From Source to Sink:
A Modeling Package for Typhoon Wave Generation, Propagation, and Inundation

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A numerical modeling approach for extreme wave generation, propagation, and inundation is presented. The modeling package consists of open ocean spectral wave models as well as nearshore circulation and inundation models. The boundary conditions are wind fields and tides. The model suite accounts for all major processes of wind-generated waves and it can be used for tropical as well as extratropical storm wave scenarios. We present validation results for Hurricane Iniki, which struck the Hawaiian Island of Kauai in 1992. The wind and pressure driven storm surge from Hurricane Iniki was less than 1.0 m in most areas but substantial wave runup, beach erosion, and devastation up to the 10 m contour were observed. This example shows the necessity to account for wave-by-wave processes in the nearshore domain to properly assess the hazards from both storm surge and storm waves.

Key Words: Storm surge, waves, wind, setup, hurricane, typhoon, inundation, runup, reefs, wave breaking, BOSZ, NEOWAVE, WAVEWATCH III

1. INTRODUCTION

The recent catastrophic typhoon Haiyan has highlighted the need for understanding and predicting the impacts of storm surges. Modeling of storm-induced coastal inundation has primarily focused on the surge generated by atmospheric pressure and surface winds with phase-averaged effects of the storm waves as setup. For example, Higaki et al.¹¹ developed a numerical model for fast storm surge forecasts that is based on forcings from atmospheric pressure and wind. However, superposed on the storm surge are surface gravity waves that can reach 40 m height near the center of a tropical cyclone. These waves interact nonlinearly with the surge and their impact can be more significant than their phase-averaged effects - especially in areas with steep bathymetry. This is of significant importance for modeling of coastal flood hazards and assessment of infrastructure vulnerability. Kennedy et al. ²¹ account for the flood event by simulating phase-resolving surf and swash-zone processes on a storm-tide level using a one-dimensional Boussinesq model along transects of uniform storm surge elevation.

The present study describes a new model package applied to Hurricane Iniki (Hawaii) with nested computational schemes that include spatial variation...
of the surge in modeling of both phase-averaged and also phase-resolving wave processes (Li et al.3). The model suite extends the existing approaches by accounting for wave generation from typhoon winds in combination with background wind fields as well as by calculating wave-by-wave transformation and inundation on top of the storm surge with a 2DH Boussinesq model. The numerical models selected for this study have been validated with laboratory and field measurements pertaining to tropical coastal environments with fringing reefs.

2. MODEL COMPONENTS

Storm-induced coastal inundation is attributed to the combined effects of tides, surge, and waves over a broad range of spatial and temporal scales. These physical processes have little interaction in the open ocean, but are inherently connected near the shore. The mean sea level (MSL) from a tidal epoch defines the water depth and provides the reference for the phase-averaged surface elevation, which increases toward the shore. Storm waves propagate on the elevated surface with phase-resolving perturbations. The scale difference between the phase-averaged and phase-resolving processes allows the use of a nesting scheme to describe the physical processes and their coupling through a suite of interoperable models. These include the non-hydrostatic circulation model NEOWAVE (Nonhydrostatic Evolution of Ocean Waves) of Yamazaki et al.4,5, the spectral wave model WW3 (WAVEWATCH3) of Tolman6, and the Boussinesq Ocean and Surf Zone model (BOSZ) of Roeber and Cheung7. Fig. 1 summarizes the model components as well as their interoperability in the model package.

The tide level at landfall plays an important role in the flood hazards. The Oregon State University Tidal Prediction Software (OTPS) defines the boundary conditions for NEOWAVE to reconstruct the tidal flow in hindcast analysis of tropical cyclones. The predictions are based on the barotropic inversion solutions of Egbert and Erofeeva8. The latest global tidal solution TPXO7.2 includes eight primary (M2, S2, N2, K2, K1, O1, P1, Q1) constituents on a 1440 x 721 global grid at 0.25° resolution.

The computation begins with a global WW3 run to define the background waves and swells generated by several sources such as extra-tropical storms, tropical cyclones, and the trade wind system from CFSR input. In Fig. 2, the regional WW3 (level-1) is two-way coupled with the global WW3 (not shown in figure). At the regional level, the wind field from the parametric hurricane model is combined with the CFSR background wind to provide the wind forcing in NEOWAVE in addition to astronomical tides. The information is then passed down to level-2 and level-3 for the nearshore computations. NEOWAVE uses the same grids as WW3.
but it runs independently from WW3 due to negligible interactions between waves and surge in the open ocean. NEOWAVE describes the regional and nearshore circulations driven by surface wind, pressure and astronomical tides. The storm surge interacts with the nearshore bathymetry resulting in locally amplified free surface elevation. Up to this point, only phase-averaged processes are considered, which cannot account for wave setup and wave runup leading to underestimation of the flood hazards when energetic waves are present at the shore.

For modeling of coastal inundation, this model suite incorporates the phase-resolving Boussinesq model, BOSZ. The regional WW3 defines the variable input wave spectrum at several locations along the 50-m contour of the BOSZ domain for generation of the incident waves (Fig. 3). Waves can be generated along a line through a source function approach based on linear superposition of all spectral components each assigned a random phase.

The initial free surface condition is based on the storm surge envelope from NEOWAVE that results from the forcing of barometric pressure, wind setup and tides. No wave setup has been accounted for yet. Steady source terms in the momentum equations of BOSZ impose the storm surge elevation as the initial surface elevation for computation of surf and swash zone processes. The individual storm waves travel freely on top of the storm surge envelope and nonlinearly interact with it. The wave setup is built internally by the individual waves in BOSZ. The final storm surge includes barometric pressure, tides, wind setup, and wave setup without double-counting of any of the components.

3. CASE STUDY

The case study involves modeling of tide, surge, and wave conditions across the Hawaiian Islands as well as coastal inundation on the south shore of Kauai during Hurricane Iniki at 1992. Iniki reached hurricane strength with a maximum sustained wind speed of 30.9 m/s at 0000 UTC September 9. The hurricane was upgraded to Cat 4 at 1200 UTC September 10. The storm attained its maximum strength at Cat 4 with 62 m/s sustained winds and a forward speed of 8 m/s at 1200 UTC September 11. Because of a mid-latitude trough over the Northwest Hawaiian Islands, Iniki sped up to an average forward speed of 11.4 m/s prior to landfall on Kauai at 0100 UTC September 12. Due to forward speed effects, the most severe wind and wave conditions occurred along the southeast shore 20 km east of the eye.

Fig. 2 shows three levels of nested grids with increasing resolution from the Pacific Ocean to the south shore of Kauai. The level-1 grid has a 5.5 km resolution. It covers the entire hurricane track for modeling of the storm wave generation and propagation. The level-2 grid covers Kauai at 550 m to resolve insular slope and shelf processes.

We model the inundation at the level-3 grids. NEOWAVE describes the phase-averaged processes across the south shore of Kauai at 55 m resolution. BOSZ utilizes a grid of 6 m resolution oriented perpendicular to the peak wave direction for calculation of wave-by-wave processes and inundation from Port Allen to Poipu. The grid extends 25 km along the coast and 8.6 km offshore to include sufficient buffers for the sponge layers and wavemaker. A Manning coefficient of 0.035 accounts for energy dissipation over sub-grid roughness reflecting the terrain and vegetation over the coastal plain in Hawaii.

4. RESULTS

The global WAVEWATCH III ran for 18 days at 0.5° resolution to fully develop the basin wide processes before coupling with the regional grid (Level-1 domain in Fig. 2). The four NDBC buoys recorded the surface elevation for 20 min at one-hour intervals for deduction of the sea state during the event. Figure 4 shows reasonable agreement of the recorded and computed significant wave heights and peak periods. These wave parameters might not fully depict the multi-modal sea state under hurricane conditions, but serve to provide a qualitative comparison.

NEOWAVE provides the tidal surge conditions in the nearshore region covered by the level-3 grid. Fig. 5 shows the storm surge envelope from NEOWAVE that is down-sampled to fit the BOSZ domain. Since the initial storm surge is only based on barometric pressure, tides and wind setup, it greatly underestimates the inundation limit indicated by white dots – especially near Port Allen and Poipu. The surge elevation is non-uniform and less than 1 m.
Fig. 6 shows a snapshot of the individual storm waves in BOSZ superposed on top of the storm surge envelope. The south shore of Kauai has steep nearshore slopes. The waves maintain large amplitude and break very close to the shore resulting in a narrow surf and swash zone, where the surface elevation and flow depth decrease rapidly. The shock-capturing capabilities in BOSZ describe the propagation of broken waves as bores and the runup processes as sheet flows (Roeber et al.9). The computed inundation follows the topography and extends into river valleys and ravines, where debris lines were not well defined due to surface runoff from precipitation. The flow depth, which reaches up to 3.0 m along the shore, provides an explanation for the coastal property damage reported by Chiu et al.10. The inundation limit extends far into the residential area of Port Allen. Near Poipu, the runup reaches a maximum of almost 10 m topographic height. The overall agreement between the computed and measured inundation is good.

The final phase-averaged water level including barometric pressure, tides, wind setup, and wave setup is shown in fig. 7. At the location of the tide gauge in Port Allen, the models provide a combined storm surge of 1.32 m, which is very close to the actual measurement of 1.33 m during the event. The wave setup from the storm waves alone is about 0.5 m at this location.

5. CONCLUSIONS

This study has assembled a package of interoperable numerical models and environment datasets and demonstrated its capability in linking storm tide and wave computations over wide spatial and temporal scales. This is accomplished through a set of common physical variables that are passed between the models over a system of nested computational grids. A spectral wave model forced by a global reanalysis dataset defines basin-scale processes, which together with a tidal program and a parametric tropical cyclone model supply the boundary conditions and forcing for computations at the regional scale.

A regional circulation model provides a phase-averaged description of the storm-water flow and coastal inundation. Through additional source terms in the governing equations, a Boussinesq model provides a wave-by-wave account of the surf zone processes on top of the irregularly shaped storm tides from the circulation model. The results indicate that wave swashing not only modifies the phase-averaged storm surge envelope, it is also an important component for the inundation and must be considered in assessment of coastal flood hazards for locations with steep bathymetry such as encountered around many island communities.

REFERENCES

Fig. 5 Initial surface elevation from NEOWAVE for wave-by-wave simulation. The storm surge envelope includes barometric pressure, tides, and wind setup. Black line indicates MSL.

Fig. 6 Snapshot from BOSZ of individual storm waves over storm surge envelope. Black line indicates MSL.

Fig. 7 Phase-averaged storm surge from BOSZ including barometric pressure, tides, wind setup, and wave setup. Black line indicates MSL and white dots denote inundation limit from observations.