Development of a Continental Scale Coastal Flood Model Using a Sub-Setting Approach

Henok Kefelegn[1,1], Hassan Mashriqui[2], Js Allen[3], Jason Ducker[3], Ryan Grout[3], Richard Gibbs[3], Julio Zyserman[3], Saeed Moghimi[4], Ali Abdolali[5], Andre Van der Westhuysen[5], Trey Flowers[3], and Edward Clark[3]

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[2]National Oceanic and Atmospheric Administration (NOAA), Office of Water Prediction, National Weather Service (NWS), Silver Spring, United States
[3]NOAA Office of Water Prediction, National Water Center, Tuscaloosa, AL, United States
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[5]NOAA Environmental Modeling Center, College Park, MD, United States

November 30, 2022

Abstract

Coastal flooding associated with hurricanes and other major storm events along the U.S. Coast results from complex interactions between freshwater flows, tides, storm surge, and wave effects. We have developed a two-way coupled model consisting of the National Water Model (NWM), the Advanced Circulation Ocean Model (ADCIRC), and WAVEWATCH III (WWIII) to quantify these interactions and compute total water levels in the coastal zone after significant riverine and coastal flooding events. This coupled continental coastal model covers the US Gulf and Atlantic Coasts, extending from the US-Canada border to the US-Mexico border. The Delft3D FM, D-Flow Flexible Mesh (D-Flow FM) model simulates coastal flooding on a 2D unstructured mesh within the National Water Model (NWM)/ADCIRC/WWIII coupled system. We developed a high quality 2D unstructured mesh using a sizing function that assigns element sizes based on proximities of coastal features at given spatial locations. Data sources used to identify relevant coastal features included NWM streamlines, the National Hydrography Dataset (NHD), and United States Army Corps of Engineers (USACE) data, allowing integration of D-Flow FM with the NWM and optimization of the number of computational points. The system obtains freshwater inflow boundary conditions to D-Flow FM from the NWM channel network. Offshore water levels boundary conditions for D-Flow FM come from the coupled ADCIRC-WWIII model. Domain sub-setting keeps runtimes within reasonable limits, as it does execution of the detailed hydrodynamic model within a user-defined area enclosing the storm landfall site. The advantage of this approach comes from the fact that the same coupled model setup allows simulation of coastal flooding for different storm events; only the sub-setting enclosure and the atmospheric forcing require updating from case to case. Model validation, consisting of water level comparisons against observations from simulations using the coupled system for historical storm events. The model simulations satisfactorily reproduced observed spatial and temporal variations of total water levels. In conclusion, this study presents performance of the sub-setting approach in reducing runtime considerably without compromising the accuracy of the coupled modeling system solution.

H45N

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[1]NOAA Office of Water Prediction, Silver Spring, MD, [2]NOAA Office of Water Prediction, National Water Center, [3]NOAA Coast Survey Development Laboratory, [4]NOAA Environmental Modeling

INTRODUCTION

PROBLEMS

SOLUTIONS

RGFGRID
- ☐ Not efficient
- ☐ Mostly manual
- ☐ Orthogonality

Regional Models
- ☐ Difficult to manage
- ☐ Coverage

New Mesh Generation Method

GOAL
- ☐ Efficiency
- ☐ Accuracy
- ☐ Flexibility

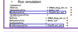
Continental Scale: Sub Modeling Approach

GOAL
- ☐ Develop a parent domain (Continental Model)
- ☐ Model any child domain with almost the same effort
- ☐ Same input files

SUB-SETTING APPROACH

Objective
- Optimize run times
- To develop a parent domain and multiple child domains with almost the same effort.
- To adaptively move child domain boundaries (allows dynamic behavior).
- Same boundary locations.

Workflow
- Determine spatial extent of child domain.
- Update MDU file with the child domain information.
- Preprocess boundary condition files.
- Run simulation

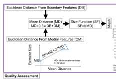


Implication
- A parent grid that spans Mexico-Canada border.
- Running simulation only for part of the grid!

Benefits
- Easiness and simplicity.
- Speeds up simulation time.
- Avoids a storm hitting at junction of static domains.
- Flexibility with spatial extent of child domain.

Subdomain Modeling: Enables assessment of local domains without requiring a full scale simulation (Baugh et al., 2015)

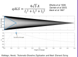
MESH GENERATION METHOD



Quality Assessment

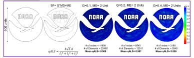
$$qALS = \frac{4\sqrt{3}A}{l_1^2 + l_2^2 + l_3^2}$$

Bhatia et al 1998; Sarrate et al 2003; Back et al 1997



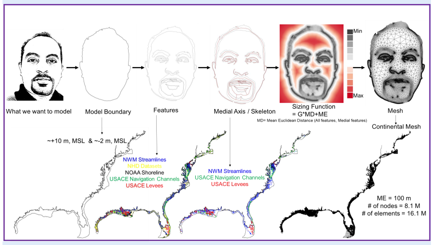
Kefelegn, Henok, "Automatic Shoreline Digitization and Mesh Element Sizing for Hydrodynamic Modeling" (2020). LSU Doctoral Dissertations. 5133. https://digitalcommons.lsu.edu/gradschool_dissertations/5133

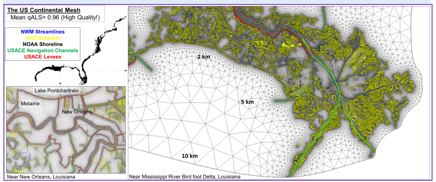
Quality Assessment



$$qALS = \frac{4\sqrt{3}A}{l_1^2 + l_2^2 + l_3^2}$$

Our methods, mesh generation and sub-setting approach, improve runtimes by up to 200 times.





Near New Orleans, Louisiana

Near Mississippi River Bird foot Delta, Louisiana

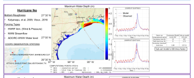
APPLICATION: MODEL RUNS

Hurricane Ike

Bottom Roughness
- Kalyanapu, et al, 2009, Vieux., 2016

Forcing Types
- HWRF Atm. (Wind & Pressure)
- NWM Streamflow
- ADCIRC-WWIII Water level

COOPS OBSERVATION STATIONS



Sub-set model is 68 times faster.

Hurricane Irma

Bottom Roughness
- Kalyanapu, et al, 2009, Vieux., 2016

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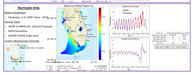

Sub-set model is 217 times faster.

Hurricane Florence

Bottom Roughness
- Kalyanapu, et al, 2009, Vieux., 201

Forcing Types
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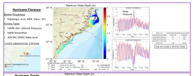

Sub-set model is 18 times faster.

Hurricane Sandy

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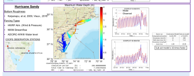

Sub-set model is 16 times faster.

CONCLUSIONS

- Developed a high quality 2D unstructured mesh using a sizing function that assigns element sizes based on proximities of coastal features at given spatial locations.
- Developed continental domain model that covers the US Gulf and Atlantic Coasts, extending from the US-Canada border to the US-Mexico border.
- Domain sub-setting reduces runtimes significantly without loss of accuracy.

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OWP OFFICE OF WATER PREDICTION

Lynker

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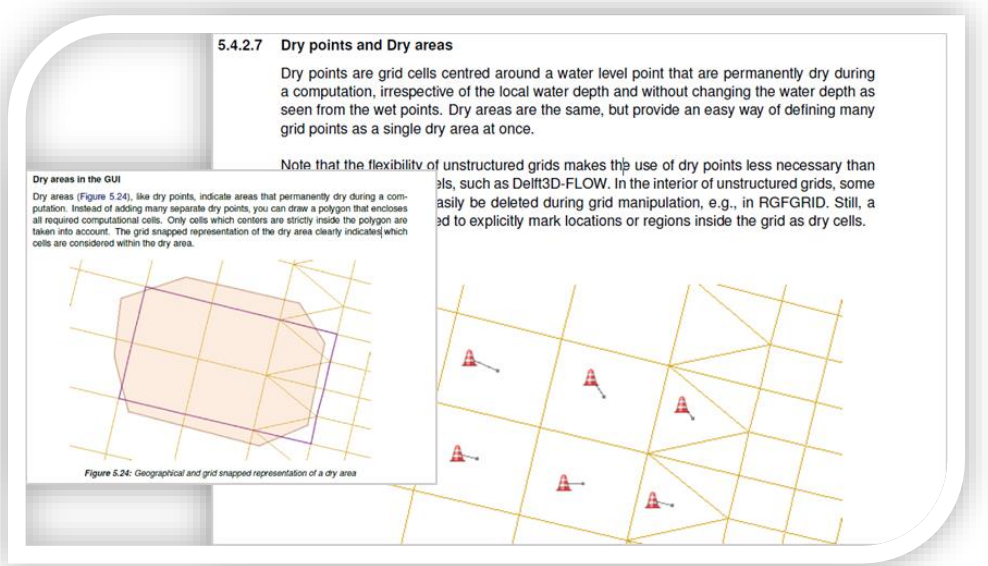
```
[geometry]
NetFile                          = SF0p4_Geog_net.nc    #
BathymetryFile                   = Bathy.xyb            #
DryPointsFile                    = FlowFM_dry.pol       #
GridEnclosureFile                =                      #
NetFile                          = SF0p4_Geog_net.nc #
BathymetryFile                   = Bathy.xyb         #
DryPointsFile                    =                   #
GridEnclosureFile                = FlowFM_enc.pol    #
```



5.4.2.7 Dry points and Dry areas

Dry points are grid cells centred around a water level point that are permanently dry during a computation, irrespective of the local water depth and without changing the water depth as seen from the wet points. Dry areas are the same, but provide an easy way of defining many grid points as a single dry area at once.

Note that the flexibility of unstructured grids makes the use of dry points less necessary than …els, such as Delft3D-FLOW. In the interior of unstructured grids, some …asily be deleted during grid manipulation, e.g., in RGFGRID. Still, a …ed to explicitly mark locations or regions inside the grid as dry cells.

Dry areas in the GUI

Dry areas (Figure 5.24), like dry points, indicate areas that permanently dry during a computation. Instead of adding many separate dry points, you can draw a polygon that encloses all required computational cells. Only cells which centers are strictly inside the polygon are taken into account. The grid snapped representation of the dry area clearly indicates which cells are considered within the dry area.

Figure 5.24: Geographical and grid snapped representation of a dry area

Implication
- A parent grid that spans Mexico-Canada border.
- Running simulation only for part of the grid!

Benefits
- Easiness and simplicity.
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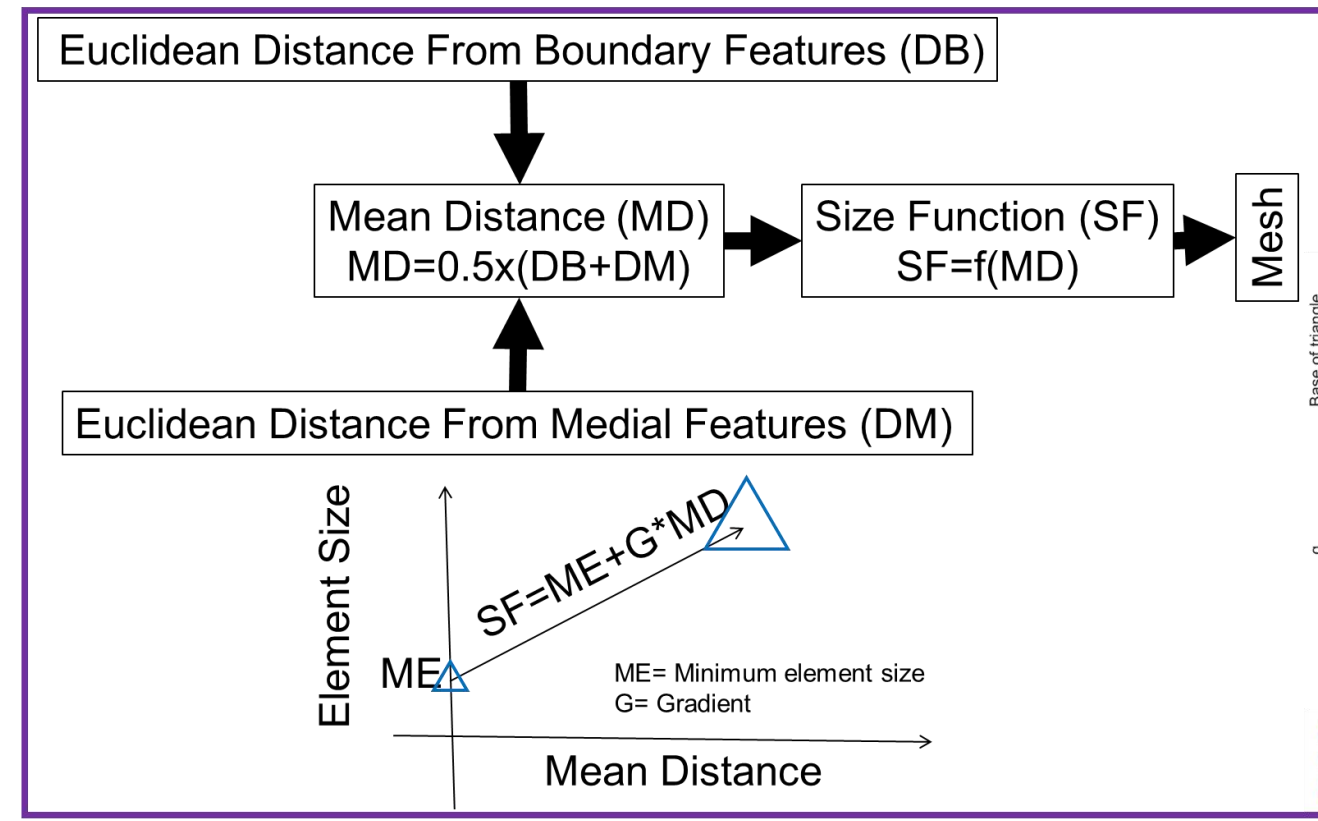
- Flexibility with spatial extent of child domain.

Subdomain Modeling: Enables assessment of local domains without requiring a full scale simulation (Baugh et al., 2015)

MESH GENERATION METHOD



Euclidean Distance From Boundary Features (DB)

Mean Distance (MD)
MD=0.5x(DB+DM)

Size Function (SF)
SF=f(MD)

Mesh

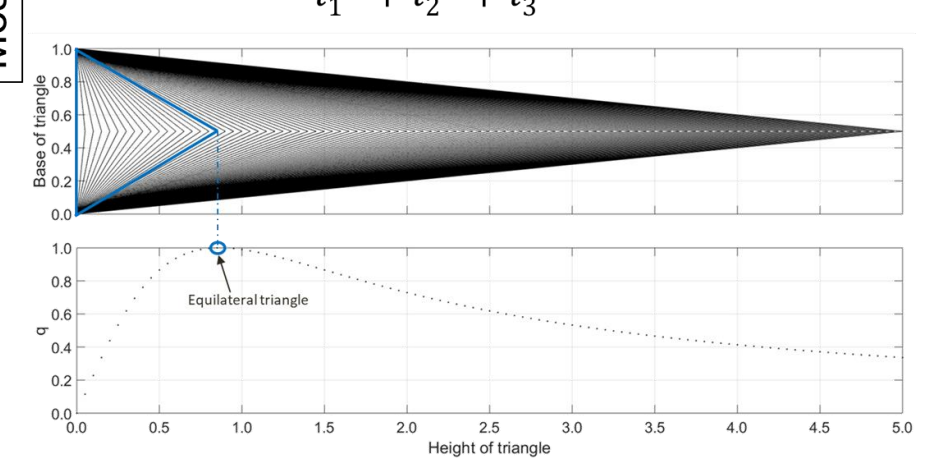
Euclidean Distance From Medial Features (DM)

ME= Minimum element size
G= Gradient

Quality Assessment

$$qALS = \frac{4\sqrt{3}\,A}{{l_1}^2 + {l_2}^2 + {l_3}^2}$$

Bhatia et al 1990; Sarrate et al 2003; Bank et al 1997



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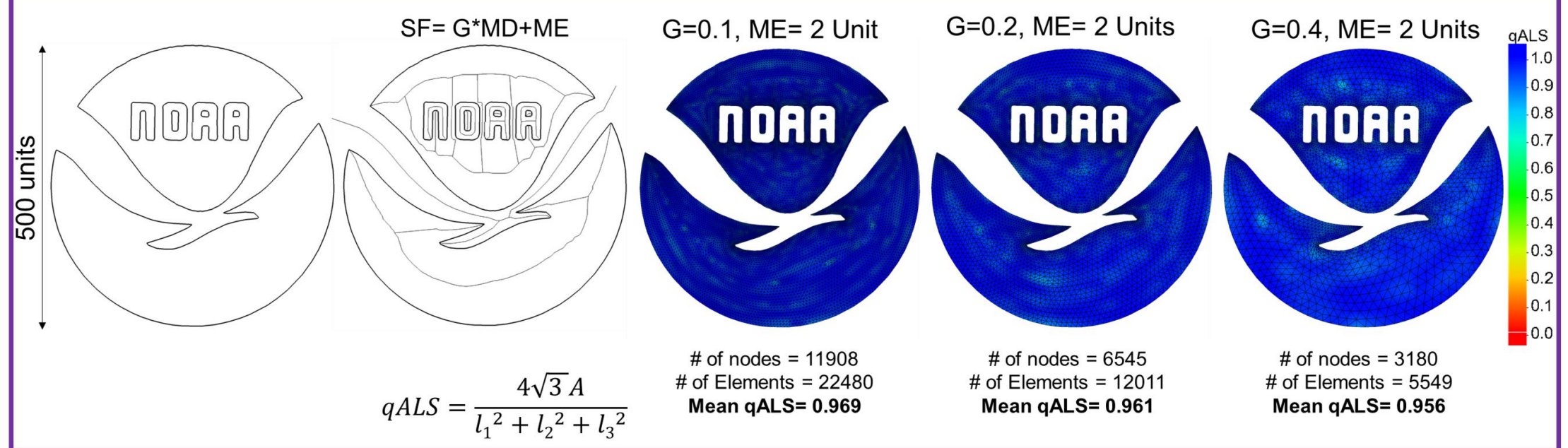
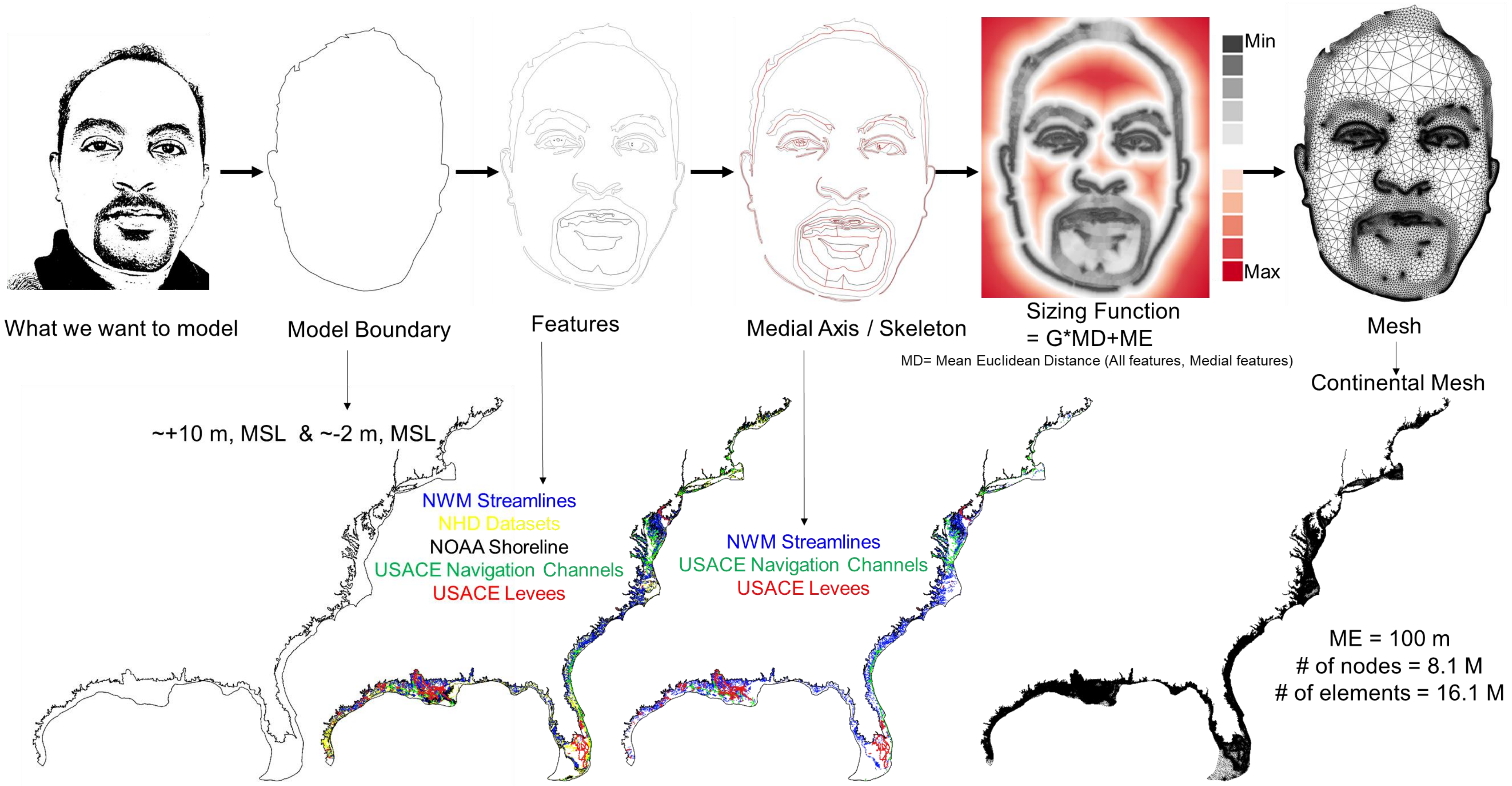
Quality Assessment



$$qALS = \frac{4\sqrt{3}\,A}{{l_1}^2 + {l_2}^2 + {l_3}^2}$$

G=0.1, ME= 2 Unit	G=0.2, ME= 2 Units	G=0.4, ME= 2 Units
# of nodes = 11908	# of nodes = 6545	# of nodes = 3180
# of Elements = 22480	# of Elements = 12011	# of Elements = 5549
Mean qALS= 0.969	**Mean qALS= 0.961**	**Mean qALS= 0.956**

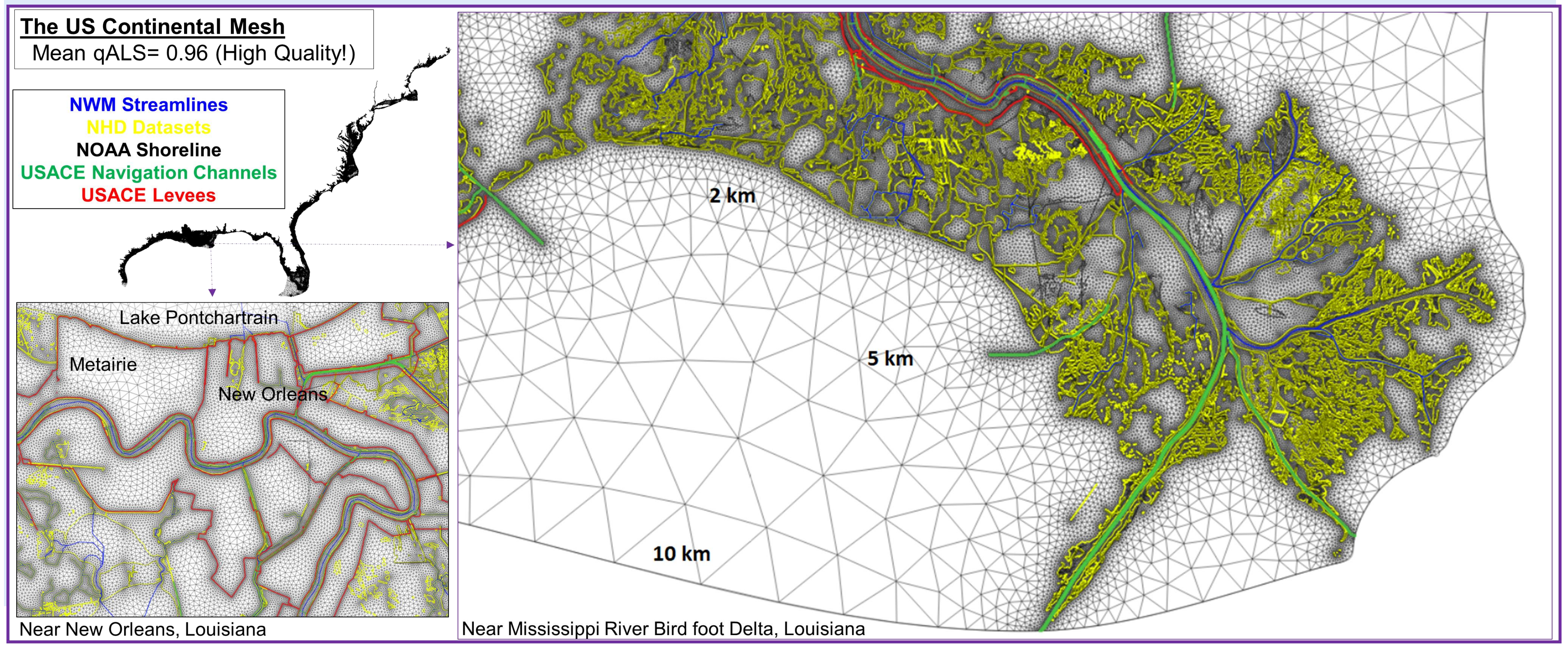
Our methods, mesh generation and sub-setting approach, improve runtimes by up to 200 times.



MD= Mean Euclidean Distance (All features, Medial features)

ME = 100 m
# of nodes = 8.1 M
# of elements = 16.1 M

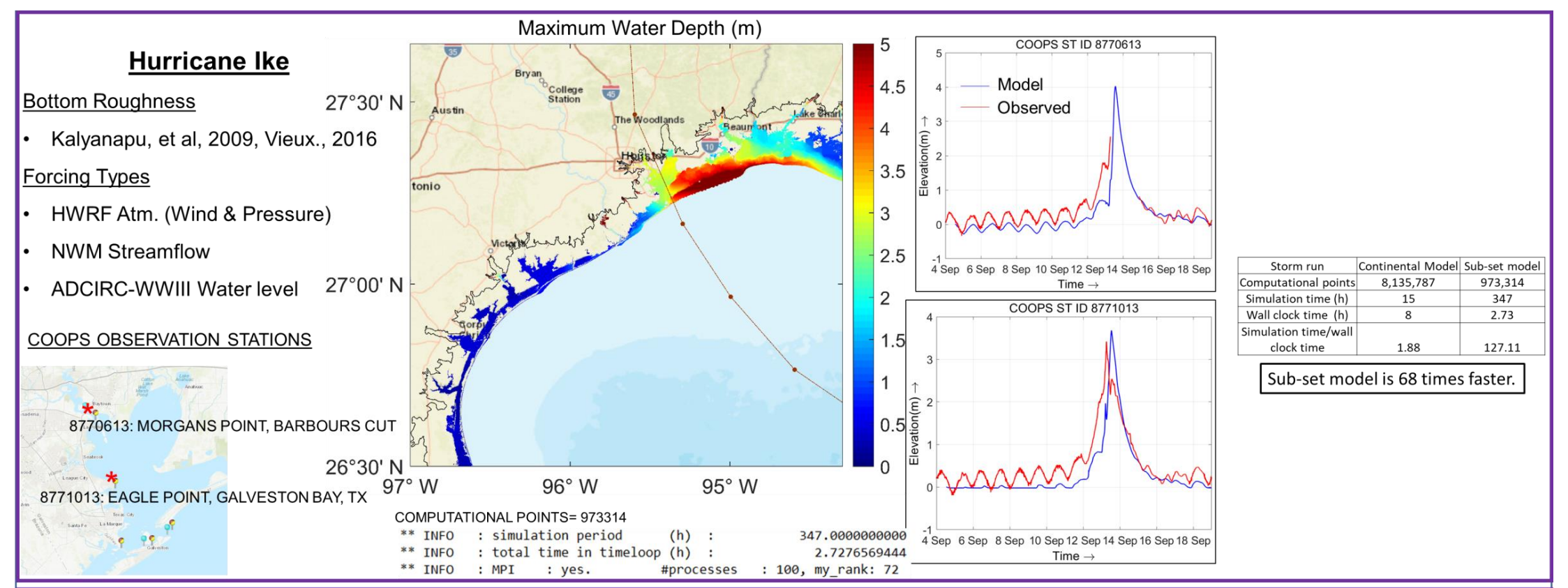
The US Continental Mesh
Mean qALS= 0.96 (High Quality!)



Near New Orleans, Louisiana

Near Mississippi River Bird foot Delta, Louisiana

APPLICATION: MODEL RUNS



Hurricane Ike

Bottom Roughness
- Kalyanapu, et al, 2009, Vieux., 2016

Forcing Types
- HWRF Atm. (Wind & Pressure)
- NWM Streamflow
- ADCIRC-WWIII Water level

COOPS OBSERVATION STATIONS

8770613: MORGANS POINT, BARBOURS CUT

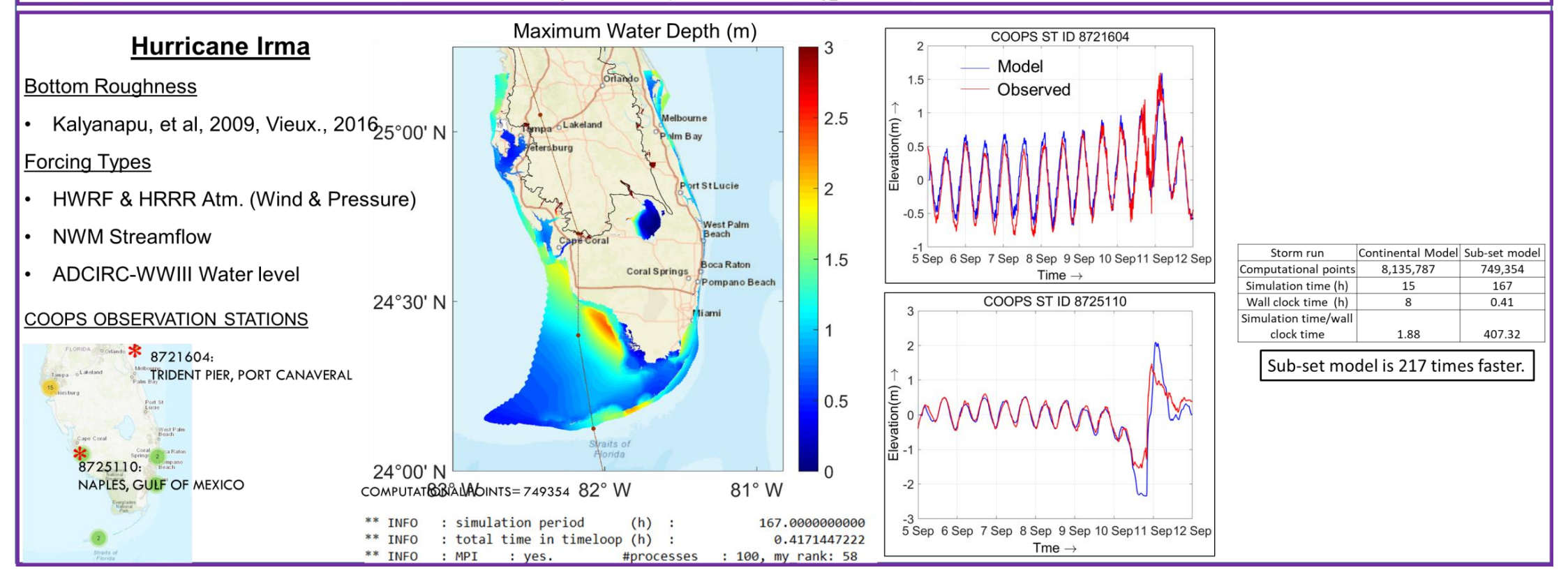
8771013: EAGLE POINT, GALVESTON BAY, TX

COMPUTATIONAL POINTS= 973314

```
** INFO   : simulation period      (h)  :        347.0000000000
** INFO   : total time in timeloop (h)  :          2.7276569444
** INFO   : MPI    : yes.        #processes    : 100, my_rank: 72
```

Storm run	Continental Model	Sub-set model
Computational points	8,135,787	973,314
Simulation time (h)	15	347
Wall clock time (h)	8	2.73
Simulation time/wall clock time	1.88	127.11

Sub-set model is 68 times faster.



Hurricane Irma

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- Kalyanapu, et al, 2009, Vieux., 2016

Forcing Types
- HWRF & HRRR Atm. (Wind & Pressure)
- NWM Streamflow
- ADCIRC-WWIII Water level

COOPS OBSERVATION STATIONS

8721604: TRIDENT PIER, PORT CANAVERAL

8725110: NAPLES, GULF OF MEXICO

COMPUTATIONAL POINTS= 749354

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** INFO   : simulation period      (h)  :        167.0000000000
** INFO   : total time in timeloop (h)  :          0.4171447222
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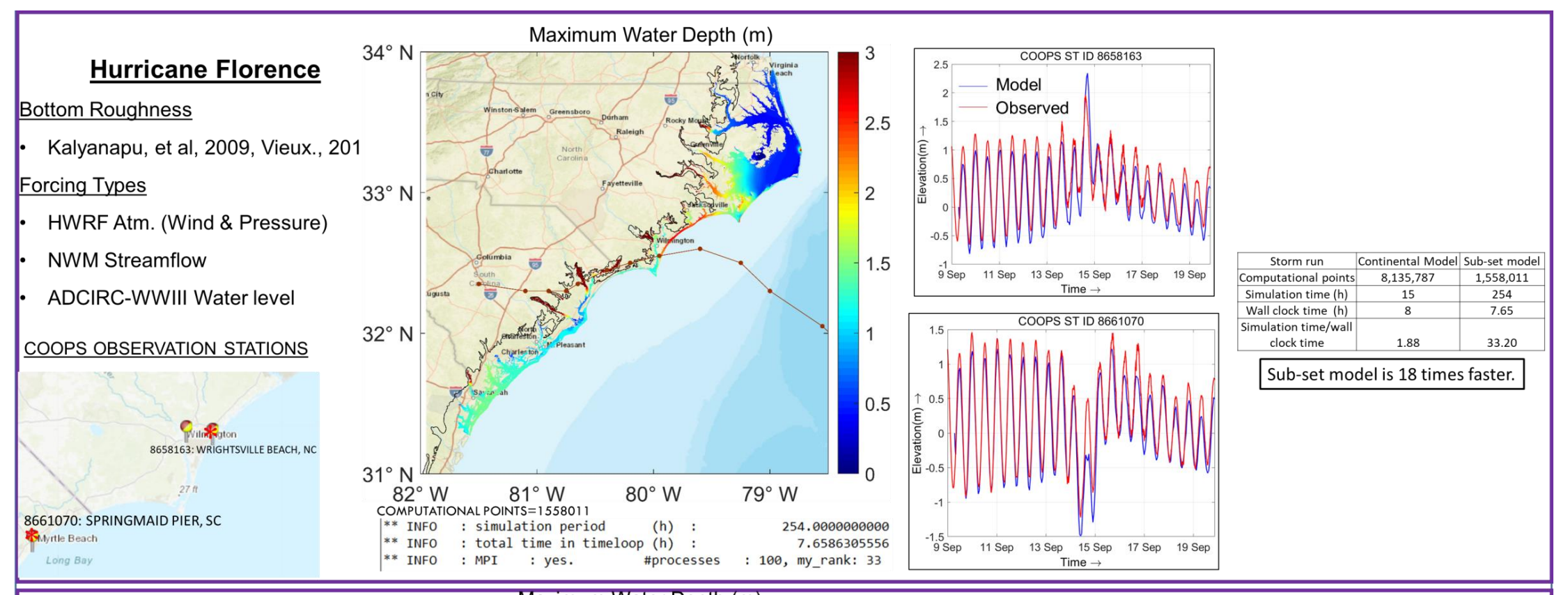
Storm run	Continental Model	Sub-set model
Computational points	8,135,787	749,354
Simulation time (h)	15	167
Wall clock time (h)	8	0.41
Simulation time/wall clock time	1.88	407.32

Sub-set model is 217 times faster.



Hurricane Florence

Bottom Roughness
- Kalyanapu, et al, 2009, Vieux., 201

Forcing Types
- HWRF Atm. (Wind & Pressure)
- NWM Streamflow
- ADCIRC-WWIII Water level

COOPS OBSERVATION STATIONS

8658163: WRIGHTSVILLE BEACH, NC

8661070: SPRINGMAID PIER, SC

COMPUTATIONAL POINTS=1558011

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** INFO   : simulation period      (h)  :        254.0000000000
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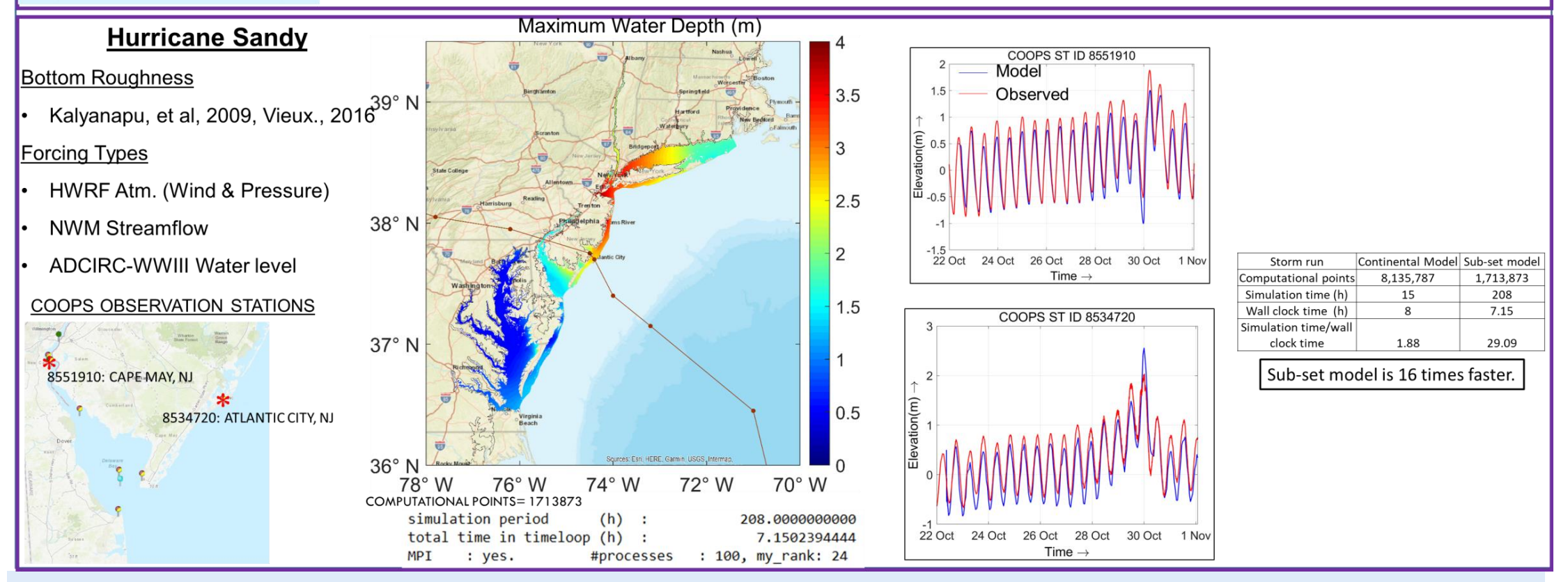
Storm run	Continental Model	Sub-set model
Computational points	8,135,787	1,558,011
Simulation time (h)	15	254
Wall clock time (h)	8	7.65
Simulation time/wall clock time	1.88	33.20

Sub-set model is 18 times faster.



Hurricane Sandy

Bottom Roughness
- Kalyanapu, et al, 2009, Vieux., 2016

Forcing Types
- HWRF Atm. (Wind & Pressure)
- NWM Streamflow
- ADCIRC-WWIII Water level

COOPS OBSERVATION STATIONS

8551910: CAPE MAY, NJ

8534720: ATLANTIC CITY, NJ

COMPUTATIONAL POINTS= 1713873

```
simulation period      (h)  :        208.0000000000
total time in timeloop (h)  :          7.1502394444
MPI    : yes.        #processes    : 100, my_rank: 24
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Storm run	Continental Model	Sub-set model
Computational points	8,135,787	1,713,873
Simulation time (h)	15	208
Wall clock time (h)	8	7.15
Simulation time/wall clock time	1.88	29.09

Sub-set model is 16 times faster.

CONCLUSIONS

- Developed a high quality 2D unstructured mesh using a sizing function that assigns element sizes based on proximities of coastal features at given spatial locations.
- Developed continental domain model that covers the US Gulf and Atlantic Coasts, extending from the US-Canada border to the US-Mexico border.
- Domain sub-setting reduces runtimes significantly without loss of accuracy.

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