Simulating Storm Surge & Inundation in Kaohsiung Area during Typhoon Fanapi in 2010

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ABSTRACT

More than 75% of the world's population lives within 100 miles from the coastline. Coastal communities and ecosystems around the world are subjected to increasing hazard of storm surge and coastal inundation due to tropical cyclones as well as climate change and sea level rise, compounded by growing coastal population and development. Coastal inundation has caused major flooding and loss of valuable lives and properties along the west coast of Taiwan. For example, major flooding occurred in the City of Kaohsiung during Typhoon Fanapi in September 2010. To mitigate the damage caused by tropical cyclone and coastal inundation, it is essential to develop an integrated modeling system for forecasting the storm surge and coastal inundation during tropical cyclones in Taiwan. This paper presents a preliminary simulation of the storm surge and coastal inundation in Kaohsiung area during Typhoon Fanapi. The modeling system is based on the 3-D curvilinear-grid hydrodynamic model CH3D, which has been used to simulate the storm surge and coastal inundation during numerous tropical cyclones in the U.S. The modeling system includes a large-scale model domain which includes the Taiwan Strait, the East China Sea and the Pacific Ocean on the east and south coasts of Taiwan, using a 500 m grid resolution. A coastal domain with 40 m resolution is used near the coastal region of Kaohsiung. Model simulation Fanapi showed excellent agreement with predicted tides in the region. A 1 m surge was simulated near Kaohsiung, which was found to agree well with data. Simulated coastal inundation show good qualitative agreement with land measured inundation, which was influenced by both coastal and inland flooding. It is feasible to use CH3D to forecast the storm surge and coastal inundation throughout Taiwan.

Keywords: Storm Surge, Coastal Inundation, Numerical Simulation, Forecasting, Fanapi, Taiwan

I.Typhoon Fanapi: Meteorological history

The tropical depression that struck parts of Taiwan and the mainland China formed on early September 14, 2010. The JTWC, the PAGASA and the JMA together monitored this depression. On the same day, this depression was upgraded into a Tropical storm, receiving the name Fanapi (Figure 1). The system then developed into a severe tropical storm, and then into a typhoon. By September 18, it reached its peak intensity. It made its first landfall, on Hualien County Taiwan at 8:40 a.m. (10:40am AEST) on September 19. Upon reentering the ocean (Taiwan Strait), Fanapi weakened into a severe tropical storm. It continued to maintain its strength before making a second landfall on Zhangpu County, Zhangzhou in Fujian province, mainland China. It then lost strength again and dissipated on September 22 (Table 1 and Figure 2).

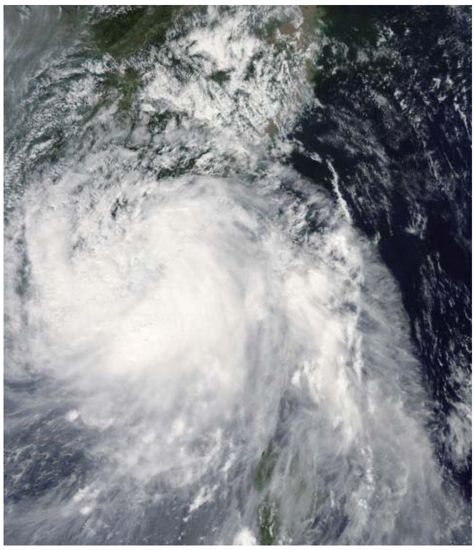


Figure 1. Fanapi leaving Taiwan for China in September, 2010.

In Taiwan the floods affected downtown Kaohsiung, including Sanmin, Nanzih, Zuoying and Gushan districts.

Total damage was estimated at $211 million USD with agricultural losses over $65 million USD while causing two direct and three indirect deaths.

Table 1. Typhoon Fanapi track and parameters

Year	Month	Day	Hour	Latitude	Longitude	Pressure	Vc	Vg	R7	R10
2010	09	14	18	19.00	129.50	1005	15	20	-	-
2010	09	15	0	19.70	128.70	1004	15	23	-	-
2010	09	15	6	20.40	128.00	1004	12	20	-	-
2010	09	15	12	20.70	127.60	998	18	25	100	-
2010	09	15	18	20.90	127.50	995	20	28	120	-
2010	09	16	0	21.40	127.70	985	25	33	120	-
2010	09	16	6	21.70	127.90	985	25	33	120	-
2010	09	16	12	21.80	128.30	970	33	43	150	50
2010	09	16	18	22.10	128.30	973	33	43	150	50
2010	09	17	0	22.30	128.30	965	35	45	180	80
2010	09	17	6	22.70	128.10	960	38	48	180	80
2010	09	17	12	23.10	127.80	960	38	48	180	80
2010	09	17	15	23.30	127.50	955	40	50	200	80
2010	09	17	18	23.20	126.90	950	43	53	200	80
2010	09	17	21	23.30	126.40	950	43	53	200	80
2010	09	18	0	23.30	126.10	950	43	53	200	80
2010	09	18	3	23.50	125.70	950	43	53	200	80
2010	09	18	6	23.70	125.30	950	43	53	200	80
2010	09	18	9	23.80	124.80	950	43	53	200	80
2010	09	18	12	23.80	124.30	950	43	53	200	80
2010	09	18	15	23.80	123.80	950	43	53	200	80
2010	09	18	18	24.00	123.10	950	43	53	200	80
2010	09	18	21	23.90	122.60	940	45	55	200	80
2010	09	19	0	23.60	121.70	940	45	55	200	80
2010	09	19	3	23.20	121.00	955	40	50	200	80
2010	09	19	6	23.20	120.50	965	35	45	200	80
2010	09	19	9	23.20	120.10	970	33	43	200	80
2010	09	19	12	23.40	119.70	970	33	43	200	50
2010	09	19	15	23.40	119.30	970	33	43	200	50
2010	09	19	18	23.50	119.00	970	33	43	200	50
2010	09	19	21	23.70	118.30	970	33	43	200	50
2010	09	20	0	24.00	117.60	970	33	43	200	50
2010	09	20	3	23.80	116.80	980	28	35	180	-
2010	09	20	6	23.60	116.00	985	25	33	150	-
2010	09	20	12	23.80	115.30	995	20	28	150	-
2010	09	20	18	24.00	113.50	1000	15	23	-	-

II.Numerical model setup

CH3D-SSMS (Figure 3) is an integrated storm surge modeling system [Sheng, et. al, 2006, 2008, 2010 a, b; Sheng and Liu 2011; Tutak and Sheng 2011] built upon the CH3D (Curvilinear-grid Hydrodynamics in 3D) circulation model [Sheng, 1987; Sheng, 1990]. The CH3D model solves the continuity equation and the horizontal momentum equations in non-orthogonal boundary-fitted horizontal coordinates and a sigma coordinate system in the vertical dimension, making it suitable for complex coastal zone applications. CH3D can be run in both 3D and 2D vertically integrated modes. A robust turbulence closure model [Sheng and Villaret, 1989] is used to represent vertical mixing, while horizontal mixing is represented with Smagorinsky type mixing coefficients. A flooding and drying algorithm based on an enhanced version of Davis and Sheng [2003] is included in the model to enable accurate simulation of storm surge and inundation. CH3D model grids and associated topography and bathymetry are developed with respect to the NAVD88 datum to enable inundation calculation.

Figure 2. Best track of Typhoon Fanapi (Taiwan).

CH3D-SSMS has the capability to use a variety of wind fields and related boundary conditions as forcing, including GFDL (Geophysical Fluid Dynamics Laboratory), NOAA/HRD H*, NAM (North Atlantic Meso-scale), NOGAPS (Navy Operational Global Atmospheric Prediction System), WRF (Weather Research and Forecast), etc. In addition, CH3D-SSMS includes a wind processing module that features two synthetic wind models – a symmetric analytical wind model, developed by Wilson [1960], Holland (1980), and an asymmetric wind model [Xie, et. al., 2006]. The wind processing module also has a capability to add dissipation of winds due to land roughness based on land cover data [IPET, 2008], and wind data assimilation.

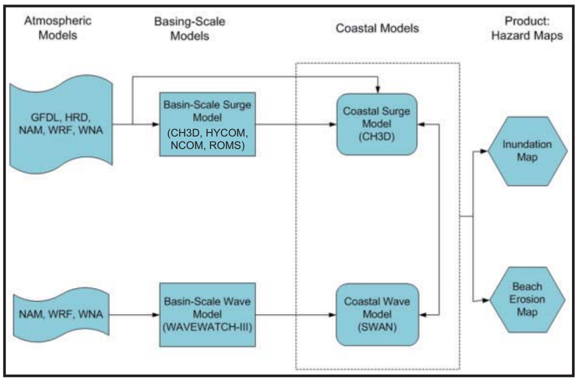


Figure 3. CH3D-SSMS modeling system diagram

Model domain

For CH3D-SSMS simulations of Typhoon Fanapi, a non-orthogonal curvilinear grid that allows for flooding and drying is setup for the Kaohsiung area in the south-western coastal zone of Taiwan as shown in Fig. 4. The non-orthogonal boundary-fitted grid contains over 240,000 grid cells with an average cell size of 100 meters near shore and cell size as fine as 40 meters in some inland areas.

Bathymetry and topography for the model domain were derived from a combination of two datasets: one data set having 500m resolution and providing elevations over sea and land and the second one having 40m resolution and providing land elevation over limited area near Kaohsiung.

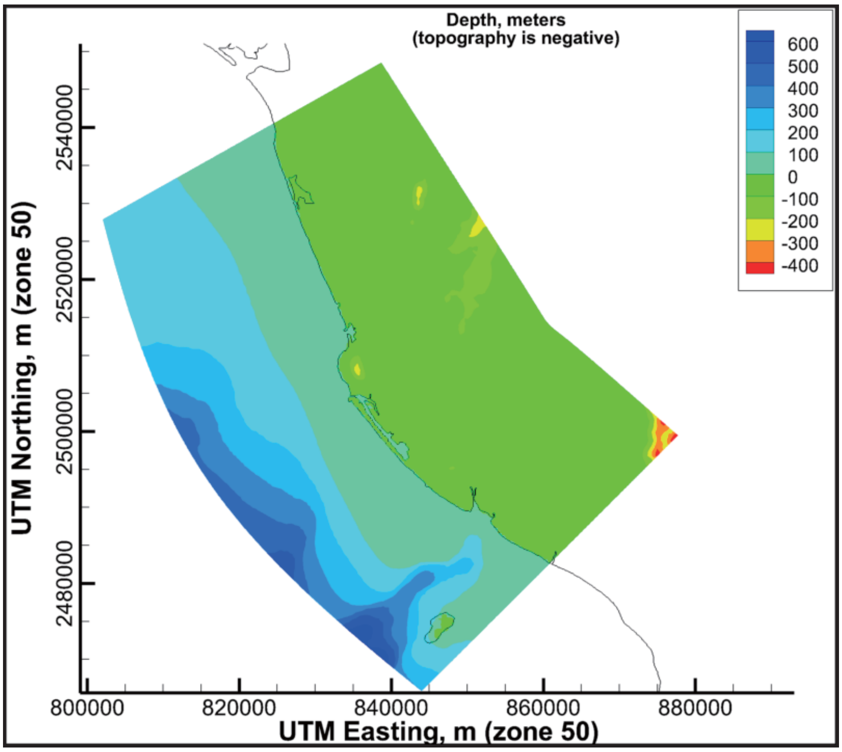


Figure 4. CH3D-SSMS TW-KS (Taiwan - Kaohsiung) computational domain

Initial condition

Numerical simulations are started with water level located at the mean sea level and a 3-day spin-up time allows tides to fully develop and properly initialize the water level before the storm reaches the model domain.

Boundary conditions

Open boundary of the model domain is defined as a combination of water level produced by the tidal constituents and water surface disturbance due to a storm central pressure deficit. The tidal constituents are extracted from the TPXO model and the following constituents are used:

- Primary: M2, S2, N2, K2, K1, O1, P1, Q1
- Long period: Mf, Mm
- Non-linear: M4, MS4, MN4

Tides were verified by running a no-wind scenario and comparing simulated tides against the prediction (only major constituents: K1, M2, N2, O1, S2 were verified) against data at three stations (Figure 5). Verification results are displayed on Figure 6.

Wind Forcing

An analytical wind model by Xie et al. [2006] was used to drive the CH3D as it allows using several wind radii (R7 and R10 in this case). Wind dissipation based on the land use classification was not used due to the lack of land use data; therefore a simplified handling of wind dissipation was used considering only two classes: sea and land.

Precipitation Data

Fanapi brought heavy rain to the area and therefore precipitation was a considerable source of flooding and needs to be included into the model. Figure 7 shows the rain fall dynamics during Fanapi as observed in the Kaohsiung area.

Model Parameters

CH3D model was run in a 2-D mode using Manning's n of 0.025 for bottom friction. The simulation duration was 5.5 days long (09/15 00:00 – 09/20 12:00), corresponding to approximately 2 hours CPU time, using a 60-second time step. Wind and pressure fields from the analytical wind model by Xie et al. [2006] are supplied at 10-minute intervals.

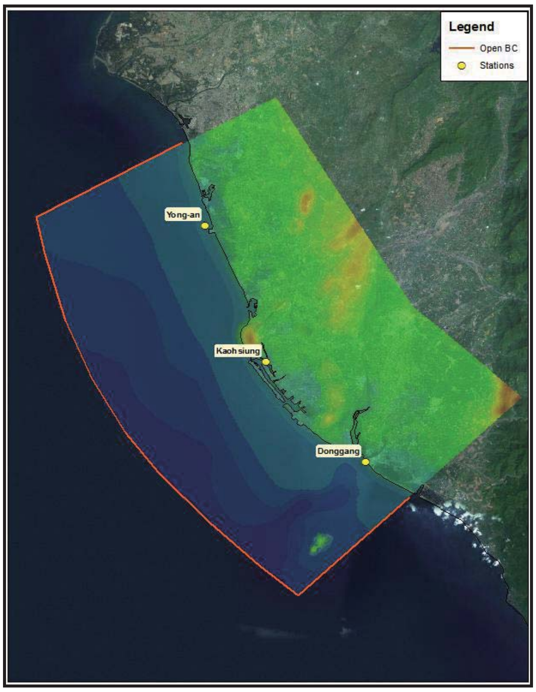
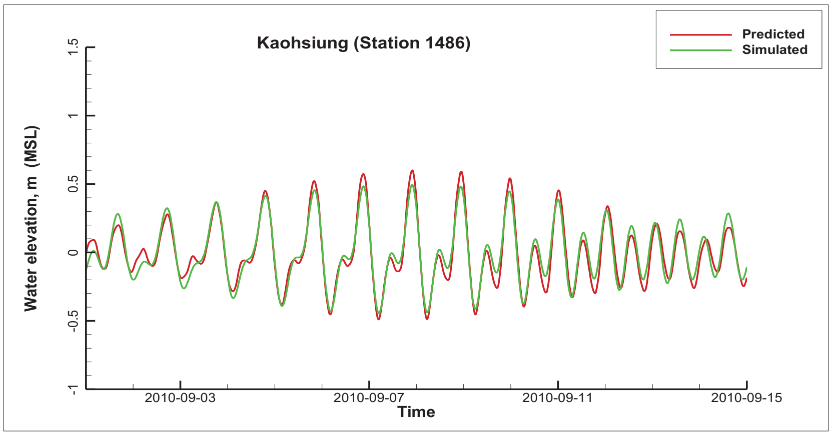
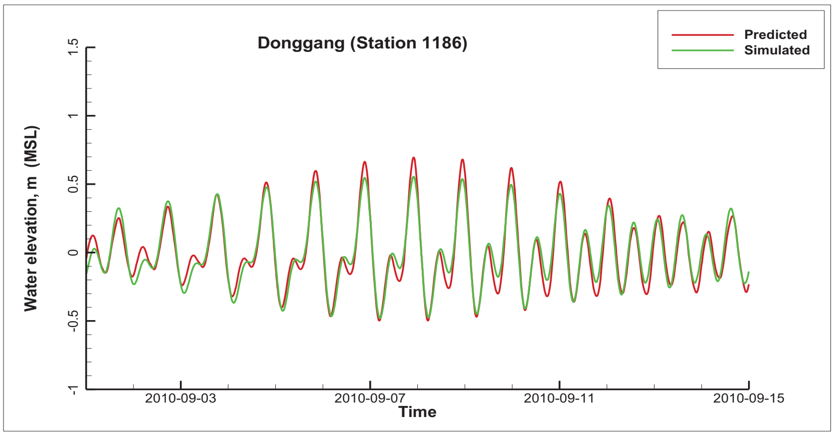


Figure 5. Open boundary of the model domain (red line) and validation stations



(a)



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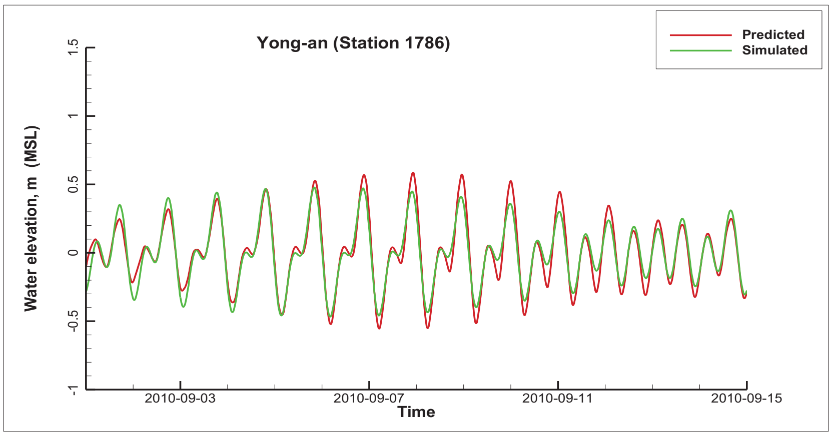

(c)

Figure 6. Simulated vs. measured tides at three stations.

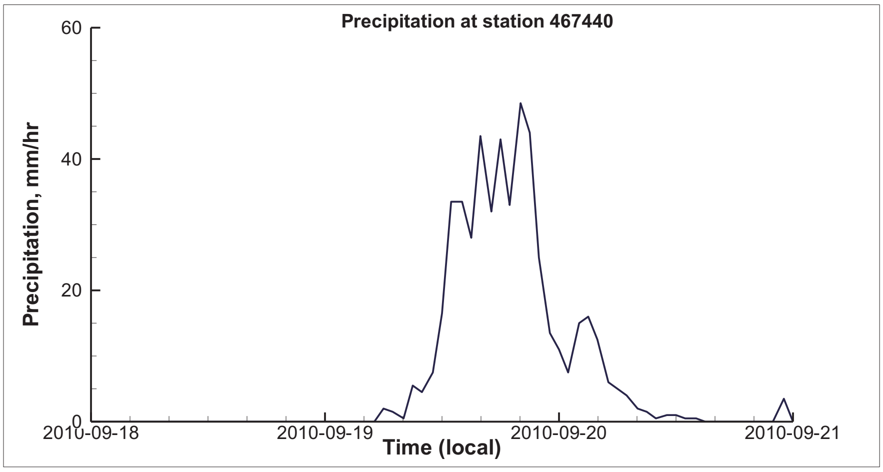

Figure 7. Precipitation data at station 467440 during Typhoon Fanapi

III.Model Results: Surge and Coastal Inundation

Simulated storm surge and inundation are shown on Figure 88 and Figure 99, respectively. The surge in the Kaohsiung Harbor is well simulated by the model. The inundation map of the Kaohsiung area agrees qualitatively with data but can be improved by gathering more and better precipitation data and inclusion of a watershed model to better represent the run-off due to precipitation.

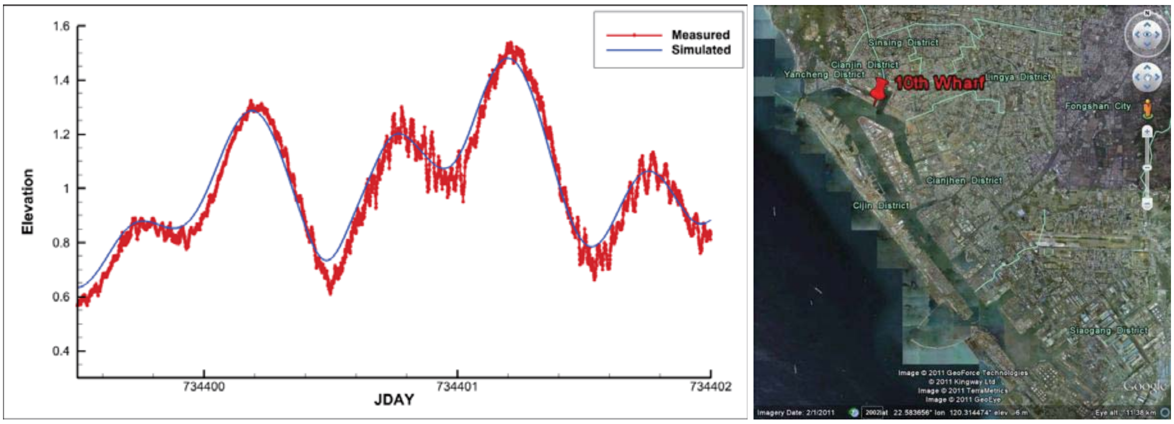

Figure 8. Storm surge at 10th wharf of Kaohsiung Harbor.

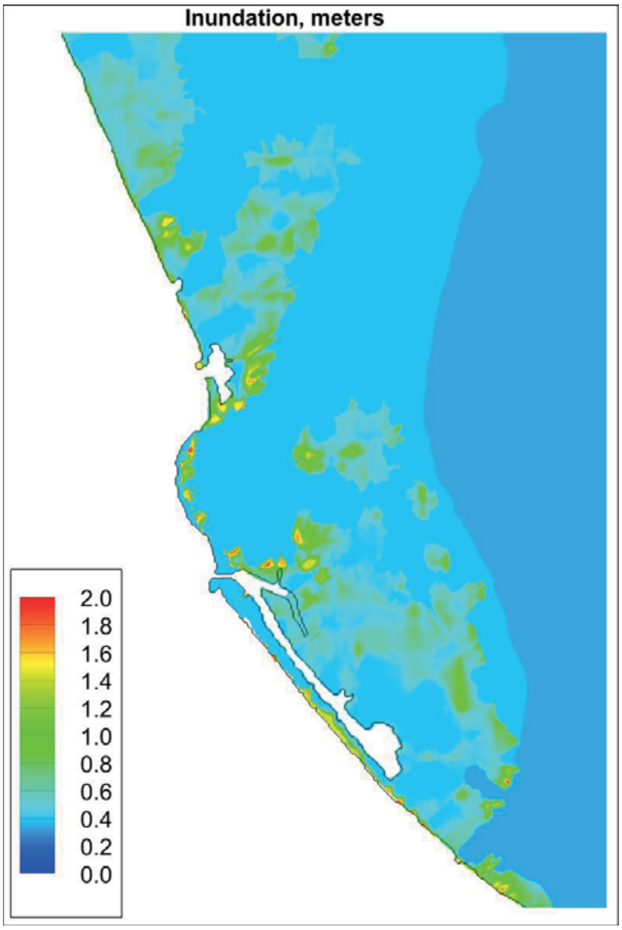

Figure 9. Inundation map for Typhoon Fanapi

IV.Summary

Storm surge and coastal inundation in Kaohsiung area has been successfully simulated using the CH3D curvilinear-grid hydrodynamics model with a high resolution (40-100m) coastal grid coupled to a coarser grid (500m). The simulated surge agrees very well with the measured surge in Kaohsiung Harbor. The simulated coastal inundation agrees qualitatively well with observed data which has considerable uncertainties. Nevertheless, it is clear that inundation in Kaohsiung was caused by both precipitation and coastal surge.

Model simulated storm coastal inundation can be improved by acquiring more and better precipitation data as well as river flow data. Due most likely to climate change impacts, precipitation in recent typhoons has increased dramatically. Climate change also affects the frequency of occurrence and intensity of typhoon, as well as sea level rise, and hence storm surge and coastal inundation. To better protect the coastal cities such as Kaohsiung and others along the West coast of Taiwan, it is important to produce risk-based coastal inundation maps which include the effects of storm surge and coastal inundation, inland flooding, precipitation, climate change, and sea level rise.

The CH3D model is highly efficient. It takes only 2 hours CPU time on a single CPU Dell to perform a 5.5 day Fanapi simulation. Therefore, it is feasible to use CH3D to develop a forecasting system for storm surge and coastal inundation in Taiwan. A data observing system is also needed to enable model verification and data assimilation.

References

IPET (2008), Performance evaluation of the New Orleans and Southeast Louisiana hurricane protection system, Draft Final Report of the Interagency Performance Evaluation Task Force, US Army Corps of Engineers, USA.

Sheng, Y.P. (1987), On modeling three-dimensional estuarine and marine hydrodynamics. Three-dimensional models of marine and estuarine dynamics, Elsevier Oceanography Series (Editor: J.C.J. Nihoul and B. Jamart), Elsevier, pp. 35-54

Sheng, Y.P. (1990), Evolution of a Three-Dimensional Curvilinear-Grid Hydrodynamic Model for Estuaries, Lakes and Coastal Waters: CH3D. Estuarine and Coastal Modeling I, ASCE, pp. 40-49.

Sheng, Y. P. and C. Villaret (1989), Modeling the effect of suspended sediment stratification on bottom exchange process. Journal of Geophysical Research, 94, pp. 14229-14444.

Sheng, Y. P., V. A. Paramygin, V. Alymov, J. R. Davis (2006), A Real-Time Forecasting System for Hurricane Induced Storm Surge and Coastal Flooding. Estuarine and Coastal Modeling, Proc. Of the Ninth International Conference, ASCE, pp. 585-602.

Sheng, Y. P., V. A. Paramygin, Y. Zhang, and J. R. Davis (2008), Recent enhancements and application of an integrated storm surge modeling system: CH3D-SSMS. Estuarine and Coastal Modeling, Proc. of the Tenth International Conference, ASCE, pp. 879-892.

Sheng, Y.P., V. Alymov, and V. A. Paramygin (2010a), Simulation of Storm Surge, Waves, Currents, and Inundation during Hurricane Isabel in 2003, J. Geophys. Res., vol. 115, C04008, pp. 1-27.

Sheng, Y. P., Y. Zhang, and V. A. Paramygin, (2010b): Simulation of storm surge, wave, and coastal inundation in the Northeastern Gulf of Mexico region during Hurricane Ivan in 2004. Ocean Modelling, 35, 314-331.

Sheng, Y.P. and T. Liu (2011), Three-dimensional simulation of wave-induced circulation: Comparison of three radiation stress formulations, J. Geophys. Res., 116, C05021, doi:10.1029/2010JC006765.

Tutak, B. and Y. P. Sheng (2011), Effect of tropical cyclones on residual circulation and momentum balance in a subtropical estuary and inlet: Observation and simulation, J. Geophys. Res., 116, C06014, doi:10.1029/2011JC006988.

Wilson, B. W. (1960), Note on Surface Wind Stress over Water at Low and High Wind Speeds. Journal of Geophysical Research, 65(10), 3377–3382.

Xie, L., Bao, S., Pietrafesa, L. J., Foley, K., and Fuentes, M., (2006), A Real-Time Hurricane Surface Wind Forecasting Model: Formulation and Verification. Monthly Weather Review 134, No. 5, May 2006, pp. 1355-1370.