J. Indian Soc. Coastal Agric. Res. 42(1):24-40(2024) https://doi.org/10.54894/JISCAR.42.1.2024.147069

Assessing Changes in Climate Extremes using CMIP6 and its Implications for Agriculture in the Ganges Delta

FAZLUL KARIM[1], YINGYING YU[2], MOHAMMAD KAMRUZZAMAN[3], UTTAM KUMAR MANDAL[4]*
TASLIMA ZAHAN[5], PRIYA LAL CHANDRA PAUL[6] and MOHAMMED MAINUDDIN[1]

[1]CSIRO Environment, Canberra, ACT - 2601, Australia
[2]CSIRO Environment, Brisbane, QLD - 4102, Australia
[3]Farm Machinery and Postharvest Technology Division, Bangladesh Rice Research Institute
Gazipur - 1701, Bangladesh
[4]ICAR-Central Soil Salinity Research Institute, Regional Research Station,
Canning Town - 743 329, West Bengal, India
[5]On-farm Research Division, Bangladesh Agricultural Research Institute,
Gazipur - 1701, Bangladesh
[6]Irrigation and Water Management Division, Bangladesh Rice Research Institute,
Gazipur - 1701, Bangladesh

Received: 03.01.2024 Accepted: 21.03.2024

Climate extremes are the major concerns due to their impact on agriculture and ecosystem services. This study examined the frequency and spatial extent of 9 climate extreme indices relevant to agriculture in the coastal region of the Ganges Delta in Bangladesh and India. The study was conducted using the latest projected future climate data from IPCC's sixth assessment report (CMIP6, Coupled Model Intercomparison Project Phase 6). Agriculture in the Ganges Delta suffers the most due to less availability of usable water; therefore, the study particularly focused on projected climate changes during the dry season (November-April), at short-term (2021- 2040), mid-term (2041- 2060) and long-term (2061-2100) basis. The results show an overall increase for both temperature and rainfall, with variations occurring spatially and temporarily. Across the region, projected maximum temperature increases are 1.3ºC and 2.2ºC for the mid and long-term, respectively under SSP245 (Shared Socioeconomic Pathways). The difference between daily maximum and minimum temperature decreases indicating a higher increase for minimum temperature compared to maximum temperature. At an annual scale, the rainfall increases by 160, 400, and 620 mm under the short, medium and long-term projections, respectively. For the same projection periods, the total rainfall during the dry season rises by 12, 42 and 41 mm, respectively. Similar increasing trend was also observed at mid and long - term projections. The intensity of 1-day and 5-day rainfall increases inboth short and long-term compared to the historical average rainfall of the region. While total rainfall increases during the dry season, the number of consecutive wet days remains unchanged and the number of consecutive dry days slightly increases across the region. It implies that shorter but more intense spells of rainfall are likely to occur during the dry season in the Sundarbans. The findings of this study are valuable for adaptation and future planning to minimize climate risks to agriculture.

(***Key words:*** *Climate risk, Agriculture, Bangladesh, West Bengal, Coastal zone*)

Rising temperature and extreme precipitation events have significant impact on agricultural productivity across the world (Islam, 2022; Ozer *et al.,* 2020; Wilson *et al.,* 2022).

This problem is exacerbated by poor environmental resource management and a lack of adaptive capacity in developing nations (Croitoru *et al.,* 2016; IPCC, 2014). The agricultural land use and land management practices need to adapt to the changes in climate spur. Therefore, understanding changes in precipitation and temperature extremes is crucial for implementing appropriate strategies to mitigate potential climate impacts on food security.

The Ganges Delta relies heavily on agriculture for food security and livelihoods unlike most of the Deltas across the world. However, this region is highly vulnerable to climate change and its ill effect. The region often experiences precipitation and temperature

**Correspondence author:* E-mail: uttam_icar@yahoo.com

extremes, which can significantly impact agricultural productivity. Recent studies have focused on understanding the changes in precipitation and temperature extremes both inland and coast in Bangladesh. Abdullah *et al.* (2022) have indicated that both coastal and inland areas were warming significantly but the rate of warming was higher in coastal areas. Similarly, Das *et al.* (2022) have estimated that the rate of increase of warm extremes is almost similar all over Bangladesh; however, with the extreme cold events, increases at a little higher rate in inland than in the coastal region. In both regions (Bangladesh and India), a greater rise in climate extremes is expected in the far future. In the Ganges Delta, growing non-rice crops successfully in the dry season depends partially on the rainfall distribution patterns especially on the occurrences of heavy rainfall (Yu *et al.,* 2019). The heavy rainfall during sowing time delays seeding because of waterlogging or causes failure of seedling emergence and growth. Modest rainfall at sowing or at other growth stages can act synergistically for crop growth and development in dry season (Islam *et al.,* 2022; Paul *et al.,* 2021; Yu *et al.,* 2019). Also, the delayed establishment of crops expose to higher temperature during flowering and grain filling stages which shortened the reproductive period and reduced yield (Paul *et al.,* 2021). So, it is essential to understand the variations in rainfall patterns during dry season.

Significant progress has also been made in projecting the climate of Bangladesh. Kamruzzaman *et al.* (2021) assessed the relative performance of CMIP6 models, and found the ACCESS-CM2 model was the best that could reliably capture the inter-annual variability of annual and seasonal rainfall and temperature. Das *et al.* (2022) assessed extreme rainfall characteristics using four CMIP6 GCMs (Global Circulation Models) for two emission scenarios. Since the simulation results depend on the models employed, it is more insightful to investigate changes in air temperature and precipitation in Bangladesh from a large set of models and under diverse scenarios.

However, their study estimated overall changes in extreme events without focusing on dry - season extremes which is more important for agricultural production and food security in the region. In this study, we have used the latest available climate data based on IPCC's 6th assessment report (AR6) (IPCC, 2018). We have investigated climate extremes most relevant to dry-season agriculture in the Ganges Delta and quantified changes. This information is crucial for adaptation and future planning to minimize risk and maximizing yield.

MATERIALS AND METHODS

Study area and data

The study includes the southwest coastal region of Bangladesh and the southeast coastal region of West Bengal in India. It lies between approximately 21°30′ N to 23°30′ N latitude and 88°00′ E to 90°30′ E longitude and covers an area of 27,200 km^2. This area is commonly known as the Ganges Delta. It includes 70 upazilas (third-level administrative unit) in Bangladesh and 19 blocks of South and North 24 Parganas district in the Indian state of West Bengal (Fig. 1). The study area is crisscrossed by several rivers that discharge into the Bay of Bengal. The area is characterized by its proximity to the Bay of Bengal and its intricate network of rivers, estuaries, and tidal flats.

The agricultural operation in this area is primarily rainfed with low cropping intensity. Due to the lack of freshwater sources, dry season crops are limited compared to other parts of both the countries. Most of the lands remain fallow in the dry season (Islam *et al.,* 2022); however, some pit-based crops like watermelon, sweet gourd, or sunflower are grown by some progressive farmers in some pocket areas. Majority of households have a pond in their home yards. The pond is the main source of freshwater for regular domestic activities including bathing, washing dishes and water for cooking foods. There are tube wells in some households, which are the source of drinking water for the village dwellers despite that the tube wells produce moderate saline water in the dry season. Soil salinity level in the dry season is medium and it decreases in the wet season. River water salinity starts to increase from December and gets maximum in April/May (25 - 30 dS m^{-1}) (Paul, 2020). The region is highly susceptible to natural disasters, particularly cyclones, storm surges, and flooding, which pose significant risks to crop yields and transport infrastructures.

The study area experiences mean daily temperatures ranging from 22 to 30.8°C throughout the year. The annual mean precipitation varies across the region, with approximately 2000 mm in the east to 1800 mm in the west (Yu *et al.,* 2019).

Historical climate data

In this study we have used weather station data as well as gridded data for downscaling and bias correction of GCM data. For location specific future predictions, we have used climate data from 6 gauging stations (5 in Bangladesh and 1 in West Bengal) from 1980 to 2020. The data were obtained from the Bangladesh Meteorological Department (BMD) and from ICAR-CSSRI, RRS, Canning Town, India. Fig. 2 shows the location of meteorological stations and simulation grids in the global climate models (GCMs). For gridded climate information, we have used satellite-based gridded historical data from the ECMWF Reanalysis v5 (ERA5) global data set, at 0.25° resolution covering the period from January 1940 to the present. ERA5 is the fifth generation European Centre for Medium - Range Weather Forecasts (ECMWF) atmospheric reanalysis of the global climate. The ERA5 is the publicly available data produced by the Copernicus Climate Change Service (C3S) at ECMWF. Based on rainfall and temperature detection metrics, ERA5 demonstrated superior performance for historical climate in Bangladesh (Islam and Cartwright, 2020). Recently, Kamruzzaman *et al.,* (2022) used the ERA5 as reference data to evaluate the efficiency of CMIP6 GCMs in modelling rainfall data over Bangladesh. The data were downloaded from the ECMWF website (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5). We have used ERA5 data for the period of 1985 to 2020 for the bias correction of GCM data.

GCM data

We have used future climate data from the IPCC's sixth assessment report (AR6) for the two Shared Socio - Economic Pathways (SSPs) scenarios, SSP245 and SSP585. These data are based on the Coupled Model Intercomparison Project Phase 6 (CMIP6) which is the 5th generation of CMIP products from the World Climate Research Programme (WCRP). All CMIP6 data are available from the World Climate Research Programme for downloading and using at no cost. Through the Australian Nation Computational Infrastructure (NCI, https://nci.org.au), we have downloaded and processed daily precipitation, maximum and minimum temperature from 26 climate models for the period of 1985 to 2100. Based on the analysis conducted in the previous studies

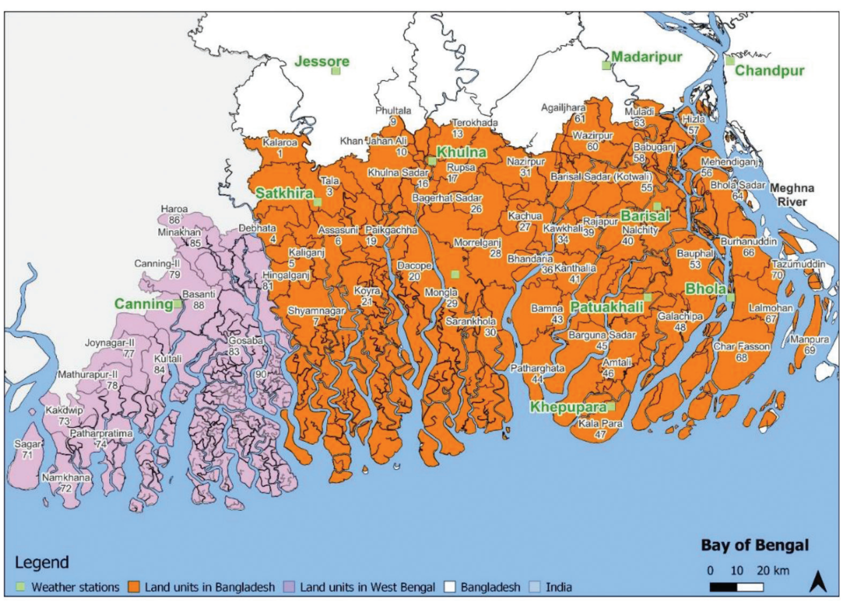

Fig. 1. *Study area map showing administrative boundary of land units in Bangladesh and West Bengal and meteorological stations in the Ganges Delta*

(*e.g.,* Islam and Cartwright, 2020; Kamruzzaman *et al.,* 2022), 18 out of 26 GCMs are used in the study (Fig. 2). It is important to note that the spatial resolution of each GCM varies from 100 to 500 km. This study only used the results from the first realization (r1i1p1f1) of each GCM to keep the evaluations consistent and to minimize the model bias.

Downscaling and bias correction of climate data

Daily GCM simulations for the period of 1985 to 2100 were downscaled at 0.25° resolution using the Simple Quantile Mapping (SQM) method (Cannon *et al.,* 2015) and then bias was corrected using ERA5 historical data. The SQM approach uses empirical quantile mapping to refine GCM simulations independently. The method includes: (i) extraction of the GCM data corresponding to each target ERA5 grid location, (ii) assessment of GCM's biases, and (iii) bias correction of future climate data. The retroactive period differences between observed and simulated cumulative distribution functions (CDFs) were calculated and applied to future simulations for a particular percentile. The ERA5 and raw GCM data were used as inputs in a non-parametric empirical equation for minimizing systematic bias. Further information on downscaling and bias correction can be found in Kamruzzaman *et al.* (2022).

Selecting climate indices

Cropping seasons in Bangladesh are broadly classified as wet (May to October) and dry (November to April) which cover the main developmental stages for *Aman* and *Boro*. The wet season crops (*e.g., Kharif* crops: *Aus* and *Aman* rice) largely depend on the characteristics of the monsoon (Islam and Mondal, 1992; Jensen *et al.,* 1993; Mainuddin *et al.,* 2015). The changes in rainfall can have either positive or negative impacts on crop yield depending on timing, location and duration of the monsoon. The starting of monsoon determines the sowing/transplanting period of *Aus* and *Aman* rice. Any delay in transplanting from the optimum period reduces yield and also exposes the crop, particularly *Aman* rice, to low rainfall period, thus requiring supplementary irrigation. Low rainfall and/or prolonged rainless period during the wet season adversely affect the yield of both *Aus* and *Aman* rice, and the impact is mostly statistically significant (Sarker *et al.,* 2012). Also, extreme rainfall and floods, quite often encountered, can drastically reduce *Aman* rice yield (Asada *et al.,* 2005; Dastagir, 2015).

Cropping in the Ganges Delta is particularly vulnerable during dry season due to shortage of freshwater (Bell *et al.,* 2019). Therefore, this study

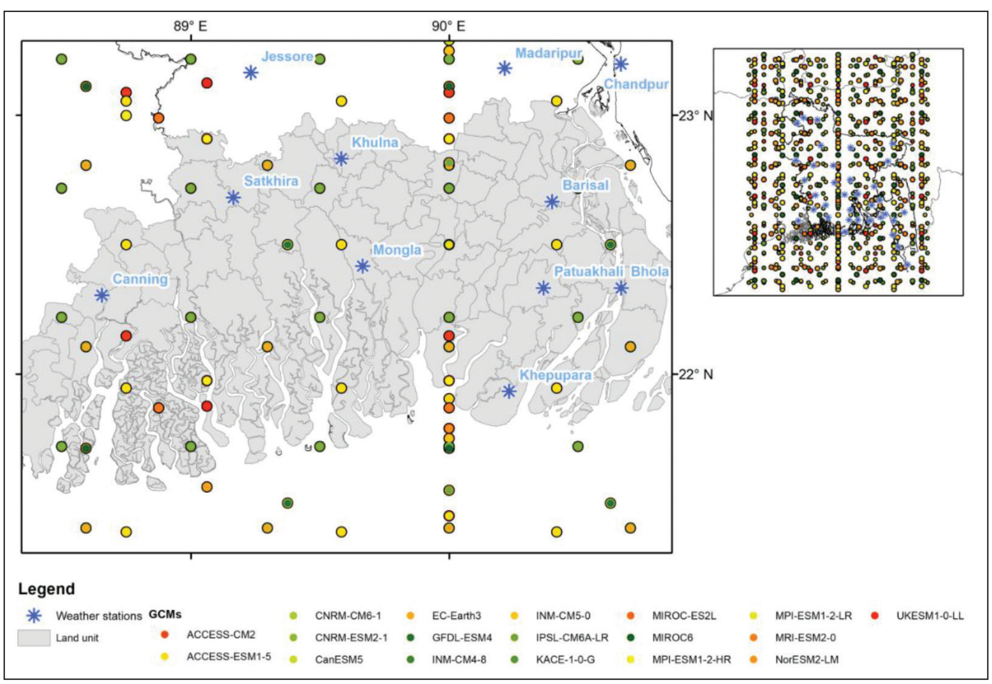

Fig. 2. *Location of weather stations and global climate models (GCMs) in the Ganges Delta*

Table 1. *List of temperature and precipitation indices used in this study*

Indices	Definition	Unit	Purpose
TMAXmean	Seasonal average of monthly maximum value of daily maximum temperature	ºC	Tendency of maximum monthly temperature
TMINmean	Seasonal average of monthly minimum value of daily minimum temperature	ºC	Tendency of minimum monthly temperature
SU25	Seasonal count of days when daily maximum temperature > 25 ºC	days	Tendency of days above maximum temperature limits for rice
DTR	Monthly mean difference between daily maximum and minimum temperature	ºC	
RX1day	Monthly maximum 1-day precipitation	mm	Examine the extreme rainfall events
RX5day	Monthly maximum consecutive 5-day precipitation	mm	Examine the extreme rainfall events
PRCPtot	Seasonal total precipitation in wet days with precipitation >= 1 mm	mm	Tendency of seasonal rainfall
CDD	Seasonal maximum number of consecutive days with precipitation < 1 mm	days	Tendency of dry conditions
CWD	Seasonal maximum number of consecutive days with precipitation >= 1 mm	days	Tendency of wet conditions

focused on climate risk during dry season. To assess changes in extreme temperature and rainfall, 9 climate indices of different climate parameters, were computed using the projected temperature and rainfall time series data (Table 1).

Assessing changes for climate extremes

We have assessed changes in future climate. Assessments were conducted for 3 different time periods, shortterm (2021-2040), mid-term (2041-2060) and long term (2061-2100). Changes in future climates are evaluated with respect to historical climate in the period of 1995 to 2020. We have investigated changes at monthly, seasonal, and annual scales. We assessed the climate extremes (*e.g.,* maximum temperature, minimum temperature, total rainfall) based on entire data series, However, changes for 9 agriculture relevant indices were estimated based on dry season (November-April) data only.

RESULTS AND DISCUSSION

Annual and seasonal temperature

Fig. 3 shows that maximum and minimum temperature in the coastal region of Bangladesh and West Bengal are increasing irrespective of GCM selection. While every GCM is different, there are consistently increasing trends for both historical (thick red line) and future projections (green line for SSP245 and blue line for SSP585). There are large uncertainties among the GCM predictions, and the uncertainties are higher for long-term predictions (*e.g.,* in the period of 2061-2100). For the short-term (2021-2040) similar increases are projected for SSP245 and SSP585. However, for the long-term (2061-2100), maximum and minimum temperature experience a greater increase by about 2ºC and 1.5ºC respectively under SSP585 scenario, compared to SSP245.

Like the annual scale, increase in mean monthly maximum and minimum temperature is predicted by most of GCMs (Fig. 4). Compared to the historical monthly average (red line), predicted temperatures are higher for all 12 months of the year and the increase is slightly higher for the SSP585 (blue line) compared to SSP245 (green line). While the trends are similar for the 2021-2040, 2041-2061 and 2061-2100 projection periods, the increase in the period 2041-2060 is higher than 2021-2040. Similarly, the increase in 2061-2100 is higher than in 2041-2060. Comparing with the historical

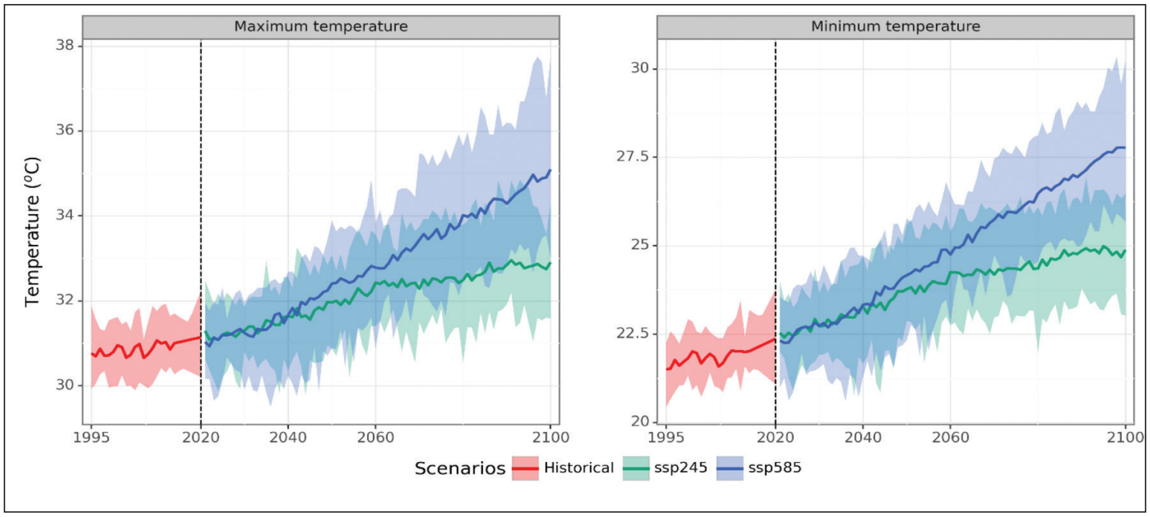

Fig. 3. *Historical and projected maximum and minimum temperature in the Ganges Delta for the SSP245 and SSP585 scenarios (red line: historical, green line: SSP245, blue line: SSP585, with shades representing range of values)*

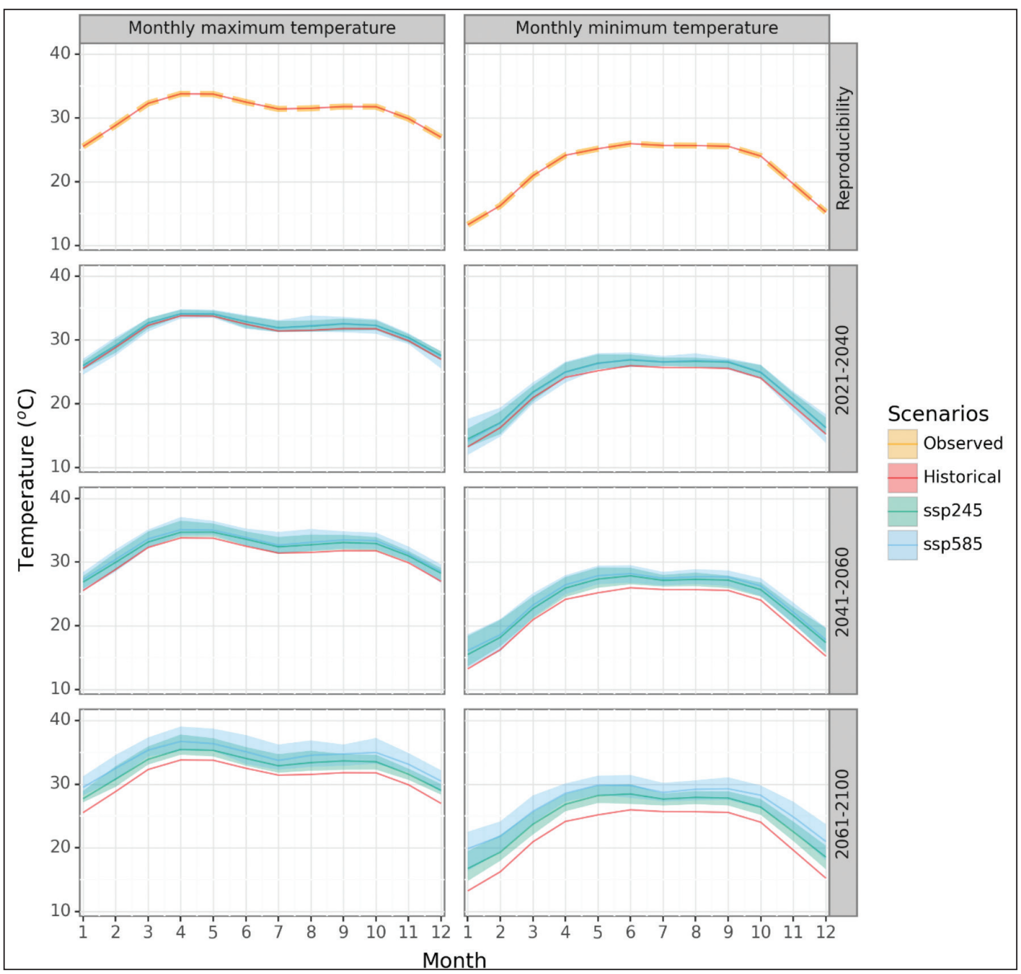

Fig. 4. *Historical and projected maximum temperature in the coastal region of Bangladesh and West Bengal for the SSP245 and SSP585 scenarios in the period of 2021-2040, 2041-2060 and 2061-2100*

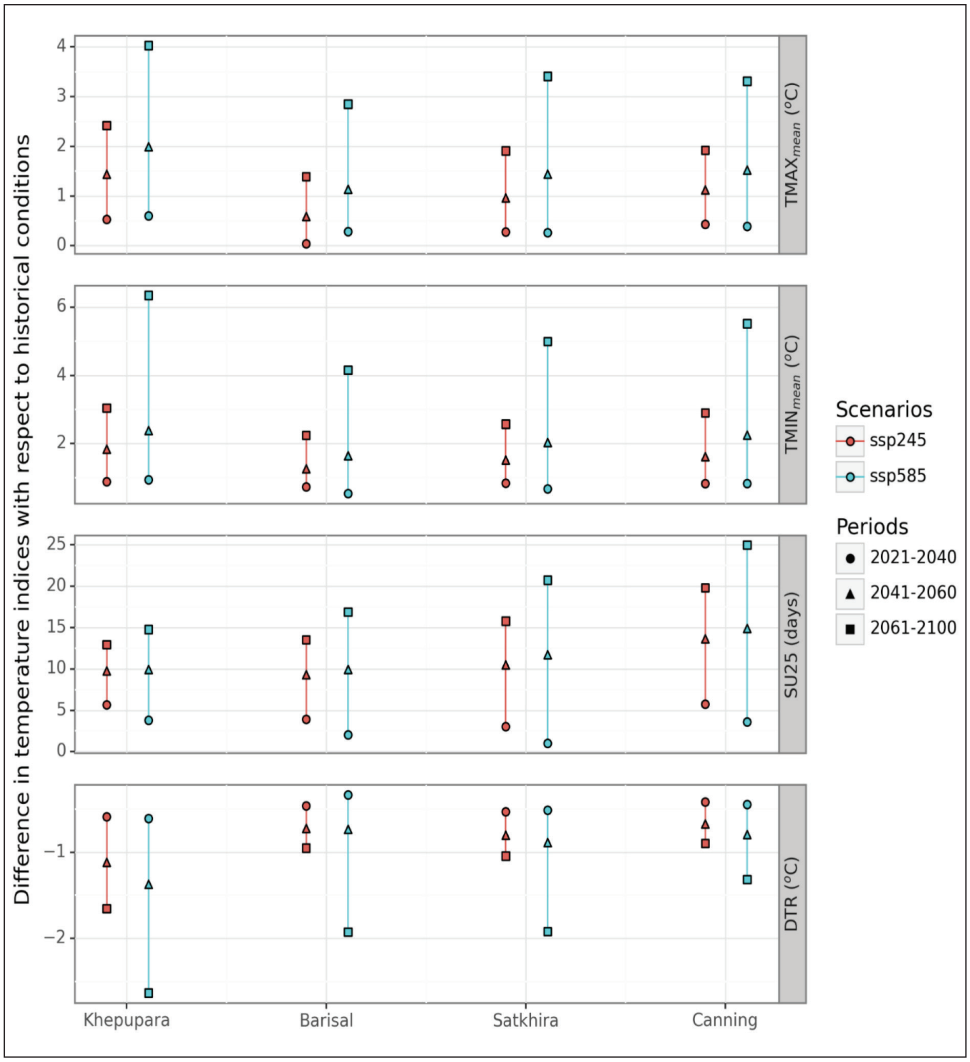

Fig. 5. *Projected changes in 4 temperature indices for dry season (November-April) compared to historical conditions in the Ganges Delta*

temperature, monthly temperature is projected to increase by 0.5 - 0.7ºC, 0.9 - 1.7ºC and 1.5 - 4ºC in the short, mid and long-term. Abdullah *et al.* (2022) also reported based on trend analysis that both coastal and inland areas of Bangladesh were warming significantly but coastal areas exhibited a higher rate of warming.

Changes in temperature extremes

Fig. 5 and Table 2 shows the spatial and temporal variations in 4 temperature indices, extracted for the dry season (November to April) at Khepupara, Barisal and Satkhira in Bangladesh and Canning in West Bengal, India. Three temperature indices (TMAXmean, TMINmean and SU25) show increasing trend under projected future climate. Across the region, for all gauges and projection periods, the increase in TMAXmean is higher for SSP585 compared to SSP245. TMAXmean increases in the range of 0.6ºC to 1.4ºC with an average of 1.0ºC in the period of 2041-2060 for the SSP245. The average increases are 0.3ºC and 1.9ºC in the period 2021-2040 and 2061-2100 respectively. The increase in maximum temperature slightly differs spatially. As the distance from the coast increase, the rise in the maximum temperature decreases. For example, in the period of 2041-2060 for the SSP245, the increase in TMAXmean with respect to the historical is 1.4ºC at Khepupara, and 0.6ºC at Barisal which is the minimum. Similar to TMAXmean, the increase in TMINmean

Table 2. *Projected increase and decrease for four temperature indices in the Ganges Delta for dry season (November-April)*

Locations	Indices	SSP245			SSP585		
		2021-2040	2041-2060	2061-2100	2021-2040	2041-2060	2061-2100
Barisal	DTR	-0.5	-0.7	-1.0	-0.3	-0.7	-1.9
	SU25	3.9	9.3	13.5	2.0	9.9	16.9
	TMAXmean	0.0	0.6	1.4	0.3	1.1	2.8
	TMINmean	0.7	1.3	2.2	0.5	1.6	4.1
Canning	DTR	-0.4	-0.7	-0.9	-0.4	-0.8	-1.3
	SU25	5.7	13.6	19.8	3.6	14.9	25.0
	TMAXmean	0.4	1.1	1.9	0.4	1.5	3.3
	TMINmean	0.8	1.6	2.9	0.8	2.2	5.5
Khepupara	DTR	-0.6	-1.1	-1.7	-0.6	-1.4	-2.6
	SU25	5.6	9.8	12.9	3.8	9.9	14.8
	TMAXmean	0.5	1.4	2.4	0.6	2.0	4.0
	TMINmean	0.9	1.8	3.0	0.9	2.4	6.3
Satkhira	DTR	-0.5	-0.8	-1.0	-0.5	-0.9	-1.9
	SU25	3.0	10.5	15.8	1.0	11.7	20.7
	TMAXmean	0.3	1.0	1.9	0.3	1.4	3.4
	TMINmean	0.8	1.5	2.6	0.7	2.0	5.0

also varies spatially and temporarily and the increase in higher for the long-term projection (*e.g.,* 2061-2100). In general, the increase in TMINmean is higher compared to TMAXmean for all gauging sites.

The days with maximum temperature greater than 25ºC (SU25) increases temporally. The increase varies between 9 to 14 days across the region with an average of 11 days in the period 2041-2060 for the SSP245. The increases are 5 and 15 days in the period 2021-2040 and 2061-2100 respectively. Unlike the TMAXmean and TMINmean, the variations in SU25 exhibit spatial difference from west to east, with the largest increase of 25 days at Canning, and the smallest of 15 days at Khepuparain the long-term projection under SSP585.

While TMAXmean, TMINmean and SU25 increases in the future, the difference between daily maximum and minimum temperature (DTR) decreases (Fig. 5). Negative DTR as shown in Fig. 5 indicates that the increase in minimum temperature is greater than in maximum temperature. Across the region, DTR varies in the range of -0.7ºC to -1.1ºC with an average -0.8ºC in the period of 2041-2060 for the SSP245. The average DTR in the periods of 2021-2040 and 2061-2100 are -0.5ºC and -1.1ºC respectively. Compared to SSP245, DTRs for SSP585 are slightly larger for all gauging sites. The average DTR in the periods 2021-2040, 2041 -2060 and 2060-2100 are -0.5ºC, -0.9ºC and -2.0ºC respectively. This finding implies that winter is becoming much shorter than the earlier period. Similar scenario is already existing in USA where winter is becoming warmer by 2.7 degrees over the normal average (ABC News, 2023).

Annual and seasonal rainfall

Across the Ganges Delta, increase in annual rainfall is projected by most GCMs with a clear increasing trend for both future scenarios as shown in Fig. 6. Thick red, green and blue lines represent average of 18 GCMs for the historical climate, SSP245 and SSP585 scenarios, respectively. Results show large uncertainties in the GCM predictions for seasonal rainfall, and the uncertainties are higher for long - term predictions (*e.g.,* in the period of 2061-2100). While some GCM predicts decrease in rainfall, majority of the models predicts increase in rainfall

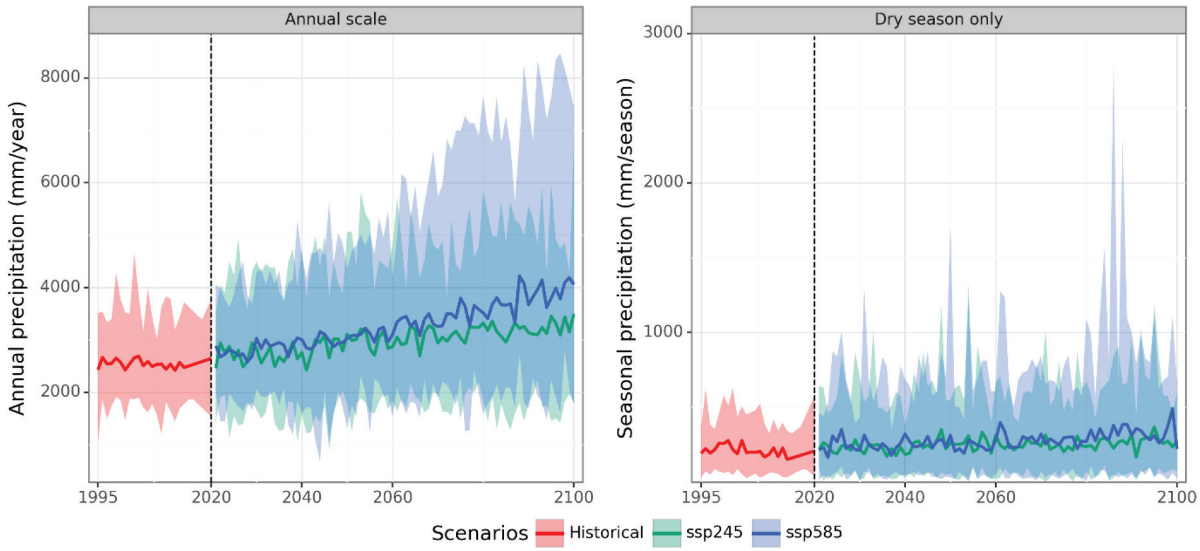

Fig. 6. *Historical and projected future rainfall in the Ganges Delta for the SSP245 and SSP585, (left) annual rainfall and (right) dry season (November-April) rainfall*

and there is an overall increasing trend in annual mean rainfall. Future predictions are 2700, 2940 and 3160 for the periods 2021-2040, 2041-2060 and 2061-2100 respectively for SSP245, showing an increase of 160, 400 and 620 mm respectively compared to historical average of 2540 mm.

Although there is a clear increasing trend for the annul mean rainfall, increase is small in the dry season (Fig. 6, right panel). At a regional scale, mean annual dry season rainfall are 224 mm (minimum: 173 mm, maximum 283 mm) for 2021-2040, 259 mm (minimum: 193 mm, maximum 351 mm) for 2041-2060 and 258 mm (minimum: 168 mm, maximum 368 mm) for 2061-2100 whereas the historical mean of 206 mm (minimum: 152 mm, maximum 278 mm) for the SSP245.

Most GCMs predicted increases for mean monthly rainfall for all 12 months and the increase is higher for long term prediction. Fig. 7 shows the monthly average rainfall in the study area for the short-term (2021-2040), mid-term (2041-2061) and long-term (2061-2100). Compared to historical monthly average, predicted rainfalls are higher for all 12 months of the year and the increase is higher for the SSP585 (blue line) compared to SSP245, particularly in the long-term. However, most increases occur during the wet season months, especially between July and September.

Changes in rainfall extremes

Across the Ganges Delta, increases for seasonaltotal rainfall as well as extreme events are projected. Fig. 8 shows spatial and temporal changes for five rainfall indices (RX1day, RX5day, PRCPtot, CDD and CWD) relevant to agriculture. Results show an increase in dry season rainfall at all gauging sites for short-term as well as long-term projections. For both future scenarios, dry season rainfall increases in the range of 31 to 51 mm across the region with an average of 42 mm in the period of 2041-2060 with respect to historical average dry - season rainfall of 206 mm. These increases are 12 mm for 2021-2040 and 41 mm for 2041-2100 (Table 3). It is important to note that at a longer time scale (2061-2100), rainfall increase is nominal compared to mid - term projection for SSP245.

The intensity of 1-day and 5-day rainfall increases both at short - term and long-term compared to historical climate. One day rainfall (RX1day) increases in the range of 8 to 15 mm with an average of 11 mm for the period 2041-2060 for SSP245, compared to historical mean of 60 mm. The increases are 4 mm and 11 mm for the 2021-2040 and 2061-2100, respectively. Similar

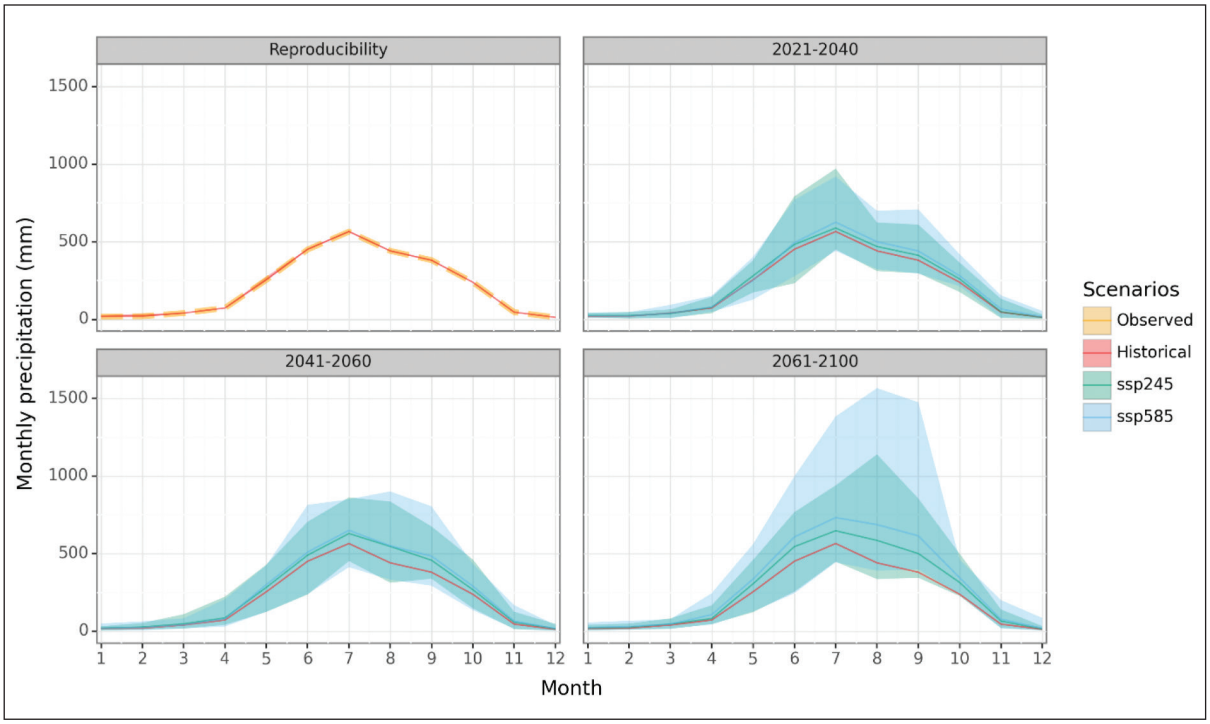

Fig. 7. *Historical and projected future monthly rainfall in in the coastal region of Bangladesh and West Bengal for different periods (rainfall are averaged in the periods 2021-2040, 2041-2060 and 2061-2100)*

to total rainfall increase in the dry season, one day maximum rainfall in the period of 2061-2100 is similar to 2041-2060. The 5-day rainfall (RX5day) increases by 26 mm for the period 2041-2060 for SSP245 compared to historical mean of 102 mm. The increases are 12 mm and 24 mm for the 2021-2040 and 2061-2100, respectively (Table 3). It is important to note that 5-day rainfall increase for long range projection is slightly less than the mid - range projection at some stations. Results are consistent with other rainfall indices but different than temperature indices.

While total rainfall increases during the dry season, the number of consecutive wet days (CWD) is about 4 days, which remains similar to historical condition. The consecutive dry days (CDD) however, slightly increase across the region. For the 2041-2060 period, CDD increases by approximate 2 days for the SSP245 compared to historical mean of 53 days. The increases are 2 and 1 days for 2021-2040 and 2061-2100, respectively (Table 3) which indicates that there will be a longer consecutive dry period between November and April in the study area, although the total rainfall is projected to increase.

Uncertainty in climate extremes

Each GCM is different in terms of input climate variables and simulation algorithms. Therefore, projected changes in future climates are not uniform between GCMs, some models predict increase while other predict decrease. The uncertainty comes from projections of climate change as the climate models are driven by emission scenarios that are plausible future projects of energy demand and supply, which are all inherently uncertain. However, when we combine results from all GCMs, we can see a general trend of increase or decrease that is most plausible.

The box and whisker plot in Fig. 9 shows estimated climate indices (4 for temperature and 5 for rainfall) using downscaled results from 18 GCMs. The horizontal line in the figure represents the 50th percentile of all GCMs, while top and bottom lines represent 75th and 25th percentile, respectively. For all indices the uncertainty is higher for predictions (SSP245 and SSP585), compared to GCM simulations for historical climate (red boxes).

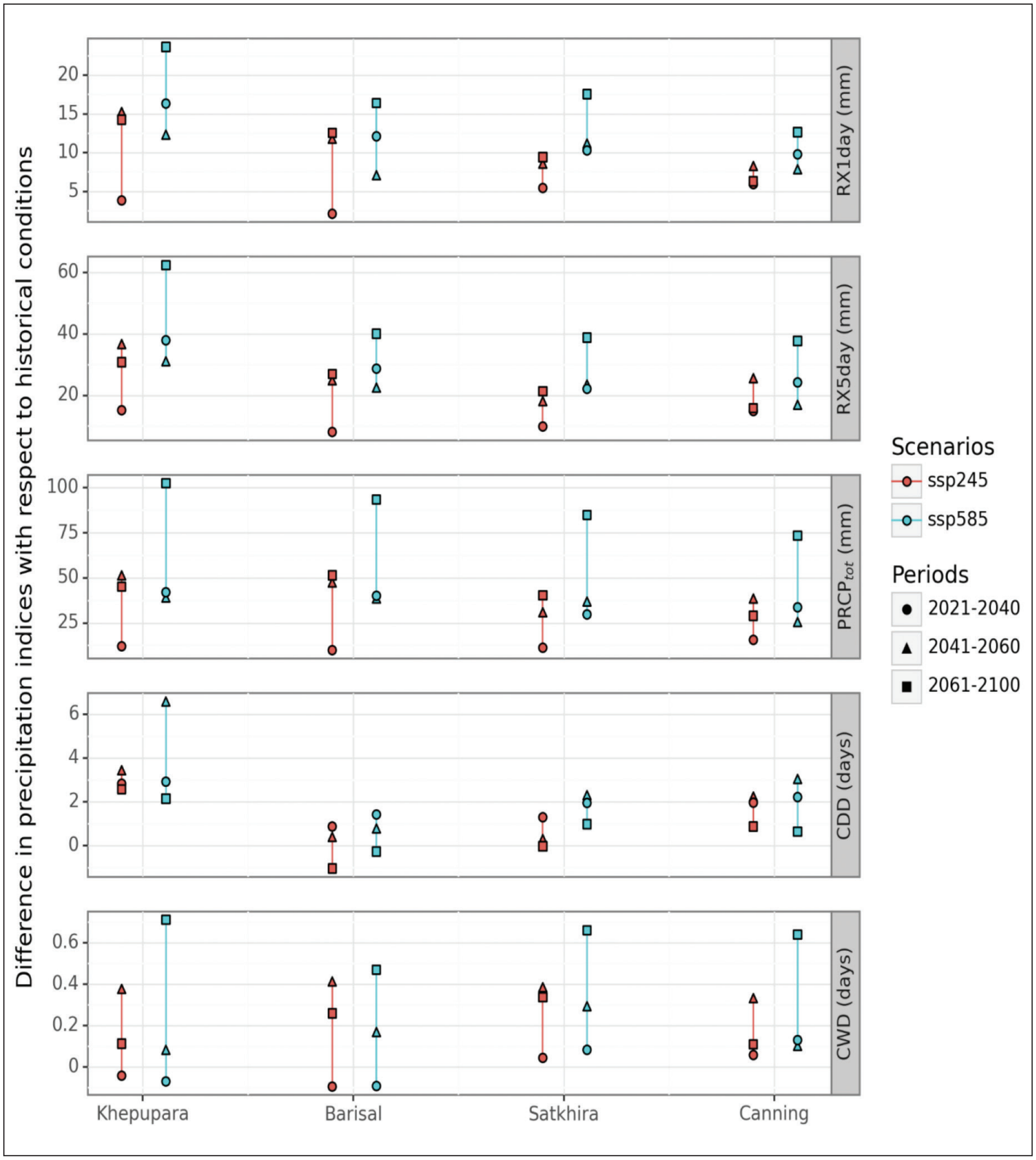

Fig. 8. *Changes to rainfall indices for the dry season (November-April) in the Ganges Delta*

Among all indices, the TMAXmean is relatively less spread out and doesn't have outliers, implying a more consistent and homogenous outcome.

Overall, the models could capture the interannual variability of annual and seasonal rainfall and temperature reliably. Similar results were reported by Kamruzzaman *et al.* (2021) to simulate annual and seasonal mean rainfall and temperature over Bangladesh. The climatic variabilities of the Ganges Delta are usually influenced by a number of global and regional scale factors such as geographic location, the effect of North-South continental scale atmospheric pressure gradient, fluctuations in the terrestrial and sea surface temperature, and so on (Islam and Neelim, 2010). The

Table 3. *Projected changes for rainfall indices during dry season (November-April) at selected gauging sites in the Ganges Delta*

Locations	Indices	SSP245			SSP585		
		2021-2040	2041-2060	2061-2100	2021-2040	2041-2060	2061-2100
Barisal	CDD	1	0	-1	1	1	0
	CWD	0	0	0	0	0	0
	PRCPtot	10	47	51	40	39	93
	Rx1day	2	12	13	12	7	16
	Rx5day	8	25	27	29	23	40
Canning	CDD	2	2	1	2	3	1
	CWD	0	0	0	0	0	1
	PRCPtot	16	39	29	34	26	73
	Rx1day	6	8	6	10	8	13
	Rx5day	15	26	16	24	17	38
Khepupara	CDD	3	3	3	3	7	2
	CWD	0	0	0	0	0	1
	PRCPtot	12,	51	45	42	39	102
	Rx1day	4	15	14	16	12	24
	Rx5day	15	37	31	38	31	62
Satkhira	CDD	1	0	0	2	2	1
	CWD	0	0	0	0	0	1
	PRCPtot	11	31	40	30	37	85
	Rx1day	5	9	9	10	11	18
	Rx5day	10	18	21	22	24	39

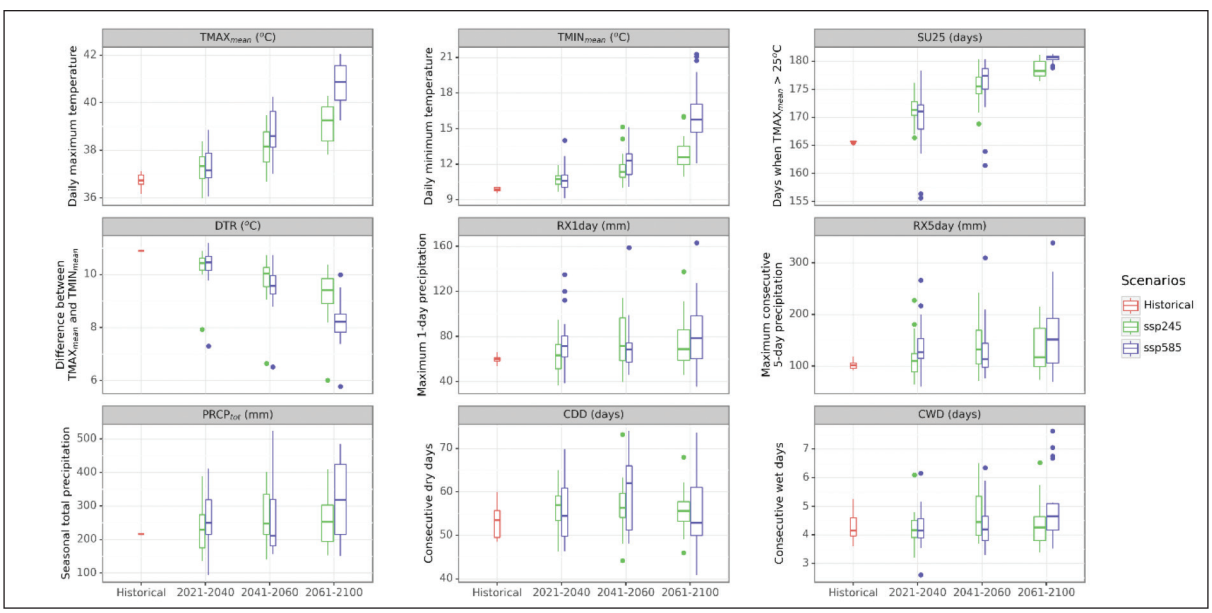

Fig. 9. *Box plot showing uncertainties for 9 climate indices for the dry season in the Ganges Delta (Khepupara) for SSP245 and SSP585 scenarios*

coastal region usually experiences more extreme events than any other parts of the country and the increasing trend in temperature is also pronounced (Ahmed *et al.,* 2022). The current study supports the findings of previous studies on changes in climate extremes. The study also identified remarkable increasing trends in maximum and minimum temperature in short-term, mid-term and long-term future up to 1.9°C. This finding is aligned with the global temperature increase of 1.5°C by 2050 and 2-4°C by 2100 as reported by IPCC (2018). The seasonal count of days with daily maximum temperature above 25°C will be varied from 5 to 15 days and the maximum counts will be in long-term future. Moreover, the uncertainty in projected seasonal rainfall could be an alarming indication for future crop production. Rising annual temperature results in greater frequency and intensity of cyclonic storms (Haque *et al.,* 2019 ; Minar *et al.,* 2013).

The mitigation and adaptation strategies for agriculture are strongly depending on the magnitude and rate of climate change and also with the associated climate risks. Agriculture is the most vulnerable sector to climate change effects and it also indirectly contributes to GHG emissions and aggravates global warming. The climate extremes are responsible for reducing the agricultural production and putting the security under pressure.

The increasing frequency or amount of heavy precipitation or uncertainty in precipitation can harm crops by eroding soil and depleting soil nutrients (Gowda *et al.,* 2018). The coastal region of Bangladesh covers about 20% of total land area and over 30% of the cultivable lands of the country (Minar *et al.,* 2013). The crop production will adversely be affected by shortening the length of crop growing season.

The future climate predictions show a significant variability in climatic patterns for climate extremes like increase in temperature, and uncertainty in rainfall with higher intensity. In a case study, Habib-ur-Rahman *et al.* (2022) quantified climate change effects on rice and wheat and tried to develop adaptation strategies for rice - wheat cropping system during mid - century (2040-2069). They predicted a yield reduction of 15.2% in rice and 14.1% in wheat by DSSAT crop model and 17.2% in rice and 12% in wheat by APSIM crop model. On the other side, in another study in the Northern part of Bangladesh, Hasan *et al.* (2019) reported that the production of rice and wheat will be increased almost double for in future period (2040) as per both APSIM and DSSAT crop models if additional irrigation supply can be provided. Therefore, there is a need of strategic plans to adopt climate - smart and resilient agricultural technologies for sustainable crop production in future under rapid changing climate. Wheat and mustard yields appear to be becoming more sensitive to minimum temperature, especially during post-anthesis period (Rao *et al.,* 2015). Though the region is not predominating wheat growing area an increase in 1°C Tmin may decline wheat yield by 7% in India. Testing of adaptation strategies like adjusting the sowing dates and growing heat tolerant cultivars at the local level needs prioritisation.

To make cropping systems intensification a reality, a number of changes in the systems need to be made in the coastal zone (Bell *et al.,* 2019) as follows: surface drainage of excess water at the end of the wet season; better understanding and use of the limited fresh groundwater; increased surface water storage capacity; planting of earlier maturity and shorter duration rice varieties during the monsoon season to provide better timeliness of *Rabi* crops in relation to water availability; increased use of salt tolerant *Rabi* cultivars, use of mulches to reduce *Rabi* season soil evaporation and hence reduce salinity build-up in surface soil.

A wide range of field crops and vegetable crops are feasible in the coastal zone, and profitable intensified cropping patterns have been identified. Among the cropping patterns that increased BCR (benefit-cost ratio) in Sundarbans region are *Kharif* rice-potato-mungbean, *Kharif* rice-mustard-mungbean, *Kharif* rice-garden pea-mungbean, *Kharif* rice-spinach-mungbean (Saha *et al.,* 2019). One of the most promising new crops introduced was zero-tillage (ZT) potato after *Kharif* rice (Maji *et al.,* 2020). The ZT potato is placed on wet soil and covered by a thick layer of rice straw mulch equivalent to 12 t ha^{-1}. The main opportunity involves changing the cropping season to use stored water from the monsoon season in the *Rabi* season when the solute potential is low and to harvest crops early enough to avoid crop stress from waterlogging, salinity/drought, heat and or storms (Bell *et al.,* 2019). Provision of field drainage for harnessing the productivity of waterlogged soils is required.

The coastal regions of India are marked as one of the traditionally backward and disadvantaged areas with low agricultural productivity due to poor quality of soil and water. Enhancing farm income and sustaining livelihoods of resource poor farmers under such fragile environment become a real challenge both for technology developers as well as policy makers. Resource poor farmers were naturally risk averters and they tend to prefer a lower outcome that is relatively certain to the prospect of a higher return associated with a greater degree of uncertainty. For achieving and continuing with higher cropping system intensification from the existing cropping system, farmers need continuous support like, more capital investment, additional knowledge on crop management and assurance of remunerative price. Contingent planning, real time weather forecasting with agro-advisory and crop insurance could increase the resilience of the system (Bhattacharyya *et al.,* 2020).

CONCLUSION

The study assessed changes in temperature and rainfall in the Ganges Delta using data from IPCC's CMIP6 for SSP245 and SSP585. We estimated changes at local and regional scales and at short (2021-2040) mid (2041-2160) and long term (2061-2100) time scales. The study particularly focused on changes during dry season (November-April) because agriculture in the Ganges Delta suffers the most due to water shortage. Across the region increases are projected for both temperature and rainfall and the increase vary spatially and temporarily. The difference between daily maximum and minimum temperature decreases which indicates higher increase for minimum temperature compared to maximum temperature. While there is a large increase in annual rainfall (*e.g.,* 400 mm for the period 2041-2060), dry season increase is only 42 mm for the same period. The intensity of 1-day and 5-day rainfall increases both at short-term and long-term. While total rainfall increases during dry season, number of consecutive wet days remains similar to historical but consecutive dry days slightly increases across the region.

The assessment of temperature and rainfall extremes provides insights into the challenges faced by the agricultural sector, especially during the dry season when freshwater is insufficient. The findings emphasize the need for climate adaptation strategies that enhance the resilience of agricultural systems. By implementing appropriate measures, such as improved water management, crop diversification, and capacity building for farmers, the region can enhance its agricultural resilience and ensure food security in the region.

CONFLICTS OF INTEREST

The authors declare that there is no comflict of interest.

REFERENCES

ABC News. (2023). *Why Winter is Getting Warmer and What it Means for the Future,* 13 March 2023. https://abcnews.go.com/US/winter-warmer-means-future/story?id=97801342 (Retrived on 14 December 2023).

Abdullah, A.Y.M., Bhuian, M.H., Kiselev, G., Dewan, A., Hassan, Q.K. and Rafiuddin, M. (2022). Extreme temperature and rainfall events in Bangladesh: A comparison between coastal and inland areas. *International Journal of Climatology* **42**(6): 3253-3273. https://doi.org/10.1002/joc.6911.

Ahmed, I., Ishtiaque, S., Zahan, T., Rashed, M.S.U., Sen, R., Hossain, M.F., Brahma, S., Ahmed, I.M., Hossain, M.A., Ali, M.A., Jahan, A.H.S., Imtiaz, S., Naher, Q., Mujahidi, T.A., Biswas, S. and Haque, M.I. (2022). Climate change vulnerability in Bangladesh based on trend analysis of some extreme temperature indices. *Theoretical and Applied Climatology* **149**(1-2): 1-22. https://doi.org/10.1007/s00704-022-04079-4.

Asada, H., Matsumoto, J. and Rahman, R. (2005). Impact of recent severe floods on rice production in Bangladesh. *Geographical Review of Japan* **78** (12): 783-793. https://doi.org/10.4157/grj.78.783.

Bell, R.W., Mainuddin, M., Barrett-Lennard, E.G., Sarangi, S.K., Maniruzzaman, M., Brahmachari, K., Sarker, K.K., Burman, D., Gaydon, D.S., Kirby, J.M., Glover, M., Rashid, M.H., Khan, M.S.I., Kabir, M.E., Rahman, M.A. and Hossain, M.B.

(2019). Cropping systems intensification in the coastal zone of the Ganges Delta: Opportunities and risks. *Journal of the Indian Society of Coastal Agricultural Research* **37**(2): 153-161.

Bhattacharyya, P., Dash, P.K. and Pathak, H. (2020). Climate change and coastal agriculture: Impacts and adaptation. *Journal of the Indian Society of Coastal Agriculture* **38**(2): 1-14.

Cannon, A.J., Sobie, S.R. and Murdock, T.Q. (2015). Bias correction of GCM precipitation by quantile mapping: how well do methods preserve changes in quantiles and extremes? *Journal of Climate* **28**(17): 6938-6959. https://doi.org/10.1175/JCLI-D-14-0075 4.1.

Croitoru, A.E., Piticar, A. and Burada, D.C. (2016). Changes in precipitation extremes in Romania. *Quaternary International* **415**: 325-335. https://doi.org/10.1016/j.quaint.2015.07.028.

Das, S., Kamruzzaman, M. and Islam, A.M.T. (2022). Assessment of characteristic changes of regional estimation of extreme rainfall under climate change: A case study in a tropical monsoon region with the climate projections from CMIP6 model. *Journal of Hydrology* **610**: 128002. https://doi.org/10.1016/j.jhydrol.2022.128002.

Dastagir, M.R. (2015). Modeling recent climate change induced extreme events in Bangladesh: *A review. Weather and Climate Extremes* **7**: 49-60. https://doi.org/10.1016/j.wace.2014.10.003.

Gowda, P., Steiner, J.L., Olson, C., Boggess, M., Farrigan, T. and Grusak, M.A. (2018). Agriculture and rural communities. In: *Impacts, Risks, and Adaptation in the United States: Forth National Climate Assessment,* Vol. II, D.R. Reidmiller, C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.), U.S. Global Change Research Program, Washington, DC, USA. pp 391-437. https://doi.org/10.7930/NCA4.2018.CH10.

Habib-ur-Rahman, M., Ahmad, A., Reza, A., Hasnain, M.U., Alharby, H.F., Alzahrani, Y.M., Bamagoos, A.A., Hakeem, K.R., Ahmed, S., Nasim, W., Ali, S., Mansour, F. and Sabagh, A.E.L. (2022). Impact of climate change on agricultural production; Issues, challenges, and opportunities in Asia. Frontiers *Plant Science* **13**. https://doi.org/10.3389/fpls.2022.925548.

Haque, M.A., Alam, M.A., Moniruzzaman, S.M. and Hoque, M.M. (2019). The impact of climate change in the coastal areas of Bangladesh affected by cyclone Bulbul. *Bangladesh Journal of Extension Education* **31**(1&2): 13-27.

Hasan, M.K. Akhter, S., Chowdhury, M.A.H., Chaki, A.K., Chawdhery, M.R.A. and Zahan, T. (2019). Prediction of changing climatic effect and risk management by using simulation approaches for rice-wheat system in Bangladesh. *Bangladesh Journal of Agricultural Research* **44**(2): 311-326.

IPCC. (2018). Summary for Policymakers. In: *Global Warming of 1.5°C*: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, V. Masson - Delmotte, P. Zhai, H.O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y.Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.), Cambridge University Press, Cambridge, United Kingdom and New York, USA. pp 3-24. https://doi.org/10.1017/9781009157940.001.

IPCC. (2014). *Climate Change 2014*, Synthesis Report, Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC, Geneva, Switzerland.

Islam, M. (2022). Impacts of climate change on water resources, agricultural production and food security: evidence from Turkiye. *Journal* *of Economy Culture and Society* **66**: 163-179. https://doi.org/10.26650/Jecs2021-1056971.

Islam, M.A. and Cartwright, N. (2020). Evaluation of climate reanalysis and space-borne precipitation products over Bangladesh. *Hydrological Sciences Journal* **65**(7): 1112-1128. https://doi.org/10.1080/02626667.2020.1730845.

Islam, M.D.J. and Mondal, M.K. (1992). Water management strategy for increasing monsoon rice production in Bangladesh. *Agricultural Water Management* **22**(4): 335-343. https://doi.org/10.1016/0378-3774(92)90041-T.

Islam, M.S., Bell, R.W., Miah, M.A.M. and Alam, M.J. (2022). Farmers' fertilizer use gaps relative to government recommendations in the saline coastal zone of the Ganges Delta. *Agronomy for Sustainable Development* **42**: 59. https://doi.org/10.1007/s13593-022-00797-1.

Islam, T. and Neelim, A. (2010). *Climate change in Bangladesh: A Closer Look into Temperature and Rainfall Data,* First edition, The University Press, Dhaka, Bangladesh.

Jensen, J.R., Mannan, S.M.A. and Uddin, S.M.N. (1993). Irrigation requirment of transplanted monsoon rice in Bangladesh. *Agricultural Water Management* **23**(3): 199-212. https://doi.org/10.1016/0378-3774(93)90028-9.

Kamruzzaman, M., Shahid, S., Islam,A.R.M.T., Hwang, S., Cho, J. and Zaman, M.A.U. (2021). Comparison of CMIP6 and CMIP5 model performance in simulating historical precipitation and temperature in Bangladesh: A preliminary study. *Theoretical and Applied Climatology* **145**: 1385-1406.

Kamruzzaman, M., Shahid, S., Roy, D.K., Islam, M.T.A.R., Hwang, S., Cho, J., Zaman, M.A.U., Sultana, T. Rashid, T. and Fatima, A. (2022). Assessment of CMIP6 global climate models in reconstructing rainfall climatology of Bangladesh. *International Journal of Climatology* **42**(7): 3928-3953

Mainuddin, M., Kirby, M., Chowdhury, R.A.R. and Shah-Newaz, S.M. (2015). Spatial and temporal variations of, and the impact of climate change on, the dry season crop irrigation requirements in Bangladesh. *Irrigation Science* **33**(2): 107-120. https://doi.org/10.1007/s00271-014-0451-3.

Maji, B., Sarangi, S.K., Mandal, U.K., Burman, D. and Balasubramaniam, P. (2020). Climate change and management options for sustainable soil health and crop production: Eastern coast of India. *Advanced Agricultural Research & Technology Journal* **IV**(1): 28-41.

Minar, M.H., Hossain, M.B. and Shamsuddin, MD. (2013). Climate change and coastal zone of Bangladesh: Vulnerability, resilience and adaptibility. *Middle - East Journal of Scientific Research* **13**(1): 114-120. https://doi.org/10.5829/idosi.mejsr.2013.13.1.64121.

Ozer, O.O., Ozden, A. and Kan, M. (2020). Impact of global climate change on agricultural production: Balkan countries in 2050. *Journal of Environmental Protection and Ecology* **21**(1): 151-158.

Paul, P.L.C. (2020). Agronomic practices increase sunflower yield in the rabi (dry) season in clay-textured, salt-affected soils of the coastal region of Bangladesh. *Unpublisehd Ph. D. Dissertation*, Murdoch University, Australia.

Paul, P.L.C., Bell, R.W., Barrett-Lennard, E.G., Kabir, E. and Gaydon, D.S. (2021). Opportunities and risks with early sowing of sunflower in a salt-affected coastal region of the Ganges Delta. *Agronomy for Sustainable Development* **41**(3): 39. https://doi.org/10.1007/s13593-021-00698-9.

Rao, B.B., Chowdary, P.S., Sandeep, V.M., Pramod, V.P. and Rao, V.U.M. (2015). Spatial analysis of the sensitivity of wheat yields to temperature in India. *Agricultural and Forest Meteorology* **200**: 192-202.

Saha, R.R., Rahman, M.A., Rahman, M.H., Mainuddin, M., Bell, R., Gaydon, D.S. (2019).

Cropping system intensification for increasing crop productivity in salt-affected coastal zones of Bangladesh. *Proceedings* **36**(1): 172. https://doi.org/10.3390/proceedings2019036172.

Sarker, M.A.R., Alam, K. and Gow, J. (2012). Exploring the relationship between climate change and rice yield in Bangladesh: An analysis of time series data. *Agricultural Systems* **112**: 11-16. https://doi.org/10.1016/j.agsy.2012.06.004.

Wilson, A.B., Avila-Diaz, A., Oliveira, L.F., Zuluaga, C.F. and Mark, B. (2022). Climate extremes and their impacts on agriculture across the eastern corn belt region of the U.S. *Weather and Climate Extremes* **37**: 100467. https://doi.org//10.1016/j.wace.2022.100467.

Yu, Y., Mainuddin, M., Maniruzzaman, M., Mandal, U.K. and Sarangi, S.K. (2019). Rainfall and temperature characteristics in the coastal zones of Bangladesh and West Bengal, India. *Journal of the Indian Society of Coastal Agricultural Research* **37**(2): 12-23.