Corrections for Subgrid Flooding Processes in Large-Domain Storm Surge Models

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Thank you

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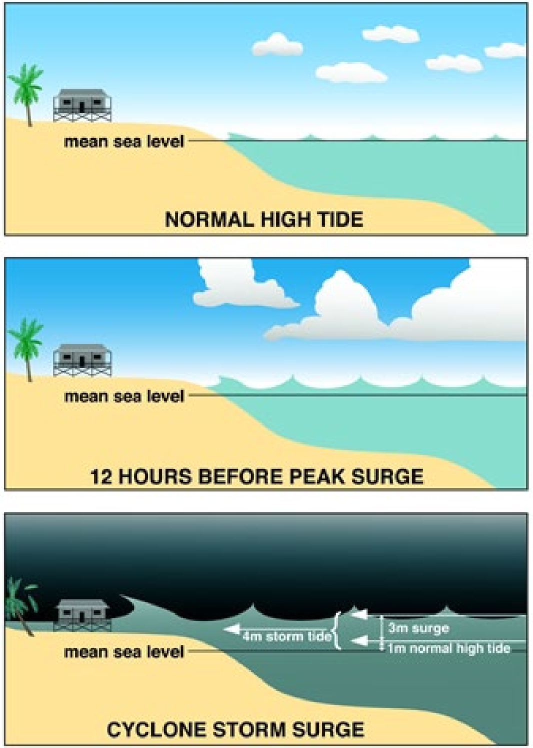
Introduction

- Introduction to storm surge
  - What is storm surge?
  - Why do we care about storm surge?
- Introduction to storm surge modeling
  - What are storm surge models?
  - How do they work?
  - Why do we need them?

What is storm surge?

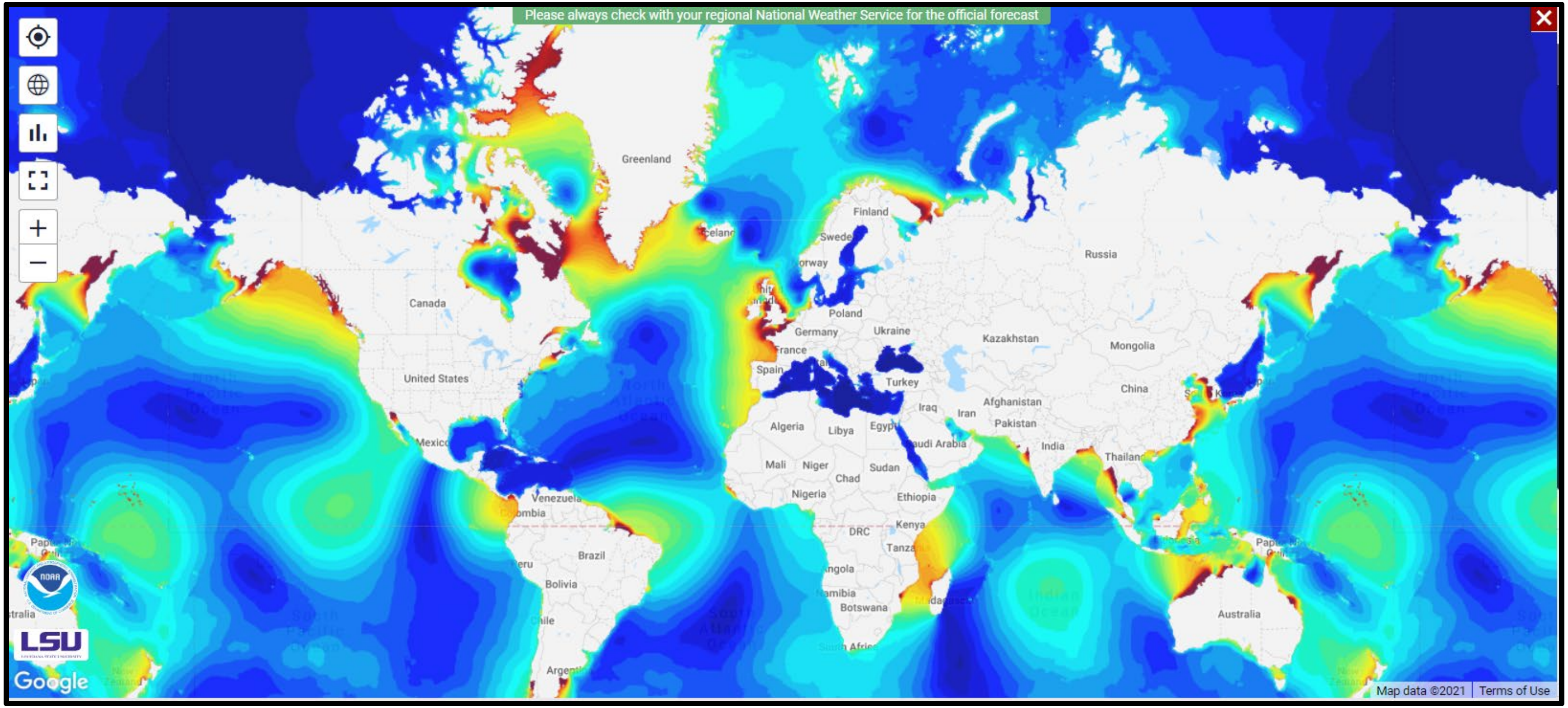


Credit: Australian Bureau of Meteorology

Storm surge flooding in New Jersey by Hurricane Sandy 2012

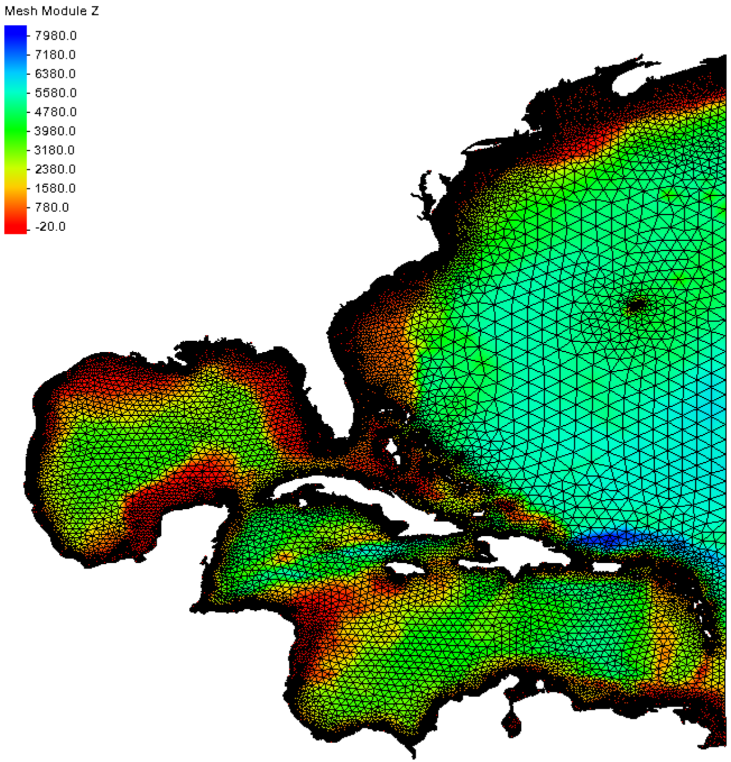
Credit: U.S. Air Force photo by Master Sgt. Mark C. Olsen

Storm surge modeling

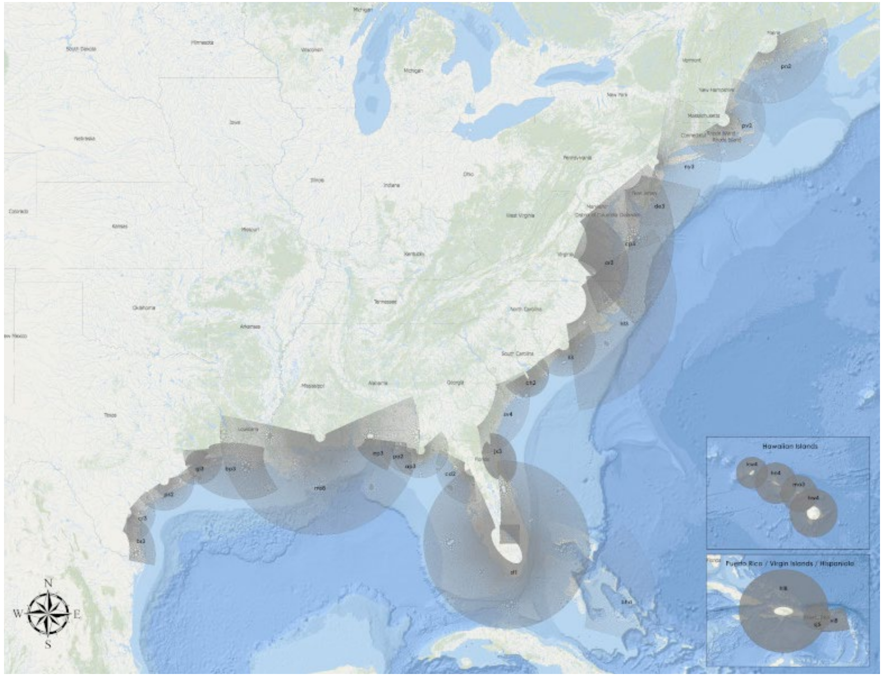


Credit: Coastal Emergency Risks Assessment (CERA)

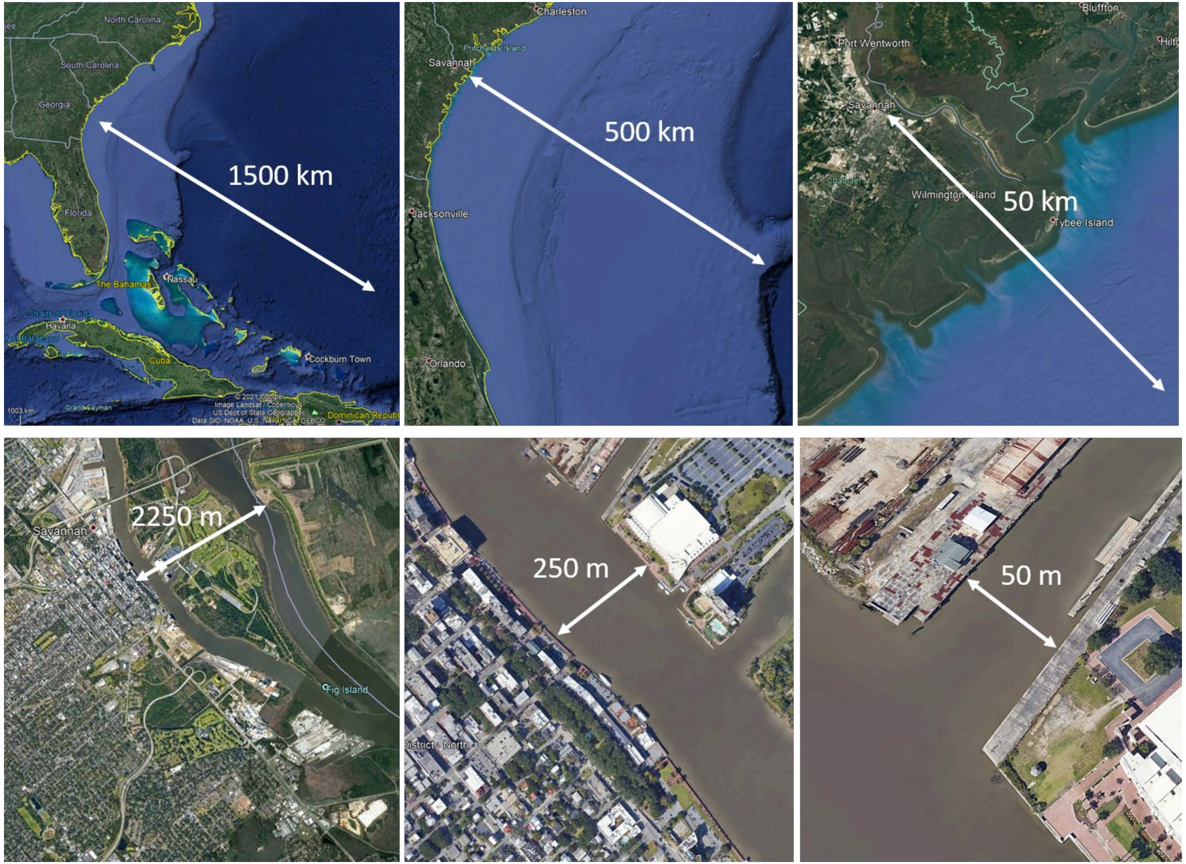
Unstructured Triangular Mesh



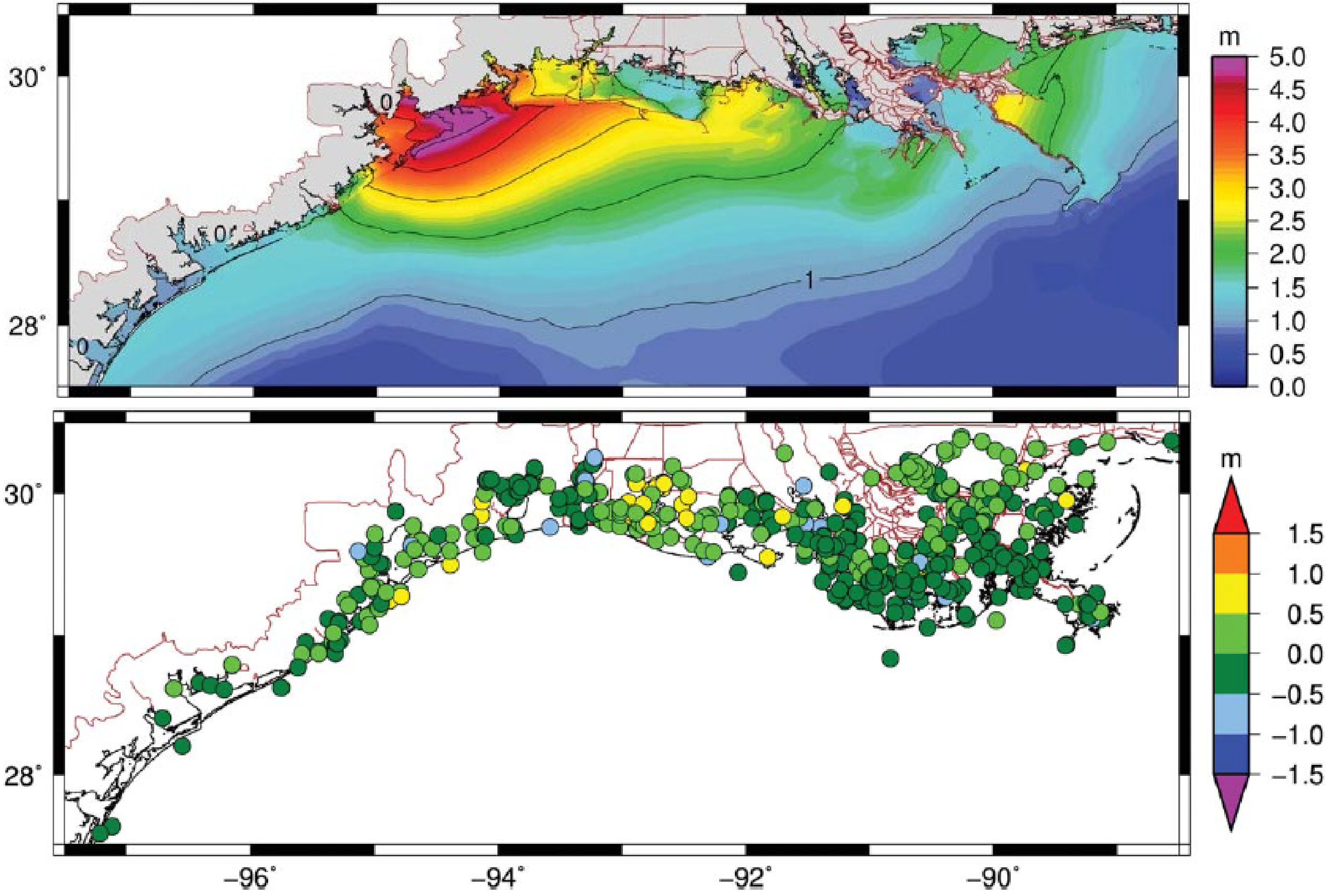
Structured Polar and Hyperbolic Grids



How do we get useful model predictions

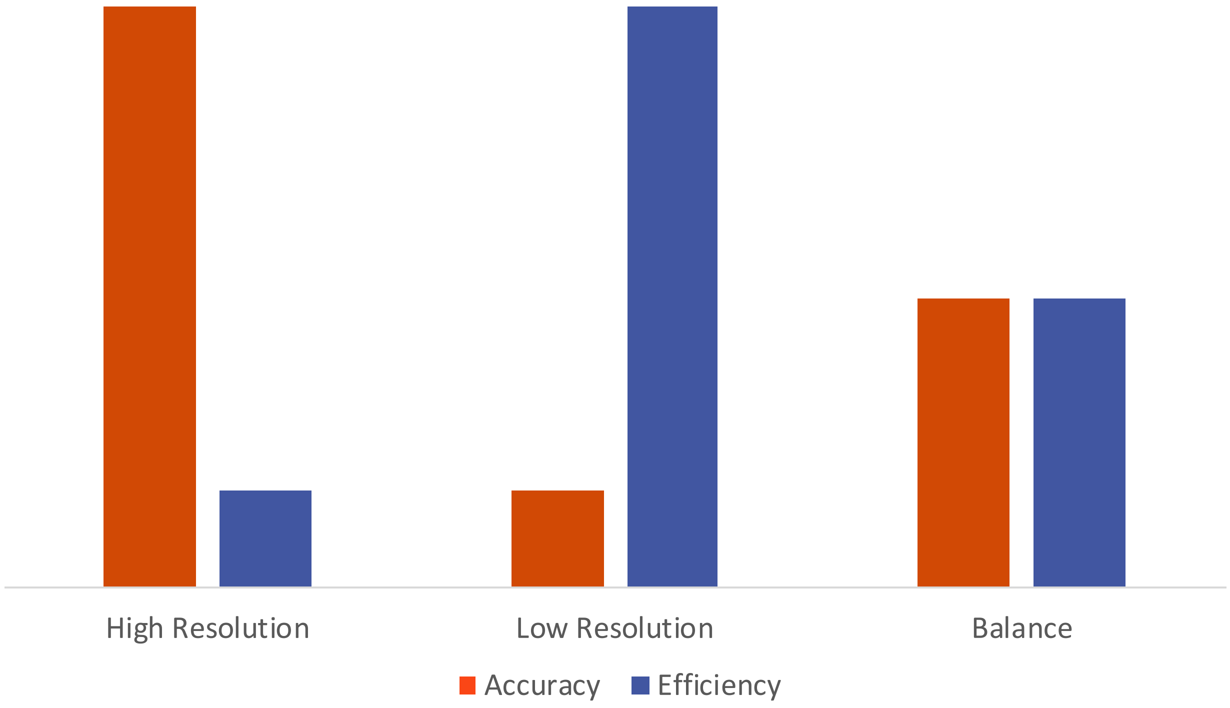


Credit: Google 2021

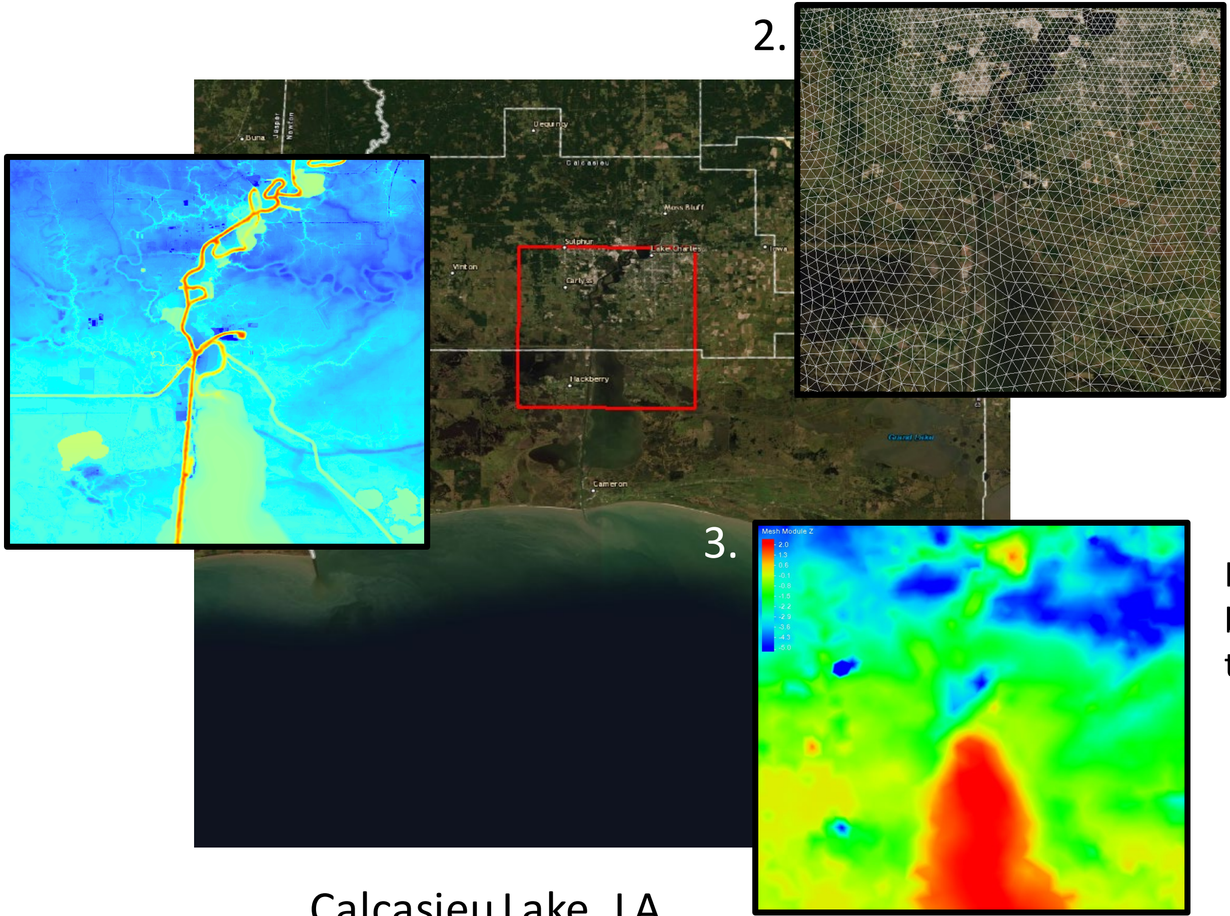


Hindcast storm surge prediction for Ike (2008) Hope et al. (2013)

How do we get useful model predictions



High resolution bathymetry of the Bayou Contraband and Northern Calcasieu Lake, LA



Calcasieu Lake, LA

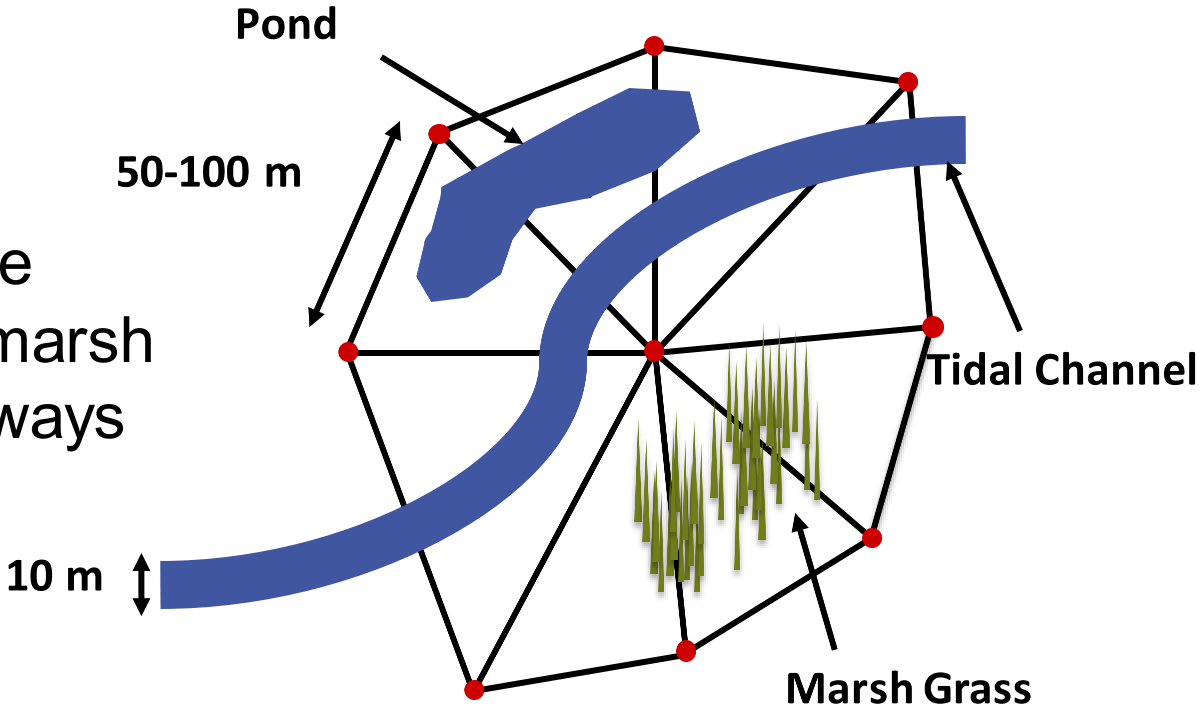
NOMAD mesh v1e MSL (HSOFS)

- This mesh is used in real-time forecasting by NOAA and the ADCIRC Prediction System (APS).

Interpolated bathymetry of the mesh

Subgrid Corrections

- Include: small scale channels, ponds, marsh grasses, and roadways

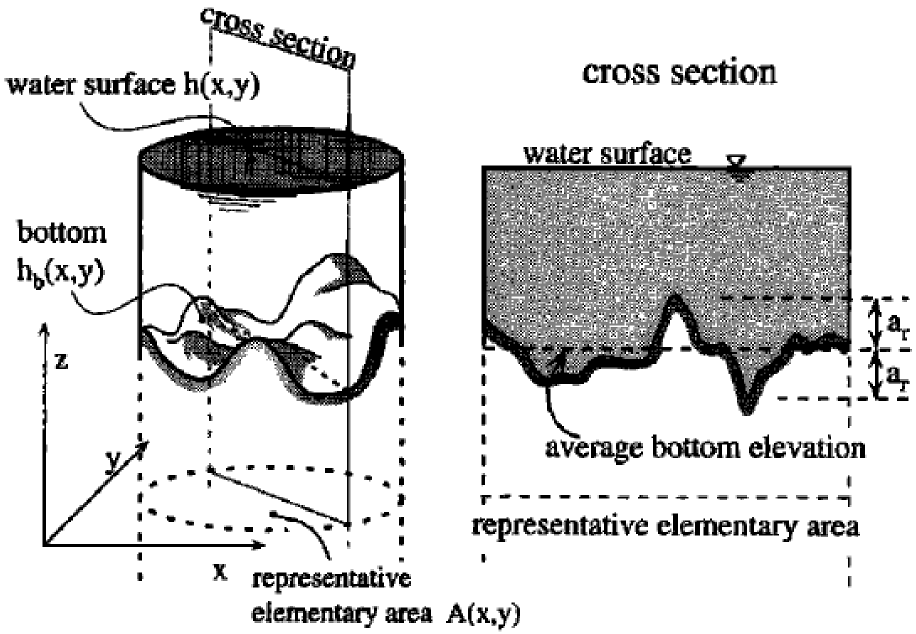


Goals

- The goal of this work is to introduce subgrid corrections into the widely used, high-scalable ADvanced CIRCulation (ADCIRC) model.
- Doing this will allow for accurate water level prediction on coarsened numerical meshes, thereby increasing the efficiency of the model.
- This will be useful not only for storm surge forecasting, but also design studies.

Literature Review

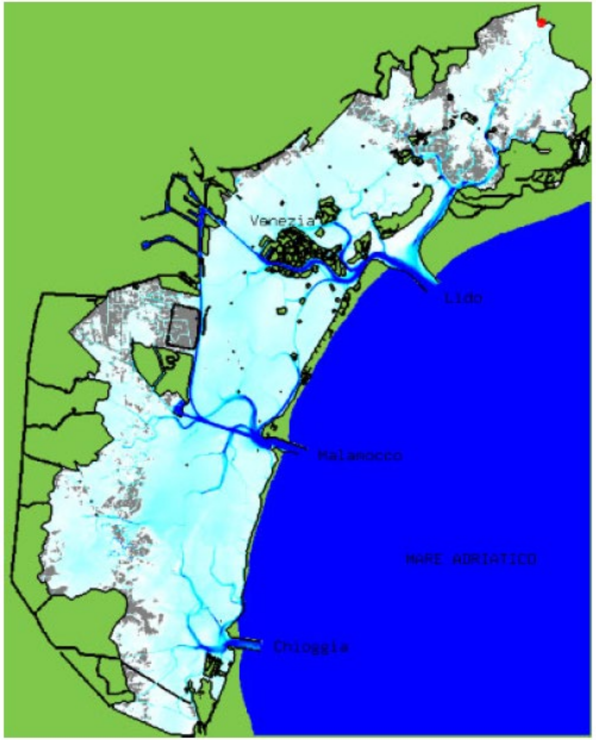
- Defina (2000) used *subgrid corrections* to advection and partially wet areas to account for changes in flow through very irregular domains.
- Found comparable results on grids ~32 x coarser.



Literature Review

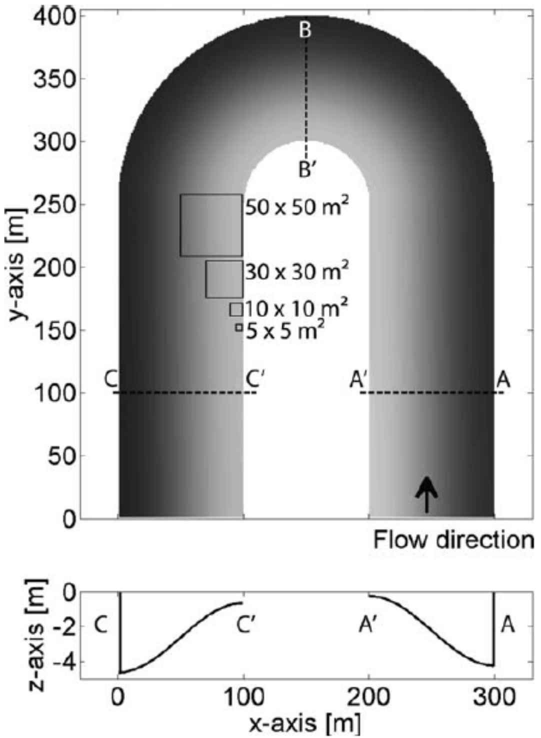
- Casulli (2009) and Casulli and Stelling (2011) made corrections to partially wet computational cells with the use of lookup tables created from high-resolution elevation data.

Grid size (m)	N_p	N_s	CPU time (s)
25	671 030	1 361 331	6526
50	172 392	352 983	1082
100	45 057	93 361	123
300	5627	11 959	16



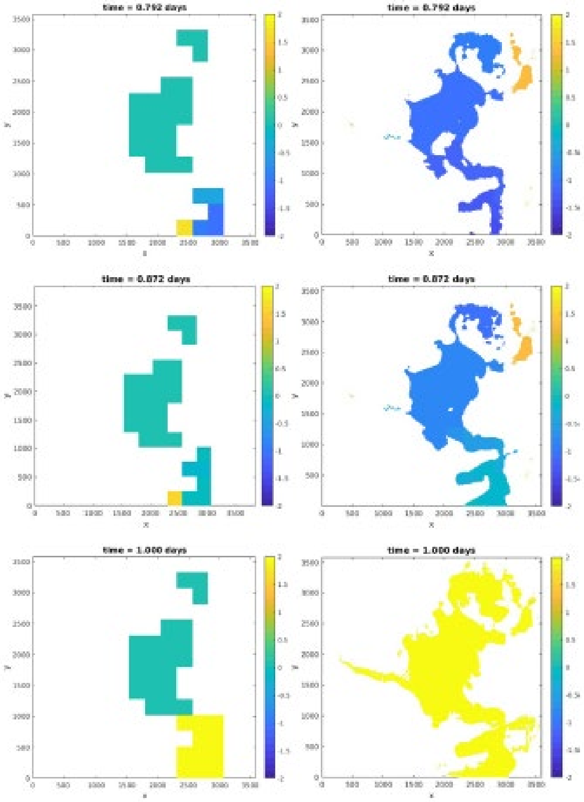
Literature Review

- Volp (2013) sought to resolve issues with bottom friction by applying *subgrid corrections* to bottom stress.
- The addition of a friction correction improved discharge and water surface slope when coarsened model results were compared to high-resolution counterparts.



Literature Review

- Kennedy et al. (2019) formalized all of this work and introduced additional *subgrid corrections* to the governing equations.
- Subgrid corrections significantly improved model accuracy and efficiency
- There is still work to be done to develop proper corrections for complex scenarios.



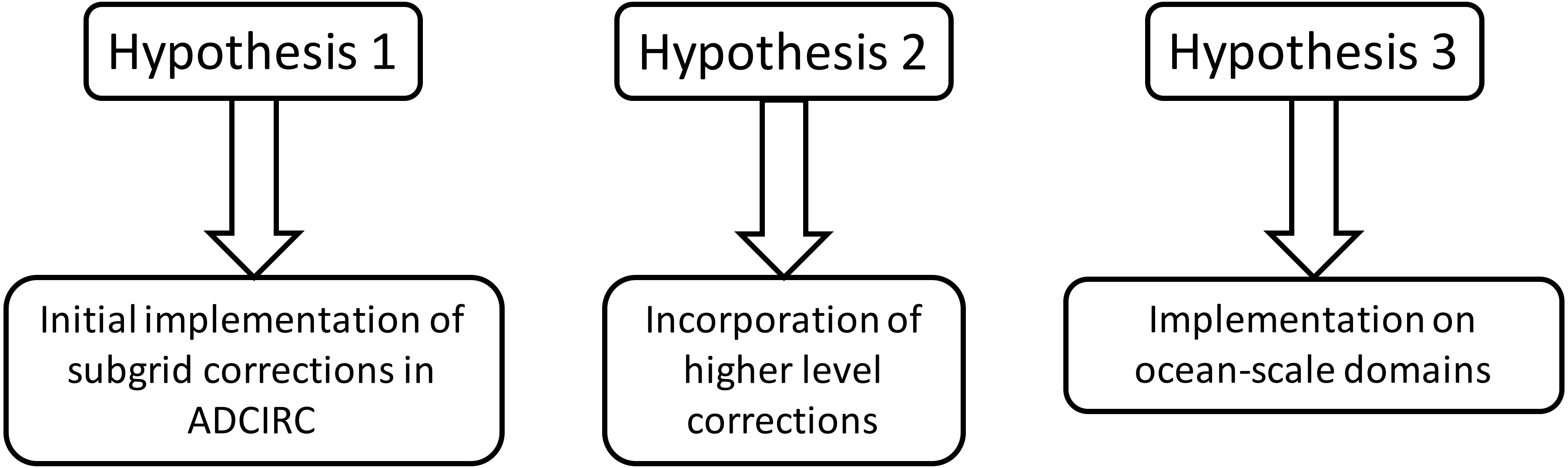
Literature Review

- Limitations of the previous work include:
  - Relatively small domains
  - Simplistic tidal forcing or relatively minor storm forcing
  - Incorporation of corrections into non-scalable numerical models

Hypotheses

1. If *subgrid corrections* are applied to partially wet elements in ADCIRC, then flow behavior at the smallest scales can be better resolved by coarsened model domains.
2. If more complex *subgrid corrections* are added to ADCIRC, then model results will be further improved.
3. If *subgrid corrections* in ADCIRC are applied to ocean-scale domains, then the applicability and usefulness of these corrections can be increased.

Roadmap


Hypothesis 1
Hypothesis 2
Hypothesis 3
Initial implementation of subgrid corrections in ADCIRC
Incorporation of higher level corrections
Implementation on ocean-scale domains

Roadmap

Hypothesis 1 → Initial implementation of subgrid corrections in ADCIRC

Hypothesis 2 → Incorporation of higher level corrections

Hypothesis 3 → Implementation on ocean-scale domains

If *subgrid corrections* are applied to partially wet elements in ADCIRC, then flow behavior at the smallest scales can be better resolved by coarsened model domains.

Level 0 Closure

- Kennedy et al. (2019) introduced *subgrid corrections* as different closures in the governing equations.
- The so-called '*Level 0*' closure corrects flow behavior at the wet/dry front.
- In the first chapter of this work, I incorporate the Level 0 closure into the governing shallow water equations, and the implement them into the ADCIRC source code.

Level 0 Closure

Theory

- The primitive shallow water equations were first averaged using techniques outlined in Kennedy et al. 2019.
- These averaged primitive equations were then transformed into the GWCE and conservative momentum equations ADCIRC uses.

Averaged Variables Theory

- To obtain the averaged variables we integrate inside each element.
- A given dummy variable Q would be averaged as follows:

$$\langle Q \rangle_G \equiv \frac{1}{A_G} \iint_{A_W} Q dA \qquad \& \qquad \langle Q \rangle_W \equiv \frac{1}{A_W} \iint_{A_W} Q dA \qquad \text{Where: } A_W = \phi A_G$$

Averaged conservative x-momentum equation

$$\frac{\partial \langle UH \rangle_G}{\partial t} + g C_\zeta \langle H \rangle_G \frac{\partial \langle \zeta \rangle_W}{\partial x} = -\frac{\partial C_{UU} \langle U \rangle \langle UH \rangle_G}{\partial x} - \frac{\partial C_{VU} \langle V \rangle \langle UH \rangle_G}{\partial y} + f \langle VH \rangle_G - g \langle H \rangle_G \frac{\partial P_A}{\partial x} + \phi \left\langle \frac{\tau_{sx}}{\rho_0} \right\rangle_W - C_{M,f} \frac{|\langle \boldsymbol{U} \rangle| \langle UH \rangle_G}{\langle H \rangle_W} + \frac{\partial}{\partial x} \tilde{E}_h \frac{\partial \langle UH \rangle_G}{\partial x} + \frac{\partial}{\partial y} \tilde{E}_h \frac{\partial \langle UH \rangle_G}{\partial y}$$

Averaged conservative y-momentum equation

$$\frac{\partial \langle VH \rangle_G}{\partial t} + g C_\zeta \langle H \rangle_G \frac{\partial \langle \zeta \rangle_W}{\partial y} = -\frac{\partial C_{UV} \langle U \rangle \langle VH \rangle_G}{\partial x} - \frac{\partial C_{VV} \langle V \rangle \langle VH \rangle_G}{\partial y} - f \langle UH \rangle_G - g \langle H \rangle_G \frac{\partial P_A}{\partial y} + \phi \left\langle \frac{\tau_{sy}}{\rho_0} \right\rangle_W - C_{M,f} \frac{|\langle \boldsymbol{U} \rangle| \langle VH \rangle_G}{\langle H \rangle_W} + \frac{\partial}{\partial x} \tilde{E}_h \frac{\partial \langle VH \rangle_G}{\partial x} + \frac{\partial}{\partial y} \tilde{E}_h \frac{\partial \langle VH \rangle_G}{\partial y}$$

Averaged GWCE

$$\phi \frac{\partial^2 \langle \zeta \rangle_W}{\partial t^2} + \frac{\partial \phi}{\partial t} \frac{\partial \langle \zeta \rangle_W}{\partial t} + \tau_0 \phi \frac{\partial \langle \zeta \rangle_W}{\partial t} - \frac{\partial}{\partial x}\left(g \langle H \rangle_G \frac{\partial \langle \zeta \rangle_W}{\partial x} \right) - \frac{\partial}{\partial y}\left(g \langle H \rangle_G \frac{\partial \langle \zeta \rangle_W}{\partial y} \right) + \frac{\partial \langle \tilde{J}_x \rangle_G}{\partial x} + \frac{\partial \langle \tilde{J}_y \rangle_G}{\partial y} - \langle UH \rangle_G \frac{\partial \tau_0}{\partial x} - \langle VH \rangle_G \frac{\partial \tau_0}{\partial y}$$

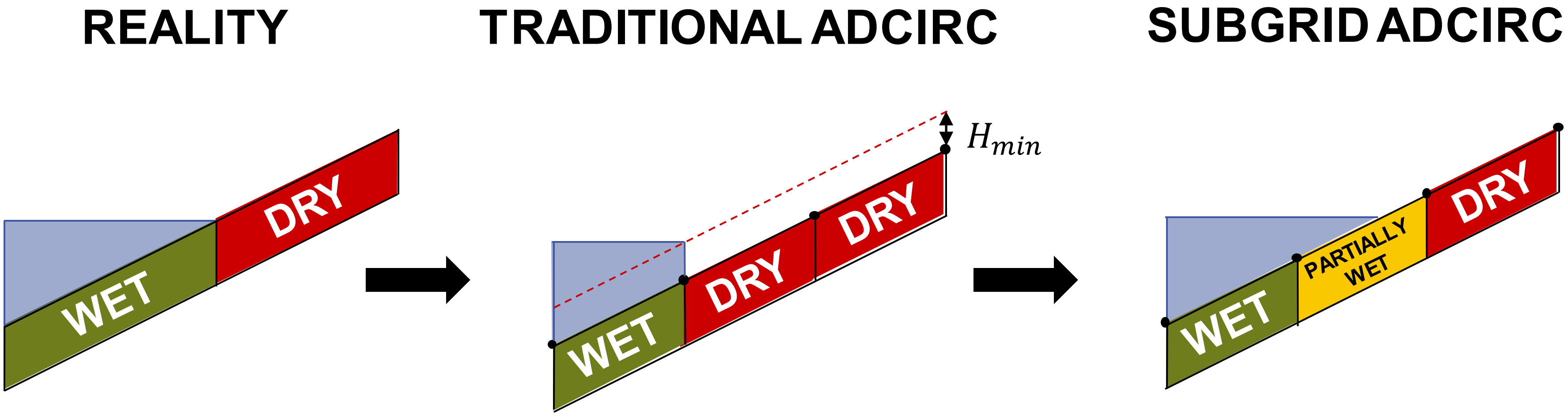
Where:

$$\frac{\partial \langle \tilde{J}_x \rangle_G}{\partial x} = (\text{RHS of x} - \text{CME}) + \tau_0 \langle UH \rangle_G$$

$$\frac{\partial \langle \tilde{J}_y \rangle_G}{\partial y} = (\text{RHS of y} - \text{CME}) + \tau_0 \langle VH \rangle_G$$

	Traditional	Level 0
Wet/dry Correction	$\phi = 0, H \leq 0$ $\phi = 1, H > 0$	$\boldsymbol{\phi = A_W / A_G}$
Advection Correction	$C_{UU} = C_{VU} = C_{UV} = C_{VV} = 1$	$C_{UU} = C_{VU} = C_{UV} = C_{VV} = 1$
Friction Correction	$C_{M,f} = C_f = \frac{gn^2}{H^{1/3}}$	$\boldsymbol{C_{M,f} = \langle C_f \rangle_G}$
Water Surface Gradient Correction	$C_\zeta = 1$	$C_\zeta = 1$

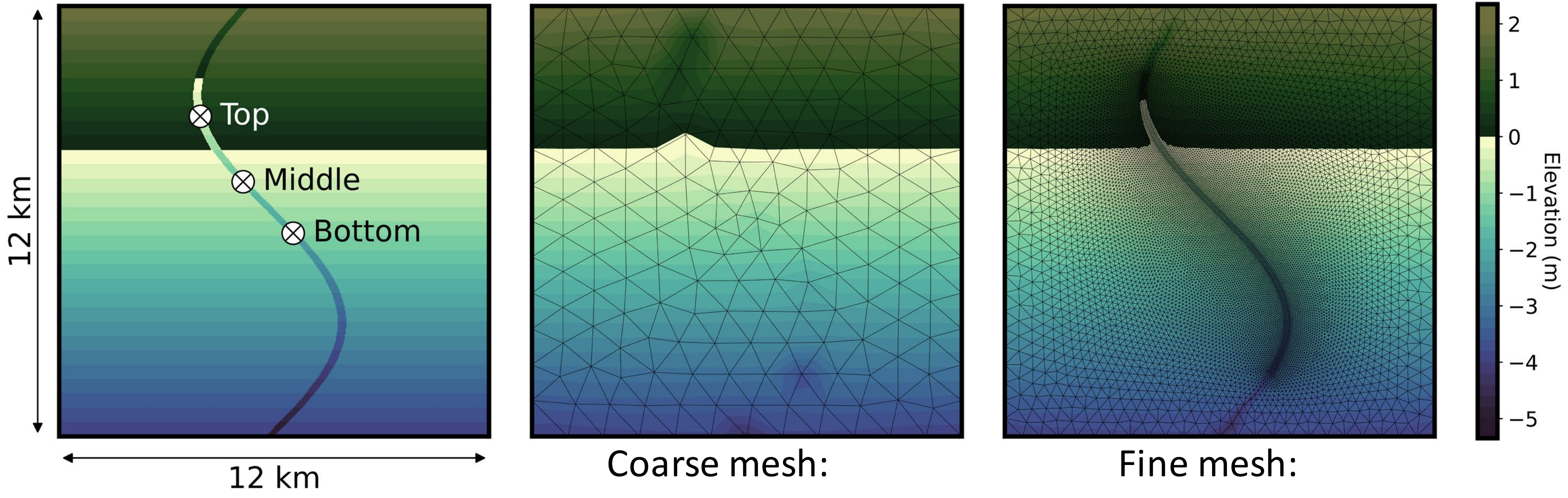
Wetting and Drying



Test Domains

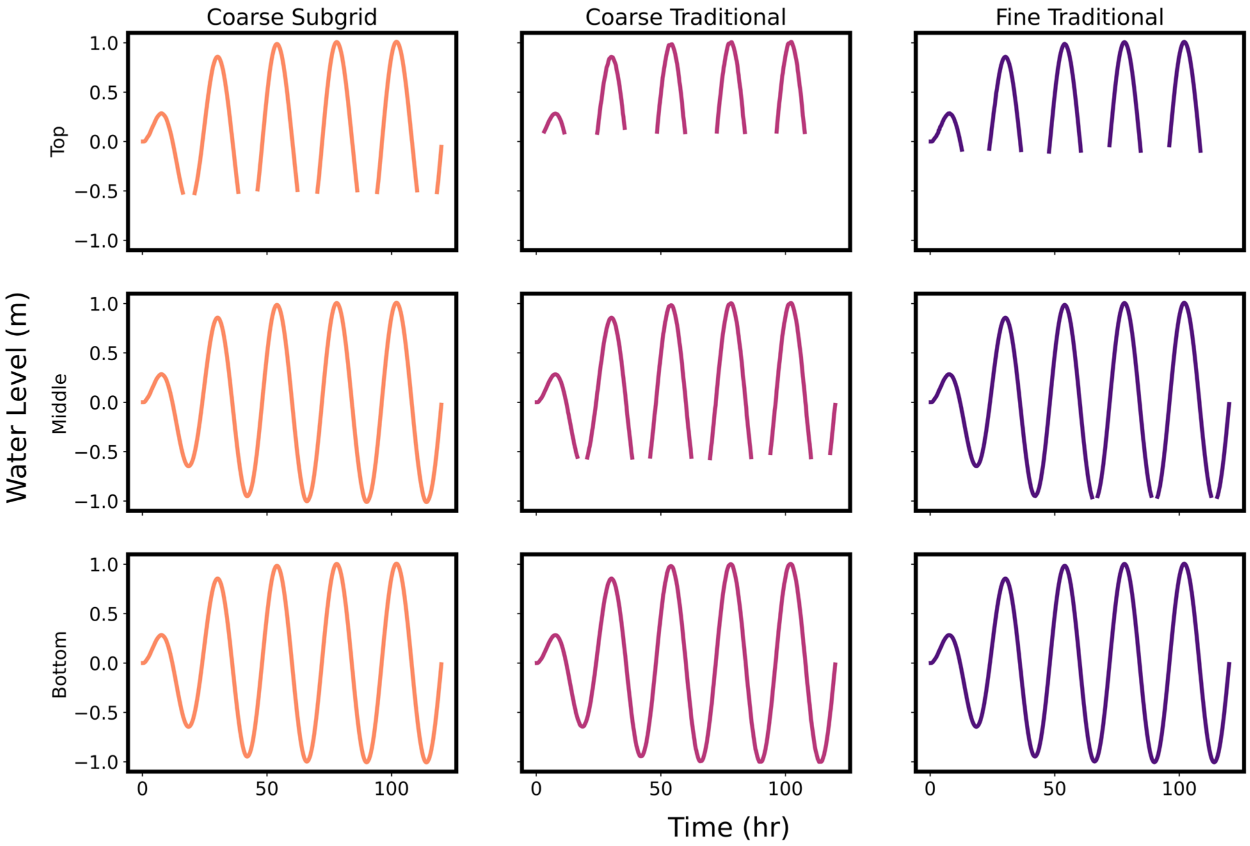
- Three domains were used to test the viability of the subgrid additions in ADCIRC:
  1. Synthetic winding channel
  2. Buttermilk Bay, Massachusetts
  3. Calcasieu Lake, Louisiana

Winding Channel



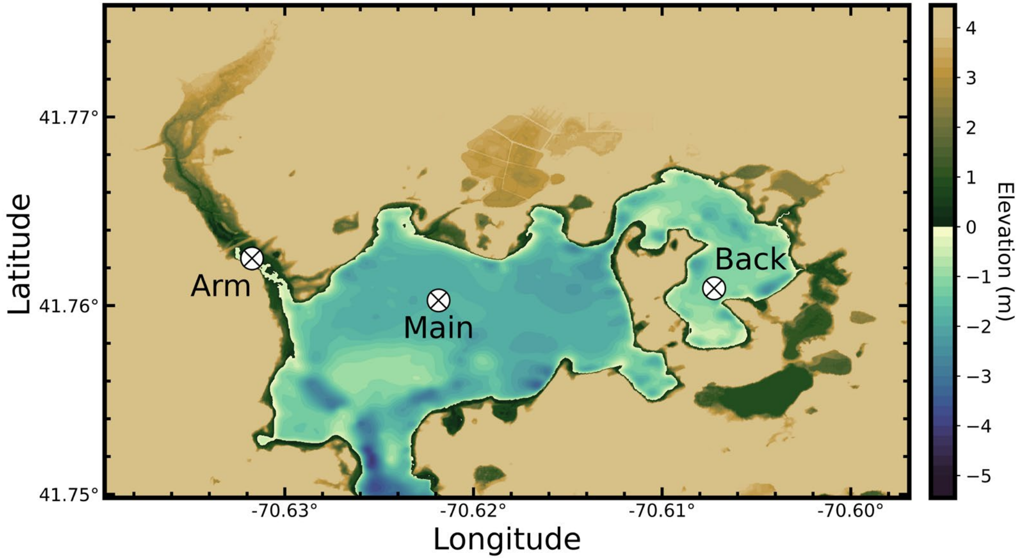
Coarse mesh:
192 Vertices
334 Elements
~ 65 times coarser

Fine mesh:
12,475 Vertices
24,852 Elements

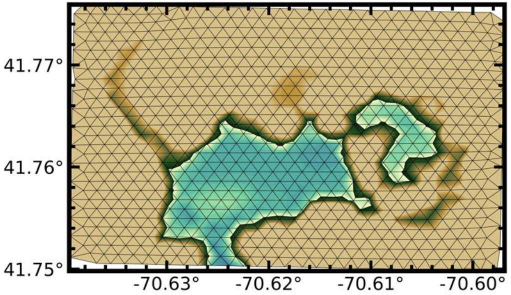


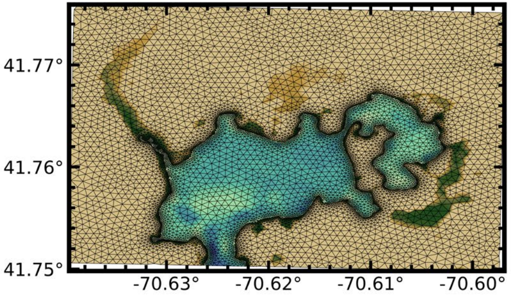
- The subgrid simulation showed superior connectivity through the winding channel than either the coarse or fine traditional solutions

Buttermilk Bay

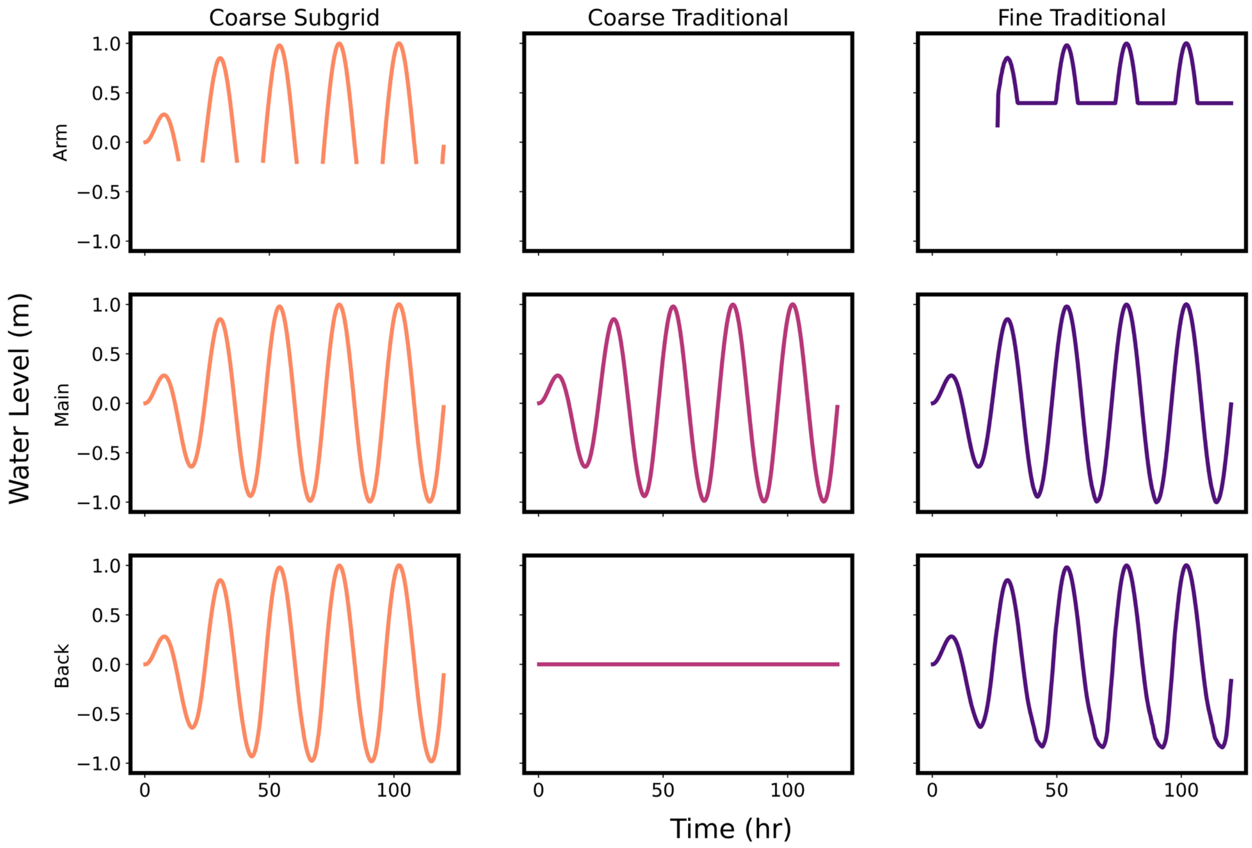


Coarse mesh:
830 vertices
1,569 elements
~ 6 times coarser





Fine mesh:
4,795 vertices
9,412 elements



The coarse traditional fails to detect water at the Arm station

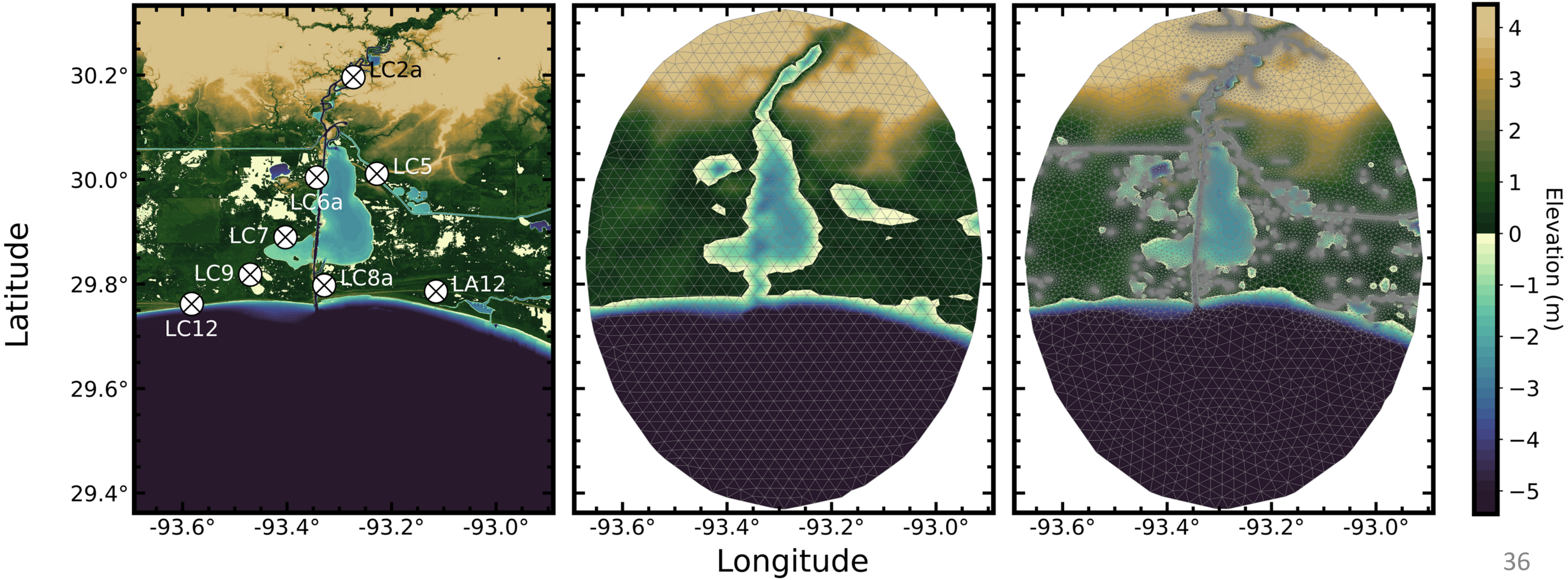
The Main Bay station serves as a control showing all simulations were forced appropriately

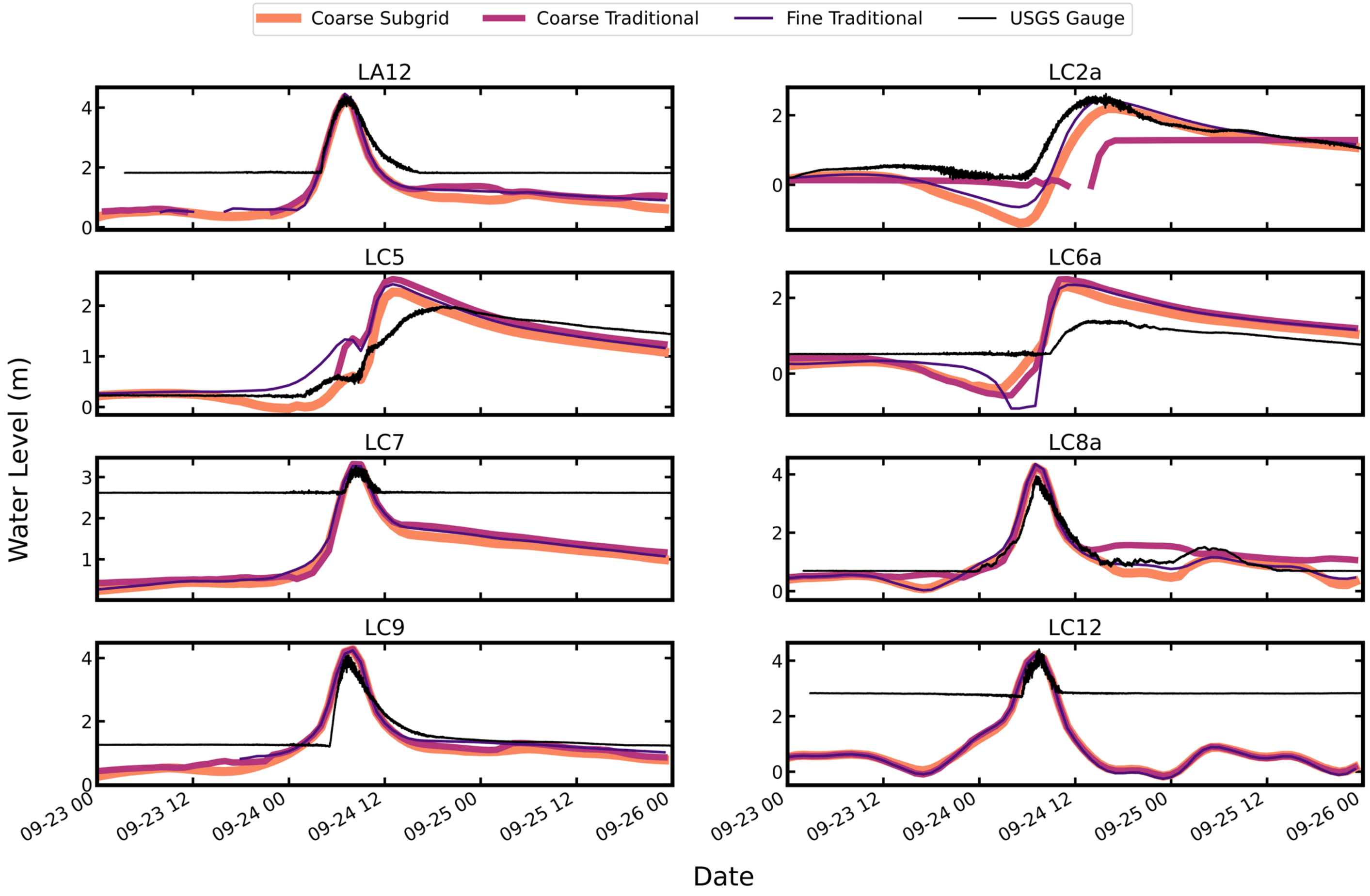
The coarse simulation fails to detect tidal connectivity at the Back Bay station.

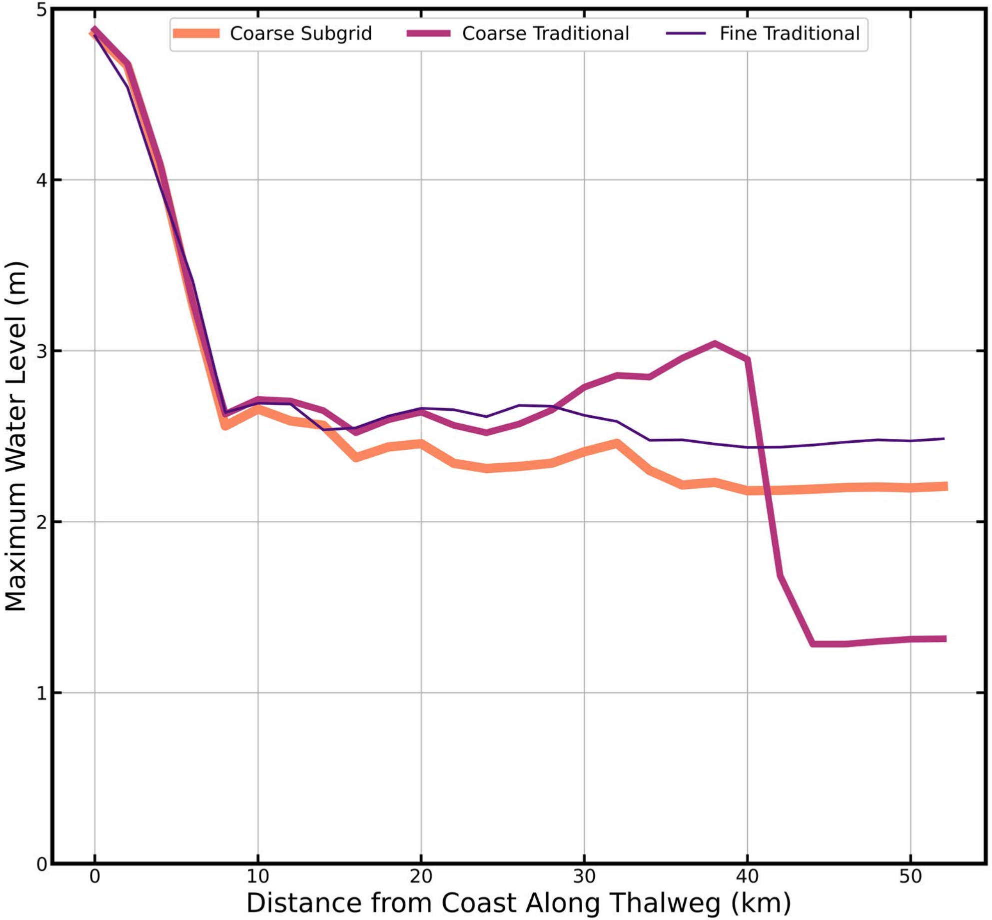
Calcasieu Lake

Coarse mesh:
1,236 Vertices
2,370 Elements
~ 33 times coarser

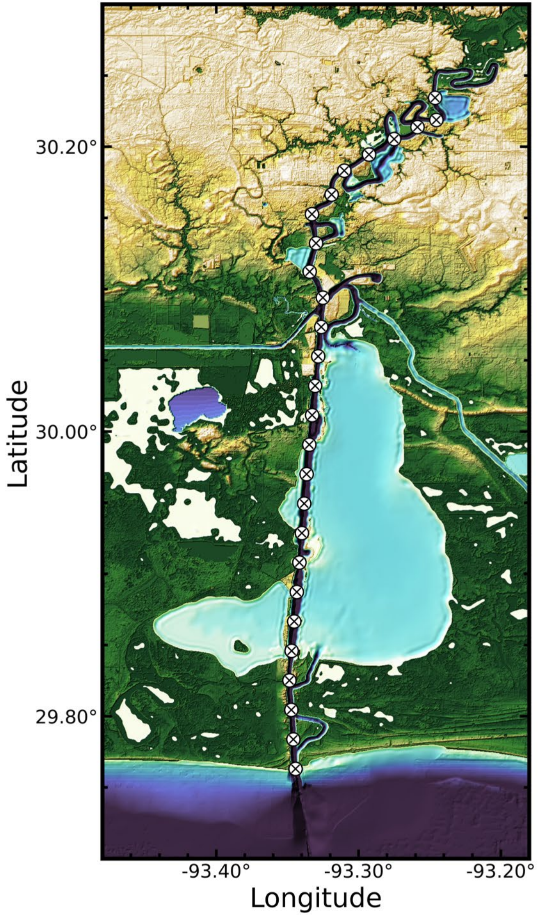
Fine mesh:
40,816 Vertices
81,321 Elements




Coarse Subgrid
Coarse Traditional
Fine Traditional
USGS Gauge
LA12
LC2a
LC5
LC6a
LC7
LC8a
LC9
LC12
Water Level (m)
09-23 00
09-23 12
09-24 00
09-24 12
09-25 00
09-25 12
09-26 00
Date



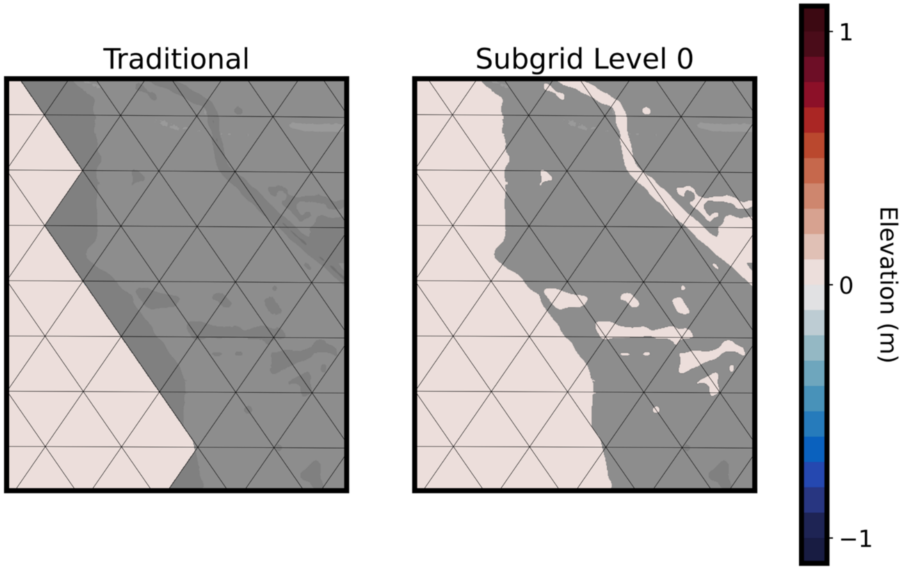
Coarse Subgrid
Coarse Traditional
Fine Traditional
Maximum Water Level (m)
Distance from Coast Along Thalweg (km)
0
1
2
3
4
5
10
20
30
40
50



Latitude
Longitude
30.20°
30.00°
29.80°
-93.40°
-93.30°
-93.20°

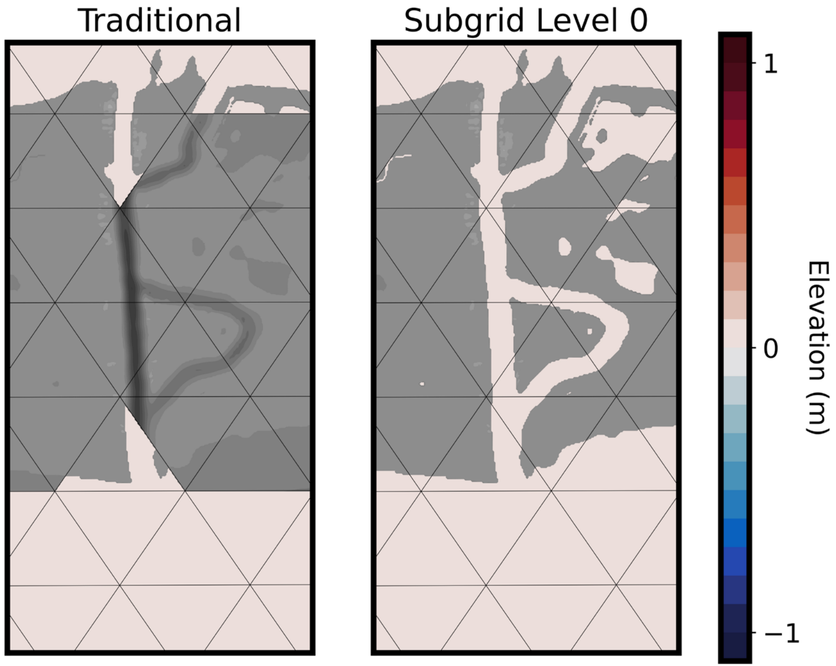
Level 0 Closure Conclusions

- The additions of Level 0 corrections into ADCIRC allowed for use of partially wet elements and vertices.
- This is a more accurate representation of the wet/dry boundary on coarsened meshes.



Level 0 Closure Conclusions

- Subgrid corrections increased the accuracy and hydraulic connectivity of the model while running on significantly coarsened meshes.



Level 0 Closure Conclusions

- For a given grid, introducing *subgrid corrections* into ADCIRC increases computational cost to the code.

Coarse Subgrid	Coarse Traditional	Fine Traditional
5,248 s	3,728 s	167,514 s

- However, these costs were small when compared to the efficiency gained by running on coarsened meshes.

Roadmap

Hypothesis 1

Initial implementation of subgrid corrections in ADCIRC

Hypothesis 2

Incorporation of higher level corrections

Hypothesis 3

Implementation on ocean-scale domains

If more complex *subgrid corrections* are added to ADCIRC, then model results will be further improved.

Motivation

- The initial implementation of subgrid corrections in ADCIRC left a few challenges:

1. Overestimation of bottom friction in the subgrid model.
2. Inability to account for small-scale variation in nonlinear advection terms.

Higher Level Corrections in ADCIRC

- Using the following equations from Kennedy et al. (2019) we correct bottom friction and advection coefficients present in the governing equations.
- These corrections will be referred to as '*Level 1*' corrections.

Friction Correction

$$C_{M,f} = \langle H \rangle_W R_v^2$$

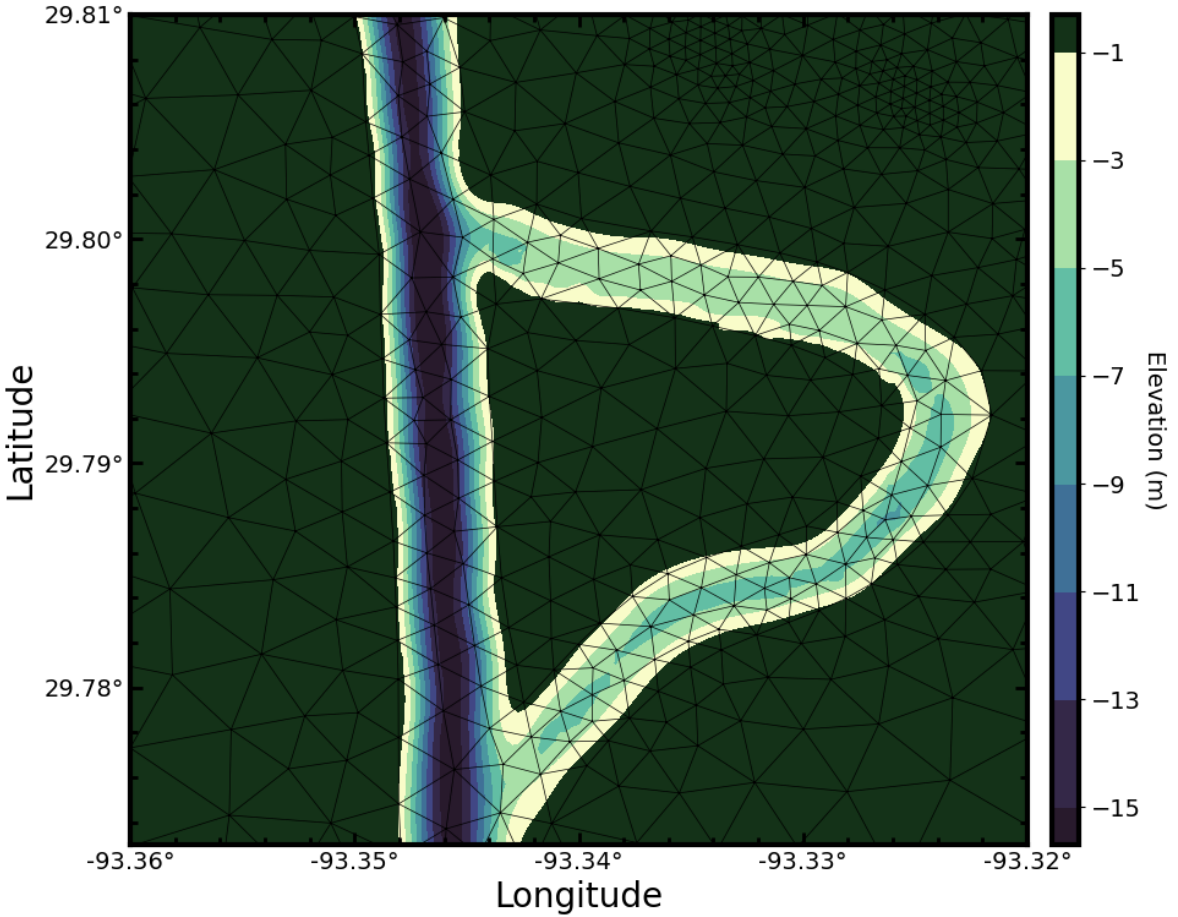
Where:

$$R_v = \frac{\langle H \rangle_W}{\left\langle H^{3/2} C_f^{-1/2} \right\rangle_W}$$

Advection Correction

$$C_{UU} = C_{VU} = C_{UV} = C_{VV} = \frac{1}{\langle H \rangle_W} \left\langle \frac{H^2}{C_f} \right\rangle_W R_v^2$$

	Traditional	Level 0	Level 1
Wet/dry	$\phi = 0, H \leq 0$ $\phi = 1, H > 0$	$\phi = A_W / A_G$	$\phi = A_W / A_G$
Advection	$C_{UU} = C_{VU} = C_{UV} = C_{VV} = 1$	$C_{UU} = C_{VU} = C_{UV} = C_{VV} = 1$	$\boldsymbol{C_{UU} = C_{VU} = C_{UV} = C_{VV} = \frac{1}{\langle H \rangle_W} \left\langle \frac{H^2}{C_f} \right\rangle_W R_v^2}$
Friction	$C_{M,f} = C_f = \frac{gn^2}{H^{1/3}}$	$C_{M,f} = \langle C_f \rangle_G$	$\boldsymbol{C_{M,f} = \langle H \rangle_W R_v^2}$
Surface Gradient	$C_\zeta = 1$	$C_\zeta = 1$	$C_\zeta = 1$

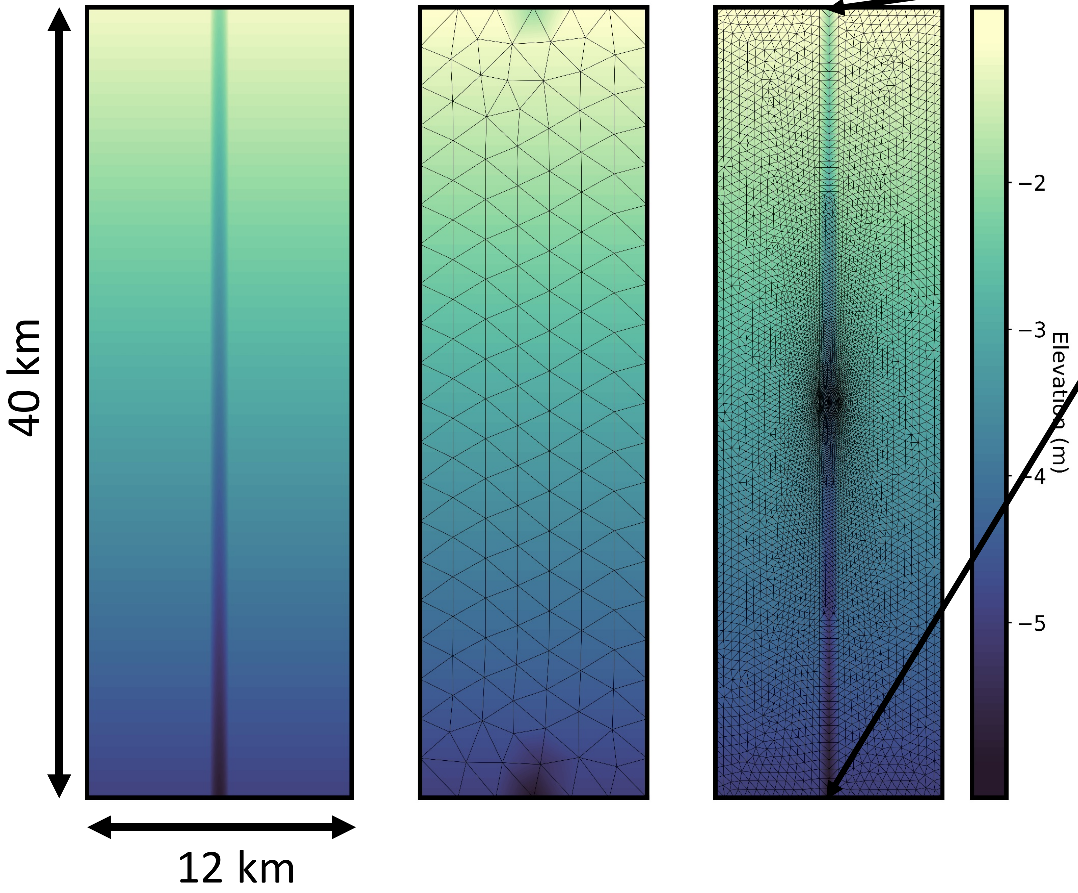

29.81°
29.80°
29.79°
29.78°
Latitude
-93.36°
-93.35°
-93.34°
-93.33°
-93.32°
Longitude
−1
−3
−5
−7
−9
−11
−13
−15
Elevation (m)

Test Cases

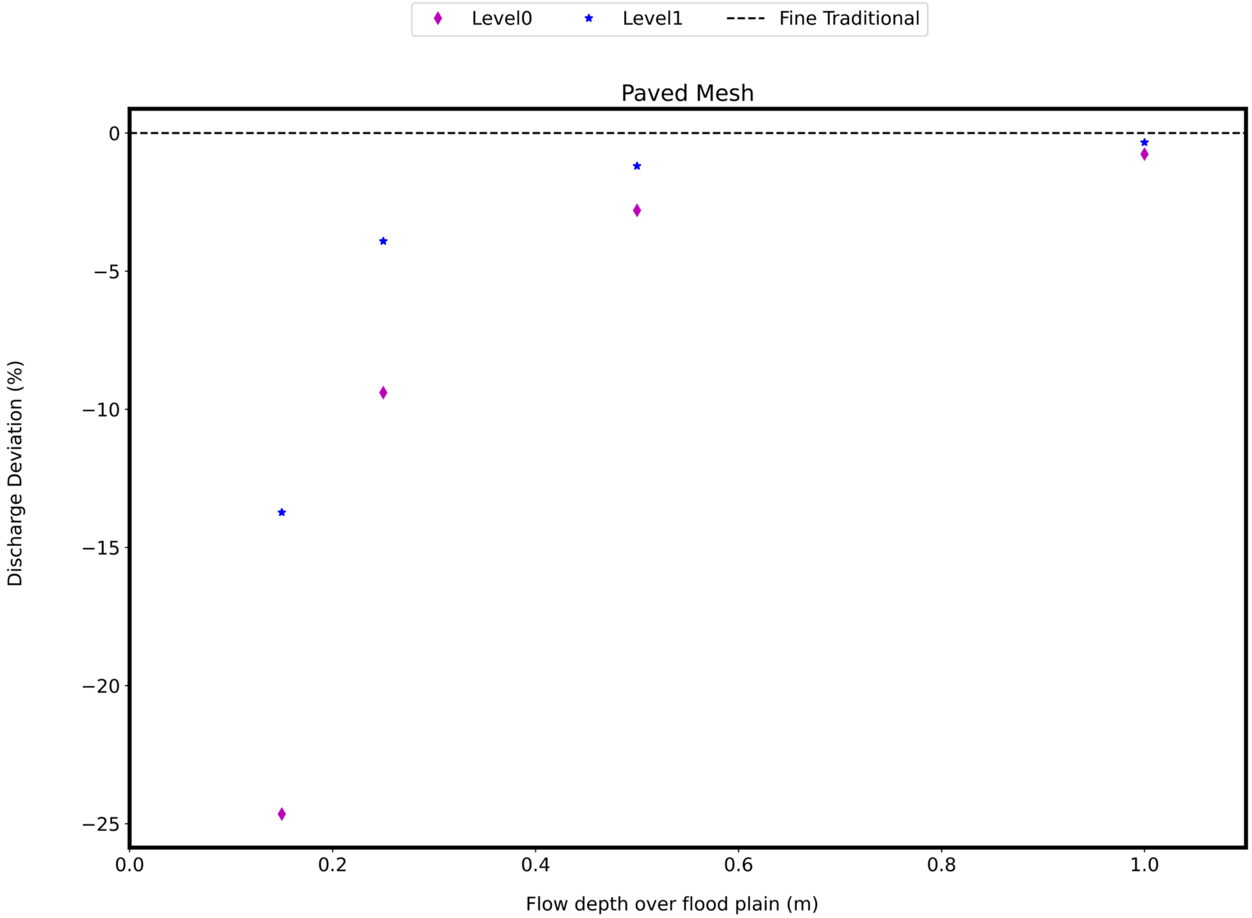
- The following test cases are planned for Level 1 correction in ADCIRC:

1. Synthetic compound channel
2. Realistic domain with hurricane winds and storm surge

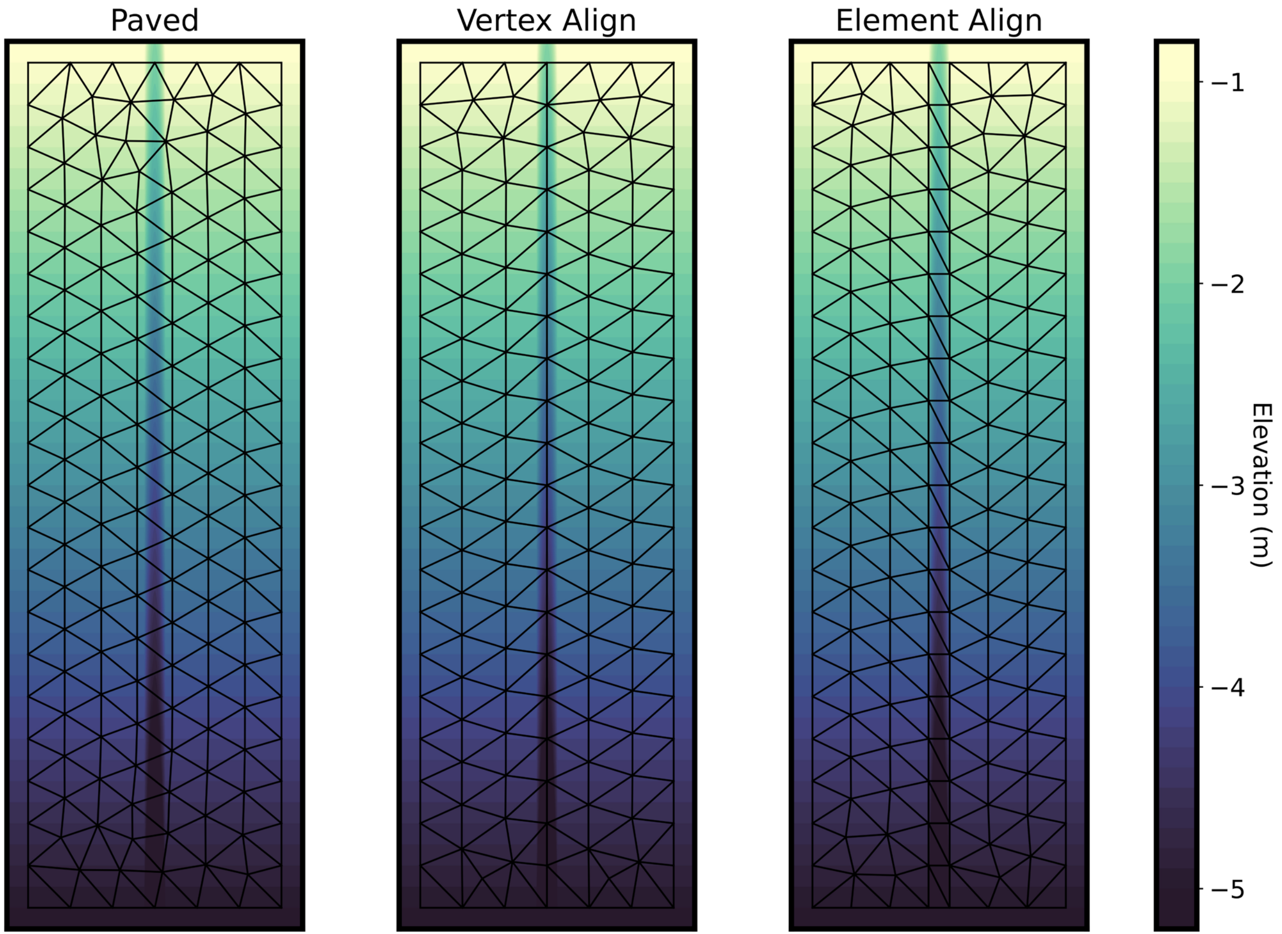
Creates a constant discharge down the domain



Constant water surface elevation


Level0
Level1
Fine Traditional
Paved Mesh
0
−5
−10
−15
−20
−25
0.0
0.2
0.4
0.6
0.8
1.0
Discharge Deviation (%)
Flow depth over flood plain (m)

How will element and vertex alignment affect these corrections?



- The realistic test case is planned to be for the region surrounding Savannah, GA.
- The large tidal range and flat topography will likely be a great place to test Level 1 corrections.
- Domain size will be similar to the Calcasieu Lake Test case

Roadmap

Hypothesis 1 → Initial implementation of subgrid corrections in ADCIRC

Hypothesis 2 → Incorporation of higher level corrections

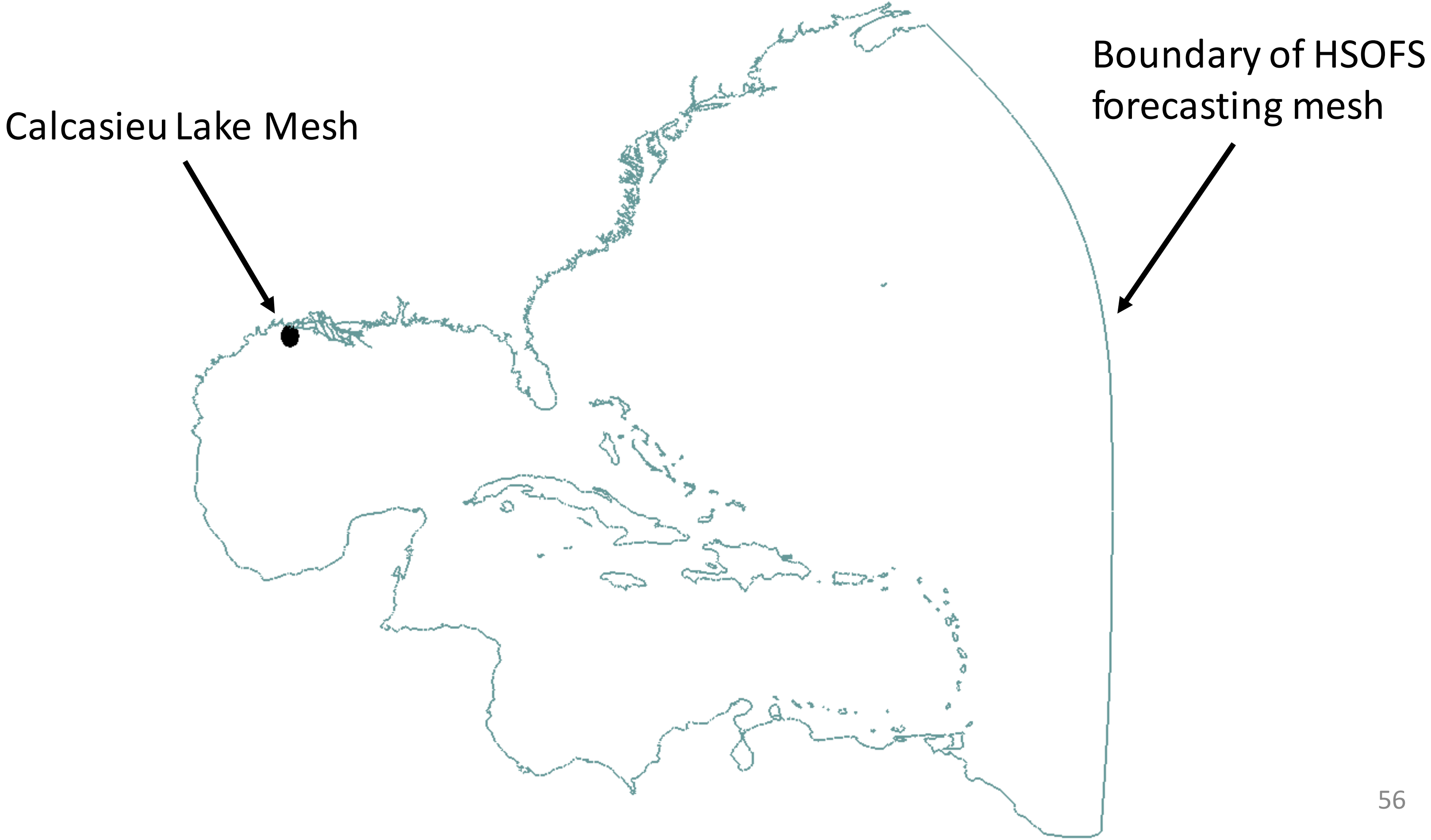
Hypothesis 3 → Implementation on ocean-scale domains

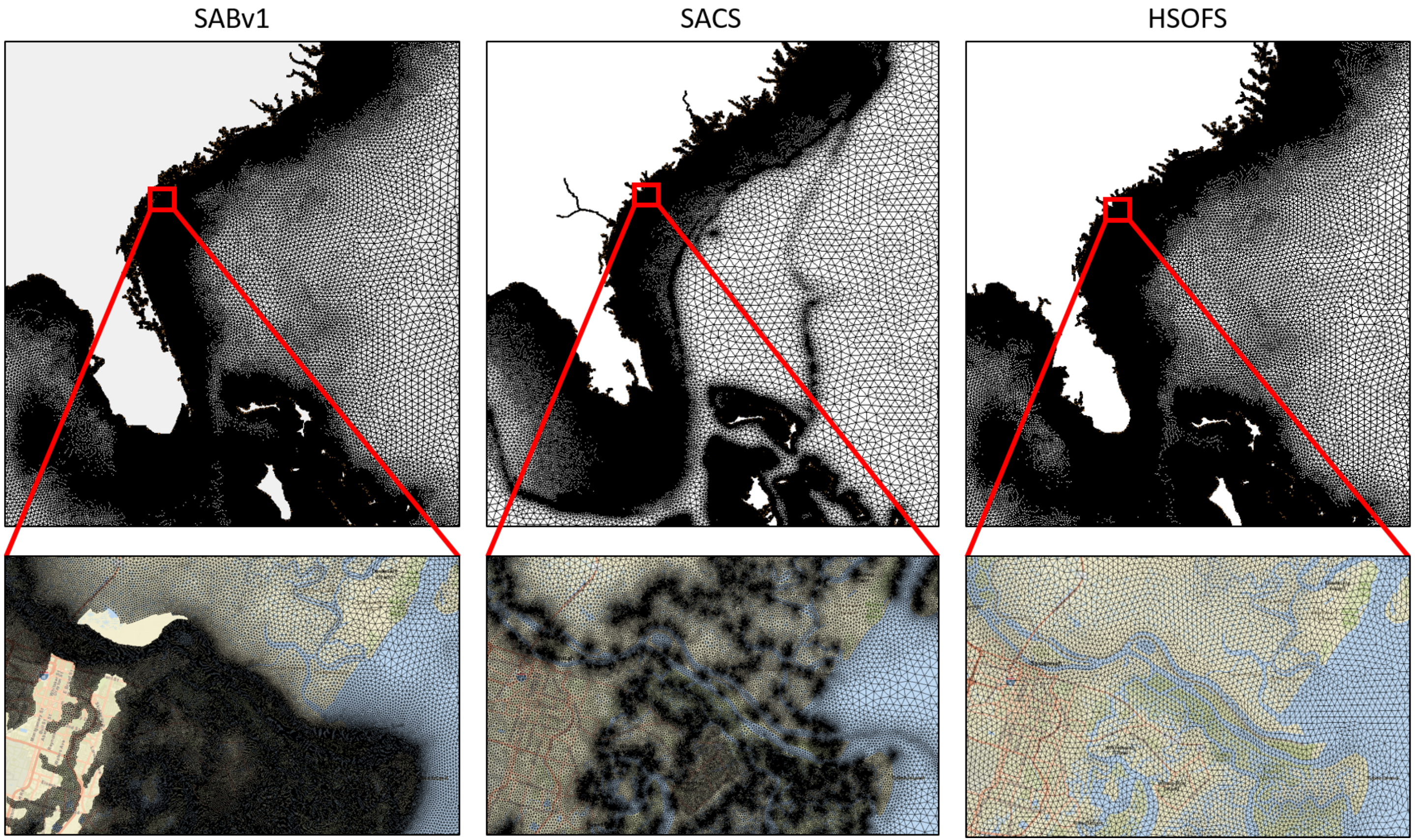
If *subgrid corrections* in ADCIRC are applied to ocean-scale domains, then the applicability and usefulness of these corrections can be increased.

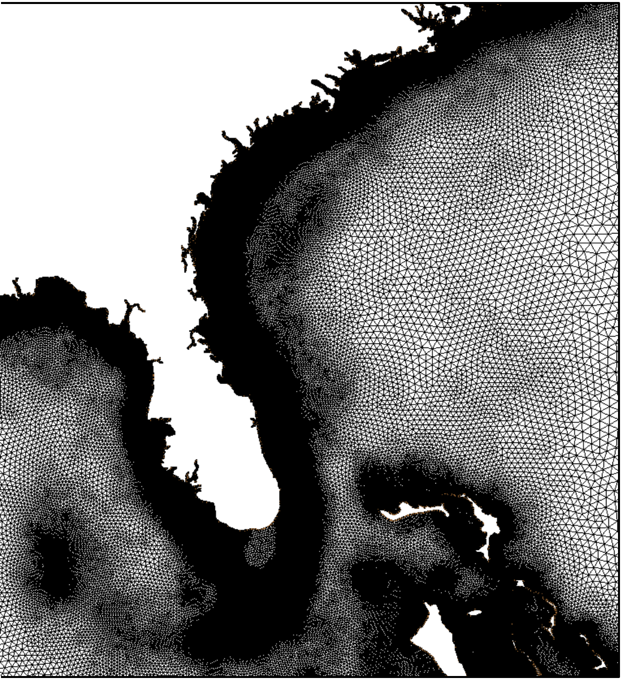
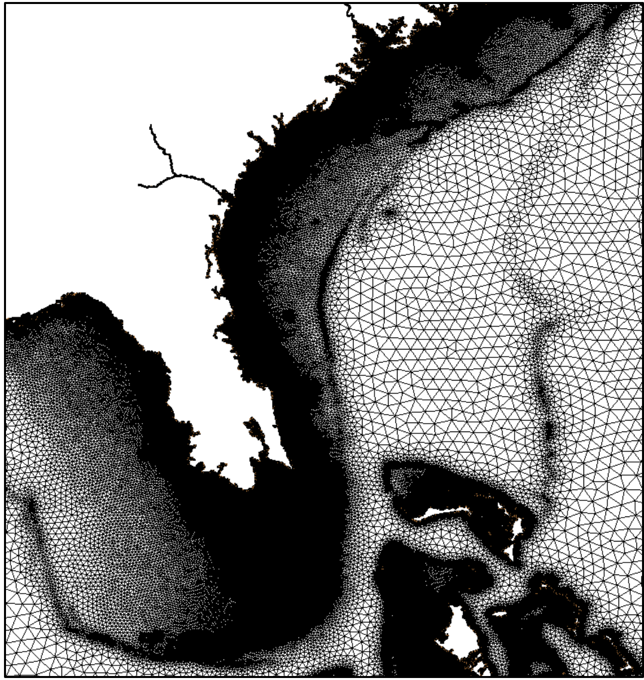
Motivation

- The initial implementation of subgrid corrections in ADCIRC left a few challenges:

1. Model domain was too small.
2. Limited data processing, stability testing, and applicability.


Calcasieu Lake Mesh
Boundary of HSOFS forecasting mesh

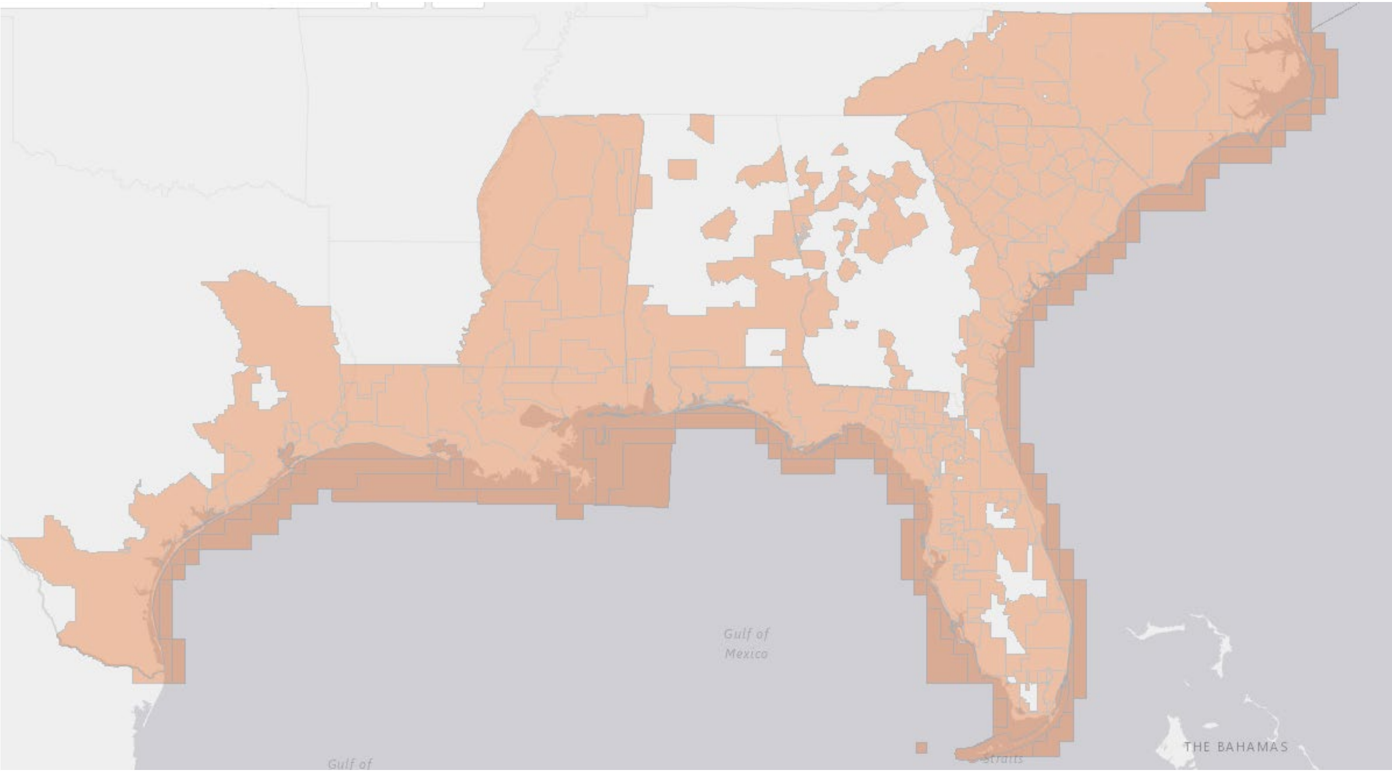

SABv1
SACS
HSOFS

HSOFS	NEW MESH	SACS
		
1,813,443 Vertices	~3,000,000 Vertices	6,179,416 Vertices
3,564,104 Elements	~6,000,000 Elements	12,288,247 Elements

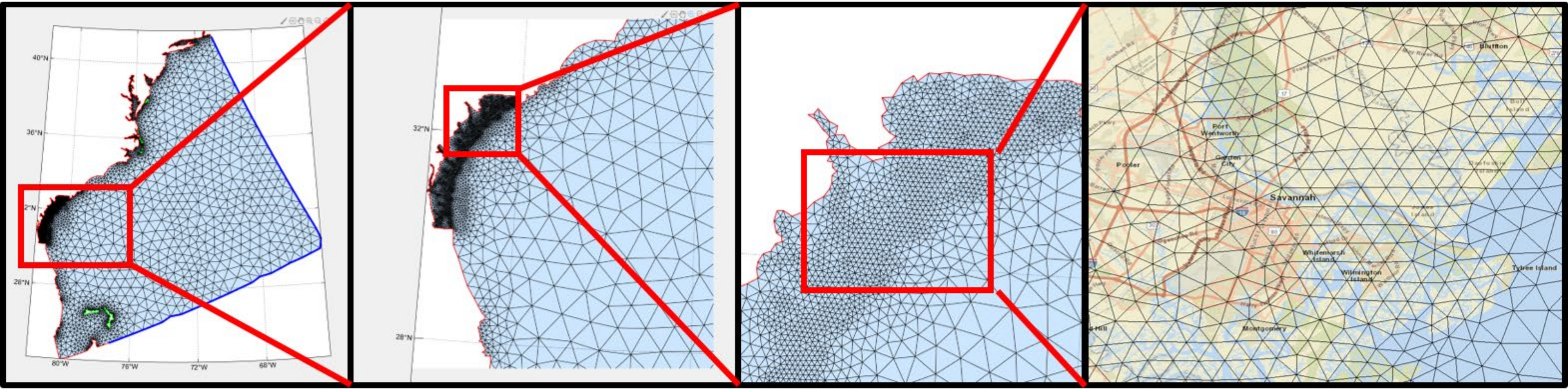
Tasks

- Collect elevation and land cover data for the SAB.
  - High resolution datasets for the nearshore area of interest
  - Low resolution data for areas away from the SAB region.
- Develop a forecast-grade mesh with emphasis on the South Atlantic Bight.
- Test this mesh both with and without subgrid corrections and compare to high-resolution mesh simulations.
- Develop visualization programs to communicate the subgrid results.

Data Collection



Mesh Development



Testing

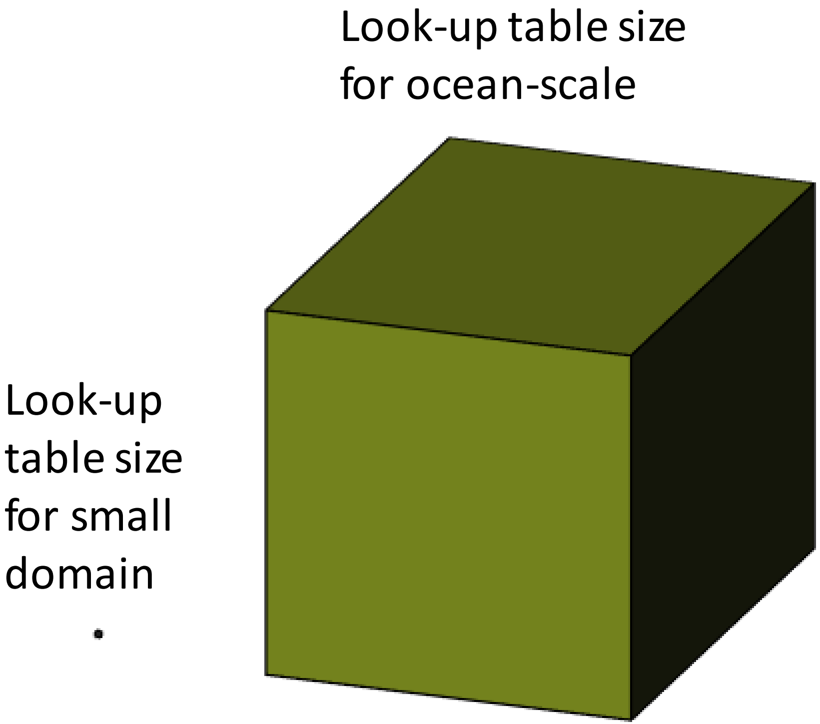
- We plan to test our mesh using Matthew (2016)
- Matthew was a shore parallel storm that affected vast stretches of the SAB.

Testing

- We will test the accuracy of the new forecasting mesh both with and without subgrid corrections against the high-resolution SACS mesh by:
  - Comparing water level time series at stations along the South Atlantic Bight.
  - Analyzing maximum water surface elevations along thalwegs of major waterways

Testing

- Test the relative computational expense of the subgrid additions.
- Large lookup tables from ocean-scale datasets could create prohibitively large storage requirements.



Timeline

Spring 2021
- Complete Level 0 Theory
- Implement Level 0 Correction in ADCIRC
- Result Analysis
- Submission to Journal

Summer 2021
- Complete Level 1 Theory
- Implement Level 1 Correction in ADCIRC
- Test Level 1 corrections

Fall 2021
- Level 1 result analysis
- Gathering ocean-scale datasets
- Subgrid code development
- SAB mesh development

Spring 2022
- Submission of Level 1 work to journal
- Testing of SAB mesh
- Subgrid code development
- SAB mesh development

Summer 2022
- Testing of SAB mesh
- Result analysis
- Incorporation of subgrid corrections into operational code

Fall 2022
- Documentation and result analysis
- Writing dissertation
- Final defense

Spring 2021 — Summer 2021 — Fall 2021 — Spring 2022 — Summer 2022 — Fall 2022

Thank you

Averaged Variable Theory

- In addition, when integrating terms that have time and space differentiation we follow rules from Whitacker 1985.

$$\left\langle \frac{\partial Q}{\partial t} \right\rangle_G = \frac{\partial \langle Q \rangle_G}{\partial t} - \frac{1}{A_G} \int_{\Gamma_W} Q \boldsymbol{U}_B \cdot \boldsymbol{n}_s \, dS$$

Averaging for temporal terms

$$\left\langle \frac{\partial Q}{\partial r} \right\rangle_G = \frac{\partial \langle Q \rangle_G}{\partial r} + \frac{1}{A_G} \int_{\Gamma_W} \boldsymbol{n}_{s,r} Q \, dS$$

Averaging for spatial terms