DIETRICH, NCSU
DAWSON, UT-AUSTIN
DHS COASTAL RESILIENCE CENTER
RESEARCH PROJECT
YEAR 3 PERFORMANCE REPORT
AND
FINAL PROJECT REPORT

Project Title:

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

Principal Investigator Name/Institution:

Joel Casey Dietrich, Assistant Professor, North Carolina State University

Co-Principal Investigators and Other Partners/Institutions:

Clint Dawson, Professor, University of Texas at Austin

Project Start and End Dates:

1/1/2016 – 6/30-2018

Short Project Description:

Coastal communities rely on predictions of waves and flooding caused by storms. 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 managers, 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.

Summary 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 inefficient when large portions of the mesh remain dry during the simulation.

In this project, we are optimizing 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 are increasing resolution by adding elements from a pre-existing mesh that has been well-validated. This procedure leverages the existing suites of meshes for the same geographic region. The adapted mesh is rebalanced among the computational cores so that geographic regions with increased resolution are not 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 is developing technologies to improve the efficiency of ADCIRC 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.

PROJECT NARRATIVE:

1. Research Need:

The goal of this research project is to speed up the ADvanced CIRCulation (ADCIRC) and Simulating WAves Nearshore (SWAN) models. The tightly-coupled ADCIRC+SWAN modeling system is used extensively by DHS and its constituent agencies for the prediction of storm-induced waves and flooding. We are improving the efficiency of the modeling system, and thus reducing its computational cost. This work is relevant to the DHS mission to ensure resilience to disasters, as articulated in its Strategic Plan and Quadrennial Review, specifically its Goals 5.1 (Objectives 5.1.1 and 5.1.2) to reduce vulnerability and mitigate risks associated with natural hazards, and its Goal 5.3 (Objective 5.3.1) to provide timely and accurate information during a storm event. The efficiency improvements in this project will allow for more model simulations in ensemble-based design applications, which 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. The efficiency improvements in this project will also allow for faster simulations in time-sensitive applications such as operational forecasting, and thus improve the communication and understanding of potential hazards.

This project will benefit DHS and the Homeland Security Enterprise in two ways: a more-efficient ADCIRC model will allow for more model runs in ensemble-based design application, and for faster simulations in time-sensitive applications such as operational forecasting. In its development of Flood Insurance Rate Maps (FIRMs), FEMA will benefit because the probabilistic framework requires a large number of simulations, which will now require fewer computational resources, and thus the studies can be completed in a shorter time and/or consider a larger suite of storms. We are working with FEMA engineers Jon Westcott, Tucker Mahoney, Christina Lindemer, and Rafael Canizares, with whom we are sharing research progress and receiving feedback on future directions. In their use of flood predictions provided in real-time by the ADCIRC community, state-level emergency managers will benefit because by now having more time to consider the forecast guidance in their decision-making. We are working with partners at the Texas State Operations Center and NC Emergency Management. We also have partners in the USACE, NOAA, and academia, as described below.

2. Project History:

This project is developing technologies to improve the efficiencies of the ADCIRC modeling system in parallel computing environments. ADCIRC utilizes an unstructured mesh, which is a highly-flexible, multi-scale representation of the coastal environment. This project is developing automated routines for an adaptive, multi-resolution approach to employ high-resolution, unstructured meshes for storm surge applications, and it is developing automated routines for the efficient re-balancing of the computational workload via parallelized domain decomposition.

Over two decades of performing storm surge hindcasting and analysis, and through the efforts of dozens of researchers in academia, government and industry, the ADCIRC community has developed extensive high-resolution models of the Gulf and Eastern Coasts of the U.S. These region-specific models have been developed to analyze storms impacting, e.g. Texas, Upper Texas-Louisiana, the Northern Gulf of Mexico, the Carolinas, the Northeast-New England region, etc. In most cases, these models are too expensive to be of use in storm surge forecasting, which requires simulations to be performed in typically 1-1.5 hours; however, the resolution within these models could provide much more accurate predictions of storm surge for use by emergency managers. This motivated our research on “adaptive mesh resolution.” The idea behind this approach is simple on the surface: use a less refined mesh when the storm is still far from land and/or the track is still uncertain, then, at some intermediate point of the calculation, stop the run, interpolate the solution onto a higher resolution mesh, and finish the simulation on this mesh. The expected outcome of this work is to provide a solution with comparable accuracy to a high-resolution simulation in much less computing time.

The first milestone in this project was to develop a fast interpolation routine that could read ADCIRC hotstart files and interpolate the results from one mesh to another. This led to the development of the beta version of the software program ADCIRpolate. The next milestone was to test the algorithm on some simple test problems. This was completed in the first year of the project. The third milestone was to extend the entire process to handle floodplain regions, which has been challenging and took several iterations until we came up with a solution. We have made substantial progress in the past year to the point where we have been able to perform a complete simulation of Hurricane Harvey, starting with coarser resolution in the Texas floodplains and running for about 1 day of simulation, then interpolating onto a higher-resolution mesh (developed specifically for hurricanes impacting Texas) for the remainder of the simulation.

The other component of this research project has been the treatment of dry regions within our high-resolution meshes. These meshes have evolved to have millions of elements in overland floodplains, so that ADCIRC can push floodwaters into these regions during the storm. However, when these regions are dry, either before / after the storm or when the storm is far away, then there is nothing for ADCIRC to compute. For the computational cores assigned to these dry regions, there is nothing to do, and thus these resources are wasted. This motivated our research on “dynamic load balancing.” The idea behind this research is to better distribute the dry regions, so that they are contained on only a few cores. Then more of the cores will be available to compute the flooding in wet regions. This technology will adapt during the storm, as regions become wet and then dry again. By better distributing the workload over the cores, ADCIRC will become more efficient for simulations of flooding into overland regions.

The first milestone in this project was to modify the existing code in ADCIRC for its domain decomposition. A new routine was added to its source code to perform the domain decomposition at the start of the simulation, so each computational core is now responsible for developing its own set of input files. This new routine can also be called periodically during the simulation, to re-perform the domain decomposition, and thus re-balance the workload among the cores. The second milestone was to test this new routine on simple test problems. In our initial tests, the efficiency gain was about 25 percent. These milestones were completed in the first year of the project. However, while working with collaborators at the University of Notre Dame, we determined that this new routine would not scale, i.e., the efficiency would not increase for larger problems on larger numbers of cores. Thus our third milestone was to rewrite this routine to use the Zoltan library for adaptive domain decomposition. This library can control how computational points are migrated between neighboring sub-domains, instead of starting each decomposition from scratch. This implementation has provided further speed-ups in the wall-clock time. We have made substantial progress in the past year, to where now the dynamic load balancing is being tested on realistic domains for realistic storms.

3. Results:

Our joint research in adaptive mesh resolution and dynamic load balancing has led to a set of outcomes and findings that will improve the efficiency of ADCIRC simulations.

The final results of the adaptive mesh resolution research can be summarized as follows. The outcomes of the research include the software ADCIRpolate, which uses many of the interpolation routines in the open-source Earth System Modeling Framework (ESMF). ADCIRpolate reads an ADCIRC hotstart file generated on one mesh (call it Mesh 1), and interpolates it onto another mesh (call it Mesh 2). If Mesh 1 and Mesh 2 cover the exact same domains, this process is straightforward. The difficulty in our project is that Mesh 1 and Mesh 2 may differ substantially, especially in floodplain areas. This required developing some extensions of the ESMF software to handle extrapolation and wetting and drying, and to make some modifications to the hostart capability of ADCIRC, which historically has been based on simply hot-starting a calculation on the same mesh/domain. Some of these modifications are still undergoing debugging and testing. However, during the past six months, we have been able to perform a complete simulation of Hurricane Harvey using this process, described below.

Hurricane Harvey proved to be a great test case for our project and for CRC-related research in general. It developed over the southwestern Gulf of Mexico during the week of August 20th, 2018. On August 23rd-24th it quickly developed from a tropical storm to a Category 4 hurricane. It made its first landfall on August 25th near Port Aransas, TX, causing extensive damage to the coastal bend region. During this time period, we worked extensively with Jason Fleming and Carola Kaiser through the CRC, our project transition partners Gordon Wells at the Texas State Operations Center and Derek Giardino at the NOAA West Gulf River Forecast Center, and the

Texas Advanced Computing Center (TACC), to operate the ADCIRC Surge Guidance System (ASGS). We generated real-time storm surge forecasts on two models with different resolutions, the recently developed NOAA Hurricane Storm Surge Forecasting on Demand System (HSOFS), which covers the entire Gulf and Eastern Coasts of the U.S., and a mesh (Texas 35h) developed specifically for Texas hurricanes, with higher resolution in the Texas floodplains. The Texas 35h results were used extensively in the Texas State Operations Center to make decisions regarding transportation, staging, evacuations, etc. Overall the ASGS performed admirably on all storms during the 2017 hurricane season.

Hurricane Harvey provided a great test case for adaptive mesh refinement. Using the best track hurricane wind information, we begin the calculation on the HSOFS mesh during the first 1-1.5 days of the storm. At that point the track was pretty well established, so we use ADCIRpolate to interpolate the results from HSOFS to the Texas 35h mesh and complete the simulation. We observed essentially no difference in the maximum water levels produced by the interpolation vs. performing the simulation entirely on the finer mesh. This result was presented at the CRC 2018 Annual Review. ADCIRpolate only takes a few minutes to do the interpolation, therefore this approach could provide substantial savings in computation time, though a complete analysis of the approach is ongoing.

After the simulation has been interpolated and continued on the high-resolution mesh, it will need to be smarter about how it handles the dry regions, which may make up half of the computational domain. Thus we have also focused our research on dynamic load balancing. For this part of our research, the outcome has been the implementation of a capability within ADCIRC to re-decompose the computational workload at selected points during the simulation. The first iteration of this implementation was within the existing ADCIRC code, by switching it to rely on the parallel version of the METIS domain decomposition library. The ADCIRC pre-processor was integrated within the regular code. The simulation is now started with the global input files, which are then localized by each core before they start their time-stepping. Then the re-decomposition was performed by writing and reading information from the hotstart files. When an imbalance was detected, the simulation would write its information to a hotstart file, close a lot of its computations, perform the re-decomposition, and then read information from the hotstart file. In this way, the information was 'migrated' between neighboring sub-domains, but by writing and reading information from the disk.

This implementation used a lot of the existing structures and routines within ADCIRC, and it was promising on small test problems. We have been testing on an idealized, rectangular domain, in which the bathymetry is varied from about 4 m below sea level to about 2 m above sea level. In this domain, about one-third of the area is dry, and about one-half of the computational points are dry. By forcing a 1-m tide at the ocean boundary, we can cause a lot of wetting and drying during the simulation, and thus test our dynamic load balancing. These tests were promising. When the simulation was performed on small numbers of cores, say 16 to 48, the speed-ups were 25 to 30 percent, which would be a significant improvement in accuracy. However, when the simulation was performed on a large number of cores, say 96 cores, then the simulation would slow down. This loss in efficiency was due to the combined effects of writing/reading information from the hotstart files, as well as the increased costs associated with putting less than 1000 mesh vertices on a core. These behaviors were also seen in tests on realistic domains. We ran a simulation of

Hurricane Irene on the high-resolution mesh to describe coastal North Carolina, which contains the floodplains surrounding Pamlico Sound, over which the storm moved and caused a lot of flooding. For tests on small numbers of cores, the speed-ups were again about 20 to 25 percent, but for tests on large numbers of cores, the speed-ups were minimal. This initial implementation has provided a lot of the framework for the dynamic load balancing, but its reliance on external hotstart files was a limitation.

In the past year, and working with collaborators at the University of Notre Dame, we have updated the framework to instead use the Zoltan library. This library was developed at the Sandia National Laboratories, is open source, and can automate the migration of simulation information through the network to neighboring sub-domains. By integrating this library within the ADCIRC code, we can now pass information without writing and reading it from the hotstart files. The simulation can proceed without having to restart so completely. This capability has been tested on the idealized, rectangular domain described above, and it has proven to scale efficiently to large numbers of cores and configurations. We are now testing it on realistic domains for tidal simulations, and the capability is continuing to scale efficiently. When this capability is implemented within ADCIRC and released to the community, it has the potential for a significant speed-up of our simulations of coastal flooding. Our ongoing research is focused on a complete analysis and testing of this dynamic load balancing.

To summarize our findings:

- We developed ADCIRpolate, a parallel software tool that interpolates/extrapolates ADCIRC hot start data from one mesh to another. It is an open source tool that will be transitioned to the ASGS, to our partners and to the ADCIRC community at large. The tool has been demonstrated to work on examples without and with floodplains, and it has been applied to Hurricane Harvey and shown to be effective.
- We implemented a dynamic load balancing within ADCIRC, first by using the existing routines and framework, and then by integrating the Zoltan library. This capability has been demonstrated to work on idealized and realistic examples for tide-driven flooding, and it is being tested now for storm-driven flooding on large domains.

4. <u>End Users and Transition Partners</u>:

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. 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 be able to 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 are working 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. This partnership is important because it connects 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, the NOAA NCEP, and the NOAA West Gulf River Forecast Center, are participating as transition partners. For partners who are focused on operational modeling with ADCIRC, these activities are taking the form of guidance about development with the goal of transitioning products to their work in the long term.

The project personnel also work closely to transition the project outcomes to the ADCIRC modeling community. These transition activities are connected 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 are working with these partners to ensure that the new modeling technologies can be incorporated within the forecasting system and the release version of ADCIRC.

During this project year, the research team facilitated the transfer of research products to these transition partners via two methods:

- Progress reports via videoconference, during which the research team shared interim results from our activities, and our transition partners provided guidance about future directions. Their feedback and suggestions are valuable as we move our research products into something useful for production.
- We are working with Jason Fleming to transition a static load balancing into the ADCIRC version used for forecasting in North Carolina, so it can benefit from a gain in efficiency. The latest development version of ADCIRC was modified so its static domain decomposition will account for the relative costs of dry and wet computational points. Preliminary tests, even with this most-basic of changes, have shown a speed-up of 10-20 percent compared to the existing release version of ADCIRC. We continue to work on more-sophisticated methods that will offer enhanced efficiency gains.
- Over the next year, ADCIRpolate will be transitioned into the ASGS with the help of Jason Fleming. We will work with Fleming on automating ADCIRpolate within the ASGS and developing a beta version of the software for the 2019 hurricane season.

Thus, we are 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.

The following testimonial is from Gordon Wells about the use of ADCIRC forecasts in the Texas State Operations Center during Harvey:

> *"In the Texas State Operations Center, where state and federal agencies coordinate the response to major disasters, ASGS web services and data products were used extensively during Tropical Storm Cindy and Hurricane Harvey, as well as for Hurricane Irma. As TS Cindy approached the Upper Texas Gulf Coast in late June, the Texas Department of Transportation (TXDOT) used ASGS forecasts available from the CERA website to monitor safe operation of the Bolivar Ferry system between Galveston Island and Bolivar Peninsula. Although the storm tide began to approach the 5-foot AMSL elevation limit on June 20-21, the ASGS forecasts showed that the limit would not be exceeded, and TXDOT management decided to continue ferry operations without interruption. Access to the ferry service allowed a Texas Army National Guard motorized company to stage from Galveston Island while assisting search-and-clear activities on Bolivar Peninsula rather than redeploying through Houston across to the eastern side of the peninsula, which would have required several hours in transit. Both TXDOT and the Texas Military Department expressed their satisfaction with the use of ASGS predictive services during TS Cindy that led them to make more effective decisions during the state's response.*
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> *"In late August, as Hurricane Harvey rapidly intensified off the Coastal Bend of Texas in late August, ASGS forecasts were again used by TXDOT to determine the timing of causeway closures to North Padre and Mustang islands, the cessation of ferry operations at Port Aransas and the continuation of swing-gate operations along the Intracoastal Waterway. Texas Task Force 1 search-and-rescue coordinators and the Texas Army National Guard used ASGS predictions of the maximum storm surge elevations to plan rapid re-entry operations into the impact region. The Texas Department of Public Safety used the ASGS forecasts to determine whether their offices and staging areas in Corpus Christi were on safe ground as well as the locations of emergency communications facilities. For several days following the initial landfall, as Harvey lingered along the Texas coastline, several state agencies and the state mass care coordinator used the forecast wind speed time series feature of the CERA web service to determine when it would be safe to move high-profile vehicles into and from damaged coastal towns.*
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> *"As field operations were winding down for Hurricane Harvey, FEMA strike team coordinators in the State Operations Center were preparing to depart for Florida and the arrival of Hurricane Irma. Impressed with the Harvey guidance products, several FEMA personnel regularly checked the ASGS forecast for the Florida Keys using the CERA web service. Initial concerns were focused on Key West, but ASGS correctly predicted the maximum impacts would occur about 10 miles to the east in the area of Cudjoe Key."*

The following testimonial is about the use of ADCIRC forecasts at the West Gulf River Forecast Center during Harvey:

> *During Harvey while at the Texas State Operations Center ADCIRC was used within the final 12 hours and after land fall to monitor the impact that the rapid intensification would have on the localized inundation along all of the Gulf Coast. By displaying accurately where surge inundation was occurring down at the local (street) level, key decisions for response were being made by multiple agencies particularly along the bays. The particular area the ADCIRC results were proven extremely useful was the funneling of water into the Lavaca Bay and other parts of Matagorda Bay. One particular issue was transferring search and rescue equipment and personnel from Rockport area (landfall location) up into Houston (severe flooding). The surge itself along with the surge preventing river flooding from draining was making several roads along the coast impassable. This made moving this equipment and personnel a challenge because time was of the essence, and turning around to find a route around the flooding would have taken hours. Working in conjunction with Texas Task Force 1 (search and rescue team) we developed a route around the flooding area. This rerouting saved a lot of time that would have been lost if these vehicles attempted to find their own path and were forced to turn around several times.*
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> *The accuracy level that ADCIRC provides from surge inundation allows the response and recovery effort on a local scale to be performed more efficiently than ever before and undoubtedly is vital to the decisions emergency managers must make as a tropical system impacts their jurisdiction.*

5. Project Impact:

This project is developing technologies to improve the efficiencies of the ADCIRC modeling system in parallel computing environments. It is developing automated routines for an adaptive, multi-resolution approach to employ high-resolution, unstructured meshes for storm surge applications, and it is developing automated routines for the efficient re-balancing of the computational workload via parallelized domain decomposition.

The initial motivation for adaptive mesh refinement was to speed up the forecast capabilities of ADCIRC and improve the ASGS. Over the next year, we will work with Jason Fleming and other ASGS developers to incorporate ADCIRpolate into the ASGS as a beta version for the 2019 hurricane season. The adaptive capability has also motivated future ADCIRC-related projects within the CRC. Our next phase will be to develop capability to interpolate HSOFS results onto a number of ADCIRC models of Texas, the Northern Gulf, the Carolinas, and the Northeast/New England. In addition, there are extensions of this work beyond hurricane forecasting. We also could substantially speed up post-storm analysis and scenario analysis by allowing for the use of high-resolution meshes targeted to specific regions and specific locations, but also allowing for pre-storm tidal spin-up and storm initiation to be executed on a coarser mesh.

The capability for dynamic load balancing has the potential to benefit all ADCIRC simulations, including the real-time forecasting in the ASGS. These routines better utilize the available computing resources by ensuring that every core is busy during the entire simulation. One benefit of these new routines is that they will be blind to the user; the workload will be rebalanced automatically, without requiring input from the user. Thus it will not be necessary for users to know Zoltan or the other mechanics of the domain decomposition. The efficiency gains will be shared by all users. These new routines will be shared (with extensive documentation and examples) with the ADCIRC modeling community, including the ASGS.

6. Student involvement and awards:

At NC State, this project has supported one graduate student: Ajimon Thomas, who is working toward a PhD in coastal engineering. He has focused on a high-resolution hindcast for Hurricane Matthew along the U.S. Atlantic coast; this hindcast will be used as a test case for both the adaptive mesh resolution and dynamic load balancing.

At UT Austin, graduate student Ardavan Behnia was involved in the project. He developed the first version of the ADCIRpolate software and performed initial testing during the first 1.5 years of the project. He received an MS degree in Computational Science, Engineering and Mathematics, but then left graduate school for personal reasons. After his departure, two research scientists took over the project, Ali Samii and Jennifer Proft.

This project has supported the following student-led publications:

- A Thomas*, JC Dietrich, TG Asher, M Bell, BO Blanton, JH Copeland, AT Cox, CN Dawson, JG Fleming, RA Luettich (2018). "Influence of Storm Timing and Forward Speed on Tide-Surge Interactions during Hurricane Matthew." *Ocean Modelling*, to be submitted.
- R Cyriac*, JC Dietrich, JG Fleming, BO Blanton, C Kaiser, CN Dawson, RA Luettich (2018). "Variability in Coastal Flooding Predictions due to Forecast Errors during Hurricane Arthur." *Coastal Engineering*, 137(1), 59-78.

and the following student-led conference presentations:

- A Thomas*, JC Dietrich, TG Asher, BO Blanton, AT Cox, CN Dawson, JG Fleming, RA Luettich. "High-Resolution Modeling of Surge during Hurricane Matthew." *15th Estuarine and Coastal Modeling Conference,* Seattle, Washington, 25 June 2018.
- A Thomas*, JC Dietrich, JG Fleming, BO Blanton, T Asher, RA Luettich. "High-Resolution Modeling of Surge during Hurricane Matthew." *ADCIRC Users Group Meeting,* NOAA Center for Weather and Climate Prediction, College Park, Maryland, 13 April 2018.
- A Thomas*, JC Dietrich, RA Luettich, JG Fleming, BO Blanton, TG Asher, SC Hagen, MV Bilskie, P Bacopoulos. "Hindcasts of Winds and Surge during Hurricane Matthew (2016): Balancing Large-Domain Coverage and Localized Accuracy." *ADCIRC Users Group Meeting*, Norwood, Massachusetts, 4-5 May 2017.

and the following student-led conference posters:

- A Thomas*, JC Dietrich, JG Fleming, BO Blanton, T Asher, RA Luettich. "High-Resolution Modelling of Surge during Hurricane Matthew (2016)." *Graduate Student Research Symposium*, North Carolina State University, 21 March 2018.
- A Thomas*, JC Dietrich, JG Fleming, BO Blanton, T Asher, RA Luettich. "High-Resolution Modelling of Surge during Hurricane Matthew (2016)." *Environmental, Water Resources, and Coastal Engineering Research Symposium*, North Carolina State University, 02 March 2018.
    - Honorable Mention

7. Interactions with education projects:

This project has initiated involvement with the CRC's MSI education partners in several ways. PI Dietrich has visited both Jackson State University (JSU, in 4 May 2016) and Johnson C. Smith University (JCSU, in 31 March 2017) to present seminars about current research in storm surge modeling and forecasting. These seminars were attended by a combination of students and faculty members at each institution. 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 seminars were well-received with many questions from the audience. The presentations have been archived on PI Dietrich's institutional web site, and notice of the seminars were shared with CRC leadership.

PI Dietrich also hosted a visit from JCSU students on 14 June 2017. The JCSU students visited NC State for a day, met with PI Dietrich and his graduate students, and learned more about their recent research in modeling of coastal hazards. Because the JCSU students have backgrounds in computer science and engineering, much of the discussion during their visit was focused on the applications of computational techniques and models into our research program. PI Dietrich invited several faculty members from inside his department to meet the JCSU students and describe their research, too. Hopefully this interaction will be another building block to connect JCSU students with research at NC State.

Co-PI Dawson at UT Austin hosted summer intern Xuesheng Qian from Jackson State University during the summer of 2016 through the CRC SUMREX program. Qian learned how to run the SWAN+ADCIRC 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 worked with Dawson and JSU researcher Bruce Ebersole to run the model for storms in the Texas Gulf Coast area.

8. Publications:

This project has supported the following student-led publications:

- A Thomas*, JC Dietrich, TG Asher, M Bell, BO Blanton, JH Copeland, AT Cox, CN Dawson, JG Fleming, RA Luettich (2018). "Influence of Storm Timing and Forward Speed on Tide-Surge Interactions during Hurricane Matthew." *Ocean Modelling*, to be submitted.

- R Cyriac*, JC Dietrich, JG Fleming, BO Blanton, C Kaiser, CN Dawson, RA Luettich (2018). "Variability in Coastal Flooding Predictions due to Forecast Errors during Hurricane Arthur." *Coastal Engineering*, 137(1), 59-78.

9. Tables:

Table 1: Documenting CRC Research Project Product Delivery

Product Name	Product Type (e.g., software, guidance document)	Delivery Date	Recipient or End User
ADCIRC forecast guidance for Texas	guidance	June-Nov 2017	G Wells and T Howard, Texas State Operations Center
ADCIRpolate	software	2019	J Fleming, Seahorse Coastal Consulting

Table 2A: Documenting External Funding

Title	PI	Total Amount	Source

Table 2B: Documenting Leveraged Support

Description	Estimated Total Value
NSF XSEDE allocation of 330K node-hours at UT-Austin and 1.1M CPU-hours at SDSC	$127,333.08
NSF XSEDE allocation of 6.6M CPU-hours combined for supercomputers at UT-Austin and SDSC	$282,311.86

Table 3: Performance Metrics:

DIETRICH-DAWSON PERFORMANCE METRICS

Metric	**Year 1** (1/1/16 – 6/30/16)	**Year 2** (7/1/16 – 6/30/17)	**Year 3** (7/1/17- 6/30/18)
HS-related internships (number)	0	0	0
Undergraduates provided tuition/fee support (number)	0	0	0
Undergraduate students provided stipends (number)	0	0	0
Graduate students provided tuition/fee support (number)	3	2	2
Graduate students provided stipends (number)	3	2	2
Undergraduates who received HS-related degrees (number)	0	0	0
Graduate students who received HS-related degrees (number)	0	0	1
Graduates who obtained HS-related employment (number)	0	0	0
SUMREX program students hosted (number)	1	0	0
Lectures/presentations/seminars at Center partners (number)	1	1	0
DHS MSI Summer Research Teams hosted (number)	0	1	0
Journal articles submitted (number)	0	0	1
Journal articles published (number)	0	0	1
Conference presentations made (number)	2	4	3
Other presentations, interviews, etc. (number)	1	4	11
Patent applications filed (number)	0	0	0
Patents awarded (number)	0	0	0
Trademarks/copyrights filed (number)	0	0	0
Requests for assistance/advice from DHS agencies (number)	0	1	0
Requests for assistance/advice from other agencies or governments	0	1	3
Total milestones for reporting period (number)	6	7	8
Accomplished fully (number)	6	3	3
Accomplished partially (number)	0	2	5
Not accomplished (number)	0	2	0

10. Year 3 Research Activity and Milestone Achievement:

Research Activities and Milestones: Final Status as of 2018
Reporting Period 7/1/2017 – 6/30/2018

Research Activities	Proposed Completion Date	% Completed	Explanation of why activity/ milestone was not reached
Extension of ADCIRpolate to incorporate floodplains and wet/dry regions	12/2017	100	
Testing of ADCIRpolate and ADCIRC for a hurricane scenario	02/2018	100	
Dynamic load balancing for an adaptive ADCIRC simulation	03/2018	50	We are progressing on both technologies (adaptive mesh resolution, dynamic load balancing), but their development has been more involved (and thus slower) than we expected. We are working to combine the two technologies to meet these completion dates.
Demonstration of adaptive approach with segments of target mesh	04/2018	50	Same.
Combined simulation with dynamic load balancing and adaptivity	06/2018	50	Same.
Refining and streamlining the technologies for widespread release	06/2018	50	Same.
Research Milestones			
Gave several interviews to local news media on storm surge	08/2017	100	

forecasting during Hurricane Harvey			
Online documentation for new technologies	03/2018	50	These milestones are all related to documentation of project technologies, which we are writing as we continue to develop them.
Submission of manuscript about adaptive approach	06/2018	50	Same.
Transfer of technologies to ADCIRC modeling community	06/2018	50	Same.

11. Year 3 Transition Activity and Milestone Status:

Transition Activities and Milestones: Final Status as of 2018
Reporting Period 7/1/2017 – 6/30/2018

Transition Activities	Proposed completion date	% completed	Explanation of why activity / milestone was not reached
Integration of mesh adaptivity technology into official ASGS	06/2018	50	This activity will be completed within the next year.
Integration of project software into release version of ADCIRC	06/2018	50	Same.
Transition Milestones			
Quarterly progress updates, feedback from transition partners	09/2017 12/2017	100	
	03/2018	50	These milestones are all related to documentation of

Documentation and examples on online Web site			project technologies, which we are writing as we continue to develop them.
Testing of mesh adaptivity technology with J Fleming and C Kaiser	03/2018	50	Same.
Release of software to transition partners, training with examples	03/2018	50	Same.