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NUMERICAL SIMULATION OF CYCLONE SIDR USING A WRF-SWAN-SURGE-TIDE COUPLED MODEL

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Computation of weather field on the basis of meteorology has significant importance for the assessment of cyclonic storm surges. The application of mesoscale WRF model for the prediction of tropical cyclones over the Bay of Bengal is quite new and challenging. The present study aims at the application of Advanced Research WRF (ARW) model for the investigation of the weather field of tropical cyclone Sidr. This study focused on the numerical simulation of Cyclone SIDR by integrating WRF (Weather Research and Forecasting), SWAN (Simulating Waves Near shore), storm surge simulation models and NAO.99b tidal prediction system. The WRF model seems to capture the actual phenomena of cyclone Sidr well in terms of track and intensity. The performance of this model can be improved and on the basis of this improved weather data, the integrated meteorology wave hind casting model can give more accurate prediction and hind casting of cyclonic storm surges in the Bay of Bengal.

Key Words: *Tropical cyclone, prediction, track, intensity, WRF model, forecasting, storm surge.*

1. INTRODUCTION

The Bay of Bengal is an ideal breeding ground for tropical cyclones. Almost 7% of the global tropical cyclones occur in the North Indian Ocean (Bay of Bengal and Arabian Sea), and they are some of the most deadly. The shallow waters of the Bay of Bengal, the low flat coastal terrain, and the funneling shape of the coast line lead to devastating losses of life and property in this region. Due to the high population density, the devastation of the cyclones is more pronounced along the coastal region of Bangladesh. During the last 48 years 18 major cyclones devastated the coastal area. Among them the 1970 and 1991 cyclones were the most severe. The most recent event was cyclone Sidr in November 2007, which caused 3,363 deaths affecting 8.9 million people and damaged houses, livestock, crops, educational institutions, roads and embankments as reported by Disaster Management Information Centre, Ministry of Food and Disaster Management of Bangladesh. Historically Bangladesh is under persistent threat from cyclones and flooding. So the timely and accurate prediction of the track and intensity of tropical cyclones is essential for Bangladesh in order to protect against the loss of lives and property.

As the synoptic and statistical methods have limitations in predicting the track and intensity of tropical cyclones beyond 24 hours, many attempts have been made to develop numerical weather prediction (NWP) models for this purpose. Concerted effort of community model development at the National Center for Atmospheric Research (NCAR) in association with the Environmental Modeling Center (EMC) of National Centers for Environmental Prediction (NCEP) resulted in making significant progress in terms of meso-scale modeling for various weather applications (Rao et al.2011). Much progress has been made in recent years in addressing real-time tropical cyclone prediction based on these community models, especially for the Atlantic and Eastern Pacific basins (Bender et al. 2007; Surgi et al. 2008). Recently a few studies have been performed for tropical cyclone prediction in the North Indian Ocean region, particularly for Bay of Bengal storms, by using NCEP Hurricane Weather Research and Forecast (HWRF) model and Advanced Research WRF (ARW) model. Rao and Tallapragada (2011) performed a comparative study of the performance of NCEP operational HWRF, NCAR ARW, and

MM5 models and reported that HWRF model was better at predicting the track and intensity of tropical cyclone Sidr and Nargis. Kumar et al. (2011) performed another study to simulate cyclone Sidr by using The Advanced Hurricane WRF (AHW) model with different domain size and boundary conditions. They reported that model domain resolution has an impact on track and intensity and the western boundary plays a significant role in controlling the track of cyclone Sidr.

The present study focused on the development and application of a coupled model by integrating the meteorological model into the wave hind casting model. The goal of this research is to investigate the actual phenomena of the cyclone more accurately by using numerical models so that a more accurate prediction and evacuation system can be designed.

2. OVERVIEW OF CYCLONE SIDR

Super Cyclone "SIDR" was one of the 10 strongest cyclones to hit Bangladesh between 1876 and 2007. It was first observed on 9 November 2007 near the southeast of the Andaman Islands with a weak low-level circulation near the Nicobar Islands. An indication that it had formed into a tropical cyclone arrived on 11 November, while located a short distance south of the Andaman Islands. On 13 November, the depression had turned into a cyclonic storm with a core of hurricane force winds. Cyclone Sidr moved northwards and was centered at 9 p.m. on 14 November 2007 about 725 km South-southwest of Chittagong port, 645 km South-southwest of Cox's Bazar port and 670 km South of Mongla port. Sidr intensified quickly, moved slowly northwestward into the Bay of Bengal, headed northward, and finally, made landfall at the Bangladesh coast as a very severe cyclone (category 4 equivalent) at approximately 1700 UTC 15 November. After the landfall, it weakened rapidly and dissipated the next day.

Cyclone Sidr hit Bangladesh's offshore islands at approximately 18:30 hours on the evening of 15 November and made landfall across the Barisal coast at 21:00 hours local time during ebb tide. The maximum wind speed of Cyclone Sidr was 69 m/s, and its lowest central pressure before landfall was 944hPa (Nasrin et al.2012, Hasegawa et al.2008).Across 30 districts of Bangladesh, 8.7 million people were affected by this cyclone. A total of 3,295 people were reported dead and approximately 53,000 people were reported missing. Approximately 1.5 million households were damaged, leaving millions of people without shelter. The estimated economic loss due to SIDR was more than US$3.1 billion (Nasrin et al.2012). Some local officials have described the damage as being even worse than that from the 1991 cyclone. The coastal cities of Patuakhali, Barguna and Jhalokati District were hit hard by a storm surge of over 5 meters. About a quarter of the world heritage site of Sunderbans were damaged. Researchers said the mangrove forest of Sunderban will take at least 40 years to recover from this catastrophe.

The Japan Society of Civil Engineering (JSCE) conducted a field survey in Bangladesh from 26 to 28 December 2007 to investigate and assess the state and mechanisms of disaster from the storm surge. The third author of the present paper served as the team leader of survey team. According to the survey report, the maximum inundation height of the surge was 9.6m at a steel tower (the inundation depth 6.5m) in the coastal area of Kuakata, which is much higher than other observation heights. The inundation height observed at the crest of the embankment in West Kuakata was 5.6m. Storm surge overtopped the embankment and inundated the area behind. However, the inundation height behind the embankment was relatively low, around 2.3m (JSCE Investigation report, 2008).

Hind casting of the storm surge of cyclone Sidr had been made using an available storm surge model by the Institute of Water Modeling (IWM) to assess the temporal variation of storm surge height and coastal flooding during the passage of the Sidr along the Bay of Bengal and across the Barisal coast. This hind casting showed surge level of 5.5 to 6m PWD, at the outfall of Baleswar River, 5m at Sarankhola and 3.5m at Hiron point. The surge level exceeds polder embankments, built to a height of+5m, PWD. But surge level does not exceed the sea facing embankment, which are at more than 6m in the Barguna, Barisal and Bagerhat districts (Emergency Response and Action Plans Interim Report 2007, Ministry of Food and Disaster Management Bangladesh)

3. DESCRIPTION OF NUMERICAL MODEL

In this study an integrated WRF (Weather Research and Forecasting)-SWAN (Simulating Waves Near shore)-Storm Surge-Tide model is used for the numerical simulation of Cyclone Sidr. The Weather Research and Forecasting (WRF) model is used to compute the weather field of Cyclone Sidr. The WRF model is being developed as a collaborative effort between the NCAR Mesoscale and Microscale Meteorology (MMM) Division, the National Oceanic and Atmospheric Administration's (NOAA), National Centers for Environmental Prediction (NCEP) and more than 150 other organizations and universities. The Advanced Research WRF (ARW) is designed to be a flexible, state-of-the-art atmospheric simulation system that is portable and efficient on available parallel computing platforms. A detailed description of WRF (ARW) was provided by Skamarock et al. (2005). SWAN is a third-generation wave model developed by Delft University of Technology that computes random, short-crested wind-generated waves in coastal regions and inland waters.

The NCAR version 3.0 of Advanced Research WRF (ARW) model with 2 way nesting was used to investigate the weather field of cyclone Sidr. The initial and boundary conditions for the large-scale atmospheric fields were derived from the 1×1 degree NCEP global final analysis (FNL) using the WPS (WRF Pre-processing System) software package. The extracted wind and pressure fields from the WRF model were applied in both SWAN and the Storm Surge model as inputs to compute the wave and surge (both wind and pressure driven surge). The storm surge model developed by Ohira and Shibayama (2012) was used, where the surge is calculated by differentiating the nonlinear long wave equation using the Leap-frog method. NAO.99b tidal prediction system is a global ocean tide model developed by Matsumoto et al (2000). The flowchart of the integrated model is shown in **Fig. 1** (Ohira and Shibayama, 2012). Finally wave, wind & pressure driven surge, and tide obtained from coupled model are combined to get the storm surge level.

For our simulation the outermost domain was fixed with 12.95 km grid spacing (230 × 250 grid points) and covers an area of 2978 km × 3237 km from 75.9°E to 102.5°E and 3.75°N to 31°N. One fixed nested domain was used with 1.85km grid spacing (365×267 grid points) that covered an area of 675 km × 494 km. **Fig. 2** shows the model domain. The model was configured with a two-way nesting option and run for 96 hours with a time step of 60 s for the parent and 10 s for the nested domain. Both parent and nest had 28 vertical layers. The model run started at 00UTC of 13 November 2007 and ended at 00UTC of 17 November 2007.

In order to see how WRF ARW works for weather field simulation another model run was performed with a relatively small outmost domain covering 79.32°E to 99.13°E and 5.06°N to 23.74°N. For this simulation the parent and the nested domain had a horizontal resolution of 9.25 km and 1.85 km respectively. The time step was 45 s for the parent and 9 s for the nested domain. All other conditions were kept the same.

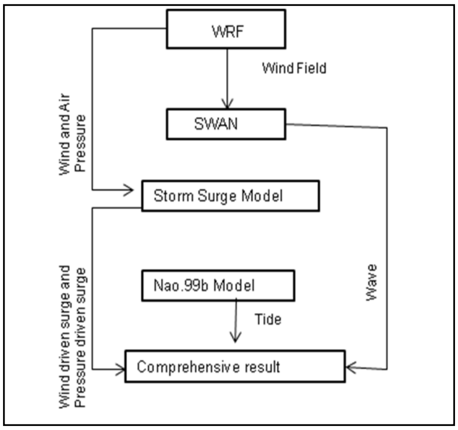

Fig.1 Model Flow (Ohira and Shibayama, 2012)

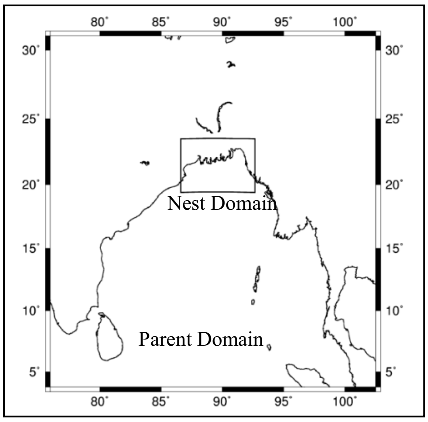

Fig.2 Model Domain for WRF ARW

The WRF ARW forecasted wind data for the nested domain (grid spacing 1.85 km) was used in the SWAN model to estimate the wave field in the coastal region of Bangladesh. For this SWAN run GEBCO 30 s bathymetry data with 1 km grid spacing was used. SWAN was run for 96 hours starting from 13 November 00UTC with a time step of 3s. For storm surge simulation, the wind and pressure data of the nest domain was used. The model was run for 96 hours with a time step of 3s.

Finally the water level is computed in the following way:

Water Level = Wind and pressure surge + Wave +Tide

4. RESULTS AND DISCUSSIONS

The 96 hour forecast of cyclone Sidr by WRF ARW shows reasonable accuracy in terms of cyclone track and intensity. **Fig. 3** shows the observed Joint Typhoon Warning Centre (JTWC) track and model simulated tracks. For the small domain model simulated initial and landfall position of the cyclone looks very close to the observed one, but the model track deflected slightly to the left from 14 November 00UTC to 15 November 06UTC. After that the simulated track shows reasonable accuracy with the observed track till landfall (landfall near 89.64°E and 21.44°N, 35 km away from the observed landfall position).

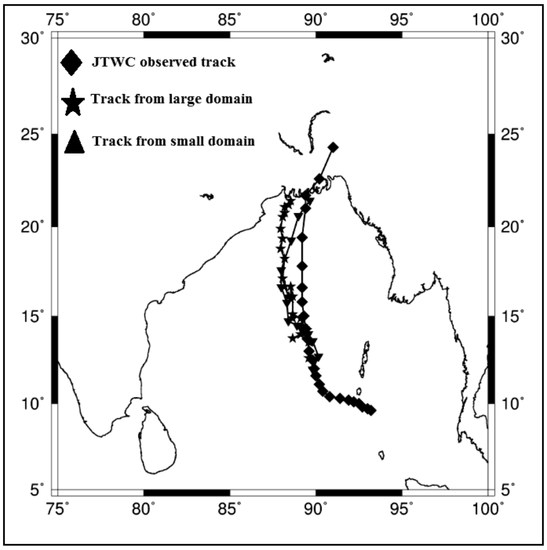

Fig.3 Observed and simulated track of cyclone

For the large domain run, the simulated track shows reasonable accuracy for the first 24 hour of simulation. However, the simulated track started to diverge toward the northwest from the actual track at 00 UTC 14 November and continued simulating slightly deflected track after that. It finally made landfall near 88.53°E and 21.4°N which is 90 km away (to the west) from the observed landfall position. Both models simulated a relatively slower moving cyclone. The simulated landfall time was around 00UTC on 16 November for both domains. In terms of cyclone intensity, the large domain run gives better forecast than the small domain. 96 hour forecasting by WRF model for the large domain gives low pressure of 970hPa near 88.06°E and 20.54°N, whereas small domain shows a low pressure of 978hPa close to 88.6°E and 19.3°N. The highest wind speed obtained is 46m/s for both domains. **Fig. 4** and **Fig. 5** show the model simulated wind and pressure field at both the initial time and after 60 hour of computation, respectively.

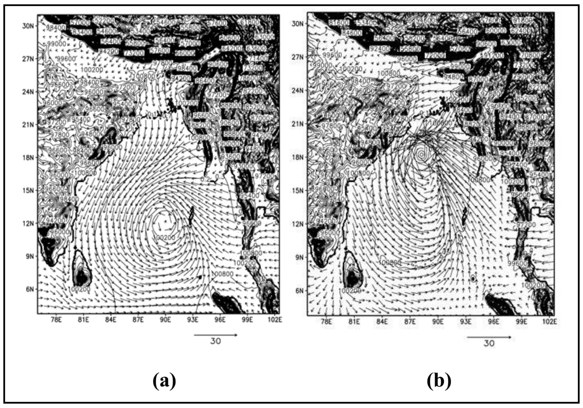

Fig.4 Wind and pressure fields at Initial time, 00 UTC on 13, November, forecasted by WRF in: (a) large domain; and (b) small domain.

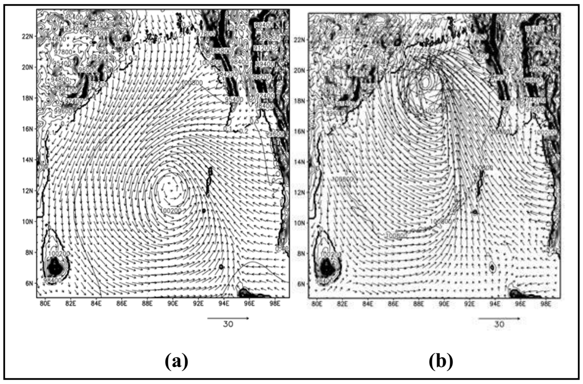

Fig.5 Wind and pressure fields after 60 hour of simulation, 12 UTC on 15, November, forecasted by WRF in: (a) large domain; and (b) small domain

The weather field simulated for the large domain was used for the simulation of wave height and surge (both wind and pressure driven surge).**Fig. 6** shows the water level measured and simulated by Institute of Water Modeling (IWM) and the water level simulated by the WRF-SWAN-Storm Surge-Tide coupled model at Hiron point. At Hiron point, IWM measured a water level of 2.3 m (IWM Final Report Volume-I, April 2009) whereas the coupled model used in the present paper simulated a water level of 4m.

For storm surge computation a small scale bathymetry is necessary. Due to the lack of fine grid bathymetry in the shallower region of the Bangladesh coast, the storm surge computed by the coupled model shows some deviation from the observed water level.

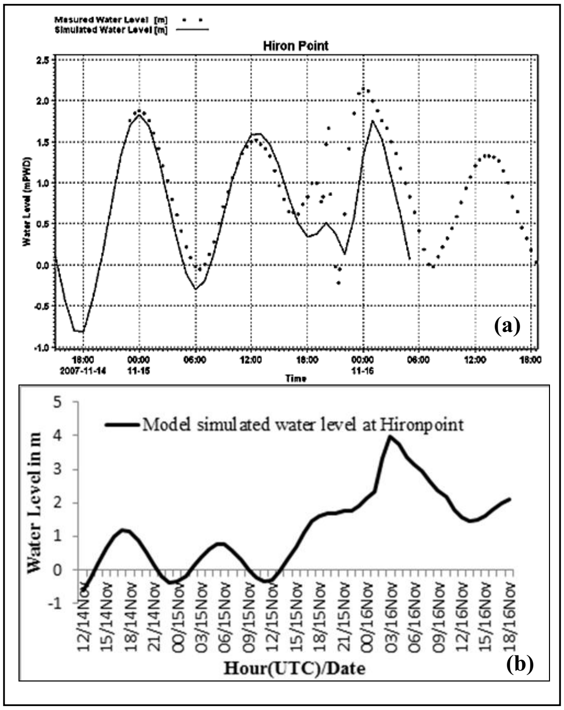

Fig.6 Time history of water level simulated by: (a) Institute of water Modeling (IWM); and (b) WRF-SWAN-Surge-Tide coupled model

5. CONCLUSIONS AND FUTURE RESEARCH

This study showcased a coupled meteorological wave hind casting model for the numerical simulation of storm surge over the Bay of Bengal and examined the accuracy of the results for the super cyclonic storm cyclone Sidr. WRF ARW model could forecast the weather field and track of Sidr well. Since the application of WRF model for the Bay of Bengal cyclones is new, further modification of this model is possible, which is expected to give a more accurate prediction and hind casting of tropical cyclones. More experiments with domain size, initial and boundary conditions as well as application of moving nest and vortex initialization technique can be helpful for the further improvement of the model.

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