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STORM-SURGE SIMULATION IN THE SOUTH CHINA SEA REGION: A NUMERICAL STUDY

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Abstract: Storm-surge flooding is a serious concern along the coastal regions of many countries in the South China Sea region which is often threatened by typhoons and super typhoons. The destruction of life and property can be minimised if the surges could be predicted in advance, thus allowing effective warnings in the threatened areas. In view of this, we have developed a vertically-integrated numerical storm-surge prediction model for the South China Sea region. The model has been applied for the simulation of storm surges associated with four typhoons/super typhoons which have struck the coasts of southern China, Thailand, Philippines and Vietnam. The model-computed surges are found to be in broad agreement with the available observations/estimates.

KEYWORDS: Numerical model, storm surges, typhoons/super typhoons, South China Sea.

Introduction

The destruction caused by storm surges associated with tropical typhoons is of serious concern along the coasts of several countries surrounding the South China Sea. In particular, the poor coastal communities in China, Philippines, Vietnam, and Thailand are most vulnerable to typhoon-generated storm surges. Storm surge problems and their mitigation in this region are described by several workers (Pham Van Ninh, 1992; McGregor, 1995; Wang and Fujiang, 1995; Wang et al., 1997; Greg Bankoff, 2002).

Despite all the best efforts of governments to protect their citizens, the region's endemic poverty and high population density coupled with the chaotic state of the atmosphere is a recipe for continued disasters which even the best-laid plans will be unable to prevent. Also, the changing marine environment may result in natural hazards, such as storm surges, affecting areas hitherto unknown to such disasters.

However, damages can be minimised if the extreme sea levels are forecasted well in advance. Development of a numerical storm-surge prediction system is one of the necessary tools to minimise the damage to life and property. In view of this, a numerical storm-surge model is developed for the South China Sea region.

Using this model, several numerical experiments are carried out to simulate the surges generated by 1996 typhoon Sally (Southern China), 1997 typhoon Linda (Thailand), 2006 typhoon Xangsane (Philippines) and 2007 typhoon Lekima (Vietnam) which struck the coasts along the South China Sea. The model-computed surges are in broad agreement with the available observational estimates.

Methodology

Domain and Grid Selection

As there are a large number of islands in the region, particularly in the Philippines, there is a need to develop a high-resolution model to represent the coastline accurately. To achieve this objective, a uniform grid resolution of 3.7 km is adopted along the latitudinal and longitudinal directions. Using stair-step boundaries and this grid resolution we are able to represent most of the islands and irregular coastal terrain. The bathymetry for the model is derived from the Earth-Topography-Two-Minute module (ETOPO2) from the National Geophysical Data Centre. The model covers an analysis area lying between 5ºS to 30ºN and 90ºE to 135ºE, and is shown in Figure 1.

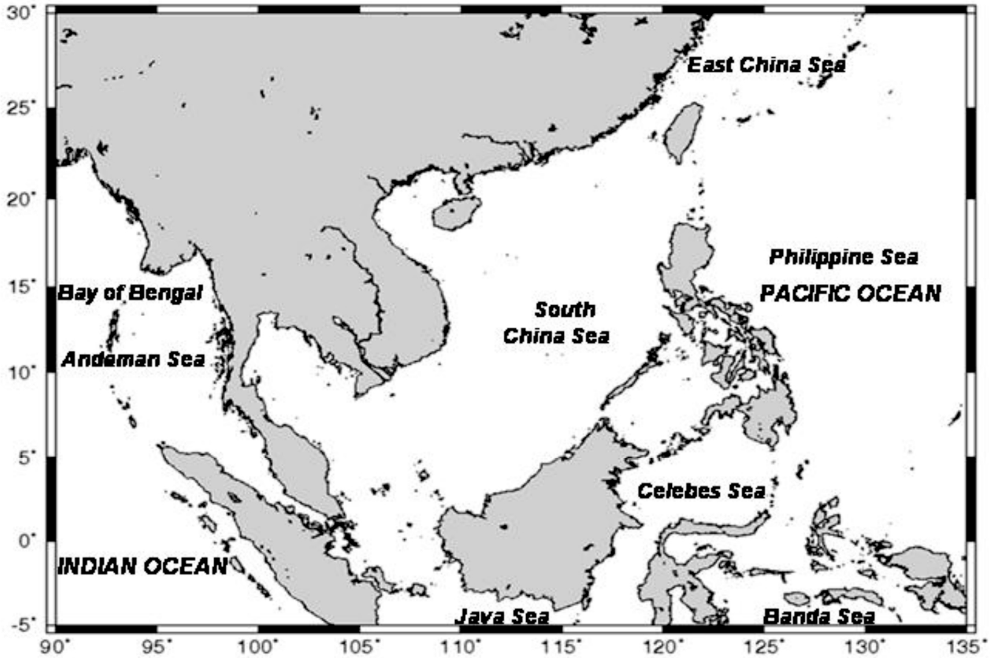

Figure 1: Analysis Area

Basic Equations

In the formulation of the model, a system of rectangular Cartesian co-ordinates are used. The origin, O, is within the equilibrium level of the free surface, Ox points towards the east, Oy towards the north and Oz is directed vertically upwards. The displaced position of the free surface is given by $z = \zeta(x, y, t)$ and the position of the sea floor by $z = -h(x,y)$.

The depth-averaged equations of continuity and momentum for the dynamical processes in the sea are given in the flux form by Dube et al. (1985)

$$\frac{\partial \zeta}{\partial t} + \frac{\partial \tilde{u}}{\partial x} + \frac{\partial \tilde{v}}{\partial y} = 0 \qquad (1)$$

$$\frac{\partial \tilde{u}}{\partial t} + \frac{\partial}{\partial x}(u\tilde{u}) + \frac{\partial}{\partial y}(v\tilde{u}) - f\tilde{v} = -g(\zeta + h)\frac{\partial \zeta}{\partial x} + \frac{F_s}{\rho} - \frac{c_f \tilde{u}}{(\zeta + h)}(u^2 + v^2)^{\frac{1}{2}} \qquad (2)$$

$$\frac{\partial\tilde{v}}{\partial t}+\frac{\partial}{\partial x}(u\tilde{v})+\frac{\partial}{\partial y}(v\tilde{v})+f\tilde{u}=-g(\zeta+h)\frac{\partial\zeta}{\partial y}+\frac{G_s}{\rho}-\frac{c_f\tilde{v}}{(\zeta+h)}(u^2+v^2)^{\frac{1}{2}} \qquad (3)$$

where

$(\tilde{u},\tilde{v}) = (\zeta+h)(u,v)$

u, v : averaged component of velocity (ms^{-1}) in the direction of x, y respectively,

ζ : sea surface elevation (m) above the mean water level,

h : water depth (m),

t : time (sec),

ρ : density of the sea water,

f : Coriolis parameter ($= 2\omega\sin\phi$),

g : acceleration due to gravity,

F_S, G_S : x and y components of the surface wind stress,

c_f: : Bottom friction coefficient ($=2.6\text{x}10^{-3}$)

The surface stresses are parameterised using a conventional quadratic law (Johns and Ali, 1980)

$$(F_s,G_s) = c_d\rho_a(u_a^2+v_a^2)^{\frac{1}{2}}(u_a,v_a)$$

where $c_d = 2.8\text{x}10^{-3}$ is the surface-drag coefficient, ρ_a is the density of the air and u_a, v_a are the x and y components of the surface wind.

Boundary Conditions

The boundary and initial conditions take the form

$$\begin{aligned}&\tilde{u}=0 \quad \text{along meridional boundaries}\\&\tilde{v}=0 \quad \text{along latitudinal boundaries}\end{aligned} \qquad (4)$$

and

$$\zeta = u = v = 0 \text{ everywhere for } t \le 0$$

At the open-sea boundaries, the radiation conditions (Heaps, 1973) are applied which lead to

$$v+\left(\frac{g}{h}\right)^{\frac{1}{2}}\zeta=0 \quad \text{along the southern open boundary} \qquad (5)$$

$$v-\left(\frac{g}{h}\right)^{\frac{1}{2}}\zeta=0 \quad \text{along the northern open boundary} \qquad (6)$$

$$u-\left(\frac{g}{h}\right)^{\frac{1}{2}}\zeta=0 \quad \text{along the eastern open boundary} \qquad (7)$$

$$u+\left(\frac{g}{h}\right)^{\frac{1}{2}}\zeta=0 \quad \text{along the western open boundary} \qquad (8)$$

Application of a radiation condition at the open-sea boundary of a model allows the propagation of energy (disturbances) only outwards from the interior in the form of a simple progressive wave. It also helps to eliminate the transient response more quickly, as a result of the frictional dissipation in the system (Flather, 1976).

The finite difference formulation and complete numerical treatment of the above equations (1-8) can be found in Dube et al. (1985).

Numerical Experimentation

The model has been used to compute the surge associated with the typhoons, which struck the coasts of different countries around the South China Sea during 1996, 1997, 2006 and 2007. The storm-surge model requires the wind-stress force as the basic input to the model. For this purpose, the wind stress is computed by using the dynamic storm model of Jelesnianski and Taylor (1973). To obtain a dynamic wind-profile in the storm model, initially a stationary, symmetric model wind-profile is taken, and then correction is applied to approximate the asymmetry due to the storm motion. The storm model represents a balance between pressure gradient, centrifugal, Coriolis and surface frictional forces for a stationary storm.

A conditionally-stable semi-explicit finite difference scheme with a staggered grid is used to solve the governing equations. With a fine-resolution grid specification of 3.7 km x 3.7 km, it is found that computational stability is achieved with a time step of 80 s. The input parameters for the above-mentioned storms are given in the Table 1

Name of the cyclone	**DP (hPa)**	**R_{max} (km)**
1996 typhoon Sally	32	25
1997 typhoon Linda	22	20
2006 typhoon Xangsane	70	40
2007 typhoon Lekima	22	25

DP - Pressure Drop R_{max} – Radius of maximum wind

Table 1: Input parameters of the storms

Results and Discussion

1996 typhoon Sally

A well-marked low-pressure area formed over the east of the Philippine Sea on the morning of September 2, 1996. It developed into a depression and lay near 10.5ºN and 141.6ºE on the morning of 3rd September at 0600 UTC. The system intensified into a deep depression on the 5th morning and it became a cyclonic storm on the afternoon of the same day, with its centre near 15.0ºN, 133.0ºE. The system moved west northwestward and further intensified into a severe cyclonic storm on the early morning of 6th, and lay centred near 16.0ºN, 131.6ºE. The system gained further strength to become a very severe cyclonic storm on the same day at 0600 UTC. It continued to gain strength and, while passing just north of the Philippines, attained maximum wind speed of 72 ms^{-1} on 7th September at 1800 UTC near 19.1ºN, 121.5ºE. Thereafter, the wind speed weakened to about 55 ms^{-1} and the system moved steadily over the South China Sea. It crossed the Luichow Peninsula of China at about 0300 UTC on 9th September, and dissipated the next day over mainland China.

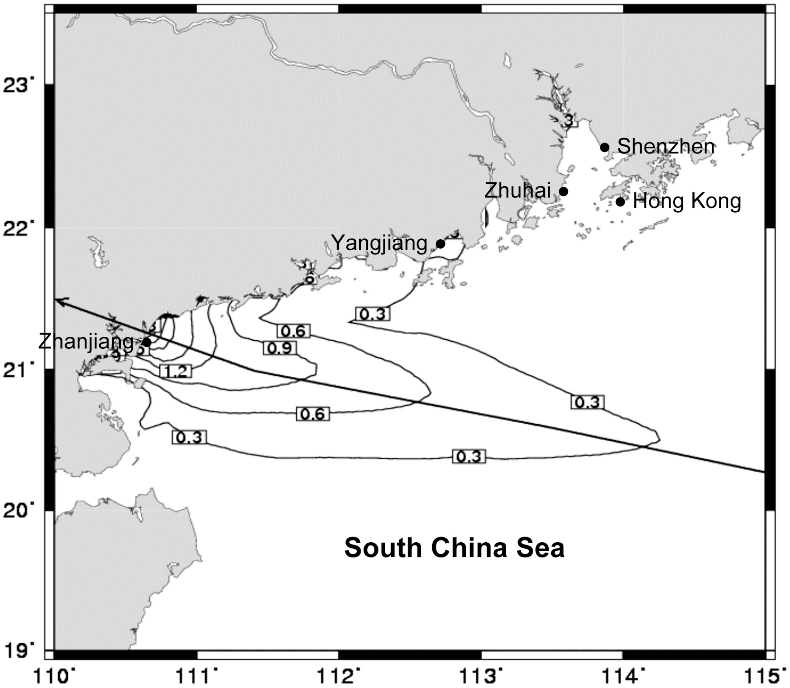

Figure 2: Surge contours (m) associated with 1996 typhoon Sally

The track of the typhoon (Fig. 2) and the relevant data are taken from the Unisys (1996). Numerical experiment is carried out with a pressure drop of 32 hPa and a radius of maximum wind of 25 km. The surge contours computed by the model are shown in Fig. 2. It may be seen that the maximum surge of 2.5 m occurred to the right of the landfall point. The computed surge value at Zhanjiang is about 2.1 m. Also, the coastal stretch near Yangjiang is found to be affected by a surge of 0.3-0.6 m. Unisys Corporation estimates the intensity of tropical cyclones and the associated range of surge heights based on the post-analysis of all available satellite images, surface data, upper-air data and radar data. It is found that the maximum computed surge height of 2.5 m is comparable with the highest value in the range of surge estimates provided by Unisys (1996).

1997 typhoon Linda

A low-pressure area formed over the eastern part of the Philippine Sea on 25th October 1997. It moved north-westwards and intensified into a depression over South China Sea on the early morning of 31st October and centred near 8.4° N, 118.4°E. Moving westwards, it intensified into a cyclonic storm by the evening of 31st. It further intensified into a severe cyclonic storm on 1st November and lay centred near 8.2°N, 110.5°E at 1200 UTC. Moving northwestwards, it continued to gain strength, entered into the Gulf of Thailand, and crossed land near Bangspan between 1100 and 1200 UTC of 3rd November. It weakened into a cyclonic storm by 4th morning and lay centred near 12.7°N, 96.8°E. The track of the typhoon is shown in Fig. 3. The relevant data for this typhoon is taken from the Unisys (1997).

The Pressure drop associated with the typhoon is taken as 22 hPa and a radius of maximum wind as 20 km. Fig. 3 depicts the surge contours at the time of landfall. It may be seen that the computed maximum surge of 1.6 m occurred to the right of the landfall point near Khow Luang. The surge values at Bangspan and M.Prachuab-khirikun are 1.2 m and 0.6 m, respectively. The maximum-computed surge height of 1.6 m is comparable to the estimated surge value provided by Unisys (1997).

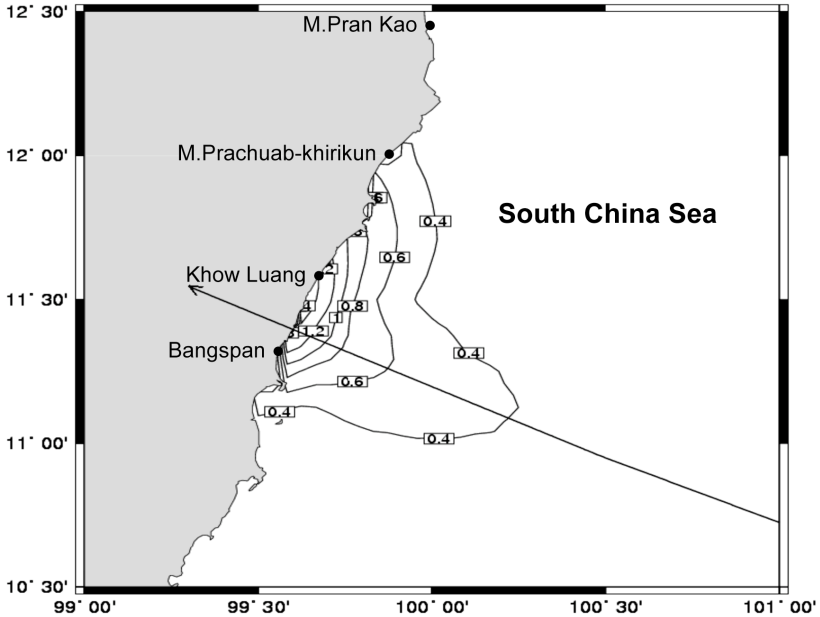

Figure 3: Surge contours (m) associated with 1997 typhoon Linda

2006 typhoon Xangsane

A cyclonic storm formed over the eastern Philippine Sea on the evening of 25th September 2006 with its centre near 11.6ºN and 128.2ºE. Moving west north-westwards, it intensified into a severe cyclonic storm on the afternoon of the 26th and into a very severe cyclonic storm by the evening of the same day, when it was centred near 12.2ºN, 126.2ºE. It made first landfall on the central Philippines island of Samar, east of the province's capital of Catarman. It continued to move west north-westwards until 27th September and it lost some power as it crossed the islands, and rebuilt only slightly as it continued to move westwards till 28th to cross the South China Sea and lay centred at 15.6ºN, 119.1ºE. Thereafter, it continued to move westwards with the speed of a very severe cyclonic storm and made 2nd landfall in Vietnam on 30th September.

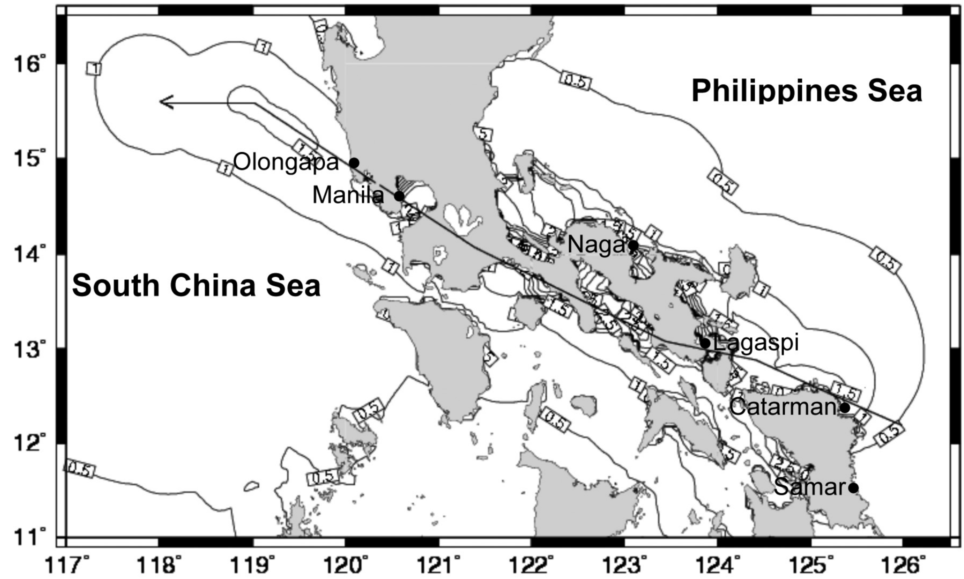

Figure 4: Surge contours (m) associated with 2006 typhoon Xangsane

The track of the cyclone (Fig. 4) and the relevant data are taken from the Unisys (2006). Numerical experiments are carried out with a pressure drop of 70 hPa and a radius of maximum wind of 40 km.

Fig. 4 shows the model-computed surge contours. It may be seen that a maximum surge of 5.2 m occurred close to the landfall point while the stations Manila, Naga, and Legaspi are affected by a surge of more than 4m. The maximum computed surge height of 5.2 m is comparable to the estimated surge value provided by Unisys (2006).

2007 typhoon Lekima

A tropical depression was formed over the South China Sea towards the west of the north Philippines island of Luzon on 30th Sept. 2007 centred at 15.5°N, 116.3°E. Moving south westwards it developed into a tropical storm at 0600 UTC and continued to gain wind speeds till 1800 UTC of 30th Sept. It moved westwards till 1800 UTC of 1st October. Afterwards, the system moved to the north-west and strengthened into a typhoon (category 1) at 1200 UTC of 2nd Oct. and lay centred at 17.8°N, 109.9°E. Subsequently, the system weakened into a tropical storm on 3rd October by 1800 UTC. Later it crossed the Vietnam coast north of Dong Hoi on 3rd near 17.8°N, 106.4°E. The typhoon track is shown in Fig. 5 and its relevant data is taken from Unisys (2007).

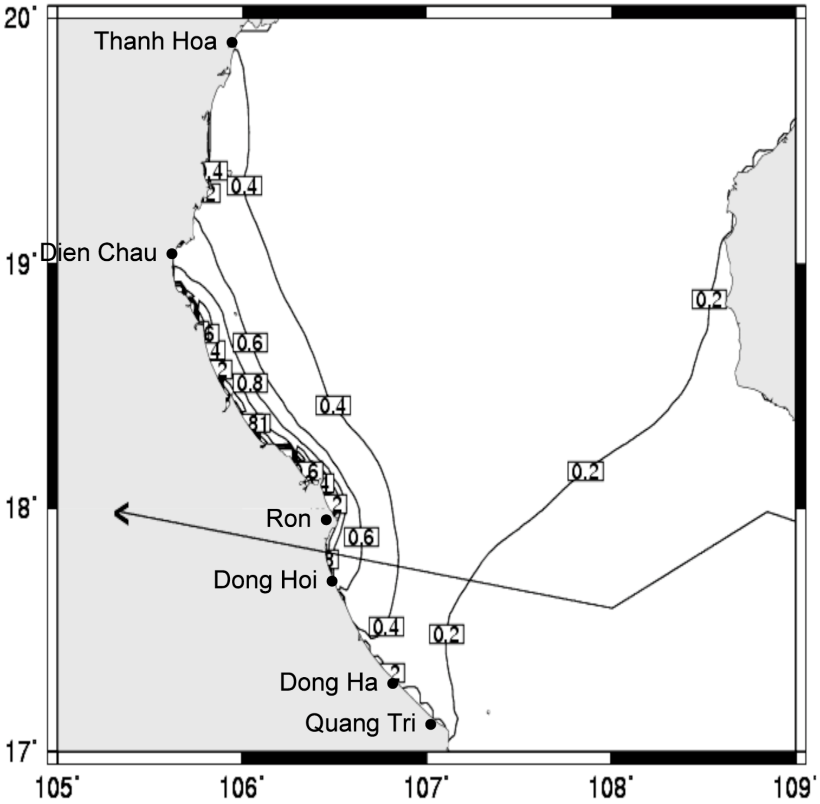

Figure 5: Surge contours (m) associated with 2007 typhoon Lekima

A pressure drop of 22 hPa together with the radius of maximum wind of 25 km is taken for the numerical computations. Fig. 5 depicts the computed surge contours. It is found that a maximum surge of 1.5 m occurred to the right of the landfall point. The coastal stretch from the north of Dong Ha to Thanh Hoa is affected by a surge of 0.4 m. The maximum computed surge height is comparable to the range of values provided by Unisys (2007). A comparison between the computed and estimated range of surge heights at the time of landfall for 1996 Sally, 1997 Linda, 2006 Xangsane and 2007 Lekima typhoons is given in Table 2.

Name of the cyclone	Computed peak surge height (m)	Estimated range of surge height (m) provided by Unisys
1996 Sally cyclone	2.5	1.8 - 2.4
1997 Linda cyclone	1.6	1.2-1.5
2006 Xangsane cyclone	5.2	3.9-5.5
2007 Lekima cyclone	1.5	1.2-1.5

Table 2: Computed and estimated range of surge heights (m)

Storm Surge as a Sustainable Science

Sustainable science is the science which can help create a more sustainable world-one where all people can have fulfilling lives. One of the scientific skills needed to create a sustainable world is to develop and use computer models to predict storm surges associated with tropical cyclones in many parts of the world in order to prevent the loss of lives and property.

An accurate prediction of storm surges is the key to sustainability which affects millions of people living in the coastal regions as it helps them to take precautionary measures in case of massive devastation due to storm surges. There can be little doubt that the number of casualties would have been considerably lower if the surges could have been predicted well in advance, allowing effective warnings in the threatened areas. The prediction must, of course, be accurate enough, as people cannot be evacuated for every approaching cyclonic storm. In view of this, we developed a location-specific fine-resolution storm-surge model for the South China Sea region.

Once a natural disaster such as the storm surge strikes a coastal strip, a massive management skill is needed to firstly move the population and other valuables to safer places and thus minimise the damage to lives and property. Using GIS and other computer-based information, the coastal zone managers could plan and manage environmentally-sensitive coastal areas, marshlands, bays and river mouths, so they can survive the onslaughts of tropical typhoons and associated surges.

Conclusion

Numerical experiments were carried out with a location-specific high-resolution model using the data of 1996, 1997, 2006 and 2007 typhoons hitting the coasts of different countries around the South China Sea. The model is able to simulate surge heights, which are in broad agreement with the estimated values provided by Unisys Hurricane Database, Unisys Corporation. The results emphasise the suitability of a fine-resolution location-specific model for a reasonable prediction of surges along some countries adjacent to South China Sea.

In the present study, the typhoon is the sole driving force for the dynamical processes in the sea. The tides have not been included in the present study, therefore, the non-linear interaction of surge and the tide has not been studied. Such an interaction may be significant if the occurrence of the surge coincides with that of the high tide. The model may be used on a real-time basis for predicting surges generated by a typhoon or a super typhoon, which may strike the coast.

In general, if there is a break in the coast, such as a river, it provides an additional path to the water to escape into the river, instead of getting piled up. The numerical model used in the present study does not take into account the effect of rivers that communicate with the South China Sea and the Philippine Sea. However, the discharge of the fresh water carried by the rivers may modify the surge height along the coasts.

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