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

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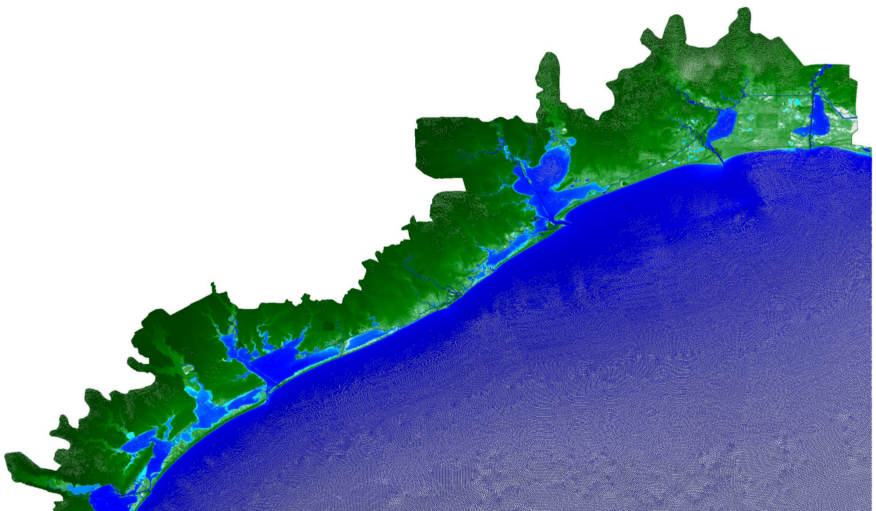
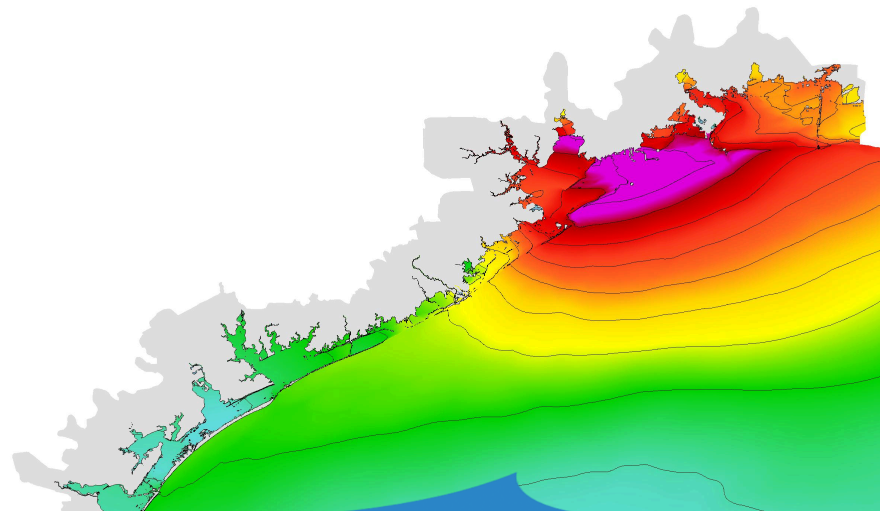
Knowledge Gaps – How can we speed up ADCIRC?

Example ADCIRC simulation for Hurricane Ike (2008):

- The mesh (on left) includes floodplains along the entire Texas coastline
- About 1/2 is wet at the start of the simulation, and only 2/3 is wet at the peak inundation (on right)
- **What can we do with the 1/3 of the mesh that is never used?**



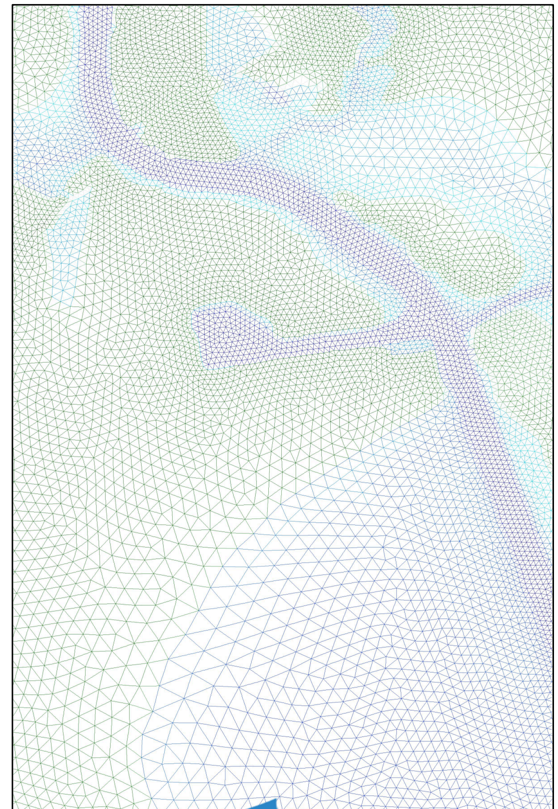


Knowledge Gaps – What about the dry regions?

ADCIRC represents a coastal region with an unstructured ***mesh***
- Millions of triangular elements, varying in size down to 10-20 m
- Water levels and current velocities are computed at the ***vertices***
- Vertices can toggle between being wet or dry

Ideally, the dry vertices would cost zero to ADCIRC
- We include them in case they are flooded by the storm
- But nothing should be happening when they are dry
- Skip them and move on

In practice, the dry vertices DO have a cost
- Minimized but not removed entirely from computations
- Need to store information in memory for later
- Dry vertex has cost of 20-50% compared to wet vertex
  - Keith Roberts (Notre Dame)



Knowledge Gaps – How to maximize efficiency for flood predictions?

The costs for the dry vertices will slow down the simulation
- ADCIRC is ''wasting'' time on regions without any water

And the slow down is made worse in a parallel computer
- The mesh is ***decomposed*** into smaller sub-meshes
- Each sub-mesh is assigned to a CPU
- Some CPUs are always working, while other CPUs have nothing to do
- **Inefficient use of computing resources**

Research Questions:
1. How can we minimize the <u>cost</u> of dry regions in ADCIRC?
2. How can we minimize the <u>use</u> of dry regions in ADCIRC?

Anticipated Project Impact

Several benefits to having a faster, adaptive ADCIRC …

1. Real-time forecasting
   - Guidance can be produced in a shorter time for each advisory
   - Ability to shift from an everyday forecast to a storm forecast without stopping the simulation
   - Flexibility for storms with uncertain landfall locations, or that impact long coastlines
   - Ability to place the right resolution at the right location at the right time

2. Flood risk mapping
   - Efficiencies can decrease time
     - Each simulation will finish faster
     - Lesser requirement for computing resources
   - Efficiencies can increase accuracy
     - Add more storms to the suite
     - Increase resolution in targeted regions

Engagement – End Users

Transition Partners (11)

FEMA	*NOAA WGRFC*
Texas SOC	*LSU CCT*
USACE ERDC	*Seahorse Coastal Consulting*
NOAA	

Transition Activities

- Quarterly videoconferences
  - Share progress reports on research findings
  - Receive feedback and suggestions from end users
  - Enable transfer of technologies
- Integrate technologies into instances of the ADCIRC Surge Guidance System
  - Texas – provide guidance to Texas State Operations Center (Howard, Wells)
  - North Carolina – integrate within workflow for NCFS (Fleming, Kaiser)

Engagement – Activities and Milestones for Y1-Y2

	Activity (A) or Milestone (M)	Completion Dates	Completed?
A	Developmental ASGS instances at UT-Austin and NCSU	03/2016	☑ 03/2016
M	Quarterly progress update, feedback from transition partners	03/2016	☑ 03/2016
M	Sharing of developmental forecast guidance with G Wells, T Howard	05/2016	☑ 07/2016
M	Quarterly progress update, feedback from transition partners	06/2016	☑ 07/2016
M	Quarterly progress update, feedback from transition partners	09/2016	☑ 12/2016
M	Quarterly progress update, feedback from transition partners	12/2016	☑ 01/2017
M	Testing of dynamic load balancing with J Fleming, C Kaiser	12/2016	
A	Integration of dynamic load balancing into release version of ADCIRC	03/2017	
M	Quarterly progress update, feedback from transition partners	03/2017	
M	Release of software to transition partners, documentation with examples	03/2017	
M	Quarterly progress update, feedback from transition partners	06/2017	

Engagement – Education Partners

Visits and seminars:

- Dietrich visited Jackson State University in May 2016
    - Seminar about his current research in storm surge and coastal flooding
    - Attended by a combination of graduate students and faculty members
- Dietrich will visit Johnson C. Smith University in March 2017
    - Seminar about research progress in this Center
    - Explore opportunities for collaboration

Hosting of PhD students via SUMREX program:

- Dawson hosted Xuesheng Qian during Summer 2016
    - Learn how to run wave and surge models on HPC resources at UT-Austin
    - Learn how to generate/modify meshes for use with ADCIRC
    - Running models for the Texas Gulf Coast area

Research Progress – Technical Approach

This project will require advancements in two areas:

1. Optimizing the use of computational resources through dynamic load balancing
2. Implementing an adaptive, multi-resolution approach to increase resolution during a simulation

Dynamic load balancing

- Reallocate computational resources to improve parallel efficiency
- Each core will be responsible for developing its own input information
- The workload will be balanced evenly among the CPUs

Adaptive, multi-resolution approach

- Start with relatively coarse resolution that may not include extensive coastal detail
- As the storm approaches a coastline, extract regions from a fine-resolution mesh within our database
- The higher-resolution floodplains will be stitched into the coarse-resolution, open-water domain
- Results will be mapped onto the new portions of the mesh, and then the simulation will continue

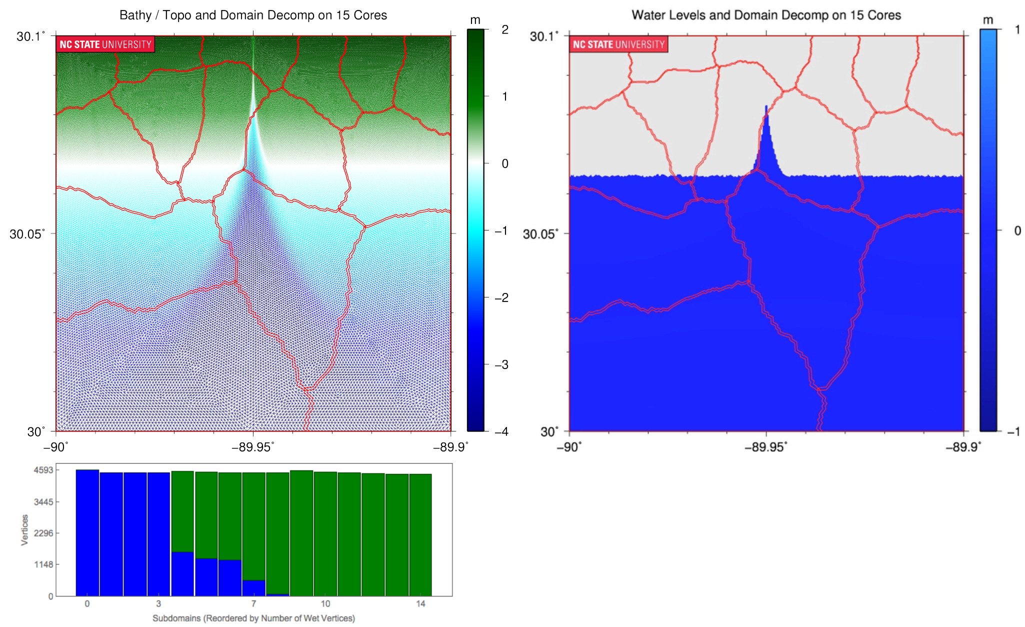
Research Progress – Dynamic Load Balancing

Simple channel and floodplain
- 64,415 vertices, depths from -4m to +2m
- Tidal range from -1m to +1m

So we expect a lot of wetting and drying
- Roughly 1/3 of the domain by size
- More of the domain by resolution

Initial decomposition is sub-optimal
- 4 CPUs start fully wet
- 5 CPUs start partly wet/dry
- 6 CPUs start fully dry

Wall-clock time of about 18.2 min



Research Progress – Dynamic Load Balancing

ADCIRC uses METIS to decompose the mesh
- Separate library, written in *C*, developed at Univ Minnesota
- Called as part of the preprocessor, before the simulation
- Previously, ADCIRC tried to put an equal number of vertices on each CPU
- Same weight for every vertex, either wet or dry

We have updated the domain decomposition
- Dry vertices have a weight of 1, wet vertices have a weight of 4
- Total number of vertices will be different on each CPU
- Distribution of work should be more even

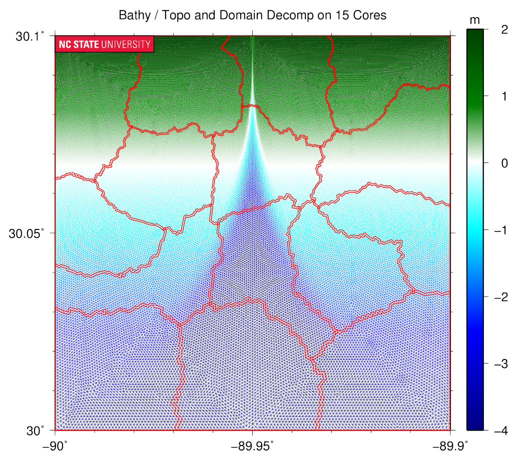
Great thing is this approach should be universal
- Can be applied to any mesh, for any number of CPUs

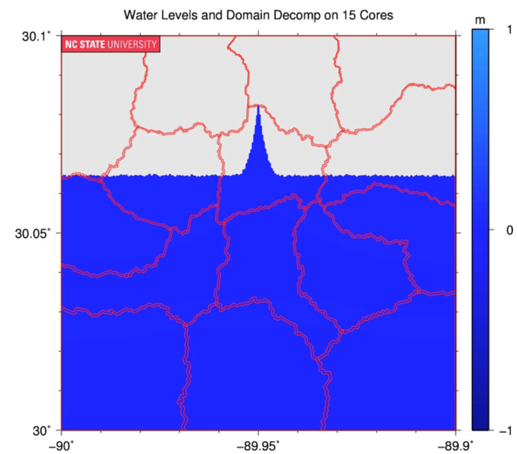
Research Progress – Dynamic Load Balancing

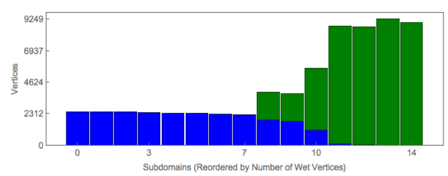
Now the vertices are decomposed unevenly
- Some CPUs have 4 times as many vertices

But the decomposition is balanced
- 8 CPUs start fully wet
- 3 CPUs start partly wet/dry
- 4 CPUs start fully dry

And the solution is unchanged
- We are getting the same tidal behavior
- Changing how we solve the problem,
  but not the answer we get







Research Progress – Dynamic Load Balancing

The next step was to move the decomposition into ADCIRC
- No longer done as a preprocessing step
- Start with the global input files (no PE subdirectories)
- Use the parallel version of METIS to determine the decomposition
- Each CPU determines its own sub-mesh

Now the decomposition can be repeated during the simulation
- When the workload gets unbalanced, we can reassign vertices to the CPUs

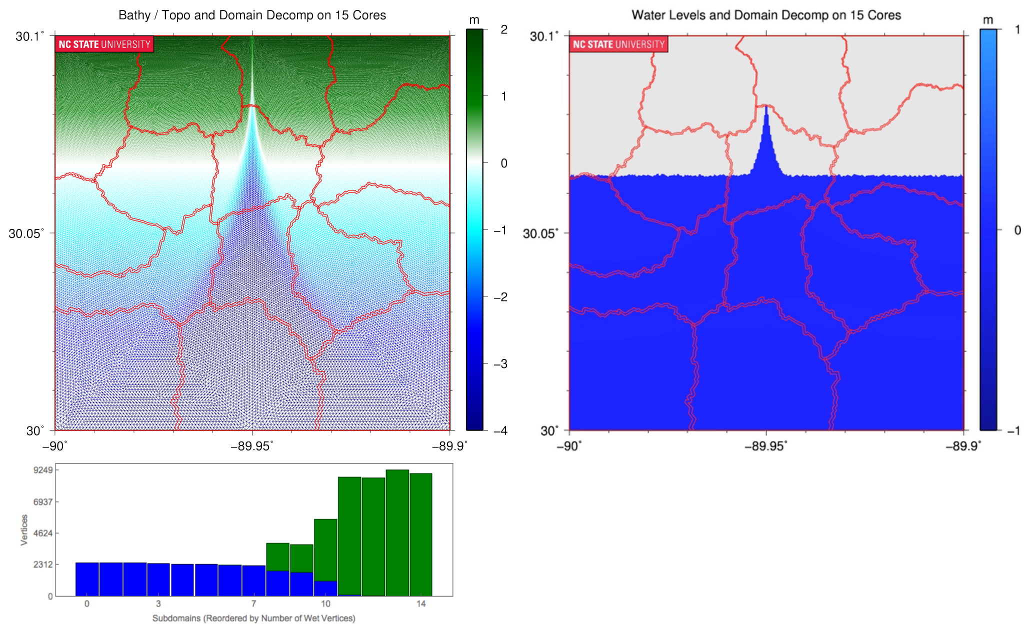
As a first try, we linked the re-decomposition to the hot-start files
- Every time ADCIRC writes its save file, it also rebalances its workload
- Can occur every day, every 12 hr, every 1 hr – Decision is for the user

Research Progress – Dynamic Load Balancing

Now the workload is rebalanced
- Redo the decomposition every 3 hr
- Continue the simulation

As dry vertices become wet
- They are moved onto other CPUs
- CPUs contribute equally to the solution

Wall-clock time of about 13.5 min
- This is a significant savings
- **Decrease of 26%**



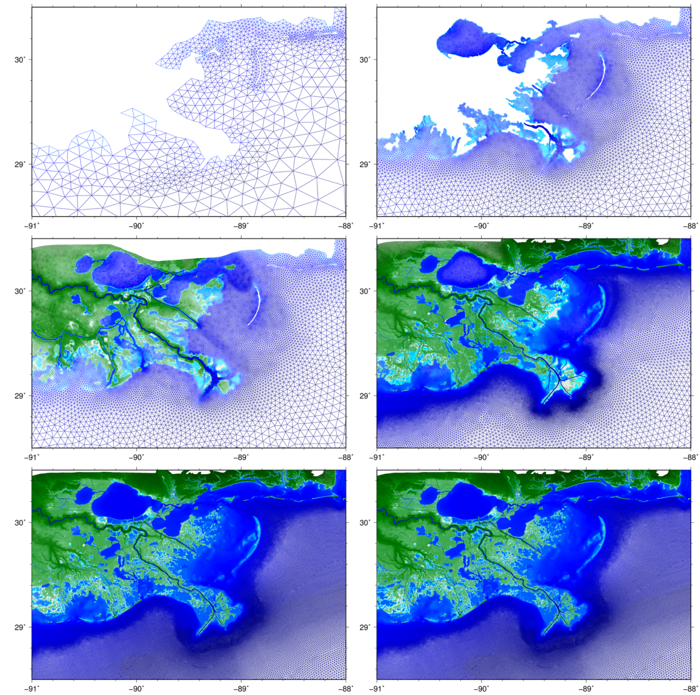
Research Progress – Adaptive, Multi-Resolution Approach

Adding floodplains during a simulation

- Begin with a coarse mesh, then switch to a fine mesh, without stopping the simulation
- Mapping between meshes via an automated framework
  - Optimized for parallel interpolation between unstructured meshes
  - Different fields are mapped with different methods (bilinear, first order conservative) to preserve the main properties of the fields (e.g. continuity)
- This process can be repeated as many times as needed to adapt to the resolution required during the simulation

Example: Hurricane approaching the coast

- Switch to a high-resolution mesh as regions start to flood



Research Progress – Adaptive, Multi-Resolution Approach

The current version of our software has the following features:

- Uses the Earth System Modeling Framework (ESMF) Library
  - Interpolation can be based on linear, conservative, and nearest-point algorithms
  - Extrapolation based on nearest-point algorithm
- ESMF meshes are created from ADCIRC input and decomposition files
  - One set for the ***source*** mesh, another set for the ***destination*** mesh
- Field re-gridding is used to map data between different meshes
  - Can be done in parallel or serial

From the user's point of view:

- Initial simulation is run on the source mesh, and its data are saved
- The source data are mapped to the destination mesh, and a new save file is written
- The simulation can be continued on the destination mesh

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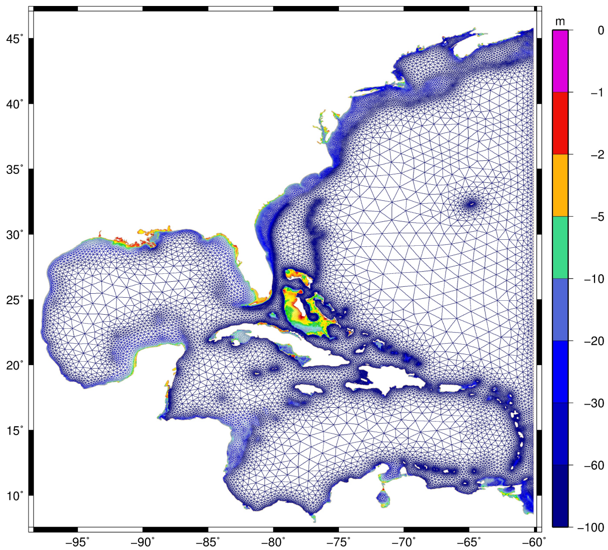
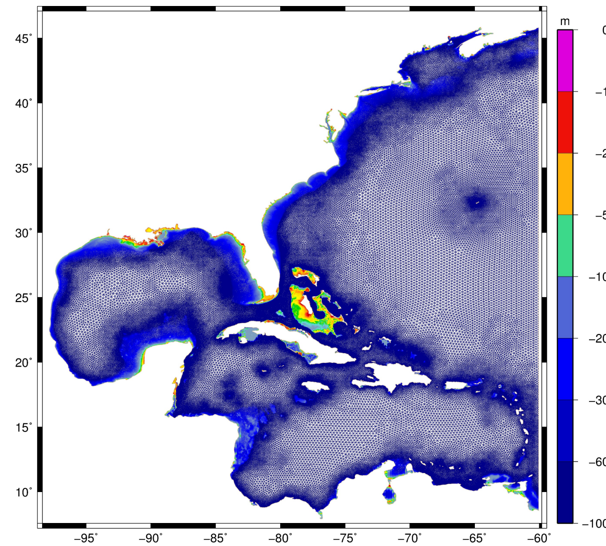
Research Progress – Adaptive, Multi-Resolution Approach

We consider two meshes of the western North Atlantic Ocean, Gulf of Mexico, and Caribbean Sea



Source: 52,774 vertices



Destination: 254,565 vertices

Research Progress – Adaptive, Multi-Resolution Approach

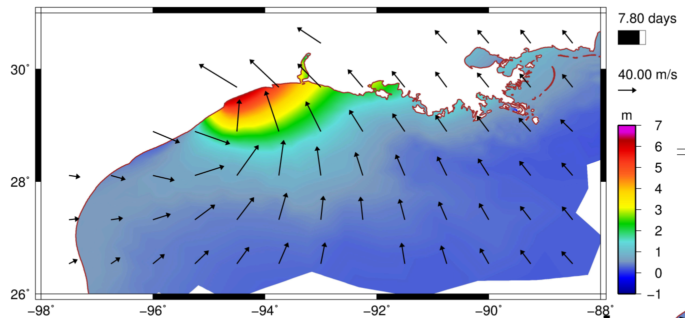
Now we only need to include the floodplains when they are likely to get wet
- Remove entirely the floodplains when the storm is far away
- Add the floodplains as the storm approaches the coast

Example simulations of hurricanes for 10 days
- Run the simulation on the coarse/source mesh for the first 6 days
- Use the interpolation module to maps the coarse/source data onto the fine/destination mesh
- Continue the simulation on the fine/destination mesh through the 10^{th} day

Initial results:
- **Average time savings of 40%**
- Results are close to a 'true' solution of all 10 days on the fine mesh

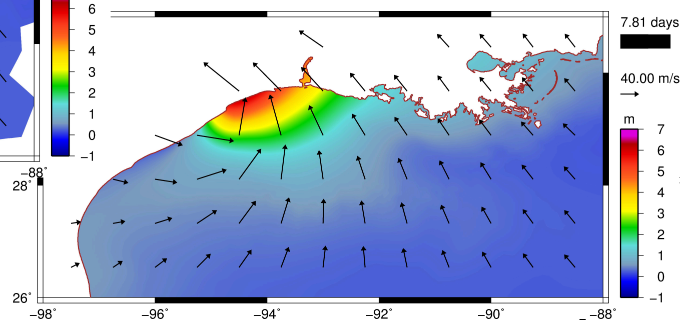
Research Progress – Adaptive, Multi-Resolution Approach

We compare the computed storm surge for all three cases

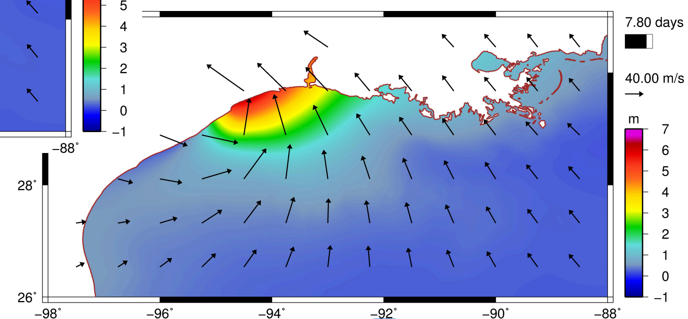


Source

Source onto Destination



Destination



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Research Progress – Adaptive, Multi-Resolution Approach

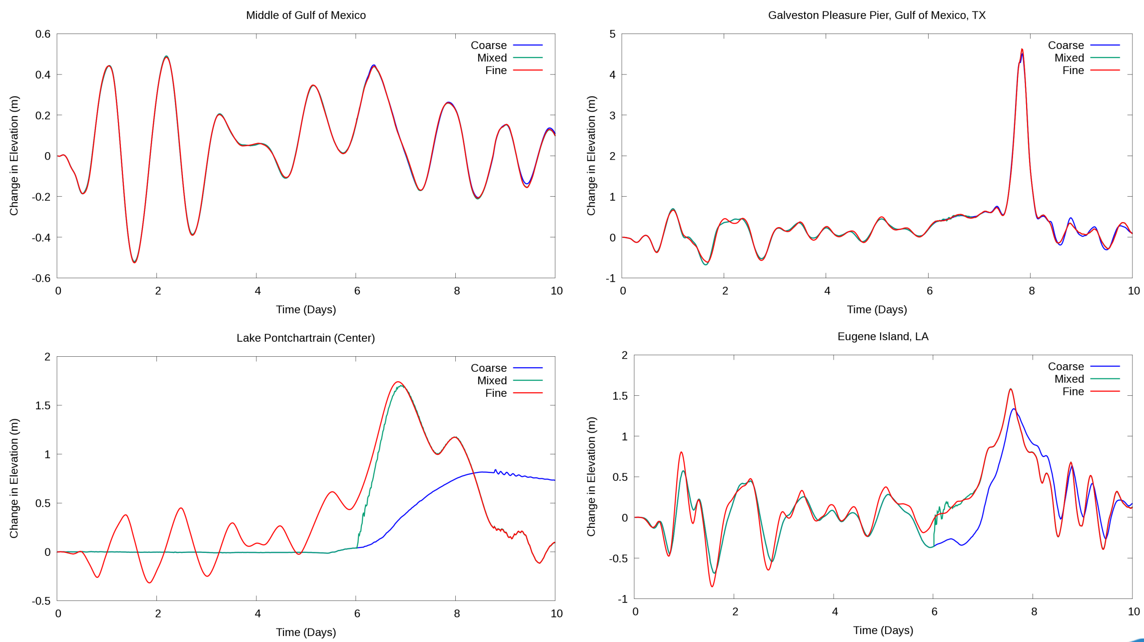
We compare results at several locations

Interior Gulf

Galveston

Lake Pontchartrain

Eugene Island



Research Progress – Summary and Future Steps

Dynamic load balancing

- Summary:
  - Domain is now re-decomposed to balance the workload among the CPUs
  - Savings of 25% in initial tests
- Future work:
  - Expand the technologies to larger problems
  - Only redo the decomposition when it is needed

Adaptive, multi-resolution approach

- Summary:
  - Developed tools to interpolate between coarse and fine meshes
  - Savings of 40% in initial tests
- Future work:
  - Expand the technologies for other ADCIRC file types
  - Add support for reading and writing different components of save files

Research Progress – Activities and Milestones for Y1-Y2

	Activity (A) or Milestone (M)	Completion Dates	Completed?
M	Presentation at ADCIRC Workshop	04/2016	☑ 05/2016
A	Parallelization of ADCIRC domain decomposition	06/2016	☑ 06/2016
A	Interpolation of ADCIRC results from coarse to fine meshes	06/2016	☑ 06/2016
A	Dynamic load balancing for a static ADCIRC simulation	12/2016	☑ 01/2017
A	Automation of interpolation routines	12/2016	☑ 12/2016
M	Presentation at national conference	12/2016	☑ 06/2016
M	Presentation at ADCIRC Workshop	04/2017	
A	Demonstration of adaptive approach with single target mesh	06/2017	
M	Submission of manuscript about dynamic load balancing	06/2017	

Proposed Follow-On Work

Plans for an additional 2 years in this project:

1. Extend the utility of our adaptive techniques for the community
   - Should be as straight-forward as possible for the user
   - Adaptivity should be triggered automatically and when it is most beneficial
   - Transition from semi-research tools to something that can be used in production

2. Extend our techniques to the SWAN nearshore wave model
   - Integral part of the wave and surge modeling system
   - Need to develop ways to move wave solution between CPUs, and onto finer meshes

3. Explore other techniques to optimize resolution in our meshes
   - Can we find ways to stabilize ADCIRC, so resolution is used only where it is absolutely needed?