NUMERICAL SIMULATION OF CYCLONIC STORM SURGES OVER THE BAY OF BENGAL USING A METEOROLOGY-WAVE-SURGE-TIDE COUPLED MODEL

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The purpose of this study was to evaluate the performance of an integrated meteorology and storm surge model for both the hind casting and prediction of future climate change intensified cyclones over the Bay of Bengal. This meteorology based storm surge model was developed and applied by integrating a mesoscale WRF model with the wave model SWAN and coastal ocean model FVCOM. The coupled model could capture the actual phenomena of historical cyclone Nargis, which made landfall in Myanmar in 2008, accurately and reproduce the total water level rise due to this event. The model was then used to also simulate future cyclones over the Bay of Bengal taking into account climate change by the year 2100.

Keywords: tropical cyclone; storm surge; climate change; numerical simulation; WRF; SWAN; FVCOM

INTRODUCTION

Tropical cyclones (TCs) and associated storm surges occasionally cause devastating disasters in the coastal regions around the Bay of Bengal. The northern part of the Bay of Bengal is especially vulnerable to storm surges and coastal flooding. The 1970 Bhola cyclone caused the death of 30,000-50,000 people (Saito et al., 2010; Frank and Hussain (1971)) in Bangladesh and India as a result of a storm surge as high as 10m. In April 1991, another very severe cyclone hit Bangladesh with a storm surge up to 6m that caused the death of 140,000 people (Madsen et al., 2004). More recently, cyclone Sidr in 2007 and cyclone Nargis in 2008 struck Bangladesh and Myanmar, respectively. Compare to neighboring countries like Bangladesh and India, cyclone induced damage was relatively low in Myanmar before Nargis. Over the last 60 years, 11 severe tropical cyclones struck Myanmar and only two of them actually made landfall in Ayeyarwady Delta. Cyclone Nargis was the worst natural disaster in the recorded history of Myanmar, where the death toll exceeded 138,000 people (Shibayama et al., 2009, 2010; Shikada et al., 2012).

Since a tropical cyclone is a hydro-meteorological phenomenon, climate change and the associated increase in sea surface temperature (SST) might have the potential to drive variations in the frequency and intensity of tropical cyclones (Alam et al., 2014). According to the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC 4AR) it is likely that future tropical cyclones (TCs) will become more intense, with larger peak wind speeds and more heavy precipitation associated with on-going increases in sea surface temperatures (SSTs). Moreover, according to all IPCC Representative Concentration Pathways (RCP) scenarios the rate of sea level rise will very likely exceed that observed during 1971 to 2010 due to increased ocean warming and loss of mass from glaciers and ice sheets (IPCC 5AR SPM). Sea level rise may result in more devastating effects as storm surge will penetrate further inland (Alam et al., 2014). However, whether this observed increase in SST rise will have any significant impact on tropical cyclone intensity or not is still a matter of debate. Webster et al., 2005, Hoyos et al., 2006, Solomon et al., 2007 and Emanuel et al., 2008 found an increase in tropical cyclone intensity due to climate change. On the other hand, Klotzbach et al., 2006 suggested that despite warming of SST by 0.2 ° to 0.4 ° there has been no significant change in overall tropical cyclone activity during 1986 to 2005 (see also Alam et al., 2014). However, Knutson et al (2010) summarised the most important work on tropical cyclone simulations, including recent research that was done using higher resolution models. According to their research, the intensity of tropical cyclones could increase by between 2 and 11% by 2100, depending on the part of the world and simulation used. Knutson et al (2010) found that the higher resolution models predict greater increases in intensity than those with lower resolutions, and as a result there is a possibility that the conventional models presently employed might be underestimating the potential future problems caused by tropical cyclones (see also Tasnim et al., 2014 for further discussions on this issue).

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Due to the lack of good quality bathymetry and observational data of historical events, storm surge modeling has always been challenging for the Bay of Bengal region. In this area, although several dynamic simulations of storm surges have been carried out, these have often involved using results from a small set of historical storms with simple adjustments (IPCC 4AR), such as adding on a mean sea level or increasing wind speeds by 10% to account for future climate change (Flather and Khandker, 1993). As a result, it is difficult to reliably quantify the range of uncertainty in estimating future coastal flooding based on these simulations. However, in this region coastal development is rapidly gathering pace and population centers are growing (Crossett et al., 2004). Storm surge and superimposed wind waves can cause large scale flooding and destruction to property and infrastructure in the low lying coastal areas of the Bay of Bengal, on a scale greater than anything experienced before. So, irrespective of future trends in tropical cyclone activity in the north Indian Ocean it is essential to develop and improve forecasting and mitigation strategies to create more resilient coastal communities.

In this study a coupled numerical model was applied for hind casting historical cyclone Nargis over the Bay of Bengal. This model integrates WRF-SWAN-FVCOM and Nao.99b tide model for the simulation of total water level rise under storm condition. At the same time an attempt was made to predict future cyclones considering the effect of climate change and sea level rise. The purpose of this study is to evaluate the performance of meteorological models in storm surge simulation over the Bay of Bengal so that it can be used as a useful tool for future weather prediction.

CYCLONE NARGIS

Cyclone Nargis was detected as a deep depression on April 26 by the Indian Meteorological Department (IMD) and as a tropical storm (TS) at 12UTC of April 27 by the Joint Typhoon Warning Center (JTWC) (Kikuchi et al., 2009). The cyclonic disturbances in the north Indian Ocean typically move along a westerly/north westerly direction. Some of them recurve from an initial north-westerly direction to a northerly direction and finally towards a north easterly direction (India Meteorological Department, 1979; Li et al., 2012; Pattanaik et al., 2009; Tasnim et al., 2014). But the special feature of Nargis was that it recurved and moved almost in an easterly direction for about 30 hours after 0600 UTC on May 1st. Nargis intensified from a relatively weak category 1 storm to an intense category 4 storm during its final 24 hours before making landfall on May 2, 2008 (Lin et al., 2009). Historically, the likelihood for a tropical cyclone occurring in April is smaller than 14% (Kikuchi et al., 2009), but just before the formation of Nargis an abnormally strong westerly event had occurred in the Bay of Bengal that lasted for about 10 days from April 16 to April 26. This westerly event played a critical role in the initiation of Nargis (Kikuchi et al., 2009). Nargis passed over this pre-existing warm ocean feature where the upper ocean warm waters extended deeper than normal and kept the deeper, colder waters from being drawn to the surface. Combined with other atmospheric conditions, this warm ocean feature allowed Nargis to intensify rapidly before landfall. This rapid intensification occurred between May 1 and 2 in the warm ocean regions where the sea surface temperature was above 30 °C, with the sea surface height also being above that what is normal in the area. On May 2, Nargis passed over the warm region and weakened slightly, though it then returned to the warm ocean feature again and continued to intensify once more. Cyclone Nargis reached its maximum intensity as a category 4 storm on the Saffir-Simpson Hurricane Scale (SSHS) around 06-12UTC on May 2nd, as it approached southern Myanmar. The minimum central pressure estimated by the Joint Typhoon Warning Center (JTWC) was 937 hPa while the Regional Specialized Meteorological Center (RSMC) for the Indian Ocean estimated its intensity as 962 hPa. The peak wind speed was 59 m/s according to JTWC and 47 m/s according to IMD. As the system moved eastward close to the coast, it maintained its intensity even up to 24 hour after landfall, causing large scale devastation due to a 6 meter high storm surge (Tasnim et al., 2014). From 1500 UTC of May 2nd it took a north-easterly course and after crossing the coast, the system maintained its intensity as a very severe cyclonic storm until the morning of the 3rd of May, gradually weakening afterwards (Tyagi et al., 2010).

NUMERICAL MODEL

For the numerical simulation of storm surge due to tropical cyclone, a coupled meteorology-wave-coastal ocean-tide model was used. This coupled model is an improved version of the OSIS model developed by Ohira et al (2012). In the current model, the 2-level storm surge model is replaced by the Finite Volume Coastal Ocean Model (FVCOM). The total water height resulting from the passage of a cyclone consists of wave, tide and surge elements (both wind and pressure driven surge), which are simultaneously calculated by using this coupled model. The flowchart of the coupled model is shown in Fig. 1 and the model step to simulate the historical cyclone is shown in Fig. 2. A detailed description of the methodology for the simulation of future cyclones is available at Ohira et al., 2012 and Tasnim et al., 2014.

The NCAR version 3.5 of Advanced Research WRF (ARW) model with 2-way nesting was used to investigate the weather field of cyclone Nargis. The initial and boundary condition in WRF was provided by using NCEP global final analysis (FNL) data using the WPS (WRF Pre-processing System) software package. The extracted wind and pressure fields from the WRF model were applied into the SWAN and FVCOM models as inputs to compute the wave and surge (both wind and pressure driven surge). FVCOM is a prognostic, unstructured-grid, Finite-Volume, free surface, three dimensional (3-D) primitive equations Community Ocean Model developed by Chen et al., 2003. A detail description of FVCOM model can be obtained from the FVCOM User Manual (July 2013). SWAN is a third-generation wave model developed by Delft University of Technology that computes random directional, short-crested wind-generated waves. NAO.99b tidal prediction system, which is a global ocean tide model developed by Matsumoto et al (2000) was used for the simulation of the tide at each point.

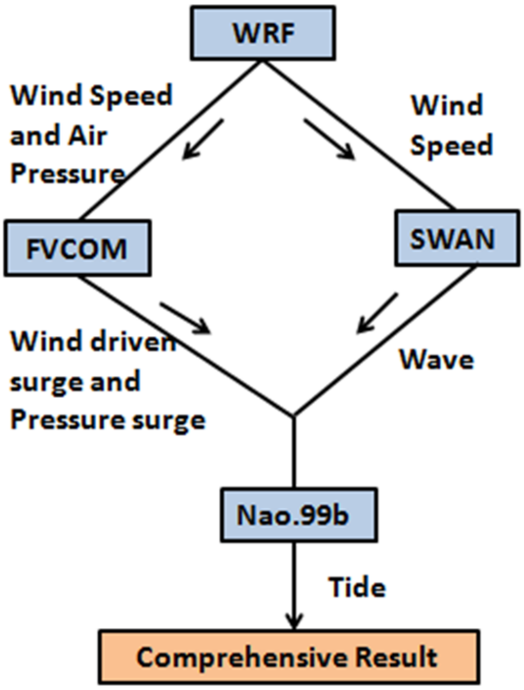

Figure 1. Model flow of the WRF-SWAN-FVCOM-Nao.99b Coupled model (Tasnim et al., 2014)

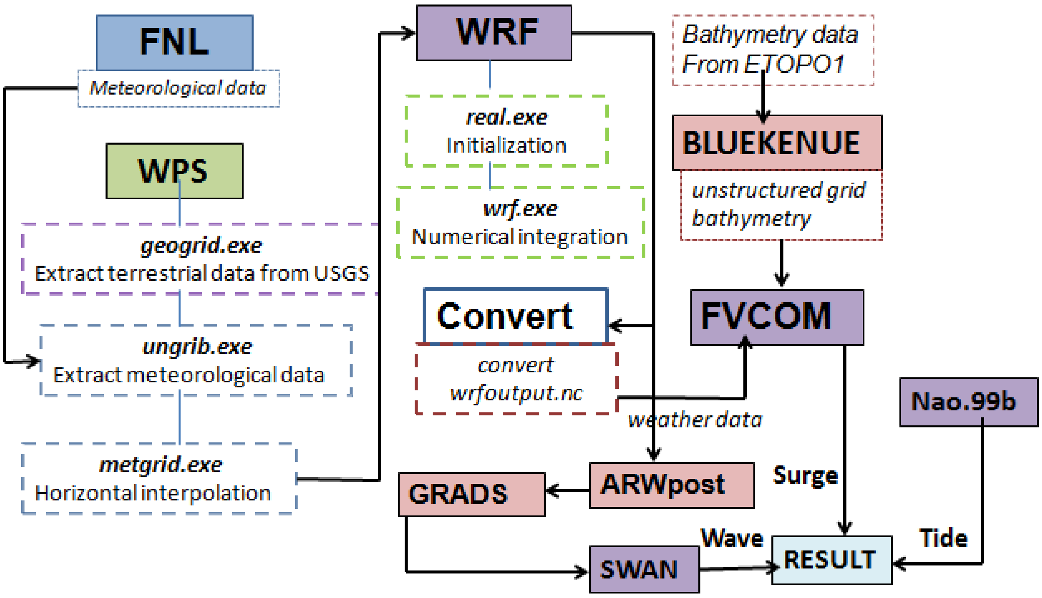

Figure 2. Model steps to simulate storm surge due to tropical cyclones

Calculation Conditions

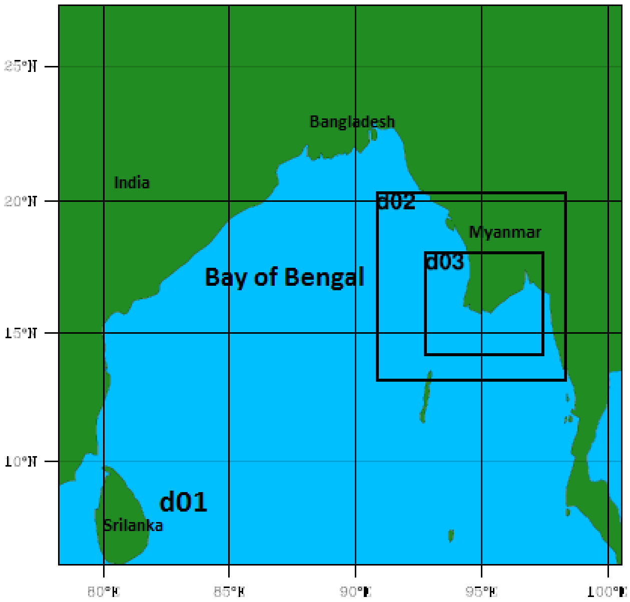

Figure 3. Model domain used for WRF ARW simulation

Tasnim et al. (2013, 2014) performed several numerical experiments to see the impact of the initial condition on cyclone track and intensity. For the case of cyclone Nargis WRF model initialization on the 30 April 12UTC shows good performance for the forecasting of both track and intensity. WRF ARW model was thus initialized on this date and configured using two-way nesting with 3 computational domains. The model was run for 108 hours with a time step of 60s for the parent domain and 20s and 10s for the nested domains, respectively. Fig. 3 shows both the parent and nested domains for the WRF simulation. The calculation conditions are summarized in Table. 1. The WRF ARW forecasted 10m wind data for the smallest domain (domain 3, horizontal resolution 1.85 km) was used in the SWAN model to estimate the wave field. For this SWAN run, data was obtained from the National Geophysical Data Centre (NGDC) ETOPO1 Database of sea floor and land elevation, using

ETOPO 1 min bathymetry data with a 1.85 km horizontal resolution. SWAN was run for 108 hours starting from 30 April 12UTC with a time step of 3s (Tasnim et al., 2014).

For the purpose of evaluating the possible impacts of global warming and sea surface temperature (SST) rise on tropical cyclone behavior over the Bay of Bengal, future climate change induced cyclones for the year 2100 were simulated on the basis of the weather field of historical cyclone Nargis. The main purpose of this future prediction was to see how a cyclone with the same strength as that of Nargis would behave in the year 2100. This simulation adopted the general weather conditions given by the IPCC 4AR scenario A1B, according to which atmospheric CO_2 concentrations will reach 720 ppm in the year 2100 in a world characterized by low population growth, very high GDP growth, very high energy use, low land use change, medium resource availability and rapid introduction of new and efficient technologies. Considering this scenario, Meehl et al (2007) projected that sea surface temperature (SST) around the Bay of Bengal should increase by +2.2 ° by the year 2100 and sea level rise would be 0.35m. Therefore in the present study, the weather field of the future cyclone was created from the historical weather data of cyclone Nargis, but increasing the SST across the whole computational domain by 2.2 degrees. Sea level rise was also taken into account though only one scenario (0.35m rise) was included, as the main purpose was to study the storm surge itself, rather than the compounded problem that sea level rise would represent for future storm surges.

Table1. Calculation conditions for wave and storm surge simulation (Tasnim et al., 2014)

WRF Version 3.5	No of Domain	3
	Area	I)5°N-27°N, 78.0°E-108.0°E II) 13°N-20.3°N, 90.8°E-98.25°E III) 14.04°N-17.86°N, 92.7°E-97.18°E
	Parent Grid Ratio	1:3:3
	Nesting Type	2 way
	Horizontal grid	I) 150 × 150, II) 151 × 151, III) 271 × 241
	Horizontal resolution	I)16650m, II)5550m , III)1850m
	Projection	Mercator
	Vertical layer number	28 Layers
	Time step	I)60s, II)20s, III)10s
	Topography data	USGS
SWAN	Area	14.04°N-17.86°N, 92.7°E-97.18°E
	Horizontal grid	271 × 241
	Horizontal resolution	1.85km
	Projection	Mercator
	Time step	3s
	Physics model	Komen
	Topography data	ETOPO1
FVCOM	Area	14.04°N-17.86°N, 92.7°E-97.18°E
	Latitude and Longditude	Latitude:15.96666 Longditude:95.01666
	Topography data	ETOPO1
	Grid resolution	Triangular grid with the length of 2 sides are 1.85km
	Software to produce triangular grid bathymetry	Blue Kenue
	Time step	5s
	number of nodes and cells	Nodes: 61180 Cells: 121370
	Element Type	T3
Nao.99b	Area	Each point

For the simulation of the storm surge, the FVCOM model with a wet-dry point treatment method was applied. In FVCOM, the horizontal grid is comprised of unstructured triangular cells which were prepared by using the data preparation, analysis and visualization software Blue Kenue (developed by Canadian Hydraulics Centre of the National Research Council Canada). The original bathymetry data in Blue Kenue was provided from ETOPO1 data (1- min latitude –longitude grid original data). In the triangular cells, the two sides of the triangle are 1.85 km, which is equal to that of WRF grid resolution of the smallest domain. The 10m wind and sea level pressure data from the WRF domain 3 was used as the atmospheric forcing in FVCOM model. The model was run for 108 hours starting from 30April 12UTC with a time step of 5 seconds (Tasnim et al., 2014).

MODEL VERIFICATION

Track and Intensity

With the initial condition of 30 April 12UTC, WRF-ARW model could hindcast the track and intensity of cyclone Nargis well. After 12 hours from initiation the simulated track showed good agreement throughout the simulation period until landfall (fig. 7a and 7b). However, after landfall the simulated track gradually deviated from the observed track, though this is not crucial for the purposes of storm surge simulation. The WRF simulated lowest cyclone center pressure was 961hPa, which was very close to the IMD observed value of 962hPa, and the simulated highest wind speed was 45 m/s. Model simulated landfall time was around 10UTC of 2nd May, which completely agreed with observation, with a landfall error of only 38km. Fig. 4 shows JTWC observed and WRF simulated track of cyclone Nargis. Fig. 5 and 6 show the time series of the cyclone center pressure and maximum wind speed of IMD observed and model simulated for Nargis in 2008.

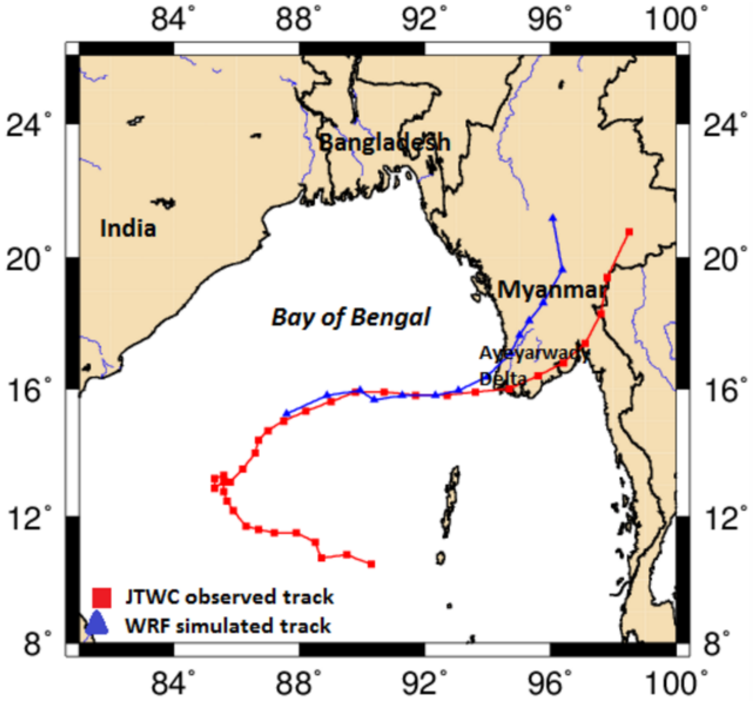

Figure 4. **JTWC observed track and WRF simulated track of Cyclone Nargis 2008**

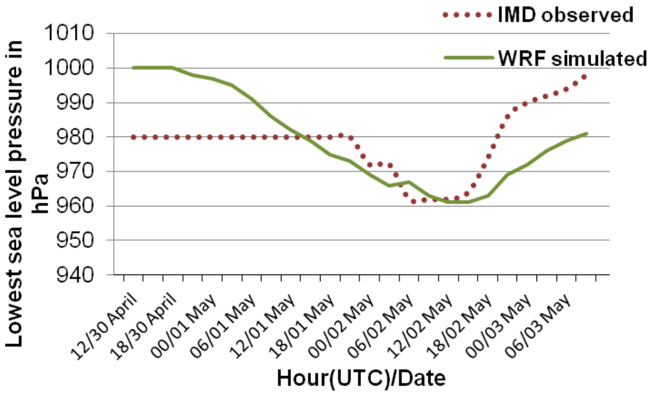

Figure 5. Time series of the observed and simulated lowest sea level pressure of Cyclone Nargis (Tasnim et al., 2014).

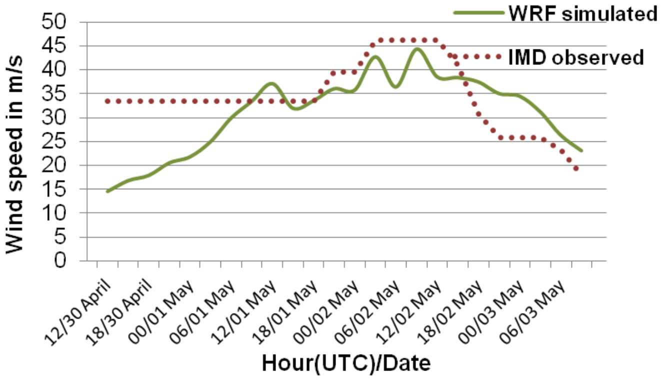

Figure 6. Time series of observed and simulated maximum wind speed of Cyclone Nargis (Tasnim et al., 2014).

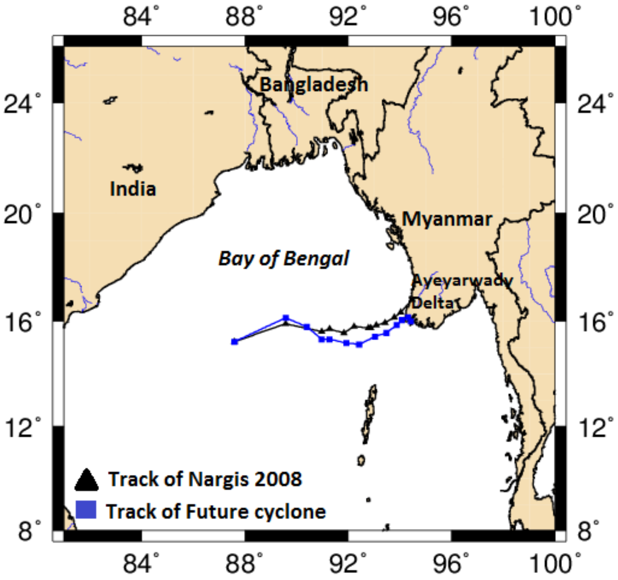

Figure 7. WRF simulated track of Cyclone Nargis 2008 and the future cyclone for the year 2100 (Tasnim et al., 2014)

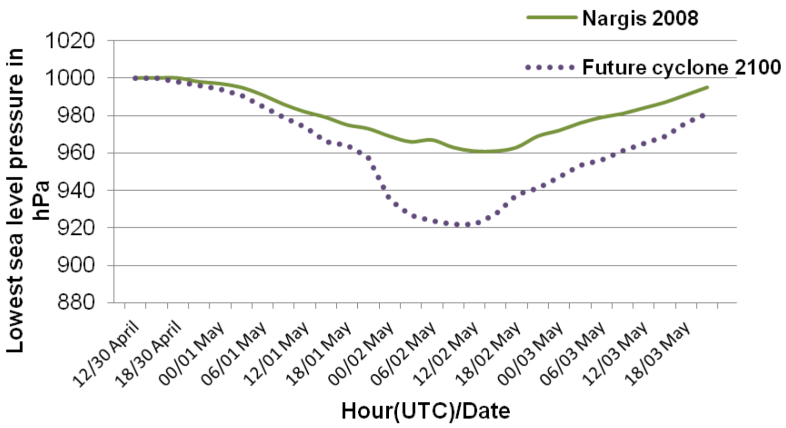

Figure 8. Comparison of cyclone center pressure of Nargis and the future cyclone (Tasnim et al., 2014).

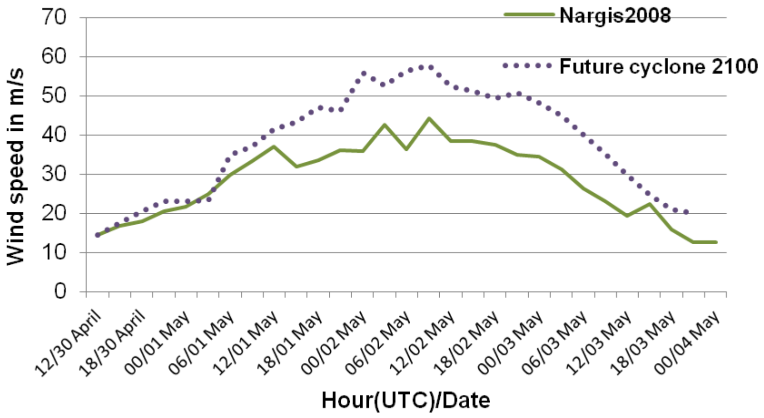

Figure 9. Comparison of maximum wind speed of Nargis and the future cyclone (Tasnim et al., 2014).

Storm Surge Due to Cyclone Nargis

The storm surge (both wind and pressure driven surge) simulated by FVCOM model lies within the range of 1 to 2.5 m for the various locations around the point of landfall. At Yangon River basin the maximum storm surge simulated was 2.5 m and at Ayeyarwady Delta area it was around 2m. For the verification of the performance of the model, the total water level simulated by the coupled model was compared with the field observations performed by Fritz et al (2010) and Shibayama et al (2009, 2010) during their field survey at Ayeyarwady Delta and Yangon, respectively. According to their observations, the highest water level lies within the range of 2.3 to 6.3 m at different locations. Fig. 12 shows selected storm surge measurement points in the Ayeyarwady Delta and Yangon River Basin. The coupled model simulated tide+surge level indicates that inundation levels would have been between 2 to 4 m. To this, the wave amplitude+ wave set up should be added, which lies within the range of 1-2m. Fig. 13 shows total water level at different locations simulated by the coupled model and Fig. 14 shows the comparison between the simulated and observed total water level at different locations. Model simulated total water level (wave+ tide+ surge) lies within the range of 2 to 4.6 m in most locations near the coast, which slightly underestimates observations.

One explanation for this difference could related to the deviation of the simulated track, which might have caused some difference with the observations since storm surge level depends on the cyclone track to a great extent. Another reason could be related to rainfall, as because of the relatively slow movement of Cyclone Nargis there was heavy precipitation in Myanmar for 3 to 4 days before the cyclone made landfall. According to NASA satellite observations, in some areas this rainfall was around 600 mm, which was 2 to 3 times higher than the expected seasonal rainfall. The WRF model simulated total precipitation was also over 400mm at some locations near Ayeyarwady Delta (Fig. 10). The result of this rainfall together with the storm surge and tide levels was that a large land area was flooded. Moreover, when high waves due to the strong winds of Cyclone Nargis came to the nearshore area, due to the already flooded topography they could not dissipate and superimposed on the existing flood level (as shown in Fig. 11). Therefore, in order to simulate the total water level in the present study, the contribution of wind and pressure surge, tide, wave set up and wave amplitude was taken into account. Since wave height is twice the wave amplitude, wave amplitude was computed as half of the nearshore significant wave height from the SWAN model output. Wave set up was also simulated from the SWAN model. Even though WRF model could simulate the total precipitation due to Cyclone Nargis, because of the complexity of converting it to a water level, the effect of rainfall and river discharge were not taken into account in this current simulation, and should be the objective of future research.

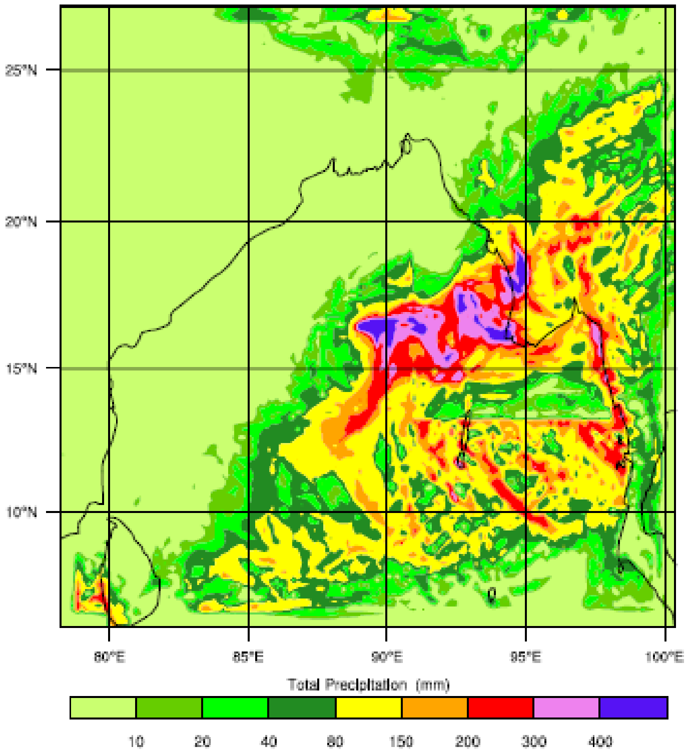

Figure 10. WRF simulated total precipitation due to Nargis 2008

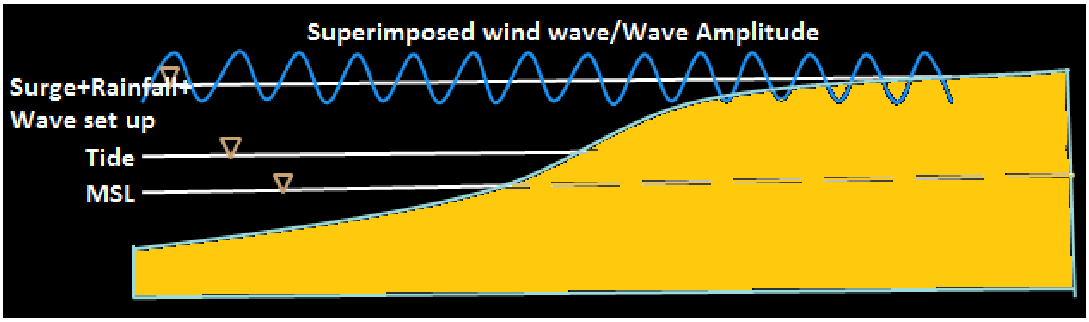

Figure 11. Mechanism of storm surge inundation at Ayeyarwady Delta.

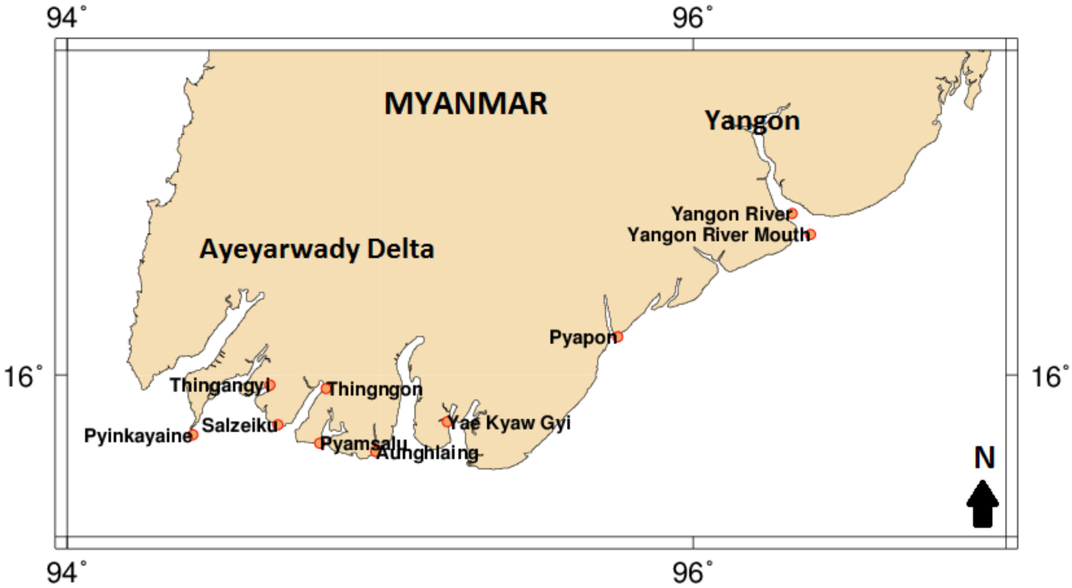

Figure 12. Storm surge measurement points at Ayeyarwady Delta and Yangon River Basin.

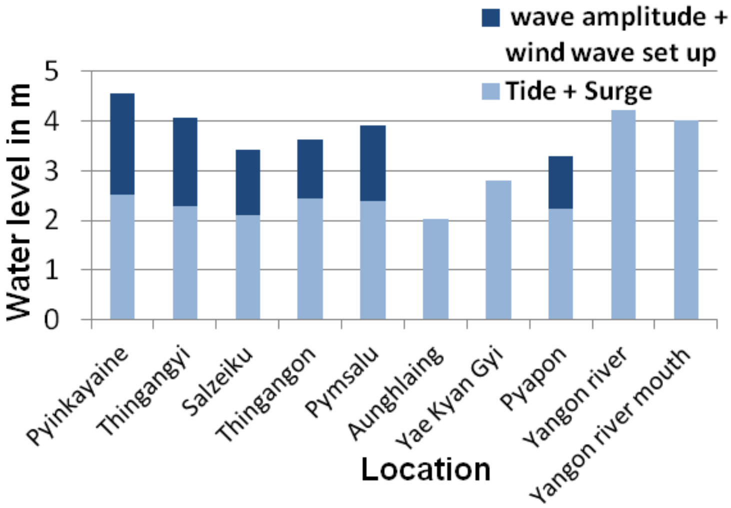

Figure 13. Total water level at different locations simulated by the coupled model (Tasnim et al., 2014)

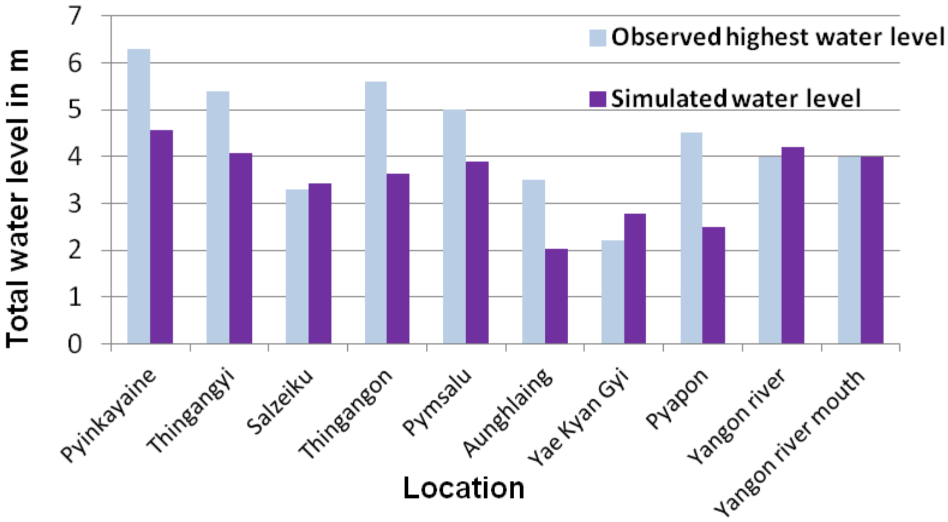

Figure 14. Comparison between the observed and simulated highest water level at different locations (Tasnim et al., 2014).

Storm Surge Due to Future Cyclone

For the future scenario WRF predicted that the cyclone intensity for the year 2100 would be much higher than that of cyclone Nargis in 2008. Due to the increase in SST, in the future more sea water evaporation will take place. As a result, the latent heat, which is the source of energy of the cyclones, will likely to increase and cause greater intensification of cyclones, as shown in Fig. 8 and 9. The model predicted a lowest pressure of 922hPa, which was 39hPa lower than that of Nargis. WRF simulated highest wind speed for the future cyclone was 60 m/s. The predicted track of the future cyclone followed almost the same route at the initial stage of development; then slightly deviated from the observed track but finally made landfall exactly at the same location as that of historical Nargis, i.e. near Pyinkayaine though 2 hours earlier. The relatively earlier landfall may be due to the increase in SST, which causes this rapid intensification of the future cyclone. Another important finding was that the climate change induced future cyclone remained stronger longer after landfall. Fig. 8 shows the simulated tracks for both the historical cyclone Nargis and the future cyclone. Figs. 8 and 9 show the comparison between cyclone Nargis and the future cyclone in terms of central pressure and maximum wind speed, respectively.

The future cyclone equivalent to Nargis in the year 2100 could cause a storm surge as high as 5 m in Ayeyarwaddy delta. Fig. 15 shows the wind and pressure surge simulated by FVCOM for Nargis 2008 and the future cyclone in the year 2100; where in all locations the surge will be more than two times higher than that of Nargis. In Ayeyarwady Delta area the storm surge lies within the range of 3 to 5 m, while in Yangon River Basin it would be 3 to 4 m high.

The predicted significant wave height for the future cyclone will also be significantly higher and at Pyinkayaine it could be almost 3m higher than that of during Nargis in 2008 (see Tasnim et al., 2014). Fig 16 shows the total water level rise for the future cyclone considering the effect of both SST and sea level rise. The total water level combining wave, tide, surge and sea level rise for the future cyclone can be as high as 7.3m, even if it took place at mean tide. If rainfall and river discharge are taken into account, this water level can be 8 to 9m if the event took place at high tide, and thus clearly the potential future risk of cyclones in Myanmar would be much greater than at present, especially if more onerous sea level scenarios are considered.

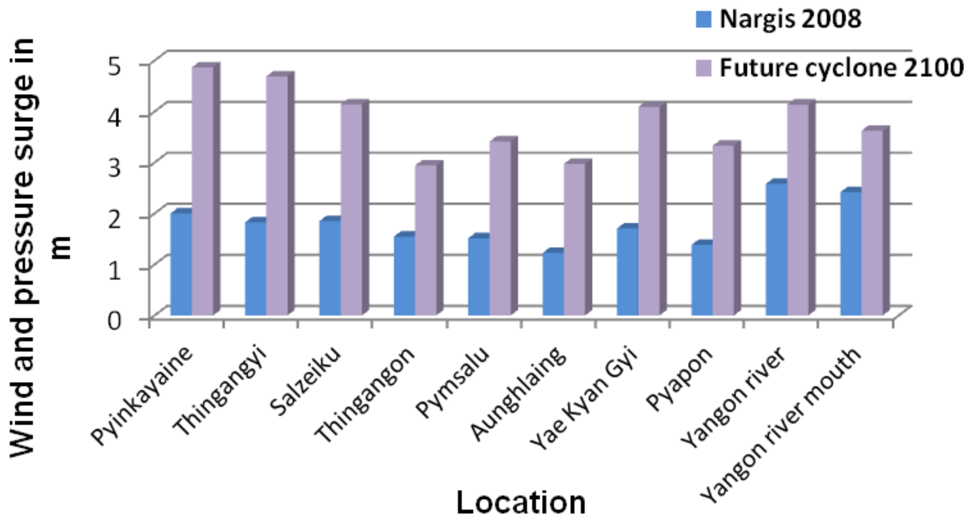

Figure 15. Comparison of storm surge (wind+ pressure surge) between Nargis 2008 and future cyclone 2100 (Tasnim et al., 2014).

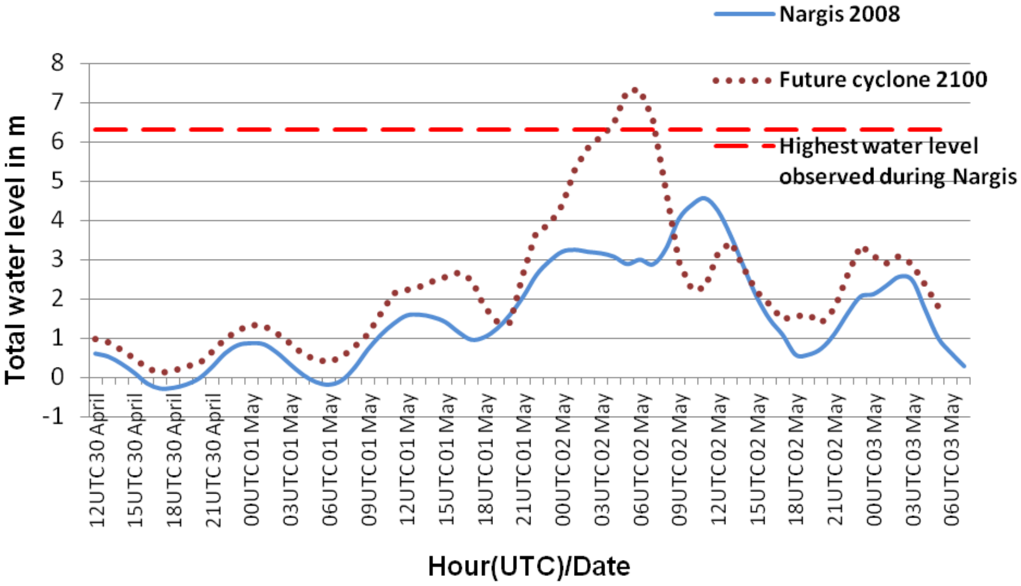

Figure 16. Observed highest water level duringNargis 2008 and simulated total nearshore water level for cyclone Nargis and the future cyclone (Tasnim et al., 2014).

DISCUSSIONS

The most important contribution of the current methodology for storm surge simulation was the integration of real time weather data with the wave and coastal ocean models to get a realistic forecast of the storm surge level. The integration of the 3-Dimensional coastal ocean model FVCOM improves the performance of the model in storm surge simulation. By using triangular unstructured gridded bathymetry in FVCOM, the wind and pressure surge could be accurately reproduced in the complex irregular coastline of the Ayeyarwady Delta. The performance of the model was very good in hindcasting historical cyclone Nargis. The predicted future cyclone in the year 2100 would have very high wind speeds, resulting in higher waves and wind driven surges. According to IPCC 5AR, even there is low confidence of any long term change in global tropical storm frequency or intensity since the no of global analyses of the changes in extreme sea level are very limited. As a result the magnitude and frequency of extreme events can still increase due the effect of the mean sea level rise (IPCC 5AR). The increase in SST and sea level rise is therefore expected to cause amplification in storm-surge heights resulting from the occurrence of stronger winds along the coastal regions of East, South and South-East Asian countries, and this research verifies this report.

However, a number of limitations are associated with the present simulation, such as the size of the target domain for the WRF ARW model. Tropical cyclone simulation over the Bay of Bengal is largely influenced by domain size and boundary conditions. Because of the very long computational time a larger domain could not be used, which might have some affect in simulating cyclone track, especially after landfall. In the WRF simulation a smaller horizontal resolution or time step might also have improved the performance of the model, though this would have also increased the computational time. Another limitation concerning the storm surge simulation was the lack of good and accurate bathymetry data of the study area. Storm surge simulation is highly dependent on accurate bathymetry data, which is very difficult to obtain for countries around the Bay of Bengal. In the present study a bathymetry mesh of 1.85 km was used, which was not fine enough to consider the inundation over land. This limitation might also have had an impact, causing some difference between the simulated water level and the observations. However, the limitation related to long computation time can be solved by using high speed computers, and are likely to diminish in the future. However, to obtain an accurate finer gridded bathymetry data it would be essential to conduct a bathymetry survey in the shallow nearshore areas of The Bay of Bengal. In this sense, the use of high resolution Shuttle Radar Topography Mission (SRTM) data in the nearshore areas can be an alternative way to prepare a fine grid bathymetry, even though the procedure can be quite complex and laborious.

For future improvement of the model proposed, the coupling with WRF- Chem i.e. incorporating greenhouse gas emissions in the meteorological field could represent an interesting research topic. The improvement of the performance of WRF model by using different data assimilation techniques is also possible, though challenging. Moreover, a direct coupling of WRF model with the Coastal Ocean models, like the coupling of the Hurricane WRF (HWRF) model with the Princeton Ocean Model (HWRF-POM coupling), might also represent a promising and challenging topic for future research.

CONCLUSIONS

In the present study a coupled model integrating four different models (WRF-SWAN-FVCOM-Nao.99b) was developed for the numerical simulation of storm surges over the Bay of Bengal. This model was an improvement of the OSIS model, replacing the 2-level storm surge model by a Finite Volume Coastal Ocean Model (FVCOM). The performance of the model was evaluated by hind casting historical cyclone Nargis over the Bay of Bengal. The model simulated track and intensity of cyclone Nargis showed good agreement with observations, deviating only 38km from the JTWC observed landfall point. The model was verified by comparing the simulated water level due to surge and tide with the observed water levels at different locations near Ayeyarwady Delta and Yangon River Basin. The model's simulated maximum water level (comprising wave, surge and tide) lies within the range of 2 to 4.6 m in most locations, whereas the observed highest water level recorded during field surveys after the event were between 2.3 to 6.3 m high. The difference between simulation and observation are believed to be mostly due to the rainfall and river discharge not being considered in the numerical simulation, though it is likely that using more accurate bathymetry and smaller grids could also improve the results of the simulation.

In addition to hindcasting the historical cyclone, an attempt was also made to predict the climate change induced future cyclones for the year 2100, considering the IPCC special report on emission scenario A1B. The predicted future cyclone was found to have a higher intensity than the historical event both in terms of wind speed and cyclone center pressure, and remained stronger longer after landfall. The predicted surge for the future cyclone was two times higher and waves were about 3 m higher than that of Nargis in 2008. Therefore, the increases in future SST and SLR may cause higher inundation levels in Myanmar, resulting from higher wave heights and wind surges.

Only one sea level and SST rise scenario were used in the current simulation, and rainfall and river discharge was not taken into account. Therefore, future studies should consider the contribution of rainfall and a wider variety of other possible scenarios to understand the effect that future storm surges and increases in sea levels will have on coastal communities around the Bay of Bengal. Such knowledge is crucial to correctly estimate adaptation strategies to improve the resilience of coastal communities, though given the low level of disaster preparedness in the area any disaster countermeasure undertaken can be considered a "no-regrets" strategy.

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