Storm-driven coastal flooding predictions from subgrid- to ocean-scales

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WHERE DISCOVERIES BEGIN

COASTAL RESILIENCE CENTER
A U.S. Department of Homeland Security Center of Excellence

Committee

Dr. Casey Dietrich

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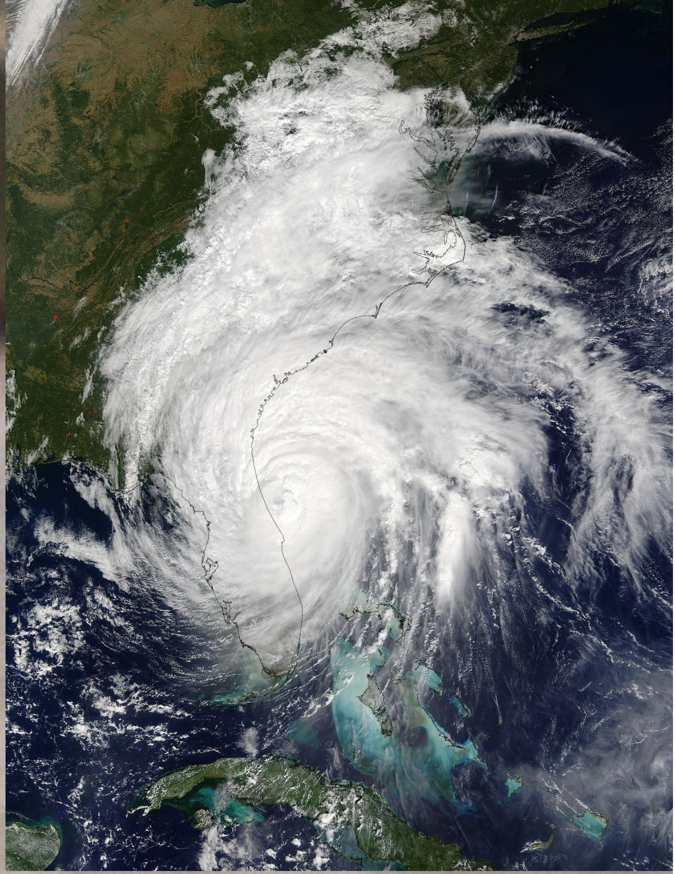
Bio

BS at University of Florida

MS at Georgia Tech

PhD NC State

Hurricane Matthew (2016)



Stephen B. Morton / Associated Press

Hurricane Irma (2017)

Johnny Milano / The New York Times

Hurricane Michael (2018)

Scott Olson / Getty Images

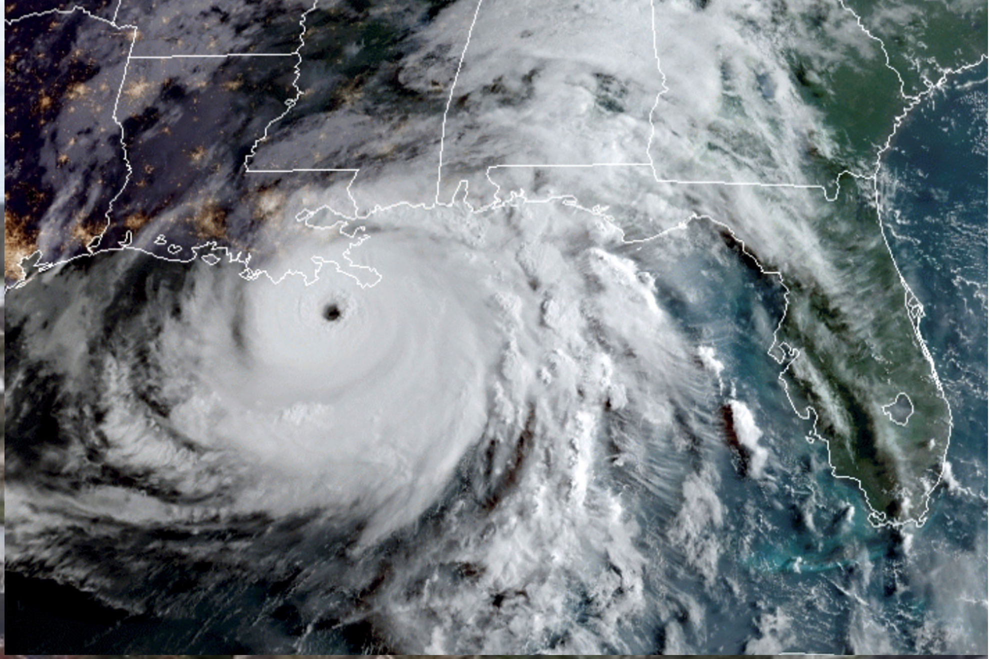
Hurricane Dorian (2019)

Photo courtesy of NCDOT.

Hurricane Laura (2020)

David J. Phillip / AP Photo

Hurricane Ida (2021)



Steve Helber / AP Photo

Hurricane Ian (2022)

Joe Raedle / Getty Images

Ricardo Arduengo / AFP / Getty Images

Why do we care about storm surge?

- Hurricane storm surge is the principal cause of loss of life and damages during a tropical cyclone event.
  - Hurricane Ian created 4.5 m of storm surge along the Southwestern Florida coast.
  - Directly caused the death of 66 people.
  - 41 of the 66 lives were claimed by storm surge.
  - Ian caused and estimated $112.9 billion in damages (Bucci et al. 2023).

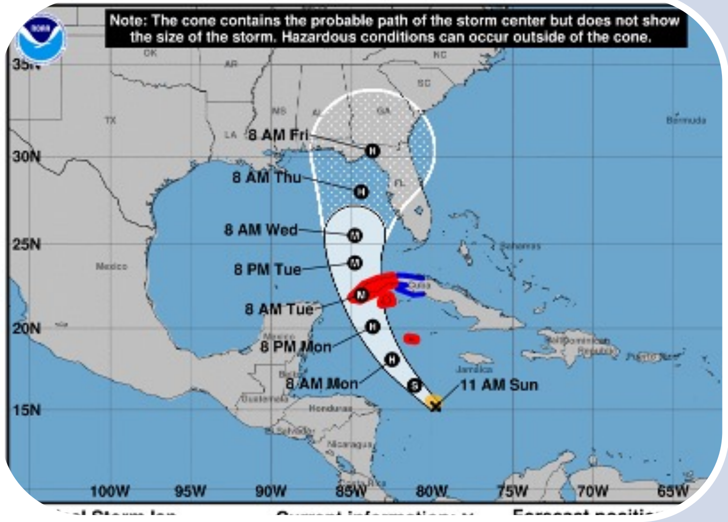

Orange County Fire Rescue's Public Information Office

HHS ASPR


Stephen M. Orlando Sentinel via AP/Dowell

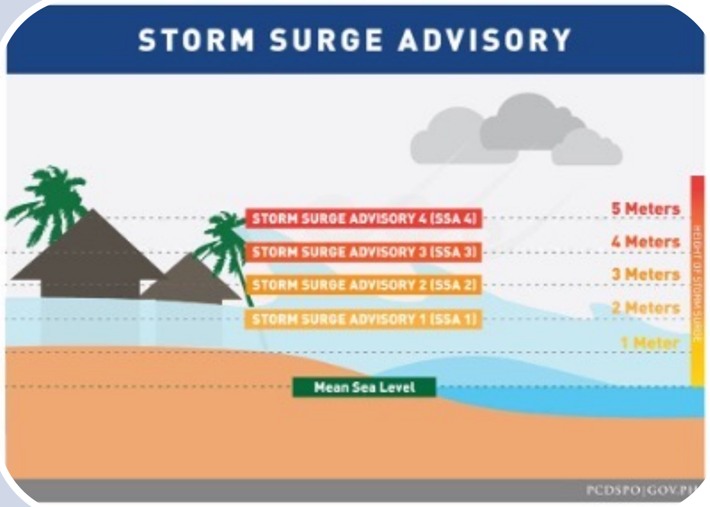
Florida Division of Emergency Management

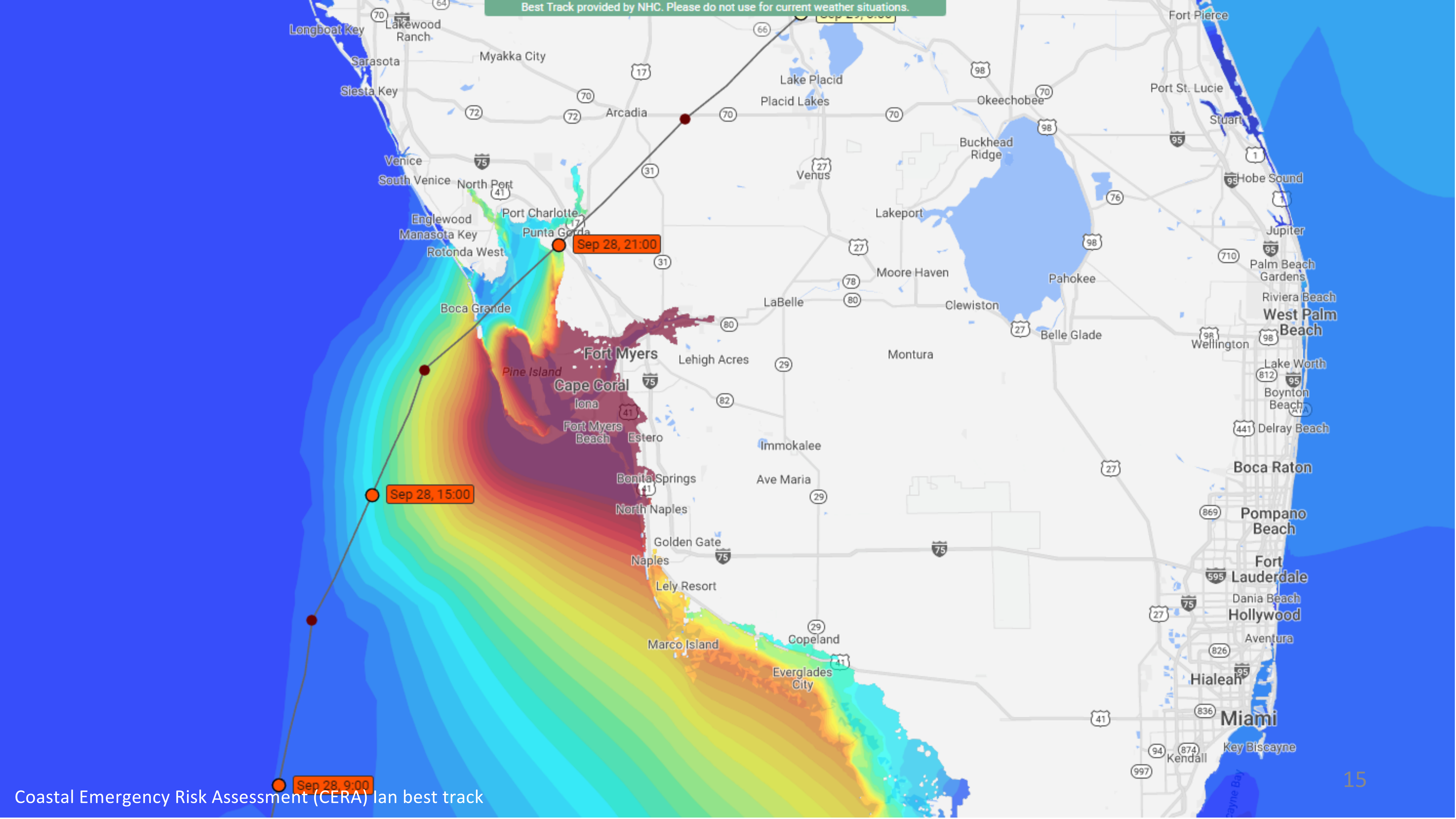
NHC Issues Storm Track and Intensity update every 6 hours



Storm surge simulations are run for latest advisory (1-3 hours)

Flood predictions are sent out to stakeholders.





Coastal Emergency Risk Assessment (CERA) Ian best track

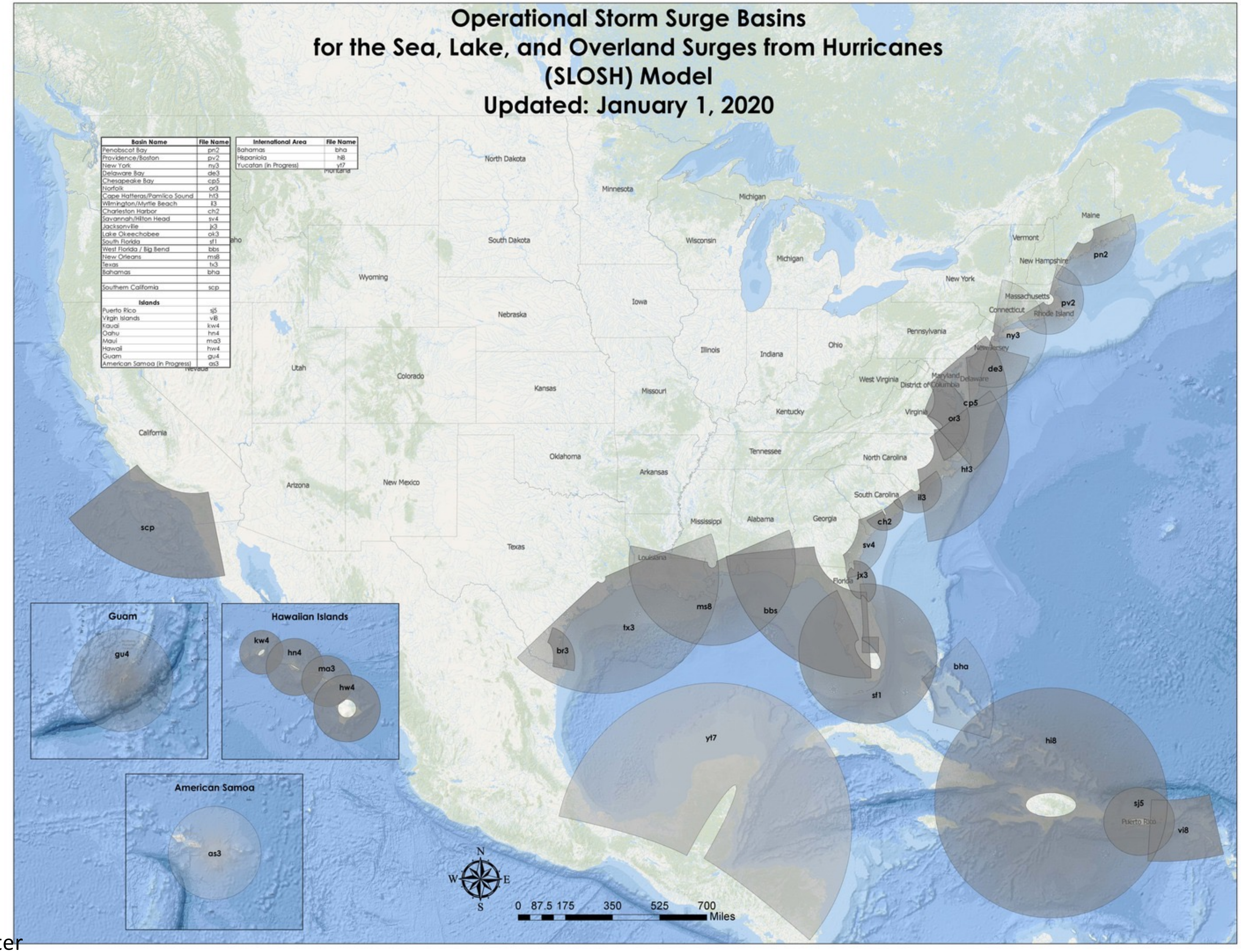
How do we predict storm surge?

- Storm surge is predicted with numerical models that use numerical grids (or meshes).
- The computational grids represent bathymetric and topographic features important to capturing flow.

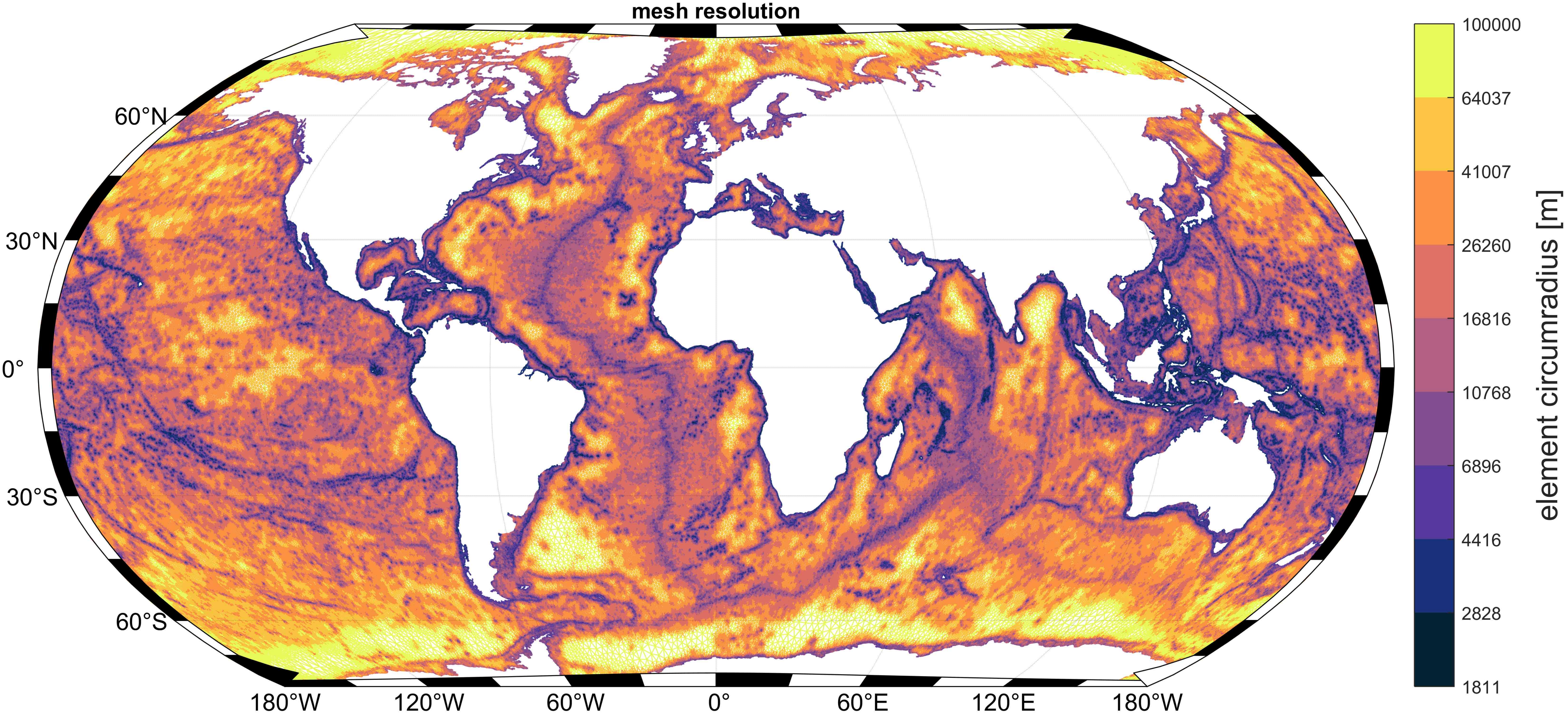
Operational Storm Surge Basins for the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) Model
Updated: January 1, 2020

Basin Name	File Name
Penobscot Bay	pn2
Providence/Boston	pv2
New York	ny3
Delaware Bay	de3
Chesapeake Bay	cp5
Norfolk	or3
Cape Hatteras/Pamlico Sound	ht3
Wilmington/Myrtle Beach	il3
Charleston Harbor	ch2
Savannah/Hilton Head	sv4
Jacksonville	jx3
Lake Okeechobee	ok3
South Florida	sf1
West Florida / Big Bend	bbs
New Orleans	ms8
Texas	tx3
Bahamas	bha
Southern California	scp
Islands	
Puerto Rico	sj5
Virgin Islands	vi8
Kauai	kw4
Oahu	hn4
Maui	ma3
Hawaii	hw4
Guam	gu4
American Samoa (in Progress)	as3

International Area	File Name
Bahamas	bha
Hispaniola	hi8
Yucatan (in Progress)	yt7

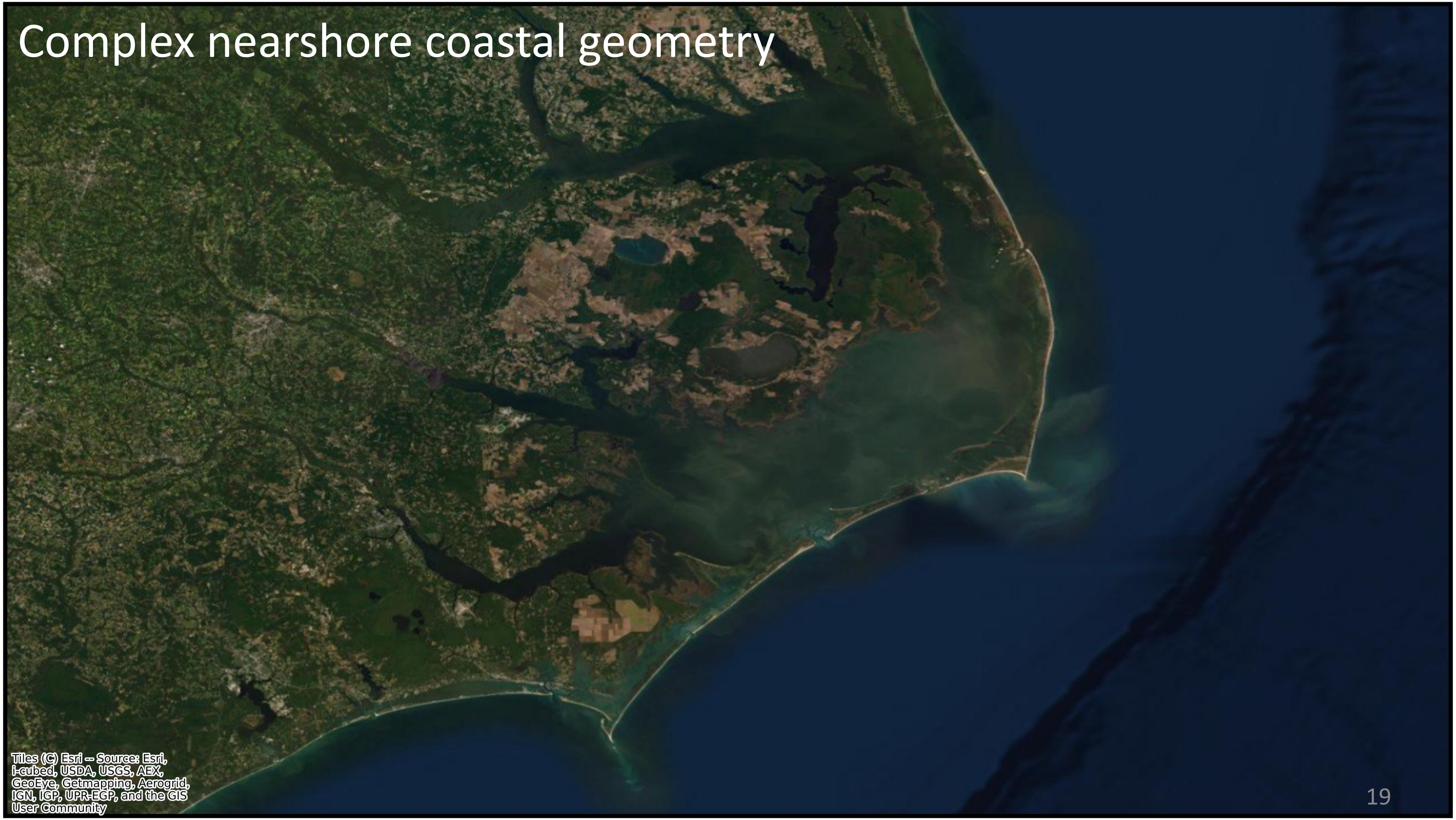


National Hurricane Center

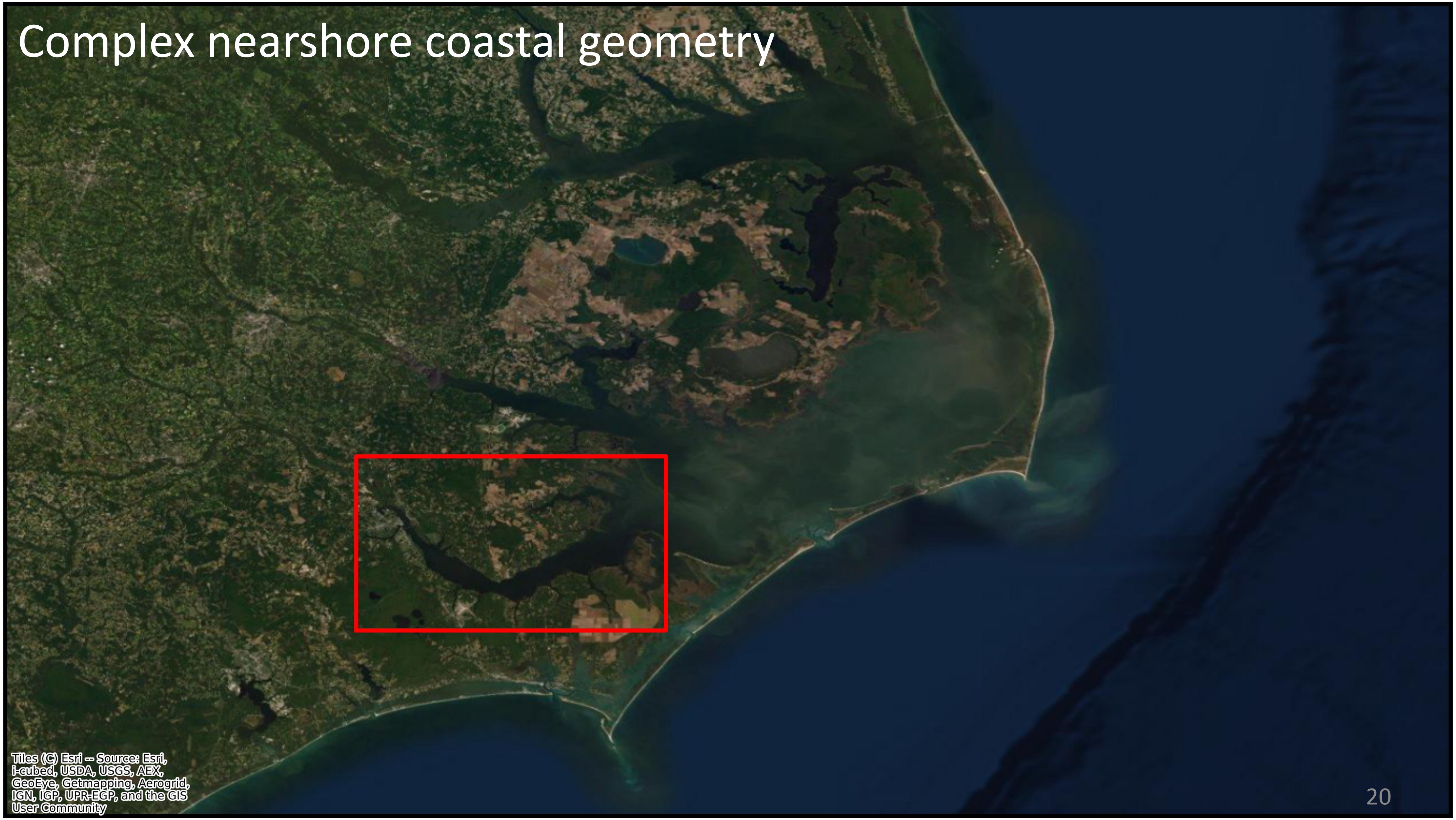


https://github.com/CHLNDDEV/OceanMesh2D

Complex nearshore coastal geometry

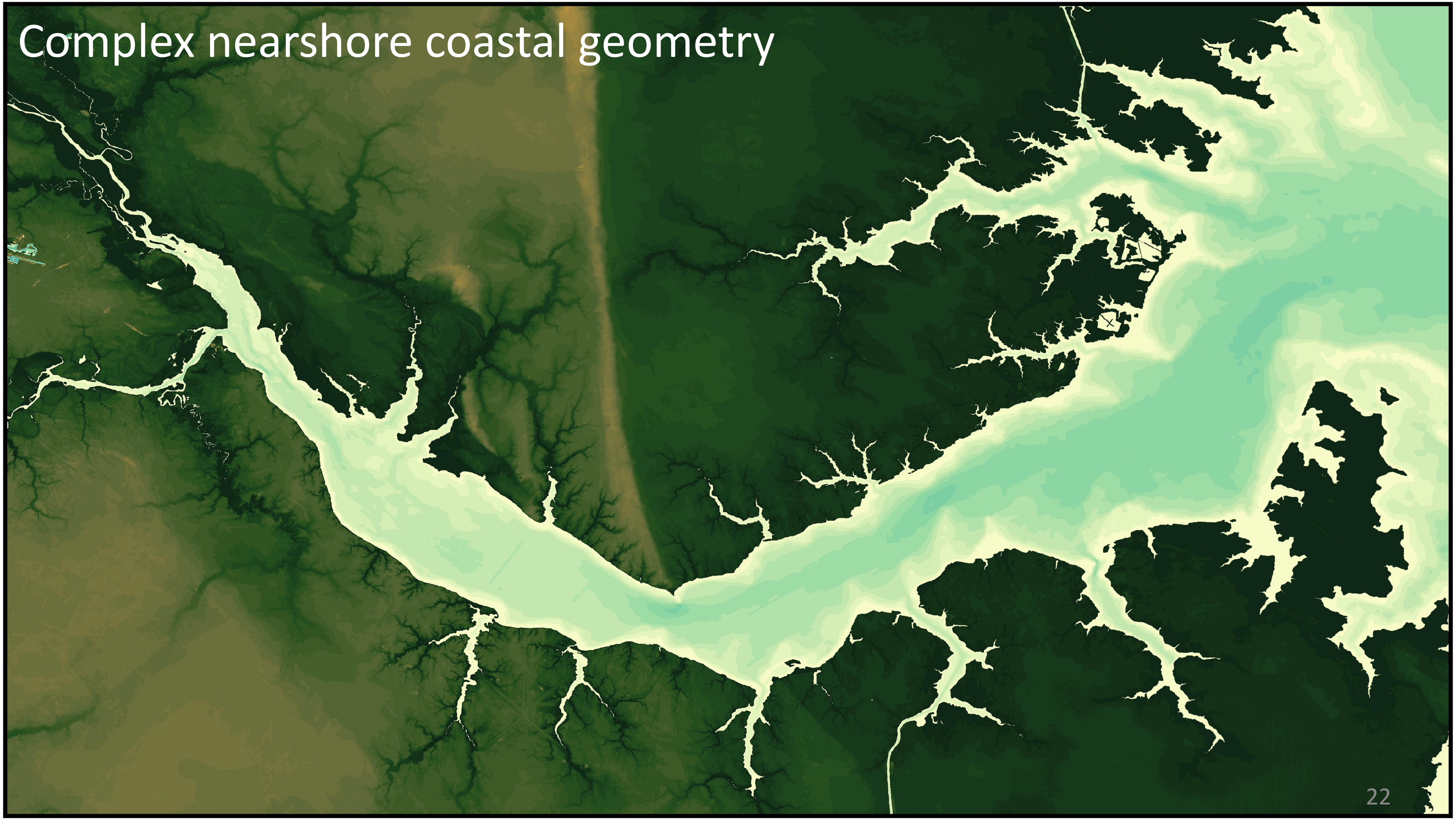


Complex nearshore coastal geometry

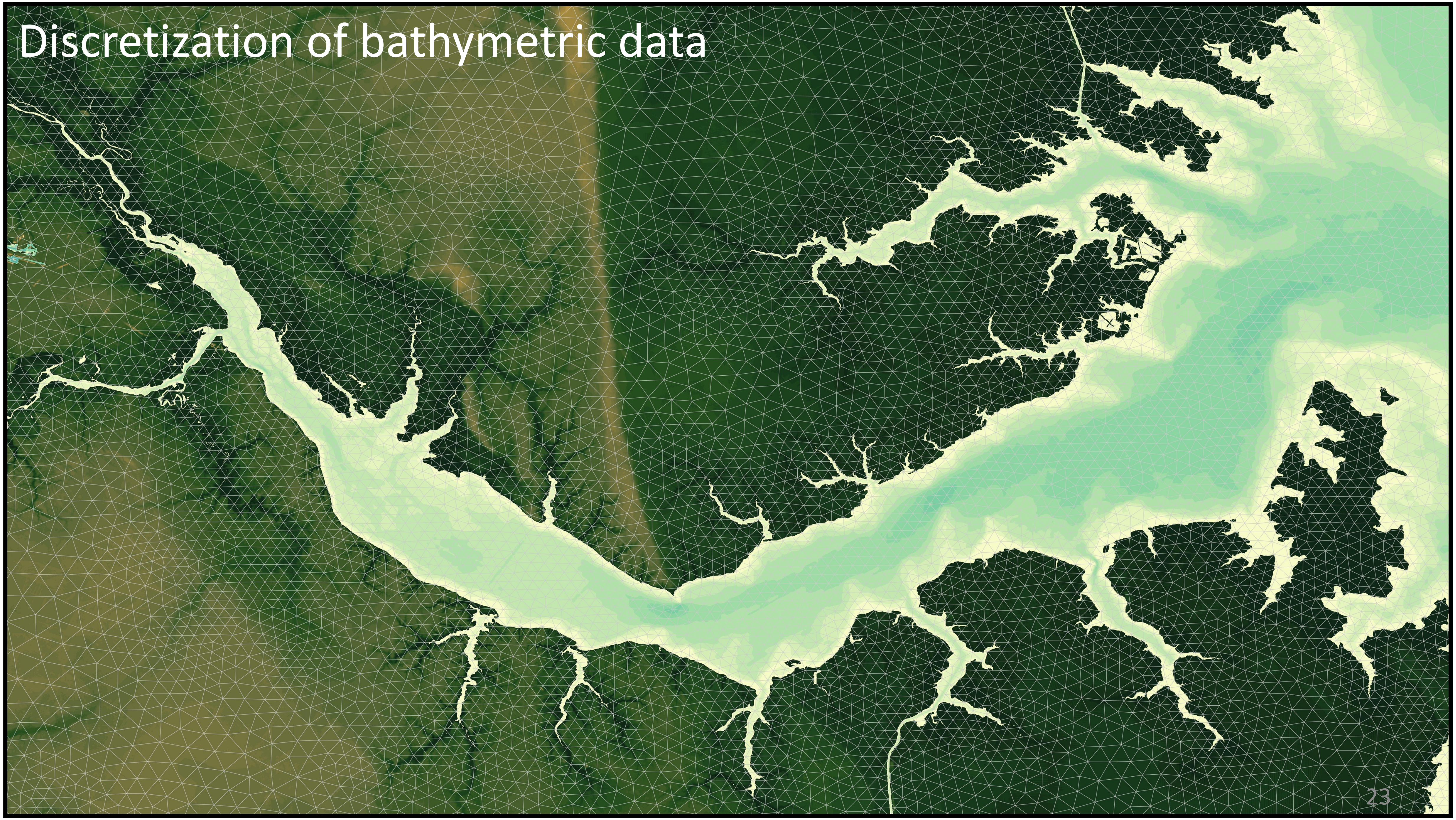


Complex nearshore coastal geometry

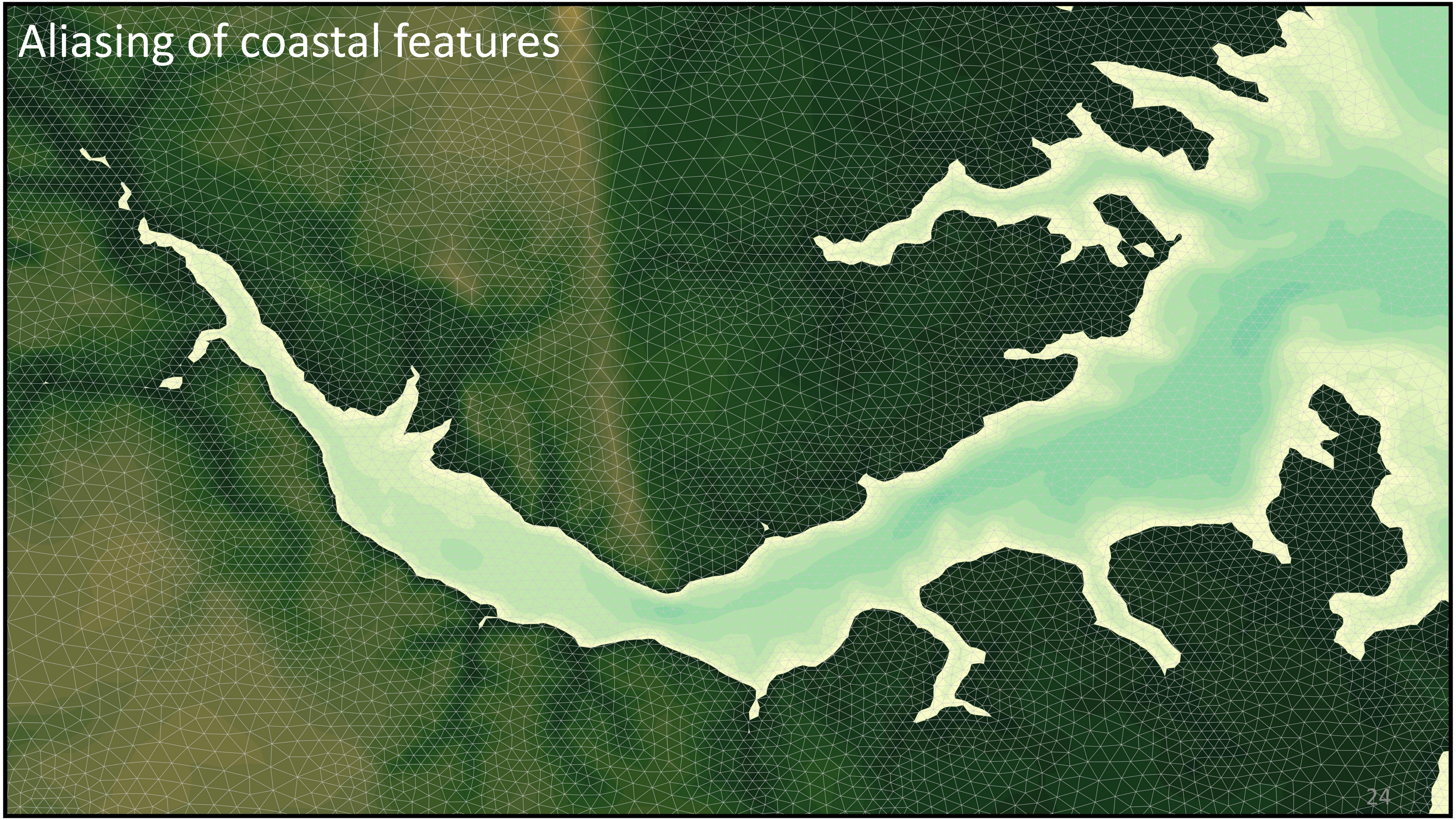
Complex nearshore coastal geometry



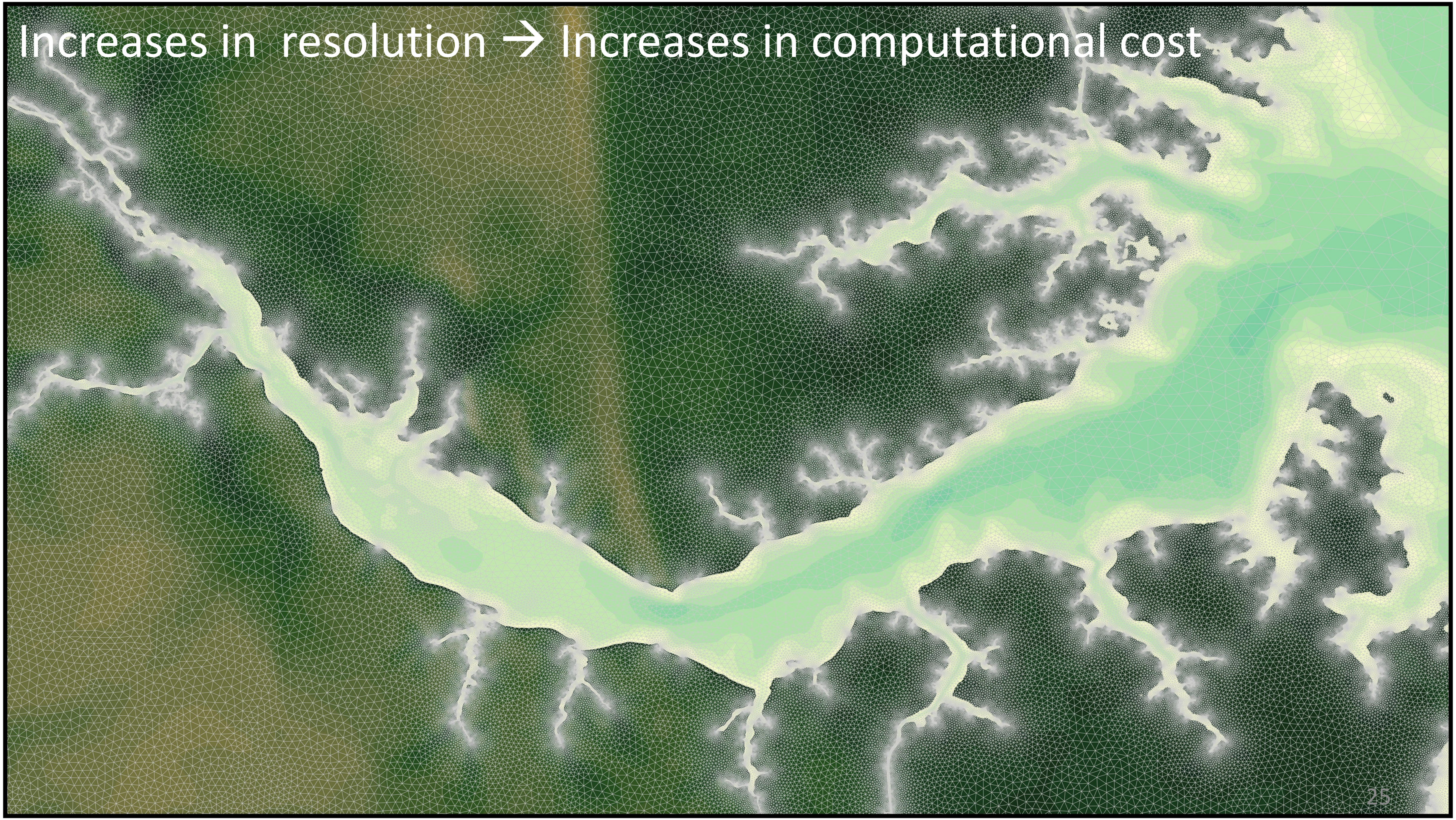
Discretization of bathymetric data



Aliasing of coastal features



Increases in resolution → Increases in computational cost

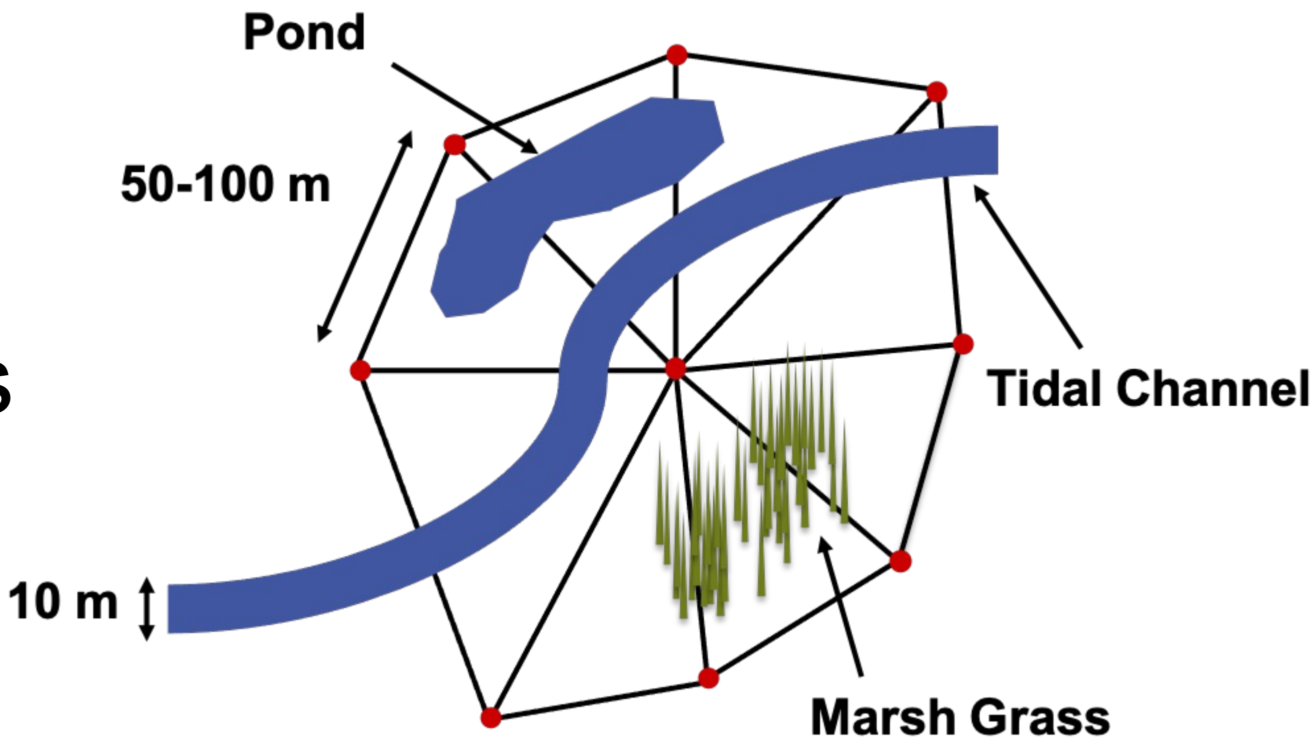


How can we improve storm surge models?

- How can we improve the current methodology used to increase accuracy in storm surge predictions?
  - Use information at the scales of critical infrastructure to improve model performance.
- How can we decrease computational cost of the model?
  - By running on coarsened domains while maintaining accurate results.

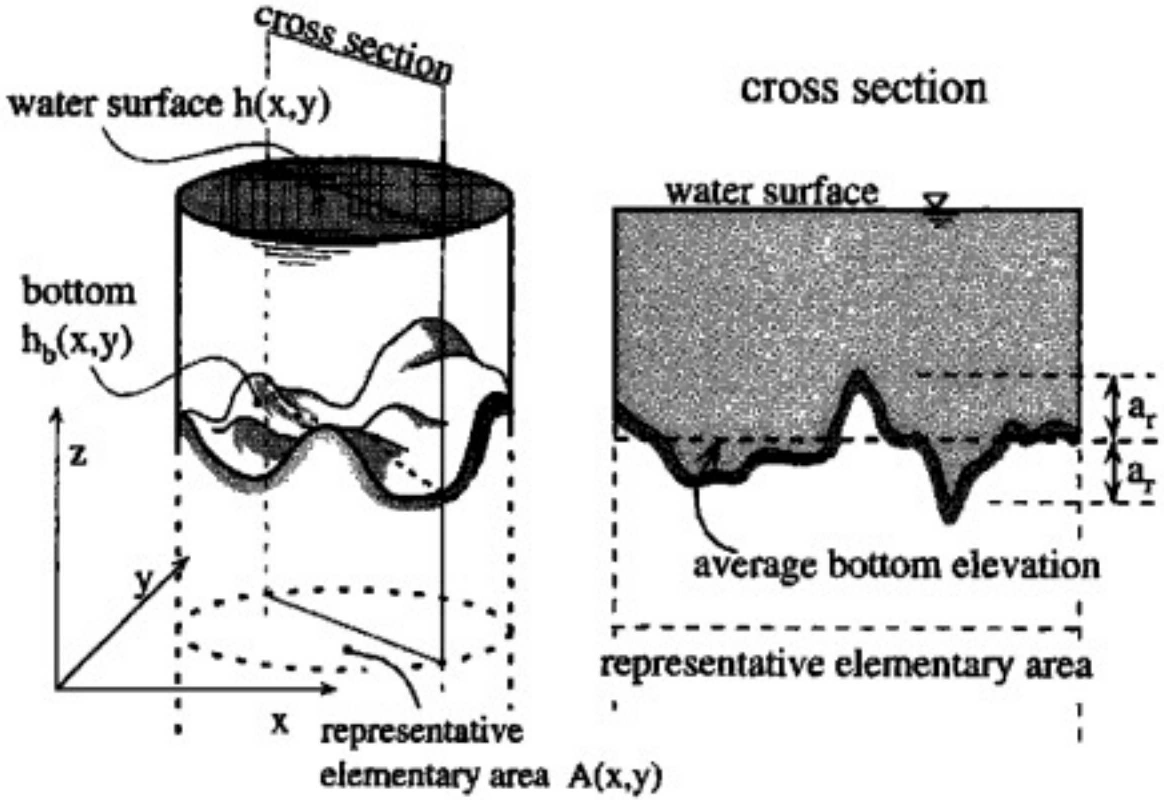
Subgrid Corrections

- *Subgrid corrections* use information at smaller scales to 'correct' flow variables (water levels and current velocities) at the model scale.



How have subgrid flows been represented?

- Flow characteristics of neighboring areas are often highly correlated in shallow water flow models.
- Correlation can be represented by averaging information at finer scales to coarsened grids without sacrificing accuracy.



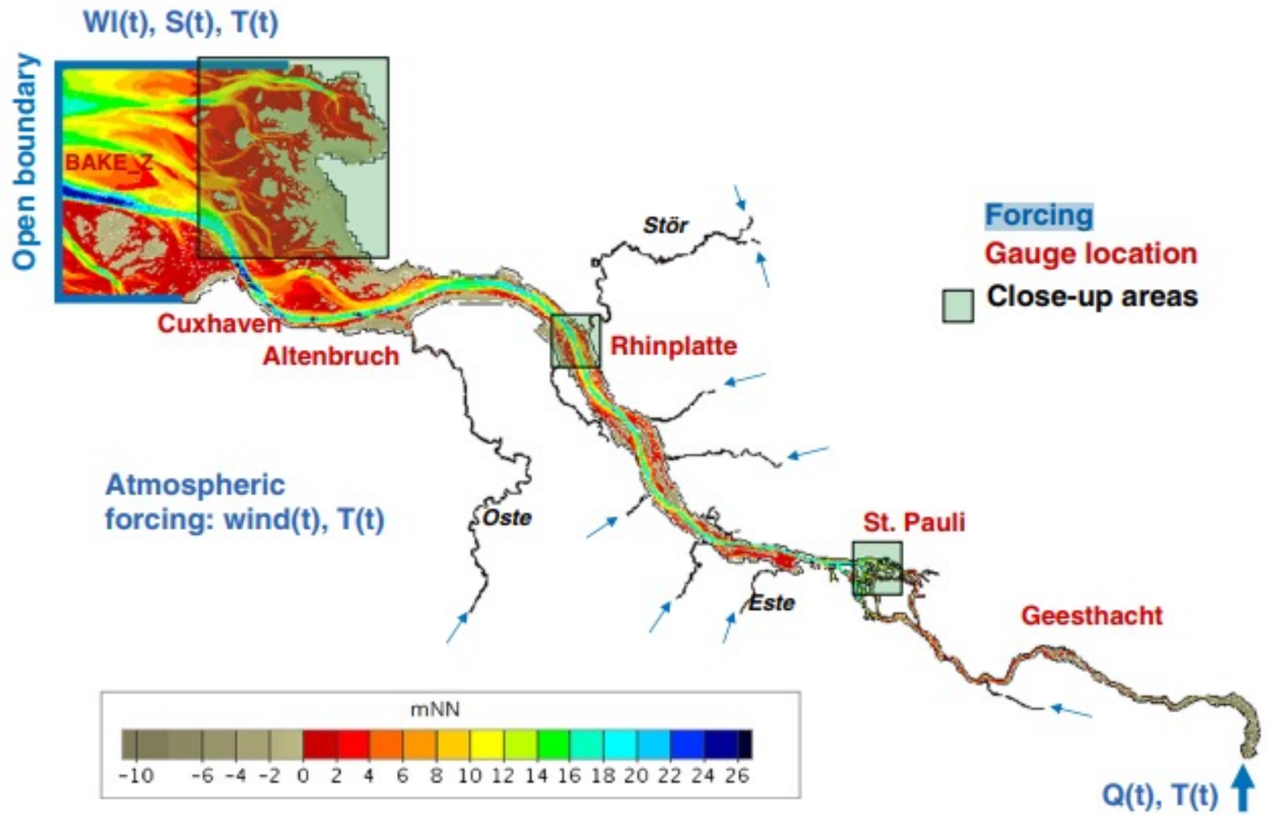
- Defina (2000) created an averaged flow model with wetting and drying based on subgrid elevations.
- Casulli (2009) introduced subgrid corrections to an elegant finite volume model.

How can we reduce computation cost?

- Computational cost in a subgrid model can be reduced by pre-computing subgrid corrections prior to running the simulation.
- These corrections can be stored in lookup tables that are referenced during the simulation.
- This method was used by Wu (2016) and Kennedy (2019) among others to save in computational cost.

How can we apply this to coastal ocean flows?

- Increasing the scale of the model moving from small test domains to regional domains in coastal areas.
- Apply coastal and ocean boundary forcing like astronomical tides, winds, and inland river flows.

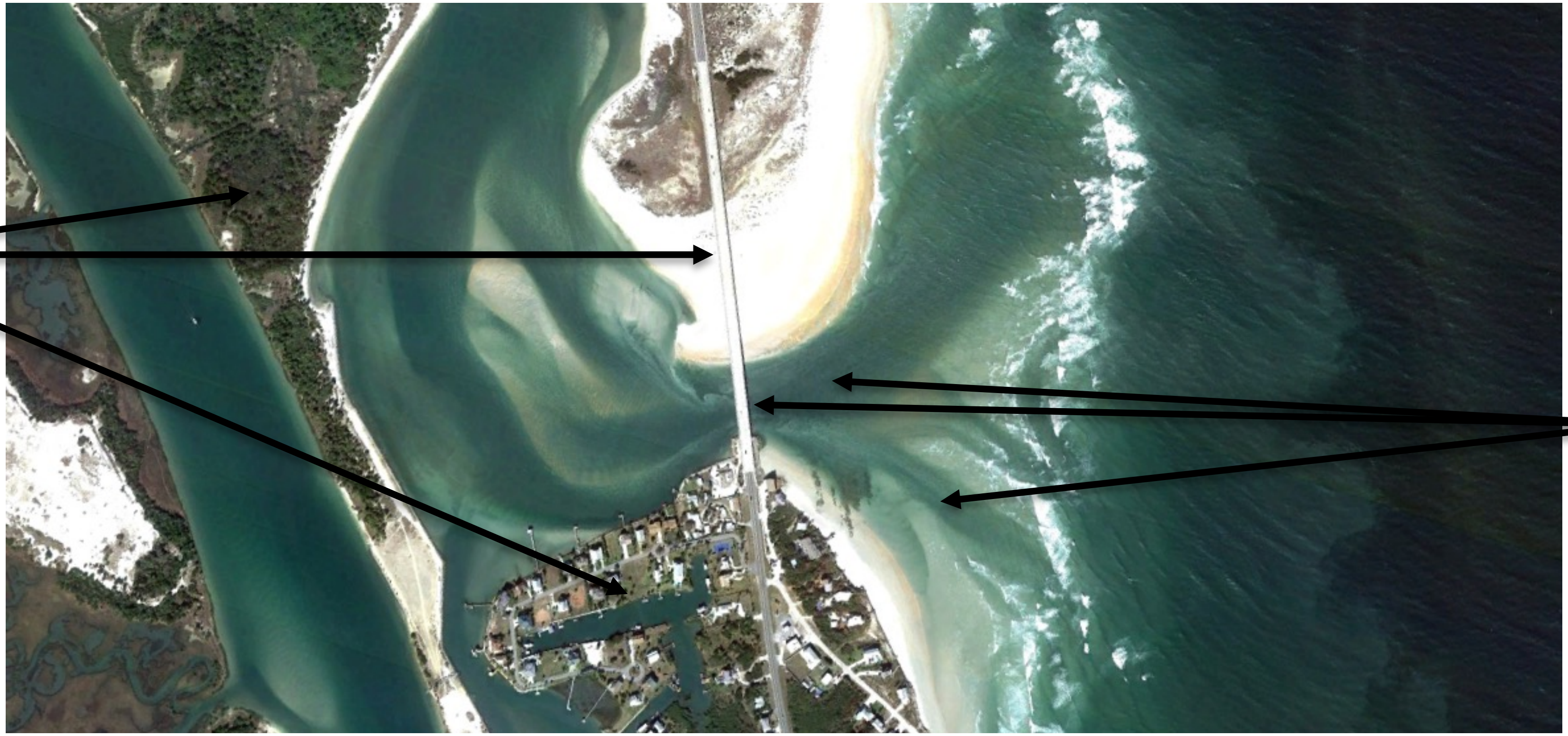


- Sehili et al. (2014) and Wang et al. (2014) applied the UnTRIM^2 model to the Elbe Estuary and New York City respectively.

How can higher-level corrections help?

- Improve flow predictions by accounting for small scale changes in bottom friction, advection, and water surface gradient in the model (Defina (2000), Volp et al. (2013), Kennedy et al. (2019)).

Different land cover type



Changes in depth and flow acceleration

Hurricane scale

Model scale

Subgrid scale

$10^5\ m$

$10^2\ m$

$10^0\ m$

Spatial Scales of Model

Gap to fill with Subgrid

What questions are we trying to answer?

1. How can we implement subgrid corrections into a widely used storm surge model?
2. How can these corrections to applied to realistic/ocean-scale domains?
3. What are some of the limitations of subgrid corrections in storm surge modeling?

Chapter 1

- How can we implement subgrid corrections into a widely used storm surge model?

Chapter 2

- How can higher-level corrections be applied to realistic/ocean-scale domains to improve flow predictions?

Chapter 3

- What are some of the limitations of subgrid corrections in storm surge modeling?

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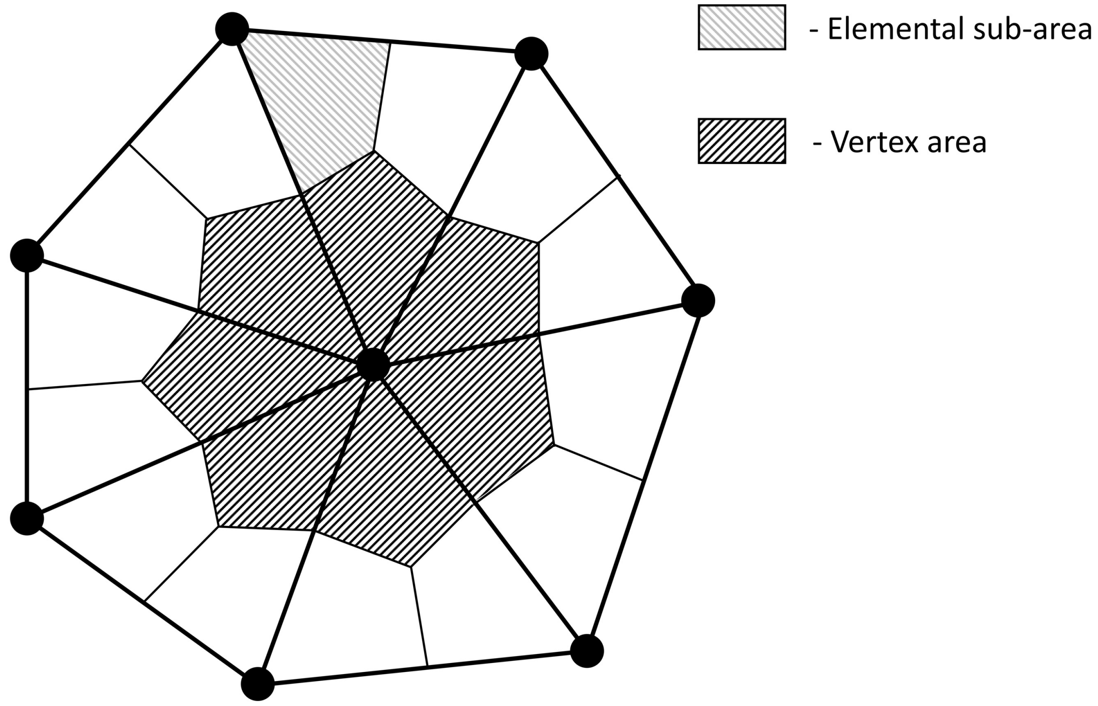
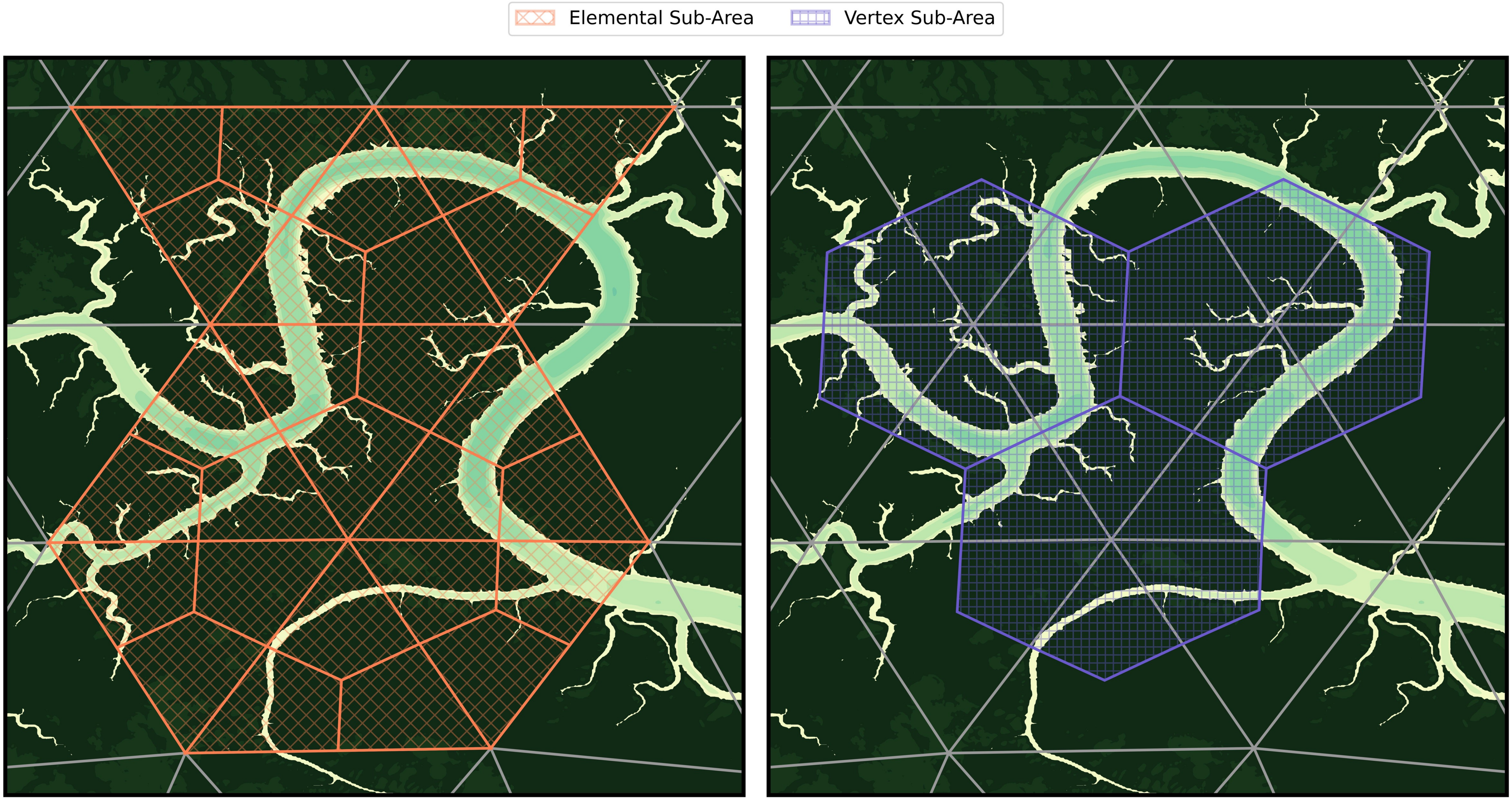
Implementation into the ADCIRC model

We implemented subgrid corrections in ADvanced CIRCulation (ADCIRC).

- Widely used for predictions of coastal circulation, storm surge, and flooding during storms.
- Solves modified forms of the shallow-water equations by using continuous-Galerkin, finite-element method on unstructured meshes.

This required a careful definition of vertex- and element-based averaging areas:



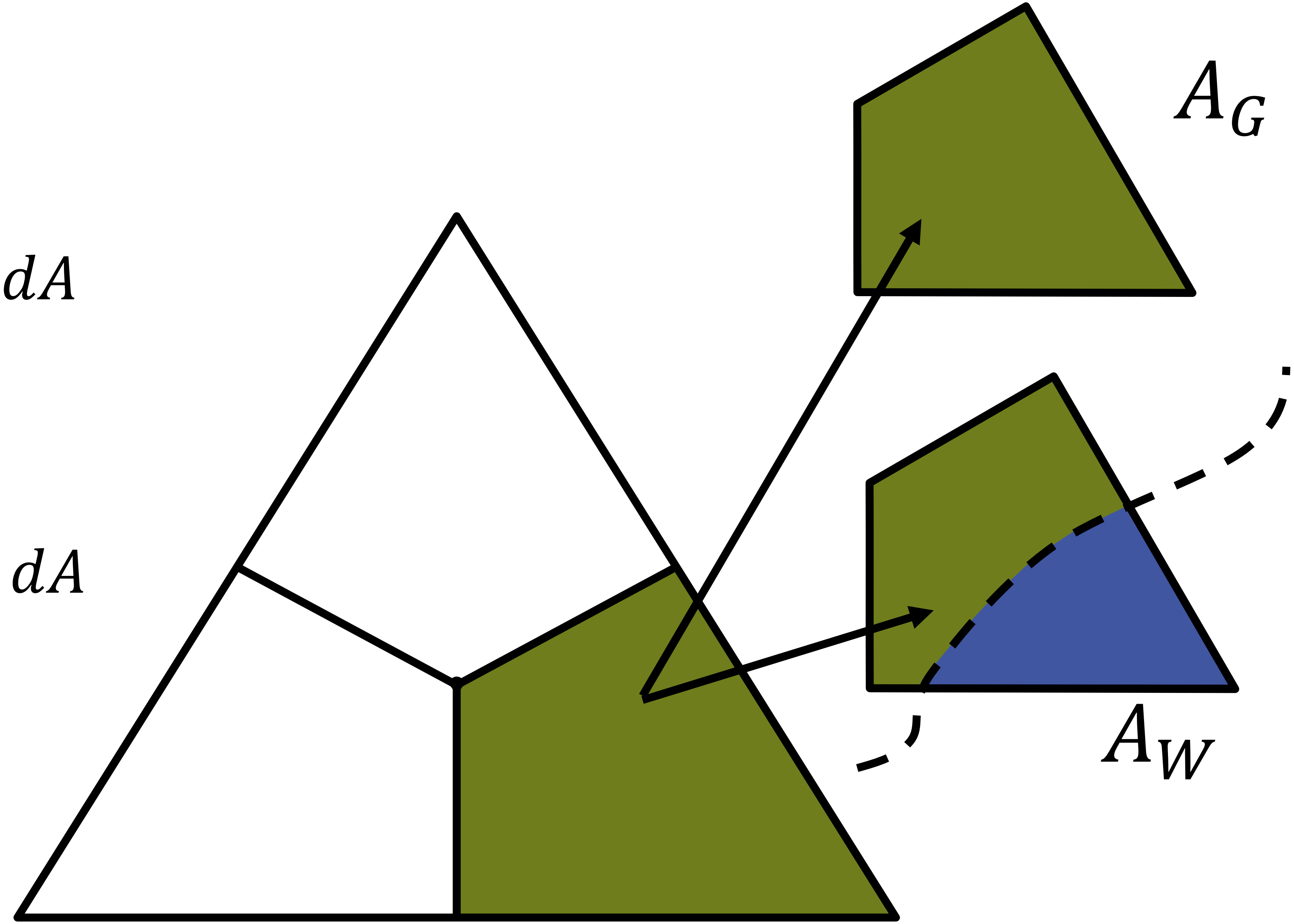

Elemental Sub-Area
Vertex Sub-Area

Averaging areas

$$\langle Q \rangle_G = \frac{1}{A_G} \iint_{A_W} Q \, dA$$

$$\langle Q \rangle_W = \frac{1}{A_W} \iint_{A_W} Q \, dA$$

$$\phi = A_W / A_G$$



Governing equations: GWCE

$$\frac{\partial^2 \zeta}{\partial t^2} + \tau_0 \frac{\partial \zeta}{\partial t} + \frac{\partial \tilde{J}_x}{\partial x} + \frac{\partial \tilde{J}_y}{\partial y} - UH \frac{\partial \tau_0}{\partial x} - VH \frac{\partial \tau_0}{\partial y} = 0$$

$$\tilde{J}_x \equiv \frac{\partial}{\partial t}(UH) + \tau_0 UH \qquad \tilde{J}_y \equiv \frac{\partial}{\partial t}(VH) + \tau_0 VH$$

Governing equations: Momentum

x-direction

$$\frac{\partial UH}{\partial t}+\frac{\partial UUH}{\partial x}+\frac{\partial VUH}{\partial y}-f\mathrm{VH}$$
$$=-\mathrm{g}H\frac{\partial \zeta}{\partial x}-gH\frac{\partial P_A}{\partial x}+\frac{\tau_{sx}}{\rho_0}-\frac{\tau_{bx}}{\rho_0}+\frac{\partial}{\partial x}\tilde{E}_H\frac{\partial UH}{\partial x}+\frac{\partial}{\partial y}\tilde{E}_H\frac{\partial UH}{\partial y}$$

y-direction

$$\frac{\partial VH}{\partial t}+\frac{\partial UVH}{\partial x}+\frac{\partial VVH}{\partial y}+f\mathrm{UH}$$
$$=-\mathrm{g}H\frac{\partial \zeta}{\partial y}-gH\frac{\partial P_A}{\partial y}+\frac{\tau_{sy}}{\rho_0}-\frac{\tau_{by}}{\rho_0}+\frac{\partial}{\partial x}\tilde{E}_H\frac{\partial VH}{\partial x}+\frac{\partial}{\partial y}\tilde{E}_H\frac{\partial VH}{\partial y}$$

Averaged momentum equation

For this study, its governing equations were averaged to the mesh scale.

- Example of momentum conservation in *x*-direction:

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

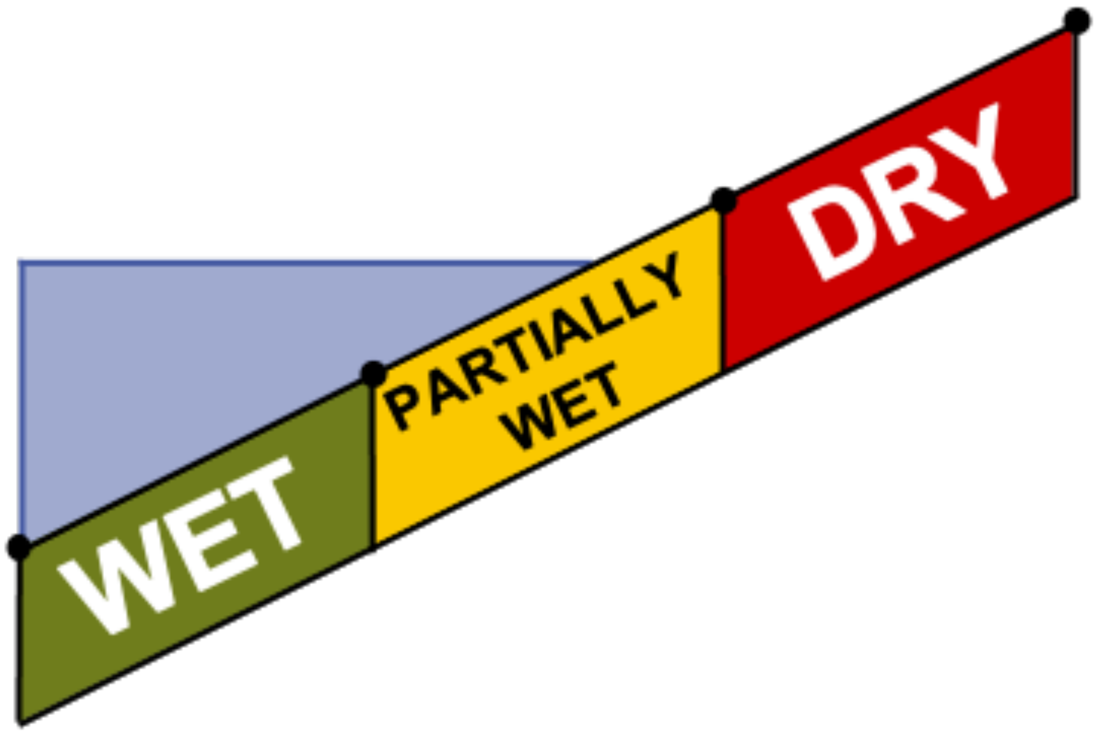
  in which the red coefficients are new closure terms.

- Similarly for momentum conservation in *y*-direction.

Changes to the wet/dry algorithm

This allows for partially wet cells/elements.

- Better connectivity through small-scale flow pathways.



This required a major revision to ADCIRC’s wet/dry algorithm.

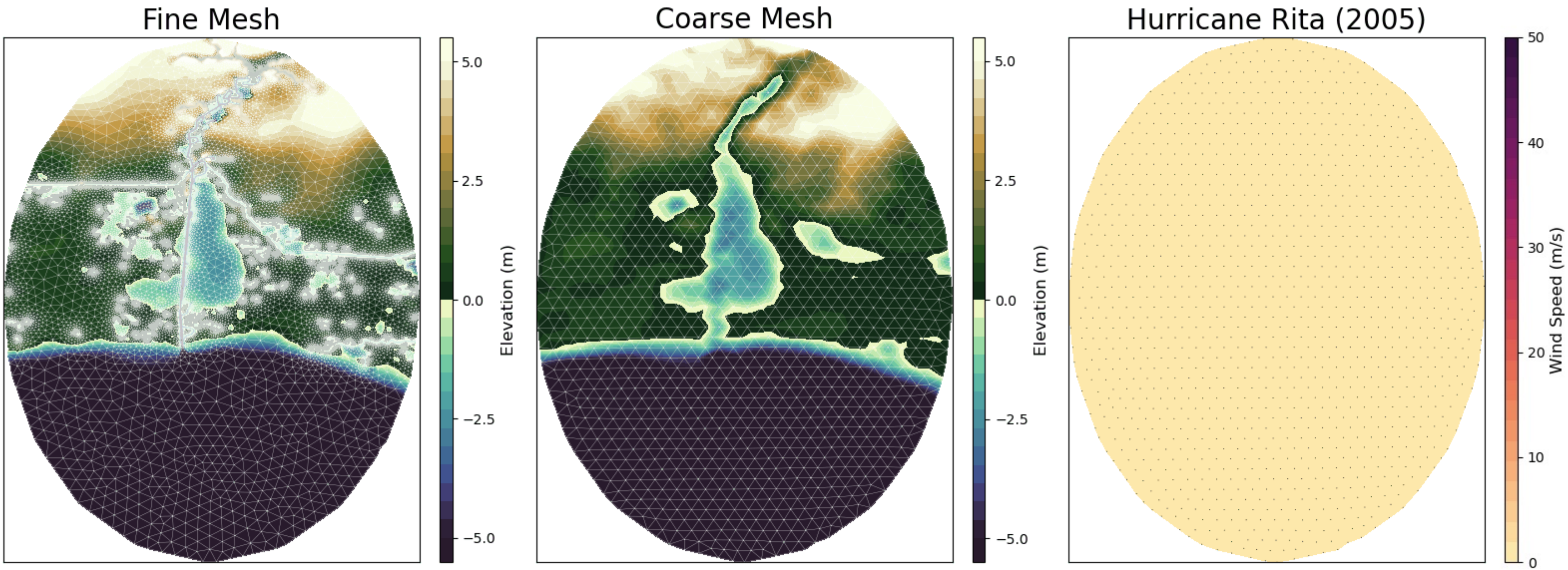
- Removed extensive logic to compare water levels and velocities between vertices.

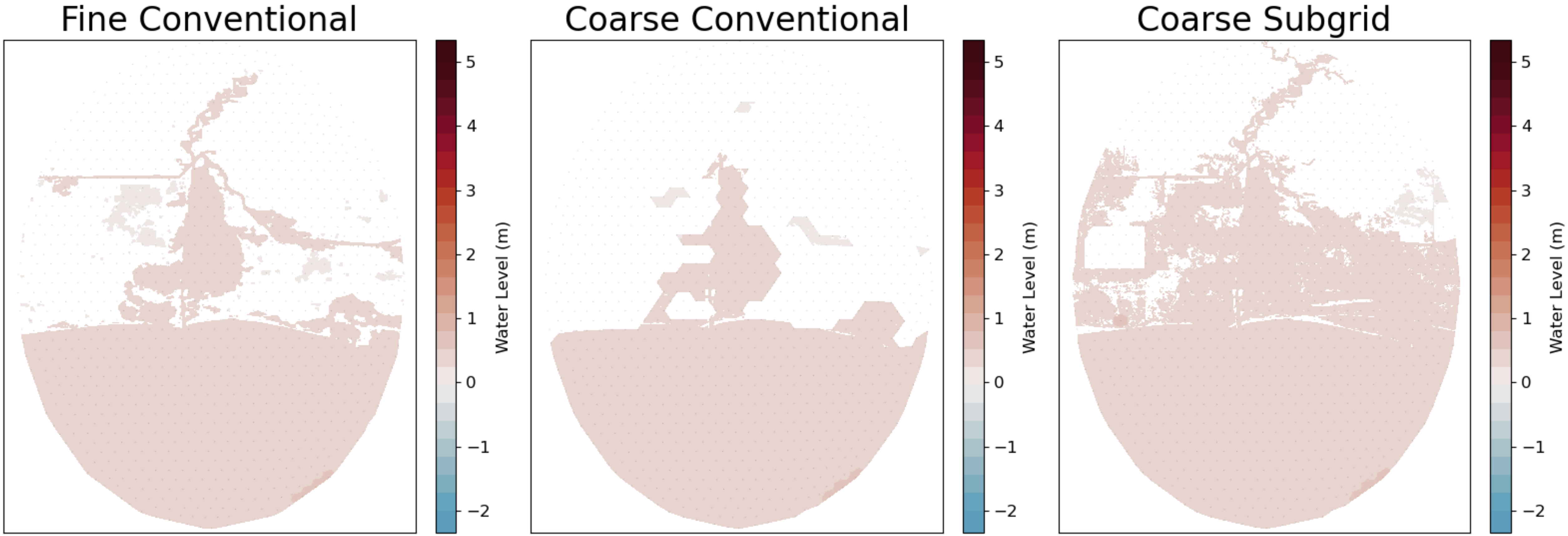
Closure coefficients for Conventional and Level 0 closures

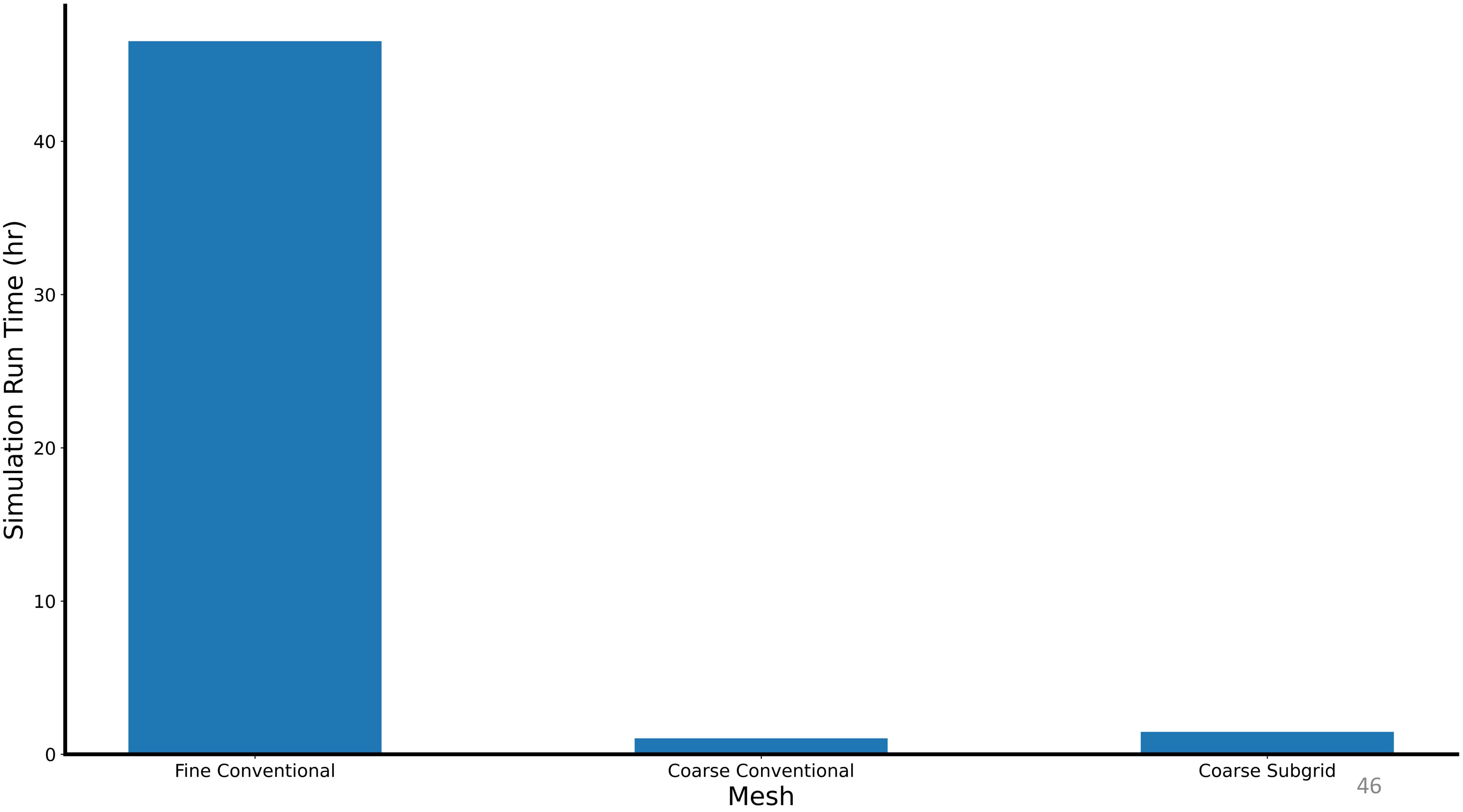
At first, we used a so-called ‘Level 0’ closure:

	Conventional	Level 0
Wet/dry	$\phi = 0 \text{ or } 1$	$\phi = A_W / A_G$
Advection	$C_{UU} = C_{VU} = C_{UV} = C_{VV} = 1$	$C_{UU} = C_{VU} = C_{UV} = C_{VV} = 1$
Friction	$C_{M,f} = C_f = gn^2 / H^{1/3}$	$C_{M,f} = \langle C_f \rangle_W$
Surface Gradient	$C_\zeta = 1$	$C_\zeta = 1$

Note the differences for the wet/dry status and friction term.


Fine Mesh
5.0
2.5
0.0
−2.5
−5.0
Elevation (m)
Coarse Mesh
5.0
2.5
0.0
−2.5
−5.0
Elevation (m)
Hurricane Rita (2005)
50
40
30
20
10
0
Wind Speed (m/s)

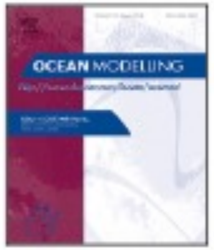

Fine Conventional
Coarse Conventional
Coarse Subgrid
Water Level (m)
5
4
3
2
1
0
−1
−2


Simulation Run Time (hr)
0
10
20
30
40
Fine Conventional
Coarse Conventional
Coarse Subgrid
Mesh

Contents lists available at ScienceDirect

Ocean Modelling

journal homepage: www.elsevier.com/locate/ocemod



Subgrid corrections in finite-element modeling of storm-driven coastal flooding

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Subgrid
ADCIRC
Wetting and drying
Shallow water equations

ABSTRACT

Coastal flooding models are used to predict the timing and magnitude of inundation during storms, both for real-time forecasting and long-term design. However, there is a need for faster flooding predictions that also represent flow pathways and barriers at the scales of critical infrastructure. This need can be addressed via subgrid corrections, which use information at smaller scales to 'correct' the flow variables (water levels, current velocities) averaged over the mesh scale. Recent studies have shown a decrease in run time by 1 to 2 orders of magnitude, with the ability to decrease further if the model time step is also increased.

In this study, subgrid corrections are added to a widely used, finite-element-based, shallow water model to better understand how they can improve the accuracy and efficiency of inundation predictions. The performance of the model, with and without subgrid corrections, is evaluated on scenarios of tidal flooding in a synthetic domain and a small bay in Massachusetts, as well as a scenario with a real atmospheric forcing and storm surge in southwest Louisiana. In these tests we observed that the subgrid corrections can increase model speed by 10 to 50 times, while still representing flow through channels below the mesh scale to inland locations.

Chapter 1

- How can we implement subgrid corrections into a widely used storm surge model?

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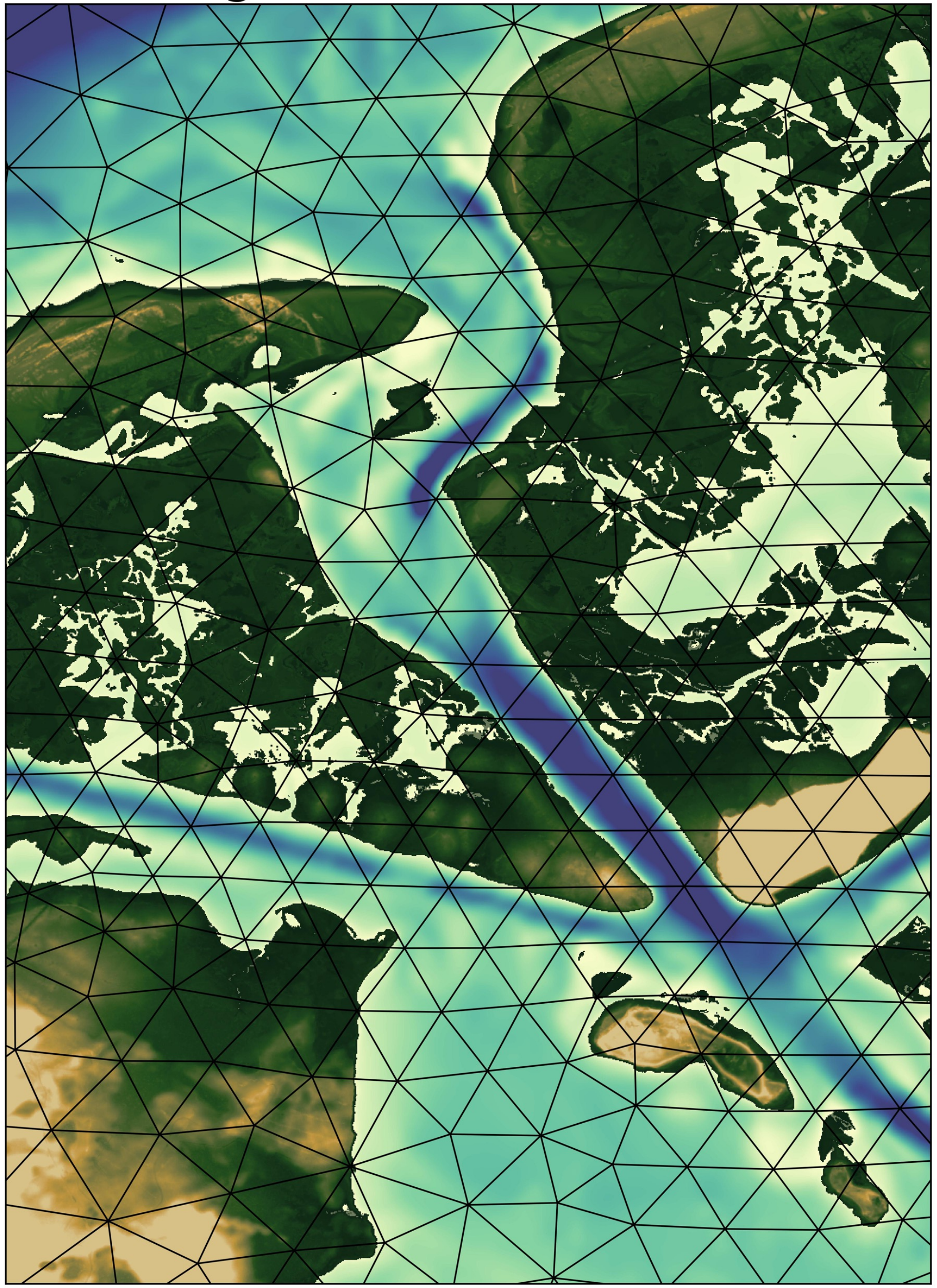
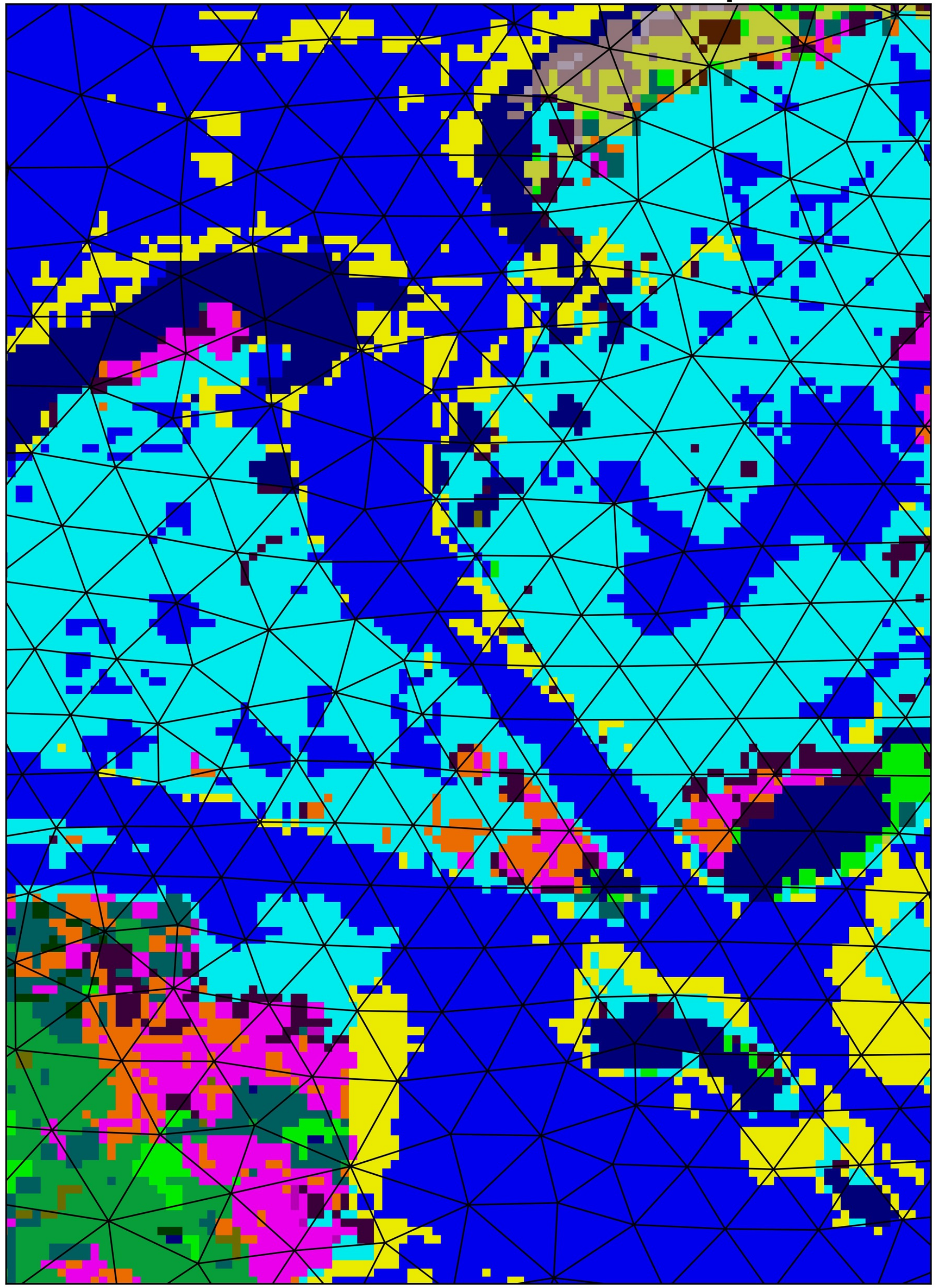
Chapter 3

- What are some of the limitations of subgrid corrections in storm surge modeling?

Digital Elevation Model



C-CAP Landcover Map



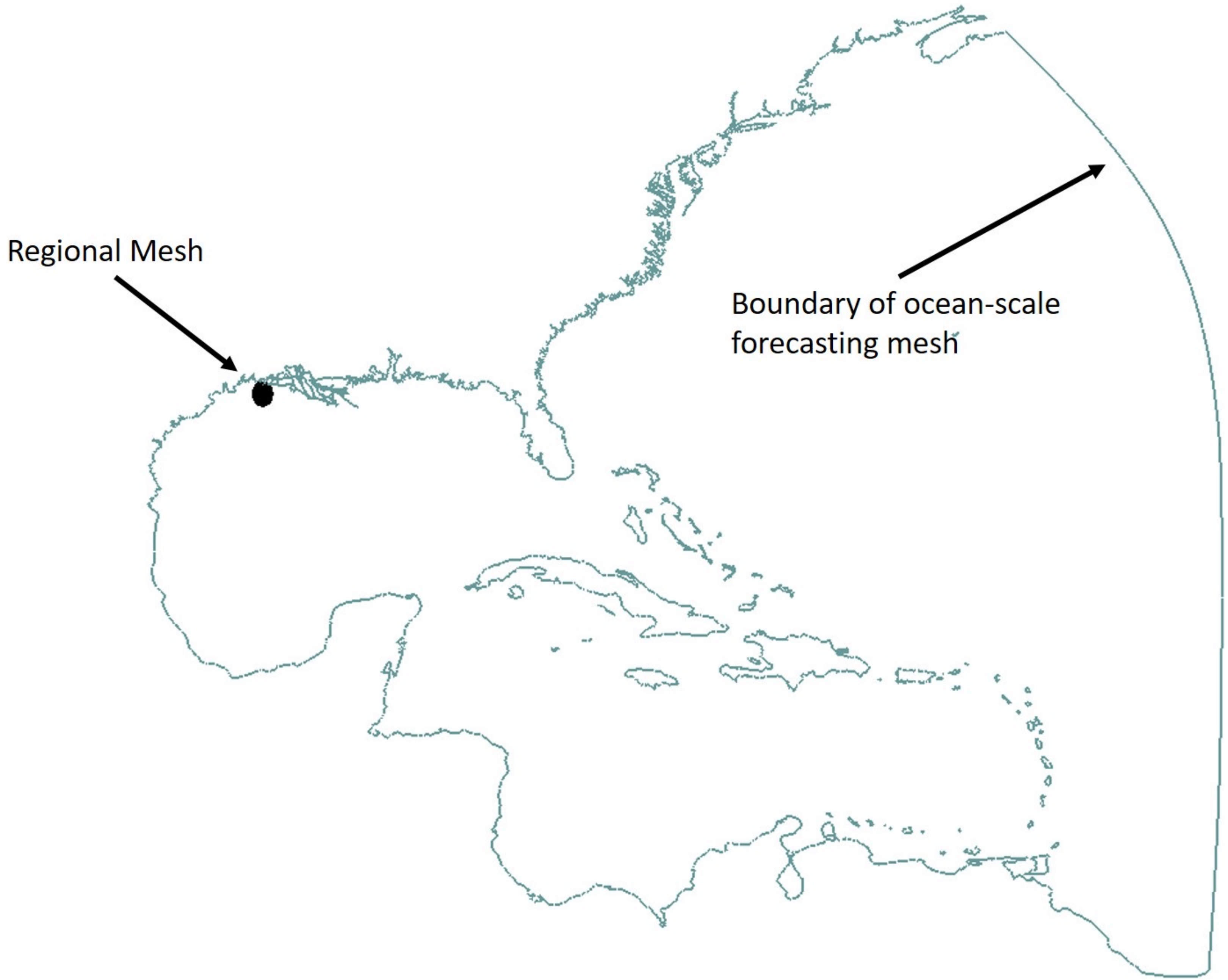
Higher-level corrections to subgrid ADCIRC

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

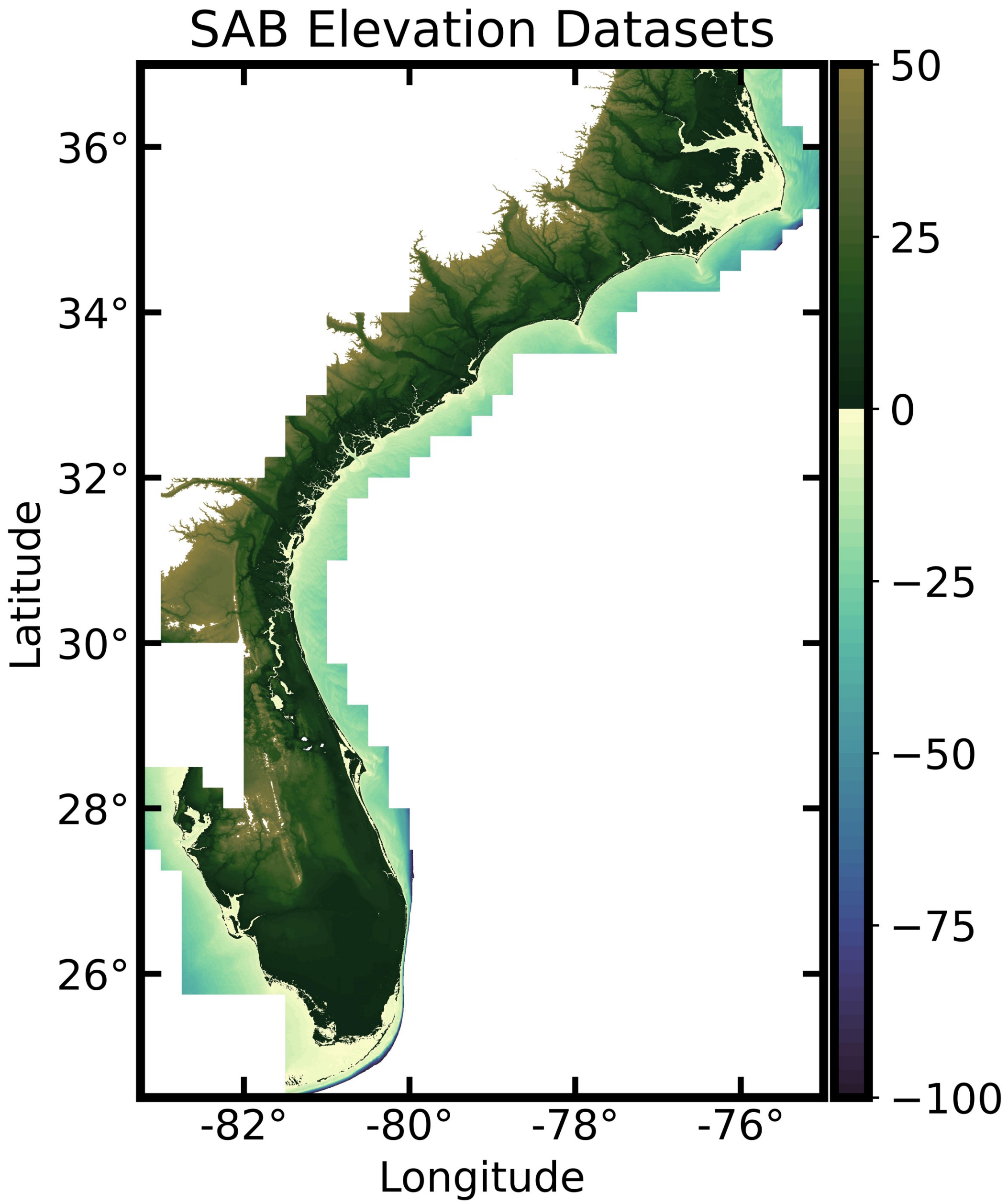
$$\text{Where: } R_v^2 = \frac{\langle H \rangle_W}{\left\langle H^{3/2} C_f^{-1/2} \right\rangle_W}$$

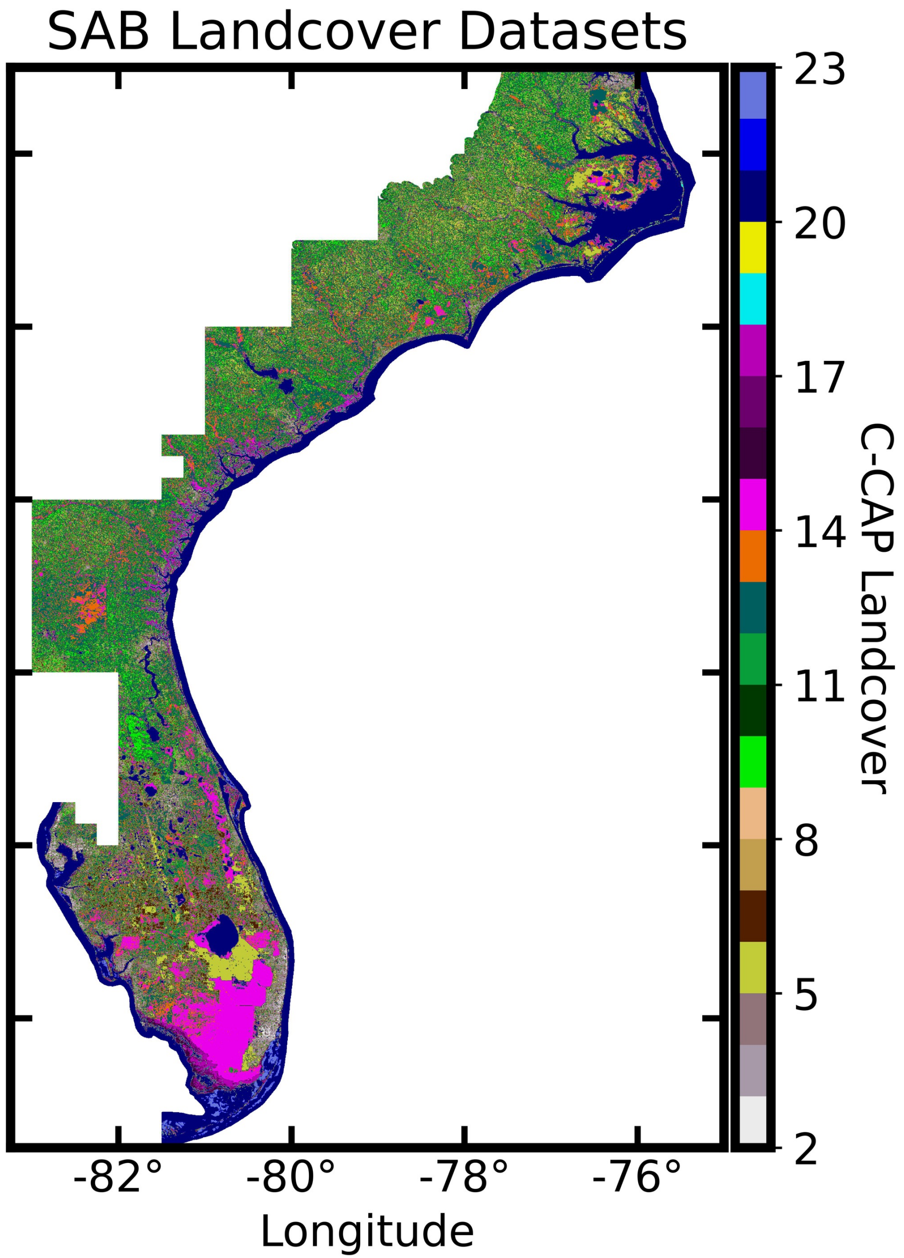
These Level 1 corrections are intended to correct inaccuracies in friction and advection predictions.

Expansion to ocean-scale storm surge modeling

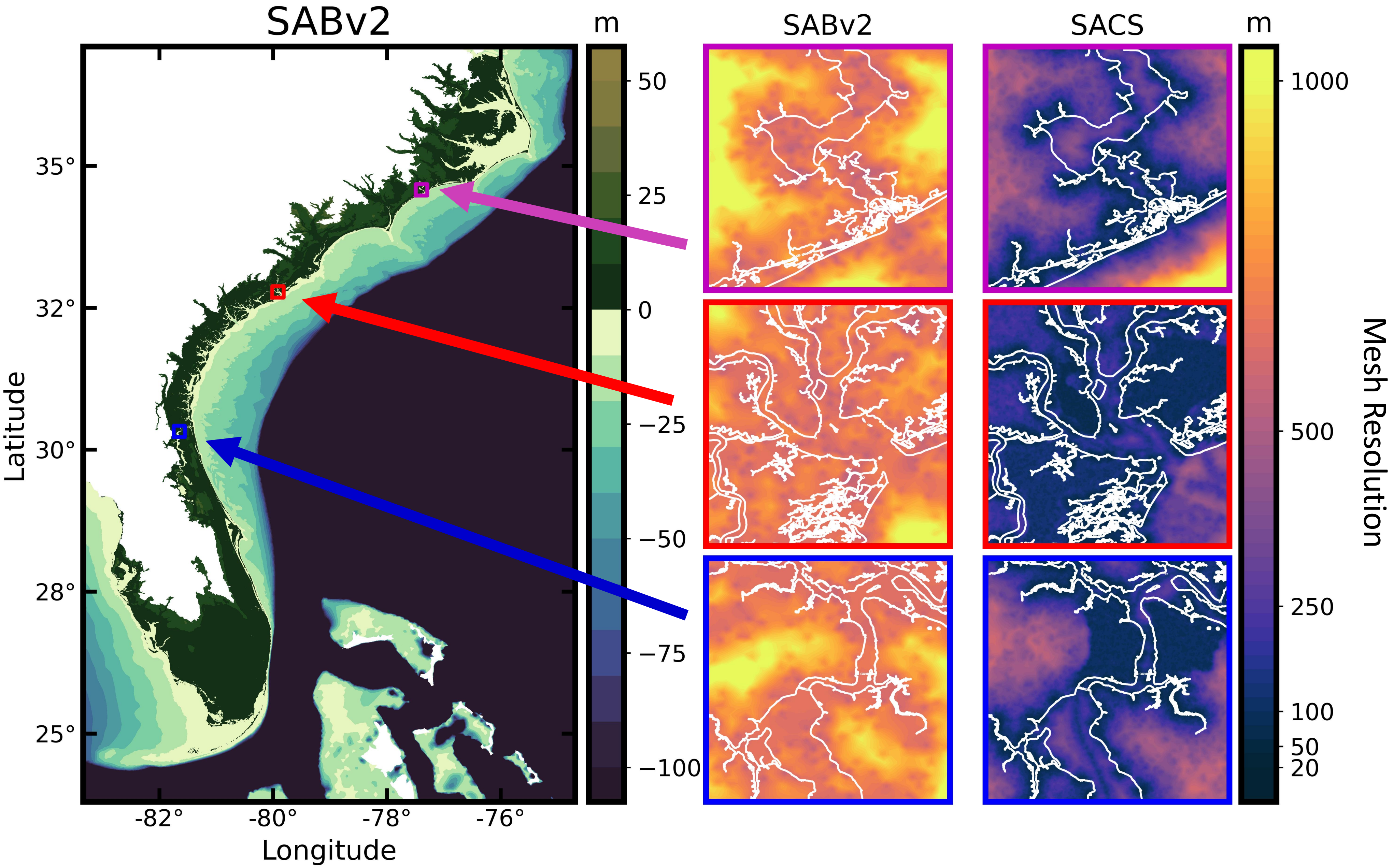


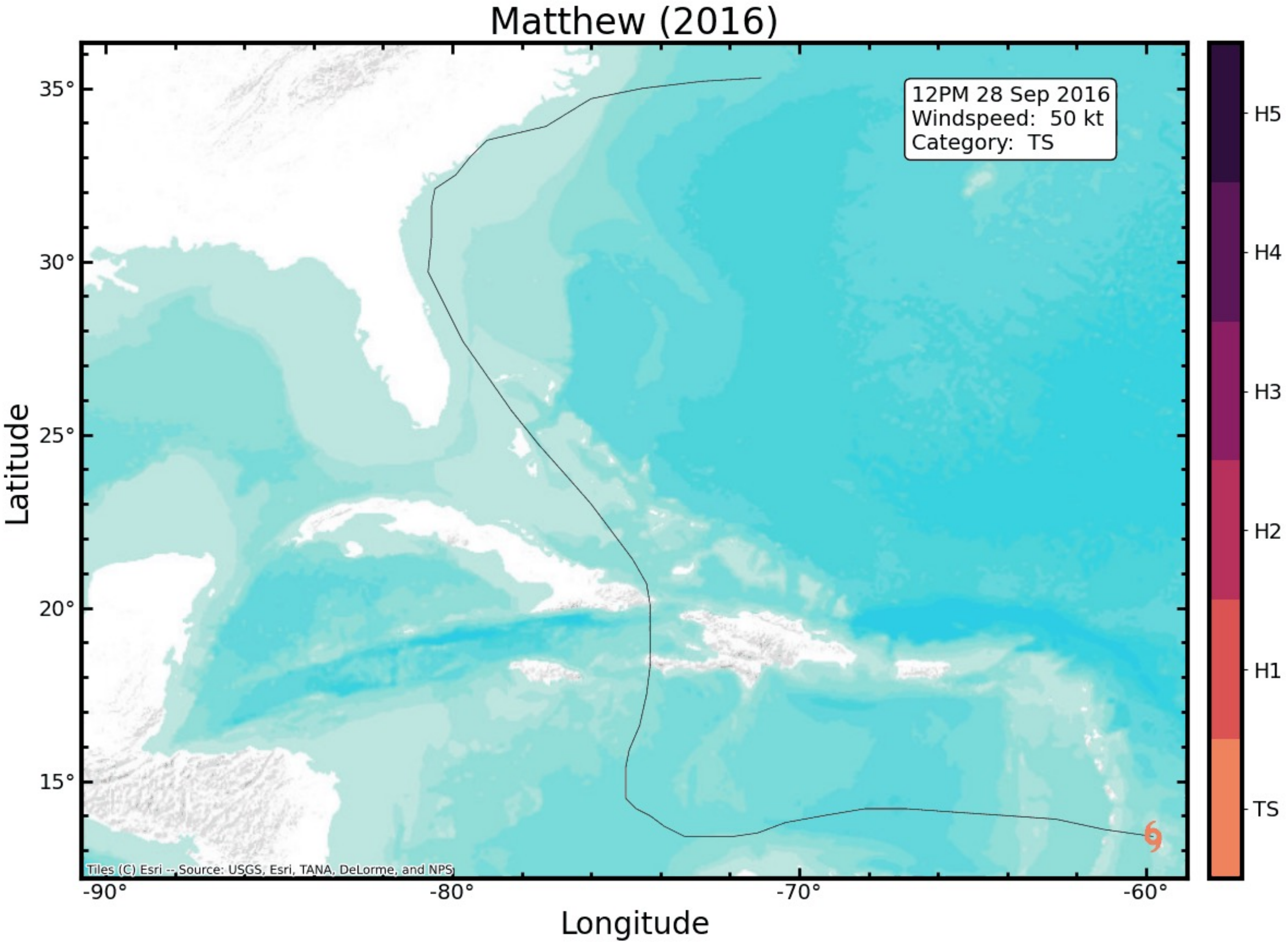
Increases to size and quantity of subgrid datasets

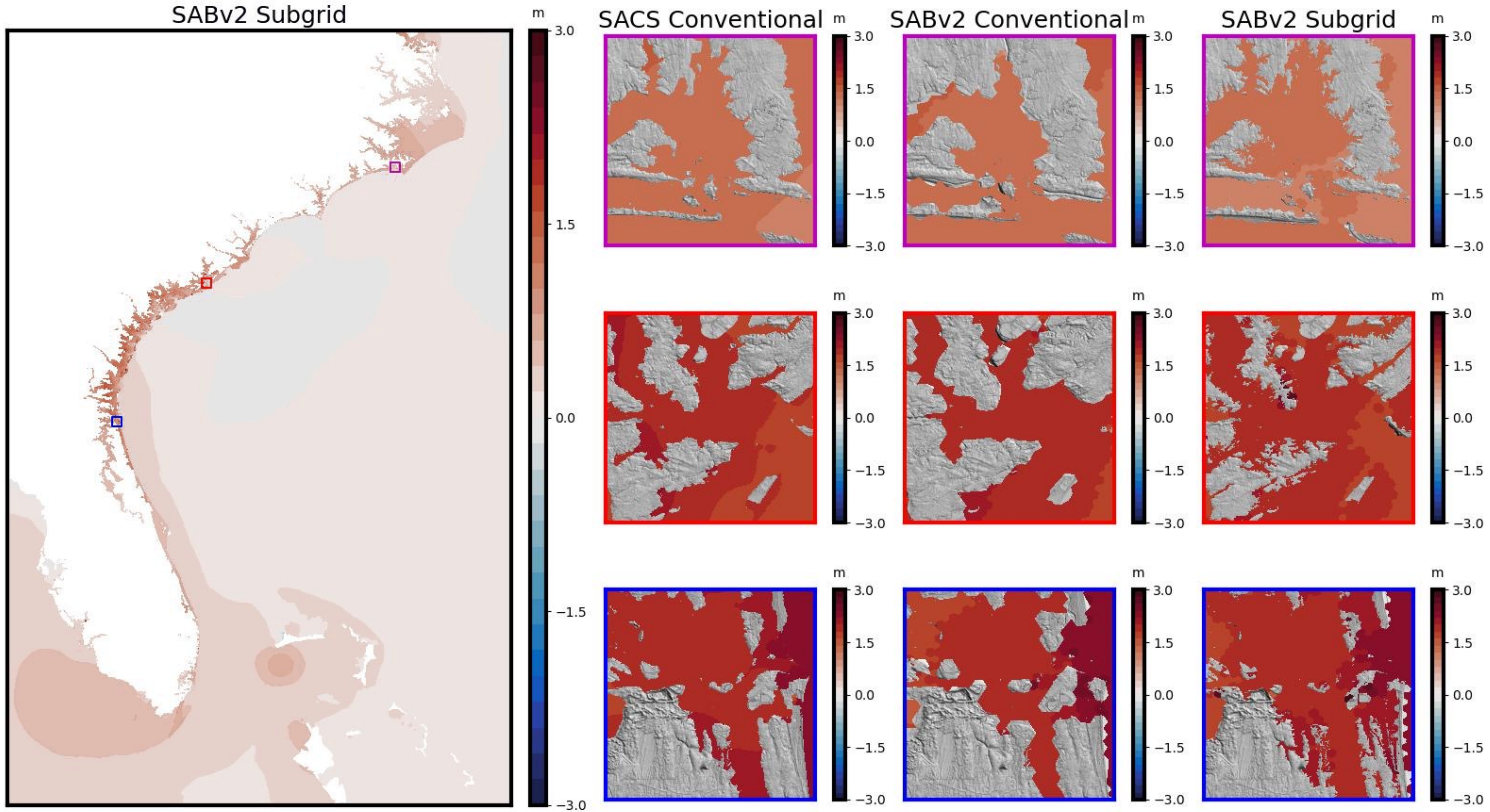




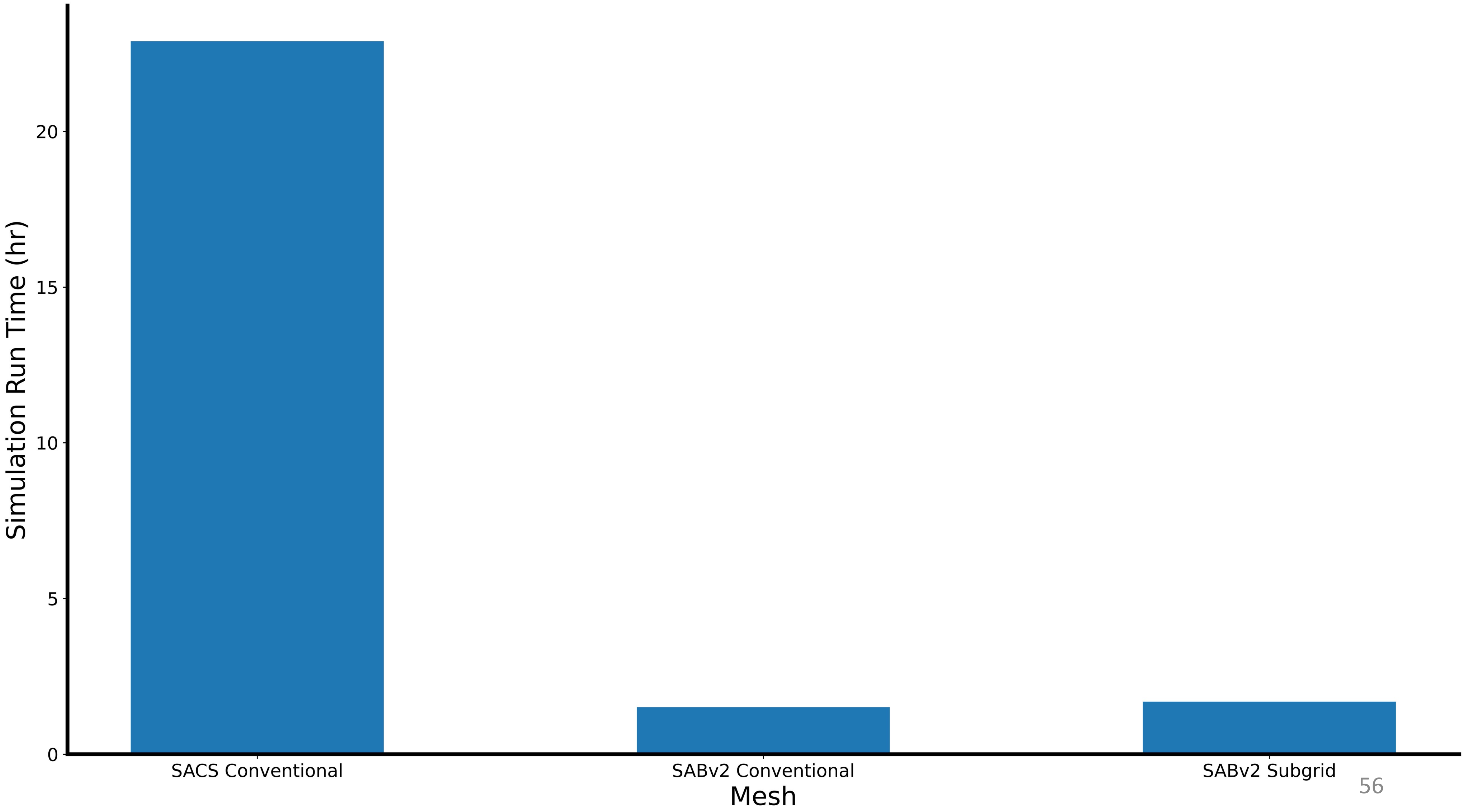
Testing on ocean-scale mesh




Matthew (2016)
12PM 28 Sep 2016
Windspeed: 50 kt
Category: TS
Latitude
Longitude
35°
30°
25°
20°
15°
-90°
-80°
-70°
-60°
H5
H4
H3
H2
H1
TS
Tiles (C) Esri -- Source: USGS, Esri, TANA, DeLorme, and NPS



SABv2 Subgrid
SACS Conventional
SABv2 Conventional
SABv2 Subgrid
m
3.0
1.5
0.0
−1.5
−3.0


Simulation Run Time (hr)
0
5
10
15
20
SACS Conventional
SABv2 Conventional
SABv2 Subgrid
Mesh

Natural Hazards
https://doi.org/10.1007/s11069-023-05975-2

ORIGINAL PAPER

Storm surge predictions from ocean to subgrid scales

Johnathan Woodruff[1] · J. C. Dietrich[1] · D. Wirasaet[2] · A. B. Kennedy[2] · D. Bolster[2]

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Abstract
The inland propagation of storm surge caused by tropical cyclones depends on large and small waterways to connect the open ocean to inland bays, estuaries, and floodplains. Numerical models for storm surge require these waterways and their surrounding topography to be resolved sufficiently, which can require millions of computational cells for flooding simulations on a large (ocean scale) computational domain, leading to higher demands for computational resources and longer wall-clock times for simulations. Alternatively, the governing shallow water equations can be modified to introduce subgrid corrections that allow coarser and cheaper simulations with comparable accuracy. In this study, subgrid corrections are extended for the first time to simulations at the ocean scale. Higher-level corrections are included for bottom friction and advection, and look-up tables are optimized for large model domains. Via simulations of tides, storm surge, and coastal flooding due to Hurricane Matthew in 2016, the improvements in water level prediction accuracy due to subgrid corrections are evaluated at 218 observation locations throughout 1500 km of coast along the South Atlantic Bight. The accuracy of the subgrid model with relatively coarse spatial resolution ($E_{\mathrm{RMS}} = 0.41$ m) is better than that of a conventional model with relatively fine spatial resolution ($E_{\mathrm{RMS}} = 0.67$ m). By running on the coarsened subgrid model, we improved the accuracy over efficiency curve for the model, and as a result, the computational expense of the simulation was decreased by a factor of 13.

Chapter 1

- How can we implement subgrid corrections into a widely used storm surge model?

Chapter 2

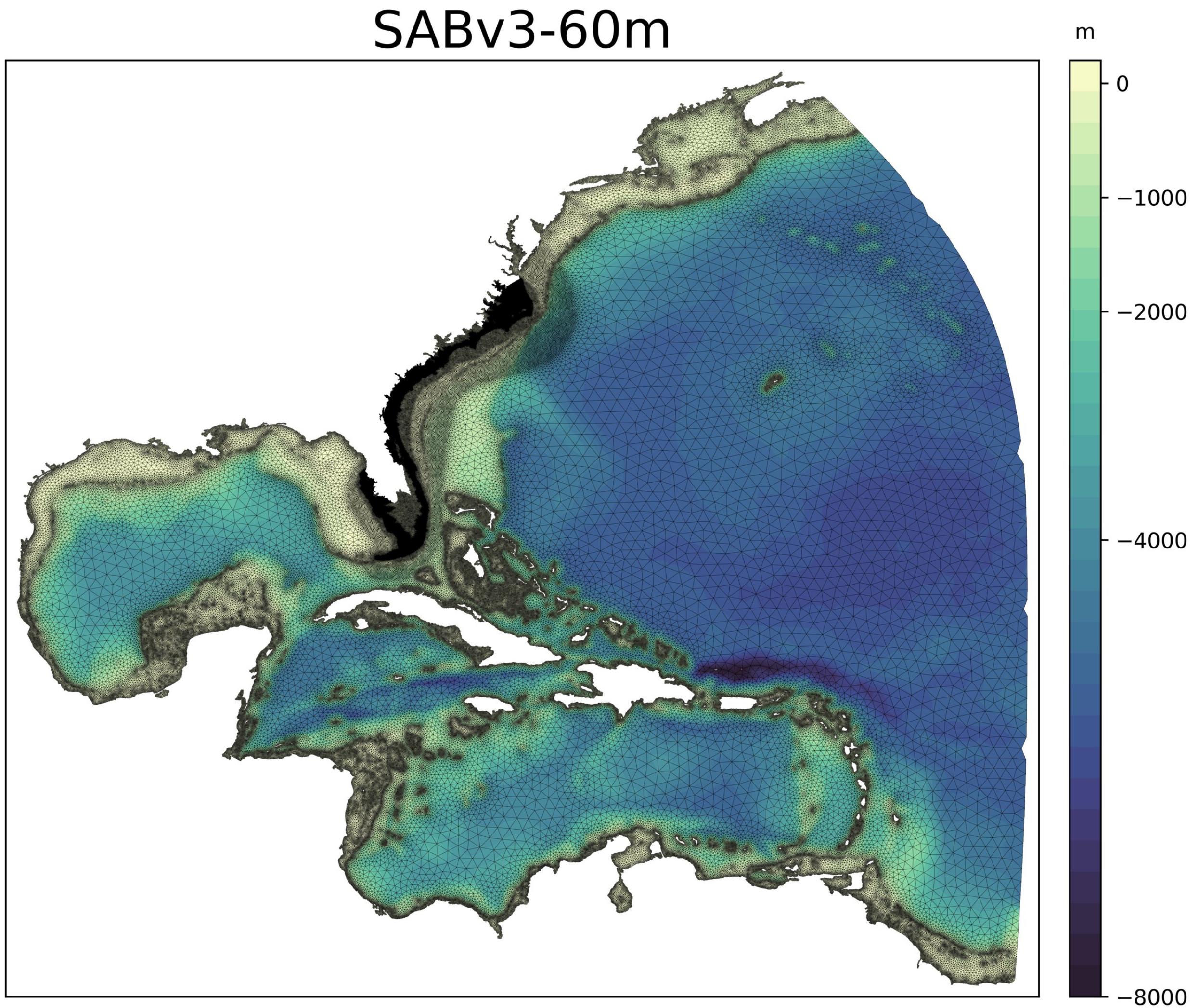
- How can higher-level corrections be applied to realistic/ocean-scale domains to improve flow predictions?

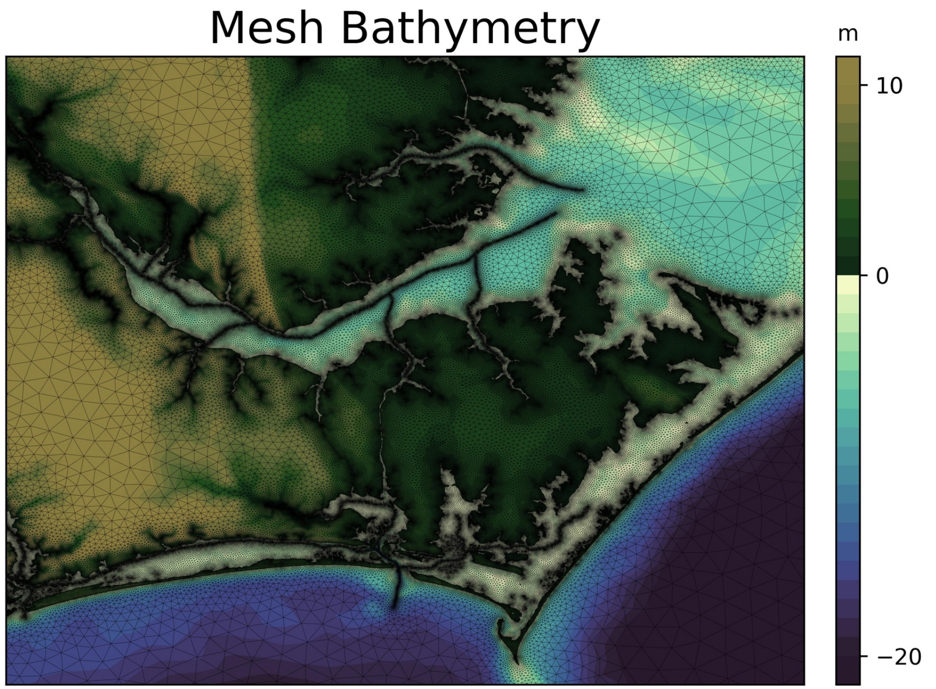
Chapter 3

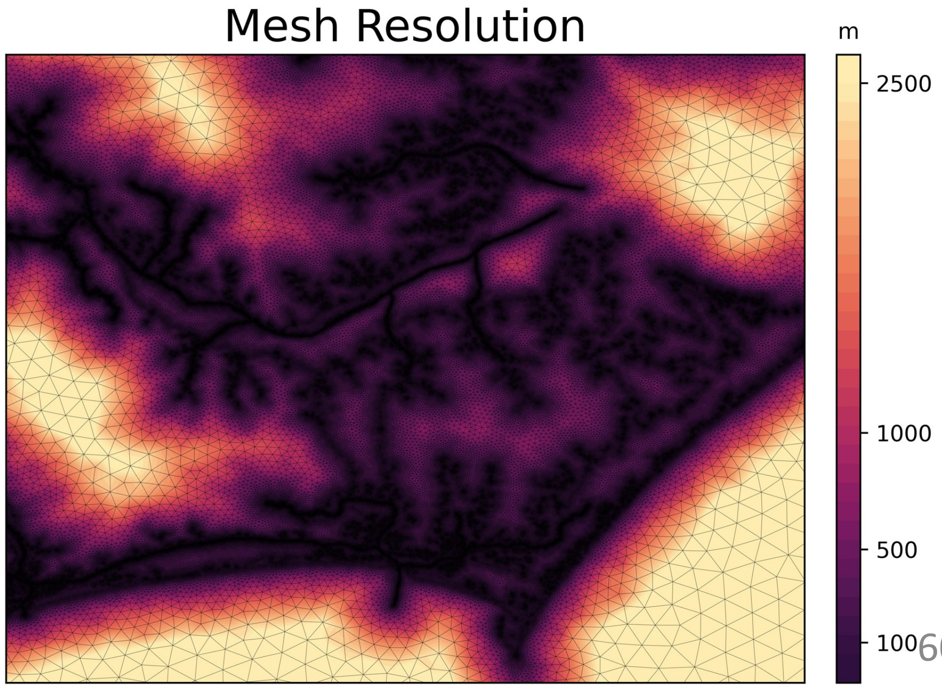
- What are some of the limitations of subgrid corrections in storm surge modeling?

How coarse is too coarse?

- How do subgrid results degrade as mesh resolution is incrementally coarsened?
- What guidelines can be established to optimize the accuracy and efficiency of ocean-scale subgrid storm surge models?







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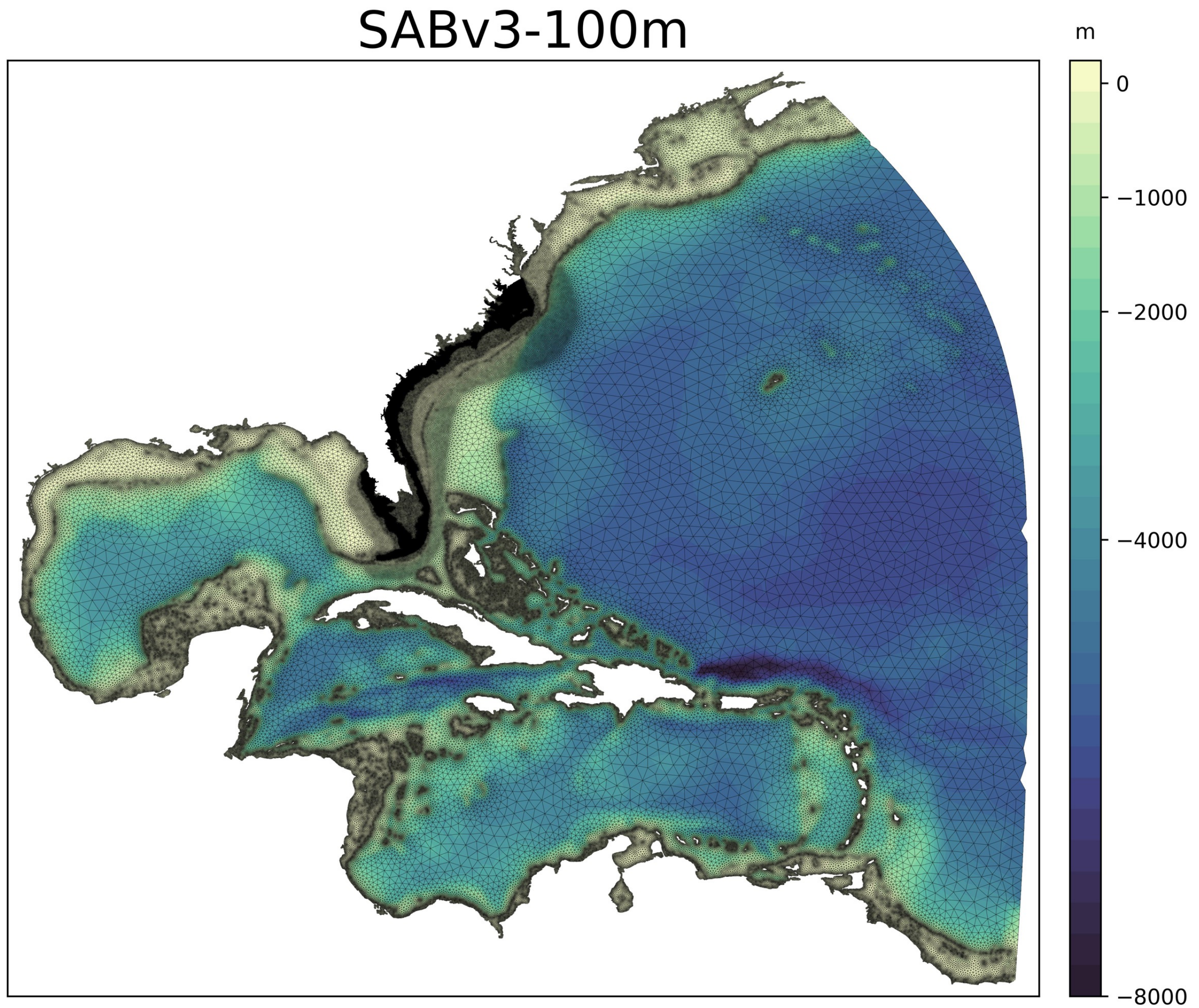
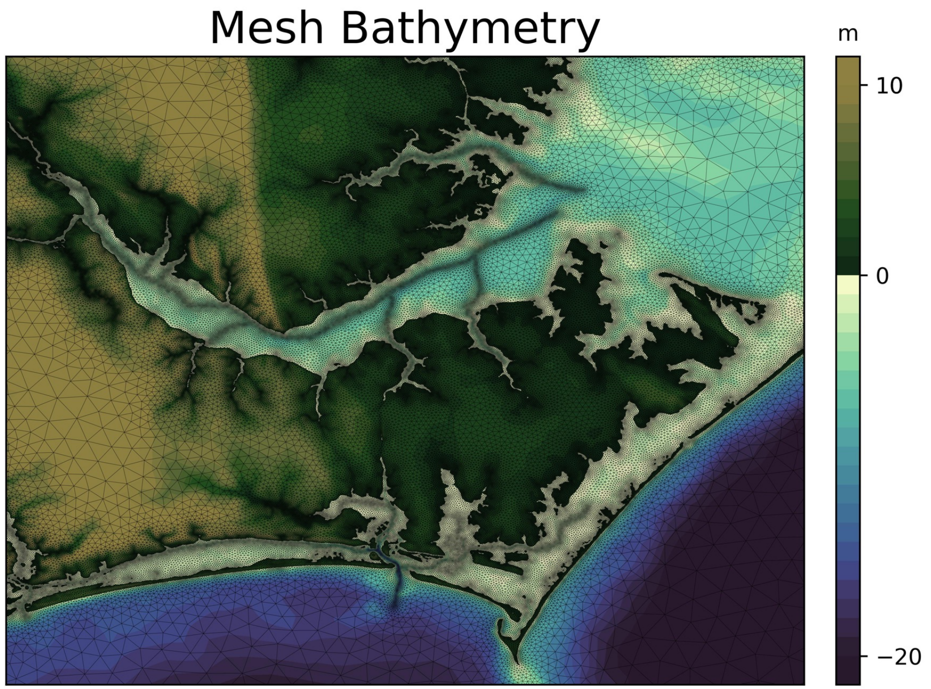
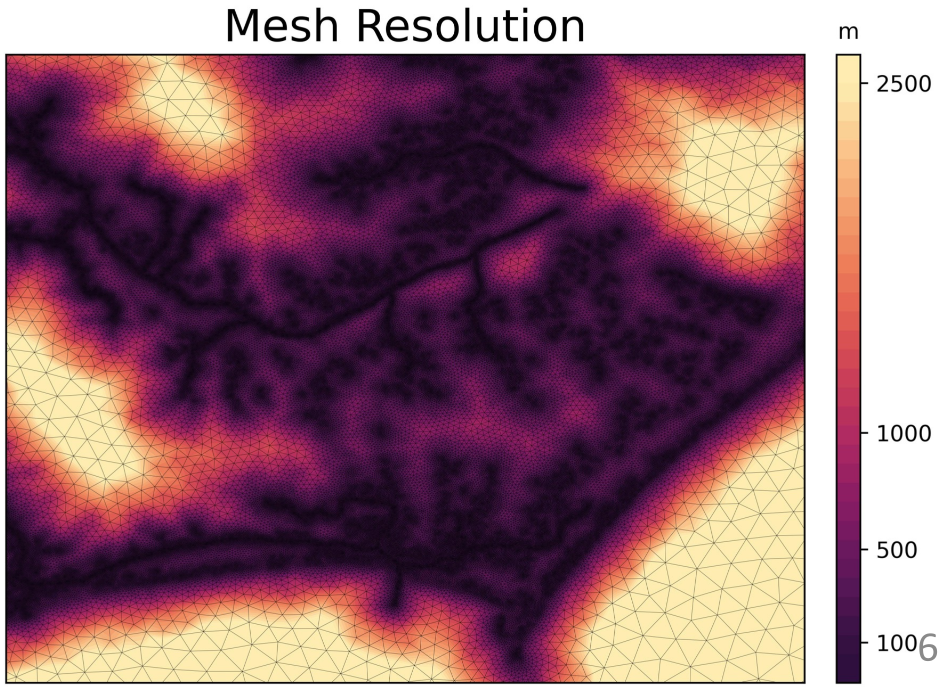
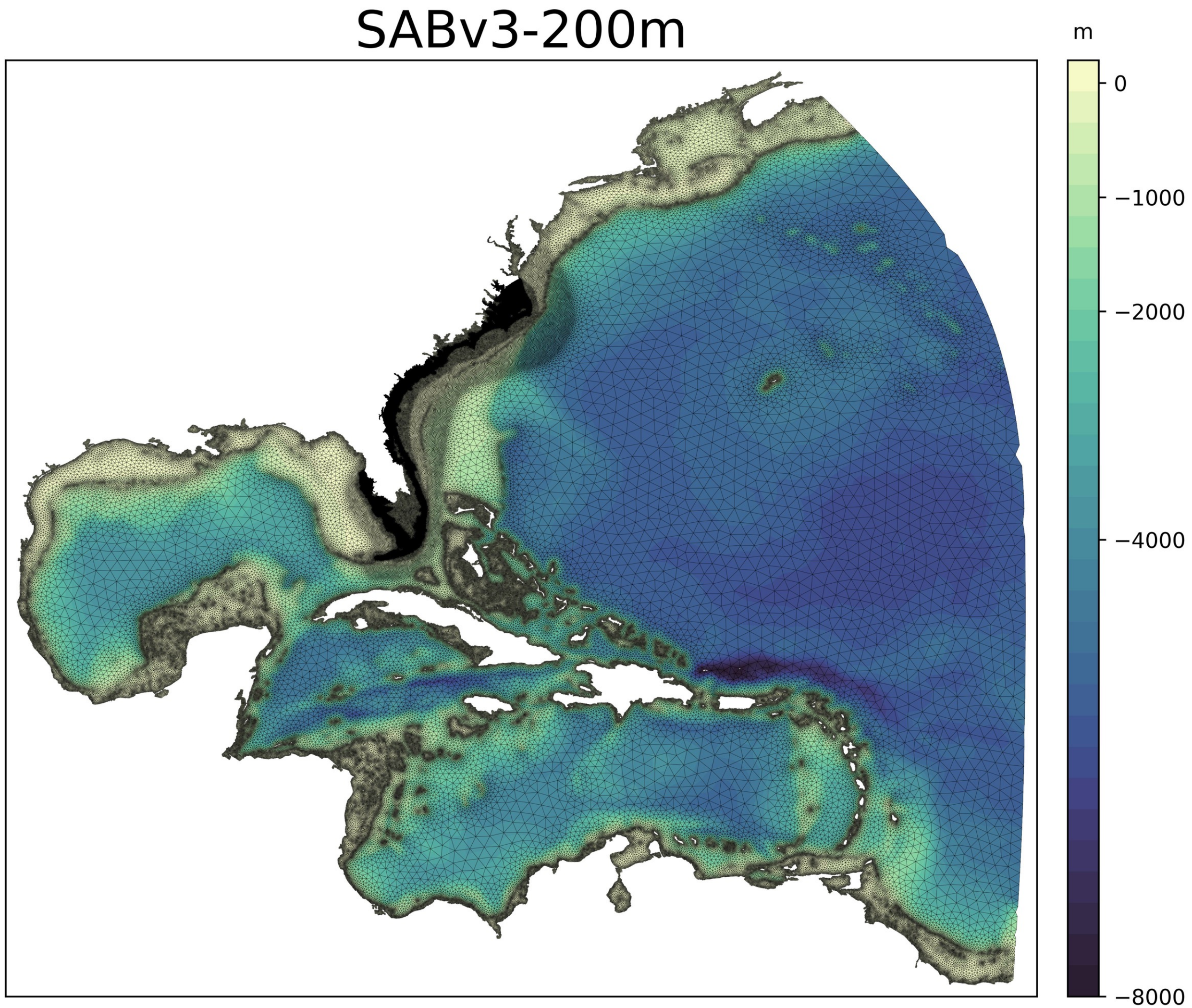


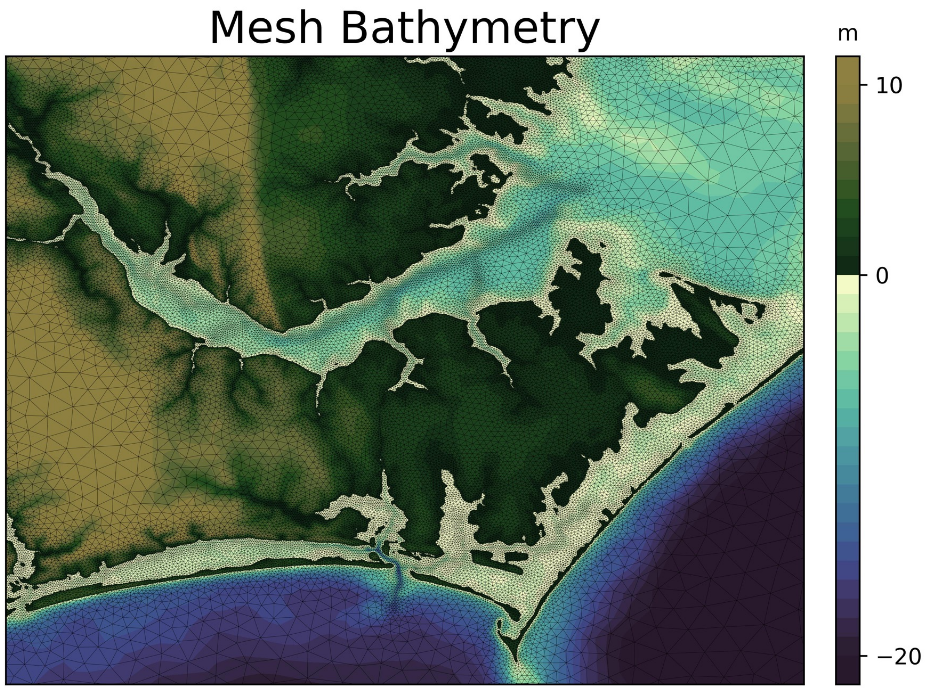


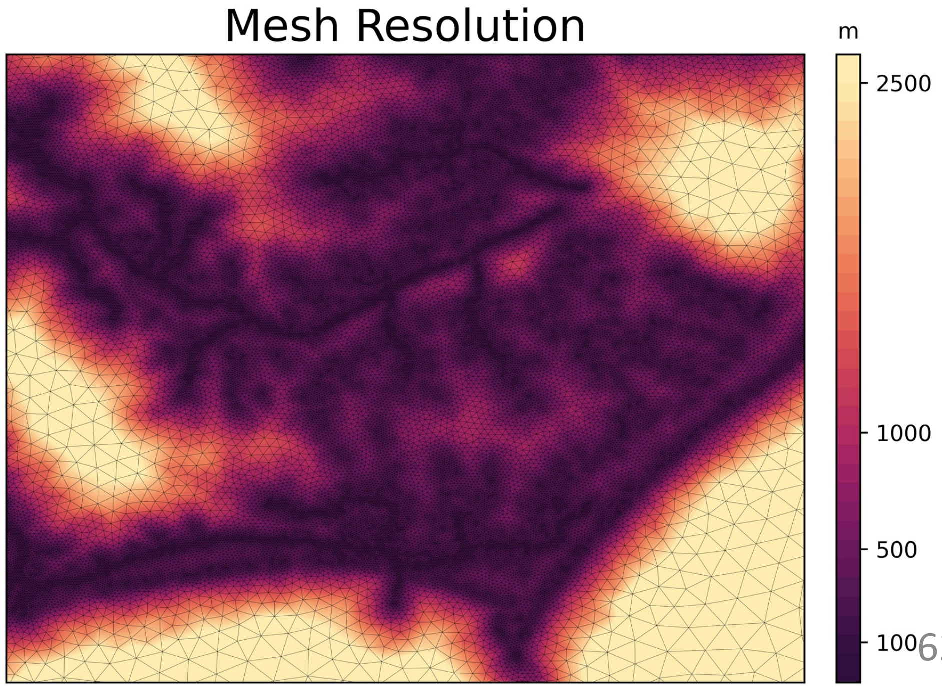


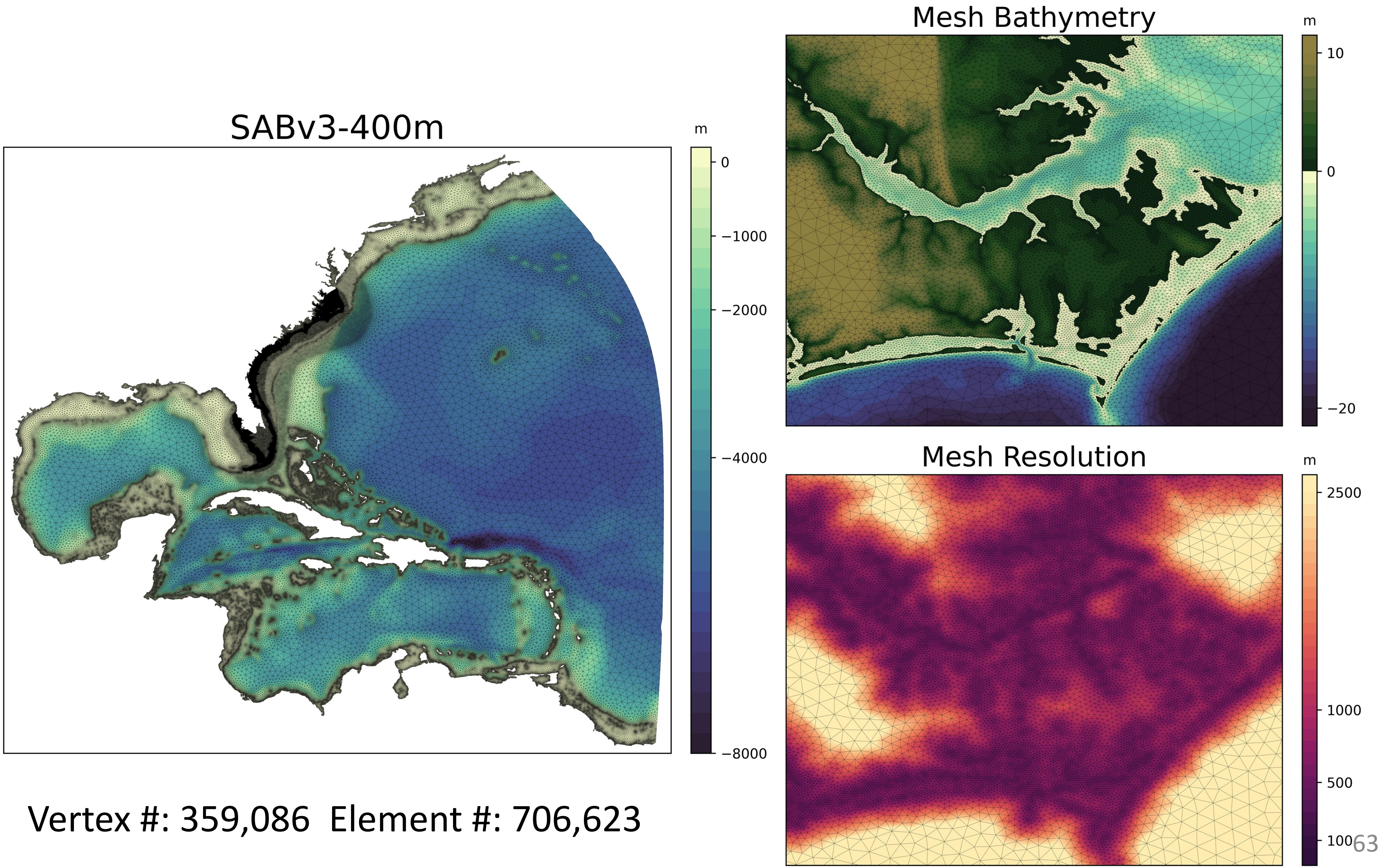
Vertex #: 1,751,839 Element #: 3,490,798



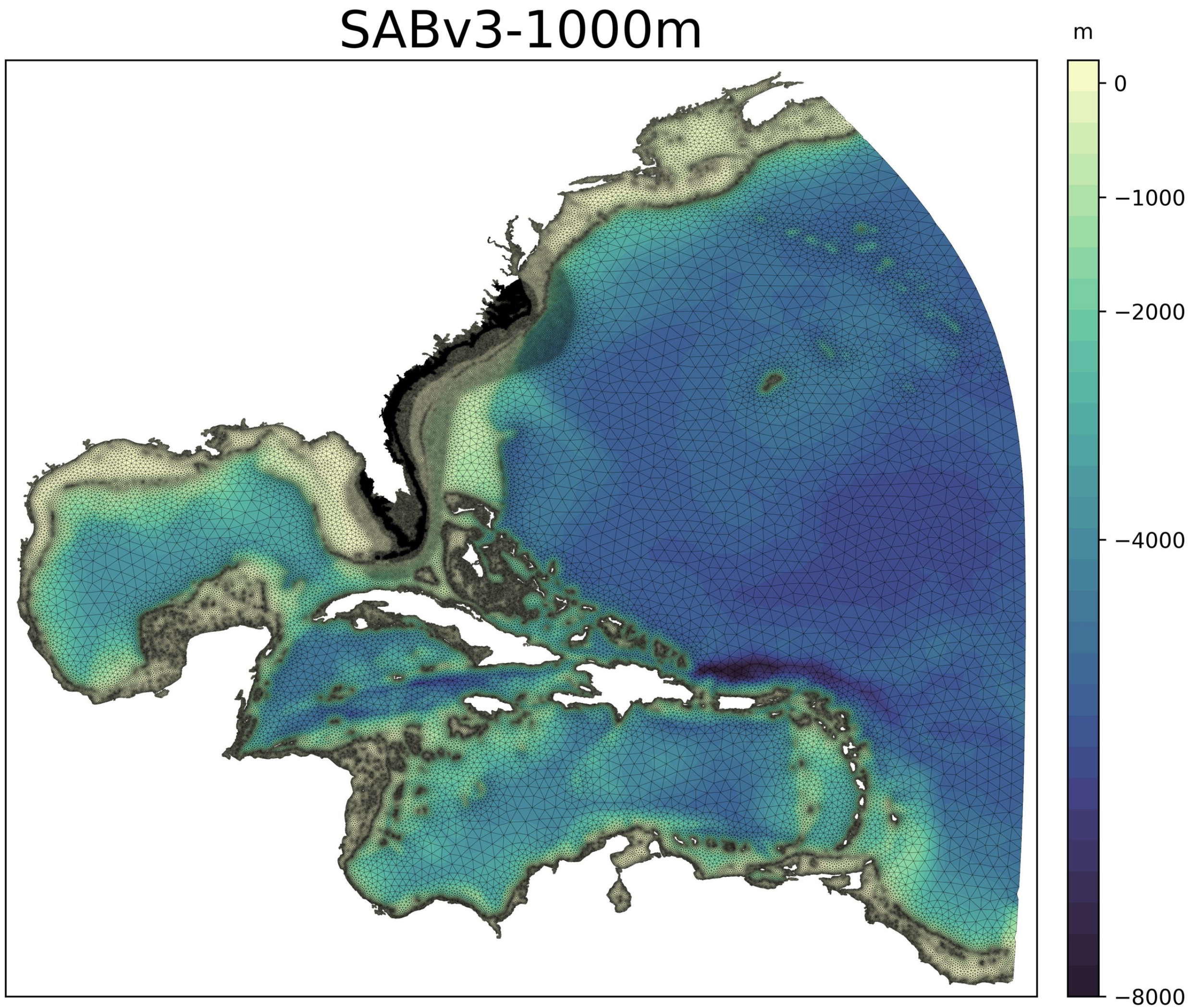
Vertex #: 754,159 Element #: 1,496,184

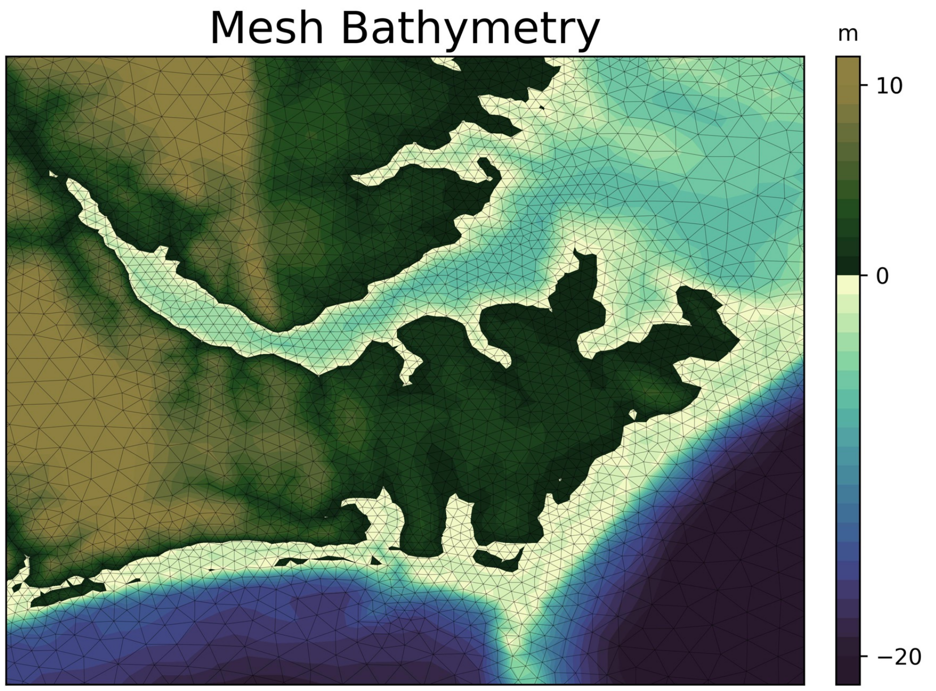


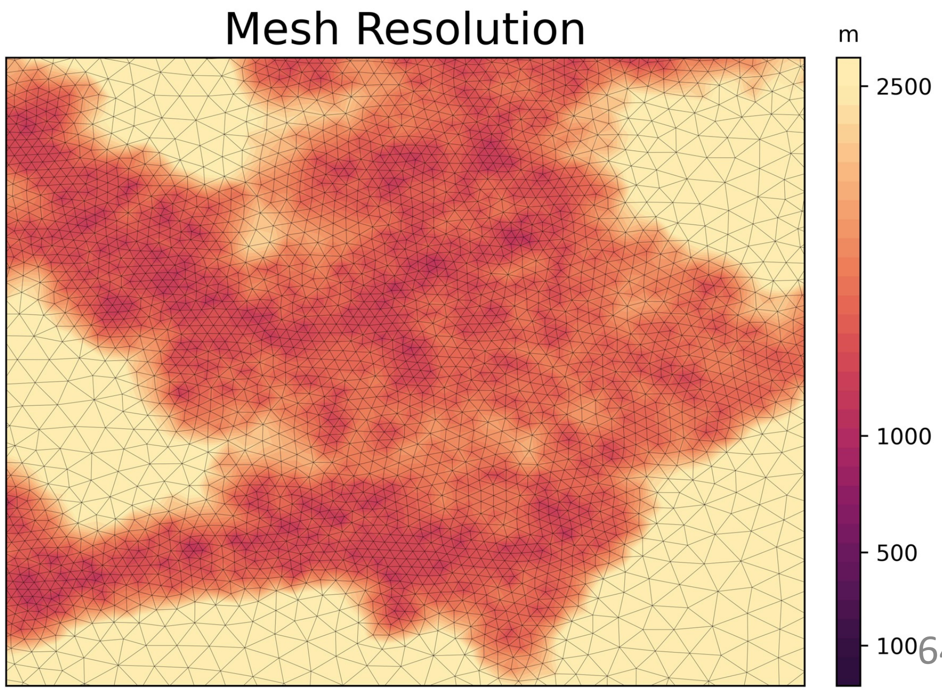




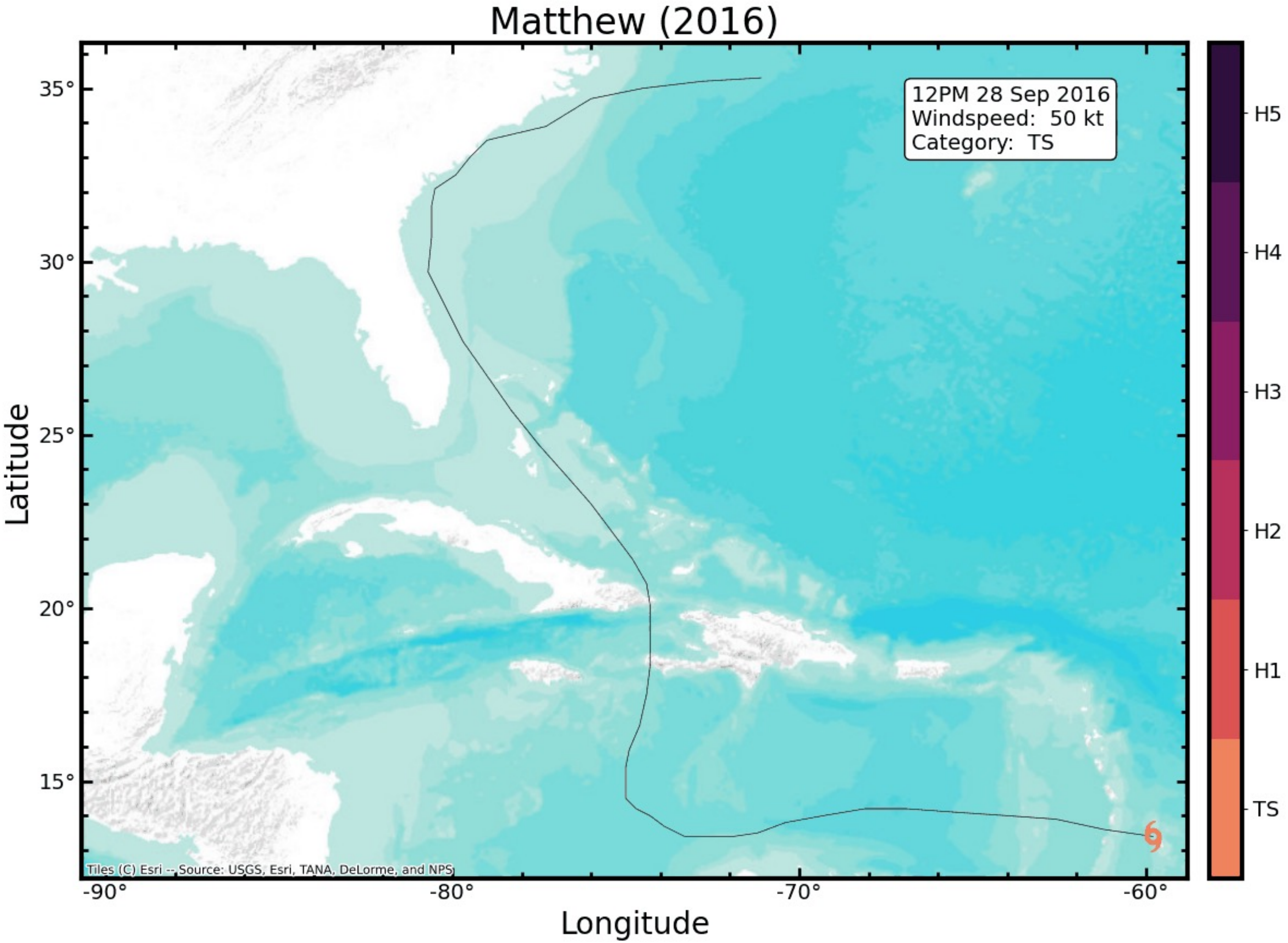
Vertex #: 359,086 Element #: 706,623

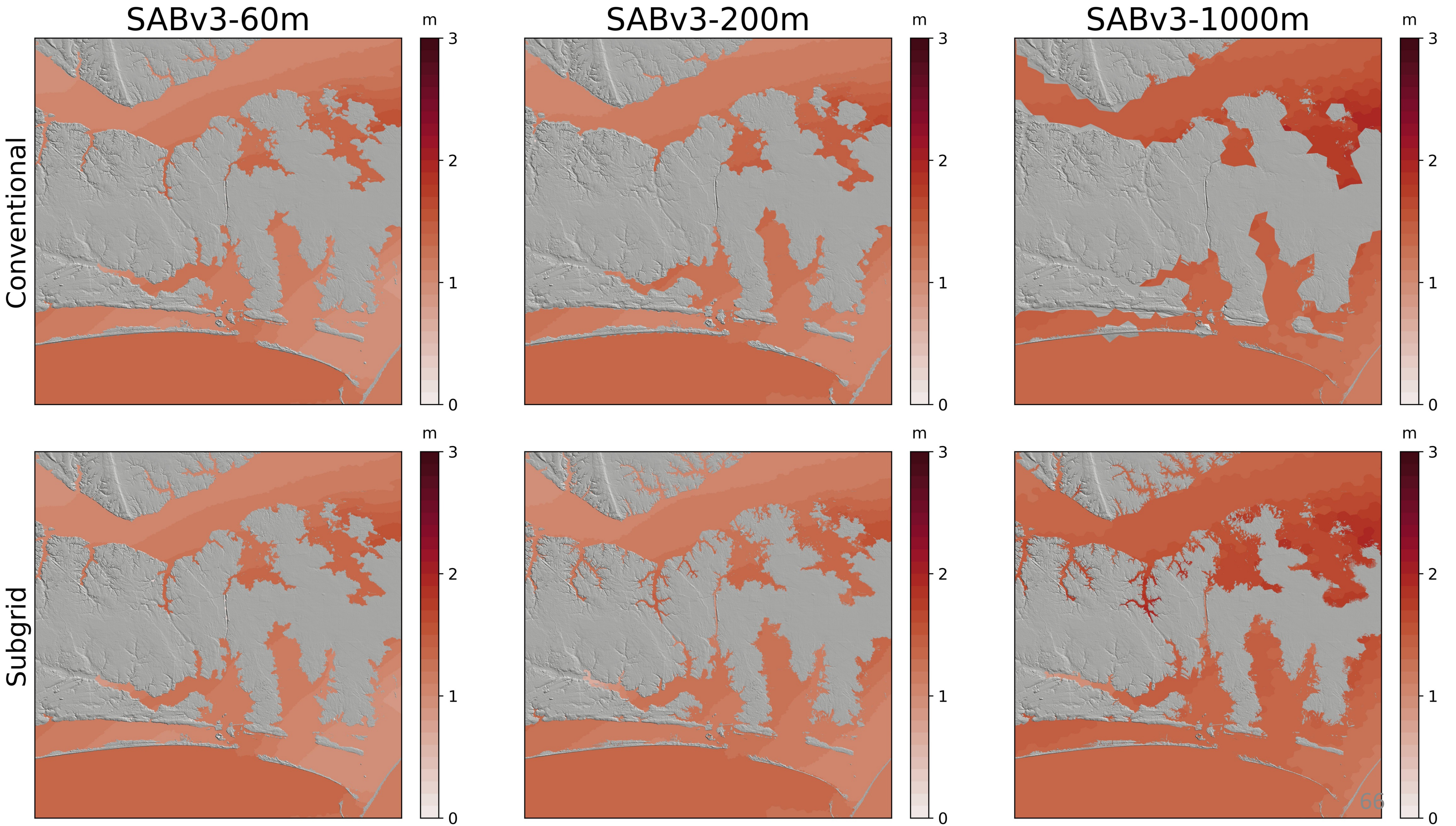




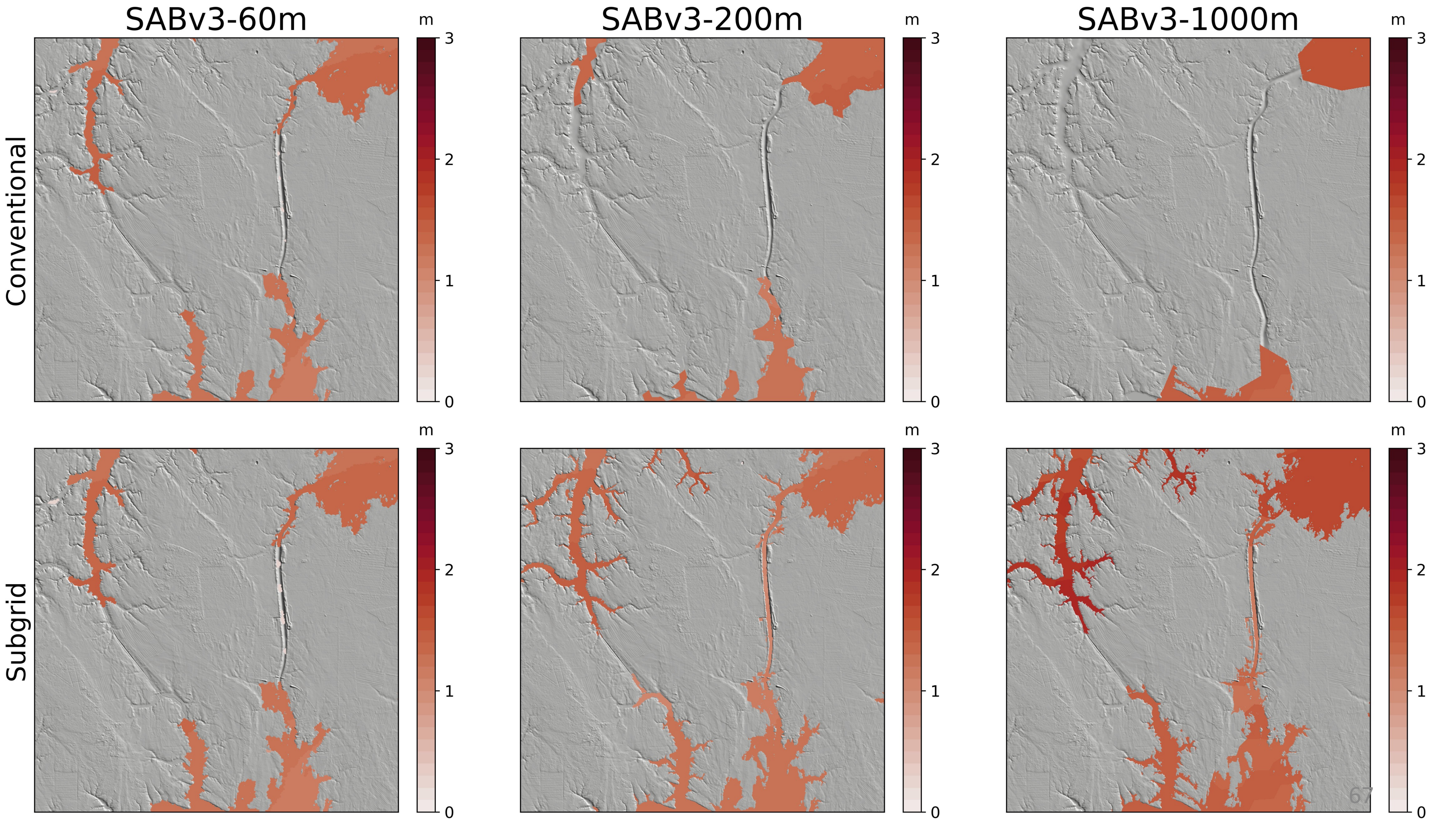


Vertex #: 178,398 Element #: 346,137

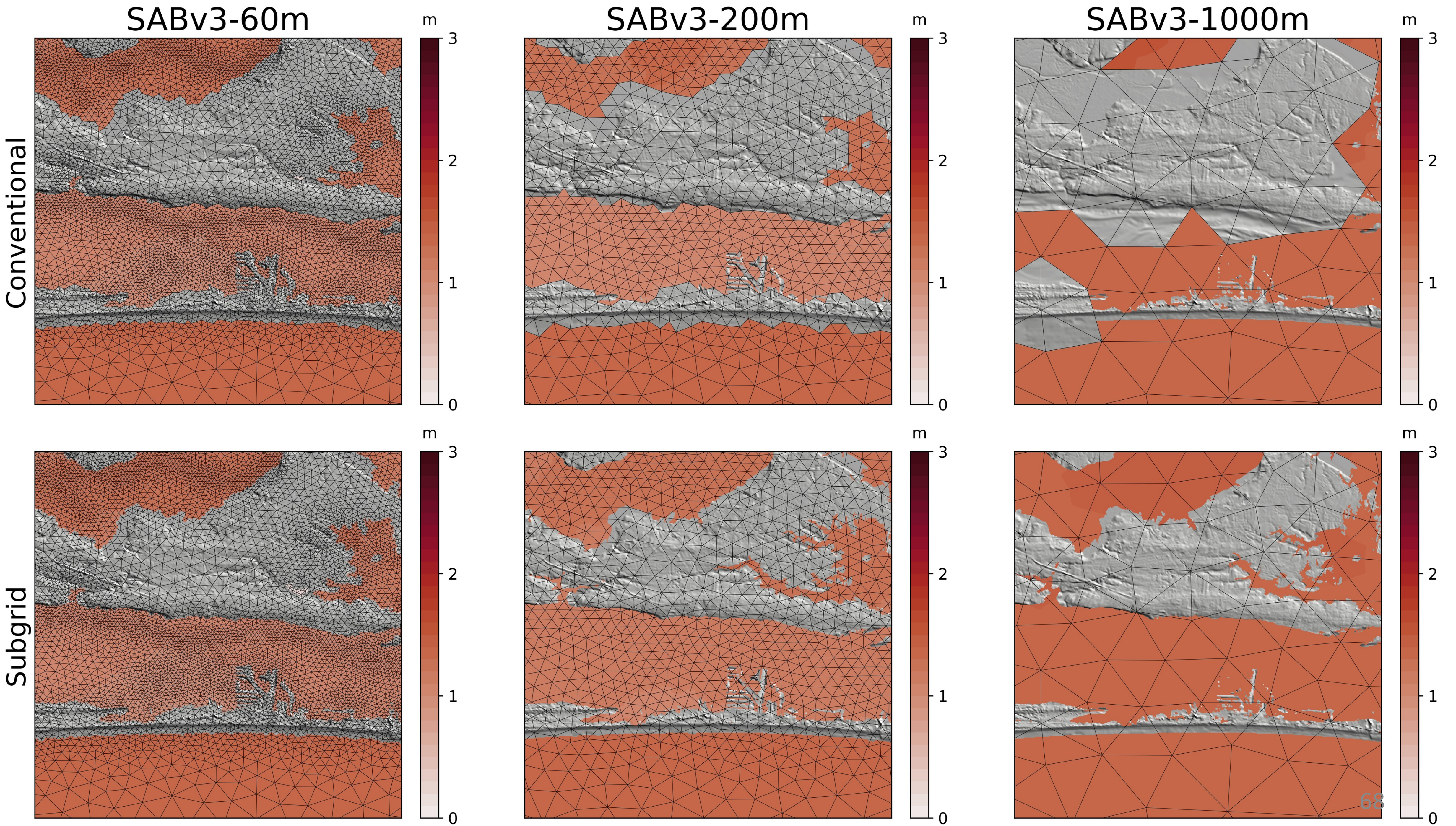

Matthew (2016)
12PM 28 Sep 2016
Windspeed: 50 kt
Category: TS
H5
H4
H3
H2
H1
TS
35°
30°
25°
20°
15°
Latitude
-90°
-80°
-70°
-60°
Longitude
Tiles (C) Esri -- Source: USGS, Esri, TANA, DeLorme, and NPS

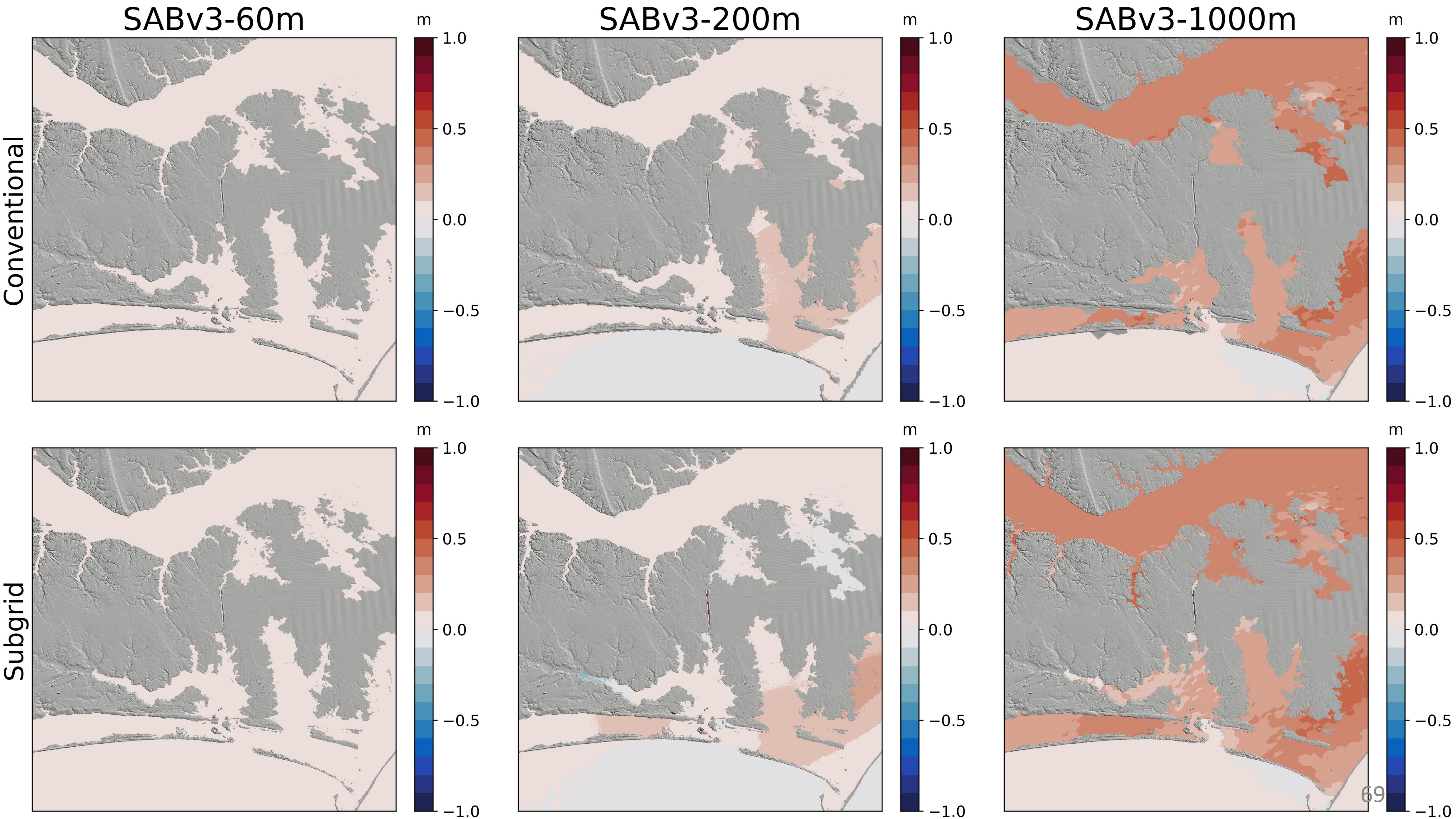


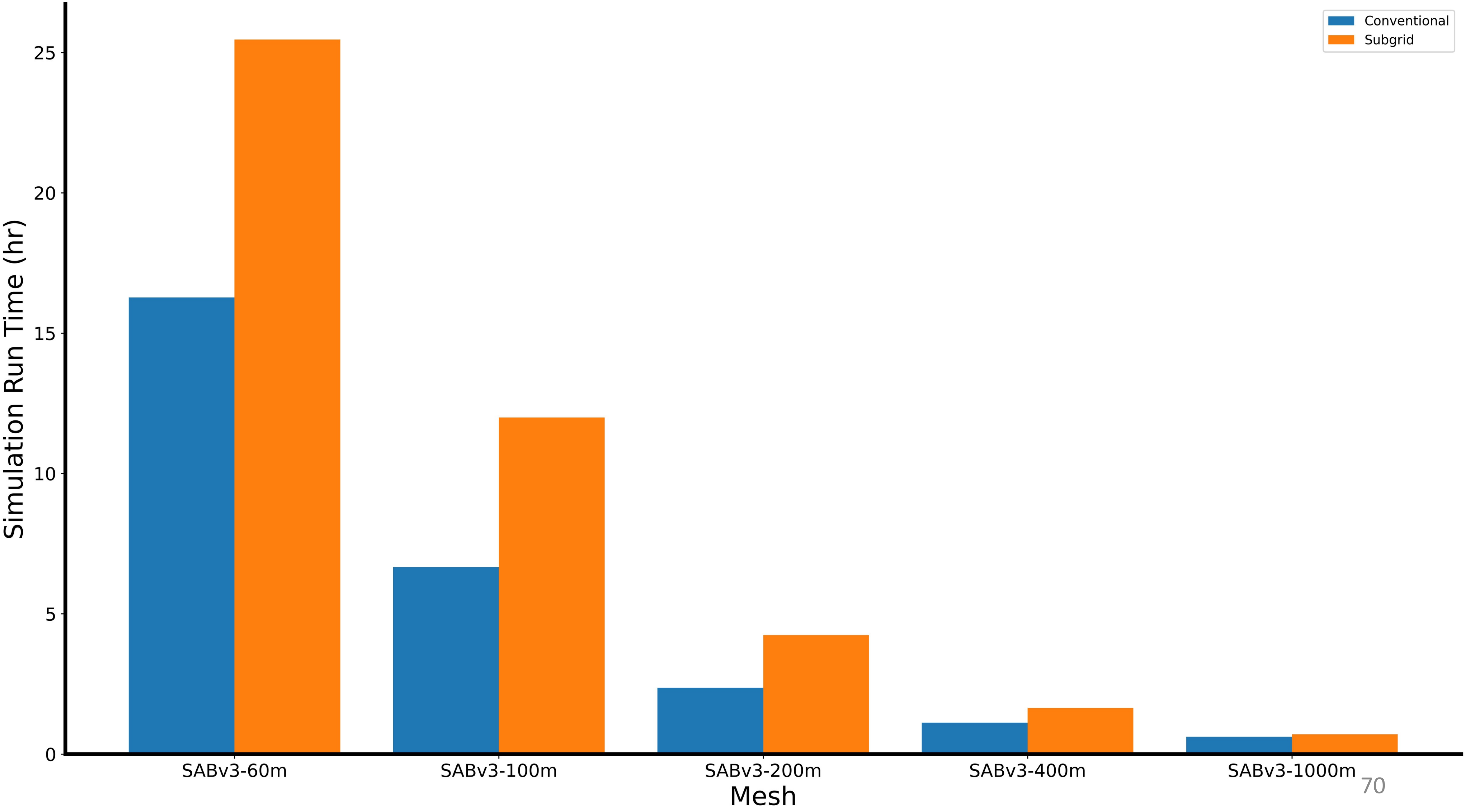
SABv3-60m
SABv3-200m
SABv3-1000m
Conventional
Subgrid
m
3
2
1
0



SABv3-60m
SABv3-200m
SABv3-1000m
Conventional
Subgrid
m
0
1
2
3


SABv3-60m
SABv3-200m
SABv3-1000m
Conventional
Subgrid
m
3
2
1
0

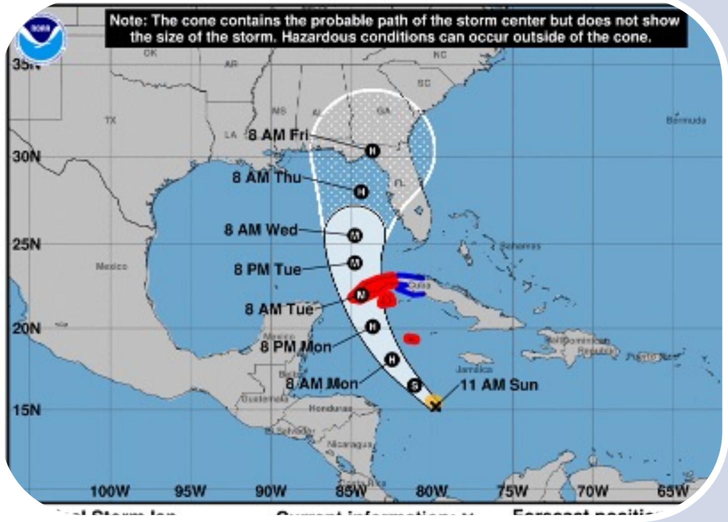

SABv3-60m
SABv3-200m
SABv3-1000m
Conventional
Subgrid
m
1.0
0.5
0.0
−0.5
−1.0


Conventional
Subgrid
Simulation Run Time (hr)
0
5
10
15
20
25
SABv3-60m
SABv3-100m
SABv3-200m
SABv3-400m
SABv3-1000m
Mesh

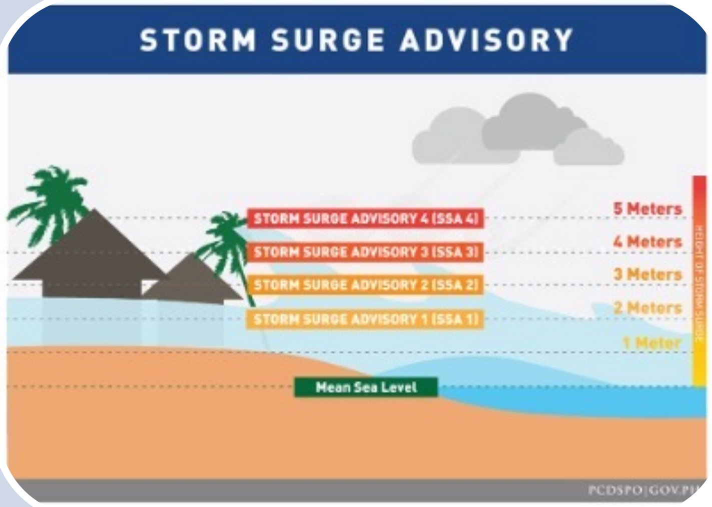
How coarse is too coarse?

- Flow connectivity through unresolved subgrid features is maintained in coarsened subgrid models.
- Flow blocking features constrain the level of coarseness that can be used.
- Resolution constraints depend on the application of the simulation and desired timing.

NHC Issues Storm Track and Intensity update every 6 hours



Reduce storm surge simulation time by running on coarsened meshes



Deliver flood predictions to stakeholders faster

ADCIRC Development Group

Development team for the ADCIRC Model

11 followers · Chapel Hill, North Carolina · http://www.adcirc.org

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Pinned

adcirc-testsuite Public
Test suite derived from examples on ADCIRC.org
Shell · 14 · 13

Repositories

Find a repository... | Type | Language | Sort

MetGet Public
Meteorological forcing acquisition and development system for ADCIRC
Python · 2 · MIT · 2 · 0 · 1 · Updated 19 hours ago

adcirc Private
ADCIRC Model Repository
Fortran · 10 · 46 · 69 (7 issues need help) · 10 · Updated last week

jlwoodr Changed back to previous version ... ca84da4 on Apr 5 · 54 commits

__pycache__	Changed back to previous version	last month
.DS_Store	Changed back to previous version	last month
README.md	Update README.md	8 months ago
subgrid_calculator copy_check.py	Changed back to previous version	last month
subgrid_calculator.py	Changed back to previous version	last month
subgrid_calculator.pyc	add some steps to see what is slowing down the reduction.	4 months ago
subgrid_calculator_old_codes.py	Created fresh .py file	9 months ago
tester.py	Added reduced vertex table	3 months ago

README.md

subgridADCIRCUtility

This set of scripts will create subgrid input files for subgrid enabled ADCIRC.

Example:

The following link will take you to a data repository (need to figure out where to put this) where you will find an example folder containing a text control file and a python script used to call the subgrid calculator for a ADCIRC mesh of Galveston Bay, TX along with several other datafiles needed to perform the subgrid calulations.

Conclusions

1. Learned that subgrid corrections can be a utilized to predict hurricane storm surge.
2. Subgrid storm surge modeling can be expanded to the ocean-scale.
3. There are constraints on how coarse we can make a subgrid storm surge model, but there is still a significant advantage.

Acknowledgements


Thank you!