DIETRICH – NCSU
DAWSON – UT-AUSTIN
DHS COASTAL RESILIENCE CENTER
ADCIRC PROJECT
YEAR 5 PROGRESS REPORT
July 1, 2019 – June 30, 2020 (Updated 12/15/2020)

I. INTRODUCTION

Project Title:

Improving the Efficiency of Flooding Predictions via Adaptive Mesh Resolution

Principal Investigator Name/Institution:

Joel Casey Dietrich, Associate Professor, North Carolina State University

Additional Research Participants/Partners:

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.

II. PROJECT NARRATIVE

1. 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 5, we are nearing completion of this technology, after a final round of rigorous testing. At NC State, we developed a mesh for the southeast U.S. coast with high-resolution of the coastal region from Florida through North Carolina. The overall mesh has about 5.6 million vertices. It was constructed with the state-scale meshes from the FEMA flood risk mapping studies for the coastal region along the South Atlantic Bight (SAB), and so we are calling it the FEMA-SAB mesh. This mesh can be used for high-resolution simulations of any storm that threatens this long coastline. We have worked with Hurricanes Matthew (2016) and Florence (2018), which affected the coast in different ways. Matthew had a shore-parallel track, and it raised water levels throughout the entire region. Florence had a shore-normal track, and its effects were focused in North Carolina.

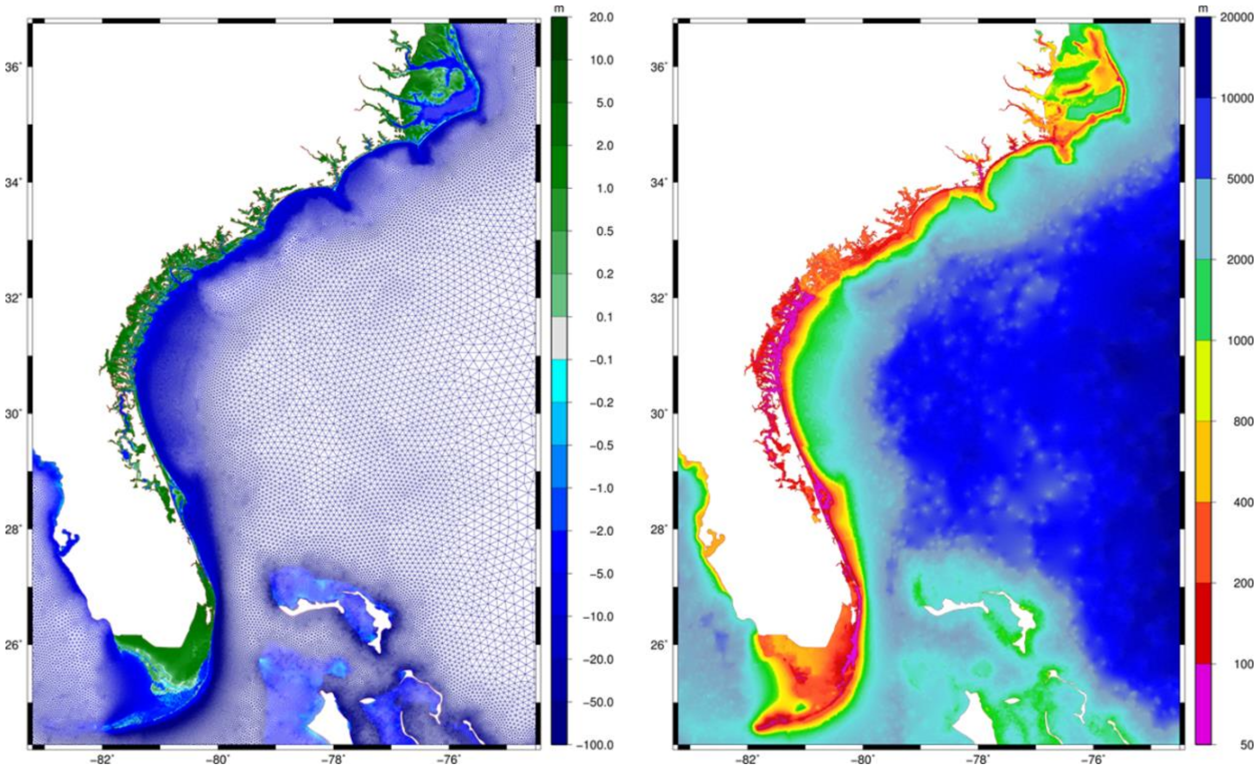

Figure: (left) bathymetry and topography (m, relative to NAVD88), and (right) resolution (m) in the new FEMA-SAB mesh for the southeast U.S. coast.

For example, we have tested the adaptive meshing technologies for simulations like what may be seen in an operational setting. For both storms, we did a full simulation on the high-resolution FEMA-SAB mesh; we denote these as the “Fine” simulations. And again for both storms, we started the simulation on the relatively-coarse HSOFS mesh and then switched onto the high-resolution FEMA-SAB mesh as the storm approached the coast; we denote these as the “Mixed” simulations. The table below gives a summary of these simulations, their accuracy relative to observed peak water levels during the storms, and their efficiency in wall-clock time. The Mixed simulations give a speed-up of 23-33 percent, which is a significant gain in efficiency. But the root-mean-square errors for the peak water levels are not changed significantly. This is encouraging, as it shows the coarse-grain adaptivity can improve the efficiency of operational forecasts without a loss in accuracy.

Table: Summary of "Fine" and "Mixed" simulations for Hurricanes Matthew (2016) and Florence (2018). Note the decrease in wall-clock times for the Mixed simulations, which maintain the accurate predictions of the peak water levels during the storms.

		Matthew (2016)		Florence (2018)	
		Fine	Mixed	Fine	Mixed
Mesh	Coarse (HSOFS)		Oct 2 - 6/12 4.5 days		Sep 7 - 11/12 4.5 days
	Fine (FEMA-SAB)	Oct 2-11 9 days	Oct 6/12 - 11 4.5 days	Sep 7 - 16 9 days	Sep 11/12 - 16 4.5 days
Accuracy	Peak WLs	580	580	190	190
	RMSE	**0.29 m**	**0.29 m**	**0.22 m**	**0.26 m**
Efficiency	Coarse		29 min		19 min
	Adcirpolate		12 min		12 min
	Fine	393 min	222 min	380 min	259 min
	Total	**393 min**	**263 min**	**380 min**	**290 min**

In a similar way, Hurricane Ike (2008) and Hurricane Harvey (2017) were simulated using the adaptive mesh technique. The same HSOFS mesh as mentioned above was used as the 'coarse' mesh but since these two storms made landfall along the Texas coast, a mesh (referred to as the 'Texas Mesh') with much higher refinement specifically around the Texas coast was utilized for the 'fine' mesh. The HSOFS mesh contains around 1.8 million nodes while the Texas mesh contains around 3.3 million. The speedup, depending on when the interpolation from 'coarse' mesh to 'fine' mesh was performed gave a speedup between 10-25 percent. In both the simulation of Ike and Harvey, the differences in inundation pattern and maximum water levels between running with the HSOFS mesh and the Texas Mesh are significant enough to be visible upon inspection.

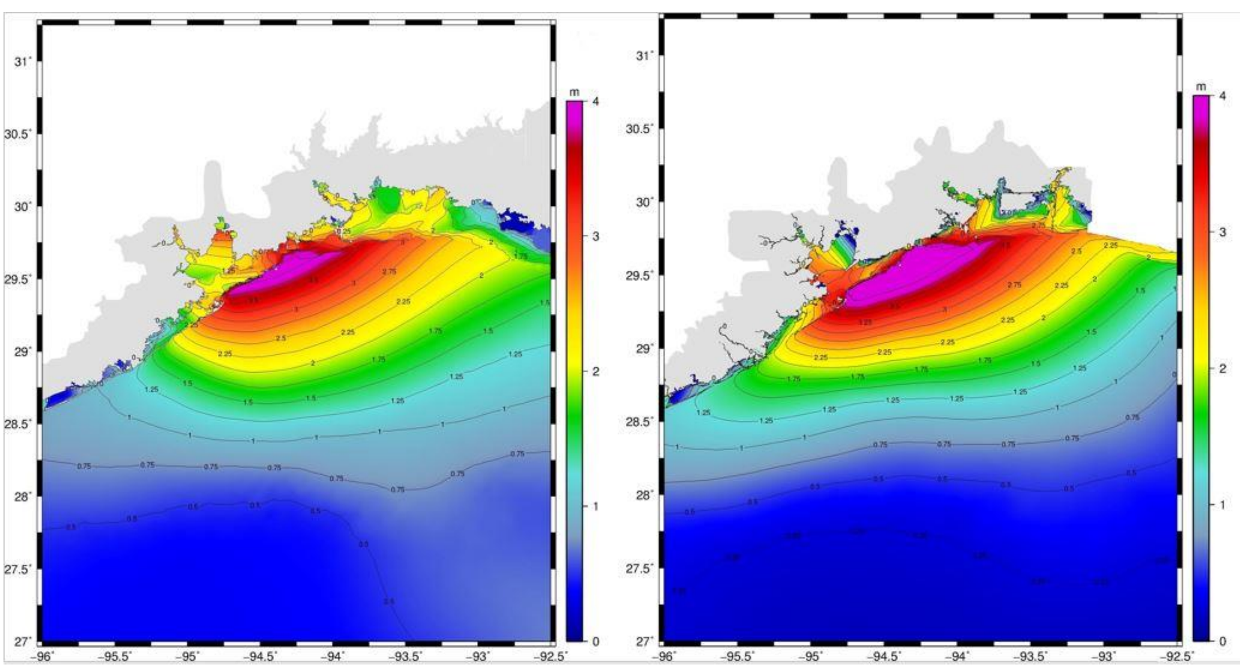

Figure above: (left) maximum water surface elevation (m, relative to NAVD88) of Hurricane Ike using HSOFS mesh, and (right) maximum water surface elevation (m) using the new adaptive meshing technique to interpolate onto Texas mesh.

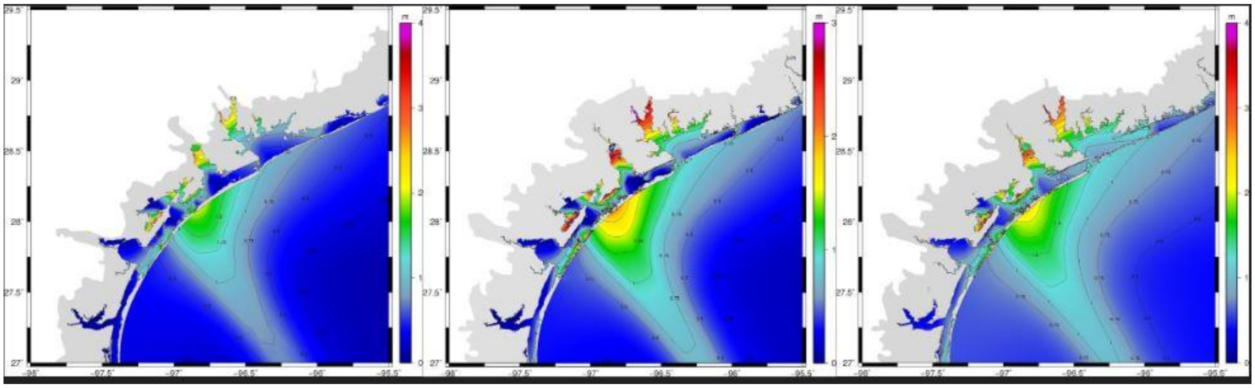

Figure: (left) maximum water surface elevation (m, relative to NAVD88) of Hurricane Harvey using HSOFS mesh, (middle) maximum water surface elevation (m) using the adaptive mesh technique and (right) maximum water surface elevation (m) using the new adaptive meshing technique to interpolate onto Texas mesh.

<u>Dynamic load balancing:</u> Another 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 5, we are nearing completion of this technology, via a set of final tests and the writing of a manuscript. 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 the scaling curves and speed-ups for the dynamic load balancing for several storms and unstructured meshes. In all cases, the dynamic load balancing is allowing for a significant decrease in the wall-clock times, and the speed-ups are between 10-20 percent. And as with the coarse-grain adaptivity, there is no trade-off in the model accuracy: the solution is unchanged. Thus the dynamic load balancing will be a significant benefit to the larger ADCIRC community, and it will lead to faster forecasts to support the mission of DHS.

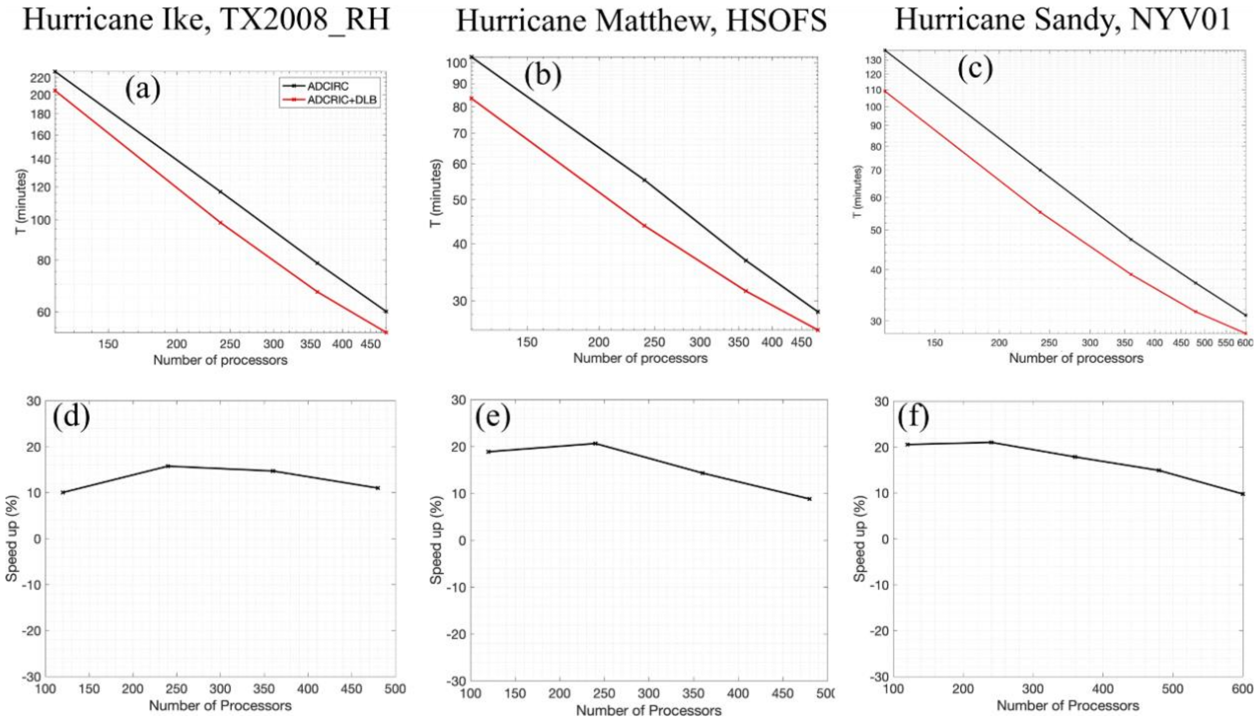

Figure: (top) scaling curves and (bottom) speed-ups for the dynamic load balancing. In the top row, the black lines are the wall-clock times for the existing ADCIRC with a static domain decomposition, while the red lines are the wall-clock times for the new ADCIRC with the dynamic load balancing. In the bottom row, the percent speed-ups are shown to be between 10-20 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 5, we added two new downscaling methods: slopes, which uses the slope of the water surface as predicted by ADCIRC in the extrapolation of the flood extents; and head loss, which uses land cover data to compute frictional losses as the water surface is extrapolated. We found that the slopes method does not change significantly the flood extents, but the head loss method is a significant improvement. In the figure below, we compare the flooding predictions from the downscaling methods to a high-resolution "truth" simulation (shown in red). The base ADCIRC simulation is an under-prediction, as its wet regions do not extend to the shoreline of this estuary. If the water surface is extrapolated as a flat surface (in a static method, shown in light blue), then the flood extents are over-predicted. But if the extrapolation does include head losses due to friction, then the flood extents are a good overall match to the truth. This is an improvement to the downscaling technology, and it will allow for better forecasts for our partners.

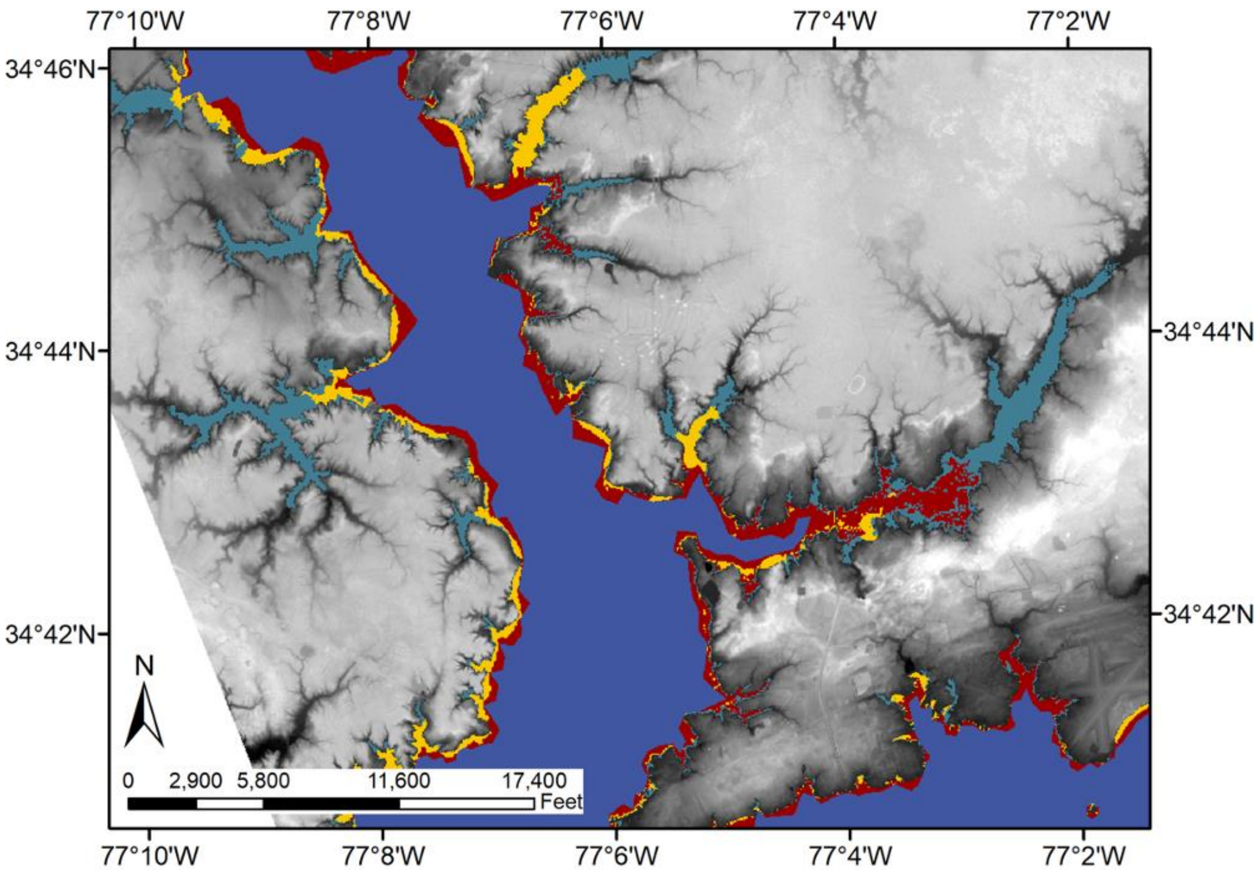

Figure: Validation of downscaling methods for an estuary in Carteret County, North Carolina, and a simulation of Hurricane Florence (2018). The water levels are shown for: (dark blue) the base ADCIRC predictions, (light blue) static extrapolation as a horizontal surface, (yellow) dynamic extrapolation to include head loss due to friction, and (red) a higher-resolution ADCIRC simulation as "truth." Note the head loss method is a better overall match to the true flood extents.

3. <u>End Users:</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. At FEMA, **coastal**

engineers 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 **decision makers** to transition the analysis products that are used for guidance by the emergency management leadership. [REDACTED] 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, **+** 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, ADCIRC forecasters, 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. <u>Transition:</u>

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 2019 hurricane season. TACC facilities were utilized during Hurricanes Barry and Dorian. We are currently preparing for the 2020 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 Dorian, 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 9 September 2019, we received the following feedback from an end user at FEMA:

> *Thank you for generating a hindcast above ground level that we can use for analytics! This is really helpful.*

And on 12 September 2019, we received the following feedback from Tom Langan, the engineering supervisor for the North Carolina Floodplain Mapping Program:

> *Just wanted to say thank you to you and Carter for providing the enhanced mapping products for NC during Hurricane Dorian. We ran the water surface elevation rasters against our building footprints to estimate coastal damages and depth in structures for the advisory and hindcast runs.*

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 5, the only unanticipated problem was the novel coronavirus and its related disruptions to the academic calendar and work arrangements. Luckily, this research project is entirely computational, and so the project personnel can continue to make progress while working remotely. As we progress into a carryover and Year 6, we will continue to work around this problem, especially the impacts on research progress due to limits on in-person interactions.

7. Student Involvement and Awards:

a) Students involved in research

At UT Austin, this project supported:

- Graduate student **Mark Loveland**, who worked primarily on the implementation of the dynamic mesh software ADCIRpolate and the testing of the software on Hurricane Harvey and Hurricane Ike. 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.
- Undergraduate student **Carter Day**, who assisted with re-calibrating the newest release version of SWAN to provide guidance to the ADCIRC community.

b) Student Demographics

- During Year 4, three graduate (Mark, Ajimon, Carter R.) and three undergraduate (Chloe, Carter H., Carter D.) students were supported on this project. Two undergraduate students (Chloe, Carter D.) are members of an under-represented group (women) in engineering.

c) Degrees Attained

- During Year 5, two of our graduate students attained their degrees. Carter Rucker defended his MS thesis in March 2020 and graduated during the Spring. Ajimon Thomas will defend his PhD dissertation and graduate during the Summer.

d) Student Awards.

N/A

8. Interactions with CRC Education Projects:

During previous years, our project personnel have been active in the SUMREX and RETALK activities, via interactions with education partners at Jackson State University and Johnson C. Smith University. However, we were not able to connect with them during Year 5. There was hope that we would host another group of students from Johnson C. Smith University to NC State (as in the summers of 2017 and 2019), but that visit was not pursued due to the novel coronavirus.

III. RESEARCH ACTIVITIES AND TRANSITION MILESTONES

1. Year 5 Research Activities and Milestone Achievements:

Year 5 Research Activities and Milestones: Status as of 6/30/2020

Research Activity	Proposed Completion Date	% Complete	Explanation of why activity / milestone was not completed
Development of hybrid mesh capability for channels	06/2021	20%	We continue to pursue this milestone. Preliminary investigation of using quadrilateral type elements in ADCIRC (by connecting two triangles) was performed by Rick Luettich's group at UNC. Upon further investigation it was decided not to pursue this avenue but to focus on improving the advection scheme and mass conservation properties in ADCIRC specifically in channels.
Improved advection schemes in ADCIRC for channel flow: We will investigate methods for providing better "hooks" into ADCIRC for coupling ADCIRC with rainfall models such as the National Water Model. The goal is to improve the mass conservation and advective capabilities of ADCIRC within channels, and potentially use hybrid meshes that combine triangular and quadrilateral elements to improve resolution across channel widths with fewer degrees of freedom	06/2021	40%	We continue to pursue this milestone. We are investigating adding a discontinuous Galerkin capability for the continuity equation in ADCIRC to improve the handling of advection and mass conservation in channels. The UT team has begun this

			work. This involves substantial code modification and testing and will continue into Year 6 pending funding.
Inclusion of simple physics in enhanced-resolution technique. The interpolation routine for the downscaling and extrapolation of forecast guidance will be extended to include overland friction and surface gradients. In its current implementation, the routine extrapolates the maximum water levels as a flat surface, which can cause an overestimation of flooding extents. By considering some simple physics, we will improve the accuracy of these routines.	03/2020	100	
Research Milestone			
Presentation at national conference	09/2019	100	
Submission of peer-reviewed manuscript about dynamic load balancing	03/2021	90	We are collaborating with Keith Roberts, who graduated from Notre Dame in 2019 and has been working as a post-doc in Brazil. This manuscript has been submitted and reviewed favorably, and the revised manuscript will be submitted soon.
Presentation at ADCIRC week	04/2020	100	
Submission of peer-reviewed manuscript about downscaling and extrapolation	03/2021	90	Ajimon Thomas has written this manuscript as a chapter in his dissertation, and this manuscript has been submitted.
Submission of peer-reviewed manuscript about improved channel flow	06/2021		We continue to pursue this milestone. This manuscript will be developed in Year 6.

2. **Year 5 Transition Activities and Milestone Achievements**:

Year 5 Transition Activities and Milestones: Status as of 6/30/2020

Transition Activity	Proposed Completion Date	% Complete	Explanation of why activity / milestone was not completed
Online documentation of new technologies. The project technologies will be documented via technical descriptions, user guides, and example files on a public Web site, either the to-be-revised ADCIRC homepage or the sites of the project PIs. (Dietrich's site already contains documentation for ADCIRC features and example files, and it is a common resource for ADCIRC users). This documentation will make it easier for all ADCIRC users to adopt and use the project technologies, thus ensuring an impact beyond the life of this project.	06/2021	50	We are nearing completion of the online documentation for the downscaling technology with head losses due to friction; this documentation has been posted online. The online documentation for the interpolation technology has been delayed as we finalize its performance.
Transfer of technologies to ADCIRC modeling community	06/2021	50	We continue to pursue this milestone. We are working with our partners to operationalize these technologies.
Integration of project software into release version of ADCIRC	06/2021	50	We continue to pursue this milestone. We are working with our partners to operationalize these technologies.
Transition 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.		100	We are no longer having regular meetings with our full set of transition partners, because the technology is mature. Instead, we have targeted meetings with specific end users for each technology.

3. **<u>Research Project Product Delivery</u>**

Year 5 Research Project Product Delivery

Product Name and Function	**Brief Product Description, including type** (e.g., software, algorithm, guidance document, knowledge product)	**Date Delivered** (or projected date of delivery)	**Recipient or End User(s)**
Downscaled forecast guidance during Hurricane Dorian	Shapefiles	09/2019	Tom Langan, NC Emergency Management
Downscaled hindcast guidance after Hurricane Dorian	Shapefiles and geo-referenced TIFFs	09/2019	FEMA

IV. PUBLICATIONS AND METRICS

1. <u>Publications:</u>

- A Gharagozlou*, JC Dietrich, A Karanci, RA Luettich, MF Overton (2020). "Storm-Driven Erosion and Inundation of Barrier Islands from Dune- to Region-Scales." *Coastal Engineering*, 158, 103674, DOI: 10.1016/j.coastaleng.2020.103674.

- 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.

<u>Student Theses and Dissertations Completed in Year 5.</u>

- Ajimon Thomas (2020). "Using a Multi-Resolution Approach to Improve the Accuracy and Efficiency of Flooding Predictions." PhD Dissertation, Department of Civil, Construction and Environmental Engineering, North Carolina State University, Raleigh, North Carolina, JC Dietrich (primary adviser).

- Carter Rucker (2020). "Improving the Accuracy of a Real-Time ADCIRC Storm Surge Downscaling Model." MS Thesis, Department of Civil, Construction and Environmental Engineering, North Carolina State University, Raleigh, North Carolina, JC Dietrich (primary adviser).

2. 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)	Year 4 (7/1/18-6/30/19)	Year 5 (7/1/19-6/30/20)
HS-related internships (number)	0	0	0	0	0
Undergraduates provided tuition/fee support (number)	0	0	0	0	0
Undergraduate students provided stipends (number)	0	0	0	2	3
Graduate students provided tuition/fee support (number)	3	2	2	3	3
Graduate students provided stipends (number)	3	2	2	3	3
Undergraduates who received HS-related degrees (number)	0	0	0	0	0
Graduate students who received HS-related degrees (number)	0	0	1	0	2
Graduates who obtained HS-related employment (number)	0	0	0	0	1
SUMREX program students hosted (number)	1	0	0	0	0
Lectures/presentations/seminars at Center partners (number)	1	1	0	0	0
DHS MSI Summer Research Teams hosted (number)	0	1	0	1	0
Journal articles submitted (number)	0	0	1	1	1
Journal articles published (number)	0	0	1	1	1
Conference presentations made (number)	2	4	3	3	2
Other presentations, interviews, etc. (number)	1	4	11	5	4
Patent applications filed (number)	0	0	0	0	0
Patents awarded (number)	0	0	0	0	0
Trademarks/copyrights filed (number)	0	0	0	0	0
Requests for assistance/advice from DHS agencies (number)	0	1	0	2	1
Requests for assistance/advice from other agencies or governments (number)	0	1	3	2	1
Dollar amount of external funding	$0	$0	$0	$0	$0
Total milestones for reporting period (number)	6	7	8	10	6
Accomplished fully (number)	6	3	3	5	2
Accomplished partially (number)	0	2	5	5	4
Not accomplished (number)	0	2	0	0	0