Forecasting of Storm Surge and Wave along Taiwan Coast

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Abstract

This paper describes the application of a coupled surge-wave modeling system CH3D-SWAN for simulating storm surge and wave along Taiwan coast. The modeling system has been used for simulating storm surge and wave in the U.S., Arabian Gulf, and Taiwan. This paper presents the hindcasting of Typhoon Soudelor in 2015 and the forecasting of the typhoon season in 2016 with Typhoon Meiji as an example. Performance of the forecasting system is assessed and future forecasting effort is discussed.

Key words: Storm Surge, Wave, Numerical Simulation, Forecasting, Taiwan

1. Introduction

In Taiwan, typhoons are an annual threat. Typhoons not only bring torrential rain, but often cause storm surge, wave, and coastal inundation that impact areas near the coast and amplifies the flooding from rainfall. The impact of tropical cyclones on the coastal regions in Taiwan depend on the characteristics of tropical cyclones and coastal regions. For example, along the southwest coast of Taiwan with low elevation and gentler bathymetric slope, major flooding often occurs due to storm surge during tropical cyclones. Typhoon Fanapi caused major flooding along the southwest coast of Taiwan in September 2010. Along the rocky northeast coast of Taiwan where the bathymetric slope is steep, waves often break very close to the coastline and contribute significantly to the storm surge. During July 2013, Typhoon Soulik caused significant storm surges and/or waves along the northeast coast of Taiwan. This is also true for Typhoon Soudelor (2015) and Meiji (2016).

Numerous storm surge studies have been conducted around Taiwan using a number of different storm surge models, e.g., CWB-1 model (Yu et al. 1994), CWB-2 model (Wu 2014), TORI (Taiwan Ocean Research Institute) model (Liau and Chen 2015), and HMTC (Harbor and Marine Technology Center) model (Lee et al. 2015). Due to the neglect of wave effect and relatively low grid resolution, however, these models did not produce accurate storm surge simulation during past typhoons including Fanapi in 2010 and Soulik in 2013. Sheng et al (2016) showed that coupled wave-surge model can significantly improve the water level predictions where waves play a major role.

In this paper, we describe the application of a coupled surge-wave modeling system CH3D-SWAN to simulation of storm surge and wave in recent typhoons of Taiwan. In the following section, we first give a brief description of the CH3D-SWAN modeling system with all the associated modules of the forecasting system and model domains. Model hindcasting of storm surge and wave during Typhoon Soudelor in 2015 is then described, followed by a description of the forecasting performance of the 2016 typhoon season using Typhoon Meji as an example. Performance of the forecasting system and future effort is then discussed.

2. The CH3D-SWAN Modeling System

This CH3D-SWAN modeling system (Sheng, et. al, 2010 a, b; Sheng and Liu 2011; Lapetina and Sheng 2015) as shown in Figure 1 is built upon the dynamically coupled CH3D (Curvilinear-grid Hydrodynamics in 3D) circulation model (Sheng, 1987; Sheng, 1990) and the SWAN (Simulating WAves Nearshore) wave model (Ris et al. 1999). 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 2D and 3D with a robust turbulence closure model (Sheng and Villaret, 1989), a Smagorinsky type horizontal mixing model, and a flooding and drying algorithm (Davis and Sheng 2003). At the air-sea interface, the shear stress is produced by wind as well as waves, while at the bottom, current-wave interaction produces enhanced bottom stress. Detailed motion and boundary condition equations are described in Sheng et al. (2010a).

CH3D-SWAN has the capability of using a variety of wind fields and related boundary conditions as forcing, including the WRF (Weather Research and Forecast) model operated by the National Center for

Environmental Prediction (NCEP), TWRF (Hsiao et al. 2010), and parametric synthetic wind model (e.g., Holland 1980). It also has the capability to add wind dissipation due to land roughness based on land cover data (Sheng et al. 2010b), and wind data assimilation. CH3D-SWAN can obtain open boundary conditions along the offshore boundary from a variety of large scale ocean circulation models, including CH3D. NCOM (Barron et al. 2004, Ko et al. 2016), and HYCOM (Bleck and Benjamin 1993), and wave models such as WaveWatchIII (Tolman 2009).

CH3D-SWAN has been compared to other storm surge models including ADCIRC (ADvanced CIRCulation Model; Luettich et al. 1992), CMEPS (Peng et al. 2004), FVCOM (Finite Volume Coastal Ocean Model; Chen et al. 2006), and SLOSH (Sea, Lake and Overland Surges from Hurricanes; Jelesnianski et al. 1992). Sheng et al. (2012) made detailed comparison of these models in terms of simulated storm surges during historic storms as well as coastal inundation maps including surge atlas and the 1% annual chance coastal inundation maps which is also known as the Base Flood Elevation (BFE) maps according to the Federal Emergency Management Agency (FEMA) of the U.S. (NAS 2009). The study showed that CH3D-SWAN is more efficient than all the other high resolution models, except the low resolution SLOSH, and equally or more accurate.

The CH3D-SWAN modeling system uses a high resolution horizontal grid that can vary from tens of meters near the coast to a few hundred meters in offshore areas. Because it uses an efficient implicit/semi-implicit algorithm to resolve surface gravity wave propagation, CH3D allows the use of relatively large time steps (1-60 s). To maintain high efficiency in CH3D simulations, a high resolution grid is usually used only in the coastal domain, which extends from the coastline to 50-100 km offshore. Figure 2 shows all the modules of the CH3D-SWAN forecasting system, including data acquisition, job management, catalog and archive, simulation, post processing, and publishing.

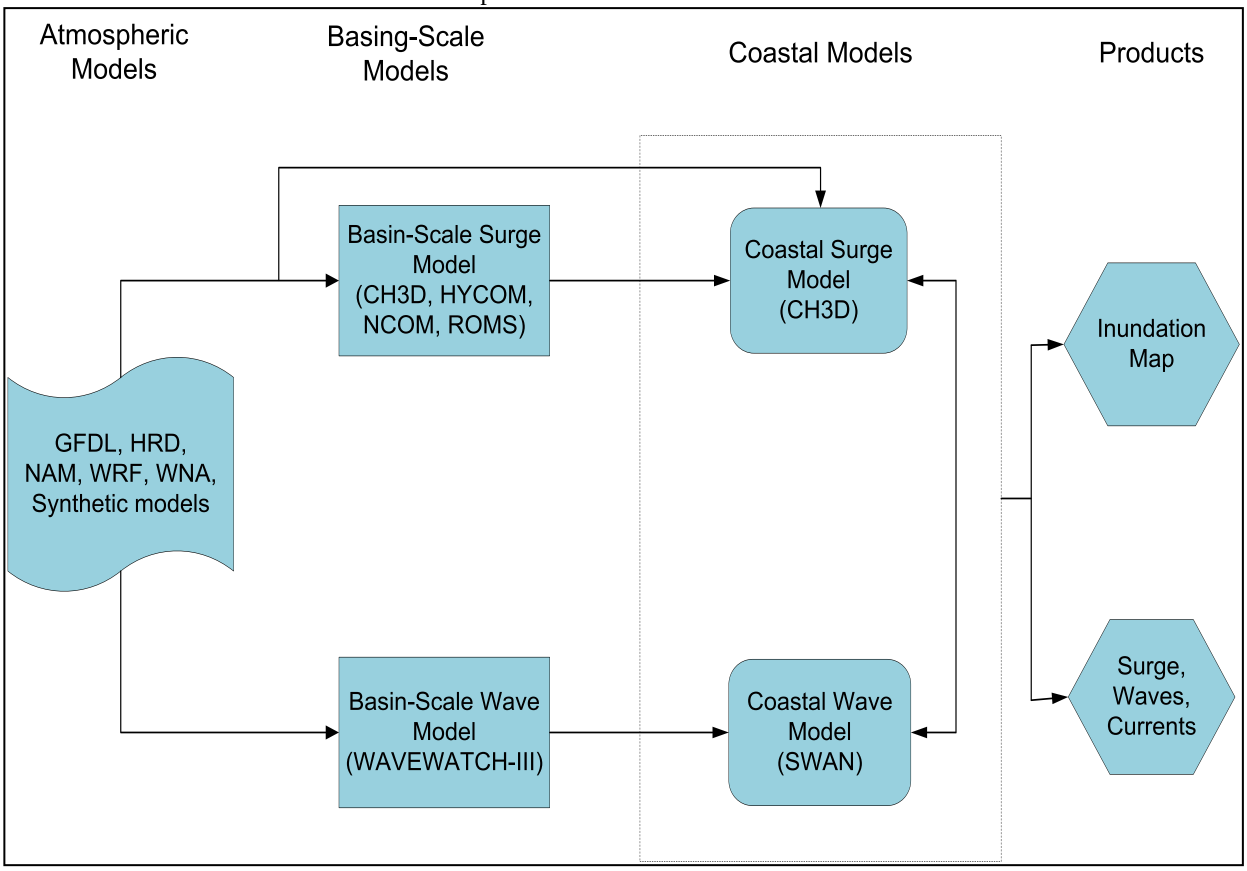

Figure 1. CH3D-SWAN Model schematics.

For CH3D-SWAN simulations in this study, we use two computational domains as shown in Figure 3(a) which differ in area covered and horizpntal grid resolution. The smaller curvilinear domain TW, as shown in the center of Figure 3(a), covers the entire Taiwan Island coastline, containing two million grid cells with the grid cell size ranging from 100-4000 m. This computational domain is nested inside a large rectangular domain TW500, with 500 m by 500 m grid resolution, which provides boundary conditions to the TW domain. The TW500 domain is always run in 2D mode and is only forced by wind and pressure fields and does not include tide effects. Figure 3(b) shows the new curvilinear grid TWN domain, with the grid size between 150-1300 m, being used for 2017. This domain combines the TW and TW500 domains and includes Kinmen and Matsu islands offshore of the Mainland China, and is more efficient than the two-domain forecasting system.

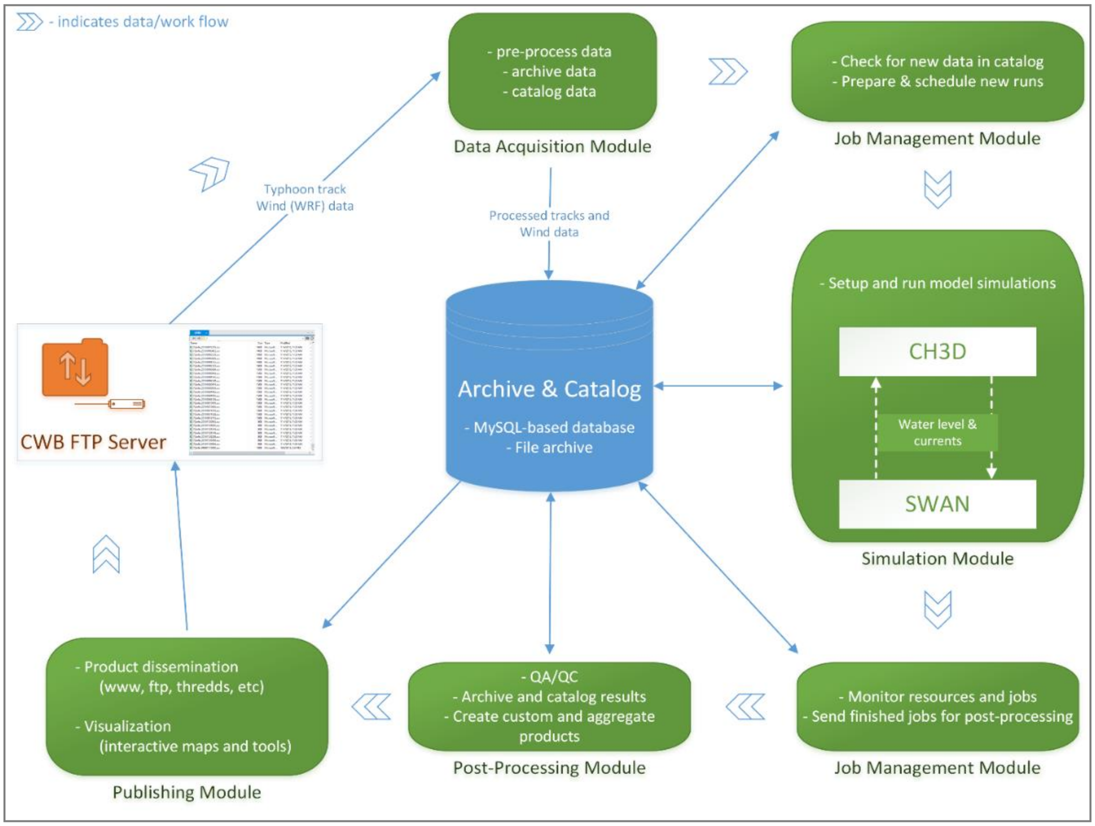

Figure 2. All modules of the CH3D-SWAN forecasting system.

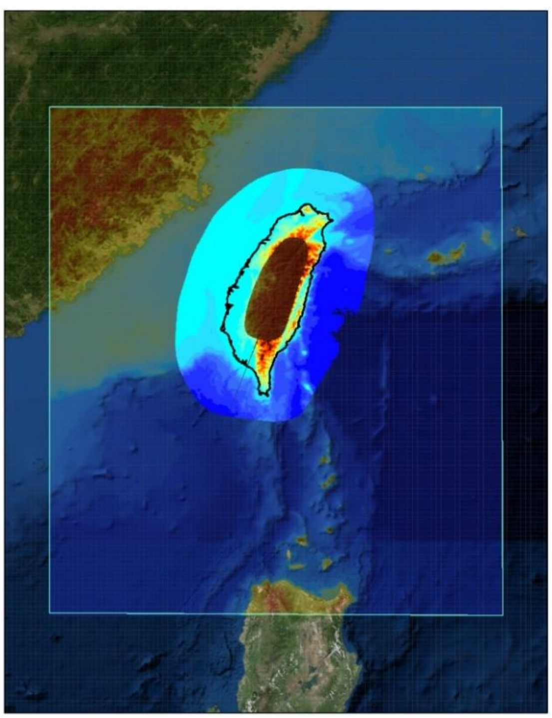

Figure 3(a). TW and TW500 domains.

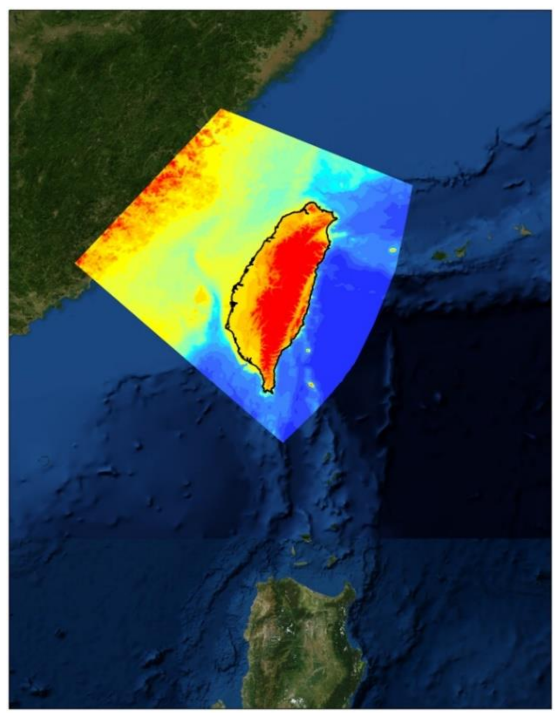

Figure 3(b). New model domain for 2017.

3. Simulation of Typhoon Soudelor (2015)

Soudelor (Figure 4) produced very large waves along the northeastern coast of Taiwan. Observed and simulated wave heioghts exceeded 11m at Hualien (Figure 5) and Guishangdao coast. Observed water level at all 32 stations are shown to be well hindcasted by the CH3D-SWAN modeling system, with relative root mean square error (RMSE) of 3-13%. Unfortunately there were missing data at key stations to allow detailed verification of wave effects on storm surge. Figure 4 shows the track of Typhoon Soudelor provided by CWB.

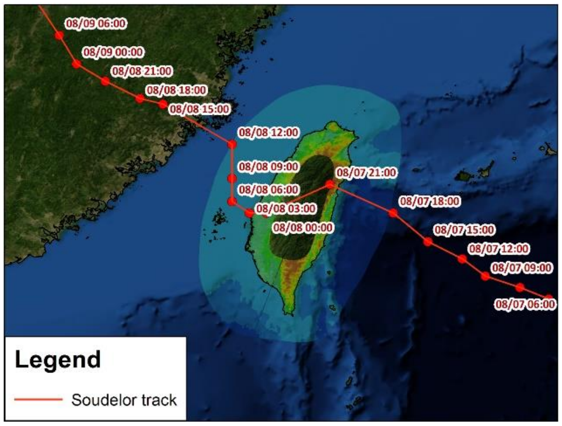

Figure 4. Track of Typhoon Soudelor (2015).

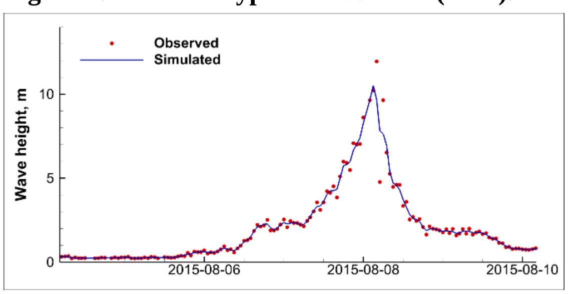

Figure 5. Simulated and observed wave height at Hualien station (46699a) during Soudelor.

4. Forecasting of Surge and Wave in 2016

We present the forecasting of Meiji (Figure 6).

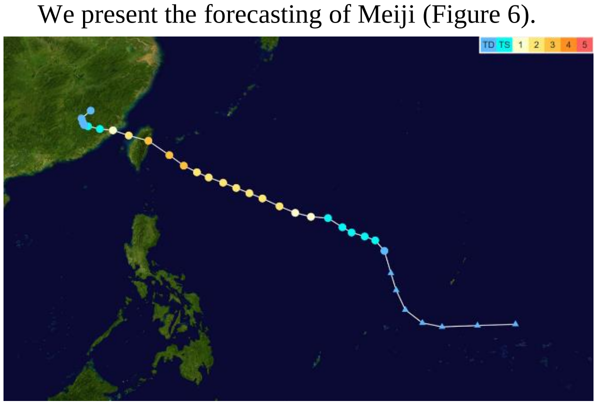

Figure 6. Track of Typhoon Meji in 2016.

The CH3D-SWAN modeling system was able to accurately forecast the water level and wave at all observation stations. As an example, we show the forecast and observed water level at Suao along the northeast coast of Taiwan during Meiji in Figure 7. Figure 8 shows that observed significant wave height up to 20 m was well predicted by the CH3D-SWAN system. The wave buoy was located offshore but the water level station was close to the shore, hence the water level is lower than expected. Sheng et al. (2016) showed that wave induced setup accounted for more than 20% of the peak surge at Longdong during Soulik.

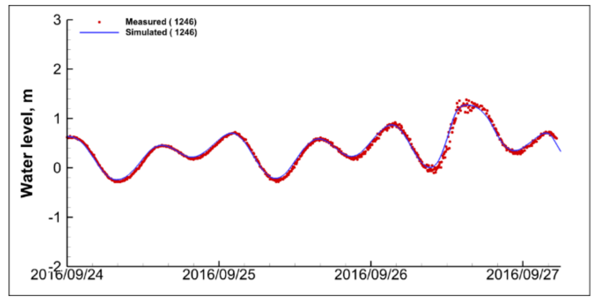

Figure 7. Forecast and observed water level at Suao.

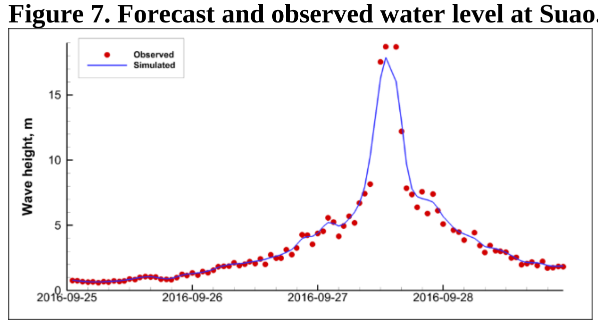

Figure 8. Observed and forecast wave height at Suao.

During the 2016 typhoon season, the CH3D-SWAN forecasting system performed quite well. The system uptime is estimated at 78% during the three months (July-September) of operation. For all 30 stations, the tide prediction has about 3-10% RMSE, the water level prediction RMSE increases from 5.8-13.5% for nowcast to 9.8-17.4% for 6-hour forecast, 11.4-18.2% for 12-hour forecast, and 20.3-31.4% for 24-hour forecast. The relative root-mean-square error (RRMSE) is obtained by dividing the RMSE by the local maximum surge or tide. The forecast wave results compared well with observed data at all wave stations. CWB tracks were used along with a parametric typhoon model (Holland 1980).

5. Discussion

The forecast error of water level increases quickly for 24-hour forecast, due to the quick decline of typhoon track/intensity forecast accuracy between 12-24 hours. This suggests the need to significantly improve the accuracy of typhoon intensity and track forecast by CWB. The TWRF forecast in 2017 will be significantly more accurate than before, but the 3-km grid resolution may not sufficiently resolve the typhoon dynamics.

The forecasting system was run efficiently using an Intel-based PC with the Intel® Core™ i7-3770 CPU @ 3.40 Ghz (4 cores/8 threads) with 32GB RAM. Wall time varies between 0.8 and 1.8 hours for each forecast cycle. The robustness of the CH3D-SWAN algorithms enabled the efficient operation of the forecasting system without the use of computer cluster with hundreds to thousands processors.

In 2017, the CH3D-TW forecasting system will be used to provide forecast of storm surge and wave in the new domain shown in Figure 3(b), using pressure and wind fields provided by the high resolution (3 km) TWRF model as well as typhoon tracks provided by the Central Weather Bureau. Simulations will be run with three different sets of forcing functions: (1) with tide only; (2) with wave only; and (3) with tide, wind, and wave. Forecast results of tide, surge, and wave at 30 stations around the island, including Kinmen and Matsu, will be available via the CWB forecast website.

Future effort will include the application of ensemble forecasting technique (e.g., Davis et al. 2010) to the CH3D-SWAN system in Taiwan. Probability distribution functions of past forecasting errors in typhoon intensity and track will be used to develop ensembles of typhoon tracks for probabilistic storm surge forecasting, to address the uncertainties associated with deterministic forecasting.

To provide super-fast forecasting, it is possible to utilize the rapid forecasting system developed by Condon et al. (2012) which makes use of archived high-resolution forecast results of storm surge, wave, and inundation during a modest number (~150) of representative synthetic typhoons with a quick and accurate interpolation algorithm. This type of rapid forecasting system can provide a quick forecast in a few minutes.

To improve the accuracy of the CH3D-SWAN for forecasting coastal inundation, it is possible to couple the forecasting system with a watershed forecast model which can provide the river flow and an improved TWRF with accurate precipitation forecase.

The CH3D-SWAN modeling system can be used to produce probabilistic coastal inundation maps for assessing the inundation risk along the Taiwan coast in the 21st century (see,e.g., Condon and Sheng 2012). The vegetation-resolving version of CH3D-SWAN can be used to assess the role of mangroves in protecting coastal communities from flooding (Sheng and Zou 2017) and to develop coastal resiliency plan.

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