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An exact reanalysis technique for storm surge and tides in a geographic region of interest

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ABSTRACT

Understanding the effects of storm surge in hurricane-prone regions is necessary for protecting public and lifeline services and improving resilience. While coastal ocean hydrodynamic models like ADCIRC may be used to assess the extent of inundation, the computational cost may be prohibitive since many local changes corresponding to design and failure scenarios would ideally be considered. We present an exact reanalysis technique and corresponding implementation that enable the assessment of local *subdomain* changes with less computational effort than would be required by a complete resimulation of the full domain. So long as the subdomain is large enough to fully contain the altered hydrodynamics, changes may be made and simulations performed within it without the need to calculate new boundary values. Accurate results are obtained even when subdomain boundary conditions are forced only intermittently, and convergence is demonstrated by progressively increasing the frequency at which they are applied. Descriptions of the overall methodology, performance results, and accuracy, as well as case studies, are presented.

1. Introduction

Coastal storms and hurricanes produce surge, flooding, and wave actions that have damaging effects on the built and natural environment. A key limiting factor in moving from the science of storm surge modeling to its practical application in engineering infrastructure assessment is one of scale: storm surge models necessarily operate over large parts of the globe because that is the scale at which storms and hurricanes operate. However, from a critical infrastructure perspective, assessment of performance and overall resilience happens over a much smaller geographic region, perhaps dealing with individual components, such as levees and seawalls, and their collective behavior. And yet surge loads, as well as other hurricane effects, are necessary to simulate effects on infrastructure at a more local level.

From an engineering perspective, assessment of infrastructure and its resilience necessitates many such large-scale simulations for a single hurricane event: this need is due to the nature of engineering analysis and design. First, one must consider different designs, arrangements, configurations, and materials, each time subjecting the system to a given storm load. Second, there are numerous failure scenarios to consider even for a single infrastructure system, such as levees: for each breach location and type, and for all such breaches in their various combinations, the impact of flooding and other damage must be assessed in order to make collective risk and reliability judgments. These quantitative results can then be used to improve the design and layout of critical infrastructure components and overall system-wide resilience.

To address the particularly important and computationally limiting issue of differences in scale, we present a workflow enabled by a new boundary condition type that combines water surface elevation, velocity, and wet/dry status for unstructured, finite element grids. As in reanalysis techniques for structural systems (Arora, 1976; Kassim and Topping, 1987), our *subdomain modeling* approach for storm surge simulation allows new results to be determined after a local modification to a grid with less effort than would be required to run the entire simulation again. Components of the workflow include a graphical user interface for extracting a geographic region of interest from a grid, the implementation of a new boundary condition type in ADCIRC (Luettich et al., 1992), a widely used storm-surge modeling code, and a low-cost verification step for comparing the results of simulations conducted on an extracted subdomain with those of the original, full domain, both before and after local modifications. The approach is exact in the sense that subdomain runs produce the same results as those that would be obtained by an equivalent simulation on a full domain, so long as the subdomain is large enough to fully contain the altered hydrodynamics.

To demonstrate the value of this approach, consider the array of possible levee failures simulated by (Simon, 2011) in a hypothetical coastal community, as shown in Fig. 1, with flooded areas outlined in white over a local street network. The process begins with an initial large-scale simulation of a storm event followed by subsequent local

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simulations, each with varying local topographies representing possible levee failure scenarios (which might be determined from other engineering analysis techniques). While the initial simulation requires a thousand CPU-hours of run-time on our setup, a subsequent local simulation takes orders of magnitude less time, since run times are proportional to grid size. Of course, as with any modeling exercise, working with subdomains requires some judgment in extracting regions large enough to contain the changes, yet small enough to minimize redundant computations. In practice, subdomains of various sizes and geometries can be extracted simultaneously from a full run and verified both before and after modifications are made.

The following sections provide background on large-scale and regional approaches for tide and surge simulation, and then move on to the subdomain modeling approach and its realization as a new boundary condition type combining water surface elevation, depth averaged water velocity, and wet/dry status (Altuntas, 2012). The approach is shown to be both accurate and well posed via testing on small, benchmark problems, as well as on large-scale simulations with subdomains of various sizes and geometries along the North Carolina coast. In later sections, we describe a user interface that is designed and implemented to support subdomain modeling, and then conclude with some general observations and ideas for future work.

2. Background

Blain et al. (1994) demonstrate the necessity and effectiveness of large-scale approaches for tide and surge modeling. They examine combinations of domain size and boundary conditions for their effects on computed storm surge characteristics in a study of Hurricane Kate (1985) along the Florida coast. For domains, the authors consider a small, semi-circular region surrounding Panama City, a larger region including the Gulf of Mexico, and a much larger one encompassing the entire western North Atlantic Ocean, the Caribbean Ocean, and the Gulf of Mexico. Combined with those domains, two different open ocean boundary forcing functions are considered: a still water boundary condition where water elevation is set equal to the mean sea level, and a boundary condition that partially accounts for meteorological forcing by imposing an inverted barometer effect. The authors conclude that small domains, whose boundaries are in regions where surge effects appear, are inadequate because those effects on the boundaries cannot be known, and hence enforced, a priori. Even somewhat larger domains, like the Gulf of Mexico, may cause difficulties if boundary conditions are to capture the effects of resonant modes, which cannot easily be quantified due to interactions with neighboring basins. Since the open ocean boundaries of the largest domain are far enough removed from the continental shelf and the Gulf of Mexico basin, the influence of the boundary condition specification is minimal, and such domains are found by the authors to be the most practical and effective.

Dietsche et al. (2007) use Hurricane Hugo (1989) to evaluate the effect of incorporating inundation areas and inland flooding in a computational domain. They present four different grids around Winyah Bay, South Carolina, along with a large-scale grid encompassing the western North Atlantic Ocean. In the study, the open ocean boundary of the large-scale grid is elevation-forced using harmonic data corresponding to tidal constituents. They observe that integrating coastal floodplains can significantly alter storm surge predictions, and that using a large-scale domain helps to capture storm surge propagation better toward the shallow regions. The authors conclude that enforcing spatially variable storm surge hydrographs on the boundaries of local grids improves storm surge prediction. In his MS thesis, Dietsche (2004) notes, however, that the use of hydrographs alone may not be sufficient, and that flux terms may be necessary for near-inlet boundaries to achieve reliable results.

Salisbury and Hagen (2007) perform a numerical parameter study to determine the influence tidal inlets have on open coast storm surge hydrographs. Four idealized inlet-bay configurations are presented with model output recorded on five points along each of eight semicircular arcs encompassing the inlet, and with recording stations located

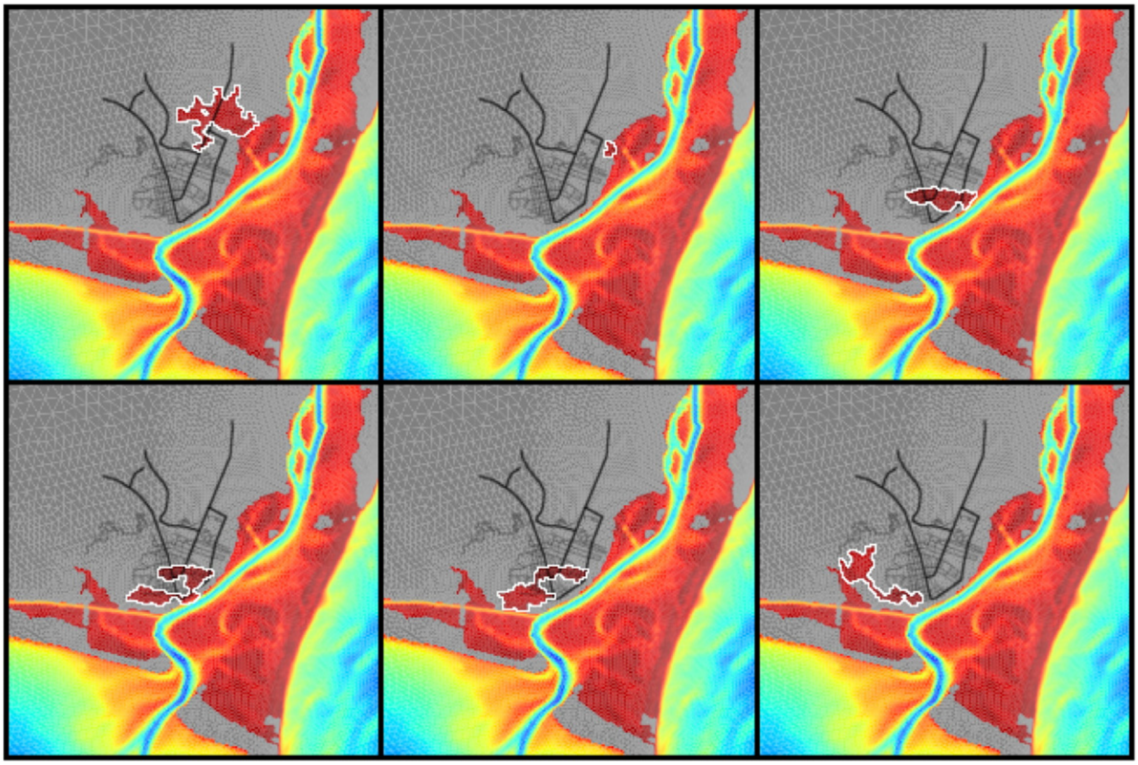

Fig. 1. Maximum water depths under various levee failure scenarios. (Flooding outlined in white, cooler colors are deeper).