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Research Article

Effect of waves, tides, and storm parameters on water level rise through numerical simulation

Pham Tri Thuc*

ABSTRACT

In this study, Rising water is caused by factors such as storm parameters, tides and waves... calculated and analyzed by the integrated numerical model SuWAT (Surge, Wave, and Tide). The SuWAT model has been applied to calculate storm surge in several Typhoons that have made landfall on the northern coast (such as Typhoons Franki-96, Washi-05, Xangxane-06, Kalmeagy-14) by different calculation methods. The results show that the influence of the tide on the rising water level is negligible in places with low tidal amplitude, and with storm landing at high tide, the water will be lower than when the storm makes landfall at low tide; The water surge due to atmospheric pressure is only significant in the offshore area when the storm intensity is still strong. Meanwhile, in the area, shoreline rise due to wind stress and wave stress accounted for the majority of the total water level rise during storms. With storm parameters, The storm surge at Hon Dau reached the highest value in case the storm's speed was 5 hours slower than the actual one. The storm surge at Cua Ong, Hon Dau, and Hon Ngu stations all increased when wind speed in the storm increased; however, Hon Ngu station had a higher increase rate. The magnitude of the water surge decreases when the pressure in the storm increases, but the increase at Cua Ong, Hon Dau, and Hon Ngu stations is completely different. The research results will be very useful in warning and forecasting storm surge in the area.

Key words: Storm surge, a coupled model of Surge, Wave, and Tide

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INTRODUCTION

In coastal areas, storms often cause water surges that flood a large area, causing many damage to people and property. The world has recently recorded many storms causing high water levels, such as Hurricane Katrina that hit New Orleans-US in August 2005, causing water surges of more than 8m, killing nearly 1.200 people and causing damage of about 75 billion USD; Typhoon Nargis made landfall in Myanmar in May 2008, killing more than 130.000 people, and especially recently, Super Typhoon Haiyan at level 17 landed in the Philippines in November 2013 causing a maximum water surge of 6.5m, killing more than 3.600 people, damage up to 14 billion USD. In the long coastal areas of Vietnam have also recorded many storms causing strong winds, high waves, and rising sea levels, such as Typhoon Washi (7/2005) which landed in Hai Phong, causing 1.95m of water rise in Do Son; Typhoon Xangsane (9/2006) made landfall in Da Nang causing water surge of more than 1.4m in Son Tra, Typhoon Ketsena (9/2009) made landfall in Quang Nam causing 2.4m water surge in Hoi An [1,2]. Sea level rise during storms mainly depends on storm parameters (central pressure drop, wind speed, radius of maximum wind zone, direction of storm movement), coastal topography (depth and shape shoreline patterns), tides, and waves (due to wind). Therefore, studying the influence of the above factors on storm surge for a specific area will have scientific significance in formulating the problem of calculating and forecasting storm surge. In Vietnam, the study of rising tides, taking into account the influence of tides has been mentioned in several research works such as Tran Tan Tien et al. [3], Nguyen Xuan Hien [4], Nguyen Tho Sao [5]. The results show that tidal influence is only significant in areas with a large tidal range, especially when storms make landfall at high tide. Meanwhile, the influence of sea waves on storm surge has only been studied in recent years. Nguyen Xuan Hien [1] calculated the wave surge according to the empirical formula in the coastal area of Hai Phong and found that the wave surge can account for 20-30% of the total storm surge. Research on wave surge by the integrated numerical model was done by Do Dinh Chien et al. [2,6] during typhoon Xangxane in September 2006 that hit Da Nang, Nguyen Ba Thuy, and colleagues [7] in the storm Kalmaegy in September 2014 made landfall in Hai Phong- Quang Ninh. The results of these studies all show that when considering

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the influence of waves in some cases, wave surge can account for 35% of the total storm surge in reserve. Worldwide, there have been many studies confirming that wave-induced surges contribute significantly to the total storm surge. In many cases, wave-induced surges can account for up to 40% of the total storm surge[8–10]. The influence of storm parameters on the water as studied by Pham Tri Thuc et al.[11], Nguyen Ba Thuy et al.[12], showed that the surge to reached the maximum value with the case of moving speed of storm is one hour slower than the actual speed, the water rises with wind speed and the magnitude of rising decreases when the pressure in the storm increases.

This study analyzes the influence of storm, tidal, and wave parameters on storm surge based on the calculation results using the SuWAT model. This model has overcome the limitations of some previously built models and technologies, which consider the interaction between tides, waves and storm surge[6,9,10,12,13]. The influence of tides and waves on storm surge is understood as the difference of the model's storm surge calculation results with and without considering tides or waves. In addition, rising water due to barometric pressure and the wind is also calculated and analyzed. The influence of storm parameters on storm surge is the result calculated by the SuWAT model for changing storm movement speed, increasing and decreasing wind speed and barometric pressure during storms[11,12]. The analytical calculation results have clarified the role and influence of storm surge components in the coastal area and offshore in the Northern coastal area.

METHODOLOGY

To study the influence of tides and waves on storm surge, the SuWAT (Surge, Wave, and Tide) integrated model calculates tides, waves and storm surges simultaneously were applied. The SuWAT model consists of two-component models based on two-dimensional nonlinear hot water equations taking into account wave stress and the SWAN model, which calculates ocean wave factors. With wave action consideration, the model can account for the variation of the resistance coefficient on the surface in the presence of waves. The theoretical basis of the SuWAT model is detailed in the works[6,9,10].

The system of two-dimensional nonlinear shallow water equations has the form[6,9,10]:

$$\begin{aligned}
&\frac{\partial M}{\partial t}+\frac{\partial}{\partial x}\left(\frac{M^2}{d}\right)+\frac{\partial}{\partial y}\left(\frac{MN}{d}\right)+gd\frac{\partial \eta}{\partial x}= \\
&fN-\frac{1}{\rho_w}\left(\tau_s^x-\tau_b^x+F_x\right)+A_h\left(\frac{\partial^2 M}{\partial x^2}+\frac{\partial^2 M}{\partial y^2}\right); \\
&\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}\left(\frac{N^2}{d}\right)+\frac{\partial}{\partial y}\left(\frac{NM}{d}\right)+gd\frac{\partial \eta}{\partial x}= \\
&-fM-\frac{1}{\rho_w}d\frac{\partial P}{\partial y}+\frac{1}{\rho_w}\left(\tau_s^y-\tau_b^y+F_y\right) \\
&\qquad +A_h\left(\frac{\partial^2 N}{\partial x^2}+\frac{\partial^2 N}{\partial y^2}\right); \\
&\frac{\partial \eta}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=0
\end{aligned} \tag{1}$$

where: t is time; η is surface water level fluctuation (m); P is atmospheric pressure (hPa); τ_b^x and τ_b^y are the bottom stress (kg/m/s^2); τ_s^x and τ_s^y are surface wind stress (kg/m/s^2); M, N are the total flow in the x and y directions (m^2/s); g is the acceleration due to gravity (m/s^2); f is the Coriolis parameter; d is the total depth, $d = \eta + h\ (m)$; ρ_w is the water density (kg/m^3); A_h is the horizontal turbulent diffusion; n is the Manning roughness coefficient (m/s$^{1/3}$); F_x, F_y is the pressure due to wave radiation stress (kg/m/s^2).

Conditions for SuWAT model: In case of tidal calculation, with East Sea grid, at the liquid boundary, the harmonic constants of 16 tidal waves (M2, S2, K1, O1, N2, P1, K2, Q1, M1, J1, D01, 2N2, h2, g2, L2, T2) are obtained from the tissue global tidal pattern as boundary conditions[14]. Details of the solution method and structure of the SuWAT model have been presented in the studies of Sooyoul Kim et al[9–12], Do Dinh Chien[6]. The calibration and testing of the SuWAT model to calculate tides, and storm surge in Vietnam was carried out in[6,7,15]. For the problem of storm surge, the model is calculated according to 4 different options: not considering tides and waves, only considering tides, consider only waves, and consider both tides and waves simultaneously. The SuWAT model to calculate storm surge receives wind and pressure fields from the analytical storm model of Fujii and Mitsuta[16]. The theoretical basis and verification of the analytical storm model have been presented in[6].

RESULTS AND DISCUSSION

Calculation and irrigation domain

To study the effects of tides, waves and storm surge for the central coastal area that the article covers, the SuWAT model is designed on a rectangular grid,

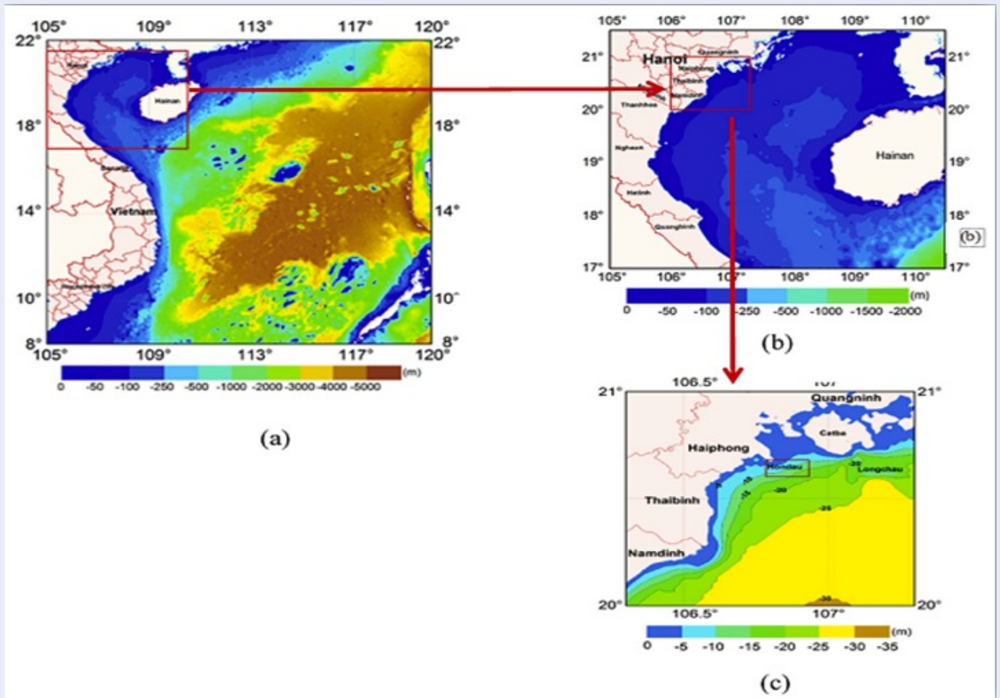

Figure 1: Geophysical domains with three levels for a coupled SuWAT model: (a) The outermost domain-D_1, (b) The intermediate domain-D_2, (c) The innermost domain-D_3.

and three layers nested domain. The largest calculation (East Sea grid-D_1) from latitude 8-22^0 N, longitude 105-120^0 E has a resolution of 4 minutes (about 7.4km), shown in Figure 1. The next nested domain (regional grid-D_2) has a resolution of 1 minute (about 1.85km), the third domain (local grid-D_3) has a resolution of 0.5 minutes (about 925m) with locations determined to cover all areas with significant water surge (greater than 0.5m). Topographic data is taken from GEBCO (General Bathymetry Chart of the Ocean) of BODC (British Ocean Data Center) with a resolution of 4 minutes for the East Sea grid, 1 minute for the domain grid and digitized from the bottom topographic map 1/100.000 scale of the General Department of Seas and Islands applies to coastal areas.

The influence of tides on storm surge

The magnitude of storm surge is the difference between the observed water level and the main tide. In some cases, the storm surge at the highest tide is not the largest, but the total water level at the highest bounce (storm tide) will cause dangers such as flooding and coastal erosion. Therefore, in warning and forecasting storm surge, hydrological fluctuations tides at the time of storm impact are always concerned.

To examine the role of tides in storm surge the article calculates storm surge caused by Typhoon Frankie-96 landfall in Nam Dinh at the time of low tide, causing water to rise to nearly 1m. The results are compared with two options for calculating storm surge, that is, with and without considering the tides, showed not much difference, shown in Figure 2a. Meanwhile, storm surge is calculated according to the option with and without considering the water level tide during Typhoon Washi-05 landfall in Nam Dinh at the time of high tide. The results show that the alternative considering the tide gives lower results, as shown in Figure 2b.

So, at locations with large tidal amplitudes (such as in the Gulf of Tonkin coast of Vietnam), the storm makes landfall at high tide, the magnitude of the storm surge will be lower than when the storm makes landfall at low tide. Therefore, when the storm makes landfall at high tide, the numerical model needs to take into account the option that takes into account the tide to calculate the medicine storm surge.

To examine the influence of tides on storm surge in areas with different millionth of magnitude, the paper used Typhoon Xangxane-06 landfall in Da Nang and the water level monitoring data according to the data

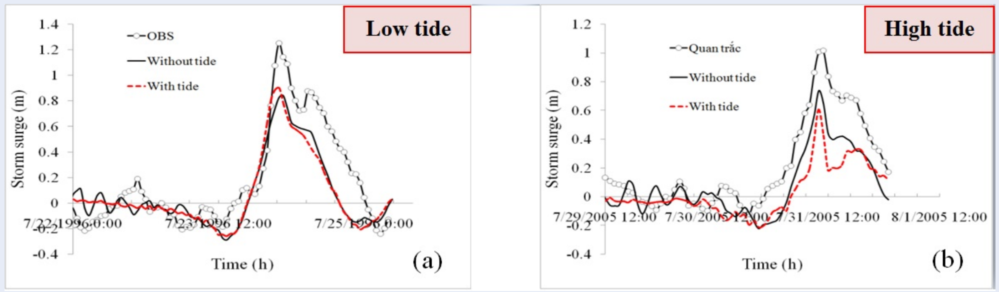

Figure 2: Storm surge at Hon Dau station according to the option: with and without considering the influence of tides in Typhoon Frankie-96 (a) and Typhoon Washi-05 (b).

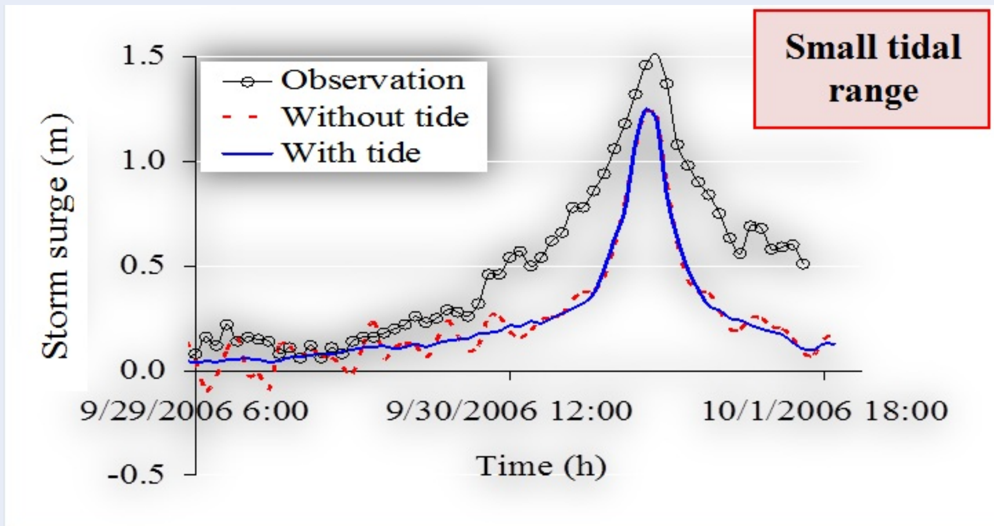

Figure 3: Storm surge at Son Tra station according to the alternative: with and without considering the influence of tides in Typhoon Xangxane-06.

hours at Son Tra meteorological station for analysis and calculation. In this case, the model calculates according to 2 options with and without considering the influence of tides (in both cases, waves are not considered). The comparative results shown in Figure 3 show that the influence of tides is not significant because the tidal amplitude at the time of storm landing is not large. There is no significant difference between the scenario of storm surge with and without tidal consideration. Therefore, when the storm hits the central coastal area of Vietnam, the storm surge forecast model does not need to consider the tides (reduce computation time and still give reliable results).

Effect of sea waves on storm surge

Description of rising and receding water due to waves, Bowen et al. experiment (1968)[17] verified the numerical model simulate wave propagation into the area. The results are shown as shown in Figure 4, showing that, in the coastal area, the water surge due to stress wave radiation accounts for a very significant part. So, when applying a numerical model to forecast storm surge, it is necessary to consider the contribution of wave surge and the integrated model of surge and wave to be used in service forecasting.

To examine the influence of waves on storm surge, the article used Typhoon Frankie-96 landfall in Nam Dinh, Typhoon Xangxane-06 landfall in Da Nang, and hourly water level monitoring data at Hon Dau and Son Tra meteorological stations for analysis. In both these storms, the model is calculated for both cases with and without considering wave influence. The comparison results shown in Figure 5 show that the influence of waves is quite large. The difference between the calculation results in the case of with and

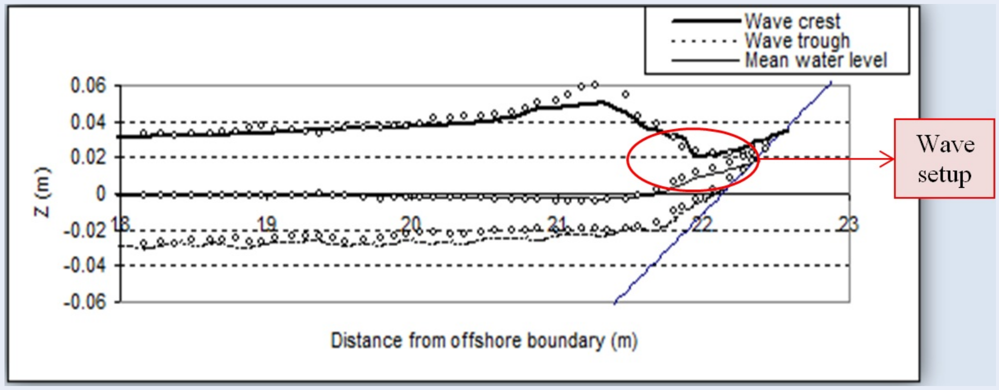

Figure 4: Description of wave surge in coastal areas[17]

without considering the influence of waves at the time of maximum water surge is about 0.3m. Comparing the magnitude of the surge calculated according to the model and the observed data, the calculated surge value is more similar to the observed data than the case without considering the wave influence (at the extreme point). The model takes into account waves; the error in calculating the water profile according to the model compared with the observed data is the mean absolute error (MAE)=0.23m and the mean squared error (RMSE)=0.37m.

The magnitude of the water surge at some locations during Typhoon Xangsale-06 in the case of the model with and without considering the wave's brother and the observed data is shown in Figure 6. At the same time, the water surge due to waves accounts for a significant proportion. When considering the influence of the party, the calculation results for observations with observed data are higher than without considering the influence of waves.

The distribution of the largest storm surge for the two cases is shown in Figure 7a-b, showing that the extent and height of the storm surge increase significantly when the model considers the storm surge's contribution due to waves. This result has shown that to improve the accuracy in service forecasting and service calculation, it is necessary to take into accountto improve the accuracy in service forecasting and service calculation, it is necessary to consider the contribution of wave surge contribution of wave in the total storm surge. At some locations near the shore, the wave surge reached 0.7m, (accounting for about 35 % of the maximum storm surge), shown in Figure 7c. The radiation power of large waves is concentrated around the right side of the storm's path and in the coastal area where the Typhoon landfall, as shown in Figure 7d.

Storm surge due to wind stress and barometric pressure

Most previous studies on storm surge have mainly focused on wind surge and the decrease in barometric pressure at the center of the storm. However, studies that separate these two components have not received much attention, mainly due to analytical formulas, which are not calculated by the numerical model.

The fluctuation of storm surge caused by wind stress, pressure, and waves in typhoon Xangxane-06 at Son Tra station is shown in Figure 8. The results show that the water rise in the coastal area is mainly due to the contribution of wind stress, followed by barometric pressure, and finally by waves. Here only storm surge caused by wind, pressure and waves in shallow coastal waters are analyzed. This is because the distribution of storm surge caused by these components can be spatially different in the affected storm area.

Figure 9a-c shows the spatial distribution of the largest storm surge caused by barometric pressure, wind stress, and waves. The results show that the rising water area due to high pressure is concentrated mainly on both sides of the storm's path, the closer to the shoreline, the less this component of rising water decreases because the pressure drop at the center of the storm decreases during the displacement to the shore. Meanwhile, the storm surge due to wind stress is mainly concentrated in the coastal area. To the right of the storm's landfall location, the work near the shoreline rises due to increased wind stress. The main cause is water accumulation in the area shore. Like storm surges due to wind stress, wave surge also concentrates mainly in coastal areas because in areas with high wave height, the depth decreases, giving rise to rupture.

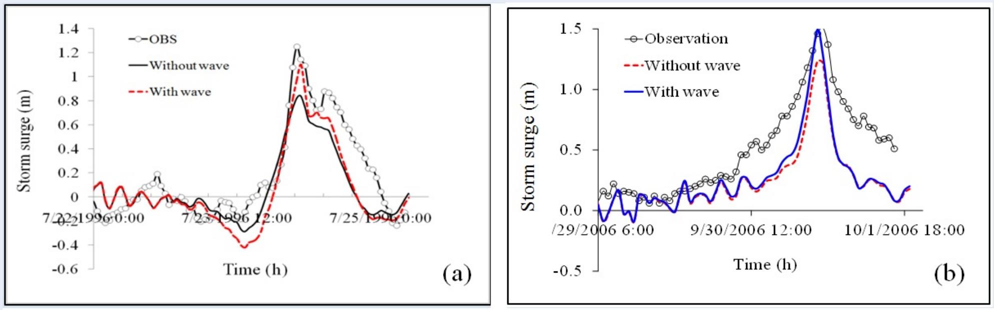

Figure 5: Storm surge at Hon Dau station during Typhoon Frankie-96 (a) and Son Tra station during storm Xangxane-06 (b) under two options with and without considering the influence of waves.

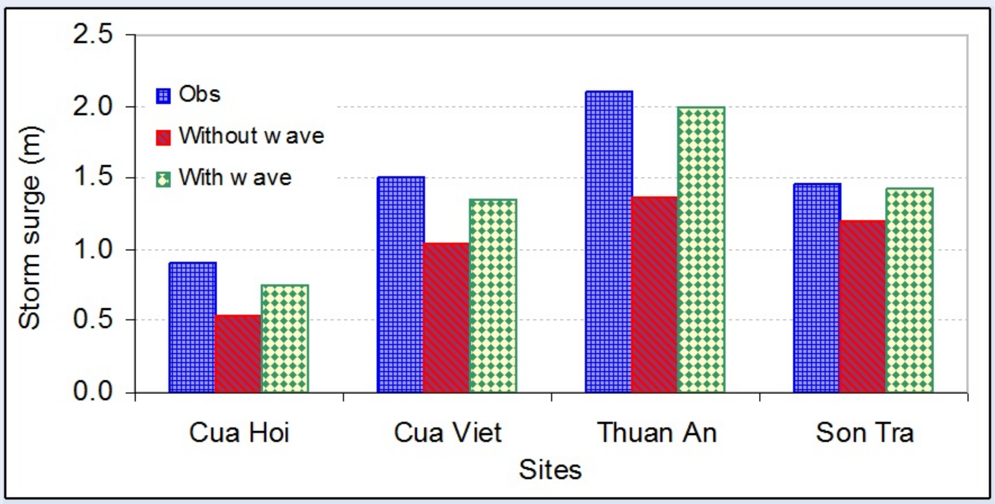

Figure 6: The highest storm surge during Typhoon Xangsane-06 was at locations along the Northern coast.

Table 1: Storm surge on the Saffir/ Simpson scale (converted) pressure at the center of the storm Wind speed Elevation.

Number	Pressure at the center of the storm [milibar]	Maximum wind speed [km/h]	Rising water height [m]	Level of destruction
1	> 980 (less than level 11)	78 - 100	0.5 - 1	small
2	968 - 979 (level 11-12)	101 - 116	1 - 2.4	medium
3	945 - 964 (level 12-15)	117 - 137	2.5 - 3.5	strong
4	920 - 944 (level 15-16)	138 - 164	3 - 5.5	extreme
5	< 920 (more than level 16)	> 164	> 5.5	disastrous

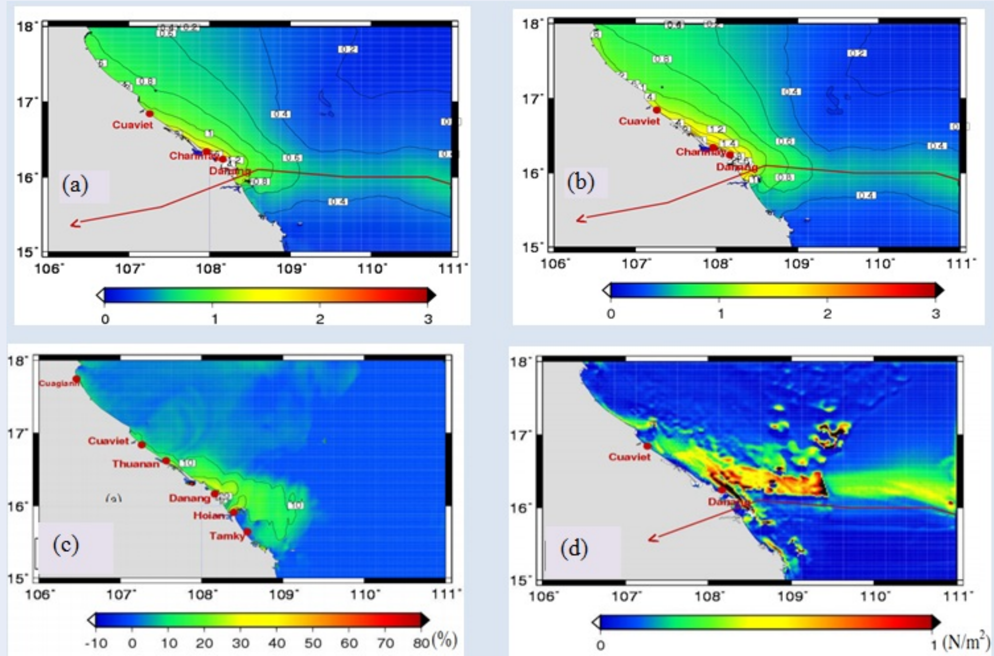

Figure 7: Distribution of maximum storm surge in the case of wave surge (a) and not taking into account wave surge (b); percentage contribution of wave surge in the total surge (c) and wave radiation stress (d) in Typhoon Xangxane-06.

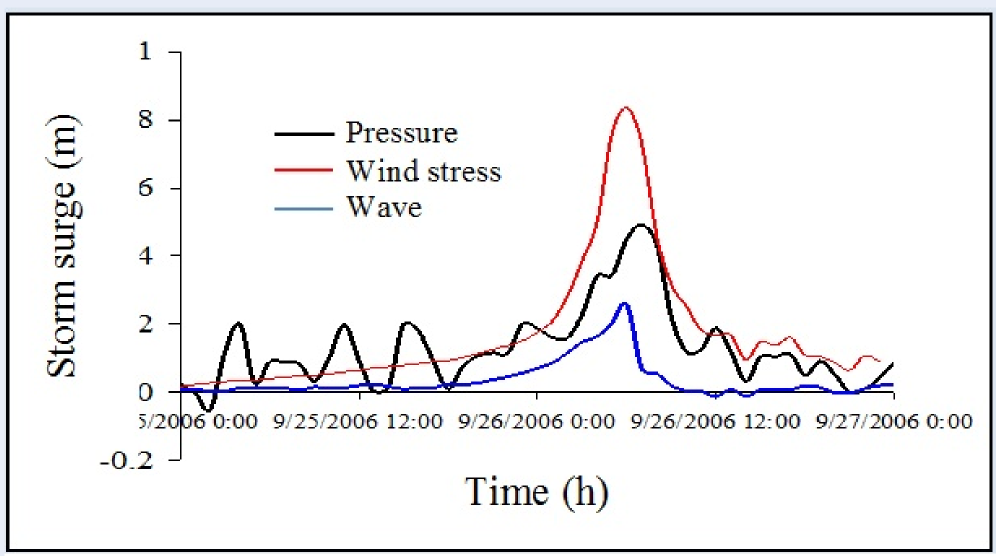

Figure 8: Pressure surge, wind stress and wave at Son Tra during Typhoon Xangxane-06.

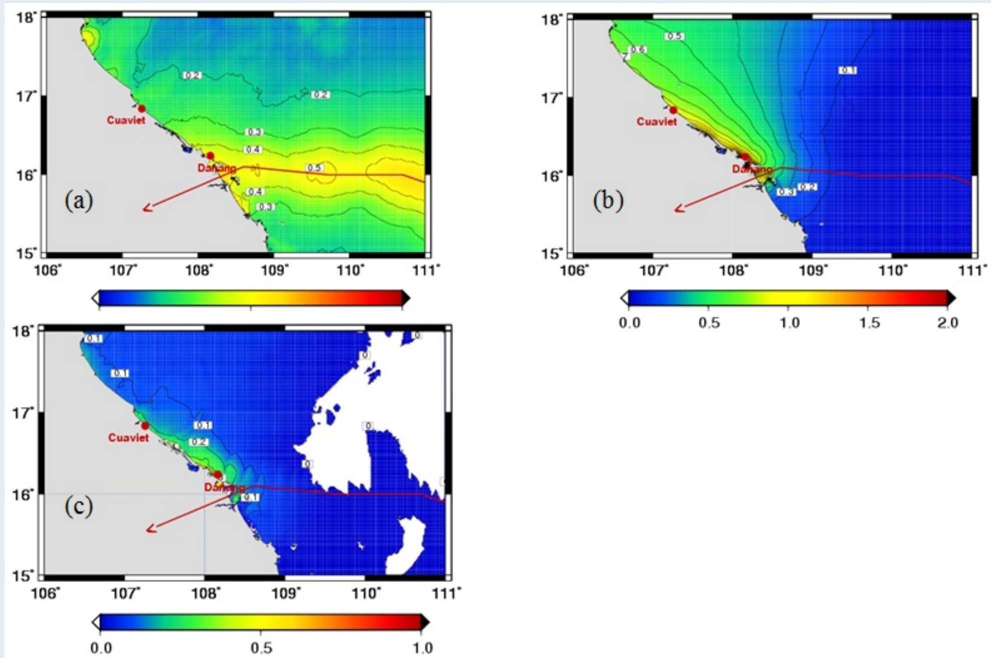

Figure 9: Distribution of the largest surge due to: (a) barometric pressure, (b) wind stress and (c) sea waves during Typhoon Xangxane in 9/2006.

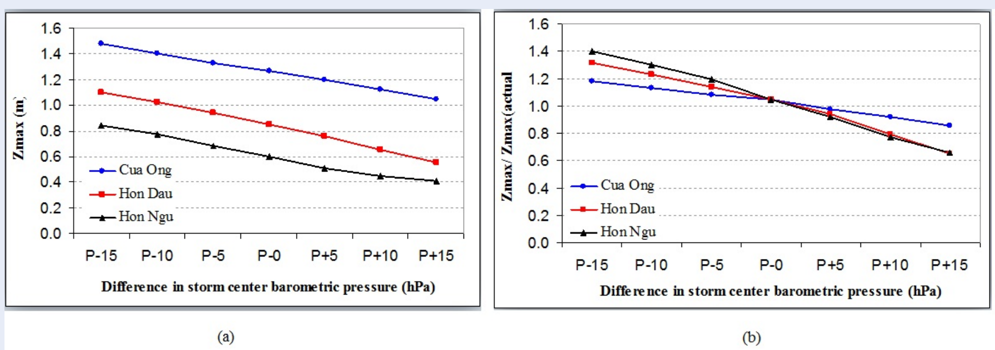

Figure 10: The change of the maximum storm surge (a) and the maximum surge rate compared to the actual (b) at Cua Ong, Hon Dau and Hon Ngu in the case of changes in storm center barometric pressure Kalmaegy-14.

Effect of storm parameters on storm surge

Effect of storm center pressure

The influence of storm center pressure on storm surge is done with the case of trajectory and other storm parameters such as travel speed, wind speed, which are kept the same but changes in barometric pressure at the center of the storm in an increasing direction (weaker storm intensity) and in a decreasing direction (stronger storm intensity) compared to the actual pressure of Typhoon Kalmaegy-14 in the range of -15hPa to +15hPa. The largest variation of water rise is according to the change of the central pressure of the storm compared to the actual at Cua Ong, Hon Dau, and Hon Ngu stations Figure 10a shows that the magnitude of the water surge at the three stations decreases as the pressure at the center of the storm increases. Figure 10b shows the largest storm surge (Zmax/ Zmax(actual)) at Cua Ong, Hon Dau, and Hon Ngu with the change of storm center pressure compared to reality. The results show that the decreasing trend of storm surge is most significant when the pressure at the center of the storm increases, but the decrease is faster at Hon Ngu than at Hon Dau.

Effect of storm movement speed

To evaluate the influence of storm movement speed on storm surge, typhoon Kanaegy-14 was kept at the same trajectory and intensity. Still it changed its speed of movement slower and faster during the storm range from -15km/h to +15km/h compared to the actual travel speed. Figure 11a-c shows the process of storm surge at Cua Ong, Hon Dau, and Hon Ngu with actual storm velocity cases, faster than 15km/h (W+15) and slower than 15km/h (W-15), faster than 10km/h (W+10) and slower than 10km/h (W-10), faster than 5km/h (W+5) and slower than 5km/h (W-5) than the actual speed of the storm. The results show that, at Cua Ong and Hon Dau, the storm surge is higher in case the speed of the storm is slower than 5km/h, while at Hon Ngu, the storm surge is higher in the case of the storm moving faster compared to the actual 5km/h. The results of the calculation of the largest storm surge at Cua Ong, Hon Dau, and Hon Ngu with the change of the storm's movement speed in Figure 11d show that the slower the storm's moving speed, the larger the storm surge at Cua Ong and vice versa for Hon Ngu station. Meanwhile, with Hon Dau station, storm surge increases when the speed is slow and reaches the maximum value at 5km/h slower than the actual speed of the storm, and then the maximum water rises decrease.

Effect of wind speed on storm surge

The relationship between the maximum height of the storm surge and the maximum wind speed that occurred (storm level) is considered on the basis of the data on the maximum storm surge with the maximum wind speed in the storm at each location corresponding mind. In fact, it is only when blowing from the sea that it can cause water to rise. Therefore, the maximum wind speed point will be counted as the maximum velocity value only for the times when the wind blows from the sea and during the operation period.

To analyze the effect of wind speed on storm surge, the article made a case that the trajectory and other storm parameters such as speed of movement and barometric pressure at the center of the storm are kept the same but the velocity changes. The wind in the storm in the direction of increasing storm intensity is weaker and decreased (stronger storm intensity) than when the actual pressure of the Kalmaegy-14 storm is in the range of -6m/s to +6m/s. The largest variation of water surge according to the change of wind speed in the storm compared to reality at Cua Ong, Hon Dau, and Hon Ngu in Figure 12a shows that the magnitude of the surge at three stations increases as the wind speed in the storm increases. Figure 12b is the ratio of the largest storm surge (Zmax/Zmax(actual)) at Cua Ong, Hon Dau and Hon Ngu with the change of wind speed in the storm compared to reality. The results showed that storm surge at 3 stations increased when wind speed increased, but the increase rate at Hon Ngu was smaller than that of Cua Ong and Hon Dau.

CONCLUSIONS

Storm surge due to common landfall storms (such as Typhoons Franki-96, Washi-05, Xangxane-06) shows that storm surge due to wind stress, followed by barometric pressure and waves. The storm surge due to wind and wave stress mainly reached large values in the coastal area to the storm's right. Meanwhile, storm surge due to barometric pressure is larger in the area near the storm's path, and the magnitude of storm surge decreases as the storm approaches the shore. The model takes into account the influence of waves has increased the accuracy of the storm surge calculation results (total rising water).

In the case of storm surge after the typhoon Kalmeagy-14 landed on the shore, when the speed of the storm increased compared to reality, the magnitude of the surge decreased at Cua Ong station (the station located to the right of the storm). At Hon Ngu station (the station located on the left side of the storm), the magnitude of the water surge increased. The storm surge at Hon Dau reached the highest value in case the storm's speed was 5 hours slower than the actual one. The storm surge at Cua Ong, Hon Dau, and Hon Ngu stations all increased when wind speed in the storm increased; however, Hon Ngu station had a higher increase rate. The magnitude of the water surge decreases when the pressure in the storm increases, but the increase at Cua Ong, Hon Dau, and Hon Ngu stations is entirely different. Cua Ong station increases slower than the other two stations.

CONFLICT OF INTEREST

The author declares that this manuscript is original and has not been published before, and there is no conflict of interest in publishing the paper.

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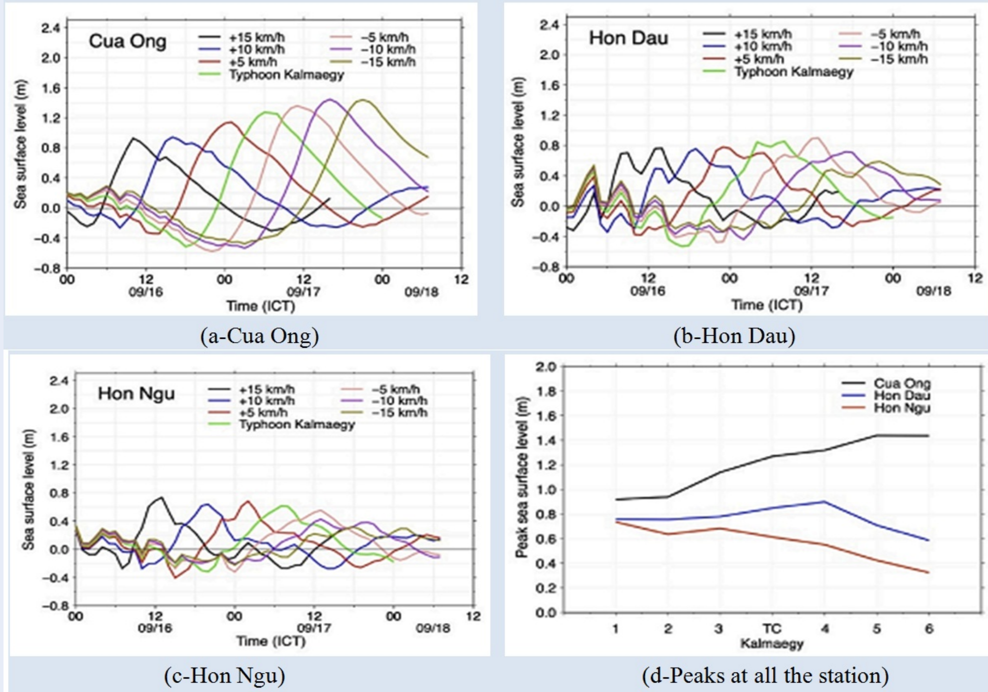

Figure 11: Time series of storm surges against the forward motion of the typhoon at Cua Ong (a), Hon Dau (b), Hon Ngu (c), and the peak (d).

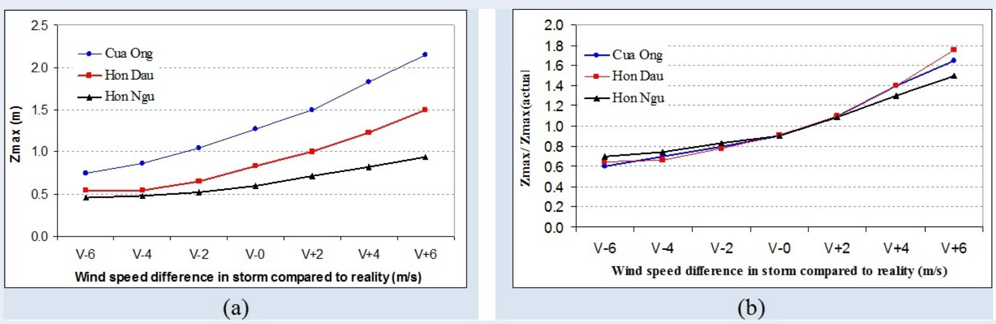

Figure 12: The largest storm surge change (a) and the highest rate of surge compared to reality (b) at Cua Ong, Hon Dau and Hon Ngu in the case of wind speed change during storm Kalmaegy-14.

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