Advances in the Unstructured WAVEWATCH III Within Earth System Modeling Framework

NATIONAL WEATHER SERVICE

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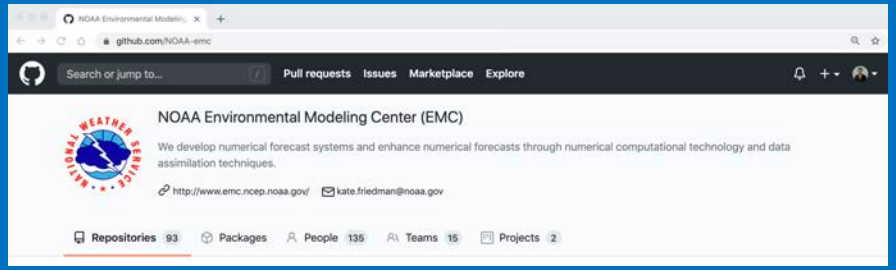
Outline

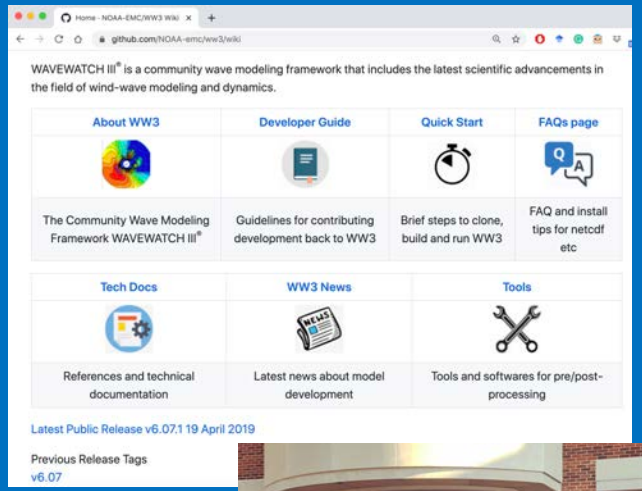
❖ WAVEWATCH III Development

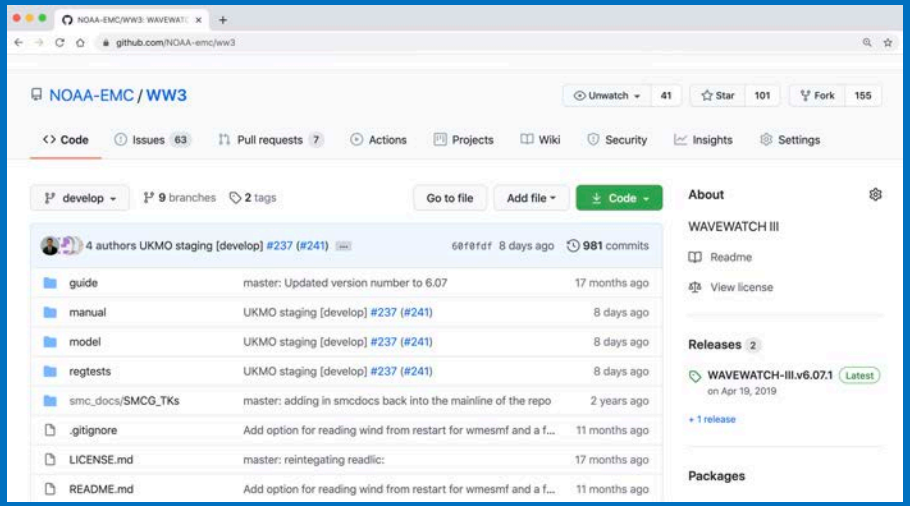
- ❑ **Performance Enhancement & New Features** (Aron Roland, Tyler Hesser & Jane M. Smith)
  - ✓ An Efficient Parallelization Algorithm
  - ✓ Implicit Numerical Solver
  - ✓ Neumann Boundary Condition
- ❑ **New Physics** (Aron Roland, Tyler Hesser & Jane M. Smith)
  - ✓ Vegetation Source Term (*VEG1*)
  - ✓ Adapted Depth Breaking Source Terms (Battjes and Janssen-*DB1* / Thornton and Guza (1983)-*DB2*)
  - ✓ Adapted Triad Interaction Source Term (*TR1*)
- ❑ **Validation**
  - ✓ Lab Cases
  - ✓ Real Case Applications (Arslaan Khalid & Celso Ferreira)
  - ❑ **Ensemble Modeling**
    - ✓ Error Propagation from Atmospheric Models
    - ✓ Uncertainty Evaluation
- ❑ **Wave-Surge Coupling** (Andre Van der Westhuysen & Saeed Moghimi, Zaizhong Ma, Avichal Mehra)
- ❑ **Conclusion & Outlook**

Open Source Software Development Paradigm

https://github.com/NOAA-emc/ww3







Wave Summer School, every July, UMD

NOAA-EMC/WW3:Ali Abdolali and Jessica Meixner
Ifremer: Mickael Accensi
ERDC/USACE: Tyler Hesser
UK MetOffice: Chris Bunney

Users Mailing List:
https://www.lstsrv.ncep.noaa.gov/mailman/listinfo/ncep.list.wwatch3.users

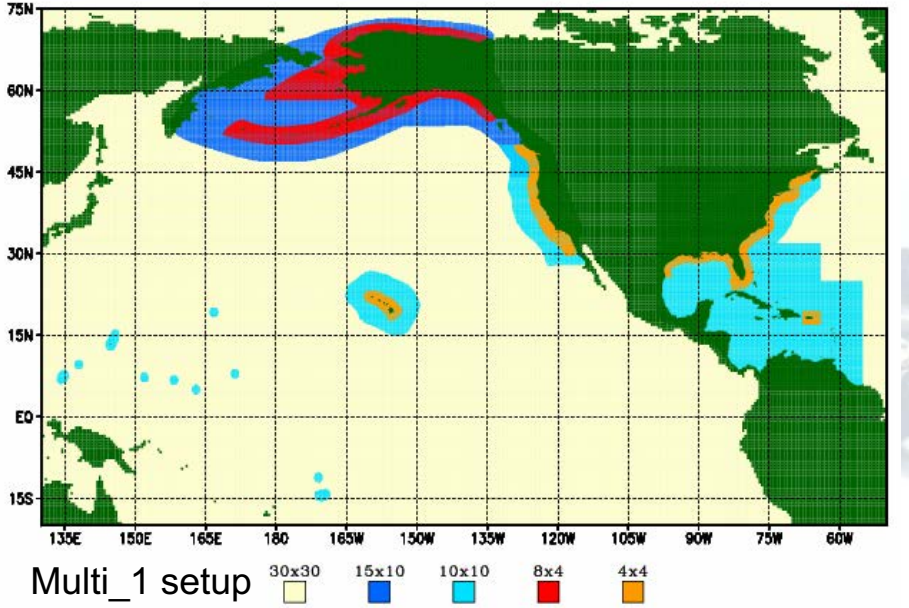
Performance Enhancement & New Features

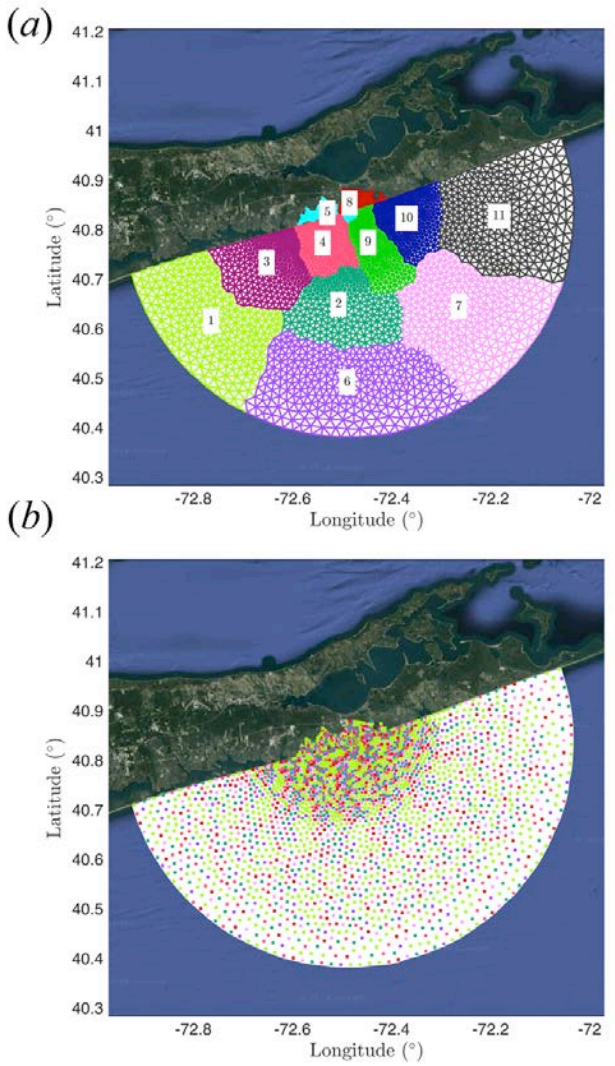
Abdolali A., Roland, A., Van Der Westhuysen, A., Meixner, J., Chawla, A., Hesser, T., Smith, J.M. and M. Dutour Sikiric (2020), Large-scale Hurricane Modeling Using Domain Decomposition Parallelization and Implicit Scheme Implemented in WAVEWATCH III Wave Model, *Coastal Engineering*, 157, 103656, https://doi.org/10.1016/j.coastaleng.2020.103656

The WAVEWATCH III® Development Group (WW3DG), 2019: User manual and system documentation of WAVEWATCH III® version 6.07. Tech. Note 333, NOAA/NWS/NCEP/MMAB, College Park, MD, USA, 326 pp. + Appendices

Domain Decomposition (DD) vs. Conventional Decomposition method in WW3 (Card Deck- CD)

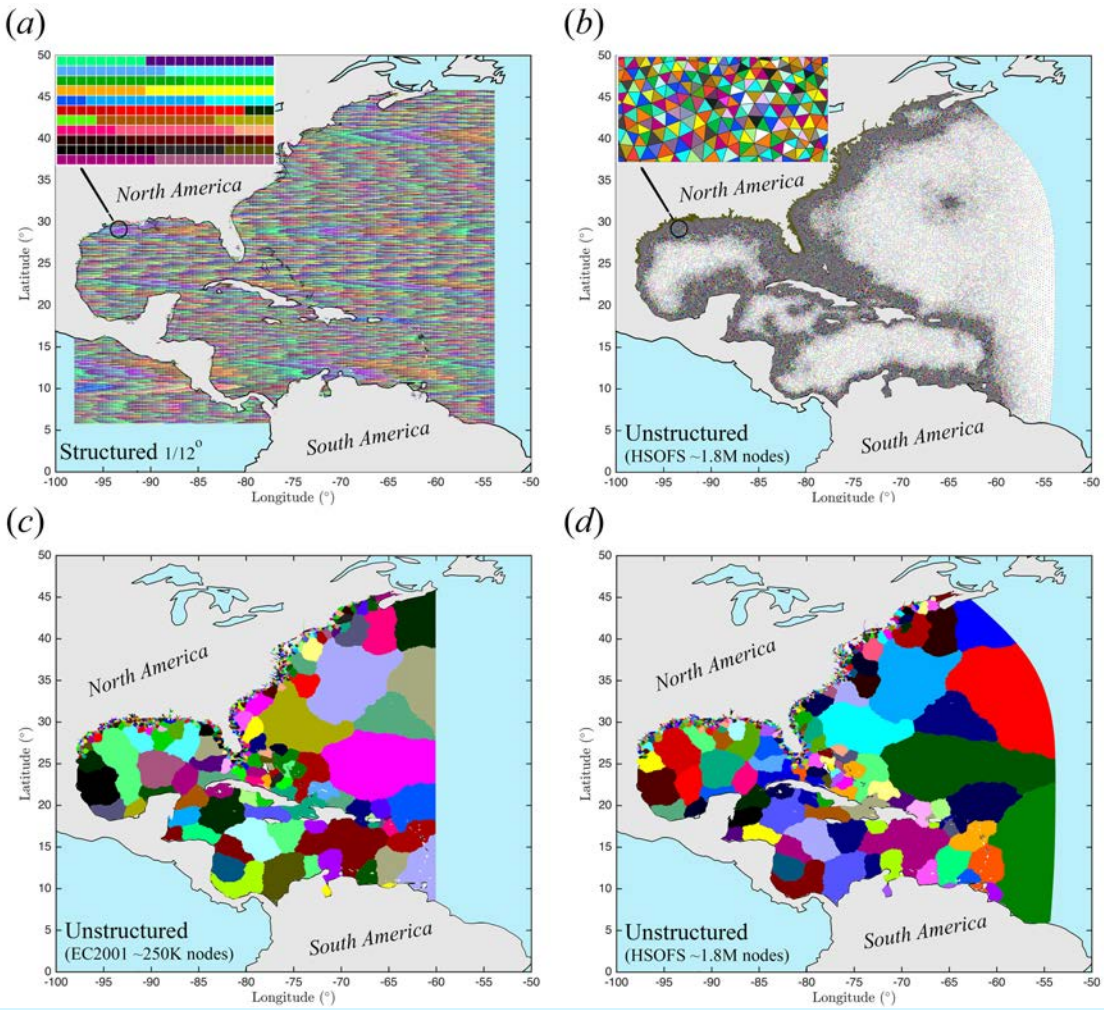
- WW3 was initially developed for structured grids.
- The multi grid capabilities were suitable for multi scale applications with structured grids.





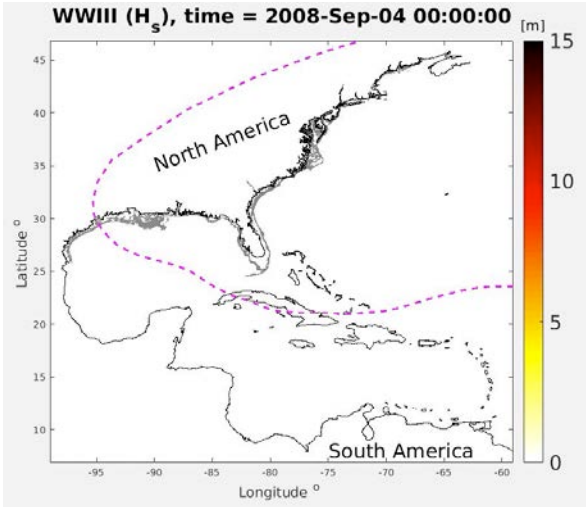
Parallelization

- Extending the capabilities of the model to have unstructured grids with CD decomposition did not impose considerable difficulties for coarse grids with less than ~2 M elements.
- Card Deck is not efficient for high resolution grid (street level) with a large number of elements.
- Coupling with Surge Model in nearshore region requires more efficient decomposition.

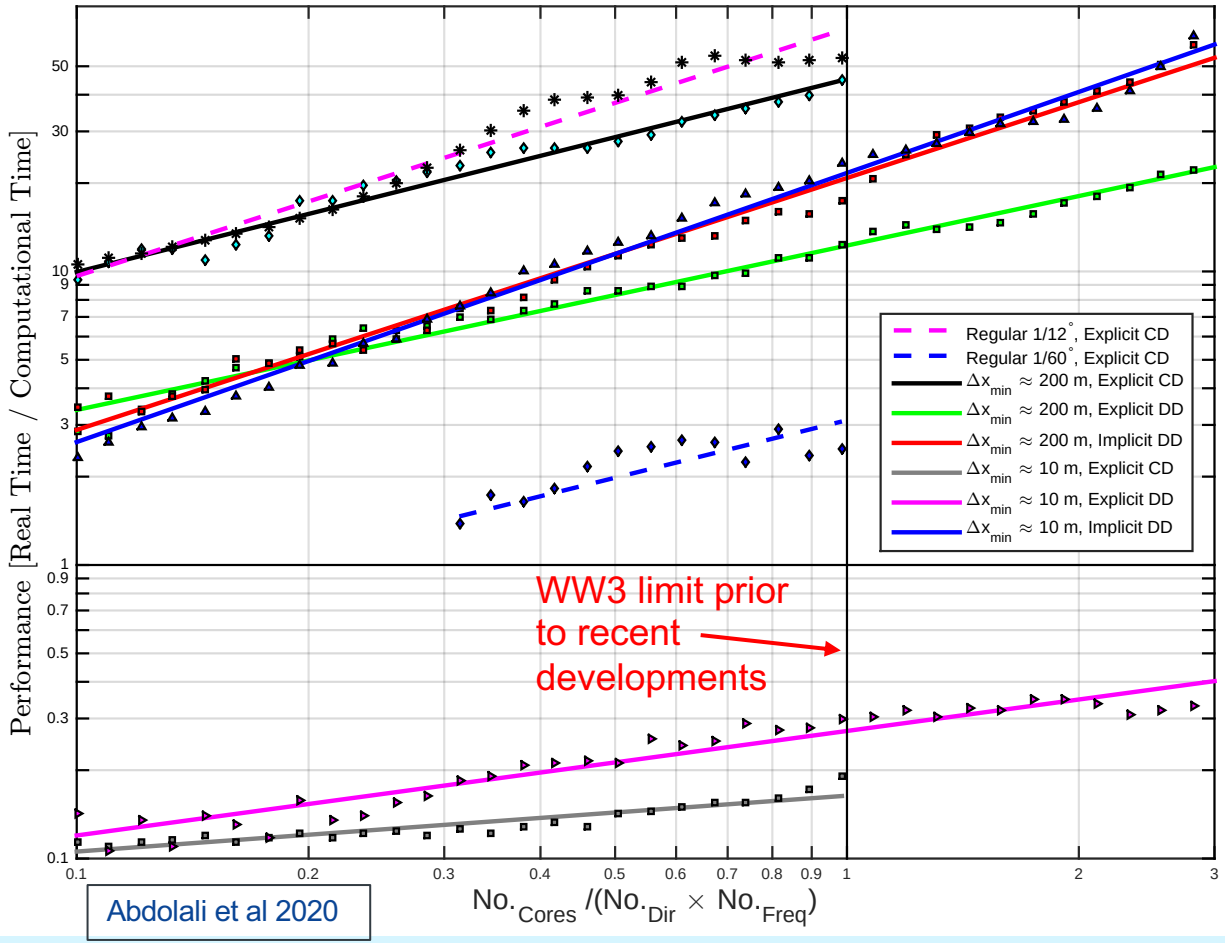


Abdolali et al. 2020

Performance



SL18 mesh (9 M nodes)
Hurricane Ike (12 days)
CPU: 2000
Computational time: 7 hrs



Abdolali et al 2020

New Physics

Vegetation Source Term in WW3

- **Wave-vegetation interaction based on Mendez and Losada (2004)**

$$\frac{\partial F}{\partial x} = -\epsilon_\nu \rightarrow \frac{\partial}{\partial x}\left[E.c_g\right] = -\epsilon_\nu$$

$$\epsilon_\nu = \frac{1}{2\sqrt{\pi}}\rho C_D b_\nu N\left(\frac{kg}{2\sigma}\right)^3 \frac{\sinh^3(k\alpha h) + 3\sinh(k\alpha h)}{3k\cosh^3(kh)} H_{rms}^3 \quad \Rightarrow \quad S_{d,veg} = -\sqrt{\frac{2}{\pi}} g^2 \bar{C}_D b_\nu N\left(\frac{\bar{k}}{\bar{\sigma}}\right)^3 \frac{\sinh^3(\bar{k}\alpha h) + 3\sinh(\bar{k}\alpha h)}{3\bar{k}\cosh^3(\bar{k}h)} \sqrt{E_{tot}} E(\sigma,\theta)$$

C_d= drag coefficient, b_ν= stem diameter, α= relative stem length, N=vegetation density

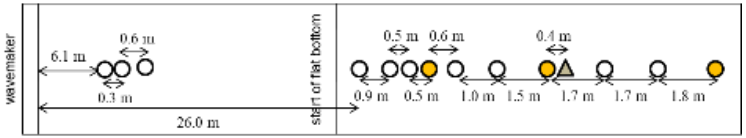
Dalrymple et al. (1984)
Mendez and Losada 2004

- **Implementation called with VEG1 switch**
- **Operates in serial or parallel, implicit or explicit, structured or**
- **unstructured grids**
- **Called after depth limited breaking but before bottom interactions**
- **Spatially and temporally variable vegetation coefficients read with ww3_prnc, or homogeneous variables in ww3_shel**

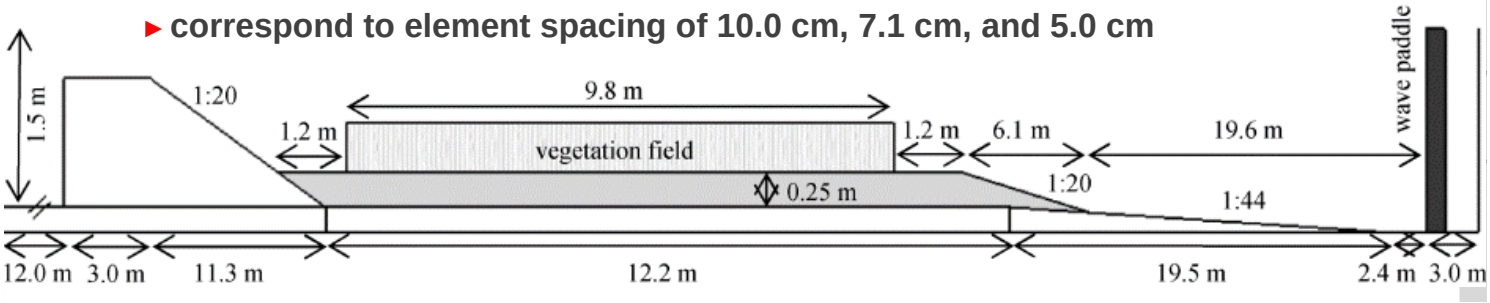
Lab Case

In collaboration with USACE
Tyler Hesser; Jane M. Smith; Mary B. Anderson

- **1.5 m-wide wave flume**
  - 64.1 m long, 1.5 m deep
- **Wave and Water Levels**
  - Depths: 30.5 cm, 45.7 cm, 53.3 cm
  - l_s/h ratios of 1.0 (emergent), 0.91, 0.78
  - Irregular waves
    - T_p ~ 1.25 s to 2.25 s
    - H_{m0} ~ ranging from 5.0 cm to 19.2 cm
- **Polyolefin tubing**
  - 6.4 mm diameter
  - 41.5 cm stem length
  - densities of 100, 200, and 400 stems/m^2
    - correspond to element spacing of 10.0 cm, 7.1 cm, and 5.0 cm

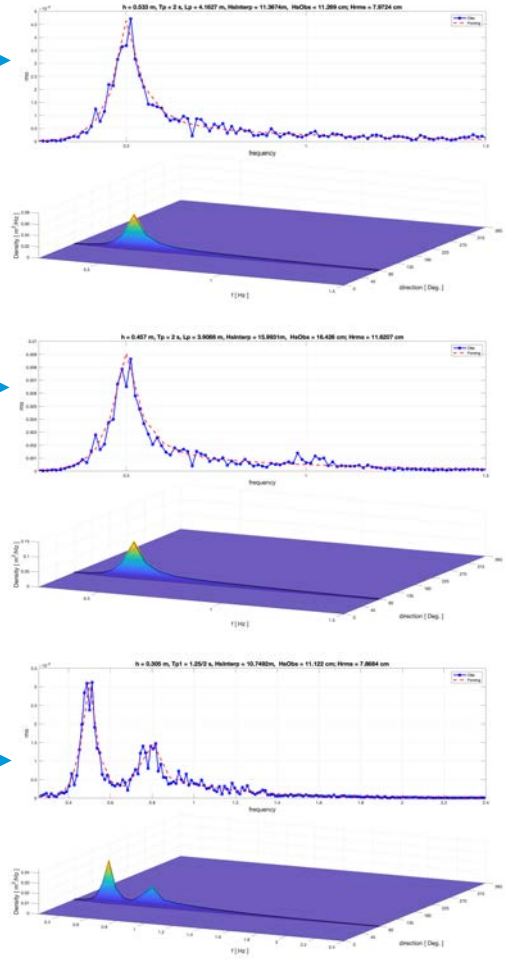


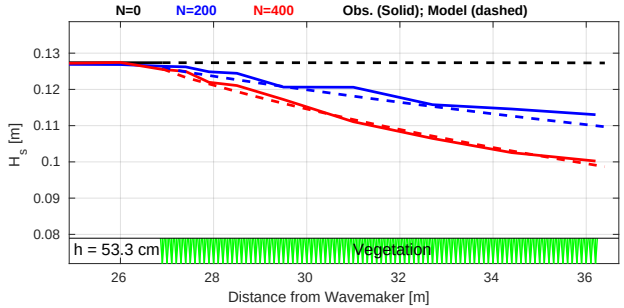
Anderson & Smith 2014

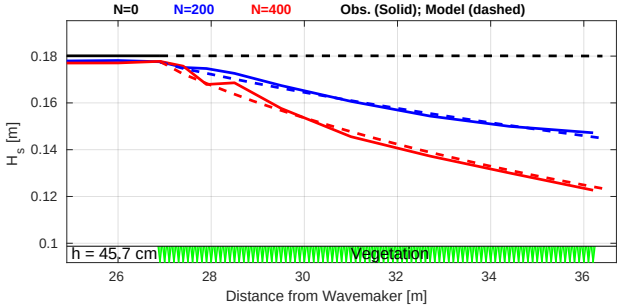


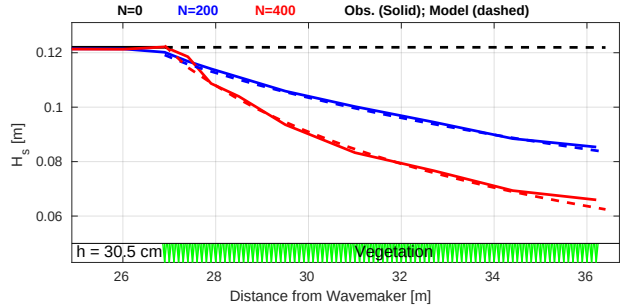
Incident single- and double-peaked irregular wave conditions measured at the beginning of the vegetation (WG 5).

Wave type	Depth h (cm)	Wave height H_0 (cm)	Peak period T_p (s)	Peak wavelength L_p (m)	l_s/h (−)	H_0/h (−)	h/L_p (−)
Single-peaked	53.3	11.1 ± 0.07	1.5	2.89	0.78	0.21	0.18
	53.3	11.0 ± 0.10	1.75	3.53	0.78	0.21	0.15
	53.3	11.2 ± 0.06	2.0	4.16	0.78	0.21	0.13
	45.7	8.1 ± 0.03	1.5	2.74	0.91	0.18	0.17
	45.7	10.9 ± 0.05	1.5	2.74	0.91	0.24	0.17
	45.7	13.9 ± 0.07	1.5	2.74	0.91	0.30	0.17
	45.7	5.0 ± 0.03	2.0	3.91	0.91	0.11	0.12
	45.7	10.7 ± 0.04	2.0	3.91	0.91	0.23	0.12
	45.7	15.3 ± 0.10	2.0	3.91	0.91	0.33	0.12
	45.7	19.2 ± 0.14	2.0	3.91	0.91	0.42	0.12
	30.5	11.3 ± 0.09	1.25	1.88	1.36	0.37	0.16
	30.5	11.0 ± 0.11	1.5	2.36	1.36	0.36	0.13
	30.5	11.2 ± 0.10	1.75	2.82	1.36	0.37	0.11
	30.5	11.1 ± 0.16	2.0	3.28	1.36	0.36	0.09
	30.5	11.2 ± 0.13	2.25	3.73	1.36	0.37	0.08
Double-peaked	53.3	13.7 ± 0.04	1.25/2.0	–	0.78	0.26	–
	53.3	10.9 ± 0.03	1.25/2.0	–	0.78	0.20	–
	45.7	13.6 ± 0.04	1.25/2.0	–	0.91	0.30	–
	45.7	10.7 ± 0.05	1.25/2.0	–	0.91	0.23	–
	30.5	13.0 ± 0.18	1.25/2.0	–	1.36	0.43	–
	30.5	10.7 ± 0.14	1.25/2.0	–	1.36	0.35	–

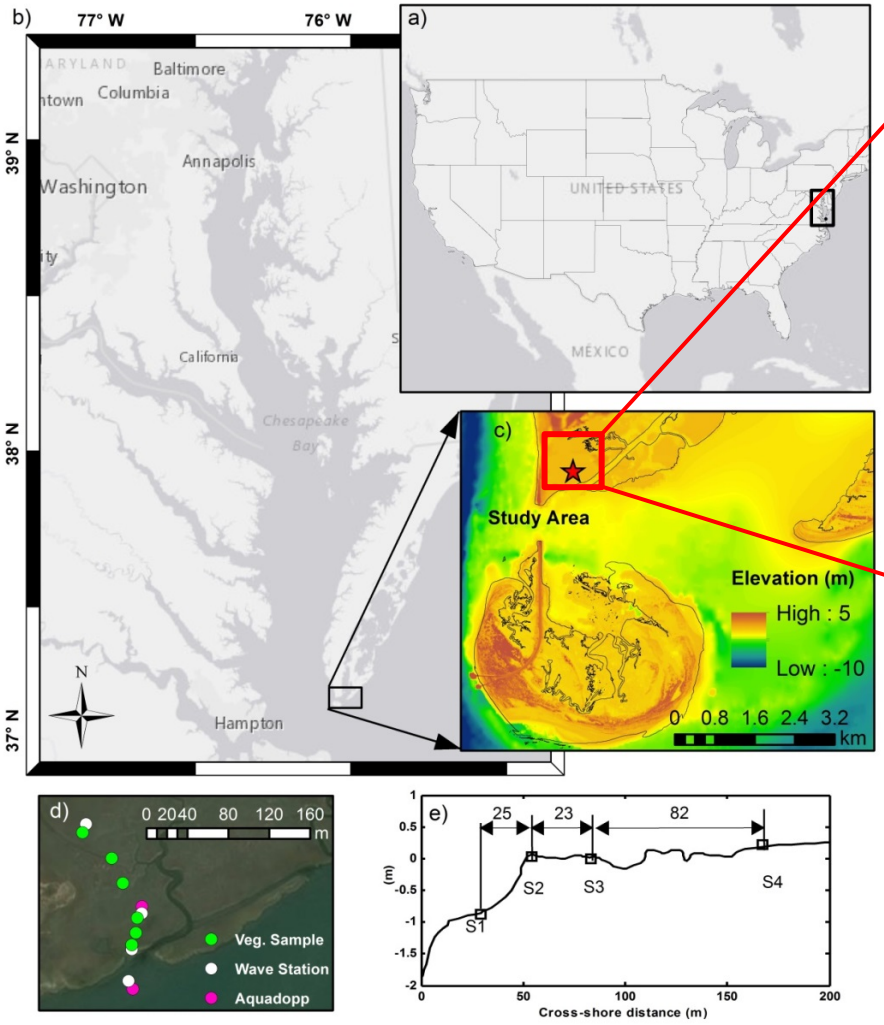








Magothy Bay



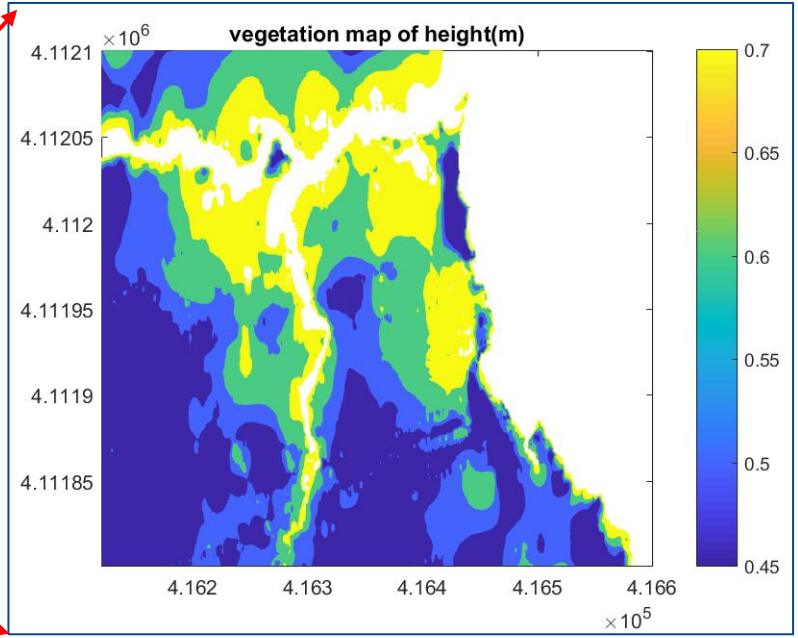
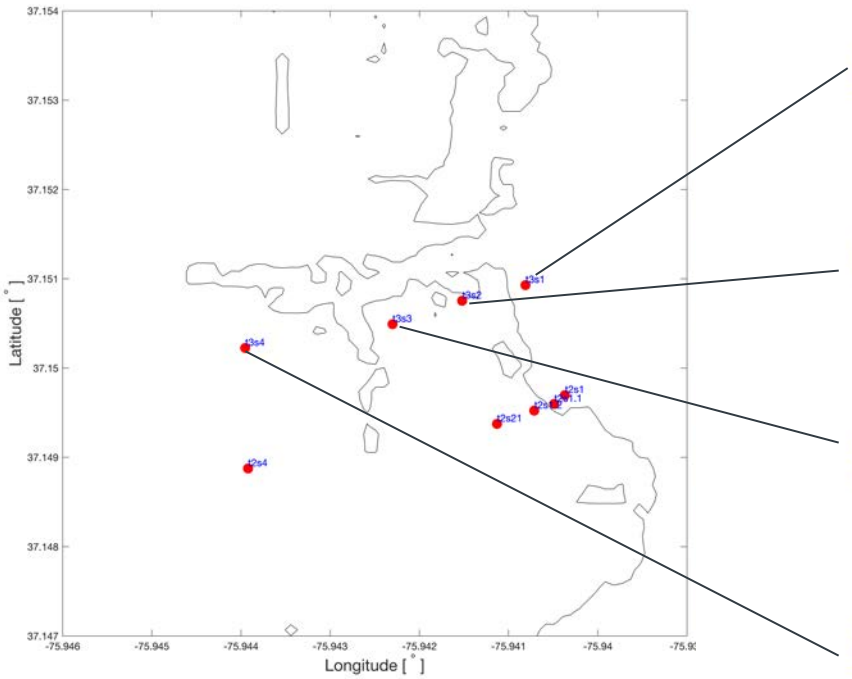
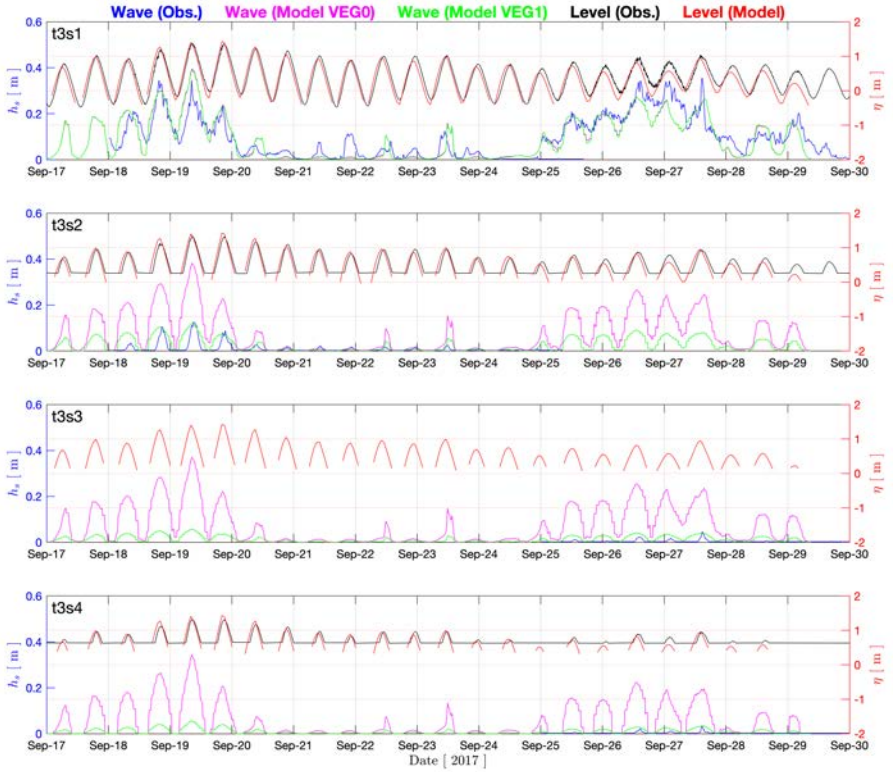


Figure: Magothy Bay, Virginia

Validation (transect 3)

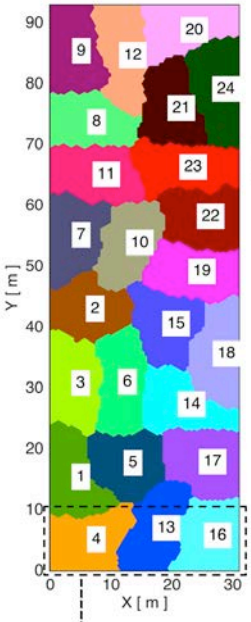


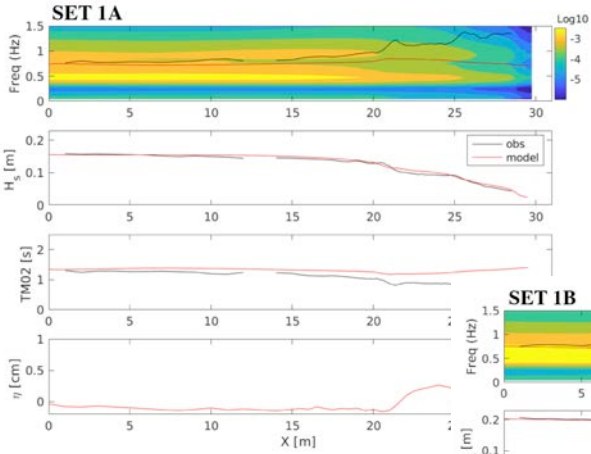


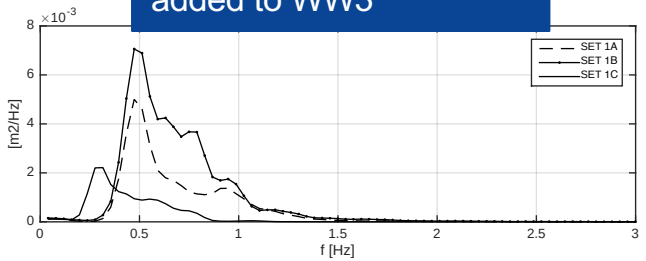
Depth breaking/triad interaction

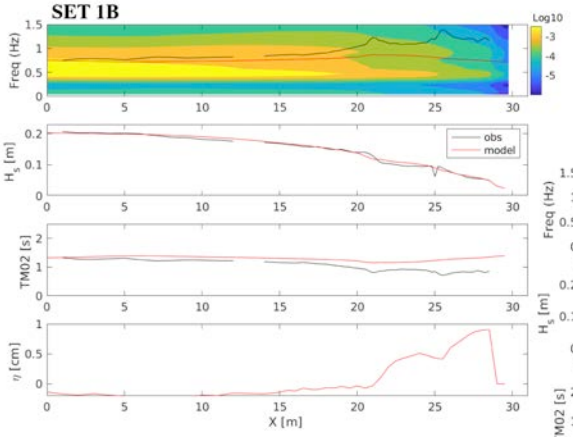
Laboratory case (boers 1996) ww3_tp2.19

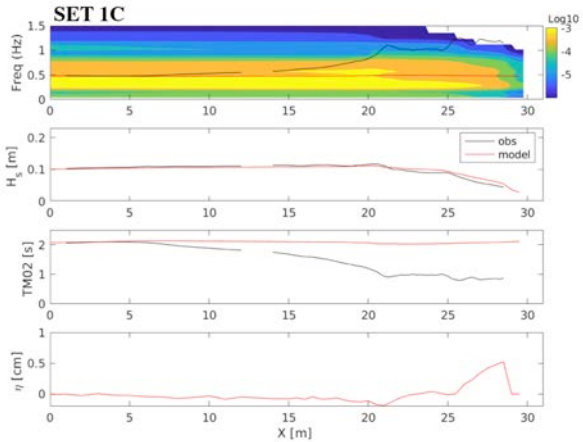
A new Neumann boundary condition is added to WW3

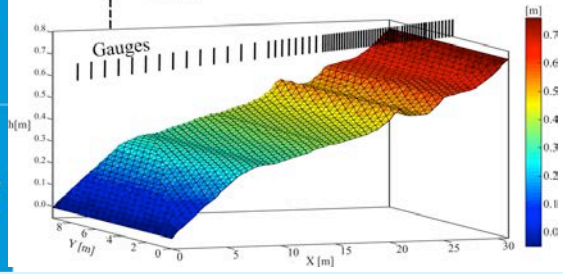








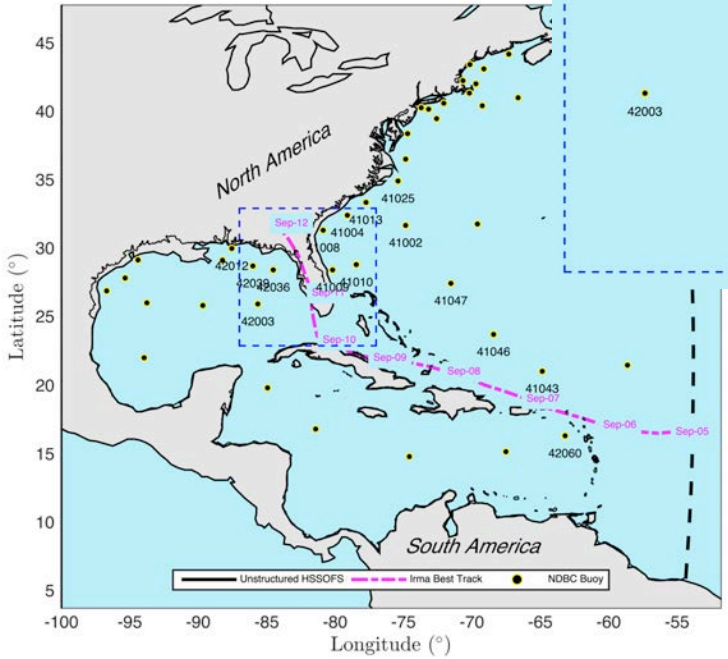




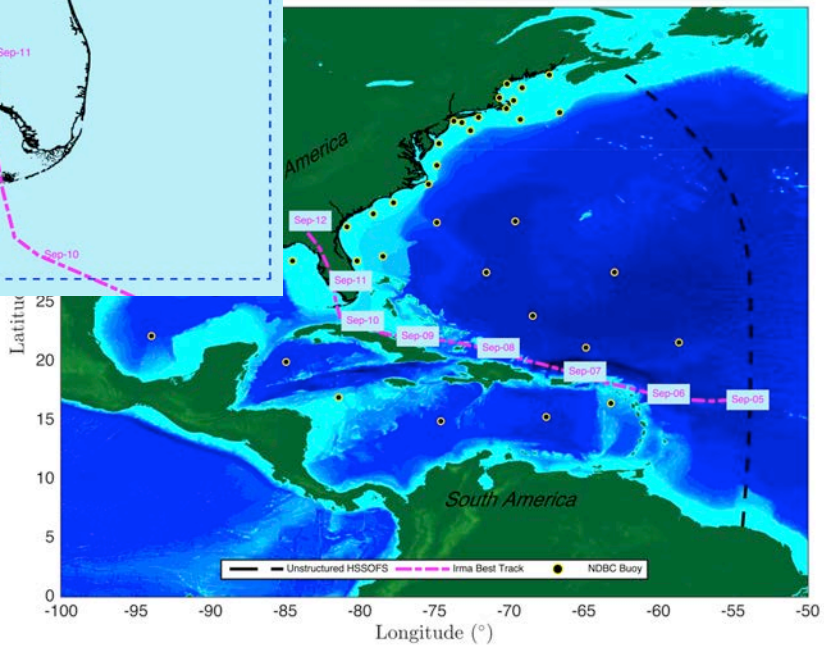
Large Scale Application

Isabel 2003
Ike 2008
Sandy 2012
Irma 2017
Florence 2018

HURRICANE Irma
Sep. 2017



HSOFS Mesh
~1.8 M nodes
~3.5 M elements
lowest resolution.: ~200m



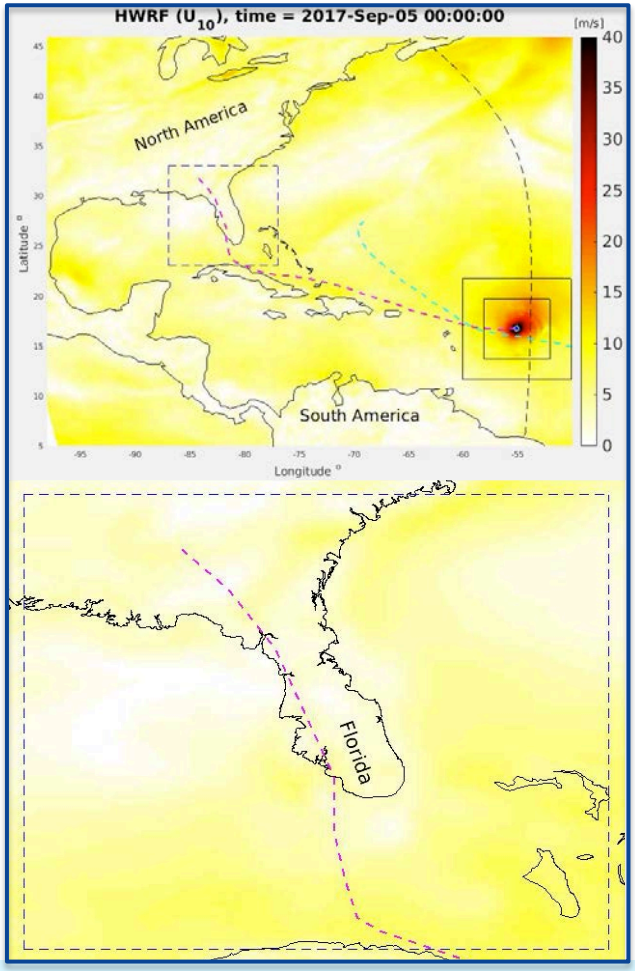
Deterministic Run

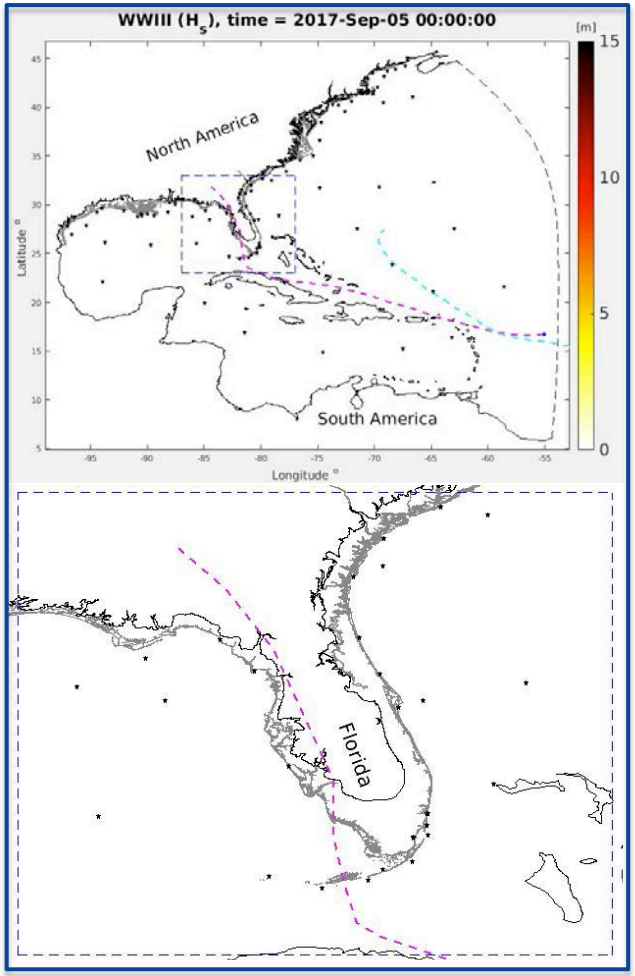
WW3

WW3 v6.07
Parallelization:
Domain Decomposition
Scheme:
Implicit
Abdolali et al 2019

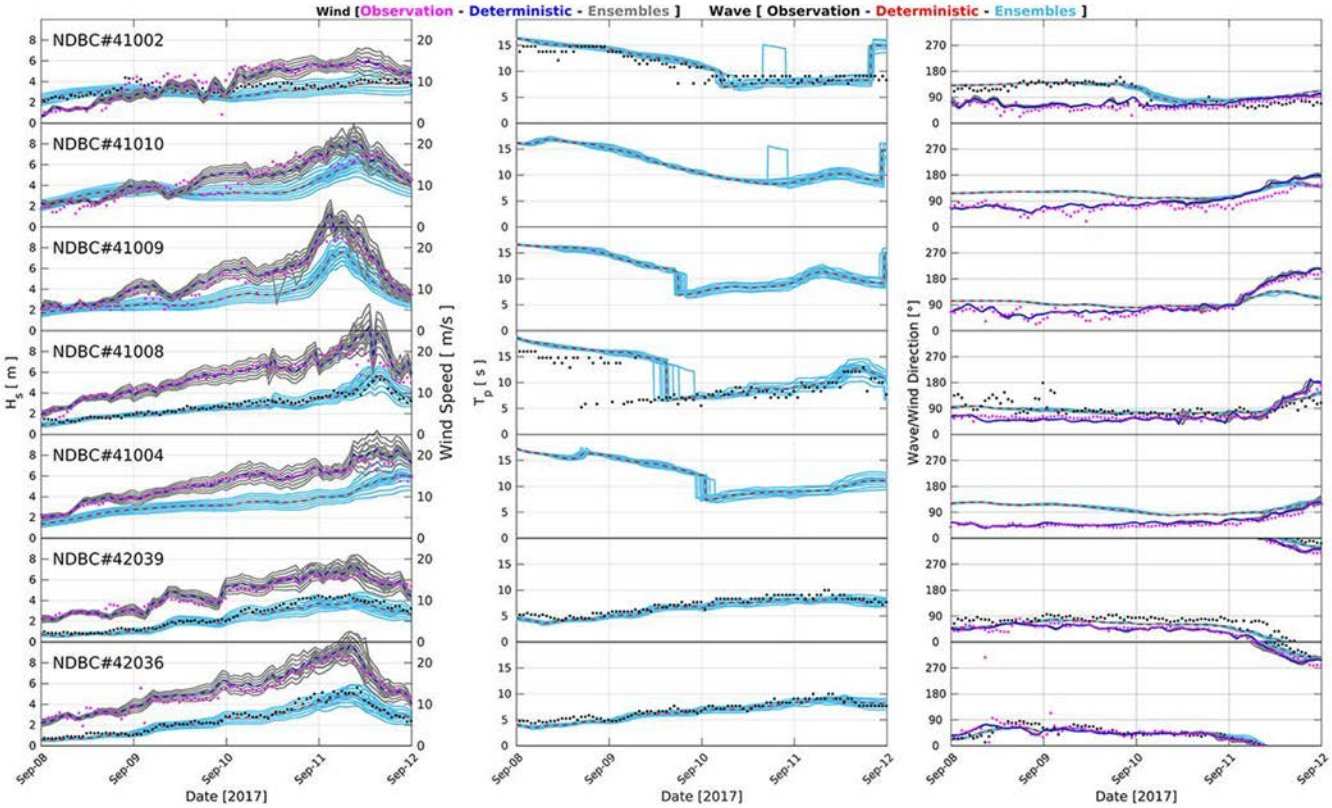
HWRF

Three moving nested grids
Data Assimilation
Ocean Coupling
40 Ensemble Members

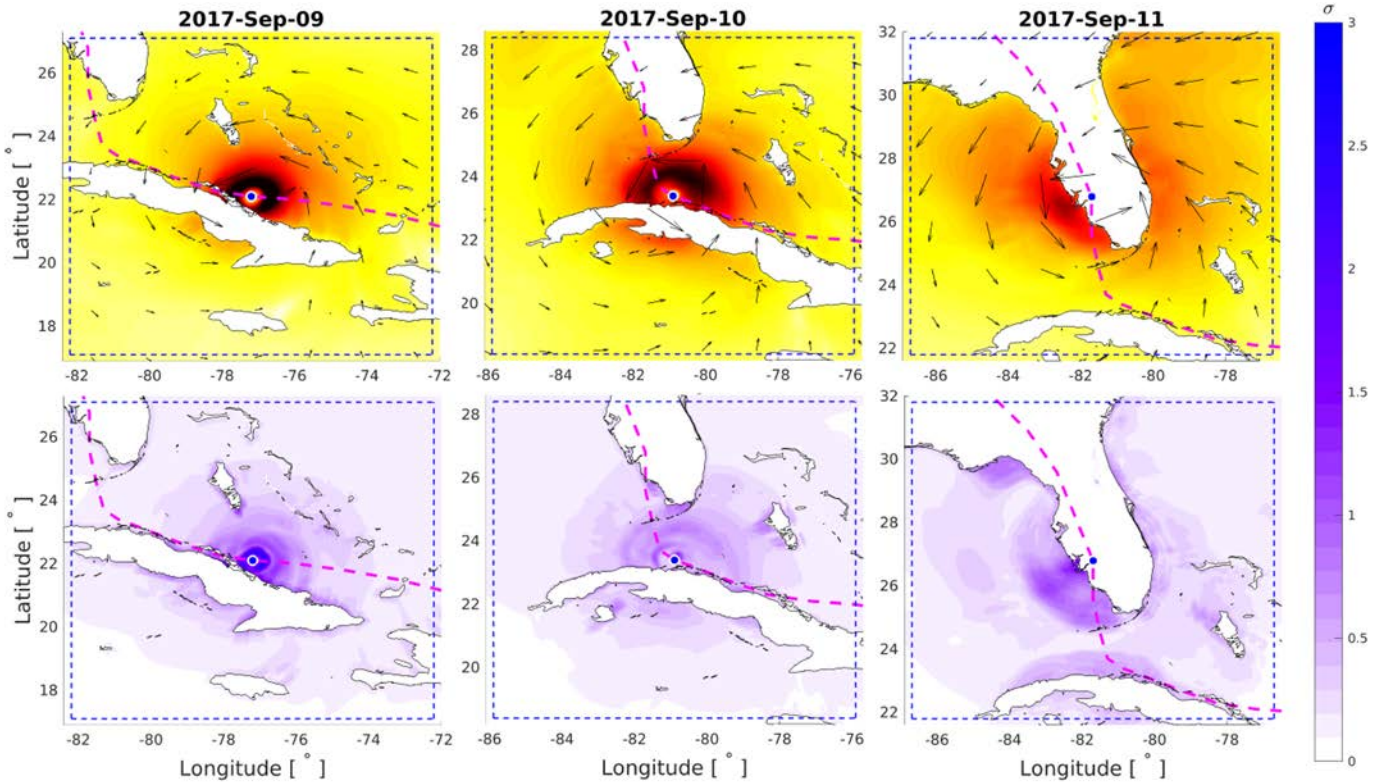




Validating HWRF and WW3 ensembles

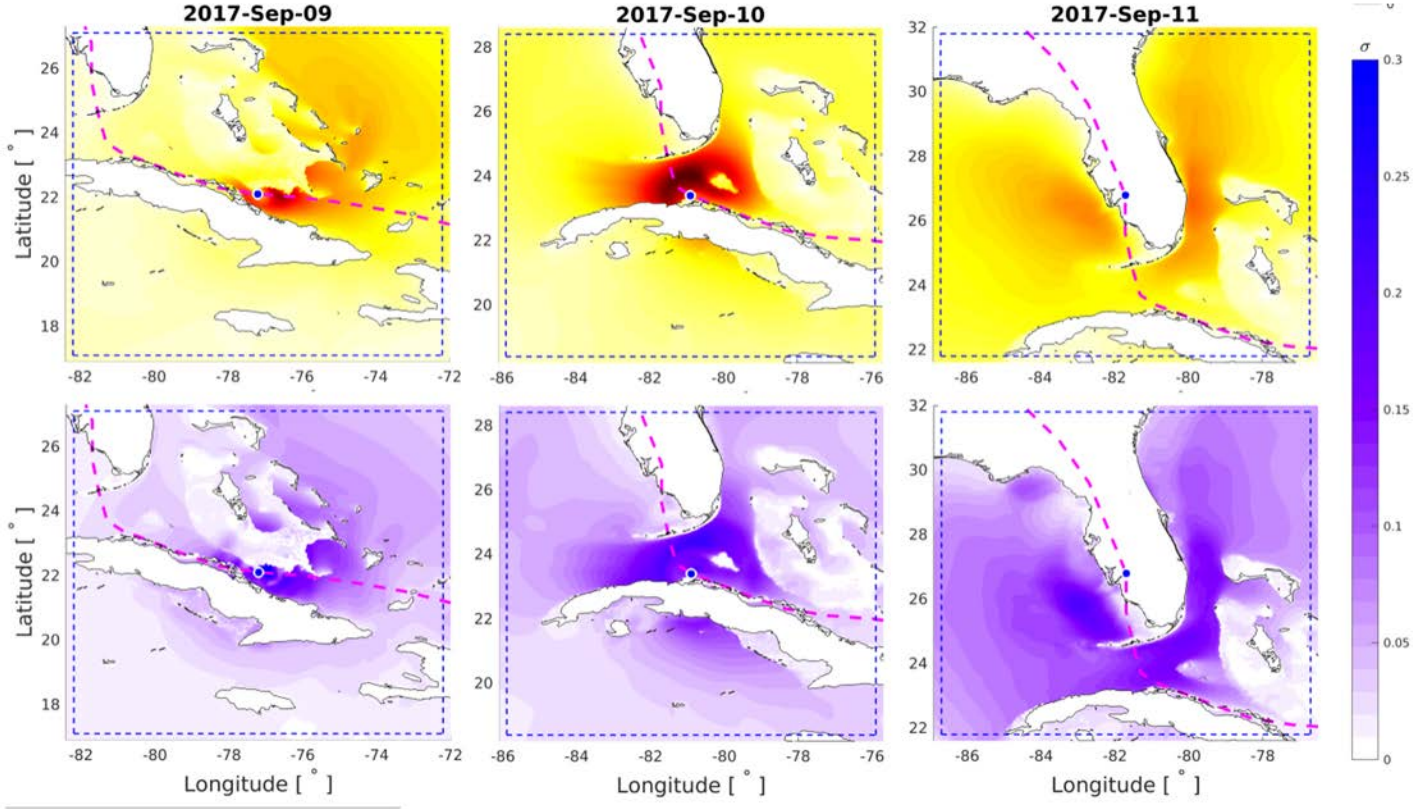


U_{10}: Ensemble Mean and StDev



Z. Ma, B. Liu, A. Mehra, A. Abdolali, A. van derWesthuysen, S. Moghimi, S. Vinogradov, Z. Zhang, L. Zhu, K. Wu, R. Shrestha, A. Kumar, V. Tallapragada, N. Kurkowski (2020), Investigating the impact of High-resolution Land-sea Masks on Hurricane Forecasts in HWRF, *Atmosphere*, 2020, (in press)

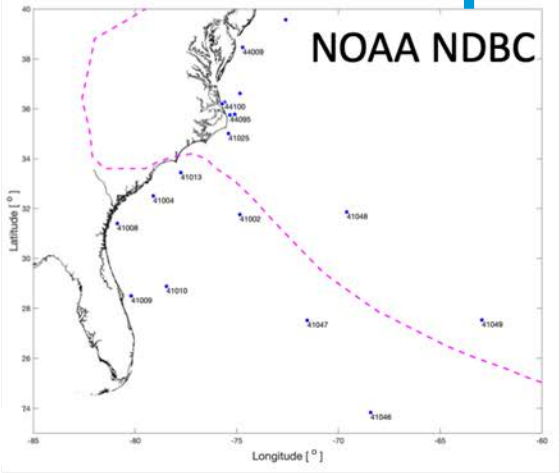
Hs: Ensemble Mean and StDev

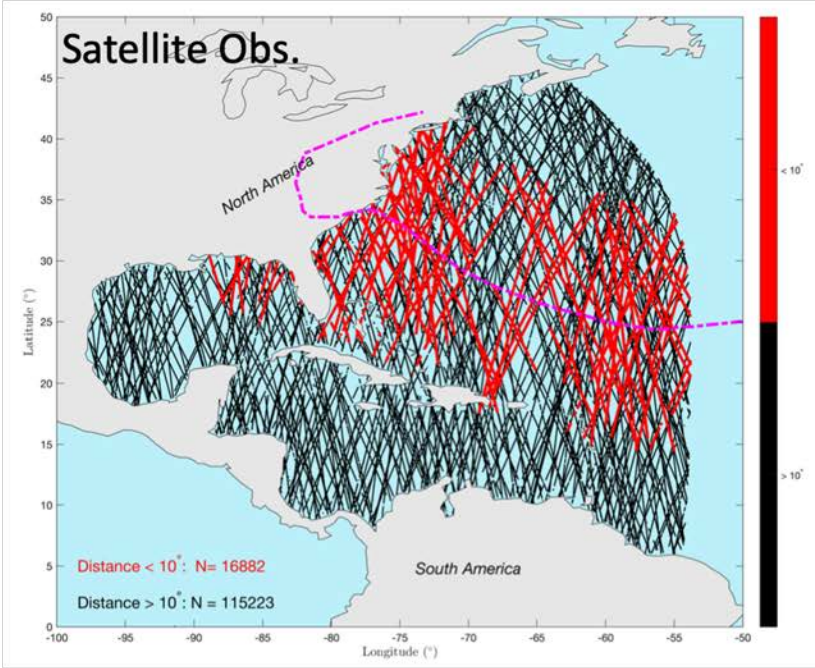


Ali Abdolali, Andre van der Westhuysen, Zaizhong Ma, Avichal Mehra, Aron Roland and Saeed Moghimi (2020) Evaluating the Accuracy and Uncertainty of Atmospheric and Wave Model Hindcasts During Severe Events Using Model Ensembles, *Ocean Dynamics* (Under Review).

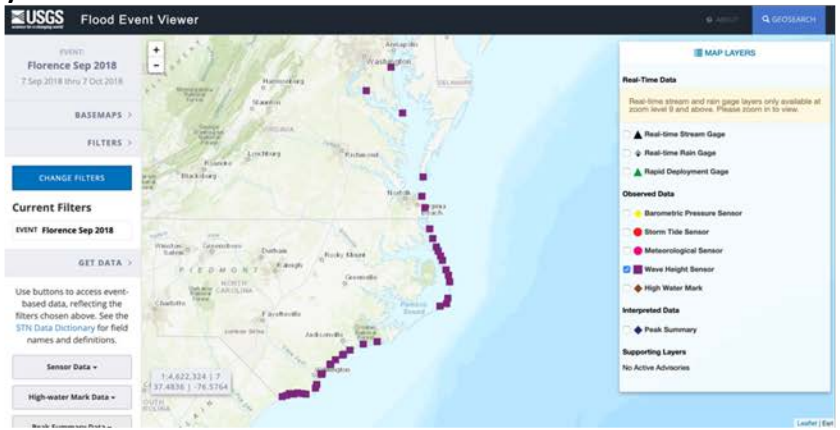
HURRICANE Florence Sep. 2018

Validation data (waves/wind)



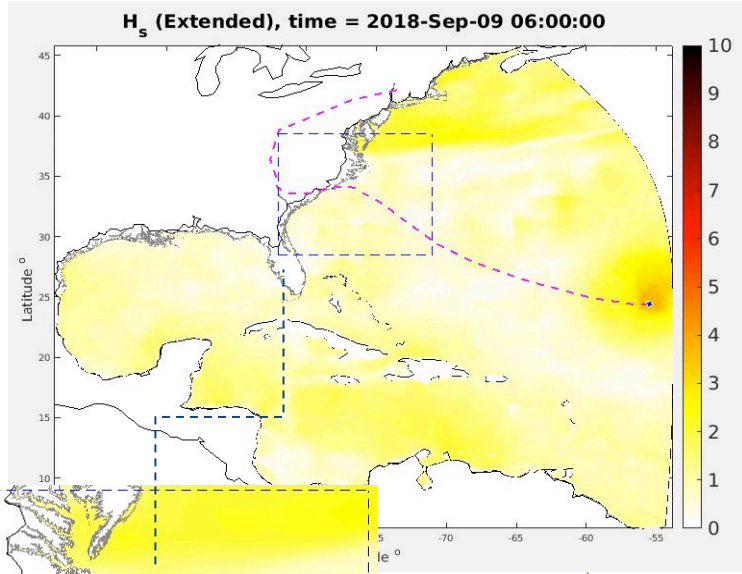


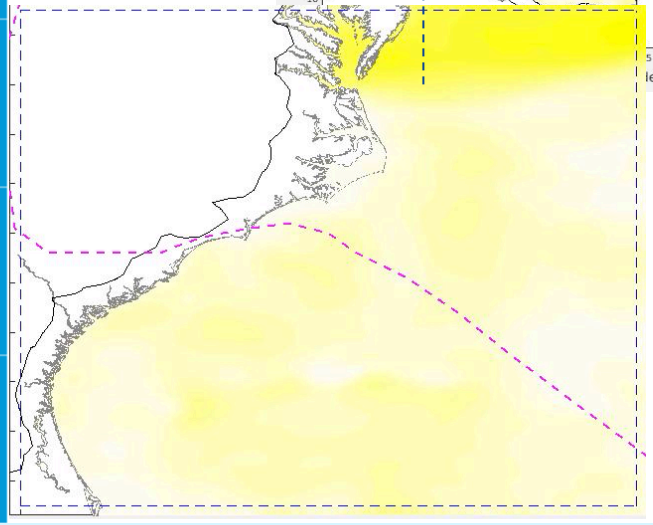
USGS Rapid Deployment



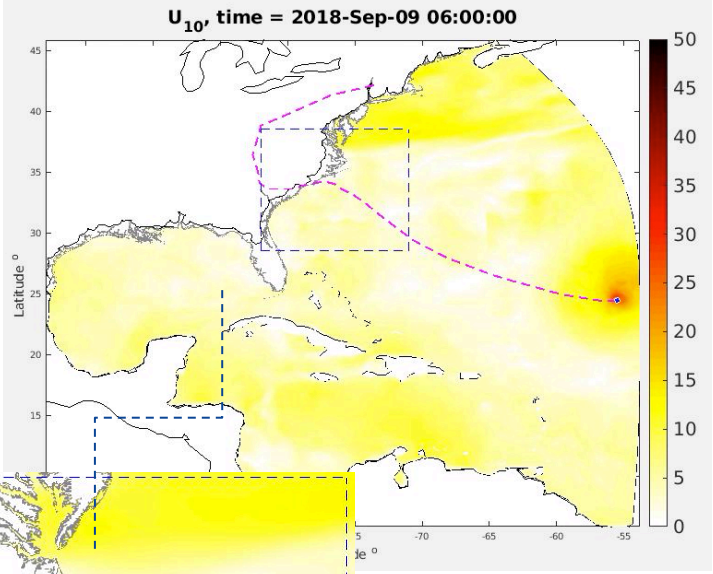
For Official Use Only - Pre-decisional information

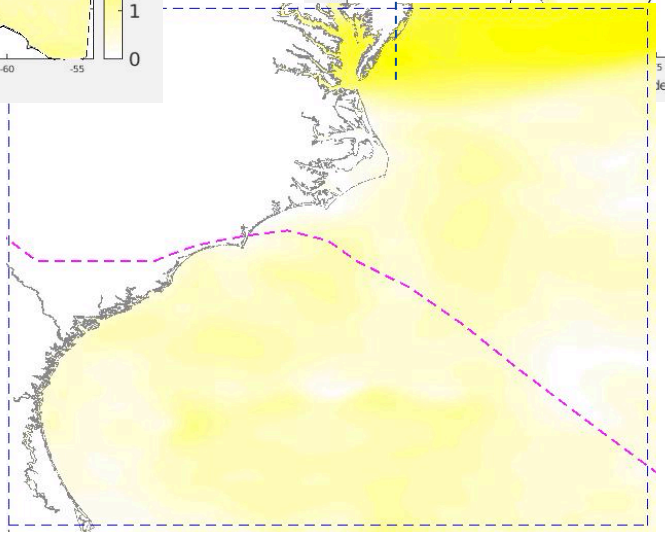
WAVEWATCH III
H_s



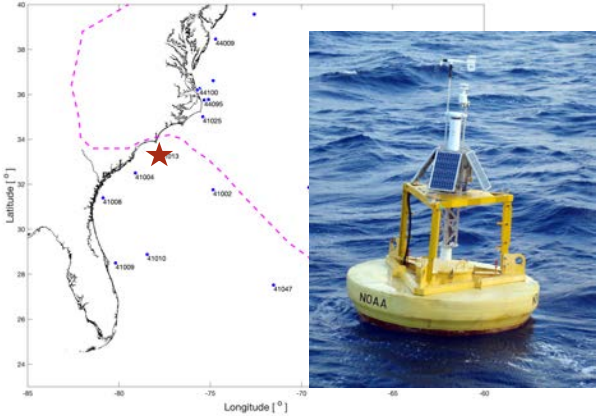


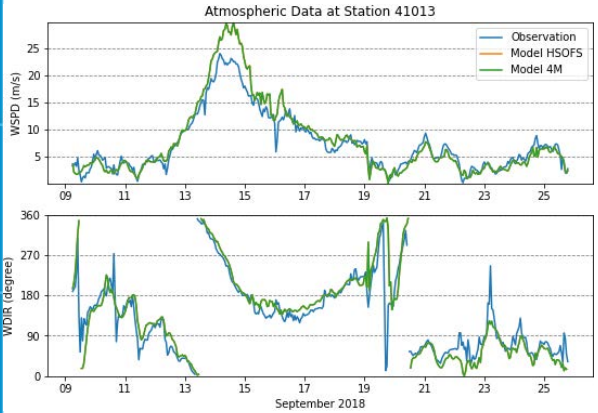
HWRF
U_{10}

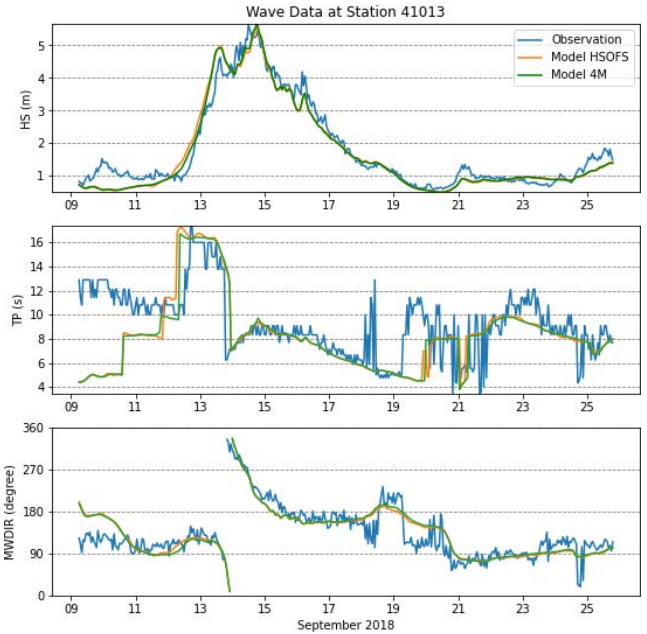


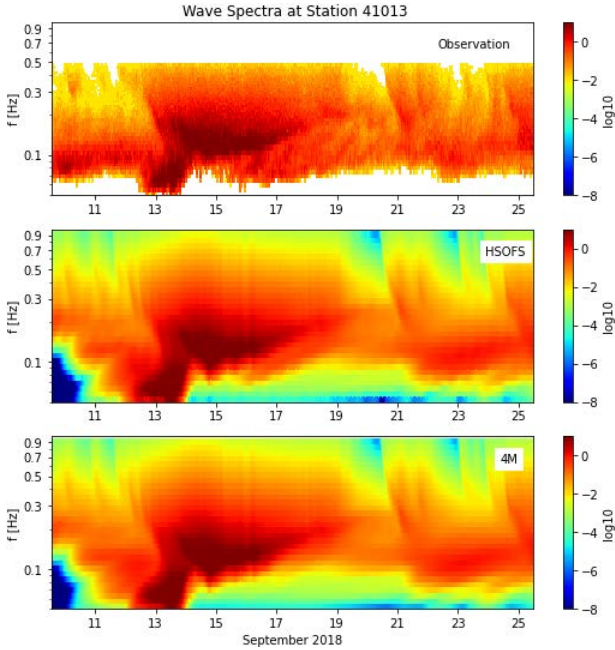


Results – NDBC









Results – USGS

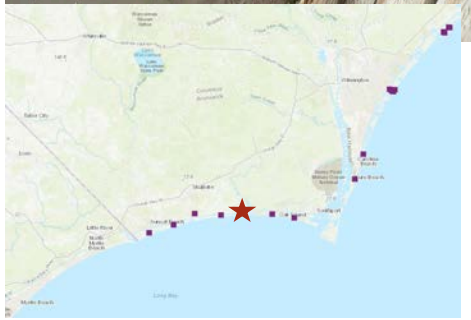
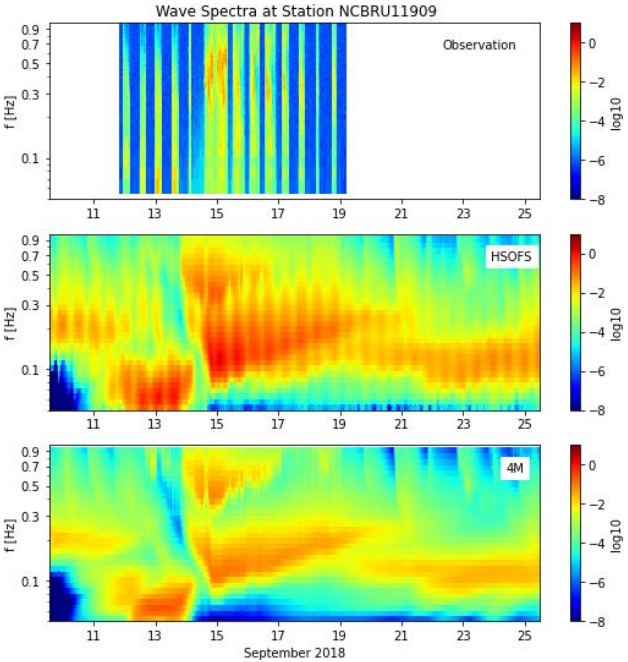
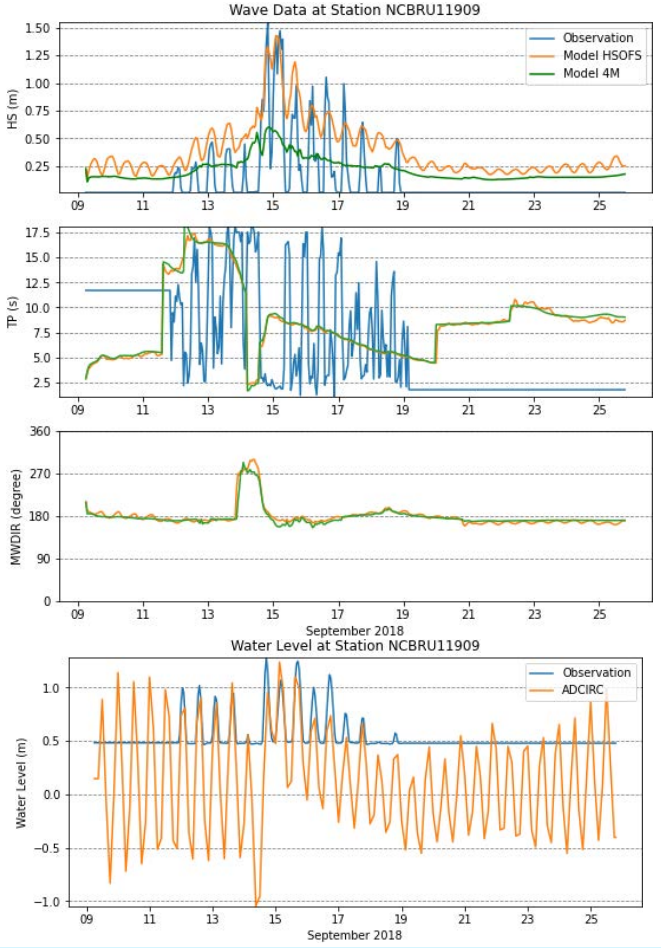


Photo of wave height sensor at Stone Chimney Rd at Lockwoods Folly Inlet, Brunswick County, NC, 09/12/2018. Photograph by Anthony Gotvald, USGS GA.





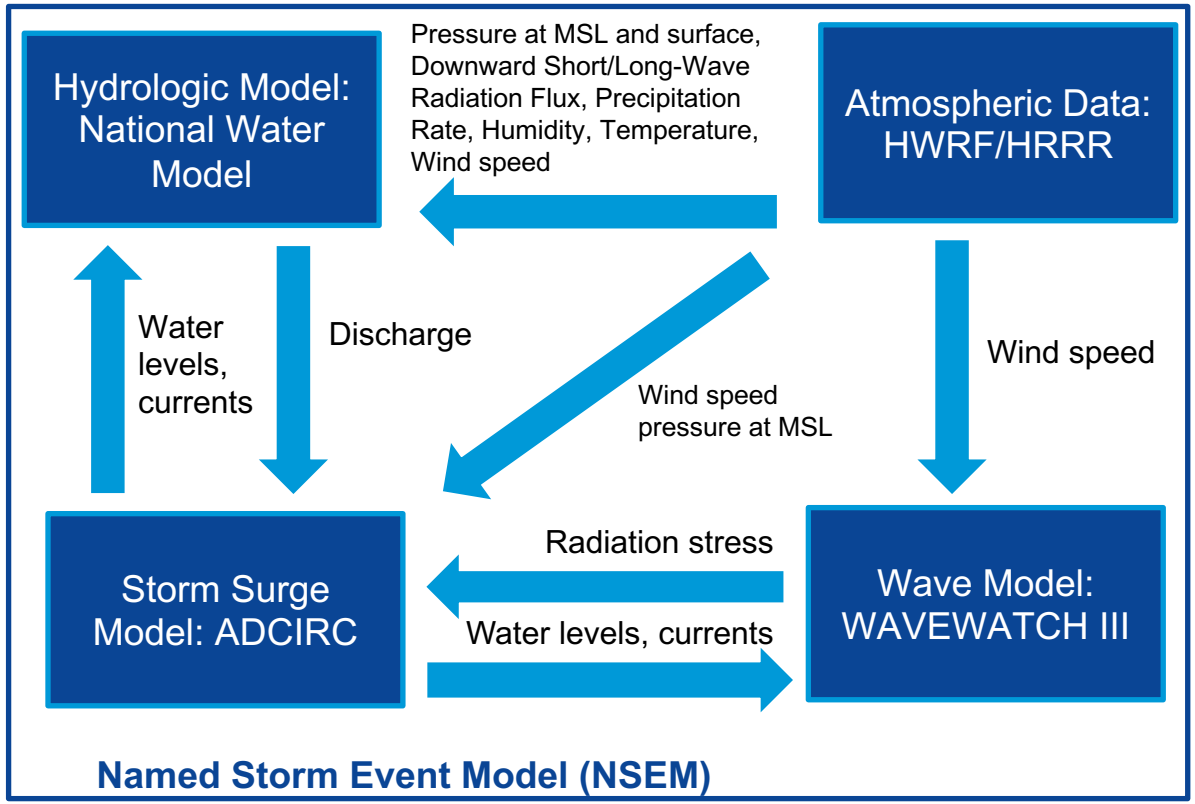
Wave-Surge Coupling

COASTAL Act

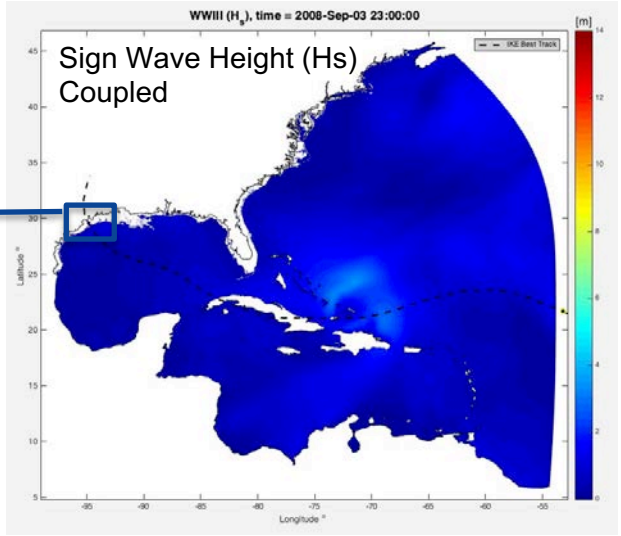
Alaska Coastal Ocean Forecast System (ALCOFS)

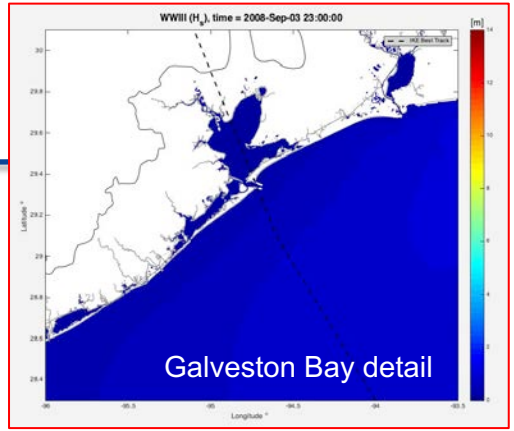
COASTAL Act: Named Storm Event Model

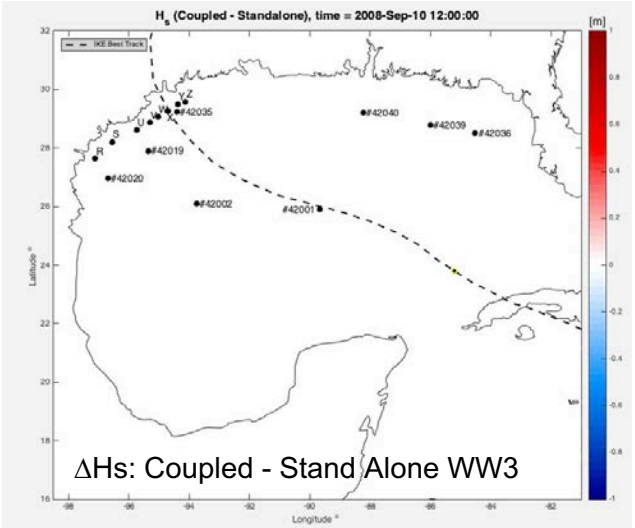
- An ADCIRC-WW3 application (“App”) in NUOPC/NEMS
- Based on NEMS interfaces or “Caps” and ESMF framework
- One-way atmospheric forcing from gridded data file (HWRF model)
- Two-way exchange between ADCIRC and WW3 models
- To include river discharge from NWM

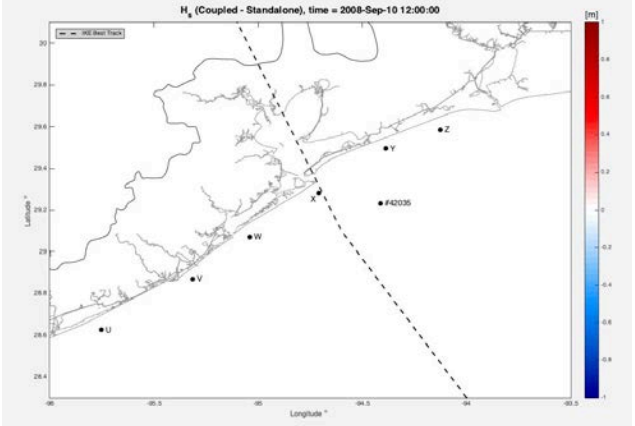


Moghimi et al. 2020
Bakhtyar et al. 2020


WWIII (Hs), time = 2008-Sep-03 23:00:00
Sign Wave Height (Hs)
Coupled
IKE Best Track
[m]
Latitude °
Longitude °

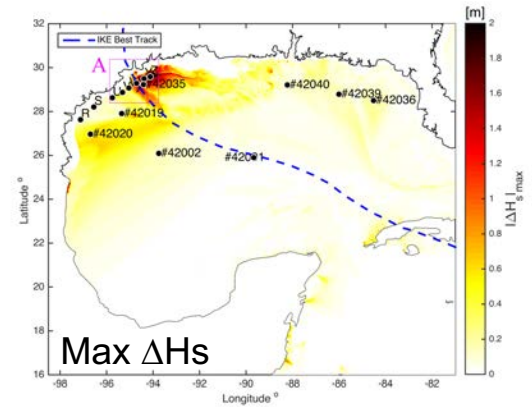

WWIII (Hs), time = 2008-Sep-03 23:00:00
Galveston Bay detail
[m]
Latitude °
Longitude °

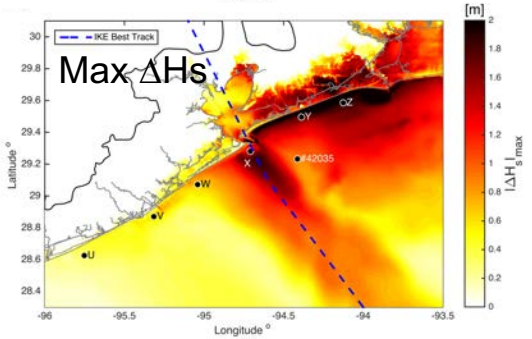

Hs (Coupled - Standalone), time = 2008-Sep-10 12:00:00
ΔHs: Coupled - Stand Alone WW3
IKE Best Track
#42035
#42040
#42039
#42036
#42019
#42020
#42002
#42001
[m]
Latitude °
Longitude °

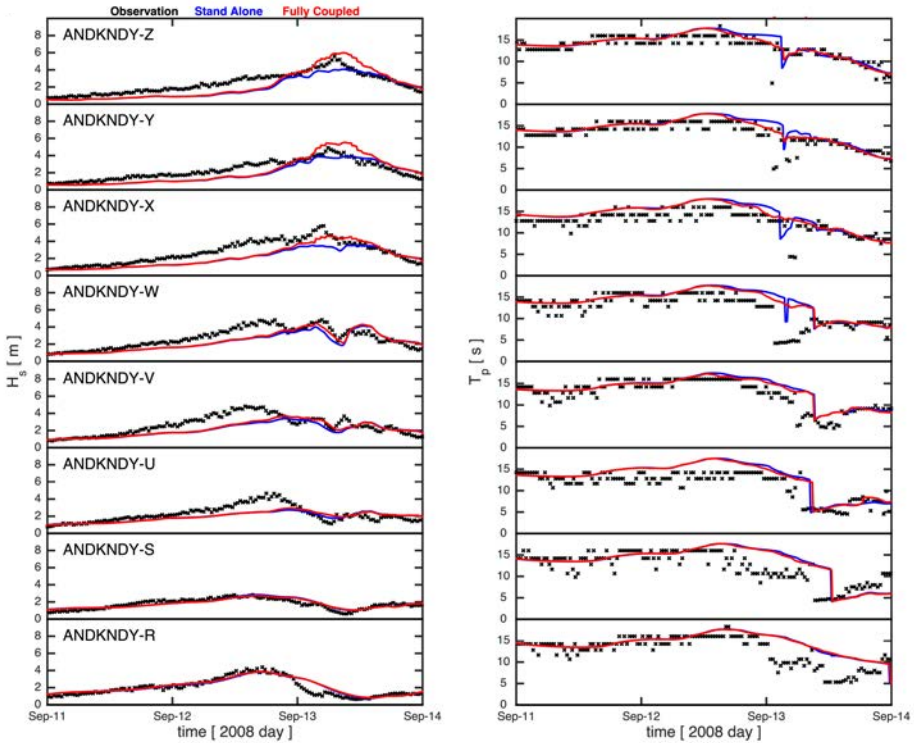

Hs (Coupled - Standalone), time = 2008-Sep-10 12:00:00
IKE Best Track
#42035
[m]
Latitude °
Longitude °

Hurricane Ike (Sept 3-14, 2008)

ADCIRC-WW3: Wave height validation (Galveston)







Moghimi, S.; Van der Westhuysen, A.; Abdolali, A.; Myers, E.; Vinogradov, S.; Ma, Z.; Liu, F.; Mehra, A.; Kurkowski, N. Development of an ESMF Based Flexible Coupling Application of ADCIRC and WAVEWATCH III for High Fidelity Coastal Inundation Studies. *J. Mar. Sci. Eng*. 2020, 8, 308.

CONCLUSION & OUTLOOK

- The memory management in WW3, mostly relying on Global Arrays, are now localized throughout the source code to be efficiently utilized within the domain decomposition parallelization concept. Localized in the sense the each CPU just knows about his domain.
- This provides us the needed flexibility on Different HPC architectures and provides the possibility to run 2-way coupled within ESMF & ADCRIC multi-million grid points unstructured grids.
- Near shore physics Implemented (Vegetation Source Term, Adapted Triad Interaction and Depth Breaking Source terms).
- Validation for Laboratory Cases and Large Scale Application for Hurricane Irma 2017 (40 ensembles), Hurricane Florence 2018 are conducted.
- Fully Coupled Wave-Surge (WW3-ADCIRC) is developed, one way coupled to NWM (Fully coupled Wave-Surge-Riverine models under development).

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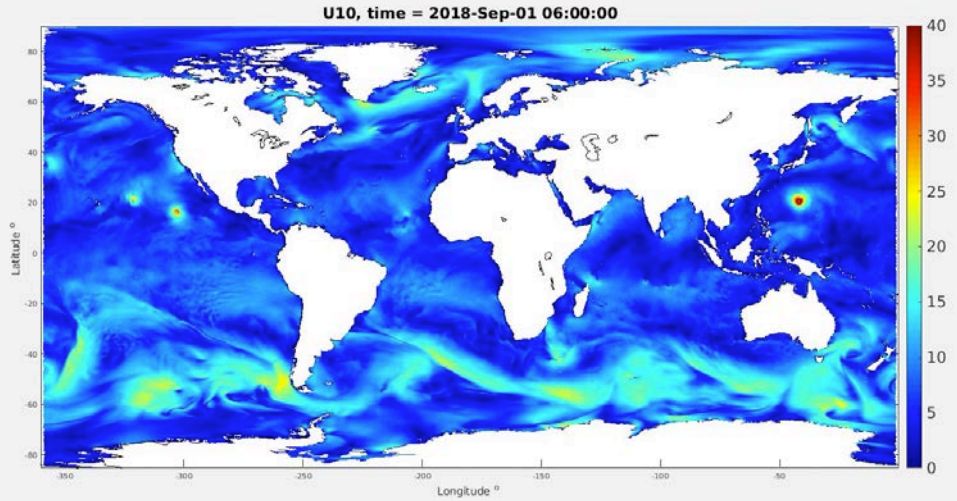

Global Unstructured Grid 5M node, 6 km minimum resolution (W/ W. Pringle & J. Westerink - ND)