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Numerical simulation of storm surge associated with severe cyclonic storms in the Bay of Bengal during 2008-11

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सार – जब भी उष्णकटिबंधीय चक्रवात आता है तब भारत और इसके निकटवर्ती क्षेत्रों में तूफानी समुद्री तरंगों की आपदाओं के कारण जान और माल की भारी हानि, तटीय ढाँचों की क्षति और कृषि को हानि पहुँचती है। नवम्बर 1970 में बंगलादेश (पहले पूर्वी पाकिस्तान) में आए एक अत्यंत पंचंड चक्रवात की वजह से लगभग 3,00,000 लोगों की जाने गईं। नवम्बर 1977 में आन्ध्र में आए चक्रवात ने भारत के पूर्वी तट को तहस नहस कर दिया जिसमें लगभग 10,000 लोगों की जाने गईं। अक्तूबर 1999 में भारत के उड़ीसा के तट पर एक प्रचंड चक्रवाती तूफान आया जिससे उस क्षेत्र में संपत्ति की अत्याधिक हानि होने के अतिरिक्त 15,000 से भी अधिक लोगों की जाने गईं। हाल ही में मई 2008 में आए चक्रवात नर्गीस से म्यांमार में लगभण 1,40,000 लोगों की जानें गईं और संपत्ति का अत्यधिक मात्रा में नुकसान हुआ। ये विश्व की सबसे बड़ी मानवीय आपदायें मुख्यतः उष्णकटिबंधीय चक्रवातों से संबद्ध हैं व समुद्री तूफानी तरंगों से प्रत्यक्षरूप से जुडी है। अतः उस क्षेत्र में संक्षिप्त पूर्वानुमान और समुद्री तूफानी तरंगों की पूर्व चेतावनी देने का प्रावधान उस क्षेत्र के हित में होता है। इस शोध पत्र का मुख्य उद्देश्य बंगाल की खाड़ी और अरब सागर में उठने वाली समुद्री तूफानी तरंगों का पूर्वानुमान करने के लिए हाल ही में विकसित किए गए मॉडलों को प्रकाश में लाना है। इस शोध–पत्र में वर्ष 2008 से 2011 के दौरान बंगाल की खाड़ी में बने प्रचंड चक्रवातों से जुड़ी समुद्री तरंगों का पूर्वानुमान लगाने/अनुकरण करने में निदर्श के निष्पादन का भी उल्लेख किया गया है।

ABSTRACT. Storm surge disasters cause heavy loss of life and property, damage to the coastal structures and the losses of agriculture in India and its neighborhood whenever a tropical cyclone approaches. About 3,00,000 lives were lost in one of the most severe cyclone that hit Bangladesh (then East Pakistan) in November 1970. The Andhra Cyclone devastated the eastern coast of India, killing about 10,000 persons in November 1977. Orissa coast of India was struck by a severe cyclonic storm in October 1999, killing more than 15000 people besides enormous loss to the property in the region. More recently the Nargis cyclone of May 2008 killed about 1,40,000 people in Myanmar as well as caused enormous property damage. These and most of the world's greatest human disasters associated with the tropical cyclones have been directly attributed to storm surges. Thus, provision of precise prediction and warning of storm surges is of great interest in the region. The main objective of the present paper is to highlight the recent developments in storm surge prediction model for the Bay of Bengal and the Arabian Sea. Paper also describes the performance of the model in forecasting/simulating the surges associated with severe cyclones formed in the Bay of Bengal during 2008 to 2011.

Key words – Storm surge, Bay of Bengal, Severe cyclonic storm, Tropical cyclone.

1. Introduction

Loss of life from storm surge inundation in the Bay of Bengal countries has been a serious issue in the last several decades. Observations clearly indicate that almost all the loss of life and most of the damage during the occurrence of a tropical cyclone is due to the storm surge. Although Sri Lanka is affected only occasionally by the storm surge, however tropical cyclones of November 1964, November 1978 and cyclone of November 1992 have caused extensive loss of life and property damage in the region. Storm surges affect Myanmar to a much less extent in comparison with Bangladesh and India. Notable storm surges, which have affected Myanmar, have been during May 1967, 1968, 1970, 1975, 1982, 1992, 1994, 2008 and 2010; of which the 1982, 1994 and 2008 (Nargis) caused the heaviest loss of life and damage. Nargis generated storm surge in excess of 4 m near

Ayeyarwady deltaic region. The entire deltaic coast of Myanmar was flooded with surges ranging from 1.5-4.5 m.

The purpose of the present paper is to give a review of recent developments in predicting the storm surges and associated coastal flooding in the Bay of Bengal during 2008-11. The period of study has been considered as 2008-11 as India Meteorological Department (IMD) carried out a forecast demonstration project (FDP) on landfalling cyclones over the region with enhanced observational and analysis tools and numerical weather prediction (NWP) modelling techniques due to modernization programme of IMD. It has been resulted in improvement in monitoring and prediction of cyclonic disturbances including track and intensity prediction. Hence, the present study would be able to evaluate the impact of better prediction of cyclone parameters on storm surge prediction.

The problem of storm surges in the North Indian Ocean region has been reviewed in detail by Ali (1979), Rao (1968, 1982), Roy (1984), Murty (1984), Murty *et al*., (1986), Das (1994), Gönnert *et al*., (2001), Dube *et al*., (1997, 2000, 2009), Dube, (2012) and Chittibabu (1999). Although the frequency of tropical cyclones in the Bay of Bengal is not high compared to northwest Pacific, the coastal regions of India, Bangladesh and Myanmar suffer most in terms of loss of life and property damage. The main factors contributing to disastrous surges in the head Bay of Bengal may be summarized as (Ali, 1979): (a) shallow coastal water, (b) convergence of the bay, (c) high astronomical tides, (d) thickly populated low-lying islands, (e) favourable cyclone track and (f) innumerable number of inlets including world's largest river system (Ganga-Brahmaputra-Meghna).

2. Data input for surge prediction

In order to achieve greater confidence in surge prediction in the Indian Seas one should have good knowledge of the input parameters for the models. These parameters include the oceanographic and meteorological parameters (including storm characteristics), hydrological input, basin characteristics and coastal geometry, wind stress and seabed friction and information about the astronomical tides. It has been seen that in many cases these input parameters strongly influence the surge development.

2.1. *Oceanographic and hydrographic data*

Data on oceanography and hydrography include:

(*i*) bathymetry,

(*ii*) astronomical tides and

(*iii*) inshore currents in closed regions.

Modelling experiments show that the surge response is very sensitive to the near-coastal bathymetry. Most of the northern Bay of Bengal is very shallow and is characterized by sharp changes in seabed contours. The shallowness of water may considerably modify the surge heights in this region, Johns *et al*., (1983a). Therefore, accurate bathymetry is needed for improved surge prediction. In general, we need bathymetry with 100 m horizontal resolution over the continental shelf. Presently reasonably good bathymetry for the model may be derived from the Earth-Topography-Two-Minute module (ETOPO2) from the National Geophysical Data Center database (Smith and Sandwell, 1997).

Astronomical tides also raise sea level as a result of the periodical movements of the celestial bodies relative to the earth. The rise due to tide may be as high as 5 m above the mean sea level at some parts of Bay of Bengal coasts. If the arrival of the surge coincides with the time of the high tides, worst devastation takes place. For instance, the most devastating surge recorded in Bangladesh that of November 1970, in which several hundred thousand people were drowned, was an occasion where peak surge and high tide coincided. In contrast, the surge of May 1990 occurred close to the low tide; in this case, instead of adding to the water levels produced by the surge, the tide had a moderating effect on maximum water level. This contributed to the relatively low death toll (currently estimated at about 300) during this surge. Therefore, in seas where the tidal range is comparable in magnitude with possible surges, it is essential to be able to predict tidal elevations accurately under all conditions. The amplification of surge becomes very complicated through its nonlinear interaction with the tide in the shallow water (Johns *et al*., 1985, Sinha *et al*., 1996, 2008, Flather 1994, Henry *et al*., 1997, Ali *et al*., 1997). Expected astronomical tides for coastal districts are annually published by Survey of India, Government of India and the same is available with the district collectors and Cyclone Warning Centers of IMD for ready reference.

Inshore currents are also known to influence the surges in the coastal region. Information on inshore currents is usually available in the form of printed charts (Gönnert *et al*., 2001). Calculation of total height of tidal wave depend on many factors including the above important factors (Harper, 2005).

2.2 *Meteorological input*

The surface wind associated with tropical cyclone is the main driving force for storm surge. In the absence of real time observations or reliable NWP product most of the operational storm surge prediction models use certain cyclone parameters and derive winds using parametric wind model. The main parameters required are:

(*i*) the pressure drop,

(*ii*) the radius of the maximum sustained wind,

(*iii*) vector motion of the storm,

(*iv*) place of landfall and

(*v*) duration of the storm.

Pressure drop is the difference between the ambient pressure and the central pressure of the storm. IMD uses Dvorak's classification of tropical cyclones in order to infer the likely pressure deficit and maximum wind from satellite imageries. On many occasions, these imageries also enable them to estimate the radius of maximum winds.

The direct effect of atmospheric pressure in producing surges is negligible compared with the surface wind stress. From hydrostatic considerations a fall of pressure of 1 hPa will lead to rise of about 1 cm in the sea level. Wind in the cyclone depends largely on the pressure drop. Wind exerts tangential as well as normal stresses on the water underneath, the latter being negligibly small compared with the former. The wind is the main force which generates storm surges. Proper computation of surface winds associated with tropical cyclones is very important for the numerical prediction of storm surges. A number of empirically based formulae have been used for computation of surface winds by several workers (Jelesnianski 1965, 1972, Isozaki 1970, Jelesnianski and Taylor 1973, Das *et al*., 1974, John and Ali 1980, Holland 1980 etc.) in their storm surge prediction models.

The position and magnitude of the peak surge along the coast depends upon the speed and direction of the storm relative to the coast. Therefore, in order to forecast accurate position of peak surge in a region, the speed, direction of the storm motion as well as the location of the landfall point must be precisely described. The knowledge about the duration of the storm is also very important in surge modelling. The storms which remain for longer period over the sea are known to generate higher sea surface elevations than the short lived cyclones (Rao *et al*., 2007).

2.3. *Hydrological input*

The main hydrological information needed is

(*i*) river discharge in the sea, and

(*ii*) rainfall distribution.

The results of river-ocean coupled mathematical models show that the discharge of fresh water carried by the rivers may modify the surge heights, especially in the northern Bay of Bengal where one of the world's largest river systems, Ganga-Bhrahmaputra-Meghna, join the sea (Dube *et al*., 1986, 2005, Ali *et al*., 1997). Another dynamic effect of these inlets and estuaries is the potentially deep inland penetration of surge originating in the sea which results in the flooding of low lying estuarine regions with saline water.

2.4. *Basin characteristics and coastal geometry*

The location of the peak surge depends mainly on the coastal geometry of the basin. Experiments suggest that the curving coasts not only shift the peak surge position but also affect its height (Dube *et al*., 1982, Johns *et al*., 1981). Because of the northward converging nature of the Bay of Bengal storm blowing straight into it may funnel the water toward the north (depending on the track of the cyclone). Convergence then leads to the piling up of a strong surge in that area (Proudman, 1955), whereas it may affect the sea level only slightly on a straight part of the coast, where the water can escape sideways.

2.5. *Surface and bottom stress*

The atmosphere transfers energy to the ocean through normal and tangential stresses on the sea surface, which is generated by pressure gradients and a vertical wind profile. The input of the energy is partly lost by the tangential stress at the sea bottom. It is exerted on the sea bed by the current immediately above it.

The formulation of surface stress is usually in the form of quadratic law. Very little information is currently available on the numerical values of the drag coefficients for strong winds. In the case of strong winds (exceeding 10 ms^{-1}) and strong currents (exceeding 1 ms^{-1} the surface and the bottom stress may be comparable ($\sim 10^{-3}$ m^2 s^{-2}).

Sea bed friction also formulated in terms of a quadratic law, but here too very little data are available on

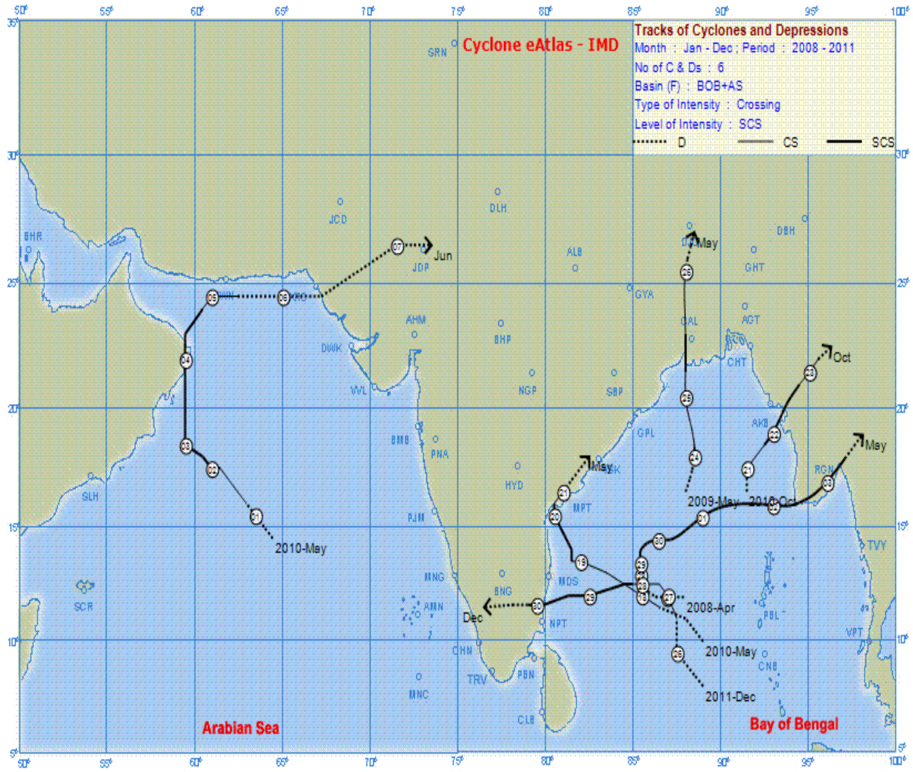

Fig.1. Tracks of landfalling severe cyclones over the north Indian Ocean during 2008-2011

the appropriate drag coefficients. Recent works how that the drag coefficient is a dynamical parameter which depends on the whole situation of the sea. Some earlier models have used sea-bed friction in terms of an Ekman spiral (Johns *et al*., 1983b). The spin-up time for a steady Ekman layer is around 3-4 days. It is probably unrealistic to use a steady Ekman layer from the very early stages of surge development.

3. Operational storm surge predictions system for the Bay of Bengal

In India, the study of numerical storm surge prediction was pioneered by Das (1972). Subsequently several workers attempted the prediction of storm surges in the Bay of Bengal (Ghosh 1977, Johns and Ali 1980, Johns *et al*., 1981). Dube *et al*., (1994), developed a real-time storm surge prediction system for the coastal regions of India, Bangladesh, Myanmar, and Sri Lanka. IIT model can be run in a few minutes on a PC in an operational office. One of the significant features of this storm surge predication system is its ability to investigate multiple forecast scenarios to be made in real time. This has an added advantage because the meteorological input needed for surge prediction can be periodically updated with the latest observations and forecast (data assimilation) from National Weather Services.

Under the auspices of Tropical Cyclone Programme of the World Meteorological Organization (WMO) the technology (IIT Model) has been transferred to the National Meteorological and Hydrological Services of the region. Present IIT model predicts only residual storm surge at the coast line (*i.e.*, water level over and above normal astronomical tides). With the advantage of simplicity in operation, this model has been used to produce and disseminate timely warnings to serve public safety. From cyclone season of 2009, Regional Specialized Meteorological Centre (RSMC), New Delhi is using IIT Model for providing ‘storm surge guidance’ to the countries of the region. As a capacity building exercise, the training on storm surge prediction is organized annually by IIT, Delhi for the cyclone forecasters from National Meteorological and Hydrological services of the region.

4. Performance of the IIT Models

The following sections describe results of numerical experiments carried out by IIT Model to simulate the

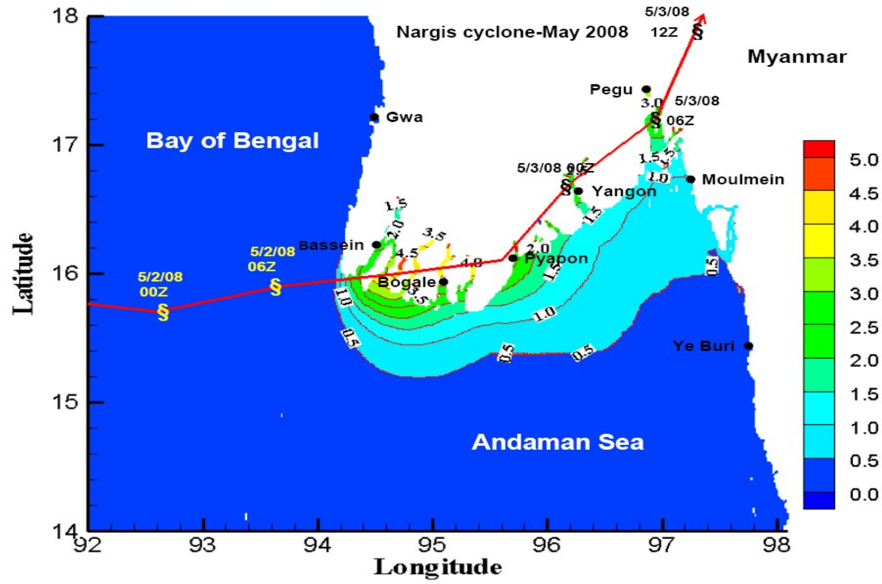

Fig. 2. Simulated peak surge (m) for 2008 Nargis cyclone

surges generated by severe cyclones, which struck the coastal regions of the countries in the Bay of Bengal during 2008 to 2011. The case of cyclonic storm JAL which produced insignificant surges has not been considered. There have been six severe cyclones (maximum sustained wind speed of 48 knots or more) including five over the Bay of Bengal and one over the Arabian Sea (Fig. 1).

4.1. *Myanmar: May 2008 Nargis Cycone (Dube et al., 2009)*

In the last week of April, an area of low-pressure was detected over the Bay of Bengal about 1150 km east-southeast of Chennai, India. At 0300 UTC on 27 April, IMD classified the system as a depression and nine hours later the system intensified into a deep depression. At 0000 UTC on 28 April, the system became cyclonic Storm Nargis while it was located about 550 km east of Chennai. On 28 April, the motion of Nargis became nearly stationary while located between ridges to its northwest and southeast. The system gained further strength to become a severe cyclonic storm by 28th May at 0600 UTC. On 1 May, after turning nearly due eastward, the system continued to gain strength and attained a maximum wind speed of 46 ms^{-1} on 2nd at 0600 UTC, as it approached the coast of Myanmar. Around 1200 UTC on 2 May, cyclone Nargis made landfall in the Ayeyarwady Division of Myanmar. Early on 3 May, it quickly weakened after turning to the northeast toward the rugged terrain near the Myanmar-Thailand border.

Fig. 2 depicts the time history of the movement of Nargis and model computed surge contours along the coast of Myanmar. The Storm surge model is integrated with a pressure drop of 65 hPa and radius of maximum winds of 25 km obtained from India Meteorological Department. It may be seen that a maximum surge of more than 4.5 m is occurred close to the landfall point. The Deltaic region of Ayeyarwady is affected by surges between 2.5 – 4.5 m. The Myanmar coast from Pyapon to Yangon is flooded with a surge of about 3 m. The computed surge values at Pegu and Moulmein are more than 3 m and 1.5 m respectively. During this cyclone the surge of the order of more than 4 m was reported by the Department of Meteorology and Hydrology, Yangon. This is in good agreement with our simulated sea level elevations.

4.2. *West Bengal : May 2009 Aila Cyclone*

At 0300 UTC of 24 May 2009 a deep depression lay centered near Lat. 18.0º N/Long 88.5º E. It intensified into a cyclonic storm 'AILA' at 1200 UTC of 24th May and lay centred near Lat. 18.5º N/Long 88.5º E. It continued to move in northerly direction and intensified into a severe cyclonic storm at 0600 UTC of 25th May and lay centred over northwest Bay of Bengal near Lat. 21.5º N/Long. 88.0º E close to Sagar Island. The system crossed West

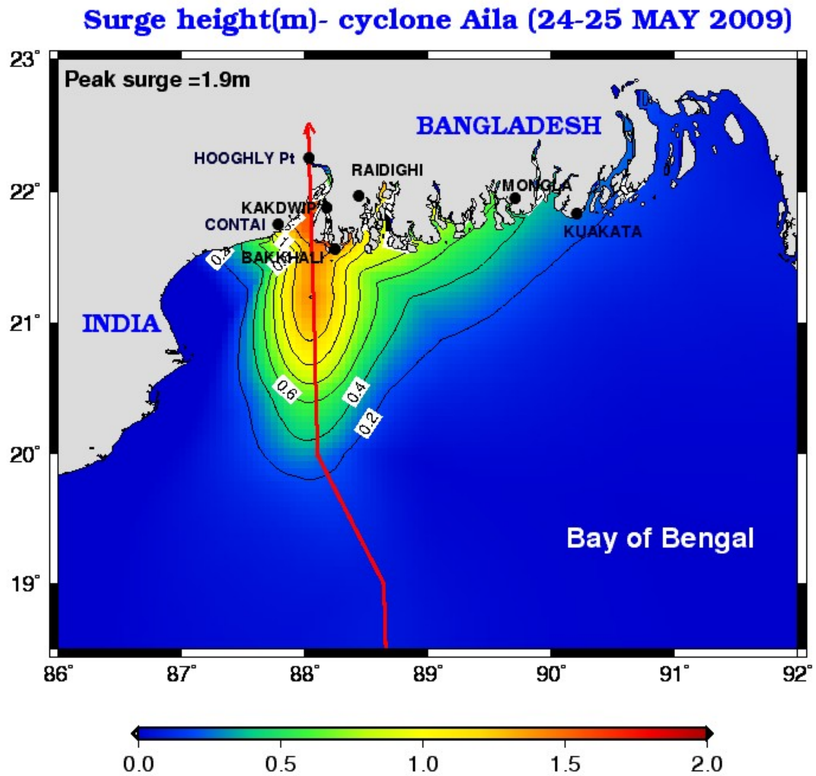

Fig. 3. Simulated peak surge (m) for 2009 Aila cyclone

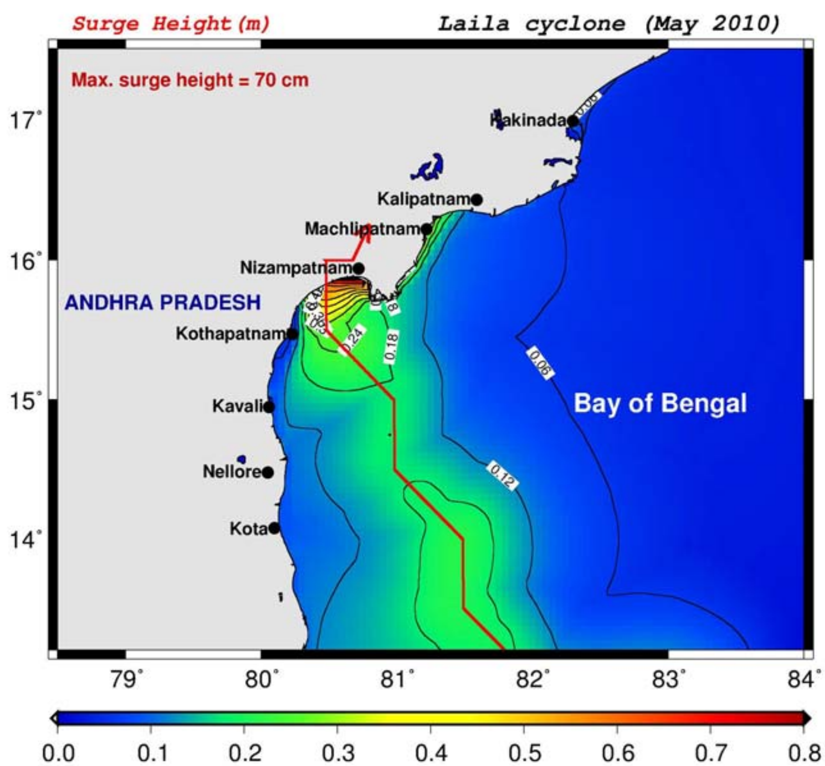

Fig. 4. Simulated peak surge (m) for 2010 LAILA cyclone

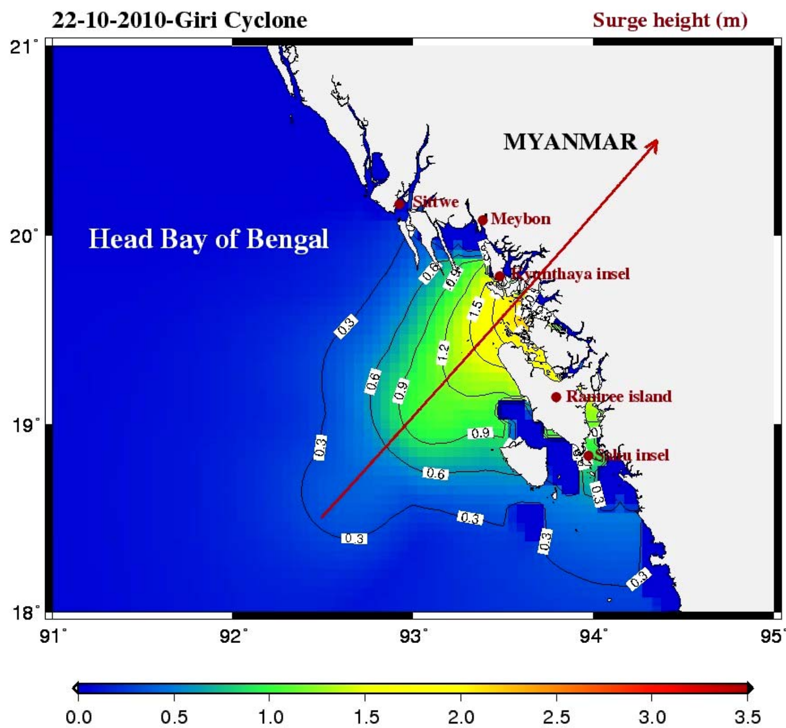

Fig. 5. Simulated peak surge (m) for 2010 Giri cyclone (Dube, 2012)

Bengal coast close to the east of Sagar Island between 1330 to 0700 UTC as a severe cyclonic storm with wind speed of 28 to 31 ms^{-1}. The lowest estimated central pressure was about 967 hPa at the time of landfall.

Computed storm surges at the time of landfall of the Aila in West Begal coast of India is shown in Fig. 3. A peak surge of about 2 m is predicted to the north of landfall. This is in agreement with the reported flooding and surge in the region (IMD, 2010).

4.3. *Andhra Pradesh : May 2010 Laila cyclone*

A low pressure area developed over the southeast Bay of Bengal on 15 May 2010. It concentrated into a depression at 0600 UTC of 17 May over the southeast Bay of Bengal. It moved in a northwesterly direction and intensified into a severe cyclonic storm LAILA. Moving in a west-northwesterly direction, it crossed Andhra Pradesh coast near Bapatla between 1100 and 1200 UTC of 20 May 2010 as a severe cyclonic storm (IMD, 2011). The cyclone slowed down during landfall period. It lay very close to coast after landfall maintaining cyclone intensity for about 12 hrs after landfall.

Computed maximum storm surge associated with the landfall of Laila is shown in the Fig. 4. Peak surge of 70 cms over and above the normal astronomical tides is predicted near Nizampatnam in Andhra Pradesh (15.88° N, 80.74° E). This prediction appear to be underestimated as IMD (2011) reported that the storm surge of 2 to 3 meters inundated the low lying areas of Guntur, Prakasham, West & East Godavari districts.

4.4. *Myanmar: May 2010 Giri Cycone (Dube, 2012)*

A low pressure area formed over the east central Bay of Bengal on 19 October 2010. It concentrated into a depression on 20 October over the same area. It intensified into a cyclonic storm, Giri at 0600 UTC of 21 October. It then moved slowly northeastwards and intensified into a severe cyclonic storm at 0300 UTC of 22 October and into a very severe cyclonic storm at 0600 UTC of the same day. It then moved relatively faster in the same direction and crossed Myanmar coast between Sittwe and Kyakpyu around 1400 UTC of 22 October 2010 with estimated sustained maximum wind speed of about 54 ms^{-1} (IMD, 2011). After the landfall, it continued to move north eastwards and weakened gradually.

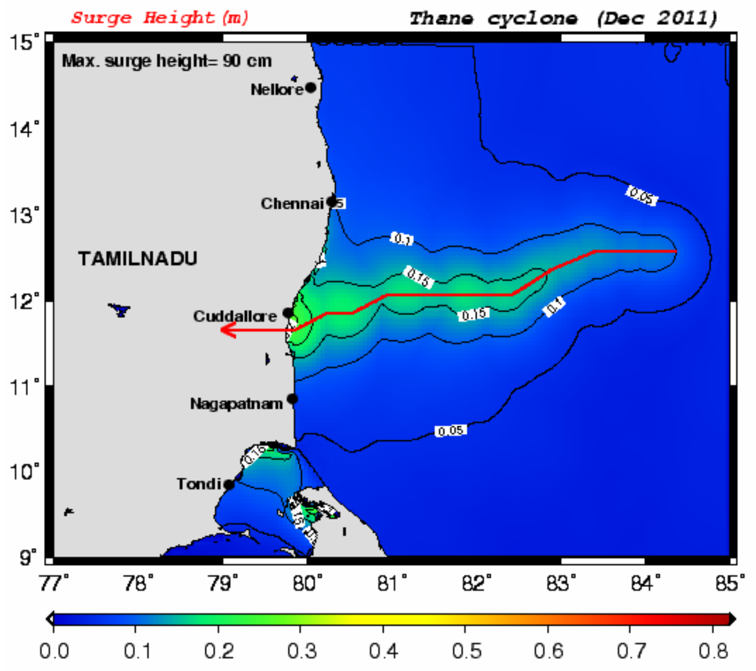

Fig. 6. Computed peak surge (m) for 2011 Thane cyclone

Computed maximum sea surface elevations for the landfall of the Giri in Myanmar is shown in Fig. 5. A peak surge of about 3.5 m is predicted at about 35 km to the north of landfall. This is in agreement with the reported flooding and surge in the region.

4.5. *East Coast of India : December 2011 Thane cyclone*

A depression formed over southeast Bay of Bengal in the evening of 25th December, 2011 and lay centred about 1000 km southeast of Chennai. It gradually moved north-northwestwards and intensified into a deep depression in the early morning of 26th December, 2011 and into a cyclonic storm 'THANE' in the same midnight. It then moved west-northwestwards and intensified into a severe cyclonic storm in the afternoon and into a very severe cyclonic storm in the evening of 28th December, 2011. It then moved west-southwestwards and crossed north Tamil Nadu & Puducherry coast between Cuddalore and Puducherry within 0100 and 0200 UTC of 30th December, 2011 with a wind speed of 33-39 ms^{-1}. After landfall, the system rapidly weakened into a severe cyclonic storm over north coastal Tamil Nadu at 0300 hrs UTC of 30th and into a deep depression around noon and into a depression in the same evening over the north Interior Tamil Nadu.

The track and associated storm surge are shown in Fig. 6. As per post-cyclone survey conducted by IMD, the storm surge of about 1 meter height inundated the low lying coastal areas of Cuddalore, Puducherry and Villuparam districts at the time of landfall of the cyclone, THANE (IMD, 2012). Computed results of maximum surge height of about 1 meter compares well with observations.

5. Conclusions

The recent developments in the storm surge forecasting for the Bay of Bengal is described. A real time storm surge prediction systems is used for computation of storm surges associated with severe cyclones during 2008-2011. The model results are in general good agreement with the available observations and estimates of the surge.

While the storm surge prediction for India in particular, and for the North Indian Ocean region in general, is generally satisfactory, improvements are needed both in storm surge model as well as meso-scale NWP model to further enhance storm surge forecasting capability in the region. One of the key issue is to estimate the total water level envelope (TWLE) at the time of cyclone landfall for issuing effective warnings in threatened areas. TWLE is the result of the combined effect of the interaction of storm surge with tides, wind waves, and several other factors. It is also very important to improve IIT Model to predict extent of coastal area likely to be inundated due to storm surges.

References

Ali, A., 1979, "Storm surges in the Bay of Bengal and some related problems", Ph. D, Thesis, University of Reading, England, 227.

Ali, A., Rahman, H., Sazzad, S. and Choudhary, H., 1997, "River discharge, storm surges and tidal interaction in the Meghna River mouth in Bangladesh", *Mausam*, **48**, 531-540.

Chittibabu P., 1999, "Development of storm surge prediction models for the Bay of Bengal and the Arabian Sea", Ph. D Thesis, IIT. Delhi, 261.

Das, P. K., 1972, "A prediction model for storm surges in the Bay of Bengal", *Nature*, **239**, 211-213.

Das, P. K., Sinha, M. C. and Balasubramanyam, V., 1974, "Storm surges in the Bay of Bengal", *Quart. J. Roy. Met. Soc*., **100**, 437-449.

Das, P. K., 1994, "On the prediction of storm surges", *Sadhna*, **19**, 583-595.

Dube, S. K., 2012, "Prediction of Storm Surges in the Bay of Bengal", *Tropical Cyclone Research and Review*, **1**, 67-74.

Dube, S. K., Sinha, P. C. and Rao, A. D., 1982, "The effect of coastal geometry on the location of peak surge", *Mausam*, **33**, 445-450.

Dube, S. K., Sinha, P. C. and Roy, G. D., 1986, "Numerical simulation of storm surges in Bangladesh using a Bay - River coupled model", *Coastal Engineering*, **10** (196), 85-101.

Dube, S. K., Sinha, P. C., Rao, A. D. and Chittibabu, P., 1994, "A real time storm surge prediction system: An Application to east coast of India", *Proc. Indian Natn. Sci. Acad*., **60**, 157-170.

Dube, S. K., Rao, A. D., Sinha, P. C., Murty, T. S., and Bahulayan, N., 1997, "Storm surge in the Bay of Bengal and Arabian Sea: The problem and its Prediction", *Mausam*, **48**, 283-304

Dube, S. K., Chittibabu, P., Rao, A. D., Sinha, P. C. and Murty, T. S., 2000, "Sea levels and coastal inundation due to Tropical cyclones in Indian Coastal Regions of Andhra and Orissa", *Marine Geodesy*, **23**, 65-74.

Dube, S. K., Sinha, P. C., Rao, A. D., Jain, Indu and Agnihotri, N., 2005, "Effect of Mahanadi river on the development of storm surge along the Orissa coast of India: A numerical study", *Pure and Appl. Geophys*, **162**, 1673-1688.

Dube, S. K., Jain, Indu, Rao, A. D. and Murty, T. S., 2009, "Storm surge modeling for the Bay of Bengal and Arabian Sea", *Natural Hazards*, **51**, 3-27.

Flather, R. A., 1994, "A storm surge prediction model for the northern Bay of Bengal with application to the cyclone disaster in April 1991", *Jr. Phys. Oceanogr*., **24**, 172-190.

Ghosh, S. K., 1977, "Prediction of storm surges on the east coast of India", *Ind. J. Meteo. Geophys*, **28**, 157-168.

Gönnert, G., Dube, S. K., Murty, T. S. and Siefert, W., 2001, "Global storm surges: theory, observations and applications", *Die Kueste*, 623.

Harper, B. A., 2005, "Recent advances in storm tide modelling in Australia, WMO International Workshop on Tropical Cyclone Landfall Processes", Macau, China, March ,17-21.

Henry, R. F., Duncalf, D. S., Walters, R. A., Osborne, M. J. and Murty, T. S., 1997, "A study of tides and storm surges in offshore waters of the Meghna estuary using a finite element model", *Mausam*, **48,** 4, 519-530.

Holland, G. J., 1980, "An analytical model of the wind and pressure profiles in hurricanes", *Monthly Weather Review*, **108**, 1212-1218.

IMD, 2010, "Report on cyclonic disturbances over North Indian Ocean during 2009", RSMC-Tropical Cyclone Report No. 05/2010, p117.

IMD, 2011, "Report on cyclonic disturbances over North Indian Ocean during 2010", RSMC-Tropical Cyclone Report No. 01/2011.

IMD, 2012, "Report on cyclonic disturbances over North Indian Ocean during 2011", RSMC-Tropical Cyclone Report No. 02/2012, 181.

Isozaki, I., 1970, "An investigation on the variations of sea level due to meteorological disturbances in the coast of the Japanese Islands (VI)", *Paper on Meteorological Geophysics*, Tokyo. XXI, **3**, 291-321.

Jelesnianski, C. P., 1965, "A numerical calculation of storm tides induced by a tropical storm impinging on a continental shelf", *Month. Wea. Rev*., **93**, 343-358.

Jelesnianski, C. P., 1972, "SPLASH I (Special Program to list Amplitudes of Surges from Hurricanes): Landfall storms", *NOAA Tech. Memo. NWS TDL*, **46**, 1-52.

Jelesnianski, C. P. and Taylor, A. D., 1973, NOAA Technical Memorandum, ERL WMPO-3, 33.

Johns, B., and Ali, A., 1980, "The numerical modelling of storm surges in the Bay of Bengal", *Quart. J. Roy. Met. Soc*., **106**, 1-8.

Johns, B., Dube, S. K., Mohanty, U. C. and Sinha, P. C., 1981, "Numerical simulation of the surge generated by the 1977 Andhra Cyclone", *Quart. J.Roy. Met. Soc*., **107**, 915-934.

Johns, B., Rao, A. D., Dube, S. K. and Sinha, P. C., 1985, "Numerical Modelling of the tide surge interaction in the Bay of Bengal", *Phil. Trans. Roy. Soc. London*, **A 313**, 507-535.

Johns, B., Sinha, P. C., Dube, S. K., Mohanty, U. C. and Rao, A. D., 1983 (a), "On the effect of bathymetry in numerical storm surge simulation experiments", *Computer and Fluids*, **3**, 161-174.

Johns, B., Sinha, P. C., Dube, S. K., Mohanty, U. C. and Rao, A. D., 1983 (b), "Simulation of storm surges using a three dimensional numerical model : An application to the 1977 Andhra cyclone", *Q. J. R. Meteorol. Soc*., **109**, 211-224.

Murty, T. S., 1984, "Storm Surges: Meteorological Ocean Tides", Department of Fisheries and Oceans, Ottawa, Canada.

Murty, T. S., Flather, R. A. and Henry, R. F. 1986, "The storm surge problem in the Bay of Bengal", *Prog. Oceanog*., **16**, 195-233.

Proudman, J., 1955, "The effect of friction on a progressive wave of tide and surge in an estuary", *Proc. Roy. Soc. London Ser*., **A 233**, 407-418.

Rao, N. S. B., 1968, "On some aspects of local and tropical storms in India", Ph. D. thesis, Univ. of Jadavpur.

Rao, A. D., 1982, "Numerical storm surge prediction in India", Ph. D. thesis, IIT Delhi, New Delhi, 211.

Rao, A. D., Dash Sujata, Babu, S. V. and Jain, Indu, 2007, "Numerical Modeling of Cyclone's Impact on the Ocean-A Case Study of the Orissa Super Cyclone", *Journal of Coastal Research*, **23**, 5, 1245-1250.

Roy, G. D., 1984, "Numerical storm surge prediction in Bangladesh", Ph. D Thesis, Indian Institute of Technology, Delhi, p188.

Sinha, P. C., Rao, Y. R., Dube, S. K. and Rao, A. D., 1996, "Numerical investigation of Tide-Surge Interaction in Hooghly Estuary", *India. Mar. Geod*., **19**, 235-255.

Sinha, P. C., Jain, Indu, Bhardwaj, N., Rao, A. D. and Dube, S. K., 2008, "Numerical Modeling of Tide-Surge Interaction along Orissa coast of India", *Nat. hazards*, **45**, 413-427.

Smith W. H. F. and Sandwell, D. T., 1997, "Global Sea Floor Topography from Satellite Altimetry and Ship Depth Soundings", *Science*, **277**(5334), 1956-1962.