

# Chapter 4

## Assessing the Impact of Climate Change on Temperature and Precipitation Over India



Sridhara Nayak and Tetsuya Takemi

**Abstract** This study explores a comprehensive assessment of future climate change in terms of the climatologies, distribution patterns, annual cycles, and frequency distributions of temperature and precipitation over India by analyzing 190 mega-ensemble experimental results. The results indicate that the annual mean surface temperatures over Indian regions are typically 25 °C or higher in the present climate (1951–2010) and are expected to increase by 3–5 °C in the future climate (2051–2110). Some desert regions in the west and tropical humid climate types in the central and south regions of the country show possible temperature increases of 4–5 °C, while the temperatures over the subtropical humid climates in the north and east regions of the country show increases of 3–4 °C. The precipitation amounts over the arid and semiarid climate types in the western region and over some tropical rainforest climate zones in the southwest region show increases of 0.5 mm d<sup>-1</sup> in the future climate, and the precipitation amounts over the temperate, rainy climate types in the northeast region show increases of more than 1 mm d<sup>-1</sup>. This study also discusses future changes in various climatic variables, including vertical velocity, air temperature, specific humidity, cloud cover, and relative humidity.

**Keywords** Climate change · Indian future climate · Large ensemble · AGCM

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## 4.1 Introduction

According to the recent reports of the Intergovernmental Panel on Climate Change (IPCC), climate change is anticipated to play a crucial role in increasing or intensifying natural disasters on Earth, particularly extreme weather events (IPCC 2014). Climate change has therefore become one of the major concerns in the world due to its impact on socioeconomic development, and the effects of climate change are mostly reflected in the increase in surface temperature and the changes in precipitation patterns and other climatic features (Pall et al. 2007; O’Gorman and Schneider 2009; Guhathakurta et al. 2011; IPCC 2012, 2014; Takemi et al. 2016).

India is a land of diverse topographies and climate types. The topography in India is characterized by various mountain ranges, plains, high plateaus, coastal plains, and deserts. The mountain ranges of India include the Western Ghats in the southwest, the Eastern Ghats in the southeast, the high Himalayan range in the north, the Aravalli Range in the northwest, and the Vindhya and Satpura Ranges in the central region. The Indo-Gangetic Plains occupy most of the central, eastern and northern parts of India, and the Thar Desert occupies most of the western part. The high plateaus of India comprise the Chota Nagpur Plateau in the east, the Deccan Plateau in the south, and the Malwa Plateau in the west. The coastal plains of India are surrounded by the Bay of Bengal and the Arabian Sea. Because of such topographical and physical variations, the climate of India consists of a wide range of climatic types, from the alpine Himalayan region in the north to the tropics in the south, including tropical rainforest, tropical monsoon, tropical wet, tropical arid, and semiarid, savanna, temperate rainy, steppe, subtropical humid, alpine and desert climate types. The major climate types in India include a desert climate in the west (less than 300 mm year<sup>-1</sup> rainfall), a wet climate in the tropics (approximately 2000 mm year<sup>-1</sup> rainfall), a wet-dry climate in the tropics (normally above 18 °C and 1500 mm year<sup>-1</sup> rainfall), a humid climate in the subtropics (within 0–27 °C and 1000–2500 mm year<sup>-1</sup> rainfall) and an alpine climate type with glaciers in the north. Therefore, understanding the climates of tropical, subtropical, temperate, and arid/semiarid regions are key to understanding the climate of India. Furthermore, understanding how global climate change affects the climate of India will provide profound knowledge on the impacts of global warming on regional-scale climates.

Occasional occurrences of natural disasters such as droughts, floods, coastal erosion, and landslides are also part of life in this land and cause severe and widespread damage (IPCC 2012, 2014). These disasters are mainly associated with weather extremes and are strongly determined by the temperature and precipitation characteristics over the target areas (e.g., Guhathakurta et al. 2011; Ojha et al. 2013). Therefore, understanding the distributions of temperature and precipitation over India is very important not only for the present climate but also for future developmental planning and decision-making aimed at resisting future climate change issues.

There have been a number of studies (Nayak and Mandal 2012; Kumar et al. 2013; Prakash et al. 2015; Kishore et al. 2016; Akhter et al. 2017; Maity et al.

2017a, b; Nayak et al. 2017, 2018; Nayak and Mandal 2019) that have investigated the distributional patterns and climatologies of temperature and precipitation over the Indian region from observational, reanalysis, and modeled datasets. In a recent study, Nayak et al. (2019) analyzed precipitation and temperature climatologies and distributions over India for the period 1981–2010 and highlighted that the 30-year mean precipitation climatology over India corresponds to  $\sim 3 \text{ mm d}^{-1}$  and the 30-year mean annual temperature over India corresponds to  $23.15 \text{ }^\circ\text{C}$ . The climate signals during the twentieth century over India also confirm remarkable changes in precipitation patterns and an increasing surface temperature trend (Sinha Ray and Srivastava 1999; Sharma et al. 2004; Dash and Hunt 2007; Niyogi et al. 2010). Kothawale and Rupa Kumar (2005) reported an increase in the mean annual temperature over India at a rate of  $0.05 \text{ }^\circ\text{C}$  per decade during the period 1901–2003. Jain and Kumar (2012) documented a warming trend in the annual mean, minimum and maximum temperatures at rates of 0.51, 0.27, and  $0.72 \text{ }^\circ\text{C}$  per century, respectively, from 1901–2007. Rao et al. (2014) also highlighted an increase in the annual minimum temperature over India of  $0.24 \text{ }^\circ\text{C}$  per 10 years during the period 1971–2009. On the other hand, studies of annual precipitation show mixed trends (decreasing over some regions and increasing over some regions) over Indian regions during the period 1901–2003 (e.g., Kothawale and Rupa Kumar 2005; Guhathakurta and Rajeevan 2008). Kumar et al. (2010) also observed similar trends in annual precipitation over Indian regions during the period 1871–2005.

Although many studies are available that have assessed past temperature and precipitation distributions and trends over India, a limited number of studies have focused on future climate changes over India. Kumar et al. (2013) highlighted possible warming over India of  $1.5 \text{ }^\circ\text{C}$  by the end of 2050 and of  $3.9 \text{ }^\circ\text{C}$  by the end of twenty-first century under the SRES A1B climate scenario compared to the temperature in 1970–1999. Patwardhan et al. (2018) also documented a possible increase in surface temperature over India of  $4\text{--}5 \text{ }^\circ\text{C}$  towards the end of the twenty-first century under the SRES A1B scenario. Patwardhan et al. (2018) reported increases in summertime (Mar–May) temperatures of  $1.6\text{--}4.1 \text{ }^\circ\text{C}$  over the northwest and west-central regions, of  $1.7\text{--}4.4 \text{ }^\circ\text{C}$  over the central northeast region, and of  $1.2\text{--}3.8 \text{ }^\circ\text{C}$  over the northeast and peninsular regions of India by the 2080s under the SRES A1B scenario with respect to the temperatures recorded in the 1970s. Chaturvedi et al. (2012) highlighted possible increases in precipitation amount over India by  $4\text{--}5\%$  by 2030 and  $6\text{--}14\%$  by 2080 under the RCP6.0 and RCP8.5 scenarios compared to the amounts in 1961–1990. Akhter et al. (2017) also documented possible increases in precipitation amounts over various Indian regions during the 2020s, 2050s, and 2080s under the RCP4.5 and RCP8.5 scenarios. Akhter et al. (2017) highlighted increases in precipitation amounts by  $12\text{--}30\%$  over some regions of northwest India, by  $3\text{--}30\%$  over some regions of western India, by  $5\text{--}18\%$  over a few parts of northeast India and by  $6\text{--}24\%$  over some regions of southern India under the RCP4.5 and RCP8.5 scenarios. All these studies clearly indicate possible increases in surface temperatures and precipitation amounts over Indian regions towards the end of the twenty-first century.

Recently, Mizuta et al. (2017) conducted mega-ensemble global climate simulations for 6000-year historical and 5400-year future (4 °C warming) climates with 100 experiments for the present climate (1951–2010) and 90 experiments for the future climate (2051–2110) by using the Meteorological Research Institute (MRI) Atmospheric General Circulation Model (AGCM) at a 60-km spatial resolution. A number of recent studies (e.g., Endo et al. 2017; Iizumi et al. 2018; Kusunoki 2018; Fujita et al. 2019) have used these mega-ensemble simulations to predict various aspects of the historical climate over different regions of the world and assess future climate change projections. Based on the limited previous studies over India, it is expected that the surface temperatures and precipitation amounts over India would increase in the future climate. Thus, understanding future climate change projections over India has become crucial for future developmental planning and monitoring climate risks. In this sense, the abovementioned mega-ensemble climate simulations should add new insights to future assessments of climate change over India because ensemble analysis always reduces uncertainties in the context of climate risk management. Thus, an attempt is made to explore a comprehensive assessment of climate change over India by analyzing the 190 mega-ensemble experimental results in two climate periods (1951–2010 and 2051–2110) and discussing the climatologies, distribution patterns, annual cycles, and frequency distributions of temperature and precipitation over India in the past 60 years and their future changes in the next 100 years.

## 4.2 The d4PDF and Analysis Procedures

The hourly precipitation and daily temperature datasets used in this study were obtained from 100 experiments of the present climate (1951–2010) and 90 experiments of the future climate (2051–2110 with +4 °C warming) from MRI-AGCM simulations at a 60-km resolution. A list of these 190 ensemble experiments is given in Table 4.1. This mega-ensemble climate simulation dataset is known as d4PDF (database for policy decision making for future climate change), and the database was collected using various initial conditions and small perturbations of sea surface temperatures (SSTs) for 6000-year historical and 5400-year future (4 °C warming) climate simulations (Mizuta et al. 2017). Here, the 6000-year historical climate simulations refer to 100 ensemble historical experiments comprising

**Table 4.1** List of 190 ensemble experiments conducted by AGCM

Model	Climate period	Total number of ensemble experiments	Resolution
MRI-AGCM	Present (1951–2010)	100	60 km
	Future (2051–2110, with 4 °C warming)	90	

*Source* (Data source) Mizuta et al. (2017)

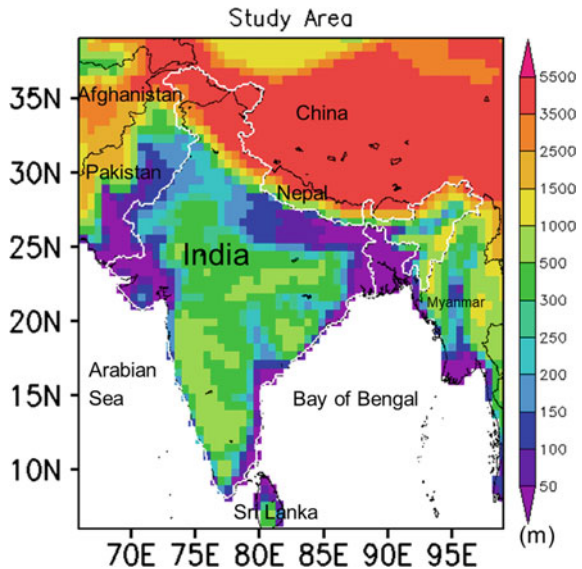
60 years each, totaling  $100 \times 60$  years of simulations. Similarly, the 5400-year future climate simulations refer to 90 ensemble future experiments comprising 60 years each, totaling  $90 \times 60$  years of simulation.

Asian precipitation-highly resolved observational data integration towards evaluation (APHRODITE) daily temperature and precipitation datasets at a  $0.25^\circ \times 0.25^\circ$  grid box for the period 1961–2007 are also used to validate the model-simulated temperature and precipitation results in the present climate. The detailed methods for the preparation of the APHRODITE temperature and precipitation data are described in Yasutomi et al. (2011) and Yatagai et al. (2012), respectively.

As described in the introduction, this study is focused on climate change over India. The topography of India and the surrounding regions is demonstrated in Fig. 4.1. A tropical rainforest climate extends in the southern and western coastal parts of the Indian subcontinent, surrounded by monsoon and savanna climate regions in the central, east, and south. In the north and northeastern parts of India, a rainy temperate climate exists. In the western parts of India, there are steppe and some arid/semiarid climate regions. The tropical humid climate type includes the tropical wet (no dry season), tropical monsoon (short dry season), and tropical wet-dry (dry in winter) climate types. The dry climate consists of subtropical steppe and desert climate types and is mostly arid/semiarid and dry. The humid subtropical (warm summer but no dry season), Mediterranean (dry, hot summer), and west coast (no dry season but warm and cool summer) climate types are included in warm temperate climates.

In the present analyses, the ensemble annual mean climatologies, annual cycles, and frequency distributions of temperature and precipitation over India are first

**Fig. 4.1** Topography of the area. The Indian Ocean is located with white on the map. *Source* (Data source) Mizuta et al. (2017)

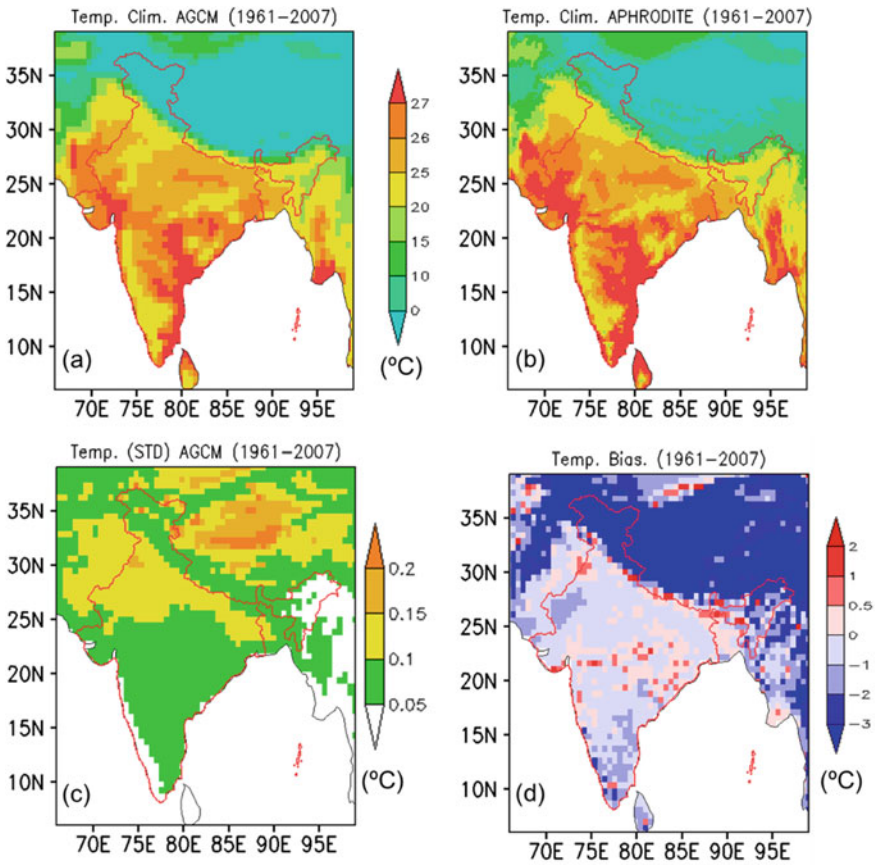


derived for the period 1961–2007 (48 years) from the AGCM simulations and are then compared with the APHRODITE observations to validate the d4PDF results over the Indian region. Then, similar analyses of temperature and precipitation are performed from the AGCM simulations for two climate periods of 60 years each: 1951–2010 for the present climate and 2051–2110 for the future climate. The climatologies of other climatic variables, including the vertical velocity, air temperature, specific humidity, cloud cover, and relative humidity, are also analyzed and discussed in this study.

### 4.3 Validation of d4PDF Data Over India

Figure 4.2 shows the temperature climatology for the period 1961–2007 from the ensemble mean of the AGCM experiments and that from the APHRODITE observations. The AGCM-simulated temperatures show that the annual mean surface temperatures over Indian regions, except over a few regions of north India, correspond to mostly 25 °C or higher during 1961–2007 (Fig. 4.2a, b). The lowest temperatures, which are approximately 0 °C or less, are noticed over some regions in northern India, and the highest temperatures of approximately 27 °C or greater are seen over some regions in southern and western India during this period. Similar temperature variations are also noticed in the APHRODITE observations except over a few regions in southern and western India (where the temperatures are  $\sim 2$  °C higher). A comparison between the AGCM-simulated climatology and the APHRODITE-observed climatology indicates that the overall temperature climatology over India is well-represented by the model. The individual ensemble climatology also shows similar results, with standard deviations in the range of 0.5–0.15 °C from the means (Fig. 4.2c). A comparison between the temperature climatology from the ensemble mean of the AGCM and that from the observations indicated that the AGCM simulations have an overall cold bias over India. The AGCM shows a large cold bias over the northern and northeastern mountainous areas; however, the magnitude of the model bias over most of the Indian regions is in the range of  $-1$  to 0.5 °C (Fig. 4.2d). The spatial correlation coefficient between the simulated and observed temperature climatologies over India is 0.99.

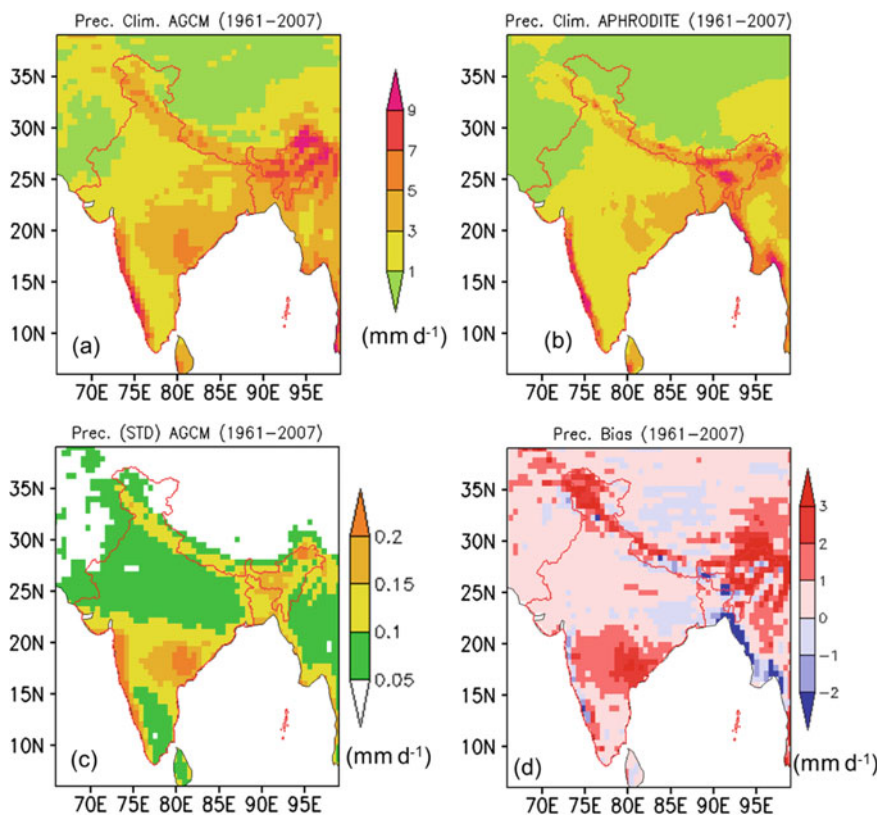
The distribution of annual mean precipitation over most of the regions in central, eastern, and northeastern India shows approximately 3–5 mm d<sup>-1</sup> of precipitation during 1961–2007 in the AGCM ensemble simulation and approximately 1–3 mm d<sup>-1</sup> over most of the other parts of India (Fig. 4.3a, b). A few areas over the northeastern regions, including the Western Ghats, received the highest amounts of precipitation ( $>7$  mm d<sup>-1</sup>) during this period. The APHRODITE observations also show mostly the same amounts of precipitation over these regions. The precipitation climatology in each individual simulation also shows similar results, with standard deviations within 0.05–0.25 mm d<sup>-1</sup> compared to the means (Fig. 4.3c). The ensemble mean precipitation climatology obtained by the AGCM shows a wet bias of 0–1 mm d<sup>-1</sup> over most of the regions of central, eastern, southern, and



**Fig. 4.2** Temperature climatologies derived from **a** the AGCM ensemble mean and **b** APHRODITE for the 1961–2000 period. **c** Standard deviations (STD) of the climatologies of temperature derived from all ensemble members. **d** Model biases in the temperature climatology. *Source* (Data source) Mizuta et al. (2017)

western India, while a large wet bias is noticed over some regions of northern, northeast, and southcentral India (Fig. 4.3d). The spatial correlation coefficient between the simulated and observed precipitation climatologies over India is 0.76.

The annual cycles and normal probability distribution functions (PDFs) of the monthly mean temperatures over India during 1961–2007 from the AGCM model simulations and those from the APHRODITE observations are presented in Fig. 4.4. The monthly mean temperature climatologies over India from the AGCM simulations indicate that the lowest temperature over India corresponds to  $\sim 15^\circ\text{C}$  during December–January and the highest temperature corresponds to approximately  $29^\circ\text{C}$  in May (Fig. 4.4a). The PDFs from monthly mean temperatures

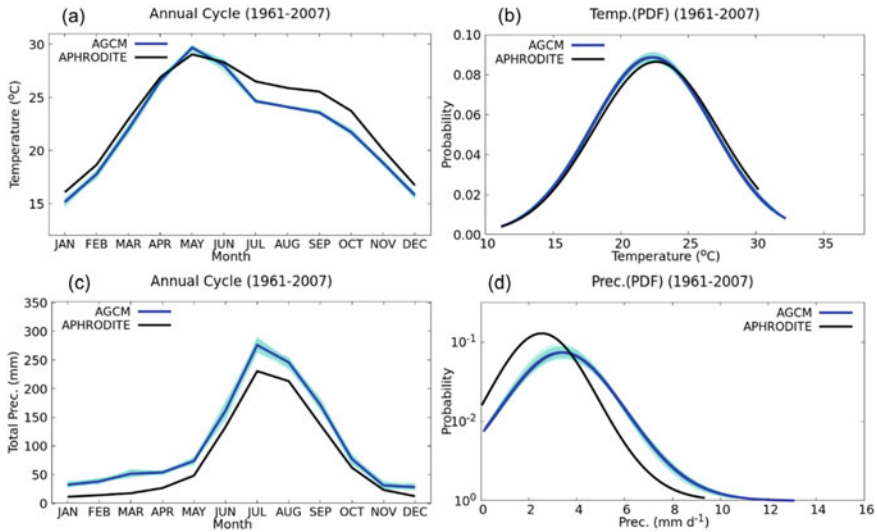


**Fig. 4.3** Precipitation climatologies derived from **a** the AGCM ensemble mean and **b** APHRDITE for the period 1961–2000. **c** Standard deviations (STD) of the climatologies of precipitation derived from all ensemble members. **d** Model biases in the precipitation climatology. *Source* (Data source) Mizuta et al. (2017)

indicate that the temperature over India in most of the months remained at approximately 22 °C during 1961–2007 (Fig. 4.4b).

The temperature patterns seen in d4PDF can be confirmed with the observed temperatures from APHRDITE, but the model values are underestimated by approximately 2 °C. Each individual ensemble simulation also shows similar temperature characteristics over India. The annual cycle of the precipitation climatology over India during 1961–2007 shows that India receives the highest amount of precipitation (240 mm or higher) in July (Fig. 4.4c). Both the AGCM model and APHRDITE observations show the same features qualitatively, although the AGCM overestimates the precipitation amount by approximately 20–30 mm in some months. The precipitation amounts for May, June, September, and December are well-captured by the model and have good agreement with the observations. The  $p$ -value between the observed precipitation amounts and the





**Fig. 4.4** Annual cycles and probability distributions (PDFs) over India derived from the AGCM ensemble and APHRODITE observations for the period 1961–2007. The upper panels (a–b) correspond to the results for temperature, and the lower panels (c–d) correspond to the results for precipitation. The thin lines in the figures correspond to the results for each ensemble member. *Source* (Data source) Mizuta et al. (2017)

d4PDF simulations was tested considering the null hypothesis as an equal mean with a 99% significance level; the  $p$ -value was found to be 0.45, which is sufficiently higher than 0.1. We thus fail to reject the null hypothesis. In other words, the differences between the observed and simulated precipitation amounts are not significant. The PDFs of monthly precipitation intensities in the AGCM simulations show precipitation intensities of approximately  $4 \text{ mm d}^{-1}$  (or  $\sim 120 \text{ mm}$  precipitation considering 30 days in a month) in most months, while the precipitation intensities are approximately  $3 \text{ mm d}^{-1}$  in the APHRODITE observations (Fig. 4.4d). Similar monthly precipitation features over India are also noticed in each individual simulation.

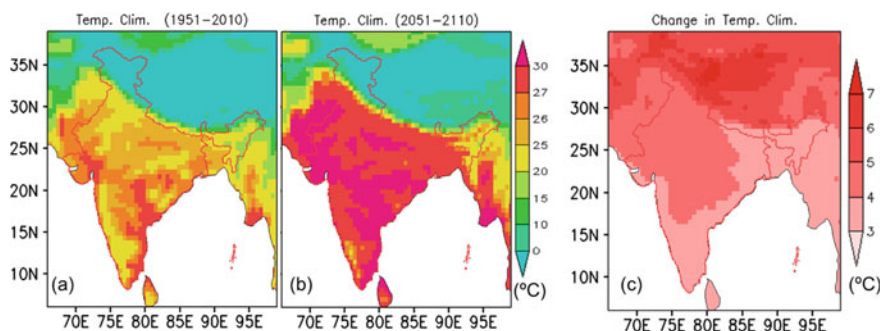
Overall, the AGCM-simulated mean temperature and precipitation climatologies, annual cycles, and frequency distributions are in good agreement with the APHRODITE observations over the Indian region.

## 4.4 Climate Change Over India Under Global Warming

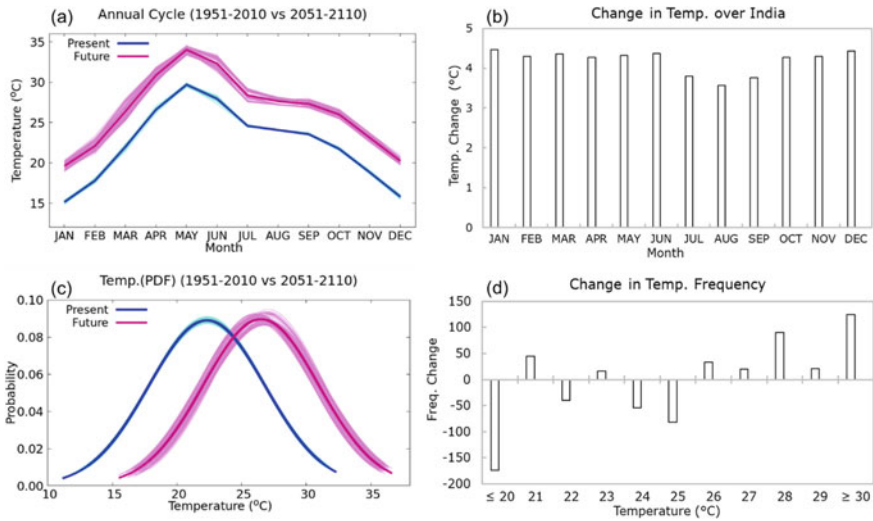
### 4.4.1 Projected Changes in Temperature Distribution

The spatial distributions of the temperature climatologies derived from the AGCM ensemble mean for the periods 1951–2010 and 2051–2110 are presented in Fig. 4.5. The annual mean surface temperature over a large part of India is noticed to be mostly 25 °C or higher in the period 1951–2010 and is expected to be mostly 27 °C or higher in the period 2051–2110 over the same regions (Fig. 4.5a, b). The results show a possible warming of 3–5 °C over the entire Indian region in the period 2051–2110 with reference to the period 1951–2010 (Fig. 4.5c). The temperatures over central and northwest India are expected to increase by 4–5 °C in the future climate, while the temperatures over a few regions of north India are projected to rise by 6 °C or more.

Figure 4.6 represents the annual cycles and frequency distributions of the monthly mean temperatures over India in two climate periods and their projected changes. The results indicate that the mean temperature over India in the future climate is expected to vary from ~20 °C in December–January to 34 °C in May (Fig. 4.6a). Each individual ensemble member also shows a similar pattern of monthly temperature over India. The monthly mean temperature is expected to increase by ~4 °C during July–September and by ~5 °C during October–June under the future climate (Fig. 4.6b). The normal probability distribution functions indicate that the monthly temperature over India is expected to shift by approximately +5 °C in the future climate (Fig. 4.6c). The temperatures over India in most months are expected to shift from ~22 °C in the present to ~27 °C in the future climate. Similar temperature characteristics are observed in each individual ensemble member. The change in the frequencies of monthly mean temperatures with a 1 °C interval bin between the two climate periods indicates that more months are expected to be warmer (26 °C or higher) in the future climate (Fig. 4.6d).



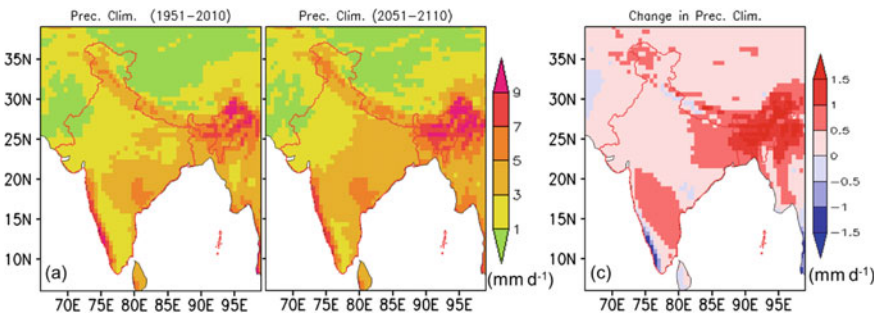
**Fig. 4.5** Temperature climatologies from the AGCM ensemble mean for **a** present and **b** future climates and **c** the future temperature changes. *Source* (Data source) Mizuta et al. (2017)



**Fig. 4.6** **a** Annual cycles in two climate periods and **b** projected changes in temperature. **c** PDFs in two climate periods and **d** projected changes in the temperature frequencies. The thin lines (a, c) correspond to the results for each ensemble member. *Source* (Data source) Mizuta et al. (2017)

### 4.4.2 Projected Changes in Precipitation Distribution

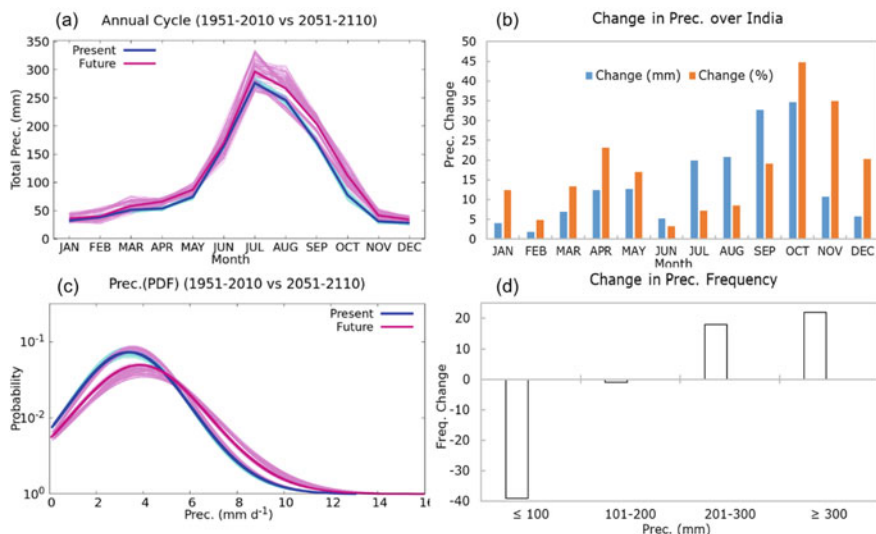
Figure 4.7 represents the precipitation climatologies derived from the AGCM ensemble experiments for two climate periods and their future changes. The figure shows that the precipitation distribution patterns in both climate periods (i.e., during 1951–2010 and 2051–2110) are almost the same over all regions of India but with higher magnitudes under the future climate except over the Western Ghats regions (Fig. 4.7a–b). The precipitation amounts increase in the future climate by approximately  $0.5\text{--}1\text{ mm d}^{-1}$  over almost all regions and decrease by



**Fig. 4.7** Precipitation climatologies from the AGCM ensemble mean for the **a** present and **b** future climates and **c** their future changes. *Source* (Data source) Mizuta et al. (2017)

approximately  $1 \text{ mm d}^{-1}$  over the west coast along the Western Ghats (Fig. 4.7c). The northeast regions of India are likely to experience relatively more precipitation in the warming future climate.

The annual cycles and frequency distributions of the monthly total precipitation amounts over India in the present and future climates and their projected changes are illustrated in Fig. 4.8. The results indicate that the total monthly precipitation over India in the future climate is expected to increase to  $\sim 300 \text{ mm}$  in July with an uncertainty range of 260–340 mm (Fig. 4.8a). The monthly total precipitation amount is likely to increase by 20–40 mm (5–45%) during July–October in the future climate and by 2–13 mm (3–35%) during November–June (Fig. 4.8b). This indicates that India is expected to receive relatively more precipitation in the monsoon season (June–September) under the future climate. The PDFs of the monthly precipitation intensities show peaks at  $4 \text{ mm d}^{-1}$  in the present and future climates, but the peaks are less frequent in the future (Fig. 4.8c). This indicates a possible reduction in the number of months in the future climate with precipitation amounts of approximately 120 mm. On the other hand, an increase in the number of months with precipitation intensities of  $7 \text{ mm d}^{-1}$  or higher is expected in the future climate. This indicates the possibility of an increased number of months being wetter in the future climate. Each individual member also shows similar characteristics in their PDFs, although some members do not show large changes in the annual cycles and the frequency patterns of precipitation in the future climate. This uncertainty behavior could be associated with the use of SST perturbations in the

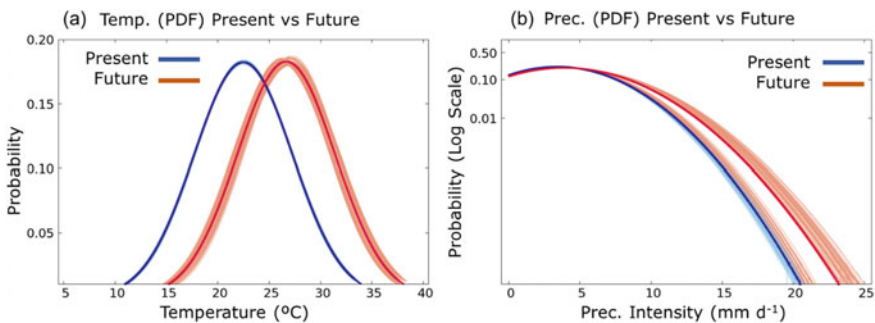


**Fig. 4.8** **a** Annual cycles in the two climate periods and **b** projected changes in precipitation. **c** PDFs for the two climate periods and **d** projected changes in the precipitation frequencies. The thin lines (**a**, **c**) correspond to the results for each ensemble member. *Source* (Data source) Mizuta et al. (2017)

simulations (e.g., Mizuta et al. 2017). For instance, Yoshioka et al. (2007) reported that changes in SSTs led to a maximum precipitation variation of  $-0.23 \pm 0.05 \text{ mm d}^{-1}$  over north African regions. The changes in the frequencies of monthly total precipitation amounts over India in the two climate periods with 100-mm interval bins indicate a possible increase in the number of months with total precipitation amounts higher than 200 mm in the future climate (Fig. 4.8d). On the other hand, there is a possibility that the number of months with total precipitation amounts lower than 200 mm will decrease in the future climate.

### 4.4.3 Projected Changes in Extreme Events

We analyzed the frequency distributions of daily mean temperatures and precipitation amounts over India as a whole to understand the occurrences of cold and warm days and of light and heavy precipitation days in present and future climates. Figure 4.9 illustrates these PDFs. The results indicated that the daily temperature in the present climate varies in the range of 11–34 °C (Fig. 4.9a), while the daily precipitation varies from no rain up to 20 mm (Fig. 4.9b). The magnitudes of the daily temperatures in the future climate show an increase of 4–5 °C compared to those in the present climate, while the intensities of daily precipitation show increases in precipitation intensities of wet days exceeding  $\sim 7 \text{ mm d}^{-1}$ . The intensities and frequencies of warm events ( $>25 \text{ °C}$ ) and strong precipitation events ( $>25 \text{ mm d}^{-1}$ ) are expected to increase in the warming future climate, indicating more severe hot days and water-related disasters over India in the future. Each ensemble experiment result also shows the same characteristics of the frequency and intensity of the daily mean temperature and precipitation.



**Fig. 4.9** Frequency distributions derived from the daily **a** temperature and **b** precipitation datasets in the AGCM ensemble experimental results for two periods: present climate and future climate. *Source* (Data source) Mizuta et al. (2017)

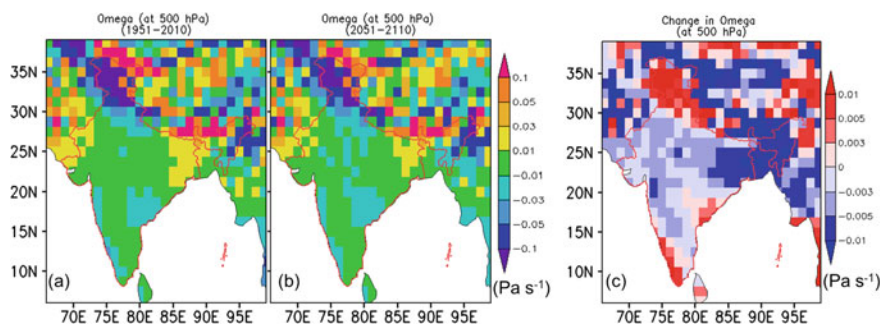
#### 4.4.4 Projected Changes in Other Climatic Variables

This section discusses the climatologies of various climatic variables, including the vertical velocity, specific humidity, relative humidity, air temperature, and cloud cover from 1951 to 2051 and from 2051 to 2110, and their future projections. Here, omega refers to the vertical velocity, which represents the rate of change in pressure in a parcel over time.

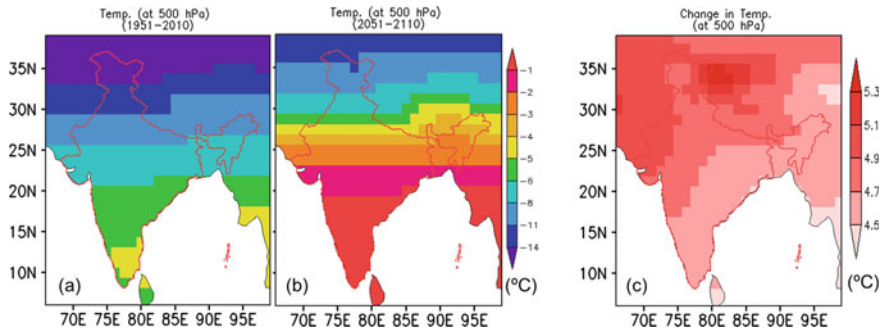
Figure 4.10 presents the annual mean omega at 500 hPa derived from the AGCM ensemble means for the two climate periods and their future changes. It shows that omega is negative over almost all Indian regions except over a few regions in eastern India in both climate periods (Fig. 4.10a, b), indicating strong upward air motions over most Indian regions. A few regions in north and northeast India show relatively strong upward air motions in both climates. However, the upward air motion is expected to be weaker over a few regions in south and north India in the warming future climate than in the present climate (Fig. 4.10c).

The annual mean temperature climatologies at 500 hPa during 1951–2010 and 2051–2110 and their projected changes are shown in Fig. 4.11. The temperatures in the upper atmosphere (at 500 hPa) are negative in both climates, with maximum values up to  $-4$  °C in the present climate and up to  $0$  °C in the future climate (Fig. 4.11a, b). The future changes in temperature (at 500 hPa) during 2051–2110 indicate increases of  $4$ – $5$  °C over the Indian regions relative to the period 1951–2010 (Fig. 4.11c). The atmosphere under the future climate is expected to be relatively warmer over the western and northern parts of India than in the other Indian regions.

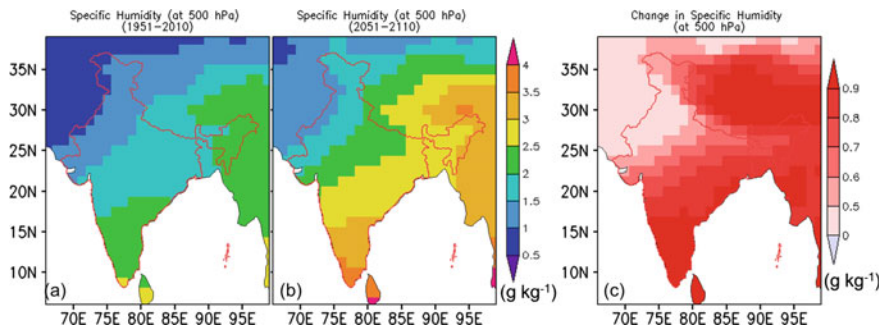
Figure 4.12 illustrates the annual mean specific humidities at 500 hPa in the two climate periods and their future changes. The spatial patterns of specific humidity in both climates are similar over almost all regions of India, but there is an increase in the overall amount of specific humidity in the future climate (Fig. 4.12a, b). The specific humidity over the southern regions of India seems to be more pronounced



**Fig. 4.10** Omega at 500 hPa from the AGCM ensemble mean for the **a** present and **b** future climates and **c** their future change. Negative signs in **(a–b)** indicate upward directions. *Source* (Data source) Mizuta et al. (2017)



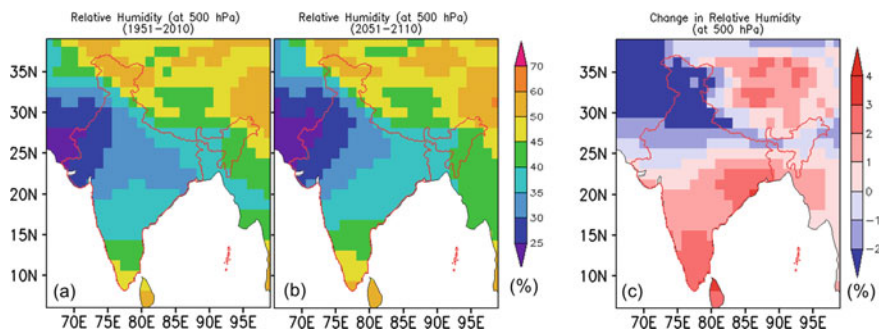
**Fig. 4.11** Temperatures at 500 hPa from the AGCM ensemble mean for the **a** present and **b** future climates and **c** their future changes. *Source* (Data source) Mizuta et al. (2017)



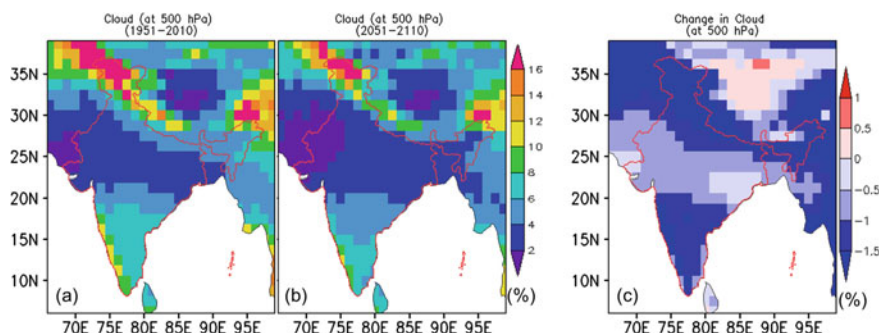
**Fig. 4.12** Specific humidities at 500 hPa from the AGCM ensemble mean for the **a** present and **b** future climates and **c** their future changes. *Source* (Data source) Mizuta et al. (2017)

compared to those of other Indian regions. The specific humidity in the future climate is expected to increase over the entire Indian region (Fig. 4.12c). A few regions in western and northern India show relatively low increases in specific humidity in the future climate.

The annual mean relative humidities at 500 hPa in both climates and their future changes are shown in Fig. 4.13. The relative humidities in both climates are maximized over some regions in south and northeast India and minimized in west India (Fig. 4.13a, b). The relative humidities in the future climate are expected to increase over the eastern, central, and western regions of India, particularly in the 12–27°N latitudinal belt, and to decrease over some regions in southern, northern, and northeastern India (Fig. 4.13c). The spatial patterns of cloud cover at 500 hPa are found to be similar in both climates but with a slightly lower percentage in the future climate (Fig. 4.14a, b). The cloud cover in the future climate is likely to decrease over the entire Indian region, although the magnitude of this decrease is below 2% (Fig. 4.14c).



**Fig. 4.13** Relative humidities at 500 hPa from the AGCM ensemble mean for the **a** present and **b** future climates and **c** their future change. *Source* (Data source) Mizuta et al. (2017)



**Fig. 4.14** Cloud cover at 500 hPa from the AGCM ensemble mean for the **a** present and **b** future climates and **c** their future changes. *Source* (Data source) Mizuta et al. (2017)

## 4.5 Discussion

This study considers various aspects of temperature and precipitation characteristics over India in the past 60 years (1951–2010) and their future changes in the next 100 years (2051–2110) by analyzing the results of 190 ensemble experiments. The climatologies, annual cycles, and frequency distributions of temperature and precipitation for the period 1961–2007 from the ensemble means of AGCM experiments over India are first compared with those from the APHRODITE observations to validate the model results. The results indicate that the AGCM-simulated climatologies, annual cycles, and frequency distributions of temperature and precipitation are in good agreement with the APHRODITE observations over the Indian region, although some cold and wet biases are noticed in the temperature and precipitation simulations, respectively (Figs. 4.2 and 4.3). Previous research (e.g., Karmacharya et al. 2017, Nayak et al. 2019) over Indian regions with various climate models has also highlighted similar cold and wet biases in the respective



models used in the studies. Therefore, simulating Indian climatology with complete accuracy has been a long-standing challenge. However, the spatial distribution of the various climate states over India in the d4PDF datasets appear to be quite reasonable (Figs. 4.2 and 4.3). The temperature climatologies over the desert climate type in the west region, the tropical wet and monsoon climate types in the west coast, central and south regions, and the temperate climate type in the north and northeast regions are well-represented in the d4PDF dataset, while those over some tropical wet-dry climate types in the southeast regions are underestimated (Fig. 4.2a, b). The d4PDF dataset reproduced the precipitation climatologies well over tropical rainforests in the south region and the arid and semiarid climate types in the west region, while it overestimated the precipitation amounts over some temperate rainy climate types in the north and northeast regions and tropical monsoon and savanna climate types in the central-east region (Fig. 4.3a, b).

The annual mean surface temperatures over most of the Indian regions are 25 °C or higher in the present climate and are expected to increase by 3–5 °C in the period 2051–2110 (Fig. 4.5). This result is consistent with the multitude of other previous studies over India (e.g., Kumar et al. 2013; Patwardhan et al. 2018). The temperatures over some desert regions in the west of the country and tropical humid climates in the central region show possible increases of 4–5 °C, while those over the subtropical humid climates in the north and east regions show increases of 3–4 °C. An increase of 4–5 °C in the air temperature at 500 hPa is also noticed over the Indian regions during the period 2051–2110 relative to the period 1951–2010 (Fig. 4.11), indicating a possible warmer atmosphere under the future climate. An increase in the temperature of ~5 °C is expected, particularly during October–June, in the future climate (Fig. 4.6b). The number of months with monthly temperatures of 26 °C or higher is also likely to increase in the future climate (Fig. 4.6d).

The spatial distributions of precipitation over India show maximum precipitation over northeast India and in the regions over the west coast along the Western Ghats in both climate periods. An increase in precipitation of approximately 1 mm d<sup>-1</sup> is expected in the future climate over most regions of India, while a decrease in precipitation of approximately 1 mm d<sup>-1</sup> is expected over the west coast regions (Fig. 4.7). The precipitation amounts over the arid and semiarid climate types in the west and in some tropical rainforests in the southwest show increases of 0.5 mm d<sup>-1</sup> in the future climate, and the precipitation amounts over the temperate rainy climate in the northeast show expected increases of more than 1 mm d<sup>-1</sup>. Most of the tropical monsoon and savanna climate type regions show possible increases of ~1 mm d<sup>-1</sup> in precipitation in the future climate, while some tropical wet regions on the southwest coast indicate possible reductions of ~1 mm d<sup>-1</sup>. The monthly precipitation over India in the future climate is expected to increase by 5–45% during the months from July to October (Fig. 4.8b). Previous studies over India (e.g., Sabade et al. 2011; Chaturvedi et al. 2012; Akhter et al. 2017) also highlighted similar magnitudes of precipitation increases in the future climate. The reason for this result could be associated with the upward motion of air, which is expected to be stronger in the future climate, together with increased specific humidity (Figs. 4.10 and 4.12). It is interesting to note that the vertical motion of air

is weaker in the future climate over the Western Ghats regions, possibly because of the decrease in precipitation on the west coast along the Western Ghats. The number of warm days ( $>25^{\circ}\text{C}$ ) and strong precipitation days ( $>25\text{ mm d}^{-1}$ ) are also expected to intensify and to occur more frequently in the warming future climate. This indicates the possible occurrence of severe hot days and water-related disasters over India in the future climate. The reason for the increase in strong precipitation days in the future climate may be attributed to the temperature increases over the Indian region, which would increase the specific humidity, according to the Clausius-Clapeyron relationship, and cause more precipitation (e.g., Nayak 2018; Nayak and Takemi 2019).

The omega values at 500 hPa indicate stronger upward motions of air over most of the Indian regions in the future climate (Fig. 4.10). The arid and semiarid climate types in the western part of the country and the temperate rainy climate types in the northeast show stronger vertical velocities in the future climate, while most of the tropical wet in the south indicates weaker vertical velocity in the future climate. The upward motion of air in the future climate is also noticed to be weakened in the north areas, which include mountainous regions. The annual mean temperature climatologies at 500 hPa show a warmer atmosphere over entire Indian regions under future climate (Fig. 4.11). The desert in the west seems to be comparatively warmer in the future compared to the other climate states of India, while some regions in the temperate climate in the east and northeast are expected to be less warm. The specific humidity at 500 hPa also shows an increase of specific humidity over entire Indian region in future climate (Fig. 4.12). The desert, arid and semi-arid climate in the west shows relatively low increase of specific humidity in future climate. The relative humidity at 500 hPa is expected to increase over east, central and west regions of India and decrease over some regions in south, north, and northeast India (Fig. 4.13). Most of the regions of tropical rainforest, monsoon, and savanna in the 12–17 N latitudinal belt show a possible increase of the relative humidity in the future climate, while a possible reduction of the relative humidity is noticed over few regions of temperate rainy climate. The cloud cover at 500 hPa are noticed mostly similar in two climate periods with a small decrease in magnitude in future climate over entire India (Fig. 4.14c). The cloud cover over the desert in the west shows relatively low decrease in the future climate, while the same over most of the tropical wet and monsoon in the south and temperate rainy in the northeast shows relatively more decrease.

The present study with mega-ensemble d4PDF climate simulations shows overall consistency results with previous studies over India in the present climate and future climate. Thus, the present results with the d4PDF dataset with historical 6000-years and future 5400-years climate simulation give an overall confidence to understand the climate of India and its different climate states starting from dry/desert to wet and tropical to temperate. Moreover, this study discussed future changes of various climatic variables which would help to understand the factors behind the climate changes over India. So this study would provide an insight towards the future assessment over Indian climate in order to reduce the uncertainties to monitor climate hazards in India.

## 4.6 Conclusions

This study investigates a comprehensive assessment of climate change over India from 190 mega-ensemble AGCM experiment results in two climate periods (1951–2010 and 2051–2110). The main focus was on the climatologies, annual cycles, and frequency distributions of temperature and precipitation over Indian region in the past 60 years and their projected future changes in the next 100 years. The model simulated ensemble mean results appeared quite reasonable in simulating climatologies, annual cycles, and frequency distributions of the temperature and precipitation over the Indian region. The temperature over Indian regions during 1951–2010 shows mostly 25 °C or higher and precipitation shows mostly 3–5 mm d<sup>-1</sup> during this period. Future AGCM simulations show an overall increase of 4–5 °C temperature and 2–45% precipitation over India in the period 2051–2110 with reference to the period 1951–2010. The consistency of these results with previous studies over India would lead to overall confidence in climate change assessments to monitor climate hazards in India in the future.

### Declarations

#### Availability of data and material

The d4PDF data (the database for Policy Decision making for Future climate change) dataset supporting the conclusions of this article is obtained from the Data Integration and Analysis System (DIAS, <http://search.diasjp.net/en/dataset>). The precipitation and temperature observation dataset supporting the validation of this study is obtained from the Asian Precipitation-Highly-Resolved Observational Data Integration Towards Evaluation (APHRODITE's Water Resources, <https://www.chikyu.ac.jp/precip/english/products.html>).

#### Competing interests

The authors declare that they have no competing interest.

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#### Authors' Contributions

SN proposed the topic, designed the study, analyzed the data and drafted the manuscript. TT helped in the interpretation and the construction of the manuscript. All authors read and approved the final manuscript.

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