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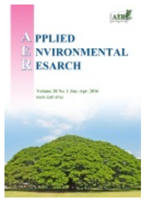

Centuries of Heat Waves over India during 20th and 21st Century

N. Naveena[1,*], G. Ch. Satyanarayana[1], K. Sivasankara Rao[2], N. Umakanth[1], A. Dhrama Raju[3]

[1] Center for Atmospheric Science, Koneru Lakshmaiah Education Foundation, Andhra Pradesh, India
[2] Andhra Pradesh State Development Planning Society, Andhra Pradesh, India
[3] India Meteorological Department, India
[*] Corresponding author: neelamnaveena.met@gmail.com

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Abstract

An assessment of temperature extremes is made for the Indian subcontinent to identify the changes since 1951 to 2015, and for the future climate periods till 2100 for all the 21 CMIP5 (Coupled Model intercomparision Project phase 5) models and the representative concentration pathways RCP4.5 and RCP8.5 were examined for the period from 1 March to 31 May to characterize the heat waves in future climates and mean maximum and mean minimum bias were evaluated for the Indian subcontinent. Later two highest recorded temperature regions were chosen Northwest & Central India (NW&CIN) and only central India (CIN) box and the features of heat waves such as intensity and frequency were evaluated up to 2100. Corresponding temperature predictions from historical runs for the period 1951–2005 of 21 global CMIP model outputs and statistics were performed with the India Meteorological Department (IMD) gridded maximum temperature data for validation. Statistical metrics of BIAS, RMSE and MAE have indicated low BIAS, high correlation and high IOA (Index of Agreement) validating CMIP climate simulations. By analyzing the statistics of all the 21 models with respect to the observational gridded data from IMD came to conclusion that among all the 21 models 5 models were performing well for Indian region and having good index of agreement with IMD. The frequencies of the days having thresholds of 40 ℃, 42 ℃ and 45 ℃ for the maximum temperature over India during the pre-monsoon are evaluated up to 21st century. All models are showing that the intensity and frequency of heat waves were increasing significantly for both RCP4.5 and RCP8.5. Specifically, the characteristics of heat waves in terms of intensity, duration and area extent are calculated and compared to heat waves of the current climate.

Keywords: Maximum temperature; Heat waves; CMIP model; Frequencies

Introduction

Climate change for global as well as regional scale can be easily determined by considering the changes in atmospheric temperature. The most significant parameter to determine the climate change on global as well as regional

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scale is the atmospheric temperature. The chief problem of climate change during the last few decades is global warming. A report by Intergovernmental Panel on Climate Change (IPCC 2014) fifth assessment report (AR5) the mean surface air temperature has increased by 0.85 ºC for the period 1880–2012 [1]. Changes in the temperature play an important role in global warming because it is not similar all over the globe. Several portions of the world have been experiencing an augmented number of heat waves in the latest decades [2–4] especially in the urban areas where higher rate of population exists [5]. In the yearly report given by IMD during 2016 for the period 1901–2016 the 2 m surface air temperature increases at the rate of 0.64 ºC/100 years [6]. In the early decades weather data indicates a substantial warming of the globe [7]. India experiences heat waves during the pre-monsoon season i.e. from March to May with highest intensity and severity is observed during May month resulting in the loss of human lives, crop failure and socio-economic loss [7–14].

For the period 1880–1950 trends of maximum and minimum temperature were studied by using 30 stations in India [15]. One of the most significant natural disaster in recent times is heat waves which has a catastrophic nature in the loss of human lives. The definition of the heat wave is different for different regions and it is generally related to continuous abnormal temperatures [16]. Several cases of heat waves were observed all around the world. The loss of human lives for 2003 heat wave in Europe is about 70,000 [17], in Russia nearly 11,000 and in Japan nearly 1,718 [18] during 2010 and in Chicago about 500 during 1995 [19] and in India highest intensity of heat wave occurred during 2015 which claimed nearly 2500 deaths and about 2320 deaths only in Andhra Pradesh and Telangana states [20]. According to the World Meteorological Organization the death rate due to heat wave will double by next 20 years [21]. Heat wave characteristics is different for different regions. For example heat wave occurred over Europe during 2003 continued for 3 months i.e., from June to August [22–23] and the heat wave occurred over US during 1995 lasts for only few days in the month of July [24–25]. Generally, heat waves lasts for few days only [26].

Greenhouse gases principally carbon dioxide plays a vital role in escalation of global men surface air temperatures since the middle of 20th century [1]. The global climate models are the preeminent tools for knowing the future changes of climate under augmented anthropogenic activities. Early studies proposed that the surface air temperature increases significantly during the midst of 20th century and also this enhancement in the temperature continues to raise in the 21st century also [16, 27–28]. As the greenhouse gas carbon dioxide has been increasing scientists reflected global warming as a frightening menace [29]. In the report given by Indian Network for Climate Change Assessment observed some of the important aspects resulted due to global warming such as sea level height increases, ice melts and temperature increases [30]. For India this report states that by 2030 India experiences an increase in temperature by 2 °C, frequency of rainy days decreases but the annual precipitation increases resulting in a devastating effects to the country as Indian economy purely depends up on agriculture.

As per Indian Meteorological Department (IMD) catalogue, Indian subcontinent practices four seasons (https://imd.gov.in/section/nhac/wxfaq.pdf). They are as follows: i) Winter season (January–February), ii) Pre Monsoon season (March–May), iii) South West Monsoon season (June–September), and iv) Post Monsoon season (October–December). With respect to the universal climate seasons practiced in the Northern Hemisphere such as winter, spring, summer and autumn. May is the warmest month during which highest maximum temperatures surpassing 40 ºC were noted over utmost parts of the Indian region. The pre monsoon months March and April symbolize the shift of the season from winter to summer and this season is marked with the increased rate of incoming solar radiation resulting in the rise in surface air temperature resulting in the rise in surface air temperature leading to instability in the atmosphere resulting in the occurrence of thunderstorms [31–33]. In general, there is a hasty reduction of temperatures with the establishment of the South-West monsoon. Nearly 70% of the total annual rainfall occurs over the Indian subcontinent during the summer monsoon season from the months June to September [34]. By the onset of south west monsoon over Kerala around June 1st the temperature drops to nearly more than 5 to 10 °C and the south westerlies winds laden with moisture spreads all over the country by first week of July.

Climate change studies have been done by some of the researchers substantially with the introduction of multi model ensembles CMIP5. These simulations are performing well and accurate with observations for temperature but precipitation simulations are very less accurate with observation [35]. The scenario RCP8.5 is the state when CO_2 concentrations are more than 1370 ppm which is almost four times higher than the current day atmospheric concentration of greenhouse gas CO_2 [36].

These global coupled CMIP5 models were capable to meet the requirements and can perform well and capture the spatial and temporal patterns of extreme heat events monthly and these events will vigorously increases in the mid of 21st century [37].

Data and methodology:

1) Data

For this present analysis of study observational daily gridded dataset of the daily maximum temperature from IMD developed by using Shepard's angular distance weighting algorithm available at 1 degree resolution for the period from 1951–2015 during the pre-monsoon period was used to analyze the present features of heat waves [38].

To investigate the future projections of heat waves up to 21st century daily maximum temperature data from all the 21 climate global CMIP5 models and their historical simulations i.e. from 1951 to 2005, future projections i.e. from 2006 to 2100 under both RCP4.5 and RCP8.5 was used [39]. Description of all the 21 CMIP5 models were given in Table 1.

RCP4.5 and RCP8.5 representative concentration pathways based on future emission trajectories depending on the increase in the concentration of greenhouse gases how the radiation increases parallel by 2100. RCP4.5 represents the enhancement of radiation 4.5 w m^{-2} by 2100 i.e. approximately 650 ppm CO_2 and RCP8.5 represents the enhancement of radiation 8.5 w m^{-2} by 2100 i.e. approximately 1,370 ppm.

2) Methodology

Firstly, all the 21 CMIP5 models daily maximum temperature which were available at 0.25° spatial resolution. Hence to compare with the observational studies of daily maximum temperature data, IMD gridded observational data is initially remapped to 0.25° spatial resolution by using bilinear interpolation method. Now by using the historical projections of CMIP5 i.e. from 1951 to 2005 period and IMD data for the same time period during the pre-monsoon season i.e. from March 1st to 31st May were taken to analyze the statistical metrics for the two boxes given in Table 2. Now Statistical analysis is carried out by using formulas from [40] Eq. 1–5.

Table 1 List of 21 CMIP-5 models details used in the study

S.No.	Model name	Abbreviation
1.	ACCESS1.0	Australian Community Climate and Earth System Simulator
2.	BNU-ESM	Beijing Normal University Earth System Model
3.	CCSM4	Community Climate System Model
4.	CESM1-BGC	Community Earth System Model
5.	CNRM-CM5	Centre National de Recherches Meteorologiques Coupled Global Climate Model, version 5
6.	CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organisation Mark 3.6.0
7.	CanESM2	Second Generation Canadian Earth System Model
8.	GFDL-CM3	Geophysical Fluid Dynamics Laboratory Climate Model, version 3
9.	GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory Earth System Model with GOLD component
10.	GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory Earth System Model with MOM, version 4 component
11.	IPSL-CM5A-LR	L'Institut Pierre-Simon Laplace Coupled Model, version 5A, low resolution
12.	IPSL-CM5A-MR	L'Institut Pierre-Simon Laplace Coupled Model, version 5A, mid resolution
13.	MIROC-ESM-CHEM	Model for Interdisciplinary Research on Climate, Earth System Model, Chemistry Coupled
14.	MIROC-ESM	Model for Interdisciplinary Research on Climate, Earth System Model
15.	MIROC5	Model for Interdisciplinary Research on Climate, version 5
16.	MPI-ESM-LR	Max Planck Institute Earth System Model, low resolution
17.	MPI-ESM-MR	Max Planck Institute Earth System Model, medium resolution
18.	MRI-CGCM3	Meteorological Research Institute Coupled Atmosphere-Ocean General Circulation Model, version 3
19.	NorESM1-M	Norwegian Earth System Model, version 1
20.	bcc-csm1-1	Beijing Climate Center Climate System Model
21.	inmcm4	Russian Institute for Numerical Mathematics Climate Model Version 4

Table 2 Details of the domain latitude and longitude range used in the study

S.No.	Region	Latitude	Longitude
1.	NW & CIN	21 to 30 °N	71 to 80 °E
2.	CIN	18 to 25 °N	76 to 82 °E

$$BIAS = \frac{1}{n}\sum_{i=1}^{n}(O_i - M_i) \qquad \text{(Eq. 1)}$$

$$CC = \frac{\sum_{i=1}^{n}(M_i-\bar{M})(O_i-\bar{O})}{\sqrt{\sum_{i=1}^{n}(M_i-\bar{M})^2}\sqrt{\sum_{i=1}^{n}(O_i-\bar{O})^2}} \qquad \text{(Eq. 2)}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|M_i - O_i| \qquad \text{(Eq. 3)}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(M_i-O_i)^2}{n}} \qquad \text{(Eq. 4)}$$

$$IOA = 1.0 - \frac{\sum_{i=1}^{n}(M_i-O_i)^2}{\sum_{i=1}^{n}(|M_i-\bar{O}|+|O_i-\bar{O}|)^2} \qquad \text{(Eq. 5)}$$

Where O_i and M_i correspond to observations and model values.

Results and discussions

Initially maximum temperatures were studied through gridded daily station measurements of maximum daily temperature from the IMD (www.imd.gov.in) for the base period i.e. from 1951 to 2015. For this study analysis of heat waves from March to May had done. As winter season ends by February and Pre Monsoon season starts from March onwards with an enhancement in temperature and also during May month maximum intensity of heat wave is observed.

1) Maximum temperature bias of 21 CMIP5 Global models from IMD gridded data

In this study primarily the observational data from the IMD is used for the period 1951–2005. From 395 Automatic Weather Stations data across India by using Shepard's distance weighted interpolation gridded maximum temperature dataset. Temperature maximum is developed which is available at 10 spatial resolution [38]. Firstly, maximum temperature data from IMD is bi-linearly interpolated to 0.25X0.25° resolution. Biases of all the 21 CMIP5 models from IMD observational data is represented in a spatial distribution plot to verify whether all these 21 global models are replicating well or not with observational data maximum temperature. Shaded values represents the maximum bias and contour represents the minimum bias of all the 21 CMIP5 global models (Figure 1). Except for few regions almost all the models are showing biases between -1 to 0.5. Negative biases indicate that the model is underestimating the values of maximum temperature with respect to observational data indicating colder temperature than real temperature and positive biases indicate that the model is overestimating resulting hotter temperatures than Maximum temperature. Gujarat state has a positive bias of nearly 2 ºC indicating that the global models were overestimating in this region whereas Northern India especially Himalayas and North East India were showing negative biases of nearly -2 ºC i.e. global models were underestimating over these regions.

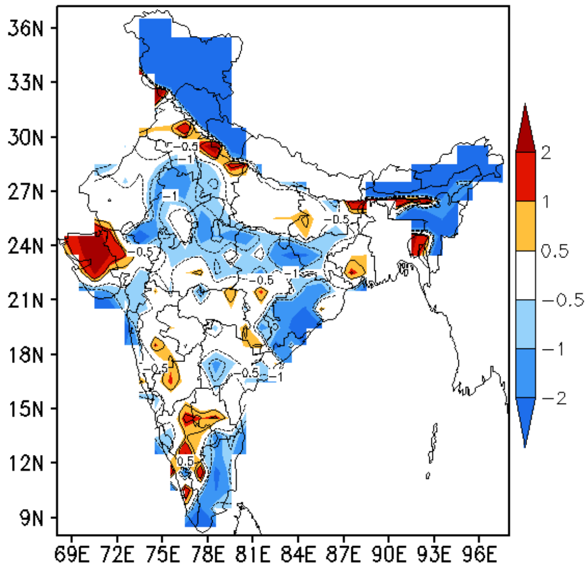

Figure 1 21 CMIP5 models bias from IMD gridded observational data, shaded indicates the maximum bias and contour indicates the minimum bias.

2) Statistical analysis of maximum temperature observational data with global models data

To calculate the statistical metrics between Maximum temperature and 21 CMIP5 models two boxes were chosen as given in Table 2.

These latitude and longitude ranges of boxes were chosen as the intensity, duration, frequency and trend analysis of spatial distribution of heat waves escalate significantly over these boxes at the rate of 4 to 7 d and 0.5 events decadal [41–43].

Almost all the models are showing less mean absolute error (MAE), RMSE (Root Mean Square Error), BIAS, MPE (Mean Percentage Error) and high Correlation Coefficient (CC) and Index of agreement (IOA) can be observed with respect to Maximum temperature. Whereas models like CCSM4, CSIRO-Mk3-6-0, GFDL-CM3, GFDL-ESM2G and MIROC-ESM-CHEM have lesser biases and correlating excellently with respect to observational data maximum temperature for both the boxes. When statistical metrics of both regions were compared with respect to observational data, CIN box is more identical when compared to NW&CIN region (Figure 2). To derive climate over India and also to analyze the characteristics of heat waves these five models are selected as they are performing well [44–46]. To give a better explanation and further experimentation Taylor's diagram was plotted to represent the simulated maximum temperature from CMIP5 and IMD for the period 1951–2005 over India (Figure 3). In this figure solid lines represents the standard deviation and dotted lines represents the correlation coefficient. All the 21 models are showing a correlation of more than 0.8.

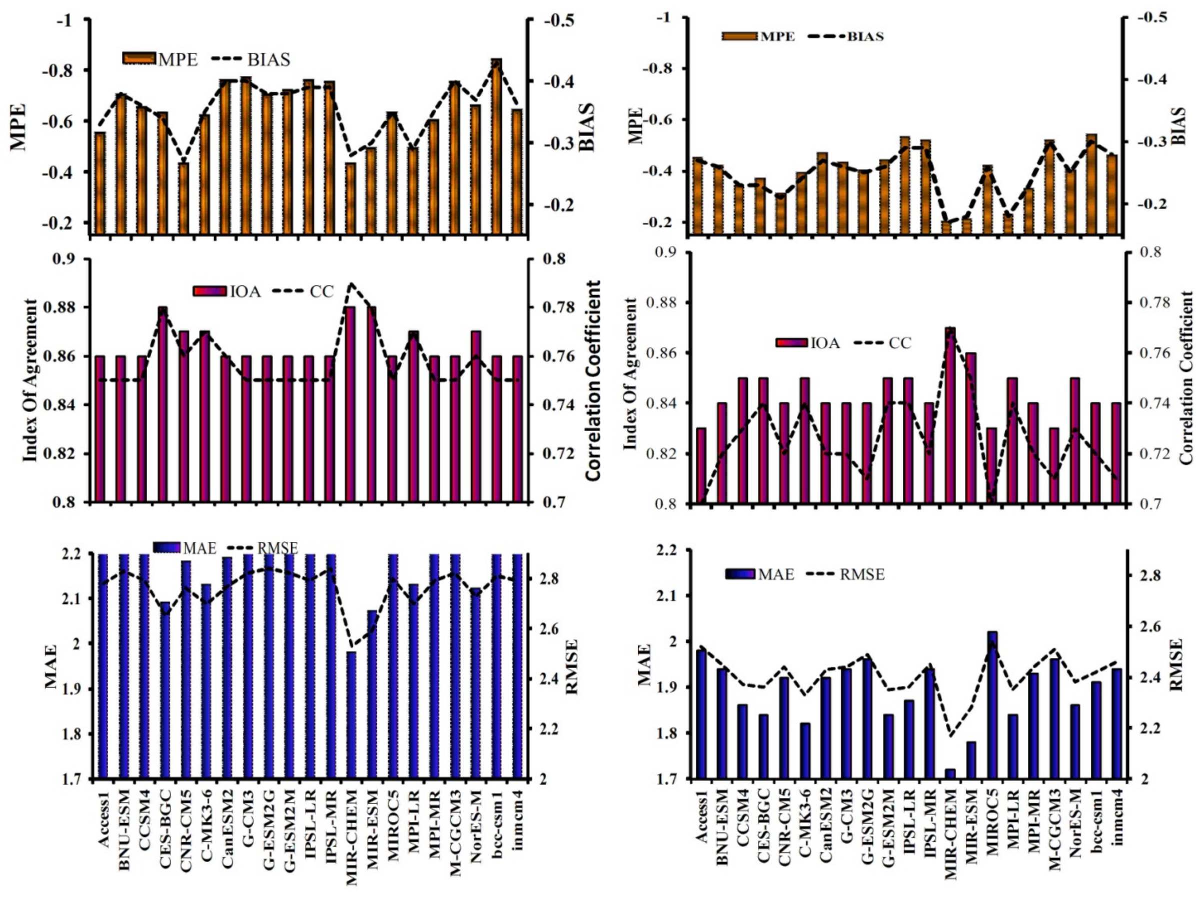

Figure 2 Statistical metrics for 21 models CMIP5 models and IMD gridded data for the two boxes (a). north west and central India (NW & CIN) and (b) central India (CIN).

3) Time series analysis of CMIP5 data for maximum temperature and frequency of heat wave for NW & central India and central India regions

Figure 4 represents the time series plot of mean maximum temperature of NW & CIN and CIN for all the 21 models from the period 1951 to 2100 for both the representative concentration pathways RCP 4.5 and RCP 8.5. Black dotted line indicates the observational gridded data from IMD up to 2015 and black straight line indicates the mean temperature. All the models are showing that the maximum temperature has increased significantly. For RCP4.5 concentration pathway the temperature increases significantly and reaches nearly 48 ºC and for RCP8.5 it reached to 50 ºC by 2100 for NW & CIN box. For CIN box under RCP 4.5 it reaches nearly 48 ºC and under RCP8.5 nearly 52 ºC.

Figure 5 represents the frequency of maximum temperature days above 40ºC from 1951 to 2100. For both the boxes and under both RCP's frequency of days above 40 ºC increases significantly. For RCP 4.5 these were about 60 d for both NW&CIN, CIN but for RCP8.5 nearly 80 d for NW&CIN and the frequency is more than 80 d for CIN by 21st century.

Figures 6 and 7 represents the frequency of days above 42 ºC and 45 ºC. Similar kind of results were replicated as seen for above 45 ºC days but with lesser number of days as represented in Figure 7.

4) Spatial distribution of mean events above 40 ºC for IMD and 5 CMIP5 models:

Maximum temperature days above 40 ºC were calculated for each and every grid point of the Indian subcontinent during the pre-monsoon season March, April and May individually for IMD and the 5 CMIP5 models which are performing well for the Indian subcontinent for a period of 30 years i.e. from 1976 to 2005 as given in Figure 8. As observed in IMD the maximum number of frequency of days above 40 ºC about 20 to 25 during May month were observed over CIN when compared to the rest of the country. The initiation of heat started during the March month with 1 or 2 d over CIN and reached maximum during May month. All the models were also showing highest frequency over CIN. These results match with a study by Satyanarayana and Dodla [47] in which three temperature zones were identified by and concluded that the third temperature zone T3 i.e. East Maharashtra or Central India is occupied with highest mean maximum temperature during May month. And also over vidardha central region of central India is occupied with highest mean maximum temperature.

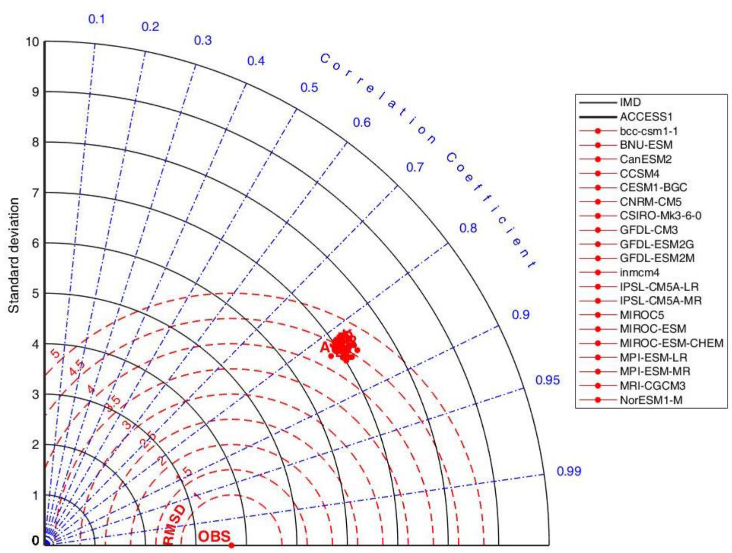

Figure 3 Taylor diagram for maximum temperature between IMD and CMIP5 individual model during the period 1951–2005 over India, dotted line represents correlation coefficient and solid line represents standard deviation.

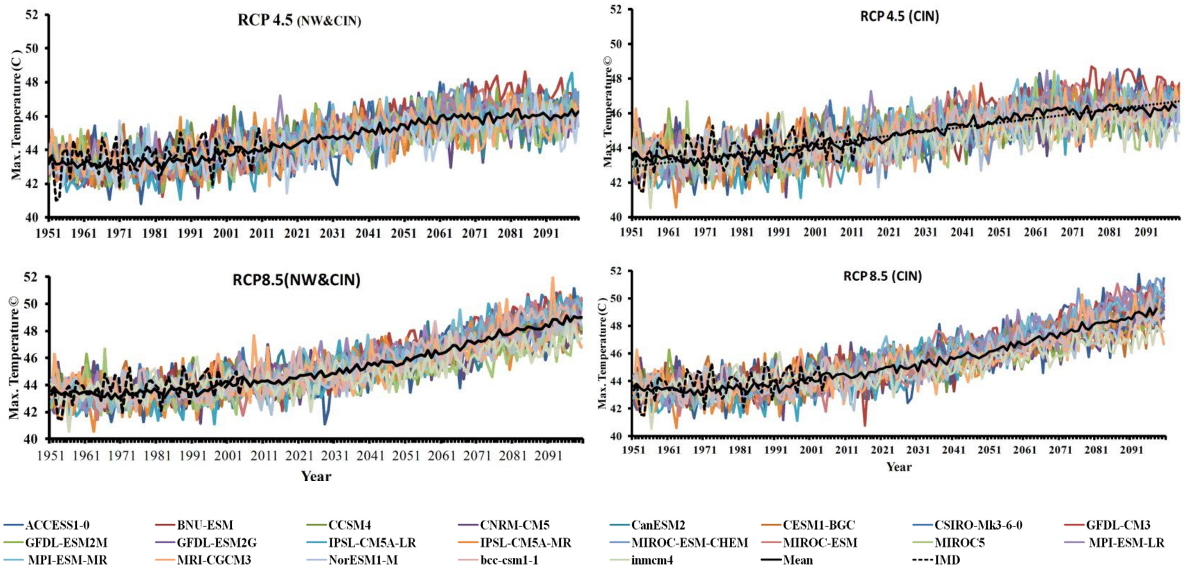

Figure 4 Time series plot of mean maximum temperature (ºC) for NW & CIN, CIN regions during March, April and May for RCP 4.5 (upper panel) and RCP 8.5 (lower panel) from 1951 to 2100.

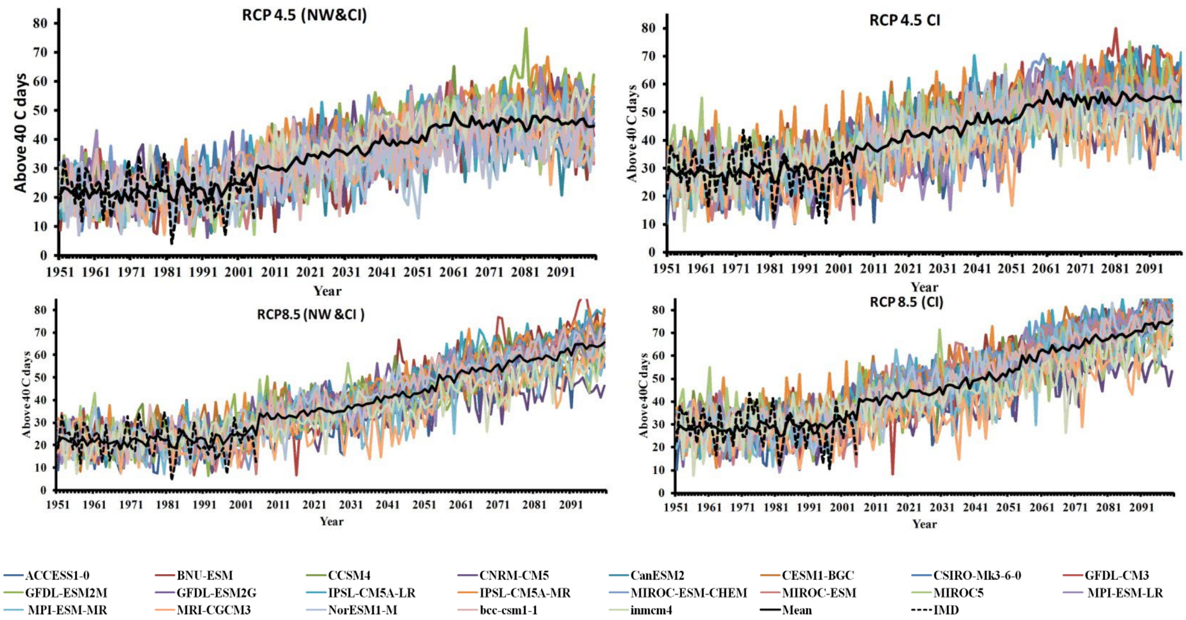

Figure 5 Time series plot of frequency of days above 40 ºC for NW & CIN, CIN regions during March, April and May for RCP 4.5 (upper panel) and RCP 8.5 (lower panel) from 1951 to 2100.

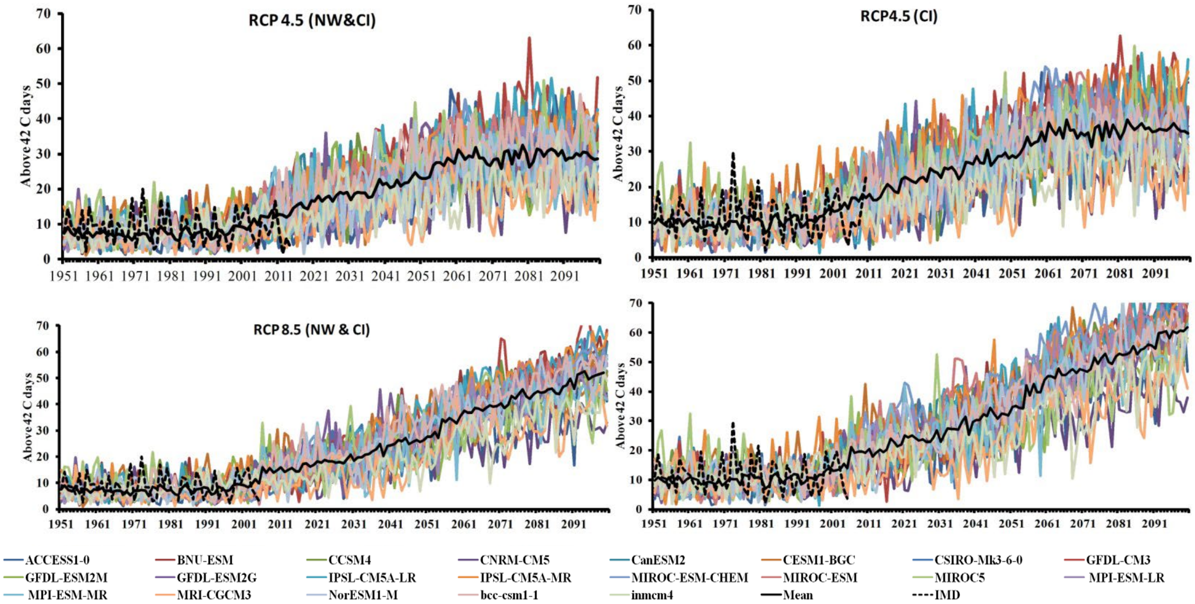

Figure 6 Time series plot of frequency of days above 42 ºC for NW& CIN, CIN regions during March, April and May for RCP 4.5 (upper panel) and RCP 8.5 (lower panel) from 1951 to 2100.

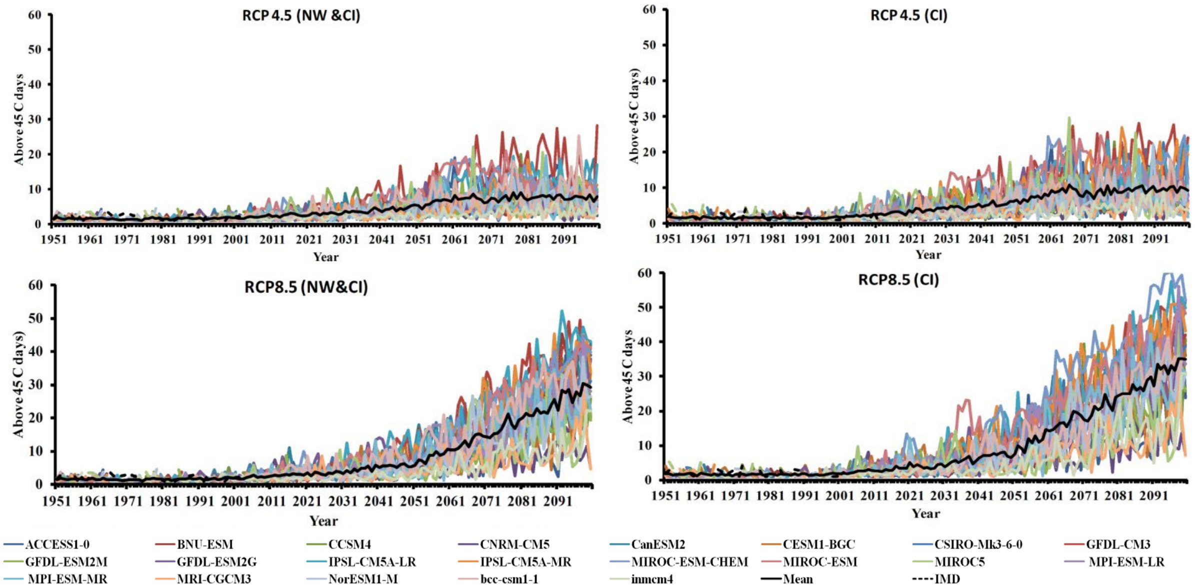

Figure 7 Time series plot of frequency of days above 45 ºC for NW&CIN, CIN regions during March, April and May for RCP 4.5 (upper panel) and RCP 8.5 (lower panel) from 1951 to 2100.

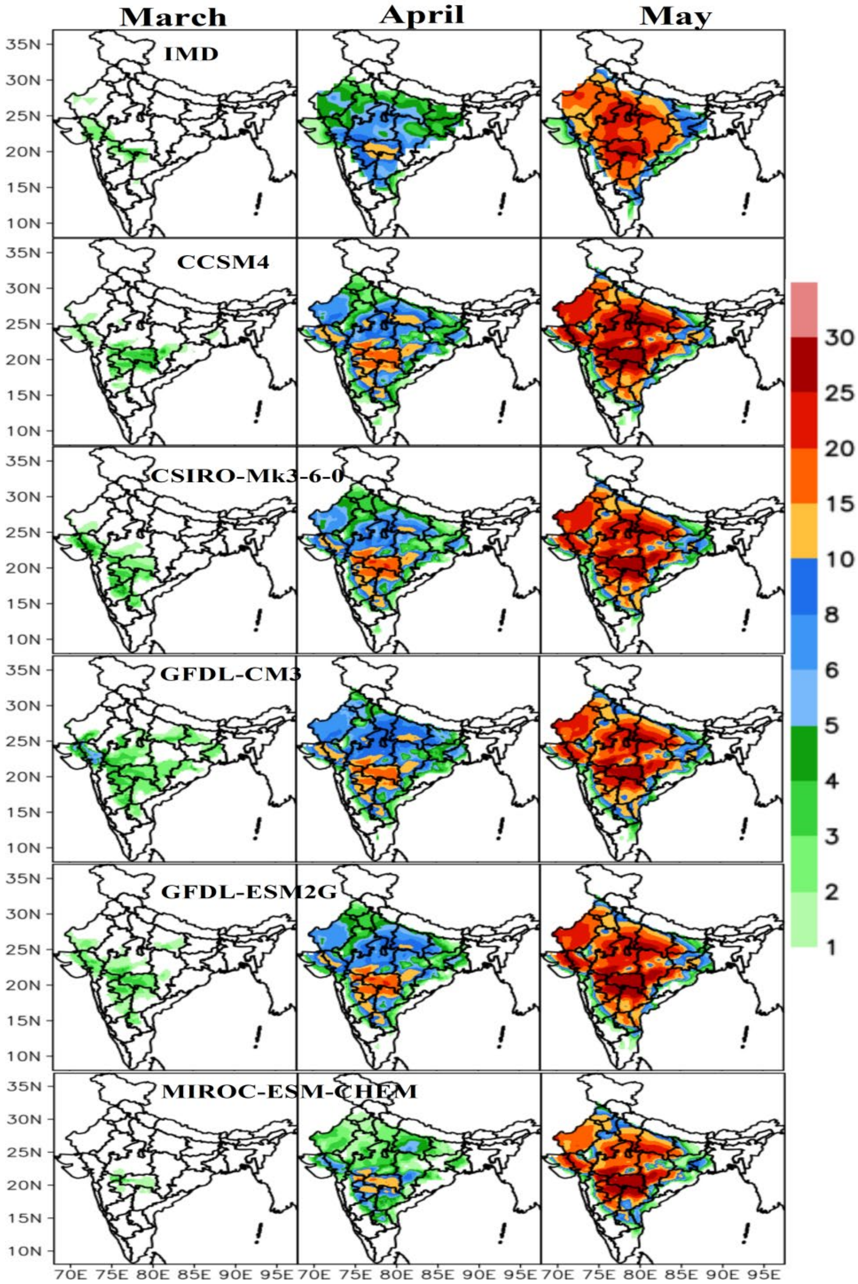

Figure 8 Mean events above 40 ºC for IMD and 5 CMIP5 models during March, April and May for the period 1976–2005.

Conclusions

In this current study the features and the characteristics of heat waves were studied for the present state and future climate change using CMIP5 models. All the 21 models mean maximum and mean minimum biases were calculated with respect to IMD data. Over few regions like Gujarat which is showing higher positive bias and for Himalayas and North East India these CMIP5 models were showing higher negative biases. Remaining part of the Indian subcontinent is showing mean biases of 21 models to be about +0.5 to -0.5 and five models were identified which are performing well.

Characteristics of heat waves such as frequency and intensity were studied for these two boxes up to 21st century and identified some important aspects such as under RCP4.5 the mean maximum temperature reaches to 48 ºC for both the boxes and under RCP8.5 it reaches to 50 ºC for NW&CIN and 52 ºC for CIN by 2100. The frequency of days above 40 ºC, 42 ºC and 45 ºC under RCP4.5 almost similar increase was observed for both the boxes but under RCP8.5 the enhancement in the frequency is observed for CIN box with respect to the NW&CIN box. This means that the CIN temperature increases at a higher rate in the future when compared to the latitude and longitude range of both NW and CIN.

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