Earth Syst Environ (2017) 1:15
https://doi.org/10.1007/s41748-017-0017-7

ORIGINAL ARTICLE

Simulation of Storm Surge in Myanmar Coast

K. W. Maw[1,2] · A. R. M. Towfiqul Islam[1,3] · Z. M. M. Sein[1,2] · M. Jinzhong[1] · J. C. Argete[4]

Received: 23 January 2017 / Accepted: 5 September 2017 / Published online: 19 September 2017

Abstract
Background Storm surge is one of the most severe disastrous hazards in the Southeast Asian region including Myanmar. In order to accurately and on time numerical prediction of a surge, it is a crucial task for disaster mitigation.
Purpose The objective of the study is to examine the predicted storm surge heights sensitivity with varying water depth. Storm parameters considered in the study include pressure drops, radius of maximum wind and duration of the storm and landfall angles in the Myanmar coast.
Method Traditional model for numerical prediction of the storm surge has some drawbacks such as a delayed intimation of expected storm surges. To overcome these shortcomings, this study used the Indian Institute of Technology, Delhi (IIT-D)-based surge model to explore the various factors of a surge in Myanmar.
Results The sensitivity results from the study demonstrate that the shallowness of the water depth and obtuse landfall angle in the Rakhine coast of Myanmar produce the highest surge height. It also shows that a fast-moving cyclone made a larger surge than slower one. The effects of wind stress forcing reveal that high-pressure drops and radius of maximum wind generate a larger surge. The peak surges are computed by the prediction model which compared to the observed values and found to be the most accuracy of the results.
Conclusion Thus, this surge model can provide an early (nearly 48 h) warming in the coastal regions of Myanmar. It can help to mitigate disaster from the consequences of storm surge in Myanmar by evacuating the local residents.

Keywords Storm surge · IIT-D model · Myanmar coast · Tropical cyclone

Electronic supplementary material The online version of this article (doi:10.1007/s41748-017-0017-7) contains supplementary material, which is available to authorized users.

✉ A. R. M. Towfiqul Islam
gm_towfique_06@yahoo.com

1 School of Atmospheric Sciences, Nanjing University of Information Science and Technology, Nanjing 210044, China

2 Department of Meteorology and Hydrology, Mayangon 11061, Myanmar

3 Department of Disaster Management, Begum Rokeya University, Rangpur 5400, Bangladesh

4 College of Science, University of the Philippines, Quezon City, Philippines

1 Introduction

Storm surge, triggered by tropical cyclone (TCs), is one of the most costly climatic hazards in the Southeast Asian region including Myanmar (Indo Jain et al. 2006), and some TCs in recent decades, e.g., Mala (2006), Nargis (2008) or Komen (2015), exhibit the extent of infrastructure losses and socioeconomic impacts on the coastal regions. These TCs impose the largest threat to the coastal communities (Klinjn et al. 2015). Thus, the intensified threats have urged researchers and practitioner communities to develop an accurately and timely forecast through a modeling approach for mitigating disaster in the vulnerable coastal regions. The coastal parts of Southeast Asian region such as Myanmar, India, Bangladesh, Pakistan and Sri Lanka are facing TCs-related storm surges in almost every year. However, it is becoming a serious concern. The integrated effects of these TCs with severe surges enter into the mouth of the estuary due to the widespread flooding in the low-lying coastal region. Several reasons responsible for the TCs associated with storm surges in the coastal regions of Myanmar include: (1) narrow bathymetric topography, (2) convergence feature of the BoB (Bay of Bengal), (3) coastal deltaic region near to the mouth of river systems and (4) people live in the coastal densely populated region (Pattanayak et al. 2016). Apart from these, land-falling TCs also contribute to the coastal inundation in the vulnerable coastal region (Dube et al. 2009).

Myanmar is located in the Southeast Asian region, and its position varies from 9.5° to 29.0°N latitude and 92°–102°E longitude (Fig. 1). The climate is mainly affected by the southwest monsoon from the Indian Ocean and cold air fluxes from the Southeast Asian region (Mie Sein et al. 2015). Aschariyaphotha et al. (2011) stated that the severe storm surge generates due to meteorological forcing and the wind forcing influence on the sea surface elevation along the coastal region. These cyclonic storms and depressions can be changed their track in the northerly or northeasterly direction toward to strike the coastal zones of Myanmar and Bangladesh. Lwin (1980) pointed out that the notable storm surges experienced in Myanmar in the month of May with the cases of May 1967, May 1968, May 1970 and May 1975. Most recent cyclone Nargis in 2008 made landfall in Myanmar, the most devastating storm, causing catastrophic destruction of about 10 million US dollar resulting in 140,000 casualties of its path (Tasnim et al. 2015). In addition, the coastal regions of Myanmar are vulnerable to the loss of life and material, as these can be easily flooded by storm surges. This loss is because of

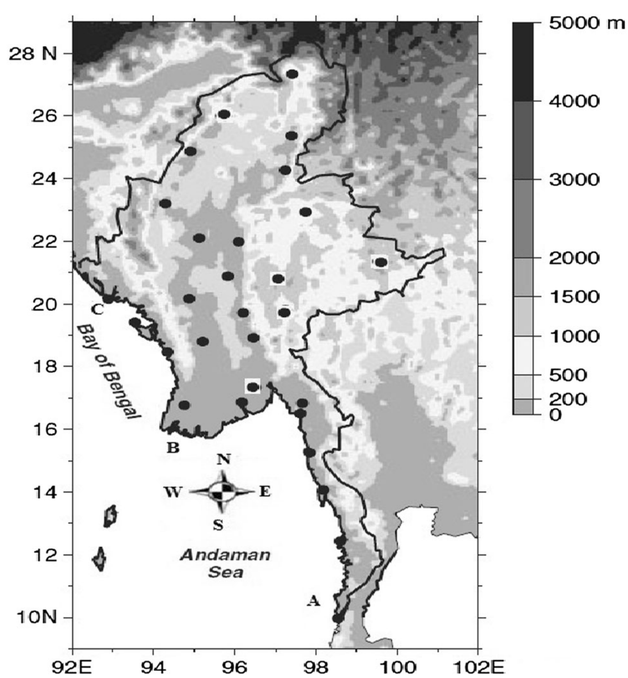

Fig. 1 Map shows the location of Myanmar. The shades represent topography and black dots denote meteorological stations. Points A to C show the area of study (after modified from Htway and Matsumoto 2011)

increasing the inhabitants of the coastal areas which provide livelihood to a large population (Webster 2008). It is a great importance to predict storm surges accurately and on time thoroughly a modeling technique for saving an enormous loss of human life and property in the vulnerable regions of Myanmar.

The prediction of a storm surge in Myanmar has been started using a simple analytical method for one-dimensional channels (Das 1972). Das et al. (1974) presented a prediction method for storm surges in the BoB with the pressure drop (Δp). Besides, Lwin and Win (1984) reformulated one with maximum wind (V_m) by combining the two equations of Miyazaki (1975) and Fletcher's (1955). Subsequently, Dube et al. (1994) have pioneered to predict a storm surge using a modeling approach in the northeast Indian coast. This model has been extensively applied in Bangladesh, Myanmar, Pakistan and Sri Lankan coasts. The significant number of researchers (e.g., Dube et al. 1985, Dube et al. 2004; Rao et al. 1997; Agnihotri et al. 2006; Indo Jain et al. 2006; Indo Jain et al. 2007; Lin et al. 2008; Dube et al. 2009; Tyagi et al. 2010; Kumar et al. 2011; Debsarma 2009; Debsarma et al. 2014; Tasnim et al. 2015) has been carried out the storm surge simulation studies to develop the model for predicting surges in the BoB. Earlier works use the 2D finite-difference surge model which was established by the Indian Institute of Technology, Delhi (IIT-D), to predict the surge accurately, and the system is fully occupied on the coastal water body. The Jelesnianski wind formulation is used to compute the wind forcing for this model using the estimated pressure drops (Mishra and Gupta 1976), and the radar reflectivity technique is employed to measure the radius of maximum wind. In fact, uncertainties are associated with parameterized wind fields that convert into huge uncertainties in the surge model prediction (Lewis et al. 2012; Lewis et al. 2014). Dube et al. (2009) have also mentioned the significance of wind forcing for predicting the surge amplitude through the modeling study over the BoB. Again, Dube et al. (2013) have highlighted the recent developments in storm surge prediction model for the BoB and the Arabian Sea and described the performance of the model in simulating the surges related to the severe TCs formed in the BoB during the 2008–2011. Recently, Rahman et al. (2017) have applied a model for estimating shallow water depth because of the surges over the Bangladesh coast using nested numerical schemes and found the reasonable results based on different investigations. Nevertheless, it is assumed that the advancement in the weather inputs may increase the accuracy of surge prediction. Thus, it is a challenging task to predict storm surges accurately. Because of land filling TCs, it is necessary to consider a surge warning system, fast evacuation of the hazard-prone regions, shelter them as a protection and integrated coastal management as well. In such challenges, an endeavor is carried out in the present study to simulate the storm surges closed related to the TCs over the Myanmar coast using the IIT-D storm surge model. A simulation study of storm surge was conducted by Indo Jain et al. (2006) in the Myanmar coast who predicted the surge heights in accordance with some real case study. But previous studies did not address adequately sensitivities of storm surge along Myanmar coast.

Therefore, this paper has been designed to elaborately illustrate the sensitivity experiments with a real case study of three giant cyclones in the Myanmar coast. The specific objectives of the study are (a) to investigate the peak surge sensitivity to basin-scale bathymetry, the landfall angle at different coastal regions, wind stress forcing and duration of the cyclone, (b) to simulate the peak surge by using IIT-D model run with real storm surge data and (c) to test the accuracy of IIT-D model by comparing the model-generated value and observed value. The functionality of this model can be reasonably applied for operational prediction of a storm surge over the coastal region of Myanmar.

2 Data and Methodology

2.1 Data and its Sources

The best track data sets (1968–2008) of storm surges and other related data sets are obtained from the UWIS (Unisys Weather Information Services) in the web link of http://weather.unisys.com/hurricane/. There are about 26 depressions and storms which made landfall in Myanmar coast during the past 40 years from 1968 to 2008; among those, nine cyclones had reported as a storm surge in Myanmar. This paper is used only three cyclones as real case studies. Case studies were done with synthetic data and actual track of three severe cyclones over the Myanmar coast. To understand the storm surge phenomena under various environmental forcing conditions, the surge values were computed based on several experiments and conditions. Case studies with the best track data from JTWC in every six-hourly position were used for each cyclone.

2.2 Description of IIT-D Model

Storm surge model (IIT-D) is a 2D finite-difference model. It is based on the vertically combined mathematical prediction system which is established by the IIT-D. This model is an integrated shallow water and nonlinear in nature with grid points and also includes semi-2D finite-difference scheme system. These grid points comprise of three kinds of point such as (1) the shallow sea water heights, (2) the zone-specific part of depth-averaged current and (3) meridional part of depth-averaged current. These are calculated by the satisfying CFL (Courant Friedrich Levi) criteria. It takes some minutes for integration 48 h (2 days). A number of variables depend on the required time steps, latitude of the open sea surface, and the E–W and N–S ranges of a particular area of interest and storm tract point as a key input parameter. Stair-step-shaped like model is employed to build in shorelines and landmasses. The generic mapping tool (GMT) is applied to mapping, the surge geo-referencing grid points and other relevant data sets for contouring and image processing purposes.

The area of analysis is located between 8°N to 23°N latitude and 90°E to 100°E longitude. A number of grid points were 121 and 182 in the X and Y directions. An identical grid distance was taken into consideration of approximately 9.1 km × 9.1 km along latitude and longitude directions. The coastal boundaries in this method were denoted by orthogonal straight line sections. The radiation type of boundary applied at the open boundary condition at 8°N latitude and at 90°E longitude directions. The bathymetry was obtained from the naval hydrographic tables that interpolated at grid points by using cubic projection interpolation schemes. The model generated the more accurate and realistic bathymetry along the continental shelf. The wind fields in the model were calculated by using the Jelesnianski wind formulation technique (Jelesnianski and Taylor 1973). The bottom pressure is calculated from the depth-averaged current by the mean of probable quadratic law with a coefficient (r) of approximately 0.0026. Three kinds of input parameters such as the geographical, oceanography and meteorological information are required to justify the surge model. The reasonable precision of bathymetry and coastline data is prerequisite condition for accurately predicting a storm surge model (Rao et al. 2009).

The model was used since 2009 by the many Southeast Asian countries for predicting storm surge. It is mentioned that the tidal data are not included in the surge model, although the water surface elevation solely influences on both the surge and astronomical tidal conditions (Pattanayak et al. 2016). In the present work, the peak storm surge was developed at the initial boundary condition and the sea surface point was quantitatively estimated. A system of rectangular Cartesian coordinate (CC) was employed for this study. The O_x point is fixed in the west direction, O_y point in the south direction and O_z point in vertically upward directions. The origin (O) is in the equal level of the free surface. The displaced positions of these surfaces are expressed by $z = \zeta\,(x, y, t)$, and the position of the sea floor is shown by $z = -h\ (x, y)$. The simple hydrodynamic equations of continuity and momentum for the dynamic processes in these surfaces can be calculated by the following Eqs. 1, 2, 3, 4 and 5, as stated by Dube et al. (1985) and Chittibabu et al. (2000):

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0, \tag{1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}-fv=-\frac{1}{\rho_0}\frac{\partial p}{\partial x}+\frac{1}{\rho_0}\frac{\partial \tau_x}{\partial z}, \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}+fu=-\frac{1}{\rho_0}\frac{\partial p}{\partial y}+\frac{1}{\rho_0}\frac{\partial \tau_y}{\partial z}, \tag{3}$$

$$\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho_0}\frac{\partial p}{\partial z}-g, \tag{4}$$

where, u, v, w are the Reynold's averaged velocities in the three directions of x, y and z, t time, p pressure, ρ density of the sea water, f Coriolis parameters, $f=2\omega\ \sin\ \Phi$ and g acceleration caused by gravity effect.

The initial boundary conditions will be

$$\left.\begin{array}{ll} u=v=w=0 & \text{at } z=-h \\ (\tau_x,\ \tau_y)=(F_B,\ G_B) & \text{at } z=-h \\ (\tau_x,\ \tau_y)=(F_S,\ G_S) & \text{at } z=\zeta \\ p=p_a & \text{at } z=\zeta \end{array}\right\}. \tag{5}$$

The continuity equations are commonly converted into transport form. The volume transport parts are defined as Eq. 6

$$U=\int_{z=-h}^{\varsigma} U\mathrm{d}z,\quad V=\int_{z=-h}^{\varsigma} v\mathrm{d}z. \tag{6}$$

The vertically integrated transport form for ocean models assumes that the nonlinear advection acceleration terms are negligible in comparison with the local terms.

The linearized long wave over depth is calculated by Eqs. 7, 8 and 9:

$$\frac{\partial U}{\partial t}=fv-\frac{1}{\rho}(\varsigma+h)\frac{\partial P_{\mathrm{a}}}{\partial x}-g(\varsigma+h)\frac{\partial \varsigma}{\partial x}+\frac{1}{\rho}[F_{\mathrm{s}}-F_{\mathrm{B}}], \tag{7}$$

$$\frac{\partial V}{\partial t}=-fU-\frac{1}{\rho}(\xi+h)\frac{\partial P_{\mathrm{a}}}{\partial y}-g(\zeta+h)\frac{\partial \zeta}{\partial y}+\frac{1}{\rho}[G_{\mathrm{S}}-G_{\mathrm{B}}], \tag{8}$$

$$\frac{\partial \zeta}{\partial t}=-\left[\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}\right], \tag{9}$$

where ζ is the sea surface elevation, U and V the transport components along x and y directions, respectively, τ_x, τ_y x and y parts, respectively, due to the Reynolds stress, p_{a} the atmospheric pressure at the water surface and (F_{S}, G_{S}) and (F_{B}, G_{B}) the components of wind and bottom stresses, respectively.

The forcing terms in Eq. 7 and 8 are (1) the Coriolis terms, (2) the reversed barometric effect, i.e., $\frac{\partial P_a}{\partial x}$ and $\frac{\partial P_a}{\partial y}$ because of fall in pressure, (3) the wind stress (F_{S}, G_{S}) and (4) the bottom stress (F_{B}, G_{B}), respectively. The Coriolis force is estimated by the location of area of interest. The forcing due to barometric changes can be ignored in this model. The surface wind and the wind stresses are computed, which are related to the pressure gradients. The pressure fields are expressed by the following Eqs. 10 and 11 (Das et al. 1974; Johns and Ali 1980)

$$p(r)=1010-\frac{\Delta P}{\left[1+\left(\frac{r}{R}\right)^2\right]}, \tag{10}$$

$$p(r)=p(\alpha)-\Delta P\exp\left(-\frac{r}{R}\right), \tag{11}$$

where R is the radial distance at which wind attained its maximum velocity, r radial distance from storm center, ΔP pressure difference between center of the storm and its outer periphery, $P(r)$ sea level pressure at radius r and $P(\alpha)$ central pressure at the cyclone.

The wind distribution is computed from the gradient wind formula which is described as Eq. 12

$$V^2=4V_{\mathrm{m}}^2\mu^2/\left(1+\mu^2\right)^2, \tag{12}$$

where $\mu = r/R$ and V_{m} = maximum wind at R.

In this study, pressure drop (ΔP) is derived from Lwin's (1980) equation. In his equation, constant value is calculated for the storms that had crossed Myanmar coasts by using historical storm data. The maximum wind speed and the pressure drop can be calculated by Eq. 13 (Lwin 1980)

$$V_{\mathrm{m}}=15.84\,(\Delta P)^{1/2}. \tag{13}$$

Johns and Ali (1980) stated that the gradient wind equation is used to compute the wind distribution equivalent to the pressure field in the following Eq. 14

$$V=\frac{fr}{2}+\left[\frac{f^2r^2}{4}+\frac{r}{\rho_a}\frac{\partial P}{\partial r}\right]^{\frac{1}{2}}. \tag{14}$$

Gradient wind depends on the Coriolis parameter, radial distance and pressure field. If the radial distance is changing with cyclone intensity, gradient wind is also changing accordingly. Therefore, it is very important to generate storm surge.

The surface stress components (F_{S}, G_{S}) due to the action of wind are expressed by conventional quadratic law as Eq. 15

$$F_{\mathrm{S}}=\rho_{\mathrm{a}}c_{\mathrm{D}}u_{\mathrm{a}}\left(u_a^2+v_a^2\right)^{1/2},\quad G_{\mathrm{S}}=\rho_{\mathrm{a}}c_{\mathrm{D}}v_{\mathrm{a}}\left(u_{\mathrm{a}}^2+v_{\mathrm{a}}^2\right)^{1/2}. \tag{15}$$

The bottom pressure is calculated from the depth-averaged current using a probable quadratic law which is given as Eq. 16

$$F_{\mathrm{B}} = \rho c_{\mathrm{f}} u \left(u^2 + v^2\right)^{1/2}, \quad G_{\mathrm{S}} = \rho c_{\mathrm{f}} v \left(u^2 + v^2\right)^{1/2}, \tag{16}$$

where u_{a} and v_{a} are the surface wind parts of x and y, ρ_{a} the air density, taken as 1.293 kg m^{-3}, c_{D} the drag coefficient (2.8×10^{-3}) and c_{f} the bottom friction coefficient (2.6×10^{-3}).

3 Results and Discussion

3.1 Sensitivity Experiments

3.1.1 Effect of Basin-Scale Bathymetry

The development of a surge nearby the shoreline is highly sensitive to the coastal geometrical feature and basin-scale bathymetrical condition due to the landfill action of TCs (Johns et al. 1983; Rao et al. 2009). Understanding such factors, the development of a storm surge over the Myanmar coast is calculated. Three basin depths such as 10, 50 and 100 m were used in this experiment. The parameters of this experiment were two points observation track to include starting point position 18.5°N and 92.5°E and ending point position 20.5°N and 94.5°E, observation time intervals 24 h, radius of maximum wind 30 km and pressure drop 35 hPa. Except basin depths, all parameters were the same in the experiment. Maximum peak surges from basin depths were 10.68, 2.74 and 1.37 m, respectively (Fig. 2a–c). The storm surge is mainly sensitive to the depth of the basin. We consider the entire basin of an equal depth of 10 m which leads to the highest surge height. It is evident that the shallowness of the water depth in coastal regions may increase the surge height maximum. The experiment demonstrates that if surge height decreases water depth increases in the region.

3.1.2 Effect of Landfall Angles

The storm surge is associated with three different directions of landfall angles including obtuse landfall angle, perpendicular landfall angle and acute landfall angle assuming near Kyaukpyu Station at Rakhine coast of Myanmar was employed in this experiment. Three different point positions such as 19.9°N and 92.0°E, 18.5° N and 92.5°E and 18.5°N and 93.2°E, duration of the cyclone 24 h, radius of maximum winds 30 km and pressure drop 50 hPa were used in this model. Maximum value of peak surges for varying different landfall angles was 4.02, 3.49 and 3.52 m, respectively (Fig. 3a–c). From these experiments, it is implied that obtuse landfall angle generates a higher surge than perpendicular and acute landfall angles. It is noted that cyclone of similar intensity with different landfall angles generates a surge with different amplitudes.

3.1.3 Wind Stress Forcing Effect

The objective of this experiment is to examine the wind stress in the entire surges calculation procedure. Meteorological input parameters are varied in terms of maximum wind radius and pressure drop.

3.1.3.1 Varying Values of Rmax (Radius of Maximum Wind) The cyclone was produced landfall at Rakhine coast, near Kyaukpyu Station, which considered along the straight line track with different radii of maximum wind. Three different values of Rmax 20, 30 and 40 km were selected in this experiment where the starting point position of the cyclone is 18.5°N and 92.5°E and ending point is 20.5°N and 94.5°E. Other parameters were used in this experiment such as water depth, observation hours 24 h and the pressure drop 45 hPa. The computed maximum values of peak surge for radius of maximum wind were

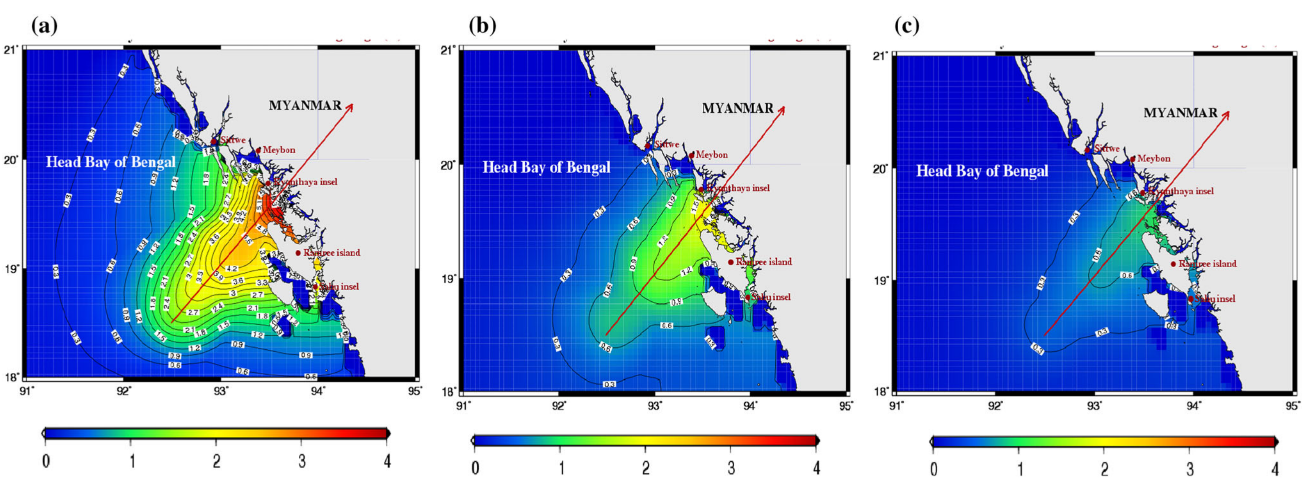

Fig. 2 Peak surges at varying water depth of 10, 50 and 100 m are 10.68, 2.74 and 1.37 m, respectively (**a–c**)

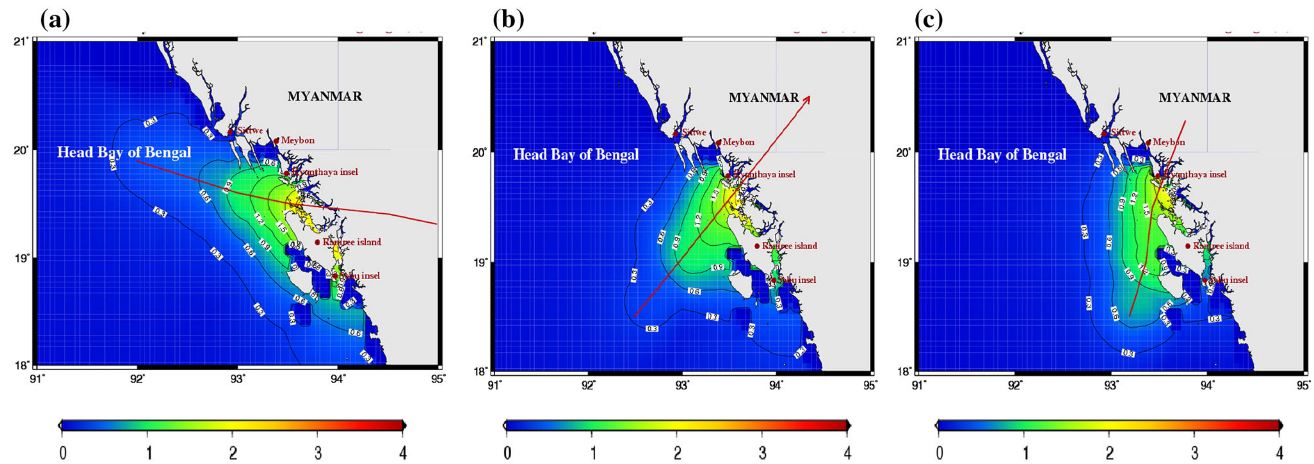

Fig. 3 Peak surges for obtuse, perpendicular and acute landfall angle at Kyaukpyu are (4.02) m, (3.49) m and (3.52) m, respectively (**a–c**)

1.88, 2.46 and 2.86 m, respectively (Fig. 4a–c). From this result, Rmax 40 km had the highest peak surge. Surge values were increasing with the increase in radius of maximum wind. Similarly, Guo et al. (2009) found that Rmax (radius to maximal wind) is the most significant factor influencing the peak storm surge among the all cyclonic variables in the Hangzhou Bay of China. Furthermore, a higher peak surge is generated by a large cyclone than a small one. Therefore, surge waves areas were greater with the increase in radius of maximum wind.

3.1.3.2 Varying Values of Pressure Drop (hPa) The cyclones were generated landfall at Rakhine coast near Kyaukpyu Station which considered along the straight track with 35, 45 and 55 hPa of pressure drop where the starting point of cyclone track was 18.5°N, 92.5°E and ending point was 20.5°N, 94.5°E. Real bathymetry, duration of the cyclone 24 h and the radius of maximum wind 30 km were used in the experiment. Model generated a peak surge for pressure drops which were 1.86, 2.46 and 2.98 m, respectively (Fig. 5a–c). It shows that higher surges are related to the large pressure drops and the impact of wind stress forcing was important in producing storm surge.

3.1.4 Effect of Duration of Cyclone

Cyclone moving along a straight track to landfall near Kyaukpyu Station at Rakhine coast was considered in this study. Straight track cyclone made landfall at two different cyclone's durations of 36 h (slow moving) and 12 h (fast moving) which were tested where starting point on cyclone track is 18.5°N, 92.5°E and ending point is 20.5°N, 94.5°E. Real water depth, pressure drop 35 hPa and the radius of

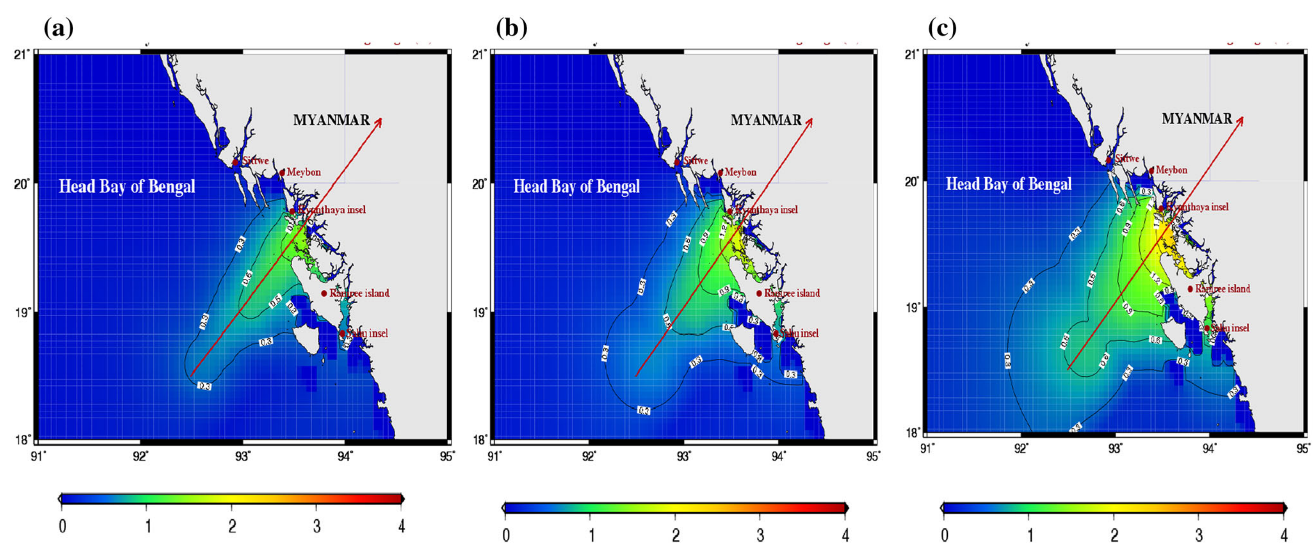

Fig. 4 Peak surges for varying values of radius of maximum wind speed of 20, 30 and 40 km are 1.88, 2.46 and 2.86 m, respectively (**a–c**)

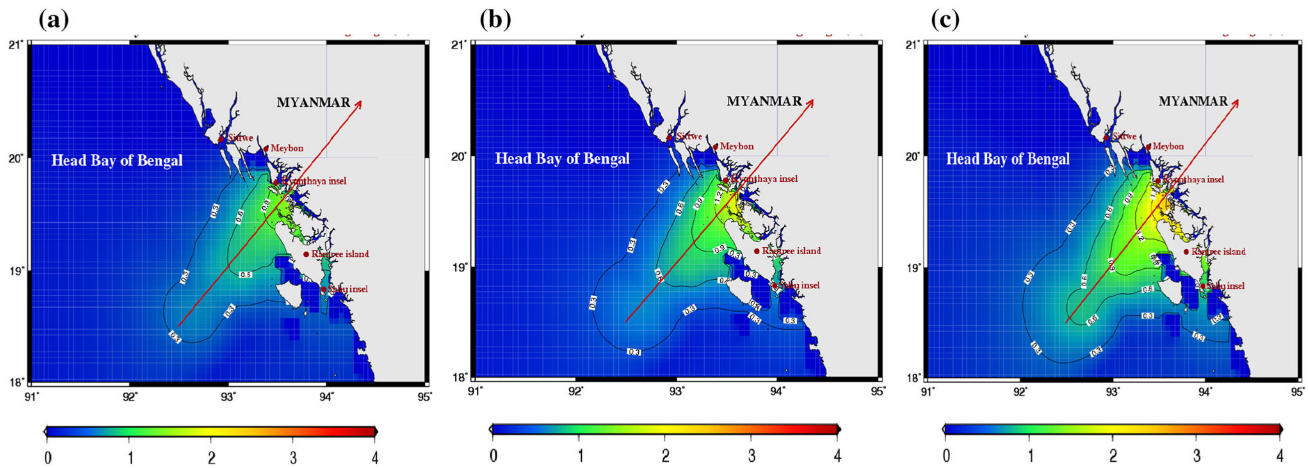

Fig. 5 Peak surges for varying values of pressure drop 35, 45, and 55 hPa are 1.86, 2.46 and 2.98 m, respectively (**a**–**c**)

maximum wind 30 km were used in the experiment. Model generated a peak surge for the varying cyclone duration (36 and 12 h) 2.22 and 2.97 m (Fig. 6a, b). The experiment indicated that a fast-moving cyclone made a larger surge than slower one. The results also reveal that a fast-moving cyclone generates the maximum surge.

3.2 Simulation of a Storm Surge: a Real Case Study

3.2.1 Simulation of 1968 May Sittwe Cyclone

The cyclonic storm made landfall with maximum sustained winds 58 ms^{-1}, and the pressure difference between the center and the outermost cyclones was 40 hPa which crossed Sittwe in May 1968. The intensity of the cyclone was severe cyclonic storm category 3. Input data of the model include actual water depth, five observational tracks and duration of cyclone 24 h before landfall. The maximum value of peak surge generated by the model was 4.2 m. The observed peak surge at Sittwe cyclone is found to be 4.3 m height (UWIS 1968). The results are consistent with the model generated the peak surge height (Fig. 7a–c). The cyclone in this case was moving nearly perpendicular to the coast. The time of landfall was 1 h ahead of the time of peak surge.

3.2.2 Simulation of 2006 April Mala cyclone

A severe cyclonic storm was crossed between the southern part of Rakhine coast and the delta area in April 2006. Mala cyclone made landfall with maximum sustained wind 59 ms^{-1}. The intensity of this cyclone was the equivalent of a category four tropical cyclones. Pressure drop was 53 hPa. Five observations track points and duration of

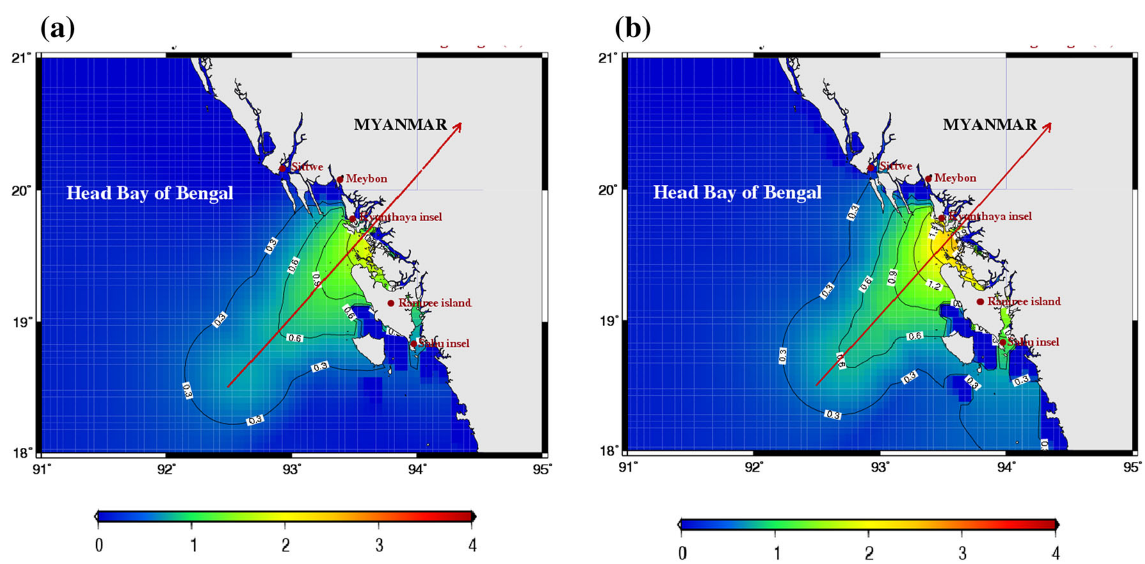

Fig. 6 Peak surges for slow moving (36 h) and fast moving (12 h) of cyclone are 2.22 and 2.97 m, respectively (**a**, **b**)

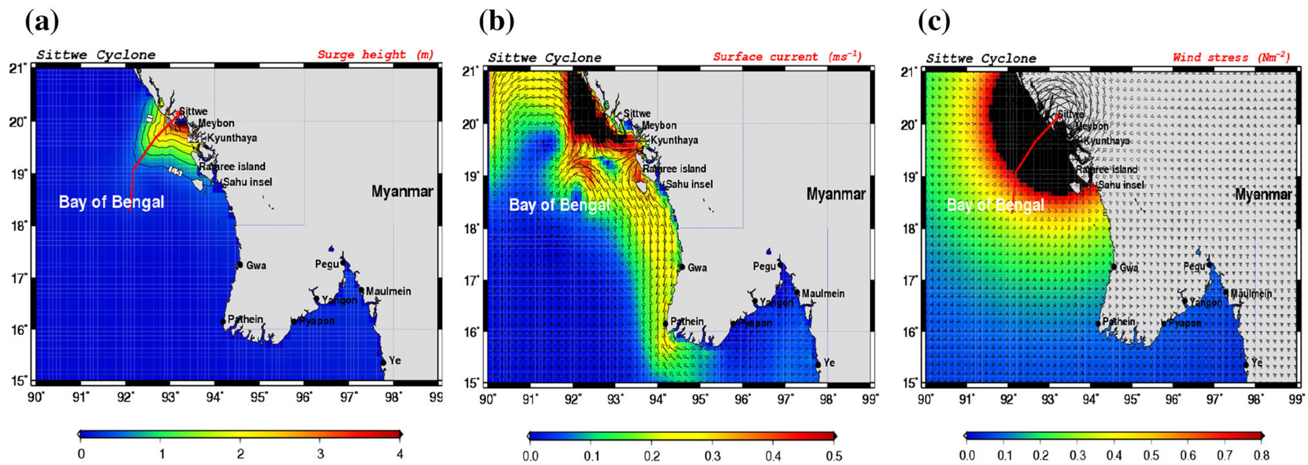

Fig. 7 Model-generated surge height is 4.2 m **a** of 1968 May Sittwe cyclone, strong surface current (m/s) **b** occurs at the left side of the cyclone track and strong wind stress (N/m^2) **c** shows at the end of the cyclone track where observed peak surge is 4.3 m

cyclone 24 h before landfalls were used in the model. The maximum value of peak surge computed by the model was 4.0 m (Fig. 8a–c). During TCs-related storm surges, the maximum surge of 4.6 m is observed over the Myanmar coast (IOC-UNESCO 1999). This is well agreed with our simulation result. Figure 8a–c shows that strong current is located at the right side of the cyclone track and strong wind stress at the end of the cyclone track. The time of landfall was also 1 h ahead of the time of peak surge.

3.2.3 Simulation of 2008 May Nargis Cyclone

Nargis Cyclone occurred in 2008 in Myanmar. It was the third largest storm surge in history, which crossed the Myanmar coast in May. This model was used maximum sustained wind of 59 ms^{-1}, pressure difference between the center and the outermost cyclones of 65 hPa, actual bathymetry with six-hourly five observations track points and duration of the cyclone 24 h before landfall. The maximum value of peak surge computed by the model was 6.4 m. It is interesting to note that storm surge water levels were almost equivalent to cyclone Nargis during the southwest monsoon onset time in Myanmar (Mie Sein et al. 2015). The observed value of peak surge is 6.7 m height (DMH 2011). Perpendicular landfall angle is found in this cyclone (Fig. 9a–c). Table 1 displays generated time of peak surge and time of landfall for three severe cyclones in Myanmar. Model-generated value is similar to the observed one. The peak surge is found in the Irrawaddy delta region of Myanmar (DMH 2011). The peak surge's height ranges from 3 to 5 m which is noticed in the Irrawaddy Division of Myanmar (RSMC 2009). The results

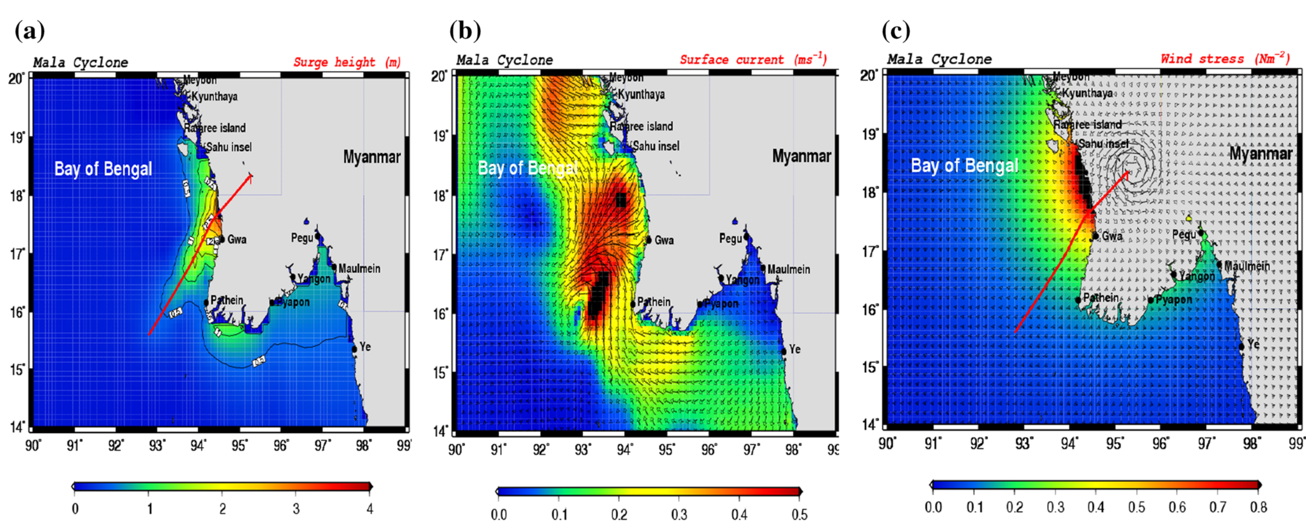

Fig. 8 Model-generated surge height is 4.0 m **a** of 2006 April Mala cyclone, strong surface current (m/s) **b** occurs right side of the cyclone track and strong wind stress (N/m^2) **c** shows at the end of the cyclone track where observed peak surge is 4.6 m

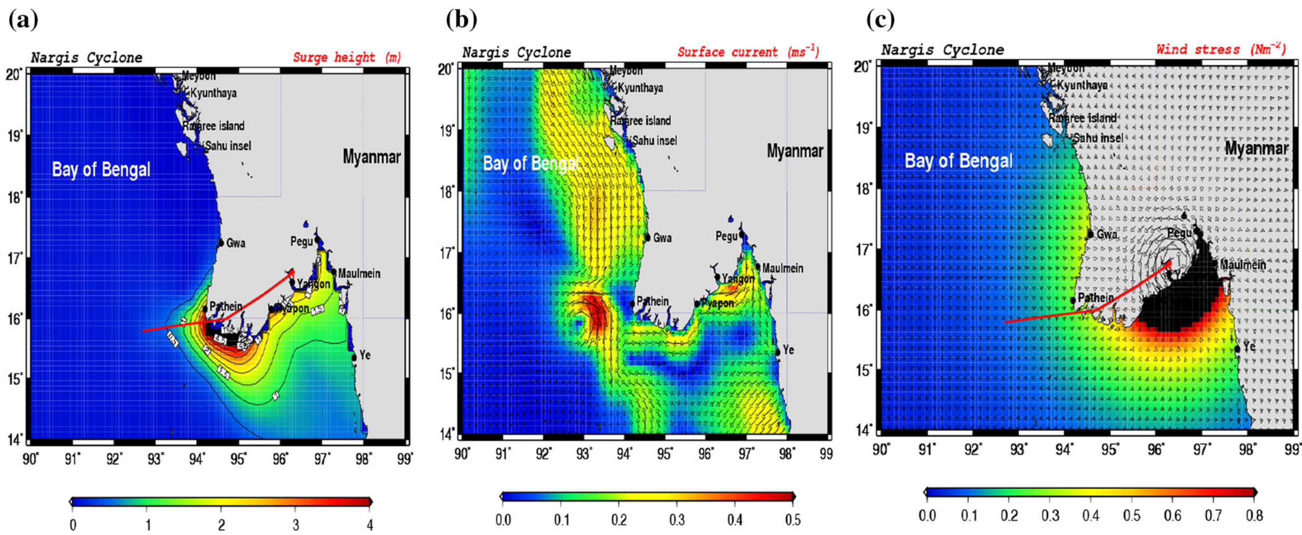

Fig. 9 Model-generated surge height is 6.4 m **a** of 2008 May Nargis cyclone, strong surface current (m/s) **b** occurs along the cyclone track and strong wind stress (N/m^2) **c** shows at the end of the cyclone track where observed peak surge is 6.7 m

Table 1 Simulated time of peak surge and time of landfall for three severe cyclones in Myanmar

Real cases cyclone	Surge height (m)	Pressure drop (hPa)	Time of peak surge (h)	Time of landfall (h)	Remarks
1968 Sittwe	4.2	51	20	21	1 h before landfall
2006 Mala	4.0	53	16	17	1 h before landfall
2008 Nargis	6.4	53	13	21	8 h before landfall

that come out through the IIT-D storm surge model compare well with the results stated according to DMH, Myanmar. The maximum sustained wind speed of 190 kph (km per hour) is found in the delta region of Myanmar during landfall actions of TCs. Lin (2009) made an observation that most of the areas of the Ayeyarwady delta are open and highly vulnerable to storm surge disasters, which can easily enter inland because of various tributaries, numerous bell-shaped river mouths and very narrow slope. Storm waves generated above 2 m high were superimposed on the peak surge level in the Ayeyarwady delta region of Myanmar (Shibayama et al. 2009; Fritz et al. 2010). Similar to this study, the simulated surge rises with enhancing the domain size primarily and then increases in constant value (Li et al. 2013). Tasnim et al. (2015) found that the simulated total water level was within the range of 3.5–4.6 m in most locations near the coast, whereas the observed maximum water level was within the range of 3.3–6.3 m. Surge wave occurred under the cyclone track due to the configuration of the coastline. Strong wind stresses were found at the end of the cyclone track. The landfall was ahead of the time of peak surge by 8 h (Table 1). Previous studies did not focus adequately the sensitivities of surge height in the coast of Myanmar (Indo Jain et al. 2006). The novelty of this study is that a detailed sensitivity analysis of a surge model with changing grid resolution reveals that the model with coarse resolution can effectively simulate the distribution of a surge closely related to the storm.

3.3 Verification of the Model Outputs

To validate the IIT-D storm surge model-computed results with observed data, this study has used the statistical test (Fig. 10). Figure 10a shows that the model-generated results at the three study sites are compared to the observed values. We have taken into consideration the ensemble and probabilistic techniques and outputs in order to predict the effective surges in the BoB (Dube et al. 2009). Significant relationship existed between the observed surge values and the model forecast values where $R^2 = 0.96$ indicated high accuracy of the model performance (Fig. 10b). Moreover, root mean square error (RMSE) is used to validate the model performance. In the real case of three cyclones, the sum of the three forecasts comes to 14.6–15.6, which is 1 lower than the sum of the observations. Hence, the forecasts are biased 0.3° too low. The mean error (ME) and RMSE were calculated for three cyclone events, which

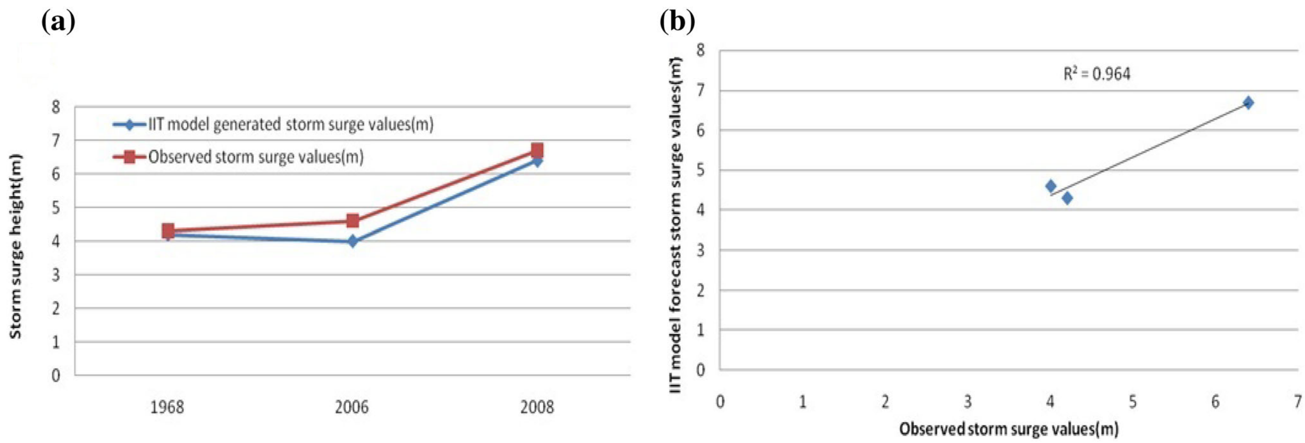

Fig. 10 **a** Comparison with the storm surge heights of the IIT model-generated values and observed values, **b** relationship between simulated model values vs. observed values

Table 2 The validation results show the IIT-D model-generated peak surge with the observed ones

TC (tropical cyclone) cases	IIT-D model peak surge (m)	Observed peak surge (m)	Bias	Mean error (m)	Root mean square error (m)
1968 Sittwe	4.2	4.3	0.3	0.3	0.39
2006 Mala	4.0	4.6			
2008 Nargis	6.4	6.7			

have a negative ME 0.3 m surge and 0.39 m RMSE (Table 2). However, the probable time and site of peak surge height generated by IIT-D based model are echoed by the similar results of the DMH (2011). The surge elevations are estimated from the model-generated results with various initial conditions over the Myanmar coast. Thus, it can be said that much difference is not noticed in the predicted surge height and the computed results accord with the observed ones.

4 Conclusions

Storm surge (IIT-D) model has been applied to forecast the surge in the vulnerable coastal region of Myanmar. A numerical simulation was performed with a storm surge model using the data of 1968 Sittwe, 2006 Mala, and 2008 cyclones which crossed the coastal region of Myanmar. The surge model was capable to simulate surges for cyclones of 1968, 2006 and 2008 which is well agreed with the observed results. The results show a reasonable prediction of storm surge along the Myanmar coast. The highest surge envelope was generated by the IIT-D model in the most cases over the Myanmar coast. The peak surge was identified on the right side of three cyclones with a considerable accuracy. The results of sensitivity experiments show that the shallowness of water in coastal regions has a larger value of surge height. The study also reveals that the time of cyclone landfall on the delta coast was more hours ahead of the time of peak surges. The large pressure drops and maximum winds produce the larger peak surge.

The surge model used in this research has not been considered the tide and the Irrawaddy River delta that influences on the eastern BoB. However, the discharge of river water may be changed the peak surge height in the Myanmar coast. In the present study, storm surge is the solely dynamic force for the driving processes in the sea. Nevertheless, this model can be employed to an actual time basis for prediction of surges generated by three cyclones which may strike the coastal region of Myanmar. The actual time surge prediction is possible by using the high-resolution surge model with an advanced forecast time of at least 2 days (48 h) before the landfall of the TCs. It is expected that this model will contribute to develop an effective surge warning system for the operational analysts, to evacuate from coastal communities rapidly and to mitigate the disaster successfully in the Myanmar coastal region.

Acknowledgements First author would like to acknowledge the WMO for providing the scholarship to perform this research project. Thanks are due to Dr. S.K. Dube, Indian Institute of Technology

Kharagpur, India, and former Director General Dr. Lwin, Department of Meteorology and Hydrology, Myanmar, for providing valuable suggestions that improved the study. We are thankful to the editor and anonymous referees for their constructive comments and helpful suggestions that enable us to upgrade the quality of this paper substantially.

References

Agnihotri N, Chittibabu P, Jain I, Sinha PC, Rao AD, Dube SK (2006) A bay-river coupled model for storm surge prediction along the Andhra Coast of India. Nat Hazards 39:83–101. doi:10.1007/s11069-005-3812-7

Aschariyaphotha N, Wongwises P, Humphries UW, Wongwises S (2011) Study of storm surge due to Typhoon Linda (1997) in the Gulf of Thailand using a three dimensional ocean model. Appl Meth Computa 217:8640–8654. doi:10.1016/j.amc.2011.03.105

Chittibabu P, Dube SK, Rao AD, Sinha PC, Murty TS (2000) Numerical Simulation of extreme sea levels using location specific high resolution model for Gujarat coast of India. Mar Geodesy 23:133–142

Das PK (1972) A prediction model for storm surges in the Bay of Bengal. Nature 239:211–213

Das PK, Sinha MC, Balasubhramanyam V (1974) Storm surges in the Bay of Bengal. Quart J Roy Met Soc 100:437–449

Debsarma SK (2009) Simulations of storm surges in the Bay of Bengal. Mar Geod J 32(2):178–198

Debsarma SK, Rahman MM, Nessa FF (2014) Simulation of Cyclone 'Aila-2009' by using WRF-ARW model and numerical storm surge model. Monit Predict Trop Cyclones Indian Ocean Climate Change. doi:10.1007/978-94-007-7720-0_23 **(U.C. Mohanty et al. (eds.), pp. 263–273)**

DMH (2011) Department of Meteorology and Hydrology, Myanmar. http://www.dmh.gov.mm/index.php? Accessed 20 Dec 2016

Dube SK, Sinha PC, Rao AD, Rao GS (1985) Numerical modeling of storm surges in the Arabian Sea: the problem and its Prediction. Mausam 48:283–304

Dube SK, Rao AD, Sinha PC, 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 SK, Sinha PC, Rao AD, Jain I, Agnihotri N (2004) Effect of Mahanadi river on the development of storm surge along the Orissa coast of India: a numerical study. Pure Appl Geophys 162:1673–1688

Dube SK, Jain I, Rao AD, Murty TS (2009) Storm surge modelling for the Bay of Bengal and Arabian Sea. Nat Hazards 51:3–27. doi:10.1007/s11069-009-9397-9

Dube SK, Poulose J, Rao AD (2013) Numerical simulation of storm surge associated with severe cyclonic storms in the Bay of Bengal during 2008–11. Mausam 64(1):193–202

Fletcher RD (1955) Computation of maximum surface winds in hurricanes. Mon Wea Rev 36(6):246–250

Fritz HM, Blount C, Thwin S, Thu MK, Chan N (2010) Cyclone Nargis storm surge flooding in Myanmar's ayeyarwady river delta, Indian ocean tropical cyclones and climate change, pp. 295–303. http://www.gtresearchnews.gatech.edu/cyclone-nargis. Accessed 20 July 2016

Guo Y, Zhang J, Zhang L, Shen Y (2009) Computational investigation of typhoon-induced storm surge in Hangzhou Bay, China. Estuar Coast Shelf Sci 85(4):530–536. doi:10.1016/j.ecss.2009.09.021

Htway O, Matsumoto J (2011) Climatological onset dates of summer monsoon over Myanmar. Int J Climatol 31:382–393. doi:10.1002/joc.2076

IOC-UNESCO (1999) Project proposal on storm surges disaster for the northern part of the Indian Ocean, Project no. IOC/INF-1131, Paris

Jain Indo, Chittibabu P, Agnihotri N, Dube SK, And Sinha PC, Rao AD (2006) Simulation of storm surges along Myanmar coast using a location specific numerical model. Nat Hazards 39(1):71–82. doi:10.1007/s11069-005-3176-z

Jain Indo, Chittibabu P, Agnihotri N, Dube SK, Sinha PC, Rao AD (2007) Numerical storm surge prediction model for India and Pakistan. Nat Hazards 42:67–73

Jelesnianski CP and Taylor AD (1973) NOAA Technical Memorandum, ERL, WMPO-3

Johns B, Ali A (1980) The numerical modelling of storm surges in the Bay of Bengal. Quart J Roy Met Soc 106:1–8

Johns B, Sinha PC, Dube SK, Mohanty UC, Rao AD (1983) On the effect of bathymetry in numerical storm surge simulation experiments. Comput Fluids 2:161–174

Klinjn F, Kreibich H, de Moel H, Penning-Rowsell E (2015) Adaptive flood risk management planning based on a comprehensive flood risk conceptualization. Mitig Adapt Strat Glob Change 20(6):845–864

Kumar A, Done J, Dudhia J, Niyogi D (2011) Simulations of cyclone Sidr in the Bay of Bengal with a high-resolution model: sensitivity to large-scale boundary forcing. Meteorol Atmos Phys 114(3–4):123–137

Lewis M, Bates P, Horsburgh K, Neal J, Schumann G (2012) A storm surge inundation model of the northern Bay of Bengal using publicly available data. Quart J R Meteorol Soc 139:358–369

Lewis M, Horsburgh K, Bates P (2014) Bay of Bengal cyclone extreme water-level estimation uncertainty. Nat Hazards 72:983–996

Li R, Xie L, Liu B, Guan C (2013) On the sensitivity of hurricane storm surge simulation to domain size. Ocean Model 67:1–12. doi:10.1016/j.ocemod.2013.03.005

Lin NM (2009) Storm surge inundation analysis of cyclone Nargis event. http://www.icharm.pwri.go.jp/training/master/publication/pdf/2010/nay.pdf. Accessed 16 Nov 2016

Lin II, Chen CH, Pun IF, Liu WT, Wu CC (2008) Warm ocean anomaly, air sea fluxes, and the rapid intensification of tropical cyclone Nargis (2008). Geophys Res Lett 36:L03817. doi:10.1029/2008GL035815

Lwin T (1980) Review of methods of storm surge prediction currently used in Burma, Report to the WMO Workshop on Storm Surges, November 10–15, 1980, Rangoon, Burma

Lwin T and Win S (1984) A Preliminary Study to Develop Technique for Storm Surge Prediction in Myanmar. Paper presented at the Research Paper Reading Session of Meteorological Sciences Division, Rangoon, Burma

Mie Sein ZM, Towfiqul Islam ARM, Maw KW, Moya TB (2015) Characterization of southwest monsoon onset over Myanmar. Meteorol Atmos Phys 127:587–603. doi:10.1007/s00703-015-0386-0

Mishra DK, Gupta GR (1976) Estimation of maximum wind speeds in tropical cyclones. Indian J Meteorol Geophys 27:285–290

Miyazaki M (1975) Numerical simulation of storm surges in Tosa Bay. Meteorol Geophys 26:55–62

Pattanayak S, Mohanty UC, Rao AD (2016) Simulation of storm surges in the Bay of Bengal using 1-way coupling between NMM-WRF and IITD storm surge model. Mar Geodesy. doi:10.1080/01490419.2016.1217957

Rahman MM, Paul GC, Hoque A (2017) A shallow water model for computing water level due to tide and surge along the coast of Bangladesh using nested numerical schemes. Math Comput Simul 132:257–276. doi:10.1016/j.matcom.2016.08.007

Rao YR, Chittibabu P, Dube SK, Rao AD, Sinha PC (1997) Storm surge prediction and frequency analysis for Andhra coast of India. Mausam 48:555–564

Rao AD, Jain I, Ramana Murthy MV, Murty TS, Dube SK (2009) Impact of cyclonic wind field on interaction of surge–wave computations using finite-element and finitedifference models. Nat Hazards 49:225–239

RSMC-tropical cyclones (2009) A report on cyclonic disturbances over North Indian Ocean during 2008. India Meteorological Department, New Delhi, p 108

Shibayama T, Takagi H, Hnu N (2009) Disaster survey after the cyclone Nargis in 2008. In: Proceedings of the 5th APAC, 2:190–193

Tasnim KM, Shibayama T, Esteban M, Takagi H, Ohira K, Nakamura R (2015) Field observation and numerical simulation of past and future storm surges in the Bay of Bengal: case study of cyclone Nargis. Nat Hazards 75:1619–1647. doi:10.1007/s11069-014-1387-x

Tyagi A, Mohapatra M, Bandyopadhyay B, Singh C, Kumar N (2010) Characteristics of very severe cyclonic storm Nargis over the Bay of Bengal during 27 April to 3 May 2008 Indian ocean tropical cyclones and climate change 2010, pp 315–325

UWIS (1968) Unisys weather information systems: http://weather.unisys.com/hurricane/indian_oc/1968/. Accessed 12 Dec 2016

Webster PJ (2008) Myanmar's deadly daffodil. Nat Geosci 1:488–490. doi:10.1038/ngeo257

K. W. Maw is studying at Department of Meteorology, PhD programme in Nanjing University of Information Science and Technology, China since 2014. She obtained her MS degree in Meteorology from the Institute of Environmental Science and Meteorology in University of the Philippines Diliman, Philippines in 2007. She worked at Department of Meteorology and Hydrology, Myanmar since 2001. Her research work focuses on the prediction of the heavy rainfall over western Myanmar using weather research and forecasting model related with tropical cyclone and Rakhine Mountain.

Dr. A. R. M. Towfiqul Islam received his PhD degree in Climate Change and Climate System, Nanjing University of Information Science and Technology, China. He received his MSc degree in Geology and Mining, University of Rajshahi, Rajshahi, Bangladesh. He works as an Assistant Professor at the Department of Disaster Management, Begum Rokeya University, Rangpur, Bangladesh. His current research focuses on climate change, drought hazard, water quality, health hazard, water resource related fields. He has successfully carried out several research works in group and individually in the fields of natural hazards, water quality management, applied climatology, and disaster management. To date, he has published several scientific articles in SCI journals related to applied meteorology and water science.

Dr. Z. M. M. Sein received her PhD degree in Meteorology, Nanjing University of Information Science and Technology, China. She also received her MS degree in Meteorology at University of Philippines, Philippines. She works at Department of Meteorology and Hydrology (Myanmar). Her current research focuses on climate variability, climate modeling related fields. To date, she has published several scientific articles in SCI journals related to meteorology field.

Dr. M. Jinzhong obtained his PhD degree in Atmospheric Science in Nanjing University of Information Science and Technology, China. He works as a Professor, doctoral supervisor. He is responsible for affairs concerning scientific research in Nanjing University of Information Science and Technology, Nanjing, China. His research interest focuses on storm-scale ensemble forecasting, ensemble Kalman Filter, 3DVAR and 4DVAR etc. He has published several scientific research papers in SCI journals.

Dr. J. C. Argete obtained her PhD degree in Meteorology from the University of Alberta, Canada in 1988. She joined the University of the Philippines in 1989 and worked to professor level until her retirement in 2010, after which she taught dynamic and physical meteorology at Qatar Aeronautical College. Her fields of specialization are tropical meteorology and satellite meteorology. Her published works dealt mainly on the use of regional climate models in relation to monsoon rainfall and tropical cyclone detection and tracking.