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A COMPARATIVE STUDY OF STORM SURGE PHENOMENON ASSOCIATED WITH THE TROPICAL CYCLONE AILA OVER THE BAY OF BENGAL USING NWP MODELS

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ABSTRACT

The coastal area of the North Bay of Bengal (BoB) is one of the most vulnerable places of tropical cyclone induced storm surge. Funneling shape of the coast cannot drive water towards the coast but amplify the surge height. Meteorological force drives sea water to the coast. In this study, prediction of cyclone induced storm surge for cyclone Aila is done by using India Institute of Technology-Delhi (IIT-D) storm surge model and Japan Meteorological Agency (JMA) storm surge model. The input files for both the models are provided by using simulated data of Weather Research and Forecasting (WRF) model and estimated data of India Meteorological Department (IMD). The results are compared with available recorded data of surge height for this cyclone. The differences in simulated output for two different input files are also studied. The maximum surge height for Aila from IIT-D model is found 3 m and from JMA model is 2 m using WRF simulated data. For IMD estimated data, it is found 3 m from IIT-D model and 2.5 m from JMA model. The simulated surge heights are found in good agreement with the available reported data of storm surges.

Keywords: *TC, Storm Surge, JMA, IIT-D*

1. INTRODUCTION

A Tropical Cyclone (TC) is one of the most destructive natural phenomena, which can be defined as a generic term for a large scale, non-frontal, low-pressure system originating over tropical and sub-tropical waters with organized convection and definite cyclonic surface wind circulation. Tropical cyclones have led to some of the most notable coastal flooding disasters in recent history. The change in atmospheric pressure in extreme wind stress results in a storm surge that temporarily raises the total water level, producing a storm tide which can flood vast areas of coastal land. Storm surges associated with TCs are one of the most devastating natural phenomena all over the world. But in Bangladesh, it is more dangerous than any other countries because of its geophysical settings. Storm surge is formed by water pushed toward the shore by the winds moving cyclonically around the storm. The maximum potential storm surge depends on a number of different factors. Storm surge is a very complex phenomenon because it is very complex depending on changes in storm intensity, forward speed, size (radius of maximum wind), central pressure etc.

Several studies have been undertaken for storm surge simulation over Bay of Bengal using different methods. Ali *et al*. (1997) have investigated river discharge, storm surges and tidal interaction in the Meghna river mouth in Bangladesh, and back water effect of tides and storm surges on fresh water discharge through Meghna estuary. Dube *et al.* (1985) have developed numerical models to observe the dynamic effect of curving coasts and the direction of motion of the storm relative to the coast on the location of peak surge. Debsarma (2009) simulated storm surges due to the severe cyclone of April 1991, the severe cyclones of 1997, and the Orissa super cyclone of 1999 using IIT-D model. He found that the model performance is good but suggested further refinement and inclusion of water discharge from Meghna estuary. Sinha *et al.* (1987) have developed numerical model to simulate storm surge and sea level rise in the Indian coast adjacent to the Bay of Bengal and the Arabian Sea. Das *et al.* (1974) have developed numerical models to observe the dynamic effect of curving coasts and the direction of the motion of the storm relative to the coast on the location of the surge. Flather *et al.*, (1994), Henry *et al.,* (1997) and Roy *et al.,* (1995) developed several models to simulate the surges associated with severe tropical cyclonic storms hitting the coast of Bangladesh. Higaki *et al.,* (2009) have developed the outline of the storm surge prediction model at the JMA. Hasegawa *et al.* (2015) developed JMA's storm surge prediction model for World Meteorological Organization (WMO) Storm Surge Watch Scheme (SSWS) and they began the development of storm surge prediction in Asia region.

In this study, we have used Weather Research and Forecasting (WRF) model to simulate minimum central pressure, maximum sustained wind and track of the cyclone. For model physics parameterization, WRF Single Moment 3 (WSM3) scheme is used as microphysics scheme, Kain-Fritch (KF) scheme is used as cumulus parameterization because this scheme includes a downdraft in the cloud (Kain, 2004) which is essential for this

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study and Yonsei State University (YSU) scheme is more sensitive with observed variables than other planetary boundary layer schemes which is founded by Rahul *et al.* (2015) in this case YSU scheme have been used as planetary boundary layer scheme. The IIT-D and JMA storm surge models are used to simulate maximum storm surge.

2. DATA USED AND MODEL DESCRIPTION

2.1 Data and WRF model Description

The National Centre for Environmental Prediction (NCEP) high resolution Global Final (FNL) Analysis data on 1.0°×1.0° grids covering the entire globe every 6-hourly has been taken as initial and lateral boundary conditions for WRF model. WRF Model is a numerical weather prediction (NWP) system which is the composition of some fully compressible non-hydrostatic equations with different prognostic variables is designed to serve both atmospheric research and operational forecasting needs. NWP refers to the simulation and prediction of the atmosphere with a computer model, and WRF is a set of software of this. The development of WRF is joint effort by several organizations to build a next-generation mesoscale forecast model and data assimilation system to advance the understanding and prediction of mesoscale weather and accelerate the transfer of research advance into two operations. The WRF effort has a collaborative one among the National Center for Atmospheric Research (NCAR), Mesoscale and Microscale Meteorology (MMM) Division (ARW version 3.8.1).

Table 1: WRF model and domain configuration

Dynamics	Non-hydrostatic	Time Integration	3rd order Runge-Kutta
Number of Domain	1	Spatial differencing scheme	6th order centered differencing
Domain center	(17.5°N, 87.5°E)	Initial conditions	Three dimensional real-data (FNL: 1°×1°)
Horizontal grid distance	20km	Microphysics scheme	WSM 3-class
Vertical coordinates	Terrain-following hydrostatic-pressure	Cumulus physics scheme	Kain-Fritsch (KF)
Number of grid points	West-East 100 points, South- North 100 points.	PBL parameterization	Yonsei State University scheme (YSU)
Run time (60 hours)	2009_05_24_0000 to 2009_05_26_1200	Land surface	5 Layer thermal diffusion Scheme
Map projection	Mercator	Radiation scheme	RRTM for long wave
Horizontal grid	Arakawa C-grid	Surface layer	Monin-Obukhov similarity theory

2.3 IIT-D Model Description

IIT-D is fully non-linear and is forced by wind stress and quadratic bottom friction. It is a vertically integrated parametric storm surge model. It is used as a menu-driven stand alone system. In this model, the applied surface wind stress is determined from a bulk quadratic law. For the numerical solution of the model equations, a stable semi explicit finite difference scheme with staggered grid is used. The staggered grid consists of three distinct types of computational points such as the sea surface elevations, the zonal and meridional components. In this model the bottom stress is computed from depth integrated current with constant co-efficient of 0.0026 (Johns *et al.,* 1983).

Table 2: IIT-D model and domain configuration

Model	Two dimensional ocean model, vertically integrated	Forecast hour	24 hours
Coordinates	Lat/Lon Cartesian grid	Calculation run	4 times /day (6 hourly)
Area	18-23°N, 83.5-94.5°E	Initial time	00, 06, 12, 18 UTC
Grid resolution	3.70 km × 3.50 km	Visualization tools	GMT
Time steps	60 seconds	Topographic data	ETOPO2

To simulate storm surge from IIT-D model, observed track data from WRF model simulated data and IMD estimated data are used. The input parameters of the model include the oceanographic and meteorological parameters, hydrological input, basin characteristics, coastal geometry, wind stress and information about the astronomical tides. In this model time, position, radius of maximum wind and pressure drop are used as input file.

2.4 JMA Storm Surge Model Description

This model was developed by Meteorological Research Institute (MRI) of JMA. JMA mainly operates two storm surge models, one is Japan area storm surge model and other is Asia area storm surge model. JMA was developed next generation's storm surge predictions system using Finite Element Method (FEM). Technique to divide region to finite elements and make unstructured grids are established (Hasegawa *et al.* 2015). This parametric storm surge model used two dimensional shallow water formulae without advection terms as its model equations. Pressure drop due to inverse barometric effect and wind setup because of strong wind are included in the model. For JMA-SSM model observed track information from WRF simulated data and IMD estimated data are used. The input file of this model contains cyclones latitudes, longitudes, maximum sustained surface wind, minimum sea level pressure, drag coefficient and normal atmospheric pressure.

Table 3: JMA storm surge model and domain configuration

Model	2- dimensional linear model	Time step	8 seconds
Grid	Lat-Lon Arakawa-C grid	Initial time	00, 06, 12, 18 (UTC)
Region	8.5-23.5°N, 80-100°E	Forecast time	72 hours
Resolution	2-min mesh	Member	1 member

3. RSULTS AND DISCUSSION

3.1 Analysis of Mean Sea level Pressure and Maximum Wind Speed

Minimum central pressure (MCP) of a tropical cyclone is great importance as it helps to measure the intensity of a Cyclone. Figure 1 show the Estimated Central Pressure (ECP) (RSMC report, 2009) and Model simulated MCP of tropical cyclone Aila. The ECP and MCP gradually decrease with time and attain peak intensity before the landfall of the system and after that both pressures increase with time. The model MWS's (Figure 2) are almost same as that of observed up to 24 hours forecast (0000 UTC 25 May). After that model simulated MWSs are lower than that of estimated MWS values for full forecast hours except in the moment when the predicted value match with estimated value. Therefore, we can say that model simulated MWS is lower than estimated value.

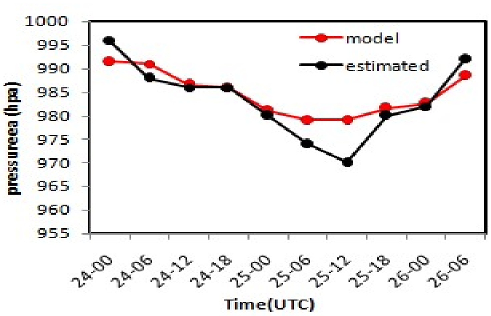


Figure 1: Comparison of minimum central pressure between WRF model simulated and IMD estimated value.

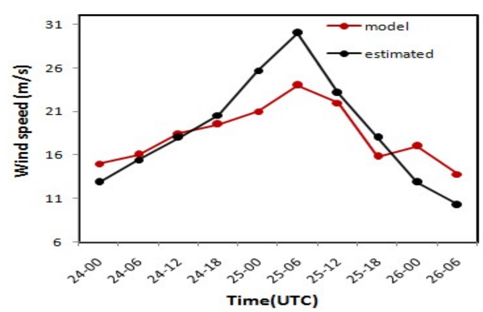


Figure 2: Variation of wind speed with time during the cyclone Aila using WRF simulated and IMD estimated value.

3.2 Distributions of Sea Level Pressure and Surface Wind

The distributions of mean sea level pressure (MSLP) are shown in the Figures 3(a-d) at 0000 UTC of 24, 0000 UTC of 25, 1200 UTC of 25 May (the day of maximum intensity), and 0000 UTC of 26 May 2009. Figures 3(a-d) shows that system changed its position with time and maximum intensity occurred before the landfall of the system. From the figure, it can be predicted that cyclone intensity increased with time and at the same time mean sea level pressure decreased. The distributions of surface wind at 0000 UTC of 24, 0000 UTC of 25, and 1200 UTC of 25 (the day of maximum intensity) and 0000 UTC of 26 May, 2009 are shown in Figures 4(a-d). The pattern of wind field distributions is asymmetric in every stage of cyclone. At 0000 UTC of 24 May, the initial stage of simulation, there is a strong wind bands in the southeast sector of system with cyclonic flow.

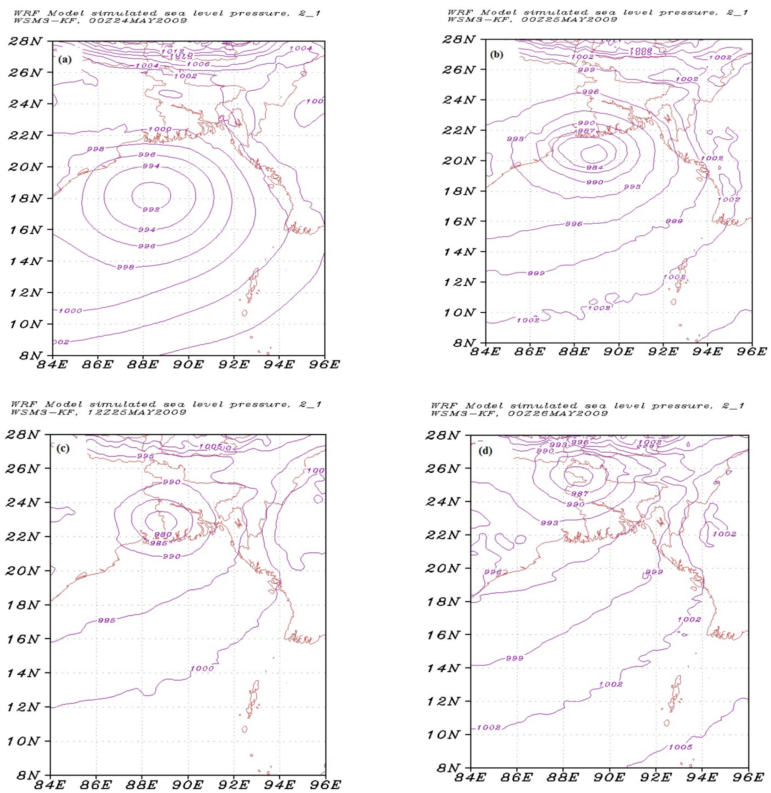


Figure 3: Distributions of MSLP at (a) 0000 UTC of 24 May, (b) 0000 UTC of 25 May, (c) 1200 UTC of 25 May (mature stage) and (d) 0000 UTC of 26 May 2009

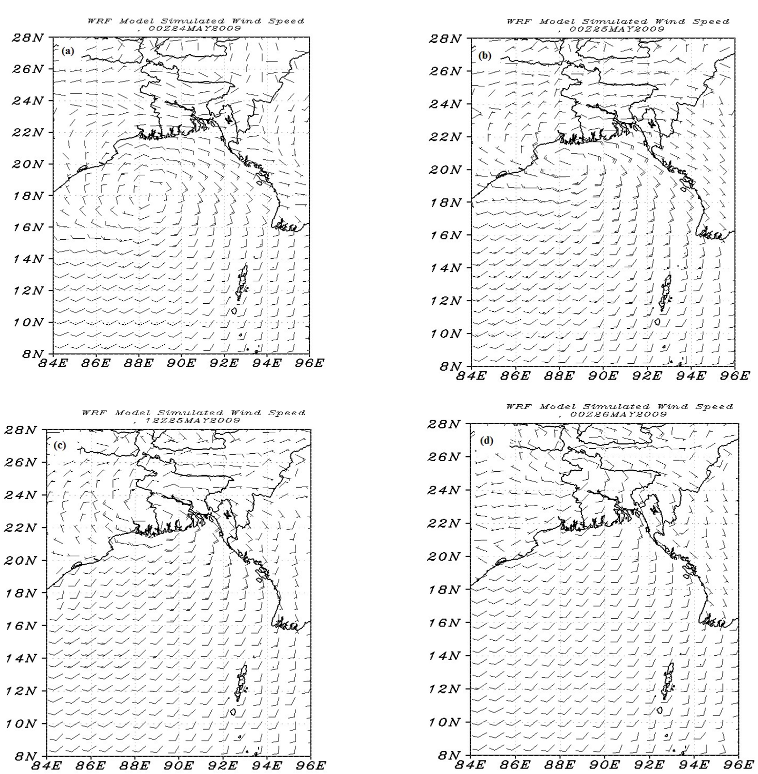


Figure 4: Distributions of wind speed in different time (a) 0000 UTC of 24 May, (b) 0000 UTC of 25 May, (c) 1200 UTC of 25 May and (d) 0000 UTC of 26 May of 2009

3.3 Analysis of Track Pattern

Cyclone track data is the most important data to simulate cyclone induced storm surge. Because, the location of the cyclone center (lat. & long.) is the fundamental requirement for both IIT-D and JMA storm surge model. For cyclone Aila, WRF model simulated track data and IMD estimated track data are plotted together in Figure 5. The track forecast of Aila is 60 hours based on the initial field at 0000UTC of 24 May. Figure 5 show that WRF model simulated track is almost parallel to the estimated track by IMD. The model was able to generate the northwestward movement of the system very well. From the observed data, it is found that landfall occur in between 0800 and 0900 UTC of 25 May, 2009 and the system crossed West Bengal coast close to east Sagar Island near at 21.8°N and 88°E. Figure 5 shows that landfall position (21.5°N, 88.2°E) for the model simulated track is very close to the estimated landfall position by IMD. Therefore, it is apparent that WRF model predicted tracks and re-curvature are in good agreement with the observed track.

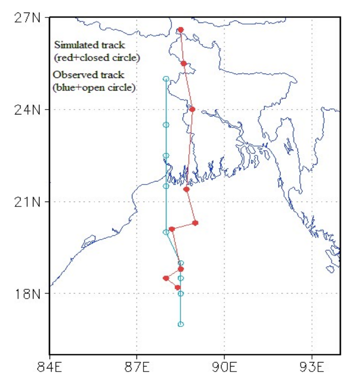


Figure 5: Track pattern of cyclone Aila using WRF model simulated data and IMD estimated data

3.4 Analysis of Maximum Storm Surge by IIT-D Model

Figures 6 (a-b) shows the IIT-D model simulated storm surge distributions over Bay of Bengal. From the figure, it is seen that the entire head of the BoB region including West Bengal and Bangladesh region was severely affected by storm surge in excess of 1 m. The maximum surge height attained approximately 3 m for both input files. The reported highest surge height of cyclone Aila is 3 m (as reported by The Daily Star, May 26, 2009). Therefore, it can be concluded that simulated maximum storm surge by IIT-D storm surge model is in good agreement with observed maximum surge height. Figures 6(a-b) also indicate that maximum surge occurred not only along the coast of adjoining mainland but also inside the river system.

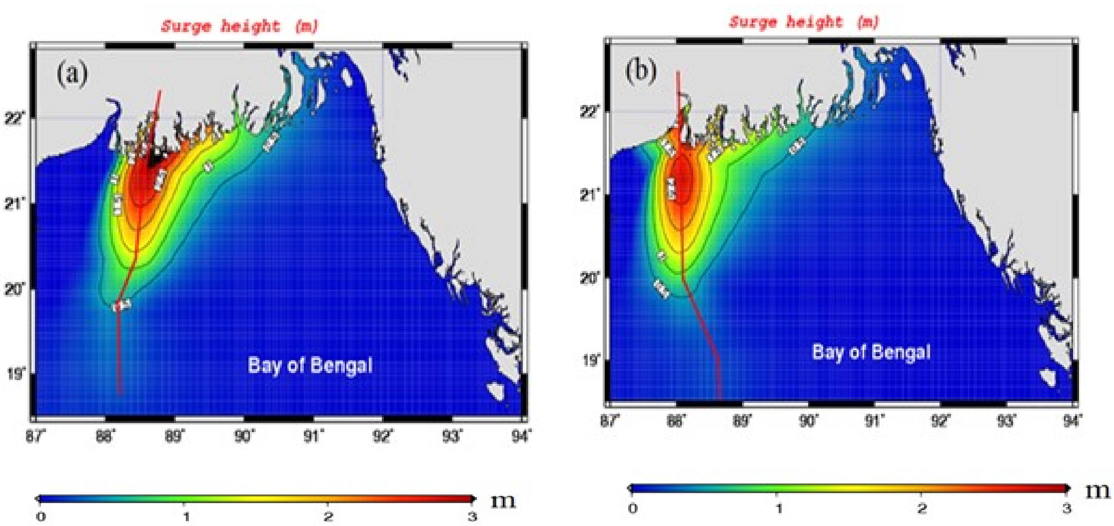


Figure 6: IIT-D model simulated storm surge distributions by using (a) WRF model simulated data as input file and (b) IMD estimated data as input file

3.5 Analysis of Maximum Storm surge by JMA-SSM Model

In this study, JMA storm surge model run input data from 1200 UTC of 24 May to 1200 UTC 25 May. From the IMD report, cyclone Aila made landfall between 0800 UTC and 0900 UTC of 25 May. From the input files the lowest central pressure is 978 hPa of WRF simulated data and 970 hPa of IMD estimated data. The maximum storm surge height generated by JMA storm surge model is presented in Figures 7(a-b). JMA storm surge model predicted maximum surge is approximately 2 m and 2.5 m using WRF model simulated track data (Figure 7a) and IMD estimated track data (Figure 7b), respectively. Surge height variation occurs because of the variation of input data. Therefore, it can be concluded that maximum surge height of cyclone Aila by JMA storm surge model is underestimated by 0.5 m and 1 m using IMD estimated data and WRF simulated data, respectively as compared to the reported maximum surge height which is 3 m (The Daily Star, May 26, 2009).

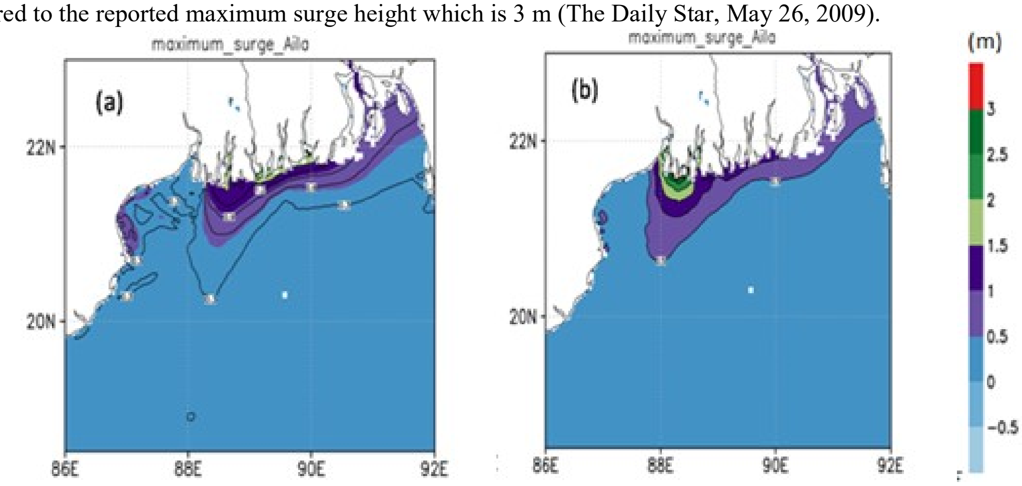
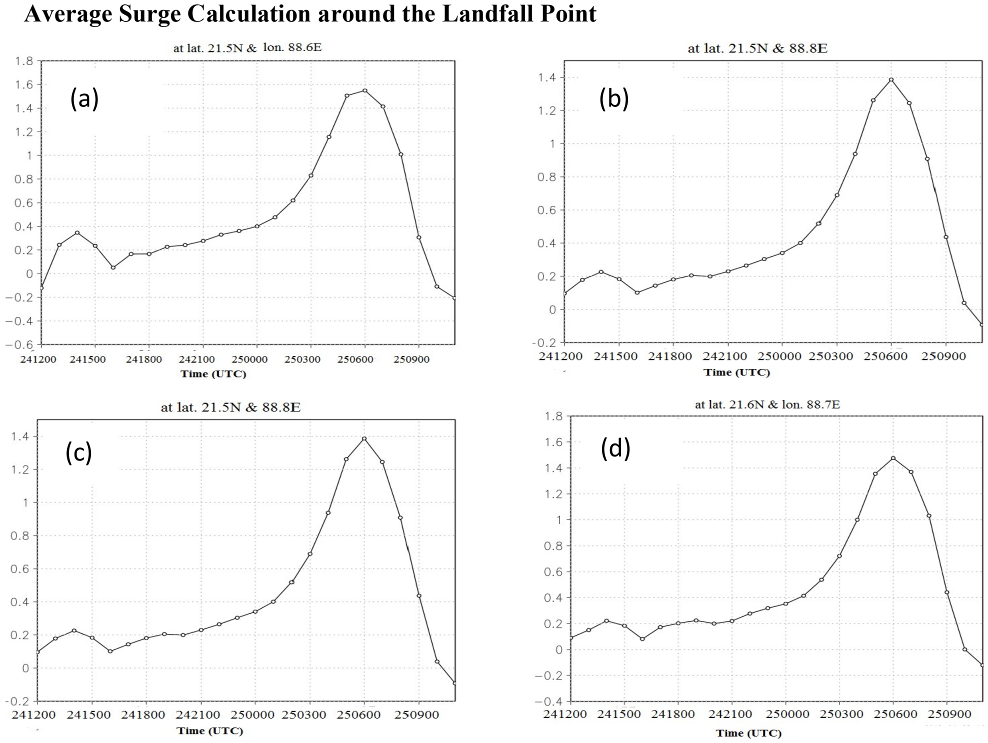


Figure 7: JMA Storm Surge model simulated storm surge distributions of cyclone Aila (a) using WRF model simulated data and (b) IMD estimated data as input file

3.6 Average Surge Calculation around the Landfall Point



Figures 8: Time series of storm surge at : (a)21.5°N, 88.6°E , (b) 21.5°N, 88.8°E, (c) 21.6°N, 88.6°E, and (d) 21.6°N, 88.8°E using WRF model output as input data for JMA storm surge model

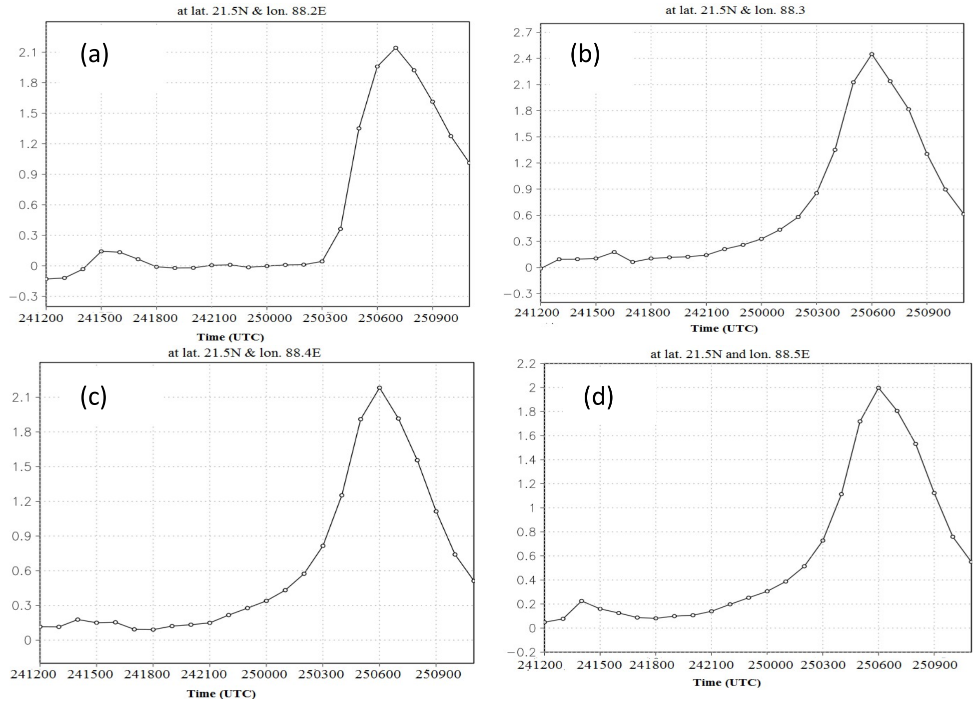


Figure 9: Time series of storm surge at : (a) 21.5°N, 88.2°E, (b) 21.5°N, 88.3°E, (c) 21.5°N, 88.4°E and (d) 21.5°N, 88.5°E using IMD estimated data as input data for JMA storm surge model

Figures 8 (a-d) and 9 (a-d) represents the time variation of storm surge at different locations around the landfall point of the TC Aila. WRF model simulated data (landfall point 21.5°N, 88.2°E) is used to evaluate the surge height in Figures 8 (a-d) and IMD estimated (landfall point 21.8°N, 88.0°E) data is used in Figures 10 (a-d). The maximum surge heights at different locations are shown in Table 4. Since maximum surge height is associated along the right part of a cyclone, we consider four different locations at right side of landfall point. The average values for both the input data are also calculated. The average maximum surge height for the TC Aila for WRF data and IMD estimated data are respectively 1.52 m and 2.2 m. Therefore, JMA storm surge model shows lower surge height for WRF model data than that of IMD.

Table 4: Average surge height calculation

Input file: WRF model data			Input file: IMD estimated data		
Location (°N, °E)	Maximum surge (m)	Average surge (m)	Location (°N, °E)	Maximum surge (m)	Average surge (m)
21.5, 88.6	1.58	1.52±0.04	21.5, 88.2	2.15	2.20±0.09
21.5, 88.8	1.40		21.5, 88.3	2.45	
21.6, 88.6	1.58		21.5, 88.4	2.20	
21.6, 88.7	1.50		21.5, 88.5	2.00	

3.7 Distributions of Storm Surge in Different Time

Cyclone Aila crossed West Bengal coast close to the east of Sagar Island between 0800 UTC & 0900 UTC of 25 May. For this reason, distributions of storm surge are taken from 0700 UTC of 25 May to 1000 UTC of 25 May (Figures are not shown) by JMA storm surge model using WRF track data as input. At 0700 UTC of 25 May, maximum surge height is approximately 1-1.5 m. At 0800 UTC, 0900 UTC and 1000 UTC of 25 May, maximum surge height is almost same and the maximum surge height is approximately 2 m. Although the movement of cyclone Aila is towards the northward direction, the maximum storm surge occurred in the Sundarban coast and moved northeastward direction.

The distributions of storm surge by JMA storm surge model using IMD estimated track data as input are taken from 0700 UTC of 25 May to 1000 UTC of 25 May. At 0700 UTC and 0800 UTC of 25 May maximum surge height is approximately 2.5 m. After 0800 UTC of 25 May, maximum surge height started to decrease. At 0900 UTC of 25 May maximum surge height is approximately 2 m. At 1000 UTC of 25 May surge height further decrease and the maximum surge height in between 1.5 to 2 m.

4. CONCLUSIONS

The WRF model simulated MCP for tropical cyclone Aila and is found 978 hPa and IMD estimated MCP was 970 hPa. The model simulated maximum wind speed for cyclone Aila is found $24ms^{-1}$ and IMD and Joint Typhoon Warning Center (JTWC) estimated maximum wind speed is 30 ms^{-1}. The model underestimated the maximum sustained wind speed by $6ms^{-1}$ (i.e. by 30%). IIT-D storm surge model simulated maximum surge heights using both WRF model simulated data and IMD estimated data are found approximately 3 m. JMA storm surge model simulated maximum surge height using WRF model simulated data is 2 m and using IMD estimated data it is 2.5 m. The maximum surge height was reported as 3 m for cyclone Aila. Therefore, the IIT-D model predicted maximum storm surge is in good agreement with the reported maximum surge height.

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