Journal of Sustainability Science and Management 2009 Volume 4 (2): 9-17

STORM SURGE ESTIMATION ALONG THE COASTS OF PENINSULAR MALAYSIA USING IDEALISED TYPHOONS

P.C. SINHA[1], INDU JAIN*, MOHD LOKMAN HUSAIN, NOOR AZHAR MOHD SHAZILI AND LOY KAK CHOON

[1]*Institute of Oceanography, Universiti Malaysia Terengganu, 21030 Kuala Terengganu, Malaysia.*
**Centre for Atmospheric Sciences, Indian Institute of Technology, New Delhi-110 016.*

** Corresponding author e-mail address: p_c_sinha@yahoo.co.in*

Abstract: A vertically-integrated numerical storm surge prediction model has been developed for the South China Sea and the Strait of Malacca regions near the east and the west coast of Peninsular Malaysia. The model has been applied to estimate the surge heights along part of the east and the west coasts of Peninsular Malaysia. Numerical experiments have been carried out by considering four idealised storms of varying size and strength to give an idea of the likely surges that may affect the coastal region. The study may be useful for planning the development and other activities along the coasts of Peninsular Malaysia.

KEYWORDS: Numerical model, storm surges, South China Sea, Strait of Malacca, Peninsular Malaysia.

Introduction

In recent years, numerical methods have been used effectively to predict storm surges. Most of the initial work on the numerical modelling of storm surges associated with cyclonic storms has been done for the Atlantic and the Pacific regions. Operational numerical storm surge models have been developed and are used routinely for several regions of the world, such as the North Sea (Flather 1976; Flather and Proctor, 1983; Materbroek et al., 1993), the Gulf of Mexico and the Atlantic coast (Jelesnianski 1979, 1989, 1992), Japan (Minato, 1996) and Australia (Tang et al., 1997). The western part of the North Pacific Ocean, particularly the South China Sea (SCS) region is frequently affected by tropical typhoons. Storm surge problem and their mitigation in this region are described by many workers (Wang and Fujiang, 1995; Konish and Tsuji, 1995; Wang et al., 1997; Wang and Wang, 1997).

Recently, several studies have been undertaken in which the changes in tropical typhoons, duration and intensity have been directly attributed to global warming. Most studies have been confined to the hurricanes in the Atlantic and have confirmed that the rising sea surface temperatures have caused more intense hurricanes (Emanuel, 2005; Webster et al., 2005; Michaels et al., 2006; Klotzback, 2006).

Also, the changing marine environment may result in natural hazards, such as storm surges, affecting areas hitherto less known to such disasters. Tropical typhoons are rarely known to hit the coastal regions of Peninsular Malaysia. However, in December 2001, Singapore and the southern part of Peninsular Malaysia were affected by typhoon Vamei resulting in heavy rains and flash flooding, in which the highest surge was reported to be about 1m.

Keeping this in view, a numerical storm surge prediction model is developed for the South China Sea and the Strait of Malacca regions near the east and the west coast of Peninsular Malaysia.

The model has been applied to estimate the surge heights along part of the east and the west coasts of Peninsular Malaysia. Numerical experiments have been carried out by considering four idealised storms of varying size and strength to give an idea of the likely surges that may affect the coastal region. The study may be useful for planning the development and other activities along the coasts of Peninsular Malaysia.

Methodology

Domain and Grid Selection

A high-resolution model with a uniform grid of 1 km is taken to represent the coastline accurately. Using stair-step boundaries and this grid resolution, we are able to represent major islands in the region and irregular coastal terrain. The bathymetry for the model is derived from the Earth-Topography-Two-Minute module (ETOPO2) of the National Geophysical Data Centre. The model covers an analysis area lying between 2ºN to 6ºN and 100ºE to 106ºE, and is shown in Fig.1.

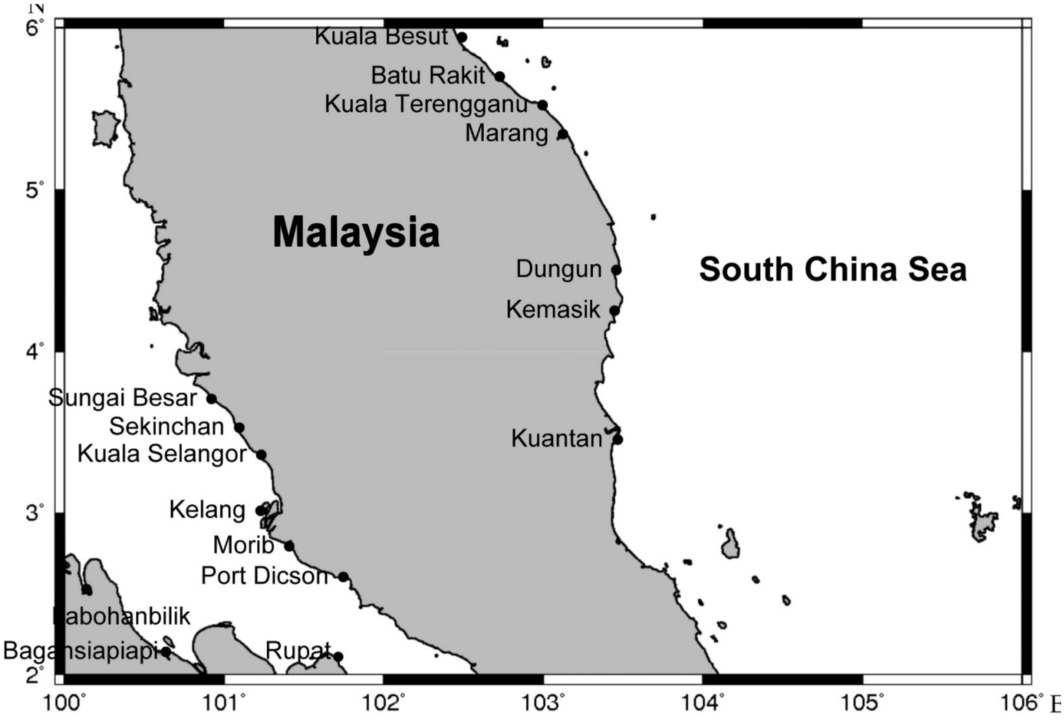

Fig 1: Analysis Area

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 west, Oy towards the south 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 ($= 2\omega\sin\varphi$),
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

$\tilde{u} = 0$ along meridional boundaries
$\tilde{v} = 0$ along latitudinal boundaries (4)

and

$\zeta = u = v = 0$ everywhere for $t \leq 0$

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

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

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

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

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

The finite difference formulation and complete numerical treatment of the above equations (1-8) can be found in Dube et al. (1985). Flather (1976) noted that the application of a radiation condition in the numerical model may remove the unrealistically large currents and grid-scale oscillations in the vicinity of the open boundary, which may possibly be produced by the application of conventional open-sea boundary conditions.

Numerical Experimentation

The model has been used to compute the surges associated with four idealised typhoons, two of which strike the east coast while the other two strike the west coast of Peninsular Malaysia. The storm surge model requires the wind stress forcing as the basic input to the model. For this purpose the wind stress is computed by using a dynamic storm model of Jelesnianski and Taylor (1973).

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 1 km x 1 km it is found that computational stability is achieved with a time step of 20s. The input parameters for the above mentioned storms are given in Table 1.

Name of the cyclone	**DP (hPa)**	**R_{max} (km)**
Typhoon I	60	30
Typhoon II	40	28
Typhoon III	40	25
Typhoon IV	30	25

DP – Pressure Drop, R_{max} – Radius of Maximum Wind

Table 1: Input parameters of the storms

Although the selection of DP and R_{max} is purely arbitrary, it is in the range of values found for many typhoons in the SCS region. The maximum pressure drop in case of typhoon Vamei was found to be 30 hPa (Juneng et al., 2007). The present paper is basically a simulation study and gives possible scenarios for storm surge estimates along a coast. Once the data for a real typhoon is made available, the model is capable of computing the likely surges in a few minutes time on a personal computer.

Results and Discussion

East Coast Model

In this section, the model has been applied to the east coast of Peninsular Malaysia. It is assumed that two idealised typhoons which formed in the South China Sea strike the east Malaysian coast. An estimate of the likely surges generated by these typhoons has been made all along the coastal region. The analysis area for the model study has been taken from 3°N to 6°N and 102°E to 106°E. The Earth-Topography-two minute (ETOPO2) data from the National Geographic Data Centre (NGDC) is used for the bathymetry of the region. Owing to the smaller size of the analysis area, a finer uniform grid resolution of 1 km has been adopted in both directions.

In the first experiment, an idealised Typhoon I, originating in the South China Sea, strikes the coast north of Dungun and generates a maximum surge of 3.0 m to the right of the point of landfall.

The surge contours computed by the model at the time of landfall are shown in Fig 2. In this case, the radius of maximum wind has been taken as 30 km and the pressure drop as 60 hPa. The model is integrated ahead in time up to 36 h. A surge of about 0.5 m has been found to affect the stations Kemasik and Kuala Besut (Fig 2). Also, the coastal stretch from Batu Rakit to Marang is affected by surges of 1- 1.5 m.

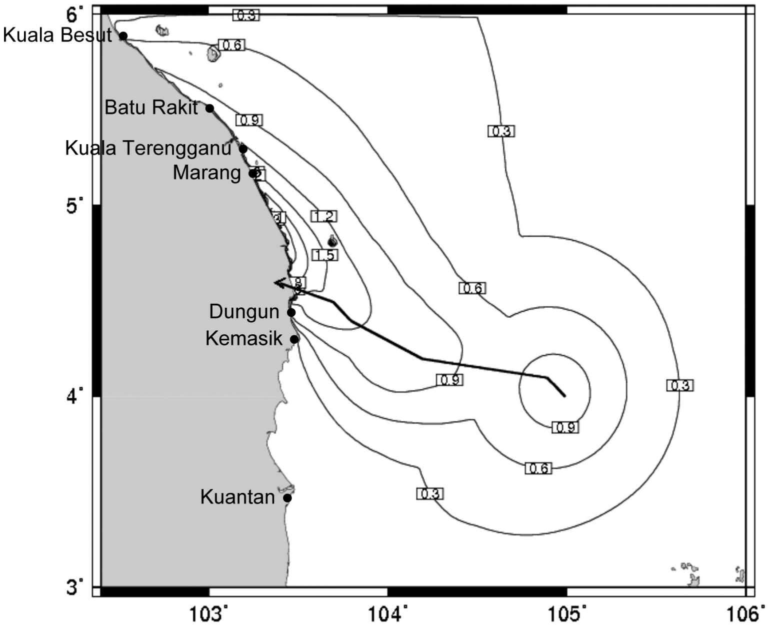

Fig 2: Peak surge contours (m) computed from Typhoon I

In the second experiment, the radius of the maximum wind of the idealised Typhoon II has been taken as 28 km while the pressure drop is 40 hPa. The model has been integrated ahead in time for 36 h and the model-computed surge contours along the east Malaysian coast are shown in Fig 3. The assumed idealised typhoon landfall is to the north of Kuala Terengganu and it is able to generate a maximum surge of 2.5 m at Batu Rakit. The coastal stretch from north of Marang to the south of Batu Rakit is affected by a surge of more than 1.5 m. It may also be seen that, at Dungun and Kuala Besut, the computed surges are about 0.2 m and 1 m, respectively.

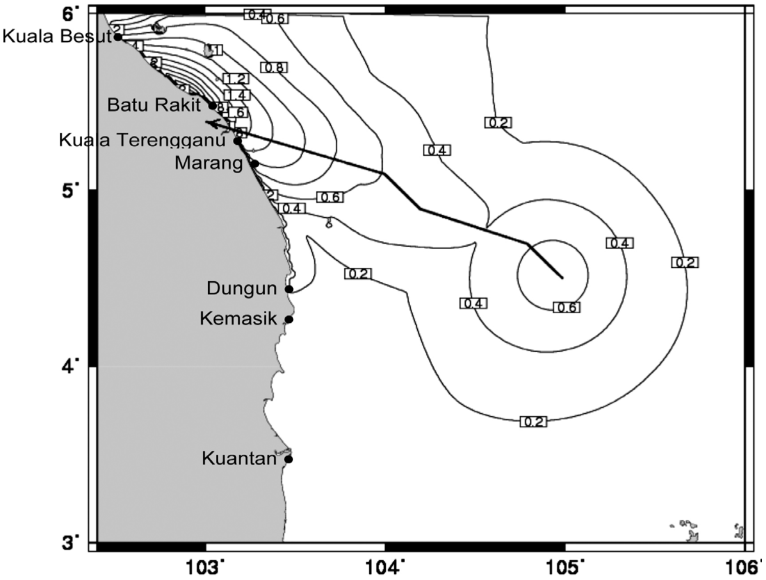

Fig 3: Peak surge contours (m) computed from Typhoon II

The assumed typhoons give an estimate of the likely surges along the east coast of Peninsular Malaysia. It may provide an idea of the extent of devastation that may take place when a typhoon strikes a Malaysian coastal region and could be used for planning purposes

West Coast Model

In this section, the model has been applied to the west coast of Peninsular Malaysia. It is assumed that the two idealised typhoons were formed in the Strait of Malacca and they strike the west coast of Peninsular Malaysia. An estimate has been made of the likely surges generated by these two typhoons all along the coastal region. The analysis area for the model study has been taken from 2°N to 4°N and 100°E to 102°E. The bathymetry of the region has been obtained using the Earth-Topography-two minute (ETOPO2) data of the National Geographic Data Centre (NGDC). A finer uniform grid resolution of 1 km has been adopted in both directions and a time step of 20 s was found to be consistent with the computational stability.

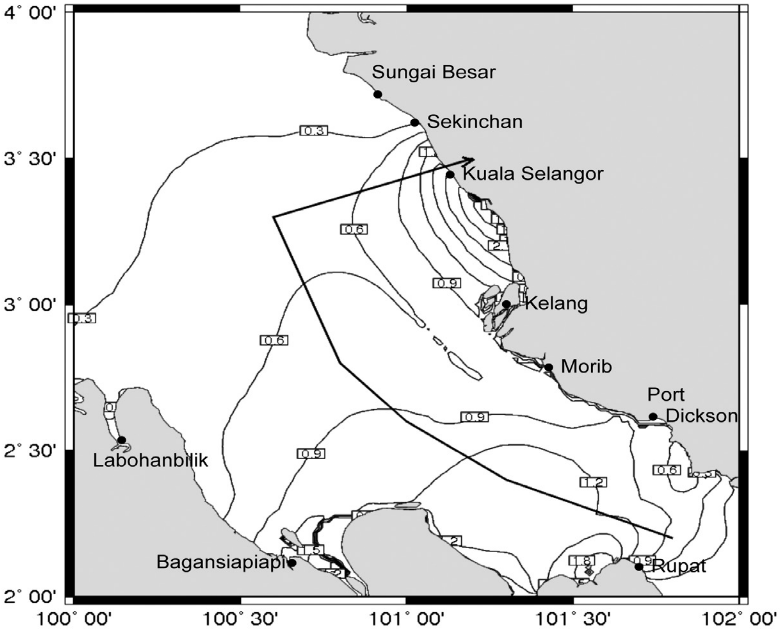

Fig 4: Peak surge contours (m) computed from Typhoon III

In the first experiment of the west coast model the Typhoon III, originating in the Strait of Malacca, strikes the coast north of Kuala Selangor and generates a maximum surge of 3.0 m to the right of the point of landfall.

The surge contours computed by the model at the time of landfall are shown in Fig 4. In this case, the radius of maximum wind of the typhoon has been taken as 25 km and the pressure drop as 40 hPa. The model is integrated ahead in time for 36 h. A surge of about 0.5 m has been found to affect the stations Sekinchan, Morib and Port Dickson (Fig 4). Also, the coastal stretch from Kuala Selangor and Kelang is affected by surges of 1.2-1.6 m.

In the second experiment for the west coast model, the radius of the maximum wind of the idealised Typhoon IV has been taken as 25 km while the pressure drop is 30 hPa. The model has been integrated ahead in time for 36 h and the model-computed surge contours along the west coast of Peninsular Malaysia are shown in Fig 5. The assumed idealized typhoon landfall is to the north of Sekinchan and it is able to generate a maximum surge of 2.2 m at Kuala Selangor. The coastal stretch from Sungai Besar to the north of Kelang is affected by a surge of more than 1.0 m. It may also be seen that, at Morib and Port Dickson, the computed surges are about 1.0 m and 0.5 m, respectively.

The two idealised typhoons give an estimate of the likely surges along the west coast of Peninsular Malaysia. They may provide an idea of the extent of devastation which may take place when a typhoon strikes the west Malaysian coast. It could be used for planning of development in the region.

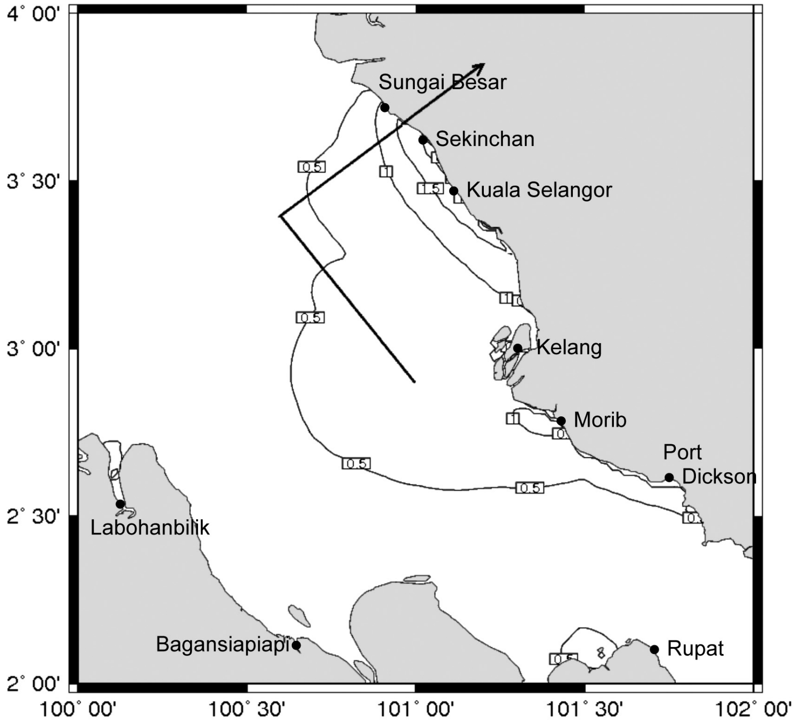

Fig 5: Peak surge contours (m) computed from Typhoon IV

Conclusion

Numerical experiments were carried out with a location-specific high-resolution model, using four idealised typhoons which hit the east and the west coast of Peninsular Malaysia. The model is able to provide an idea of the extent of devastation that may be witnessed when a typhoon strikes a Malaysian coast. The results emphasise the suitability of a fine-resolution location-specific model for a reasonable estimation of surges along the Malaysian coasts. However, an estimate of the likely surges generated by these four idealised typhoons may be useful for planning of development and other activities in the coastal regions of Peninsular Malaysia. 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 the present study, the typhoon is the sole driving force for the dynamical processes in the sea. However, 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.

In general, if there is a break in the coast, such as a river, it provides an additional path for 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 Strait of Malacca. However, the discharge of the fresh-water carried by the rivers may modify the surge height along the coasts.

References

Dube, S.K., Sinha, P.C., Rao, A.D. and Rao, G.S. (1985). Numerical modelling of storm surges in the Arabian Sea, Appl. *Math. Modelling* 9: 289 294.

Emanuel, K. (2005). Increasing destructiveness of tropical cyclones over the past 30 years, *Nature* 436:686-688.

Flather. R. A. (1976). Results from a storm surge prediction model of the northwest European continental shelf for April, Nov, Dec. 1973, IOS Rep. No.24, Institute of Oceanographic Sciences, Bidston Observatory, England, 33pp.

Heaps, N. S. (1973). Three- dimensional numerical model for the Irish Sea, *Geophys. J. R. Astron. Soc.* 35: 99-120.

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

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

Juneng, L., Tangang, F.T., Reason, C.J.C., Moten, S., Hassan, W.A.W.(2007). Simulation of tropical cyclone Vamei (2001) using the PSU/NCAR MM5 model, *Meteorol. Atmos. Phys.* 97: 273-290.

Klotzbach, P.J. (2006). Trends in global tropical cyclone activity over the past twenty years (1986-2005), *Geophysical Research Letters* 33: L10805.

Konishi, T. and Tsuji, Y. (1995). Analyses of storm surges in the western part of the Seto Inland Sea of Japan caused by Typhoon 9119, *Continental Shelf Research* 15: 1795-1823.

Michaels, P.J., Knappenberger, P.C. and Davis, R.E. (2006). Sea-surface temperatures and tropical cyclones in the Atlantic basin. *Geophysical Research Letters* 33: L09708.

Unisys Hurricane Database, Unisys Corporation.
http://weather.unisys.com/hurricane/n_indian/index.html.

Wang, Xinian and Fujiang Y. (1995). Storm surge, China National report on Physical Sceinces of the Ocean. XXIth general assembly of IUGG, Boulder, Colorado, 76-79.

Wang, Xinian, Fujiang Y. and Qinjiang Y. (1997). Research and application of numerical models of typhoon surges in China seas, *Mausam* 48: 595-608.

Wang, Xiuqin and Wang J. (1997). The calculation of maximum elevation due to storm surge by using joint probability method, *Mausam* 48: 587-594.

Webster, P.J., Holland, G.J. Curry,J.A. and Chang, H.R. (2005). Changes in tropical cyclone number, duration, and intensity in a warming environment, *Science* 309: 1844-1846.