Dear Editor and Referees,

Thank you for your helpful comments and suggestions. All these suggestions helped us to improve the manuscript from its initial version. Please find our responses to the comments and suggestions below.

Reply to Anonymous Referee #1

This paper presents the results of numerical experiments to investigate the impact of sea level rise induced by climate change on the extent and severity of the inundation caused by tropical cyclone (TC) storm surges in coastal Bangladesh. As the authors correctly point out, the approach used is a quite simple one and does not take into account relevant aspects such as possible future modifications in TC tracks and intensity and morphological changes. Nevertheless, the manuscript is an original contribution to the issue of climate change-induced hazards and the results of the study provide interesting suggestions for mitigation measures to be taken by policy makers and can encourage further research about this topic. The manuscript is quite well organized and written, even though the presentation of the results is somewhat confusing in some parts and should be revised and made clearer. In my opinion, the paper can be accepted for publication after the following comments are addressed.

We appreciate the comments from referee and would like to thank for evaluations and feedback which helped to improve the manuscript.

General comment #1: *The description of results in Sections 3.2-3.4 can be sometimes confusing and has to be improved. The authors in some cases comment about absolute values of inundated areas extent in km2 or storm surge height, in other cases provide information about percent variations of simulated values with respect to present time and percentages related to the same quantities appear even inconsistent (see, e.g. lines 363 and 372). This is particularly the case of Section 3.4, where the discussion about Figure 7 is hard to follow. Lines 310-314 seem to repeat what stated in lines 295-301 but numbers are slightly different. The caption of Figure 7 itself is wrong, because each of the four plots shows the comparison of present time water level with both the considered future scenarios. Also, the higher percent variation in storm surge height at Charchanga station obtained for TC Aila with respect to Sidr is not intuitive and the authors should provide some interpretation attempt. In conclusion, my suggestion is to thoroughly revise this sections and to add one or more tables (e.g. one for inundation extent and another one for storm surge height) containing both the absolute values and the percent variations with respect to the present time scenario.*

Thank you for pointing out these problems. In the revised manuscript, we've updated it by adding both the absolute values and percent variations in the write up to make it easier to follow. Two separate tables were also added both for inundated area and storm surge level and their percent change to identify the differences easily.

In the initial submission of manuscript, some errors existed in Section 3.4. We apologize for this mistake. We conducted another round of more thorough check when we worked on the revision and identified these errors. In the revised manuscripts, those errors were corrected. But these corrections did not change the major conclusions. Corrections that were made in Section 3.4 are as follows:

Line 295 [Revised line 279]: 2.13 meters instead of 2.3 meters.

Line 296 [Revised line 280]: 13.90% instead of 21%.

Line 297 [Revised line 281]: 28.88% instead of 37%.

Line 298 [Revised line 282]: 2.41 m instead of 2.6 m.

Line 300 [Revised line 284-285]: 14.02% instead of 14% …. 1.87 meters instead of 2.24 meters……33.54% instead of 31%........2.19 m instead of 2.59 m.

Line 302 [Revised line 288-289]: 22.48% instead of 22%..........1.29 meters instead of 1.61 meters.

Line 304 [Revised line 290]: 51.94% instead of 51%

Line 307 [Revised line 293]: 3.07 meters instead of 3.01 meters…….22.80% instead of 50%

Line 308 [Revised line 294]: 54.80% instead of 68%.

A new table (Table 6) with all the calculations was also added in the manuscript.

Based on the corrected calculations, we've also updated figure 7. In the initial submission, Figure 7a was mentioned as "TC Sidr at Barisal" and Figure 7b was mentioned as "TC Sidr at Charchanga". Actually, Figure 7a was representing TC Sidr at Charchanga and Figure 7b was representing TC Sidr at Barisal. We've corrected these mistakes in the updated manuscript.

We've also corrected the calculation error in line 363 [revised line 356] and 372 [revised line 365]. In line 363 [revised line 356], it should be 28.31% - 53.00% as shown in newly added Table 5. In line 372 [revised line 364], it was incorrectly written as 38% and 48%. It should be 31% and 53%, based on the calculation shown in Table 5. In the revised version, it was corrected. Also, in line 374 [revised line 365], the percentage values were corrected and it should be 28.31% and 46.52% instead of 25% and 34%.

Caption of Figure 7 was also updated based on the suggestion.

An additional paragraph and a new column in Table 6 was added based on the comment of reviewer #2 to represent the relation between SLR and the additional increase of storm surge level. Following underlined paragraph was added at the end of section 3.4 [Revised line 295-305]:

To analyze the linearity/non-linearity of storm surge level with respect to SLR, we conducted additional experiments based on 5 SLR scenarios; present-day sea level, 0.26 m of SLR, 0.33 m of SLR, 0.4 m of SLR, 0.47 m of SLR, 0.54 m of SLR, respectively. Results from these experiments are presented in Table 6.

For the case of TC Sidr in Barisal and Charchanga stations, storm surge level increased almost linearly with respect to the addition of water due to the effect of SLR. For example, with an SLR of 0.47 m, the increases of storm surge level with respect to present day in Barisal and Charchanga stations were 0.45 m and 0.44 m, respectively (Table 6). On the other hand for the case of TC Aila, with an SLR of 0.26 m, the increases in storm surge level were found 0.29 m and 0.57 m respectively for the Barisal and Charchanga station (Table 6). Though the storm surge level is increasing almost linearly with the addition of sea water, however, there are still differences found between them, which could be influenced by the modification of ocean bathymetry to incorporate the effect of SLR. The margin of differences is higher for the Charchanga station comparing it with the Barisal station. The coarse resolution of topography near that area might be responsible for that.

Following are the two tables that were added in the updated manuscript for section 3.3, section 3.4 and updated Figure 7.

Table 5. Comparison of inundated area between present day & future SLR scenarios and calculated change in percentage with respect to present day scenario.

Scenario	**TC Sidr**		**TC Aila**	
	Inundated Area (km^2)	**(%) increase**	**Inundated Area (km^2)**	**(%) increase**
Present-day	1860.00		1208.00	
Mid-21st-century	2436.60	31.00	1550.00	28.31
End-21st-century	2845.80	53.00	1770.00	46.52

Table 6. Comparison of storm surge level between present day & future SLR scenarios and increase in storm surge level with respect to the present day scenario for the case of TC Sidr and TC Aila in Barisal and Charchanga observational stations. The SLR scenarios of 0.33 m, 0.40 m and 0.47 m were used to examine the linearity/non-linearity of increase in storm surge level with respect to SLR conditions.

SLR Scenarios (m)	TC SIDR				TC AILA			
	Barisal		Charchanga		Barisal		Charchanga	
	surge(m)	increase(m) and %	surge(m)	increase(m) and %	surge(m)	increase(m) and %	surge(m)	increase(m) and %
0.00 (present-day)	1.87	n/a	1.64	n/a	1.29	n/a	2.50	n/a
0.26 (mid-21st-century)	2.13	0.26 (13.90%)	1.87	0.23 (14.02%)	1.58	0.29 (22.48%)	3.07	0.57 (22.80%)
0.33	2.21	0.34 (18.18%)	1.95	0.31 (18.90%)	1.66	0.37 (28.68%)	3.22	0.72 (28.80%)
0.40	2.26	0.39 (20.85%)	2.00	0.36 (21.95%)	1.75	0.46 (35.65%)	3.42	0.92 (36.8%)
0.47	2.32	0.45 (24.06%)	2.08	0.44 (26.83%)	1.82	0.53 (41.08%)	3.67	1.17 (46.80%)
0.54 (end-21st-century)	2.41	0.54 (28.88%)	2.19	0.55 (33.54%)	1.96	0.67 (51.94%)	3.87	1.37 (54.80%)

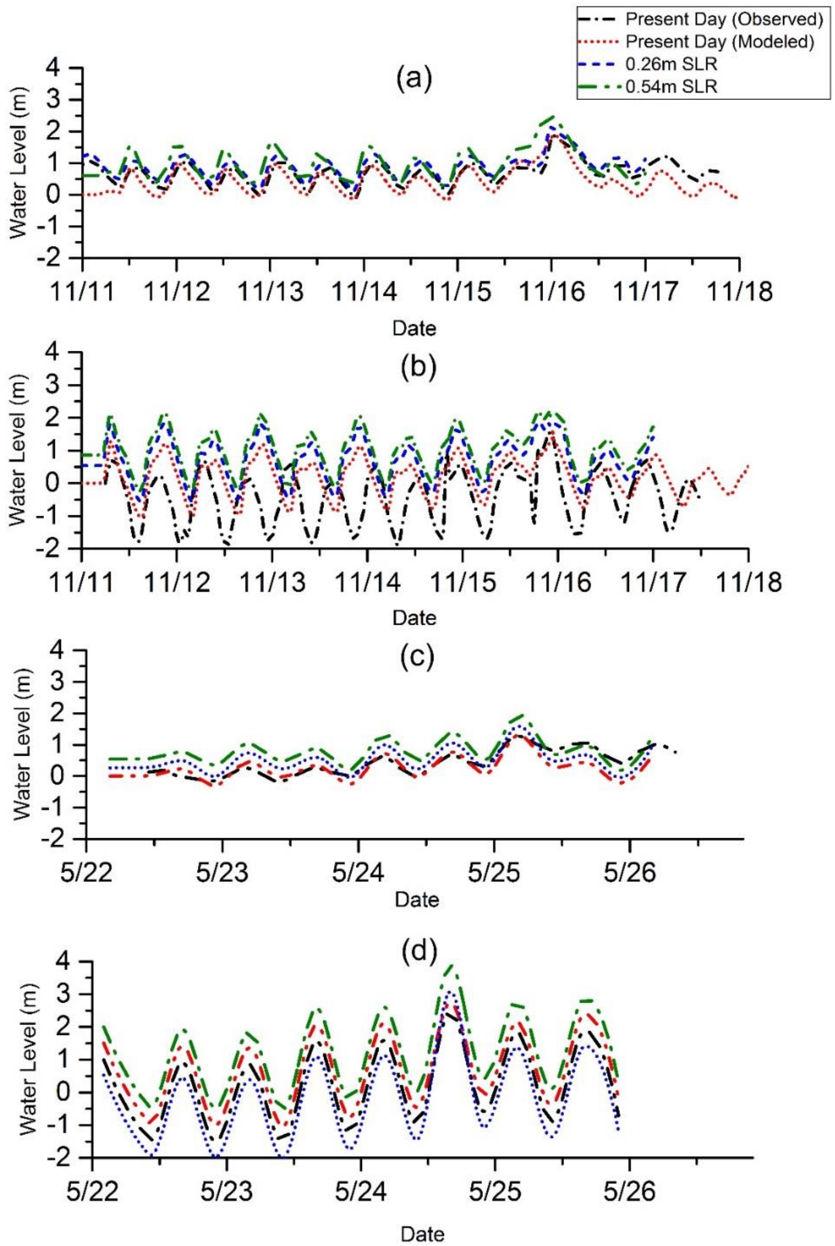

Figure 7. Comparison of storm surge water level between present day and future SLR scenarios. (a) TC Sidr at Barisal (b) TC Sidr at Charchanga (c) TC Aila at Barisal (d) TC Aila at Charchanga. The observed, modeled present-day, mid-of-21st century and end-of-21st century storm surge levels are denoted by the solid, red dashed, blue dotted, and greenred dash-dottted lines, respectively.

Specific comments:

#1

Please check the correspondence between the references in the list and the citations in the text. For instance, the works by Mohal et al. (2006) and by Vatvani et al. (2002) seem to be missing in *the text. Also, the reference to the Delft3D-FLOW manual is not coincident (Delft Hydraulics in the text vs. Hydraulics, D. in the reference list.*

Mohal et al. (2006) was removed from the reference list since it was not cited in the main text. Vatvani et al. (2002) should be in section 2.1.3 but somehow it went missing. In the updated manuscript, it was added at the end of section 2.1.3. Along with that, we've also added the refence from Holland (1980) at the end of section 2.1.3.

Reference to the Delft3D-FLOW manual was also corrected in the reference list. Thank you for pointing out these errors.

A general revision of the whole text is needed to eliminate several typing and punctuation errors, uppercase and lowercase letter usage, and missing or unnecessary blanks.

A general revision has been carried out to eliminate typing, punctuation and grammar errors.

***#2** Line 55: replace locale with locales.*

Corrected

***#3** Line 310-314 are redundant.*

Removed.

***#4** At the end of the Introduction, a brief paragraph illustrating the structure of the manuscript should be added.*

Thank you for the suggestion. We've added the following paragraph at the end of introduction section: [Revised line 105-109]:

The structure of the paper is as follows: brief description of the Delft3D Flow model and the methodologies used to simulate future changes in storm surge and inundation, to generate ensemble projections of storm surge inundation were discussed in section 2, In section 3, validation of the model results, present day storm surge inundation scenarios, ensemble projection of storm surge inundation and future change in storm surge level were presented. Section 5 includes, discussion on model results and the uncertainties associated with the future projections. Finally, section 5 presents the concluding remarks on research findings.

***#5** In Equations (2) and (3), the term P0 is not defined.*

It's the density of water. We've corrected it in the updated version.

***#6 Line 143:** replace weas with was.*

Corrected.

#7 Lines 145-147: *please provide some information about the native resolution of the topography and bathymetry data used.*

We've added the details on bathymetry and topography section.

In line 145, "The land elevations are specified using the data from the Center for Environmental and Geographic Information Services (CEGIS), Bangladesh" since they're based NASA's Shuttle Radar Topography Mission (SRTM) 90m resolution datasets.

Following lines were added in the 2.1.2 Model Grid and Bathymetry sections:

In this study, the land topography data were obtained from NASA's Shuttle Radar Topography Mission (SRTM) 90-m resolution datasets (Figure 1b). The ocean bathymetry wais specified using the data from the General Bathymetric Chart of the Oceans 30-arc-sec interval gridded data (BODC, 2003, Figure 1b).

#8 Line 156: the reference should be to the work by Holland (1980), I suppose.

Actually, it should be Hemming et al. (1995) instead of Hemming et al. (1980). Delft3D uses Wind Enhancement Scheme (WES) which is based on Holland's Wind Model (1980) in order to bring asymmetry by applying the translation speed of the cyclone center displacement as steering current and by introducing rotation of wind speed due to friction.

#9 In Equation (6) the term e is not defined.

It's the base of the natural logarithm (=2.71828182846) (Delft Hydraulics, 2011). We've included this information in the revised version.

#10 In Equation (8) the definition of MAE is not correct.

Corrected.

#11 Line 218-219: the BIWTA acronym has been already introduced and can be used without the full explanation.

Corrected.

#12 Line 376: replace "the probable range of inundated are" with "the most probable range of inundated area extent".

Replaced.

#13 Line 480: replace representing with represent.

Replaced.

#14 Lines 506-508: uppercase letter are unnecessary for measured and modeled water level.

Corrected.

#15 Line 556: replace showing with is showing.

Corrected.

#16 Table 2: 12 historical TC tracks are used in ensemble projection as mentioned in Sections 2.2 and 3.3.1. In my opinion, a further figure illustrating each track and/or just a table listing the main characteristics of each storm (e.g. name, intensity, day of landfall, etc) would be useful.

Thank you for the suggestion. We've included Table 2 with the information of 12 historical TC tracks that were used for ensemble projections.

Table 2 List of 12 historical TC events used for ensemble projection of storm surge inundation

Name	Date	Landfall
Tropical storm 13	14-18 November, 1973	Noakhali
Cyclone 12	23-28 November, 1974	Bhola
Tropical storm 19	07-12 November, 1975	Chittagong
Tropical storm 1	22-25 May, 1985	Noakhali
Cyclone 4	21-30 November, 1988	Khulna
Cyclone 2	22-30 April, 1991	Chittagong
Cyclone 2	26 April – 30 May, 1994	Cox's Bazar

Cyclone 4	18-25 November, 1995	Cox's Bazar
Cyclone 1	13-20 May, 1997	Noakhali
Tropical storm 4	24-27 October, 2008	Barguna
Tropical storm Mahasen	10-16 May, 2013	Patuakhali
Tropical storm Roanu	18-21 May, 2016	Chittagong

#17 Table 3: the third row with average values of statistical indicators can be eliminated, because averaging just two values is poorly significant.

Thank you. It was eliminated.

Reply to Anonymous Referee #2

The paper addresses the potential influence of SLR on the flooding exposure during tropical cyclones in Bangladesh. The hydrodynamic model Delft-FLOW is used to simulate two historical storms and some future scenarios reflecting SLR of different magnitudes and uncertainties due to TC intensity and timing with respect to the tidal phase. Model results are validated against tide gauge measurements during the TC events. Further the authors investigate how inundated area and storm surge height would be changed if SLR would be present, assuming the properties of TCs remain unchanged. They conclude that even considering uncertainties of present-day TC properties the amount of flooded land would increase dramatically. The paper is well composed and clearly written. The objectives, methodology and results are sufficiently described. The discussed problematic is relevant and adds to the insight of the SLR consequences at regional scale. The approach of separating the sources of uncertainty and selecting a single trigger (here SLR) for the analysis contributes to better understanding of the potential changes in the local system.

We would like to thank the referee for the evaluation and for providing feedback which helped to improve the manuscript. Please find our responses below for general and minor comments.

However, as the authors also pointed out, there are many unconsidered conditions like changes in TCs intensity, morphology, river discharge, etc. This undermines the value of particular resultant numbers if they are considered without more generalized conclusions. For example, what would happen if the SLR of 0.4 or 0.7m occurs? Some discussion going beyond the presented two SLR case studies would be appropriate. I propose to put the results described in the Section 3.4 in relation with the SLR values and not only with the present-day inundated area/storm surge height. It would be interesting to see the direct comparison (in % or absolute values) of changes in storm surge height with respect to SLR, e.g. for TC Sidr and Charchanda it would be 0.27m increase for

0.26m SLR, which is basically a linear addition of SLR magnitude on top of the present-day surge, and 0.62m change for 0.54m of SLR, which has a considerable non-linear contribution. This could give an insight into the (non)linearity of the storm surge and SLR interactions for particular area.

Thank you for the suggestion. In the initial submission of manuscript, some errors existed in Section 3.4. We apologize for this mistake. We conducted another round of more thorough check when we worked on the revision and identified these errors. In the revised manuscripts, those errors were corrected. But these corrections did not change the major conclusions. Corrections that were made in Section 3.4 are as follows:

Line 295 [Revised line 279]: 2.13 meters instead of 2.3 meters.

Line 296 [Revised line 280]: 13.90% instead of 21%.

Line 297 [Revised line 281]: 28.88% instead of 37%.

Line 298 [Revised line 282]: 2.41 m instead of 2.6 m.

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Line 307 [Revised line 293]: 3.07 meters instead of 3.01 meters…….22.80% instead of 50%

Line 308 [Revised line 294]: 54.80% instead of 68%.

A new table (Table 6) with all the calculations regarding storm surge level was also added in the manuscript.

Based on the corrected calculations, we've also updated figure 7. In the initial submission, Figure 7a was mentioned as "TC Sidr at Barisal" and Figure 7b was mentioned as "TC Sidr at Charchanga". Actually, Figure 7a was representing TC Sidr at Charchanga and Figure 7b was representing TC Sidr at Barisal. We've corrected these mistakes in the updated manuscript.

Regarding the relation between SLR and the additional increase of storm surge level following underlined paragraph was added at the end of section 3.4. Also, the results from these experiments were added in Table 6. Thank you for giving the idea to analyze this relation. [Revised line 295-305]:

To analyze the linearity/non-linearity of storm surge level with respect to SLR, we conducted additional experiments based on 5 SLR scenarios; present-day sea level, 0.26 m of SLR, 0.33 m of SLR, 0.4 m of SLR, 0.47 m of SLR, 0.54 m of SLR, respectively. Results from these experiments are presented in Table 6.

For the case of TC Sidr in Barisal and Charchanga stations, storm surge level increased almost linearly with respect to the addition of water due to the effect of SLR. For example, with an SLR of 0.47 m, the increases of storm surge level with respect to present day in Barisal and Charchanga stations were 0.45 m and 0.44 m, respectively (Table 6). On the other hand for the case of TC Aila, with an SLR of 0.26 m, the increases in storm surge level were found 0.29 m and 0.57 m respectively for the Barisal and Charchanga station (Table 6). Though the storm surge level is increasing almost linearly with the addition of sea water, however, there are still differences found between them, which could be influenced by the modification of ocean bathymetry to incorporate the effect of SLR. The margin of differences is higher for the Charchanga station comparing it with the Barisal station. The coarse resolution of topography near that area might be responsible for that.

In the revised manuscript, we've added two other new tables. Table 2 was added to list the TC names that were used to make ensemble projections. Table 5 was added to summarize the results from storm surge inundation section.

Table 2 List of 12 historical TC events used for ensemble projection of storm surge inundation

Name	**Date**	**Landfall**
Tropical storm 13	14-18 November, 1973	Noakhali
Cyclone 12	23-28 November, 1974	Bhola
Tropical storm 19	07-12 November, 1975	Chittagong
Tropical storm 1	22-25 May, 1985	Noakhali
Cyclone 4	21-30 November, 1988	Khulna
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Cyclone 2	26 April – 30 May, 1994	Cox's Bazar
Cyclone 4	18-25 November, 1995	Cox's Bazar
Cyclone 1	13-20 May, 1997	Noakhali
Tropical storm 4	24-27 October, 2008	Barguna
Tropical storm Mahasen	10-16 May, 2013	Patuakhali
Tropical storm Roanu	18-21 May, 2016	Chittagong

Table 5. Comparison of inundated area between present day & future SLR scenarios and calculated change in percentage with respect to present day scenario.

Scenario	**TC Sidr**		**TC Aila**	
	Inundated Area (km^2)	**(%) increase**	**Inundated Area (km^2)**	**(%) increase**
Present-day	1860.00		1208.00	
Mid-21st-century	2436.60	31.00	1550.00	28.31
End-21st-century	2845.80	53.00	1770.00	46.52

Table 6. Comparison of storm surge level between present day & future SLR scenarios and increase in storm surge level with respect to the present day scenario for the case of TC Sidr and TC Aila in Barisal and Charchanga observational stations. The SLR scenarios of 0.33 m, 0.40 m and 0.47 m were used to examine the linearity/non-linearity of increase in storm surge level with respect to SLR conditions.

SLR Scenarios (m)	TC SIDR				TC AILA			
	Barisal		Charchanga		Barisal		Charchanga	
	surge(m)	increase(m) and %	surge(m)	increase(m) and %	surge(m)	increase(m) and %	surge(m)	increase(m) and %
0.00 (present-day)	1.87	n/a	1.64	n/a	1.29	n/a	2.50	n/a
0.26 (mid-21st-century)	2.13	0.26 (13.90%)	1.87	0.23 (14.02%)	1.58	0.29 (22.48%)	3.07	0.57 (22.80%)
0.33	2.21	0.34 (18.18%)	1.95	0.31 (18.90%)	1.66	0.37 (28.68%)	3.22	0.72 (28.80%)
0.40	2.26	0.39 (20.85%)	2.00	0.36 (21.95%)	1.75	0.46 (35.65%)	3.42	0.92 (36.8%)
0.47	2.32	0.45 (24.06%)	2.08	0.44 (26.83%)	1.82	0.53 (41.08%)	3.67	1.17 (46.80%)
0.54 (end-21st-century)	2.41	0.54 (28.88%)	2.19	0.55 (33.54%)	1.96	0.67 (51.94%)	3.87	1.37 (54.80%)

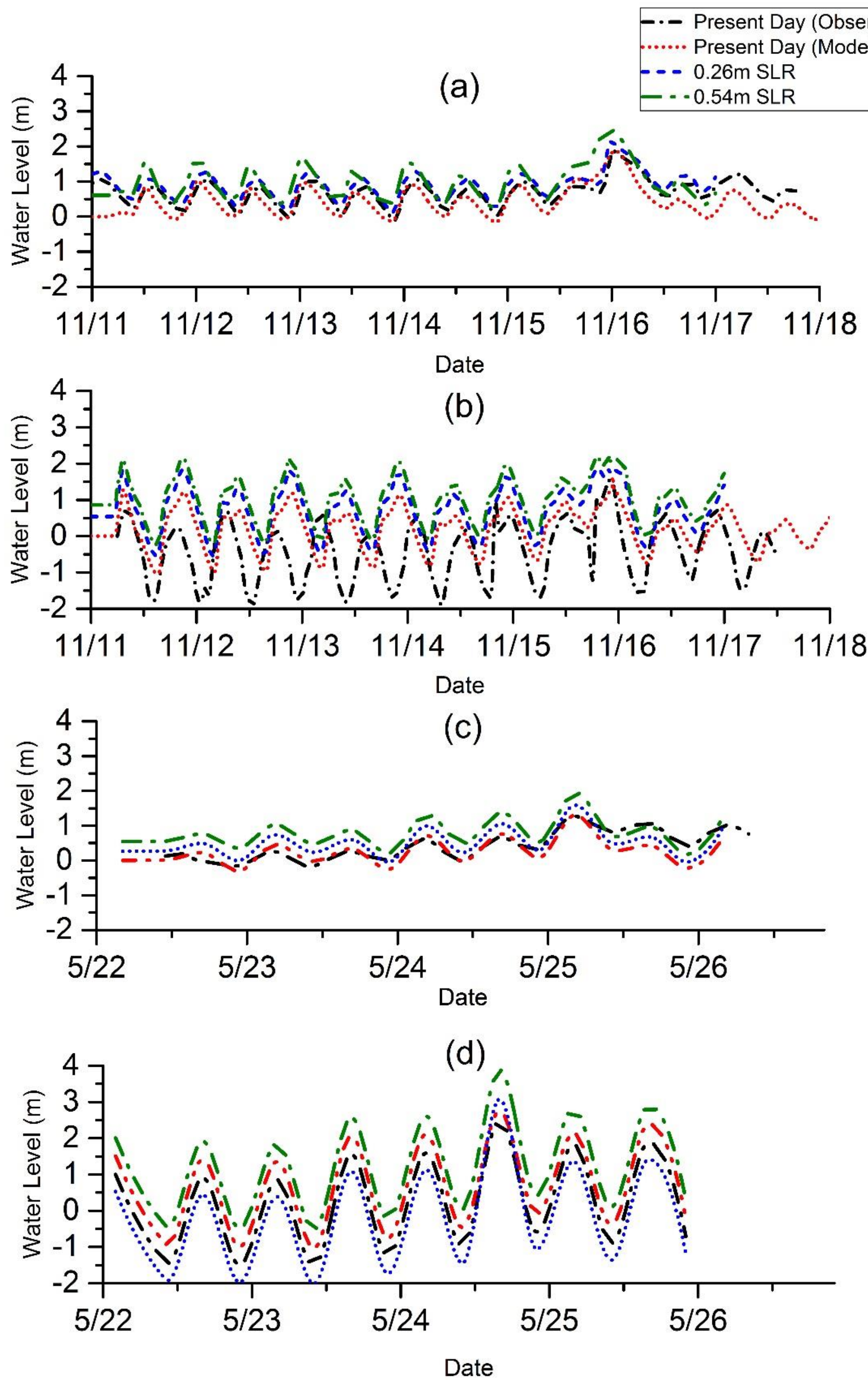

Figure 7. Comparison of storm surge water level between present day and future SLR scenarios. (a) TC Sidr at Barisal (b) TC Sidr at Charchanga (c) TC Aila at Barisal (d) TC Aila at Charchanga. The observed, modeled present-day, mid-of-21st century and end-of-21st century storm surge levels are denoted by the solid, red dashed, blue dotted, and greenred dash-dottted lines, respectively.

It would be very helpful to include the terrain map of the model region with land elevation and land/water mask for better understanding of the present day situation and possible impacts. It could be combined with Figure 1 or not. Some names on Figure 1 would be also helpful (like main rivers, measurement location names, etc).

We've added an additional figure showing the elevation of land and river as Figure 1b in the updated manuscript. The area near the coastal zone are very flat which can be seen from the figure 1b. This make the region vulnerable to flooding easily even under normal astronomical tide conditions. We've also shown the location of Ganges, Brahmaputra and Meghna river on Figure 1a. Two separate colors were used to represent the two observational stations. Thank you for the suggestion. Following is the updated Figure 1.

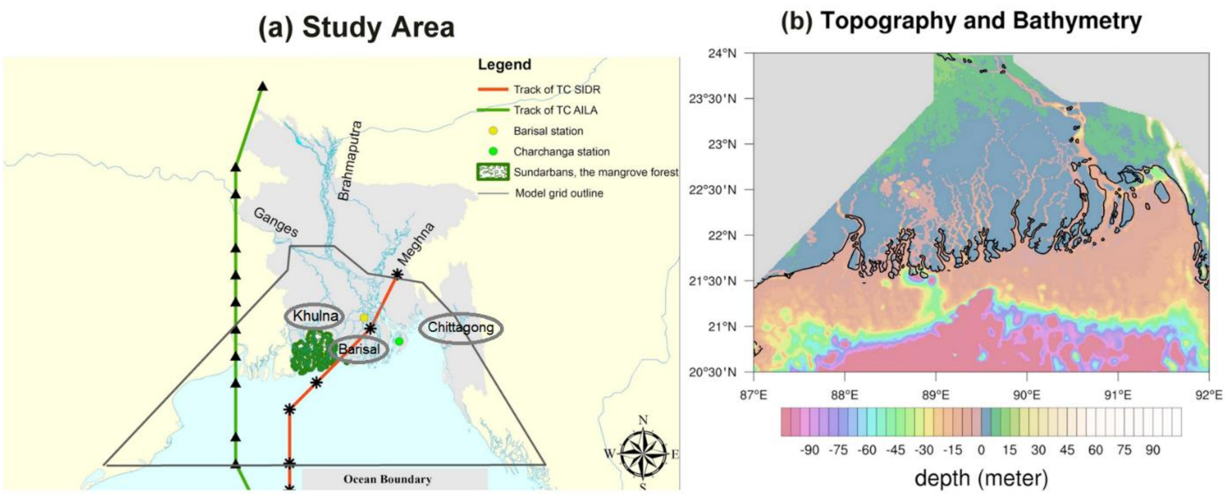

Figure 1. (a) Map of the study area for this work. The red and green lines represent the tracks of TC Sidr and TC Aila respectively. Area marked with green color indicates the Sundarban mangrove forest region. Two circles over the study area are the observation stations of Bangladesh Inland Water Transport Authority (BIWTA). The black colored outline shows the extent of model grid over the region. (b) Topography and bathymetry of the model domain. Negative depth values are representing water bodies (ocean and rivers) and positive depth values area representing land.

Minor Comments:

- p2. lines 55-56: "... causing deaths ... of lives". Please reformulate ('causing deaths of people' OR 'causing loss of lives')

Corrected.

- p3. line 83: please coordinate singular/plural forms "the impact ... are debatable"

Corrected.

- p4. lines 110-114: this passage looks like repetition of the previous one. Please remove or reformulate.

Removed.

- p5. line 143: ". . . weas . . ." typo?

Corrected.

- p5. lines 151-171: It is not quite clear from this description whether Delft3D has special module for generating wind and pressure fields from the TC track. If yes, and it ". . . slightly improves the original WES. . .", why the authors are still using WES and not Delft3D? If not, and wind and pressure are firstly generated by WES method and then fed to the Delft3d, then the description is misleading.

For storm surge simulations with Delft3D-FLOW, a Wind Enhance Scheme (WES) following Holland has been devised to generate tropical cyclone wind field (Delft Hydraulics, 2011). It's a built-in function in Delft3D-FLOW module. The earlier version of WES was developed by UK Met Office (Hemming et al. 1985). Later, it was further improved by Delft3D-FLOW by applying the translation speed of the cyclone center displacement as steering current and by introducing rotation of wind speed due to friction. All the version of WES is based on Holland's Wind Model (Holland, 1980). So, in this paper we used the improved version of WES (Delft Hydraulics, 2011) which is a built-in function of Delft3D-FLOW program. In the revised manuscript, we've added the citation of Delft3D-FLOW module's WES in section 2.1.3.

- p6. line 193: ". . . Storm surge. . ." -> "storm surge"

Corrected.

- p7. line 209: by tidal data the water elevation is meant? What type of instrument has been used, tide gauge?

By tidal data, we meant the water level elevation. Bangladesh Inland Water Transport Authority (BIWTA) uses auto tide gauge which provides hourly measurement of water level near the coast.

- p7. line 212: "(-ve)infinity . . ." typo?

Actually by using (-ve)infinity, we meant negative. we've changed it to 'negative' in the revised version to remove the confusion.

- p8. lines 269-272: repeated passage, please remove

Removed. Thank you for pointing that out.

- p10. lines 310-313: please review or remove the passage, it does not describe Figure 7.

Removed.

- *p10. line 317: ". . . future TCs remain the same strength. . ." – either 'keep the same strength' or 'remain of the same strength'*

Corrected.

- *p10. line 322: "one of the methods we experimented in this study. . ." – either 'methods with which we experimented. . .' or 'methods that we tested'*

Corrected.

- *p10. line 327-328: ". . . the results looked much realistic. . ." -> . . . the results looked much more realistic. . .*

Corrected.

- *p10. Lines 344-345: ". . .focus of the paper is to predict the future scenarios. . ." – please change 'predict' to assess/estimate/develop ". . . and comparison with. . ." -> 'and to compare with'*

Corrected.

- *p11. line 360: ". . . first floor is kept transparent. . ." – What does transparent mean in this context? Why is it relevant here?*

To reduce confusion, this has been changed to "In TC shelters, the first floor should be kept above the high surge waters."

- *Figures 3b and 7a: for the case of TC Sidr in Charchanga the timeseries of measured and modelled water levels look somewhat different and out of phase. Do the authors have an explanation for this?*

I think here you mean 3b and 7b. For the case of TC Sidr in Charchanga station (Figure 3b and Figure 7b), there's a slight shift in phase occurred during the period of November 13 to November 15. This could be due to the presence of a seiche near the gauge that interfered with the astronomical tide, and the seiche was not resolved in the model simulation, which caused the discrepancy.

Reply to Anonymous Referee #3

The paper uses numerical modelling to analyze the effects of sea level rise (SLR) on the storm surge generated by tropical cyclones (TC) in the Bangladesh coast and the associated inundation on that area. Model results are validated using observations of two previous TC and a number of *additional simulations are made to study future scenarios. The manuscript is pretty well written, although it can be improved following the suggestions detailed below. Besides the assumptions made to simplify the high level of uncertainty, the obtained results show how SLR would increase the inundation associated to TC in this area and can help coastal managers to design adaptation measures to deal with these problems. Therefore, the manuscript fits the scope of NHESS and may be published provided the authors address the following comments.*

We would like to thank the referee for the evaluation and for providing feedback which helped to improve the manuscript. Please find our responses below for general and minor comments.

General comments –

The authors should justify why they use the SLR projections from AR4 (IPCC, 2007) (line 60) instead of those from AR5 (IPCC, 2013), although they are based on the worst AR4 scenario (A1F1, line 72). Taking into account that regional SLR rates are much higher than the global rate (lines 64-66) and that global SLR projections from AR5 are worse than AR4, the scenarios considered by the authors could be too optimistic.

The SLR projections used in this research is from Caesar et al. (2017; under review) which is based on IPCC AR5. We've modified the manuscript text to clarify and added the information about AR5.

In this proposed work, we will use the SLR projections from Caesar et al. (2017; under review), which **is** based on IPCC AR5 and suggests a projection of SLR of 26 cm for the mid-21st century (2040 -2060) and 54 cm for the end-21st century (2079 -2099).

- A number of geographical sites are cited in the text (e.g. Bay of Bengal and Andaman Sea (line 37); Ganges, Brahmaputra, Meghna rivers (line 92); Baguna (lines 97 and 100); Patuakhali (lines 99 and 106); Khulna (lines 100 and 106); Jhalokati (line 100); Chandpur (line (106), Sundarban (lines 238, 239, 240)) that should be placed in a map to facilitate the reading of the text. In the same way, a figure showing the topography of the area would be very useful. In addition, the shorelines should be clearer in figures 1, 4, 5 and 8, to better understand the magnitude of the flooded areas.

Thank you for the suggestion. We've updated Figure 1 and added another one with that to represent the topography and bathymetry of the study area as Figure 1b. We've made the shorelines more clear in the updated figures (Figure1, 4, 5, 8). The location of the Ganges, Brahmaputra and Meghna river was also marked on the map. Green colored area is showing Sundarban forest and its under Khulna division. In addition, the landfall locations of the storms were marked on the map. Since Patuakhali, Barguna and Jhalokathi are under the Barisal division, we've marked the Barisal division on the map. And Chandpur is under the Chittagong division and it was also marked on the map.

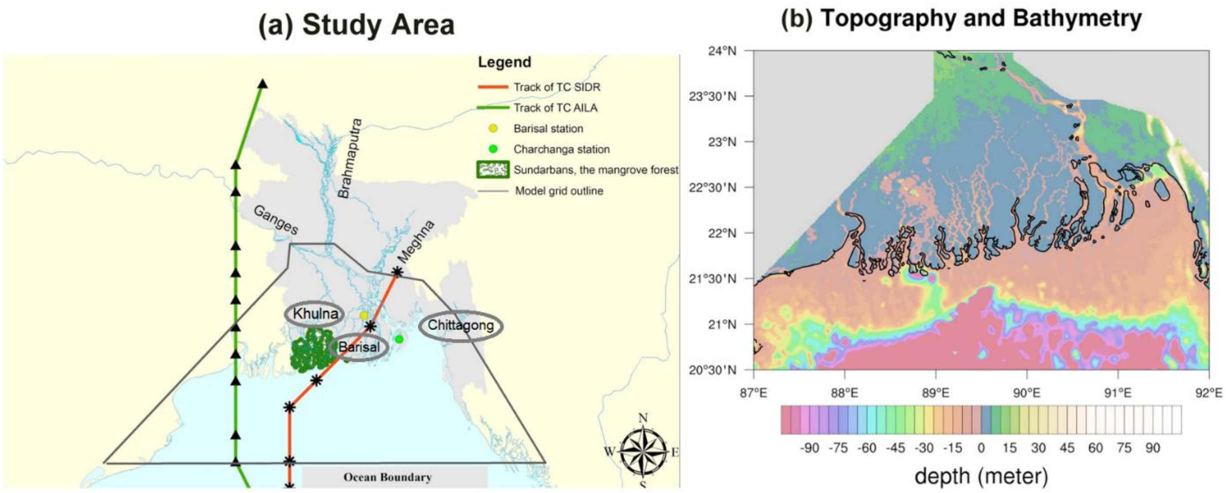

Figure 2. (a) Map of the study area for this work. The red and green lines represent the tracks of TC Sidr and TC Aila respectively. Area marked with green color indicates the Sundarban mangrove forest region. Location of the Ganges, Brahmaputra and Meghna rivers are shown on the map. Khulna, Barisal and Chittagong which are landfall locations for the historical TCs used for ensemble projection, shown inside a circular box on the map. Two circles over the study area are the observation stations of Bangladesh Inland Water Transport Authority (BIWTA). The black colored outline shows the extent of model grid over the region. (b) Topography and bathymetry of the model domain. Negative depth values represent water bodies (ocean and rivers) and positive depth values areas represent land.

- In lines 201-206 the authors discuss the potential influence of the tide level on the inundation and indicate that different simulations have been performed considering diverse tide conditions, which are summarized in Table 2. However, nowhere is the magnitude of the tides shown. A description of tide features is necessary to understand the influence of this factor in the inundation.

In line 192, we've added this:

For example, the tides shown in Figures 3 and 7 as the water level oscillations have amplitudes as high as 3 m, which could significantly affect the extension of flooded area, depending on whether the storm's landfall coincides with a high tide or a low tide.

And in line 196, we've added the following:

The change of timing in these tide-related experiments was implemented by modifiying the tracks of the storms so that their landfalls coincide with a high tide, a tide, or a zero-tide condition, in addition to their actual tidal phases.

- The writing of sections 3.2, 3.3, 3.4 and 4 is a little bit confusing with the mixing of percentages, inundation areas and water levels. Perhaps the results could be summarized in a table to ease the understanding of the changes associated to each scenario.

Thank you for the suggestion. We've added two new tables for section 3.3 and 3.4. in addition to that, we've added a new Table 2 showing the TC tracks that were used in the ensemble projections.

Table 5. Comparison of inundated area between present day & future SLR scenarios and calculated change in percentage with respect to present day scenario.

Scenario	**TC Sidr**		**TC Aila**	
	Inundated Area (km^2)	**(%) increase**	**Inundated Area (km^2)**	**(%) increase**
Present-day	1860.00		1208.00	
Mid-21st-century	2436.60	31.00	1550.00	28.31
End-21st-century	2845.80	53.00	1770.00	46.52

Table 6. Comparison of storm surge level between present day & future SLR scenarios and increase in storm surge level with respect to the present day scenario for the case of TC Sidr and TC Aila in Barisal and Charchanga observational stations. The SLR scenarios of 0.33 m, 0.40 m and 0.47 m were used to examine the linearity/non-linearity of increase in storm surge level with respect to SLR conditions.

SLR Scenarios (m)	TC SIDR				TC AILA			
	Barisal		Charchanga		Barisal		Charchanga	
	surge(m)	increase(m) and %	surge(m)	increase(m) and %	surge(m)	increase(m) and %	surge(m)	increase(m) and %
0.00 (present-day)	1.87	n/a	1.64	n/a	1.29	n/a	2.50	n/a
0.26 (mid-21st-century)	2.13	0.26 (13.90%)	1.87	0.23 (14.02%)	1.58	0.29 (22.48%)	3.07	0.57 (22.80%)
0.33	2.21	0.34 (18.18%)	1.95	0.31 (18.90%)	1.66	0.37 (28.68%)	3.22	0.72 (28.80%)
0.40	2.26	0.39 (20.85%)	2.00	0.36 (21.95%)	1.75	0.46 (35.65%)	3.42	0.92 (36.8%)
0.47	2.32	0.45 (24.06%)	2.08	0.44 (26.83%)	1.82	0.53 (41.08%)	3.67	1.17 (46.80%)
0.54 (end-21st-century)	2.41	0.54 (28.88%)	2.19	0.55 (33.54%)	1.96	0.67 (51.94%)	3.87	1.37 (54.80%)

Table 2 List of 12 historical TC events used for ensemble projection of storm surge inundation

Name	**Date**	**Landfall**
Tropical storm 13	14-18 November, 1973	Noakhali
Cyclone 12	23-28 November, 1974	Bhola
Tropical storm 19	07-12 November, 1975	Chittagong
Tropical storm 1	22-25 May, 1985	Noakhali
Cyclone 4	21-30 November, 1988	Khulna
Cyclone 2	22-30 April, 1991	Chittagong
Cyclone 2	26 April – 30 May, 1994	Cox's Bazar
Cyclone 4	18-25 November, 1995	Cox's Bazar
Cyclone 1	13-20 May, 1997	Noakhali
Tropical storm 4	24-27 October, 2008	Barguna
Tropical storm Mahasen	10-16 May, 2013	Patuakhali
Tropical storm Roanu	18-21 May, 2016	Chittagong

- *Lines 321-324: In the discussion about the used methods, the authors say that they "included the increased sea level in open ocean boundary instead of adding it into the whole ocean depth". In my opinion this makes no sense because it introduces a discontinuity in the water level that physically is not possible. As the authors say, this produces an additional pressure gradient force acting towards the coast. Therefore, the obtained results are spurious. I suggest removing any reference to this method, including figure 8.*

This method was actually not used in this study to simulate future storm surge inundation. This method was used by some previous studies (Pickering et al. 2012) which we included in the revised text [Revised line 313]:

Rather, we included this as part of sensitivity experiments to show how the inundation could be different based on the consideration of SLR in the model. In the later part, we also clarified by mentioning this [Revised line 318-320]:

To make the future SLR simulation realistic, we considered the increased sea level in ocean bathymetry and increased the depth by 0.26 and 0.54 m, respectively, by considering land submergence near the coast. In that case, the result looked much more realistic than the previous one and this is the method we followed in this paper.

Some of the presented results seem inconsistent:

o In Figure 5 the comparison of inundated areas between present day and future climate scenarios is shown. In this figure, there are several small areas of yellow color indicating zones flooded under present conditions but not flooded during future SLR conditions. The authors should explain why these low lying coasts are flooded with present SLR and not with higher SLR, contrary to what would be expected.

We've added the following explanations regarding this in the manuscript [Revised line 252 – 255]

However in Figure 5, there are several small areas of yellow color indicating zones flooded under present conditions but not flooded during future SLR conditions. This is because Figure 5 showed snapshots of the inundation conditions at one particular time. Some areas may experience alternating wetting and drying conditions, which may explain why some areas are flooded with present SLR and not with higher SLR: this is so only at that particular time. The authors expect that those areas are flooded at other times.

o In lines 226-227 the authors say: "the measured water level variation displayed larger amplitudes than did the model output". Observing Figure 3b, the trend seems the opposite (for positive values) and the red line (modeled) is located above the black one (observed). On the contrary, negative values and total oscillations are greater in the case of observed data. I suggest clarifying this point

Thank you for pointing this out. We've updated the text [Revised line 217-219]

….the measured water level variation displayed smaller amplitudes than did the model output for positive tides and larger amplitudes than the modeled water level for negative tides, perhaps due to the coarse resolution of bathymetry.

o When comparing water levels of Figure 7 and Figure 3, the observed and modelled values are different in panels (a) and (b) of both figures. It looks like in one of both figures, these panels are exchanged.

We've made correction for calculated values of storm surge level in section 3.4 and relevant Figure 7.

In the initial submission of manuscript, some errors existed in Section 3.4. We apologize for this mistake. We conducted another round of more thorough check when we worked on the revision and identified these errors. In the revised manuscripts, those errors were corrected. But these corrections did not change the major conclusions. Corrections that were made in Section 3.4 are as follows:

Line 295 [Revised line 279]: 2.13 meters instead of 2.3 meters.

Line 296 [Revised line 280]: 13.90% instead of 21%.

Line 297 [Revised line 281]: 28.88% instead of 37%.

Line 298 [Revised line 282]: 2.41 m instead of 2.6 m.

Line 300 [Revised line 284-285]: 14.02% instead of 14% …. 1.87 meters instead of 2.24 meters……33.54% instead of 31%........2.19 m instead of 2.59 m.

Line 302 [Revised line 288-289]: 22.48% instead of 22%..........1.29 meters instead of 1.61 meters.

Line 304 [Revised line 290]: 51.94% instead of 51%

Line 307 [Revised line 293]: 3.07 meters instead of 3.01 meters…….22.80% instead of 50%

Line 308 [Revised line 294]: 54.80% instead of 68%.

A new table (Table 6) with all the calculations regarding storm surge level was also added in the manuscript.

Based on the corrected calculations, we've also updated figure 7. In the initial submission, Figure 7a was mentioned as "TC Sidr at Barisal" and Figure 7b was mentioned as "TC Sidr at Charchanga". Actually, Figure 7a was representing TC Sidr at Charchanga and Figure 7b was representing TC Sidr at Barisal. We've corrected these mistakes in the updated manuscript.

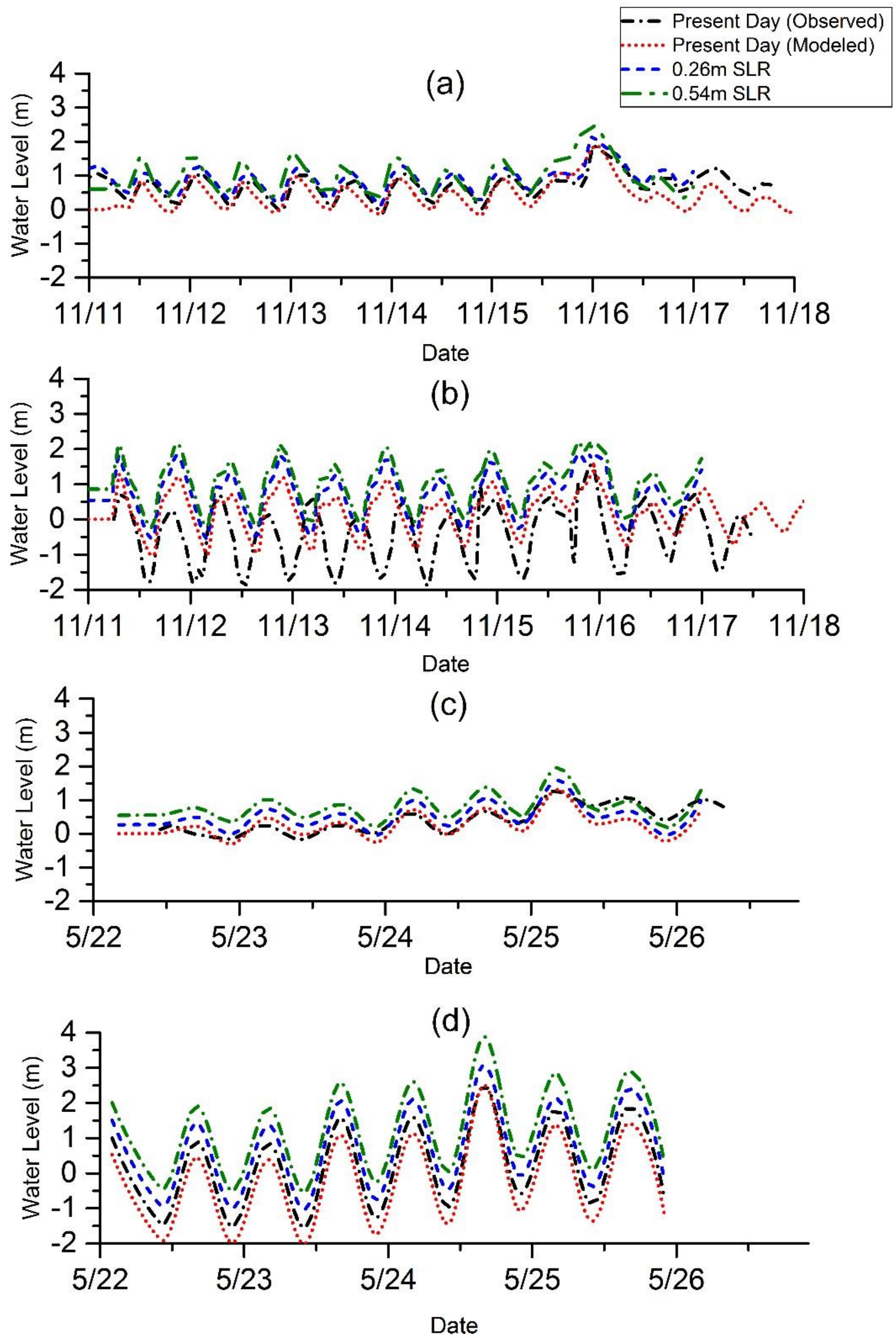

Figure 7. Comparison of storm surge water level between present day and future SLR scenarios. (a) TC Sidr at Barisal (b) TC Sidr at Charchanga (c) TC Aila at Barisal (d) TC Aila at Charchanga. The observed, modeled present-day, mid-of-21st century and end-of-21st century storm surge levels are denoted by the black dash-dotted, red dotted, blue dashed, and green dash-dottted lines, respectively.

Specific comments –

Lines 55-56: "the deaths of hundreds of thousands of lives". Better "the loss of hundreds of thousands of lives". This sentence is very similar to the following one: "This type of coastal flooding. . .", so probably both sentences could be combined into one.

Thank you. We've updated the text and merged these lines [Revised line 53-55].

The geomorphological characteristics of the region have made the locale locales prone to major TC events, events which have occurred multiple times in the past, directly causing loss of hundreds of thousands of lives, property, livelihoods and the economy of the country (Haque, 1997).

- *Line 83: "The impact of climate change. . ... are still debatable" should be "The impact of climate change. . ... is still debatable" or "The impacts of climate change. . ... are still debatable".*

Thank you. It's corrected.

- *Line 88: "will be method of this study", better "will be the method of this study".*

Corrected.

- *The name of a district is written differently: Patuakhali (line 99), Patukhali (line 106), Pataukhali (line 106). Please be consistent and use only one name.*

Sorry about the mistakes. We've corrected these in the updated manuscript.

- *Lines 110-114: This paragraph seems a repetition of a previous one.*

Removed.

- *Lines 129-130: P0 and f are not defined in equations (2) and (3).*

It's now corrected. Thank you.

- *Line 156: The reference Heming et al. (1980) is missing or there is a mistake and should be Heming et al. (1995).*

It should be Heming et al. (1995). Thank you.

- *Line 167: The meaning of e is not defined in equation (6).*

It's the base of the natural logarithm (=2.71828182846) (Delft Hydraulics, 2011). We've included this information in the revised version.

- *Line 178: "methods described in Zhang et al. (2012) was followed" should be "methods described in Zhang et al. (2012) were followed".*

Corrected.

- Line 184: "boundary was shown in Figure 1", better "boundary is shown in Figure 1". - Line 206: ". . .in making ensemble projections shown in Table 2" should be ". . .in making ensemble projections are shown in Table 2"

Corrected.

- Line 212: "(-ve)" looks a typo.

It's now corrected.

- Line 215: Equation (8) is wrong. The MAE is obtained by comparing observations with model results

Corrected.

- Line 234: "the two TCs considered were shown in Figure 4.", better : "the two TCs considered are shown in Figure 4."

Thank you. We've corrected it.

- Lines 262-263: Please substitute "square kilometers" by "km2".

Corrected.

- Lines 269-272: This paragraph is a repetition of the previous one.

Thanks for pointing this out. We've removed those lines.

- Lines 310-313 are redundant with the previous paragraphs and although they coincide with Figure 7 caption (which is wrong), they do not describe Figure 7.

Sorry about the mistake. We've removed that paragraph and corrected the caption of Figure 7

- Line 351: "SLR conditions; which is. . .", better "SLR conditions, which is. . .".

Thank you. We've corrected this.

- References: Alam (1996), Mohal et al. (2006) and Vatvani et al. (2002) are listed in References but are not cited in the text.

Alam (1996) and Mohal et al. (2006) were removed from the updated manuscripts. Vatvani et al. (2002) should be in line 168. In addition to that, references regarding WES (Delft Hydraulics, 2011) was added in line 156 and was listed in references list.

- *The reference corresponding to Delft3D model is cited in the text as Delft Hydraulics (2006) but is listed as Hydraulics, D. (2006). Please be consistent.*

Sorry about that. We've updated that.

- *Figure 7 caption is wrong and it does not describe this figure, since the results of both future scenarios are included in each figure.*

Caption is now updated as follows [Revised line 515 - 517]

Figure 7. Comparison of storm surge water levels between present-day and future SLR scenarios. (a) TC Sidr at Barisal (b) TC Sidr at Charchanga (c) TC Aila at Barisal (d) TC Aila at Charchanga. The observed, modeled present-day, mid-21st-century and end-21st-century storm surge levels are denoted by the black dash-dotted, red dotted, blue dashed, and green dash-dottted lines, respectively.

Response to Editor's Comment:

Dear Dr. Piero Lionello,

We would like to thank you for handling this manuscript and providing useful comments and suggestions. We've considered those suggestions in our further revised manuscript. Please find the following responses.

Concerning your answer to reviewer 1, I am a bit puzzled by the new values. It is not clear why they have changed (You mention "corrected calculations"), and I would appreciate receiving a more detailed explanation.

In the initial submission of manuscript, some errors existed in Section 3.4. We apologize for this mistake. We conducted another round of more thorough check when we worked on the revision and identified these errors. In the revised manuscripts, those errors were corrected. But these corrections did not change the major conclusions.

Further, these new values contains a number of digits that appear well beyond their precision (e.g. rms in table 4). Please, adopt a number of digits that is consistent with the precision of the values.

Sorry about that. We've edited the all the values in result sections and considered two digits after the decimal point to make it consistent with other calculated values.

Concerning reviewer 2, It is not clear to me whether you answered correctly to her/his comment. The reviewer asked to insert the direct comparison (percent or absolute values) of changes in storm surge height with respect to SLR in order to evaluate the presence of nonlinear effects (changes of storm surge being larger or smaller than SLR). The caption of the tables 6 and 7 are not sufficiently descriptive (please improve them), but my understanding is that you are reporting the percent increase with respect to storm surge levels. I suggest you eventually add a new column.

Thank you for your suggestion. We've added a new column showing the additional increase in storm surge level due to SLR effect and merged all the results regarding Storm Surge Level in Table 6.

Table 6. Comparison of storm surge level between present day & future SLR scenarios and increase in storm surge level with respect to the present-day scenario for the case of TC Sidr and TC Aila in Barisal and Charchanga observational stations. The SLR scenarios of 0.33 m, 0.40 m and 0.47 m were used to examine the linearity/non-linearity of increase in storm surge level with respect to SLR conditions.

SLR Scenarios (m)	TC SIDR				TC AILA			
	Barisal		Charchanga		Barisal		Charchanga	
	surge(m)	increase(m) and %	surge(m)	increase(m) and %	surge(m)	increase(m) and %	surge(m)	increase(m) and %
0.00 (present-day)	1.87	n/a	1.64	n/a	1.29	n/a	2.50	n/a
0.26 (mid-21st-century)	2.13	0.26 (13.90%)	1.87	0.23 (14.02%)	1.58	0.29 (22.48%)	3.07	0.57 (22.80%)
0.33	2.21	0.34 (18.18%)	1.95	0.31 (18.90%)	1.66	0.37 (28.68%)	3.22	0.72 (28.80%)
0.40	2.26	0.39 (20.85%)	2.00	0.36 (21.95%)	1.75	0.46 (35.65%)	3.42	0.92 (36.8%)
0.47	2.32	0.45 (24.06%)	2.08	0.44 (26.83%)	1.82	0.53 (41.08%)	3.67	1.17 (46.80%)
0.54 (end-21st-century)	2.41	0.54 (28.88%)	2.19	0.55 (33.54%)	1.96	0.67 (51.94%)	3.87	1.37 (54.80%)

Ensemble Projection of the Sea Level Rise Impact on Storm Surge and Inundation in the Coastal Bangladesh

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Abstract.

The hydrodynamic model Delft3D is used to study the impact of Sea Level Rise (SLR) on storm surge and inundation in the coastal region of Bangladesh. To study the present-~~-~~day inundation scenario, the tracks of two known tropical cyclones (TC) were used: Aila (Category 1; 2009) and Sidr (Category 5; 2007). Model results were validated with the available observations. Future inundation scenarios were generated by using the strength of TC Sidr, TC Aila and an ensemble of historical TC tracks but incorporating the effect of SLR.

Since future change in storm surge inundation under SLR impact is a probabilistic incident, that's why a probable range of future change in inundated area was calculated by taking in~~-~~to consideration the uncertainties associated with TC tracks, intensities and landfall timing.

The model outputs showed that~~,~~ the inundated area for TC Sidr, which was calculated as 1860 km^2, would become 31% higher than the ~~present day~~present-day scenario if ~~a SLR~~an SLR of 0.26 ~~meter~~m occurs during the mid-~~21st-~~21st-century climate scenario. Similar to that, an increasing trend was found for the end~~- of the~~ 21st~~-~~-century climate scenario. It was found that with ~~a SLR~~an SLR of 0.54 ~~meter~~m, the inundated area would become 53% higher than the ~~present day~~present-day case.

Along with the inundation area, the impact of SLR was examined for the changes in future storm surge level. A significant increase of 13.90~~21~~% was found in storm surge level for the case of TC Sidr in Barisal station if an SLR~~Sea Level Rise~~ of 0.26 ~~meter~~m occurs ~~at~~ in the mid~~dle- of the~~ 21st-century. Similar to that, an increase of 28.88~~37~~% was found in storm surge level with ~~a SLR~~an SLR of 0.54 ~~meter~~m in this location for the end~~- of the~~ 21st ~~century~~ century climate scenario.

Ensemble projections based on uncertainties of future TC events also showed that, for a change of 0.54 ~~meters~~m in SLR, the inundated area would range between 3500-3750 km^2 whereas for ~~present day~~present-day SLR simulations it was found within the range of 1000-1250 km^2

These results revealed that even if the future TCs remain at the same strength as at present, the projected changes in SLR will generate more severe threats in terms of surge height and the extent of inundated area.

1. Introduction

In addition to routine inundation from upstream river water and the downstream tides, the coastal part of Bangladesh is frequently flooded by storm surges induced by tropical cyclones (TCs). Typically, TC-induced storm surges in this area initiate in the central or southern part of the Bay of Bengal or near the Andaman Sea. TCs normally occur during April – May, the pre-monsoon period, and again from October – November, the post monsoon period. Harris (1963) mentioned that five basic processes (i.e., pressure, direct wind, earth's rotation, waves and rainfall effects) cause water level rise under storm conditions. Pietrafesa *et al.* (1986) also pointed out that high water at the mouths of coastal estuaries, bays, and rivers can block discharges of upstream waters and contribute to upstream flooding; a non-local effect. Among these processes, storm surges form primarily due to the TC wind stresses mechanically driving the surface frictional layer onshore. Assuming an idealized balance between pressure gradient force and surface wind stress with assumed small bottom stress, the surge related to TC wind stress can be expressed as $\Delta h = \frac{\tau_w L}{g \rho h}$, where L is the fetch of the wind (the distance over which the wind blows), τ_w is the wind stress due to the friction between the moving air and water surface, g is the gravity, ρ is the density of water, h is the depth near the coast (Hearn, 2008). Also, as a secondary process, due to the differences in pressure level, the water level rises in the areas of low atmospheric pressure and falls in the areas of high atmospheric pressure, which is how the rising water level offsets the low atmospheric pressure to keep the total pressure constant (Harris *et al*., 1963).

According to Murty et al. (1986), the surge amplifies as it approaches the coast due to the shallow continental shelf of the Bay of Bengal and hence it causes massive flooding in the low-lying coastal areas. A large percentage of the Bangladesh population resides in the ~~low~~ low-lying coastal regions of the country. Most of the areas near the coastal zone of Bangladesh have been formed by the process of riverine sedimentation and because of that the ~~low~~ low-lying areas are relatively flat and as such are susceptible to flooding even under normal astronomical tide conditions. Furthermore, the triangular shape of the Bay of Bengal region makes storm surges more distressing, as a funneling effect occurs. The geomorphological characteristics of the region have made the ~~locale~~ locales prone to major TC events, events which have occurred multiple times in the past, directly causing loss ~~the deaths of hundreds of thousands~~ of lives ~~(Haque, 1997). This type of coastal flooding associated with the changes in coastal water level due to storms passing over the sea causes great loss of human lives~~, property, livelihoods and the economy of the country (Haque, 1997).

Future climate change scenarios may further exacerbate the threats of TC-induced storm surge and inundation. According to the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC 4AR), there is a high probability of major changes in TC activity across various ocean basins including the Arabian Sea and the Bay of Bengal. According to Milliman et al. (1989), this Ganges-Brahmaputra-Meghna Delta region has long been characterized as a highly vulnerable zone due to its exposure to the increasing trend of SLR. According to the SLR analysis done by the South Asian Association for Regional Cooperation based on the 22-year records of observed sea level at Charchanga, Cox's Bazar and Hiron Point, sea level is rising at rates of 6.0, 7.8 and 4 mm/year, respectively in those three locations (SMRC, 2003). These rates are much higher than the global rate of SLR (~ 3.2 mm/year) over the last 25 years (Pietrafesa et al., 2015~~6~~). Based on Warrick et al. (1996), the sea level in the Bay of Bengal is also influenced by local factors including tectonic setting, deltaic processes, and sediment load; for example, the coastal region of Bangladesh has been subsiding due to the pressure on the Earth's crust from the sediment with thick layers that have formed over millions of years. Warrick et~~.~~ al. (1996) also analyzed the recent history of land accretion and suggested that the subsidence is also balanced by land accretion due to sediment supply from the coast. These physical phenomena have been shaping the coast of Bangladesh over the past 100 years. A global SLR of 26-59 cm has been projected over the next 84 years to 2100 by the IPCC under the scenario A1F1 (Meehl et al. 2007). In this proposed work, we will use the SLR projections from Caesar et al. (2017; under review), which is based on IPCC AR5 and suggests a projection of SLR of 26 cm for the mid-21st ~~-~~century (2040 -2060) and 54 cm for the end-21st ~~-~~century (2079 -2099).

Previous studies have analyzed the likely impact of climate change, especially SLR, on storm surge and inundation in this region. Using hydrodynamic models, Ali (1992) showed that with an increase of 1.0 and 1.5 ~~meters~~m of SLR, 10% and 15.5%, respectively, of the entirety of Bangladesh would get flooded under the strength of future TCs. Karim and Mimura (2008) used a 1-D hydrodynamic model to study the inundation under several scenarios of climate and for the case of future TCs by changing sea surface temperature, SLR, wind speed and sea level pressure. Based on their results, Karim and Mimura (2008) concluded that with an increase of 2°C in SST and 0.3 ~~meters~~m of SLR, the flood risk area would be 15.3% more than the ~~present day~~present-day risk area and the depth of flooding would increase by as much as 22.7% within 20 km from the coastline. Both Ali (1992) and Karim & Mimura (2008) considered SST rise and future strength of TCs in simulating the future storm surge and inundation.

However, the impacts of climate change on the frequency and intensity of TCs are still debatable (Knutson *et al*., 2010). The projection of the TC characteristics in the Bay of Bengal region is unclear as well. To improve these uncertainties, a reasonable method to examine the impact of future SLR on storm surge and inundation would be to construct an ensemble of tracks and intensities of possible land-falling TCs along the Bangladesh coast based on the historical TC records. From this statistical approach, we can quantify the probable impact of TC tracks under future SLR change. To date, such an approach has not been done and will be the method of this study.

We first use Delft3D to simulate the ~~present day~~present-day storm surge and inundation using the strength of two recent TCs (~~TC~~ Sidr and ~~TC~~ Aila) and validate the simulations with observational data. Future storm surge and inundation scenarios were then generated by incorporating the projected SLR.

The study was carried out in the Ganges-Brahmaputra-Meghna Delta regions (Figure 1a). According to Integrated Coastal Zone Management Plan, 19 districts of Bangladesh located near the Bay of Bengal area were defined as the coastal areas. We've considered all those in this study. We selected two TC cases in this study, a strong Saffir-Simpson(SS) Category-5 that directly hit the study area, TC Sidr, and the other a ~~SS~~ Category -1 storm that made landfall in the ~~South-West~~ southwest part of the study domain, TC Aila.

TC Sidr made landfall near Barguna district (Figure 1a) in 2007, causing ~ 3000 human fatalities and leaving millions homeless. This categoryCategory-5 cyclone is considered one of the most powerful cyclones in the past 15 years to have made landfall in Bangladesh, which affected over nine million people living across in the Bangladesh coastal areas. The districts of Patuakhali, Khulna, Barguna and Jhalokathi were badly affected. During TC Sidr, around 15% of the affected people took refuge in nearby cyclone shelters. In the village of Angul Kata in Barguna district, around 1500 people took shelter in eight reinforced pillars to protect themselves from the tidal surge of around 5 metersm. If there had been no shelters, the death toll could have reached into the hundreds in that area.

The other cyclone studied in this paper, TC Aila (Figure 1a) occurred in the Bay of Bengal region in 2009. Although a categoryCategory-1 storm, Aila caused ~ 190 deaths and affected 4.8 million people, the devastation that left a long long-term impact. The locales mainly affected were Khulna, Patuakhali and Chandpur. The storm surge due to Aila broke a dam in Patauakhali and submerged five villages, destroying a huge number of homes and leaving thousands of people homeless. Most of the people living in those affected areas took shelter in the nearest cyclone shelters. According to government sources, approximately 2,500,000 houses had been destroyed completely and 3,700,000 houses had been damaged.

The structure of the paper is as follows: brief description of the Delft3D Flow model and the methodologies used to simulate future changes in storm surge and inundation, to generate ensemble projections of storm surge inundation were discussed in section 2, In section 3, validation of the model results, present daypresent-day storm surge inundation scenarios, ensemble projection of storm surge inundation and future change in storm surge level were presented. Section 54 includes discussion onof model results and the uncertainties associated with the future projections. Finally, section 5 presents the concluding remarks on research findings.

TC Sidr made landfall near Barguna district (Figure 1) in 2007, causing ~ 3000 human fatalities and leaving millions homeless. TC Aila occurred in the Bay of Bengal region in the year 2009 (Figure 1). Although a category-1 storm, Aila caused ~ 190 deaths and affected 4.8 million people, devastation that left a long term impact. The locales mainly affected were Khulna, Patukhali and Chandpur. The storm surge due to Aila broke a dam in Pataukhali and submerged five villages, destroying huge number of homes and leaving thousands of people homeless.

2. Methodology

2.1 Modeling Methodology

2.1.1 Application of Numerical Model

For the purpose of developingTo develop a the present daypresent-day and future inundation scenario in the coastal regions of Bangladesh, the Delft3D-FLOW (Delft Hydraulics, 2006), a multidimensional (2D or 3D) hydrodynamic and transport simulation program that calculates non-steady flow and transport phenomena resulting from tidal and meteorological forcing was used. Delft3D-FLOW solves the unsteady shallow water equation in two dimensions (depth-averaged) or in three dimensions. The system of equations consists of the horizontal equations of motion, the continuity equation, and the transport equations for conservative constituents. The equations are formulated in orthogonal curvilinear co-ordinatescoordinates or in spherical co-ordinatescoordinates. Delft3D – FLOW module's two-dimensional, depth averaged flow equations can be applied for modeling tidal waves, storm surges, tsunamis, harbor oscillations (seiches) and transport of pollutants in vertically well-mixed flow regimes. In this paper Delft3D's 2D mode for barotropic depth-integrated flow has been applied. The equations are listed below.

$$\frac{\partial \zeta}{\partial t} + \frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\left[(d+\zeta)\upsilon\sqrt{G_{\eta\eta}}\right]}{\partial \xi} + \frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\left[(d+\zeta)v\sqrt{G_{\xi\xi}}\right]}{\partial \xi} = Q$$

(1)

$$\frac{\partial u}{\partial t} + \frac{u}{\sqrt{G_{\xi\xi}}}\frac{\partial u}{\partial \xi} + \frac{v}{\sqrt{G_{\eta\eta}}}\frac{\partial u}{\partial \eta} + \frac{uv}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial \sqrt{G_{\xi\xi}}}{\partial \eta} - \frac{v^2}{\sqrt{G_{\xi\xi}\sqrt{G_{\eta\eta}}}}\frac{\partial \sqrt{G_{\eta\eta}}}{\partial \xi} - fv + \frac{g}{\sqrt{G_{\xi\xi}}}\frac{\partial \zeta}{\partial \xi} = -\frac{1}{\rho\rho_0\rho_0\sqrt{G_{\xi\xi}}}\frac{\partial P_{atm}}{\partial \xi} + F_\xi$$

(2)

$$\frac{\partial v}{\partial t} + \frac{u}{\sqrt{G_{\xi\xi}}}\frac{\partial v}{\partial \xi} + \frac{v}{\sqrt{G_{\eta\eta}}}\frac{\partial v}{\partial \eta} + \frac{uv}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial \sqrt{G_{\xi\xi}}}{\partial \eta} - \frac{u^2}{\sqrt{G_{\xi\xi}\sqrt{G_{\eta\eta}}}}\frac{\partial \sqrt{G_{\xi\xi}}}{\partial \eta} + fu + \frac{g}{\sqrt{G_{\xi\xi}}}\frac{\partial \zeta}{\partial \xi} = -\frac{1}{\rho\rho_0\rho_0\sqrt{G_{\eta\eta}}}\frac{\partial P_{atm}}{\partial \eta} + F_\eta$$

(3)

where ξ, $\boldsymbol{\eta}$ are the spatial co-ordinatescoordinates, ζ is representing water level above some horizontal plane of reference (m), u & and v are the velocities in the ξ and $\boldsymbol{\eta}$ direction (m/s), d is the water depth below some horizontal plane of reference (m), f is the coriolis forcing due to the rotation of the earth, g is the acceleration of gravity (m/s^2), P_{atm} is the atmospheric pressure at water surface (kg/m/s^2), Q is the discharge of water, evaporation or precipitation per unit area (m/s) , ρ_0 representingis the the density of water, $\sqrt{G_{\xi\xi}}$ is the coefficient used to transfer one coordinate system into another one (m), F_ξ are the turbulent momentum flux in ξ-direction (m/s^2), F_η are the turbulent momentum flux in $\boldsymbol{\eta}$-direction (m/s^2). Along with the appropriate set of initial and boundary conditions, the above-mentioned set of equations have been solved on an Arakawa-C type finite difference grid. Delft3D- FLOW manual (Delft Hydraulics, 2006) contains detailed information about these numerical aspects.

2.1.2 Model Grid and Bathymetry

The grid was set up using spherical coordinates, as displayed in Figure 1a. -The grid spacing varies from a minimum of 125 metersm to a maximum of 1140 metersm. The finer resolution weas applied over land for calculating the inundation or wetting process accurately.

In this study, the land topography data were obtained from NASA's Shuttle Radar Topography Mission (SRTM) 90-m resolution datasets (Figure 1b). The bathymetries of the rivers and estuaries are specified using the cross sections measured by the Institute of Water and Flood Management, Bangladesh. The land elevations are specified using the data from the Center for Environmental and Geographic Information Services (CEGIS), Bangladesh. The ocean bathymetry waiis specified using the data from the General Bathymetric Chart of the Oceans 30-arc-sec interval gridded data (BODC, 2003, Figure 1b). Bathymetry and topographic data werehave been interpolated over the model domain using triangular interpolation and grid-cell averaging methods of Delft3D (Delft Hydraulics, 2006).

2.1.3 Wind and Pressure Field

Track data of TCs Sidr and Aila were obtained from the Indian Meteorological Department (www.imd.gov.in). Using those data as input, TC surface winds and mean sea level pressure fields were generated using the Wind Enhancement Scheme (WES) (Heming et al. 1995) method based on the analytical equation by Holland (1980). Delft3D slightly improved the original WES by introducing TC asymmetry. Unlike some pervious previous method that incorporates TC wind asymmetry information from observations (Xie et al. 2006), in WES the asymmetry was brought about by applying the translation speed of the cyclone center displacement as steering current and by introducing rotation of wind speed due to friction (Delft Hydraulics, 2011,Heming et al. 199580).

According to the Holland's equation, gradient wind speed $V_g(r)$ at a distance r from the Centre of the cyclone is expressed as the following:

$$V_g(r) = \left[\frac{AB(p_n - p_c)\exp\left(-\frac{A}{r^B}\right)}{\rho r^B} + \frac{r^2 f^2}{4}\right]^{0.5} - \frac{rf}{2} \frac{r f}{4} rf/2$$

(4)

Here ρ is the density of air, p_c is the central pressure and p_n is the ambient pressure, the Coriolis parameter is represented by f . A and B are determined empirically; with the physical meaning of A as the relation of pressure or wind profile relative to the origin, and parameter B defining the shape of the profile. Delft3D introduces a central pressure drop of $p_d = p_n - p_c$. By equating $\frac{dV_g}{dr} = 0$, and assuming f=0 in the region of maximum winds where the Coriolis force is small compared to the pressure gradient and centrifugal forces, the radius of maximum winds R_w can be given as follows:

$$R_w = A^{1/B} \quad (5)$$

Thus, R_w is independent of the relative values of ambient and central pressure and is defined entirely by the scaling parameters A and B. Substitutions lead to the expression for the maximum wind speed V_m

$$V_m = \left[\frac{Bp_d}{\rho e}\right]^{0.5} \quad (6)$$

Where *e* is the base of the natural logarithm (=2.71828182846).

Complete details about this method can be found in the user manual of Delft3D Flow (Delft Hydraulics, 2006), . Holland (1980), and Vatvani et al. (2002).

The circular grid of TC wind fields used in this study consists of 36 columns and 500 rows and the data were updated at 6 hourly intervals throughout its movement until the landfall. Figure 2 shows a snapshot of the wind field of TC Sidr over the model domain, before landfall, generated using Holland's equation above.

2.1.4 Roughness

The spatially varying Manning's Roughness value ~~has been~~was defined based on land cover, such as vegetation, rivers, and ocean (Table 1). In the study domain, a mangrove forest, Sundarbans, is located in the Southwest region, near TC Sidr's landfall location (Figure 1a). Sakib et al. (2015) found that Sundarban plays a significant role as a buffer in reducing the total inundation during TC passages. Therefore, in this study, the mangrove region wa~~i~~s considered.

In selecting the roughness values, methods described in Zhang et al. (2012) were~~as~~ followed and slightly modified values were defined for the study area based on the vegetation types in that area.

2.1.5 Boundary conditions

Upstream boundaries were specified as discharges at the mouths of the three major rivers; the Ganges, the Brahmaputra & the Upper Meghna; obtained from the Bangladesh Water Development Board (BWDB) as daily discharge. The downstream ocean boundary was defined by the Topex/Poseidon Inverse Tidal model, based on Egbert et al. (1994) Location of the downstream ocean boundary is~~was~~ shown in Figure 1a.

2.2 Calculation Procedure for ~~Present Day~~Present-day and Future Storm Surge and Inundation Scenario

To generate storm surge and inundation for ~~present day~~present-day climate scenario, upstream discharge and downstream water level data from the ~~present day~~present-day were used. For future SLR scenarios, ~~present day~~present-day hydrodynamic conditions and the strengths of ~~present day~~present-day TCs were used but the future sea level was modified based on the SLR projections by Caesar et al. *(2017; under review)*. Scenarios were generated for both the ~~Mid~~mid-~~21st~~ 21st-century and the ~~End~~end-~~21st~~ 21st-century time horizons for these TCs, Sidr and Aila. Finally, comparisons were made in terms of storm surge and inundation to identify the changes between ~~present day~~present-day and future SLR scenarios.

Now, future s~~S~~torm surge inundation due to SLR is a probabilistic event that requires proper addressing of the uncertainties associated with the input parameters. To address the future tropical cyclone uncertainties and obtain statistically significant results, we created an ensemble of tropical cyclone tracks. The ensemble tracks were generated from different historical tropical cyclones that made landfall over the study domain with different intensities (Table 2). Along with the uncertainties associated with future landfall locations, the intensity of Sidr-like and Aila-like TCs may be different. So, to address the uncertainty with the intensity, we increased and decreased their intensity by 10% to simulate a probable range of future storm surge inundation.

Storm surge inundation can also be different based on landfall timing. If the a storm would madeke landfall during the high astronomical tide condition, its flooding would have beenbe much higher at that time than what could happen during a low astronomical tide condition. For example, the tides shown in Figures 3 and 7 as the water level oscillations have amplitudes as high as 3 m, which could significantly affect the extension of flooded area, depending on whether the storm's landfall coincides with a high tide or a low tide. We note that TC Sidr and TC Aila made landfall during the high tide conditions, which may not always be applicable for the future TCs. To also address uncertainties with the TC landfall timing, experiments were conducted by changing the timing of landfall to identify the impact of high tide and low tide on storm surge and inundation. The change of timing in these tide-related experiments was implemented by modifiying the tracks of the storms so that their landfalls coincide with a high tide, a tide, or a zero-tide condition, in addition to their actual tidal phases. Here in this study, future storm surge inundation scenarios caused by the ensemble tracks will then be simulated by incorporating the projected SLR. By taking all these parameters into consideration, we conducted a total 108 ensemble simulations (36 for each; present daypresent-day and two SLR scenarios). Parameters that were considered in making ensemble projections are shown in Table 23.

3. Results

3.1 Validation of the Model

Hourly tidal data from the Bangladesh Inland Water Transport Authority (BIWTA) was used to evaluate the performance of the model used in this study. The model simulation's root mean square error (RMSE)[7], mean absolute error (MAE)[8] and dimension-less Nash-Sutcliffe coefficient (E)[9] (Nash and Sutcliffe, 1970) were calculated and listed in Table 43. A Nash-Sutcliffe coefficient ranges between negative (-ve)infinity (no skill simulation) and one (perfect simulation).

$$\boldsymbol{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(X_{obs,i} - X_{model,i})^2}{n}} \qquad (7)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|X_{obs,i} - X\hat{X}_{model,iobs}\right| \qquad (8)$$

$$\boldsymbol{E} = 1 - \frac{\sum_{i=1}^{n}(X_{obs,i} - X_{model})^2}{\sum_{i=1}^{n}(X_{obs,i} - \overline{X_{obs}})^2} \qquad (9)$$

The simulated water levels were compared against the measured data from Bangladesh Inland Water Transport Authority (BIWTA) at two locations: Barisal and Charchanga (Figure 1a). Barisal station is located more towards the inland whereas Charchanga is located near the coastline where the grid cell resolution was coarse. But none of them are in the open ocean water, which is important to get a clear idea about storm surge level. TC Sidr made landfall near the Barisal Station (Figure 1a) and the impact of the storm surge was clearer at the Barisal station than that of TC Aila, which made landfall outside the model domain (Figure 1a); therefore, its impact was not as clear as that of Sidr.

In Figure 3(a) for TC Sidr at the Barisal station, the modeled water level, including storm surge and astronomical tides, was slightly lower than the observations, and at the Charchanga station (Figure 3b) the measured water level variation displayed larger smaller amplitudes than did the model outputs for positive tides and for negative tides, larger amplitudes than the modeled water level for negative tides, perhaps due to the coarse resolution of bathymetry. Similar types of variations between measured and modeled water level were found for TC Aila (Figure 3c and Figure 3d). Nevertheless, the modeled water level variations during TCs Sidr and Aila agreed reasonably well with measured data; as also confirmed by the calculated ~~average~~ RMSE, MAE and Nash-Sutcliffe coefficient(Table 4). Therefore, we conclude that the method can be used to study the impact of SLR on storm surge and inundation in future climate change scenarios.

3.2 ~~Present Day~~Present-day Inundation Scenario

The storm surge inundation scenarios due to the two TCs considered are~~were~~ shown in Figure 4.

It can be seen from Figure 4 that the area flooded by TC Sidr (yellow shade+red shade) was much higher than the area flooded by TC Aila (white shade+red shade), a result that is consistent with the fact that the category-5 TC Sidr was much stronger than the category-1 TC Aila and directly hit the study area. The maximum sustained wind speed for TC Sidr was 260 km/h whereas for TC Aila it was 110 km/h. The landfall location of Sidr was on the Eastern side of Sundarban, while for Aila, the landfall location was towards the Western side of Sundarbans. That explains why the inundations due to TC Sidr were located near the eastern side of Sundarban, whereas for Aila, the inundation was located mainly in the western part. The extent of inundation due to Sidr (1860 km^2) was 54~~35~~% larger than that of Aila (1208 km^2)

Sakib et al. (2015) showed that Sundarban acted as a buffer zone in reducing the impact of Sidr and thereby reduced much of the potential inundation depth and extent of flooding. As mentioned before, in the model simulation the impact of Sundarban was realized using a higher Manning's roughness value as resistance for the surge to travel.

3.3 Impact of Future Climate Scenarios on Storm Surge Inundation

Future inundation scenarios were generated for two different time horizons: one for the mid-~~21st~~ 21st century and the other for the end~~- of the~~ 21st century. The initial ocean water level was raised by 0.26 ~~meters~~m and 0.54 ~~meters~~m for the mid-~~21st~~ 21st century and end-~~21st~~ 21st century, respectively. The upstream river discharge and downstream ocean water level were used from ~~present day~~present-day climate scenarios.

In this section we seek to answer the question: if ~~present day~~present-day's TCs were to happen in future SLR scenarios, what storm surge and inundation hazard would they cause? Therefore, the tracks and intensities of the two ~~present day~~present-day TCs, Sidr and Aila, were used as the model wind input parameters.
The model simulated inundated areas and the percent variations were shown in Table 5 and Figure 5. Figure 5 shows that under future SLR scenarios, the inundated areas caused by TCs Sidr and Aila would be significantly higher than those under the present-day climate condition, as indicated by the white color shaded areas~~, for the TCs with the same strengths and landfall paths~~. For the category-5 TC Sidr, the inundated area would be 31% (2436.60 km^2)and 53%

(2845.80 km^2) higher than present daypresent-day's 1860 km^2 inundated area, in mid-21st century century (0.26 meterm SLR) and end of -21st -century (0.54 meterm SLR) climate scenarios, respectively (Figure 5a and Figure 5b) Similarly, for the category-1 TC Aila, a category 1 storm, there would be an increase in inundated areas. The calculated simulated inundated areas for TC Aila under mid-21st century century and end of-21st century century werewas found to be 1550 km^2 (28.31%)square kilometers and 1770 km^2 (46.52%)square kilometers, -respectively (Figure 5c and Figure 5d) whereas for the present-day scenario it was found to be 1208 km^2.square kilometers. However in Figure 5, there are several small areas of yellow color indicating zones flooded under present conditions but not flooded during future SLR conditions. This is because Figure 5 showed snapshots of the inundation conditions at one particular time. Some areas may experience alternating wetting and drying conditions, which may explain why some areas are flooded with present SLR and not with higher SLR: this is so only at that particular time. The authors expect that those areas are flooded at other times.

All these simulations were donecarried out using the present- day tides, upstream river discharges and theTC tracks and strengths, with only the initial sea water level raised to reflect the effect of the projected future SLR. of present day TCs; while changing the initial sea water level to reflect the effect of SLR. Therefore, the results suggest that even if the future TCs strengths, the tides, and river discharges remain the same as in the present-day climate condition, future SLR would significantly increase the inundated area, by as high as 53%..

All of these simulations were done using present day tides, river discharges and the track and strength of present day TCs; while changing the initial sea water level to reflect the effect of SLR. Therefore, the results suggest that even if the future TCs strengths, the tides and river discharges remain the same as in the present, future SLR would significantly increase the inundated area.

3.3.1 Ensemble Projection of Future Storm Surge Inundation under SLR Conditions

As discussed in section 2.2 that, the future change in storm surge inundation can be different based on the intensity, landfall location and timing of future TCs. By considering all those these uncertainty factors mentioned in Table 23, a column plot was created (Figure 6) for present daypresent-day sea level and future SLR scenarios. Ensemble simulation outputs also showed an evidence forevident increase in the inundated area under the effect of SLR. For the present daypresent-day scenario (black column), out of 36 simulations, frequency of storm surge inundation incidents that would likely occur between the range of 1000-1250 km^2 is 13. whereas for 0.26 metersm of SLR(red column), peak of the column shifted towards right side with a maximum frequency of inundation events occurred within the range of 2000-2250 km^2 (10 times out of 36 simulation results). And for 0.54 metersm of increase in sea level (blue column), the peak of the column shifted more towards the right and the maximum number of simulation outputs (11 out of 36 simulations) showed the range of inundation to be within 3500-3750 km^2. These results show that even the change in intensities of future TCs are indefinite and the landfall timing is uncertain, increase in sea level is going to increase the area of inundation.

3.4 Impact of Sea Level Rise on Future Storm Surge Level

In addition to the inundation area, SLR would also greatly affect storm surge levels. Similar to the approach used in the inundation study (Section 3.3), TCs Sidr- and Aila-induced storm surges in the future SLR scenarios were simulated using their recorded strengths.

The simulated storm surge water levels in future SLR scenarios were compared with both the observed and model generated ones under the ~~present day~~present-day scenarios (Figure 7). It is to be mentioned that, while generating the future water level under the effect of SLR, the baseline was~~is~~ only changed~~ing~~ by considering the SLR effect and based on that factor the future storm surge level was calculated. Other than that, the water level is the same as ~~present day~~present-day TCs.

From Figure 7a and Table 6 we can see that for the case of TC Sidr the simulated storm surge level would become 2.13 ~~meters~~m ~~(Figure 7a)~~ in Barisal station which is around 13.90~~21~~% higher than the ~~present day~~present-day scenario. Similar to that, under the end-~~of~~ 21st ~~century~~-century 0.54 ~~meters~~m SLR scenario in Barisal, the storm surge would be around 28.88~~37~~% higher ~~(Figure 7a.)~~ than the ~~present day~~present-day scenario and the peak water level would reach 2.41~~6~~ m.

Increase in storm surge was found at the Charchanga station also. For TC Sidr, under the mid-21st ~~century~~-century scenario (0.26 ~~meter~~m SLR), the model simulated storm surge level was found to be 14.02~~14~~% higher (1.87~~2.24~~ ~~meters~~m) ~~(Figure 7b)~~ than the ~~present day~~present-day and 33.54~~31~~% higher (2.19~~59~~ m) (Figure 7b, Table 6) than the ~~present day~~present-day for the end-~~of~~ 21st ~~century~~-century (0.54 m SLR) climate scenario. It is to be noted that, ~~there's~~ a slight phase shift in the model simulation ~~in phase~~ occurred ~~for~~at this station ~~during the period of~~from November 13 to November 15. This could happen due to the presence of seiche. However, for rest of the period, phase variations are similar to the observed ones.

For TC Aila in Barisal, under the mid-21st-century SLR scenario the Storm Surge would become 22.48~~2~~% higher (1.58 m) than the ~~present day~~present-day, which was 1.29~~61~~ ~~meters~~m ~~under the 0.26 meters~~m ~~SLR condition for the mid-21st century-century climate scenario~~ (Figure 7c, Table 6). During the end-~~of~~ 21st ~~century~~-century climate scenario, the increment would become even higher as the SLR would be 0.54 ~~meter~~m. Storm s~~S~~urge under the 0.54 m end-21st-century SLR condition would be 51.94~~1~~% higher (1.96 ~~meters~~m) ~~(Figure 7c~~) than the present day. ~~under the 0.54 meters~~m ~~SLR condition at the end of the century.~~

At Charchanga, the storm surge would be higher than the ~~present day~~present-day condition for TC Aila. ~~For the mid-21st century-century~~ U~~u~~nder the 0.26 ~~meters~~m mid-21st-century SLR scenario, the storm surge would become 3.07 ~~1~~ ~~meters~~m which is ~~around~~ 22.80~~50~~% higher than the ~~present day~~present-day condition (Figure 7d, Table 6). And for ~~the~~ end- ~~of~~ 21st -century, this would become 54.80~~68~~% higher (3.87 m) than the present day ~~as the SLR would reach 0.54 m (Figure 7d)~~.

~~In order t~~To analyze the linearity/non-linearity of storm surge level with respect to SLR, we conducted additional experiments based on 5 SLR scenarios; ~~present day~~present-day sea level, 0.26 m of SLR, 0.33 m of SLR, 0.4 m of SLR, 0.47 m of SLR, 0.54 m of SLR, respectively. Results from these experiments are presented in Table 6.

For the case of TC Sidr in Barisal and Charchanga station, storm surge level increased almost linearly with respect to the addition of water due to the effect of SLR. For example, with ~~a SLR~~an SLR of 0.47 ~~meters~~m, the increase of storm surge level with respect to present day in Barisal and Charchanga stations were 0.45 m and 0.44 m, respectively (Table 6). On the other hand for the case of TC Aila, with ~~a SLR~~an SLR of 0.26 ~~meters~~m, the increase in storm surge level were found 0.29 m and 0.57 m respectively for the Barisal and Charchanga station (Table 6). Though the storm surge level is increasing almost linearly with the addition of sea water, however, there~~'s~~ are still differences found between them, which could ~~. This could~~ be influenced by the modification of ocean bathymetry to incorporate the effect of SLR. The margin of differences is higher for the Charchanga station comparing it with the Barisal station. The coarse resolution of topography near that area might be responsible for that.

~~The 0.26 m SLR for the mid-21st century would increase the water level, and the surge peak would be much higher at 2.4 m than the present day observed value at 2.0 m (Figure 7a). Figure 7b shows the same comparison, but for a 0.54 m SLR in the end-of-21st century scenario. For this case, the difference between the present day and end-of-21st century peak water level is much higher than what we found in the mid-21st century climate scenario.~~

~~4. Discussions~~

4. Discussions

In this paper, we showed that even if the future TCs keep~~remain~~ the same strength like the ~~present day~~present-day ones their impact will be much higher in a changing climate due to the effect of SLR. Several other factors not included in the modeling could make the storm surge and inundation situation far worse than that shown in the modeling result. These factors include mangrove coverage decrease, morphological changes, TC strength increase, and upstream river discharge changes.

For including the effect of future SLR in the model simulations, several methodologies were examined. One of the methods with which~~that~~ we experimented in this study was to include the increased sea level in open ocean boundary instead of adding it in to the whole ocean depth by keeping the coastline fixed. This method was used by some previous studies (Pickering et al. 2012). However, i~~I~~n such a case, an additional pressure gradient force was found acting towards the coast which made the inundated area much higher. Therefore, ~~-~~this method was not used in this study. Instead, in this study, the future SLR was added to the whole ocean domain depth.

~~In order t~~To make the future SLR simulation realistic, we considered the increased sea level in ocean bathymetry and increased the depth by 0.26 and 0.54 m, respectively, by considering land submergence near the coast. In that case, the result looked much more realistic than the previous one and this is the method we followed in this paper. For example, for the case of TC Aila under the end-of 21st-21st-century scenario where we used a SLRan SLR of 0.54 m SLR at the open ocean boundary instead of adding it to ocean depth and using the hydrodynamic conditions from the present day, the total inundated area was found to be 79% higher than the present daypresent-day one. Similar to that, for the mid-21st-21st-century scenario (a 0.26 m SLR), the inundated area was found to be 69% more than the present daypresent-day scenario. But when we added the SLR in ocean depth, the mid-21st century-century and end-of 21st century century inundated area were found to be 28% and 46% higher than the present daypresent-day scenario. This increase in inundated area was much less than the one that we found by adding the SLR in the open ocean boundary. Figure 8 displays the differences in the inundated area based on the consideration of SLR in the model input.

As discussed earlier, TC Sidr made landfall near Sundarban, where the mangrove forest zone acted as a buffer in reducing the impact of the storm surge flood. That is why, even though it was a TC 5, its impact was not as high as it might have been expected to be. In this study, the roughness of the mangrove forest zone on the South-West part of Bangladesh was considered to be fixed for the present daypresent-day as well as for future scenarios. But Mukhopadhyay et al. (2015) predicted that 17% of the total mangrove cover could disappear by 2105. If this decreasing trend of vegetation were considered in this study, the flooded area could be much higher.

Morphological changes were not considered in this study. But according to Goodbred et al. (2003), each year the eastern estuary, the central estuary and the western estuariesy are losinglose land at a rate of 0.13 cm/year, 0.16 cm/year and 0.16 cm/year, respectively. This could also lead to increased inundated areas for future scenarios. But as the focus of the paper is to estimate predict the future scenario of storm surge and inundation due to the effect of SLR and to compare comparisons with the present daypresent-day scenarios, it is important that we keep the roughness and morphological changes constant so that consistent comparisons can be made.

Some previous research showed that there could be increases in hurricane strength and landfall probability in the future due to global climate change (Haarsma et al. 2013, Bender et al. 2010, Bengtsson et al. 2007). Though we slightly modified the present-day TC strengths and selected 12 historical TC tracks to reduce landfall uncertainties and to make ensemble projection of future storm surge inundation, strength may be much higher than the ones that we considered for this study. In such case, the devastation could well be much higher under projected SLR conditions,; which is very alarming

In this paper, we used the present-day river discharge data as an upstream boundary for generating future inundation scenarios. But using the INCA-N, an Inland Catchment Modeling system and considering the projected climatic & and socio-economic scenarios, Whitehead et al. (2015) showed that, there will would be a significant increase in future monsoon intensities due to the impact of climate change. That would make future flooding scenarios much worse than those experienced presently. So, based on the changes in TC intensity, river discharges, and land-use changes, the situation could well become more badly impacted than what we found in this study.

The findings of our study are important for local governments to consider while they make new management and policy decisions and to improve TC preparedness plans by increasing numbers of shelters and heights. Generally, iIn TC shelters, the first floor is should be kept above the transparent due to the risk of high surge waters. Our study showed that, in the future, there ~~will~~ would be an increase in surge level from a minimum of 13.90~~5~~% up to 54.80~~70~~% if a TC 1 or a TC 5 makes landfall under increased SLR conditions (Table 6). So, the authority may consider increasing the height of the first floor considering the future risk of an increase in storm surge level and safety of local populations. Also, our model outputs showed that the inundated area increase would range from 28.31%-53.00% (Table 5) ~~percent~~ if there's any TC 1 or TC 5 was to make landfall with SLRs of 0.26 m or 0.54 m. This shows that a huge number of new areas are going to face the impacts of storm surge inundation and by considering this issue, it is high time to increase the number of TC shelters in the coastal areas of Bangladesh.

5. Conclusion

Employing the Delft3D-FLOW model, we simulated coastal storm surge and inundation for ~~present day~~present-day and future SLR scenarios and compared the changes between them. After validating the ~~present day~~present-day model, simulations were conducted for mid-21st ~~century~~ -century and end-~~of~~ 21st ~~century~~ -century climate scenarios where the SLR has been considered as 0.26 m and 0.54 m respectively. The model results showed that, with an increase of 0.26 m and 0.54 m SLR, there would be an increase of 31~~8~~% and 53~~48~~% of inundated area respectively if TC Sidr was to made landfall with its ~~present day~~present-day strength. There would also be an increase of 28.31~~5~~% and 46.52~~34~~% in inundated area if ~~category~~Category-1 TC Aila would make landfall with its ~~present day~~present-day strength but under the condition of 0.26 m and 0.54 m respectively. Outputs from the ensemble projections showed that, even if the TC intensities, landfall location and timings are uncertain, the most probable range of inundated area extent would shift from 1000-1250 km^2 (present day) to 2000-2250 km^2 (under 0.26 ~~meter~~m SLR scenario) and 3500-3750 km^2 (under 0.54 ~~meter~~m SLR scenario). Besides the inundated area, we also investigated the changes in storm surge level if TC Sidr and TC Aila would make landfall under future SLR conditions. Similar to the inundated area, increases in storm surge levels were found for future scenarios. The significant increase in simulated storm surge and inundation hazards highlights the need for the local governments to improve cyclone preparedness in future SLR scenarios.

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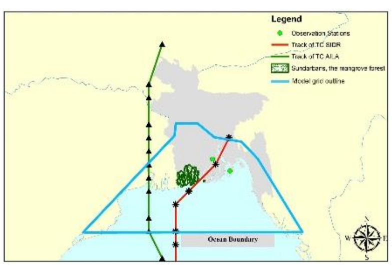


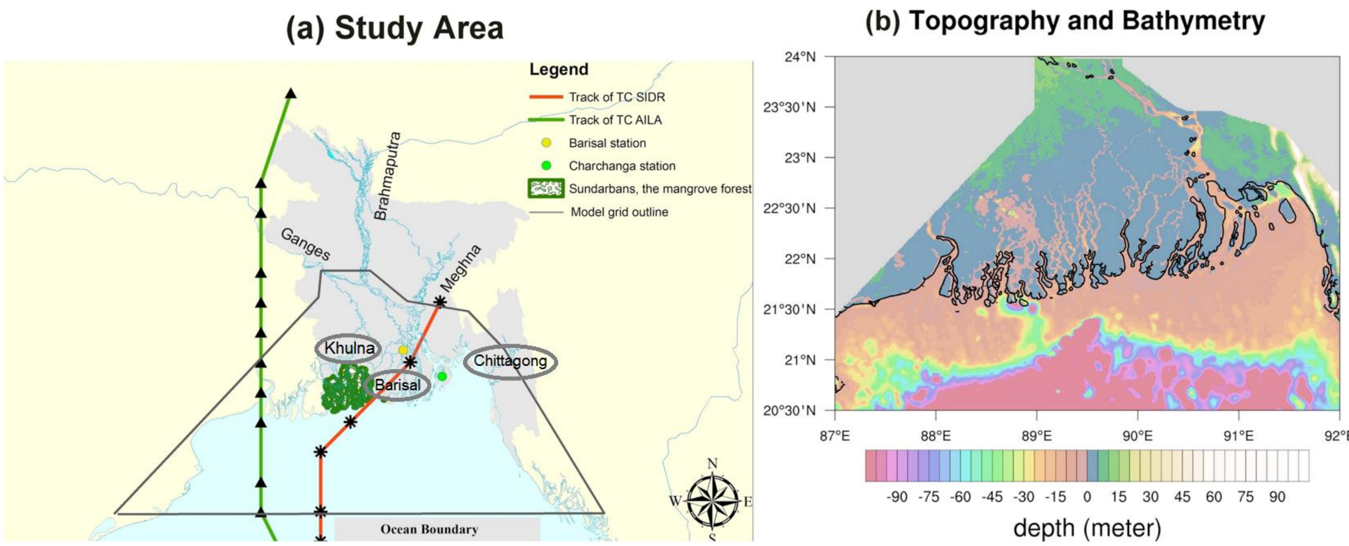


Figure 1. (a) Map ~~showing~~of the study area for this work. The red and green lines represent~~ing~~ the tracks of TC Sidr and TC Aila respectively. The ~~Area~~ area marked with green color indicates the Sundarban mangrove forest region. Location of the Ganges, Brahmaputra and Meghna rivers are shown on the map. Khulna, Barisal and Chittagong which are landfall locations for the historical TCs used for ensemble projection, shown inside a circular box on the map. Two ~~green~~ circles over the study area are the observation stations of Bangladesh Inland Water Transport Authority (BIWTA). The ~~blue~~ black colored outline shows the extent of model grid over the region. (b) Topography and bathymetry of the model domain. Negative depth values ~~are~~ represent~~ing~~ water bodies (ocean and rivers) and positive depth values areas represent~~ing~~ land.

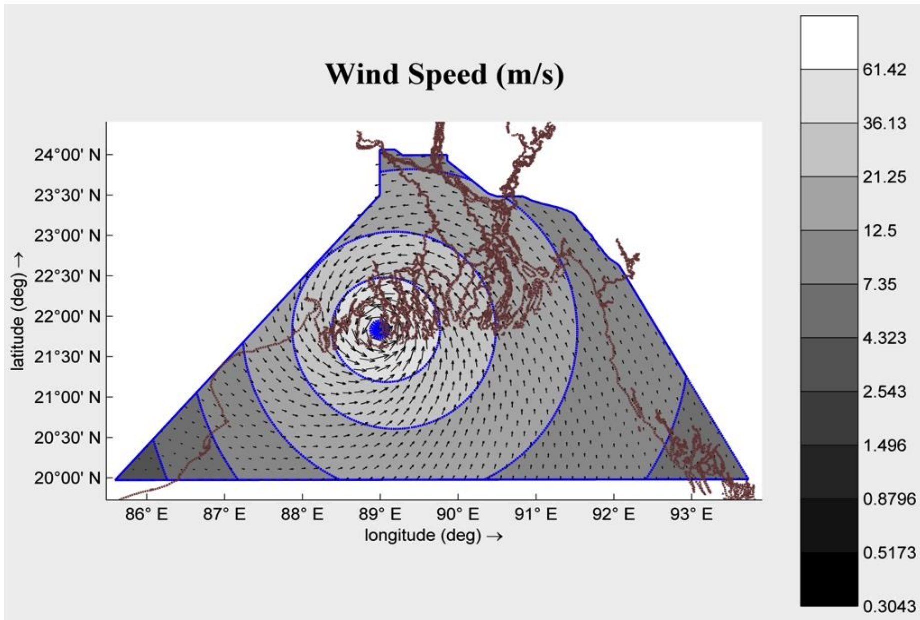


Figure 2. Distribution of the wind field over the model domain for TC Sidr during landfall generated using Holland's Equation.

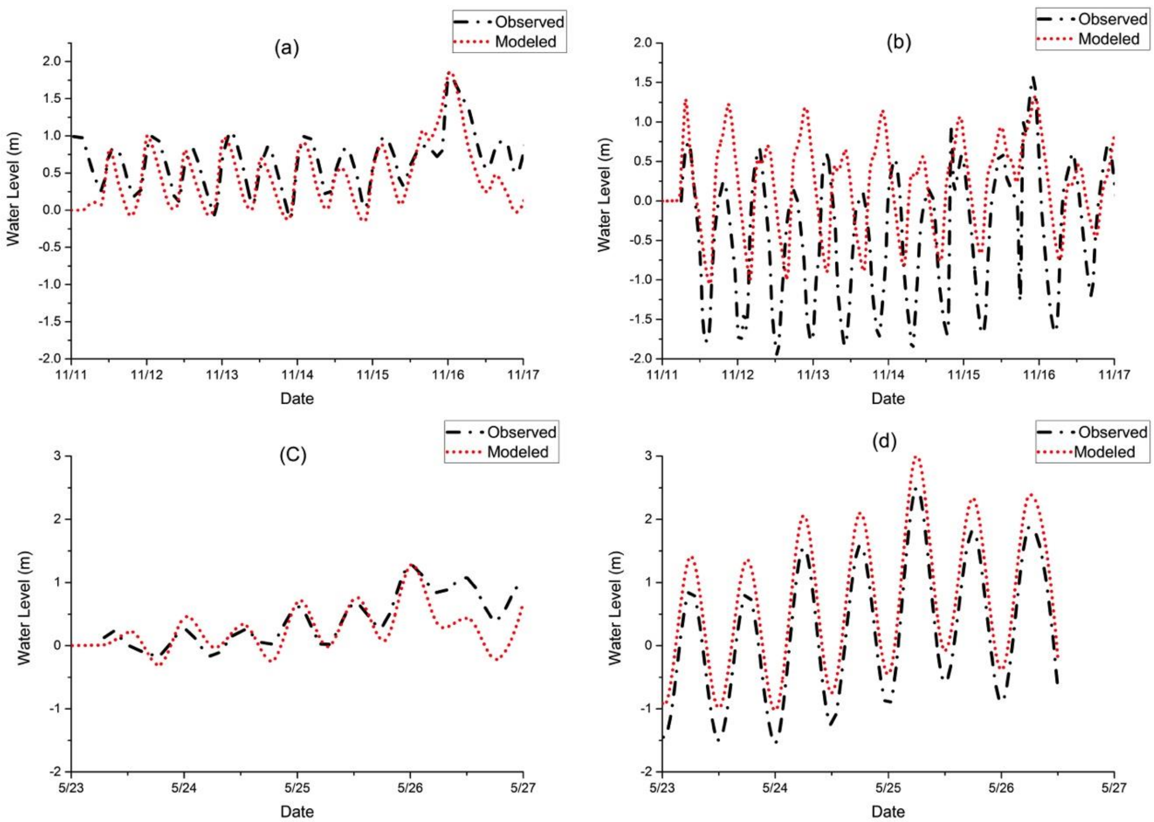


Figure 3. Comparison of observed and modeled Wwater Llevel for TC Sidr and TC Aila in Barisal and Charchanga observation stations. (a) mMeasured and Mmodeled Wwater Llevel comparison for TC Sidr in Barisal, (b) Mmeasured and Mmodeled Wwater Llevel comparison for TC Sidr in Charchanga, (c) Mmeasured and Mmodeled Wwater Llevel comparison for TC Aila in Barisal, (d) Mmeasured and Mmodeled Wwater Llevel comparison for TC Aila in Charchanga.

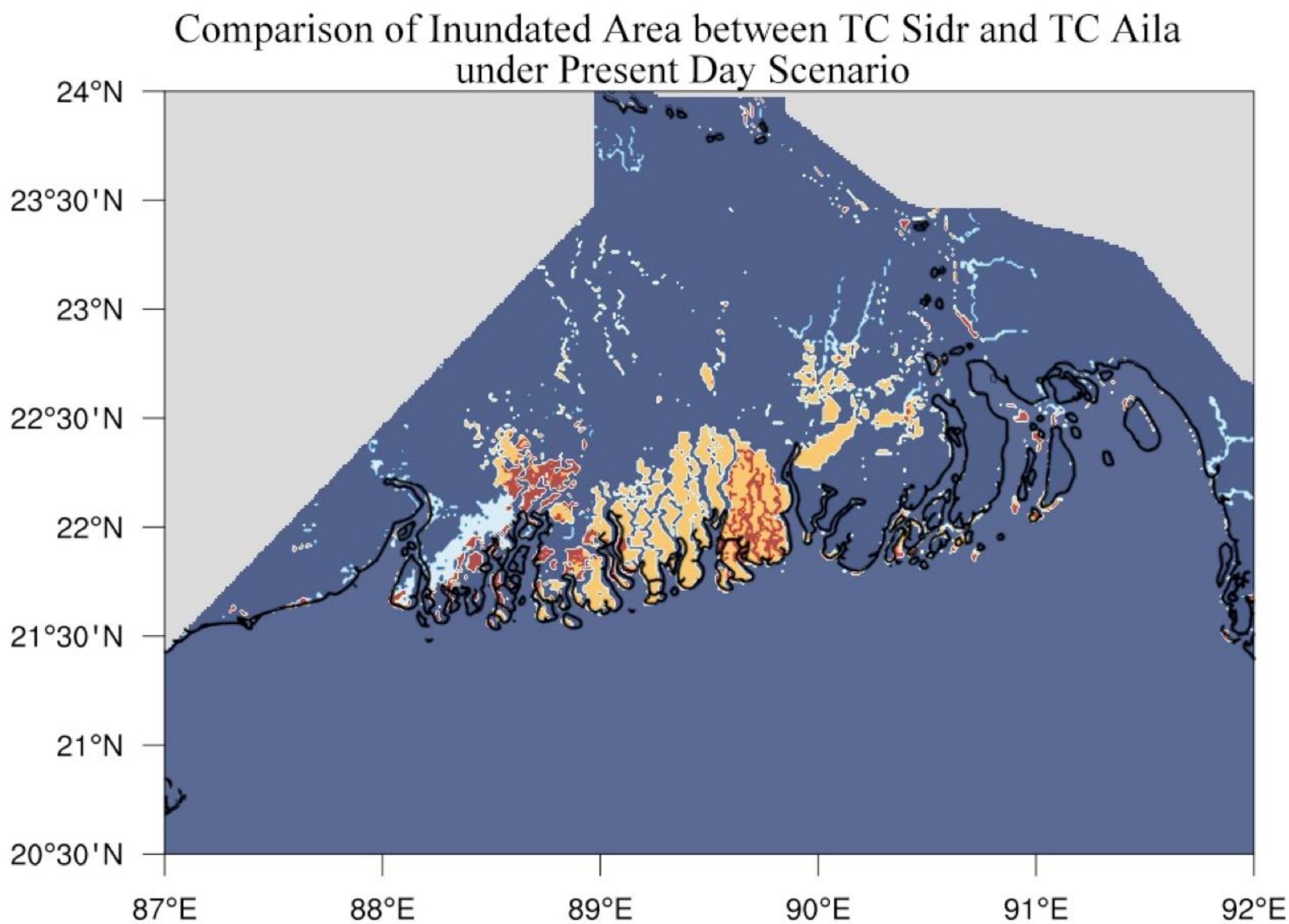


Figure 4. Yellow colors denotes the areas flooded by TC Sidr but not in Aila, and the white color representing the area inundated by TC Aila but not in Sidr. Red color is the area flooded by both TC Sidr and TC Aila. Blue color is showing the non-flooded area (either land or constant water).

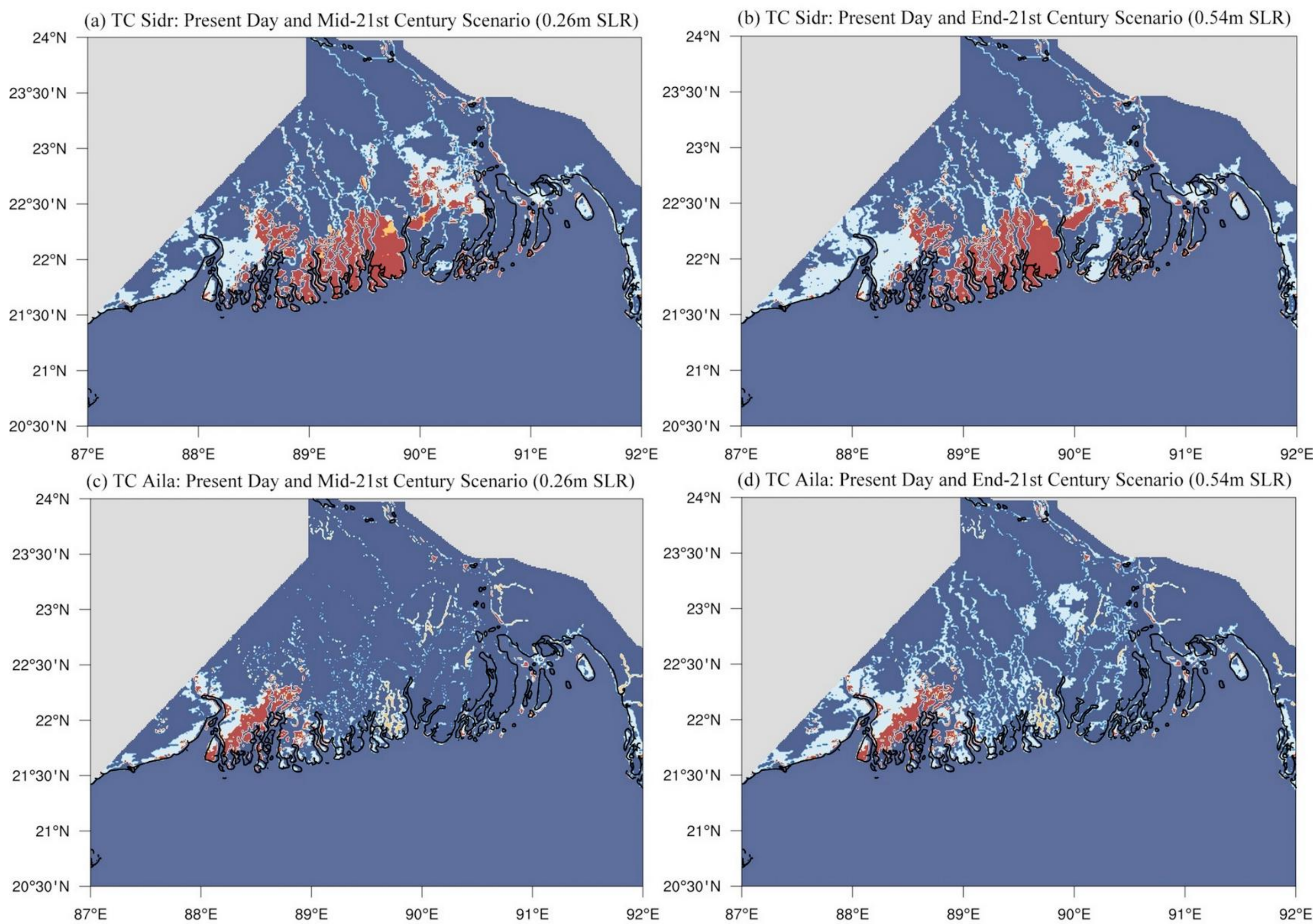


Figure 5: Comparison of inundated area between ~~present day~~present-day and future climate scenarios for (a) TC Sidr mid-21st ~~century~~ century 0.26m SLR (b) TC Sidr end-21st ~~century~~ century 0.54m SLR (c) TC Aila mid-21st ~~century~~ century 0.26m SLR (d) TC Aila end-21st ~~century~~ century 0.54m SLR. White color is representing the increased flooded areas that were not in ~~present day~~present-day scenario but the increase due to future SLR. Red color is showing the inundated areas that were similar both for

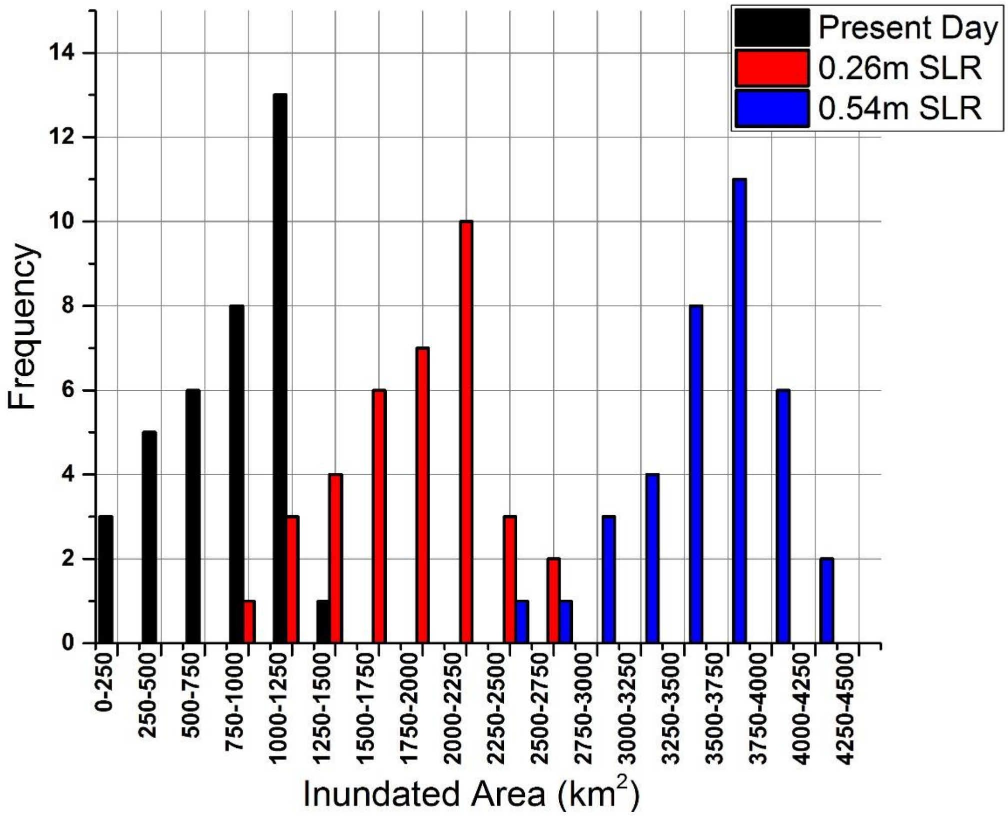
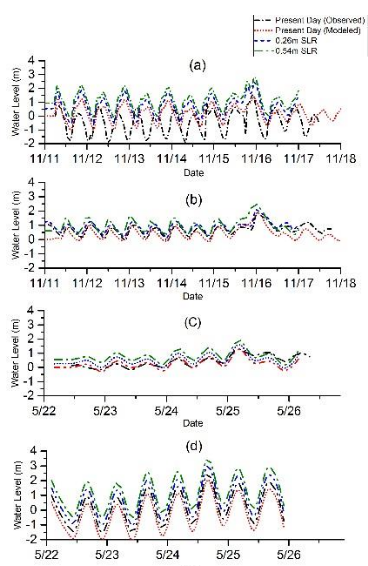
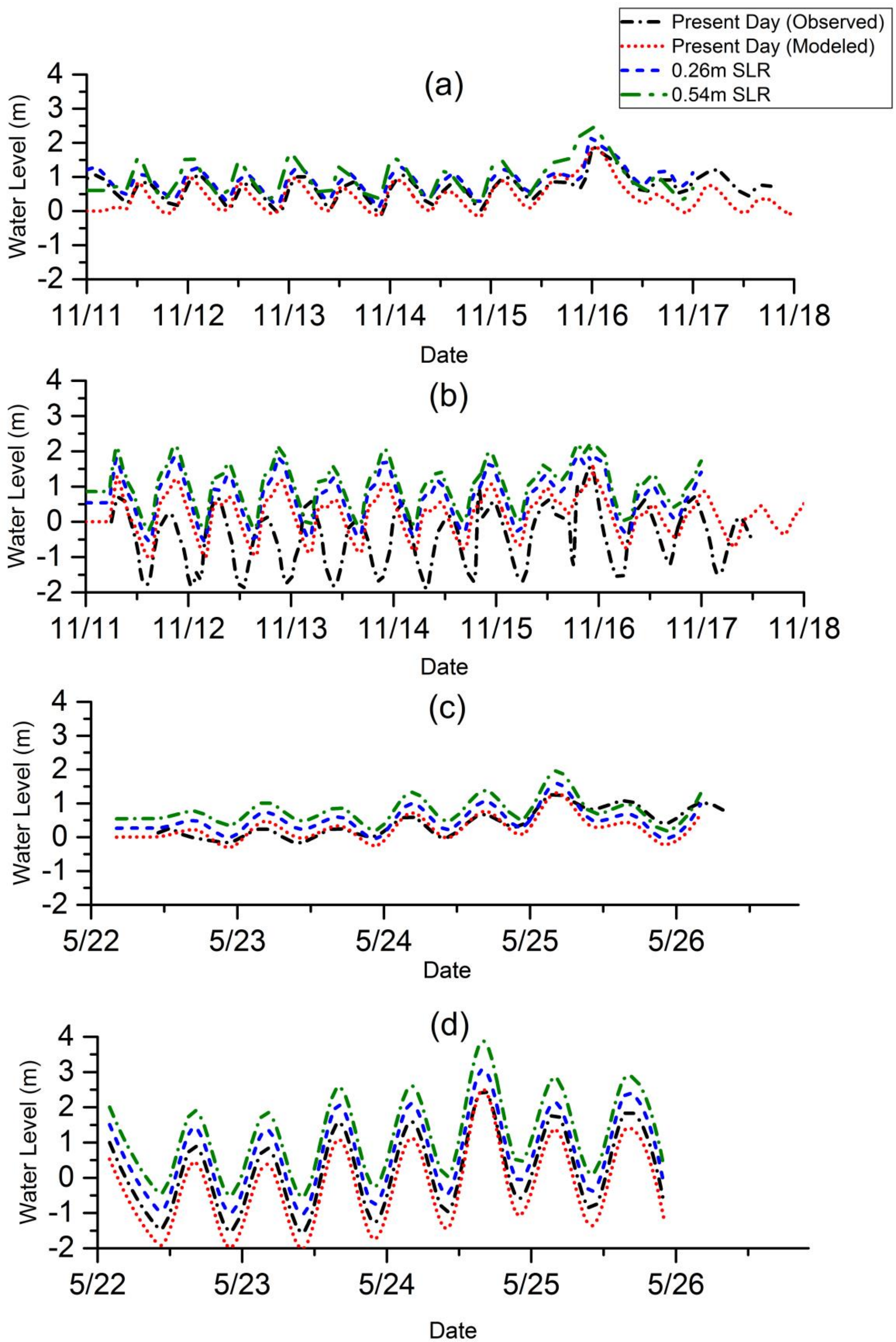


Figure 6: Ensemble projection of the future SLR impact on storm surge inundation. The column in black color is representing the inundation events for ~~present day~~present-day sea level condition, red colored one is for 0.26 ~~meter~~m of SLR and blue colored column is for 0.54 ~~meter~~m of SLR conditions. In total 108 simulations were conducted for present and two future SLR scenarios.





Present Day (Observed)
Present Day (Modeled)
0.26m SLR
0.54m SLR
(a)
Water Level (m)
4
3
2
1
0
-1
-2
11/11
11/12
11/13
11/14
11/15
11/16
11/17
11/18
Date
(b)
Water Level (m)
11/11
11/12
11/13
11/14
11/15
11/16
11/17
11/18
Date
(c)
Water Level (m)
5/22
5/23
5/24
5/25
5/26
Date
(d)
Water Level (m)
5/22
5/23
5/24
5/25
5/26
Date

Figure 7. Comparison of storm surge water levels between present daypresent-day and future SLR scenarios. (a) TC Sidr at Barisal (b) TC Sidr at Charchanga (c) TC Aila at Barisal (d) TC Aila at Charchanga. The observed, modeled present-day, mid-of-21st century-century and end-of 21st century21st-century storm surge levels are denoted by the black dash-dottedsolid, red dasheddotted, blue dotteddashed, and greenred dash-dottted lines, respectively.

present-dayrepresentingl

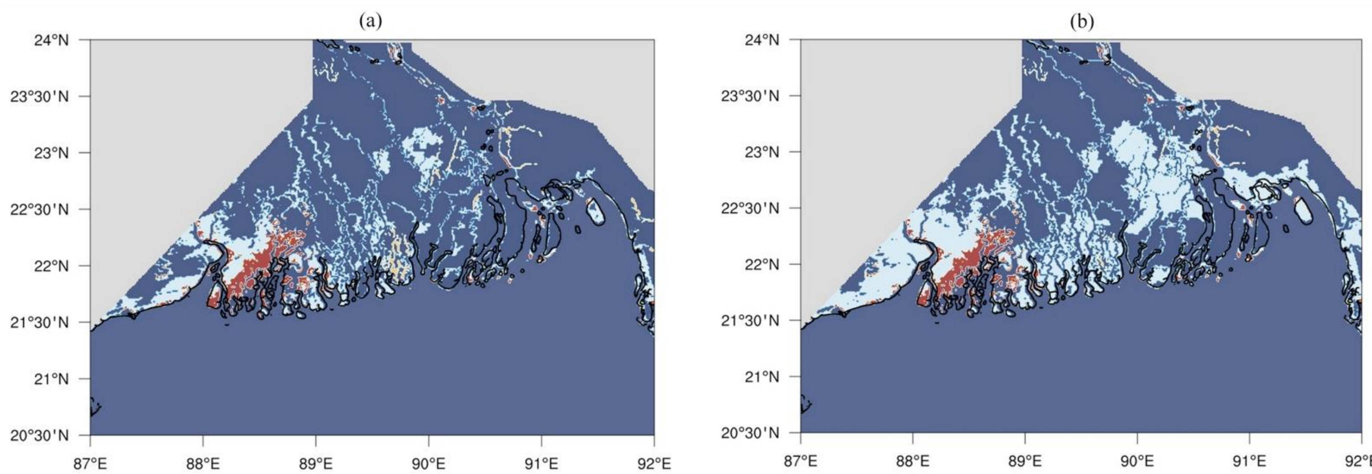


Figure 8. Comparison of inundated areas for TC Aila between present daypresent-day and end-21st 21st-century (0.54m SLR) scenario. White color is representing the increased flooded areas that were not in present daypresent-day scenario but the increase due to future SLR. -Red color is showing the inundated area that's similar both for present daypresent-day and future scenario case. Blue areas are either land or constant waters (those which are already water at the model initialization time). Figure (a) is representing the inundated area when SLR was considered on ocean depths instead of adding it in to the open ocean boundary and figure Figure (b) is showing the inundated area when we considered the SLR on ocean boundary.

Table 1 Manning's Roughness Coefficient for different land coverings.

Land cover	Manning's coefficient
River	0.015
Mangrove	0.080
Ocean	0.01
Land	0.025

Table 2 List of 12 historical TC events used for ensemble projection of storm surge inundation

Name	**Date**	**Landfall location**
Tropical storm 13	14-18 November, 1973	Noakhali
Cyclone 12	23-28 November, 1974	Bhola
Tropical storm 19	07-12 November, 1975	Chittagong
Tropical storm 1	22-25 May, 1985	Noakhali
Cyclone 4	21-30 November, 1988	Khulna
Cyclone 2	22-30 April, 1991	Chittagong
Cyclone 2	26 April – 30 May, 1994	Cox's Bazar
Cyclone 4	18-25 November, 1995	Cox's Bazar
Cyclone 1	13-20 May, 1997	Noakhali
Tropical storm 4	24-27 October, 2008	Barguna
Tropical storm Mahasen	10-16 May, 2013	Patuakhali
Tropical storm Roanu	18-21 May, 2016	Chittagong

Table 32: Parameters considered for ensemble projection of storm surge inundation which includes the TC intensities, tidal conditions and the SLR scenarios.

TC name	**Intensities**	**Tide conditions**	**SLR**
TC Sidr	+10%, present day, -10%	High Tide, low tide, actual tide, zero tide	Present day, 0.26 meterm, 0.54 meterm
TC Aila	+10%, Present day, -10%	High Tide, low tide, actual tide, zero tide	Present day, 0.26 meterm, 0.54 meterm
12 historical TC tracks	Actual intensities	Actual tide conditions	Present day, 0.26 meterm, 0.54 meterm

Table 43. Computed values of RMSE, MAE and Nash-Sutcliffe coefficient for both TC Sidr and TC Aila

Stations	TC Sidr			TC Aila		
	RMSE (m)	MAE (m)	NASH	RMSE (m)	MAE (m)	NASH
Barisal	0.23	0.16	0.85	0.33	0.24	0.65
Charchanga	0.26	0.19	0.80	0.28	0.17	0.73
Average	**0.245**	**0.175**	**0.825**	**0.305**	**0.205**	**0.69**

Table 5. Comparison of inundated area between present daypresent-day & future SLR scenarios and calculated change in percentage with respect to present daypresent-day scenario.

Scenario	**TC Sidr**		**TC Aila**	
	Inundated Area (km^2)	**(%) increase**	**Inundated Area (km^2)**	**(%) increase**
Present-day	1860.00		1208.00	
Mid-21st-century	2436.60	+31.00	1550.00	+28.31
End-21st-century	2845.80	+53.00	1770.00	+46.52

Table 6. Comparison of storm surge level between present day & future SLR scenarios and increase in storm surge level with respect to the present day scenario for the case of TC Sidr and TC Aila in Barisal and Charchanga observational stations. The SLR scenarios of 0.33 m, 0.40 m and 0.47 m were used to examine the linearity/non-linearity of increase in storm surge level with respect to SLR conditions.

SLR Scenarios (m)	**TC SIDR**				**TC AILA**			
	Barisal		**Charchanga**		**Barisal**		**Charchanga**	
	surge(m)	**increase(m) and %**	**surge(m)**	**increase(m) and %**	**surge(m)**	**increase(m) and %**	**surge(m)**	**increase(m) and %**
0.00 (present-day)	1.87	n/a	1.64	n/a	1.29	n/a	2.50	n/a
0.26 (mid-21st-century)	2.13	0.26 (13.90%)	1.87	0.23 (14.02%)	1.58	0.29 (22.48%)	3.07	0.57 (22.80%)

0.33	2.21	0.34 (18.18%)	1.95	0.31 (18.90%)	1.66	0.37 (28.68%)	3.22	0.72 (28.80%)
0.40	2.26	0.39 (20.85%)	2.00	0.36 (21.95%)	1.75	0.46 (35.65%)	3.42	0.92 (36.8%)
0.47	2.32	0.45 (24.06%)	2.08	0.44 (26.83%)	1.82	0.53 (41.08%)	3.67	1.17 (46.80%)
0.54 (end-21st-century)	2.41	0.54 (28.88%)	2.19	0.55 (33.54%)	1.96	0.67 (51.94%)	3.87	1.37 (54.80%)

Present-day21st-21st-Present-day21st-21st-