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Cyberinfrastructure for Dynamic Data-Driven Predictions of Inundation Hazards under Climate Change and Sea Level Rise

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Introduction

More than 53% of the U.S. population lives in coastal regions, which are home to a wealth of natural and economic resources. Globally, the average density of people living in coastal areas is several times higher than the average density. Many megacities with more than 8 million people each are located in the coastal zone worldwide. Coastal flooding caused by geo-hazards (earthquakes and landslides) and atmospheric-oceanic hazards (tropical cyclones and extra-tropical storms) has killed millions of people living in coastal regions in the last two hundred years. This threat to humanity increases as coastal populations in the world continue to grow and the sea level continues to rise.

The northern Gulf of Mexico, in particular the Louisiana Gulf coast, is very susceptible to the impacts of frequent tropical storms and hurricanes due to its tropical/subtropical location and unique bathymetric, geometric, and landscape features. Severe coastal flooding, enormous property damage, and loss of life are ubiquitously associated with tropical cyclone landfalls, and this devastation was no more evident than during Hurricanes Katrina and Rita in 2005 and Gustav and Ike in 2008. Over 1800 people lost their lives and several major coastal populations were crippled for months after the hurricanes passed.

Tsunamis are ocean waves generated by impulsive geophysical events such as earthquakes, underwater landslides, subaerial landslides and volcanic activity. Although a tsunami wave height may be small in the open ocean, the entire water column is usually set in motion. Hence, as these waves approach coastlines, shoal up and eventually break, their intensity is amplified by the concentrating effect of shallow depths, and the resulting bore has great destructive power.

Tsunamis have become one of the major coastal hazards for many increasingly populated coastal areas, both in the U.S. and worldwide. The recent devastating earthquake-generated tsunamis, such as Japanese Honshu tsunami (March 11, 2011), Indian Ocean tsunami (Dec. 26, 2004) and Haiti tsunami (Feb. 23, 2010), took a major toll on human life and affected an entire ocean basin and coasts around the world.

Although the energy comes from different part of the earth system, coastal flooding generated by hurricanes and tsunamis shares many similarities. *Our vision is to develop a unified and standardized flood hazard prediction system that integrates computational and observational data to dynamically drive statistical and mathematical models for different types of inundation in both riverine and coastal environments. Our plan is to build this infrastructure on the Cactus* *computational framework*. The flood hazards include, but not limited to, coastal and riverine flooding due to tropical cyclones and extra-tropical storms, tsunamis due to earthquakes and landslides, and riverine flooding due to dam break and levee breach. Such a dynamic data-driven system will serve as the infrastructure for flood data and knowledge management and enabling scientific discoveries.

Computational Data

Among existing storm surge models, the ADCIRC (advanced circulation, Luettich and Westerink, 2004; Westerink et al. 2008) model has been routinely used by federal agencies, university researchers and engineering industry for storm surge forecast and parametric studies. The Federal Emergency Management Agency (FEMA) and the U.S. Army Corps of Engineers (USACE) have employed the ADCRIC model to produce an extensive database of storm surges generated by hundreds of hypothetical hurricanes for the development of 100-year flood maps and design of levee systems for flood protection in New Orleans in the post-Katrina studies. Recently, a fully-coupled storm surge and hurricane wave model (SWAN+ADCIRC) has been developed (Dietrich et al. 2010) and is being utilized by the State of Louisiana to update its Master Plan for coastal protection and restoration.

Given a hurricane forecast provided by the National Hurricane Center (NHC), a parametric wind model (Hu et al., 2011) for asymmetric hurricanes can be used to generate the surface wind that is merged with the large-scale background wind field provided by the National Center for Environmental Prediction (NCEP). Driven by hurricane and background wind fields, the fully-coupled wave-surge model predicts both storm surge and ocean waves. The ADCIRC model solves the depth-integrated shallow-water equation in spherical coordinates using the finite-element method while the SWAN model (Booij et al. 1999) solves the spectral wave action balance equation with different time steps. The fully coupled model allows for the interaction of wave and surge in coastal regions through the exchange of water levels, currents and radiation stresses (e.g., Chen et al. 2008).

The fully-coupled SWAN and ADCIRC use the same unstructured mesh that covers part of the Atlantic Ocean and the entire Gulf of Mexico. For instance, the SL15 mesh for the Louisiana coast has about 2.4 M nodes and 4.7M elements. The mesh resolution varies from 24 km in the Atlantic Ocean to about 50m in Louisiana and Mississippi. Seven tidal constituents are considered by harmonic constants at the open boundary. The time steps are 1 hr and 1 s for SWAN and ADCIRC, respectively. The coupled model runs parallel on a supercomputer from the Louisiana Optical Network Initiative (LONI), Queenbee, which has 668 nodes and each node has two 2.33 GHz Quad Core Xeon 64-bit Processors and 8 GB Ram. By using 102 nodes (816 cores), the running time is about 1 hr for the simulation of one actual day. If this fully-coupled surge and wave model is used to predict the waves and surges of 500 hypothetical hurricanes for extreme value analysis for the Louisiana coast alone, 100 TB of data would be generated. Such a database of computational data of storm surge and waves is valuable for data mining and dynamic data-driven forecast of an approaching hurricane. *Similar databases are needed to mitigate hazards for hurricane-prone areas in the U.S., and to enable scientific discovery. These databases should contain observational and computational data and would require a national infrastructure to archive, access, manage, update, and maintain.*

Efforts for the prediction of tsunami wave propagation and coastal inundation have been made in recent decades by scientists all over the world. Instruments for direct observations were deployed in the ocean basin, including seismometers, tide gages, buoys, and GPS stations. Tide gauge data provide rapid estimates of the likely location and extent of the tsunami source area (e.g., Lay et al., 2005). Numerical models, most of which are based on the nonlinear shallow water equations (NSWE), have been developed to predict the basin-scale tsunami wave propagation and coastal inundation (Titov et al., 2005). Recently, Boussinesq wave models have proved to be superior to the NSWE-based models for tsunami simulations, especially for landslide-generated tsunamis, in terms of physical features in modeling dispersive and breaking waves (Lynett et al., 2003, Tappin et al., 2008). The University of Delaware has recently developed a hierarchy of new models for tsunami generation, propagation and inundation. These include the 3D non-hydrostatic wave model with a moving bottom (Ma et al., 2011, Non-Hydrostatic Model, NHWAVE), the spherical Boussinesq wave model based on weakly nonlinear and weakly dispersive Boussinesq equations (Shi et al., 2011a, Kirby et al., 2011), and the FUNWAVE-TVD model based on the fully nonlinear Boussinesq model (Wei et al., 1995, Chen, 2006) and the Total-Variation-Diminishing (TVD) solver to improve the model performance in predicting wave runup, breaking and coastal inundation (Shi et al., 2011a, 2011b). The models have recently passed all the PMEL benchmark tests required by NOAA NHTMP for tsunami simulation and tsunami wave runup (Tehranirad et al., 2011).

For efficient forecast of co-seismic tsunamis, NOAA Center for Tsunami Research have been developing a tsunami propagation database based on numerical model runs (MOST, Titov, 1997) using the pre-defined unit tsunami sources along the known and potential earthquake zones in the Pacific, Atlantic, and Indian oceans. According to the NOAA report by Gica et al. (2008), 1160 unit sources have been simulated to provide Pacific, Atlantic and India ocean coverage. The propagation database can provide the computed maximum wave amplitudes and arrival time at offshore of an arbitrary coast by exploiting the linearity of the generation and propagation dynamics when tsunami sources are determined. The most important use of the database is that, as real time tide gage or buoy data are obtained, the earthquake source characteristics can be derived from an inversion of the gage data (Tang et al., 2006).

It is anticipated that new-generation tsunami models will be used in the future to update or develop new tsunami propagation databases which are a collection of tsunami propagation model results based on the pre-defined unit tsunami sources at selected locations along know and potential earthquake zones. The databases will provide a powerful tool to quickly and accurately capture earthquake source characteristics by integrating the pre-computed data and inversing the tide gauge or buoy data close to an earthquake site. The determined tsunami source will be used to drive the propagation and inundation models to produce a timely forecast for tsunami warning and emergency response. Similar to hurricane inundation prediction, *a unified and standardized national infrastructure is highly desirable to archive, access, manage, update and utilize both observational and computational data for tsunami inundation hazard prediction and mitigation.*

New-Generation of Computational Infrastructure

We propose to develop a next generation architecture enabling capabilities for many application types of inundation hazard mitigation. We will leverage powerful software already used by application communities in production scientific work, collectively used by well over a dozens of different research groups worldwide, such as Cactus.

The Cactus Framework (Goodale et al. 2003) is an open source, modular, highly portable, programming environment for collaborative high-performance computing, now primarily developed at LSU. Cactus has a generic parallel computational toolkit with components providing e.g. parallel drivers, coordinates, boundary conditions, elliptic solvers, interpolators, reduction operators, and efficient I/O in different data formats. Generic interfaces are used, (e.g. an abstract elliptic solver API) making it possible to develop improved components which are immediately available to the user community. Cactus is used by numerous application communities internationally, including Numerical Relativity, Climate Modeling, Astrophysics, Biological Computing, CFD, and Chemical Engineering. It is a driving framework for many computing projects. Cactus is distributed with a unigrid MPI parallel driver, but codes developed in it can also already use multiple adaptive mesh refinement drivers with minimal or no changes to the code, including Carpet (Schnetter et al. 2003) etc. Unstructured mesh drivers are being incorporated, and the ADCIRC and FUNWAVE-TVD code, central to this project, will be ported to Cactus. An open source toolkit for CFD using GPU is also under development through CCT. Cactus already has many desirable capabilities: portability; platform independence, parallel checkpoint/restart; and very importantly, generic parameter steering, http, and other monitoring interfaces; performance monitoring; and logging.

Summary

Focusing on the rich, urgent and relevant scientific problems of inundation modeling in riverine and coastal environments, we propose to create a unified and standardized cyberinfrastructure for a new generation of dynamic data-driven predictions of flood hazards based on the existing computational framework **Cactus** and emerging standards. We have identified the similarities of coastal flooding caused by geo-hazards (earthquakes and landslides) and atmospheric-oceanic hazards (tropical cyclones and extra-tropical storms) and the needs for a national infrastructure to archive, access, manage, update and utilize both observational and computational data and to enable scientific discoveries for inundation hazard mitigation. The real time coupling of computational and observational data and complex workflows will allow dynamically invoking more accurate models and algorithms as a hurricane and tsunami approaches the coast, choosing appropriate computing resources, comparing model results with actual observations, and coupling inundation models with evacuation and warning systems to reduce hurricane or tsunami flooding damage. Such a national infrastructure for inundation hazards will facilitate inter-disciplinary collaborations, as hazard mitigation is not only a subject of geosciences but also involves many other disciplines, such as engineering and social sciences.

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