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ORIGINAL ARTICLE

Centennial Heat Wave Projections Over Pakistan Using Ensemble NEX GDDP Data Set

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Abstract

Heat waves are one of the extreme weather events affecting as many people as with other climatic hazards such as droughts and floods. Due to rise in global temperatures, the occurrences of heat waves are likely to exacerbate in many regions in future. The projections for future heat waves over Pakistan are analyzed in this study. The heat waves calculation has been done using the latest NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) data set which composed of 21 Global Climate Models (GCMs) statistically downscaled at 0.25° × 0.25° spatial resolution. The heat waves analysis is done with ensemble modelling approach and using two definitions of heat waves: the Heat waves Duration Index (HWDI) and fixed method approach. Two climate change scenarios; RCP4.5 and RCP8.5 are used for investigating future heat wave projections. The historical heat waves are calculated from 1976–2000 and future projected changes are analyzed in three 25 year time spans: 2025–2049, 2050–2074 and 2075–2099. Two metrics heat wave events and heat wave days are separately shown. The results indicate an increase in both number of heat wave events and heat wave days in Pakistan. The most vulnerable areas for future heat waves are northern areas, plains of Sindh and Punjab, the central and western parts of Baluchistan, and all regions of Khyber Pakhtunkhwa (KPK). The increased number of heat waves in northern areas of the country could result in rapid snow melting and can cause flooding downstream. The agricultural regions of the country would be highly vulnerable to increasing number of heat waves.

Keywords Heat waves · NEX-GDDP · Climate Change · HWDI · GCMs

1 Introduction

Heat waves are extreme events that can cause a significant impact on human health, environment and ecosystem (Welbergen et al. 2008; Karoly 2009). There has been an increase in the occurrences and intensity of heat waves in many parts of the world since 1950 (Perkins et al. 2012). The repercussions of climate change are likely to increase the intensity and duration of heat waves in future (Field et al. 2012; Coumou and Rahmstorf 2012). Heat waves have serious implications for human health. A careful study of 1949 cases of cities affected with heat waves shows a higher mortality associated by rise in temperature (Mora et al. 2017). Urban communities and ecosystems are adversely affected by heat waves due to urban heat island effect (Depietri et al. 2012). Some of the worst heat waves in past include the 2003 European heat waves which resulted in more than 70,000 deaths (Robine et al. 2008). The heat wave in Russia in 2010 has caused around 11,000 deaths (Shaposhnikov et al. 2014).

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An estimated 400 people died in California, US in 2006 heat waves (Ostro et al. 2009). In India, 1500 people died in 2013 and 2500 people died due to intense heat waves in 2015 (Mazdiyasni et al. 2017). Pakistan has experienced a severe heat wave in June 2015. More than 1300 people died in that heat wave event in Karachi in June 2015 (Saeed et al. 2016).

Heat waves are generally defined as period of extremely high temperatures that can last up to several consecutive days. Though there is no unique definition of heat wave, some indices have been developed for measurement of heat waves. One such index is Heat Wave Duration Index (HWDI). HWDI is defined as a period of at least six consecutive days when daily maximum temperature exceeds the mean maximum temperature by 5 °C, and is termed as one heat wave event (Frich et al. 2002). This index is suited well to the geographic extent of Pakistan. Pakistan lies in the subtropical region with warmer temperatures in the southern half of country and there has been a rising trend in temperature in northern areas (Sheikh et al. 2009). We have used HWDI to represent two metrics of heat waves, one is the number of heat wave events and other is the number of heat wave days. The other definition used in the study is fixed method and is based on fixed threshold of 45 °C; i.e., if the temperature $\geq$ 45 °C for five consecutive days or more than it is termed as one heat wave event (Zahid and Rasul 2012).

Today climate models are considered to be the most sophisticated tools for projecting the future climate under different greenhouse gas scenarios (Almazroui et al. 2016; Almazroui et al. 2017). In one such study using climate modeling data, the risks of future heat waves with a mortality rate in the eastern United States are studied by (Wu et al. 2014) and have concluded an estimated 1403 and 3556 deaths per year under RCP4.5 and RCP8.5, respectively. The risk of high mortality rates with climate change scenarios and adaptation strategies is studied by Anderson et al. (2016) in 82 US communities. They have presented that at least seven high mortality heat waves are expected in 2061–2080 under RCP8.5 compared to RCP4.5. The changes in future heat waves projections over Europe are studied by (Jacob et al. 2014) using EURO Cordex climate modeling setup. Their results indicate an increase in number of heat waves in Europe by the end of this century.

Pakistan is home to more than 200 million people and is higly vulnerable to the impacts of climate change. There has been an increase in mean maximum temperature of Pakistan during 1961–2007 (Zaman et al. 2009). The southern Punjab, north eastern and coastal areas of Sindh are vulnerable to increased summer heat index which poses serious health implications (Zahid and Rasul 2010). Heat waves are likely to affect both urban and rural communities in Pakistan as well as key economic sectors such as agriculture and livestock (Saeed et al. 2016). Despite a critical issue, very few studies have been done on heat waves in Pakistan. Only two studies have been published in peer-reviewed journals (Zahid and Rasul 2012) and Saeed et al. (2017a). In the first study, Zahid and Rasul 2012 have studied the historical heat waves in Pakistan using observed stations data and have concluded an increase in the magnitude of heat waves in Pakistan during the period of 1961–2009. The other study which is the only work on future projections of heat waves over Pakistan is done by Saeed et al. (2017a). Utilizing three regional climate models (RCMs) and RCP8.5 concentration pathway, they have presented the first heat waves projections for Pakistan. The study has also projected the future heat waves for summer and winter months separately. Two methods, fixed approach and relative approach, were used in the study. Fixed approach was defined for a count of days with maximum temperature exceeding 45 °C for five consecutive days and relative method with number of days when daily maximum temperature is greater than mean maximum temperature by 5 °C for consecutive 5 days. An increase in heat waves has been projected by all three regional models over Pakistan and also by the ensemble of these models.

Although Saeed et al. (2017a) used high resolution regional climate models, however, the number of climate models was limited to only three. In order to obtain robust results, it is recommended to use ensemble of higher number of climate models in order to obtain the robust results suitable for policy making (Almazroui et al. 2017b; Saeed and Athar 2017; Knutti 2008; Madadgar and Moradkhani 2014). In the current study, we have presented a multi-model ensemble of NEX-GDDP data set to calculate future projections of heat waves under RCP4.5 and RCP8.5 concentration pathways. NEX- GDDP data set is bias corrected statistically downscaled at 0.25° $\times$ 0.25° resolution and composed of output of coupled model intercomparison project phase 5 (CMIP5) derived 21 GCMs. Pakistan being an agrarian country is largely dependent on agriculture productivity and heat waves have a profound effect on crops (Mueller et al. 2014).

2 Study Area

Pakistan has one of the steepest gradients in the world. HKH (Hindukush–Karakoram–Himalaya (HKH) mountains encompass the Northern and Western border of the country. The geographic area can be divided into northern highlands, alluvial plains of Indus River and Baluchistan plateau. The longitudinal axis is 61°–78° and latitude is 23°–38°. There is a great spatial variation of climate in Pakistan. The southern part of the country has generally hot and dry climate, whereas high altitudes snow covered northern areas have cold climate. Some parts of northern areas experience hot summers as well and temperatures in those areas reach as high as 40 °C. Figure 1 represents the topographic map of Pakistan.

3 Data and Methodology

The definitions used in this study require daily maximum temperature for heat wave calculations. Daily maximum temperatures used in this study are obtained from NEX GDDP data set (Thrasher et al. 2012; dataset URL: https://nex.nasa.gov/nex/projects/1356/). NEX-GDDP data set consists of global daily downscaled projections for two emission scenarios RCP4.5 and RCP8.5 and is based on 21 GCMs statistically downscaled at 0.25° × 0.25°. The data set is available from 1950–2100 with historical observations from 1950–2005 and projections from 2006–2100. The downscaled data set is derivative of 21 GCMs (as shown in Table 1) under CMIP5.

The climatology of ensemble NEX-GDDP data set is first compared spatially with observed data set to ensure the validity of the ensemble. A comparison of simulated and observed number of heat waves events is done for both definitions. The changes in daily maximum temperatures are shown spatially for future projections 2025–2049, 2050–2074 and 2075–2099 and are represented as difference from baseline period 1976–2000. Historical heat waves are then calculated for baseline period (1976–2000) and the future heat wave projections are similarly divided in 25-year time slices from 2025–2099, i.e., 2025–2049, 2050–2074 and 2074–2099. The HWDI first calculates the average maximum temperature at each of the grid points for baseline period; then, based on daily maximum temperature for any time span, it calculates the number of events where daily maximum temperature exceeds the average maximum temperature by 5 °C for at least six consecutive days. The HWDI is calculated separately for all GCMs. An ensemble median of HWDI for all GCMs is plotted as difference of future time spans from baseline period. The heat wave analysis is done for JJAS (June, July, August, and September), DJFM (December, January, February, March) and AM (April, May). Similar methodology is followed while making calculations for fixed method. HWDI is used for the analysis of JJAS and DJFM similar to Saeed et al. (2017a) and fixed method is used

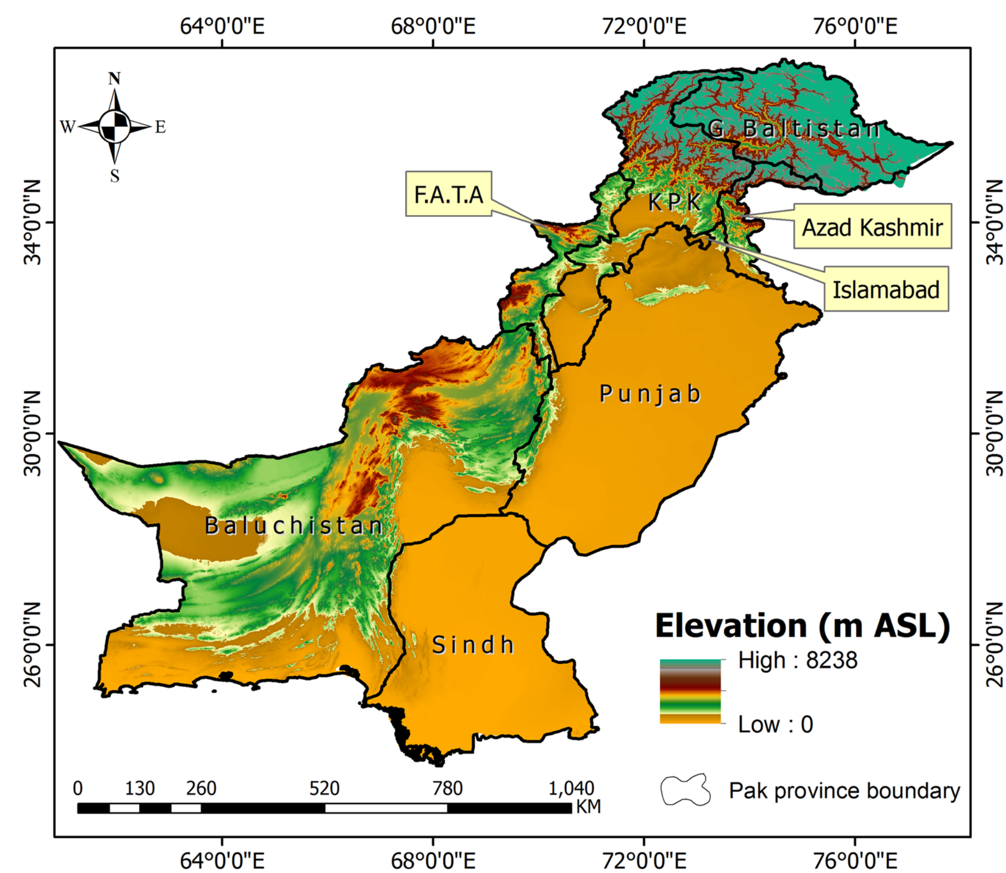

Fig. 1 Topography of Pakistan along with four provinces, i.e., Sindh, Baluchistan, Punjab and KPK and other administrative units Gilgit Baltistan, Azad Kashmir and FATA

Table 1 21 GCMs of NEX-GDDP dataset (Source: Thrasher et al. 2012)

Id	Name	Country	Id	Name	Country
1	Access 1-0	Australia	12	INMCM4	Russia
2	BCC-CSM 1-1	China	13	IPSL-CM5A-LR	France
3	BNU-ESM	China	14	IPSL-CM5A-MR	France
4	CanESM2	Canada	15	MIROC-ESM	Japan
5	CCSM4	US	16	MIROC-ESM-CHEM	Japan
6	CESM1-BGC	US	17	MIROC5	Japan
7	CNRM-CM5	France	18	MPI-ESM-LR	Germany
8	CSIRO-MK3-6-0	Australia	19	MPI-ESM-MR	Germany
9	GFDL-CM3	US	20	MRI-CGCM3	Japan
10	GFDL-ESM2G	US	21	NORESM1-M	Norway
11	GFDL-ESM2M	US			

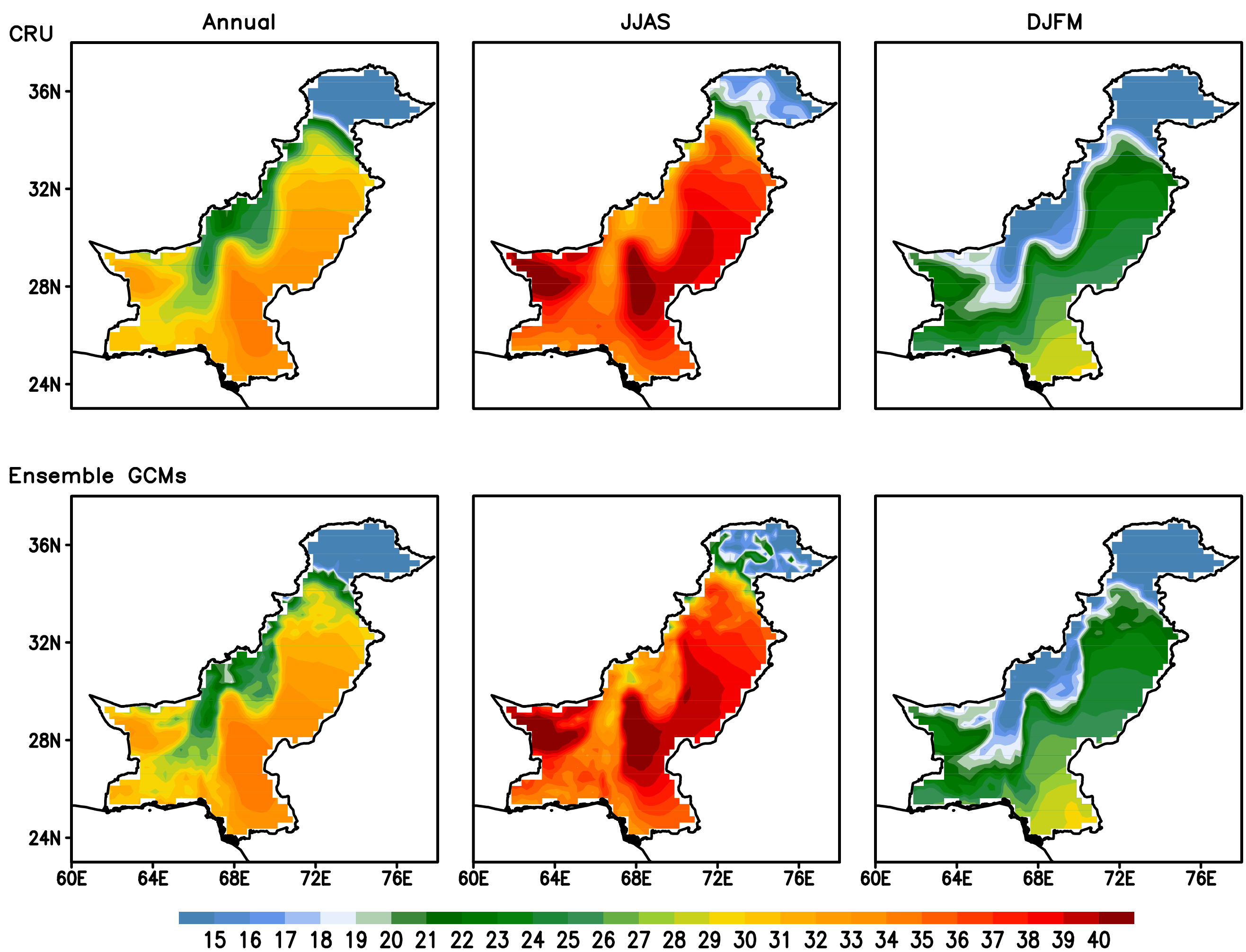

Fig. 2 Ensemble mean of maximum annual, summer and winter temperatures (°C) over Pakistan averaged over the years 1976–2000 against CRU data. Top row shows CRU and bottom row shows Ensemble GCMs

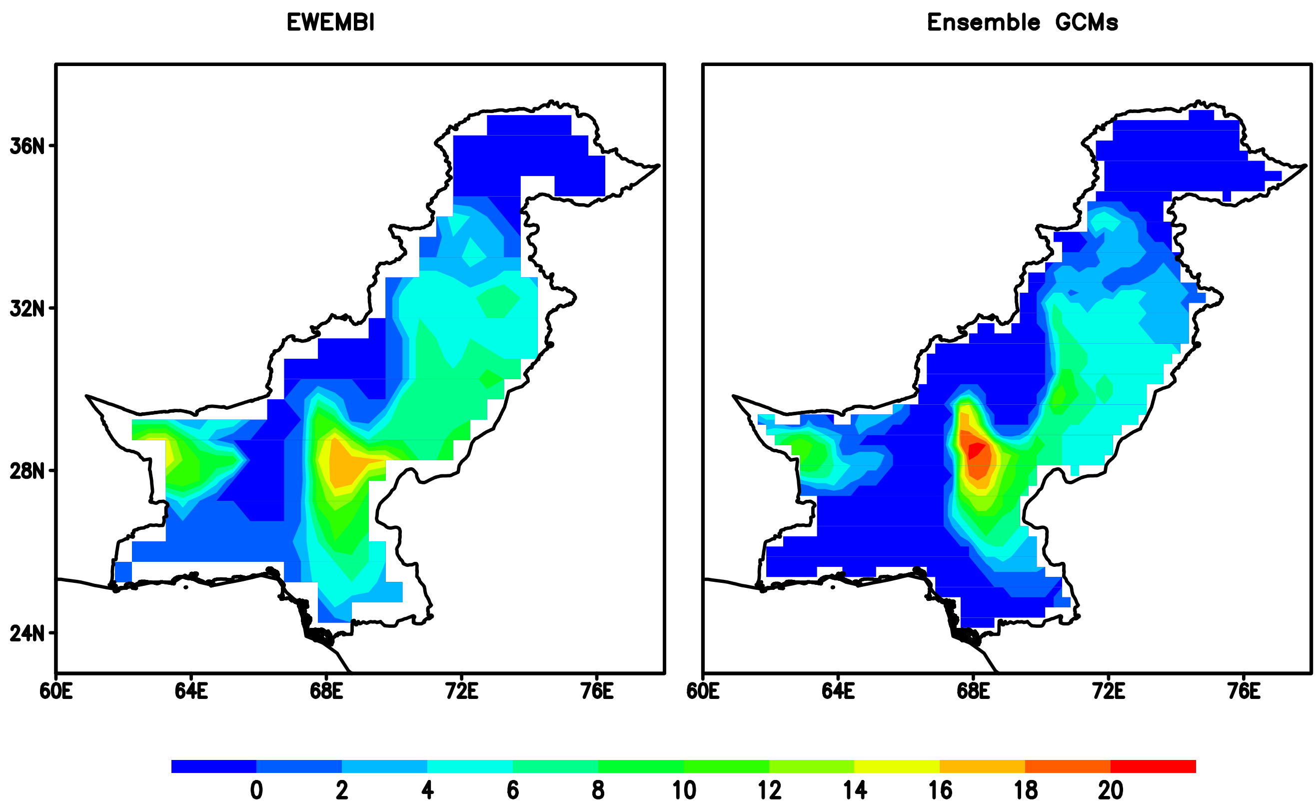

Fig. 3 Number of heat wave events based on EWEMBI and Ensemble NEX-GDDP GCMs using fixed method

for the analysis of AM and JJAS since the temperature remains less than 45 °C during DJFM. The trend analysis is done using Mann–Kendal trend test and the range of 21 GCMs showing number of heat wave events and days for HWDI is represented with box plots.

4 Results

Figure 2 shows the maximum annual, summer and winter temperatures of NEX-NASA GDDP data compared with climate research unit (CRU). CRU is a Global gridded data set and is based on observed stations data. The spatial resolution of CRU data is 0.5° and for comparison the resolution of CRU data is regrided to 0.25° to match with the NEX-GDDP data set resolution. The results show a close proximity of ensemble models with CRU data. A distinctive pattern of low temperatures over higher elevations of HKH mountains as compared to the plains is obvious from Fig. 2. Moreover, summer temperatures are characterized by very higher temperatures over Indus plains. The comparison of number of heat wave events shown by simulation and observed data is represented in Figs. 3 and 4. Here, we have used daily maximum temperature data from EWEMBI (E2OBS, WFDEI and ERAI data Merged and Bias-corrected for ISIMIP) as proxy for observed data (Frieler et al. 2016). The resolution of EWEMBI data set is 0.5°. The results show that NEX-GDDP has shown consistent spatial patterns compared to observed heat waves; however, the magnitude of number of heat wave events has shown variation. The EWEMBI data show more spatial coverage of heat waves in fixed approach (Fig. 3) and higher number of heat wave events compared to NEX-GDDP for HWDI (Fig. 4).

Changes in daily maximum temperature for AM, JJAS, ON and DJFM under RCP4.5 for different time spans 2025–2049, 2050–2074 and 2075–2099 are presented in Fig. 5. A maximum increase in temperature can be observed in all time spans and for each month's classification. It is interesting to note that the northern half of the country (characterized by snow and glaciers in its northern most extent) in general has shown higher increase in the maximum temperature as compared to the southern half. Moreover, in DJFM and AM, the increase over the fertile Indus plains remains higher than the other months. The changes in first time span, 2025–2049, are under 2.25 °C for all months, 3.25 °C change in 2050–2074 and maximum rise of 4 °C is observed towards the end of century. As mentioned earlier, RCP4.5 is a moderate emission scenario with the control on

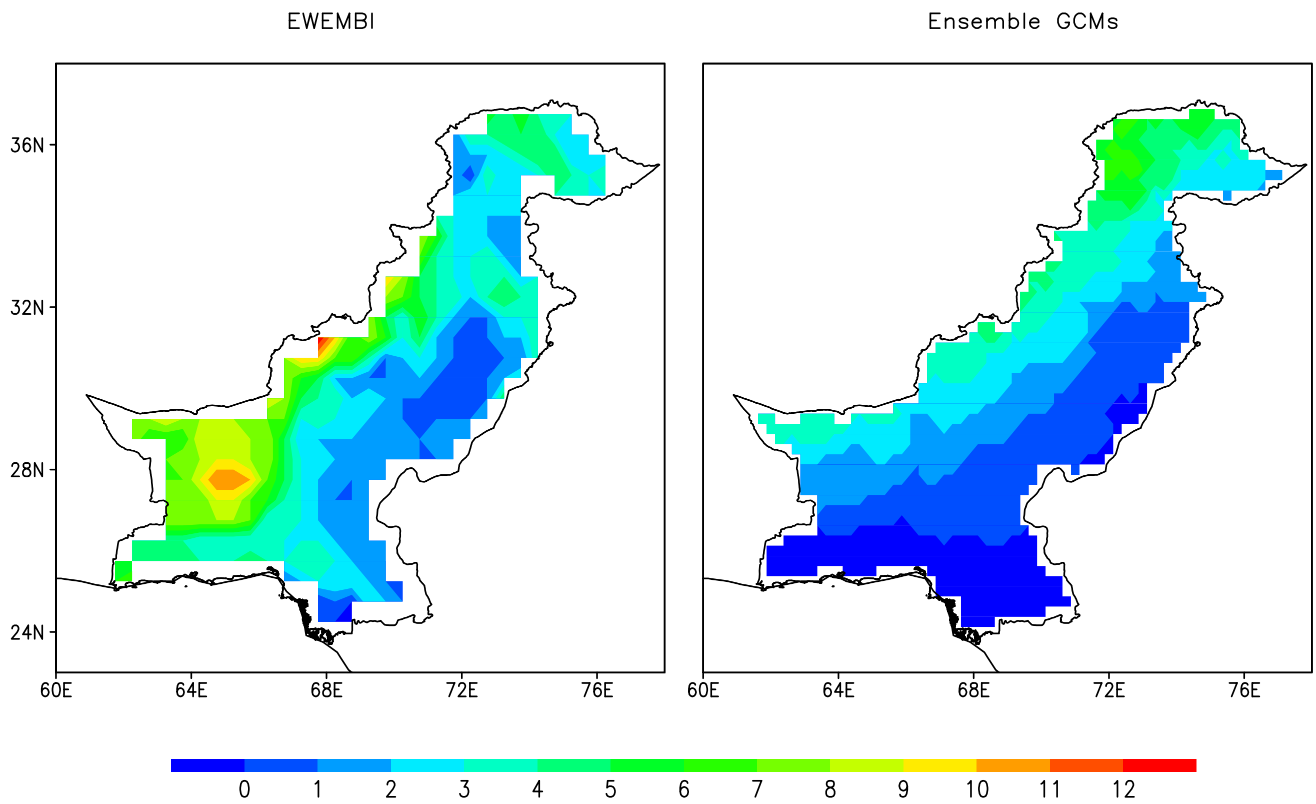

Fig. 4 Number of heat wave events based on EWEMBI and Ensemble NEX-GDDP GCMs using HWDI

greenhouse gas emission likely to achieve towards the mid of 21st century.

Figure 6 shows the daily maximum temperature change for RCP8.5. As RCP8.5 is high emission scenario with global greenhouse gases likely to increase towards the end of century, therefore, a similar pattern to Fig. 5 (RCP 4.5) is observed but with higher magnitude of change. Once again, the northern areas have shown higher increase in JJAS than the southern region. The results show a maximum increase of 2.75 °C in 2025–2049, 4.75 °C in 2040–2069 and highest increase of 6 °C towards the end of century.

4.1 Changes in Heat Wave Events Fixed Method

The fixed approach has been used to calculate heat waves for the months of AM and JJAS. The temperatures in these months often reach 45 °C in Punjab and Sindh. Figure 7 shows the projected number of heat wave events for AM for both scenarios. The maximum concentration of projected heat wave events lies in Southern Punjab and eastern Sindh with maximum number of heat waves events reaching 45. In the central and upper Punjab, some areas of KPK and western Baluchistan also show increasing trend towards the end of this century.

Figure 8 represents heat wave events for JJAS. The higher number of heat waves is projected to be in central Punjab, upper Sindh and upper and western Baluchistan. The maximum number of heat waves projected would be more than 50 in these regions. The Punjab is densely populated province of Pakistan and also constitutes the highest population of the country. The risks of mortality associated with heat waves would be higher in these regions.

4.2 Changes in Heat Wave Events HWDI

The temperature threshold of 45 °C is too high to cover the climatic extent of entire Pakistan for heat wave analysis. Therefore, in this section HWDI is used which calculates number of heat waves based on the long-term climatology of each grid point. Figure 9 represents the heat wave events for JJAS. The northern areas of the country show more number of heat waves than the southern half. The maximum number of heat waves in northern areas in RCP4.5 in last time span is found to be 65 whereas in RCP8.5 the number goes to 100 heat waves. The spatial pattern of heat waves in RCP8.5 is consistent with the earlier study of Saeed et al. (2017a). In northern areas, the melting of snow due to high temperatures can affect the glaciers which sustain the water resources of

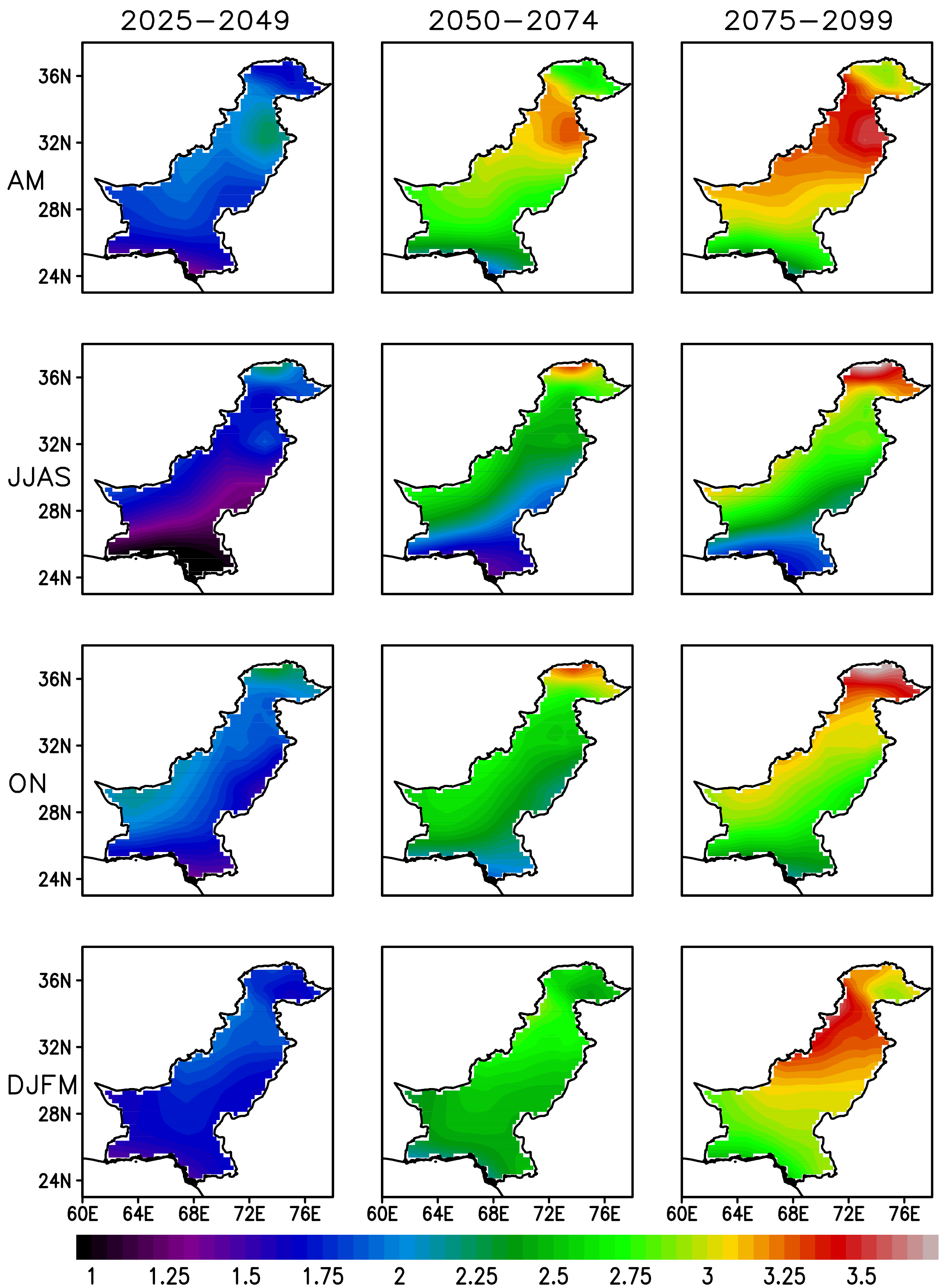

Fig. 5 Changes in daily maximum temperature (°C) between future time spans 2025–2049, 2050–2074 and 2074–2099 and baseline period 1976–2000 for AM, JJAS, ON and DJFM for RCP4.5

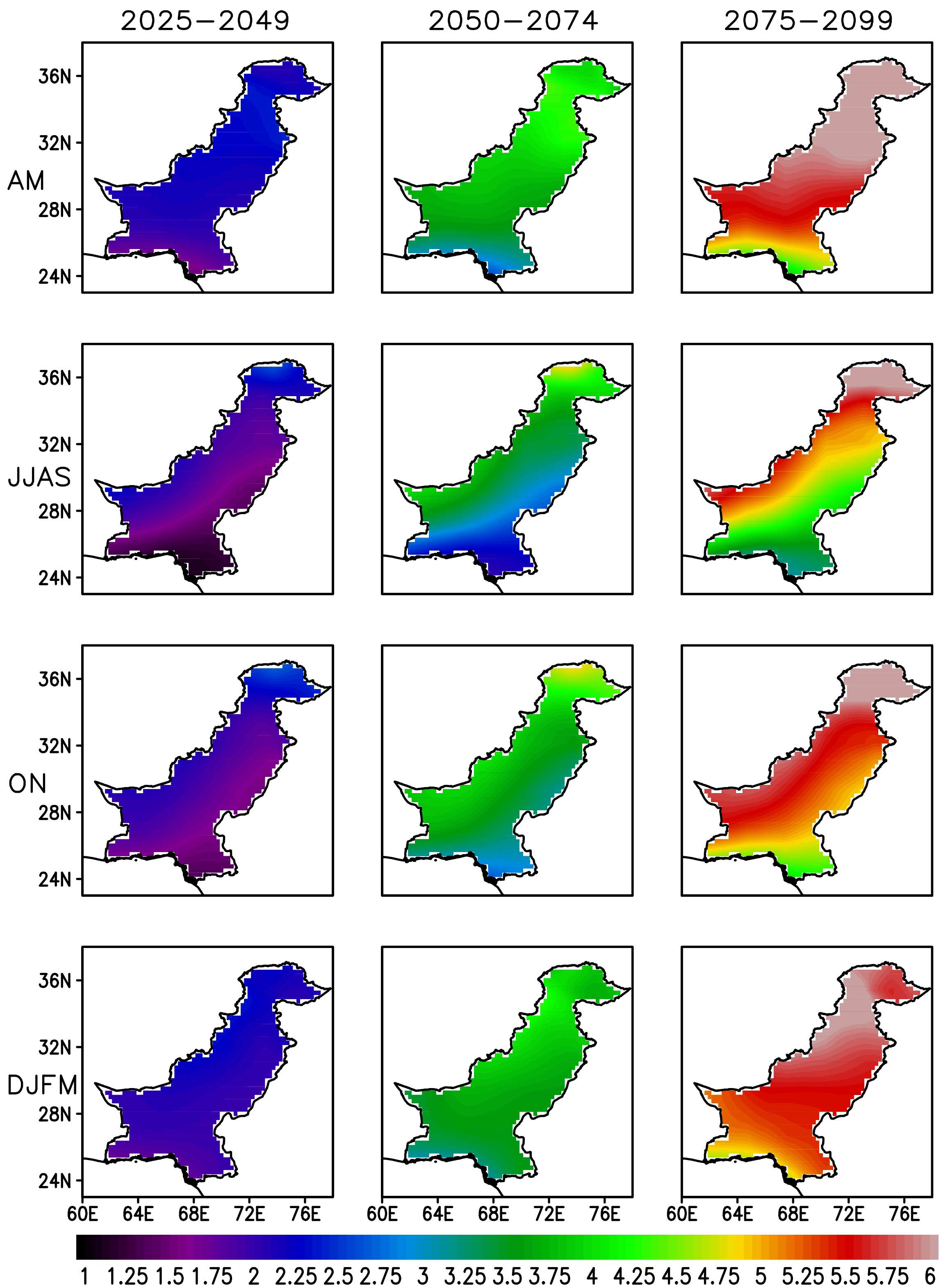

Fig. 6 Changes in daily maximum temperature (°C) between future time spans 2025–2049, 2050–2074 and 2074–2099 and baseline period 1976–2000 for AM, JJAS, ON and DJFM for RCP8.5

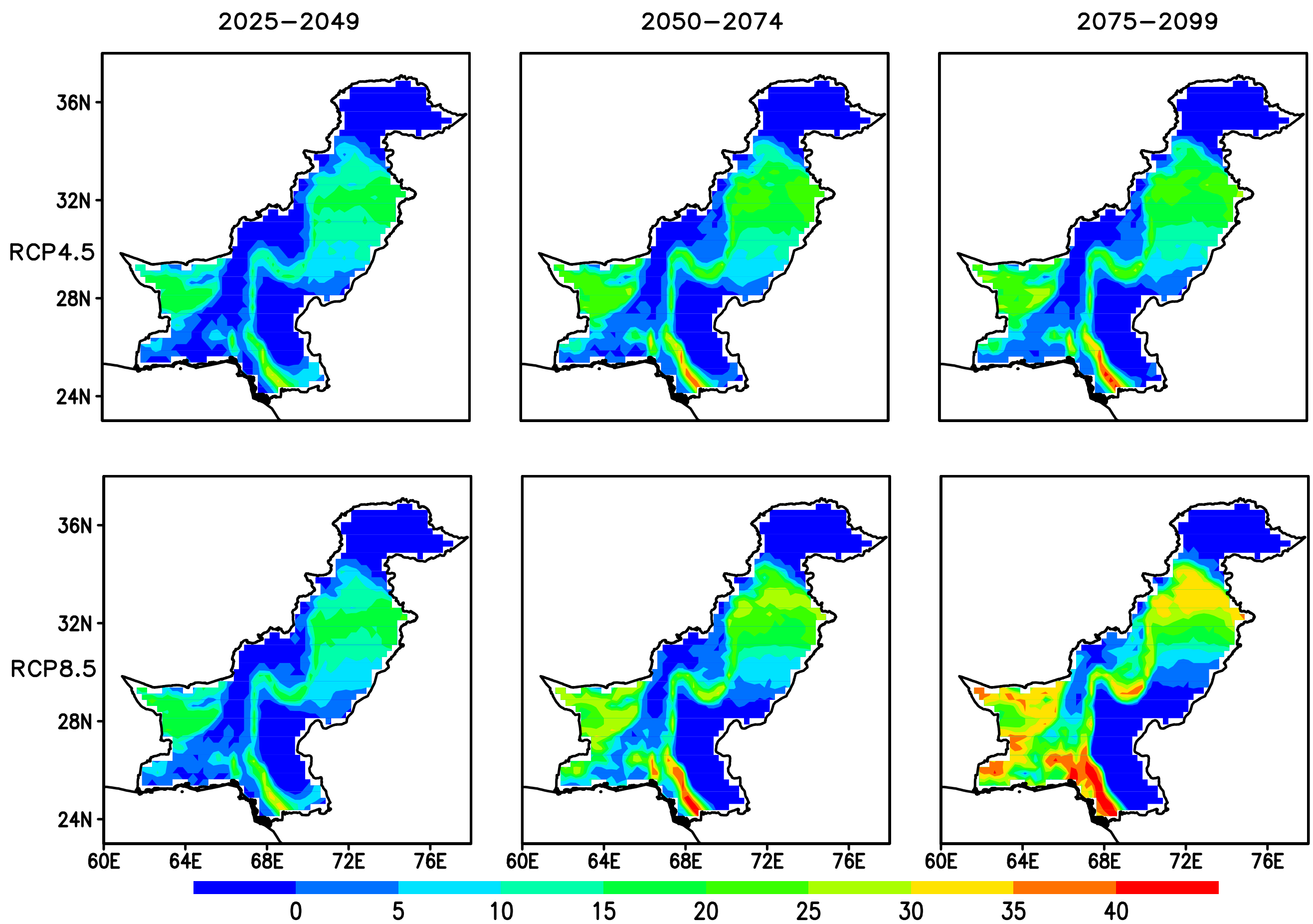

Fig. 7 The multi-model median of changes in number of heat wave events for time spans, 2025–49, 2050–74 and 2075–99 as differences from the reference period 1976–2000 for AM using fixed method. Top row shows RCP4.5 and bottom row shows RCP8.5

the country. The rapid melting of glaciers can lead to glacial lake outburst floods (GLOF) also and can create significant damage due to floods.

Figure 10 represents heat waves for DJFM. The results show an increased number of heat waves in Punjab and Sindh province in middle and last time spans with consistent increase in both scenarios. Wheat is the major crop of the winter season and also supports the large agriculture economy of the country. The fertile lands of Punjab and Sindh are mainly cultivated with wheat crops in winter. This increase in winter time heat waves may impact the production of wheat, hence having negative repercussions for the agrarian economy of the country.

4.3 Changes in Heat Wave Days HWDI

This section details the number of heat wave days that are represented by HWDI in JJAS and DJFM. The heat wave days are the number of days which correspond to the heat wave events shown earlier. One heat wave event consists of at least six consecutive days; the total number of days in each of these events is discussed in this section.

The number of heat wave days varies from 50 to 650 for JJAS under RCP4.5 and 50 to 1600 days with RCP8.5 (Fig. 11). As discussed by Saeed et al. (2017a), the 1600 days means an average increase of 64 days per year. The increase in number of days is consistent with the higher number of heat wave events shown in Fig. 6. The northern areas of the country show a higher number of heat wave days compared to the southern half and are a great threat for the health of snow packs and glaciers. The number of days in middle and last time span in RCP8.5 in Punjab varies from 250 to 1250 days roughly making it 10 to 50 days each year in these time spans. Any such day could lead to the chances of mortality during these months.

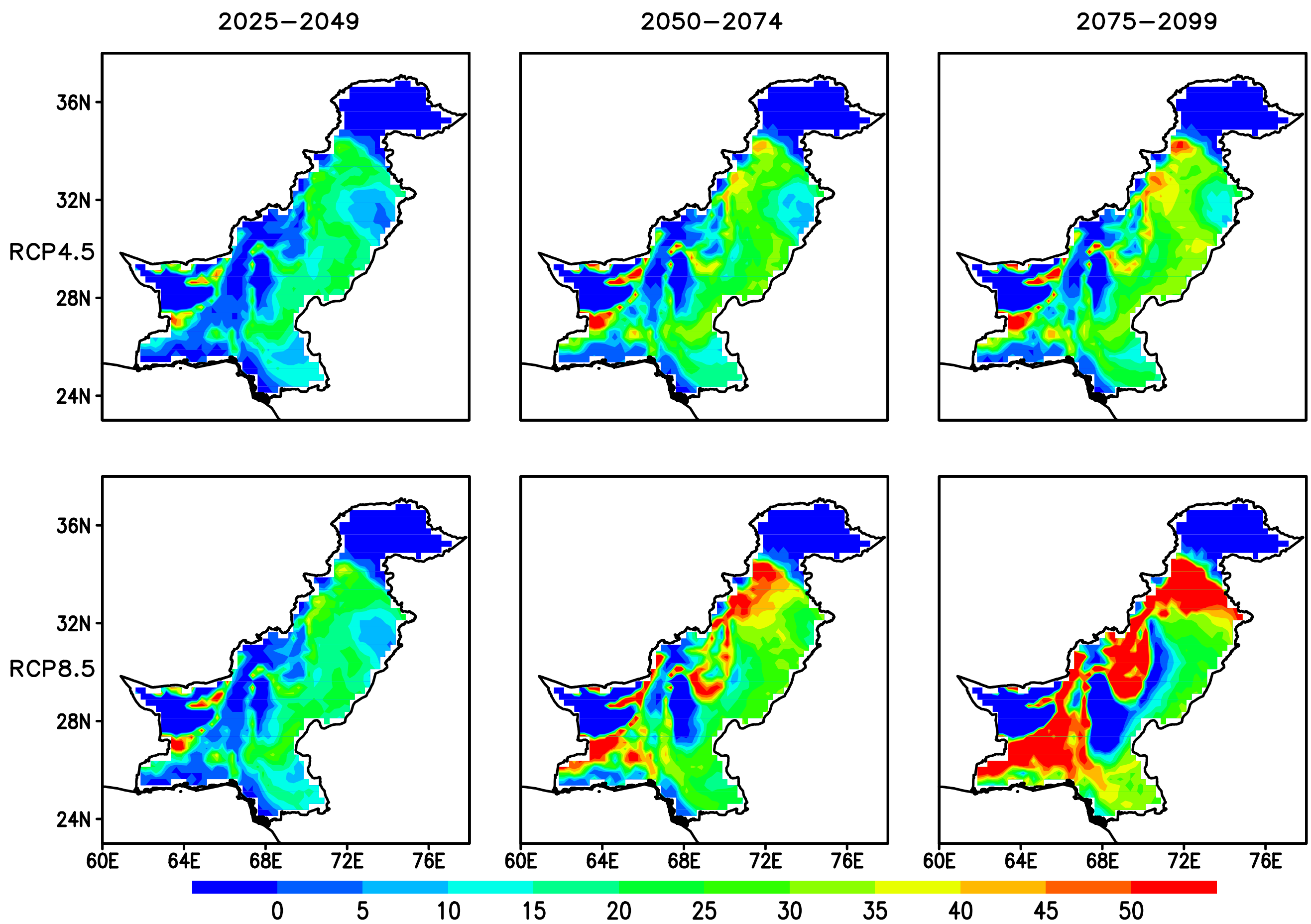

Fig. 8 The multi-model median of changes in number of heat wave events for time spans, 2025–49, 2050–74 and 2075–99 as differences from the reference period 1976–2000 for JJAS using fixed method. Top row shows RCP4.5 and bottom row shows RCP8.5

A much higher number of heat wave days could be seen in DJFM (Fig. 12). The maximum number of heat wave days in RCP4.5 is projected to be 550 and 1750 days with RCP8.5. The agriculture areas of Sindh and Punjab would be severely affected as heat waves would increase irrigation demand for winter crops. Sindh and southern Punjab are already drought prone areas; the concurrence of heat waves and droughts could impact the socio-economic activities of these regions.

4.4 Trend Analysis and Box Plot

The trend analysis has been done with the non-parametric Mann-Kendal (MK) trend test. The MK test gives a monotonic trend in the data. The MK test shows a significant trend in number of heat wave days and events at p value less than 0.05 significance level. The test has been evaluated for HWDI for both JJAS and DJFM. Table 2 shows the trend statistics of MK test.

The range between the 21 GCMs for number of heat wave events and days has been shown with the box plot. The box plot shows the variation in the data set with minimum and maximum values represented by the lines extending from the box and the bottom and top edge of the box gives the values of lower and upper quartile. The dashed line in the center is median value and symbol inside the box is the mean of data values. Figures 13 and 14 show the box plot for number of

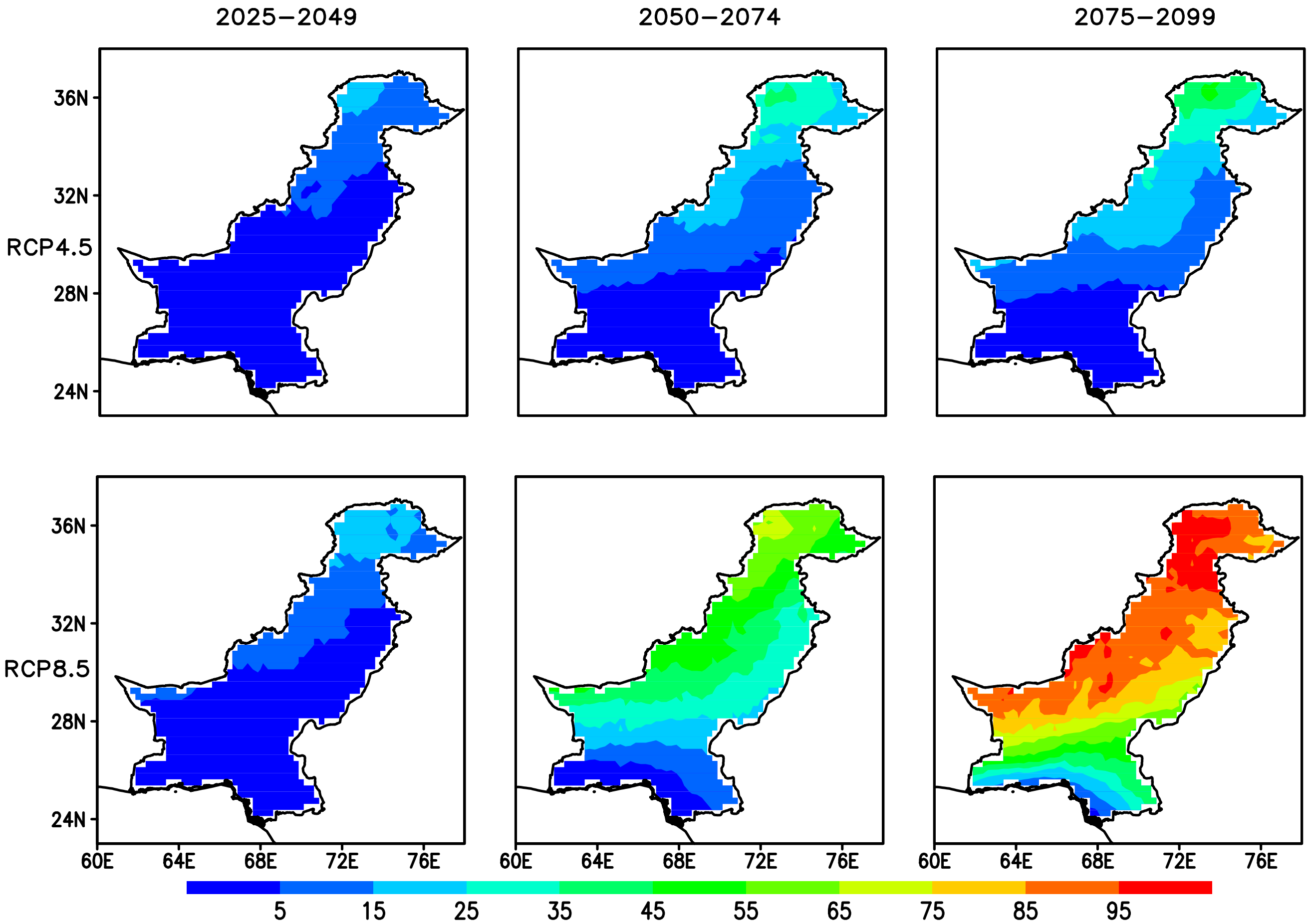

Fig. 9 The multi-model median of changes in number of heat wave events for time spans, 2025–49, 2050–74 and 2075–99 as differences from the reference period 1976–2000 for JJAS using HWDI. Top row shows RCP4.5 and bottom row shows RCP8.5

heat wave events and days for JJAS calculated for HWDI and Figs. 15 and 16 represent box plot for DJFM for HWDI.

5 Summary and Conclusion

Based on a comprehensive analysis of 21 GCM's data for two RCP scenarios obtained from NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP), we evaluated heat wave projections over Pakistan. The study shows an overall increasing trend, both in terms of total number of heat wave events as well as number of heat wave days in future. This projected increase in temperatures and subsequently heat waves in northern areas is also consistent with the findings of Burhan et al. (2015) and Saeed et al. (2017a).

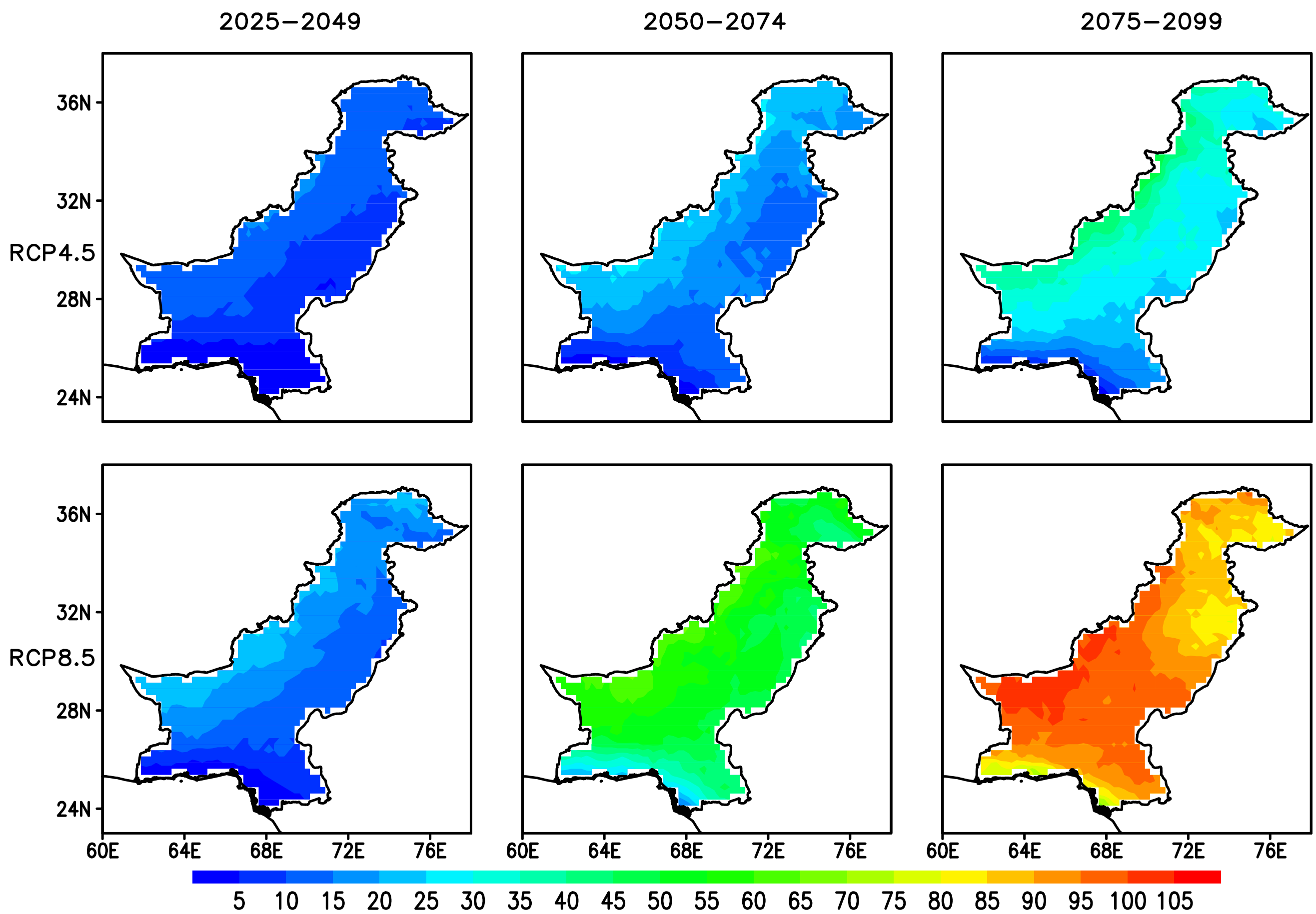

Fig. 10 The multi-model median of changes in number of heat wave events for time spans, 2025–49, 2050–74 and 2075–99 as differences from the reference period 1976–2000 for DJFM using HWDI. Top row shows RCP4.5 and bottom row shows RCP8.5

The results towards the end of the century (2075–2099) showing the maximum number of heat wave events using fixed approach in AM are 45 and JJAS are 50; the maximum number of heat wave events with HWDI in JJAS is 65 with RCP4.5 and 100 with RCP8.5, in DJFM 50 events under RCP4.5 and 110 with RCP8.5; the maximum number of heat wave days in JJAS is 650 days with RCP4.5 and 1600 with RCP8.5 and in DJFM the heat wave days are found to be 550 in RCP4.5 and 1750 with RCP8.5.

The projected increase in number of heat waves in northern areas also poses risk of flooding in Pakistan due to rapid snow melting. Pakistan is already vulnerable to such events; e.g., in 2005 flooding in Pakistan is attributed to the melting of snow in Kabul and Indus rivers which severely impacted the summer time crop production of the country (Saeed et al. 2017). Besides flooding, the agriculture sector of the country is also sensitive to direct impact of the heat waves. In their study over Pakistan, Mueller et al. (2014) found that not only the summer, but also the winter crops are sensitive to the heat waves. The increased number of heat waves during summer season has severed repercussions to human health and well-being.

Heat waves also have indirect effects which cannot be ignored. For example, Saeed et al. (2016) studied the

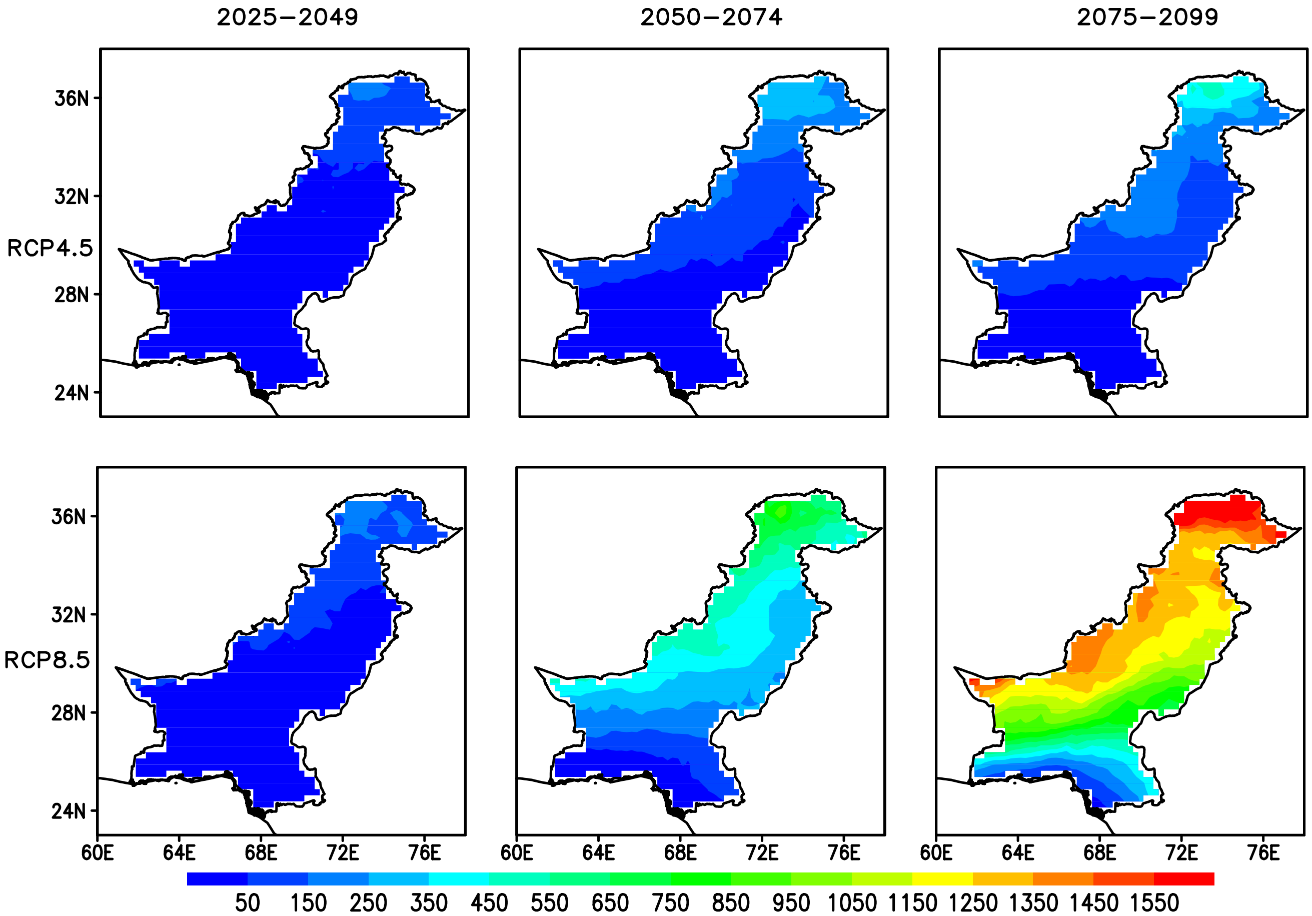

Fig. 11 The multi-model median of changes in number of heat wave days for time spans, 2025–49, 2050–74 and 2075–99 as differences from the reference period 1976–2000 for JJAS using HWDI (days). Top row shows RCP4.5 and bottom row shows RCP8.5

impact of winter time heat waves on rural to urban migration and found a positive link. Winter time heat wave results in crop production loss, which in turn results in the rural to urban migration causing unplanned rapid urbanization. This further enhances the urban heat island effects resulting in the severity of urban heat waves. In June 2015 Karachi, which hosts around 20 million people, witnessed sever heat wave resulting in deaths of more than 1200 people. Therefore, the increase in heat waves poses not only environmental but also the developmental challenges for the country. Pakistan is already vulnerable to the impacts of climate change. The results presented in this study are of utmost importance in devising policy recommendations and adaptation strategies to combat the impacts of heat waves in future.

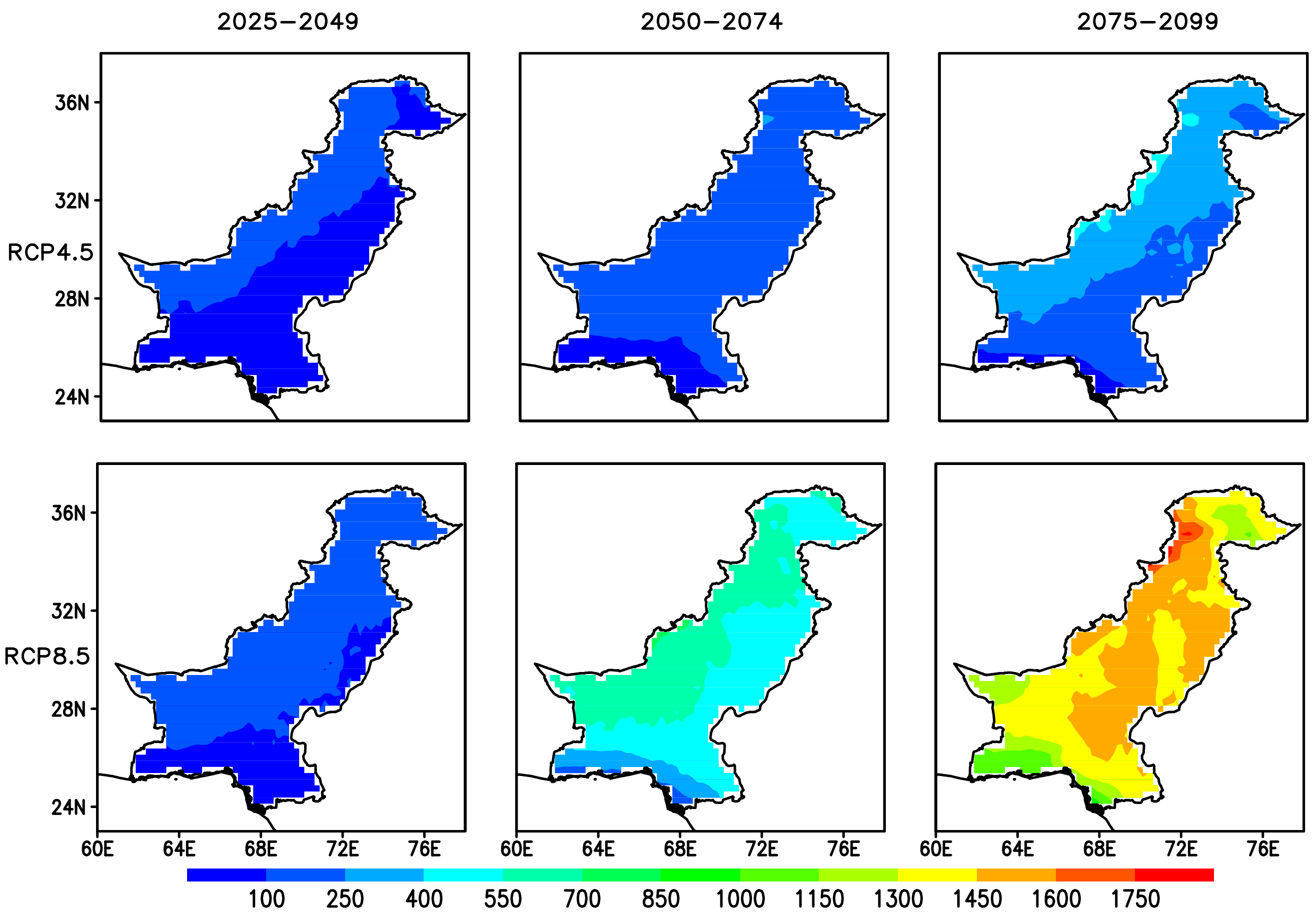

Fig. 12 The multi-model median of changes in number of heat wave days for time spans, 2025–49, 2050–74 and 2075–99 as differences from the reference period 1976–2000 for DJFM using HWDI (days). Top row shows RCP4.5 and bottom row shows RCP8.5

Table 2 MK test statistics

Seasons			Z	S	M–K τ	Significance level
JJAS	RCP4.5	Events	57.006	6.73E+06	0.5634	$p<0.05$
		Days	74.805	9.00E+06	0.7132	
	RCP8.5	Events	79.874	9.55E+06	0.7725	
		Days	80.381	9.62E+06	0.7739	
DJFM	RCP4.5	Events	71.947	8.68E+06	0.6864	
		Days	72.151	8.72E+06	0.6799	
	RCP8.5	Events	76.228	9.20E+06	0.7236	
		Days	81.137	9.80E+06	0.7639	

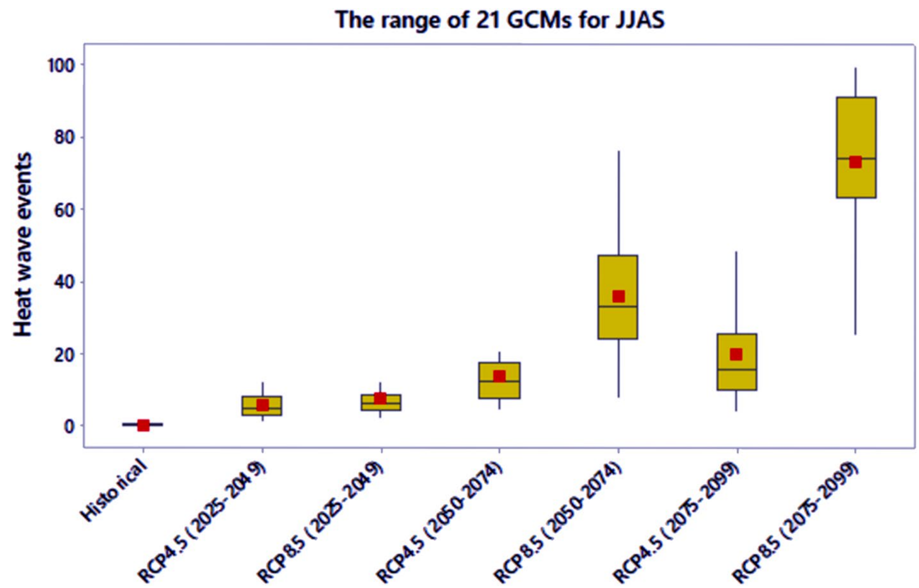

Fig. 13 Box plot showing range of 21 GCMs for number of heat wave events for JJAS

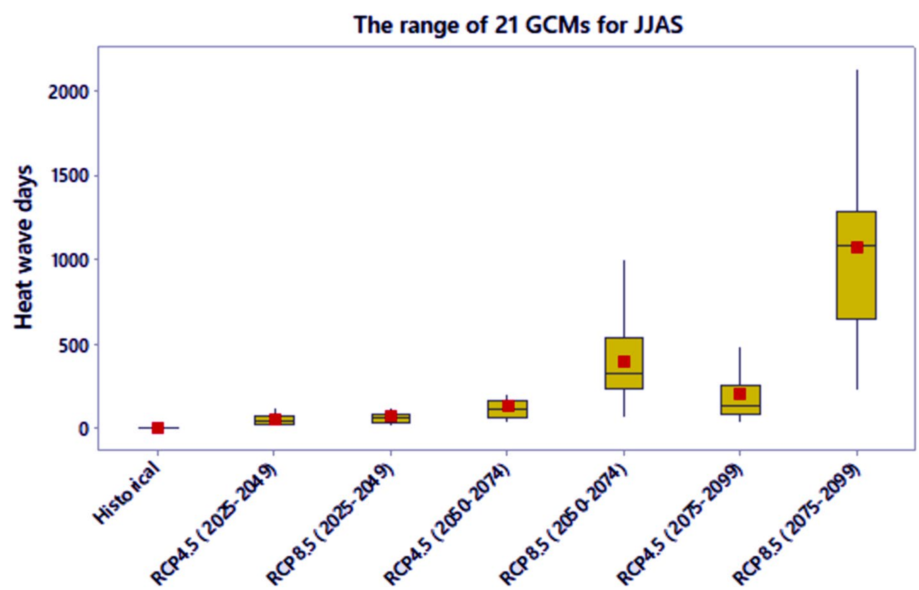

Fig. 14 Box plot showing range of 21 GCMs for number of heat wave days for JJAS

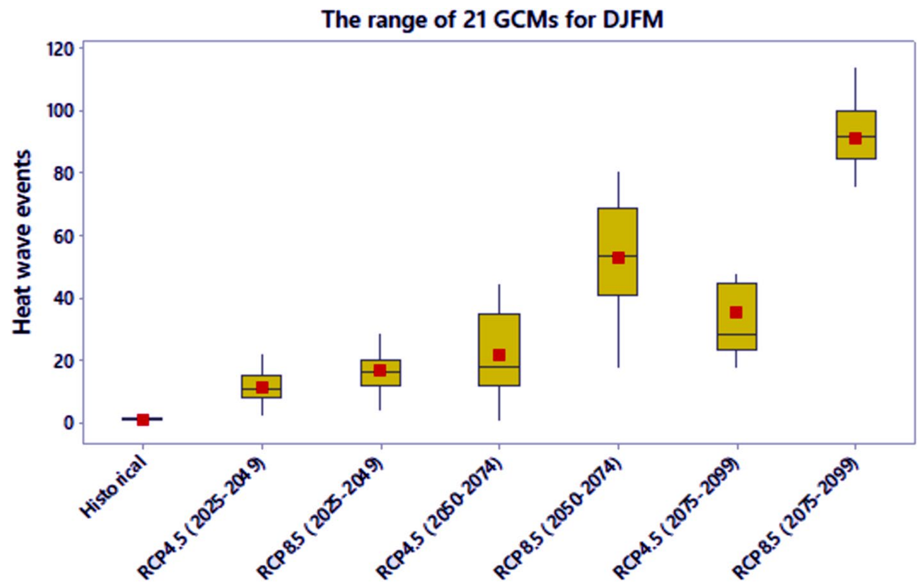

Fig. 15 Box plot showing range of 21 GCMs for number of heat wave events for DJFM

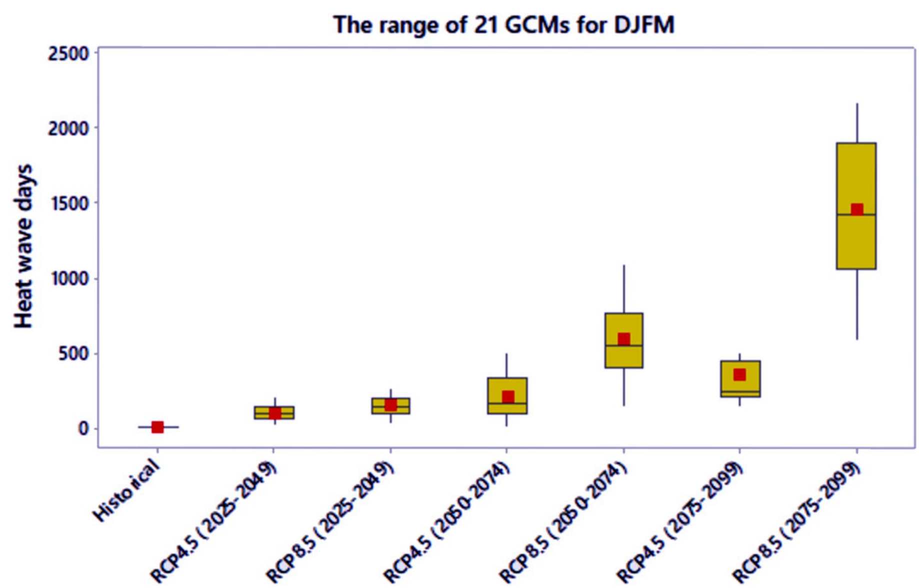

Fig. 16 Box plot showing range of 21 GCMs for number of heat wave days for DJFM

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Compliance with ethical standards

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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