.8 | 22.3 |
| October | 28.7 | 1.5 | 43.9 | 12.7 | 44.5 | 6.9 | 43.3 | 6.1 | 42.1 | 8.9 |
| November | 3.9 | 0.5 | 3.9 | 0.8 | 5.0 | 1.6 | 5.9 | 2.4 | 4.6 | 1.2 |
| December | 3.6 | 1.0 | 3.8 | 1.6 | 4.2 | 2.5 | 4.8 | 1.8 | 3.3 | 1.9 |

**Table 5.** Multimodel ensemble mean and inter model variation (std.) in monthly precipitation in the state of Madhya Pradesh for the Historic (1971-2000) and projected future climate for the period of 2046-2075.

| Month | Historic | | RCP 2.6 | | RCP 4.5 | | RCP 6.0 | | RCP 8.5 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | Std. | Mean | Std. | Mean | Std. | Mean | Std. | Mean | Std. |
| January | 9.1 | 0.9 | 10.4 | 1.8 | 9.0 | 1.8 | 9.2 | 3.0 | 9.5 | 3.5 |
| February | 7.4 | 1.5 | 8.5 | 1.1 | 7.5 | 0.9 | 7.7 | 2.1 | 6.4 | 0.8 |
| March | 5.1 | 1.0 | 6.2 | 1.9 | 5.3 | 2.0 | 6.4 | 1.1 | 4.8 | 0.6 |
| April | 2.7 | 0.8 | 3.0 | 0.3 | 3.1 | 1.6 | 3.1 | 0.4 | 3.1 | 0.9 |
| May | 5.6 | 0.8 | 5.3 | 1.3 | 7.1 | 1.7 | 6.1 | 1.5 | 5.7 | 1.1 |
| June | 109.9 | 6.6 | 115.6 | 8.4 | 124.2 | 14.2 | 123.5 | 9.6 | 117.6 | 11.1 |
| July | 284.1 | 16.0 | 304.2 | 52.6 | 289.3 | 41.6 | 322.7 | 44.2 | 287.7 | 44.6 |
| August | 314.7 | 22.3 | 342.5 | 9.3 | 311.9 | 36.6 | 351.9 | 26.3 | 319.9 | 50.2 |
| September | 177.4 | 21.0 | 198.4 | 12.2 | 188.4 | 22.0 | 201.5 | 7.7 | 187.9 | 27.0 |
| October | 28.7 | 1.5 | 46.8 | 7.7 | 42.5 | 7.1 | 51.0 | 10.9 | 52.9 | 11.7 |
| November | 3.9 | 0.5 | 5.4 | 2.3 | 4.7 | 2.0 | 6.7 | 4.2 | 5.2 | 1.6 |
| December | 3.6 | 1.0 | 3.9 | 2.3 | 3.3 | 2.6 | 4.1 | 3.1 | 3.1 | 1.0 |

Figure 18(a) shows multimodel ensemble mean precipitation for the historic period (1951-2005) obtained from the five best CMIP5 models. It was observed that the multimodel ensemble mean reproduced the observed spatial variability and the magnitude of the monsoon season precipitation. Similar to the observations, the monsoon season precipitation varied between 600 and 1100 mm with the higher values in the southern parts while lower values in the northern part of the state. Ensemble mean changes in the monsoon season precipitation for the RCP 2.6, 4.5, 6.0, and 8.5 showed that the majority of the state is projected to become wetter under the RCP 2.6 and 6.0 scenarios (Figure 19). Moreover, some regions in the state are projected to experience an increase in the monsoon season precipitation by 50-75 mm. On the other hand, moderate changes in the monsoon season precipitation were noticed under the projected future climate for the RCP 4.5 and 8.5 scenarios (Figure 19). Moreover, the eastern part of the state is projected to receive reduced monsoon season precipitation in the Near (2016-2045) term period under the RCP 4.5 scenarios. While majority of the RCPs showed increases in the monsoon season precipitation, projected declines under the RCP4.5 underscores adaptation strategies that include the potential declines in the monsoon season precipitation in the coming years (Figure 19c). Projected changes in each district of the state of MP in the monsoon season precipitation are presented in Table 6.

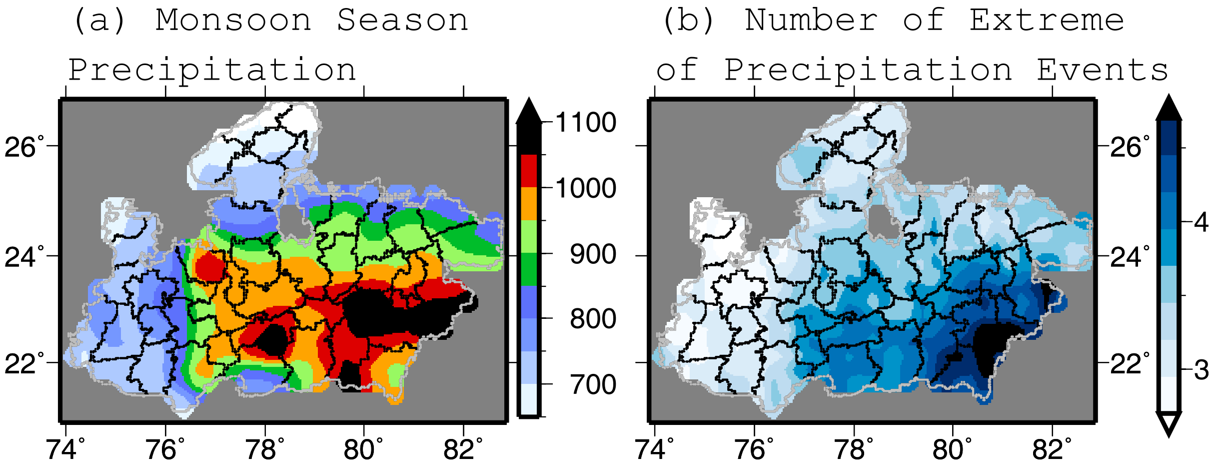


**Figure 18:** Historic ensemble mean (1951-2005) of (a) Monsoon season precipitation, (b) number of extreme events (above 95th percentile of rainy days for the base period).

**Box 9**

- Majority of the selected RCPs showed that the monsoon season precipitation is projected to increase in Madhya Pradesh under the projected future climate
- The monsoon season precipitation is projected to decline in the Near (2016-2045) under the RCP 4.5
- Projected increase in the monsoon season precipitation is higher in the RCP 2.6 and 6.0 than RCP 4.5 and 8.5
- Projected increases in the monsoon season precipitation are in the range of 5-15% under different RCPs
- Central and southern regions of the state are likely to experience an increased precipitation while eastern region may face a decline in the Near term climate under RCP 4.5
- Number of extreme precipitation events are projected to increase under most of the RCPs in Madhya Pradesh except for the RCP 4.5

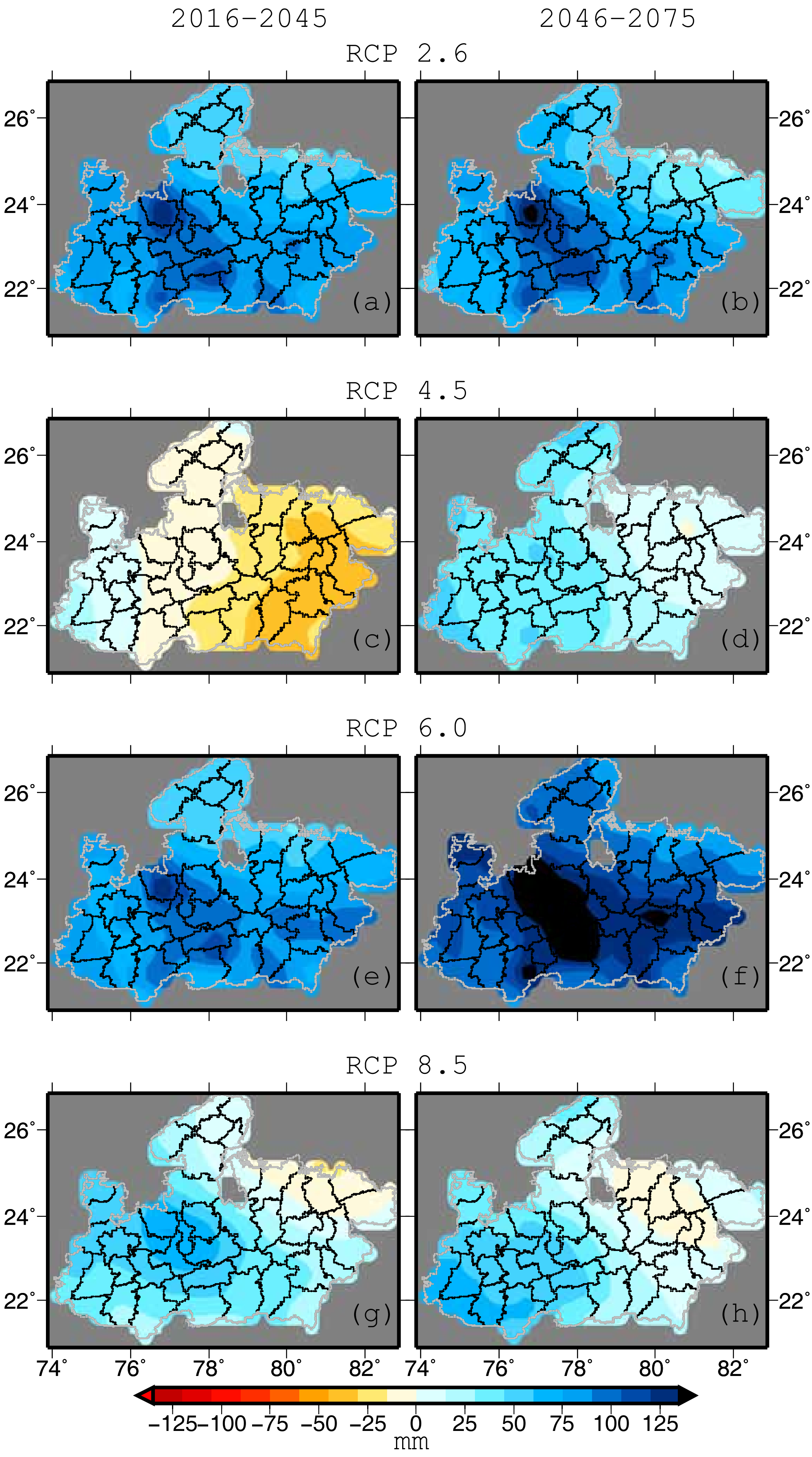


**Figure 19:** Multimodel ensemble mean projected changes (mm) in the monsoon season precipitation for the Near and Midterm climate. Changes were estimated against the historic mean for the reference period (1971-2000).

**Table 6:** District level multimodel ensemble mean projected changes (mm) in the monsoon season precipitation under the RCP 2.6, 4.5, 6.0, and 8.5 for the Near (2016-2045) and Mid (2046-2075) term climate.

| District | RCP 2.6 | | RCP 4.5 | | RCP 6.0 | | RCP 8.5 | |
|---|---|---|---|---|---|---|---|---|
| | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 |
| Anuppur | 84.99 | 72.57 | -37.43 | 4.42 | 95.25 | 122.94 | 18.95 | 0.14 |
| Ashoknagar | 60.79 | 65.49 | -7.83 | 27.12 | 63.42 | 107.12 | 31.67 | 12.81 |
| Balaghat | 78.80 | 85.37 | -32.57 | 18.84 | 81.92 | 104.73 | 28.26 | 15.69 |
| Barwani | 76.86 | 68.28 | 15.51 | 48.65 | 83.46 | 102.04 | 32.64 | 72.69 |
| Betul | 89.36 | 89.54 | -19.38 | 38.77 | 84.97 | 118.47 | 37.75 | 41.97 |
| Bhind | 50.54 | 51.35 | -1.01 | 40.79 | 45.92 | 84.63 | 7.65 | 24.71 |
| Bhopal | 102.94 | 112.98 | -3.54 | 44.90 | 103.33 | 148.75 | 72.29 | 49.09 |
| Burhanpur | 72.14 | 72.74 | -3.71 | 41.50 | 73.63 | 98.02 | 21.51 | 55.76 |
| Chhatarpur | 55.67 | 47.67 | -24.68 | 7.87 | 57.58 | 92.64 | 0.45 | -2.80 |
| Chhindwara | 88.85 | 89.40 | -28.41 | 30.46 | 89.27 | 120.74 | 37.93 | 29.79 |
| Damoh | 70.23 | 65.35 | -25.11 | 12.03 | 73.63 | 113.51 | 22.79 | 2.83 |
| Datia | 48.44 | 52.52 | -8.42 | 28.93 | 47.49 | 90.01 | 2.92 | 12.99 |
| Dewas | 85.86 | 88.55 | -1.90 | 39.62 | 81.83 | 115.20 | 51.90 | 52.22 |
| Dhar | 78.83 | 68.64 | 14.33 | 43.21 | 78.76 | 103.73 | 39.96 | 63.81 |
| Dindori | 86.47 | 83.49 | -32.88 | 11.54 | 93.57 | 124.74 | 25.23 | 3.48 |
| East_Nimar | 94.61 | 98.61 | -6.72 | 44.05 | 93.08 | 124.31 | 35.03 | 59.31 |
| Guna | 80.43 | 87.21 | -2.62 | 36.49 | 80.79 | 127.16 | 47.92 | 22.76 |
| Gwalior | 51.16 | 57.70 | -5.19 | 37.70 | 50.62 | 96.90 | 9.50 | 21.12 |
| Harda | 96.22 | 102.45 | -11.41 | 44.16 | 91.96 | 130.22 | 46.00 | 57.41 |
| Hoshangabad | 103.28 | 109.45 | -19.61 | 42.18 | 102.13 | 145.33 | 54.06 | 50.29 |
| Indore | 78.20 | 73.92 | 7.70 | 39.27 | 73.58 | 101.57 | 43.27 | 55.78 |
| Jabalpur | 88.72 | 89.10 | -30.42 | 14.85 | 92.86 | 135.49 | 32.67 | 9.34 |
| Jhabua | 80.01 | 66.16 | 15.50 | 46.38 | 80.85 | 110.08 | 45.71 | 64.52 |
| Katni | 75.13 | 66.33 | -30.29 | 7.31 | 78.90 | 117.67 | 18.17 | -0.85 |
| Mandla | 84.37 | 87.54 | -32.23 | 14.61 | 89.28 | 123.45 | 30.19 | 9.37 |
| Mandsaur | 79.37 | 79.72 | 4.23 | 41.86 | 74.17 | 117.48 | 55.74 | 39.01 |
| Morena | 53.80 | 57.60 | -1.99 | 46.84 | 50.53 | 95.44 | 12.96 | 31.78 |
| Narsinghpur | 84.34 | 88.31 | -24.56 | 25.31 | 88.42 | 128.41 | 42.72 | 23.60 |
| Neemuch | 80.03 | 80.20 | 4.93 | 45.19 | 75.70 | 121.99 | 57.23 | 37.75 |
| Panna | 55.24 | 41.22 | -29.26 | 3.54 | 58.42 | 90.38 | 0.41 | -3.96 |
| Raisen | 93.00 | 100.77 | -10.70 | 39.16 | 95.19 | 138.57 | 62.06 | 40.51 |
| Rajgarh | 118.57 | 126.05 | -1.59 | 43.44 | 115.31 | 164.29 | 69.41 | 42.66 |
| Ratlam | 77.65 | 69.12 | 9.07 | 40.88 | 72.10 | 108.70 | 52.53 | 50.14 |
| Rewa | 58.78 | 30.74 | -21.63 | 6.18 | 65.63 | 85.59 | -13.07 | 8.66 |
| Sagar | 77.13 | 79.25 | -17.03 | 22.70 | 80.64 | 124.21 | 38.53 | 14.77 |
| Satna | 57.05 | 36.70 | -31.18 | 1.10 | 62.21 | 91.28 | -8.60 | -1.84 |
| Sehore | 98.03 | 105.16 | -7.81 | 42.97 | 95.19 | 137.18 | 62.23 | 53.20 |
| Seoni | 88.24 | 91.15 | -34.45 | 19.24 | 90.50 | 125.24 | 34.65 | 17.77 |
| Shahdol | 78.15 | 64.08 | -34.41 | 4.69 | 86.15 | 117.07 | 12.52 | -0.23 |
| Shajapur | 94.95 | 97.60 | -0.45 | 38.85 | 89.65 | 130.05 | 61.17 | 45.47 |
| Sheopur | 56.81 | 65.64 | -2.25 | 40.86 | 54.82 | 101.66 | 24.08 | 23.90 |
| Shivpuri | 50.23 | 59.11 | -6.76 | 29.77 | 52.55 | 97.83 | 16.59 | 12.62 |
| Sidhi | 63.88 | 35.53 | -25.83 | 4.09 | 72.09 | 92.17 | -0.95 | 8.73 |
| Tikamgarh | 49.78 | 51.54 | -17.74 | 14.41 | 52.15 | 93.70 | 3.92 | 0.71 |
| Ujjain | 81.99 | 77.04 | 6.98 | 38.59 | 75.71 | 110.42 | 51.86 | 50.56 |
| Umaria | 72.95 | 59.78 | -32.22 | 4.35 | 78.25 | 113.34 | 12.65 | -1.89 |
| Vidisha | 88.46 | 95.79 | -5.71 | 36.69 | 91.30 | 136.89 | 59.23 | 30.53 |
| West_Nimar | 73.55 | 70.66 | 7.00 | 41.16 | 74.08 | 96.35 | 32.19 | 60.76 |

Extreme precipitation events are projected to increase under the climate warming [*Min et al.*, 2011] and it has been reported that precipitation extremes have increased in a few regions of India during the recent decades [*Goswami et al.*, 2006; *Ghosh et al.*, 2012; *Ali et al.*, 2014]. Multimodel ensemble mean of the extreme precipitation events in the state showed that the downscaled and bias corrected data reproduced the observed precipitation extremes reasonably well during the period of 1951-2013 (Figure 18b). Both observed and downscaled data for the period of 1951-2013 showed higher frequency of extreme precipitation events in the south-east part of the MP. Multimodel ensemble mean projected changes in extreme precipitation events showed an increase under the RCP 2.6 and 6.0 (Figure 20). However, moderate increases are projected under the RCP 4.5 and 8.5 scenarios in the Mid (2046-2075) term climate (Figure 20). Results also showed that ensemble mean frequency of extreme precipitation events is projected to decline in the eastern part of the state in the Near (2016-2045) term climate. This decline in the frequency of extreme precipitation events is likely to be associated with the projected decline in the monsoon season precipitation in the same part of the region. Results indicate that under the most of the RCPs, the frequency of the extreme precipitation is projected to increase in the state under the climate warming. However, frequency of extreme precipitation may decline in the eastern half of the state in the Near term climate under the RCP 4.5 scenario. Projected increases in the extreme precipitation events may have consequences for agriculture as well as infrastructure. For instance, untimely extreme precipitation events may have profound implications on crop production and socio-economic livelihood of the people. Multimodel ensemble mean projections of extreme precipitation frequency are presented in Table 7, which highlight that many of the districts in the state of MP are projected to experience an increase of 1-2 events per year in future.

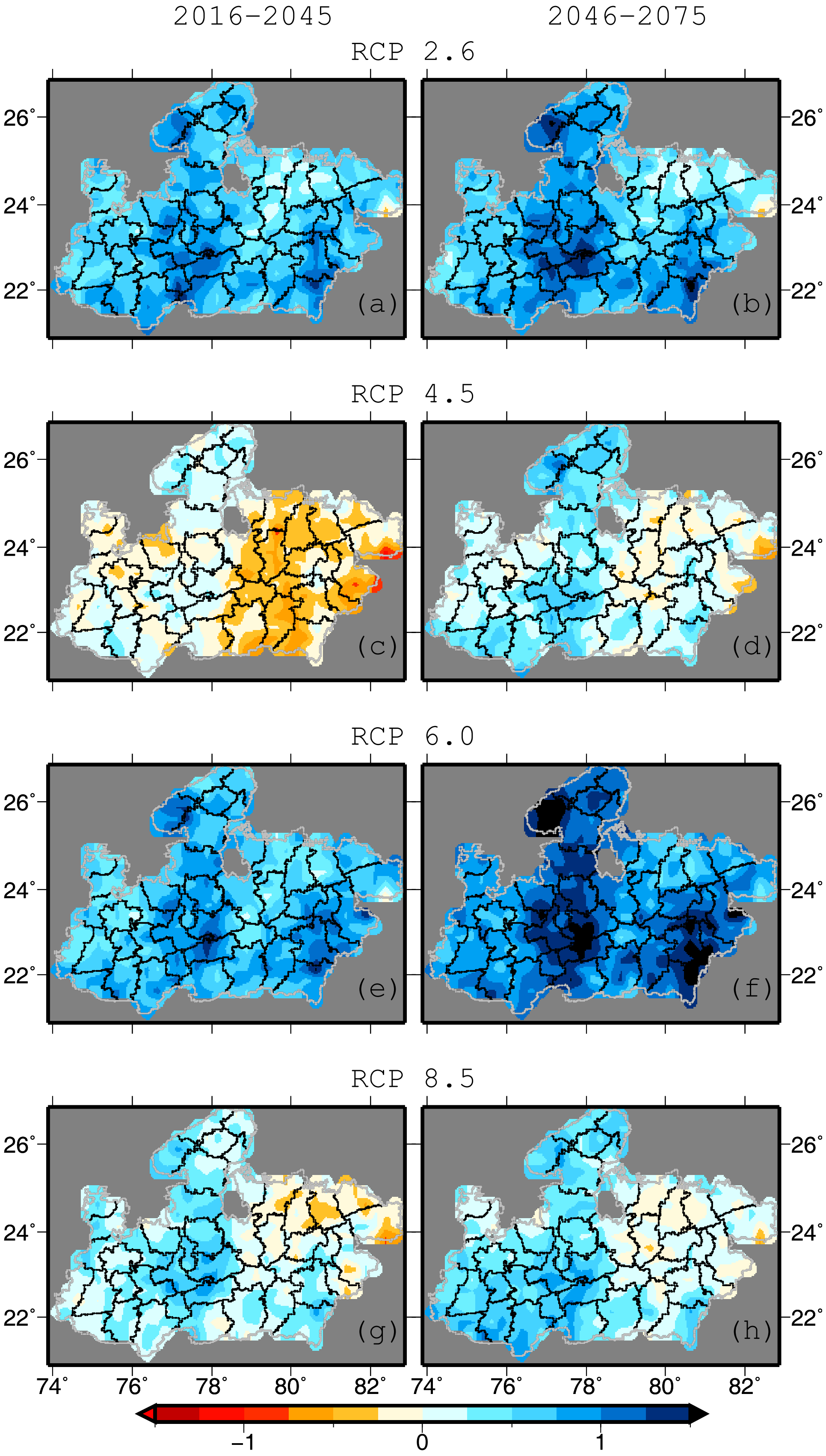


**Figure 20.** Multimodel ensemble projected changes in number of extreme wet events (i.e. change in number of events above threshold estimated using 95th percentile from historic period of rainy days. base period: 1971-2000. Rainy days are days on which precipitation is greater than 1 mm)

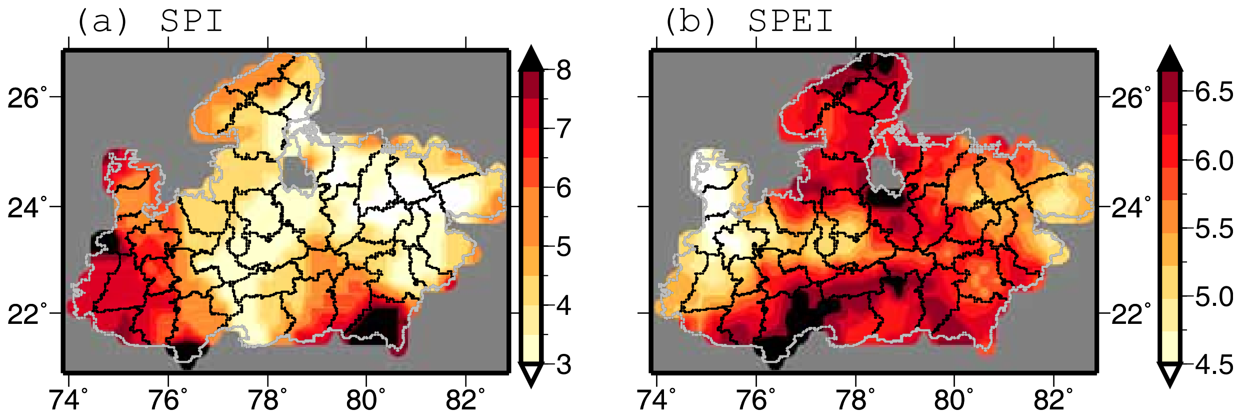
**Table 7:** Multimodel ensemble mean changes in frequency of extreme precipitation events per year under the projected future climate.

| District | RCP 2.6 | | RCP 4.5 | | RCP 6.0 | | RCP 8.5 | |
|---|---|---|---|---|---|---|---|---|
| | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 |
| Anuppur | 0.56 | 0.49 | -0.75 | -0.32 | 0.59 | 0.91 | 0.01 | -0.21 |
| Ashoknagar | 0.77 | 0.89 | 0.12 | 0.40 | 0.89 | 1.35 | 0.49 | 0.41 |
| Balaghat | 0.87 | 1.06 | -0.33 | 0.24 | 0.87 | 1.30 | 0.37 | 0.33 |
| Barwani | 0.74 | 0.72 | 0.10 | 0.45 | 0.77 | 1.05 | 0.17 | 0.75 |
| Betul | 0.82 | 0.87 | -0.10 | 0.32 | 0.71 | 1.11 | 0.24 | 0.52 |
| Bhind | 0.73 | 0.74 | 0.22 | 0.56 | 0.66 | 1.13 | 0.23 | 0.58 |
| Bhopal | 0.72 | 0.98 | -0.01 | 0.25 | 0.72 | 1.25 | 0.46 | 0.44 |
| Burhanpur | 0.92 | 0.82 | 0.07 | 0.45 | 0.75 | 1.04 | 0.21 | 0.83 |
| Chhatarpur | 0.37 | 0.44 | -0.26 | 0.02 | 0.51 | 0.76 | -0.08 | -0.01 |
| Chhindwara | 0.69 | 0.84 | -0.28 | 0.19 | 0.70 | 1.03 | 0.20 | 0.34 |
| Damoh | 0.37 | 0.41 | -0.48 | -0.08 | 0.48 | 0.88 | -0.02 | -0.04 |
| Datia | 0.76 | 0.82 | 0.17 | 0.46 | 0.71 | 1.18 | 0.25 | 0.48 |
| Dewas | 0.78 | 0.93 | 0.02 | 0.35 | 0.67 | 1.05 | 0.49 | 0.56 |
| Dhar | 0.52 | 0.56 | 0.04 | 0.19 | 0.57 | 0.85 | 0.19 | 0.52 |
| Dindori | 0.83 | 0.86 | -0.30 | 0.12 | 1.02 | 1.38 | 0.11 | 0.12 |
| East_Nimar | 0.83 | 0.92 | -0.06 | 0.33 | 0.77 | 1.04 | 0.25 | 0.60 |
| Guna | 0.72 | 0.91 | 0.00 | 0.27 | 0.79 | 1.19 | 0.41 | 0.35 |
| Gwalior | 0.67 | 0.90 | 0.19 | 0.59 | 0.78 | 1.22 | 0.17 | 0.44 |
| Harda | 0.94 | 1.12 | 0.06 | 0.49 | 0.85 | 1.16 | 0.39 | 0.66 |
| Hoshangabad | 0.99 | 1.22 | 0.02 | 0.55 | 1.01 | 1.41 | 0.63 | 0.71 |
| Indore | 0.47 | 0.56 | -0.14 | 0.19 | 0.58 | 0.80 | 0.18 | 0.53 |
| Jabalpur | 0.63 | 0.65 | -0.40 | 0.05 | 0.79 | 1.21 | 0.22 | 0.09 |
| Jhabua | 0.54 | 0.42 | -0.03 | 0.13 | 0.47 | 0.74 | 0.18 | 0.48 |
| Katni | 0.63 | 0.68 | -0.21 | 0.12 | 0.79 | 1.12 | 0.05 | 0.07 |
| Mandla | 0.89 | 0.97 | -0.33 | 0.18 | 1.03 | 1.38 | 0.31 | 0.26 |
| Mandsaur | 0.48 | 0.55 | -0.09 | 0.15 | 0.49 | 0.84 | 0.24 | 0.20 |
| Morena | 0.65 | 0.79 | 0.06 | 0.49 | 0.58 | 1.11 | 0.25 | 0.43 |
| Narsinghpur | 0.46 | 0.48 | -0.39 | -0.05 | 0.41 | 0.74 | 0.06 | 0.08 |
| Neemuch | 0.52 | 0.58 | -0.12 | 0.13 | 0.51 | 0.91 | 0.31 | 0.17 |
| Panna | 0.30 | 0.26 | -0.37 | -0.09 | 0.47 | 0.66 | -0.17 | -0.06 |
| Raisen | 0.85 | 1.10 | 0.05 | 0.42 | 0.93 | 1.34 | 0.65 | 0.62 |
| Rajgarh | 0.78 | 0.92 | -0.23 | 0.11 | 0.77 | 1.10 | 0.26 | 0.29 |
| Ratlam | 0.57 | 0.63 | -0.05 | 0.18 | 0.59 | 0.92 | 0.33 | 0.42 |
| Rewa | 0.51 | 0.28 | -0.15 | 0.06 | 0.69 | 0.83 | -0.18 | 0.15 |
| Sagar | 0.56 | 0.62 | -0.27 | 0.08 | 0.58 | 0.96 | 0.10 | 0.09 |
| Satna | 0.34 | 0.28 | -0.28 | -0.05 | 0.45 | 0.67 | -0.25 | 0.00 |
| Sehore | 1.00 | 1.21 | 0.14 | 0.55 | 0.96 | 1.39 | 0.67 | 0.74 |
| Seoni | 0.63 | 0.83 | -0.43 | 0.08 | 0.79 | 1.12 | 0.19 | 0.22 |
| Shahdol | 0.67 | 0.69 | -0.33 | 0.08 | 0.90 | 1.20 | 0.08 | 0.07 |
| Shajapur | 0.68 | 0.80 | -0.02 | 0.15 | 0.64 | 1.08 | 0.46 | 0.43 |
| Sheopur | 0.89 | 1.16 | 0.20 | 0.73 | 1.01 | 1.54 | 0.51 | 0.59 |
| Shivpuri | 0.70 | 0.94 | 0.16 | 0.50 | 0.82 | 1.25 | 0.33 | 0.46 |
| Sidhi | 0.48 | 0.28 | -0.31 | -0.07 | 0.64 | 0.83 | -0.15 | 0.08 |
| Tikamgarh | 0.54 | 0.63 | -0.06 | 0.28 | 0.70 | 1.06 | 0.12 | 0.19 |
| Ujjain | 0.54 | 0.58 | -0.12 | 0.13 | 0.40 | 0.79 | 0.18 | 0.36 |
| Umaria | 0.78 | 0.62 | -0.20 | 0.17 | 0.90 | 1.16 | 0.17 | 0.12 |
| Vidisha | 0.73 | 0.89 | -0.04 | 0.28 | 0.81 | 1.25 | 0.47 | 0.36 |
| West_Nimar | 0.75 | 0.80 | 0.18 | 0.44 | 0.72 | 0.92 | 0.30 | 0.65 |

### 4.2.2 Drought and Wet Periods

Since the majority of the state of MP is under agriculture, understanding the nature of drought and wet spells under the projected future climate is vital. Similar to the observed period, the drought and wet periods for the monsoon season were estimated using the SPI and SPEI. For the analysis, only severe, extreme, and exceptional drought and wet periods were calculated using the threshold of -1.3 and +1.3, respectively. Multimodel ensemble mean frequency of severe, extreme, and exceptional droughts were estimated for the historic (1951-2005) period using the SPI and SPEI (Figure 21). It was found that the selected models reasonably captured the observed drought frequency in the state. Moreover, the frequency of severe droughts estimated using SPEI was higher than SPI, which highlight that air temperature can play an important role in the drought frequency under the projected future climate (Figure 21a, b).

Number of Monsoon Season Droughts



Number of Extreme Wet Monsoon Season

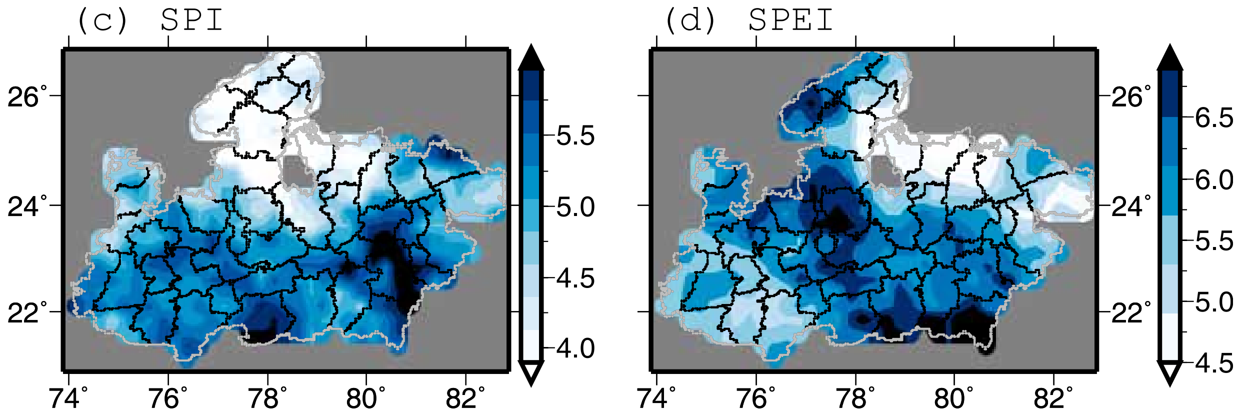


**Figure 21:** (a) number of monsoon seasons (1951-2005) during which grid cell faced severe-exceptional monsoon season drought (based on SPI <-1.3; base period: 1971-2000) from ensemble mean of GCMs. (b) same as (a) but based on SPEI (c) number of monsoon season which faced extreme flooding (based on SPI > 1.3) (d) same as (c) but based on SPEI.

Figure 22 shows the projected changes in drought frequency estimated using 4-month SPI at the end of the monsoon season. Projections of the severe, extreme, and exceptional droughts were developed for the Near (2016-2045) and Mid (2046-2075) periods and for the RCP 2.6, 4.5, 6.0, and 8.5. Results show that multimodel ensemble mean frequency of droughts is projected to decline under the RCP 2.6 and 6.0 scenarios (Figure 22). However, drought frequency is projected to increase under the RCP 4.5 for the Near term and RCP 8.5 for the Midterm climate (Figure 22, Table 8). Projected changes in drought frequency are consistent with the changes in the monsoon season precipitation. Once again, it is worth to note that the RCP 4.5 is the most representative scenario and therefore an increase in drought frequency in the state in the Near term climate is likely. Results indicate that the state may prepare adaptation plans that considers both increases as well as declines in the frequency of severe, extreme, and exceptional droughts under the projected future climate. Increased frequency of drought may pose tremendous pressure on the agriculture and water resources sectors. Moreover, to minimize the damage due to droughts under the projected future climate the state may need a proactive approach for water and agriculture management strategies.

Increased warming under the projected future climate may have serious implications for drought frequency in the state of MP (Figure 23). For instance, drought frequency estimated using the SPEI showed that drought are projected to become more frequent under all the selected RCPs. Despite the projected increase in the monsoon season precipitation, an increased air temperature will lead to high atmospheric water demands, which in turn can reduce the water availability for agriculture. These results show that for the projected future climate, it is important to consider the role of air temperature for drought assessment. Results showed that droughts are likely to occur once in 2-3 years under the projected climate in some parts of the state (Figure 23, Table 9).

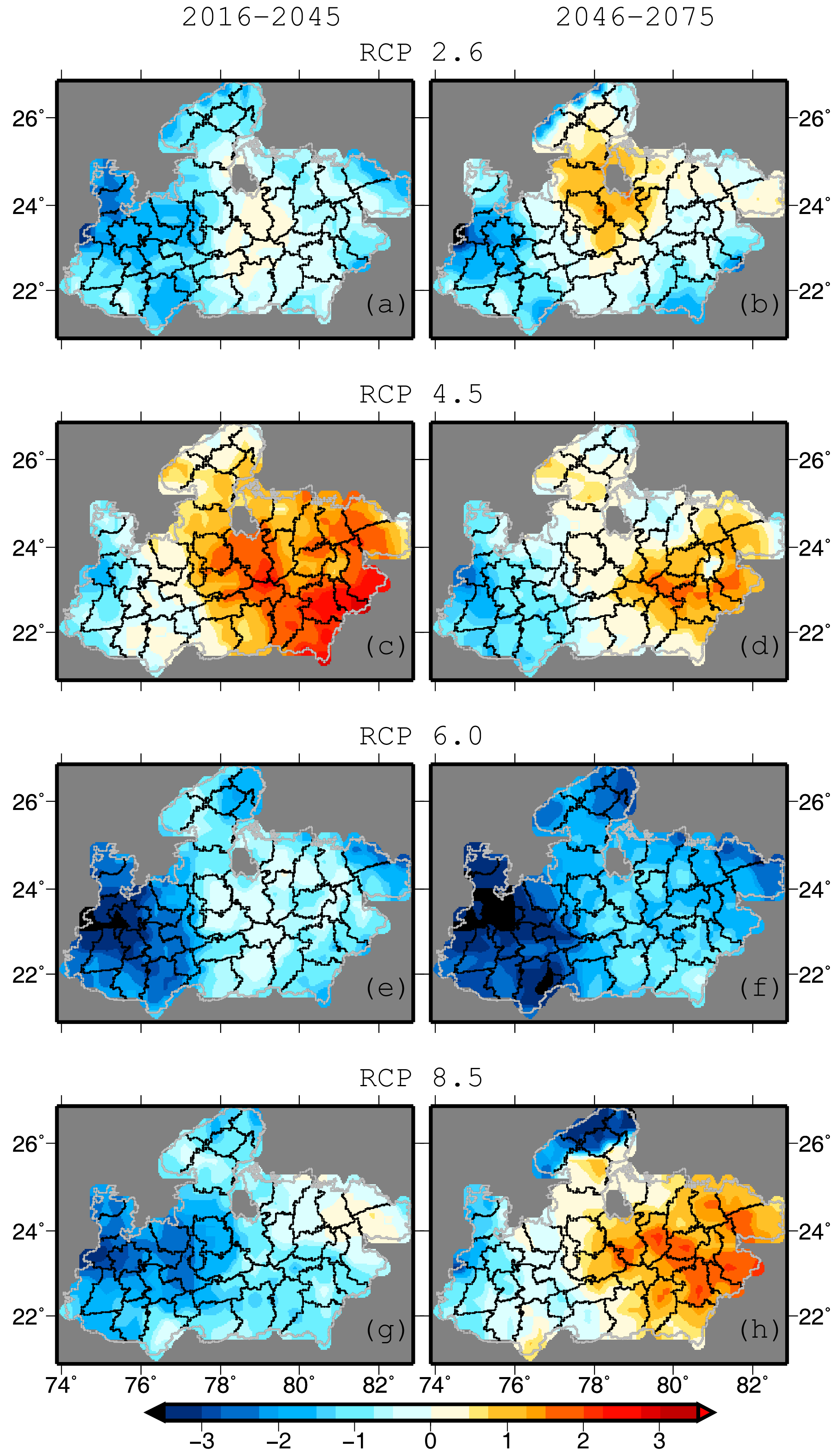


**Figure 22:** Ensemble mean projected change in number of severe-exceptional monsoon season drought years (in 30 years; estimated based on Standardized Precipitation Index < -1.3) Reference period: 1971-2000.

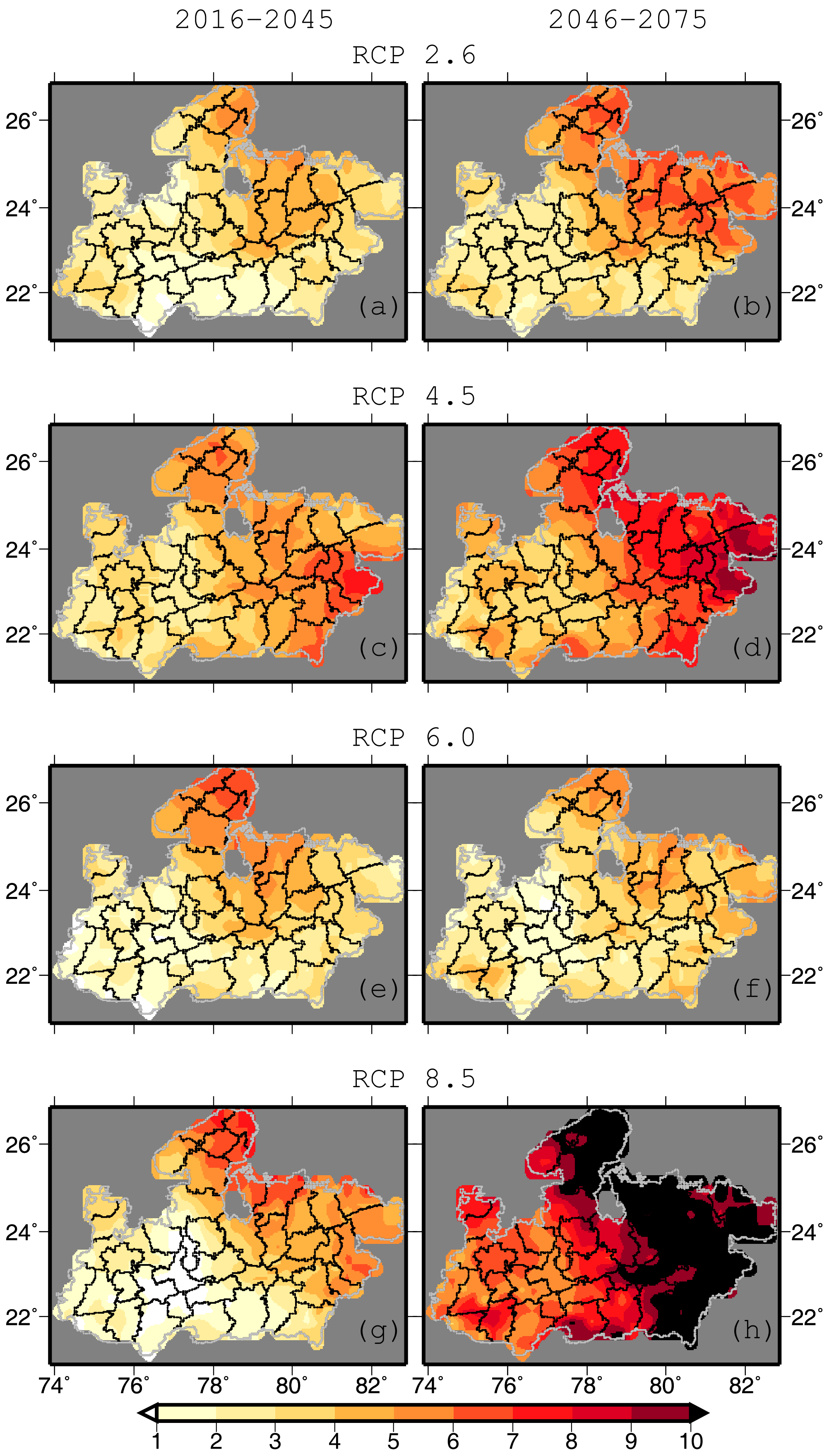


**Figure 23:** Ensemble projected change in number of severe-exceptional monsoon season drought years (in 30 years; estimated based on Standardized Precipitation Evapotranspiration Index < -1.3). Reference period: 1971-2000.

**Table 8:** Ensemble mean change in number of severe-exceptional monsoon season droughts (in 30 years; SPI < -1.3).

| District | RCP 2.6 | | RCP 4.5 | | RCP 6.0 | | RCP 8.5 | |
|---|---|---|---|---|---|---|---|---|
| | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 |
| Anuppur | -3.67 | -2.67 | 1.00 | 0.00 | -1.00 | -2.00 | -0.67 | 1.00 |
| Ashoknagar | -4.29 | -0.43 | -2.71 | -1.43 | -4.14 | -3.86 | -3.86 | -2.14 |
| Balaghat | -3.50 | -0.79 | 0.07 | -0.43 | -4.00 | -2.14 | -1.07 | -1.43 |
| Barwani | -1.40 | -0.40 | -1.80 | -1.00 | -3.00 | -3.00 | 0.80 | 0.20 |
| Betul | -2.33 | -0.67 | -0.42 | 1.17 | -2.25 | -1.17 | -0.42 | -0.25 |
| Bhind | -3.67 | -2.83 | -1.17 | 1.67 | -3.83 | -6.17 | -2.17 | 0.33 |
| Bhopal | -3.33 | -1.00 | -1.33 | -0.67 | -4.00 | -4.33 | -4.67 | -2.00 |
| Burhanpur | -1.00 | 0.50 | -1.00 | -0.50 | -1.75 | -1.50 | 2.00 | 1.75 |
| Chhatarpur | -3.17 | -1.08 | -0.50 | -0.25 | -1.58 | -3.83 | -2.75 | -1.50 |
| Chhindwara | -3.00 | 0.59 | -0.41 | 0.29 | -2.94 | -0.94 | -1.47 | -0.24 |
| Damoh | -2.91 | 1.00 | 0.18 | -0.82 | -2.36 | -3.09 | -2.18 | -0.55 |
| Datia | -4.25 | -4.00 | -2.25 | 0.75 | -4.00 | -6.25 | -3.75 | -1.25 |
| Dewas | -1.44 | -1.78 | 0.11 | 1.11 | -2.78 | -2.67 | -1.44 | -0.33 |
| Dhar | -1.18 | -1.55 | -0.73 | -0.82 | -2.64 | -1.82 | 0.82 | 0.27 |
| Dindori | -3.56 | -0.33 | 1.44 | 0.89 | -3.00 | -2.89 | -1.67 | -0.22 |
| East_Nimar | -1.45 | -1.64 | 0.00 | 0.64 | -1.45 | -1.73 | 1.36 | -0.09 |
| Guna | -4.56 | -0.89 | -3.00 | -2.11 | -4.78 | -4.78 | -4.00 | -1.67 |
| Gwalior | -2.50 | -3.00 | -2.00 | 1.00 | -3.83 | -4.33 | -2.17 | 0.33 |
| Harda | -2.00 | -1.20 | 0.00 | 1.00 | -1.60 | -0.40 | -0.80 | -0.20 |
| Hoshangabad | -2.75 | 0.25 | -0.50 | 0.25 | -2.38 | -0.50 | -2.38 | -1.25 |
| Indore | -0.40 | -1.40 | 0.80 | 1.20 | -2.60 | -2.20 | 0.60 | 1.40 |
| Jabalpur | -3.20 | 0.20 | 0.80 | 0.60 | -3.80 | -2.80 | -1.60 | -0.80 |
| Jhabua | -2.11 | -2.11 | -1.78 | -2.00 | -4.00 | -3.22 | -0.67 | -0.22 |
| Katni | -4.00 | -0.67 | 0.22 | -0.89 | -3.22 | -3.00 | -2.89 | -0.89 |
| Mandla | -3.70 | 0.00 | 0.70 | 0.60 | -4.10 | -3.10 | -1.50 | -1.50 |
| Mandsaur | -5.67 | -3.33 | -3.00 | -2.67 | -5.33 | -6.17 | -4.50 | -1.17 |
| Morena | -1.50 | -2.17 | -1.67 | 1.17 | -3.17 | -4.17 | -1.83 | 0.67 |
| Narsinghpur | -2.67 | 1.83 | 0.17 | 0.50 | -1.83 | -0.50 | -1.17 | -0.83 |
| Neemuch | -5.75 | -1.75 | -3.00 | -3.25 | -4.38 | -5.13 | -4.38 | -1.25 |
| Panna | -2.77 | -0.31 | 0.00 | -0.85 | -1.31 | -3.00 | -2.15 | -0.69 |
| Raisen | -2.83 | 1.25 | -0.33 | 0.00 | -2.08 | -1.42 | -2.92 | -0.83 |
| Rajgarh | -4.10 | -1.50 | -2.40 | -2.30 | -5.50 | -5.10 | -4.30 | -1.50 |
| Ratlam | -4.71 | -4.71 | -3.71 | -3.57 | -5.29 | -5.29 | -4.29 | -2.29 |
| Rewa | -4.40 | -2.90 | -0.60 | -1.30 | -3.10 | -4.40 | -2.60 | -1.10 |
| Sagar | -2.46 | 2.31 | 0.08 | -0.54 | -1.62 | -2.38 | -2.08 | -0.77 |
| Satna | -3.00 | -1.20 | 0.00 | -0.80 | -1.30 | -3.20 | -2.10 | -0.20 |
| Sehore | -2.33 | -1.22 | -0.67 | 0.22 | -4.00 | -3.33 | -2.89 | -1.00 |
| Seoni | -3.31 | 0.46 | 0.92 | 0.77 | -3.23 | -2.00 | -0.85 | -0.08 |
| Shahdol | -3.09 | -1.64 | 0.36 | 0.18 | -1.45 | -2.27 | -1.27 | -0.45 |
| Shajapur | -3.33 | -3.00 | -2.11 | -1.78 | -5.67 | -5.67 | -3.78 | -1.22 |
| Sheopur | -3.60 | -3.50 | -1.60 | 0.40 | -3.70 | -4.50 | -1.70 | 0.80 |
| Shivpuri | -4.93 | -2.80 | -3.07 | 0.07 | -3.53 | -4.00 | -3.00 | -1.27 |
| Sidhi | -4.53 | -3.27 | -0.47 | -1.00 | -2.00 | -3.00 | -1.27 | 0.93 |
| Tikamgarh | -4.00 | -1.40 | -2.60 | 0.00 | -2.20 | -3.00 | -4.00 | -3.00 |
| Ujjain | -3.11 | -3.56 | -1.89 | -1.44 | -4.89 | -5.00 | -2.78 | -0.89 |
| Umaria | -3.50 | -0.83 | 0.00 | -1.00 | -1.83 | -2.83 | -2.50 | -1.00 |
| Vidisha | -3.45 | 0.00 | -1.82 | -0.82 | -3.64 | -3.82 | -4.00 | -1.73 |
| West_Nimar | -0.42 | -0.50 | 0.08 | 0.08 | -2.50 | -2.42 | 1.92 | 0.67 |

**Table 9:** Ensemble mean changes in number of severe-exceptional monsoon season droughts (in 30 years; SPEI < -1.3).

| **District** | **RCP 2.6** | | **RCP 4.5** | | **RCP 6.0** | | **RCP 8.5** | |
|---|---|---|---|---|---|---|---|---|
| | **2016-2045** | **2046-2075** | **2016-2045** | **2046-2075** | **2016-2045** | **2046-2075** | **2016-2045** | **2046-2075** |
| Anuppur | 3.27 | 5.93 | 7.53 | 9.53 | 3.33 | 4.87 | 6.07 | 12.40 |
| Ashoknagar | 3.37 | 4.80 | 4.37 | 5.83 | 4.49 | 3.66 | 4.31 | 9.57 |
| Balaghat | 2.44 | 2.73 | 5.67 | 7.13 | 2.70 | 3.63 | 2.81 | 11.31 |
| Barwani | 2.32 | 2.68 | 2.20 | 2.56 | 1.16 | 2.64 | 1.28 | 5.48 |
| Betul | 1.42 | 3.20 | 3.70 | 5.03 | 2.62 | 2.82 | 1.65 | 8.27 |
| Bhind | 5.17 | 6.13 | 4.87 | 7.60 | 6.40 | 5.27 | 7.00 | 11.03 |
| Bhopal | 2.33 | 2.53 | 2.47 | 3.87 | 2.33 | 1.13 | 0.47 | 5.87 |
| Burhanpur | 0.95 | 2.05 | 3.15 | 4.70 | 0.90 | 1.90 | 1.35 | 6.20 |
| Chhatarpur | 4.85 | 6.08 | 5.02 | 7.73 | 5.37 | 4.62 | 6.30 | 11.27 |
| Chhindwara | 1.64 | 3.06 | 4.01 | 4.74 | 2.36 | 2.62 | 1.56 | 8.19 |
| Damoh | 4.56 | 5.64 | 5.02 | 7.15 | 4.60 | 4.33 | 4.65 | 10.02 |
| Datia | 5.45 | 6.20 | 5.70 | 7.90 | 6.45 | 5.00 | 6.90 | 10.90 |
| Dewas | 1.82 | 2.49 | 3.02 | 3.71 | 1.40 | 1.73 | 0.96 | 5.82 |
| Dhar | 3.02 | 2.87 | 2.73 | 3.76 | 1.78 | 3.05 | 1.53 | 6.24 |
| Dindori | 2.64 | 3.87 | 6.00 | 6.76 | 2.80 | 2.80 | 4.51 | 10.76 |
| East_Nimar | 1.15 | 2.13 | 2.80 | 3.98 | 1.58 | 1.56 | 1.11 | 6.00 |
| Guna | 2.02 | 3.22 | 3.07 | 4.60 | 3.27 | 2.38 | 2.31 | 7.78 |
| Gwalior | 4.80 | 5.87 | 5.80 | 7.07 | 5.93 | 4.73 | 6.13 | 10.23 |
| Harda | 1.52 | 2.76 | 2.68 | 3.88 | 1.92 | 2.04 | 0.80 | 6.16 |
| Hoshangabad | 1.83 | 2.80 | 3.03 | 3.63 | 2.13 | 2.10 | 1.20 | 6.60 |
| Indore | 1.96 | 2.56 | 3.08 | 3.48 | 1.96 | 2.24 | 1.20 | 5.64 |
| Jabalpur | 4.12 | 4.44 | 5.32 | 6.68 | 3.88 | 3.20 | 4.12 | 10.44 |
| Jhabua | 3.00 | 2.64 | 2.47 | 2.91 | 1.13 | 2.49 | 1.56 | 5.58 |
| Katni | 4.49 | 5.67 | 5.73 | 7.84 | 4.11 | 3.64 | 4.69 | 11.36 |
| Mandla | 3.04 | 3.48 | 5.64 | 6.72 | 2.94 | 3.30 | 3.94 | 10.92 |
| Mandsaur | 2.17 | 2.93 | 3.67 | 4.57 | 2.63 | 2.30 | 3.07 | 6.97 |
| Morena | 4.27 | 5.93 | 5.63 | 7.13 | 6.23 | 5.17 | 6.63 | 10.40 |
| Narsinghpur | 4.23 | 4.93 | 5.07 | 6.17 | 4.20 | 3.87 | 3.67 | 10.10 |
| Neemuch | 2.20 | 3.15 | 3.48 | 4.70 | 3.10 | 2.33 | 3.35 | 7.70 |
| Panna | 4.57 | 6.18 | 5.00 | 7.65 | 4.51 | 4.89 | 5.09 | 10.89 |
| Raisen | 3.10 | 3.87 | 3.90 | 4.50 | 3.45 | 2.95 | 1.98 | 7.38 |
| Rajgarh | 1.92 | 2.26 | 2.68 | 3.60 | 1.96 | 1.22 | 1.28 | 6.00 |
| Ratlam | 2.37 | 2.46 | 2.91 | 3.57 | 1.71 | 2.23 | 2.06 | 5.83 |
| Rewa | 3.46 | 6.08 | 4.04 | 7.86 | 3.06 | 4.10 | 5.46 | 10.18 |
| Sagar | 4.03 | 4.80 | 4.57 | 5.85 | 4.38 | 3.80 | 4.11 | 8.88 |
| Satna | 4.34 | 6.08 | 4.36 | 7.38 | 3.80 | 3.80 | 4.98 | 10.44 |
| Sehore | 1.98 | 2.53 | 2.69 | 3.64 | 1.60 | 1.69 | 0.76 | 5.73 |
| Seoni | 2.12 | 2.80 | 4.54 | 5.49 | 2.29 | 2.49 | 2.20 | 9.43 |
| Shahdol | 3.20 | 5.75 | 6.58 | 8.67 | 3.40 | 3.96 | 5.56 | 11.96 |
| Shajapur | 2.44 | 2.64 | 3.16 | 3.96 | 2.02 | 1.84 | 2.02 | 6.53 |
| Sheopur | 2.76 | 4.70 | 4.76 | 5.76 | 5.00 | 3.44 | 4.48 | 9.08 |
| Shivpuri | 3.75 | 5.51 | 5.24 | 6.80 | 5.39 | 3.75 | 5.32 | 10.21 |
| Sidhi | 3.09 | 5.92 | 4.92 | 8.96 | 2.68 | 4.33 | 5.20 | 10.64 |
| Tikamgarh | 4.32 | 5.68 | 5.16 | 7.92 | 5.60 | 3.84 | 6.20 | 10.84 |
| Ujjain | 2.84 | 2.76 | 3.31 | 4.24 | 2.02 | 2.58 | 2.24 | 6.53 |
| Umaria | 3.93 | 6.07 | 6.53 | 8.50 | 3.70 | 3.97 | 4.80 | 12.27 |
| Vidisha | 3.09 | 3.64 | 3.55 | 4.55 | 3.58 | 2.78 | 2.16 | 7.89 |
| West_Nimar | 2.67 | 2.95 | 3.38 | 4.83 | 2.07 | 3.55 | 1.80 | 7.55 |

Changes in the number of wet monsoon season were estimated for the projected future climate for the RCP 2.6, 4.5, 6.0, and 8.5 (Figure 24, 25). To understand changes in extreme wet periods during the monsoon season under the projected future climate SPI and SPEI were used. Multimodel ensemble mean changes in frequency of extreme wet monsoon season were estimated with respect to the historic reference (1971-2000) period for the Near (2016-2045) and Mid (2046-2075) term climate. Consistent with the projected changes in the monsoon season precipitation, changes in the frequency of wet seasons under the projected future climate showed uncertainty based on the RCPs. For instance, wet monsoon seasons based on just precipitation (SPI) showed an increase in the frequency under the RCP 2.6, and 6.0 in both Near and Mid term periods across the state of MP. On the other hand, extreme wet monsoon seasons are projected to increase or decline in some parts of the state under the RCP 4.5 and 8.5 scenarios (Figure 24). Results based on SPEI are consistent with the SPI for the RCP 2.6 and 6.0, however, substantial declines are projected under the RCP 4.5 and 8.5 scenarios in the extreme wet monsoon seasons for both Near (2016-2045) and Mid (2046-2075) climate (Figure 25). Changes in the extreme wet monsoon season frequency for each district are reported in Table 10.

**Box 10**

- Considering drought projections based on precipitation (SPI), frequency of severe, extreme, and exceptional droughts is projected to decline in RCP 2.6 and 6.0
- Droughts in Madhya Pradesh are projected to become more frequent in Near term under RCP 4.5 and in Midterm under RCP 8.5
- Increased air temperature under the projected future climate will enhance the drought frequency in Madhya Pradesh
- Drought based on SPEI are projected to increase across the state under all the RCPs
- Frequency of extreme wet monsoon seasons are projected to increase under the RCP 2.6 and 6.0 scenarios in Madhya Pradesh

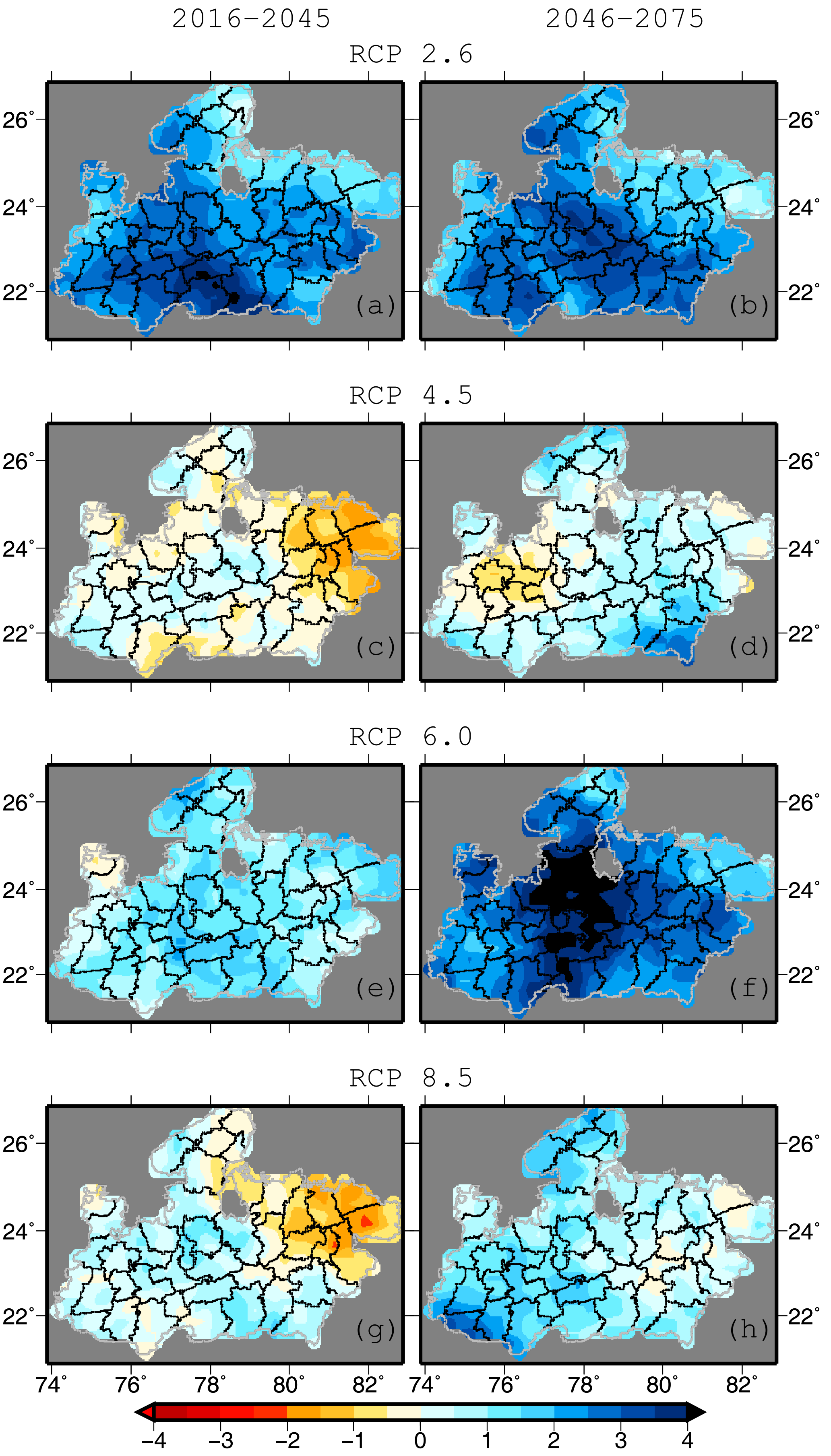


**Figure 24.** Ensemble mean projected change in number of wet monsoon seasons (based on SPI > 1.3)

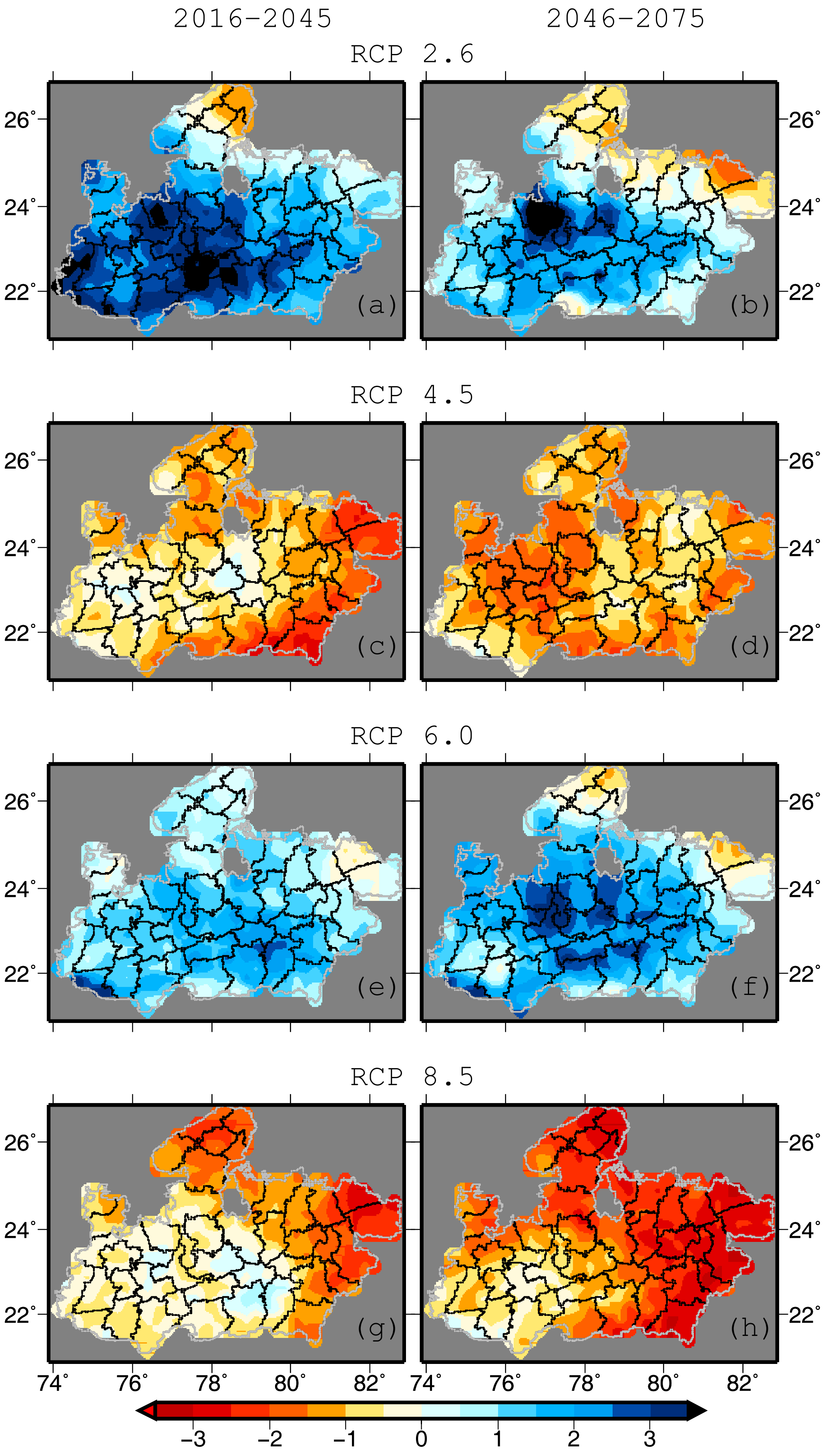


**Figure 25.** Ensemble mean projected changes in number of wet monsoon seasons (based on SPEI > 1.3)

**Table 10:** Ensemble mean changes in number of wet monsoon season (per 30 years; SPEI > 1.3)

| District | RCP 2.6 | | RCP 4.5 | | RCP 6.0 | | RCP 8.5 | |
|---|---|---|---|---|---|---|---|---|
| | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 |
| Anuppur | 1.60 | 0.33 | -1.87 | -1.53 | 0.87 | 0.80 | -2.07 | -2.93 |
| Ashoknagar | 1.66 | 0.43 | -1.37 | -1.46 | 0.54 | 1.83 | -1.00 | -2.23 |
| Balaghat | 1.66 | 0.37 | -2.46 | -1.46 | 1.24 | 0.91 | -1.30 | -2.77 |
| Barwani | 3.32 | 1.76 | -0.24 | -0.20 | 2.88 | 2.64 | -0.36 | 0.12 |
| Betul | 2.87 | 1.08 | -1.32 | -1.58 | 1.08 | 1.73 | -0.45 | -1.42 |
| Bhind | -1.30 | -0.67 | -1.27 | -1.27 | 0.30 | -0.80 | -1.97 | -2.93 |
| Bhopal | 3.20 | 3.20 | -0.53 | -1.60 | 1.87 | 3.40 | -0.67 | -0.87 |
| Burhanpur | 2.35 | 1.35 | -1.30 | -0.60 | 1.00 | 2.00 | -0.95 | -0.75 |
| Chhatarpur | 0.88 | -0.28 | -1.00 | -1.12 | 1.15 | 1.12 | -1.22 | -2.25 |
| Chhindwara | 2.85 | 1.69 | -1.29 | -1.06 | 1.72 | 1.87 | -0.02 | -1.51 |
| Damoh | 1.71 | 1.16 | -0.76 | -1.09 | 1.24 | 2.00 | -0.85 | -2.36 |
| Datia | -1.30 | -0.95 | -1.05 | -1.30 | 0.50 | -0.05 | -1.90 | -2.75 |
| Dewas | 2.67 | 2.20 | -0.33 | -1.71 | 1.27 | 1.62 | -0.24 | -0.33 |
| Dhar | 2.80 | 1.09 | -0.65 | -1.25 | 0.89 | 0.82 | -0.47 | -0.95 |
| Dindori | 2.20 | 1.31 | -1.76 | -1.16 | 1.27 | 1.69 | -1.67 | -2.62 |
| East_Nimar | 3.15 | 2.09 | -0.91 | -1.25 | 1.45 | 1.91 | -0.47 | -0.60 |
| Guna | 2.20 | 1.56 | -1.20 | -1.64 | 1.02 | 2.09 | -0.53 | -2.07 |
| Gwalior | -0.53 | -0.57 | -1.00 | -1.13 | 0.57 | -0.20 | -1.97 | -2.50 |
| Harda | 3.12 | 1.92 | -0.68 | -1.64 | 1.20 | 1.92 | -0.36 | -0.76 |
| Hoshangabad | 3.73 | 2.05 | -0.60 | -1.08 | 1.78 | 2.60 | -0.38 | -0.85 |
| Indore | 2.48 | 1.88 | -0.04 | -1.56 | 1.20 | 0.96 | -0.36 | -0.60 |
| Jabalpur | 2.44 | 2.04 | -0.88 | -1.00 | 1.96 | 2.16 | -0.32 | -2.16 |
| Jhabua | 3.29 | 0.80 | -0.53 | -0.82 | 0.82 | 1.22 | -0.40 | -0.82 |
| Katni | 1.93 | 0.98 | -1.18 | -0.87 | 1.18 | 2.09 | -1.40 | -2.58 |
| Mandla | 2.14 | 1.16 | -1.64 | -0.98 | 1.80 | 1.76 | -1.20 | -2.50 |
| Mandsaur | 1.83 | 0.57 | -1.27 | -1.77 | 0.20 | 2.00 | -0.97 | -1.87 |
| Morena | -0.73 | -0.67 | -1.20 | -1.07 | 0.43 | -0.60 | -2.03 | -2.63 |
| Narsinghpur | 2.53 | 1.83 | -0.13 | -0.80 | 2.17 | 2.17 | 0.07 | -1.60 |
| Neemuch | 2.35 | 0.35 | -0.95 | -1.33 | 0.38 | 2.05 | -0.85 | -1.53 |
| Panna | 1.35 | -0.06 | -1.05 | -0.65 | 0.88 | 1.28 | -1.34 | -2.29 |
| Raisen | 3.12 | 2.42 | -0.18 | -1.18 | 1.68 | 2.58 | -0.07 | -1.07 |
| Rajgarh | 3.34 | 3.74 | -0.82 | -1.60 | 1.68 | 2.70 | -0.34 | -1.36 |
| Ratlam | 2.29 | 1.03 | -0.31 | -1.23 | 0.97 | 1.94 | -0.34 | -1.37 |
| Rewa | 0.30 | -1.54 | -2.22 | -1.38 | -0.26 | -0.76 | -2.62 | -2.74 |
| Sagar | 2.54 | 2.26 | -0.22 | -0.89 | 1.66 | 2.58 | -0.34 | -1.66 |
| Satna | 1.06 | -0.24 | -1.52 | -0.62 | 0.40 | 0.50 | -1.74 | -2.28 |
| Sehore | 3.24 | 2.62 | -0.56 | -1.82 | 1.44 | 2.49 | -0.38 | -0.64 |
| Seoni | 2.72 | 1.62 | -1.46 | -1.15 | 2.25 | 2.05 | 0.08 | -1.97 |
| Shahdol | 1.45 | 0.44 | -1.69 | -1.36 | 0.65 | 0.78 | -2.07 | -2.84 |
| Shajapur | 2.93 | 2.00 | -0.71 | -1.82 | 1.13 | 2.20 | -0.13 | -1.18 |
| Sheopur | 1.00 | 0.14 | -0.82 | -0.84 | 0.84 | 0.66 | -1.50 | -1.94 |
| Shivpuri | 0.63 | -0.03 | -1.24 | -1.04 | 0.69 | 1.15 | -1.56 | -2.16 |
| Sidhi | 0.91 | -0.61 | -2.15 | -1.32 | 0.09 | -0.07 | -2.43 | -2.69 |
| Tikamgarh | 0.36 | -0.52 | -1.56 | -1.64 | 1.16 | 1.40 | -1.60 | -2.44 |
| Ujjain | 2.53 | 1.42 | -0.13 | -1.62 | 1.24 | 1.69 | -0.44 | -1.16 |
| Umaria | 1.70 | 0.63 | -1.13 | -0.87 | 0.87 | 1.30 | -1.70 | -2.57 |
| Vidisha | 2.64 | 2.25 | -0.84 | -1.65 | 1.25 | 2.42 | -0.47 | -1.65 |
| West_Nimar | 2.47 | 1.20 | -0.53 | -0.90 | 1.18 | 0.68 | -0.67 | -0.62 |

### 4.2.3. Air Temperature

Multimodel ensemble mean changes based on downscaled and bias corrected data for the five best CMIP5 models were estimated for all the RCPs and for the Near (2016-2045) and Mid (2046-2075) term climate. Changes in mean monthly temperature for the projected future climate are shown in Figure 26. All the RCPs indicated a significant warming in all the months in the state of MP under the projected future climate. Warming is projected to become more prominent in the late 21st century (Figure 26). On an average, mean air temperature is projected to rise 1-1.2 °C in the Near (2016-2045) term climate under the selected RCPs. However, the state is projected to witness higher increases in air temperature during the Mid (2046-2075) term period under the projected RCPs (Figure 26 Table 11, 12). Moreover, the RCP 6.0 and 8.5 showed more prominent warming in the state. Changes for the individual months and intermodel variation can be obtained from Table 11 and 12.

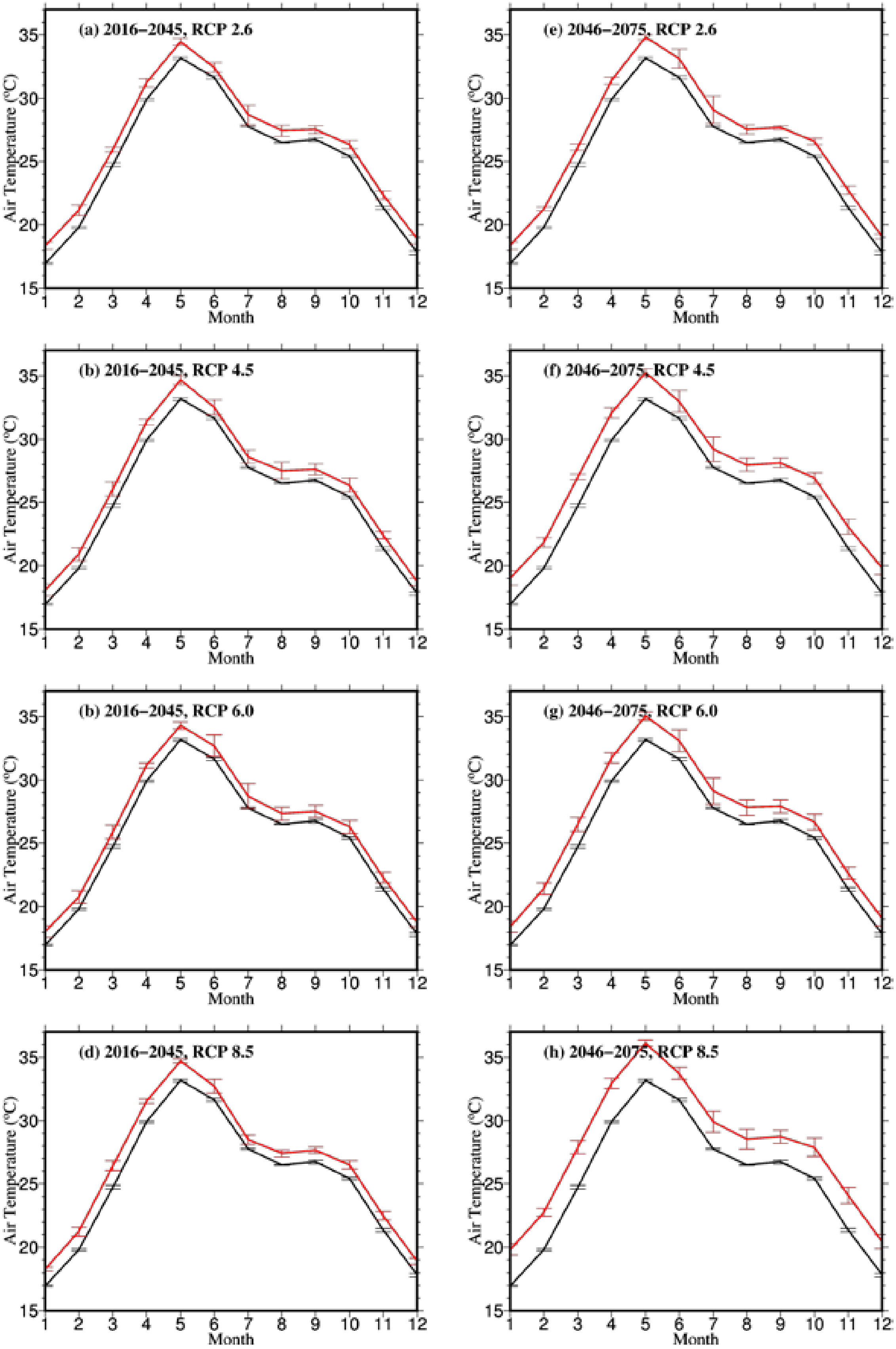


**Figure 26:** Multimodel ensemble mean projected changes (red) under the projected future climate in the mean monthly air temperature for the Near and Mid term climate for the selected RCPs. Changes were estimated with respect to historic mean monthly air temperature for the reference (1971-2000) period. Error bars show intermodel variation in the five best CMIP5 models.

**Table 11.** Multimodel ensemble mean and inter model variation (std.) in monthly mean air temperature in the state of Madhya Pradesh for the Historic (1971-2000) and projected future climate for the period of 2016-2045.

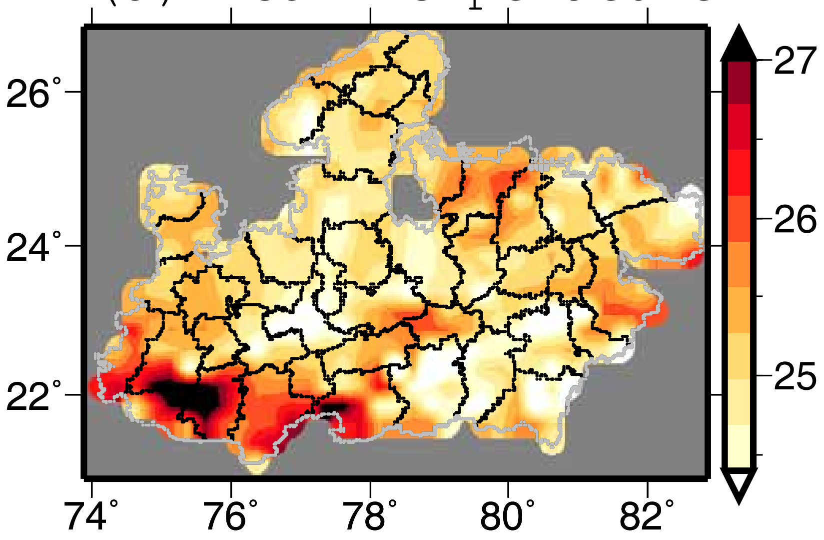
| Month | Historic | | RCP 2.6 | | RCP 4.5 | | RCP 6.0 | | RCP 8.5 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | Std. | Mean | Std. | Mean | Std. | Mean | Std. | Mean | Std. |
| January | 17.0 | 0.1 | 18.4 | 0.3 | 18.1 | 0.5 | 18.0 | 0.4 | 18.3 | 0.1 |
| February | 19.8 | 0.1 | 21.2 | 0.4 | 20.9 | 0.5 | 20.7 | 0.5 | 21.2 | 0.4 |
| March | 24.7 | 0.2 | 26.0 | 0.2 | 26.1 | 0.6 | 25.9 | 0.5 | 26.4 | 0.4 |
| April | 29.9 | 0.1 | 31.2 | 0.3 | 31.3 | 0.2 | 31.1 | 0.2 | 31.5 | 0.2 |
| May | 33.2 | 0.1 | 34.5 | 0.3 | 34.6 | 0.4 | 34.3 | 0.3 | 34.7 | 0.2 |
| June | 31.6 | 0.1 | 32.4 | 0.4 | 32.5 | 0.6 | 32.7 | 0.9 | 32.7 | 0.5 |
| July | 27.8 | 0.0 | 28.7 | 0.8 | 28.6 | 0.5 | 28.7 | 1.0 | 28.5 | 0.4 |
| August | 26.5 | 0.0 | 27.5 | 0.4 | 27.5 | 0.6 | 27.3 | 0.5 | 27.4 | 0.3 |
| September | 26.7 | 0.1 | 27.5 | 0.3 | 27.6 | 0.4 | 27.5 | 0.5 | 27.7 | 0.3 |
| October | 25.4 | 0.1 | 26.3 | 0.3 | 26.4 | 0.6 | 26.3 | 0.5 | 26.5 | 0.3 |
| November | 21.4 | 0.1 | 22.4 | 0.3 | 22.4 | 0.3 | 22.3 | 0.4 | 22.5 | 0.3 |
| December | 17.8 | 0.1 | 18.9 | 0.3 | 18.7 | 0.3 | 18.7 | 0.3 | 18.9 | 0.3 |

**Table 12.** Multimodel ensemble mean and inter model variation (std.) in monthly mean air temperature in the state of Madhya Pradesh for the Historic (1971-2000) and projected future climate for the period of 2046-2075.

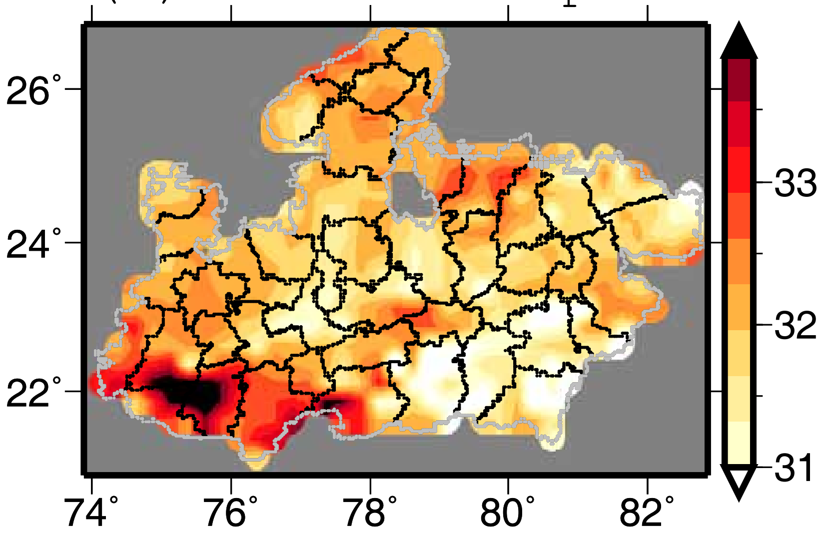
| Month | Historic | | RCP 2.6 | | RCP 4.5 | | RCP 6.0 | | RCP 8.5 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | Std. | Mean | Std. | Mean | Std. | Mean | Std. | Mean | Std. |
| January | 17.0 | 0.1 | 18.4 | 0.3 | 19.0 | 0.6 | 18.4 | 0.4 | 19.8 | 0.4 |
| February | 19.8 | 0.1 | 21.3 | 0.1 | 21.8 | 0.4 | 21.4 | 0.4 | 22.8 | 0.3 |
| March | 24.7 | 0.2 | 26.1 | 0.3 | 27.0 | 0.2 | 26.5 | 0.6 | 27.9 | 0.5 |
| April | 29.9 | 0.1 | 31.4 | 0.3 | 32.1 | 0.4 | 31.7 | 0.4 | 32.9 | 0.4 |
| May | 33.2 | 0.1 | 34.8 | 0.2 | 35.2 | 0.3 | 35.0 | 0.3 | 36.1 | 0.2 |
| June | 31.6 | 0.1 | 33.1 | 0.7 | 33.0 | 0.9 | 33.1 | 0.9 | 33.7 | 0.5 |
| July | 27.8 | 0.0 | 29.1 | 1.1 | 29.2 | 1.0 | 29.1 | 1.0 | 29.9 | 0.8 |
| August | 26.5 | 0.0 | 27.5 | 0.4 | 28.0 | 0.5 | 27.8 | 0.6 | 28.5 | 0.8 |
| September | 26.7 | 0.1 | 27.7 | 0.2 | 28.1 | 0.4 | 27.9 | 0.5 | 28.7 | 0.5 |
| October | 25.4 | 0.1 | 26.6 | 0.3 | 26.9 | 0.4 | 26.7 | 0.6 | 27.9 | 0.7 |
| November | 21.4 | 0.1 | 22.7 | 0.3 | 23.1 | 0.6 | 22.6 | 0.5 | 24.1 | 0.6 |
| December | 17.8 | 0.1 | 19.1 | 0.2 | 19.8 | 0.5 | 19.0 | 0.6 | 20.4 | 0.6 |

Figure 27 shows multimodel ensemble mean of average, maximum and minimum annual temperature for the state of MP. From the results, it can be seen that the multimodel ensemble mean annual air temperatures are well represented in the downscaled and bias corrected high resolution dataset that was developed for the state. The variation in mean annual air temperature was between 24-28 °C. On the other hand, the mean annual maximum and minimum temperature varied between 31-37 and 17-20°C in the multimodel ensemble mean for the historic period. Here, it can be noted that the changes under the projected future climate in mean, maximum, and minimum annual average temperatures were estimated with respect to the historic reference period (1971-2000). Consistent with the projections for mean monthly temperatures for the state, mean annual temperature is projected to increase by 1-1.2 °C under all the RCPs in the Near (2016-2045) term climate. However, based on multimodel ensemble mean projections, mean annual temperature is projected to increase between 1.8 to 3.0 °C across the state (Figure 28). Moreover, the RCP 8.5 scenarios showed higher increases ranging between 2.5 to 3.5 °C in the multimodel ensemble mean annual air temperature in the state of MP in the Mid (2046-2075) term projections. Results also suggest that majority of the district of the state may face increases of 1°C and 2.0°C in mean annual temperature under the projected future climate (Table 13).

(a) Mean Temperature



(b) Maximum Temperature



(c) Minimum Temperature

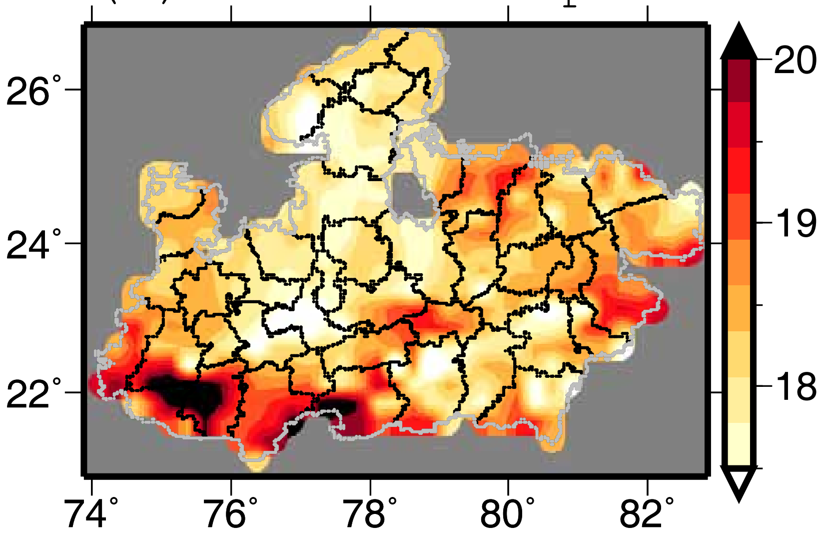


**Figure 27:** Multimodel ensemble mean air temperature (1951-2005) of (a) daily mean, (b) Maximum, and (c) minimum temperature.

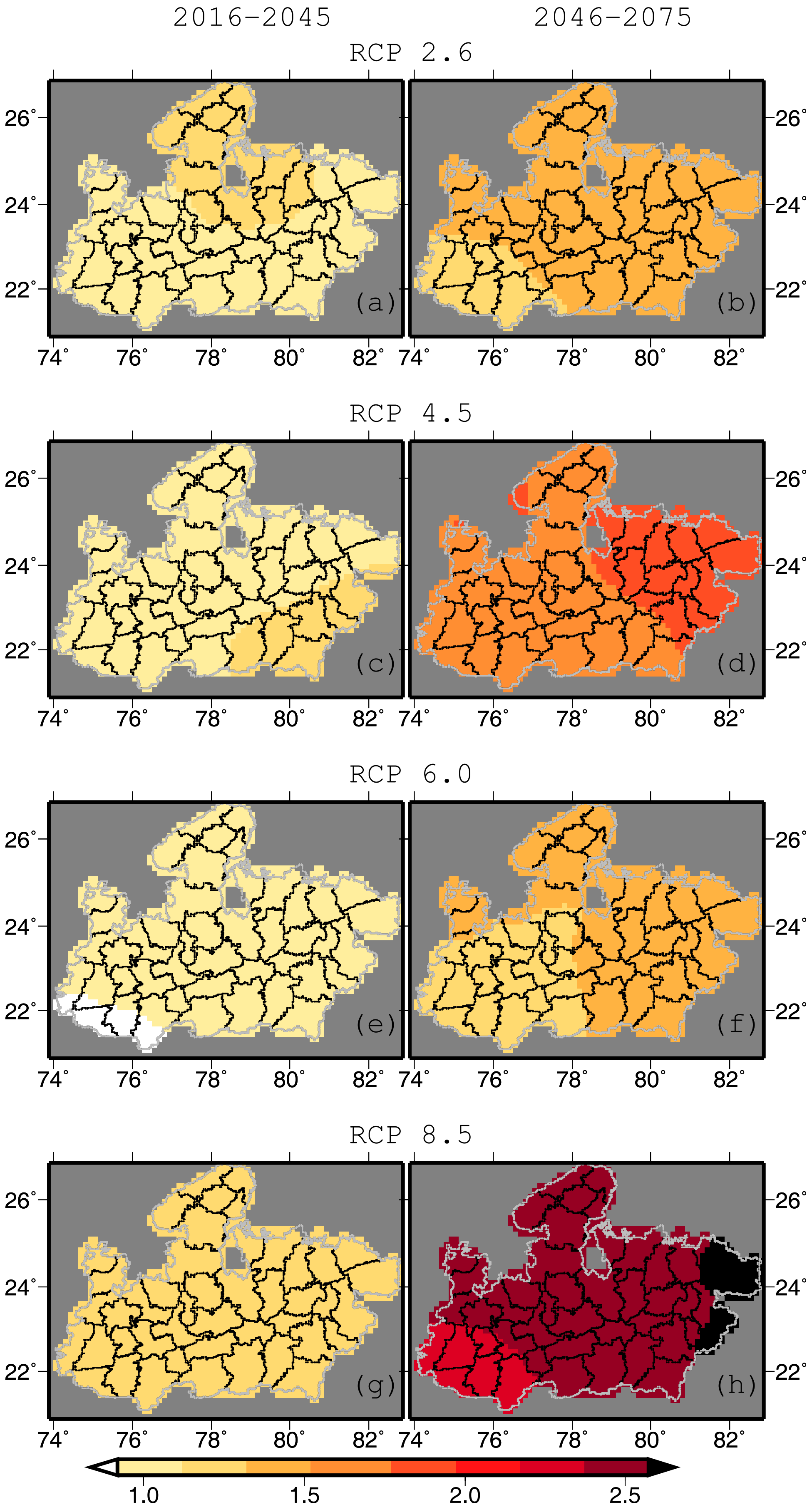


**Figure 28:** Ensemble projected change in mean annual of daily mean temperature.

**Table13:** Multimodel ensemble mean change in mean daily air temperature (ºC)

| District | RCP 2.6 | | RCP 4.5 | | RCP 6.0 | | RCP 8.5 | |
|---|---|---|---|---|---|---|---|---|
| | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 |
| Anuppur | 1.07 | 1.40 | 1.15 | 1.82 | 0.98 | 1.41 | 1.24 | 2.58 |
| Ashoknagar | 1.13 | 1.45 | 1.05 | 1.76 | 1.01 | 1.32 | 1.22 | 2.52 |
| Balaghat | 1.02 | 1.38 | 1.16 | 1.75 | 0.97 | 1.40 | 1.26 | 2.55 |
| Barwani | 1.00 | 1.23 | 0.96 | 1.56 | 0.89 | 1.19 | 1.14 | 2.21 |
| Betul | 1.05 | 1.34 | 1.10 | 1.69 | 0.96 | 1.29 | 1.20 | 2.44 |
| Bhind | 1.16 | 1.49 | 1.06 | 1.72 | 1.04 | 1.43 | 1.25 | 2.55 |
| Bhopal | 1.11 | 1.38 | 1.06 | 1.72 | 0.97 | 1.30 | 1.20 | 2.47 |
| Burhanpur | 1.00 | 1.24 | 1.01 | 1.60 | 0.90 | 1.21 | 1.15 | 2.27 |
| Chhatarpur | 1.14 | 1.48 | 1.06 | 1.79 | 0.99 | 1.35 | 1.21 | 2.53 |
| Chhindwara | 1.05 | 1.38 | 1.13 | 1.72 | 0.97 | 1.34 | 1.22 | 2.50 |
| Damoh | 1.13 | 1.46 | 1.09 | 1.79 | 0.97 | 1.34 | 1.19 | 2.52 |
| Datia | 1.16 | 1.49 | 1.07 | 1.75 | 1.04 | 1.39 | 1.25 | 2.55 |
| Dewas | 1.07 | 1.32 | 1.04 | 1.67 | 0.96 | 1.26 | 1.18 | 2.39 |
| Dhar | 1.02 | 1.27 | 0.99 | 1.61 | 0.93 | 1.23 | 1.17 | 2.29 |
| Dindori | 1.07 | 1.42 | 1.15 | 1.79 | 0.97 | 1.39 | 1.23 | 2.56 |
| East_Nimar | 1.03 | 1.27 | 1.04 | 1.64 | 0.93 | 1.23 | 1.16 | 2.33 |
| Guna | 1.12 | 1.42 | 1.05 | 1.75 | 1.03 | 1.33 | 1.22 | 2.50 |
| Gwalior | 1.16 | 1.49 | 1.08 | 1.74 | 1.06 | 1.40 | 1.26 | 2.55 |
| Harda | 1.06 | 1.32 | 1.06 | 1.67 | 0.95 | 1.26 | 1.18 | 2.39 |
| Hoshangabad | 1.08 | 1.37 | 1.09 | 1.71 | 0.97 | 1.31 | 1.21 | 2.47 |
| Indore | 1.05 | 1.29 | 1.02 | 1.65 | 0.96 | 1.25 | 1.17 | 2.34 |
| Jabalpur | 1.10 | 1.44 | 1.12 | 1.77 | 0.96 | 1.35 | 1.20 | 2.53 |
| Jhabua | 1.02 | 1.28 | 0.99 | 1.61 | 0.94 | 1.25 | 1.17 | 2.30 |
| Katni | 1.11 | 1.46 | 1.10 | 1.80 | 0.96 | 1.35 | 1.19 | 2.53 |
| Mandla | 1.06 | 1.42 | 1.15 | 1.77 | 0.97 | 1.38 | 1.23 | 2.55 |
| Mandsaur | 1.08 | 1.38 | 1.05 | 1.74 | 1.05 | 1.36 | 1.23 | 2.46 |
| Morena | 1.16 | 1.50 | 1.08 | 1.72 | 1.06 | 1.44 | 1.27 | 2.55 |
| Narsinghpur | 1.09 | 1.43 | 1.11 | 1.75 | 0.97 | 1.34 | 1.20 | 2.52 |
| Neemuch | 1.09 | 1.40 | 1.07 | 1.76 | 1.07 | 1.39 | 1.26 | 2.49 |
| Panna | 1.13 | 1.48 | 1.07 | 1.80 | 0.97 | 1.35 | 1.20 | 2.54 |
| Raisen | 1.11 | 1.41 | 1.08 | 1.74 | 0.97 | 1.32 | 1.20 | 2.49 |
| Rajgarh | 1.10 | 1.38 | 1.04 | 1.73 | 1.01 | 1.31 | 1.20 | 2.47 |
| Ratlam | 1.05 | 1.33 | 1.02 | 1.69 | 1.00 | 1.31 | 1.20 | 2.40 |
| Rewa | 1.10 | 1.47 | 1.07 | 1.81 | 0.99 | 1.41 | 1.23 | 2.58 |
| Sagar | 1.13 | 1.45 | 1.08 | 1.77 | 0.98 | 1.33 | 1.19 | 2.52 |
| Satna | 1.12 | 1.48 | 1.08 | 1.81 | 0.98 | 1.37 | 1.21 | 2.55 |
| Sehore | 1.09 | 1.35 | 1.06 | 1.70 | 0.97 | 1.29 | 1.19 | 2.44 |
| Seoni | 1.05 | 1.41 | 1.14 | 1.74 | 0.96 | 1.36 | 1.22 | 2.53 |
| Shahdol | 1.09 | 1.43 | 1.13 | 1.81 | 0.97 | 1.39 | 1.23 | 2.57 |
| Shajapur | 1.08 | 1.35 | 1.04 | 1.71 | 1.00 | 1.30 | 1.19 | 2.44 |
| Sheopur | 1.16 | 1.48 | 1.09 | 1.76 | 1.09 | 1.41 | 1.28 | 2.55 |
| Shivpuri | 1.15 | 1.47 | 1.07 | 1.76 | 1.05 | 1.36 | 1.25 | 2.54 |
| Sidhi | 1.09 | 1.44 | 1.11 | 1.82 | 0.98 | 1.42 | 1.25 | 2.60 |
| Tikamgarh | 1.15 | 1.48 | 1.07 | 1.78 | 1.02 | 1.34 | 1.22 | 2.53 |
| Ujjain | 1.06 | 1.32 | 1.03 | 1.68 | 0.99 | 1.29 | 1.18 | 2.39 |
| Umaria | 1.10 | 1.45 | 1.12 | 1.81 | 0.97 | 1.37 | 1.20 | 2.55 |
| Vidisha | 1.12 | 1.42 | 1.05 | 1.75 | 0.98 | 1.32 | 1.20 | 2.50 |
| West_Nimar | 1.02 | 1.26 | 1.00 | 1.61 | 0.92 | 1.21 | 1.16 | 2.28 |

Multimodel ensemble mean changes in annual maximum temperature were estimated for the state of MP under the projected future climate (Figure 29). Mean annual maximum temperature is projected to rise by 1-1.3 °C in the Near term climate. However, an increase of more than 3°C in the mean annual maximum temperature is projected for the state of MP under the RCP 8.5 Scenario (Figure29). District level analysis of the multimodel ensemble mean annual maximum temperature suggested that the majority of the district in the state are projected to witness more than 1°C rise in the Near term and more than 2 °C increase in the Mid (2046-2075) climate (Table 14).

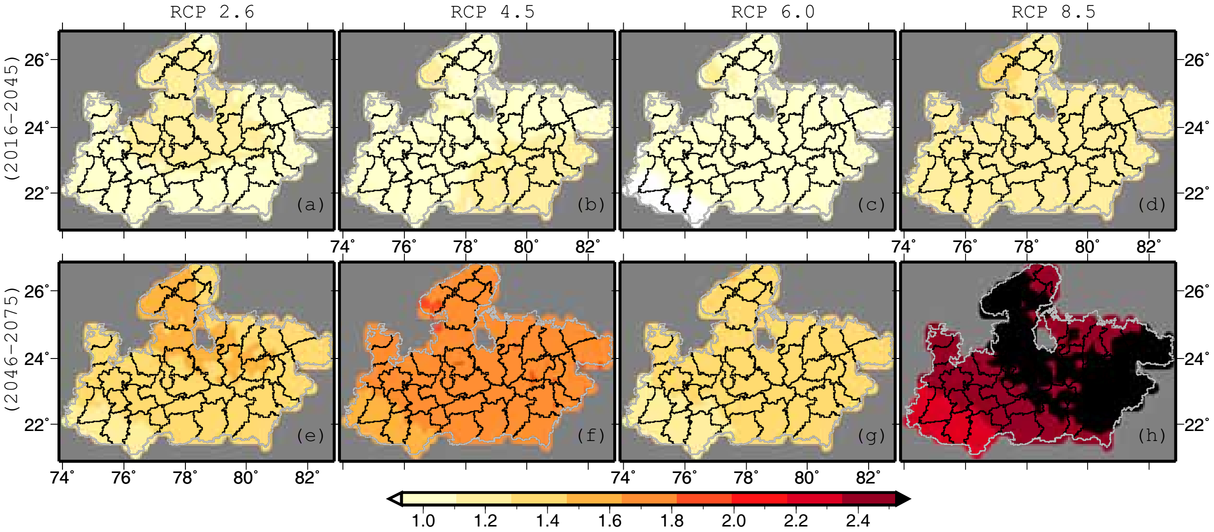


**Figure 29:** Multimodel ensemble mean projected change in mean annual maximum temperature (°C).

**Table14:** Ensemble mean projected changes in mean annual maximum temperature (°C)

| District | RCP 2.6 | | RCP 4.5 | | RCP 6.0 | | RCP 8.5 | |
|---|---|---|---|---|---|---|---|---|
| | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 |
| Anuppur | 1.04 | 1.37 | 1.12 | 1.80 | 0.95 | 1.37 | 1.24 | 2.57 |
| Ashoknagar | 1.17 | 1.49 | 1.10 | 1.80 | 1.05 | 1.36 | 1.27 | 2.55 |
| Balaghat | 1.00 | 1.36 | 1.15 | 1.73 | 0.95 | 1.38 | 1.24 | 2.52 |
| Barwani | 1.00 | 1.23 | 0.96 | 1.56 | 0.88 | 1.19 | 1.14 | 2.21 |
| Betul | 1.06 | 1.35 | 1.11 | 1.70 | 0.97 | 1.31 | 1.22 | 2.45 |
| Bhind | 1.10 | 1.44 | 1.00 | 1.66 | 0.98 | 1.38 | 1.19 | 2.49 |
| Bhopal | 1.16 | 1.42 | 1.10 | 1.75 | 1.00 | 1.32 | 1.23 | 2.51 |
| Burhanpur | 0.99 | 1.22 | 0.98 | 1.59 | 0.88 | 1.21 | 1.13 | 2.26 |
| Chhatarpur | 1.12 | 1.46 | 1.05 | 1.76 | 0.97 | 1.33 | 1.19 | 2.51 |
| Chhindwara | 1.06 | 1.39 | 1.13 | 1.72 | 0.97 | 1.34 | 1.22 | 2.51 |
| Damoh | 1.14 | 1.46 | 1.10 | 1.79 | 0.98 | 1.34 | 1.19 | 2.53 |
| Datia | 1.11 | 1.44 | 1.03 | 1.70 | 0.99 | 1.35 | 1.19 | 2.53 |
| Dewas | 1.08 | 1.35 | 1.06 | 1.70 | 0.98 | 1.30 | 1.20 | 2.40 |
| Dhar | 1.02 | 1.27 | 0.99 | 1.60 | 0.93 | 1.23 | 1.17 | 2.29 |
| Dindori | 1.06 | 1.41 | 1.14 | 1.79 | 0.97 | 1.38 | 1.21 | 2.55 |
| East_Nimar | 1.03 | 1.28 | 1.04 | 1.63 | 0.93 | 1.23 | 1.16 | 2.32 |
| Guna | 1.17 | 1.47 | 1.10 | 1.80 | 1.07 | 1.37 | 1.28 | 2.55 |
| Gwalior | 1.14 | 1.48 | 1.06 | 1.73 | 1.03 | 1.39 | 1.25 | 2.53 |
| Harda | 1.06 | 1.33 | 1.06 | 1.67 | 0.96 | 1.27 | 1.20 | 2.40 |
| Hoshangabad | 1.10 | 1.40 | 1.11 | 1.74 | 0.98 | 1.33 | 1.22 | 2.49 |
| Indore | 1.05 | 1.29 | 1.03 | 1.66 | 0.98 | 1.27 | 1.19 | 2.35 |
| Jabalpur | 1.11 | 1.45 | 1.13 | 1.79 | 0.97 | 1.36 | 1.20 | 2.53 |
| Jhabua | 1.01 | 1.28 | 0.98 | 1.60 | 0.93 | 1.25 | 1.17 | 2.29 |
| Katni | 1.11 | 1.47 | 1.11 | 1.81 | 0.98 | 1.36 | 1.19 | 2.55 |
| Mandla | 1.07 | 1.43 | 1.15 | 1.79 | 0.98 | 1.39 | 1.24 | 2.57 |

| District | RCP 2.6 | | RCP 4.5 | | RCP 6.0 | | RCP 8.5 | |
|---|---|---|---|---|---|---|---|---|
| | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 |
| Mandsaur | 1.10 | 1.39 | 1.07 | 1.75 | 1.06 | 1.37 | 1.24 | 2.46 |
| Morena | 1.14 | 1.47 | 1.06 | 1.70 | 1.05 | 1.43 | 1.25 | 2.54 |
| Narsinghpur | 1.11 | 1.43 | 1.12 | 1.75 | 0.98 | 1.35 | 1.21 | 2.53 |
| Neemuch | 1.07 | 1.39 | 1.06 | 1.75 | 1.06 | 1.38 | 1.24 | 2.48 |
| Panna | 1.10 | 1.45 | 1.05 | 1.79 | 0.95 | 1.34 | 1.18 | 2.51 |
| Raisen | 1.14 | 1.43 | 1.10 | 1.76 | 0.99 | 1.35 | 1.23 | 2.53 |
| Rajgarh | 1.16 | 1.43 | 1.09 | 1.78 | 1.06 | 1.36 | 1.25 | 2.51 |
| Ratlam | 1.04 | 1.33 | 1.03 | 1.69 | 0.99 | 1.31 | 1.20 | 2.40 |
| Rewa | 1.06 | 1.41 | 1.03 | 1.76 | 0.94 | 1.35 | 1.18 | 2.53 |
| Sagar | 1.15 | 1.46 | 1.09 | 1.79 | 1.00 | 1.35 | 1.21 | 2.54 |
| Satna | 1.08 | 1.45 | 1.04 | 1.77 | 0.94 | 1.33 | 1.17 | 2.52 |
| Sehore | 1.12 | 1.39 | 1.09 | 1.74 | 0.99 | 1.31 | 1.21 | 2.47 |
| Seoni | 1.04 | 1.40 | 1.14 | 1.74 | 0.96 | 1.37 | 1.21 | 2.53 |
| Shahdol | 1.08 | 1.41 | 1.12 | 1.79 | 0.95 | 1.37 | 1.21 | 2.55 |
| Shajapur | 1.12 | 1.39 | 1.09 | 1.76 | 1.04 | 1.34 | 1.24 | 2.48 |
| Sheopur | 1.18 | 1.51 | 1.12 | 1.81 | 1.11 | 1.44 | 1.31 | 2.58 |
| Shivpuri | 1.16 | 1.49 | 1.08 | 1.78 | 1.07 | 1.37 | 1.28 | 2.55 |
| Sidhi | 1.05 | 1.40 | 1.08 | 1.79 | 0.94 | 1.39 | 1.22 | 2.57 |
| Tikamgarh | 1.14 | 1.46 | 1.05 | 1.76 | 1.01 | 1.31 | 1.21 | 2.52 |
| Ujjain | 1.08 | 1.34 | 1.05 | 1.70 | 1.01 | 1.31 | 1.21 | 2.41 |
| Umaria | 1.10 | 1.44 | 1.12 | 1.80 | 0.97 | 1.37 | 1.20 | 2.54 |
| Vidisha | 1.16 | 1.45 | 1.09 | 1.79 | 1.02 | 1.35 | 1.24 | 2.54 |
| West_Nimar | 1.02 | 1.26 | 1.00 | 1.61 | 0.92 | 1.21 | 1.15 | 2.28 |

Multimodel ensemble mean projections for the mean annual minimum temperature showed consistent results of increases across the state (Figure 30). Similar to the results of mean annual average and maximum air temperature, mean annual minimum temperature is projected to increase significantly in both the periods and in all the RCPs. A warming of 1-3°C in mean annual minimum temperature is likely under the projected future climate, with prominent increases in the eastern part of the state (Figure 30). Moreover, the district level analysis also suggested increases of 1-3 °C in majority of the district in the state of MP under the projected future climate (Table 15). Projected changes in mean, maximum, and minimum temperatures indicate profound implications in the areas of agriculture, water resources, and energy demands in future. Crop production in the state under the projected future climate may witness a decline due to increase in night time temperature. Moreover, due to increased air temperature, irrigation demands are likely to increase in future, which may in turn affect the water management strategies.

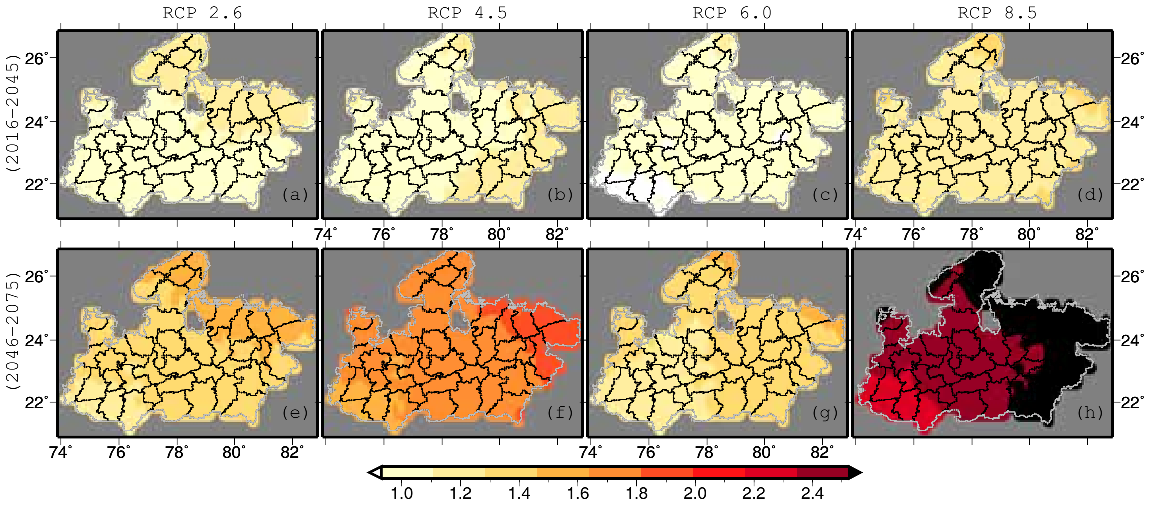


**Figure 30:** Ensemble mean projected change in mean annual minimum temperature (°C).

**Box 11**

- On an average, mean air temperature is projected to rise 1-1.2 °C in the Near (2016-2045) term climate under the selected RCPs
- The state is projected to witness higher increases in air temperature during the Mid (2046-2075) term period under the projected RCPs
- The RCP 8.5 scenarios showed higher increases ranging between 2.5 to 3.5 °C in the multimodel ensemble mean annual air temperature in the state of MP in the Mid (2046-2075) term projections
- District level analysis of the multimodel ensemble mean annual maximum temperature suggested that the majority of the district in the state are projected to witness more than 1°C rise in the Near (2016-2045) term and more than 2 °C increase in the Mid (2046-2075) climate
- Significant increases are projected in mean temperature across Madhya Pradesh under the future climate.

**Table15:** Ensemble mean projected changes in mean annual minimum temperature (°C)

| **District** | **RCP 2.6** | | **RCP 4.5** | | **RCP 6.0** | | **RCP 8.5** | |
|---|---|---|---|---|---|---|---|---|
| | **2016-2045** | **2046-2075** | **2016-2045** | **2046-2075** | **2016-2045** | **2046-2075** | **2016-2045** | **2046-2075** |
| Anuppur | 1.09 | 1.43 | 1.18 | 1.83 | 1.00 | 1.44 | 1.25 | 2.60 |
| Ashoknagar | 1.09 | 1.40 | 1.01 | 1.72 | 0.98 | 1.29 | 1.17 | 2.48 |
| Balaghat | 1.04 | 1.41 | 1.18 | 1.78 | 0.99 | 1.41 | 1.28 | 2.57 |
| Barwani | 1.00 | 1.23 | 0.96 | 1.56 | 0.90 | 1.19 | 1.15 | 2.22 |
| Betul | 1.03 | 1.33 | 1.09 | 1.68 | 0.95 | 1.28 | 1.18 | 2.42 |
| Bhind | 1.22 | 1.55 | 1.12 | 1.77 | 1.11 | 1.47 | 1.31 | 2.61 |
| Bhopal | 1.06 | 1.34 | 1.01 | 1.70 | 0.95 | 1.28 | 1.16 | 2.44 |
| Burhanpur | 1.01 | 1.26 | 1.04 | 1.62 | 0.92 | 1.21 | 1.17 | 2.29 |
| Chhatarpur | 1.16 | 1.50 | 1.08 | 1.82 | 1.01 | 1.36 | 1.23 | 2.55 |
| Chhindwara | 1.05 | 1.37 | 1.12 | 1.71 | 0.96 | 1.33 | 1.22 | 2.49 |
| Damoh | 1.12 | 1.46 | 1.08 | 1.78 | 0.96 | 1.34 | 1.18 | 2.51 |
| Datia | 1.20 | 1.54 | 1.10 | 1.79 | 1.09 | 1.43 | 1.30 | 2.57 |
| Dewas | 1.05 | 1.29 | 1.03 | 1.65 | 0.95 | 1.23 | 1.16 | 2.37 |
| Dhar | 1.03 | 1.27 | 0.99 | 1.62 | 0.94 | 1.23 | 1.17 | 2.29 |
| Dindori | 1.08 | 1.44 | 1.16 | 1.80 | 0.98 | 1.40 | 1.25 | 2.57 |
| East_Nimar | 1.03 | 1.27 | 1.03 | 1.64 | 0.92 | 1.23 | 1.17 | 2.33 |
| Guna | 1.08 | 1.38 | 1.00 | 1.70 | 0.98 | 1.29 | 1.17 | 2.46 |
| Gwalior | 1.18 | 1.50 | 1.09 | 1.76 | 1.08 | 1.41 | 1.28 | 2.57 |
| Harda | 1.06 | 1.30 | 1.07 | 1.67 | 0.95 | 1.25 | 1.17 | 2.38 |
| Hoshangabad | 1.06 | 1.35 | 1.08 | 1.68 | 0.95 | 1.29 | 1.19 | 2.45 |
| Indore | 1.04 | 1.29 | 1.02 | 1.64 | 0.93 | 1.23 | 1.15 | 2.34 |
| Jabalpur | 1.09 | 1.43 | 1.11 | 1.76 | 0.95 | 1.35 | 1.19 | 2.52 |
| Jhabua | 1.03 | 1.28 | 0.99 | 1.63 | 0.95 | 1.25 | 1.18 | 2.32 |
| Katni | 1.11 | 1.45 | 1.09 | 1.78 | 0.94 | 1.35 | 1.19 | 2.52 |
| Mandla | 1.05 | 1.41 | 1.14 | 1.76 | 0.95 | 1.38 | 1.22 | 2.54 |
| Mandsaur | 1.07 | 1.37 | 1.04 | 1.73 | 1.05 | 1.34 | 1.21 | 2.47 |
| Morena | 1.18 | 1.52 | 1.09 | 1.75 | 1.08 | 1.44 | 1.28 | 2.56 |
| Narsinghpur | 1.07 | 1.42 | 1.10 | 1.75 | 0.95 | 1.34 | 1.20 | 2.50 |
| Neemuch | 1.10 | 1.42 | 1.09 | 1.77 | 1.08 | 1.41 | 1.27 | 2.51 |
| Panna | 1.15 | 1.50 | 1.10 | 1.81 | 1.00 | 1.36 | 1.22 | 2.56 |
| Raisen | 1.08 | 1.39 | 1.06 | 1.71 | 0.95 | 1.28 | 1.17 | 2.46 |
| Rajgarh | 1.05 | 1.33 | 1.00 | 1.68 | 0.96 | 1.26 | 1.15 | 2.42 |
| Ratlam | 1.05 | 1.34 | 1.02 | 1.70 | 1.00 | 1.31 | 1.20 | 2.40 |
| Rewa | 1.15 | 1.52 | 1.12 | 1.86 | 1.04 | 1.47 | 1.28 | 2.63 |
| Sagar | 1.10 | 1.43 | 1.06 | 1.75 | 0.95 | 1.31 | 1.18 | 2.49 |

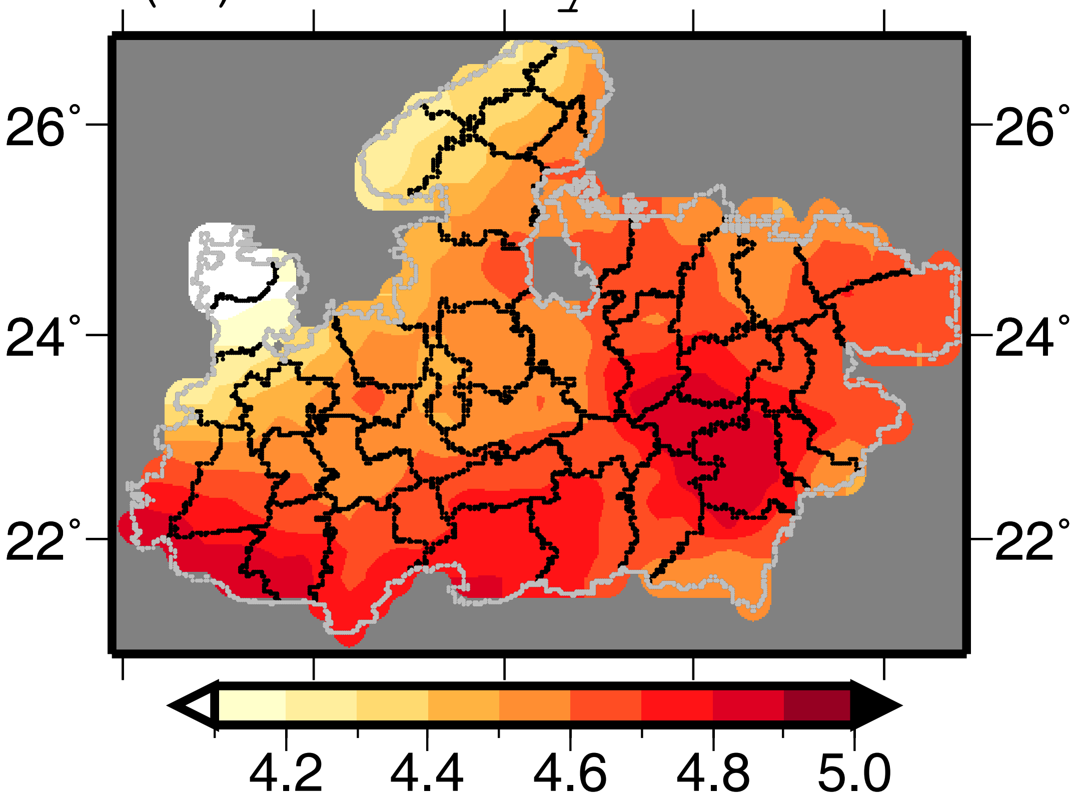
| District | RCP 2.6 | | RCP 4.5 | | RCP 6.0 | | RCP 8.5 | |
|---|---|---|---|---|---|---|---|---|
| | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 |
| Satna | 1.15 | 1.50 | 1.11 | 1.85 | 1.02 | 1.41 | 1.25 | 2.59 |
| Sehore | 1.06 | 1.32 | 1.04 | 1.66 | 0.95 | 1.27 | 1.17 | 2.41 |
| Seoni | 1.06 | 1.41 | 1.15 | 1.75 | 0.97 | 1.36 | 1.23 | 2.53 |
| Shahdol | 1.10 | 1.46 | 1.15 | 1.83 | 1.00 | 1.41 | 1.24 | 2.59 |
| Shajapur | 1.05 | 1.32 | 0.99 | 1.66 | 0.96 | 1.26 | 1.14 | 2.39 |
| Sheopur | 1.13 | 1.45 | 1.07 | 1.72 | 1.06 | 1.39 | 1.26 | 2.52 |
| Shivpuri | 1.14 | 1.45 | 1.06 | 1.74 | 1.03 | 1.34 | 1.23 | 2.52 |
| Sidhi | 1.12 | 1.47 | 1.14 | 1.85 | 1.02 | 1.45 | 1.28 | 2.63 |
| Tikamgarh | 1.16 | 1.50 | 1.08 | 1.79 | 1.02 | 1.38 | 1.24 | 2.55 |
| Ujjain | 1.04 | 1.31 | 1.01 | 1.67 | 0.97 | 1.26 | 1.16 | 2.37 |
| Umaria | 1.11 | 1.47 | 1.11 | 1.81 | 0.96 | 1.37 | 1.20 | 2.56 |
| Vidisha | 1.08 | 1.38 | 1.02 | 1.70 | 0.95 | 1.28 | 1.16 | 2.46 |
| West_Nimar | 1.02 | 1.25 | 1.01 | 1.61 | 0.92 | 1.22 | 1.16 | 2.28 |

### 4.2.4 Temperature Extremes (Hot Days, Hot Nights, and Heat Waves)

Under the projected climate temperature extremes are likely to increase. The analysis of temperature extremes (hot days, hot nights, and heat waves) was carried out using the daily downscaled and bias corrected climate change projections for the state of MP. The analysis was performed for the two periods: Near (2016-2045) and Mid (2046-2075). Moreover, multimodel projected changes in temperature extremes were estimated for the RCP 2.6, 4.5, 6.0, and 8.5. Changes under the projected future climate in the frequency of hot days, hot nights, and heat waves were estimated with respect to 1971-2000 as the reference period. Number of hot days and hot nights were estimated using the 95th percentile threshold of daily maximum and minimum temperature for the hottest three months in the reference period (1971-2000). Moreover, changes under the projected future climate were estimated using the same 95th percentile threshold that was estimated for the historic reference period.

Figure 30 shows the ensemble mean frequency of hot days and hot nights per year during the historic period (1951-2005). It was observed that during the historic period the multimodel ensemble mean frequency of hot days and hot nights varied between 4-5 days in the state of MP (Figure 31). Moreover, observed frequency of the hot days and hot nights was captured reasonably well in the multimodel ensemble for the historic period. Results showed that the frequency of hot days was relatively higher in the southern part of the state while the frequency of hot nights was higher in the central part of the state. These results are consistent with the daily maximum and minimum temperatures.

(a) Hot Days



(b) Hot Nights

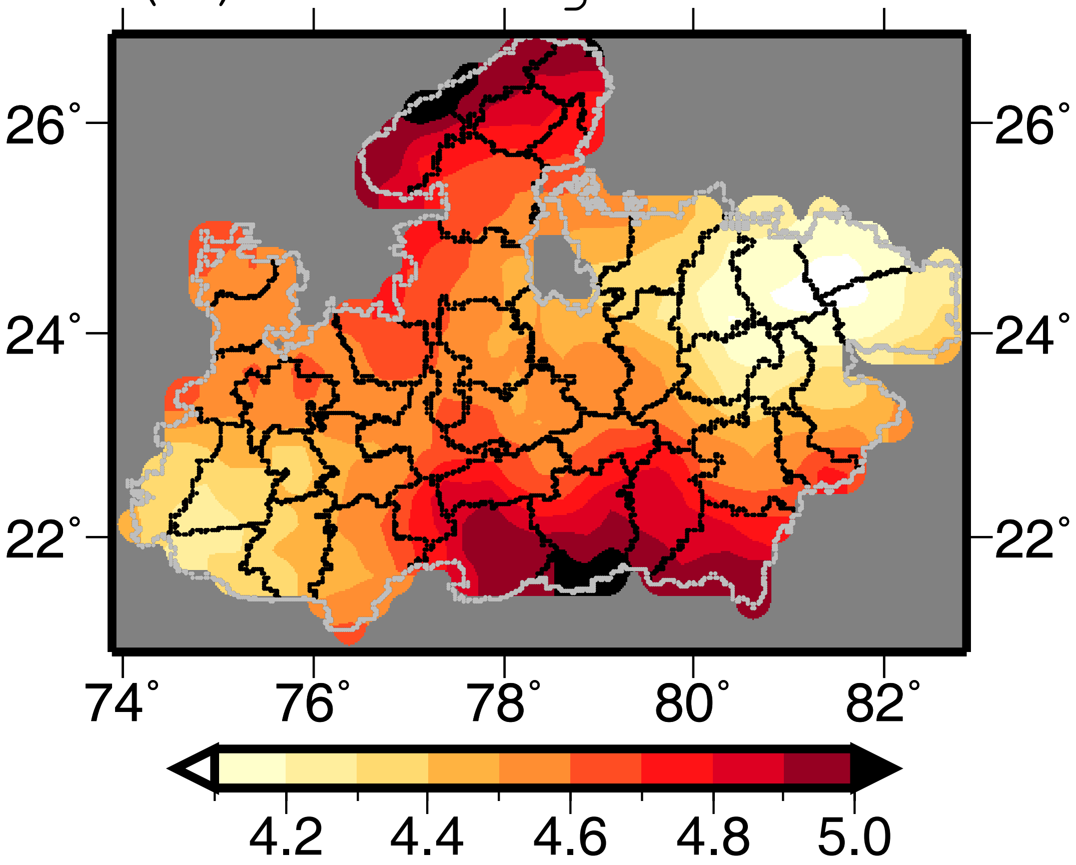


**Figure 31:** Historic ensemble of mean (1951-2005) (a) number of hot days, and (b) nights.

Multimodel projections for the hot days under the projected future climate showed that the state may witness a 2-3 fold increase in the number of hot days in the Near (2016-2045) term climate. The projected increase under the RCP 8.5 scenarios were larger than that of the other RCPs (Figure 32). Moreover, for the Near term climate, hot days are projected to become more frequent under the most of the RCPs in the southern part of the state. Multimodel ensemble mean projections for the number of hot days are likely to increase by 4-6 times under the Mid (2046-2075) term scenarios. Moreover, in the RCP 8.5, some part of the state of MP may witness an increase of 20-30 days per year in the number of hot days (Figure 32, Table 16). Multimodel ensemble mean changes in the frequency of hot days for the district in the state showed that the districts located in the eastern and southern part of the state may face a prominent increase in the number of hot days under the projected future climate. Here it is worth to note that the changes in the frequency of hot days can be associated with the increases in mean air temperature in the state under the projected future climate.

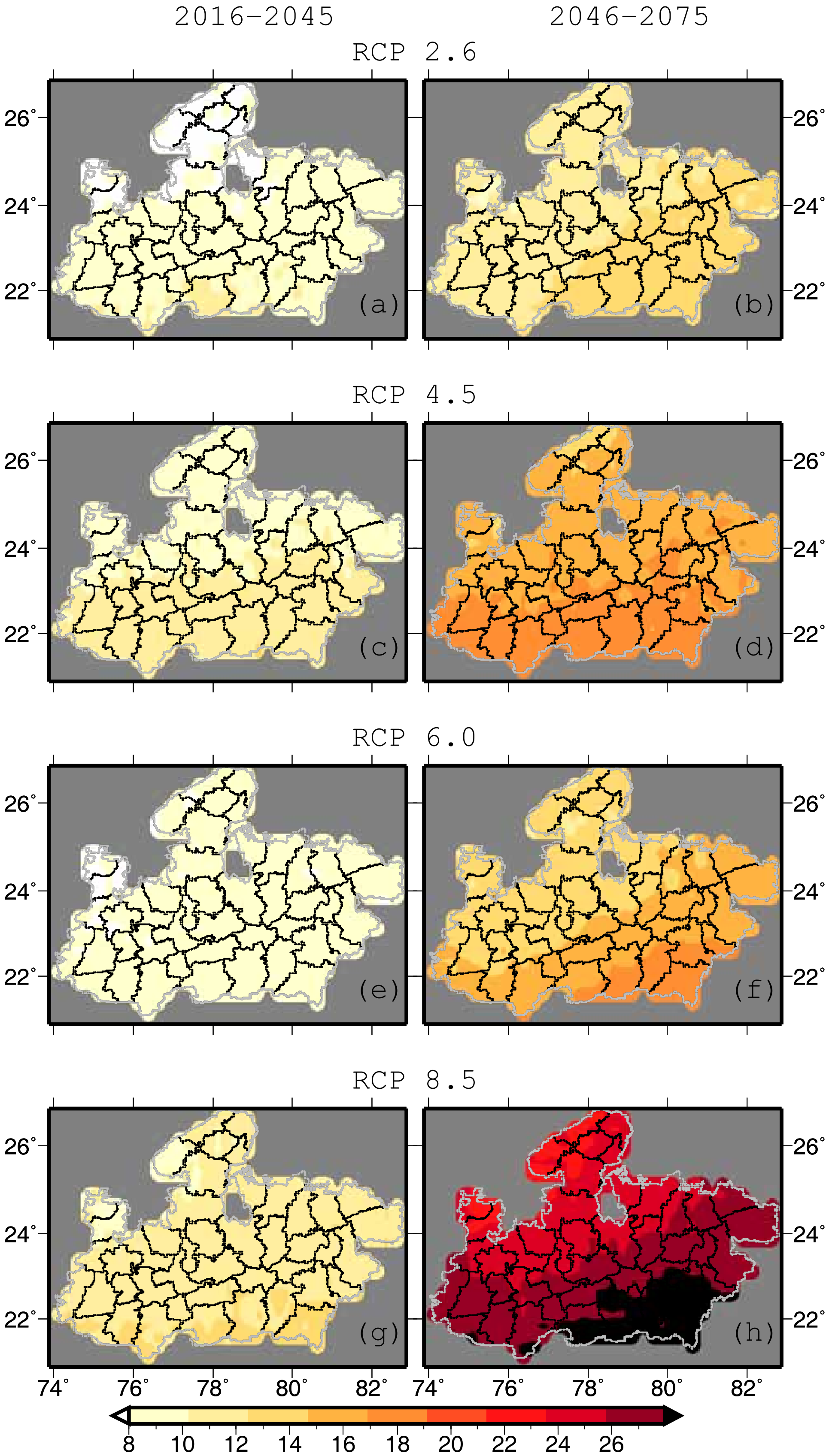


**Figure 32:** Ensemble projected change in frequency of hot days [per year; i.e. above 95th percentile of maximum temperature during (1971-2000)].

**Table 16:** Multimodel ensemble mean projected change in frequency of hot days per year under the projected future climate

| District | RCP 2.6 | | RCP 4.5 | | RCP 6.0 | | RCP 8.5 | |
|---|---|---|---|---|---|---|---|---|
| | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 |
| Anuppur | 8.96 | 13.14 | 10.70 | 16.59 | 8.48 | 16.26 | 11.48 | 27.16 |
| Ashoknagar | 8.04 | 11.45 | 9.64 | 15.83 | 8.45 | 13.22 | 10.70 | 24.61 |
| Balaghat | 9.92 | 13.69 | 11.73 | 17.40 | 8.59 | 17.86 | 12.98 | 29.20 |
| Barwani | 9.85 | 11.23 | 11.09 | 17.94 | 8.94 | 15.41 | 12.40 | 27.64 |
| Betul | 10.40 | 13.26 | 12.18 | 17.82 | 9.46 | 16.72 | 12.44 | 28.31 |
| Bhind | 8.04 | 11.67 | 8.65 | 14.72 | 8.62 | 13.43 | 10.81 | 23.70 |
| Bhopal | 9.10 | 11.80 | 10.26 | 15.97 | 8.10 | 13.57 | 10.89 | 25.24 |
| Burhanpur | 10.17 | 12.05 | 11.61 | 18.33 | 9.36 | 16.04 | 12.62 | 28.12 |
| Chhatarpur | 8.28 | 12.32 | 9.50 | 16.27 | 8.84 | 13.99 | 11.10 | 24.99 |
| Chhindwara | 10.07 | 13.34 | 11.69 | 17.56 | 9.24 | 17.03 | 12.36 | 28.50 |
| Damoh | 9.02 | 12.56 | 10.36 | 16.54 | 8.73 | 14.78 | 11.15 | 26.22 |
| Datia | 7.23 | 11.48 | 8.89 | 14.92 | 8.91 | 12.76 | 10.34 | 24.44 |
| Dewas | 8.91 | 11.28 | 10.77 | 16.69 | 8.36 | 13.94 | 11.22 | 25.80 |
| Dhar | 9.30 | 11.20 | 11.01 | 17.51 | 8.48 | 14.46 | 11.76 | 26.56 |
| Dindori | 9.34 | 13.32 | 11.01 | 16.96 | 8.70 | 16.67 | 12.00 | 27.97 |
| East_Nimar | 9.99 | 12.17 | 11.62 | 17.84 | 9.16 | 15.49 | 12.24 | 27.29 |
| Guna | 7.90 | 11.30 | 9.64 | 15.49 | 8.38 | 13.17 | 10.36 | 24.00 |
| Gwalior | 7.98 | 11.20 | 8.58 | 15.06 | 8.45 | 12.71 | 10.55 | 23.62 |
| Harda | 9.91 | 12.24 | 11.49 | 17.43 | 9.22 | 15.92 | 11.92 | 26.85 |
| Hoshangabad | 9.84 | 12.86 | 11.39 | 17.51 | 8.91 | 15.87 | 12.13 | 27.59 |
| Indore | 9.16 | 11.15 | 10.66 | 17.01 | 8.69 | 14.20 | 10.94 | 26.18 |
| Jabalpur | 9.52 | 13.13 | 10.87 | 17.13 | 9.23 | 16.07 | 11.67 | 27.94 |
| Jhabua | 9.11 | 11.16 | 10.41 | 17.03 | 8.32 | 14.45 | 11.76 | 26.83 |
| Katni | 9.18 | 12.98 | 10.59 | 16.93 | 8.77 | 15.55 | 11.49 | 26.92 |
| Mandla | 9.57 | 13.63 | 11.46 | 17.09 | 8.76 | 17.20 | 12.18 | 28.71 |
| Mandsaur | 7.79 | 10.32 | 9.32 | 14.70 | 7.61 | 12.76 | 9.74 | 23.55 |
| Morena | 7.65 | 10.96 | 8.61 | 14.18 | 8.39 | 12.73 | 10.40 | 23.26 |
| Narsinghpur | 9.44 | 12.98 | 10.86 | 17.16 | 8.99 | 15.70 | 11.70 | 27.40 |
| Neemuch | 7.71 | 10.72 | 9.02 | 15.25 | 7.79 | 12.78 | 10.14 | 23.57 |
| Panna | 8.57 | 12.32 | 9.91 | 16.51 | 8.65 | 14.71 | 11.31 | 25.63 |
| Raisen | 9.20 | 12.15 | 10.75 | 16.95 | 8.90 | 14.83 | 11.20 | 26.48 |
| Rajgarh | 8.35 | 11.17 | 9.76 | 16.39 | 8.62 | 13.17 | 10.78 | 24.85 |
| Ratlam | 8.39 | 10.68 | 9.83 | 16.18 | 8.26 | 13.40 | 10.97 | 25.40 |
| Rewa | 8.85 | 12.90 | 9.62 | 16.54 | 8.77 | 15.39 | 11.69 | 26.44 |
| Sagar | 8.65 | 11.90 | 9.90 | 16.23 | 8.64 | 14.12 | 10.93 | 25.65 |
| Satna | 8.75 | 12.66 | 9.95 | 16.70 | 8.52 | 14.85 | 11.56 | 26.12 |
| Sehore | 9.32 | 11.78 | 10.69 | 17.01 | 8.65 | 14.27 | 11.17 | 25.85 |
| Seoni | 9.79 | 13.60 | 11.41 | 17.67 | 8.95 | 17.13 | 12.30 | 28.71 |
| Shahdol | 9.22 | 13.07 | 10.52 | 16.50 | 8.64 | 15.73 | 11.69 | 26.84 |
| Shajapur | 8.43 | 11.09 | 10.20 | 16.05 | 8.44 | 13.68 | 10.68 | 25.15 |
| Sheopur | 7.66 | 10.90 | 8.94 | 14.96 | 8.34 | 12.77 | 10.12 | 23.46 |
| Shivpuri | 7.75 | 11.45 | 9.24 | 15.42 | 8.63 | 12.72 | 10.55 | 23.83 |
| Sidhi | 9.02 | 12.69 | 9.73 | 16.41 | 8.56 | 15.52 | 11.75 | 26.98 |
| Tikamgarh | 7.74 | 11.75 | 9.27 | 15.97 | 8.83 | 13.24 | 10.75 | 24.64 |
| Ujjain | 8.63 | 11.17 | 10.40 | 16.29 | 8.04 | 13.73 | 10.63 | 25.15 |
| Umaria | 9.17 | 12.81 | 10.39 | 16.65 | 9.01 | 15.66 | 11.67 | 26.89 |
| Vidisha | 8.61 | 11.37 | 9.76 | 15.80 | 8.45 | 13.69 | 10.67 | 25.35 |
| West_Nimar | 9.68 | 11.82 | 11.14 | 17.76 | 8.72 | 14.96 | 12.08 | 27.12 |

Projections for the number of hot nights are consistent with the hot days for the future climate in the state of MP (Figure 33). It was found that the frequency of hot nights will increase even more that the number of hot days under the projected future climate. Under most of the selected RCPs, the frequency of hot nights are projected to increase by 2-3 fold in the Near (2016-2045) term climate (Figure 33). However, the state is projected to experience a six fold rise in the number of hot nights in the Mid (2046-2075) term climate (Figure 33). Moreover, many districts are projected to experience an increase of 10-30 hot nights under the projected future climate (Table 17).

Changes in the frequency of heat waves under the projected climate were estimated using the daily maximum temperature data from the five best CMIP5 models. Results showed that the frequency of heat waves is projected to increase substantially under the projected future climate (Figure 34). In the Near term climate, projections indicated that majority of the state may experiences rise of more than 1 heat wave in every two years (Figure 34, Table 18). Moreover, the frequency of heat waves is projected to increase to 1-2 heat waves every year under the projected future climate in most of the districts in the state.

**Box 12**

- Significant increases are projected in number of hot days, hot nights, and heat waves in Madhya Pradesh under the future climate.
- The state may witness a 2-3 fold increase in the number of hot days in the Near (2016-2045) term climate while 4-6 times in the Mid (2046-2075) term climate
- The frequency of hot nights is projected increase even more that the number of hot days under the projected future climate
- Many districts of Madhya Pradesh are projected to experience an increase of 10-30 hot nights under the projected future climate
- The frequency of heat waves is projected to increase to 1-2 heat waves every year under the projected future climate in most of the districts in the state.

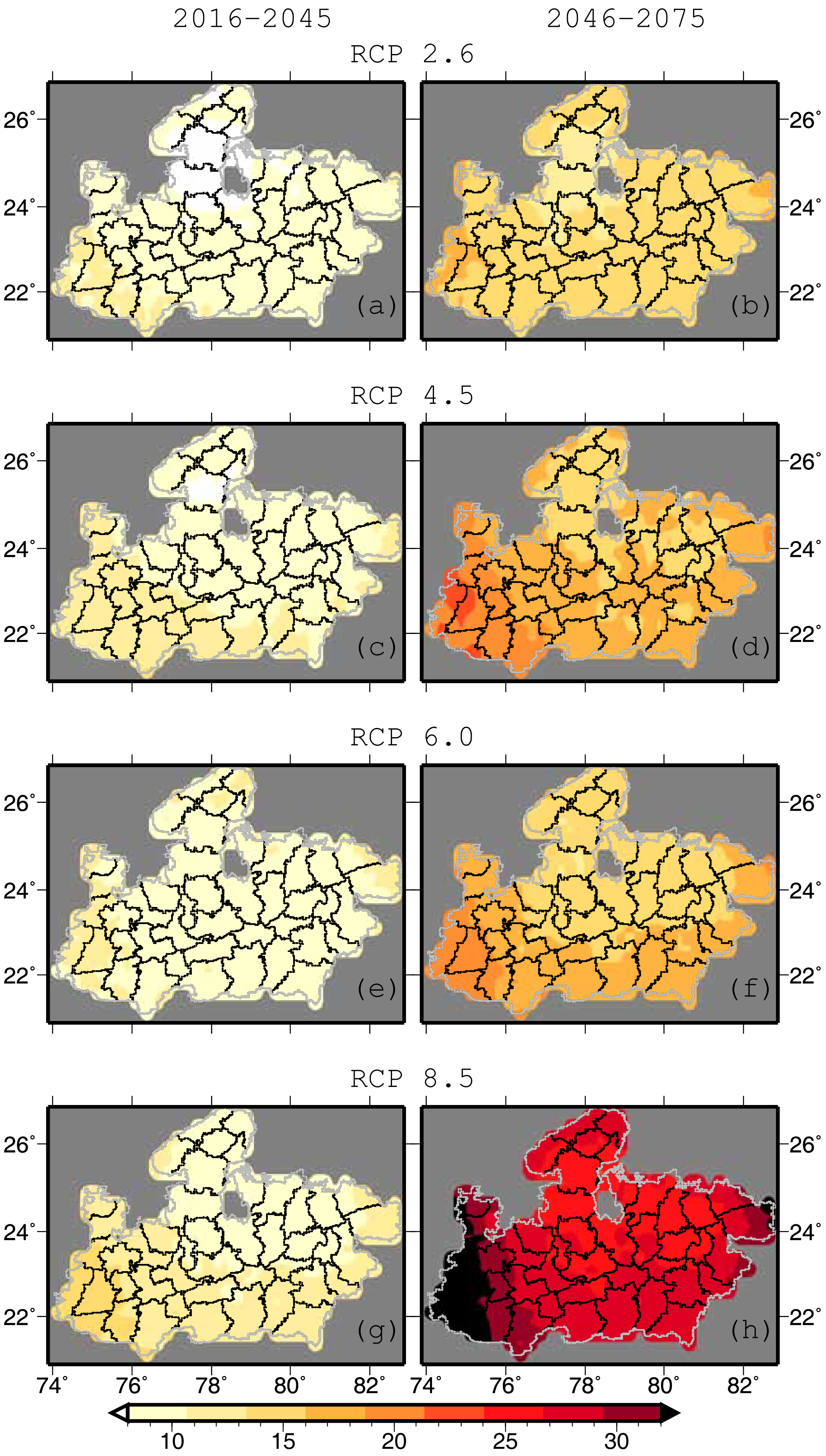


**Figure 33:** Ensemble mean projected change in frequency (per year) of hot nights.

**Table 17:** Ensemble mean projected change in number of hot nights per year under the projected future climate

| District | RCP 2.6 | | RCP 4.5 | | RCP 6.0 | | RCP 8.5 | |
|---|---|---|---|---|---|---|---|---|
| | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 |
| Anuppur | 9.54 | 15.38 | 10.88 | 17.40 | 10.16 | 17.59 | 11.57 | 29.86 |
| Ashoknagar | 7.45 | 12.50 | 8.60 | 15.26 | 9.48 | 13.38 | 9.52 | 25.30 |
| Balaghat | 9.56 | 14.91 | 10.64 | 16.65 | 9.49 | 17.87 | 11.95 | 28.22 |
| Barwani | 10.84 | 15.62 | 12.03 | 21.07 | 10.75 | 19.65 | 14.05 | 34.11 |
| Betul | 10.26 | 14.65 | 11.77 | 17.78 | 10.36 | 17.37 | 12.25 | 28.34 |
| Bhind | 8.61 | 14.10 | 8.88 | 15.94 | 10.85 | 14.90 | 9.58 | 27.48 |
| Bhopal | 8.22 | 13.16 | 10.13 | 16.79 | 9.60 | 15.09 | 10.64 | 26.71 |
| Burhanpur | 11.00 | 14.50 | 12.95 | 19.76 | 10.37 | 18.37 | 13.34 | 30.64 |
| Chhatarpur | 8.14 | 13.83 | 8.99 | 16.16 | 10.09 | 14.37 | 10.23 | 26.47 |
| Chhindwara | 9.36 | 14.62 | 10.70 | 16.54 | 9.81 | 16.93 | 11.45 | 27.66 |
| Damoh | 8.43 | 14.15 | 9.46 | 16.15 | 9.56 | 14.99 | 10.02 | 26.56 |
| Datia | 8.10 | 13.65 | 8.39 | 15.56 | 10.06 | 14.21 | 9.88 | 26.34 |
| Dewas | 9.87 | 14.31 | 11.24 | 17.86 | 10.18 | 16.60 | 11.99 | 28.81 |
| Dhar | 10.80 | 15.92 | 12.70 | 21.11 | 11.01 | 19.44 | 14.39 | 34.14 |
| Dindori | 9.66 | 14.66 | 10.49 | 16.51 | 9.74 | 16.79 | 11.12 | 28.01 |
| East_Nimar | 10.57 | 14.59 | 12.10 | 19.02 | 10.32 | 17.73 | 12.81 | 29.60 |
| Guna | 7.56 | 12.77 | 8.80 | 15.59 | 9.15 | 14.01 | 9.87 | 25.42 |
| Gwalior | 8.05 | 13.65 | 8.71 | 15.05 | 10.69 | 14.27 | 9.47 | 26.76 |
| Harda | 10.10 | 14.58 | 11.93 | 18.54 | 10.43 | 17.03 | 12.70 | 28.63 |
| Hoshangabad | 9.20 | 14.09 | 10.82 | 16.99 | 10.04 | 16.28 | 11.34 | 26.99 |
| Indore | 10.36 | 15.01 | 11.95 | 19.77 | 10.24 | 18.06 | 13.05 | 30.87 |
| Jabalpur | 9.19 | 14.79 | 10.23 | 16.50 | 9.64 | 16.11 | 11.09 | 27.27 |
| Jhabua | 10.95 | 16.41 | 12.31 | 21.58 | 11.25 | 20.19 | 14.62 | 36.48 |
| Katni | 8.70 | 13.86 | 9.55 | 15.61 | 9.34 | 15.01 | 10.07 | 25.90 |
| Mandla | 9.09 | 14.73 | 10.31 | 16.29 | 9.47 | 16.63 | 11.20 | 27.59 |
| Mandsaur | 9.11 | 14.53 | 10.98 | 19.06 | 10.59 | 17.42 | 12.13 | 30.39 |
| Morena | 8.01 | 14.22 | 9.03 | 15.66 | 10.18 | 15.09 | 9.89 | 27.26 |
| Narsinghpur | 9.05 | 14.20 | 9.93 | 16.67 | 9.53 | 16.00 | 10.86 | 27.45 |
| Neemuch | 9.52 | 15.41 | 11.34 | 19.00 | 10.74 | 17.88 | 12.68 | 31.37 |
| Panna | 8.26 | 13.82 | 8.79 | 15.88 | 9.65 | 14.47 | 10.03 | 25.96 |
| Raisen | 8.47 | 13.69 | 9.79 | 16.37 | 9.67 | 14.96 | 10.56 | 26.34 |
| Rajgarh | 8.69 | 13.38 | 10.09 | 16.74 | 9.85 | 15.26 | 11.01 | 27.08 |
| Ratlam | 10.42 | 15.93 | 11.95 | 20.71 | 11.36 | 19.08 | 14.01 | 33.58 |
| Rewa | 8.99 | 14.96 | 9.73 | 16.66 | 10.33 | 16.26 | 10.50 | 28.21 |
| Sagar | 8.08 | 13.56 | 9.10 | 15.90 | 9.55 | 14.46 | 9.86 | 26.39 |
| Satna | 8.27 | 13.91 | 8.91 | 15.81 | 9.64 | 14.77 | 10.20 | 25.67 |
| Sehore | 9.09 | 13.91 | 10.75 | 17.42 | 9.76 | 15.96 | 11.25 | 27.58 |
| Seoni | 9.35 | 14.86 | 10.66 | 16.23 | 9.68 | 17.04 | 11.32 | 27.75 |
| Shahdol | 9.01 | 14.67 | 9.87 | 16.50 | 9.73 | 16.04 | 10.76 | 27.70 |
| Shajapur | 9.10 | 13.94 | 10.47 | 17.71 | 10.01 | 16.01 | 11.45 | 28.17 |
| Sheopur | 8.13 | 13.70 | 9.18 | 15.89 | 10.19 | 14.87 | 10.33 | 26.80 |
| Shivpuri | 7.28 | 12.82 | 7.97 | 14.81 | 9.72 | 13.58 | 9.25 | 25.39 |
| Sidhi | 9.89 | 15.71 | 10.53 | 17.68 | 10.54 | 17.20 | 11.48 | 30.10 |
| Tikamgarh | 7.70 | 13.43 | 8.40 | 15.61 | 9.76 | 14.02 | 9.64 | 26.08 |
| Ujjain | 9.93 | 15.25 | 11.60 | 19.44 | 10.62 | 17.77 | 13.02 | 31.22 |
| Umaria | 8.59 | 14.23 | 9.53 | 15.28 | 9.11 | 15.33 | 10.02 | 26.15 |
| Vidisha | 8.00 | 13.24 | 9.15 | 15.94 | 9.45 | 14.51 | 10.10 | 26.34 |
| West_Nimar | 10.80 | 15.15 | 12.41 | 20.05 | 10.55 | 18.73 | 13.38 | 31.38 |

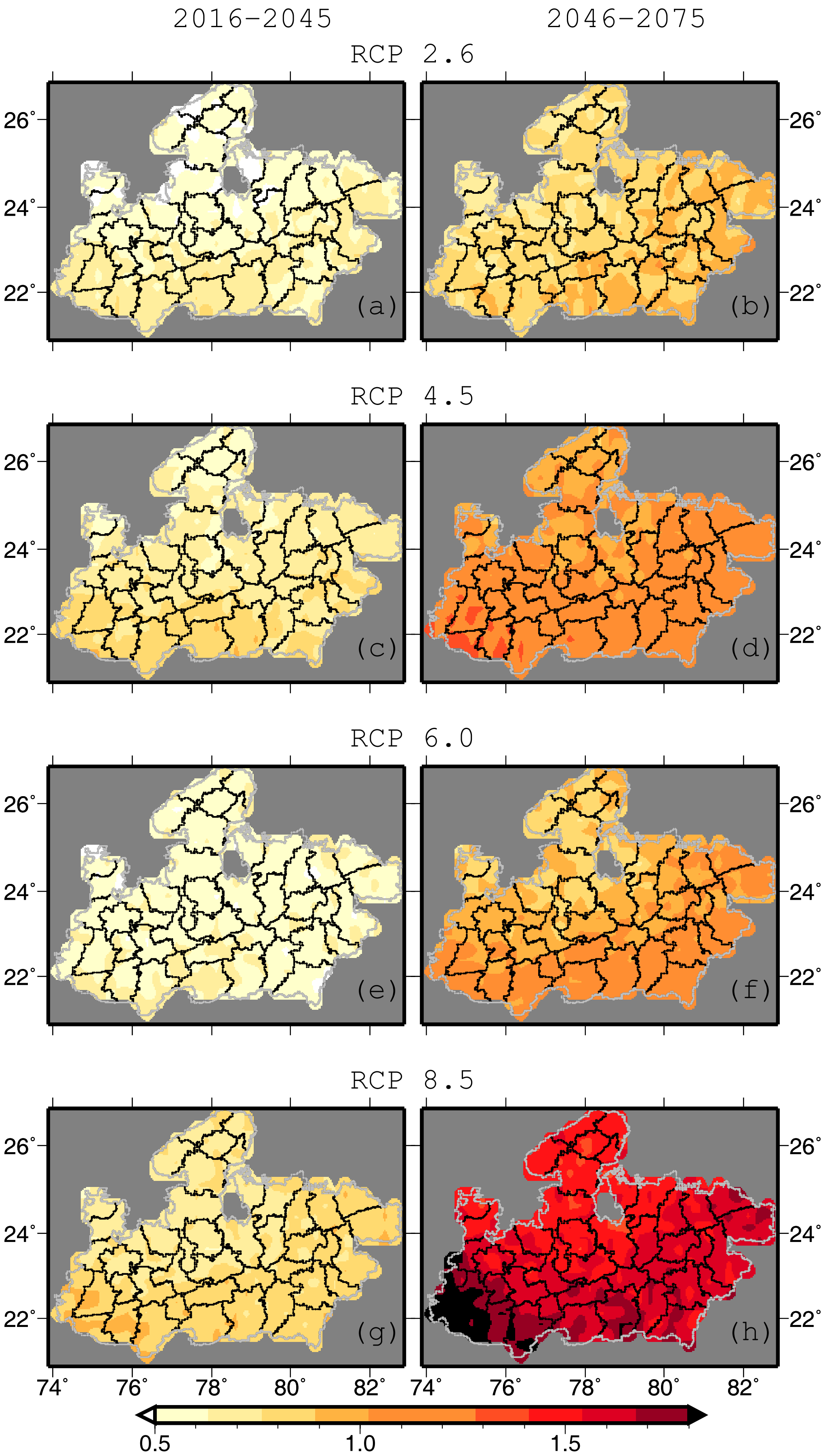


**Figure 34:** Ensemble mean projected change in frequency of heat waves per year under the projected future climate.

**Table 18:** Ensemble mean change in frequency of heat waves per year under the projected future climate.

| District | RCP 2.6 | | RCP 4.5 | | RCP 6.0 | | RCP 8.5 | |
|---|---|---|---|---|---|---|---|---|
| | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 | 2016-2045 | 2046-2075 |
| Anuppur | 0.65 | 0.98 | 0.80 | 1.11 | 0.63 | 1.11 | 0.83 | 1.57 |
| Ashoknagar | 0.51 | 0.77 | 0.63 | 1.03 | 0.58 | 0.85 | 0.69 | 1.48 |
| Balaghat | 0.65 | 0.90 | 0.77 | 1.12 | 0.56 | 1.12 | 0.84 | 1.63 |
| Barwani | 0.68 | 0.80 | 0.82 | 1.31 | 0.66 | 1.13 | 0.89 | 1.87 |
| Betul | 0.71 | 0.91 | 0.84 | 1.19 | 0.66 | 1.10 | 0.84 | 1.67 |
| Bhind | 0.56 | 0.79 | 0.59 | 0.99 | 0.60 | 0.90 | 0.74 | 1.48 |
| Bhopal | 0.53 | 0.80 | 0.69 | 1.04 | 0.53 | 0.86 | 0.64 | 1.49 |
| Burhanpur | 0.73 | 0.79 | 0.83 | 1.21 | 0.68 | 1.07 | 0.87 | 1.80 |
| Chhatarpur | 0.56 | 0.84 | 0.64 | 1.01 | 0.60 | 0.91 | 0.75 | 1.48 |
| Chhindwara | 0.69 | 0.89 | 0.81 | 1.15 | 0.62 | 1.09 | 0.83 | 1.67 |
| Damoh | 0.58 | 0.85 | 0.67 | 1.05 | 0.60 | 0.94 | 0.73 | 1.54 |
| Datia | 0.52 | 0.78 | 0.63 | 0.97 | 0.62 | 0.91 | 0.73 | 1.52 |
| Dewas | 0.62 | 0.78 | 0.74 | 1.13 | 0.58 | 0.95 | 0.77 | 1.60 |
| Dhar | 0.66 | 0.79 | 0.80 | 1.24 | 0.61 | 1.06 | 0.86 | 1.81 |
| Dindori | 0.63 | 0.91 | 0.77 | 1.10 | 0.61 | 1.07 | 0.81 | 1.61 |
| East_Nimar | 0.69 | 0.88 | 0.83 | 1.20 | 0.62 | 1.09 | 0.84 | 1.73 |
| Guna | 0.52 | 0.78 | 0.67 | 1.02 | 0.58 | 0.91 | 0.70 | 1.49 |
| Gwalior | 0.54 | 0.78 | 0.57 | 1.01 | 0.55 | 0.87 | 0.74 | 1.44 |
| Harda | 0.67 | 0.86 | 0.82 | 1.16 | 0.66 | 1.14 | 0.88 | 1.63 |
| Hoshangabad | 0.69 | 0.90 | 0.78 | 1.18 | 0.61 | 1.09 | 0.83 | 1.63 |
| Indore | 0.65 | 0.77 | 0.73 | 1.21 | 0.62 | 1.04 | 0.78 | 1.68 |
| Jabalpur | 0.63 | 0.88 | 0.71 | 1.08 | 0.63 | 1.00 | 0.81 | 1.65 |
| Jhabua | 0.66 | 0.81 | 0.77 | 1.24 | 0.61 | 1.03 | 0.86 | 1.84 |
| Katni | 0.63 | 0.90 | 0.74 | 1.09 | 0.61 | 1.02 | 0.78 | 1.60 |
| Mandla | 0.62 | 0.88 | 0.71 | 1.10 | 0.57 | 1.08 | 0.81 | 1.61 |
| Mandsaur | 0.53 | 0.71 | 0.65 | 0.96 | 0.54 | 0.86 | 0.66 | 1.50 |
| Morena | 0.51 | 0.74 | 0.58 | 0.94 | 0.59 | 0.89 | 0.75 | 1.49 |
| Narsinghpur | 0.63 | 0.85 | 0.71 | 1.10 | 0.62 | 1.01 | 0.79 | 1.59 |
| Neemuch | 0.50 | 0.72 | 0.62 | 1.05 | 0.53 | 0.87 | 0.69 | 1.51 |
| Panna | 0.58 | 0.88 | 0.69 | 1.09 | 0.56 | 0.99 | 0.78 | 1.54 |
| Raisen | 0.58 | 0.81 | 0.71 | 1.10 | 0.60 | 0.96 | 0.74 | 1.54 |
| Rajgarh | 0.55 | 0.75 | 0.67 | 1.07 | 0.59 | 0.87 | 0.72 | 1.50 |
| Ratlam | 0.58 | 0.73 | 0.68 | 1.14 | 0.56 | 0.92 | 0.75 | 1.67 |
| Rewa | 0.62 | 0.90 | 0.69 | 1.14 | 0.61 | 1.06 | 0.82 | 1.62 |
| Sagar | 0.57 | 0.79 | 0.65 | 1.00 | 0.57 | 0.92 | 0.73 | 1.49 |
| Satna | 0.60 | 0.90 | 0.69 | 1.14 | 0.59 | 1.02 | 0.81 | 1.58 |
| Sehore | 0.65 | 0.81 | 0.73 | 1.10 | 0.61 | 0.95 | 0.77 | 1.57 |
| Seoni | 0.65 | 0.91 | 0.76 | 1.14 | 0.58 | 1.11 | 0.80 | 1.63 |
| Shahdol | 0.67 | 0.94 | 0.75 | 1.09 | 0.58 | 1.06 | 0.81 | 1.57 |
| Shajapur | 0.58 | 0.78 | 0.71 | 1.07 | 0.59 | 0.97 | 0.75 | 1.56 |
| Sheopur | 0.53 | 0.76 | 0.62 | 0.98 | 0.56 | 0.85 | 0.71 | 1.48 |
| Shivpuri | 0.53 | 0.79 | 0.63 | 1.02 | 0.58 | 0.85 | 0.73 | 1.46 |
| Sidhi | 0.65 | 0.90 | 0.69 | 1.12 | 0.60 | 1.07 | 0.84 | 1.64 |
| Tikamgarh | 0.51 | 0.82 | 0.63 | 1.02 | 0.57 | 0.87 | 0.71 | 1.45 |
| Ujjain | 0.60 | 0.79 | 0.74 | 1.09 | 0.54 | 0.95 | 0.73 | 1.57 |
| Umaria | 0.65 | 0.82 | 0.74 | 1.12 | 0.61 | 1.03 | 0.83 | 1.57 |
| Vidisha | 0.57 | 0.77 | 0.66 | 0.99 | 0.55 | 0.88 | 0.69 | 1.51 |
| West_Nimar | 0.69 | 0.86 | 0.78 | 1.25 | 0.61 | 1.06 | 0.88 | 1.79 |

# 5. Linking Impacts to Adaptation

## 5.1 Introduction

According to the Copenhagen Commitments (2009) by world leaders, "to achieve the ultimate objective of the Convention to stabilize greenhouse gas concentration in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system, we shall, recognizing the scientific view that the increase in global temperature should be below 2$^{O}$C, on the basis of equity and in the context of sustainable development, enhance our long-term cooperative action to combat climate change. We recognize the critical impacts of climate change and the potential impacts of response measures on countries particularly vulnerable to its adverse effects and stress the need to establish a comprehensive adaptation programme including international support". The Cancun Agreement (2010) strengthened this resolution to limit the global temperature increase below 2$^{O}$C over the pre-industrial levels. The Durban Outcome (2011) stressed that, even if the two-degree scenario is met, developing countries, especially the poorest and most vulnerable, will still need much more support to adapt to the change that is already embedded in the global climate system. The Warsaw Agreement (2013) agreed to bind nations together into an effective global effort to reduce emissions rapidly enough to chart humanity's longer-term path out of the danger zone of climate change, while building adaptation capacity. The Lima COP 20 (2014) agreed on elevating adaptation onto the same level as the curbing and cutting of curbing greenhouse gas emissions. Manuel Pulgar-Vidal, the Minister of the Environment of Peru and the COP-20 President, said "Lima has given new urgency towards fast tracking adaptation and building resilience across the developing world—not least by strengthening the link to finance and the development of national adaptation plans" (http://newsroom.unfccc.int/lima/lima-callfor-climate-action-puts-world-on-track-to-paris-2015/).

Climate change is projected to have severe adverse impacts on India's population, natural eco-systems, and socio-economic parameters. India's vulnerability to climate change impacts is profound since around 650 million Indians are dependent on rain-fed agriculture for their livelihoods; around 250 million Indians live along a 7500 km of coastline that is at high risk due to sea level rise and extreme weather events; many of the 10,000-odd Indian glaciers are receding at a rapid rate; and deforestation is happening. India occupies 2.4% of the global land area, supports 17% of the global population and contributes less than 4% of global greenhouse gas emissions. Sustainable development is at the core of Indian planning process and India has been making huge efforts for enhancing the quality of life of her people including sustained poverty alleviation efforts. The number of people below poverty line has declined from 469 million to about 388 million during 2005 to 2010. Even then roughly three-fourths of Indian population lives below a daily income of US$ 2 (PPP). This also highlights the extent of number of people who are vulnerable to adverse impacts of a changing climate.

India is much concerned about climate change impacts.

According to IPCC AR5, adaptation and mitigation are complementary strategies for reducing and managing the risks of climate change. The below 2$^{O}$C target also unequivocally includes the combined and cumulative risks of mitigation and adaptation actions. These risks however are over different time scales – with adaptation risks being faced now.

For instance, the global insurance industry, the largest industry in the world at total direct premiums of about 4.8 trillion US$ in 2014 (over double the Indian GDP), had insured losses due to natural disasters in the United States alone in the first half of 2015 at $12.6 billion, well above the $11.2 billion average in the first halves of 2000 to 2014, according to a July 2015 presentation by Munich Re and the Insurance Information Institute (http://www.iii.org/fact-statistic/catastrophes-us). In Canada, claims on the insurance industry reached $3.2-billion in 2013, after floods, hail and ice storms caused devastating damage across the country, (http://

www.theglobeandmail.com/report-on-business/economy/severe-weather-leads-to-record-32-billion-in-insurance-payouts/article16405099/). This is roughly twice the next highest year on record and a tenfold increase from the losses sustained a decade ago. Similarly in the UK, the wettest winter on record is likely to result in £446 million being paid in insurance claims to customers whose homes, businesses, and vehicles were flooded during the two-month period 23 December 2013 to 28 February 2014 (https://www.abi.org.uk/News/News-releases/2014/03/6-7-million-a-day-in-insurance-claimsfrom-customers-hit-by-the-recent-flooding).

The estimate for a single heavy rain event in Uttarakhand, India in 2013 is estimated cost US $ 1.1 billion economic losses (EMDAT, 2015).

The subsequent sections provide a framework to assess the Adaptation Gap.

### 5.2 What is Adaptation to climate change?

The changing climate is posing unprecedented challenges to existing human and economic activities, natural ecosystems, and man-made ecosystems in many ways. Firstly, it is creating new risks for their existence as well as safe and economically viable operations. For instance, infrastructure assets are planned with some visibility of magnitude and type of potential climate induced risks (Hallegatte, 2009). However due to climate change, new dimensions are being added to the risk profile of these assets. Climate is changing the conceptual basis of risks and some specific risks may become more critical for the asset in future, which are either not visible today or do not hold importance in the basket of risks that the asset currently faces (Stern, 2007). Secondly, climate change appears to exacerbate the existing risks faced today. For example, higher variability in the Indian monsoons and temperature profiles temporally and spatially could make certain crops uncultivable in present form at locations where they are being cultivated presently. Similarly floods and droughts could become more uncertain and severe. Thirdly, climate change threatens the usable life span of assets, products and even services. Regulatory or product and technology risks could make the asset redundant sooner than the planned lifespan or physical risks could reduce the usable life of the asset (Peter & Grimm, 2008). Tourism services face major uncertainty due to changing weather conditions and unpredictable weather at tourist destinations during peak tourist seasons. Finally, it creates allied risks that arise out of disruptions in network of infrastructure such as supply chain risks (Schenker-Wicki, Inauen, & Olivares, 2010).

In human systems, the process of adjustment to actual or expected climate and its effects in order to moderate harm or exploit beneficial opportunities is normally termed as Adaptation. In natural systems, this process of adjustment to actual climate and its effects, and human interventions that may facilitate adjustment to expected climate is called Adaptation. Adaptation is supposed to reduce risks and enhance resilience of natural and man-made systems towards adverse impacts of climate change.

Risks can only be managed and cannot be completely eliminated. The palliative financial burden, as discussed in subsequent chapters and demonstrated through an example of Uttrakhand tragedy in north India during June 2013, could be huge and economic implications can only be evaluated till the first or the second order and therefore the total indirect palliative impacts may be lower than the actual losses that many sectors and regions may face. Therefore, the choice of right adaptation practices may not always be easy to determine as the costs are unambiguous. The preventive costs may therefore many a times appear to be infructuous. Further, the concave nature of (preventive and palliative) adaptation cost curve could also mean that the relationships between prevention costs and palliative damage costs due to an event may be directly related or inversely related, depending upon the type of investment and its purpose under discussion. For instance, construction of a dam to avoid drought is a preventive mechanism and some expenditure would be required for the same. But if drought does happen subsequently, one may have to spend on palliative damages as well. The palliative costs may be high at times due to food grain prices going up on supply-demand shortages etc. It may appear that the expenditure on building the dam was infructuous in the first place as it did not prevent droughts from occurring. This also shows a direct relationship between preventive and palliative costs as expenditure is required to restore the damages due to an event for which some preventive expenditure was already made. On the other hand, the same dam may also be used as a flood prevention mechanism. In such a situation, if it does present floods from occurring, palliative costs would be minimum, indicating an inverse relationship between preventive and palliative costs. Consequently, it becomes important to plan for potential climate-induced risks keeping in view the other factors like the time frame for results in case of a particular adaptive practice or costs for inducing the adaptive measure, what all types of risks the practice covers etc.

According to IPCC AR5 report of WG-2, benefits from adaptation therefore can already be realized in addressing current risks, and can be realized in the future for addressing emerging risks. However economic impact estimates completed over the past 20 years vary in their coverage of subsets of economic sectors and depend on a large number of assumptions, many of which are disputable, and many estimates do not account for catastrophic changes, tipping points, and many other factors. With these recognized limitations, the incomplete estimates of global annual economic losses for additional temperature increases of ~2°C are between 0.2 and 2.0% of income (±1 standard deviation around the mean; medium evidence, medium agreement). Losses are more likely than not to be greater, rather than smaller, than this range (limited evidence, high agreement). Additionally, there are large differences between and within countries. Losses accelerate with greater warming (limited evidence, high agreement) (IPCC, 2014).

### 5.3 What is Adaptation Gap?

The UNEP Adaptation Gap (2014) defines it generically as the difference between actually implemented adaptation and a societally set goal, determined largely by preferences related to tolerated climate change impacts, and reflecting resource limitations and competing priorities. Developing countries such as India have national targets on development with poverty alleviation, education, health, energy, water, and provision of infrastructure being among the top priorities. These are mostly aligned with the Millennium Development Goals (MDGs) for 1990-2015 and also the Sustainable Development Goals for 2015-2030. Resource limitations and competing priorities put constraints on achieving these goals. Changing climate dynamically interacts with these goals and may or may not adversely impact them. Adaptation gap therefore is perceived as a dynamic concept in this report.

Strong mitigation actions today could reduce the climate change induced impacts on various systems after a few years. Uncovered mitigation gap today, could therefore lead to a larger adaptation gap in longer-term. However it should also be noted that any mitigation action today will not be able to fill the adaptation gap in short to medium-terms, which have been caused by unbridled GHG emissions from Annex-1 countries in the past. It would only reduce the adaptation gap in the longer-term. That is the adaptation dividend of current mitigation actions would be realized in future. Therefore common but differentiated responsibility (CBDR) paradigm of climate actions under UNFCCC does not only require more mitigation by developed countries now so that the world does not face much adverse consequences in future, but also more support by them to developing and least developed countries to fill their present adaptation gaps.

Apart from this time gap between mitigation induced impact reductions achieved in future and impacts occurring now that would need adaptation, adaptation is also locale specific as against a more global character of mitigation. One million tons of GHG emissions mitigated in a developed country would have the same mitigating effect of one million tons of GHG emissions mitigated in a developing country due to fungibility of mitigation actions. But one million litres of additional potable water made available to a water-affluent location will have much less positive externalities than one million litres of potable water made available to a water-starved region. Adaptation actions, and therefore actions to reduce Adaptation Gap, have to be very locale specific.

The most vulnerable communities and systems, in all probabilities, would not have contributed to their present climate misery due to their almost miniscule GHG emissions in the past. They may not be even aware of the global reasons of the climate impacts they have to face today and tolerate without any choice. Therefore tolerable impacts should ideally not be included as part of the adaptation that is already occurring for they may be involuntary, and should ideally be included in the Adaptation Gap. Someone is already paying to bridge this gap – may be the individuals concerned themselves or their governments – both should not be ideally doing it under a Common But Differential Responsibility (CBDR) paradigm. Examples for involuntary tolerated adaptation could be the adverse impacts due to changed excessive heat wave patterns in a developing country.

We define the various adaptation needs through a risk coverage paradigm, rather than a simple gap based relationship.

### 5.4 Adaptation Gap and Adaptation Dilemma

We consider the decisions on how much climate change impact risks are acceptable and how much are not acceptable. The unacceptable risks constitute Adaptation Gap (Figure 35). Therefore determining the right balance between preventive and palliative adaptation measures determines the Adaptation Gap. For any society, there remains a range of risks that are acceptable. What constitutes as acceptable risk is a function of several factors that include level of development, preparedness, resources, norms and values that any society places on goods, services and human life. Beyond this range of acceptable risks, societies are faced with the possibility of being impacted in an unacceptable way. Such impacts have damage costs associated with them and are typically unacceptable to a society.

Risk coverage depends upon resources available and competing priorities. The unacceptable risks may be due to lack of understanding of those risks currently, or lack of available resources to cover those risks, or due to a conscious decision to tolerate those risks, or a combination of these. The Adaptation Gap is basically risks that one would like to cover but is unable to cover. Tolerated risks are therefore generally considered part of the Adaptation Gap if they indicate forced and involuntary choices. The risk coverage process induces Adaptation Dilemma that is how much risks are acceptable and how much are not. The latter may or may not be covered given the resources available and their opportunity costs.

Climate change adaptation measures heavily depend on the risk perceptions and management strategy to cover these risks. Managing all risks through adaptation could be an expensive proposition. For instance, according to the 12th Five-Year Plan of the Government of India (2013), adaptation costs for new infrastructure could be in the range of 3–10 per cent of the total investment, although for certain sectors and locations this may be higher. The number for existing infrastructure is likely to be as high as 25 per cent of their present construction costs (Planning Commission, 2013), and could therefore run into trillions of dollars. We discuss these issues in subsequent chapters.

Excessive adaptation and prior over estimation of risks leads to a type 1 or α error. It means that one plans for some event but it does not take place. In our earlier example, this could be building a dam for drought prevention, but the drought does not happen. The decision to build a dam may therefore be looked as infructuous in hindsight, since it could be difficult to estimate potential losses that could have occurred if a drought would have happened, especially depending upon its intensity and time of occurrence, both of which are hypothetical in this case.

On the other hand, under investment in risk mitigation and adaptation strategies leads to a type 2 or β error, that is, one does not plan for an event to occur, but it occurs. In the example above, one does not built any dams thinking that no droughts or floods would occur, but they do occur. The palliative damages could be very high in such a situation. Under adaptation means that risk assessment may have been inadequate.

Therefore, nations invest in mitigating risk e.g. building a wall to prevent flooding associated with sea level rise. These investments are borne by individual actors, groups of individuals or governments as preventive costs. However, it often happens that not all risk can be covered. This uncovered risk can be classified into three types – uncovered risk, residual risk and intolerable risk. Each of these risks is associated with an increasing set of palliative damage costs and requires different mechanisms to mitigate the same. The first would generally have a palliative cost. These could be transferred to a third party but at a high premium, which may not be acceptable to the affected party since α error exists. The residual risks are generally involuntary and have damage costs. The Intolerable risks have huge costs, including deaths and migrations. The decision about the quantum of risk to be covered (i.e. acceptable versus unacceptable) and the associated resource investment is termed as the 'Adaptation Dilemma'. The policy dilemma therefore is how much to invest a priory in adaptation. Climate proofing natural or manmade systems does not mean that all possible risks are eliminated; it just implies that they have been made more resilient towards climate-induced risks. Thus the adaptation dilemma revolves around choosing an acceptable level of risk from a wide spectrum and covering the unacceptable risks appropriately.

### 5.5 Adaptation Gap is a dynamic concept

It must also be recognised that the Adaptation Gap is dynamic in nature and is based upon possible future transitions – both climate change parameters and resilience of the population and various eco-systems. Future climatic parameters could shift towards right with a changed mean, a changed distribution, or a combination of both. For instance, current rainfall distribution may just shifts towards right (Figure 36) retaining its distribution pattern. If we assume that the resilience of populations and various eco-systems do not change over time, then the Adaptation Gap would increase in future. In case the distribution also changes with much higher variance (Figure 36), the Adaptation Gap could be much larger in future. Therefore, gap analysis must be a periodic exercise based on the most recent science.

Moreover as various RCPs could manifest in future, the Adaptation Gaps would be different under alternate RCPs. For instance, the Adaptation gap under RCP 8.5 scenario would be much more than that under an RCP 2.6 scenario.

Since nations have to hedge for the worst possible impacts, the adaptation policies and measures may have to be ready for RCP 8.5 extremes. This also means that more and more resources have to be committed to adaptation and as per CBDR, more and more resources have to flow to developing countries and emerging economies from developed countries.

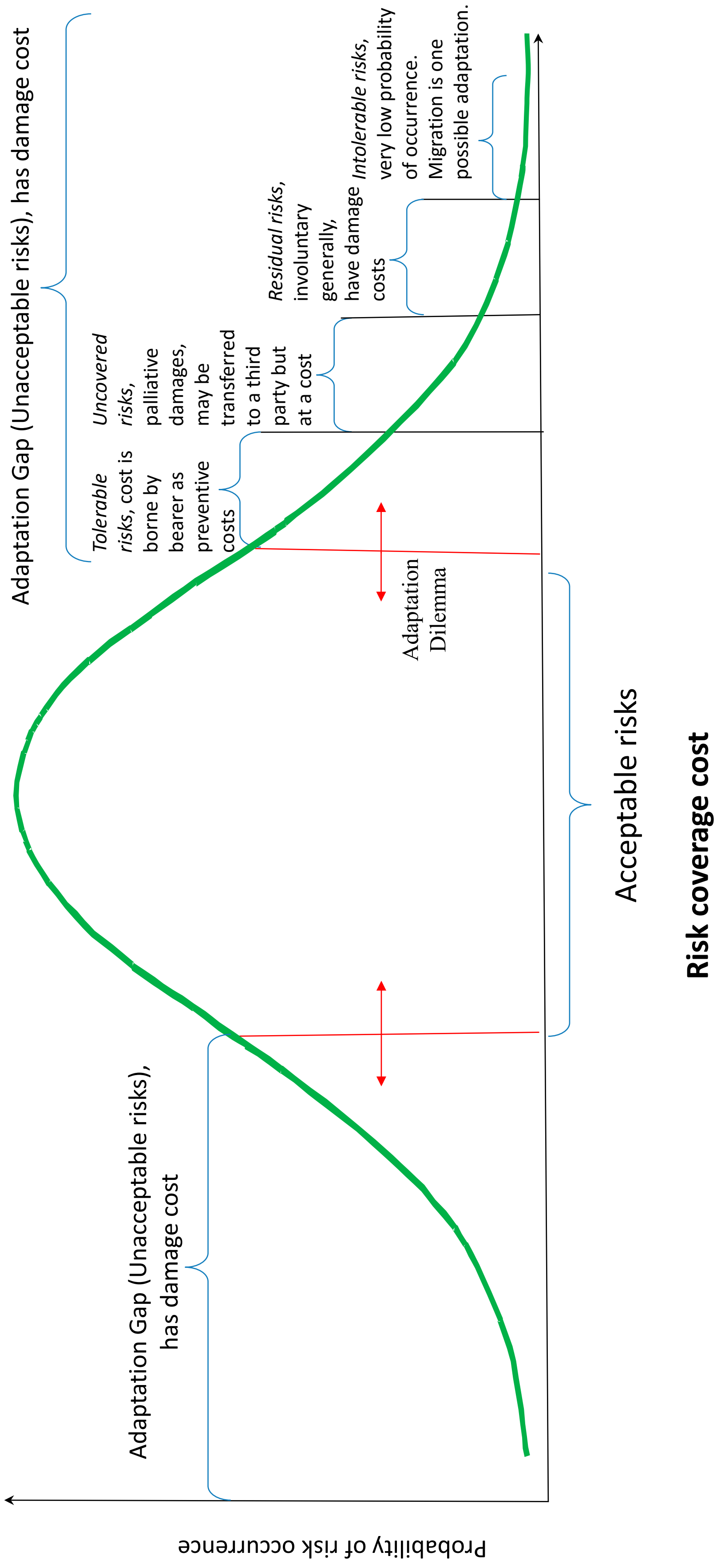


**Figure 35:** Risks and costs associated with adaptation gap

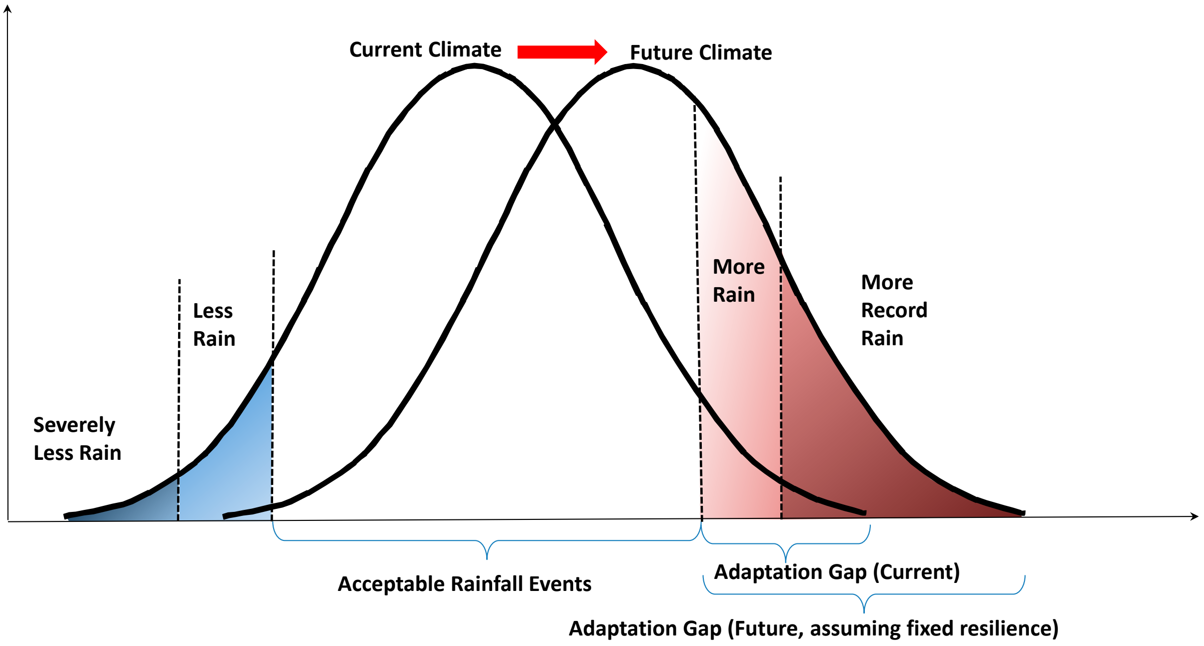


**Figure 36:** Adaptation Gap enhances in future

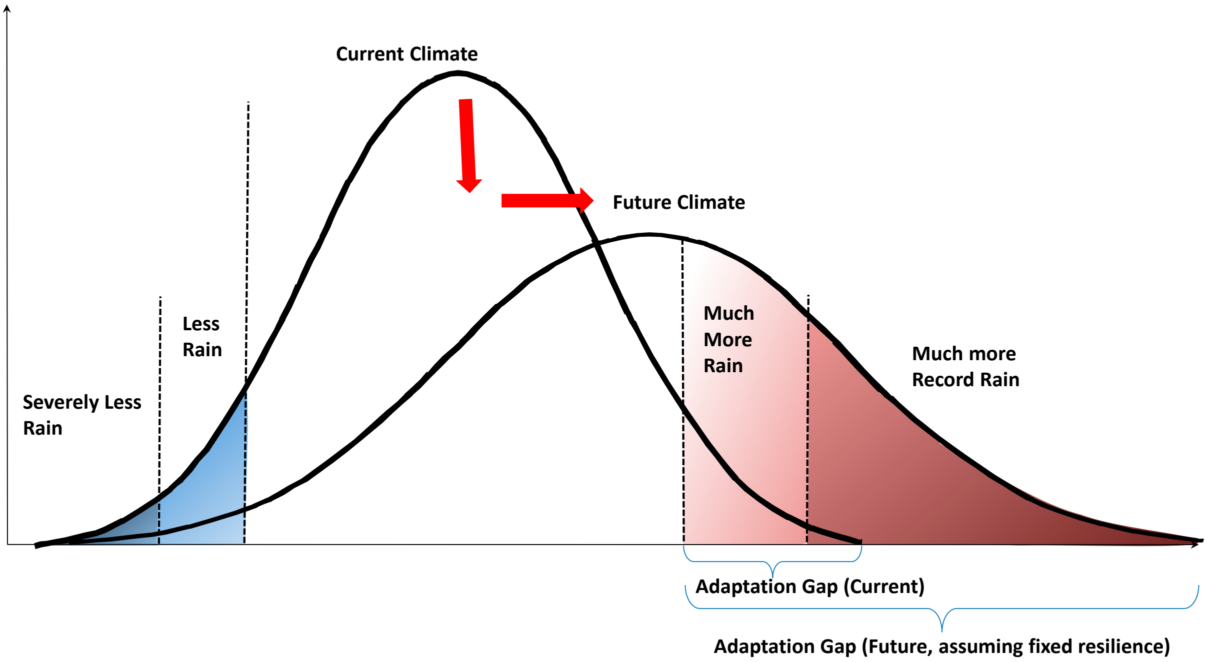


**Figure 37:** Adaptation Gap enhances much more in future

### 5.6 Ways of filling the Adaptation Gap

Conventionally, Adaptation Gaps may be filled in through managing the associated risks – either covering them through preventive investments or through paying the palliative costs of unacceptable risks. Involuntarily tolerated risks and also the residual risks form part of the uncovered risks in an adaptation gap. All the unacceptable risks, in turn, may be covered by the bearer or someone else through a prior arrangement where in the palliative damages are restored by a third party (the impacted party, the host country government, international bodies, reinsurer or someone else). Since CBDR is not currently implemented in adaptation effectively, these unacceptable risks (and associated palliative costs) mostly fall on the host country governments as a sovereign obligation, and to a very lesser extent on developed country parties and multilateral donor agencies who take these as a welfare measure and not as a liability measure. It may also be argued that US$ 100 billion/year by 2020 contribution commitment to the Global Climate Fund by developed country parties is based on a Welfare paradigm, and if this paradigm is changed to a Liability paradigm based on consistent and unequivocal IPCC findings on anthropogenic nature of climate change, the CBDR damage payments towards filling the Adaptation Gaps in all developing countries and emerging economies could be almost 10-times than this amount. Strong CBDR regimes in future would therefore change adaptation finance flows and technology transfers in favour of developing countries.

Risk management can be classified under four possible response options - avoid, mitigate, retain, and transfer the risk. The first two responses (avoidance and mitigation) may be categorized as risk control and the latter two (retention and transfer) as risk financing. The normal approach to risk management is to control all those risks that could be controlled within the physical resources available and finance the remainder. Effectively, risk financing funds those losses that remain after the application of risk control techniques, including both those risks accepted as not being able to be controlled and those where controls proved inadequate to contain the risk (AACI, 2003). All these response options are summarized below (Kapshe, 2012).

### 5.6.1 Risk Avoidance

An entity chooses to proceed with a particular investment on the basis of its perception of risk and whether the entity is willing to assume the risk; effectively the threshold is the tolerance for risk. This tolerance for risk will be a function of both the willingness to accept the risk and also the circumstances in which the entity is operating. If investors in a country, for instance, become too risk averse then investments in human and economic activities, and man-made ecosystems may dry down. However, it will not be possible for the government not to invest in their development even if the perceived risks of future climate change are high in any region. Therefore, risk avoidance for climate change related impacts may not be a suitable choice for governments in most of the human and economic activities, natural ecosystems, and man-made ecosystems if these are otherwise expected to contribute towards development.

### 5.6.2 Risk Mitigation

The measures such as loss prevention and loss control can be categorized as risk mitigation. In a traditional insurance context these measures may include security measures and safety standards. In many instances adherence to required risk mitigation measures is a prerequisite for any project to be sanctioned. There is a need to revise the safety standards in view of the likely climate change impacts in future, as the present day standards do not have any explicit consideration for these impacts.

### 5.6.3 Risk Transfer

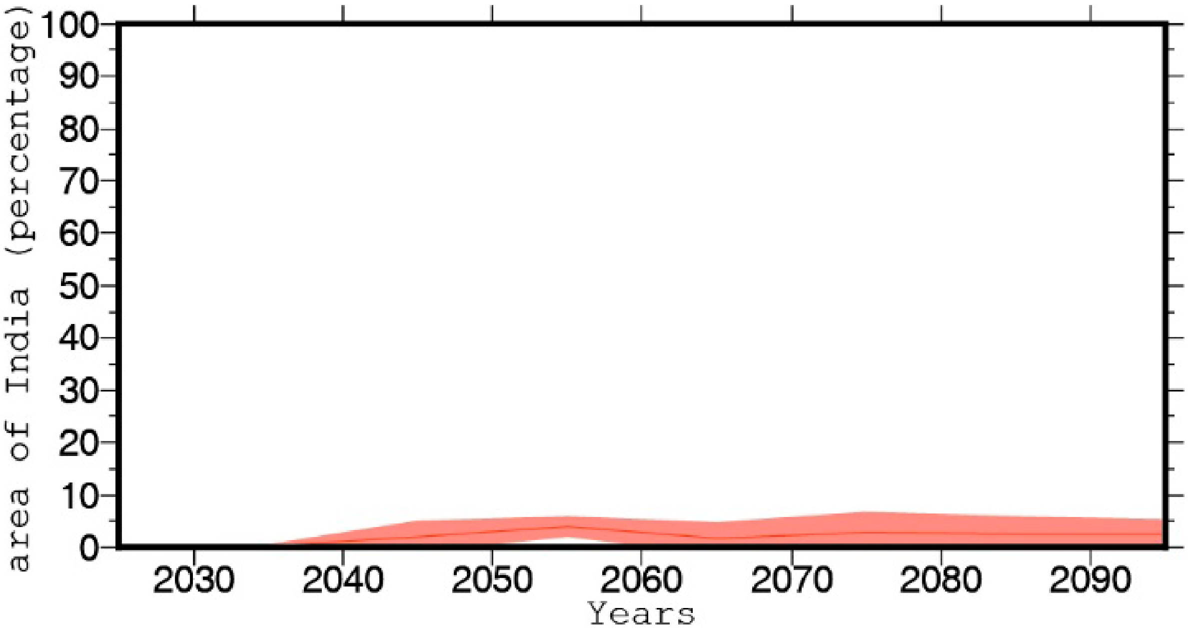
A risk that one organization is unwilling to bear may be transferred to another. This is what is commonly understood as insurance! In exchange for the payment of an agreed amount (the premium), the insurer agrees to indemnify the client for losses that result from specified perils. Options and hedges also operate to transfer risk from one party to another. In some instances the counter-parties may be entities specifically established to engage in the hedging or option trading, but in many instances they will be entities whose risk arises from the opposite movement in a price or volume of supply. In case of infrastructure projects there are many mechanisms existing for transfer of risks arising from the perceived uncertainties. However, there are no well-developed mechanisms specially designed to transfer the climate change impact risks.

### 5.6.4 Risk Retention

Risk retention can result from both a voluntary and involuntary action. Voluntary retention of risk results from a conscious decision to accept that a certain level of risk from any source should be retained rather than transferred to another party at a cost. Voluntary risk retention also includes acceptance of a level of risk that may be imposed by insurers. Involuntary risk retention occurs when a firm fails to identify and deal with a risk from within or outside the business and thus bears the risk unknowingly. Failure to recognize or understand a risk results in retention of the risk, which the firm will have to face in eventuality of the occurrence of event.

## 6. Implications for Alternate Scenarios

We have projected the future climate under alternate scenarios for Madhya Pradesh. We use those results to articulate Adaptation gaps. The adaptation gap increases in future (Figure 38) as temperature distributions shift to right in the near term (2016-2045), and longer term (2046-2075) for RCP 2.6 scenario. These shifts are more pronounced under RCP 4.5, RCP 6 and RCP 8.5. This expansion of the adaptation gaps would require more financial resources to be committed for managing heat related mortality, morbidity, damage to eco-systems and space cooling. Many species may get extinct, including vegetative, land based, marine and aerial. The financial implication estimations are around 80% more in real terms than present.



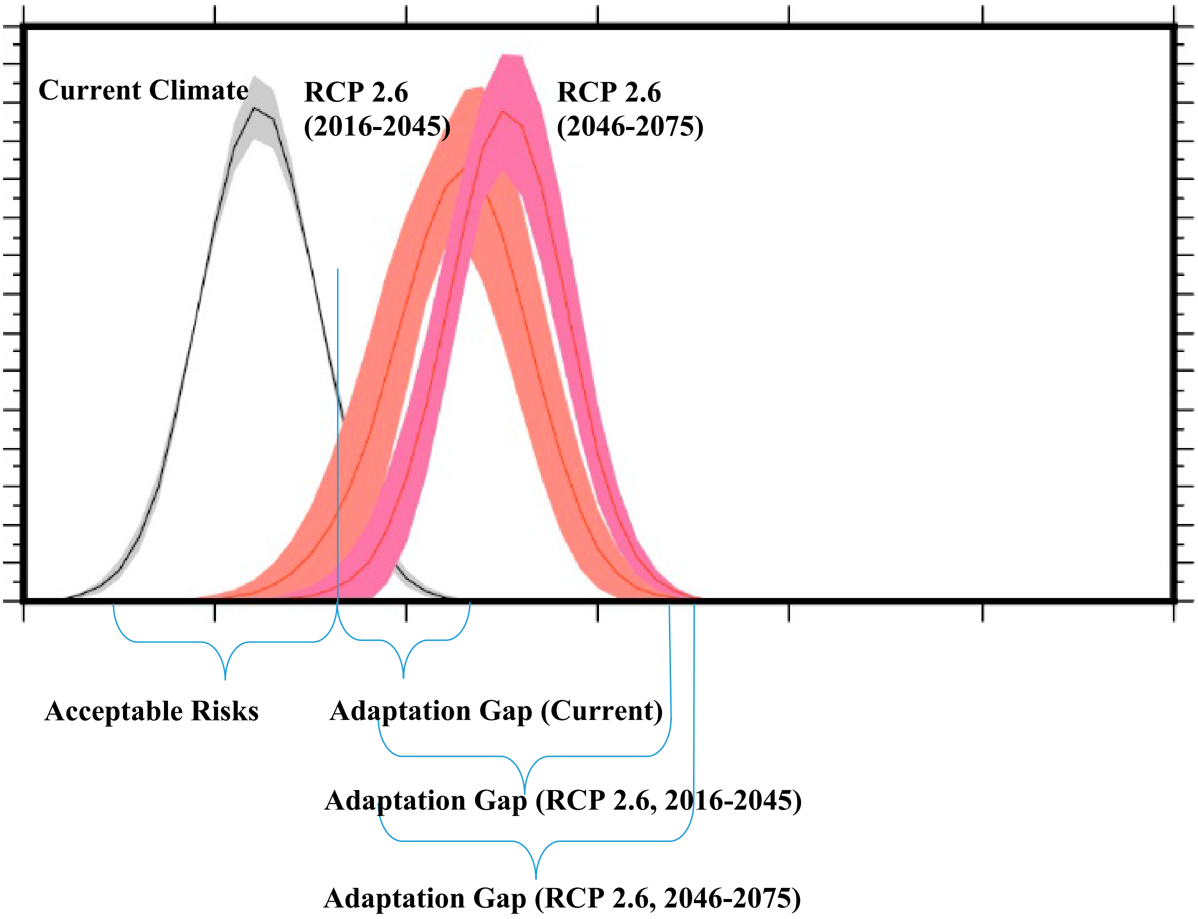
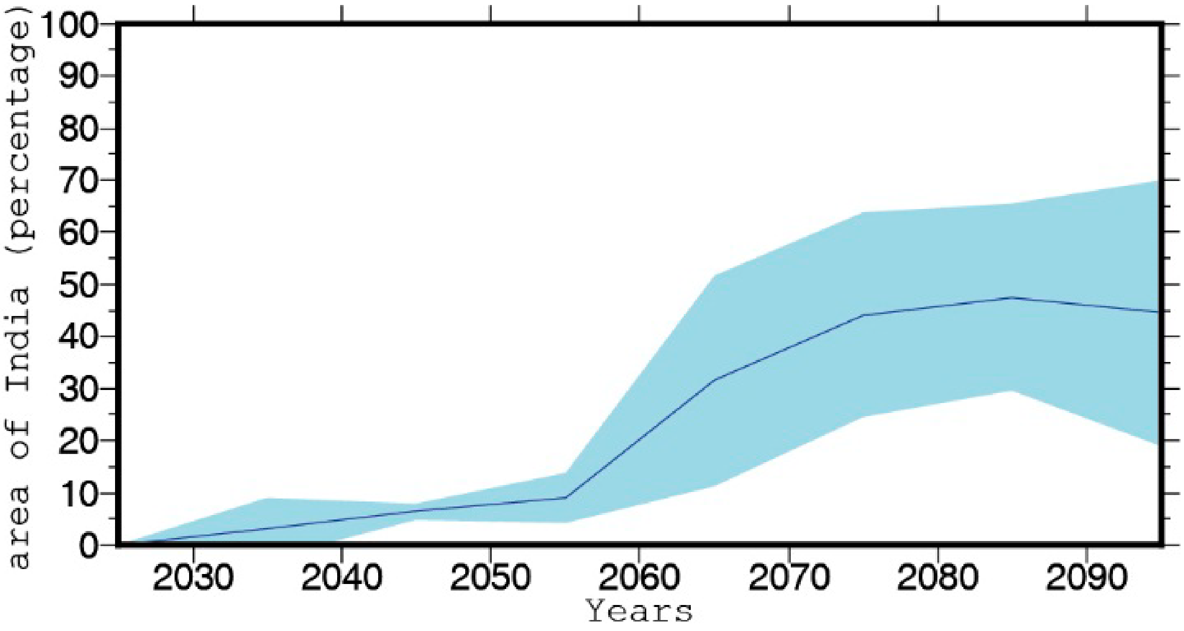


**Figure 38:** Articulating financial gap in adaptation under RCP 2.6 future projections



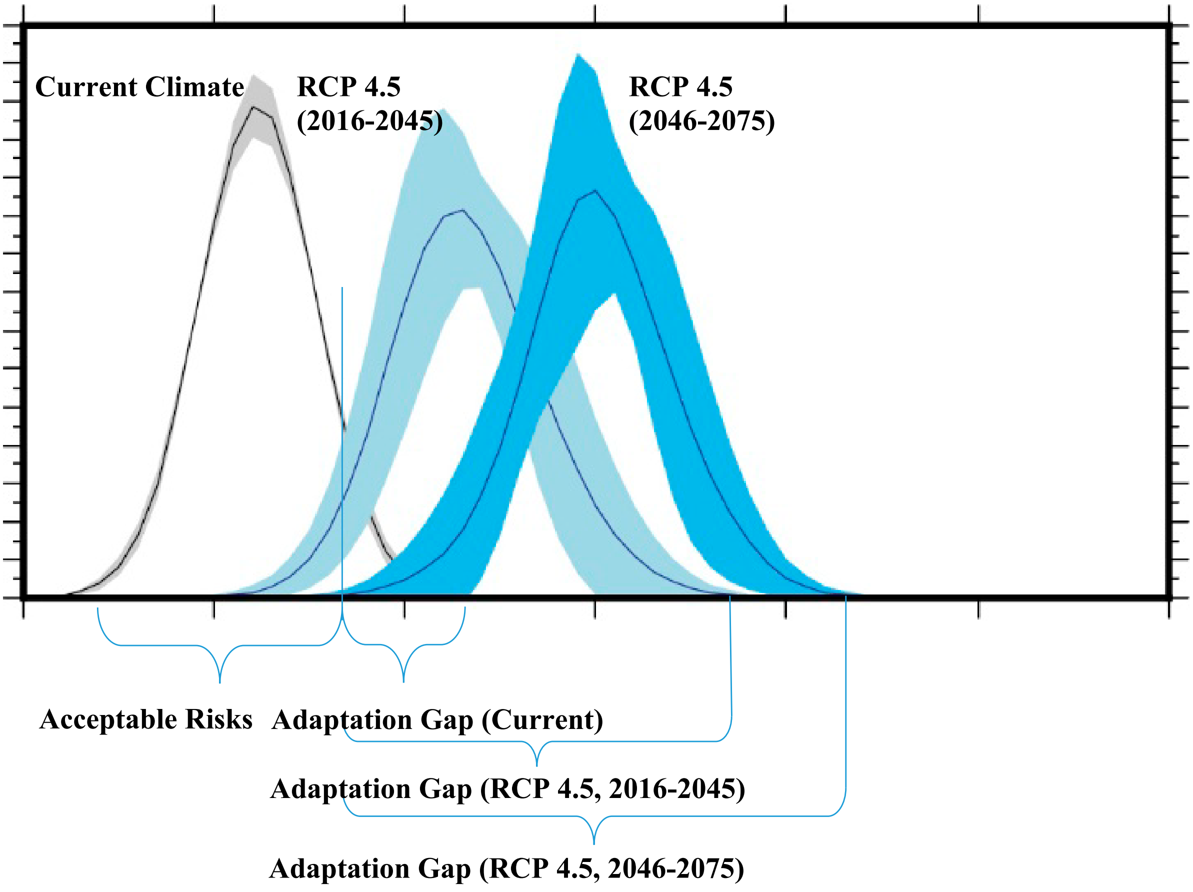


**Figure 39:** Articulating financial gap in adaptation under RCP 4.5 future projections

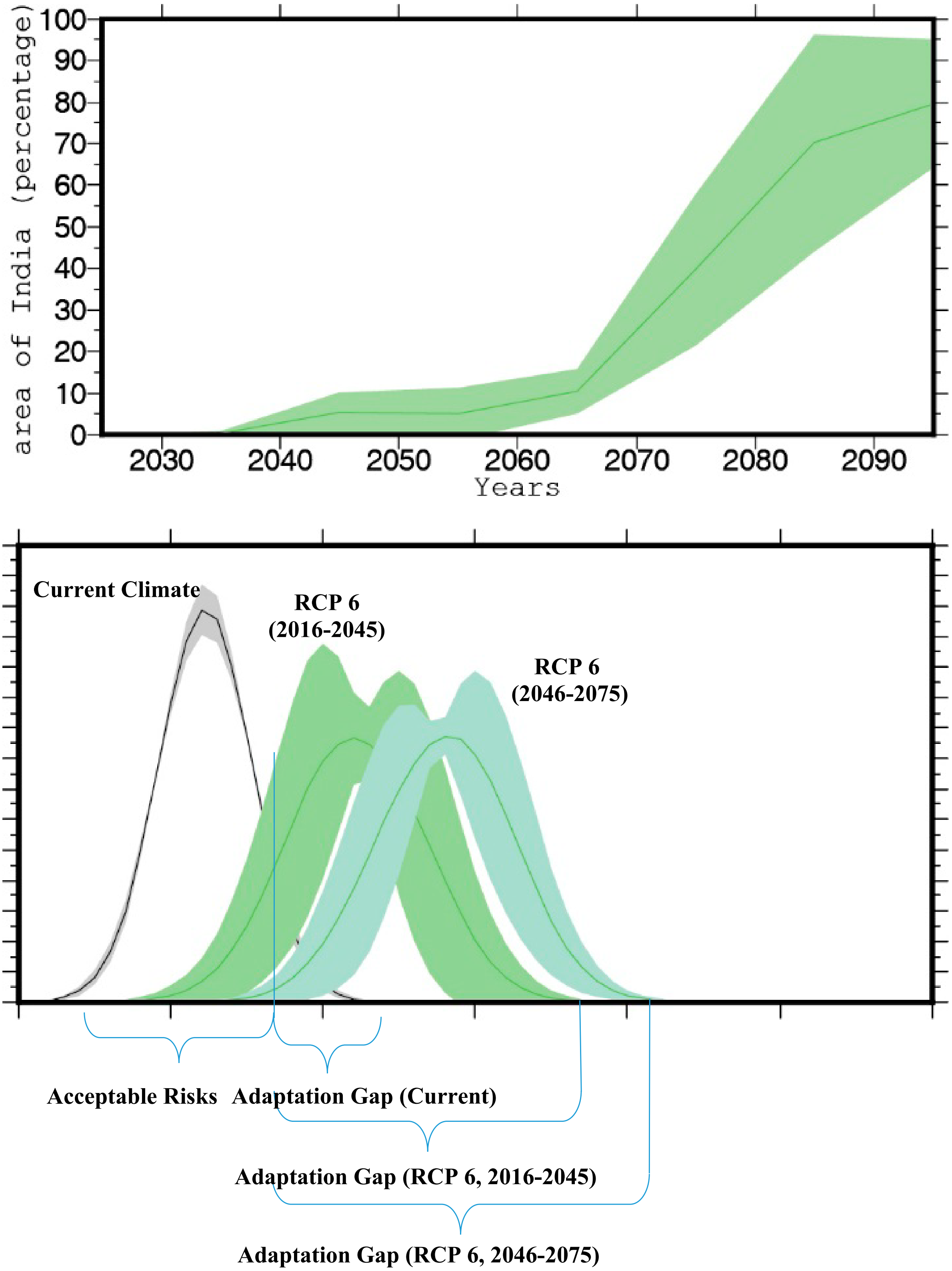
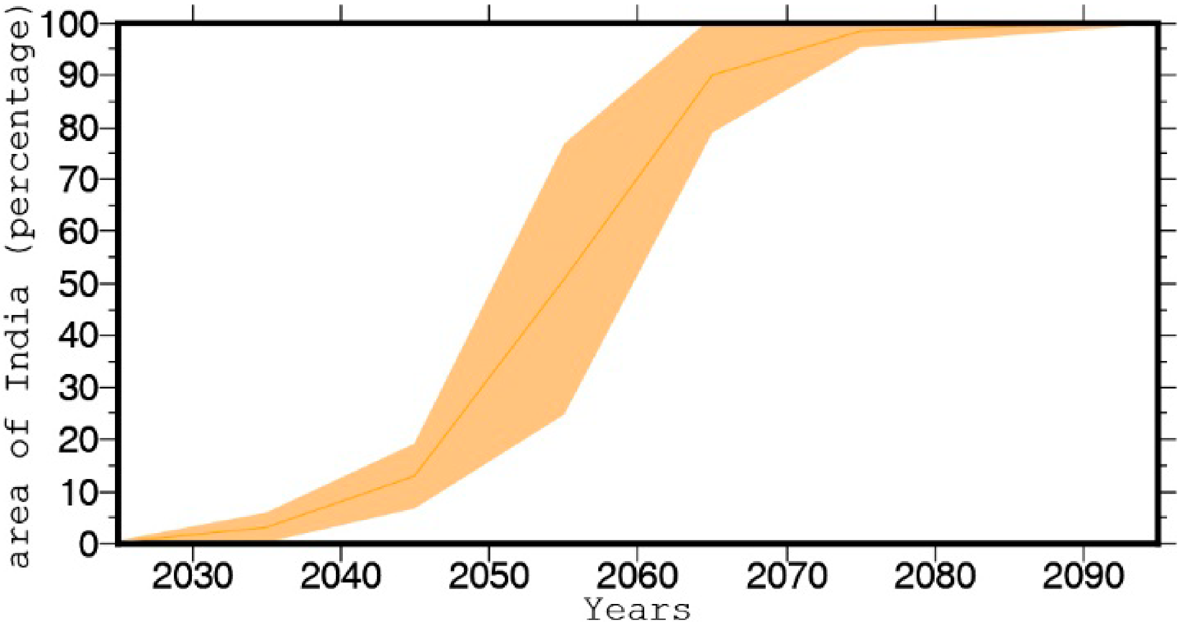


**Figure 40:** Articulating financial gap in adaptation under RCP 6 future projections



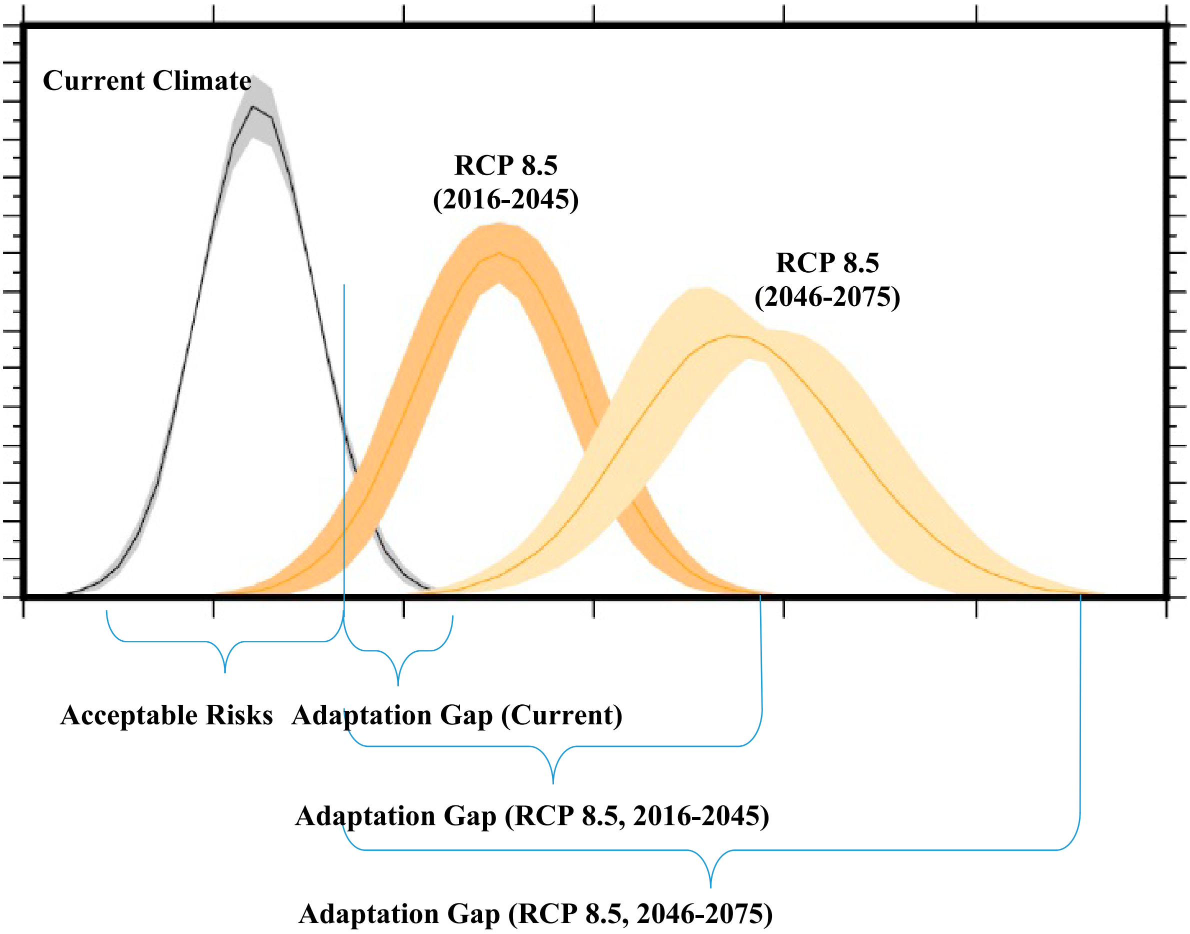


**Figure 41:** Articulating financial gap in adaptation under RCP 8.5 future projections

Under future climate change, it is evident that there is a right-ward shift in the distribution of risk. The shifts imply that new and additional financial investments are required to cover risks. It can be seen from Figures 38 to 41 that this spread may increase upto 2.5 times for RCP 2.6 and upto 4 times for RCP 8.5. This change in spread requires understanding the dynamic concept of acceptable risk and investing accordingly. Preventive adaptation to "expand" the range of acceptable risks would require much more investment as the risk profile is projected to shift to the right. This shift is crossing the right tails of present climate risk distributions under RCP 4.5, 6 and 8.5 during 2016-2045 itself. Almost no overlap remains during 2046-2075 risk profiles and the current risk profile. Most of the risks in future would therefore fall under unacceptable domains, thus increasing the palliative costs much faster. This also implies that future would become much more uncertain and risky, therefore increasing the chances of β errors much more. α errors may almost become negligible since whatever preventive measures would be taken, there would be hardly any chance of them going wasted.

Two approaches can be used while making these additional investments – wait and watch or take advance preventive actions. The wait and watch approach requires taking adaptation action (and investments) in future. This strategy implies lower preventive costs in the short term, but may lead to higher palliative costs in future. This is because a higher proportion of risk may be uncovered. The advance preventive actions require making investments now. This strategy implies higher expenditure in the short term, but may lead to lesser palliative costs in future. This is because a larger proportion of risk is covered. These investments can be made in advance as the infrastructure is being built (advance strategy) or retrospectively (wait and watch approach). Therefore, there is an inherent trade-off between these two strategies. Governments are required to choose optimal investments based on the risk they want to cover.

## 7. Conclusions

Based on the analysis for the observed and projected climate for the state of MP, the following conclusions can be drawn:

- Mean monsoon season precipitation declined significantly in the state of MP during the period of 1951-2013. Declines in the monsoon season precipitation were more concentrated in the eastern parts of MP during the period of 1951-2013. The five most deficit years during the monsoon season occurred in 1979, 1965, 2007, 1966, and 2009. The five most monsoon season precipitation surplus years occurred in 1961, 2013, 1994, 1973, and 1990. The lowest monsoon season rainfall occurred in 1979 (597 mm) and the highest in 1961 (1372mm) in Madhya Pradesh.
- Frequency of extreme precipitation events has increased in a few regions while declined in the others in Madhya Pradesh during the period of 1951-2013
- Droughts have become more frequent and wide-spread during the recent decades in Madhya Pradesh. The five most wide-spread droughts based on SPI occurred in 1965, 1979, 2007, 2009, and 2000 with areal extent of 65, 63, 46, 31, and 30%, respectively. The five most wide-spread droughts based on SPEI occurred in 1965, 1979, 2009, 1987, and 2007 with areal extents of 76, 72, 53, 48, and 44%, respectively. Moreover, areal extents have increased for the droughts occurred in the recent years in Madhya Pradesh
- The number of hot days increased substantially after 1990 in MP. The five years with the highest number of hot days were 2010, 1993, 1988, 1973, and 1998. The period between 1951 and 2000 experienced more number of hot nights than the most recent period. The five years with the most number of hot nights were 1953, 1958, 1952, 1998, and 2010. A decline in the number of cool nights in the state of MP was observed till 2005; however, the number has increased during the recent period. Moreover, the frequency of heat waves has increased after the 1980 in the Madhya Pradesh
- Changes under the projected future climate were estimated using the high resolution downscaled and bias corrected data for the RCPs 2.6, 4.5, 6.0, and 8.5 using the output from the five best CMIP5 models. The five best models were selected after a careful evaluation of the 40 CMIP5 and 9 CORDEX South Asia models.
- Based on changes in mean air temperature during the period of 2006-2013, the most representative RCP for Madhya Pradesh is RCP 4.5 while the North-central regions of Madhya Pradesh can be represented with RCP 6.0 and 8.5. Based on RCP 4.5, about 10% of

the state is projected to witness more than 2ºC warming by 2035. Moreover, based on RCP 8.5, about 30% of Madhya Pradesh is projected to experience more than 2ºC increase by 2050.

- Precipitation during the monsoon season in Madhya Pradesh is projected to increase by 5-15% in most of the RCPs. However, the monsoon season precipitation is projected to decline in the eastern part of the state in the Near (2016-2045) term under the RCP 4.5. On the other hand, precipitation extremes are projected to become more frequent under the projected future climate in Madhya Pradesh.
- Frequency of severe, extreme, and exceptional droughts is projected to decrease under RCP 2.6 and 6.0. However, droughts are projected to become more frequent in RCP 4.5 in the state in Near term climate. Increased warming under the projected future climate will lead to an increased severity, frequency, and areal extent of droughts in the state.
- Temperature extremes including hot days, hot nights, and heat waves are projected to increase significantly under the future climate in the state. The state is projected to witness 1-2 heat waves every year under the projected future climate.
- Uncertainty in the projections may be due to different representative concentration pathways (RCPs) as well as climate models. Therefore, it would be essential to understand the best possible RCPs that a region follows based on the past record and then select the projected changes under the future climate.

## 8. Recommendations for Policy Makers

Based on the changes in the observed and projected climate in the state of MP, the following specific recommendations are made for the state of Madhya Pradesh:

1. The state of MP experienced significant warming and decline in the monsoon season precipitation during the recent decades. As the warming in air temperature is larger in the post-monsoon (October-Rabi) season, it might have detrimental impacts on agriculture. The results showed that there might be serious implications on agriculture in both Rabi and Kharif seasons. Weaker monsoon and elevated temperature often lead to more irrigation requirements, which pose a tremendous pressure on surface and groundwater resources. Therefore, a decline in groundwater table and depletion of aquifer is obvious. To deal with this situation, a more detailed district level natural resource assessment needs to be performed and policy can be made of each district separately. Moreover, an emphasis on farm water management strategy and on improving water use efficiency is required.

2. As changes in both extreme and mean air temperature are visible from the observations and climate projections, their impacts on agriculture and different crops should be analysed for the different agro-ecological regions. Increase in the night time temperature (minimum temperature) could cause adverse impacts on crop production and may lead to shift in cropping periods. Results from this study indicate that there is a requirement of a long-term policy to improve crop cultivars to tackle the problem of climate change and its possible impacts on agriculture and water resources sectors.

3. Observed and projected increases in mean and extreme temperature can lead to increases in evapotranspiration that will cause soil moisture depletion. Frequent depletion in soil moisture may lead to agricultural droughts. Moreover, increased warming and heat waves in future can lead to increased demands for residential cooling. Therefore, policy will be required to evaluate distributed impacts on energy sector due to climate change in the state of MP.

4. Increased frequency of temperature extremes (hot days, hot nights, and heat waves) will have serious implications on residential energy demands as well as on tourism industry.

5. Projected increase in the frequency of extreme precipitation events will cause damage to infrastructure, urban flooding, as well as losses in crop production.

6. Overall, this study highlights the need of a local level strategy to deal with the problem of climate change and a proactive policy at district level will be required to minimize losses because of climate variability and climate change.

Adaptation responses are embedded in complex socio-economic environments and influenced by a variety of stakeholders such as state and national governments and civil society, international communities including governments and multilateral agencies, and other private actors. Further, the extent and type of responses to fill various Adaptation Gaps are contingent upon several drivers. Therefore, to understand the different gap fillings related to adaptation, a comprehensive approach is suggested (Figure 42).

At the core of this approach are the sustainable development goals for India. The sustainable development of the Indian population (and associated climate resilience) is contingent on several factors that include climate change variables, sustainable development goals, resources, products and services available and policies and measures that are in place.

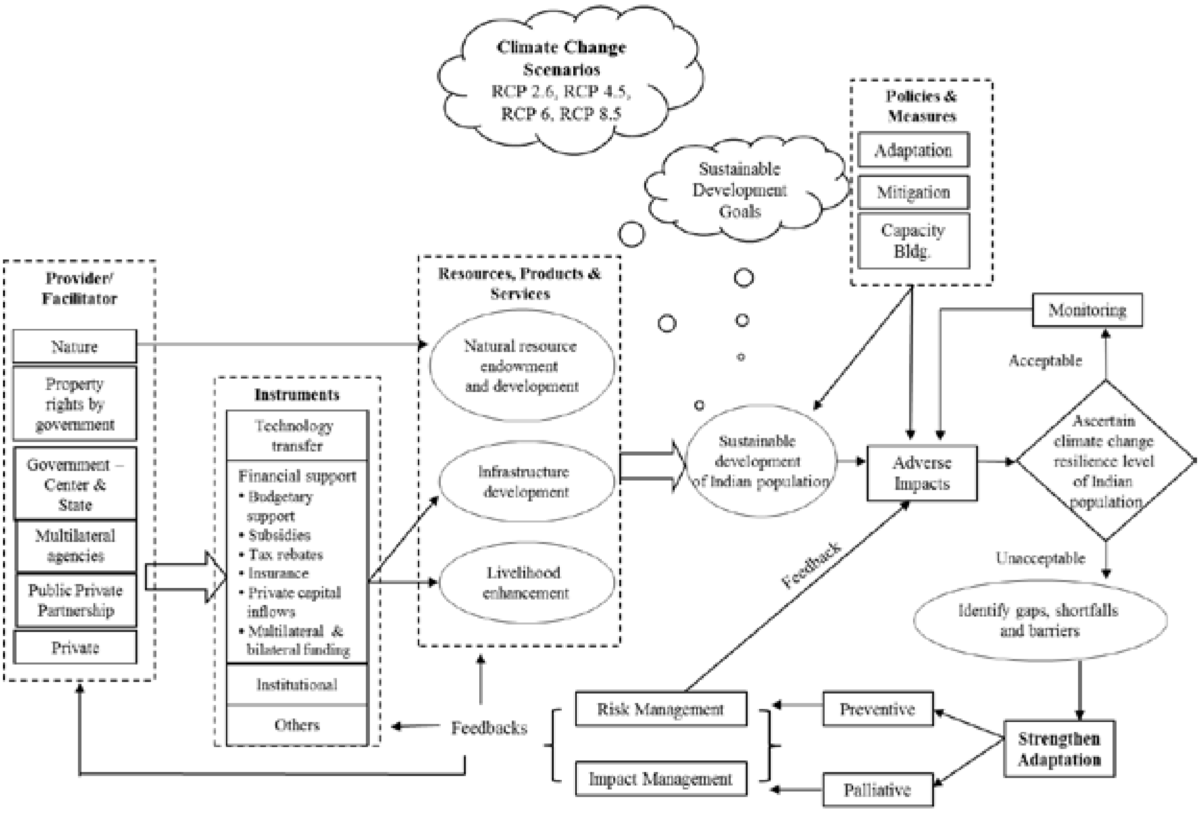


Figure 42: Filling the Adaptation Gap

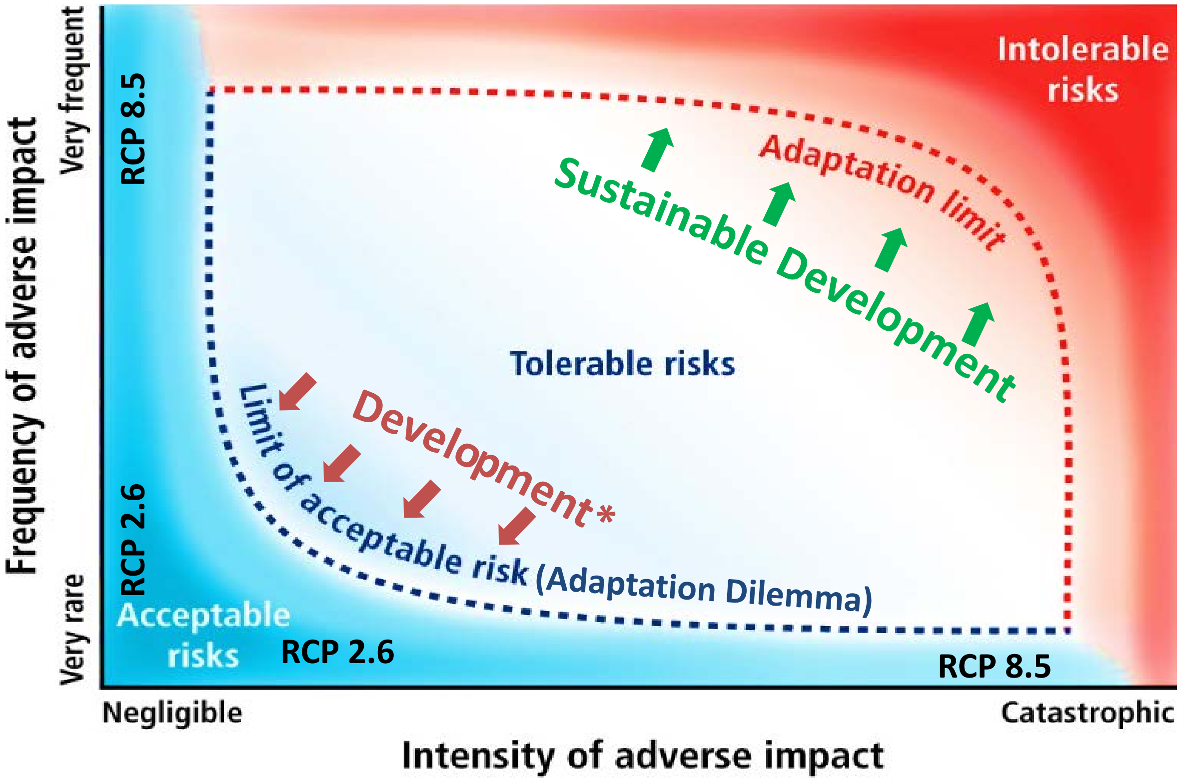
The impact of climate change variables (radiative forcing) in future will be an outcome of current and future mitigation efforts. Strong mitigation efforts will result in lower radiative forcing trajectories (e.g. RCP 2.6 scenario). Lower radiative forcing trajectories are associated with lower impacts from climate change and consequently lower adaptation responses. Scenarios in which radiative forcing levels are higher (e.g. RCP 6.0 or RCP8.5) would typically result in greater impacts thereby requiring greater adaptation measures. However, impacts and adaptation needs are likely to increase in a non-linear fashion as we transition from lower to higher radiative forcing trajectories.

The climate change variables will interact with current system conditions and sustainable development variables. The system condition variables may naturally pre-dispose certain sectors or populations to be more vulnerable to climate change variables as compared to others. For instance, poverty may be pre-disposed to loss of livelihoods due to lack of social, educational and health related capital. Impacts are likely to be less if development is spread evenly across different sectors and is equitable. These sustainable development variables will be driven partly by the policies and measures that are put in place. A complex combination of these variables will simultaneously determine the level of resilience and impacts.

If the resilience to these impacts is within acceptable limits, then continuous monitoring will be required. However, if the impacts are within unreasonable limits, then identifying gaps, shortfalls and barriers are important to strengthen adaptation. Adaptation measures could either be preventive (i.e. minimizing risk of impacts) or palliative (i.e. minimizing loss and damage after impacts have occurred).

Both require different approaches, but are complementary in nature and need to be carried out simultaneously. The preventive approach requires projecting impacts (and uncertainties) under future climate. This analysis can inform development of adaptation responses often using a 'no regrets' approach. The palliative approach requires responding to often unanticipated climate impacts in a swift manner. It also involves developing adaptation responses to minimize future impacts. Feedbacks from these will serve as inputs to fine-tune policy instruments and resource use by various stakeholders thereby influencing sustainable development of the Indian society. Based on this framework, the knowledge, financial, capacity building and institutional gaps were studied.

Figure 43 highlights that adaptation, mitigation and development are linked. There is a limit of acceptable risk and there is a limit to adaptation. The line defining the limit of acceptable risk is the adaptation dilemma. Sometimes, however, more risks appear to be acceptable to a very vulnerable population. This may be due to maldevelopment enhancing the risks to unwilling individuals and communities, who have to willy-nilly accept these. This is different than enhancing the limits of acceptable risks through positive developmental actions (preventive costs of adaptation) to enhance resilience of individuals and communities. Similarly the adaptation limit frontier could be enhanced through sustainable development.



**Note:** * Sometimes mal-development enhances the risks individuals and communities have to accept willy-nilly. This is different than enhancing the limits of acceptable risks through positive developmental actions (preventive costs for adaptation) to enhance resilience of individuals and communities.

**Source:** Adapted from Figure 16.1, WG2, AR5

**Figure 43:** Adaptation, Mitigation and development are linked

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