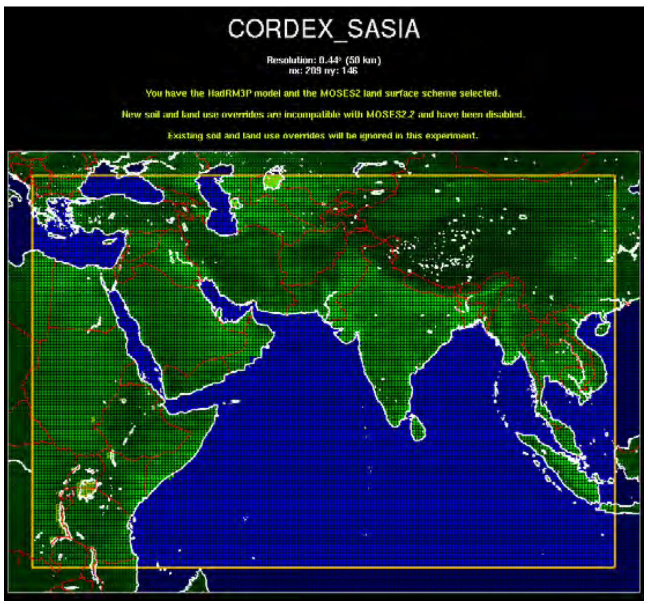
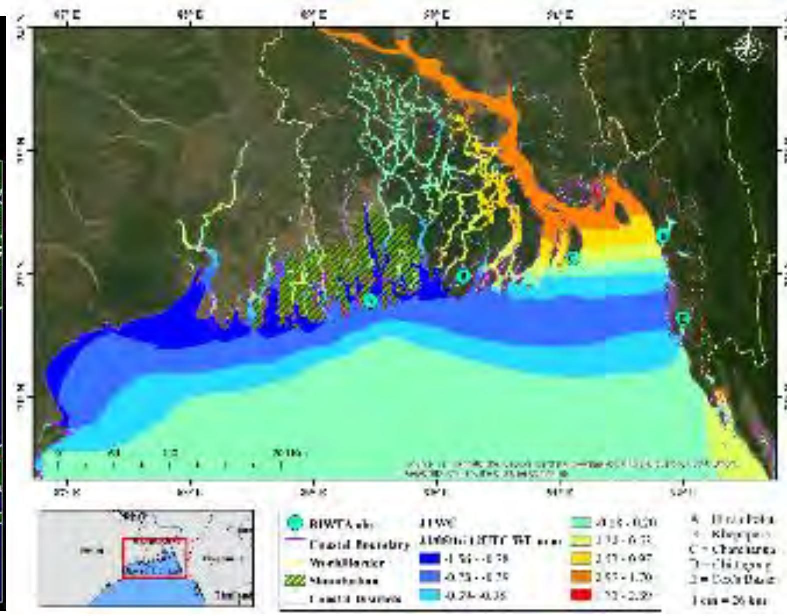
TRAINING ON “Spatial and temporal climate change analysis using CORDEX regional climate models over South Asia for Bangladesh”

Regional Climate Change Impact Assessment for Bangladesh using CORDEX data





Professor A.K.M. Saiful Islam

Institute of Water and Flood Management (IWFM)
Bangladesh University of Engineering and Technology (BUET)

Lecture outline

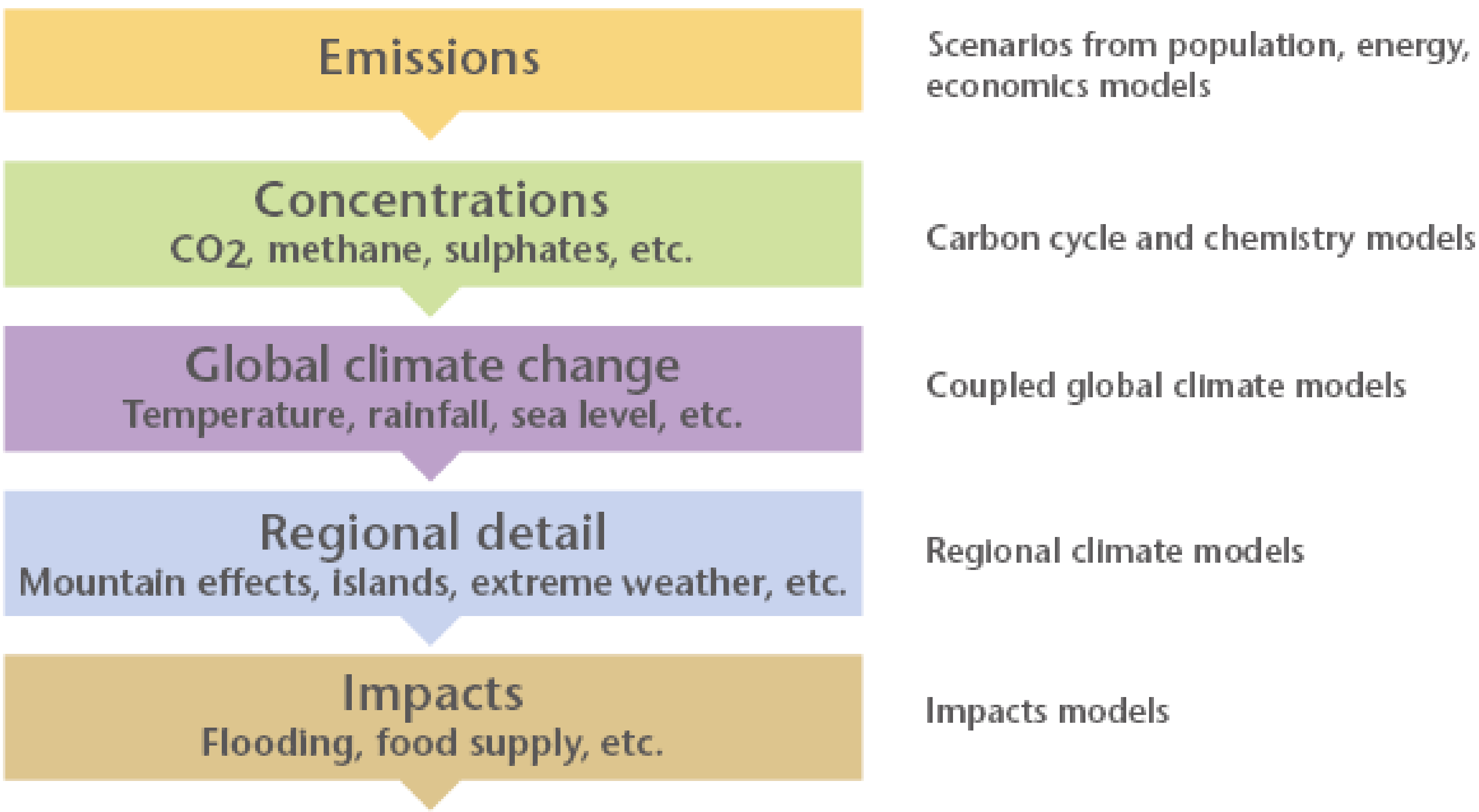
- Regional Climate Modeling (RCM)
- Multi-model Ensemble Regional Climate Projections for Impact studies using CORDEX simulations
- Changes in temperature and Rainfall Extremes in the future
- Changes in Metrological Droughts in the future
- Changes in Low and High Flows in GBM River Systems
- Changes in Permanent Inundation due to Sea Level Rise
- Changes in the Boro and Aman Rice yields in the future
- Changes in the climate vulnerability of the coastal Bangladesh

Regional Climate modeling

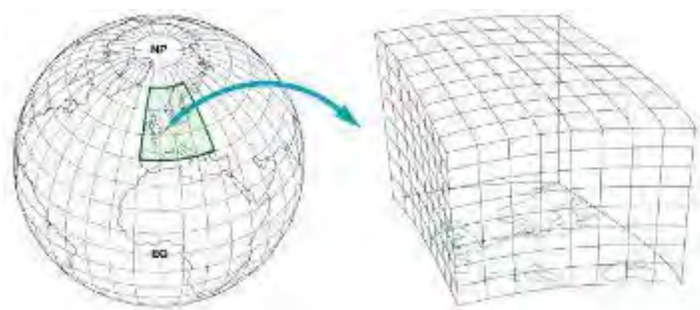
- An RCM is a tool to add small-scale detailed information of future climate change to the large-scale projections of a GCM. RCMs are full climate models and as such are physically based and represent most or all of the processes, interactions and feedbacks between the climate system components that are represented in GCMs.
- They take coarse resolution information from a GCM and then develop temporally and spatially fine-scale information consistent with this using their higher resolution representation of the climate system.
- The typical resolution of an RCM is about 50 km in the horizontal and GCMs are typically 500~300 km

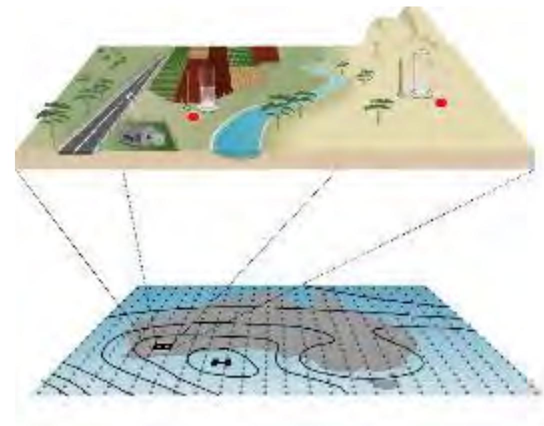
Regional details of Climate Change

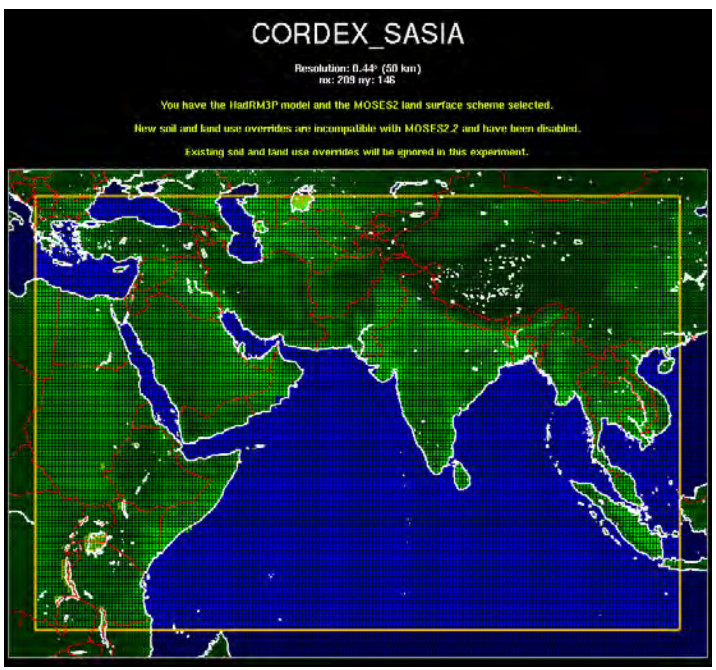
Predicting impacts of climate change



Regional Climate Modeling (RCM) for Bangladesh over CORDEX: South Asia







- GCM provides output more than 150km resolution which is not enough to capture mesoscale processes.
- RCM daily output with horizontal resolution 50km are available for South Asia CORDEX domain.
- Predictions are considered for extreme emission scenarios, RCP 8.5
- Climate output data have been bias corrected.

Fahad et al. (2016)

RCM Projections using CIMP5 data

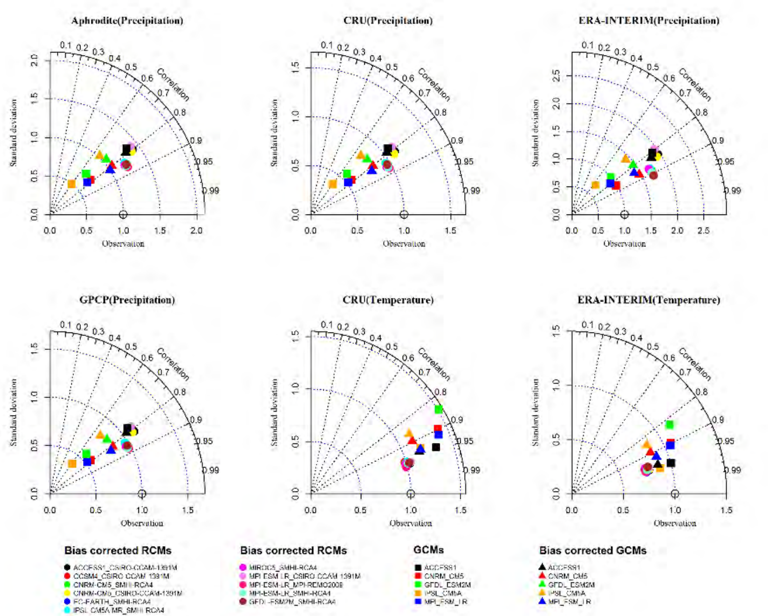
GCM	Ensemble	RCM	RCP8.5 (Year of Crossing)		
			SWL 1.5	SWL 2	SWL 4
ACCESS1-0	r1i1p1	CSIRO-CCAM-1391M	2034	2046	2085
CCSM4	r1i1p1	CSIRO-CCAM-1391M	2016	2031	2079
CNRM-CM5	r1i1p1	SMHI-RCA4	2032	2046	2088
CNRM-CM5	r1i1p1	CSIRO-CCAM-1391M	2032	2046	2088
EC-EARTH	r12i1p1	SMHI-RCA4	2019	2035	2083
CM5A-MR	r1i1p1	SMHI-RCA4	2020	2034	2069
MIROC5	r1i1p1	SMHI-RCA4	2038	2052	-
MPI-ESM-LR	r1i1p1	CSIRO-CCAM-1391M	2021	2040	2083
MPI-ESM-LR	r1i1p1	MPI-CSC-REMO2009	2021	2040	2083
MPI-ESM-LR	r1i1p1	SMHI-RCA4	2021	2040	2083
GFDL-ESM2M	r1i1p1	SMHI-RCA4	2040	2055	-

Specific Warming Levels (SWLs)

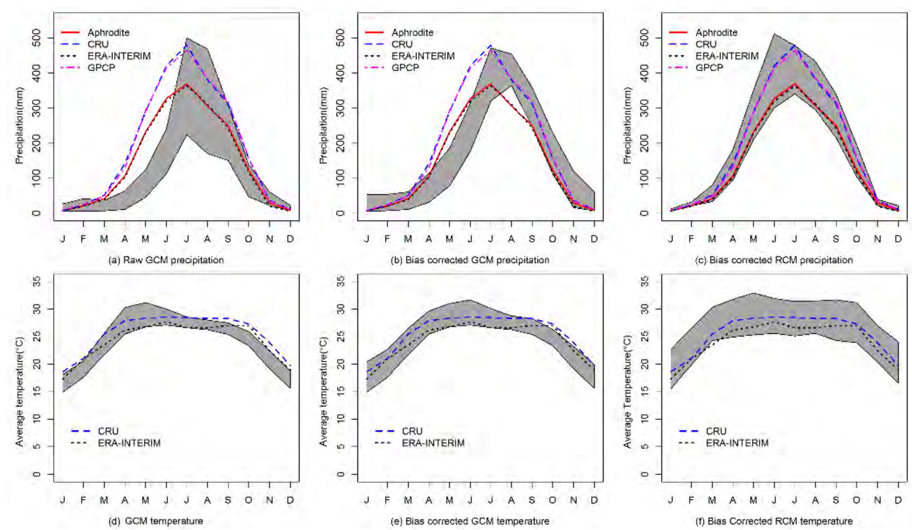
It is the mean annual global temperature increase by the end of the century related to preindustrial period (1880). Paris Agreement in 2015 emphasis on reducing GHGs to keep the increase of global mean temperature below 2C and effort should be made to reduce further to 1.5C with respect to pre-industrial period.

Performance of RCMs over the Region

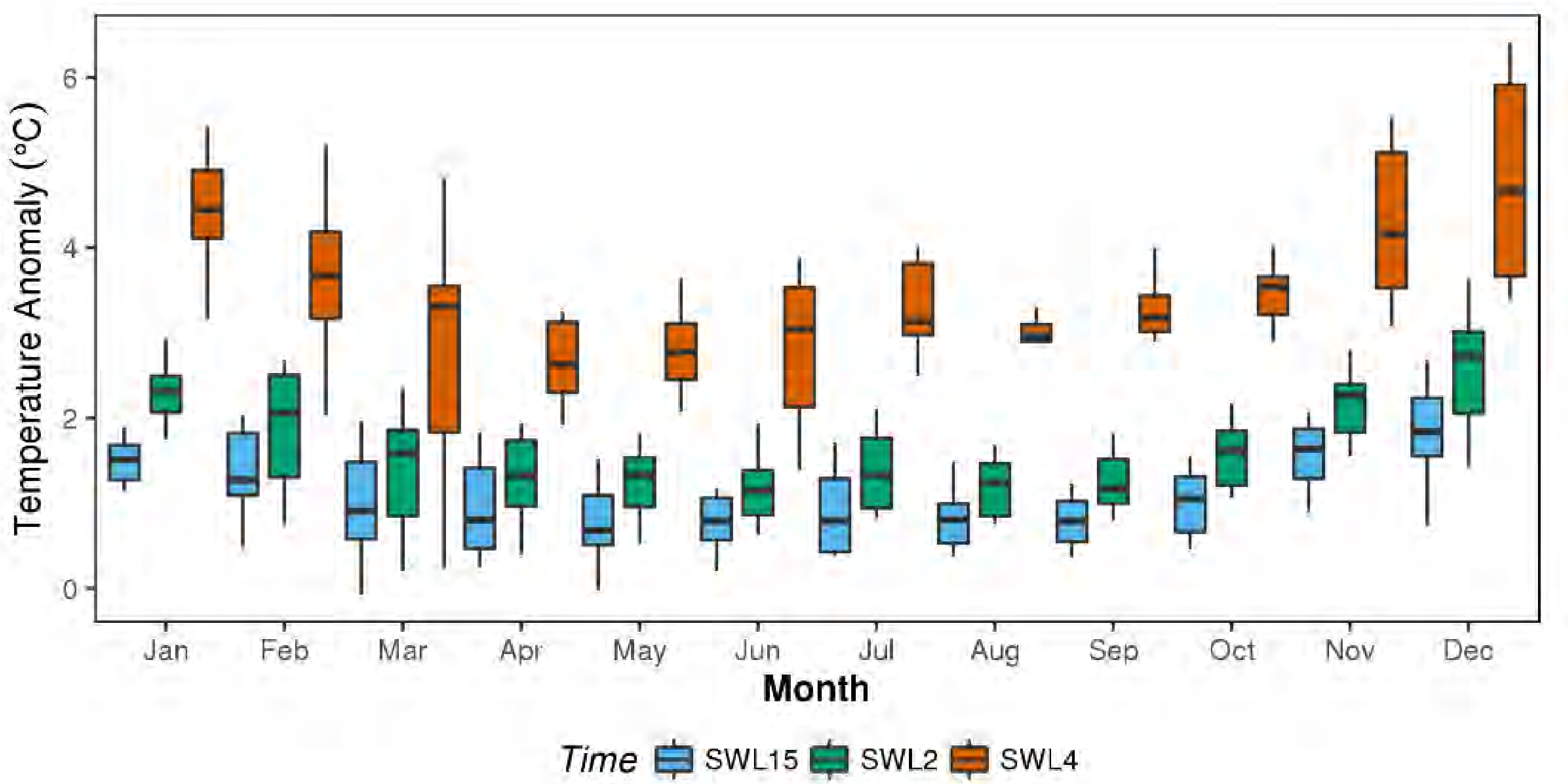
Taylor diagrams showing correlation and standard deviations of precipitation and temperature between various observed gridded data sets and climate model outputs derived from 5 GCMs, 5 bias-corrected GCMs and 11 bias-corrected RCMs during the historical period of 1971–2000.



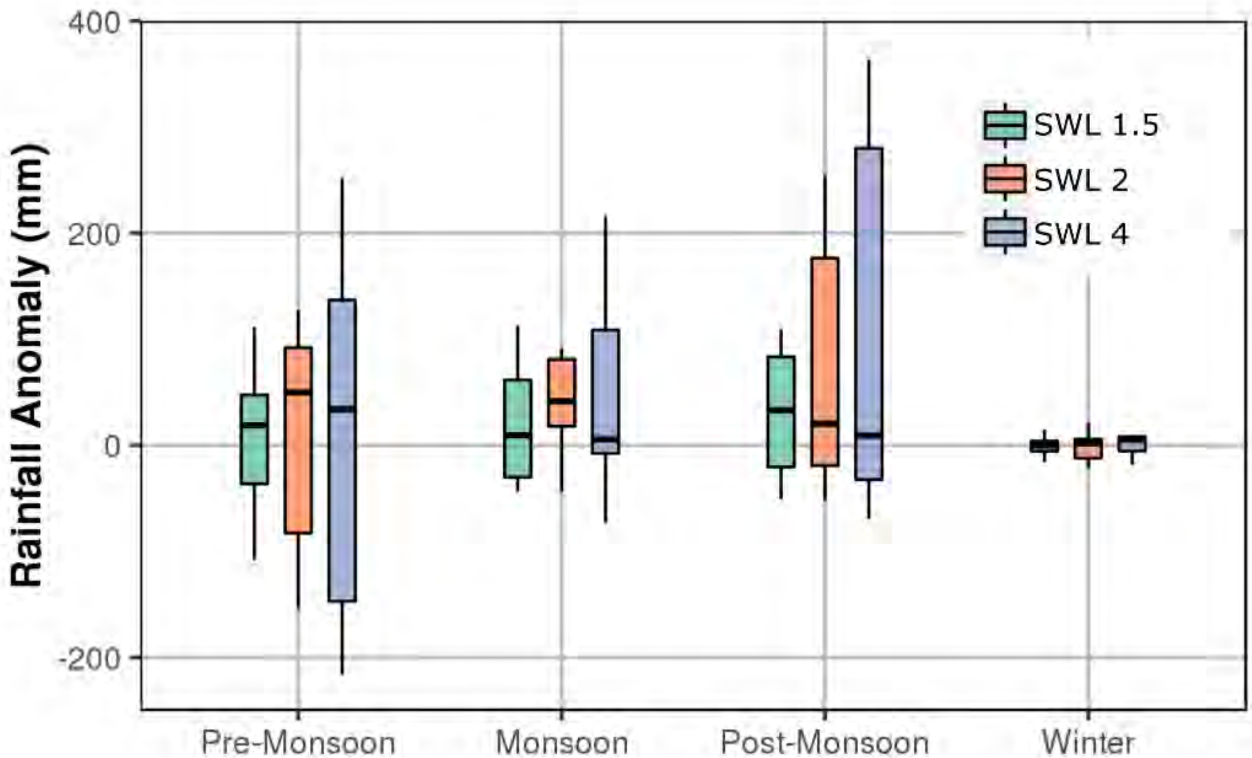
Comparison of annual cycle of precipitation between (a) observed data sets and raw GCM, (b) observed data sets and bias-corrected GCM and (c) observed data sets and bias-corrected RCM output for the historical period of 1971–2000. Comparison of annual cycle of temperature between (d) observed data sets and raw GCM, (e) observed data sets and bias-corrected GCM and (f) observed data sets and bias-corrected RCM output for the historical period of 1971–2000



Changes of mean monthly temperature over Bangladesh at SWLs

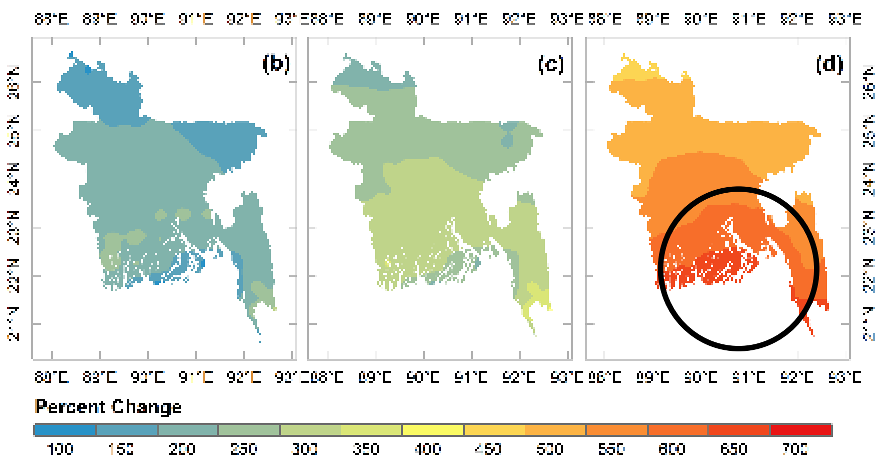


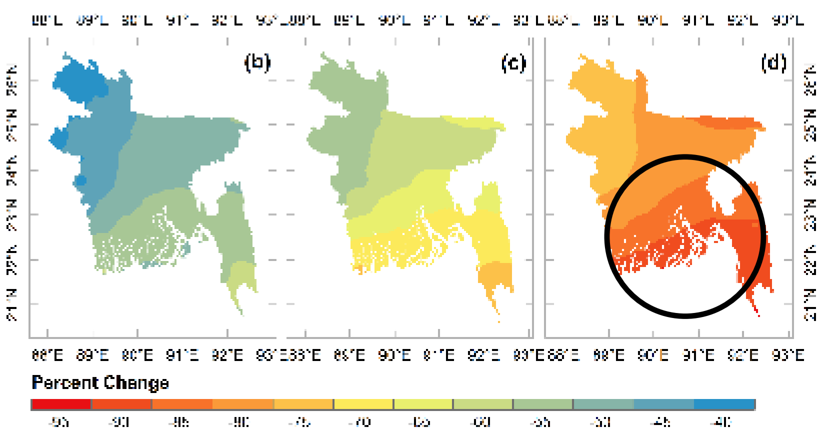
Changes of mean seasonal rainfall over Bangladesh at SWLs



Temperature extremes are increasing – heatwave and health stress will be more intense and frequent

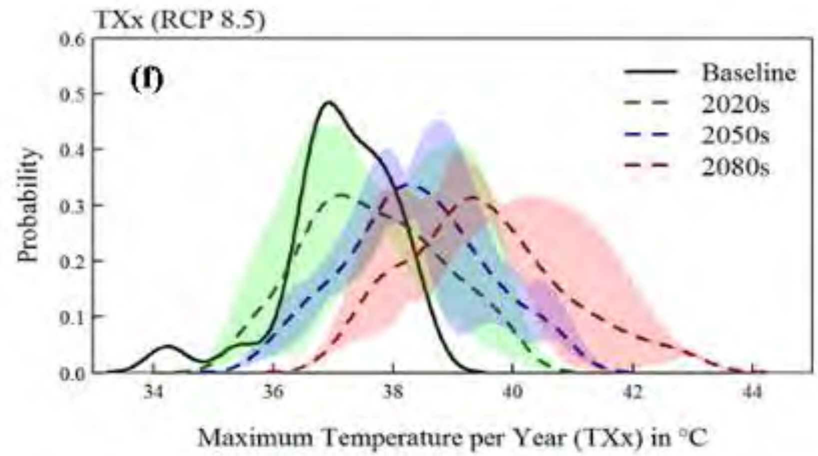
TX90P – Percentage of days when maximum temperature is higher than 90th percentile value.

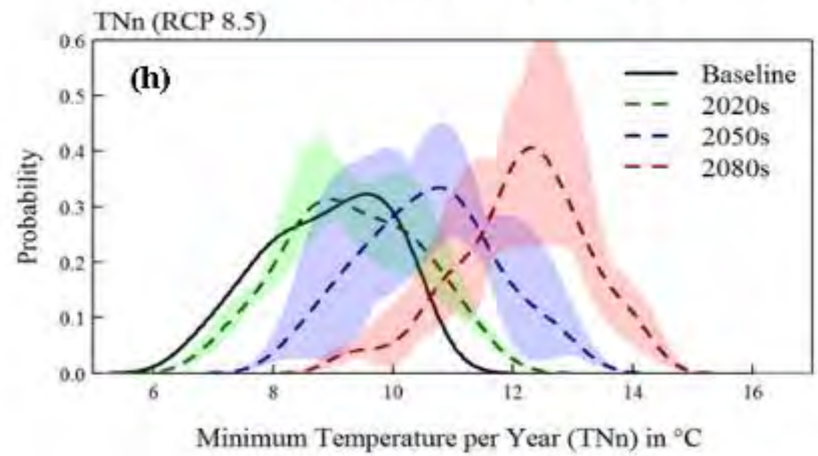




TX10P- Percentage of days when maximum temperature is lower than 10th percentile value

TXx- maximum of daily maximum temperature

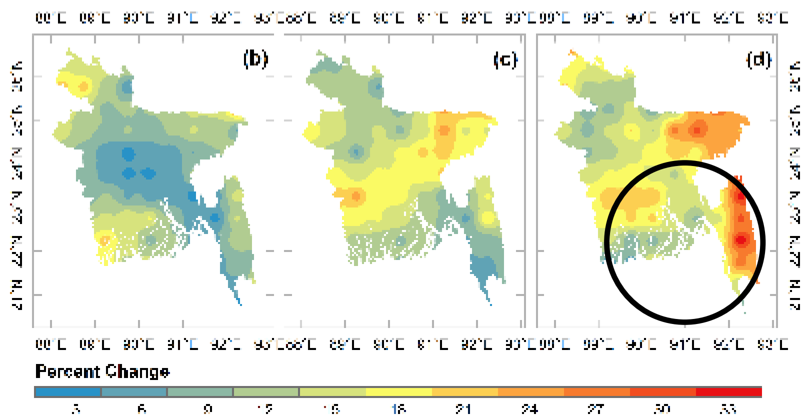


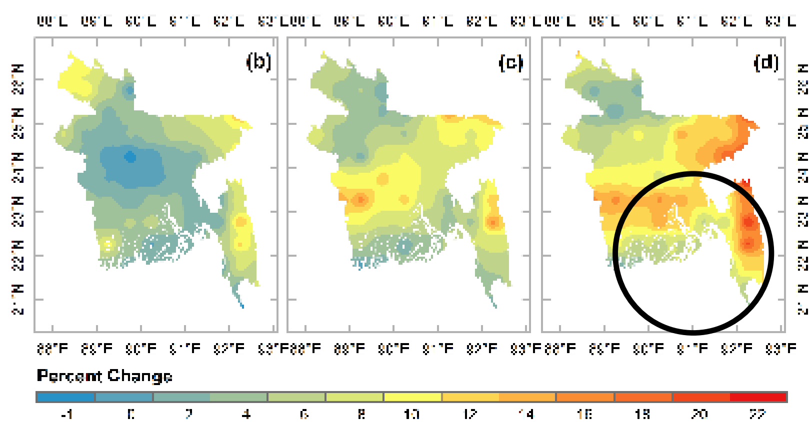


TNn- minimum of daily minimum temperature

Changes of Extreme Rainfall - more flash floods and landslides are expected

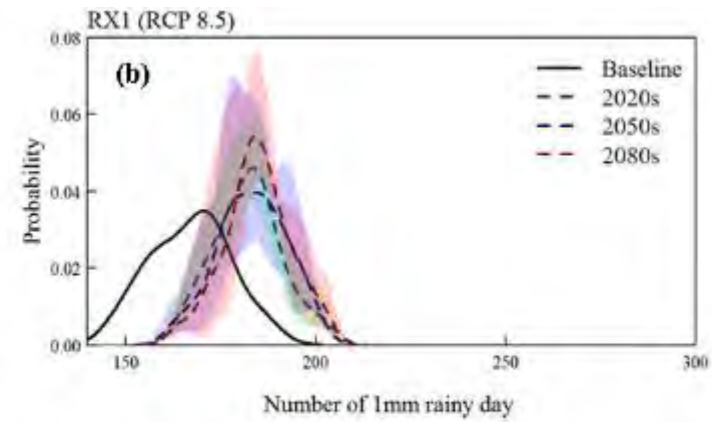
Rx1- maximum 1-day rainfall

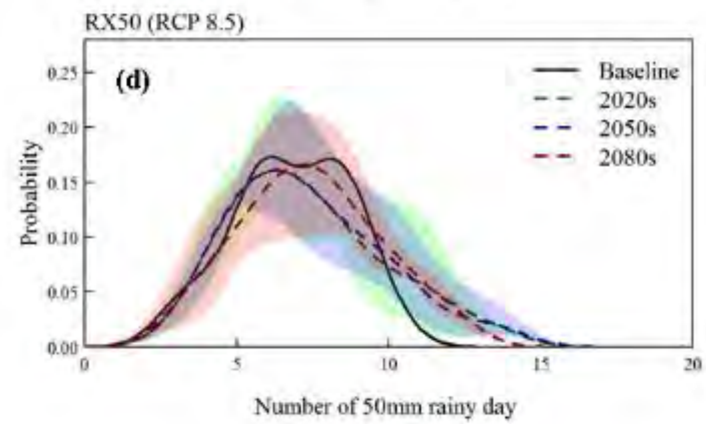




Rx50- number of days when rainfall > 50mm

Rx1- maximum 1-day rainfall

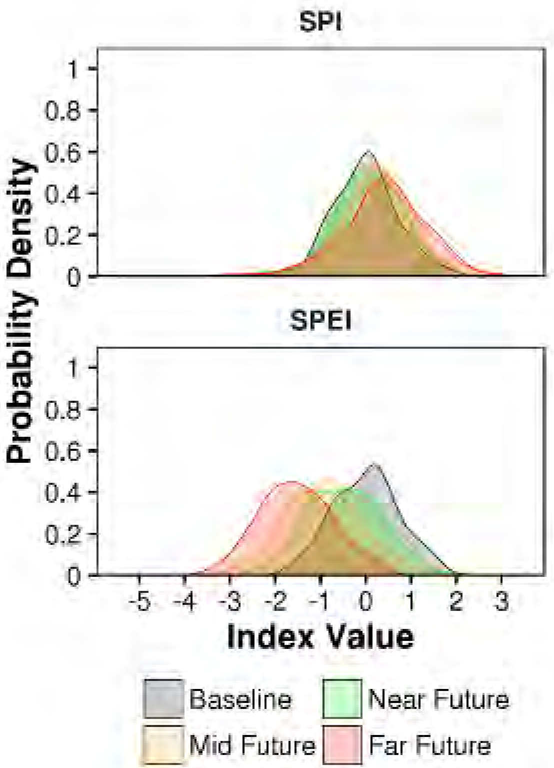




Rx50- number of days when rainfall > 50mm

Changes of Meteorological Droughts

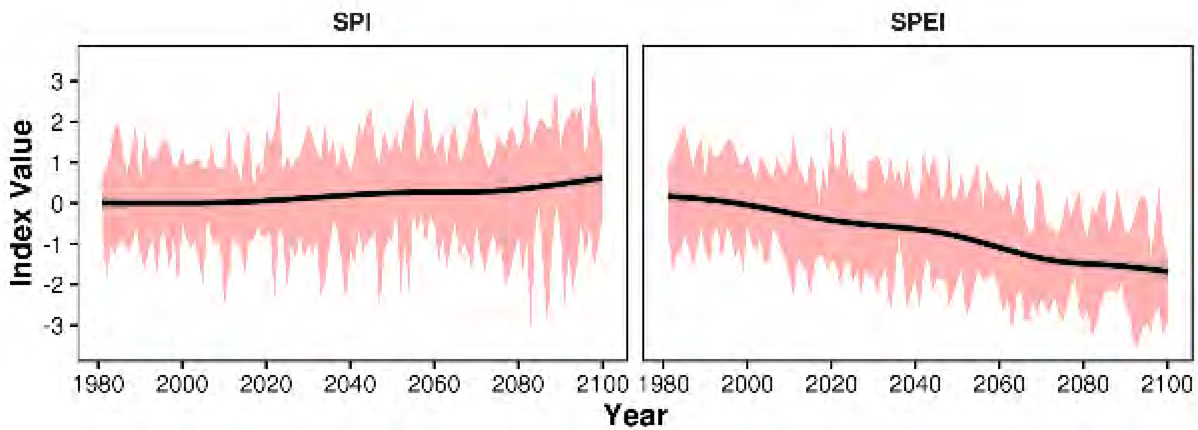
Standard Precipitation Index (SPI) and Standard Precipitation and Evapotranspiration Index (SPEI)



Density distribution of SPI and SPEI values at 3 Month time-scale.

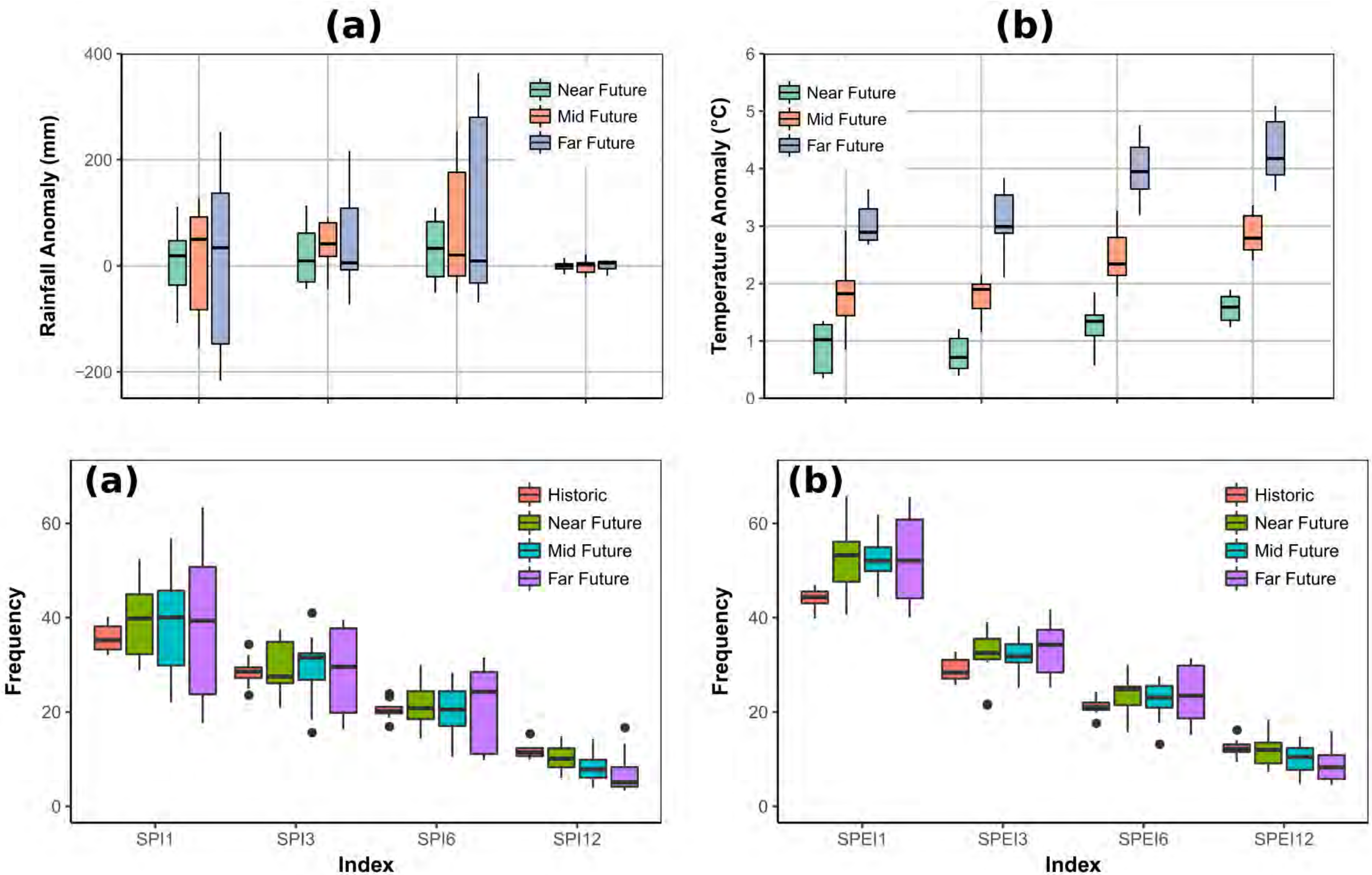
Both SPI and SPEI are calculated relative to a baseline period of 1981 to 2010.

Drought Category	SPI/SPEI Values
No drought	0 ≤ Index
Near normal/Mild drought	-1.0 < Index < 0
Moderate drought	-1.5 < Index ≤ -1.0
Severe drought	-2.0 < Index ≤ -1.5
Extreme drought	Index ≤ -2.0



Ensemble time series of SPI (left panel) and SPEI Throntwhie (right panel) at 12-month timescale averaged over the country. The red patch is the ensemble spread of the index values.

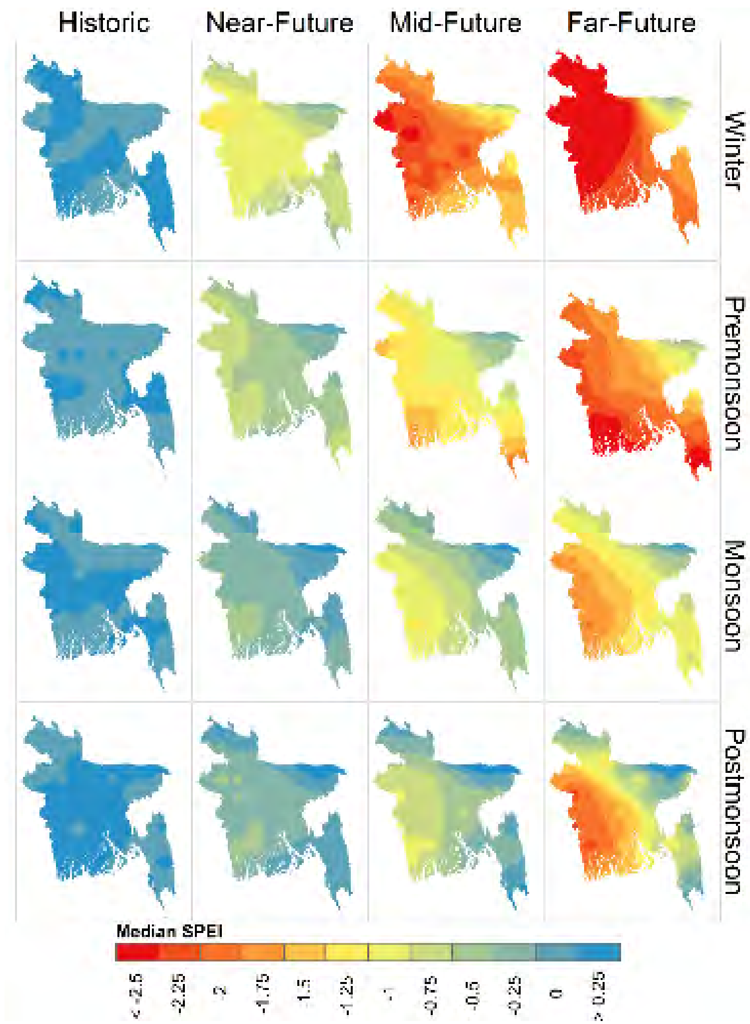
Changes of droughts for different SWL



Projected future median SPEI values over Bangladesh from 11 ensemble of Regional Climate Model (RCM).

Spatial Changes of Meteorological Droughts

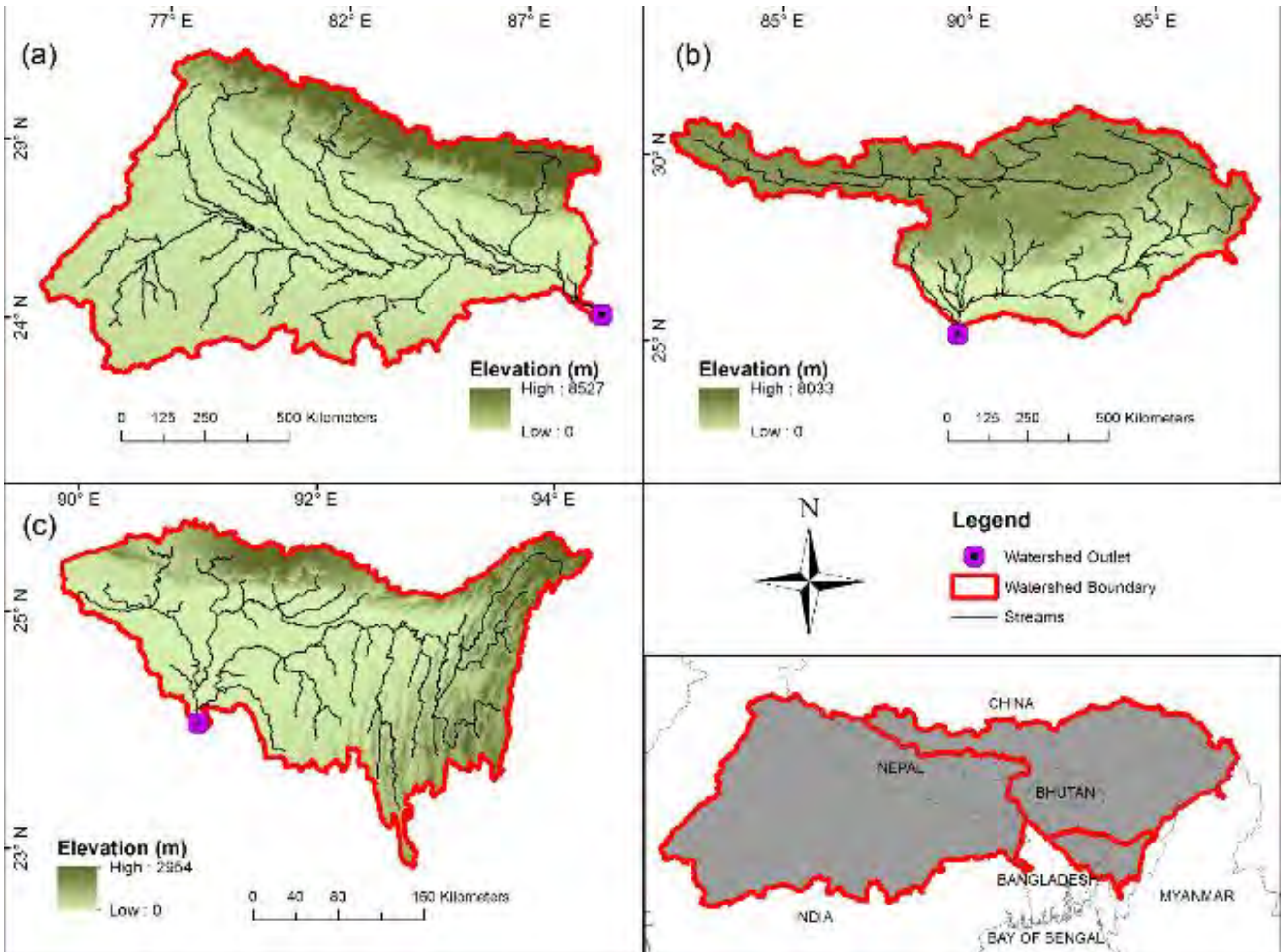
- Inclusion of evapotranspiration in the evaluation of drought is important in the context of global warming.
- The country is expected see more and more deviation from the climatic mean condition.
- At the end of the century, the climate of the country may settle to a condition which may be considered "moderate drought" compared to current climate.
- Long meteorological drought will impact the agriculture and socio-economic condition.



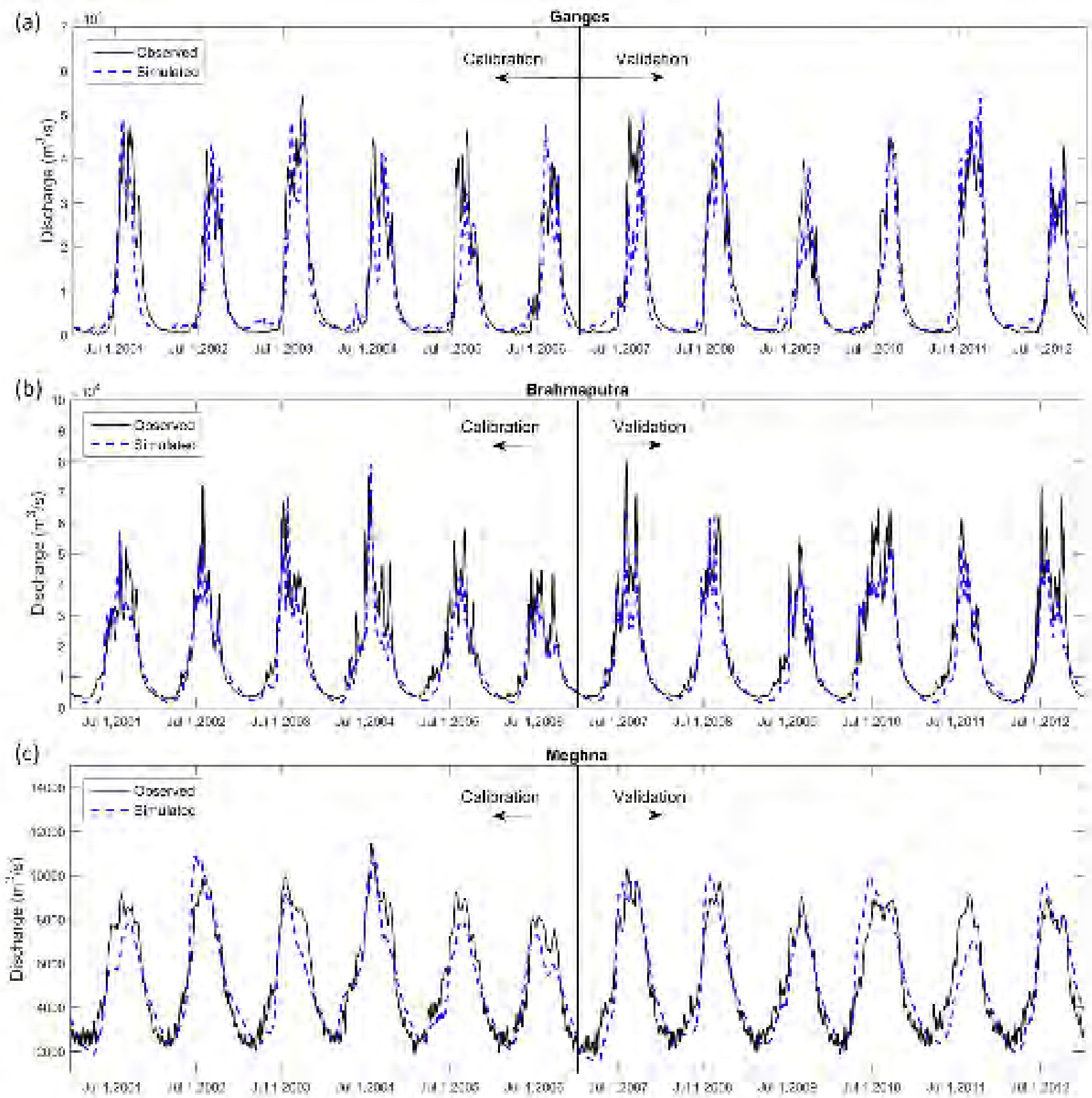
Percentage of area affected with time

Ganges-Brahmaputra-Megha Basins

The GBM basins are located over India (64%), China (18%), Nepal (9%), Bangladesh (7%) and Bhutan (3%), and the elevation of the basins range from about 0 to above 8000 m above mean sea level (amsl).



SWAT Model Evaluation for GBM basins



- Model developed using SRTM 90m DEM, GlobCover landuse map, FAO Digital Soil Map of the World and WFDEI weather data.
- Model has been calibrated for 2001-2006 and validated for 2007-2012
- Model has been evaluated using Coefficient of determination (R20, Nash Coefficient of Efficiency (NSE), Percentage of Bias (PBIAS) and Root Mean Square Error (RSR)

Model calibration and validation using statistical Indicators

1. Correlation coefficient: $$R^2 = \left[\frac{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{mean})(Y_i^{sim} - Y_i^{simmean})}{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{mean})^2 \sum_{i=1}^{n}(Y_i^{sim} - Y_i^{simmean})^2}\right]$$

2. Nash and Sutcliffe coefficient: $$NSE = 1 - \left[\frac{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{mean})^2}\right]$$

3. Root mean-square error (RMSE) – observations standard deviation ratio (RSR): $$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\sqrt{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{sim})^2}}{\sqrt{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{mean})^2}}$$

4. Percent bias (PBIAS): $$PBIAS = \left[\frac{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{sim}) \quad * 100}{\sum_{i=1}^{n}(Y_i^{obs})}\right]$$

Where, Y_i^{obs} is the ith observation for the constituent being evaluated, Y_i^{sim} is the ith simulated value for the constituent being evaluated, Y^{mean} is the mean of observed data for the constituent being evaluated, $Y^{simmean}$ is the mean of simulated value for the constituent being evaluated, and n is the total number of observations.

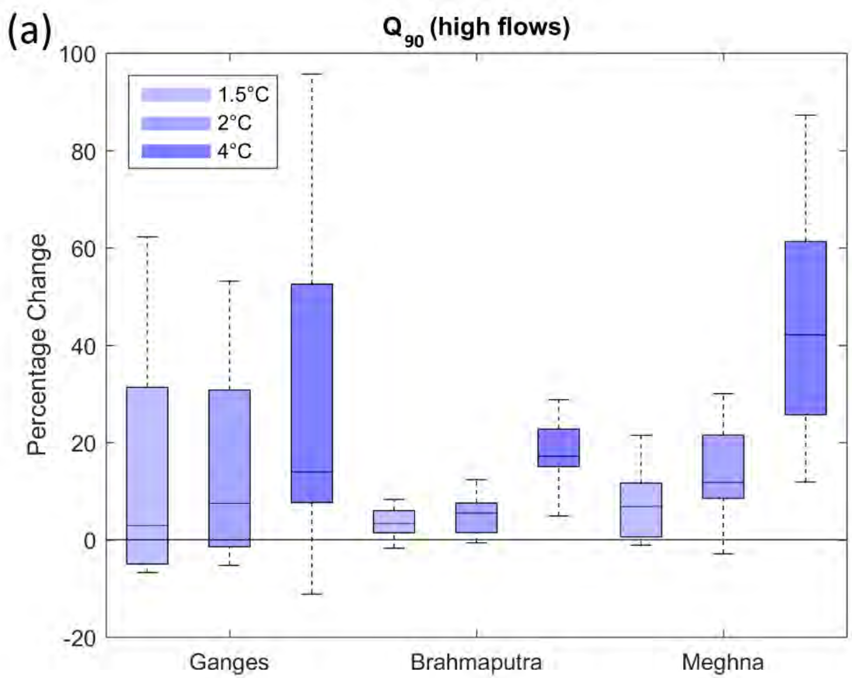
Performance of the SWAT models during calibration and validation periods

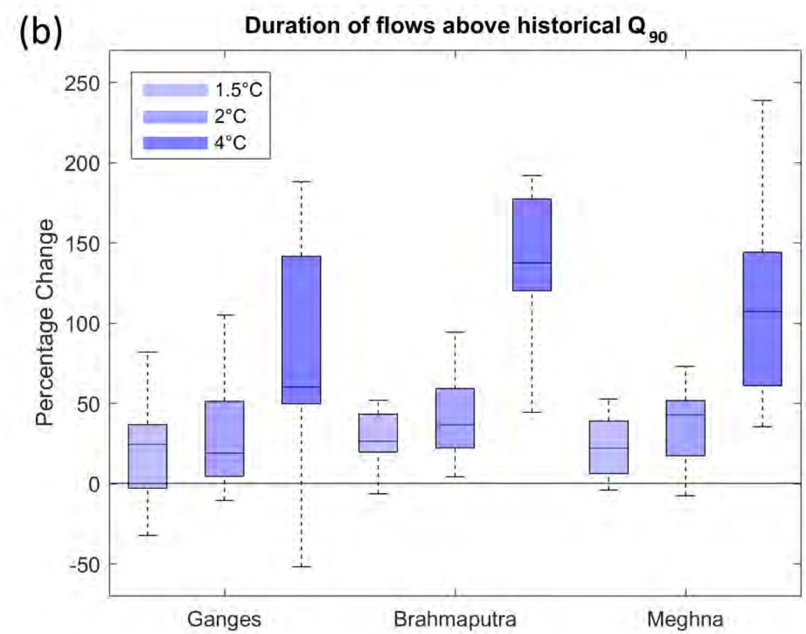
Statistical Indicators		NSE	R^2	PBIAS	RSR
Ganges	Calibration	0.80	0.81	12.47	0.44
	Validation	0.77	0.79	15.52	0.49
Brahmaputra	Calibration	0.81	0.84	15.23	0.43
	Validation	0.79	0.83	17.51	0.47
Meghna	Calibration	0.85	0.86	5.33	0.38
	Validation	0.83	0.85	5.84	0.41

High flows and flood duration will be more increasing in the future

Q90 Flow

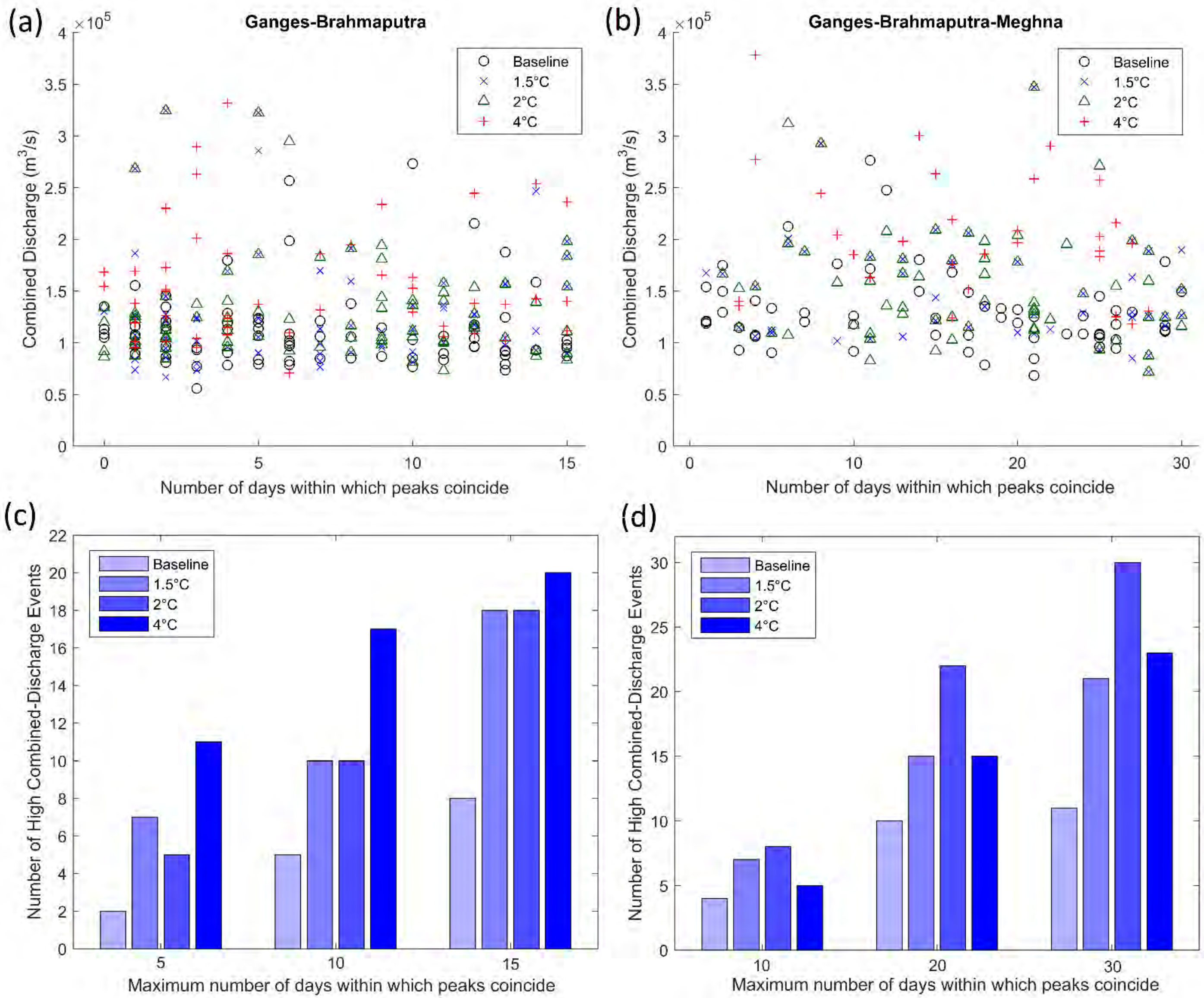
Duration of Q90





The ensemble-median values of the changes of Q90 flow at 1.5°C, 2°C, and 4°C are about 3%, 7%, and 14% for the Ganges; 4%, 5%, and 22% for the Brahmaputra; and 9%, 12%, and 42% for the Meghna, respectively

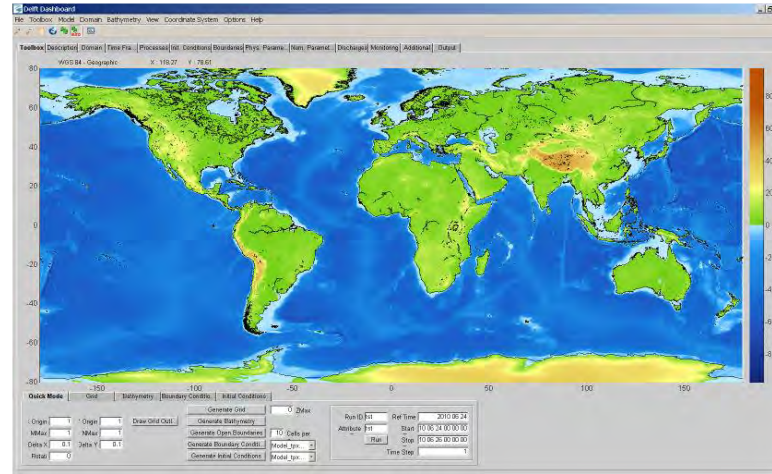
Peak synchronization of GBM Rivers

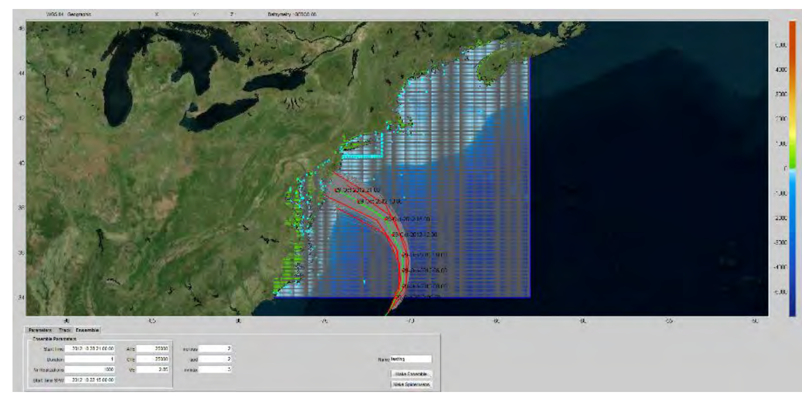


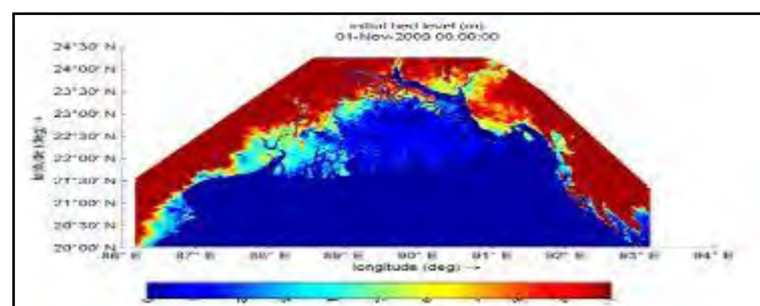
Coastal modeling using Delft3D

- DELFT3D- FLOW is a multi-dimensional (2D or 3D) hydrodynamic (and transport) simulation program which calculates unsteady flow and transport phenomena that result from tidal and meteorological forcing on a rectilinear or a curvilinear, boundary fitted grid.

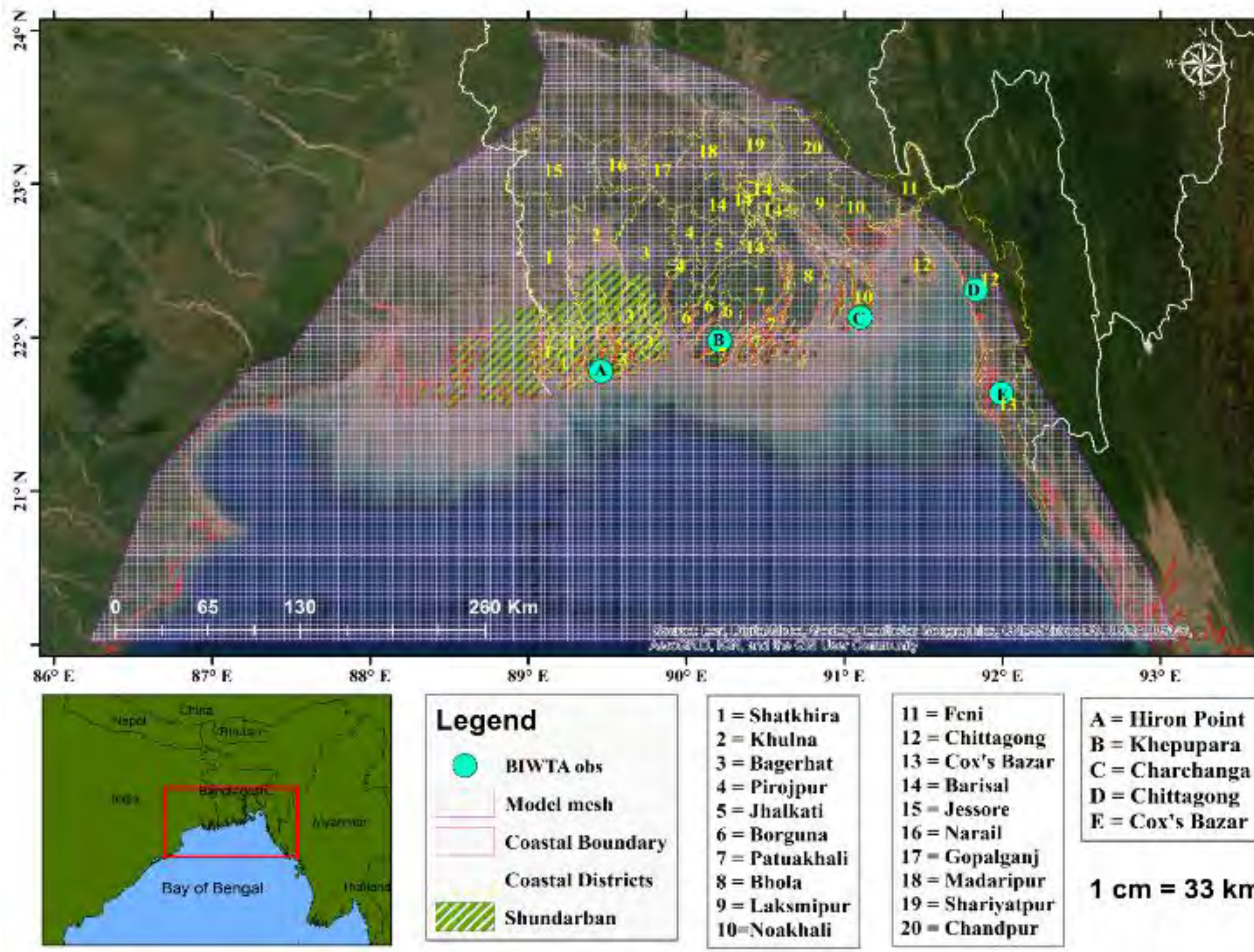
- Using Delft3D-dash board model can be setup, simulate, calibrate and validate over a region of interest. Using the Advanced Cyclone Toolbox and possible cyclone tracks, boundary conditions can be generated to derive the Delft3D model for study inundation patterns.



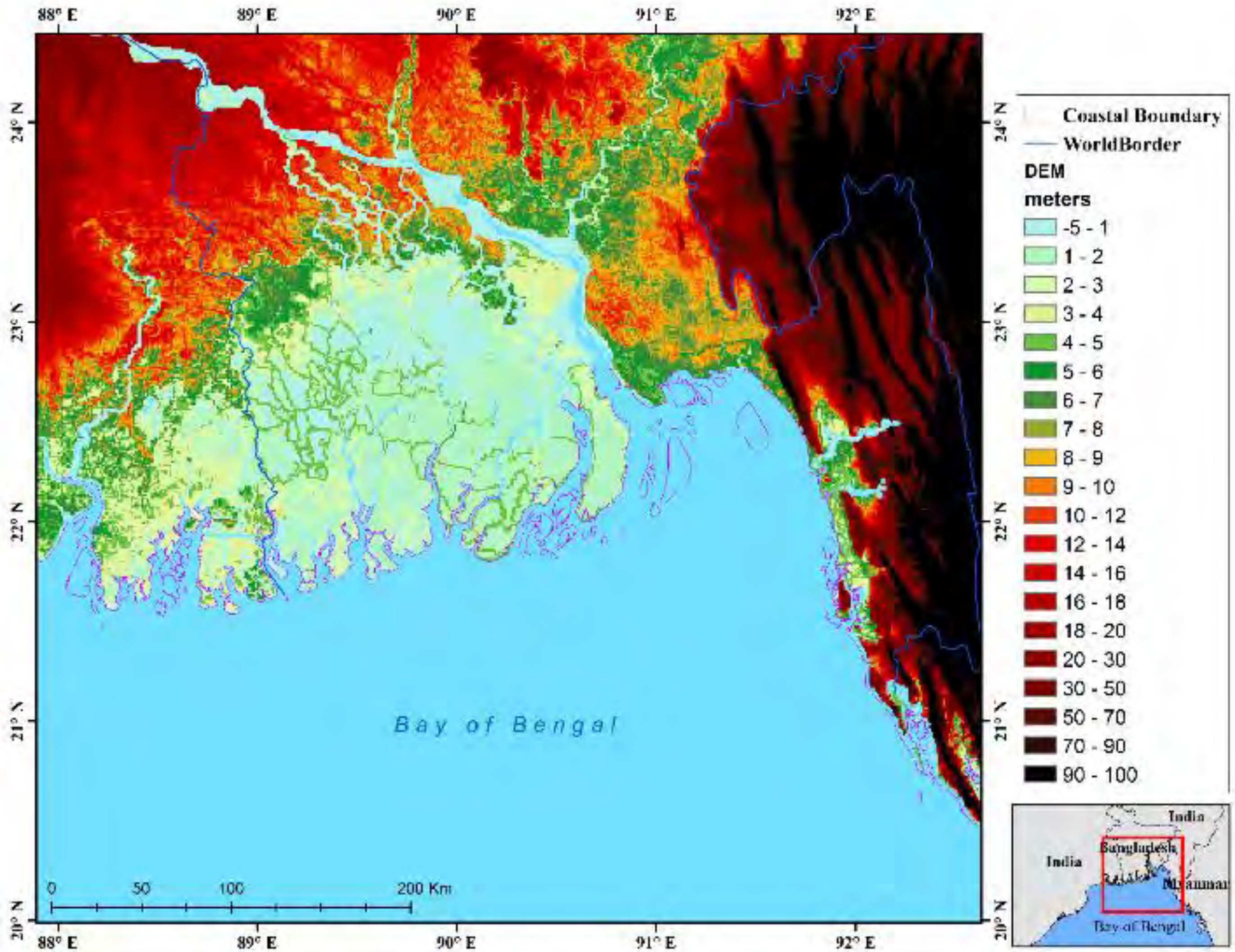




Delft3D Modeling Domain, Grid and BIWTA & BWDB Observation Stations



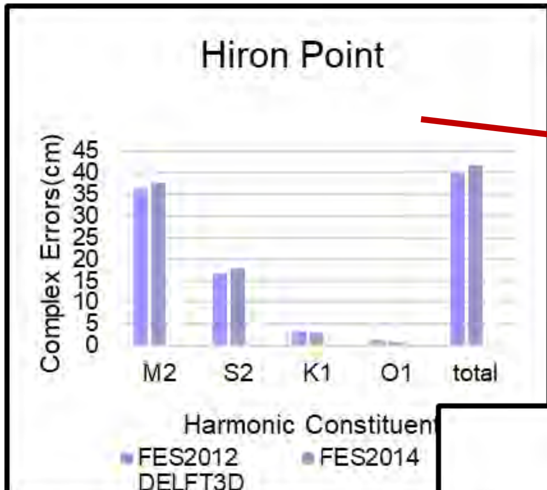
Topography of the Coast and Bathymetry of the Bay of Bengal

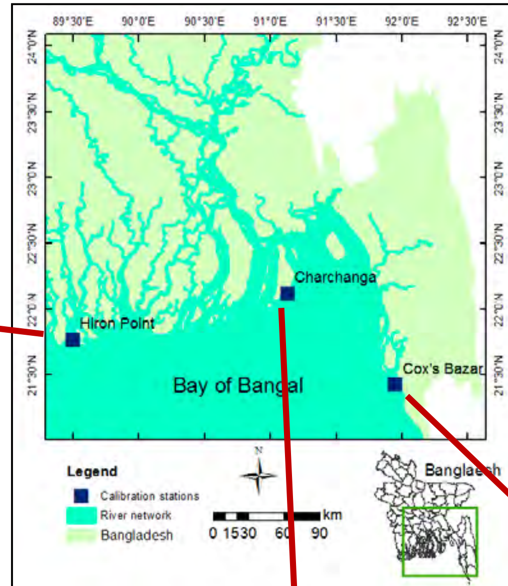


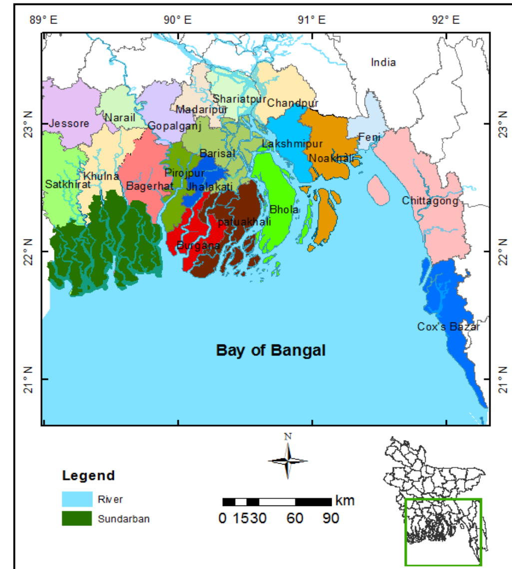
Bathymetry data has been collected from GEBCO data sets and also survey from BWDB, Bangladesh Navy and IWFM of BUET.

Model evaluation: Complex Error of all tidal constituents

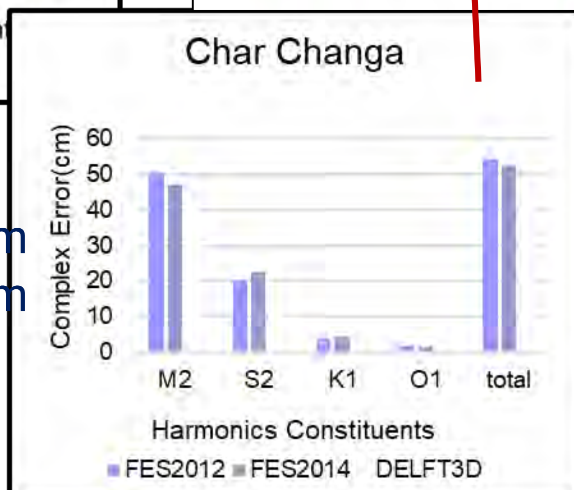
Hiron Point
FES2014: 41.9 cm
DELFT3D: 17.5 cm

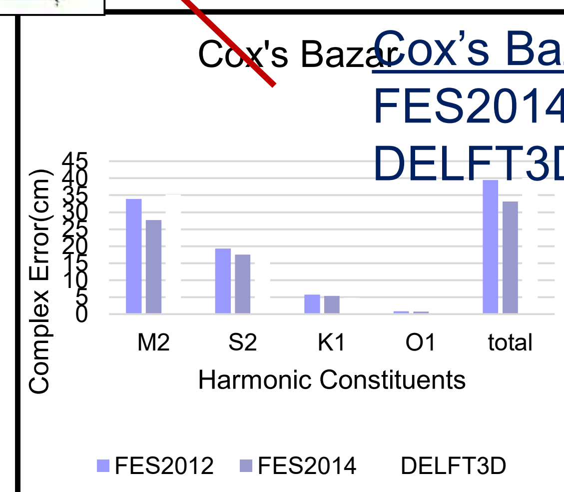






Char Changa
FES2014: 52.6 cm
DELFT3D: 44.8 cm

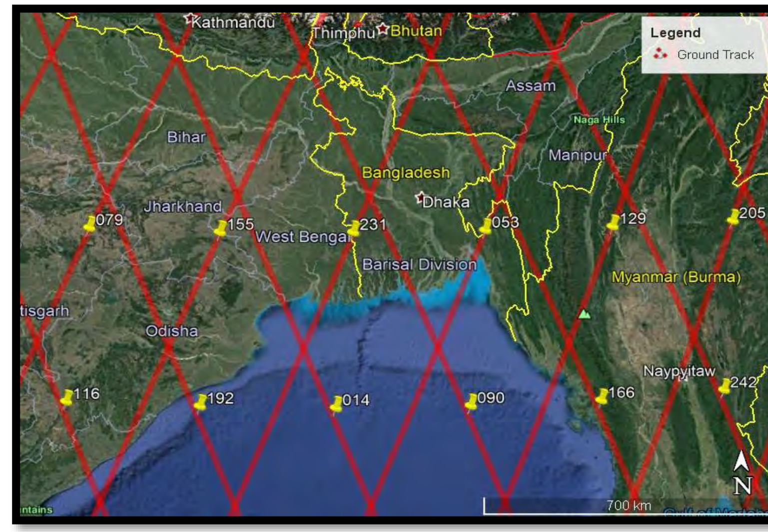


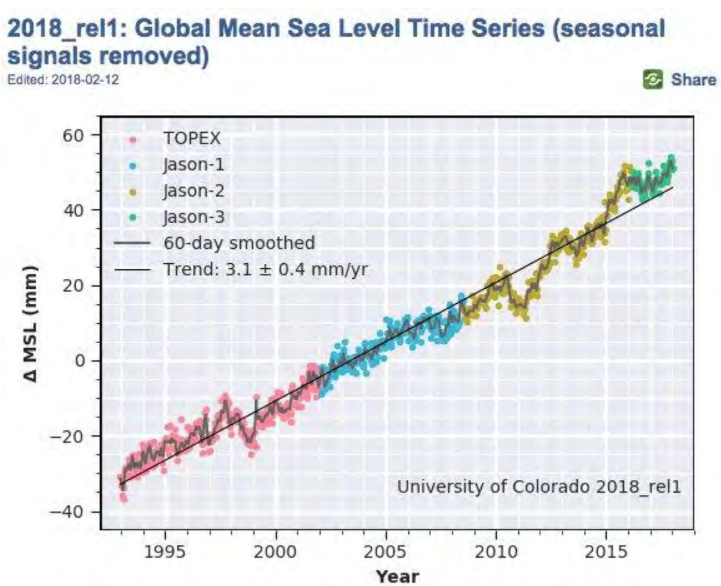


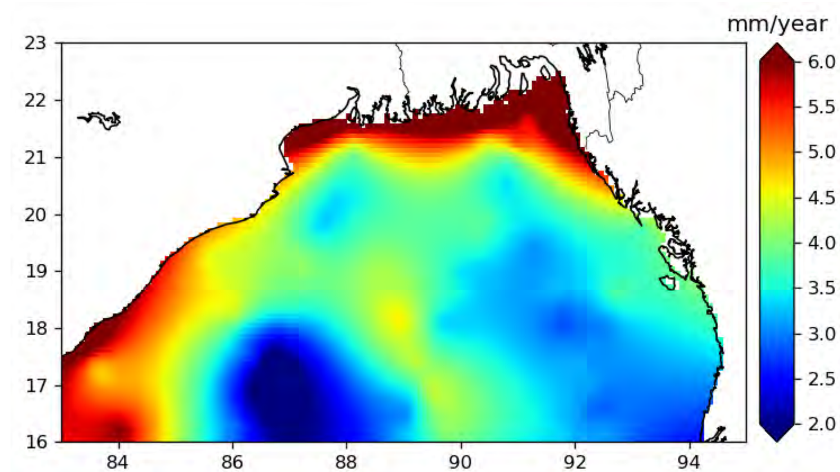
Cox's Bazar
FES2014: 37.6 cm
DELFT3D: 40.2 cm

Observed trend of water level estimated from monthly satellite altimetry data (DOE, 2020)

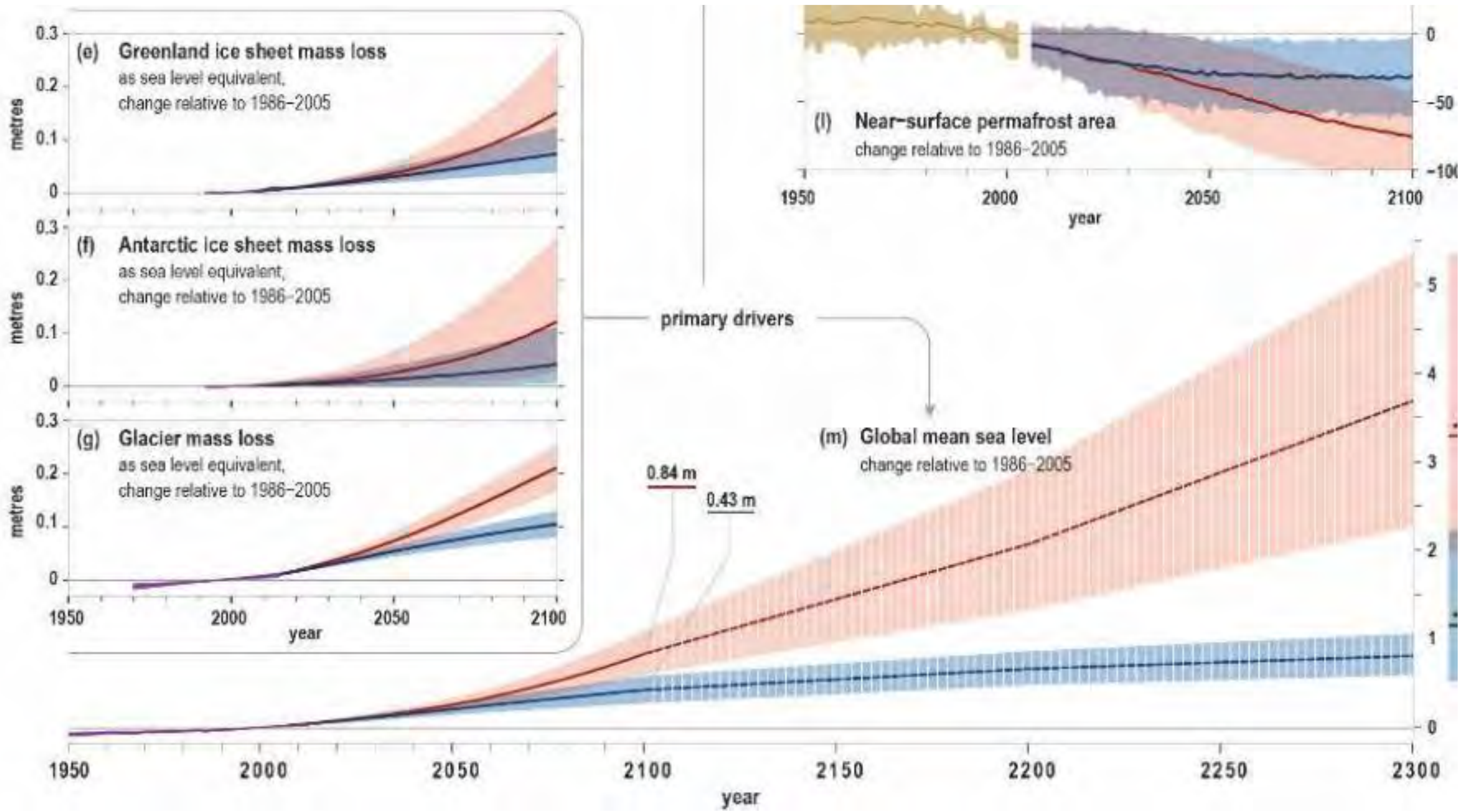
Mission Name	Organization	Operation Period	Temporal Resolution
T/P	NASA/CNES	1992 – 2002	10 days
Jason – 1	NASA/CNES	2002 – 2013	10 days
Jason – 2	NASA/CNES/NOAA/EUMETSAT	2008 – to date	10 days
Jason – 3	NOAA/CNES/EUM	2016 – to date	10 days



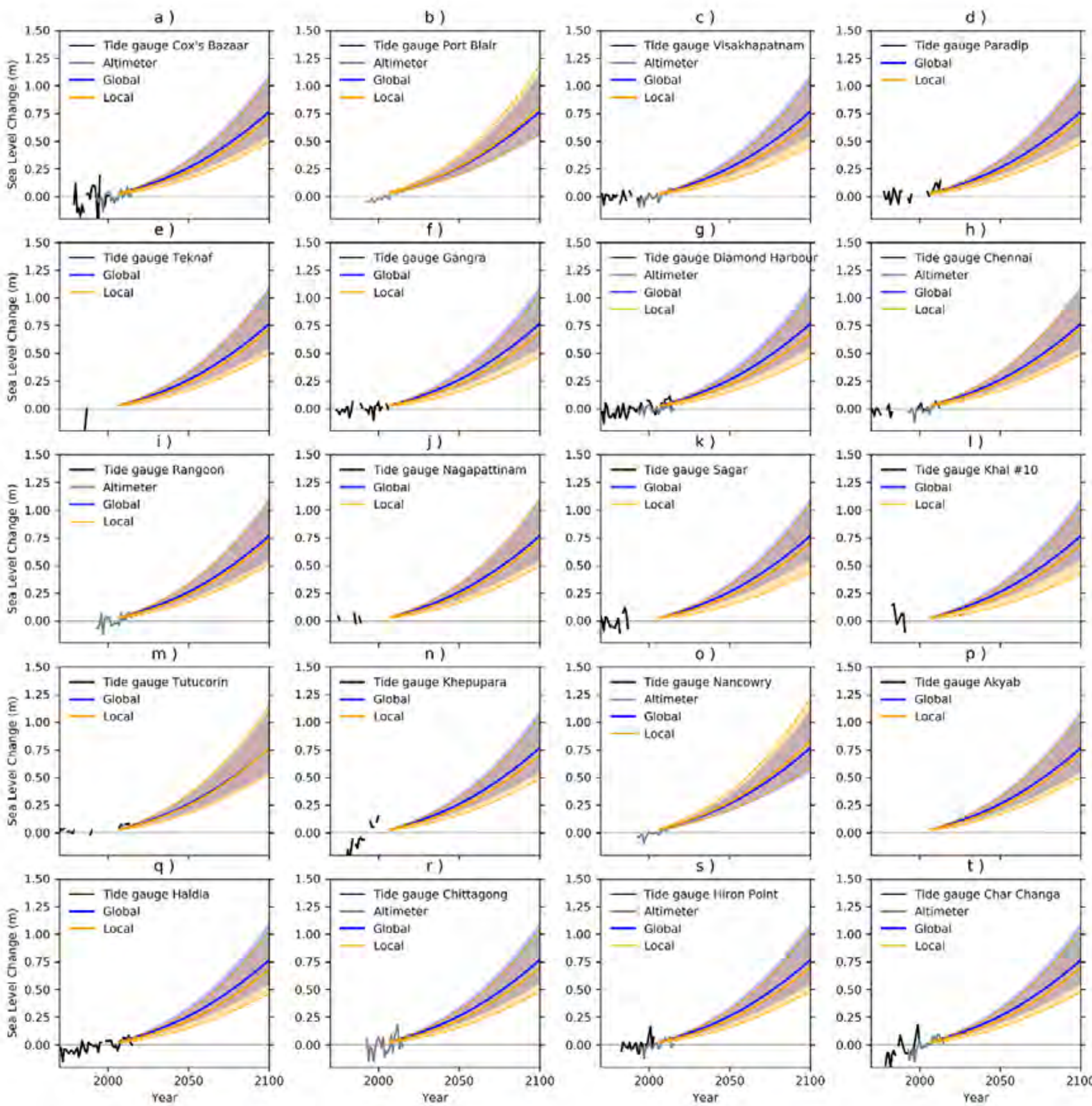




Projected Ice loss and SLR (SROCC, 2019)



21st century sea level projections for RCP8.5 at tide gauge locations in the Bay of Bengal (ARRCC, 2020)



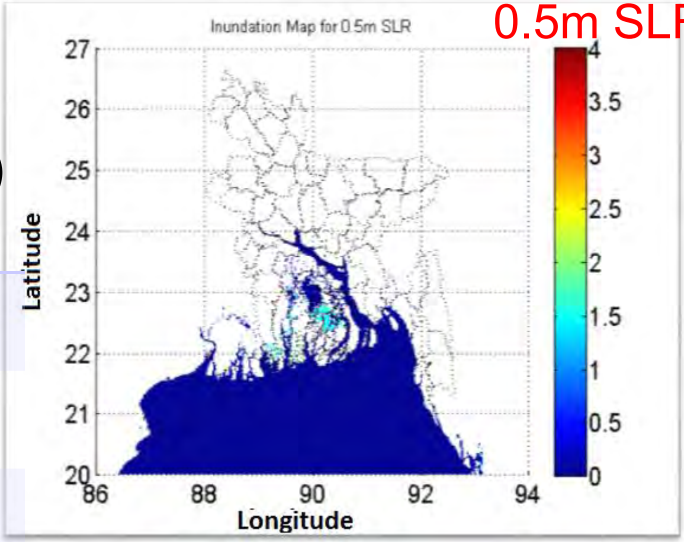
2081-2100	RCP2.6	RCP4.5	RCP8.5
Coxs Bazaar	0.17-0.62	0.3-0.68	0.4-0.86
Port Blair	0.24-0.66	0.34-0.73	0.45-0.92
Visakhapatnam	0.16-0.6	0.27-0.68	0.39-0.84
Paradip	0.16-0.6	0.28-0.67	0.39-0.84
Teknaf	0.17-0.62	0.29-0.68	0.4-0.85
Gangra	0.15-0.6	0.28-0.66	0.38-0.83
Dmnd Harbour	0.14-0.58	0.26-0.64	0.37-0.81
Chennai	0.19-0.62	0.29-0.71	0.43-0.89
Rangoon	0.19-0.62	0.29-0.69	0.41-0.86
Nagapattinam	0.2-0.61	0.3-0.71	0.42-0.89
Sagar	0.16-0.57	0.24-0.68	0.33-0.89
Khal Ten	0.2-0.55	0.25-0.66	0.34-0.89
Tuticorin	0.24-0.6	0.31-0.71	0.45-0.93
Khepupara	0.16-0.61	0.28-0.67	0.39-0.84
Nancowry	0.24-0.66	0.34-0.73	0.46-0.92
Akyab	0.18-0.62	0.29-0.68	0.41-0.85
Haldia	0.14-0.58	0.26-0.64	0.37-0.81
Chittagong	0.17-0.62	0.29-0.68	0.41-0.86
Hiron Point	0.15-0.61	0.28-0.67	0.39-0.84
Moulmein Two	0.22-0.59	0.28-0.7	0.37-0.92
Charchanga	0.16-0.6	0.28-0.67	0.39-0.84
Ko Taphao Noi	0.22-0.65	0.33-0.73	0.44-0.91

Changes of Inundation due to SLR

Permanent Inundation

SLR (m)	Inundated Area (square km)	Area Percent of Bangladesh	Affected Population (million)
0.5m	2000	1.6	2.5
1m	3930	3.8	6
1.5m	5300	5.1	8

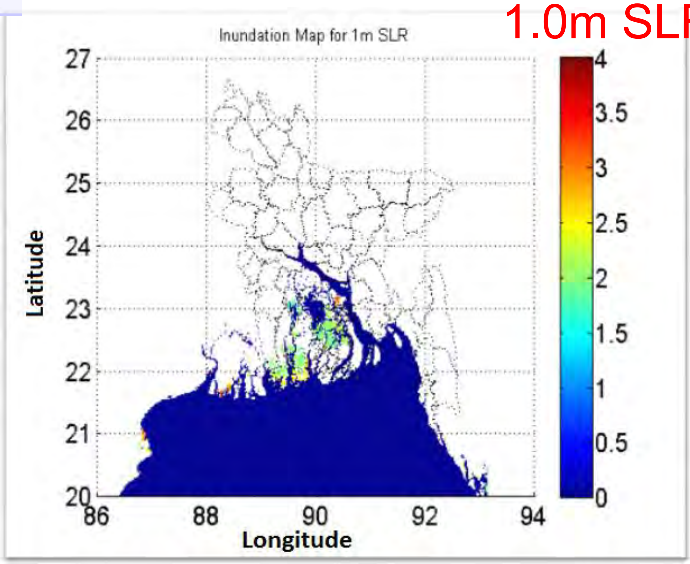
0.5m SLR



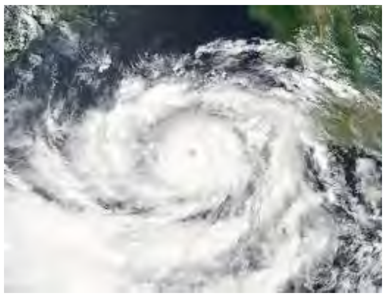
Inundation of the Sundarbans

SLR (m)	Inundated Area (square km)	% of inundation Area
0.5m	491	11.37
1m	1847	42.78
1.5m	2635	61.04

1.0m SLR

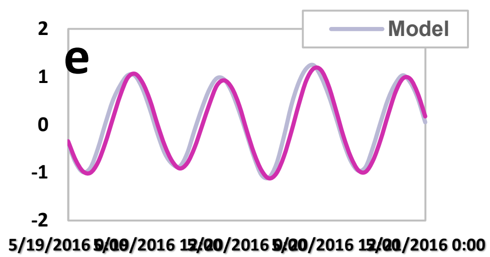


Changes of the inundation and impact of the coastal cyclones (SIDR, AILA and Roanu) due to SLR

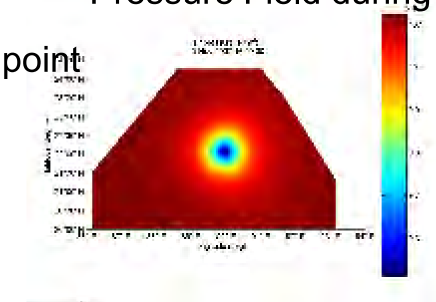


Cyclone SIDR
Nov 15 2007

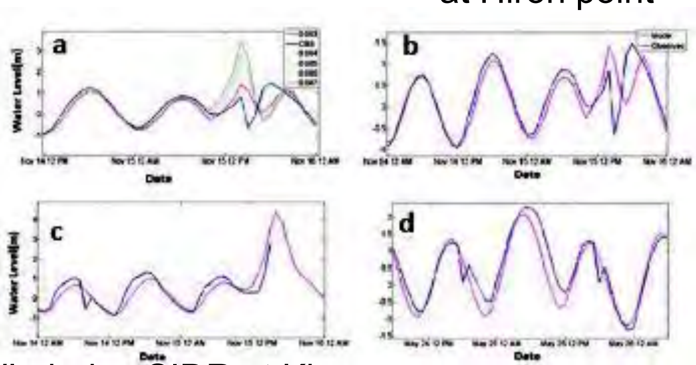
WL during Roanu at Hiron point



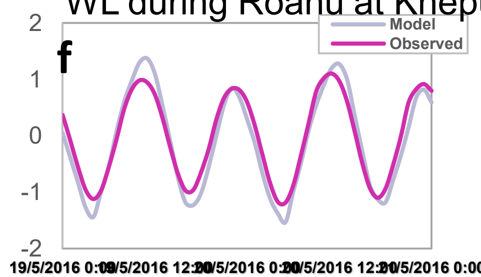
Pressure Field during SIDR



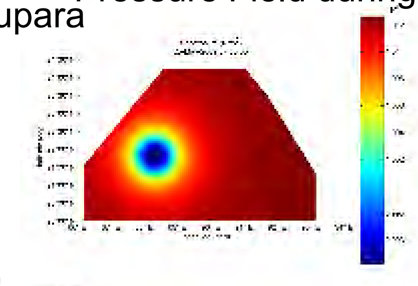
WL during SIDR at Hiron point



WL during Roanu at Khepupara



Pressure Field during AILA



WL during SIDR at Khepupara

WL during AILA at Hiron point

Calibration and Validation of Model for SIDR, AILA and ROANU at Hiron point and Khepupara. Suffix a,b,c for SIDR. Suffix d for AILA. Suffix e,f for ROANU.

Shaha et al. (2016)

Changes of inundation patterns or cyclone Sidr (2007), Aila (2009) and Roanu (2016)

	Sidr			Aila			Roanu		
	Area	%	p	Area	%	P	Area	%	P
Only cyclone	1484	1.2	1.9	1999	1.5	2.3	676	0.46	0.52
0.5m SLR	3380	2.6	4.1	4226	3.3	5.1	2912	1.97	2.24
1m SLR	5777	4.4	7.0	6216	4.8	7.5	7832	5.31	6.02
1.5m SLR	7588	5.8	9.1	7497	5.8	9.0	12550	8.5	9.65

***Inundation Area in Km^2, % of area w.r.t. country and Affected population in Million**

Shaha et al. (2016)

Changes of inundation patterns or cyclone Sidr (2007), Aila (2009) and Roanu (2016)

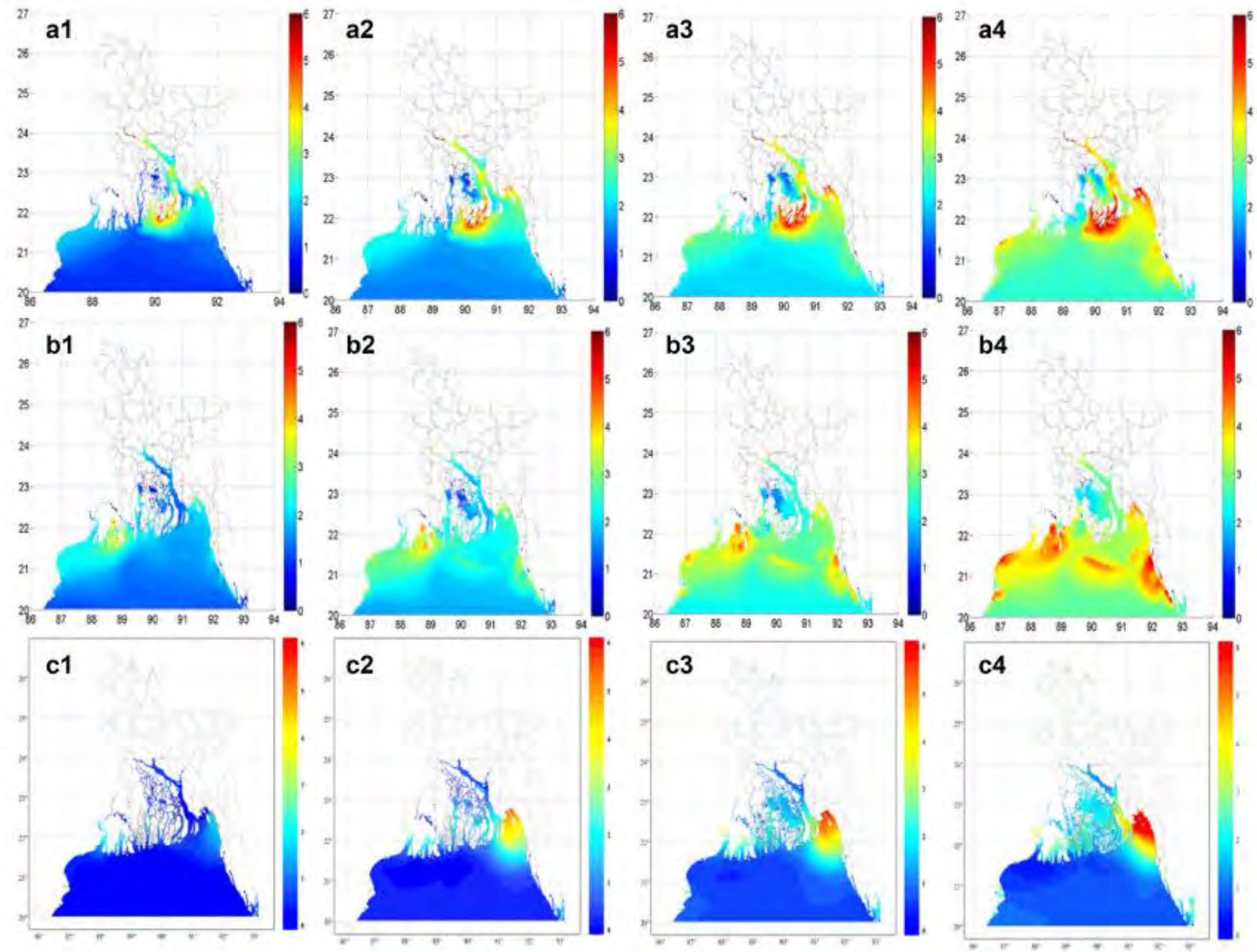
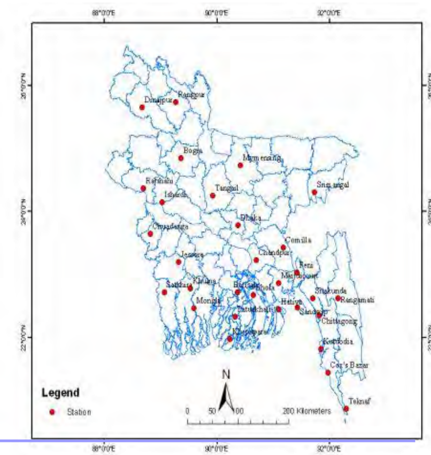


Figure 4. Maximum water level for cyclones under different SLR conditions. Suffix (a) for Sidr, (b) for Aila and (c) for Roanu. Suffix 1 for cyclone with the current sea level, 2 for cyclone plus 0.5-m SLR, 3 for cyclone plus 1.0-m SLR and 4 for cyclone plus 1.5-m SLR.

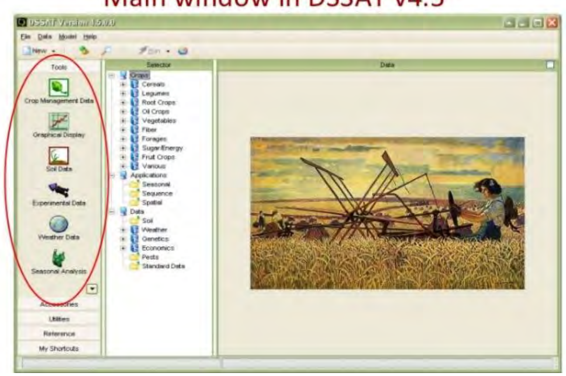
Rahman et al. (2016)

Crop Modeling using DSSAT (Decision Support System for Agro-technology Transfer)

- Extreme climate change will pose threat on various dimensions and Agriculture is one of them.
- About 75% of our agricultural land is rice and it covers 28% of GDP.



Main window in DSSAT v4.5



Hasan et al. (2016)

Real Name	Brridhan29
Height	95 cm
Duration of growth	160 days
Grain quality	Medium
Yield (Kg/hectares)	7500
Developed on	1994
Developed by	Bangladesh Rice Research Institute (BRRI)

Crop management data for simulations of BR29 in DSSAT

Parameter	Input Data
Planting Method	Transplant
Transplantation Date	November 21
Planting distribution	Hill
Plant population at seedling	40 plants/ m^2
Plant population at emergence	35 plants/ m^2
Row spacing	20 cm
Planting Depth	5 cm
Transplant age	15-20 days
Fertilizer Application	90 kg/ha applied equally in 3 phases after 15, 35 and 55 days of transplant respectively
Irrigation	1000 mm applied in 15 applications with 7 days interval in 1st month and 10 days interval later
Harvest	May 1

Default values of the genetic coefficients of Boro rice

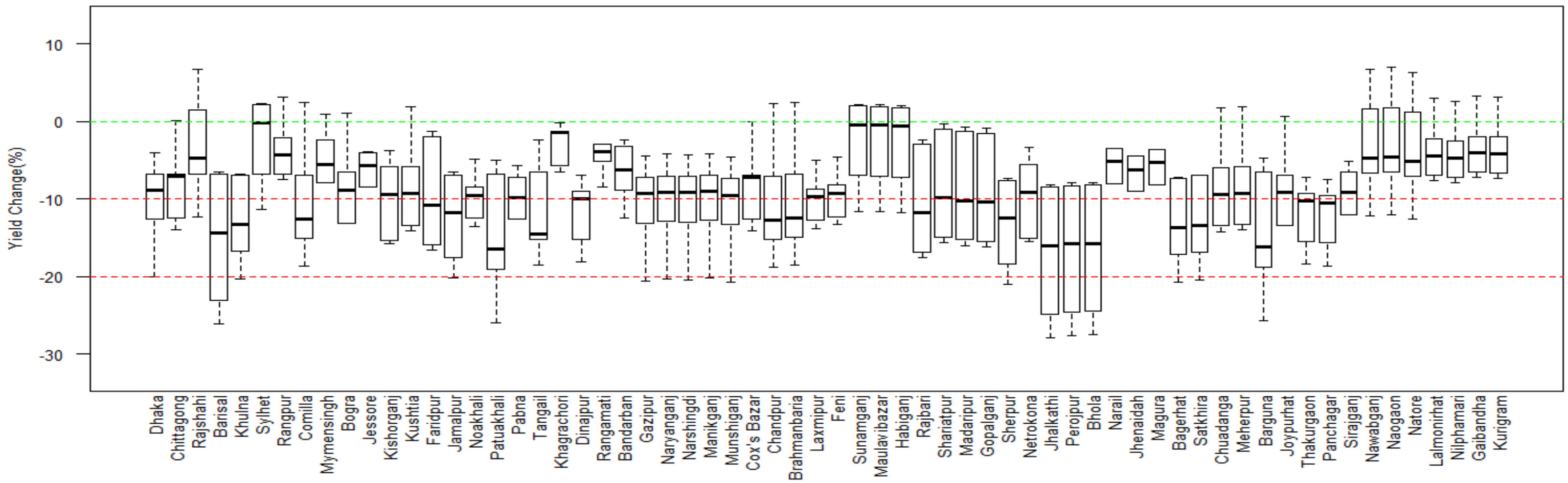
Coefficient ID	Name of coefficient	Default Value
P1	Basic vegetative phase coefficient	650
P20	Critical photoperiod at maximum growth rate	90
P2R	Extent in delay of panicle initiation	400
P5	Time from emergence to maturity	13
G1	Potential spikelet number coefficient)	0.65
G2	Single grain weight in gm in ideal condition	0.25
G3	Tillering coefficient	1.0
G4	Temperature tolerance coefficient	1.0

Values of the genetic coefficients in some important locations (divisions)

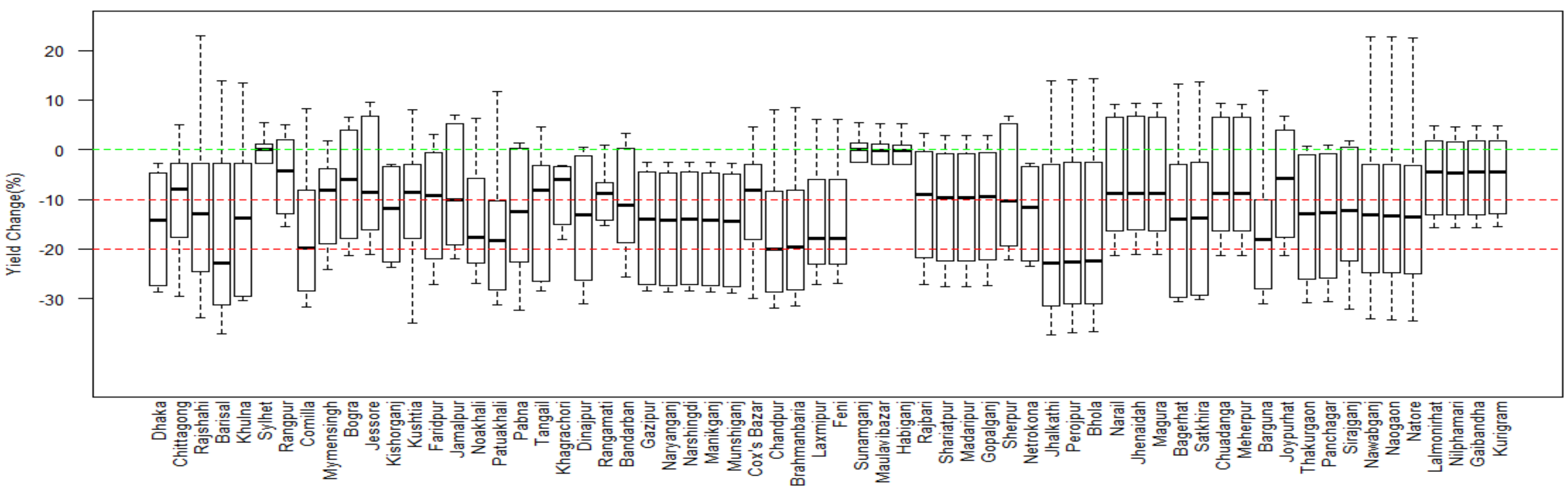
Region	P1	P2R	P5	P20	G1	G2	G3	G4	RMSE (Calibration)	RMSE (Validation)
Dhaka	647	93	415	12.9	67	0.26	1.0	1.0	260	125
Chittagong	645	87	395	12.9	62	0.25	1.0	1.0	312	213
Rajshahi	647	93	415	12.9	67	0.26	1.0	1.0	317	106
Barisal	648	90	400	13	67	0.25	1.0	1.0	192	141
Khulna	648	90	400	13	67	0.25	1.0	1.0	211	139
Sylhet	650	90	400	13	67	0.25	1.0	1.0	169	140

Changes of Boro rice yield at 2C and 4C SWL

2C

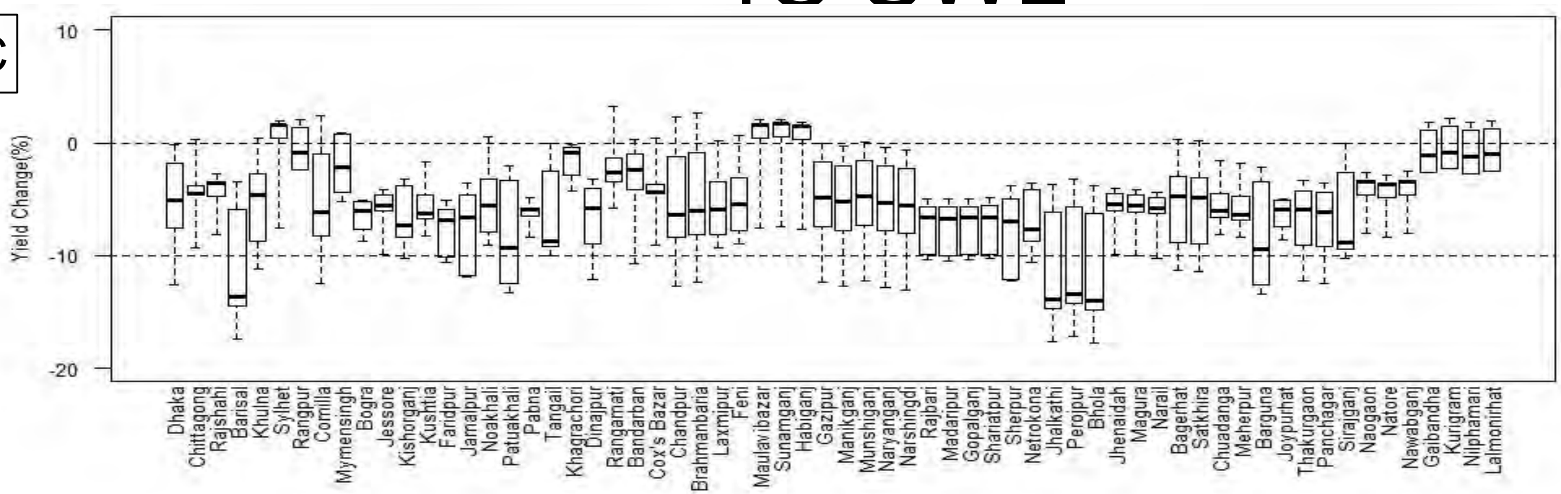


4C

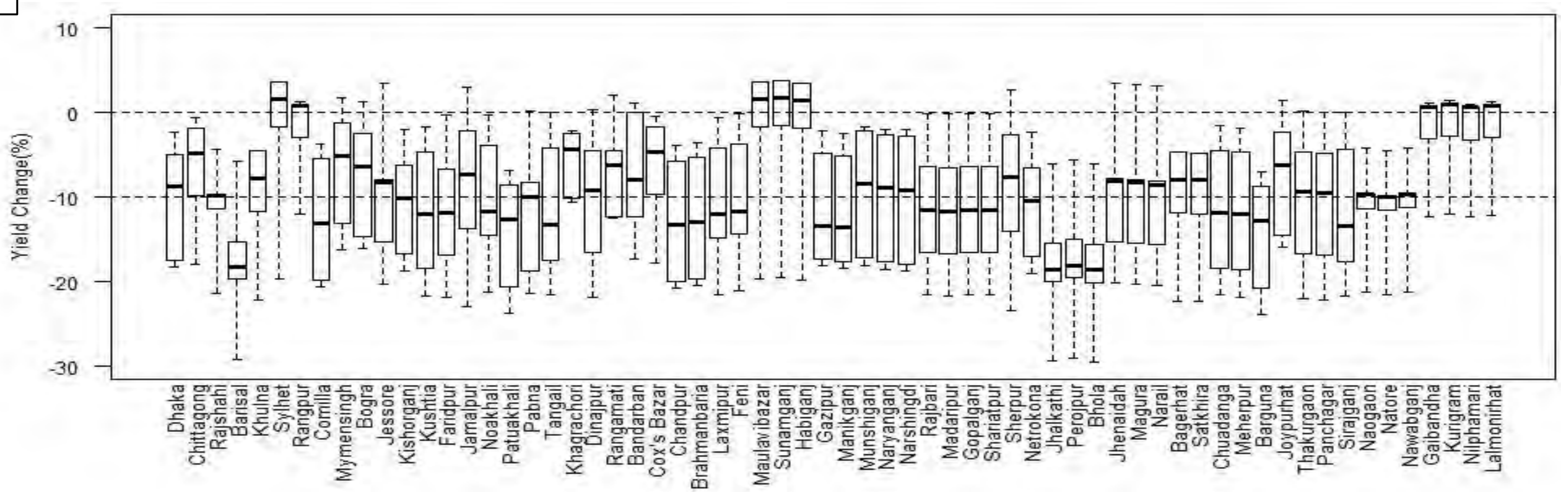


Changes of Aman rice yield at 2C and 4C SWL

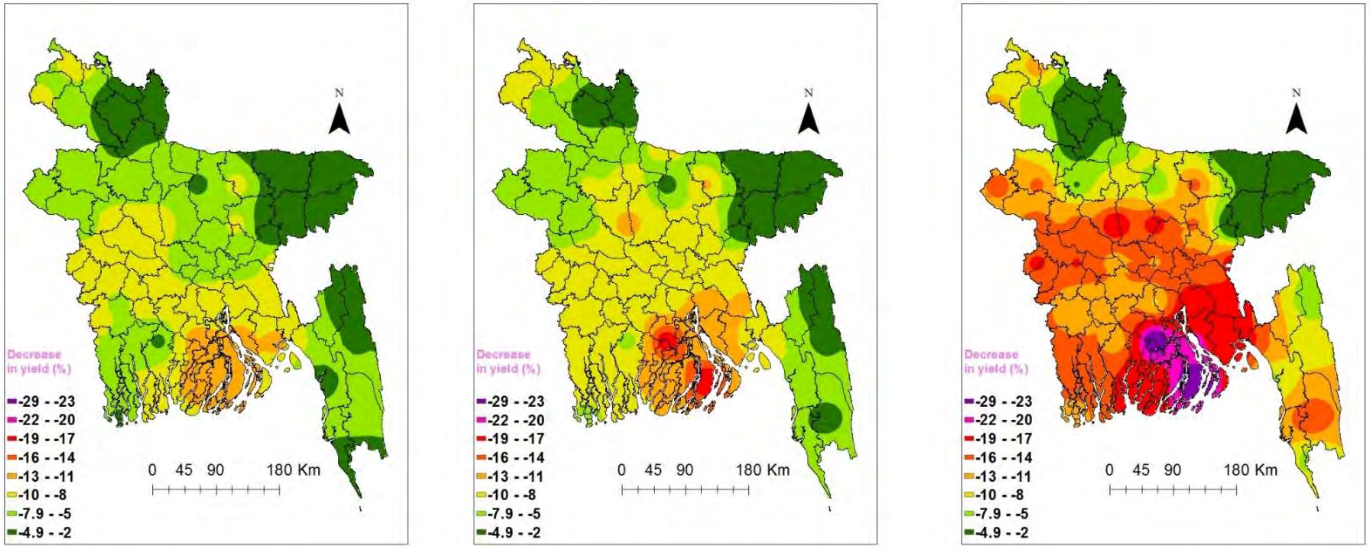
2C



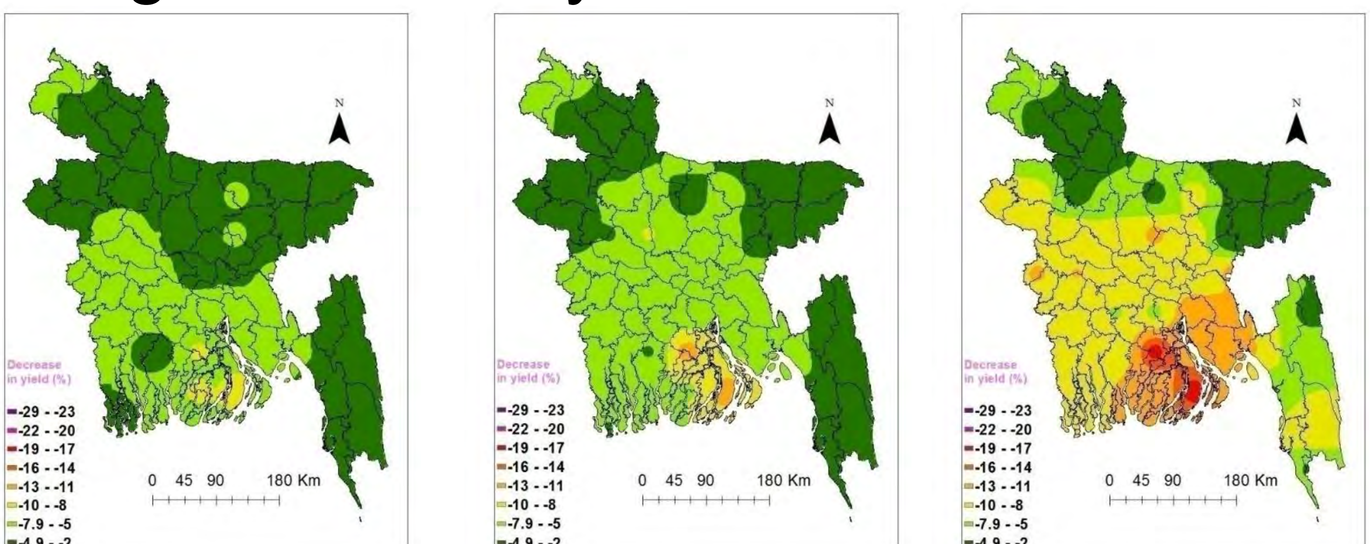
4C



Changes of Boro yield at 1.5C, 2C, 4C SWLs



Changes of Aman yield at 1.5C, 2C, 4C SWLs



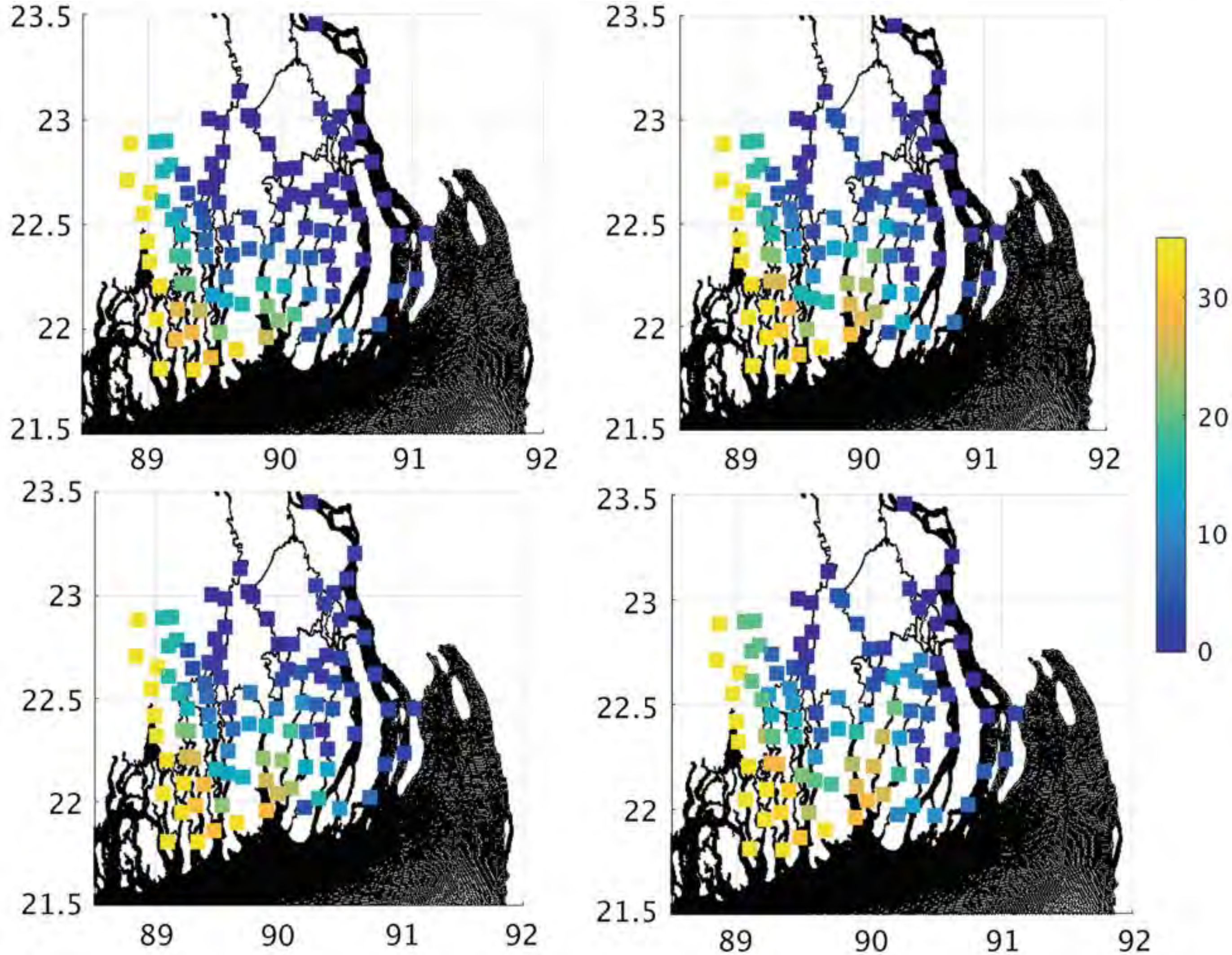
Salinity in coastal Bangladesh

Table 17.1

Summary of scenario runs with annual river discharge over time discussed in this chapter

Scenario	Description	Climate and management	MSLR (cm)	Year	Annual river discharge (m^3)	‘Wet’ or ‘dry’
1	Baseline	Q0+business as usual	0.0	2000–2001	9,928,407	
2	Mid-century	Q0+business as usual	31.96	2047–2048	13,979,424	Wet
3	Mid-century	Q8+less sustainable	27.06	2050–2051	10,011,085	Dry
4	End century	Q8+more sustainable	58.77	2082–2083	16,517,208	Wet
5	End century	Q0+business as usual	59.01	2097–2098	10,978,254	Dry

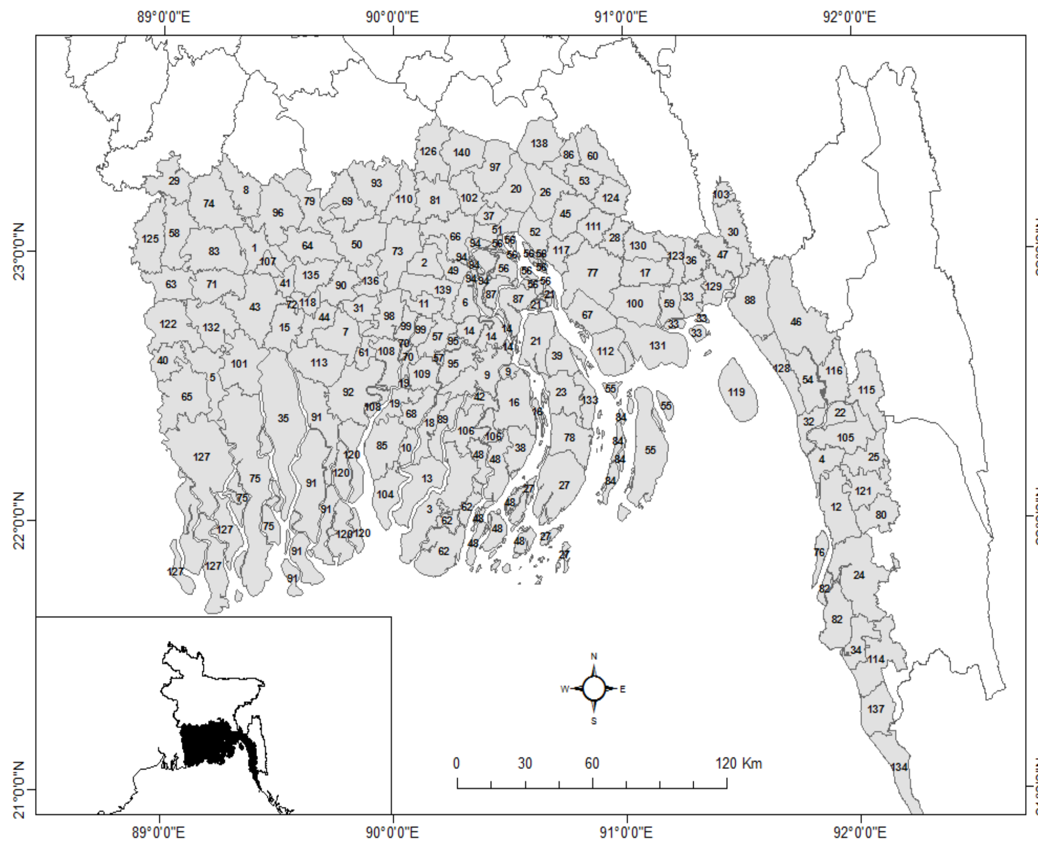
Annual maximum salinities for 103 selected points under the four future scenarios



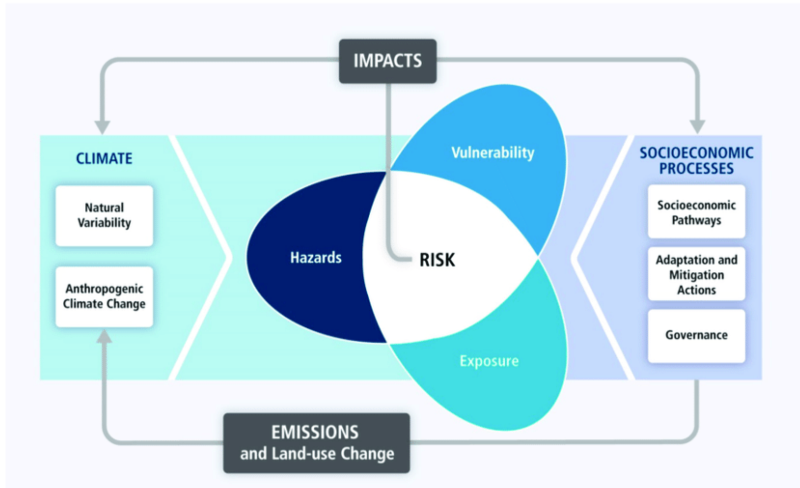
Bricheno et al., 2018

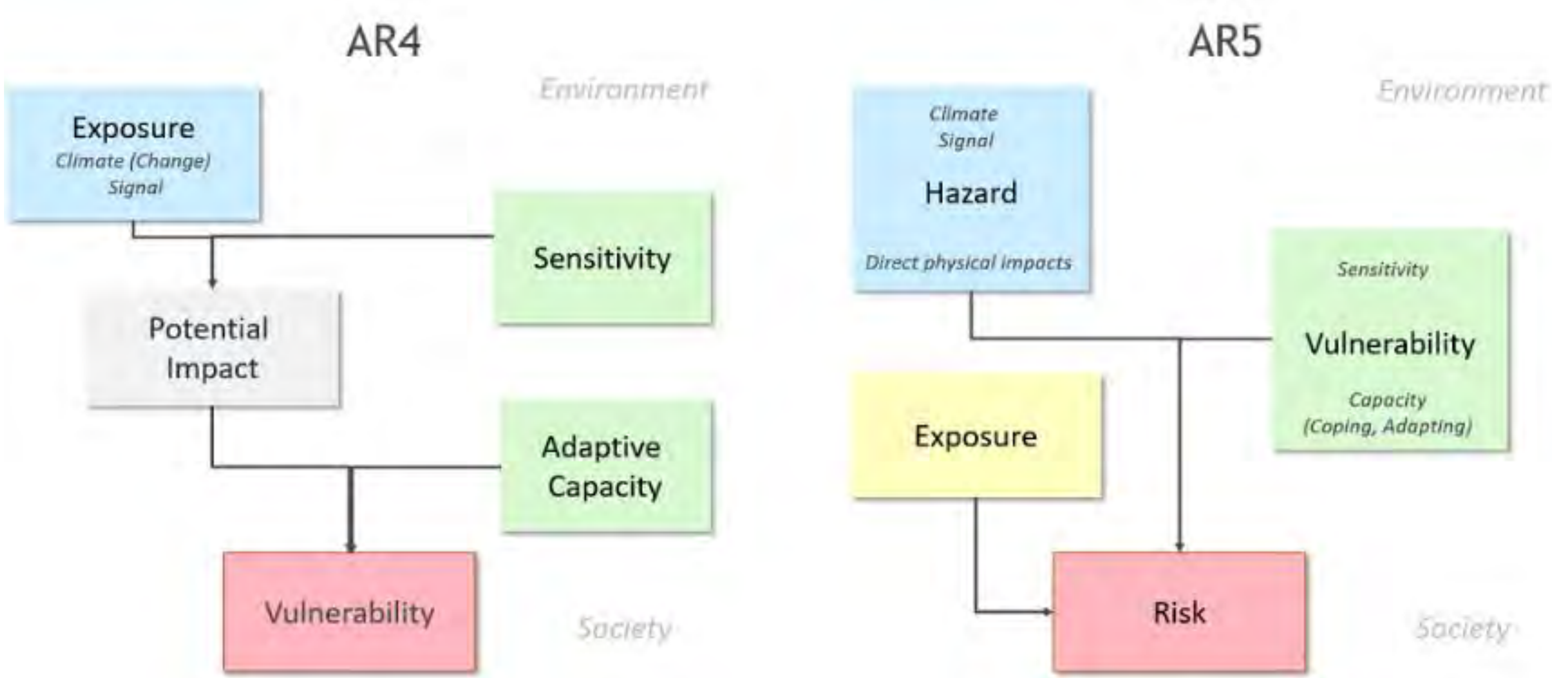
Socioeconomic vulnerability assessment using indicators based multivariate analysis

- Coastal areas of Bangladesh is very much prone to various natural disasters such as cyclone, storm surge, river erosion, flood, salinity intrusion, erratic weather condition, etc.
- 19 coastal districts were selected for the analysis where 140 Upazilas are included



Coastal vulnerability due to climate change following IPCC Framework of assessing vulnerability





Principle component analysis conducted to determine weight of the indices

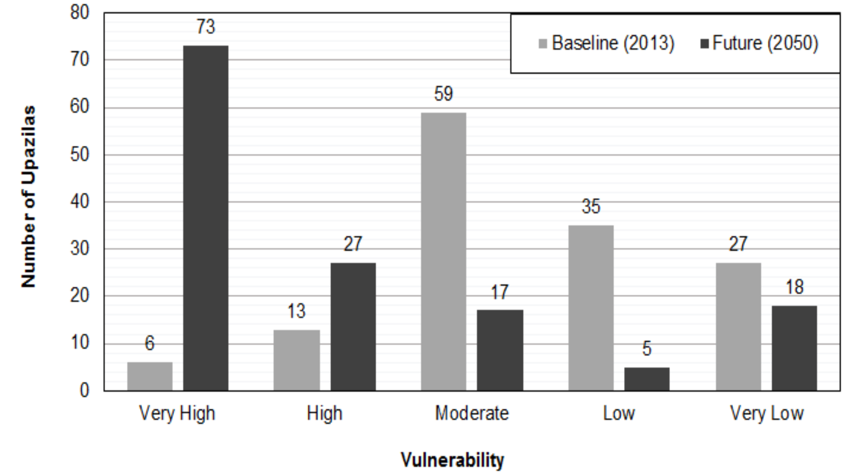
5 SENSITIVITY INDICATORS

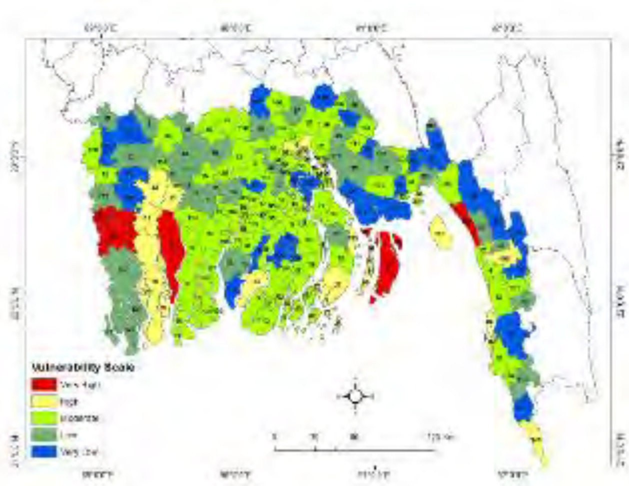
7 EXPOSURE INDICATORS

19 ADAPTIVE CAPACITY INDICATORS

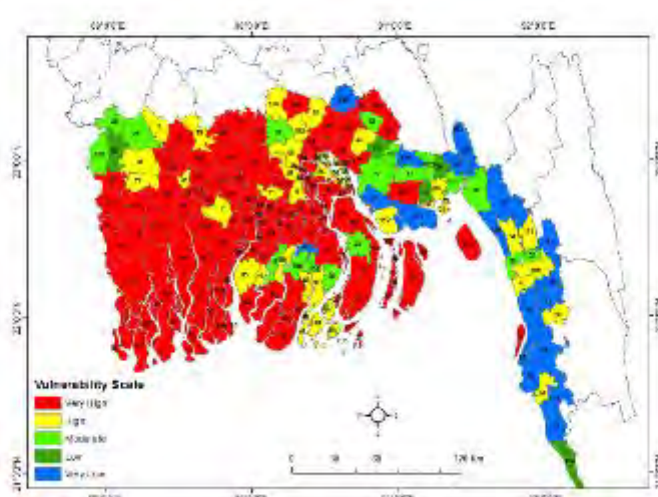
Coastal Vulnerability in preset and in the future (2050)

A total of 140 upazilas (administrative unit) under 19 coastal districts of Bangladesh has been selected as study At present, 6 upazilas come under very high, 13 upazilas under high, 59 upazilas under moderate, 35 upazilas under low and 27 upazilas under very low category of vulnerability





Present (2013)



Future (2050s)

In future, 73 upazilas are mapped as very high, 27 upazilas as high, 17 upazilas as moderate, 5 upazilas as low and 18 upazilas as very low scale of vulnerability

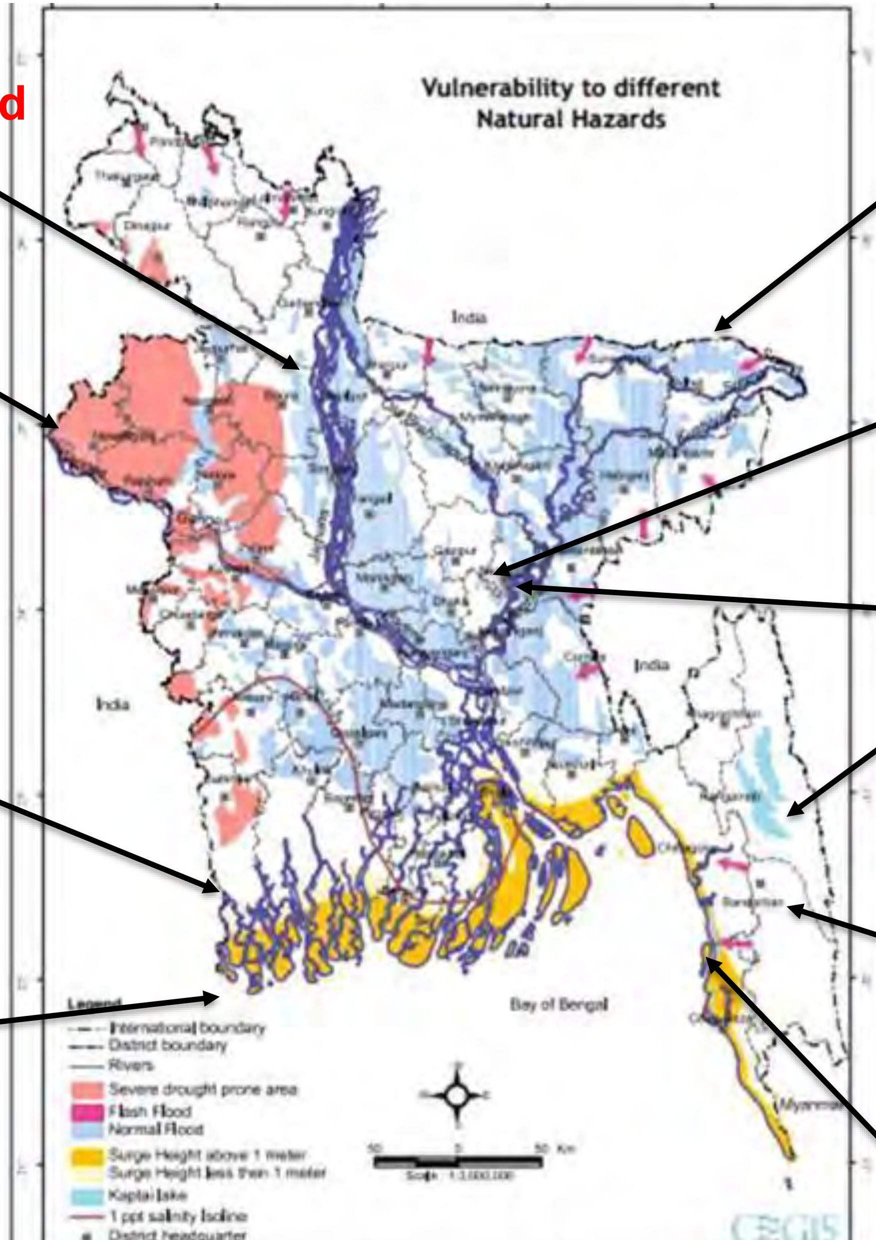
Hazards Expected to Change under Global Warming

Riverine Flood
More intense & frequent

Drought
More frequent & Severe

Salinity
Continue to Increase

Sea level Rise
Continue to Rise



Map source: Dastagir et al., 2015

Flash Flood
More severe & frequent

Urban flood
More frequent & intense

Heatwave
Prolonged

Flash flood
More intense

Landslides
Frequent

Cyclone and storm sur
Cyclone more intense
Increased Surge

Key Messages

- Extreme Rainfall over Bangladesh will be increased in the future. Chances of flash flood and land slides will be increased.
- Projected changes in mean annual precipitation and temperature over the basins are larger in 4°C than in 1.5°C or 2°C. Changes are greater over Meghna basin than Brahmaputra basin.
- Annual discharges of the Meghna basin change almost linearly with changes in the annual basin-averaged precipitation, while changes in discharges of the Brahmaputra basin are less sensitive to changes in precipitation.
- Mean monthly flows are projected to increase the most in July (for Brahmaputra and Ganges) and in June (for Meghna).
- Floods are likely to increase in both rivers as well as flood durations.
- However, Hydrological droughts are likely to decrease in both rivers along with drought durations.
- SLR rise will also cause permanent inundations in some parts of the coastal areas of Bangladesh.
- Under high emission RCP 8.5 scenarios the mean yield of Boro rice will decrease about 10% during 2030’s and about 20% by 2100.

Publications on floods and climate change

- Attributing the 2017 Bangladesh floods from meteorological and hydrological perspectives. Hydrology and Earth System Sciences, 23, 1409-1429, doi:10.5194/hess-23-1409-2019
- Attributing the 2017 Bangladesh floods from meteorological and hydrological perspectives. Hydrology and Earth System Sciences, 23, 1409-1429, doi:10.5194/hess-23-1409-2019
- Determining Flash Flood Danger Level at Gauge Stations of the North East Haor Regions of Bangladesh. Journal of Hydrological Engineering, 24(4), 05019004.
- Observed Trends in Climate Extremes over Bangladesh from 1981 to 2010. Climate Research , 77(1), 45-61.
- Future floods in Bangladesh under 1.5°C, 2°C and 4°C global warming scenarios. Journal of Hydrological Engineering, 23(12), 04018050.
- Challenges for flood risk management in flood prone Sirajganj region of Bangladesh. Journal of Flood Risk Management, e12450.
- A global network for operational flood risk reduction. Environmental Science & Policy, 84, 149-158.
- Regional changes of precipitation and temperature over Bangladesh using bias corrected multi-model ensemble projections considering high emission pathways. International Journal of Climatology, 38(4), 1634-1648. doi: 10.1002/joc.5284.
- Assessing High-End Climate Change Impacts on Floods in Major Rivers of Bangladesh Using Multi-Model Simulations. Global Science and Technology Journal, 6(2), 1-14.
- Impact of High-End Climate Change on Floods and Low Flows of the Brahmaputra River. Journal of Hydrologic Engineering, 22 (10), doi: 10.1061/%28ASCE%29HE.1943-5584.0001567.
- Extreme flows and water availability of the Brahmaputra River under 1.5°C and 2°C global warming scenarios, Climatic Change, pp 1-17, doi: 10.1007/s10584-017-2073-2.
- Hydrological response to climate change of the Brahmaputra basin using CMIP5 General Circulation Model ensemble. Journal of Water and Climate. doi:10.2166/wcc.2017.076.
- Assessing extreme rainfall trends over the northeast regions of Bangladesh, Theoretical and Applied Climatology, 1-12, doi: 10.1007/s00704-017-2285-4.

Publications on cyclone and storm surges

- Projected changes of inundation of cyclonic storms in the Ganges–Brahmaputra–Meghna delta of Bangladesh due to SLR by 2100. Journal of Earth System Science, 23, 1409-1429.

- Towards improved storm surge models in the northern Bay of Bengal. Continental Shelf Research, 135, pp.58-73. doi:10.1016/j.csr.2017.01.014.

- Mapping of Climate Vulnerability of the Coastal Regions of Bangladesh using Principal Component Analysis. Applied Geography, 102, 47-57.

- Seasonal modulation of M2 tide in the northern Bay of Bengal. Continental Shelf Research, 137:154-162, doi:10.1016/j.csr.2016.12.008.

- Tidal intrusion within a mega delta: An unstructured grid modelling approach. Estuarine, Coastal and Shelf Science, 182(5):12-26, doi:10.1016/j.ecss.2016.09.014.

- Improved bathymetric dataset and tidal model for the northern Bay of Bengal. Marine Geodesy. 39(6), pp. 422-438, doi:10.1080/01490419.2016.1227405.

- Modelling the increased frequency of extreme sea levels in the Ganges–Brahmaputra–Meghna delta due to sea level rise and other effects of climate change. Environ. Sci.: Processes Impacts, 2015 (17) 1311-1322 , doi:10.1039/C4EM00683F.

- Field investigation on the performances of the coastal structures during Cyclone SIDR, Natural Hazards Review, ASCE, Vol. 12, pp. 111-116.031 doi:10.1061/(ASCE)NH.1527-6996.0000