DIETRICH - NCSU
DHS COASTAL RESILIENCE CENTER
RESEARCH PROJECT
YEAR 4 PROGRESS REPORT
July 1, 2018 – June 30, 2019

Project Title:

Improving the Efficiency of Flooding Predictions via Adaptive Mesh Resolution

Principal Investigator Name/Institution:

Casey Dietrich, Assistant Professor, North Carolina State University

Other Research Partners/Institutions:

Clint Dawson, Professor, The University of Texas at Austin

Short Project Description:

Coastal communities rely on predictions of flooding caused by storms. Computational models are essential for making these predictions, but 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 and accuracy of a widely-used, predictive model for coastal flooding. Its representation of the coastal environment will adapt during the storm, to better utilize the computing resources and ultimately provide a faster prediction.

1. Introduction and Project Overview:

The goal of this research project is to speed up the ADvanced CIRCulation (ADCIRC) modeling system, which is used extensively by DHS and its constituent agencies for the prediction of storm-induced 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, 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. Results:

During Year 4, our research was focused on three related topics: (A) the continued development and testing of technologies for a coarse-grain mesh adaptivity, (B) the continued development and testing of dynamic load balancing, and (C) the refinement of techniques for downscaling and visualizing the forecast guidance as a post-processing step. We discuss our results for each of these topics:

Adaptive mesh techniques: 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 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 hotstart capability of ADCIRC, which historically has been based on simply hot-starting a calculation on the same mesh/domain. We also note that ESMF operates in parallel, thus the interpolation from one mesh to the next can be done very efficiently.

During Year 4, we made significant progress on hardening these technologies, so that they can be used for a variety of meshes and storms. This hardening required an extensive testing by the project teams at both institutions. At UT Austin, the tests have been for hurricanes that impacted the Texas coast, such as Ike (2008) and Harvey (2017). These storms had tracks that were shore-perpendicular, and so they are amenable to the adaptive meshing technologies. The simulation can be started on a low-resolution mesh with limited coverage of the floodplains while the storm is located offshore, and then it can be switched onto a higher-resolution mesh as the storm approaches the coast. We have shown that, if the switch is performed early so the model can adjust to the additional resolution and coverage, then the results can be nearly identical to a full simulation on the higher-resolution mesh. For example, in the figure below, we show the maximum water levels predicted for Harvey, both with a full, high-resolution simulation (on the left) and for an adaptive simulation (on the right). In this simulation, the calculation was started on the NOAA Hurricane Surge On-Demand Forecast System (HSOFS) ADCIRC mesh, which is used in operational mode by NOAA and has coverage of the entire eastern U.S. and Gulf of Mexico coasts. After 1 day of simulation, we interpolated the results onto a higher-resolution mesh developed specifically for the Texas coast, that has improved representation of inland channels and flood plains (the same mesh used in the left half of the figure below). The results are nearly identical, thus indicating that there is no loss in accuracy, even while gaining an improvement in efficiency. The adaptive simulation is faster but gives the same flooding predictions.

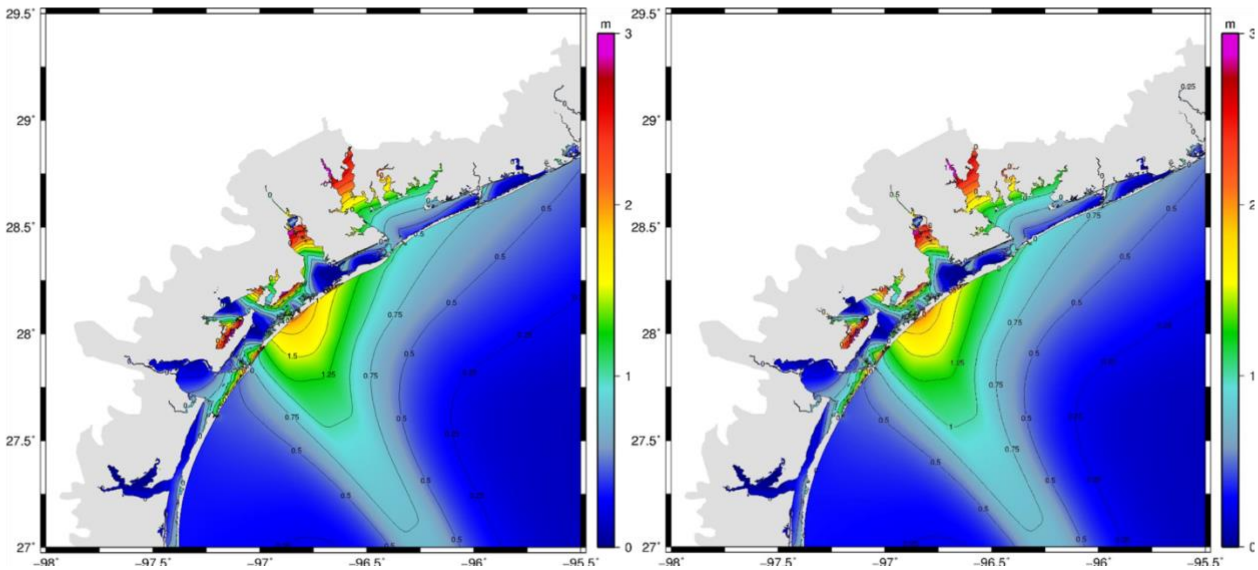

Figure: Maximum water levels (m) predicted for Hurricane Harvey (2017): (left) for a full simulation on a high-resolution mesh, and (right) for an adaptive simulation in which the mesh was changed. The results are nearly identical.

At NC State, the tests have been for Hurricane Matthew (2016), which had a shore-parallel track along the southeast U.S. coast. The storm stayed offshore of Florida and Georgia, made a brief landfall in South Carolina, and then tracked past North Carolina and into the Atlantic Ocean. This storm has been our focus for several years, and PhD student Ajimon Thomas just published a manuscript about how the storm interacted with the tides over several days as it moved offshore. Matthew is a perfect test for the adaptive meshing technologies, because they allow for higher-resolution floodplains to be excluded as the storm is far away, included as the storm passes, and then removed again as the storm moves away.

For example, we have tested the adaptive meshing technologies for a simulation of Matthew with six meshes. It starts on a coarsely-resolved mesh with coverage only in open water (so no floodplains), and then it slowly adds and subtracts the following higher-resolution components as the storm moves northward:

- 4.50 days: open-water
- 0.75 days: add Florida
- 0.75 days: add Georgia and South Carolina
- 0.75 days: add North Carolina
- 0.75 days: subtract Florida
- 1.5 days: subtract Georgia and South Carolina

Thus, we include the full coastline (with higher-resolution floodplains for all four states) only during the 0.75 days when the storm is affecting them. At other points in the simulation (both before and after), we include only the floodplains that are affected, and we exclude everything else. The adaptive meshing technologies were able to map the interim solution from mesh to mesh without any problems, and the final results were nearly identical to a full simulation on the higher-resolution mesh (similar to the findings above from Harvey).

We have been working to develop a mesh for this same region (the southeast U.S. coast), but with much higher resolution to give a more-accurate representation of the coastal features and surge response. This mesh has been developed by combining the FEMA meshes for floodplain mapping studies in this region. The overall mesh (shown below) has about 5.6 million vertices and provides coverage from south Florida through North Carolina. We are doing preliminary tests on this mesh to confirm stability and accuracy, and then we will use it to continue hardening and testing the adaptive meshing techniques.

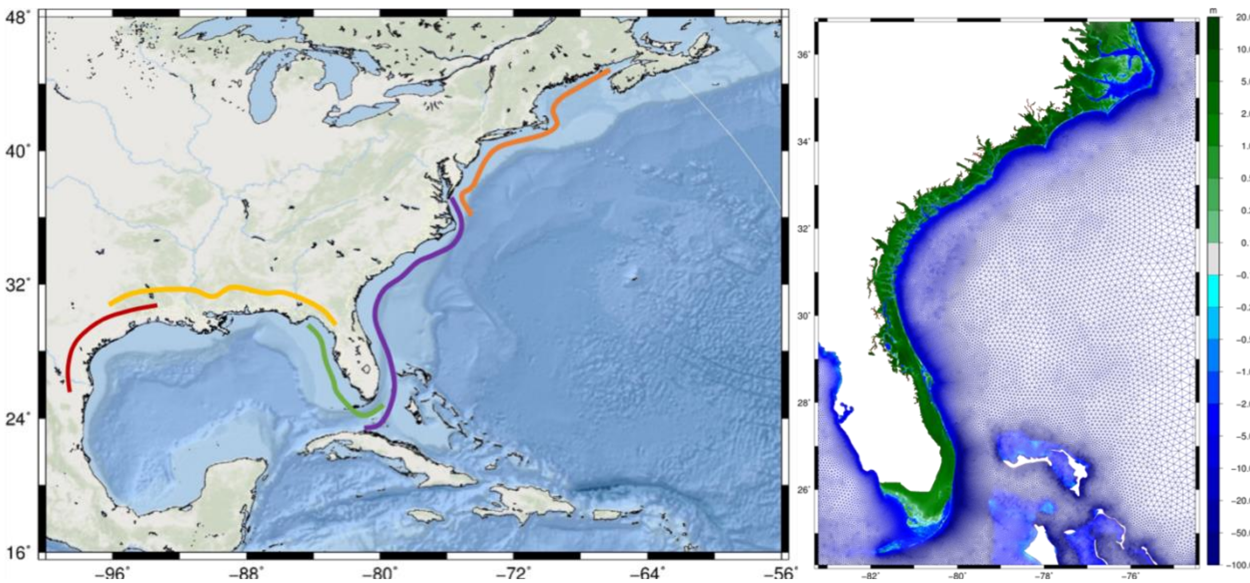

Figure: (left) schematic of higher-resolution meshes with coverage of floodplains along the U.S. coast from Texas through Maine, and (right) early version of the higher-resolution mesh for the southeast U.S. coast.

Dynamic load balancing: The other component of this research project has been the treatment of dry regions within our high-resolution meshes. 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. Working with collaborators at Notre Dame, we rewrote the dynamic load balancing 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.

During Year 4, we continued to harden and test this routine on a variety of idealized and realistic simulations of coastal flooding. By using an idealized domain with a controlled flooding, we evaluated the performance and scalability of the routine over a range of parallel configurations. We have shown the routine can provide near-theoretical speed-ups, where the theoretical speed-up is when the dry vertices do not have any cost. The routine can scale to hundreds of CPUs at the same rate as if the dry vertices are excluded entirely from the mesh. We continue to harden the routine by streamlining the migration of information between CPUs, so it uses fewer steps and handles better the memory and libraries. We have also extended the migration to include station data, nodal attributes, and levee information.

For storms on realistic domains, the dynamic load balancing is allowing for significant speed-ups over a base simulation. In the figure below, we show a typical workload for a simulation on a higher-resolution mesh. The red lines are the boundaries between the sub-meshes sent to the CPUs; these sub-meshes can be redistributed at checkpoints during the simulation. For a simulation of Hurricane Florence (2018), the speed-up is about 20 percent, with no change in the solution. Thus, the dynamic load balancing is providing a benefit in wall-clock times with no trade-off in the model accuracy. We are continuing to work on documenting this feature so it can be released to the model community.

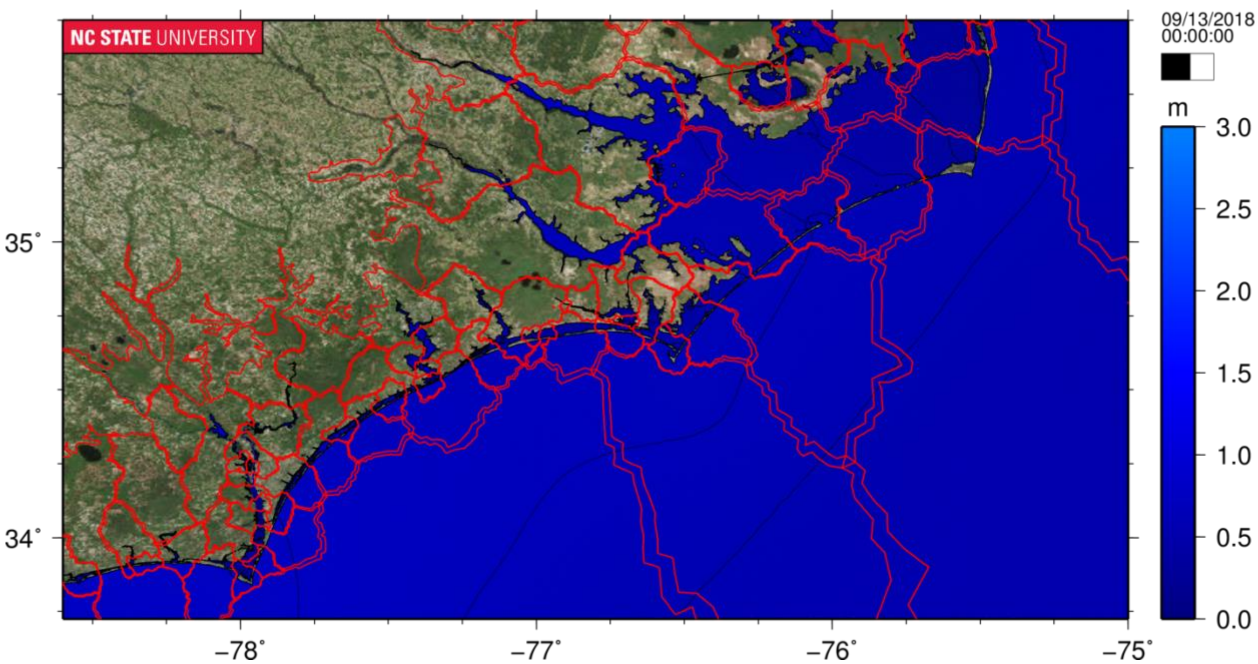

Figure: Example of load balancing for a simulation of Hurricane Florence (2018) in North Carolina. The red lines show the boundaries between the sub-meshes sent to each CPU; these sub-meshes are redistributed at checkpoints during the simulation to maintain an even workload among the CPUs. For this simulation, the overall speed-up was about 20 percent.

<u>Downscaling and visualization of forecast guidance:</u> When the flooding forecast guidance is shared with stakeholders, it is shared typically in an online mapping system (CERA) or via GIS shapefiles. The advantage of the GIS shapefiles is that they can then be integrated within the workflows of our stakeholders, who may want to combine them with other datasets for flooding forecasts or critical infrastructure. Although the GIS shapefiles have infinite resolution, in the

sense that they are vector-based representations of the ADCIRC results, they are still limited by the mesh resolution used by ADCIRC. This mesh resolution may vary downward to 10-20 m in specific small-scale channels, but more typically the mesh resolution is 100-500 m throughout the coastal zone. This resolution can prevent the representation by ADCIRC of smaller-scale infrastructure, including roadways and buildings, which are critical for decision-makers. We have developed a technology to downscale ADCIRC guidance to a finer resolution in a DEM, and then extrapolate the water levels to where they should intersect with the topography.

During Year 4, we extended this technology so it can be used for any ADCIRC flooding predictions in any geographical region. The user can specify a high-resolution digital elevation model (DEM) from any source, and the technology will downscale the ADCIRC water levels onto that data set. We have tested extensively for storms along the U.S. Gulf and Atlantic coasts. In the figure below, we show the difference between the maximum water levels from an ADCIRC simulation and from the downscaling process. The ADCIRC resolution is too coarse to allow the water to push far into the estuaries, but the downscaling does extend the water surface until it intersects with the topography. This process will provide a better depiction of the flooding extents.

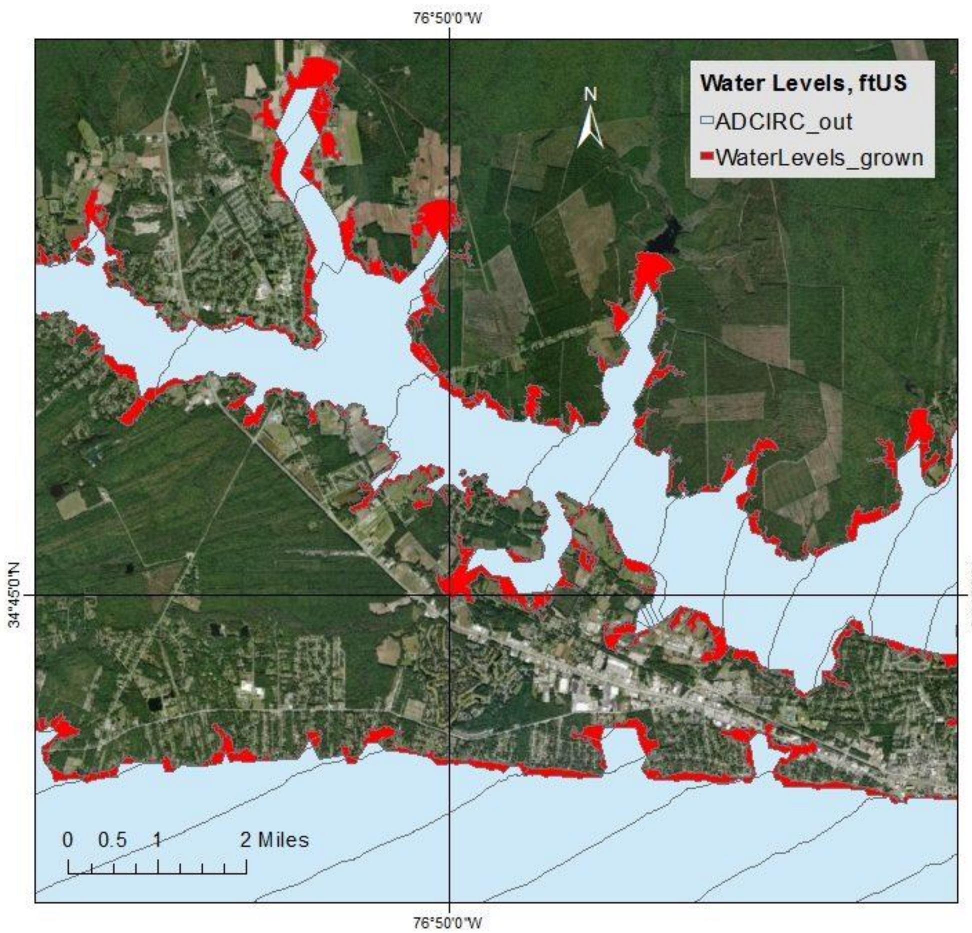

Figure: ADCIRC vs. extrapolated water levels, plan view. This image shows the difference in prediction of flooding extents, with the pale blue portion representing the original ADCIRC flooding extents and red representing the extrapolated extents.

3. 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. At FEMA, several end users are participating 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 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 with **Gordon Wells** to transition the analysis products that are used for guidance by the emergency management leadership. Dr. Wells has worked with forecast guidance for the Texas coastline in previous seasons and is 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. With the USACE Engineer Research and Development Center, with the NOAA NCEP, and with the NOAA West Gulf River Forecast Center, multiple end users 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.

4. Transition:

The project team has transitioned the research results, both in real-time during storm events, as well as in activities to benefit the community in the longer-term.

During storms, the project team continues to support the ADCIRC real-time forecasting activities, which have a direct benefit to DHS constituent agencies and other emergency managers. At UT Austin, the team continued to work with Jason Fleming and Carola Kaiser to update the ASGS on supercomputers at the Texas Advanced Computing Center (TACC) and provide support for the CERA and the Texas State Operations Center during the 2018 hurricane season. TACC facilities were utilized during Hurricanes Florence and Matthew. We are currently preparing for the 2019 hurricane season. The UT Austin team will be working with Jason Fleming and Brett Estrade to provide operational ASGS support for storms that threaten the Texas coast.

At NC State, the project team also supported real-time forecasting during Florence, specifically by using the downscaling technologies to provide guidance products to collaborators at FEMA and NC Emergency Management (NCEM). For every forecast advisory, we sent products to NCEM to show the maximum water levels at higher-resolution in coastal NC. On Wednesday, September 8, 2018, or less than 2 days before Florence made landfall, we received the following feedback from Tom Langan, the engineering supervisor for the North Carolina Floodplain Mapping Program:

> *Forecasts have been working great. Really appreciate you running script. We are using for coastal flood damage estimates with our building footprints and comparing to a similar analysis with P-surge.*

After the storm, we also shared products with partners at FEMA, who were interested to see our best-available hindcast. The maximum water levels from ADCIRC were downscaled onto a higher-resolution DEM, and then provided as a geo-referenced TIFF to help with their post-storm work.

The project team has also worked to transition our results in more-general ways outside of hurricane season. The UT Austin team and our end user Gordon Wells worked with Jason Fleming in setting up the "ADCIRC Texas Week," an ADCIRC boot-camp specifically targeted to the Texas ADCIRC user base. This event was held on the University of Texas campus the week of April 8-12, 2019.

At NC State, we have released the downscaling technologies as open-source software with a full documentation. They can be downloaded from this site:

- https://ccht.ccee.ncsu.edu/downscaling-flooding-inundation-extents-using-kalpana/

which provides examples for using the technology, including input files and commands. These technologies have already been adopted by partners in the ADCIRC community, including at George Mason University and Taylor Engineering.

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. We are working with Jason Fleming and other ASGS developers to incorporate ADCIRpolate into the ASGS as a beta version. The adaptive capability has also motivated future ADCIRC-related projects within the CRC. We are working 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 are speeding 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 are being shared (with extensive documentation and examples) with the ADCIRC modeling community, including the ASGS.

6. Unanticipated Problems:

During Year 4, the only unanticipated problem was a delay in funding for the ADCIRC-related projects in the CRC. We received the first half of our Year 4 funding during Dec/Jan, or about halfway through the project year. As of June, we have not received the second half of our Year 4 funding. These delays have made it necessary to use other funding sources to support partially our students, who then cannot focus entirely on this CRC project. These delays have also hindered our ability to collaborate with the other ADCIRC-related projects on the implementation of our project technologies. We are hopeful that the remaining Year 4 funds will be received early in Year 5 (along with the entirety of the Year 5 funds), so that we can finish strong.

7. Student Involvement and Awards

CRC Supported Students

At UT Austin, this project supported:

- Graduate student **Mark Loveland**. Mark worked primarily on the implementation of the dynamic mesh software ADCIRpolate and the testing of the software on Hurricane Harvey. He worked with NCSU students to train them on the use and installation of the software and the ESMF library.

At NC State, this project supported:

- Graduate student **Ajimon Thomas**, who worked primarily on testing the ADCIRpolate software for Hurricane Florence, as well as developing a mesh for the southeast U.S. coast.
- Graduate student **Carter Rucker**, who worked primarily on generalizing the downscaling technologies, including their release as open-source software with extensive documentation.
- Undergraduate student **Chloe Stokes**, who assisted Ajimon with mesh editing.
- Undergraduate student **Carter Howe**, who assisted with programming improvements for visualization software to support the project.

Student Demographics:

During Year 4, three graduate (Mark, Ajimon, Carter R.) and two undergraduate (Chloe, Carter H.) students were supported on this project. One undergraduate student (Chloe) is a member of an under-represented group (women) in engineering.

Degrees Attained:

During Year 4, no degrees were obtained by our students. However, Ajimon passed his PhD proposal defense, and both Ajimon and Carter R. are on track for graduation during Year 5.

Awards

During Year 4, no awards were achieved by our student.

8. Interactions with Education Projects:

Fourteen students (and four faculty members) in CRC's JCSU Summer Research Program visited the Department of Civil, Construction, and Environmental Engineering at NC State on Thu Jun 13. The students shared presentations about their research projects, and then learned about computing- and resilience-related opportunities at NC State. Here is the full agenda.

The JCSU students shared three presentations about summer research on topics like traffic contraflow, disease outbreaks, and tornado characteristics, and on methods including fuzzy inference systems and data mining. About 30 students and faculty from NC State attended the presentations, noted the connections with their ongoing research, and asked questions about how the summer projects can be continued into the future.

Then three NC State faculty members shared presentations about their research, ranging from agent-based models of environmental systems, to computer vision techniques to inform construction, to predictive models for coastal flooding. There was a lot of student engagement, especially because most of the NC State research was presented by graduate students, who also interacted informally with the visitors during their visit.

Figure: Casey Dietrich (at far left) posing with Ahmed Faik and faculty and students from Johnson C. Smith University during their visit to NC State on Thu Jun 13.

9. <u>Publications:</u>

- A Gharagozlou*, JC Dietrich, A Karanci, RA Luettich, MF Overton. "Storm-Driven Erosion and Inundation of Barrier Islands from Dune- to Region-Scales." *Coastal Engineering*, in review.
- A Thomas*, JC Dietrich, TG Asher, M Bell, BO Blanton, JH Copeland, AT Cox, CN Dawson, JG Fleming, RA Luettich (2019). "Influence of Storm Timing and Forward Speed on Tide-Surge Interactions during Hurricane Matthew." *Ocean Modelling*, 137, 1-19, DOI: 10.1016/j.ocemod.2019.03.004.
- 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. DOI: 10.1016/j.coastaleng.2018.02.008.

Student theses and dissertations

None to report.

10. Year 4 Research Activities and Milestone Achievements:

Reporting Period 7/1/2018 – 6/30/2019			
Research Activity	Proposed Completion Date	% Complete	Explanation of why activity / milestone was not completed
Development of coarse-resolution, base mesh	08/2018	100	
Extension of enhanced-resolution technique to entire U.S.	02/2019	100	
Development of fine-resolution, target meshes: • Western Gulf • Northern Gulf • Eastern Gulf • Southern Atlantic • Central Atlantic • Northern Atlantic	 03/2019 06/2019 03/2019 03/2019 03/2019 06/2019	50	Delay in funds. We are working on the meshes for the southeast Atlantic and western Gulf, and collaborating with partners in the other CRC projects on the other meshes.
Operationalization of interpolation routines. These routines allow for the downscaling and extrapolation of forecast guidance, so it can be shared at higher-resolution to stakeholders. These routines are run currently as a post-processing step at NCSU, but they will be operationalized to be included in the ASGS workflows at UNC, LSU, UT, etc.	06/2019	50	Delay in funds. These routines have been released as open-source software, and we will work with our partners to operationalize them.
Research Milestone			
Presentation at ADCIRC Week	04/2019	100	
Submission of peer-reviewed manuscript	06/2019	25	Delay in funds.

about adaptive approach			

11. <u>Year 4 Transition Activities and Milestone Achievements:</u>

Reporting Period 7/1/2018 – 6/30/2019			
Transition Activity	Proposed Completion Date	% Complete	Explanation of why activity/milestone was not completed
Sharing of geoTIFF forecast guidance with FEMA. The forecast guidance for maximum water levels during Florence was shared as high-resolution shapefiles to stakeholders during Florence, including to FEMA. These shapefiles contain the downscaled and extrapolated guidance as described below in the research technical description. Then, after the storm, this guidance was converted into raster format as geo-referenced TIFF (geoTIFF) images, which contain the same information but at a constant resolution. These geoTiff guidance products were used by FEMA as part of its post-Florence analyses.	09/2018	100	
Transfer of mesh adaptivity technology into official ASGS. This technology will allow for the continuation of a simulation on a different ADCIRC mesh, and thus for forecasts to start on a coarse mesh and then continue on a finer mesh with higher-resolution coverage at the expected landfall location. This technology is the key component of our project and is described below in the research technical description.	06/2019	50	Delay in funds. We will work with our partners to operationalize these technologies.
Transition Milestone			
Sharing of forecast guidance with G Wells, T Howard, who work at the Texas State Operations Center Division of Emergency Management. They communicate the guidance to stakeholders and decision-makers to support emergency activities	08/2018	100	

during storms, including during Harvey in 2017. Dawson has a long relationship with them and has passed guidance to them for at least 10 years, and so we include this ongoing transition as a milestone.			
Quarterly progress updates, feedback from transition partners. These updates are provided as videoconferences, in which Dietrich and Dawson share their research progress as short presentations, with an emphasis on what is novel since the previous update. Most of the update is a discussion about ongoing and future research directions, and we are careful to solicit feedback and suggestions from our partners. This feedback is then used to improve the utility of our technologies as we develop them during the project.	09/2018 12/2018 03/2019 06/2019	50	Delay in funds. We are sharing research progress with our partners as it becomes mature and ready for feedback.

12. <u>Tables:</u>

Table 1: <u>Research Project Product Delivery</u>

Product Name	**Product Type** (e.g., software, guidance document, knowledge product)	**Delivery Date**	**Recipient or End User(s)**
Downscaled forecast guidance during Florence	Shapefiles	09/2018	Tom Langan, NC Emergency Management
Downscaled hindcast guidance after Florence	Shapefiles and geo-referenced TIFFs	09/2018	FEMA

Table 2: Performance Metrics

Metric	**Year 1** (1/1/16 –	**Year 2** (7/1/16 –	**Year 3** (7/1/17-6/30/18)	**Year 4** (7/1/18-6/30/19)
HS-related internships (number)	0	0	0	0
Undergraduates provided tuition/fee support	0	0	0	0
Undergraduate students provided stipends (number)	0	0	0	2
Graduate students provided tuition/fee support	3	2	2	3
Graduate students provided stipends (number)	3	2	2	3
Undergraduates who received HS-related degrees	0	0	0	0
Graduate students who received HS-related degrees	0	0	1	0
Graduates who obtained HS-related employment	0	0	0	0
SUMREX program students hosted (number)	1	0	0	0
Lectures/presentations/seminars at Center partners	1	1	0	0
DHS MSI Summer Research Teams hosted	0	1	0	1
Journal articles submitted (number)	0	0	1	1
Journal articles published (number)	0	0	1	1
Conference presentations made (number)	2	4	3	3
Other presentations, interviews, etc. (number)	1	4	11	5
Patent applications filed (number)	0	0	0	0
Patents awarded (number)	0	0	0	0
Trademarks/copyrights filed (number)	0	0	0	0
Requests for assistance/advice from DHS agencies	0	1	0	2
Requests for assistance/advice from other agencies or governments (number)	0	1	3	2
Dollar amount of external funding	$0	$0	$0	$0
Total milestones for reporting period (number)	6	7	8	10
Accomplished fully (number)	6	3	3	5
Accomplished partially (number)	0	2	5	5
Not accomplished (number)	0	2	0	0