**DIETRICH, NCSU**

**DHS Coastal Resilience Center**

**Research Project:**

**Annual Project Performance Report**

Covers reporting period January 1, 2016 – June 30, 2016

1. **Project Title:**

   Improving the Efficiency of Wave and Surge Models via Adaptive Mesh Resolution

2. **Principal Investigator / Institution:**

   Joel Casey Dietrich, Assistant Professor, North Carolina State University

3. **Other Research Participants/Partners:**

   Clint Dawson, Professor, University of Texas at Austin

4. **Short Project Description:**

   Coastal communities rely on predictions of waves and flooding caused by storms. These predictions are used during the storm to make decisions about resource deployment and evacuation, and these predictions are also used between storms for design and to establish insurance rates for local homeowners. Computational models are essential for making these predictions, but they can be costly. A typical prediction can require hundreds or even thousands of computational cores in a supercomputer, and several hours of wall-clock time. In this project, we will improve the performance of a widely-used, predictive model. Its representation of the coastal environment will adapt during the storm, to better utilize the computing resources and ultimately provide a faster prediction. This speed-up will benefit coastal communities, including emergency management personnel, who will have more time to make decisions during the storm event. It will also benefit long-range planners, such as flood mappers, who will be able to consider larger, more-accurate models in the same amount of time.

5. **Abstract:**

   Storm-induced waves and flooding can be predicted using computational models such as the ADCIRC+SWAN modeling system, which has been used by DHS and its constituent agencies for mapping of floodplain flood risk and forecasting of storm surge and inundation. This modeling system has been shown to be efficient in parallel computing environments. It is implemented on static meshes and with a static parallelization, and thus it does not evolve as a storm approaches and inundates a

coastal region. This implementation can be suboptimal when large portions of the mesh remain dry during the simulation.

In this project, we will optimize the parallel implementation of ADCIRC by using a large-scale adaptivity, in which a mesh will be refined by incorporating entire portions of another, higher-resolution mesh. Instead of subdividing an individual element, we will increase resolution by adding elements from a pre-existing mesh that has been well-validated. This procedure will leverage the existing suites of meshes for the same geographic region. The adapted mesh will be rebalanced among the computational cores so that geographic regions with increased resolution will not be concentrated on a disproportionally-small number of cores, and so that the time spent on inactive regions is minimized. These technologies will decrease the computational cost and better utilize the available resources.

This project will develop technologies to improve the efficiency of ADCIRC+SWAN simulations, thus allowing for more model runs in ensemble-based design applications, and for faster simulations in time-sensitive applications such as operational forecasting. These outcomes will increase the accuracy of flood risk products used in building design and the establishment of flood insurance rates, and thus lessen the impact of a disaster. These outcomes will also improve the communication and understanding of potential hazards.

6. **End users:**

The proposed enhancements to efficiency will benefit all model users, including several DHS agencies with missions related to coastal flooding. In its development of Flood Insurance Rate Maps (FIRMs), FEMA will benefit because the probabilistic guidance requires a large number of deterministic simulations, and the approach described in this project will require fewer computational resources. For example, if a flood mapping study would see an efficiency gain of, say, 10 percent, then the study could be completed in a shorter time. Alternatively, that efficiency gain could be reinvested into increasing the mesh resolution and/or considering a larger suite of storms, and thus increasing the accuracy of the model results. FEMA stakeholders have agreed to participate as transition partners. The project will also help to speed the delivery of projected flood inundation levels associated with coastal storms, thereby assisting FEMA as well as state and local emergency managers to plan for coastal evacuations and deployment of resources and personnel. In addition, the Coast Guard will benefit from faster guidance about waves and surge and therefore can make operational decisions about the possible relocation of assets in advance of an oncoming storm. The project personnel will continue to work with the transition team to identify additional end-users in these and other DHS constituent agencies.

With the Texas State Operations Center, the project personnel will work to transition the analysis products that are used for guidance by the emergency management leadership. They have worked with forecast guidance for the Texas coastline in previous seasons, and are supportive of the proposed work to improve the speed of the forecasts. This partnership is important because it will connect the products with end users at the state and local levels.

The proposed work will also benefit ADCIRC model users at other federal agencies. The USACE Engineer Research and Development Center, NOAA NCEP, and the NOAA West Gulf River Forecast Center have agreed to participate as transition partners. In some cases, and especially for partners who are focused on operational modeling with ADCIRC, these activities will take the form of guidance about development with the goal of transitioning products to their work in the long term.

The project personnel will also work closely to transition the project outcomes to the ADCIRC modeling community. These transition activities will connect with **Jason Fleming** and **Carola Kaiser**, who are key members of the Coastal Emergency Risks Assessment (CERA) group. They operate the forecasting systems for regions along the U.S. Gulf and Atlantic coasts, and they visualize and communicate the forecast guidance via a Google Maps application. Dr. Fleming also manages the software repository for the development of ADCIRC. The project personnel will work with these partners to ensure that the new modeling technologies can be incorporated within the forecasting system and the release version of ADCIRC.

The PIs have scheduled for quarterly videoconferences with the end users identified above. We held our first videoconference on Wednesday, 30 March 2016, and we shared our preliminary results for the static load balancing, which has improved the speed of ADCIRC by about 20 percent in our initial tests. That videoconference resulted in the following action items:

- Work with Jason Fleming (Seahorse Coastal Consulting) to push our preliminary code changes into the ADCIRC code repository, for use in testing for the upcoming season.
- A USACE ERDC stakeholder was concerned about how the additional cuts in the subdomains and how this will work for finer resolution meshes. This comment will lead to future research on how to optimize the domain decomposition.
- A NOAA stakeholder noted that the research will have a clear benefit to NOAA operational forecasting. Later that morning, he shared an unstructured mesh with floodplain coverage from Texas through Maine, which we will use for initial testing of the adaptive meshing.
- Teresa Howard and Gordon Wells (Texas State Operations Center) asked about connections of the dynamic adaptivity with the web mapping tools that they use, which may lead to future research directions. They also suggested a connection with NOAA West Gulf River Forecast Center; that stakeholder has since agreed to be an end user for this project.

Thus we are already working with our transition partners, and information is flowing in both directions. They have identified some future directions for our research, and we are sharing our technologies with them. The project technologies will be shared as they become available, and our transition partners will be trained and then test the technologies for applications ranging from operational forecasting to engineering design. The technologies developed in this project will also be released to the ADCIRC modeling community. This work will require the development of extensive documentation and example files, which will be hosted online, and the integration of the software into the release version of ADCIRC.

7. **Explanation of Changes:**

This project has not had any changes to its approved workplan.

8. **Unanticipated Problems:**

This project has not had any unanticipated problems or challenges.

9. **Project Outcomes:**

This project will develop technologies to improve the efficiencies of the ADCIRC+SWAN modeling system in parallel computing environments. It will develop automated routines for an adaptive, multi-resolution approach to employ high-resolution, unstructured meshes for storm surge applications, and it will develop automated routines for the efficient re-balancing of the computational workload via parallelized domain decomposition. These routines will better utilize the available computing resources by ensuring that every core is busy during the entire simulation. These routines will be shared (with extensive documentation and examples) with the ADCIRC modeling community, including the ASGS for operational forecasting.

These technologies will decrease the time required for an ADCIRC simulation, thus allowing for more model simulations in ensemble-based design applications, and for faster simulations in time-sensitive applications such as operational forecasting. These outcomes will increase the accuracy of flood risk products used in building design, land use planning and the establishment of flood insurance rates, and thus lessen the impact of a disaster. These outcomes will also improve the communication and understanding of potential hazards to individuals, community officials, the insurance industry, and government agencies.

The project has made a lot of progress in the first six months, in three key areas. First, we have focused on code modifications to ADCIRC to improve its load balancing. The pre-processor was rewritten to improve its decomposition of the domain for use on a parallel computer. Before, all regions were treated equally, regardless of whether they were in the open ocean or far into the floodplain, and the result was that the overall workload was not distributed evenly across the cores in the parallel computer.  Some cores were working much harder than others.  Now, the domain is decomposed twice; the wet regions are split evenly among the cores, and then the dry regions are split evenly among the cores.  All cores are contributing equally to the overall workload at the start of the simulation.  This is the first step toward a dynamic rebalancing, in which the domain will be decomposed periodically during the simulation to optimize efficiency, and which is a necessary step toward the adaptivity in the third part of this project.  Preliminary results are promising.  In a hindcast of Hurricane Irene (2011) using the state-of-the-art ADCIRC model for North Carolina, the improved load balancing caused a speed-up of about 20 percent for simulations of tides, winds, and coastal flooding.  This 20-percent speed-up is significant because it will lead to shorter simulations in real-time forecasting, and thus more time for the guidance in each forecast cycle to be interpreted by end users.

Second, we are exploring methods to optimize the design of unstructured meshes in coastal regions.  ADCIRC uses unstructured meshes because it allows for increased resolution to represent small-scale flows in inlets, near barrier islands, within bays and estuaries, and over floodplains.  The ADCIRC community has become smarter about how to design meshes and where to increase the resolution, but these methods are still *ad hoc*.  The mesh designer has to make an educated guess about where the resolution will be needed, based on previous experiences.  This project is developing techniques to quantify the mesh-related errors in the ADCIRC simulation, and then use those errors to design better meshes.  The error measures are localized, related to mass balance and solution convergence, and can be used to show how regions within the mesh will perform relative to each other.  If one region has lower errors but another region has higher errors, then resolution could be moved between regions to better distribute the errors in the solution.  This is another step toward the adaptivity in the third part of this project.  Initial results are promising.  In hindcasts of Irene (2011) and Isabel (2003), we are quantifying the errors and examining their spatial distributions.  Then we will redesign the mesh to better distribute the errors, and ultimately improve the accuracy of the simulation.

Third, we are developing techniques to map solutions between meshes with varying levels of resolution.  By using the interpolation techniques within the Earth System Modeling Framework (ESMF), the solution from one mesh (e.g. a coarser mesh) is mapped onto a different (e.g. finer) mesh, in a way that is fast and conservative.  The simulation may start with the coarser mesh, then add resolution in regions near where the storm is projected to make landfall, and then continue on this finer mesh until new information becomes available.  The results from the coarser mesh will be used to hot-start the continued simulation on the finer mesh.  We have a prototype framework working already, and initial results are promising.  We have developed an automated tool called the ADCIrpolate to map the results between meshes, and we have performed initial testing of the system by using results from a coarser mesh to hot-start a simulation on a finer mesh of the East Coast of the U.S.  The comparison of the results has shown a near-identical match between simulations on coarse-only, coarse-then-fine, and fine-only meshes.  This is a necessary step toward a multi-resolution adaptivity during storm forecasts.

## 10. Research Activity and Milestone Progress:

### Research Activities and Milestones: Progress to Date

| **Reporting Period 1/1/2016 – 6/30/2016** | | | |
|---|---|---|---|
| **Research Activity** | Proposed Completion Date | % Complete | Additional information about activity / milestone |
| Parallelization of ADCIRC domain decomposition | 06/2016 | 100 | Described above |
| Interpolation of ADCIRC results from coarse to fine meshes | 06/2016 | 100 | Described above |
| **Research Milestone** | | | |
| Presentation at ADCIRC workshop | 04/2016 | 100 | This workshop was held at USACE ERDC on 5-6 May 2016, and is attended by users and developers of the ADCIRC modeling system.  We presented preliminary results about the optimization of unstructured mesh construction, described above. |

## 11. Transition Activity and Milestone Progress:

### Transition Activities and Milestones: Progress to Date

| Reporting Period 1/1/2016 – 6/30/2016 | | | |
|---|---|---|---|
| **Transition Activity** | Proposed Completion Date | % Complete | Additional information about activity / milestone |
| Developmental ASGS instances at NCSU and UT-Austin | 03/2016 | 100 | These are research-grade versions of the forecasting systems used elsewhere for real-time guidance during storms. Our local versions are not run daily, but they can be started as necessary. In previous years, we have used an instance at UT-Austin to provide guidance directly to partners at the Texas State Operations Center. These instances will allow us to test our research products before passing them to the community. |
| **Transition Milestone** | | | |
| Quarterly progress updates, feedback from transition partners | 03/2016<br>06/2016 | 100<br>100 | We received feedback from Jason Fleming, Mary Cialone, Jesse Feyen, Teresa Howard, and Gordon Wells, on topics ranging from test cases to consider, to ways to transfer information to the community, to additional partners to include. Please see the discussion in Section 6 above. |
| Sharing of developmental forecast guidance with G Wells, T Howard | 05/2016 | 100 | As noted above, in previous years, we have used a research-grade version of the forecasting system at UT-Austin to provide guidance directly to these partners at the Texas State Operations Center. This instance was in place for the 2016 hurricane season. |

## 12. Interactions with education projects:

This project has initiated involvement with the CRC's MSI education partners in two ways. First, PI Dietrich visited Jackson State University (JSU) in early May and presented a seminar about current research in storm surge modeling and forecasting. The seminar was on 4 May 2016, and it was attended by a combination of graduate students and faculty members from JSU. The first half of the seminar was a summary of the last decade of PI Dietrich's research, with a focus on storm surge modeling along the northern Gulf coast, and with an emphasis on experiences in graduate school and beyond. The second half of the seminar was an introduction to and preliminary results from this CRC project. The seminar was well-received with many questions from the audience. The presentation has been archived on PI Dietrich's institutional web site, and notice of the seminar was shared with CRC leadership.

Second, Co-PI Dawson is hosting a PhD student from JSU at UT-Austin during this summer under the CRC SUMREX program. Xuesheng Qian is a PhD candidate in coastal engineering, and is visiting UT-Austin to learn the SWAN+ADCIRC wave and surge models. Qian has learned how to run the model on the HPC machines at UT Austin, how to use the Surface Water Modeling System to generate/modify finite element meshes and data used in the models, how wind files are generated and used, and has been working with Dawson and JSU researcher Bruce Ebersole to run the model for storms in the Texas Gulf Coast area. With this training, Qian will be able to teach other researchers at JSU how to run the model.

## 13. Publications:

This project does not yet have any articles submitted for publication.

## 14. CRC Performance Metrics:

| CRC Performance Metrics | | | |
|---|---|---|---|
| **Metric** | **Research** | **Education** | **Center** |
| Courses/certificates developed, taught, and/or modified | | See Table | |
| Enrollments in Center-supported courses/certificates | | | |
| HS-related internships (number) | 0 | | |
| Undergraduates provided tuition/fee support (number) | 0 | | |
| Undergraduate students provided stipends (number) | 0 | | |
| Graduate students provided tuition/fee support (number) | 3 | | |
| Graduate students provided stipends (number) | 3 | | |
| Undergraduates who received HS-related degrees | 0 | | |
| Graduate students who received HS-related degrees | 0 | | |
| Certificates awarded (number) | | | |
| Graduates who obtained HS-related employment | 0 | | |
| SUMREX program students hosted (number) | 1 | | |
| Lectures/presentations/seminars at Center partners | 1 | | |
| DHS MSI Summer Research Teams hosted (number) | 0 | | |
| Journal articles submitted (number) | 0 | | |
| Journal articles published (number) | 0 | | |
| Conference presentations made (number) | 2 | | |

| | | | |
|---|---|---|---|
| Other presentations, interviews, etc. (number) | 1 | | |
| Patent applications filed (number) | 0 | | |
| Patents awarded (number) | 0 | | |
| Trademarks/copyrights filed (number) | 0 | | |
| Requests for assistance/advice from DHS agencies | 0 | | |
| Requests for assistance/advice from other Federal | 0 | | |
| Total milestones for reporting period (number) | 6 | | |
| Accomplished fully (number) | 6 | | |
| Accomplished partially (number) | 0 | | |
| Not accomplished (number) | 0 | | |
| Product/s delivered to end-user/s (description and | See Table | | |
| External funding received | See Table | | |
| Leveraged support | | | |
| Articles on Center-related work published on website | | | |
| Coverage in media, blogs (number) | | | |
| Social media followers (number) | | | |
| Posts to social media accounts (number) | | | |
| Events hosted (number) | | | |
| Website hits (number) | | | |

## Table for Documenting CRC Research Project Product Delivery

| Product Name | Product Type | Approx. Delivery | Recipient or Anticipated End |
|---|---|---|---|
| ADCIRC forecast | Guidance | June-Nov 2016 | G Wells and T Howard, Texas |
| | | | |

## Table for Documenting External Funding and Leveraged Support

| External Funding | | | |
|---|---|---|---|
| Title | PI | Total Amount | Source |
| Travel funds to Computational Methods in Water Resources Conference to present research findings | Dietrich | $1,112.19 | NCSU CCEE Department |
| | | | |

| Leveraged Support | |
|---|---|
| Description | Estimated Annual Value |
| NSF XSEDE allocation of 5.7M CPU-hours combined for supercomputers at UT-Austin, NICS and SDSC | $199,767.50 |