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Adaptive mesh refinement for storm surge

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ABSTRACT

An approach to utilizing adaptive mesh refinement algorithms for storm surge modeling is proposed. Currently numerical models exist that can resolve the details of coastal regions but are often too costly to be run in an ensemble forecasting framework without significant computing resources. The application of adaptive mesh refinement algorithms substantially lowers the computational cost of a storm surge model run while retaining much of the desired coastal resolution. The approach presented is implemented in the GEOCLAW framework and compared to ADCIRC for Hurricane Ike along with observed tide gauge data and the computational cost of each model run.

1. Introduction

As computer technology advances, scientists continually attempt to use numerical modeling to better predict a growing number of high-impact geophysical events. In particular, coastal hazards have become an increasing concern as the world's population continues to grow and move towards the coastline, in Fact 44% of the world's population lives within 150 km of the coast and 8 of the 10 largest cities in the world lie in that range (UN Atlas). As a consequence, loss of life and property is becoming a larger concern than ever before. One of the most recurring and wide spread hazards to many coastal communities is the inundation of coastlines that is associated with strong storms, one part of which is known as storm surge. A storm surge is a rise in the sea accompanying extratropical or tropical cyclones, the strongest examples of which are hurricanes and typhoons. Storm surges can cause massive amounts of damage, as was demonstrated by Hurricane Katrina, which caused an estimated $81 billion of damage (Blake et al., 2007). Of the world's largest cities, 4 lie within threat zones from tropical cyclones. With the mounting evidence that severe storms may be increasingly common (Contribution of Working Group I), the task of modeling these events becomes even more critical to communities along the coasts.

Modeling of storm surges was first carried out by local empirical observations. Unfortunately, for more severe storms such as Katrina, these types of prediction can grossly under-predict storm surge size and effect. By the 1960s, scientists started using computer simulations to predict storm surge but, because these simulations were limited in resolution and size, these models had the same short-comings as the empirically-based models. It was not until recently with increased observational evidence, improved efforts in modeling underlying physical processes, and increases in available computational power that substantial progress has been made simulating large-scale storm surge for use in hazard planning.

The current state-of-the-art numerical models for storm surge simulations rely on single-layer depth-averaged equations for the ocean and make assumptions about the ocean's response to a storm. The National Weather Service (NWS) utilizes a storm surge model called "Sea, Lake and Overland Surges from Hurricanes", or SLOSH, which uses local grids defined for many regions of the United States coastline, to make predictions (Jelesnianski et al., 1992). These simulations are efficient enough that ensembles of runs can be made quickly for multiple different hurricane paths and intensities. This capability can be critical for effective forecasting due to the uncertainty in the storm forecast. The primary drawback to using the SLOSH model is the limited domain size and extents allowed due to the grid mapping used and formulation of the equations.

Another model currently in use is the Advanced Circulation Model (ADCIRC), a finite element model which has been applied to southern Louisiana (Westerink et al., 2008) and recently to Hurricane Ike (Hope et al., 2008). One of the key advantages ADCIRC has it its use of an unstructured grid. Unstructured models allow easy application of variable resolution, especially at the coastline where fine scale features need to be resolved. They can also map to coastlines in a way even a cleverly mapped structured grid cannot. Another advantage of unstructured grids relates to the

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importance of including entire ocean basins for surge predictions (Blain et al., 2007; Li et al., 2013). Unstructured grids can allow the domain of the numerical model to stretch well away from coastlines to include ocean basins while reducing the cost of the model by substantially decreasing resolution in the basin compared to the coastal regions. Unfortunately these models, even with the above advantages, can still be computationally costly and require a large amount of computing resources in order to compute ensemble forecasts without the degradation of their resolution benefits.

In this paper we present an alternative computational framework and methodology to bridge the gap between the numerical cost of the unstructured grid storm surge models and the efficient but unresolved models currently in use at the NWS. The approach leverages adaptive mesh refinement (AMR) algorithms to retain the resolution required to resolve coastal inundation but only when necessary so that ensemble calculations are still feasible. This is accomplished by allowing nested structured grids of variable resolution to vary in time and space thereby capturing the spatial advantages of the unstructured grid approach but only when needed, and therefore decreasing the computational cost substantially. The framework in question, GEOCLAW, has successfully been used previously for tsunami modeling where similar computational requirements are present (Berger et al., 2011).

2. Numerical approach

The mathematical model for storm surge we will consider uses the classical shallow water equations with the addition of appropriate source terms for bathymetry, bottom friction, wind friction, non-constant surface pressure and Coriolis forcing which can be written as

$$\begin{aligned} &\frac{\partial}{\partial t}h + \frac{\partial}{\partial x}(hu) + \frac{\partial}{\partial y}(hv) = 0, \\ &\frac{\partial}{\partial t}(hu) + \frac{\partial}{\partial x}\left(hu^2 + \frac{1}{2}gh^2\right) + \frac{\partial}{\partial y}(huv) \\ &\quad = fhv - gh\frac{\partial}{\partial x}b + \frac{h}{\rho}\left(-\frac{\partial}{\partial x}P_A + \rho_{\text{air}}C_w|W|W_x - C_f|\vec{u}|u\right) \\ &\frac{\partial}{\partial t}(hv) + \frac{\partial}{\partial x}(huv) + \frac{\partial}{\partial y}\left(hv^2 + \frac{1}{2}gh^2\right) \\ &\quad = -fhu - gh\frac{\partial}{\partial y}b + \frac{h}{\rho}\left(-\frac{\partial}{\partial y}P_A + \rho_{\text{air}}C_w|W|W_y - C_f|\vec{u}|v\right) \end{aligned} \tag{1}$$

where h is the fluid depth, u and v the depth-averaged horizontal velocity components, g the acceleration due to gravity, ρ the density of water, ρ_{air} the density of air, b the bathymetry, f the Coriolis parameter, $W = [W_x, W_y]$ is the wind velocity at 10 meters above the sea surface, C_w the wind friction coefficient, and C_f the bottom friction coefficient. The value of C_w is defined by Garratt's drag formula (Garratt, 1977) as

$$C_w = \min(2 \times 10^{-3}, (0.75 + 0.067|W|) \times 10^{-3}) \tag{2}$$

and the value of the friction coefficient C_f is determined using a hybrid Chezy–Manning's n type friction law

$$C_f = \frac{gn^2}{h^{4/3}}\left[1 - \left(\frac{h_{\text{break}}}{h}\right)^{\theta_f}\right]^{\gamma_f/\theta_f} \tag{3}$$

where n is the Manning's n coefficient and $h_{\text{break}} = 2$, $\theta_f = 10$ and $\gamma_f = 4/3$ parameters control the form of the friction law.

The numerical approach proposed to solve (1) falls under a general class of high resolution finite volume methods known as wave-propagation methods, described in detail in LeVeque (2002). These methods are Godunov-type finite volume methods requiring the specification of a Riemann solver to update each grid cell in the domain. On top of these methods adaptive mesh refinement is employed to allow for variable spatial and temporal resolution as the simulation progresses. These methods have been implemented together in GEOCLAW, a package that was originally designed to model tsunamis (LeVeque et al., 2011) and other depth-averaged flows (Berger et al., 2011; George and Iverson, 2011; Mandli et al., 2011). The rest of this section is dedicated to describing the salient points of the AMR approach and how storm surge physics are represented in GEOCLAW. A brief review of wave-propagation methods can be found in Appendix A along with a basic outline of the Riemann solver employed in Appendix B.

2.1. Adaptive mesh refinement

Adaptive mesh refinement is a core capability of GEOCLAW as it allows the resolution of disparate spatial and temporal scales common to geophysical applications such as storm surge and tsunamis. The patch-based AMR approach used in GEOCLAW employs a set of overlapping logically rectangular grids that correspond to one of many levels of refinement. The first of these levels, enumerated starting at $\ell = 1$, contains grids that cover the entire domain at the coarsest resolution. The subsequent levels $\ell \geqslant 2$ represent progressively finer resolutions by a set of prescribed ratios r^ℓ in time and space such that

$$\Delta x^{(\ell+1)} = \Delta x^{(\ell)}/r_x^{(\ell)}, \quad \Delta y^{(\ell+1)} = \Delta y^{(\ell)}/r_y^{(\ell)}, \quad \text{and} \quad \Delta t^{(\ell+1)} = \Delta t^{(\ell)}/r_t^{(\ell)}.$$

Each subsequent level is properly nested within the union of grids in the next level coarser (see Fig. 1 for an example of the structure of these nested grids). With this hierarchy of grids, the evolution of the solution follows as:

1. Evolve the level 1 (coarsest) grids one time step to t^{n+1}.
2. Fill the ghost cells of all level 2 grids by temporal and spatial interpolation.
3. Evolve the level 2 grids the number of time steps determined by $\Delta t^{(2)}$ needed to reach t^{n+1}.
4. Recursively continue to fill in ghost cells, evolving each level ℓ after the coarser level $\ell - 1$ has been evolved until all levels are at time t^{n+1}.
5. Fill in regions where the grids overlap with the best available data using interpolation.
6. Adjust coarse cell values adjacent to finer cells to preserve conservation of mass (see Berger and LeVeque (1998) for a discussion on this topic).

The key benefit of adaptive mesh refinement is the ability to change resolution as the simulation progresses. This is done in a process that involves using a local criteria to flag each cell that requires refinement to the next level. The algorithm then clusters the flagged cells into new rectangular patches which attempts to minimize the number of grids created and the number of grid cells unnecessarily refined (Berger and Rigoutsos, 1991). After the new grid structure is created, the previous solution values are copied into the new grid cells if no change in resolution was required or an interpolation and averaging is performed to either coarsen or refine the data available from a different level of refinement.

For the shallow water equations there are three primary areas where care must be taken when implementing adaptive mesh refinement. The first involves the interpolation of the solution and bathymetry. When interpolating where the water column is at rest but bathymetry is varying, using the depth h as the interpolation field will lead to a sea surface η that is not at rest and will result in the creation of spurious waves. To avoid this, interpolation is done with the sea surface instead. From this the depth is computed and the resulting momentum interpolated. This process can be performed in wet cells while conserving mass and momentum. This is not the case in the near shore where cells may change from their wet (or dry) state. In order to avoid spurious waves