Simulating Storm Surge of Typhoon Haiyan using Adaptive Mesh Refinement

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1. Introduction

In November 2013 the coastal city of Tacloban in the Philippines was devastated by Typhoon Haiyan, one of the most intense tropical cyclones (TCs) to make landfall ever recorded, generating storm surge of up to 5m. Storm surge is a major concern for coastal communities around the globe and the assessment of such worst-case TCs is important for disaster prevention and mitigation. Furthermore, climate change is projected to affect TC distributions including changes to storm tracks, intensity, and genesis frequency but impacts to coastal hazard distributions remains poorly understood. In particular, surge levels are highly dependent on storm track relative to local geographic features, so careful understanding of TC behavior as well as ensemble modeling are necessary to make robust projections. However, since coastal inundation modeling occurs over a large range of spatial scales, with storm tracks extending thousands of kilometers and man-made structures spanning tens of meters, numerical simulation can be costly. To resolve fine scales along coastlines while minimizing total computation costs we implement a model with adaptive mesh refinement (AMR) that dynamically adjusts gridsize to track features of interest. In this study we present a validation of this storm surge model using hindcast atmospheric conditions of the TC Haiyan event compared with field survey measurements.



Figure 1. Wind fields of TC Haiyan generated by WRF used as forcing terms. Boxes indicate regions of higher refinement generated by the AMR routine.

2. Storm Surge Model and Source Terms

For the numerical storm surge model we use GeoClaw, an open-source finite volume solver for depth-averaged flows with AMR. In this study the effect of waves and tides are not considered but inundation over land is considered. The governing equations are the nonlinear shallow water equations over uneven bathymetry with forcing terms:

$$\frac{\partial}{\partial t}h + \frac{\partial}{\partial x}(hu) + \frac{\partial}{\partial y}(hv) = 0$$

$$\frac{\partial}{\partial t}(hu) + \frac{\partial}{\partial x}\left(hu^{2} + \frac{1}{2}gh^{2}\right) + \frac{\partial}{\partial y}(huv) = fhv - gh\frac{\partial b}{\partial x} + \frac{h}{\rho}\left(\frac{-\partial P}{\partial x} + \rho_{air}C_{w}|W|W_{x} - C_{f}|\vec{u}|u\right)$$

$$\frac{\partial}{\partial t}(hv) + \frac{\partial}{\partial x}(huv) + \frac{\partial}{\partial y}\left(hv^{2} + \frac{1}{2}gh^{2}\right) = -fhu - gh\frac{\partial b}{\partial y} + \frac{h}{\rho}\left(\frac{-\partial P}{\partial y} + \rho_{air}C_{w}|W|W_{y} - C_{f}|\vec{u}|v\right)$$
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where h is water column height, u and v are depth-averaged velocities, g is the gravitational constant, f is the Coriolis parameter, b is bathymetry, ρ and ρ_{air} are densities of water and air, P is sealevel pressure, C_w is the Mitsuyasu & Kusaba wind stress coefficient, C_f is the Manning's *n* bottom friction coefficient, and W=(W_x,W_y) is wind speed.

Atmospheric conditions are given by hindcast data generated by a 1km regional model (WRF) with boundary conditions provided by the JMA Global Spectral Model. Bathymetry is given by GEBCO with resolution of 30 arc-seconds (roughly 1km), and topography in the target area is given by a high-resolution digital terrain model provided by JICA. Initially, the computational domain is coarsely gridded (~20km) using a rectangular mesh, and as the simulation progresses the mesh is dynamically and locally refined to a maximum resolution of ~100m based on water height, current speed, and intensity of atmospheric forcing (see Figure 1).

3. Numerical Results and Conclusions

Simulation of Typhoon Haiyan storm surge results in maximum surge at Leyte Bay of over 5m (Figure 2), which corresponds closely to observations. Inundation extent matched well with observations but was overestimated in some regions. Comparison of simulated maximum inundation heights with in-situ measurements provided by the JSCE-PICA joint survey show reasonably good match, with a RMSE error of about 2.5m. In some locations the wave effect was much more prominent than surge, and in these cases inundation was greatly underestimated.



Figure 2. Left: Simulated maximum water levels and inundation extent observed from survey (red dots). Right: Comparison of max water height from field measurements and simulation.

Using AMR greatly reduces computation time – a simulated 3-day scenario with a max resolution of 200m can take 1-2 hours using 32 threads. Furthermore, the computation cost depends on the severity of the storm surge, so for ensemble modeling most runs will have lower cost than this worst-case scenario. Low cost models are vital to performing efficient ensemble projections for coastal inundation, which is important for hazard estimation and mitigation considering the influence of climate change, and AMR methods provide a useful and effective tool for these projections.

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