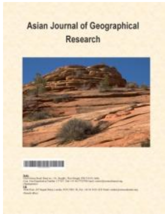

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Global Warming and Sea Level Rising: Impact on Agriculture and Food Security in Southern Coastal Region of Bangladesh

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Authors' contributions

This work was carried out in collaboration between both authors. Author MAA managed the literature searches and analyses of the study and wrote the first draft of the manuscript. Author MAHK wrote the protocol and designed the study. Both authors read and approved the final manuscript.

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ABSTRACT

Climatologically, the entire southern coastal belt of Bangladesh is most vulnerable than the other parts of the country due to its spatial geo-morphological settings. Global warming and sea level rise are already observed and predicted to be occurred more with time. These bring real negative consequences on the agricultural production and food security, and livelihood for the people live in the coastal areas. Therefore, the study was conducted to analyze the effect of global warming and sea level rise on the agriculture and food security in southern coastal areas of Bangladesh. Both primary and secondary sources of information were collected. Stakeholder consultation, direct field visits and interview of climate affected people in the coastal region were carried out for collecting information on land-use and cropping patterns and adaptation measures to be taken to boost crop production against global warming and sea level rise. By the middle and end of the twenty first century, global annual mean temperature is predicted to be increased about 1.5^{o}C and 2.5^{o}C, respectively. These projected warming will lead to about 14, 32 and 88 cm sea level rise by 2030, 2050 and 2100, respectively which would cause inundation of about 8, 10 and 16 percent of total

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land masses in Bangladesh. Most of the coastal parts and associated islands of Khulna and Barisal divisions and western part of Chattagram division lie within one meter from sea level where incursion of saline water is common. It is predicted that these areas will be inundated and unsuitable for crop production due to upcoming sea level rise. The predominant crop in entire coastal belt is transplanted *Aman* with sporadic occurrences of *Aus* rice. The land in *Boro* rice season either loosely occupied by mungbean, grass pea, cowpea, groundnut, soybean, potato, sweet potato, chili etc or remained fallow until the following monsoon. A systemic analysis of all of the cyclones that originated from the Bay of Bengal since 1961 indicated that most devastating cyclones formation occurred from last quarter of April through May and from middle of October to November just prior to the harvest of *Boro* and *Aman* crops, respectively. Therefore, *Boro* and *Aman* rice harvests are mostly unpredictable every year posing great threat to the food security of the coastal people. These areas are criss-crossed by innumerable water canals or channels especially in Barisal and Khulna divisions which can be utilized for *Boro* rice cultivation in dry season despite some levels of salinity. Cultivation of salt-tolerant crop varieties could mitigate such hindrances. Introduction of saline tolerant *Boro* rice in coastal cropping patterns and/or advancing the harvesting times by a fortnight in both *Aman* and *Boro* rice seasons to avert cyclonic havoc not only ensure food security but also turn the entire coastal belt into a food surplus region.

Keywords: Agriculture; Bangladesh; climate change; coastal area; food security; global warming; IPCC, salinity intrusion; sea level rise.

1. INTRODUCTION

The effects of climate change are geographically inequitable, variable and unpredictable with potentially devastating consequences on water resources, agriculture, infrastructure, livelihoods, biodiversity and cultures. There is unequivocal evidence that the global surface (earth-atmosphere) is being warming because of an increased concentration of greenhouse gases in the earth atmosphere. According to the Intergovernmental Panel on Climate Change (IPCC) [1], continued greenhouse gas emission at or above current rates would cause further warming and induce changes in global climate system during the 21st century that would very likely be larger than those observed during the past centuries. The global mean temperature has risen about 0.7°C to 0.8°C on average above pre-industrial levels [2]. By the middle and end of the current century, global annual mean temperature is predicted to be increased about 1.5°C and 2.5°C, respectively. Global warming will lead to thermal expansion of sea water, together with melting of glaciers and sea-ice, the resultant effect of which is the rise in sea level. As per IPCC [1], global mean temperature is predicted to be increased from 1.8°C (B1 scenario) to 4°C (A1FI scenario) and respective sea level will be risen 0.18 m to 0.59 m at the end of twenty first century. A 0.1 m to 0.5 m rise in sea level as predicted by most of the estimates by the middle of this century will pose a great threat to the agriculture and livelihoods of people in low-lying coastal areas of the world including about one fifth of the total land masses of Bangladesh [3-4] (Map 1).

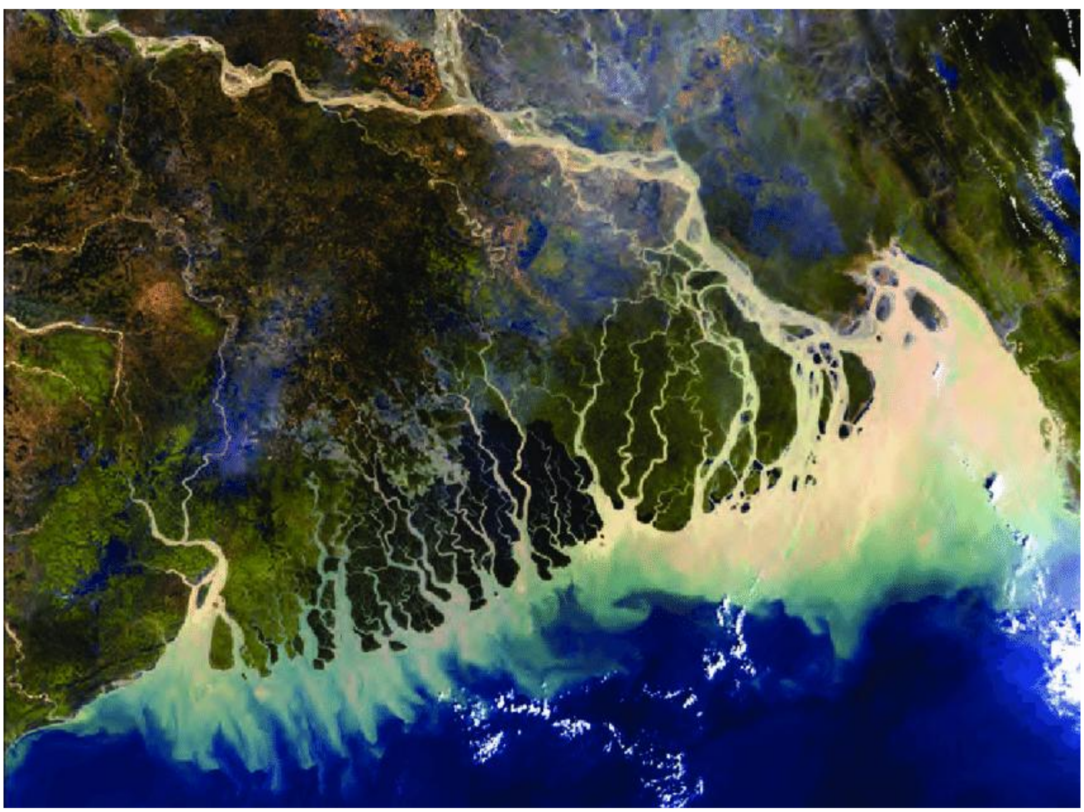
The coastal region is worldwide recognized as an extremely vulnerable area. The Bangladesh coast is located in between the Indian coast and Myanmar's Peninsula that formed on top of a cone or funnel shaped sea-land structure which invites most of the tropical sea-cyclones. Total coastal area of Bangladesh is about 47,203 square kilometers covering nineteen districts predominantly under the Barisal, Khulna and Chattagram divisions where near about fifty million people, about 28 percent of total country's population live. Impacts of global warming and sea level rise should have real consequences on the livelihood of the coastal people of Bangladesh as it is affected by cyclones with heavy storm surges, tidal flooding, erosion of the land masses, drainage congestion, salinity intrusion etc [5-9]. Therefore, agriculture in southern low-lying areas of Bangladesh is likely to become increasingly difficult to sustain. The land mass of Bangladesh being already quite limited and its population density is one of the highest in the world, continuous land engulfing by rising sea water will only bring grave consequences forcing the coastal people to become climatic refugees [10-11]. A generalized radiation or diffusion model predicted that 0.9 million people will migrate due to sea level rise in Bangladesh by 2050 and 2.1 million by 2100, largely internally, with substantial implications for nutrition, shelter and employment in destination areas [12]. These climatic refugees will exert immense pressure on the already existing vulnerable food securities.

Therefore, collection of relevant information relating to the degree of global warming and sea level rise and its consequences on the land uses and population are essential in formulating policies for agriculture and food security in the southern coastal regions of Bangladesh. The existing cropping patterns and livelihoods will make the people more vulnerable to cope with the negative impacts of those consequences. But proper policy formulation and its execution may avert food insecurity in that area. Therefore, the study was undertaken for the following objectives:

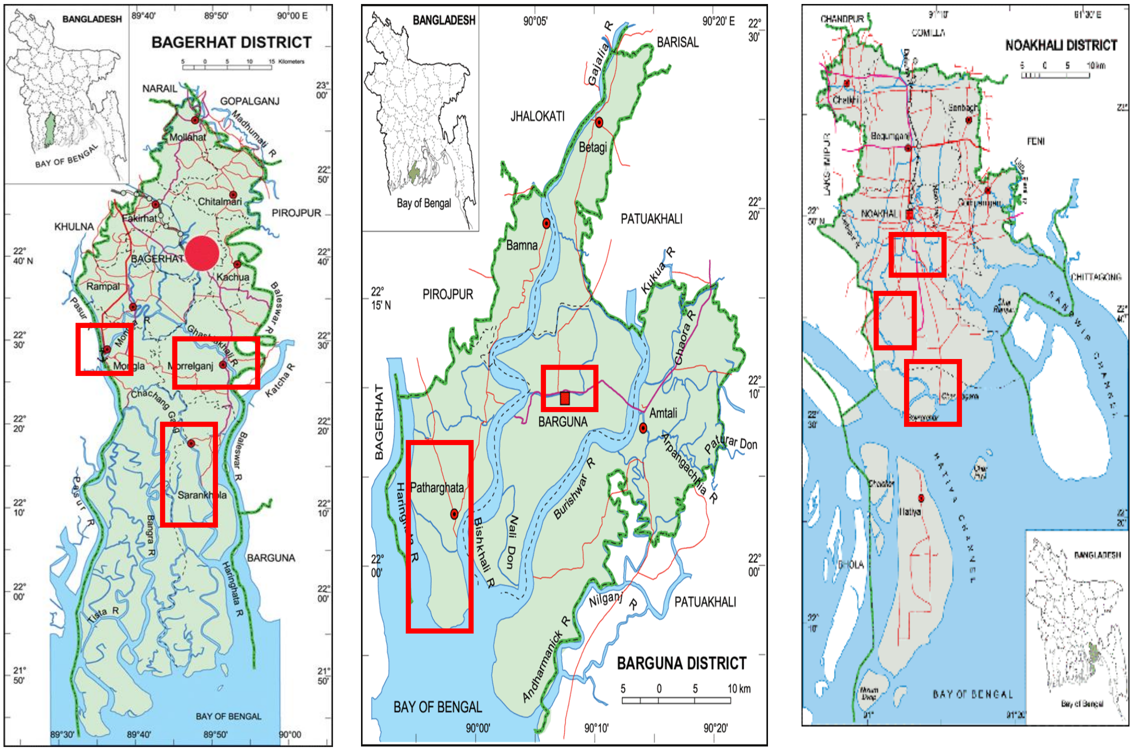
- To evaluate the observed and predicted global warming and sea level rise especially for Bangladesh along with their impacts on coastal land masses and agriculture;
- To assess the land-use and cropping patterns of coastal areas of Bangladesh;
- To formulate the sustainable model for food security against global warming and related consequences in southern coastal areas of Bangladesh.

2. MATERIALS AND METHODS

The study was conducted in the Department of Crop Botany, Bangladesh Agricultural University, Mymensingh. Both primary and secondary sources of data have been collected. The coastal area of Bangladesh from where the data were collected covers three sub-national administrative units like Khulna, Barisal and Chattagram divisions. Relevant information on global warming and sea-level rising have been accumulated by consulting books, journals, periodicals, browsing internets, personal communications, attending seminars and symposia, and visiting various institutes or organizations. Data on climatic parameters like temperature, rainfall, cyclones, and tidal surges etc from 1961 were collected from Bangladesh Meteorological Department (BMD), Ministry of Defense, Government of Bangladesh (GoB).



Map 1. A satellite view of the Bangladesh coastline. Image acquired by ESA's MERIS sensor on 8 November 2003. Image Credit: European Space Agency (ESA)



Map 2. Primary data collection sites (red rectangular or square areas) from Bagerhat, Barguna and Noakhali districts [13-15]

The land uses as well as cropping patterns of the coastal areas of Khulna, Barisal and Chattagram divisions have been collected through stakeholder consultation with responsible Officer-in-Charge like Deputy Director (DD) and Upazila Agriculture or Extension Officer (UAO or UEO) of Department Agricultural Extension (DAE), Ministry of Agriculture, GoB. Coastal people those who directly affected by climate change threats were face-to-face interviewed to know their agricultural practices and cropping patterns that are being affected by such threats. The data collection sites were Sarankhola and Mongla (the Sundarbans) upazilas of Bagerhat district from Khulna division, Patharghata upazila of Barguna district from Barisal division, and Sudharam and Char Jabbar of Sadar upazila and Hatiya upazila of Noakhali district from Chattagram division (Map 2). Additionally, direct field visits or on-spot observations were performed on locations of interest from Khulna, Bagerhat, Satkhira, Barisal, Jhalokathi, Barguna, Patuakhali and Noakhali districts of coastal regions. Best adaptation measures to save crop production for the coastal people to tackle the threats from global warming and sea level rise were explored.

3. RESULTS AND DISCUSSION

3.1 Emission of Green House Gases: Carbon Dioxide (CO_2)

The measurements collected at Mauna Loa Observatory show a continuous increase in mean atmospheric carbon dioxide (CO_2) concentration from 313 parts per million by volume (ppmv) in March 1958 to 406 ppmv in November 2018 [16], with a current increase of 2.48 ± 0.26 (mean ± 2 std dev) ppmv CO_2 per year (Fig. 1) [17-18]. The principal cause of such increase in atmospheric CO_2 was anthropogenic activities like combustion of fossil fuels, and has been accelerating in recent years. As CO_2 is one of the major greenhouse gases, this has significant implications on global warming.

3.2 Observed and Predicted Global Warming

The historical time series of global temperature anomaly from 1880 to 1935 was found consistently negative (Fig. 2) [19]. In contrast, from 1980 it was found constantly positive till now having highest anomalies of +0.4 to +0.6°C. Such increase in global temperature especially during recent past might have been associated with the increased concentration of greenhouse gases like carbon dioxide (Fig. 1), methane, ozone, nitrous oxide, chlorofluorocarbons etc in the atmosphere due to the increased burning of the fossil fuels and some other causes for rapid industrialization and urbanization.

Changes in global mean temperature over the common time periods for various analyses of datasets as reported in IPCC 5th Assessment Report (AR5) [20] were found higher in recent times than the previous periods. It is most alarming to observe that temperature increase in recent times was much higher as much 0.15°C per decade (i.e 0.015°C per year) in 1979-2012 for all the datasets reported in the AR5.

The IPCC [1] in 4th Assessment Report (AR4) predicted that the global temperature at the end of twenty first century may exceed the limit of about 2°C with a fluctuation of about 1 to 3.5°C from the mean. The IPCC [20] in AR5 predicted that the global mean surface temperature will be increased from 1.0 to 2.0°C during 2046-2065 period and from 1.0 to 3.7°C during 2081-2100 period (Table 1; Fig. 3). However, Gaterell [21] predicted much higher warming from climate models and said that if the warming continues at currents rate, the average global temperature will be likely to risen by 4°C to 6°C by the end of the current century. Such warming of global atmosphere would melt the glaciers and ices at higher rates as compared to recent past which will further contribute to the rise of sea level.

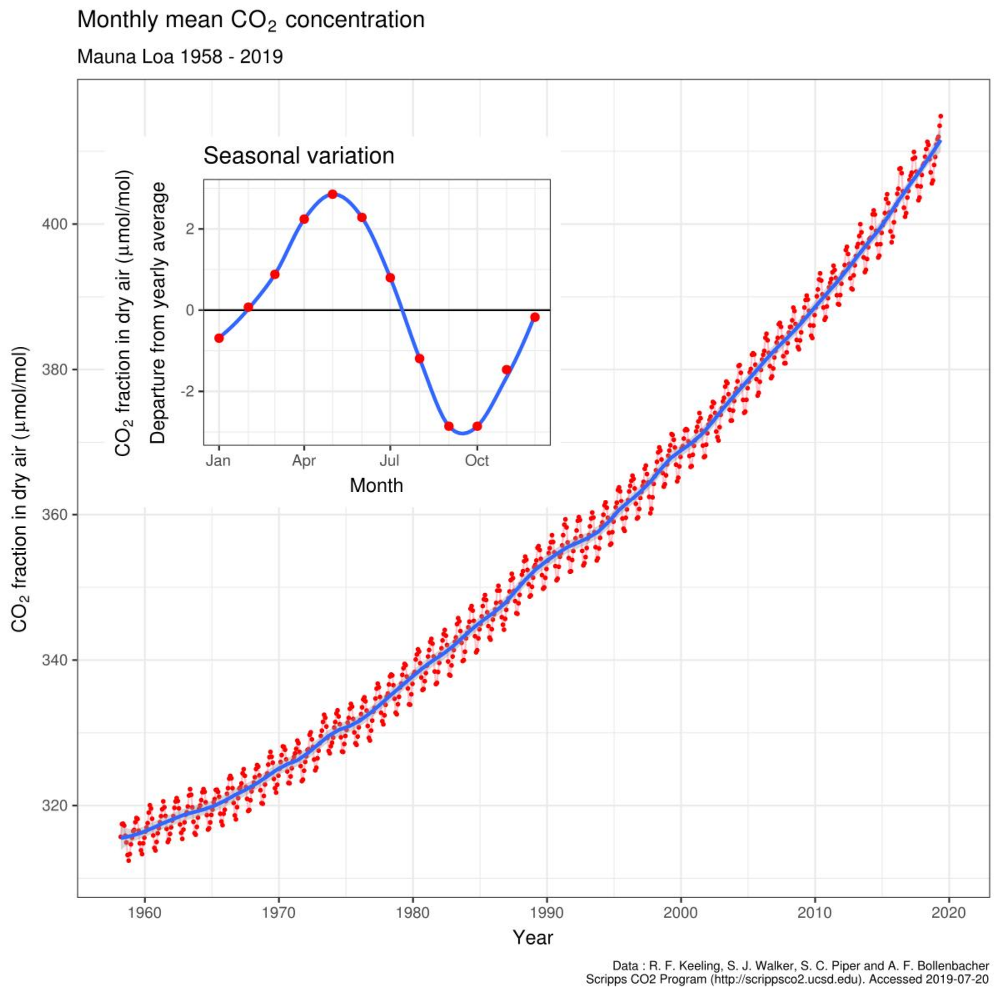


Fig. 1. Atmospheric carbon dioxide (CO_2) concentrations from 1958 to 2019 taken at the Mauna Loa Observatory on the island of Hawaii from 1958 to the present day [18]. It is known as the Keeling Curve, the name for the scientist Charles David Keeling, who started the monitoring program and supervised it until his death in 2005

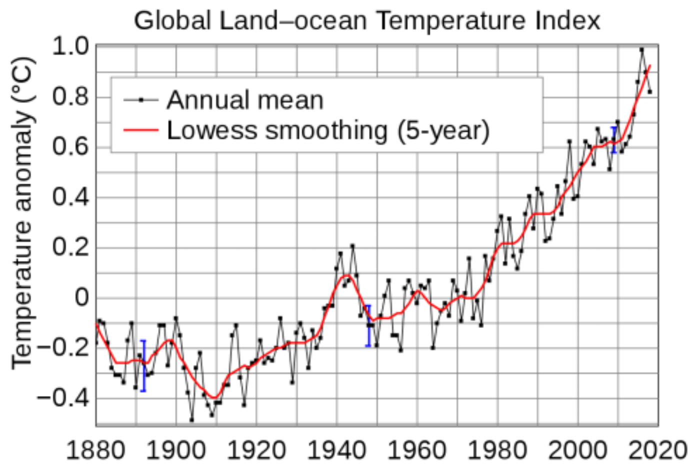


Fig. 2. Observed global temperature anomaly from 1880 to present, with base period 1951-1980 [19]. The solid black line is the global annual mean and the solid red line is the five-year lowess smooth. The blue uncertainty bars (95% confidence limit) account only for incomplete spatial sampling

Table 1. Predicted global temperature towards 2046-2065 and 2081-2100 periods under various scenarios [20]

Parameter[a]	Scenario[b]	2046-2065		2081-2100	
		Mean	**Likely range**	**Mean**	**Likely range**
Global mean surface temperature change (°C)	RCP2.6	1.0	0.4 – 1.6	1.0	0.3 – 1.7
	RCP4.5	1.4	0.9 – 2.0	1.8	1.1 – 2.6
	RCP6.0	1.3	0.8 – 1.8	2.2	1.4 – 3.1
	RCP8.5	2.0	1.4 – 2.6	3.7	2.6 – 4.8

[a]Based on the Coordinated Modelling Intercomparison Project Phase 5 (CMIP5) ensemble; anomalies calculated with respect to 1986–2005.' [b]RCP = Representative Concentration Pathway. The RCP2.6, RCP4.5, RCP6.0 and RCP8.5 are labelled after a possible range of radiative forcing values (2.6, 4.5, 6.0, and 8.5 W/m^2, respectively) in the year 2100

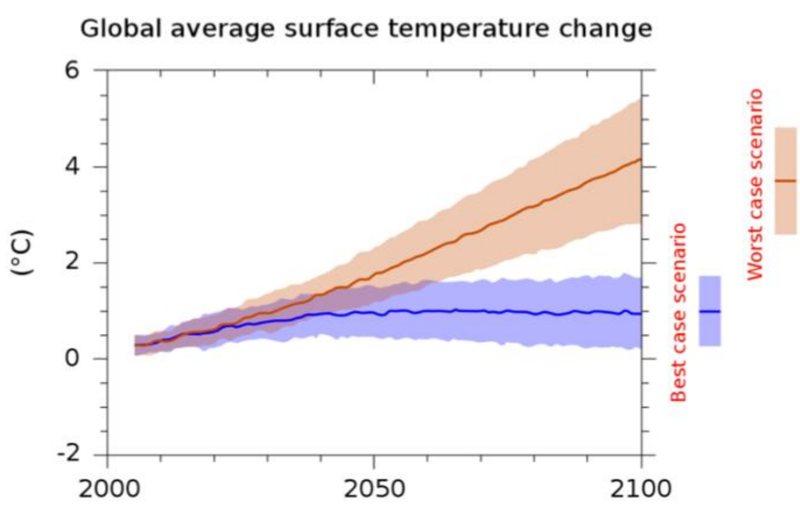


Fig. 3. Predicted global temperature to the year 2100 (relative to 1986-2005) [20]. The assessed likely range is shown as a shaded band. The RCP2.6 and RCP8.5 are regarded as 'best' and 'worst' case scenarios, respectively

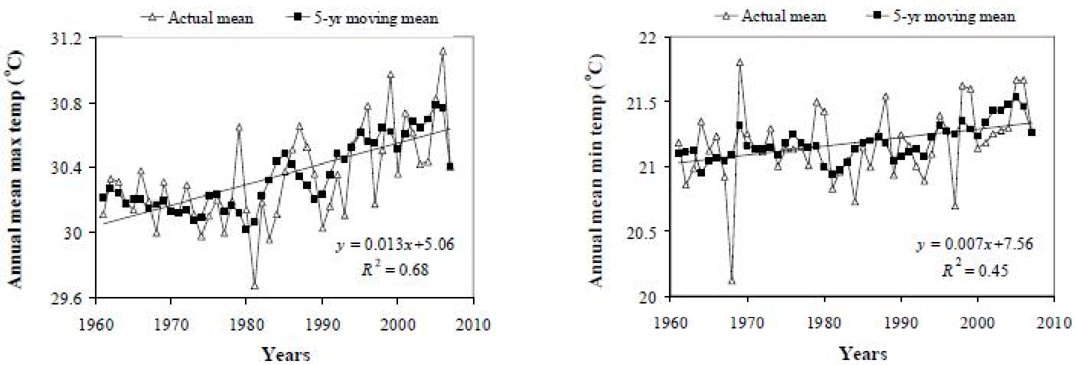


Fig. 4. Annual mean maximum and mean minimum temperatures of Bangladesh from 1961 to 2007. Data represent averaged from 24-34 meteorological observatories throughout the country. R^2 is the coefficient of determination

3.3 Observed Temperature Trend in Bangladesh with Future Projections

National mean maximum and mean minimum temperatures for the period from 1961 to 2007 were found in increasing trend (Fig. 4). That means global warming has played significant role to increase mean maximum temperature of Bangladesh. The slope of the 5-year moving average for mean maximum temperature was found steeper (0.013) than that for mean minimum temperature (0.007).

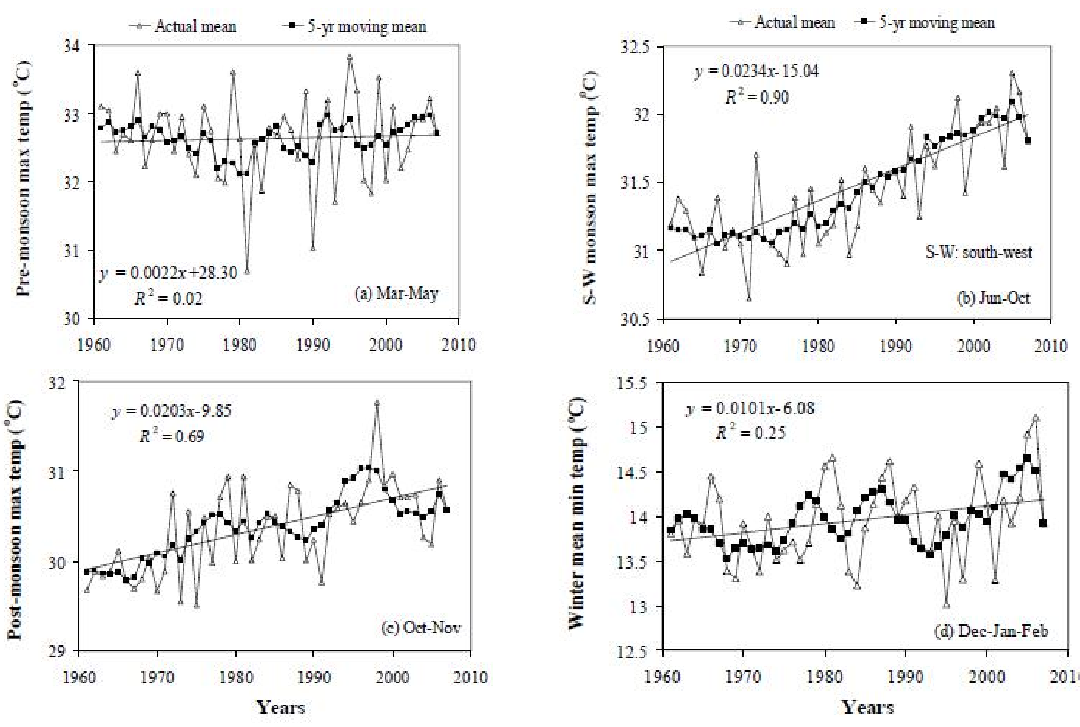


Fig. 5. National mean maximum temperatures during (a) pre-monsoon, (b) south-west monsoon and (c) post-monsoon seasons, and (d) mean minimum temperature during winter season in Bangladesh from 1961 to 2007. The period from June to September is referred to as the 'South-west monsoon' period. Wind from southwest direction or from south that brings heavy rainfall to southern Asia in the summer. South-west monsoon period is the major rainy season for Bangladesh where whole country receives nearly 75 percent of its total annual rainfall. R^2 is the coefficient of determination

National mean maximum temperatures at pre-monsoon season from March to May, south-west monsoon season from June to September and post-monsoon season from October to November and mean minimum temperature during winter season from December to February are presented in Fig. 5. Although mean maximum temperature in pre-monsoon season shown static trend or increased a little (slope of 5-year moving average was 0.0022). But mean maximum temperatures for south-west monsoon and post-monsoon seasons are found as continually increasing trend (slope of 5-year moving average exceeded 0.02) since 1961. Mean minimum temperature in winter season was also found in increasing trend with moderate slope.

Annual mean temperature in Bangladesh has crossed very little but 25°C (Table 2). All the maximum temperature traits in annual and pre-monsoon, south-west monsoon and post monsoon seasons have exceeded 30°C. Although annual minimum temperature exceeds 20°C but winter minimum temperature ranked in about half of the annual mean temperature of the country.

Mean summer and mean winter temperatures at 2010 for the coastal divisions (Chattgram, Barisal and Khulna divisions) of Bangladesh and their projection towards 2050, 2075 and 2100 are shown in Table 3 [7,22]. Summer temperature clearly appeared about 8°C higher than the winter temperature (around 20°C). Mean summer temperature decreased with longitude i.e. from western (Khulna) to eastern (Chattagram) coast of Bangladesh. However, inverse pattern of temperature for changing longitude was noticed for the mean winter temperature. Predicted increase of temperature towards the 2050, 2075 and 2100-year was found higher in Khulna division for summer temperature but that found higher in Chattagram division for winter temperature. The Barisal division for both cases was ranked in middle position. Ahmed and Alam [23] reported that average temperature is predicted to be increased 1.3°C and 2.6°C for the 2030 and 2075, respectively. Hasan *et al.* [24] reported that temperature will rise up to 3.5ºC at 2050 and 4.5ºC at end of the 21st century where winter will get warm faster than summer.

Predicted national temperature at the end of the twenty first century to be exceeded 1°C with 21 percent higher in winter than the summer season (Table 3). That means for the effect of global warming, winter season in Bangladesh might be either shortened or disappeared in future. Therefore, many cool-demand crops like wheat, onion, garlic, radish, carrot, cabbage, cauliflower etc being cultivated since time immemorial in Bangladesh are under threat of global warming.

3.4 Observed Rainfall Trend in Bangladesh with Future Projections

The national average annual mean total rainfall was found in increasing trend with time (Fig. 6). Extreme yearly fluctuations for rainfall at all the seasons are noticeable since 1961 (Fig. 7). However, the slope of regression lines computed from 5-year moving average indicated that the amount of rainfall was in increasing trend especially at post-monsoon season (Fig. 7c). The slope of rainfall trend appeared to be most static for winter season (Fig. 7d). Most rains in Bangladesh occurred during monsoon period especially during south-west monsoon while winter period received minimum rain about less than 2 percent (Table 2). Pre-monsoon period received 18 percent rain of a year. In contrast post monsoon time received the half of the amount of rain that occurred during pre-monsoon season. The effects of 2°C and 4°C increase in mean temperature were speculated for defining 'moderate' and 'severe' climate change scenarios and speculated a rise in peak monsoon rainfall by 18 and 33 percent, respectively [25].

Table 2. Average temperature and rainfall in Bangladesh from 1961 to 2007

Trait	Average temperature (°C)	Average rainfall (mm)
Annual minimum	21.17 ± 0.29	-
Annual maximum	30.33 ± 0.29	-
Annual mean	25.75 ± 0.30	2417 ± 246
Pre-monsoon maximum	32.63 ± 0.63	435 ± 121
South-west monsoon maximum	31.43 ± 0.39	1736 ± 189
Post monsoon maximum	30.34 ± 0.49	215 ± 92
Winter minimum	13.94 ± 0.46	38 ± 23

Table 3. Projection of mean temperature across the coastal divisions of Bangladesh (from an analysis of temperature data of BMD from 1948 to 2010)

Division	Summer temperature (°C)				Winter temperature (°C)			
	2010-base	Change on 2010-base value			2010-base	Change on 2010-base value		
		2050	2075	2100		2050	2075	2100
Chattagram	28.14	0.43	0.69	0.96	20.83	0.44	0.71	0.99
Barisal	28.49	0.23	0.38	0.52	20.09	0.07	0.11	0.15
Khulna	29.23	0.52	0.84	1.16	19.91	0.30	0.49	0.68
National	28.61	0.45	0.73	1.01	20.03	0.54	0.88	1.22

Source: Awal et al. [7] and Awal [22]

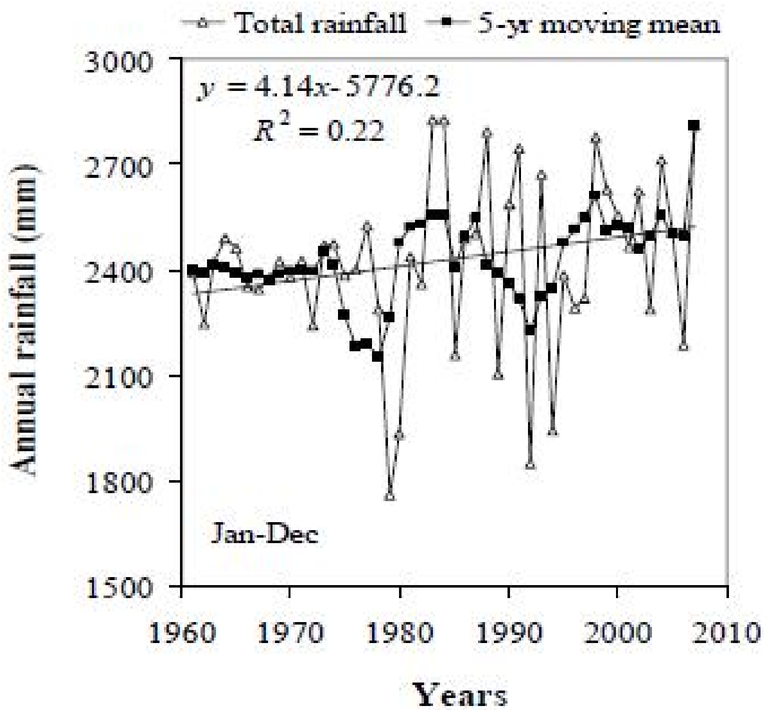
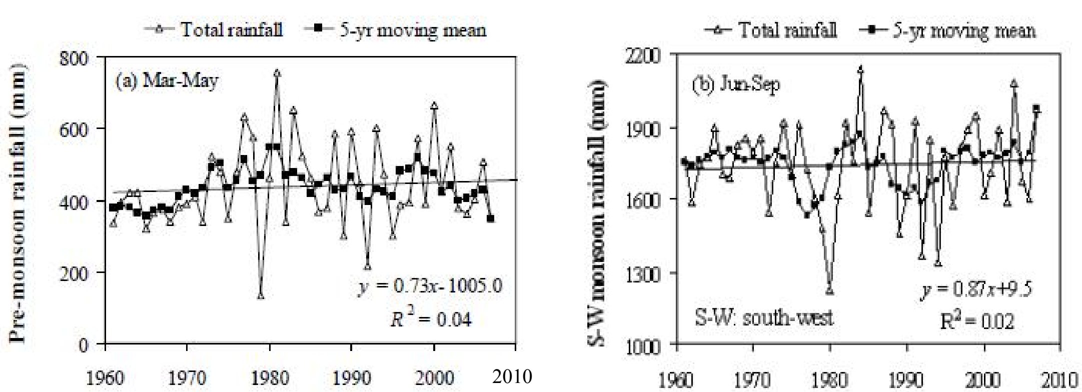


Fig. 6. National mean total annual rainfall in Bangladesh from 1961 to 2007. Data represent averaged from 24-34 meteorological observatories throughout the country. R^2 is the coefficient of determination



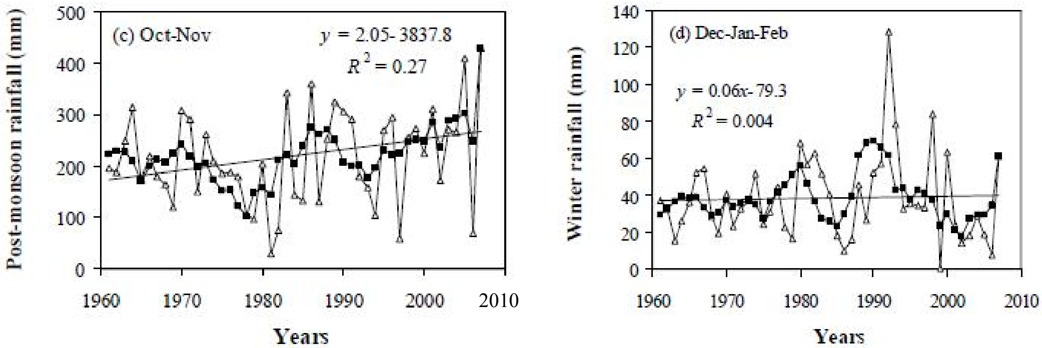


Fig. 7. Mean total rainfall at (a) pre-monsoon, (b) south-west monsoon, (c) post-monsoon and (d) winter seasons in Bangladesh from 1961 to 2007. R^2 is the coefficient of determination. Refer to Fig. 5 for the explanation of the seasons

3.5 Observed Glacier Mass Balance and Global Sea Level Rise

Glacier mass balance is a very sensitive and direct indicator of global warming. From 1950, glacier mass balance was negative except for a few years during Sixty's (Fig. 8). Year to year fluctuation in glacier thickness was clearly observed. From 1980 to 2012 the mean cumulative thickness loss of glaciers was about 10 meters. It was occurred due to contemporary global warming and one the main causes for observed sea level rise.

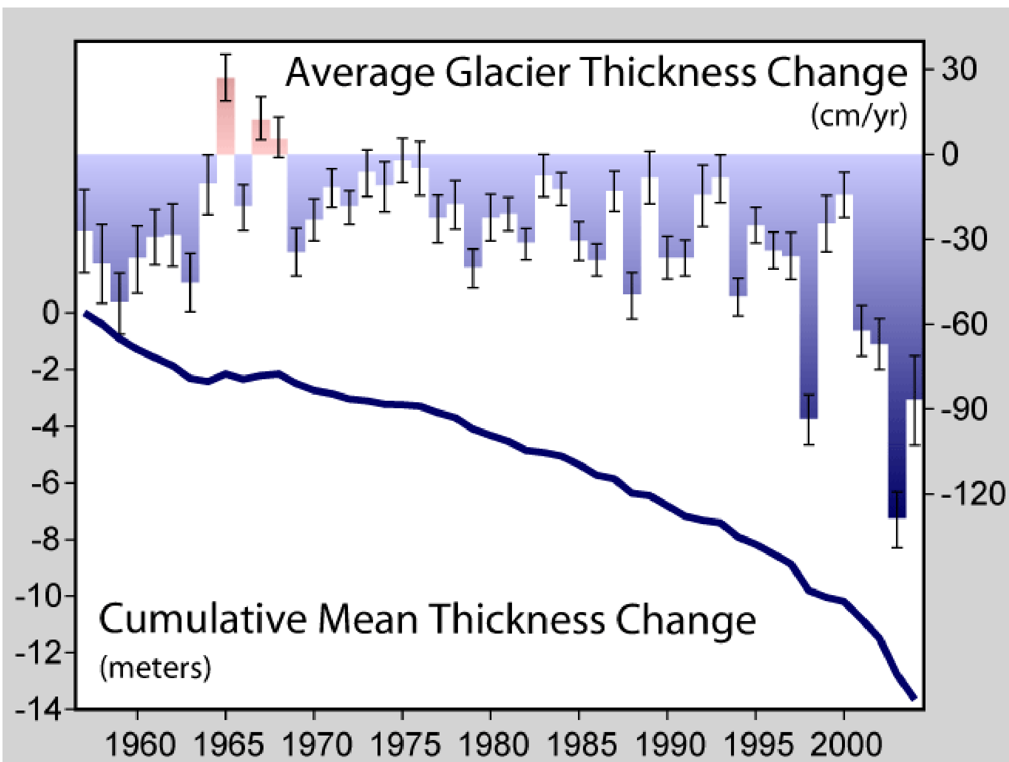


Fig. 8. Annual glacier thickness change (global glacial mass balance) in the last half century, reported to the World Glacier Monitoring Service (WGMS) and National Snow and Ice Data Center (NSIDC) [26]. The downward trend in the late 1980s is symptomatic of the increased rate and number of retreating glaciers

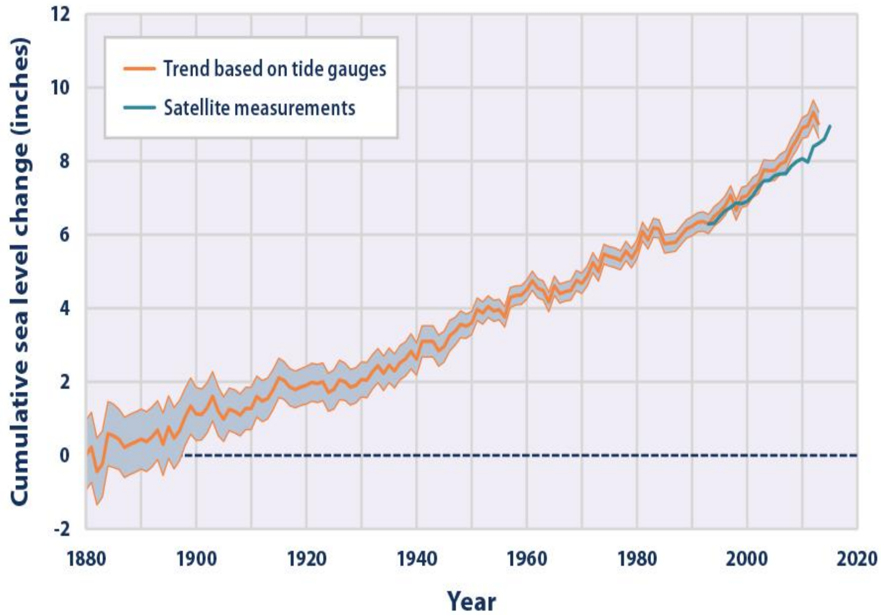


Fig. 9. Global average absolute sea level change, 1880–2015 [27]

With a continuous global warming scenarios (Fig. 2) and associated glacier melting (Fig. 8) there was a concomitant rising of sea level by about 15-20 cm that occurred during the 20th century (Fig. 9).

The IPCC has recently made a comparison between observed sea level rise (SLR) with its model values for the time periods of 1961-2003 and 1993-2003 (Table 4). The observed SLR that measured with tide gauge record from 1961 to 2003 was reported as 1.8 mm per year with an uncertainty about 0.5 mm per year. The value with satellite measurement has exceeded 3 mm per year with an uncertainty about 0.7 mm per year from 1993 to 2003. The missing SLR as described the gap between the SLR from climate contributions and observed SLR for satellite measurement was found as little as 0.3 mm per year as compared to the tide gauge measurement (0.7 mm per year). Melting of glaciers and ice caps was the principal source of sea level rise during the 1961-2003 time periods. However, thermal expansion of ocean water has played dominant role as high as double the contribution than the contribution from melting of glaciers and ice caps during the 1993-2003 time periods. It is a good synchronization between rapid global warming along with fast sea level rise that occurred in recent times.

Table 4. Contributions to sea level rise based upon observations (left columns) compared to models used in IPCC 4th Assessment Report (AR4) [1]

Sources of Sea Level Rise	Sea Level Rise, SLR (mm yr^{-1})			
	1961–2003		1993–2003	
	Observed	Modelled	Observed	Modelled
Climate contributions from				
A. Thermal expansion	0.42 ± 0.12	0.5 ± 0.2	1.6 ± 0.5	1.5 ± 0.7
B. Glaciers and ice caps	0.50 ± 0.18	0.5 ± 0.2	0.77 ± 0.22	0.7 ± 0.3
C. Greenland Ice Sheet	0.05 ± 0.12[a]		0.21 ± 0.07[a]	
D. Antarctic Ice Sheet	0.14 ± 0.41[a]		0.21 ± 0.35[a]	
E. Sum of SLR (A+B+C+D)	1.1 ± 0.5	1.2 ± 0.5	2.8 ± 0.7	2.6 ± 0.8
F. Observed total SLR	1.8 ± 0.5 (tide gauges)		3.1 ± 0.7 (satellite altimeter)	
Difference (F-E)	0.7 ± 0.7		0.3 ± 1.0	

[a]*Prescribed based upon observations*

3.6 Predicted Global Sea Level Rise

The future sea level rises by 2100 projected in the 1st to 4th Assessment Reports of IPCC are 31-110 cm (Business as usual scenario), 13-94 cm, 9-88 cm and 18-59 cm, respectively [1,28-30]. That means with time progressed, the IPCC has gradually minimized the values of the sea level rises which to be occurred at the end of the current century. Recently, IPCC [20] in 5th Assessment Report (AR5) predicted that global mean sea level will be risen about 40 cm to 63 cm (Table 5; Fig. 10). The SLR predicted to be increased 24 cm to 30 cm for the lowest (RCP2.6) to highest RCP scenarios (RCP8.5) during 2046-2065 periods. The projected values of SLR at the end of the twenty first century were found almost double (40-63 cm) than that to be occurred during the 2046-2065 period. However, the upper range of SLR for RCP8.5 estimate may could exceed 80 cm during 2081-2100 period.

3.7 Observed Sea Level Rise in Bangladesh

Bangladesh uses the tide gauge data from some coastal stations of Bangladesh Inland Water Transport Authority (BIWTA) and Bangladesh Water Development Board (BWDB) for measuring the sea level rise. Tide gauges, usually placed on piers, measure the sea level relative to a nearby geodetic benchmark. For this purpose, data from Ninety's are reported by Climate Change Cell of the Department of Environment, GoB [31]. Analysis from both regression slope and Sen's slope showed that water level of Bay of Bengal has already risen in Bangladesh coast (Table 6). The SLR increases from western coast (Khulna) towards the eastern one (Chattagram) and the observed values of SLR (>6 mm per year) are far higher than the measured SLR that occurred globally (3.1 mm per year during the 1993-2003 period) (Table 4).

Table 5. Predicted global mean sea level rise towards 2046-2065 and 2081-2100 periods under various scenarios [20]

Parameter[a]	Scenario[b]	2046-2065		2081-2100	
		Mean	Likely range	Mean	Likely range
Global mean sea level rise (m)	RCP2.6	0.24	0.17 – 0.32	0.40	0.26 – 0.55
	RCP4.5	0.26	0.19 – 0.33	0.47	0.32 – 0.63
	RCP6.0	0.25	0.18 – 0.32	0.48	0.33 – 0.63
	RCP8.5	0.30	0.22 – 0.38	0.63	0.45 – 0.82

[a]Based on the Coordinated Modelling Intercomparison Project Phase 5 (CMIP5) ensemble; anomalies calculated with respect to 1986–2005. Refer to Table 1 for the explanation of RCP

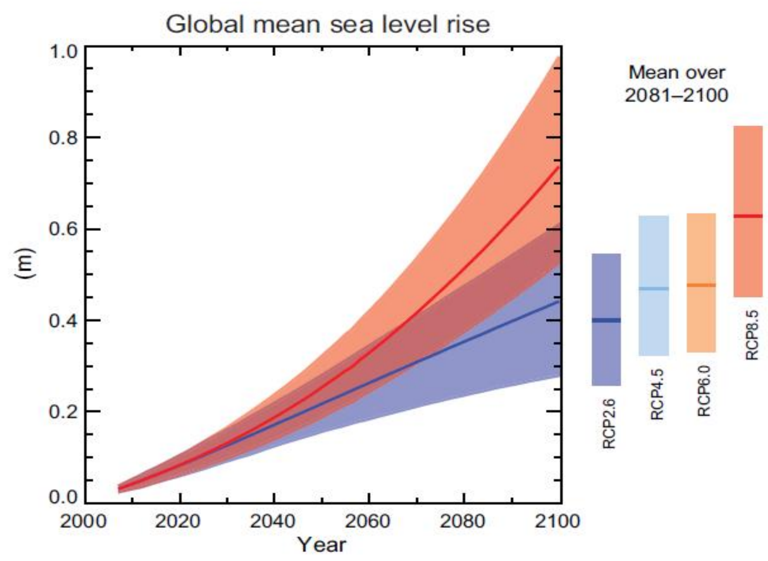


Fig. 10. Projection of global mean sea level rise over the 21st century relative to 1986-2005 [20]. The assessed likely range is shown as a shaded band. Refer to Table 1 for the explanation of RCP. The RCP2.6 and RCP8.5 can be treated as 'best' and 'worst' case scenarios, respectively

Table 6. Water level increase trend according to tidal gauge record at some southern coastal stations of Bangladesh over 3 decades since eighty's [31]

Tidal station	Coordinate		Analysis period	[a]Water level increase rate (mm yr^{-1}) based on	
	Latitude (°N)	Longitude (°E)		Regression slope	Sen's slope
Hiron Point	21.82	89.46°	1981-2013	8	7
Char Changa	22.13	91.10	1980-2012	6	6
Sandwip	22.49	91.42	1977-2012	10	10
Cox's Bazar	21.43	92.01	1980-2012	11	13

[a]Significant at 1% level of probability based on Mann-Kendall test

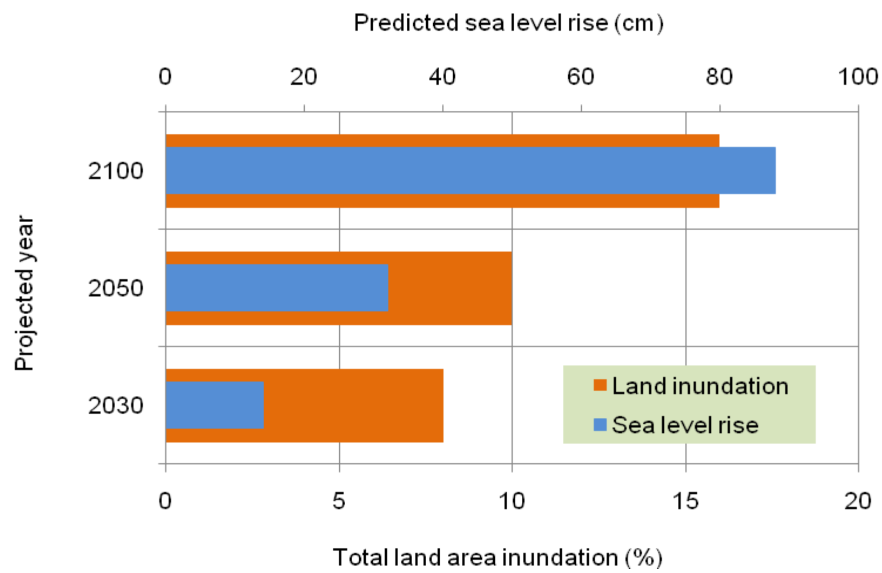


Fig. 11. Land area inundation in Bangladesh coast due to sea level rise for the predicted increase of temperature 1.0°C, 1.4°C and 2.4°C towards 2030, 2050 and 2100, respectively [32]

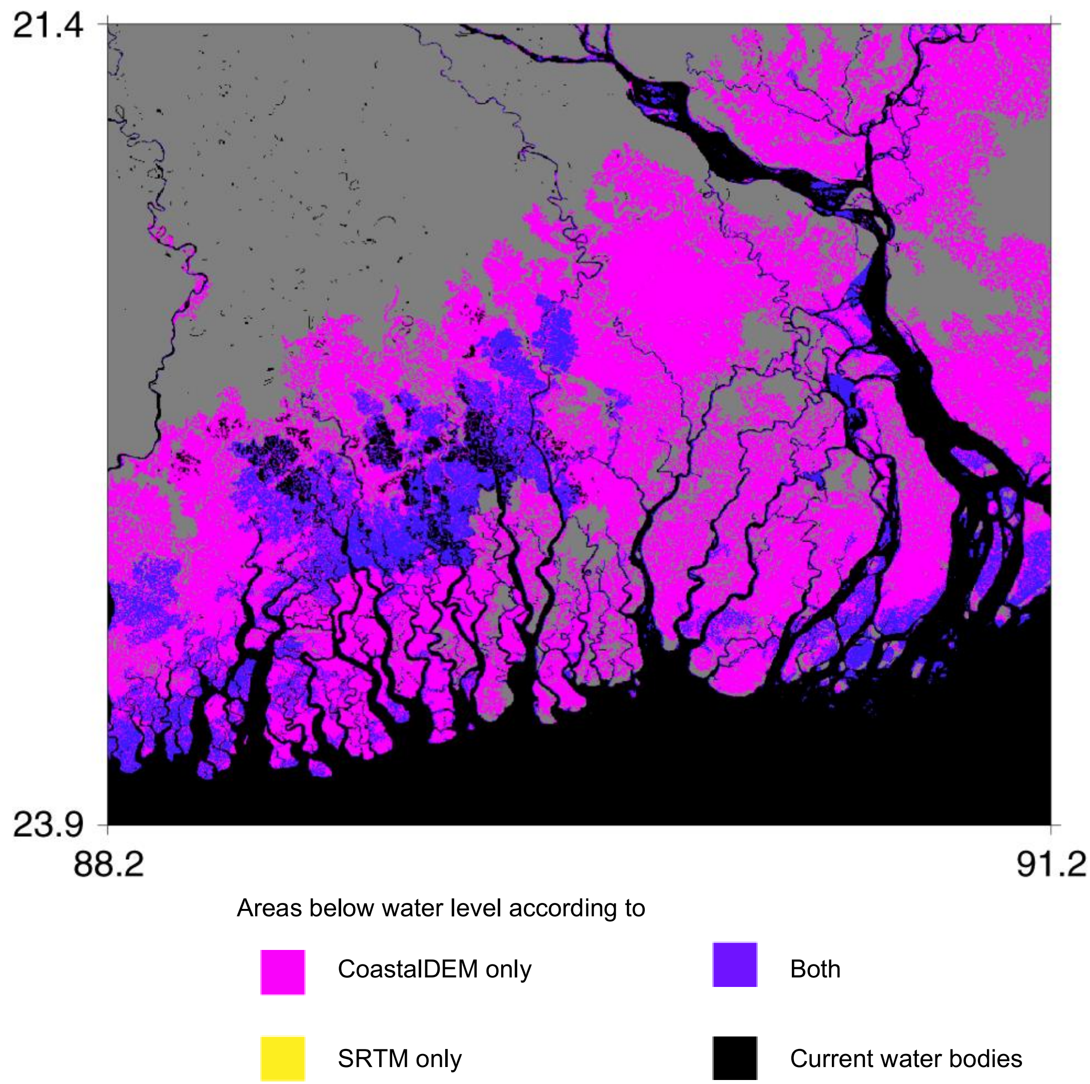
3.8 Predicted Sea Level Rise and Land Inundation in Bangladesh Coast

It is predicted from an estimation of the Water Resources Planning Organization of Ministry of Water Resources, GoB that about 14, 32 and 88 cm sea level rise may occur at 2030, 2050 and 2100, respectively which could inundate about 8, 10 and 16 percent of total land mass of Bangladesh (Fig. 11) [32]. At base line situation i.e. 0 (zero) rise in the sea level, a total of 1572085 ha land is inundated at any depth in 16 coastal districts out of 19 due to monsoon flood. Further rise in sea level will expand inundation areas where Patuakhali, Barisal and Khulna regions would be the most affected.

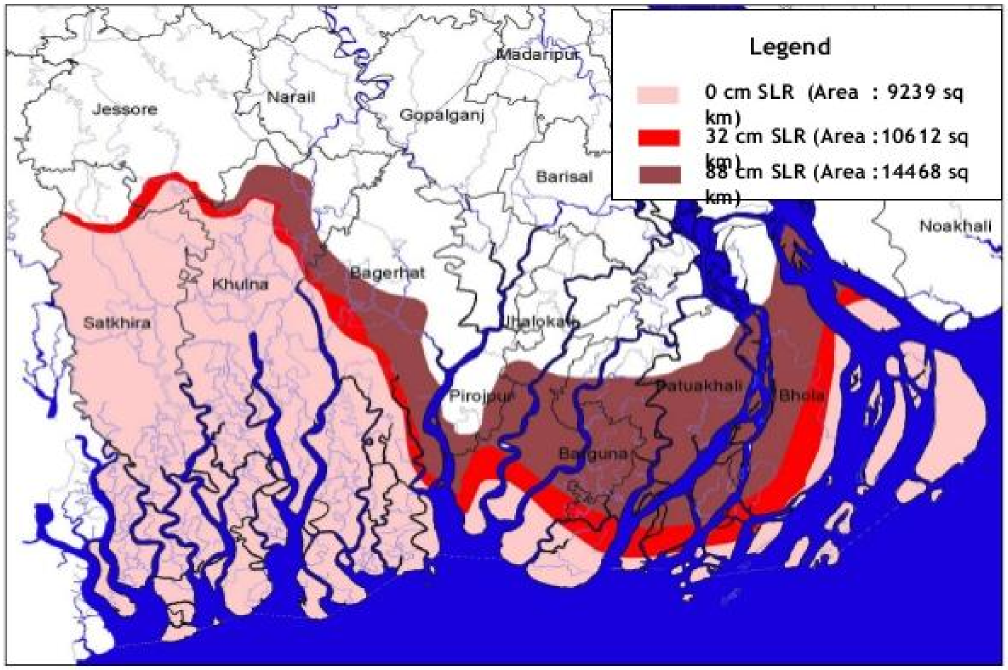
The sea level rise is speculated to be 30 and 100 cm for the increase of average temperature as 2°C (moderate climate change scenario) and 4°C (extreme climate change scenario), respectively [25]. Mahtab [33] considered a median value by taking the mean of the two limits and adding 10 cm for local subsidence, which provided for 100 cm 'net sea level rise' by the year 2050. Total area of Bangladesh coastal zone is about 47,203 km^2 that includes 19 districts viz. Barguna, Barisal, Bhola, Jhalokati, Patuakhlai and Pirojpur districts under Barisal division; Bagerhat, Jessore, Khulna, Narail and Satkhira districts under Khulna division; Chandpur, Chattagram, Cox's Bazar, Feni, Lakshmipur and Noakhali districts under Chattagram division, and Gopalganj and Shariatpur districts under Dhaka division. Most of the coastal parts and associated islands of Khulna and Barisal divisions and western parts of Chattagram division lie within 1 m from sea level [8-9] where incursion of saline water is common. It is predicated that these areas will be inundated and unsuitable for crop production due to sea-level rise in the next 50 years. In a recent study, Kulp and Strauss [34] reported that a major part of coastal areas of Bangladesh which comprised southern areas of Khulna division, most part of Barisal division and western part of Chattagram division will be inundated due to sea level rise at the end of twenty first century (Map 3).

3.9 Intrusion of Salinity in Southern Areas of Bangladesh: Observed and Predicted

Southern coastal areas of Bangladesh are affected by salinity with varying intensities. About 83.3 million hectares of coastal land in 1973 was affected by salinity that had been increased to 102 million hectares (mha) in 2000 and 105.6 mha in 2009 and continuing to increase [35]. That means, from 1973 to 2009 time period, salinity intrusion lands increased about 27 percent in southern Bangladesh, spreading into non-coastal areas as well. Projected land area inundation due to sea level rising would lead to result habitat loss and this will turn more land unsuitable for crop production due to water logging as well as salinity (Map 4) [36].



Map 3. Land area inundation in Bangladesh predicted by CoastalDEM and SRTM given the median K17/RCP 8.5/2100 sea-level projection. Gray areas represent the dry land. Vertical and horizontal axis labels denote latitude (°N) and longitude (°E), respectively. DEM = Digital Elevation Model, SRTM = Shuttle Radar Topography Mission. Map Credit: Kulp and Strauss [34]

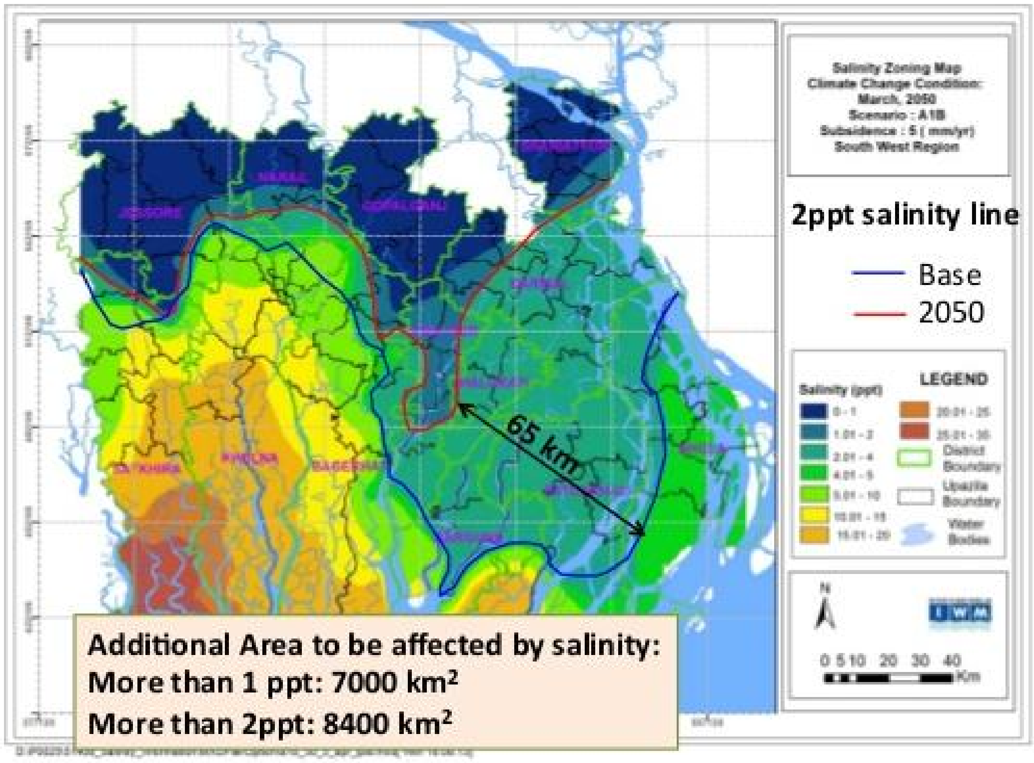


Map 4. Projected salinity intrusion due to sea level rise (SLR) [36]

Still, there is an abundant fresh water pocket for irrigation throughout the dry season in south central zone of Bangladesh i.e. in Barisal division (Map 5). This fresh water source will remain suitable for irrigation all over the year even in changing climate with 22 cm SLR at 2030. However, it is predicted that such fresh water pocket in Barisal region is likely to be more saline (2-4 ppt) with 52 cm sea level rise, in 2050 [37].

3.10 Intensification of Tropical Cyclone with Storm Surges and Associated Coastal Flooding

Global warming increases sea surface temperatures which raise the maximum potential energy that a storm can reach, increases the rainfall that drops during the storm, rises sea level which increases the distance inland that storm surges reach. The rapid warming of the Indian Ocean including Bay of Bengal due to climate change is leading to more cyclones pummelling South Asia, as storms gather more quickly and become more intense [38]. Most the cyclone that forms in the Bay of Bengal hits Bangladesh coast due to the spatial geo-morphological settings of the surrounding areas. Awal *et al.* [7] and Awal [39] recently analyzed the tropical cyclones which stroke Bangladesh coast over the centuries and found that the number of cyclonic hits had increased and a cyclone is struck in Bangladesh coast with every 1.2-year time. The Barisal division is most sensitive to cyclonic hit despite entire coast is vulnerable for that [39]. The storm surges associated with cyclone is intensified leading to create coastal flooding and water logging condition via overtopping of polders and breaches in the embankments. Historical devastating cyclones like BHOLA cyclone (on 12 November 1970), GORKY (29 April 1991), SIDR (15 November 2007) and AILA (25 May 2009) which struck Bangladesh coast in recent past. Very recently, cyclone AMPHAN that struck on Bangladesh and West Bengal (India) coasts on 20 May 2020, flooded or submerged larger areas with higher magnitude of devastations than the devastations caused by the previous ones ever (Photographs 1 and 2). Such extreme weather events in close proximity have highlighted the cumulative impact of global warming. Storm surge's flooding is one of the causes for intrusion of soil salinity or salinity with water logging in low-lying coastal areas of Bangladesh and makes the areas unsuitable for agricultural practices and crop production.



Map 5. Effect of sea level rise on 2 ppt salinity contour (A1B, 2050). The IPCC's AIB (balanced) scenario describes a future world of very rapid economic growth, low population growth, and the rapid introduction of new and more efficient technologies, with a balanced emphasis on all energy sources. Map Credit: Institute of Water Modelling (IWM), Dhaka, Bangladesh

Photograph 1. Coastal areas in Patuakhali district inundated as extremely severe cyclone AMPHAN crossed coastal districts of Bangladesh on 20 May 2020. Photo Credit: STAR [40]

Photograph 2. Tidal surge during cyclone AMPHAN broke the embankment on Kholpetua River and flooded hundreds of houses in Napitkhali area of Gabura union in Shyamnagar upazila of Satkhira district. Photo Credit: UNB [41]

3.11 Land-use and Cropping Patterns in Southern Coastal Areas of Bangladesh

The land-use and cropping patterns from coastal areas were collected though stakeholder consultation, face-to-face interviews of local farmers and direct field visits, and the summarized version in most of the costal belt under Barisal, Khulna and Chattagram divisions are shown in Table 7. The unique feature is that the cropping pattern in the areas is totally *Aman* rice dependant especially transplanted *Aman* (Photograph 3), whereas the *Boro* and *Aus* rice are of sporadic in occurrence (Photograph 4). Some farmers cultivate only transplanted *Aman* extended from August to November using upstream water flow due to monsoon flash when the salinity effects are getting moderate to mild, whereas the land remains fallow for rest of the year (Photographs 5 and 6). Some farmers grow vegetables, potato, sweet potato, soybean, watermelon, groundnut and pulses as grass pea, mungbean or cowpea after harvest of transplanted *Aman* (i.e., in *Boro* rice season). In *Boro* rice season (December-May), the land-use pattern in Barisal division is characterized by bare or fallow condition (Photograph 6), Khulna division with shrimp culture (Photograph 7) and Chattagram division with pulses and vegetable cultivation. Fishing is a traditional and most popular source of income of people of onshore and offshore islands like Hatyia upazila of Noakhali district (Photograph 8).

Table 7. Existing land-use and cropping patterns in the coastal zone of Bangladesh

Division	**Major cropping pattern**[a]		
	Aman **(Jul-Nov)**	***Boro/Rabi*** **(Dec-May)**	***Aus/Kharif***[b] **(May-Aug)**
Khulna	Shrimp, scattered transplanted *Aman*, mixed shrimp + transplanted *Aman*	Shrimp/Fallow/mixed shrimp + *Boro*	Shrimp/*Aus*
Barisal	Transplanted *Aman*, broadcast *Aman*	Mostly fallow, scattered winter vegetables and pulses	Mostly fallow, scattered *Aus*
Chattagram	Transplanted *Aman*, broadcast *Aman*	Pulses, groundnut, soybean, watermelon, vegetables, chili, scattered *Boro*	*Aus*, fallow

[a]*Aman, Boro and Aus seasons refer the time where rice varieties which are planted in mid July, November-December and March-April, and harvested in mid November-December, March-April and mid June-July, respectively.* [b]*Kharif cropping season refers from July to October during the south-west monsoon*

Shahidullah *et al.* [42] analyzed the existing cropping patterns in greater Noakhali region and found that dominant cropping pattern was single transplanted *Aman* rice which alone occupied about 35 percent of net cropped area. Whereas *Boro*–*Fallow*–transplanted *Aman*, *Fallow*–*broadcast Aus*–transplanted *Aman* and single *Boro* respectively occupied about 14, 11 and 11 percent of the net cropped area. Recently, Lazar *et al.* [43] reported that farms practiced in the coastal areas in the 1990 was mono cropping (i.e. having only one season crop) with transplanted *Aman* rice, but recently other crops have been cultivated in two and three cycles per year.

3.12 Sea Level Rising Effects on the Sundarbans Mangrove Vegetation – a World Heritage site

The Sundarbans is the largest productive contiguous mangrove forest in the world, located in the south-western part of Bangladesh (Map 6) [44]. The United Nations Educational, Scientific and Cultural Organisation (UNESCO) declared three wildlife Sanctuaries of the Bangladesh Sundarbans as World Heritage Site in 1997. The biodiversity of the Bangladesh Sundarbans includes numerous species of phytoplankton, zooplankton, microorganisms, fungi, bacteria, benthic invertebrates, molluscs, reptiles, amphibians, mammals etc. The forest (around six thousand square kilometer) houses 334 species of flora, 49 species of mammals, as many as 400 species of fish, 315 species of birds and 53 species of reptiles [45-46]. Royal Bengal Tiger (*Panthera tigress*) is the iconic flagship species of this forest. More than 3.5 million people living around the Sundarbans are directly or indirectly dependent on the ecosystem services of the forest [47]. It is predicted that up to 30 percent of animal and plant species of the Sundarbans could be wiped out by a global temperature rise of 2.7-4.5^{o}C [48].

Photograph 3. Vast land under growing transplanted *Aman* rice in Char Jabbar of Noakhali district of Chattagram division. Photo Credit: Authors

Photograph 4. Sporadic cultivation of *Boro* rice in Morelganj upazila of Bagerhat district of Khulna division. Photo Credit: Authors

Photograph 5. Vast cultivable land remains fallow during the *Boro* rice season in many places of Bagerhat district of Khulna division. Photo Credit: Authors

Photograph 6. Vast cultivable land remains fallow during the *Boro* rice season in many places of Barisal division. Photo Credit: Authors

Photograph 7. Shrimp culture is popular than rice cultivation in saline prone areas of Mongla upazila of Khulna district. Photo Credit: Authors

Photograph 8. Fishing is one of the major enterprises in Hatiya upazila of Noakhali district under Chattagram division. Photo Credit: Authors

Map 6. A satellite image of the Bangladesh Sundarbans [44]. The Sundarbans appears deep green, surrounded to the north by a landscape of agricultural lands, which appear lighter green, towns, which appear tan, and streams, which are blue

Through photosynthetic process of plants, the Sundarbans acts as a larger sink for reducing the atmospheric CO_2. For example, the Indian part's Sunderbans having 2118 sq km of total mangrove forest cover, have soaked in 4.15 crore tonnes of carbon dioxide, valued at around $79 billion in the international market [49]. So, it can be simply imagined how much CO_2 is depleting from the atmosphere by the Sundarbans of Bangladesh parts as it occupies more than double the areas of the forest than the forest areas occupied by the Indian parts.

The Sundarbans acts as a natural shield against cyclones and storm or tidal surges for the inhabitants and properties at the leeward side. It experiences increased inundation due to sea level rise. It has been postulated that 84 percent of the Sundarbans area will be inundated with 32 cm sea level rise in 2050 and almost whole land area of the Sundarbans will be subjected to inundation with 88 cm sea level rise [33]. It is predicted using high resolution elevation data that with a 28 cm sea level rise that is likely to occur in the next 50-90 years from 2000, remaining tiger habitat in the Sundarbans of Bangladesh would decline by 96 percent and the number of breeding individuals would be reduced to less than twenty [50]. Mukul *et al.* [51] recently predicted that due to the combined effect of climate change and sea-level rise, there will be no suitable Bengal tiger habitat remaining in the Sundarbans by 2070. They also suggested some key strategies like enhancing terrestrial protected area coverage, regular monitoring, law enforcement, awareness-building among local residents etc which needed to ensure long-term survival and conservation of the Bengal tiger in the Bangladesh Sundarbans.

Salinity intrusion due to SLR and other causes may pose a threat to some mangrove species like Sundri (*Heritiera fomes* – the principal species of the Sundarbans), Shingra (*Cynometra ramiflora*), Passur (*Xylocarpus* granatum) etc. In contrast, more salt-tolerant species, such as Goran (*Ceriops roxburgii*), Jhana (*Rhizophora mucronata*), etc will come to occupy these sites [48]. Due to habitat loss for predicted sea level rise, provisional services that providing timber, fuel wood, fish, thatching materials, honey, medicines and waxes etc, ecosystem services that facilitating tourism, biodiversity, carbon sequestration, etc and other essential services of the Sundarbans may be affected by global warming, sea level rise and associated changes [52-53]. Therefore, the mangrove vegetation of the Sundarbans of Bangladesh is most vulnerable to global warming and predicted sea-level rising. Thus, it is a crying need for the policy makers to save this mangrove region from any unwanted situations like timber collection, hunting, crop production or other human interventions.

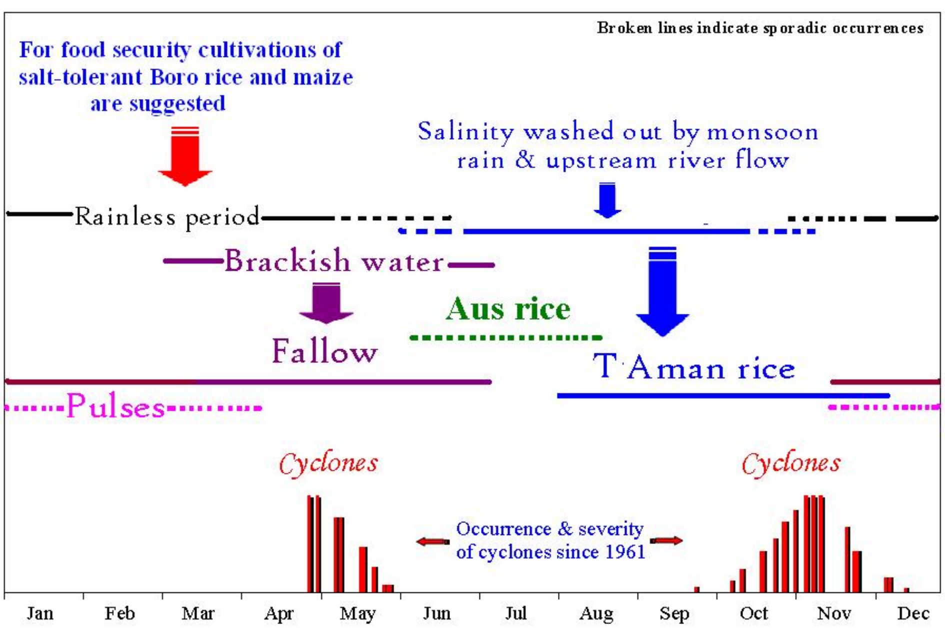


Fig. 12. Coastal zone climate and land-use pattern scenarios and proposed model for food security. Sketch Credit: Authors

3.13 Conceptual Model for Food Security

An analysis of all of the cyclones that hit Bangladesh coast since 1961 indicated that most devastating cyclones struck from last quarter of April through May and from middle of October to November just prior to the harvest of *Boro* and *Aman* rice crops, respectively (Fig. 12). Awal *et al.* [7] and Awal [39] supported this spatial pattern of cyclonic hit. To ensure food security, thus a model for the coastal people is proposed in order to address the effect of global warming and upcoming sea level rise. During the *Rabi* season (from October to March) immediately after the harvest of the transplanted *Aman*, the researchers and extension workers should devote their endeavour to cultivate HYV *Boro* rice even by utilizing the brackish water. And the harvest of this *Boro* crop must be completed before the last week of April since the subsequent days are very likely prone to tropical cyclones. Likewise the *Aman* rice season should be rearranged in such a way so that harvesting is ensured at the later part of October since the days thereafter with the beginning of November are often subjected to tropical cyclones.

Aquaculture ponds for fish culture are likely to provide a mechanism for coping after a disaster, in spite of the cost of repairing them. Thus, the aquaculture development can be promoted for income and food security for rural households in coastal areas of Bangladesh [54]. However, the aquaculture development should occur in areas where it will not compromise other ecosystem functions, such as mangroves. The use of fast-growing fish to shorten the production cycle that allows early harvest can be recommended [55].

Therefore, the befitted policies can be formulated as [56]

- Vast areas of coastal zones remain fallow during the *Boro* rice season due to lack of proper initiatives by the farmers, researchers and extension workers to bring these land under *Boro* paddy cultivation. And this happens mainly because of the prejudice conceived by the local people about non productivity of crops due to salinity or brackish water. But with identical landscapes in Indonesia, the Philippines, Cambodia and other places of tropical Asia it has been possible to produce enough crops for the inhabitants. Therefore, it is essential for the researchers and extension workers to explore the possibilities of cultivating *Boro* rice and/or other crops in the regions by irrigating fields with available water from the innumerable channels or canals located in the vicinity (Photographs 3-8);
- Advancing the present cropping patterns in both *Boro* and *Aman* rice seasons by a fortnight should go a long way in avoiding the tropical sea cyclones and tidal surges which are just occurring and will continue to occur twice in a year that commensurate with the harvesting time of these crops, and if so, it will mean a good harvest of rice, the main cereal of the country;
- Introduction of salt-tolerant crops [57] of *Boro* rice, wheat, maize, mustard, pulses etc with using mulches [58-63] will contribute to additional production of food grains and boost food security;
- Development of submergence tolerant rice varieties capable of thriving tidal surges and coastal floods [57] should be an alternative option for food security;
- The aquaculture development with fish and shrimp cultures can be promoted for income and food security for the rural households, where possible;
- Embankment should be constructed following coastal design i.e. with extended mild slopes oriented to the sea or surge path that will slowed down the fury of tidal waves and surges; thus saving the crops, lives and properties of coastal inhabitants;
- The slope faces of embankments need to be vegetated mostly by rows of open canopied monocotyledonous trees like palmyra palm, date palm, coconut, betel nut etc which have the ability to withstand severe cyclone at the same time reduce the wind velocity.

4. CONCLUSION

Evidences are indicative that the global warming has already set in as a result of increased concentration of greenhouses gases in the atmosphere. In addition to formation of cyclones and other potential changes, global warming will lead to about 32 cm rises in sea level by the middle of the twenty first century. The inequitable, varied and unpredictable effects of global warming and sea-level rising should have devastating consequences on coastal agriculture and livelihoods of people living therein. The negative impacts will engulf the whole nation but more severe for coastal inhabitants where near about fifty million people could become at risk of climatic refugees, hunger and food insecurity.

The coastal zone at present is a mono-cropped area predominately occupied by transplanted *Aman* rice in the wet season, mostly fallow or occupied by sporadic *Boro* rice, pulses, vegetables and other crops in rest of the year. The area is mostly characterized by net-work of rivers and criss-crossed of innumerable canals and channels with easy vicinity of water which is considered to be brackish during the dry season.

The key findings can be concluded as

- The food production in the coastal region of Bangladesh is already vulnerable due to the cyclonic storm, tidal surges, salinity intrusion and impeded drainage. The global warming and associated sea level rise will further aggravate this situation;

- In all projections it is apparent that a 1.5°C to 2.5°C global warming will lead to about 14, 32 and 88 cm sea level rise in 2030, 2050 and 2100, respectively which may inundate about 8, 10 and 16 percent of total areas of Bangladesh. Therefore, agriculture in low-lying coastal areas is likely to become increasingly difficult to sustain;

- Most of the coastal parts and associated islands of Khulna and Barisal divisions and western parts of Chattagram division lie within 1 m from sea level where incursion of saline water is common. It is predicated that these areas will be inundated and unsuitable for crop production due to sea-level rise in the next 50 years;

- The predominant crop in coastal belt is *Aman* rice especially transplanted *Aman* with sporadic occurrences of *Aus* rice, and some pulses, vegetables, groundnut etc in *Boro* rice season and there remains vast scope for expansion and boosting production of the new crops;

- Crop cultivation is seriously hampered in dry season due to either lack of water or presence of salinity in surface water or in soil. Therefore, vast areas of land remain fallow in *Boro* rice season. But the research and extension approaches to bring this vast land under alternate cropping patterns or crops seem inadequate.

Tropical cyclone with storm surges that form in the Bay of Bengal lashes Bangladesh coast twice in a year, the most severe ones occurring in late October to mid November and late April to May. Both periods coincide with the harvesting (maturity) time of major cereals i.e. *Aman* rice and *Boro* rice, respectively. Therefore, to mitigate the ill effects of global warming and ensuring additional crop production for food security the policy makers, researchers, extension workers, GO and NGO bodies should set urgent priority to advance the harvesting time of the *Aman* and *Boro* crops by a fortnight, and introduce *Boro* rice and other cereals and vegetables in the dry season. If succeeded, the above practices not only ensure the food security but will turn the entire area into a food surplus zone. The food security can additionally be supplemented or complemented with promoting aquaculture development with using fast-growing fish that allows early harvest.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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