Identifying the Earliest Signs of Storm Impacts to Improve Hurricane Flooding Forecasts

M.S. Thesis Defense

6/21/21

Autumn Poisson

COASTAL RESILIENCE CENTER

A U.S. Department of Homeland Security Center of Excellence

NC STATE UNIVERSITY

Acknowledgements

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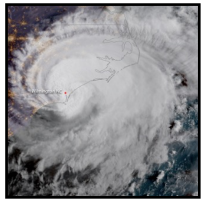
[2]Center for Geospatial Analytics, North Carolina State University, Raleigh, NC
[3]Seahorse Coastal Consulting, LLC, Morehead City, NC

About Me

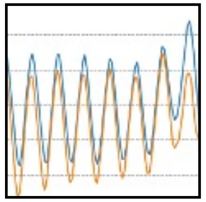
- From Grand Rapids, Michigan
- Attended the University of Michigan
  - B.S. Environmental Science in 2011
  - M.S. Ecology in 2014
- Fun Facts:
  - Worked in natural resources, environmental education and project management
  - Competed in Olympic Weightlifting
  - Lived on small island in the Pacific Ocean (Rota, MP)

Outline

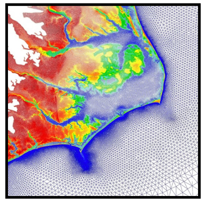
Introduction



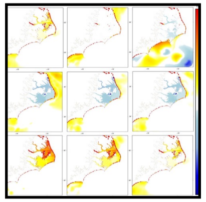
Background and
Previous Work



Motivation and
Remaining Questions



Methods



Results

Discussion

Conclusions and
Future Work

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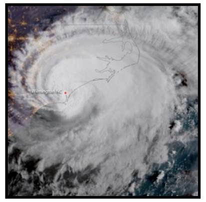

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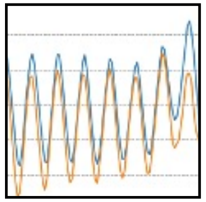

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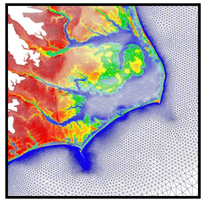

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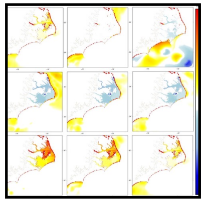

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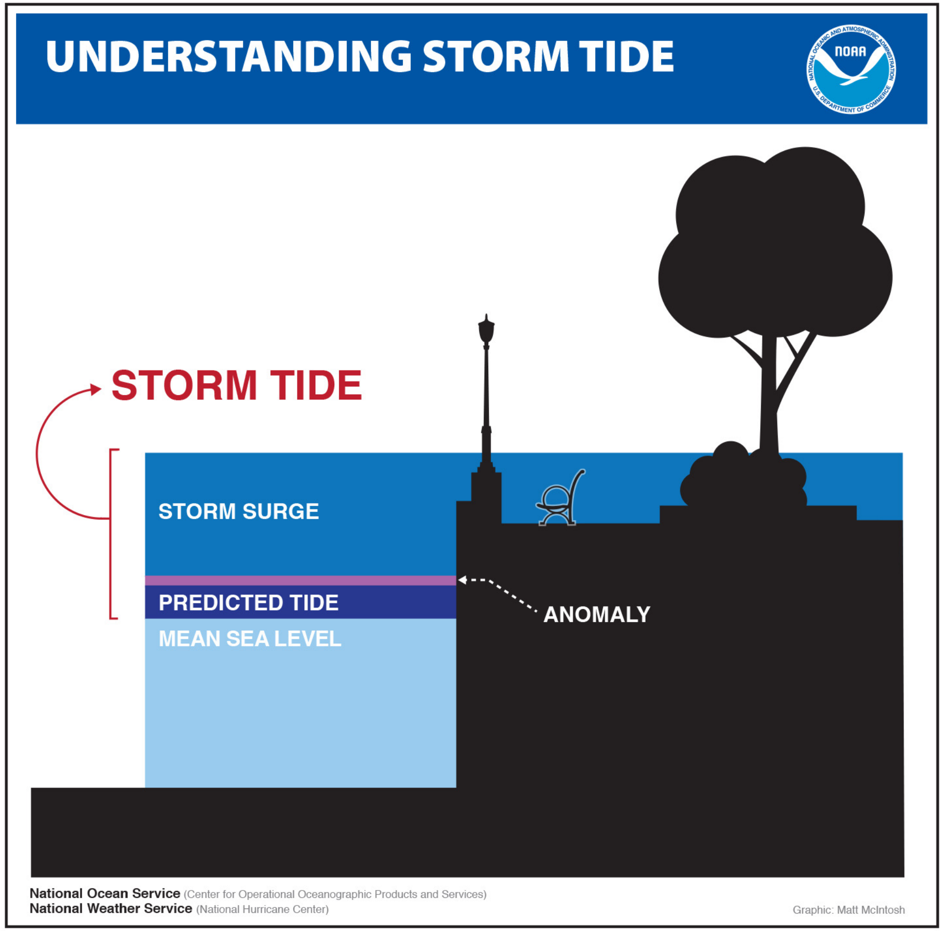
Storm Surge

- The rise in water levels above normally occurring tides caused by storm forces
- Leading to flooding, and damage and destruction of both life and property
- Most dangerous component of a hurricane causing close to 50% of storm related deaths



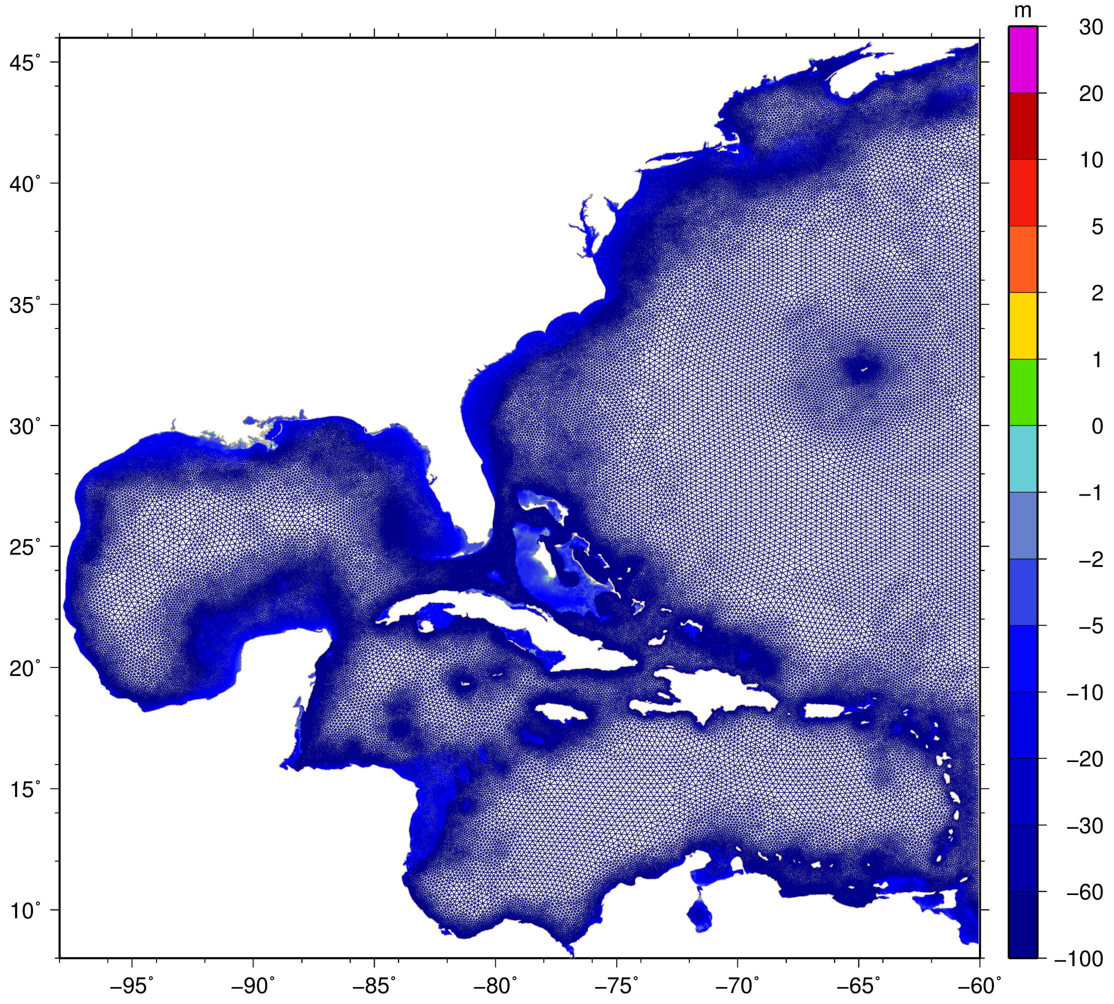
Importance of Storm Surge Prediction

- Close to 40% of the US population lives in coastal shoreline counties
- Storm intensity increasing in recent years
- Need to know when and where and how long flooding will occur

Galveston Island, Hurricane Ike (Source: Houston Chronicle)

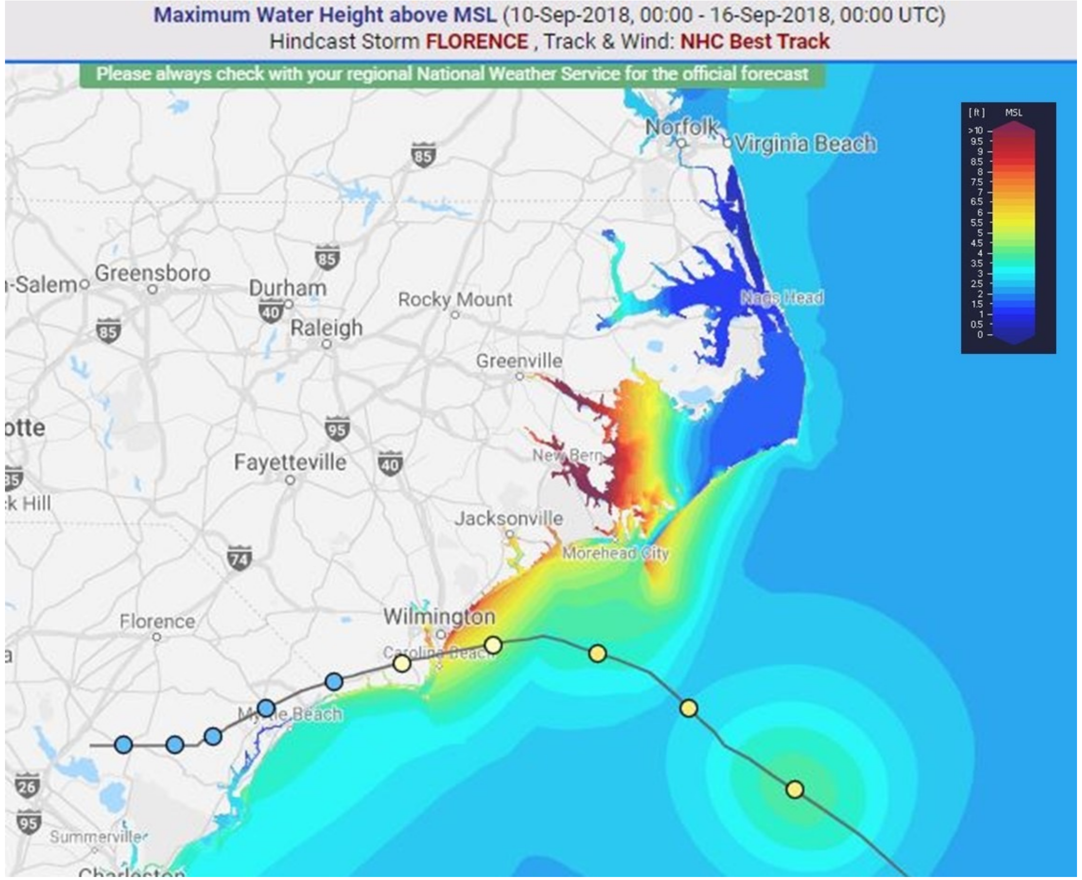
ADCIRC

- ADvanced CIRCulation
- Finite-element model that solves the 2D, depth-integrated, shallow water equations for conservation of mass and momentum
- Unstructured meshes represent the domain with varying levels of resolution
- Used for both forecasting and hindcasting storms



ADCIRC Prediction System (APS)

- Supports real-time forecasting of ADCIRC through an automated system
- Hurricane Florence: ran advisories 46-68
  - Several included ensemble members with 50% track veer left and right
- Results shared with emergency managers, stakeholders, and general public



Fleming et al. 2007

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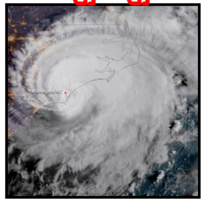

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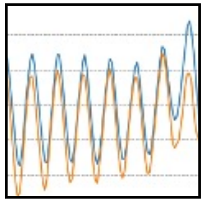

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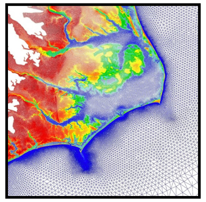

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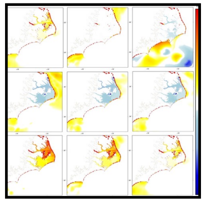

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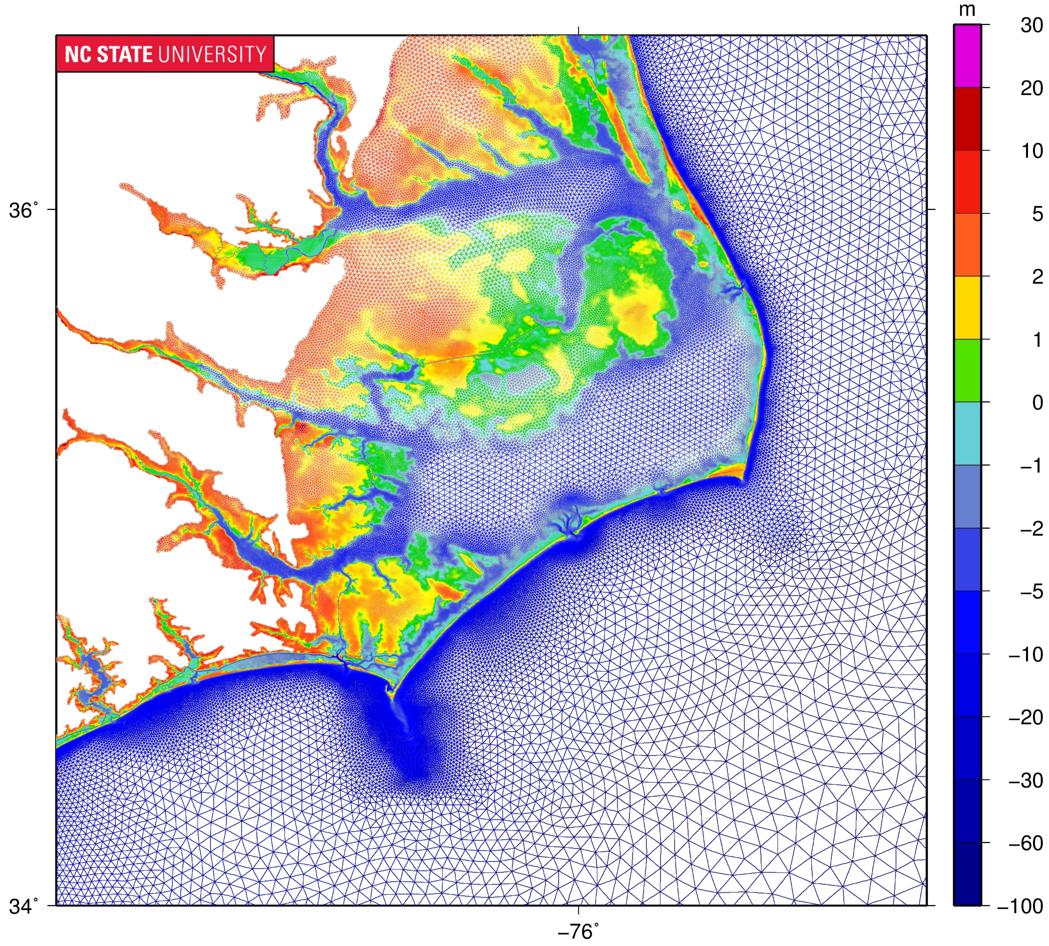
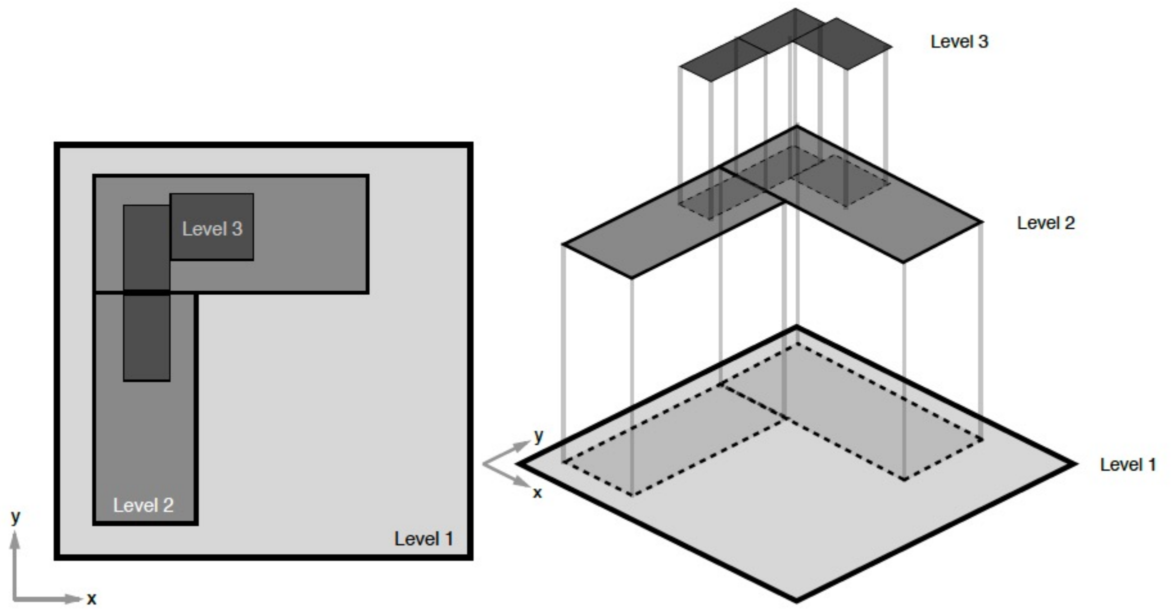
Background

- Real-time predictions finding balance between efficiency and accuracy
- Storm surge modeling involves many phases and scales
  - Open ocean
  - Propagation into nearshore
  - Inundation of coastal region
  - Impact on coastal structures
- High-resolution meshes include millions of nodes, some which never wet



Existing Methods for Adaptive Resolution

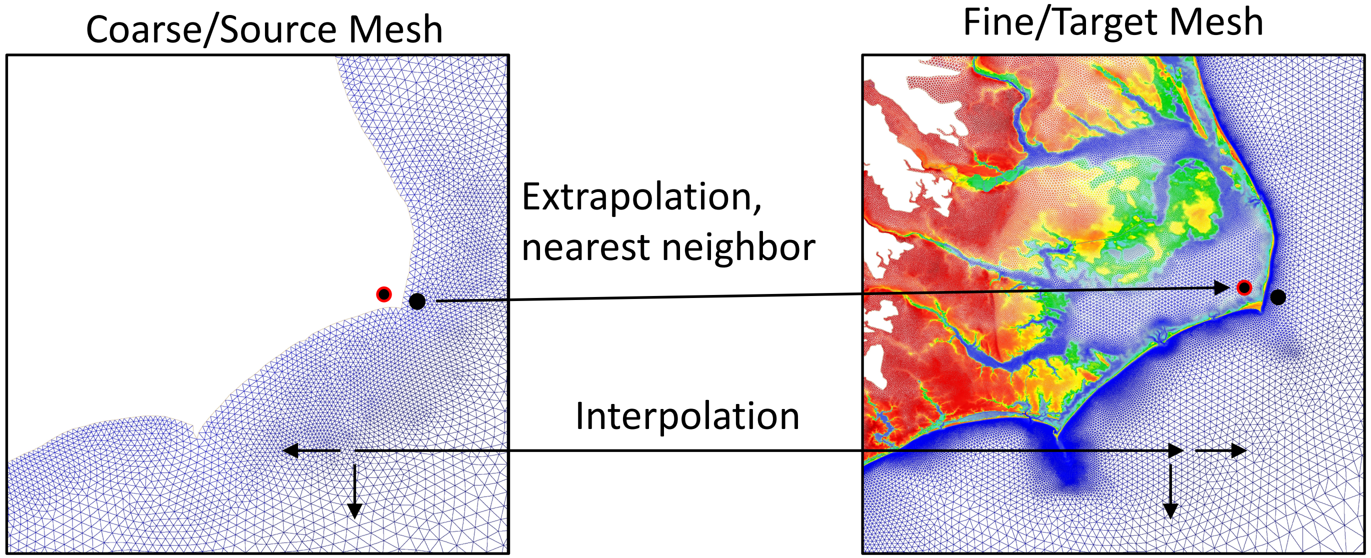
- Increase cell resolution during a simulation or using nested meshes
- Reduce computational costs of storm surge model simulation
- Allows for ensemble predictions
- Refinement occurs when water level or water currents reach given threshold, cell distance from storm eye, storm intensity and wind speeds, etc.



Mandli & Dawson 2014, Qin et. al 2019

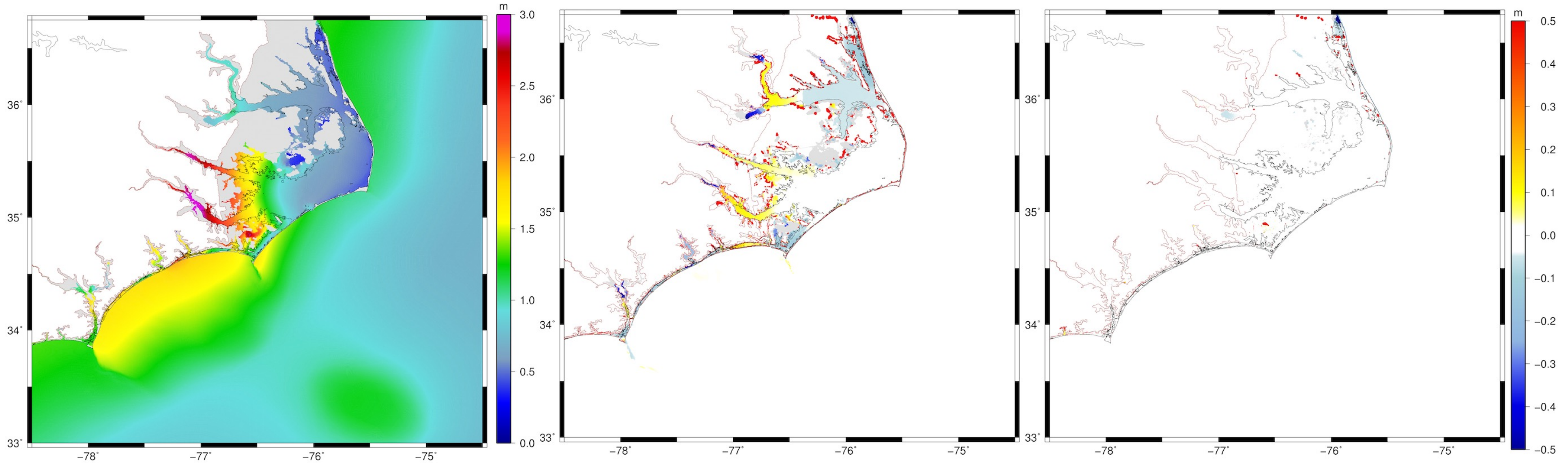
Adcirpolate

- A toolset for parallel interpolation between unstructured meshes
- Developed by collaborators at U.T. Austin
- Implemented via the Earth System Modeling Framework (ESMF)
- Proper checks to take care of wetting/drying state of elements
- Convert a binary localized hot-start file from the coarse mesh simulation to a binary globalized hot-start file for the fine mesh simulation



Previous Work

- Use a relatively coarse resolution (HSOFS ~400m) initially, 3 days
- As storm approaches coastline and starts to affect water levels along the coast, 0000 UTC 13 September, switch to fine-resolution mesh (FEMA-SAB) remaining 6 days, **without doing a cold-start**
- Map results from coarse to fine mesh using *Adcirpolate* and continue simulation on fine mesh
- The Mixed approach retains the accuracy of the *Fine* (FEMA-SAB) results and a 53% save in time



Florence max water levels from Fine (left), difference between HSOFS and FEMA-SAB simulation (middle), and difference between FEMA-SAB and mixed simulation (right) (Thomas et al. 2021)

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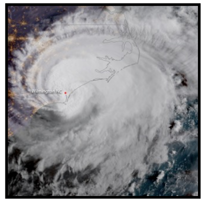

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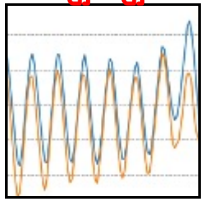

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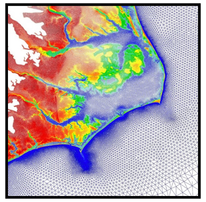

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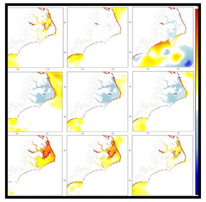

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Motivation

What we know:

- Need for higher mesh resolution in coastal regions of interest
- Improve the efficiency of flooding predictions in real-time
- Multi-resolution approach shows promise with increased efficiency and maintenance of accuracy

What we hope to learn:

- When and why do we switch?
- How long to run on coarse vs. fine mesh?
- When are storm effects seen at the coast?

Hypothesis

It is hypothesized that, if the trigger is selected as the earliest sign of high winds or water levels, then the simulation will maintain its accuracy during the storm while receiving an efficiency boost before the storm.

- Triggers: elevated coastal and inland water levels and wind speeds
- Meshes: EC2001 (~250K nodes), NC9 (~620K nodes)
- Storm: Hurricane Florence

Goal and Objectives

- **Goal**
  - Understand which storm variable(s) is(are) the most important triggers for determining when to switch mesh resolutions during a forecast
- **Objectives**
  - Evaluate simulations on coarse mesh, fine mesh, and mixed meshes
  - Determine storm effects on parameters of wind speeds, coastal water levels, and inland water levels and select trigger values from the different parameters (i.e. 0.3, 0.4 and 0.5 m elevated water levels)
  - Use a two-part (coarse/EC2001 and fine/NC9) simulation for Florence to test efficiency gains comparing to high-resolution simulation
  - Quantify accuracy with comparison to a single high-resolution Florence simulation as well as to real-time observation data

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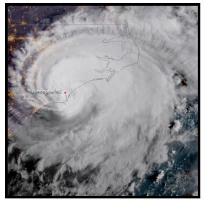

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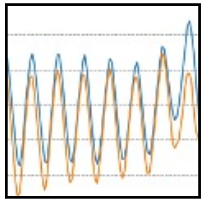

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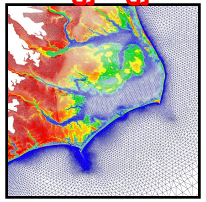

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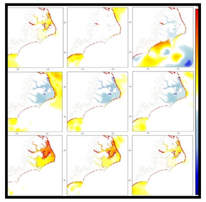

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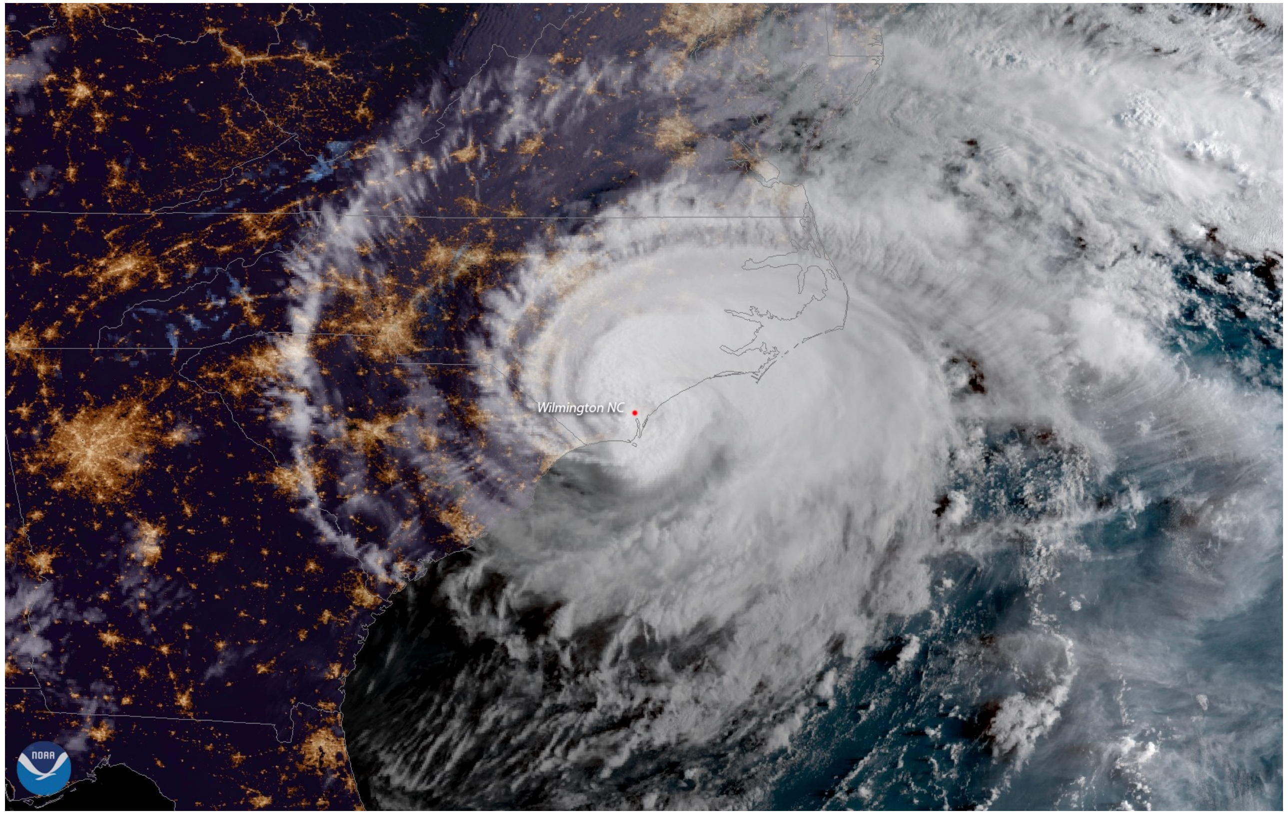
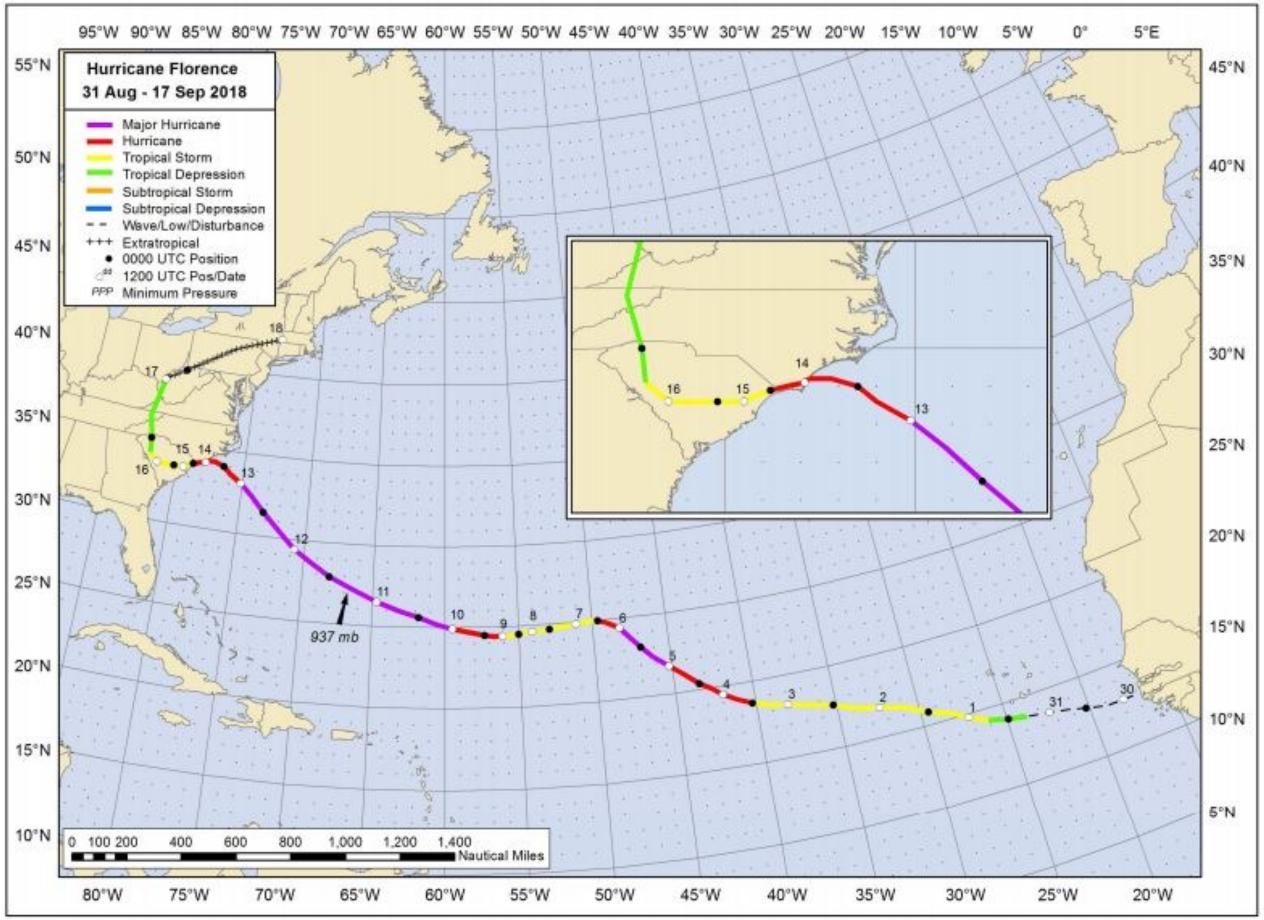
Hurricane Florence

- Landfall September 14th, 2018, at 1115 UTC (7:15 am EDT) near Wrightsville Beach, NC
- Reached peak category 4, made landfall as category 1
- Wind speeds at landfall: 40 m/s
- Rainfall exceeded 1 m in some regions
- Inundation up to 3 m along Neuse River and above 2 m near Pamlico River



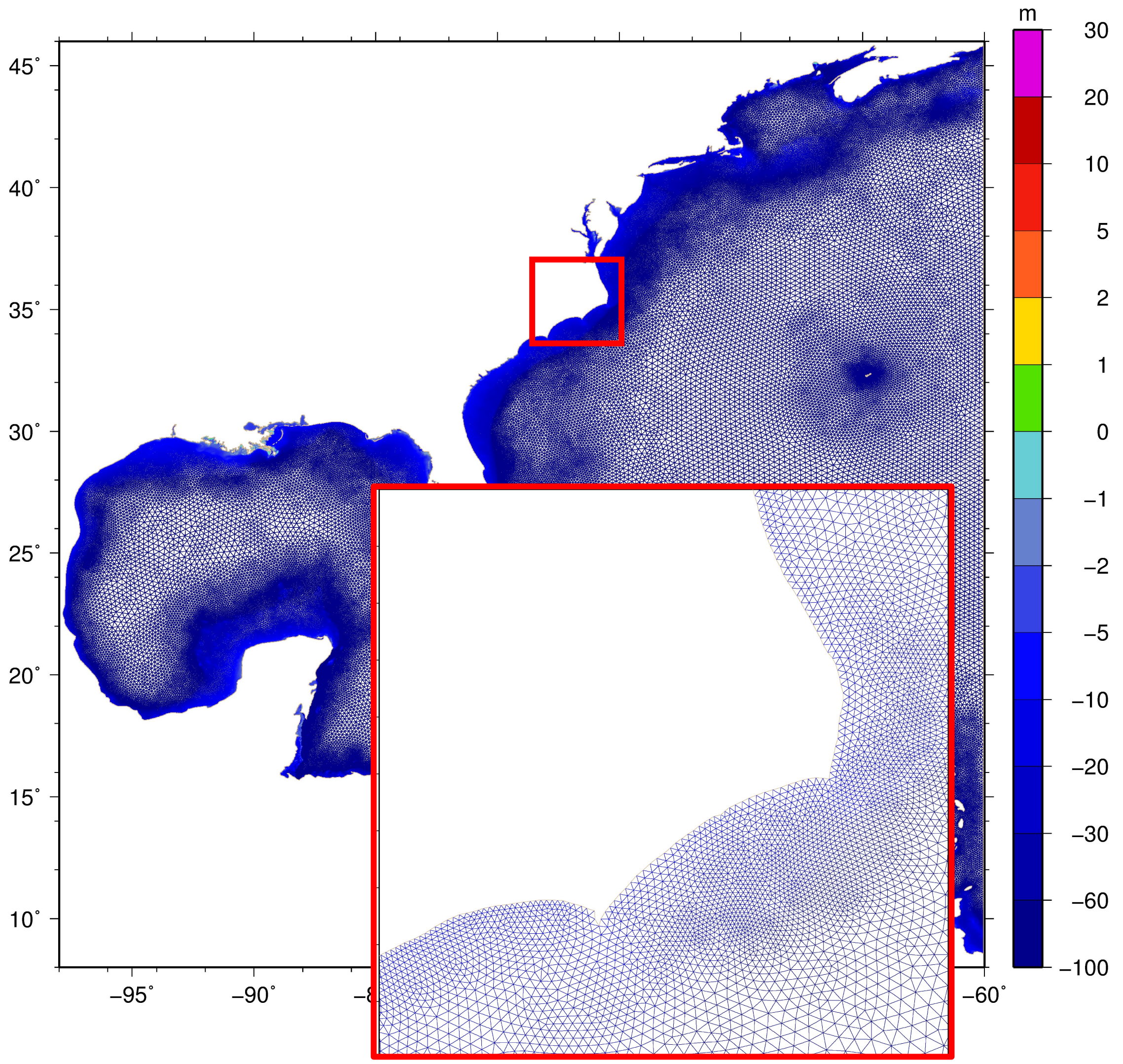
Why Hurricane Florence?

- Shore normal approach (perpendicular to coast)
- Allows for single switch for trigger testing from coarse mesh to fine mesh

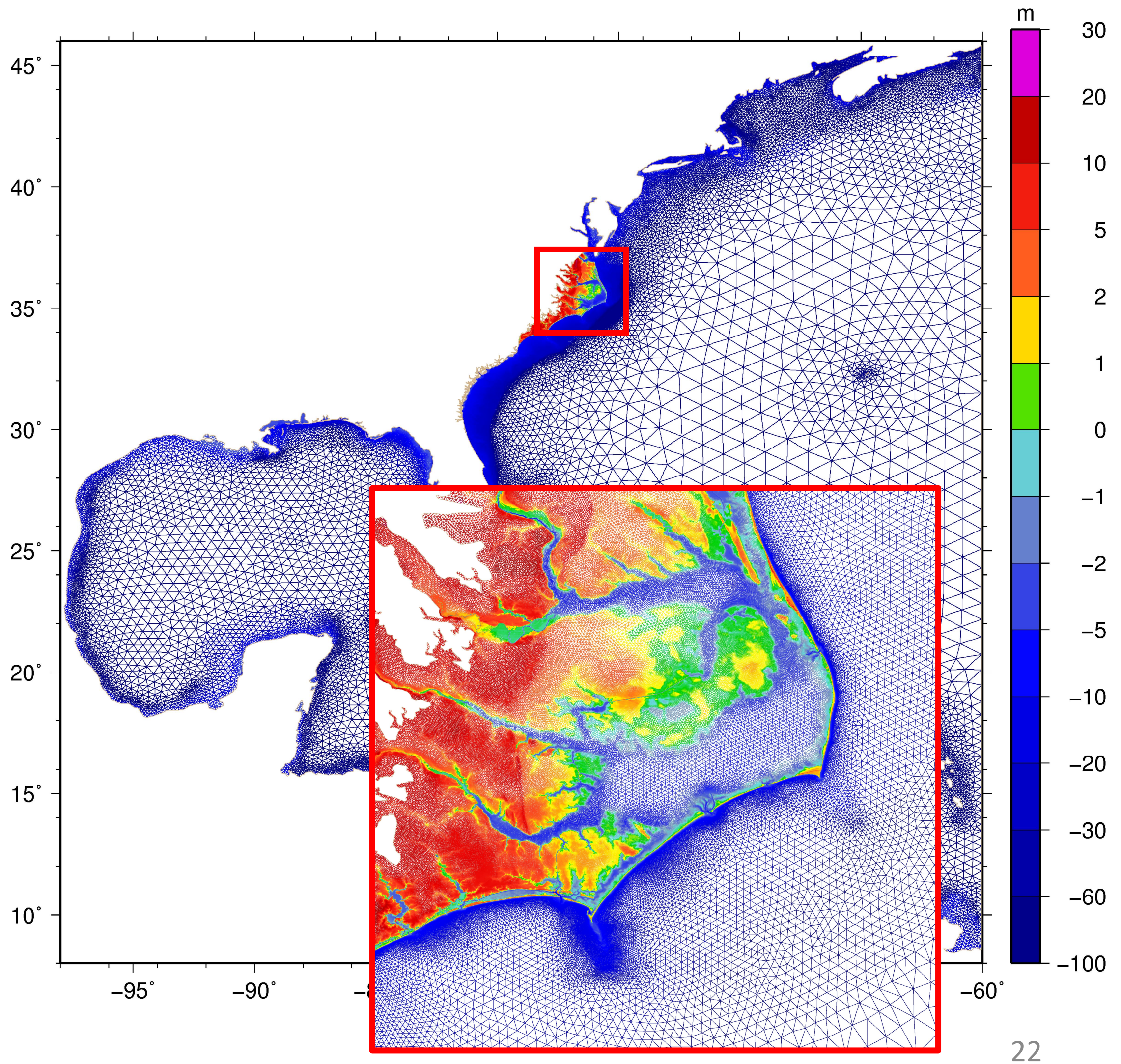


Meshes Used

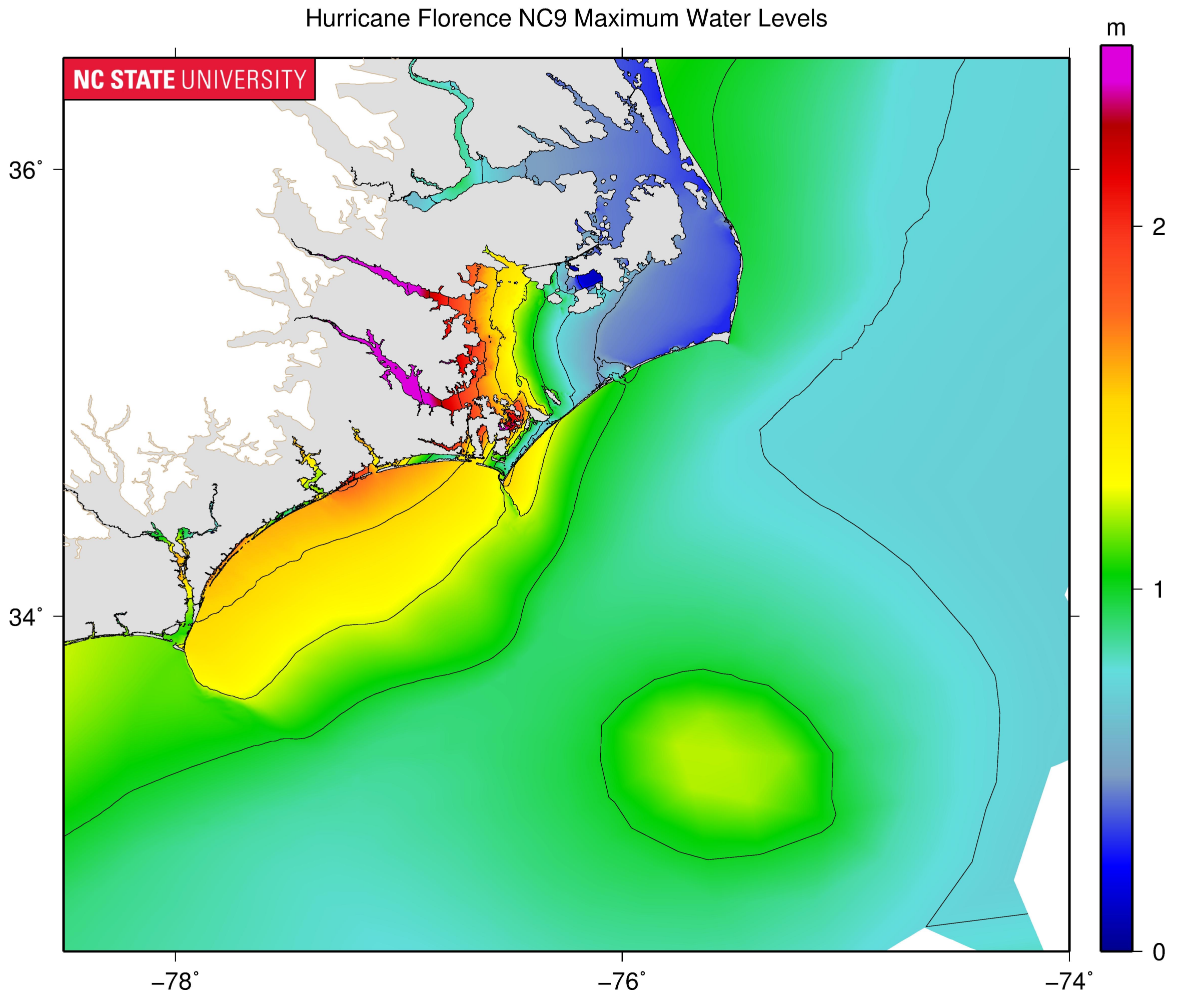
Coarse/Source Mesh



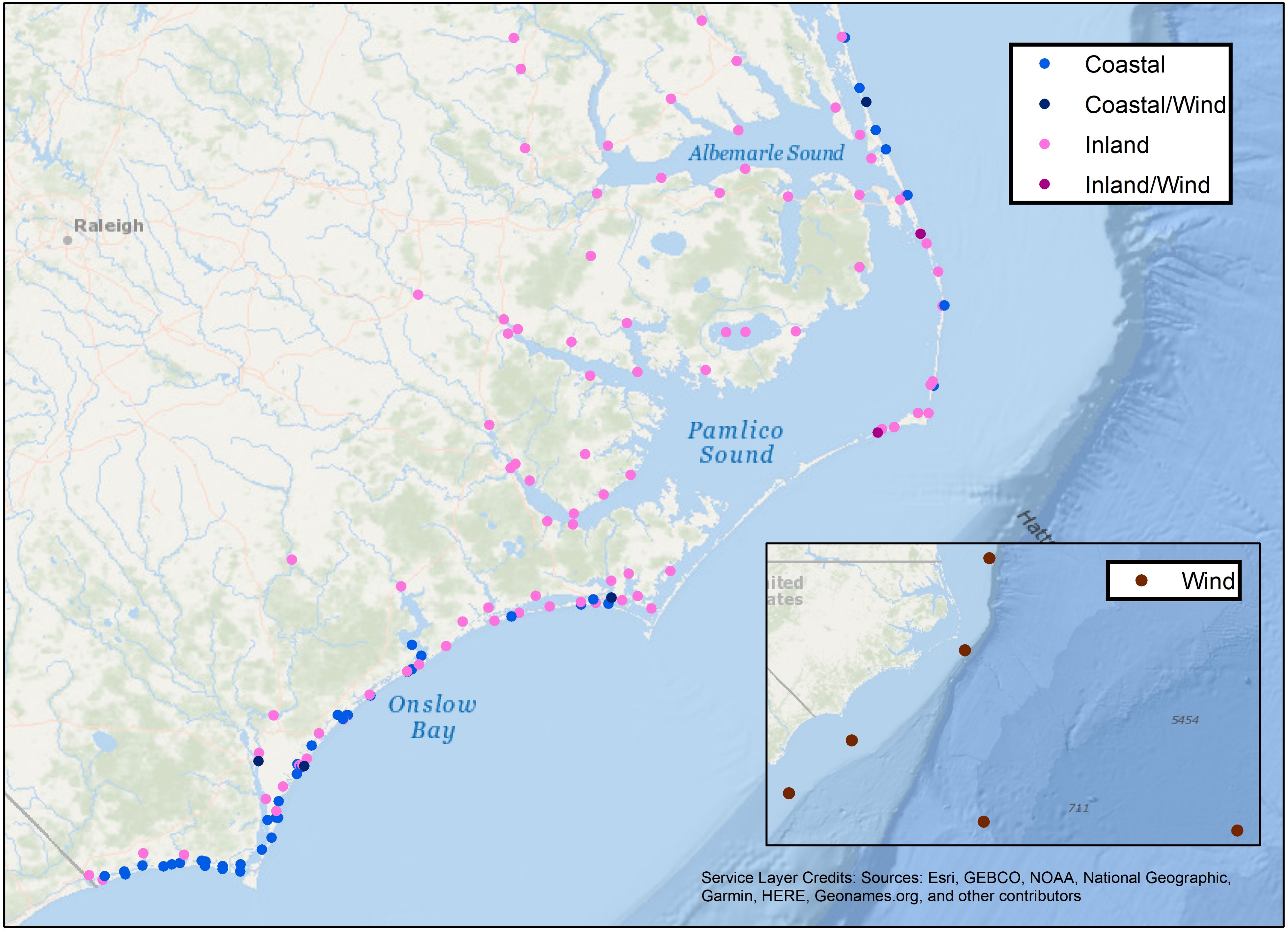
Fine/Target Mesh



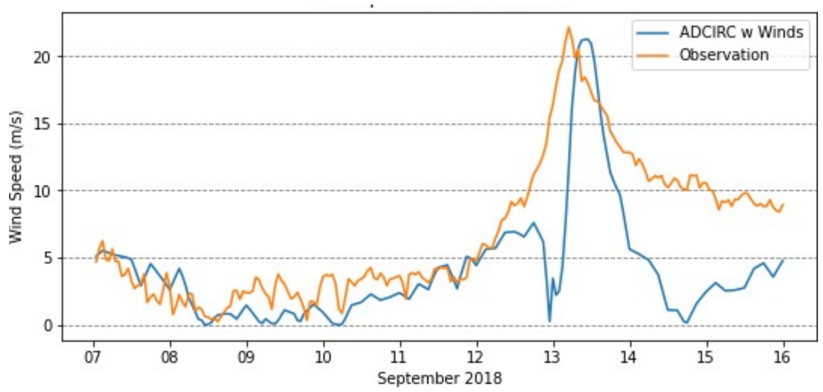
Florence Simulation NC9

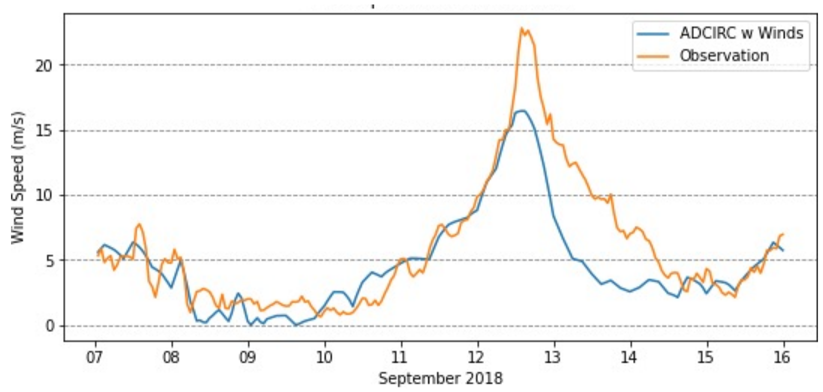


- Full fine/high-resolution simulation on NC9 mesh (~620K nodes, ~1.2M elements)
- Coldstart: 15 days, 23 August 00:00 to 7 September 00:00 2018 UTC
- Hotstart: 9 days, 7 September 00:00 to 16 September 00:00 2018 UTC
- Used as ‘truth’ or the fine simulation for comparing to the mixed simulations


Coastal
Coastal/Wind
Inland
Inland/Wind
Raleigh
Albemarle Sound
Pamlico Sound
Onslow Bay
Wind
5454
711
Service Layer Credits: Sources: Esri, GEBCO, NOAA, National Geographic, Garmin, HERE, Geonames.org, and other contributors

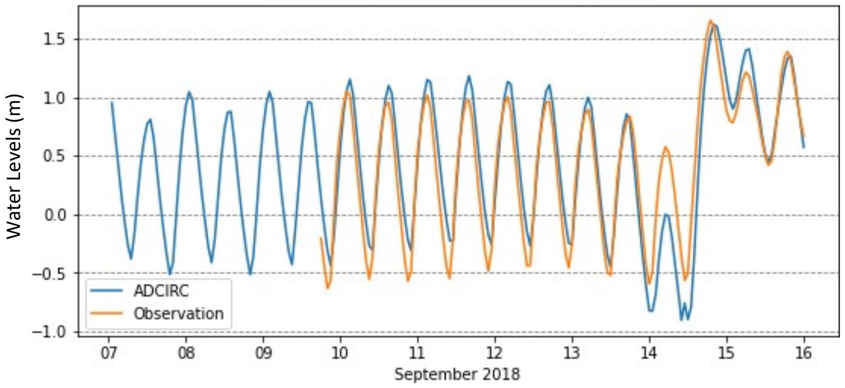
Winds

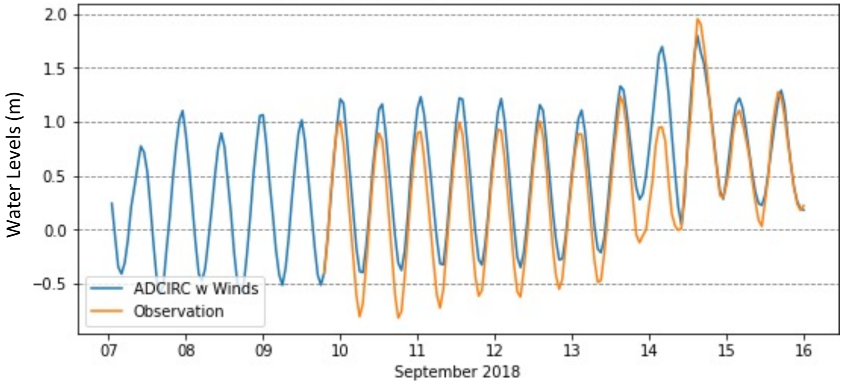




W > 8 m/s
W > 10 m/s
W > 15 m/s

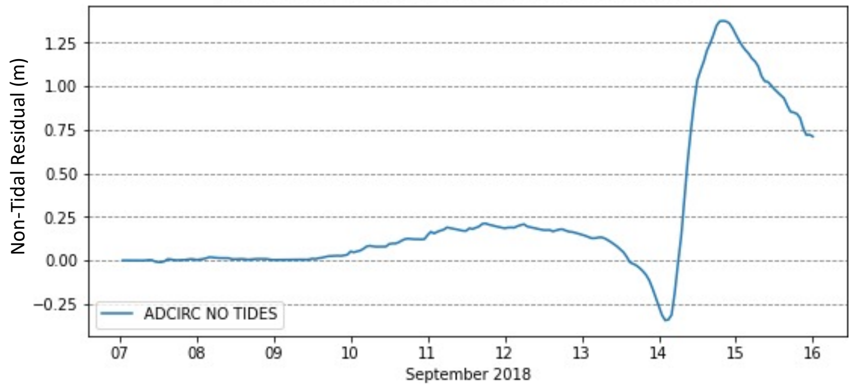
Maximum Tide

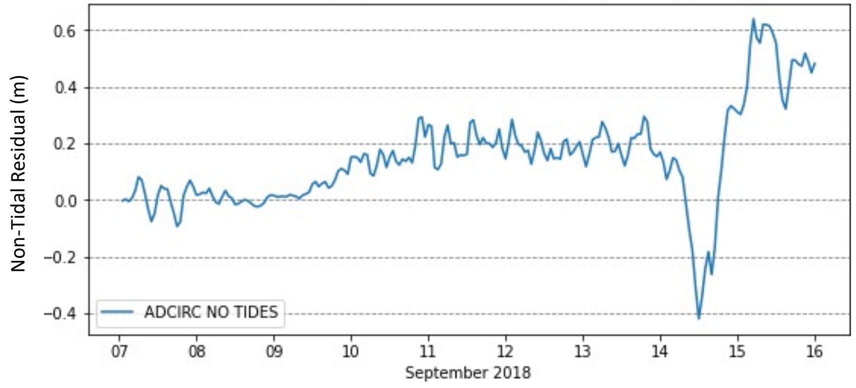




$\eta > 1.1 * \eta_{max}$
$\eta > 1.2 * \eta_{max}$
$\eta > 1.3 * \eta_{max}$

Non-Tidal Residual





$\lvert\eta_{NTR}\rvert > 0.3$ m
$\lvert\eta_{NTR}\rvert > 0.4$ m
$\lvert\eta_{NTR}\rvert > 0.5$ m

Suite of Triggers

Wind Trigger	Value	Offsets
WT1	W > 8 m/s	0 hr, 12 hr, 24 hr
WT2	W > 10 m/s	0 hr, 12 hr, 24 hr
WT3	W > 15 m/s	0 hr, 12 hr, 24 hr

Coastal Trigger	Value	Offsets
CWLT1	$\eta > 1.1^* \eta_{max}$	0 hr, 12 hr, 24 hr
CWLT2	$\eta > 1.2^* \eta_{max}$	0 hr, 12 hr, 24 hr
CWLT3	$\eta > 1.3^* \eta_{max}$	0 hr, 12 hr, 24 hr
CWLT10	$\lvert\eta_{NTR}\rvert > 0.3$ m	0 hr, 12 hr, 24 hr
CWLT20	$\lvert\eta_{NTR}\rvert > 0.4$ m	0 hr, 12 hr, 24 hr
CWLT30	$\lvert\eta_{NTR}\rvert > 0.5$ m	0 hr, 12 hr, 24 hr

Inland Trigger	Value	Offsets
IWLT1	$\eta > 1.1^* \eta_{max}$	0 hr, 12 hr, 24 hr
IWLT2	$\eta > 1.2^* \eta_{max}$	0 hr, 12 hr, 24 hr
IWLT3	$\eta > 1.3^* \eta_{max}$	0 hr, 12 hr, 24 hr
IWLT10	$\lvert\eta_{NTR}\rvert > 0.3$ m	0 hr, 12 hr, 24 hr
IWLT20	$\lvert\eta_{NTR}\rvert > 0.4$ m	0 hr, 12 hr, 24 hr
IWLT30	$\lvert\eta_{NTR}\rvert > 0.5$ m	0 hr, 12 hr, 24 hr

η_{max}= tidal maximum from tides only simulation
η_{NTR}= non-tidal residual (winds minus tides)

Error Metrics

Accuracy

- E_{RMS}, Root-mean-squared error

$$E_{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} E_i^2}$$

- B_{MN}, Bias

$$B_{MN} = \frac{\frac{1}{N}\sum_{i=1}^{N} E_i}{\frac{1}{N}\sum_{i=1}^{N} |O_i|}$$

- E_i is the difference between predictions and observations
- O_i is the absolute value of the observed water level

Efficiency

- Actual speedup $S_{actual} = \frac{T_{\text{fine}}}{T_{\text{mixed}}}$

- Theoretical speedup $S_{\text{theoretical}} = \frac{NT}{\sum_{i=1}^{n} N_i T_i}$

- T_{fine} is the total wall-clock time for the *Fine* simulation in seconds
- T_{mixed} is the total wall-clock time for the approach including the times for switching in seconds
- *N* is the number of vertices in the Fine mesh, N_i is the number of vertices on component meshes
- *T* is the total days of Fine simulation and T_i is the total days on each component mesh

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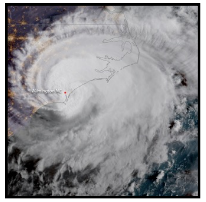

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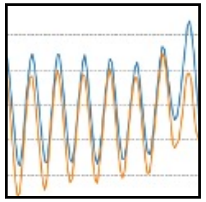

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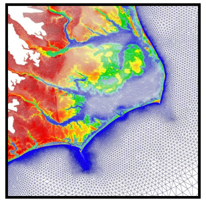

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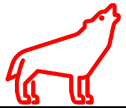

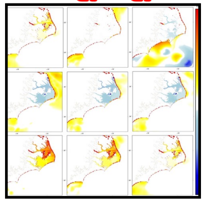

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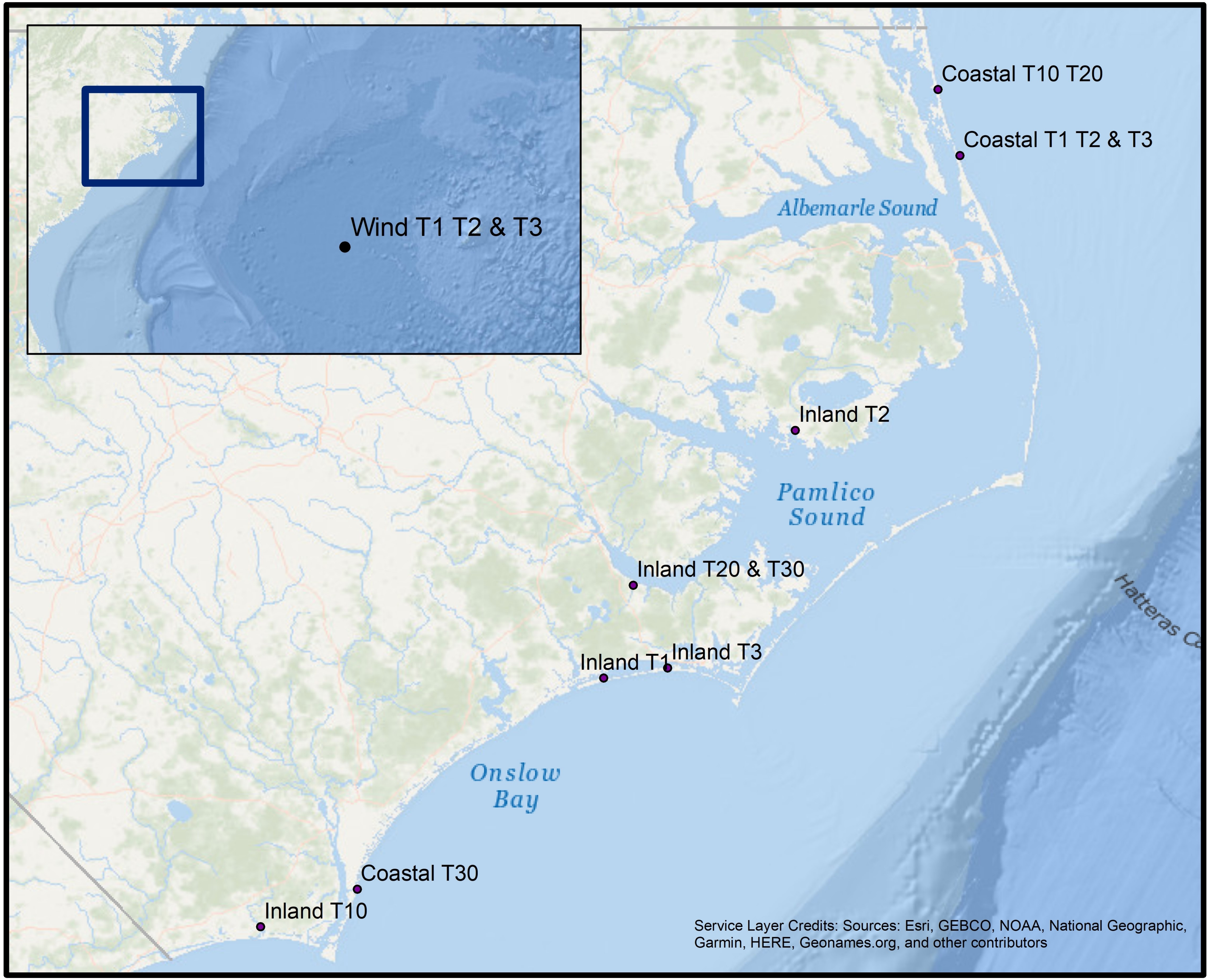


Coastal T10 T20
Coastal T1 T2 & T3
Albemarle Sound
Wind T1 T2 & T3
Inland T2
Pamlico Sound
Inland T20 & T30
Hatteras
Inland T1
Inland T3
Onslow Bay
Coastal T30
Inland T10
Service Layer Credits: Sources: Esri, GEBCO, NOAA, National Geographic, Garmin, HERE, Geonames.org, and other contributors

Wind Triggers

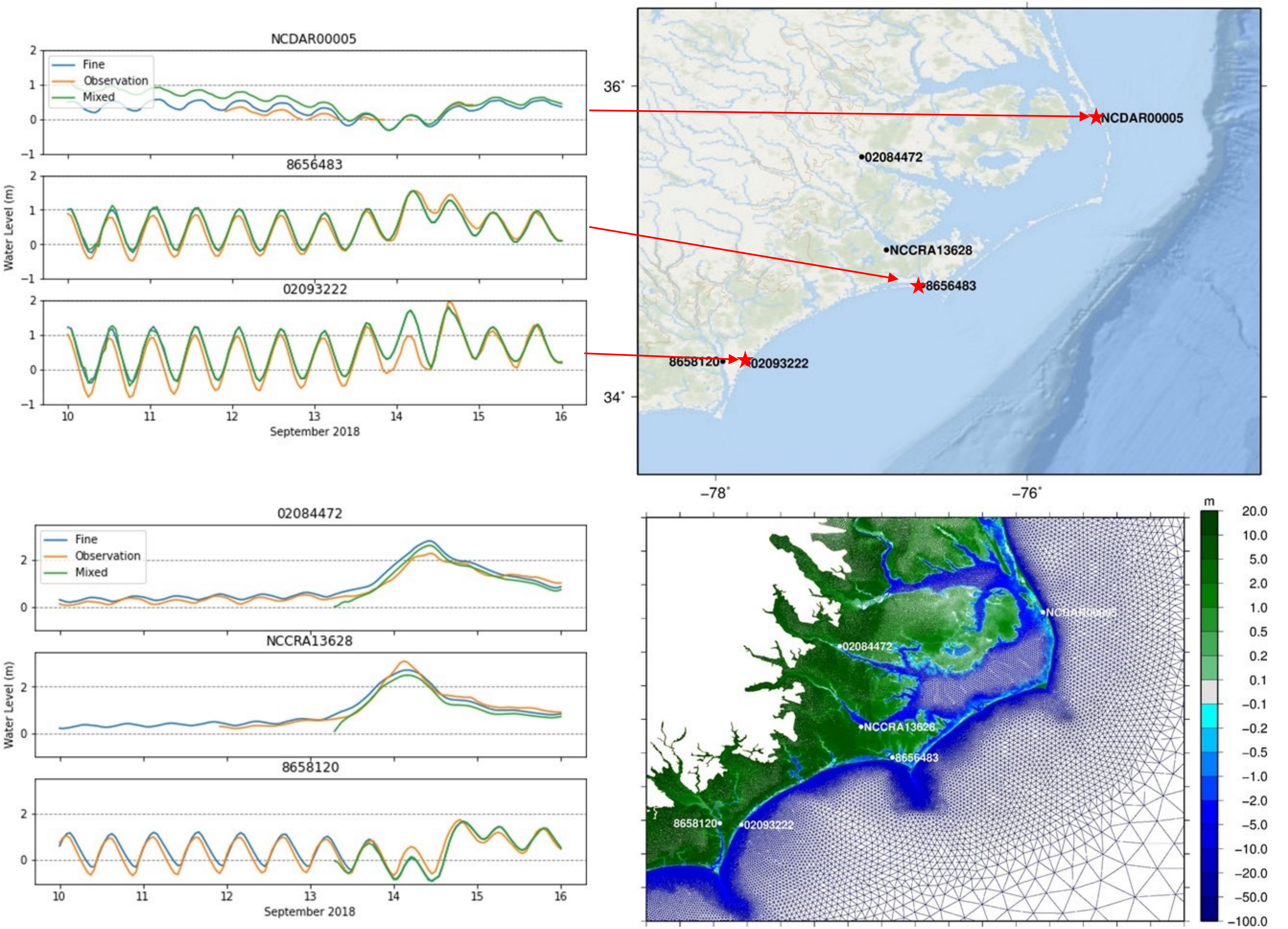
Trigger	Offset	Simulation Switch Date	Run Duration (days)		
			Coarse	Fine	Total
WT1 (8 m/s)	24 hr	1800 UTC 10 Sept, 2018	3.75	5.25	9
	12 hr	0600 UTC 11 Sept, 2018	4.25	4.75	9
	0 hr	1800 UTC 11 Sept, 2018	4.75	4.25	9
WT 2 (10 m/s)	24 hr	0300 UTC 11 Sept, 2018	4.125	4.875	9
	12 hr	1500 UTC 11 Sept, 2018	4.625	3.250	9
	0 hr	0300 UTC 12 Sept, 2018	5.125	3.875	9
WT3 (15 m/s)	24 hr	0900 UTC 11 Sept, 2018	4.375	4.625	9
	12 hr	2100 UTC 11 Sept, 2018	4.875	4.125	9
	0 hr	0900 UTC 12 Sept, 2018	5.375	3.625	9

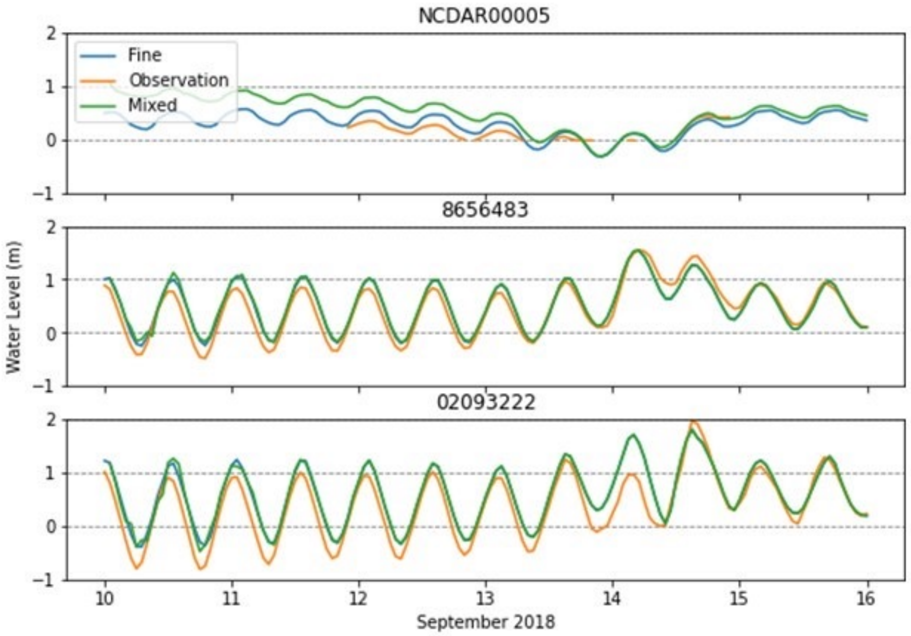
Coastal Triggers

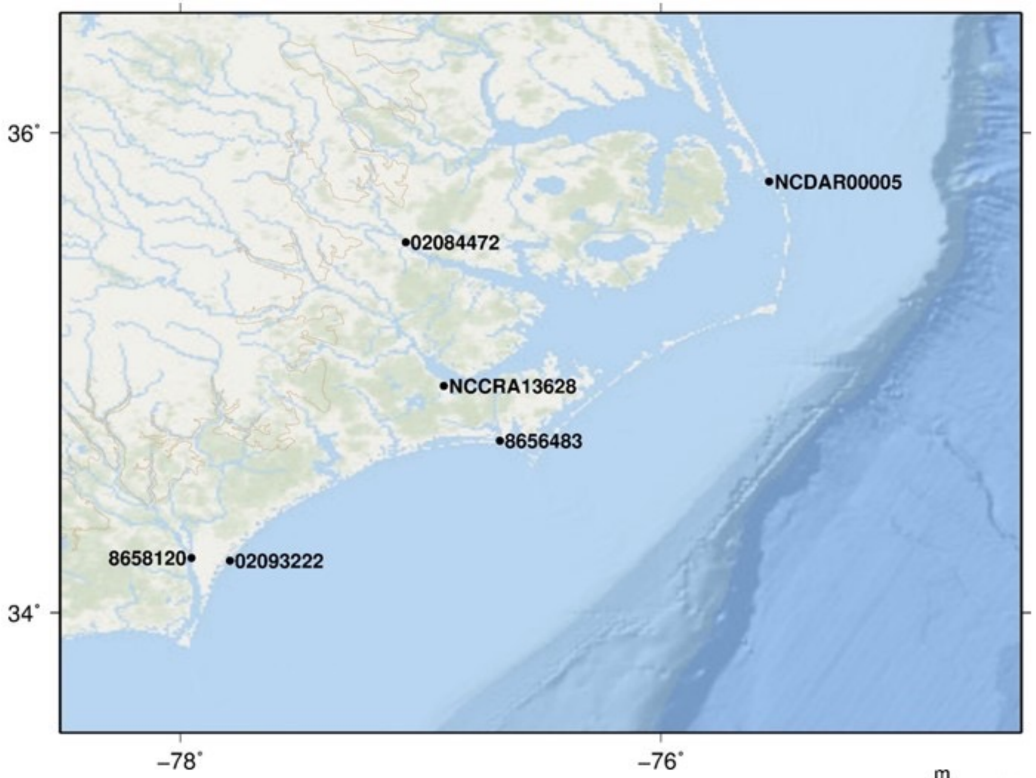
Trigger	Value	Offset	Simulation Switch Date	Run Duration (days)		
				Coarse	Fine	Total
CWLT1, CWLT2, CWLT3	1.1x	0 hr	0000 UTC 10 Sept, 2018	3	6	9
	1.2x	0 hr	0000 UTC 10 Sept, 2018	3	6	9
	1.3x	0 hr	0000 UTC 10 Sept, 2018	3	6	9
CWLT10, CWLT20, CWLT30	0.3 m	0 hr	0000 UTC 10 Sept, 2018	3	6	9
	0.4 m	0 hr	1200 UTC 10 Sept, 2018	3.5	5.5	9
	0.5 m	0 hr	1500 UTC 13 Sept, 2018	6.625	2.375	9

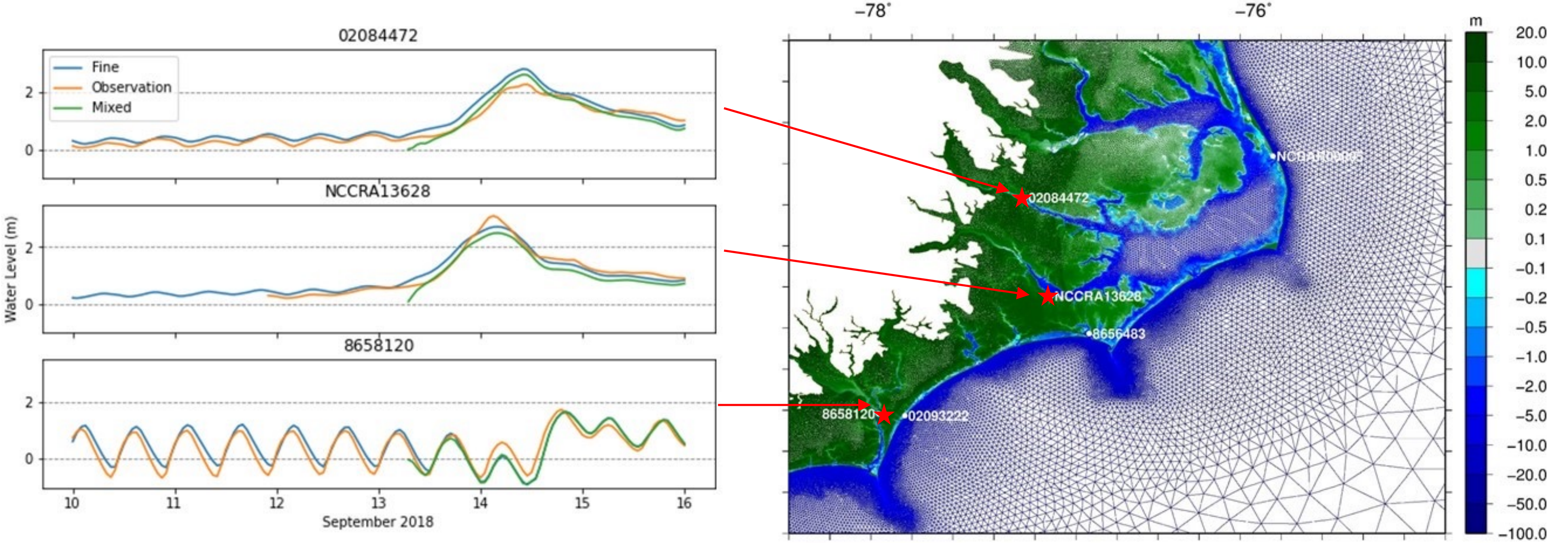
Inland Triggers

Trigger	Value	Offset	Simulation Switch Date	Run Duration (days)		
				Coarse	Fine	Total
IWLT1, IWLT2, IWLT3	1.1x	0 hr	0300 UTC 10 Sept, 2018	3.125	5.875	9
	1.2x	0 hr	1800 UTC 10 Sept, 2018	3.75	5.25	9
	1.3x	0 hr	0300 UTC 11 Sept, 2018	4.125	4.875	9
IWLT10, IWLT20, IWLT30	0.3 m	0 hr	2100 UTC 10 Sept, 2018	3.875	5.125	9
	0.4 m	0 hr	0300 UTC 13 Sept, 2018	6.125	2.825	9
	0.5 m	0 hr	0600 UTC 13 Sept, 2018	6.25	2.75	9


NCDAR00005
8656483
02093222
Fine
Observation
Mixed
Water Level (m)
September 2018
36˚
34˚
−78˚
−76˚
NCDAR00005
02084472
NCCRA13628
8656483
8658120
02093222
02084472
NCCRA13628
8658120
m
20.0
10.0
5.0
2.0
1.0
0.5
0.2
0.1
−0.1
−0.2
−0.5
−1.0
−2.0
−5.0
−10.0
−20.0
−50.0
−100.0


NCDAR00005
8656483
02093222
Fine
Observation
Mixed
Water Level (m)
September 2018

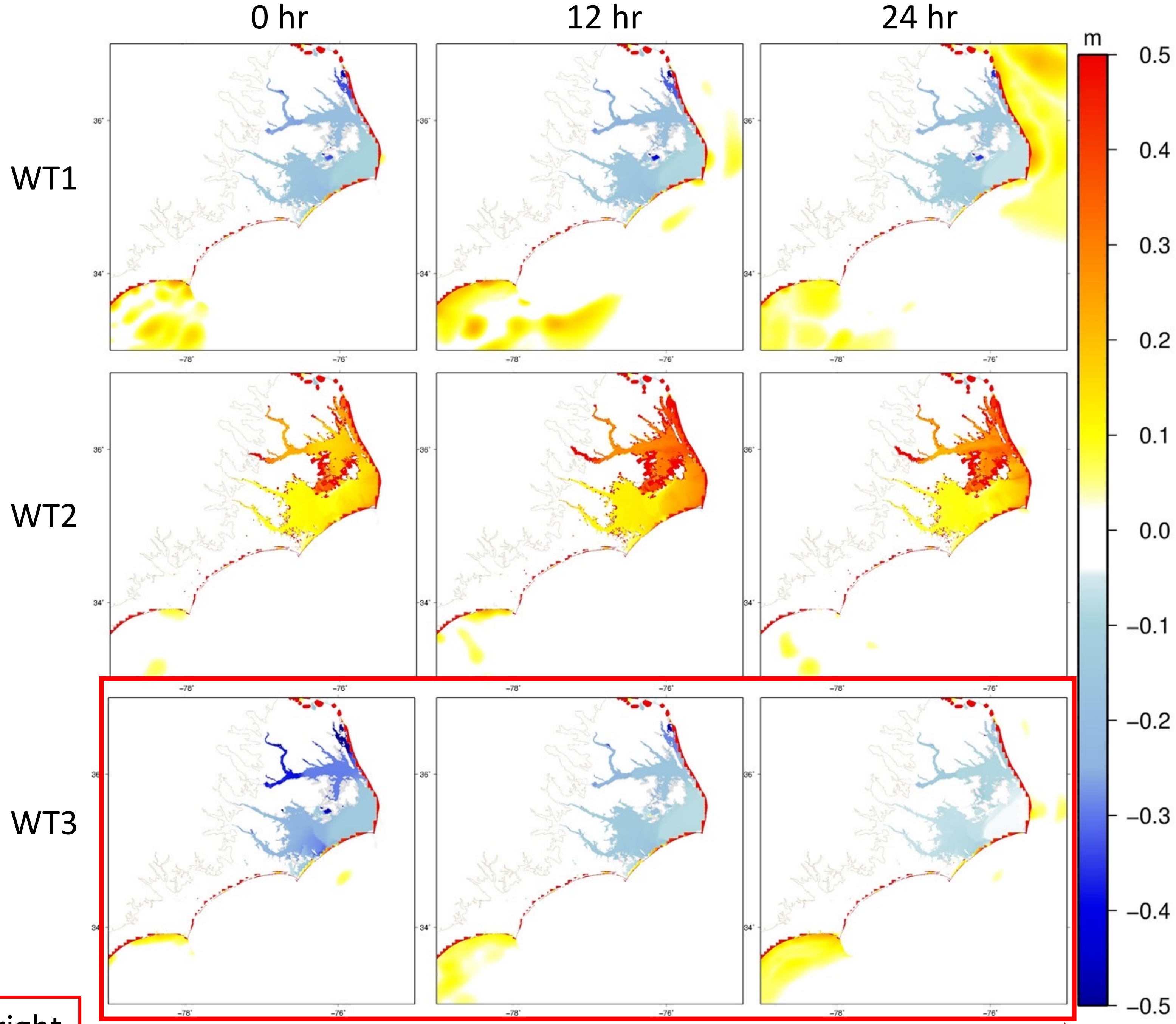

36°
34°
−78°
−76°
NCDAR00005
02084472
NCCRA13628
8656483
8658120
02093222


02084472
NCCRA13628
8658120
Fine
Observation
Mixed
Water Level (m)
September 2018
m
20.0
10.0
5.0
2.0
1.0
0.5
0.2
0.1
−0.1
−0.2
−0.5
−1.0
−2.0
−5.0
−10.0
−20.0
−50.0
−100.0
NCCRA13628
8656483
8658120
02093222

Wind Results - Accuracy

Comparison	Offset	WT1		WT2		WT3	
		RMSE	B_{MN}	RMSE	B_{MN}	RMSE	B_{MN}
Vs. Fine	24hr	0.11	-0.17	[illegible]	[illegible]	0.07	-0.10
	12hr	0.13	-0.19	[illegible]	[illegible]	0.10	-0.16
	0hr	0.12	-0.18	0.10	0.14	0.14	-0.23
Vs. Obs	24hr	0.23	-0.07	0.28	0.52	0.21	0.07
	12hr	0.23	-0.11	0.30	0.59	0.22	-0.04
	0hr	0.24	-0.10	0.29	0.51	0.25	-0.20

Increasing
error values



Mixed over predicts

Mixed under predicts

Improve left to right

Coastal Results - Accuracy

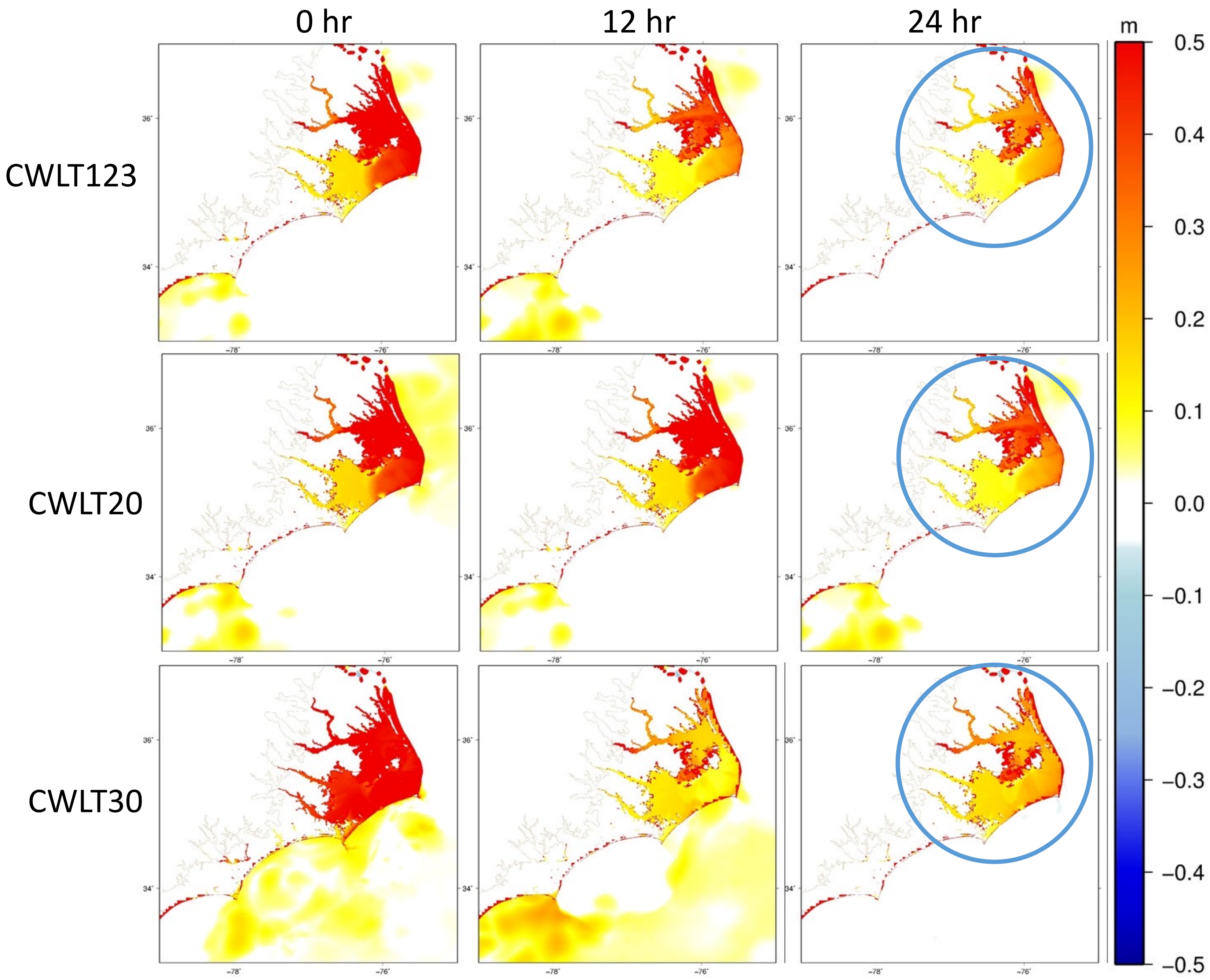
Comparison	Offset	CWLT123		CWLT20		CWLT30	
		RMSE	B_{MN}	RMSE	B_{MN}	RMSE	B_{MN}
Vs. Fine	24hr	0.10	0.17	0.11	0.20	0.10	0.17
	12hr	0.11	0.20	0.15	0.28	0.11	0.15
	0hr	0.15	0.28	0.15	0.28	0.20	0.39
Vs. Obs	24hr	0.28	0.53	0.29	0.56	0.31	0.56
	12hr	0.29	0.56	0.33	0.72	0.30	0.46
	0hr	0.33	$\boxed{0.72}$	0.34	$\boxed{0.74}$	0.40	$\boxed{0.90}$

Closer to landfall = larger errors

Coastal Results - Accuracy

Comparison	Offset	CWLT123		CWLT20		CWLT30	
		RMSE	B_{MN}	RMSE	B_{MN}	RMSE	B_{MN}
Vs. Fine	24hr	0.10	0.17	0.11	0.20	0.10	0.17
	12hr	0.11	0.20	0.15	0.28	0.11	0.15
	0hr	0.15	0.28	0.15	0.28	0.20	0.39
Vs. Obs	24hr	0.28	0.53	0.29	0.56	0.31	0.56
	12hr	0.29	0.56	0.33	0.72	0.30	0.46
	0hr	0.33	0.72	0.34	0.74	0.40	0.90

Closer to landfall = larger errors



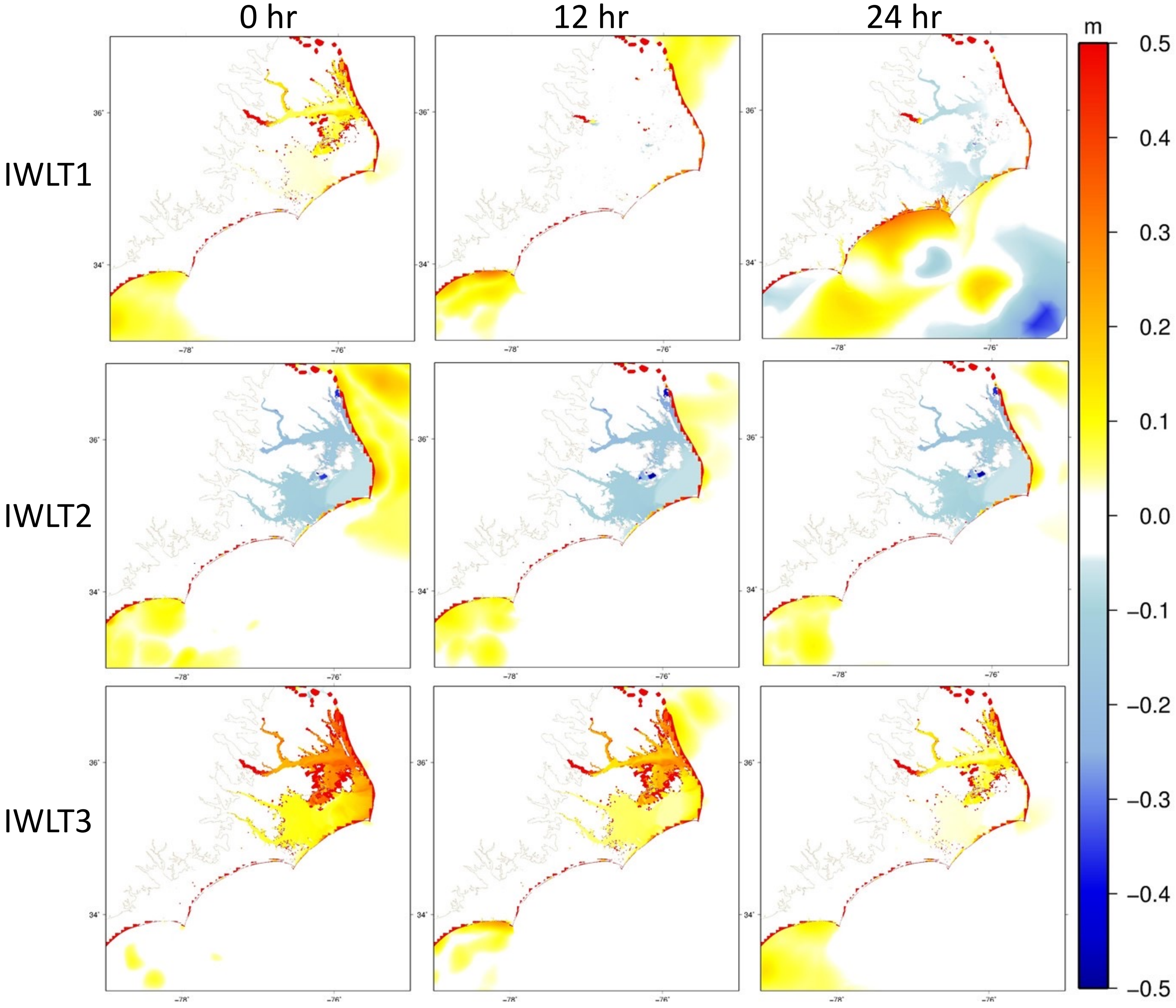
Why does sound side have largest errors?

Inland Results - Accuracy

Comparison	Offset	IWLT1		IWLT2		IWLT3	
		RMSE	B_{MN}	RMSE	B_{MN}	RMSE	B_{MN}
Vs. Fine	24hr	0.24	-0.06	[illegible]	[illegible]	0.05	-0.01
	12hr	0.04	-0.03	[illegible]	[illegible]	0.03	-0.01
	0hr	0.06	0.04	0.11	-0.18	0.06	-0.02
Vs. Obs	24hr	0.40	0.12	0.29	0.43	0.25	0.30
	12hr	0.22	0.16	0.29	0.44	0.26	0.40
	0hr	0.25	0.30	0.30	0.44	0.28	0.52

Observations compared to fine

Tidal Maximum



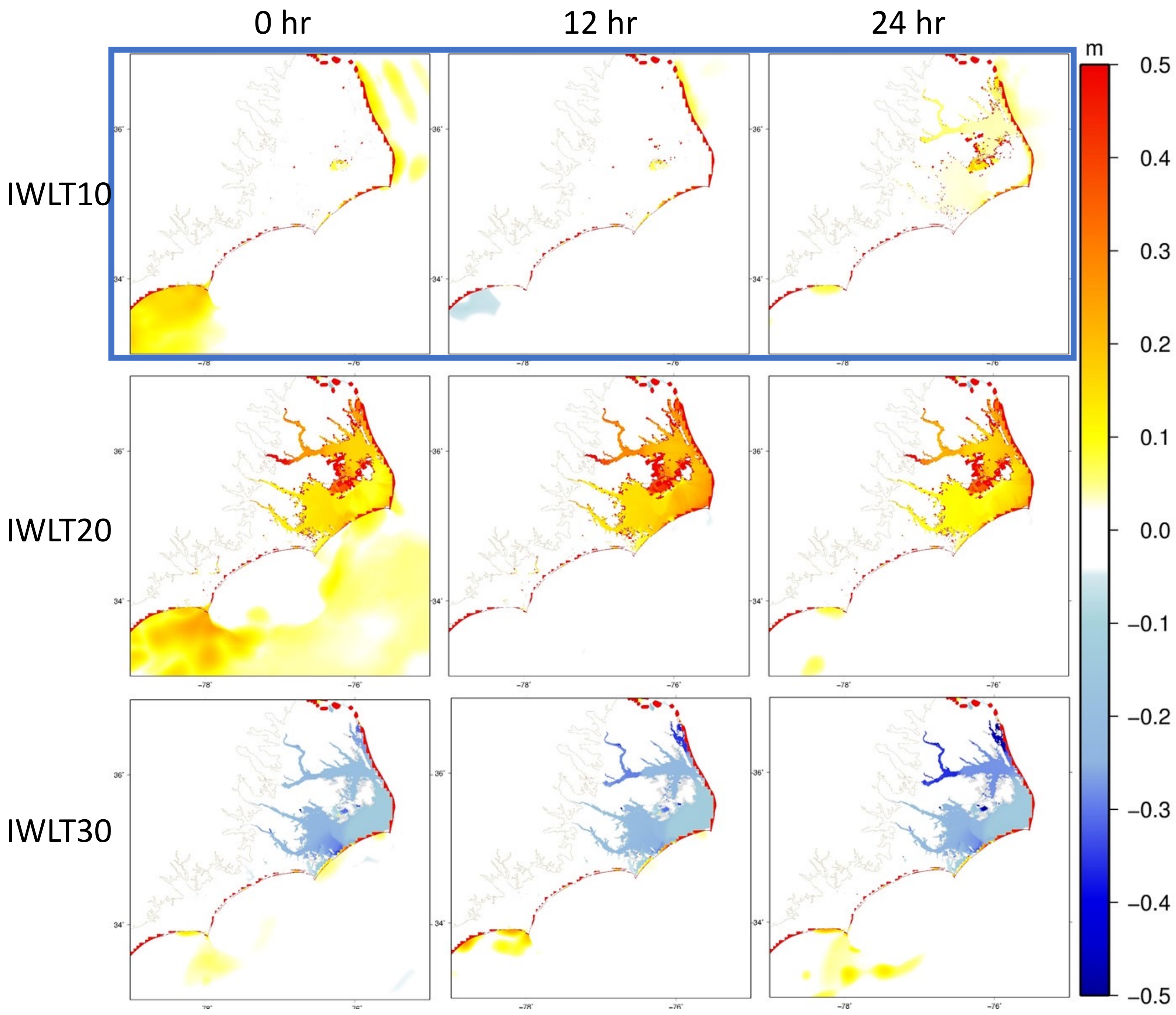
Inland Results - Accuracy

Comparison	Offset	IWLT10		IWLT20		IWLT30	
		RMSE	B_{MN}	RMSE	B_{MN}	RMSE	B_{MN}
Vs. Fine	24hr	0.05	-0.06	0.10	0.13	0.15	-0.25
	12hr	0.02	0.00	0.10	0.17	0.12	-0.20
	0hr	0.03	-0.01	0.11	0.15	0.12	-0.18
Vs. Obs	24hr	0.25	0.33	0.29	0.51	0.25	-0.20
	12hr	0.23	0.22	0.31	0.56	0.24	-0.12
	0hr	0.22	0.21	0.30	0.46	0.24	-0.11

2100 UTC 10 Sept, 2018

Closer to landfall time

Non-Tidal Residual



Look significantly better than others we have seen?

HPC Hardware and Efficiency

- Wall-clock times are sensitive to hardware on the NCSU High Performance Computing (HPC) system
- The HPC is a heterogeneous cluster, includes state-of-the-art equipment such as the newest CPUs and GPUs while maintaining older resources as long as feasible
- Simulations submitted to nodes of varying age and speed

Wind Results - Efficiency

Trigger	Offset	***Mixed*** (Time in seconds)				***Fine***	**% Save in time**	S_{actual}	$S_{theoretical}$
		Coarse	*Adcirpolate*	Fine	Total				
WT1	24hr	1264	162	3295	4721	7870	40%	1.67	1
	12hr	1549	167	2747	4463	7870	43%	1.76	1.39
	0hr	2688	149	1532	4369	7870	44%	1.80	1.45
WT2	24hr	1610	202	1553	3365	7870	57%	2.34	1.37
	12hr	3132	171	3136	6439	7870	18%	1.22	1.44
	0hr	2369	158	2410	4937	7870	37%	1.59	1.51
WT3	24hr	2676	193	5802	8671	7870	-10%	0.91	1.40
	12hr	3219	188	7423	10830	7870	-38%	0.73	1.47
	0hr	2065	281	2571	4917	7870	38%	1.60	1.55

Increase in efficiency

Coastal Results - Efficiency

Trigger	Offset	***Mixed*** (Time in seconds)				***Fine***	**% Save in time**	S_{actual}	$S_{theoretical}$
		Coarse	*Adcirpolate*	Fine	Total				
CWLT12, 3	0hr	1180	80	2307	3567	7870	55%	2.21	1.25
	12hr	1257	85	2005	3347	7870	57%	2.35	1.20
	24hr	3399	94	5397	8890	7870	-13%	0.89	1.15
CWLT20	24hr	955	154	9935	11044	7870	-13%	0.71	No apparent trend
	12hr	643	182	2587	3412	7870	57%	2.31	1.25
	0hr	4833	181	3355	8369	7870	-6%	0.94	1.30
CWLT30	24hr	2786	175	1560	4521	7870	43%	1.74	1.59
	12hr	4471	202	1221	5894	7870	25%	1.34	1.67
	0hr	1642	203	2462	4307	7870	45%	1.83	1.77

Inland Results - Efficiency

Trigger	Offset	***Mixed*** (Time in seconds)				***Fine***	**% Save in time**	**S_{actual}**	**$S_{theoretical}$**
		Coarse	*Adcirpolate*	Fine	Total				
IWLT1	24hr	477	96	5157	5730	7870	27%	1.37	[illegible]
	12hr	1564	173	3379	5116	7870	35%	1.54	[illegible]
	0hr	1347	103	3112	4562	7870	42%	1.73	1.26
IWLT2	24hr	614	90	4016	4720	7870	40%	1.67	1.22
	12hr	650	123	3159	3932	7870	50%	2.00	1.27
	0hr	843	178	2807	3828	7870	51%	2.06	1.33
IWLT3	24hr	739	90	2187	3016	7870	62%	2.61	1.26
	12hr	716	88	1994	2798	7870	64%	2.81	1.31
	0hr	1487	127	3386	5000	7870	36%	1.57	1.37

All positive with increasing efficiency

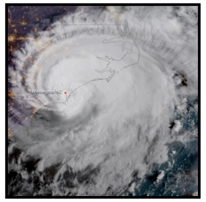
Inland Results - Efficiency

Trigger	Offset	***Mixed*** (Time in seconds)				***Fine***	**% Save in time**	S_{actual}	$S_{theoretical}$
		Coarse	*Adcirpolate*	Fine	Total				
IWLT10	24hr	1028	94	2718	3840	7870	51%	[illegible]	[illegible]
	12hr	671	89	3240	4000	7870	49%	[illegible]	[illegible]
	0hr	777	88	5176	6041	7870	23%	1.30	1.34
IWLT20	24hr	1010	85	1491	2586	7870	67%	3.04	1.51
	12hr	1107	87	1057	2251	7870	71%	3.50	1.59
	0hr	2991	95	1683	4769	7870	39%	1.65	1.67
IWLT30	24hr	2422	137	1988	4547	7870	42%	1.73	1.53
	12hr	111	88	2678	3877	7870	51%	2.02	1.61
	0hr	1628	85	2778	4491	7870	43%	1.75	1.70

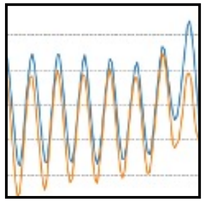
All positive efficiency gains

Outline

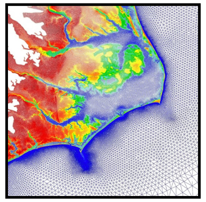
Introduction



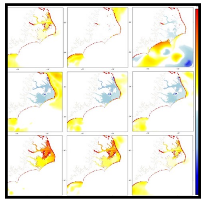
Background and Previous Work



Motivation and Remaining Questions



Methods

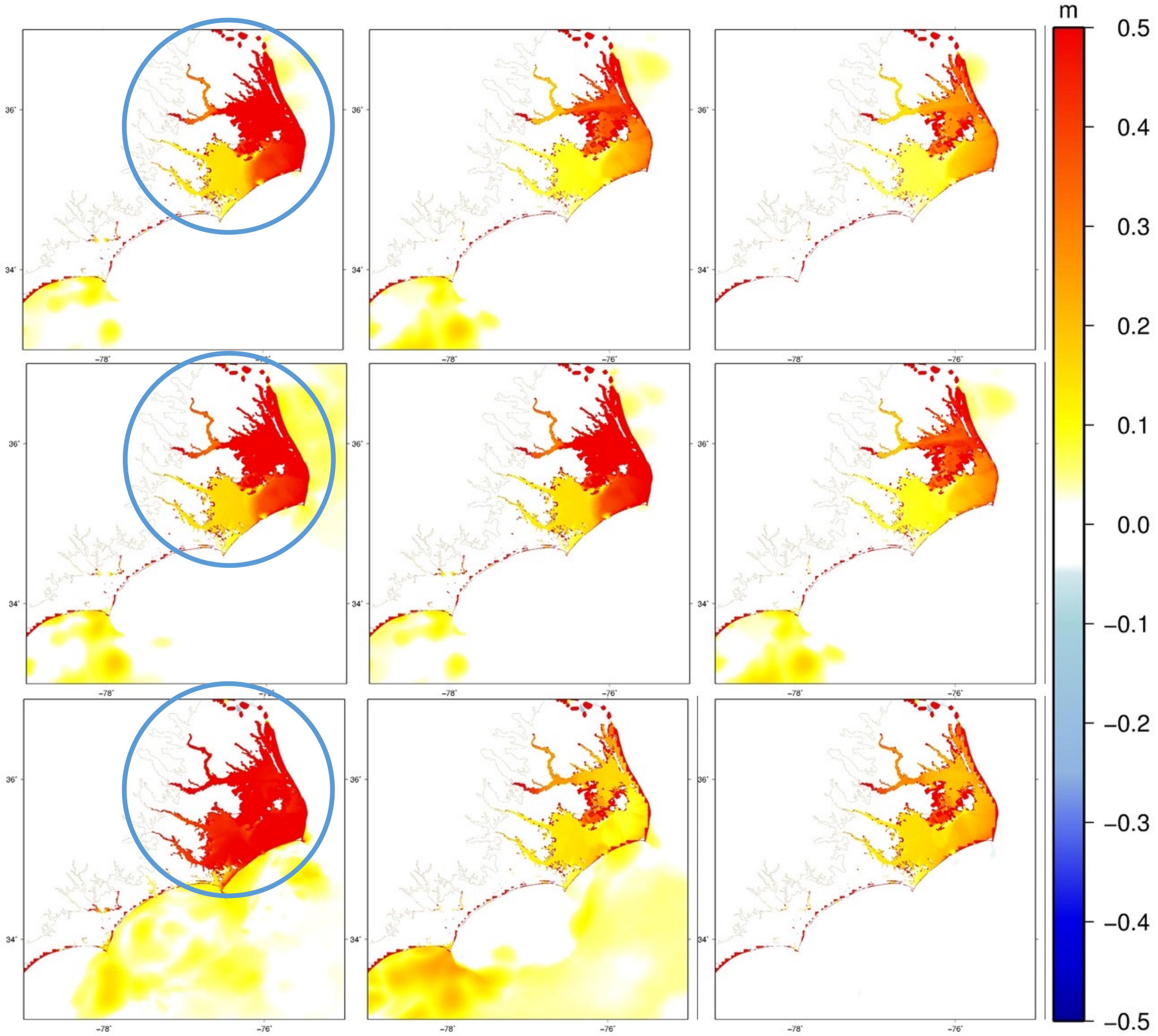


Results

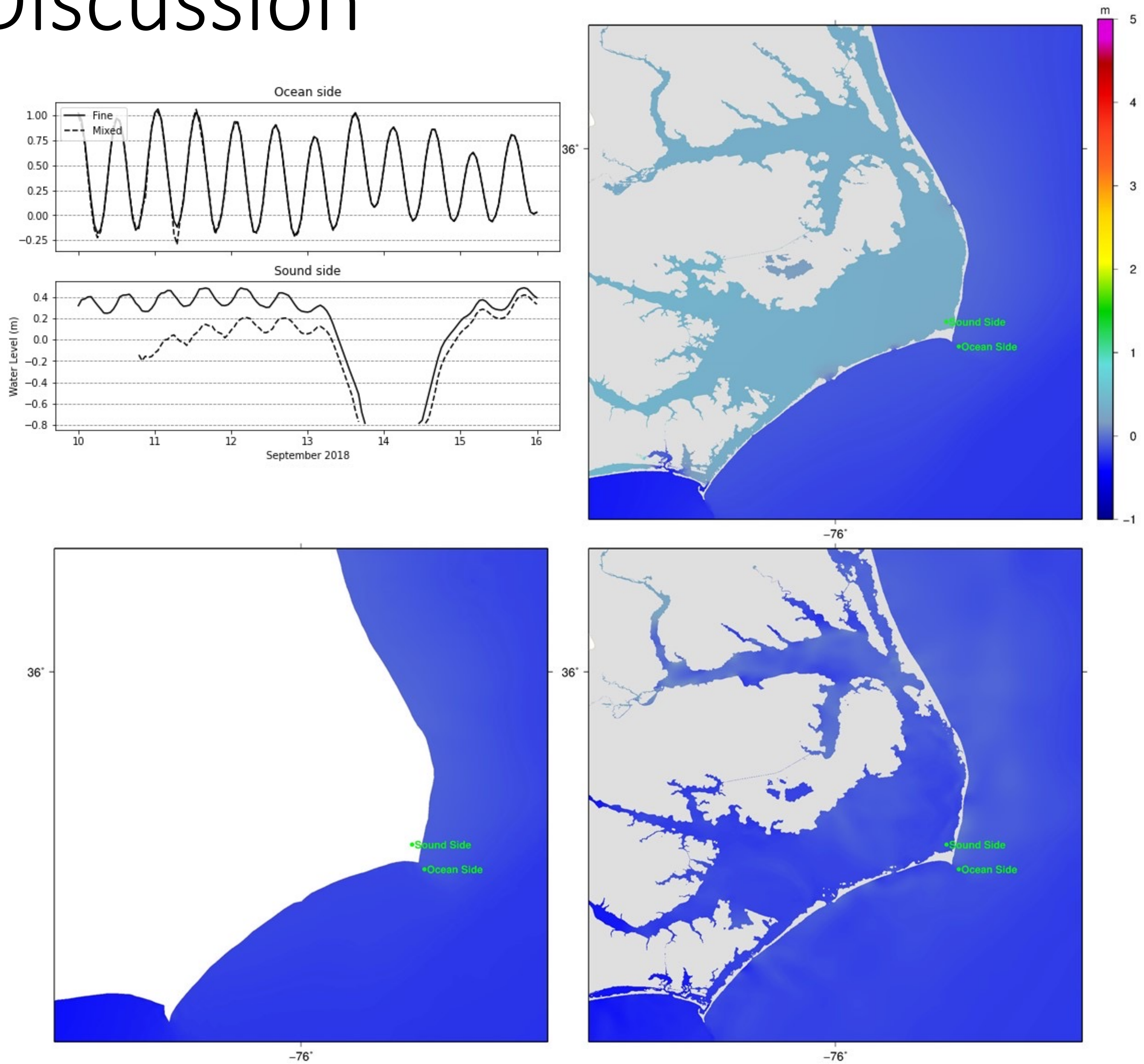
Discussion

Conclusions and Future Work

Why does sound side have largest errors?



Mesh Discussion

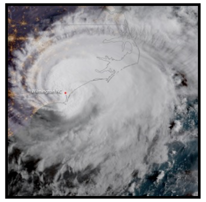


Recommendation

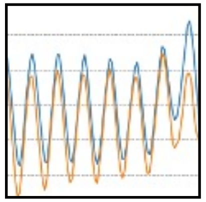
- Almost all simulations show increases in efficiency with fewer showing high levels of accuracy compared to full fine simulation
- Based on results the trigger with most significant results were for the inland based triggers:
  - 10% and 30% above tidal maximum (IWLT1 and IWLT3)
  - 0.3 m above/below non-tidal residual (IWLT10)
- Switches occurred approximately 4 days prior to landfall

Outline

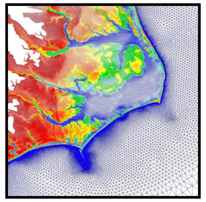
Introduction



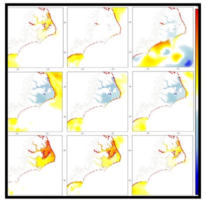
Background and
Previous Work



Motivation and
Remaining Questions

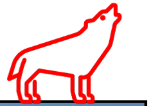


Methods



Results

Discussion



Conclusions and
Future Work

Summary

- Efficiency gains were substantial for simulations on mixed meshes
  - Average efficiency gain of 37%
  - IWLT1: 38%, IWLT3: 54%, IWLT10: 41%
- Accuracy losses were minimal, even with triggers switching from the coarse/source to fine/target mesh late in the simulation
  - Average RMSE: 0.11 m, Bias: 0.02 m
  - IWLT10: RMSE: 0.03 m, Bias: -0.02 m
- All triggers are viable for mixed-mesh simulation using *Adcirpolate* particularly inland water level triggers
- The timing of the switch between meshes should be informed by their floodplain coverage's

Future Work

- Try different trigger values for those implement in this research
- Include a larger suite of triggers, think about those available during real-time forecasting
- Expand station coverage to include a larger spatial area
- Test with other storms in other geographic locations
- Run simulations on same set of nodes on computing cluster and multiple times to gain averages for wall-clock times

Thank You!