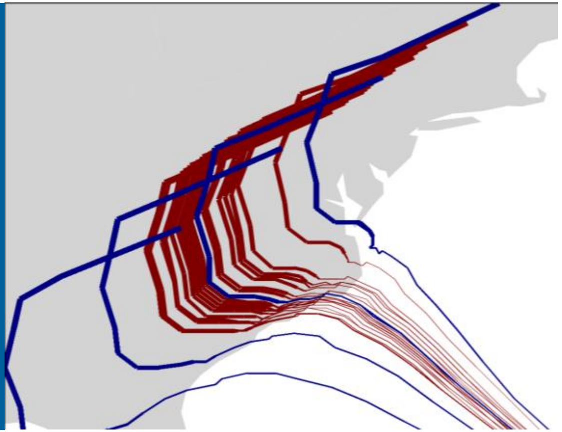
COASTAL Act funding from National Oceanic and Atmospheric Administration (NOAA) through Virginia Institute of Marine Science (VIMS)

Quantifying and Reducing Uncertainty in Hurricane-driven Coastal Flooding Hindcast Simulations



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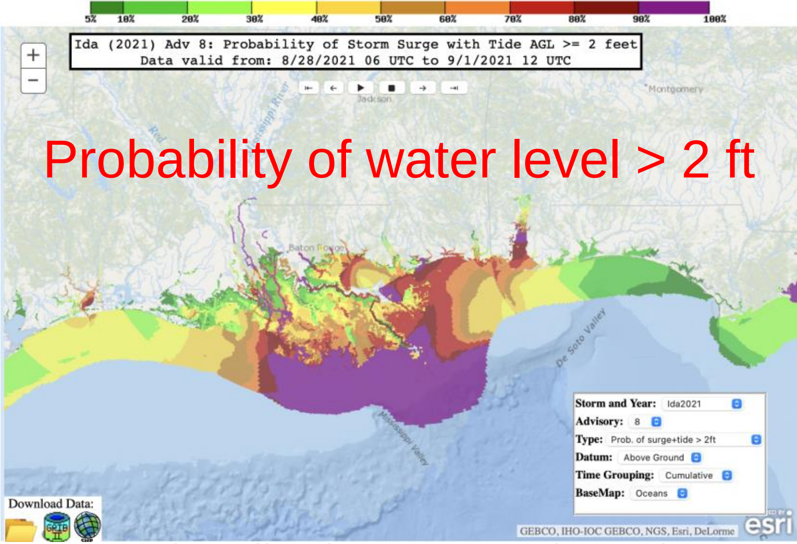
OCT 3, 2023

Project Aims

Exploratory Work

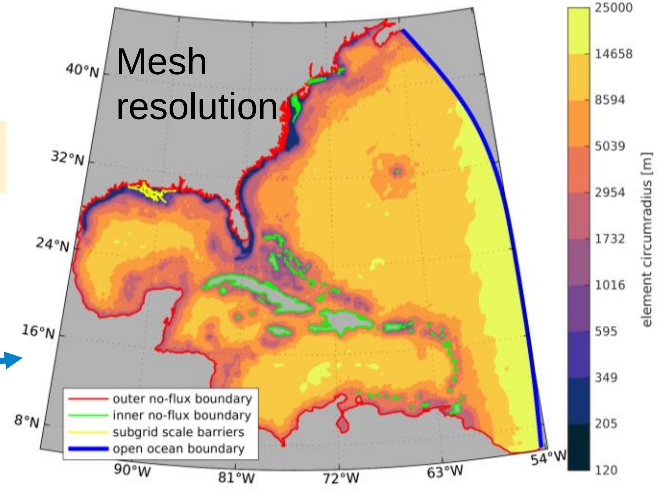
1) **Probabilistic** representation of storm tide and inundation predictions.
2) **Model parameter constraints and uncertainty** for hindcasts.



https://slosh.nws.noaa.gov/psurge/

Problem to Solve

- To do this even with **computationally costly** models that restrict size of ensemble in operational setting
  - Surge + tides (+ wind waves) on high-resolution meshes



HURRICANE STORM TIDE UQ METHODOLOGY

Outline of Methodology

1) **Perturb parameters** of forecasted tropical cyclone (e.g., trajectory, intensity, and size) in a realistic and **efficient** way.

2) **Simulate coastal flooding** in the landfall region of ensemble perturbation from 1) using hydrodynamic model.

3) **Perform probabilistic analysis / uncertainty quantification (UQ)** of water levels / flood-depth for the affected regions, providing useful outputs
   - Hindcast: sensitivity and uncertainty maps
   - Forecast: sensitivity, exceedance water levels/probability maps

1) HURRICANE PERTURBATION

https://github.com/noaa-ocs-modeling/EnsemblePerturbation

4 variables perturbed based on historical forecast errors

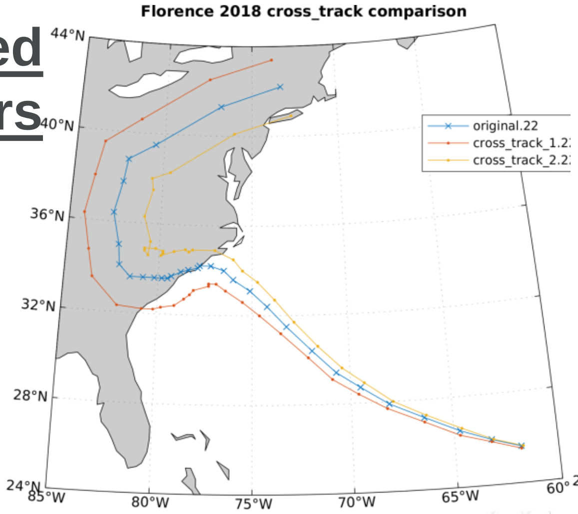
Following similar method to P-Surge

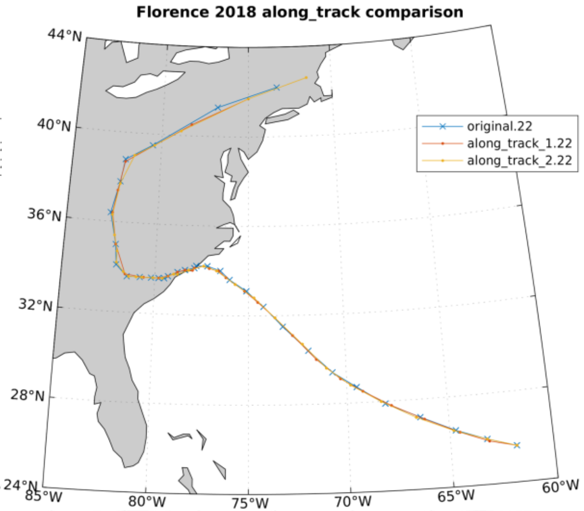
a) **Cross-track [normal]**
   - offset forecast location by perpendicular distance

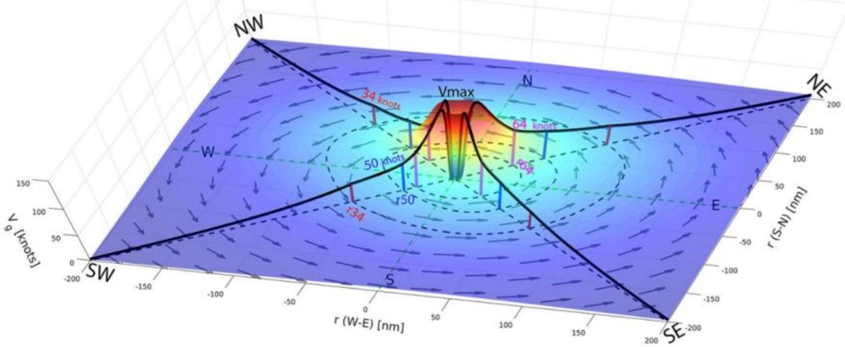
b) **Along-track [normal]**
   - offset forecast location up/down the track

c) **Storm intensity [normal]**
   - Vmax: maximum wind speed
   (central pressure also adjusted accordingly)

d) **Storm size [uniform]**
   - Rmax: radius of maximum wind speed
   - r34, 50, 64-kt radii for Generalized Asymmetric Holland Model (GAHM) parametric vortex







Abdolali, A., et al. (2021). *Ocean Dynamics*, https://doi.org/10.1007/s10236-020-01426-9

1) FORECAST ERROR TABLES

https://github.com/noaa-ocs-modeling/EnsemblePerturbation

TABLE A1. Mean absolute forecast error: cross track (n mi). VT = forecast validation time.

	Initial V_{max} (VT = 0)		
VT (h)	<50 kt	50–95 kt	>95 kt
0	4.98	2.89	1.85
12	16.16	11.58	7.79
24	23.10	16.83	12.68
36	28.95	21.10	17.92
48	38.03	27.76	25.01
72	56.88	47.51	40.48
96	92.95	68.61	60.69
120	119.67	103.45	79.98

TABLE A3. Mean absolute forecast error: V_{max} (kt).

	Initial V_{max} (VT = 0) (kt)		
VT (h)	<50	50–95	>95
0	1.45	2.26	2.80
12	4.01	5.75	7.94
24	6.17	8.54	11.53
36	8.42	9.97	13.27
48	10.46	11.28	12.66
72	14.28	13.11	13.41
96	18.26	13.46	13.46
120	19.91	12.62	13.55

Hindcast

TABLE A4. Upper- and lower-bound forecast errors: R_{max} (sm); sm = U.S. statute mile.

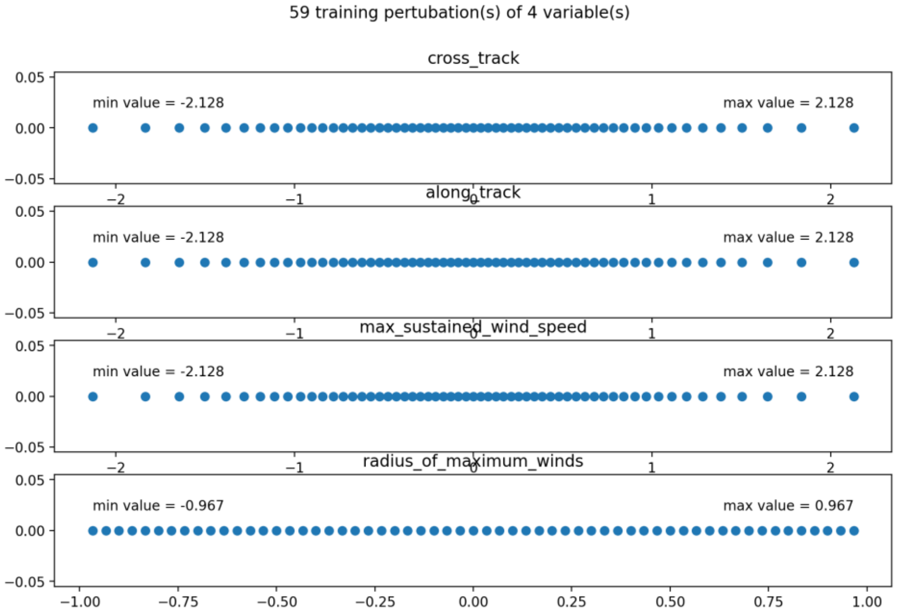
	Initial R_{max} (VT = 0) (sm)				
VT (h)	<15	15–25	25–35	35–45	>45
~~0~~	~~[0.00, 0.00]~~	~~[0.00, 0.00]~~	~~[0.00, 0.00]~~	~~[0.00, 0.00]~~	~~[0.00, 0.00]~~
12	[−17.15, 2.47]	[−13.29, 5.74]	[−11.26, 10.56]	[−14.82, 18.24]	[−22.40, 25.43]
24	[−23.55, 2.31]	[−18.16, 9.45]	[−17.93, 13.31]	[−12.13, 21.01]	[−18.04, 34.39]
36	[−24.90, 4.20]	[−25.18, 9.24]	[−14.88, 17.36]	[−11.19, 24.89]	[−1.08, 43.22]
48	[−30.57, 3.64]	[−29.75, 9.80]	[−13.36, 18.98]	[−8.47, 31.64]	[8.46, 43.78]
60	[−37.83, 1.33]	[−27.25, 10.07]	[−13.70, 19.29]	[−6.35, 31.09]	[8.18, 43.14]
72	[−45.11, −0.99]	[−24.75, 10.35]	[−14.04, 19.60]	[−4.24, 30.54]	[7.93, 42.51]
96	[−55.26, −3.72]	[−29.71, 13.94]	[−11.43, 19.67]	[0.37, 30.46]	[2.49, 38.55]
120	[−61.26, −9.56]	[−35.46, 11.77]	[−11.71, 19.62]	[−0.84, 32.59]	[3.19, 40.56]

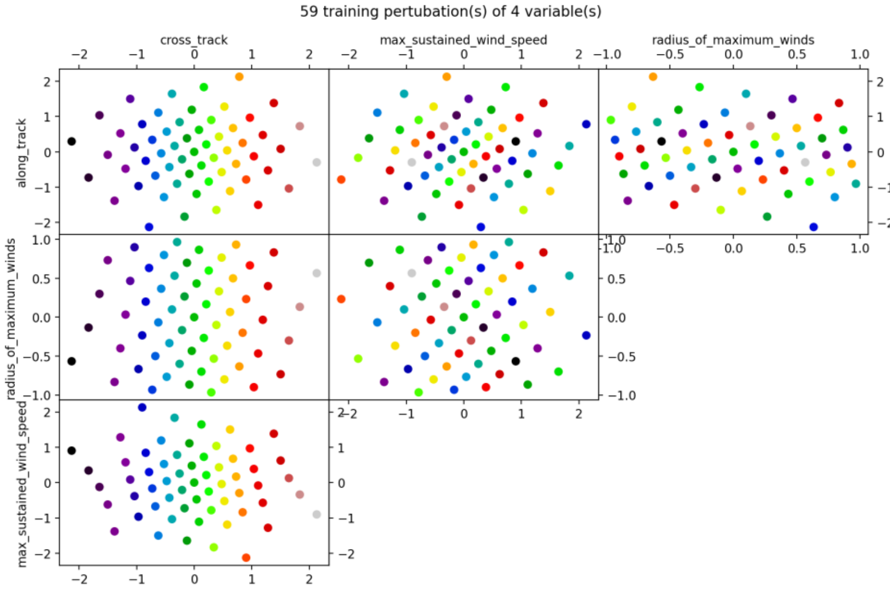
Linear extrapolation to 0-hr for hindcast

Pringle, William J, Zachary Burnett, Khachik Sargsyan, Saeed Moghimi, and Edward Myers. 2023. "Efficient Probabilistic Prediction and Uncertainty Quantification of Tropical Cyclone-Driven Storm Tides and Inundation." *Artificial Intelligence for the Earth Systems* 2 (2): e220040. https://doi.org/10.1175/AIES-D-22-0040.1.

1) PERTURBATION – QUASI-MONTE CARLO

Low-discrepancy Korobov sequence





Sampling has a determined structure

- **96.7% of distribution with 59 members**
- **95% of distribution with 39 members**
- **90% of distribution with 19 members**

2) STORM TIDE SIMULATION

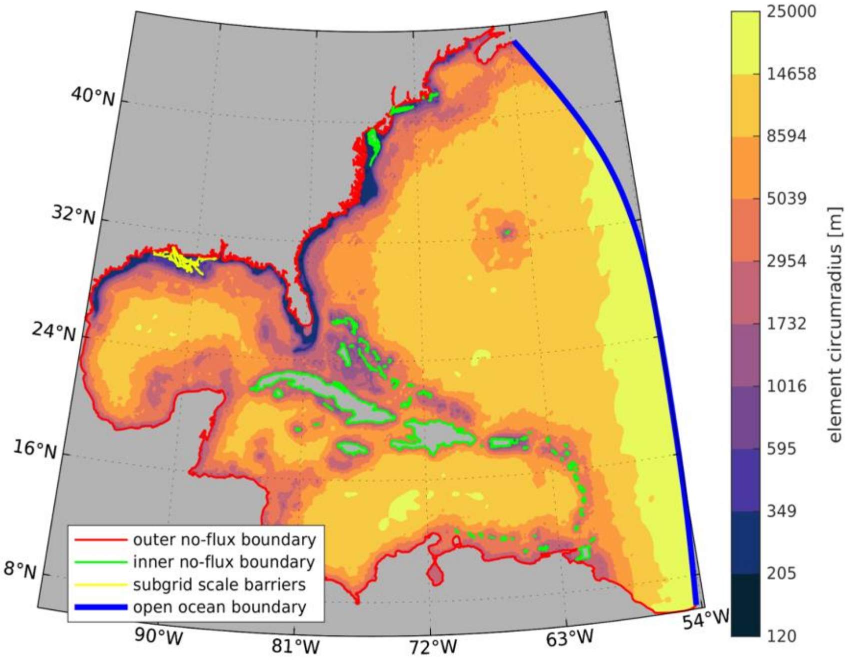
ADCIRC

- ➔ ADCIRC v55 2D hydrodynamics
- ➔ Astronomical tides
- ➔ Built-in Holland 1980, CLE15, and GAHM vortex models

SCHISM

- ➔ SCHISM in 2D mode
- ➔ Astronomical tides
- ➔ Coupled with Parametric Hurricane Modeling System (PaHM) using GAHM vortex model

Resolution of $HSOFS_{2016}$



Open-source python libraries

- ➔ CoupledModelDriver handles [coupled] model setup (generates input files)
- ➔ EnsemblePerturbation generates multiple instances of model setup

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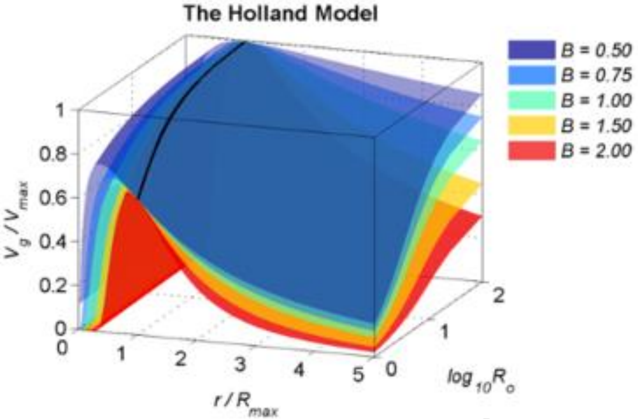
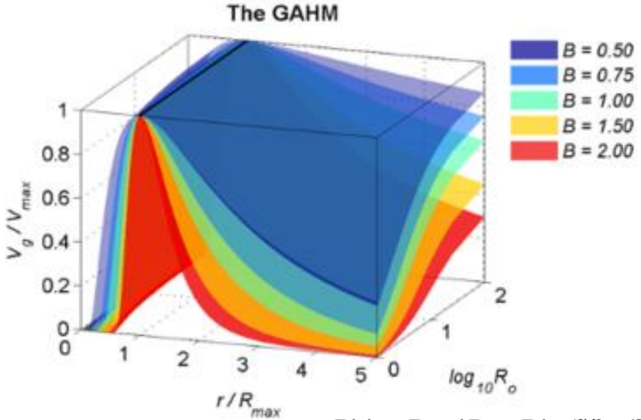
2) PARAMETRIC HURRICANE VORTEX MODELS

Partially Empirical





Holland less accurate for small Ro

$$R_o = \frac{Nonlinear\,Acceleration}{Coriolis\,force} \approx \frac{V_{max}^2 / R_{max}}{V_{max} f} = \frac{V_{max}}{R_{max} f}$$

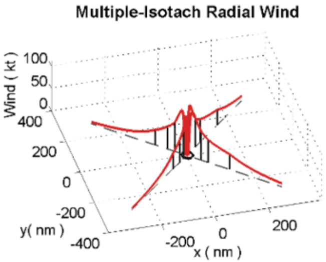
$$P(r) = P_c + (P_n - P_c) e^{-(R_{max}/r)^B} \quad (6)$$

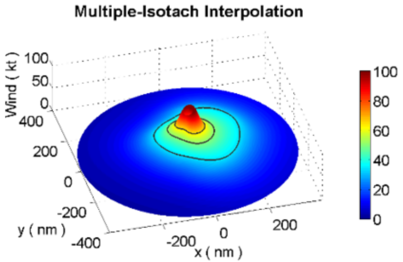
$$V_g(r) = \sqrt{(V_{max})^2 e^{1-(R_{max}/r)^B} (R_{max}/r)^B + (\frac{rf}{2})^2} - \frac{rf}{2} \quad (7)$$

$$P(r) = P_c + (P_n - P_c) e^{-\varphi (R_{max}/r)^{B_g}} \quad (12)$$

$$V_g(r) = \sqrt{V_{max}^2 (1 + 1/R_o) e^{1-(R_{max}/r)^{B_g}} (R_{max}/r)_g^B + (\frac{rf}{2})^2} - \frac{rf}{2} \quad (13)$$

GAHM uses multiple isotach interpolation for all 4 quadrants





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https://wiki.adcirc.org/Generalized_Asymmetric_Holland_Model

2) PARAMETRIC HURRICANE VORTEX MODELS

CLE15 merges theoretical models for inner and outer regions

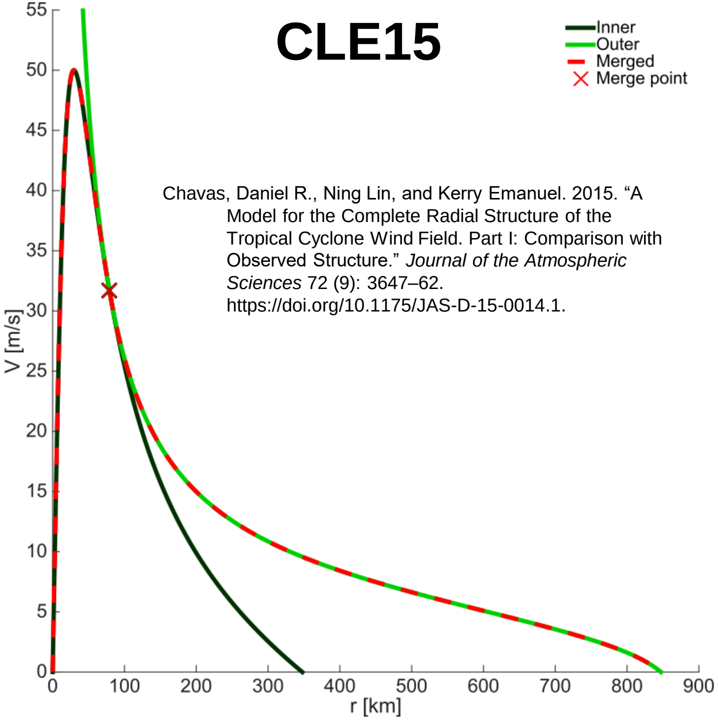
Inner:

Emanuel, Kerry, and Richard Rotunno. 2011. "Self-Stratification of Tropical Cyclone Outflow. Part I: Implications for Storm Structure." *Journal of the Atmospheric Sciences* 68 (10): 2236–49. https://doi.org/10.1175/JAS-D-10-05024.1.

Outer:

Emanuel, K. (2004). Tropical cyclone energetics and structure. In E. Fedorovich, R. Rotunno, & B. Stevens (Eds.), Atmospheric Turbulence and Mesoscale Meteorology: Scientific Research Inspired by Doug Lilly (pp. 165-192). Cambridge: Cambridge University Press. doi:10.1017/CBO9780511735035.010

CLE15



Chavas, Daniel R., Ning Lin, and Kerry Emanuel. 2015. "A Model for the Complete Radial Structure of the Tropical Cyclone Wind Field. Part I: Comparison with Observed Structure." *Journal of the Atmospheric Sciences* 72 (9): 3647–62. https://doi.org/10.1175/JAS-D-15-0014.1.

Background winds as function of forward speed, *Vs*

Varying factor with radial wind fraction

- $\frac{V_r}{V_{max}}|V_s|$ (ADCIRC; Luettich & Westerink, 2004)

H80/GAHM

Empirically derived constant reduction factor with angle 20 deg counter-clockwise

- $.55|V_s|$ (LC12; Chavas and Lin, 2012)

CLE15

3) UQ ANALYSIS METHOD

1. Find an approximation of input-output map: **the surrogate**
   - Polynomial Chaos (PC), or

$$U \simeq \sum_{k=0}^{K} u_k \Psi_k(\boldsymbol{\xi})$$

Input PC

$$Z = f(U) \simeq \sum_{k=0}^{K} c_k \Psi_k(\boldsymbol{\xi})$$

Output PC

   - **Neural Network (NN)**

   on a reduced dimension space (PCA)

2. Compute sensitivity indices (GSA)

Main Effect Sobol Index

$$S_i = \frac{Var[\mathbb{E}(Z(\boldsymbol{\xi}|\xi_i))]}{Var[Z(\boldsymbol{\xi})]}$$

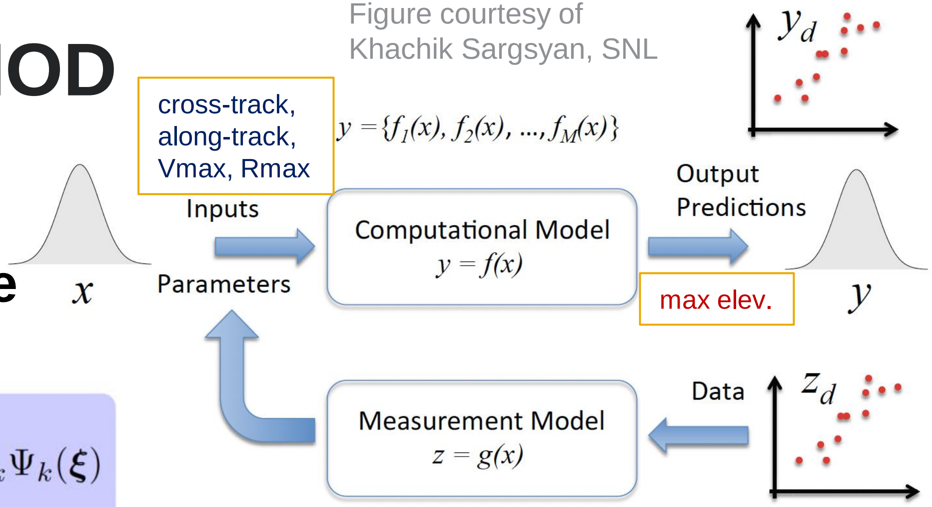
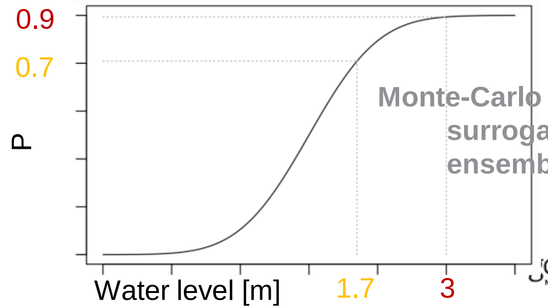


Figure courtesy of Khachik Sargsyan, SNL

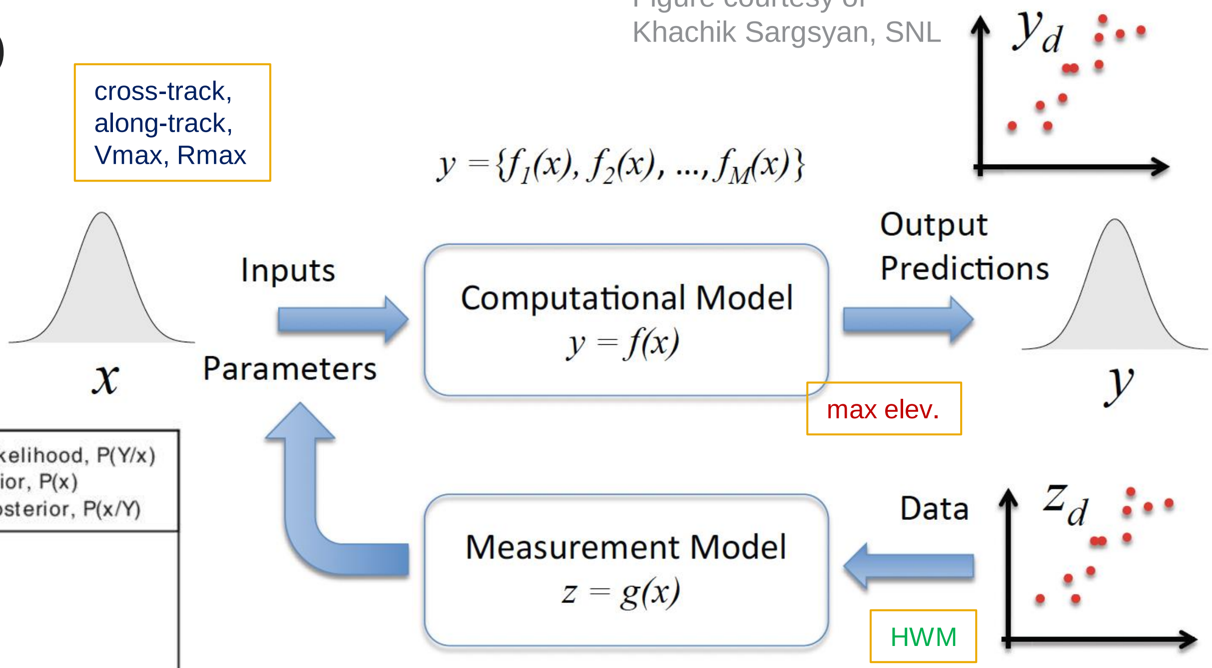
3. Build CDF of PC to get the **exceedance probabilities/heights**

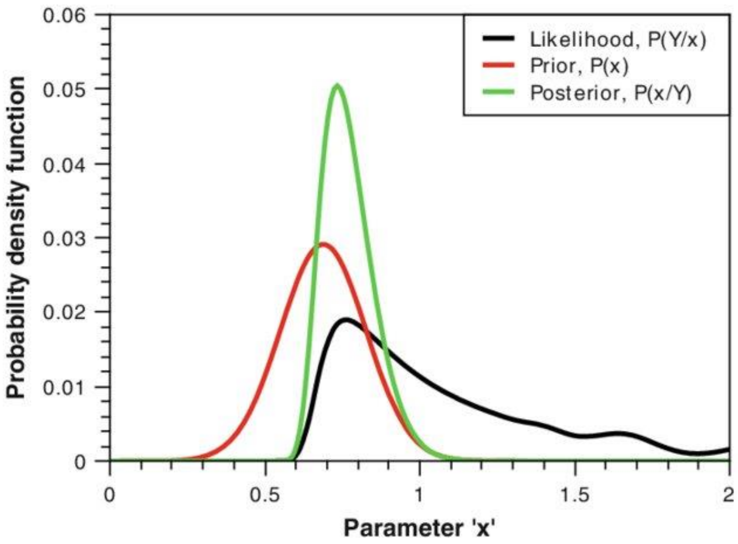


Monte-Carlo sampling of surrogate with a large ensemble (~10^{4-5})

3) INVERSE UQ

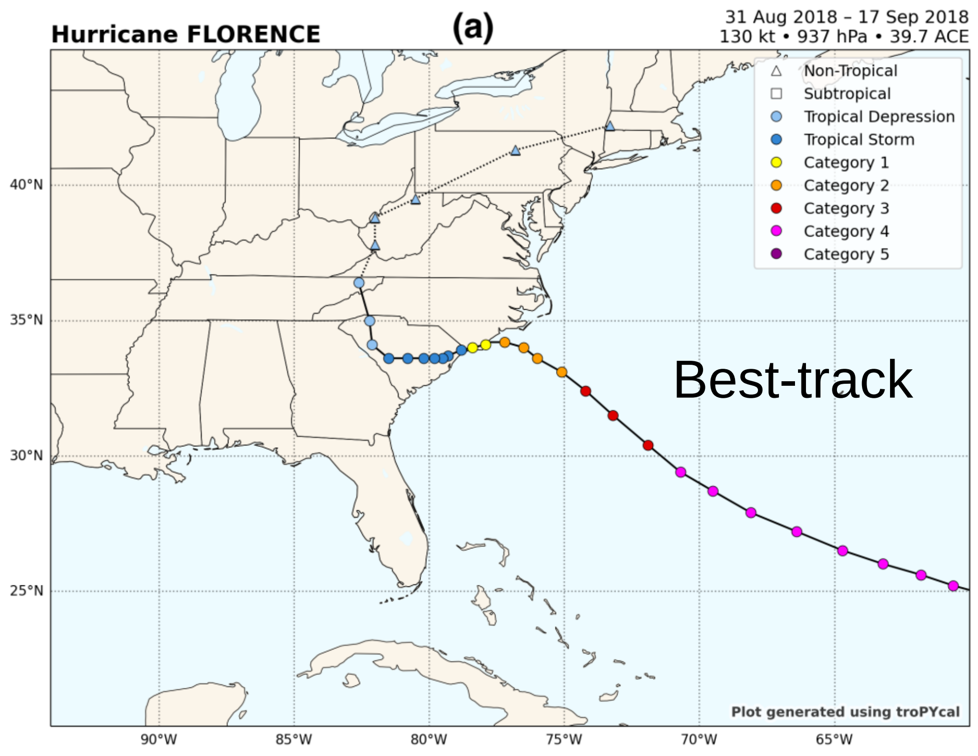
Figure courtesy of
Khachik Sargsyan, SNL

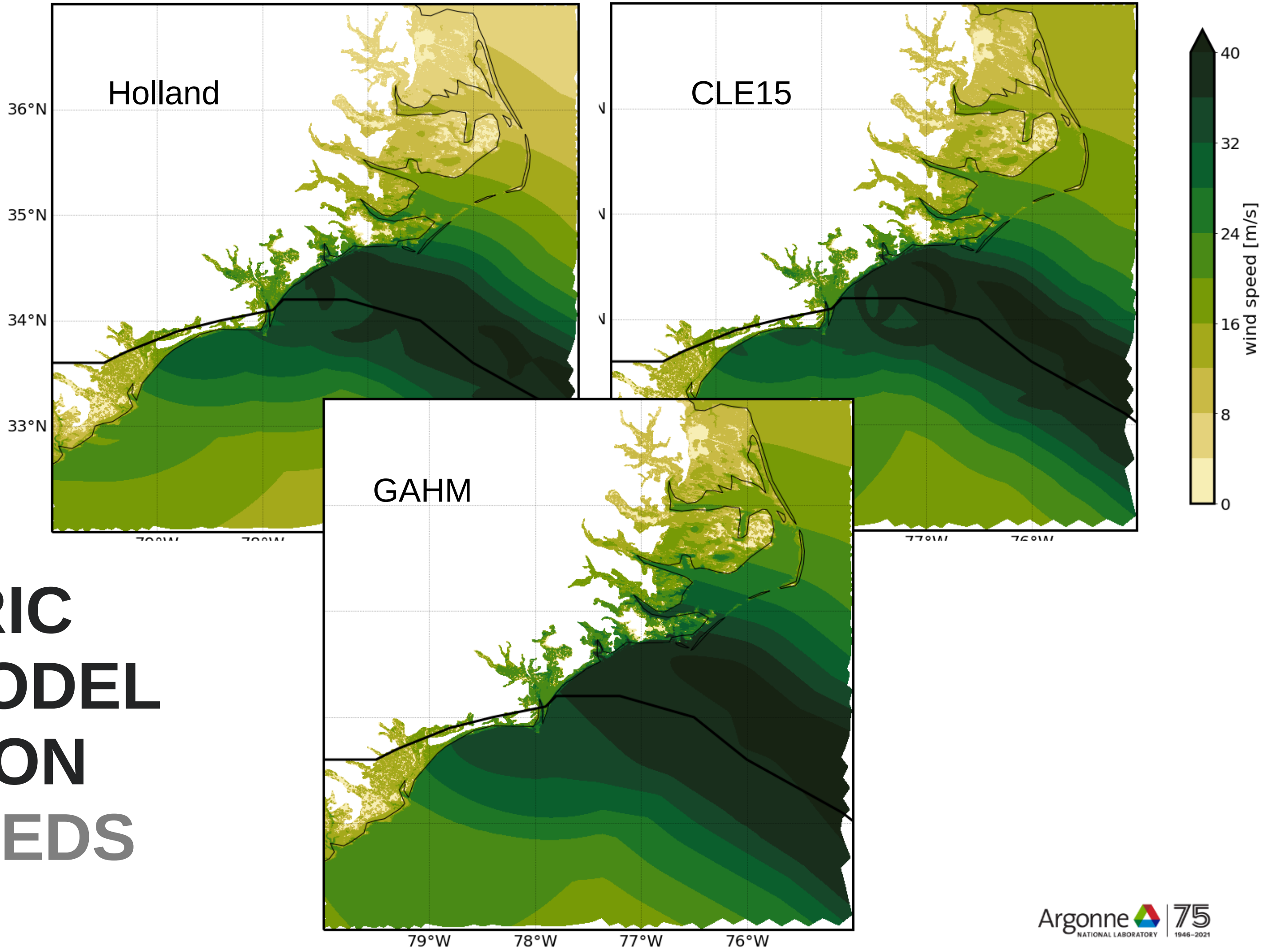




Sample surrogate with Markov Chain Monte Carlo (MCMC) and use Bayesian Inference with HWM observations to converge to constrained posterior set of parameters

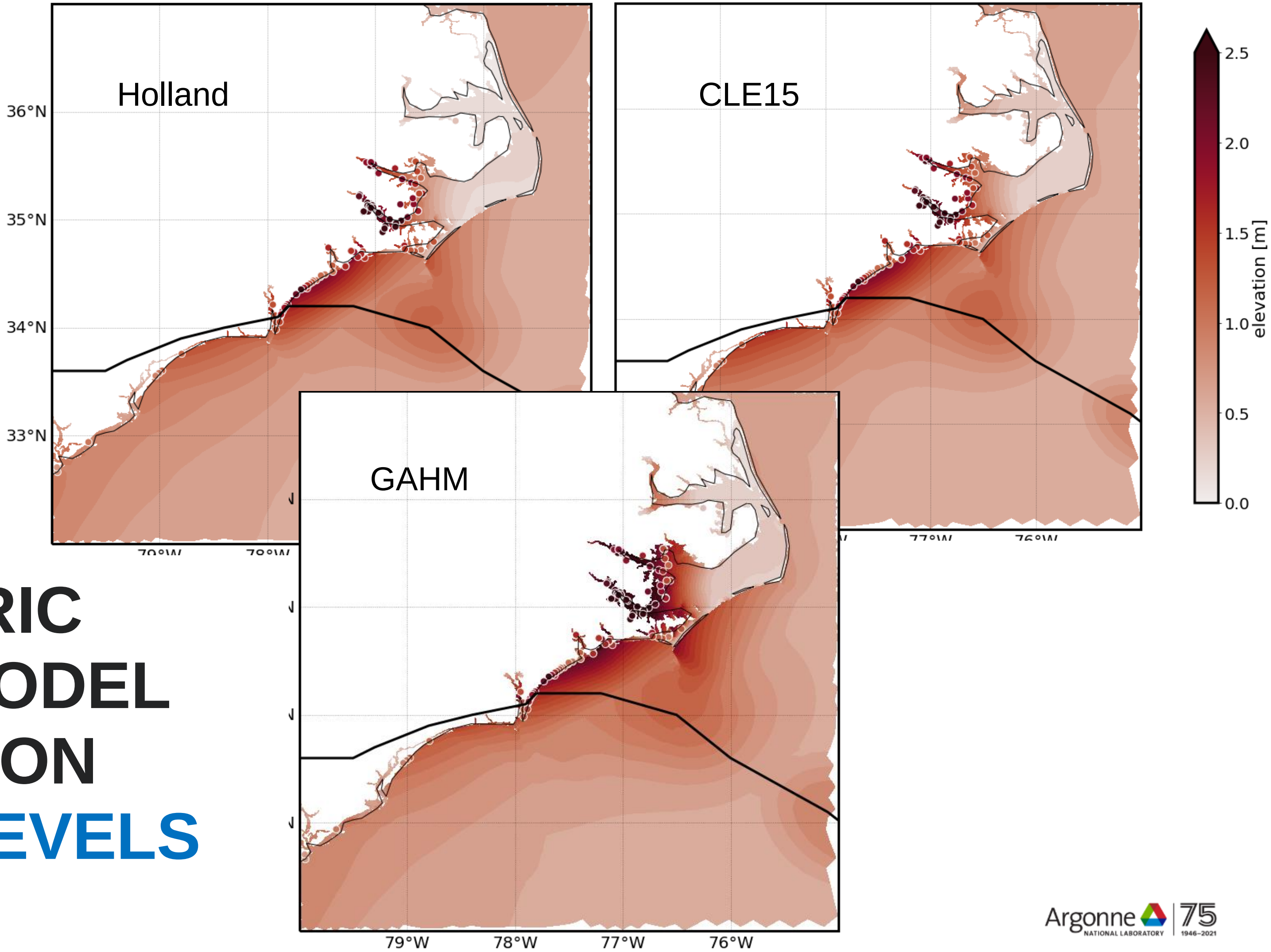
RESULTS: HURRICANE FLORENCE 2018





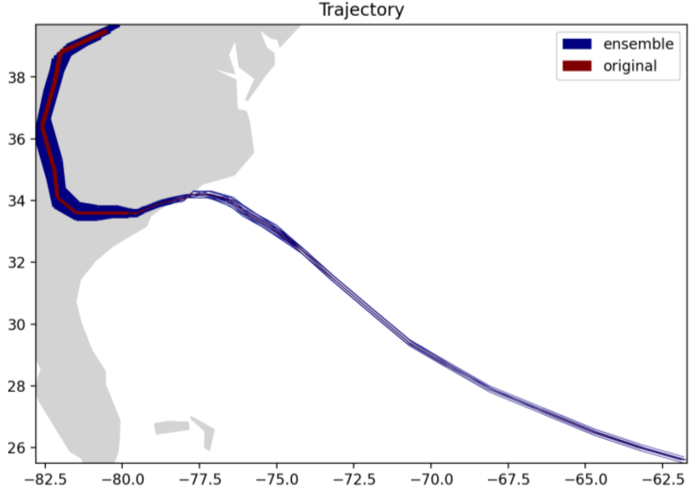
PARAMETRIC VORTEX MODEL COMPARISON - WIND SPEEDS

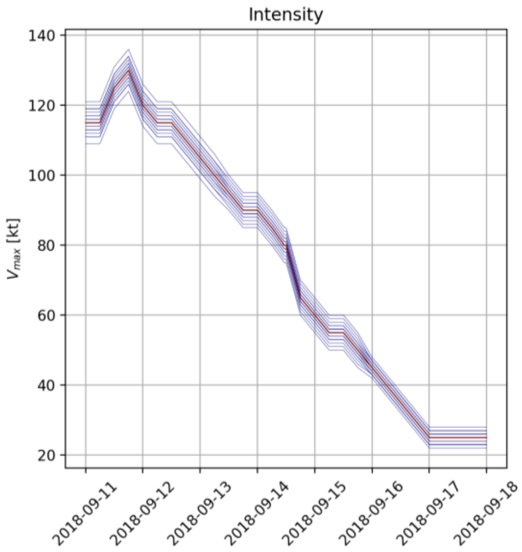
High water marks

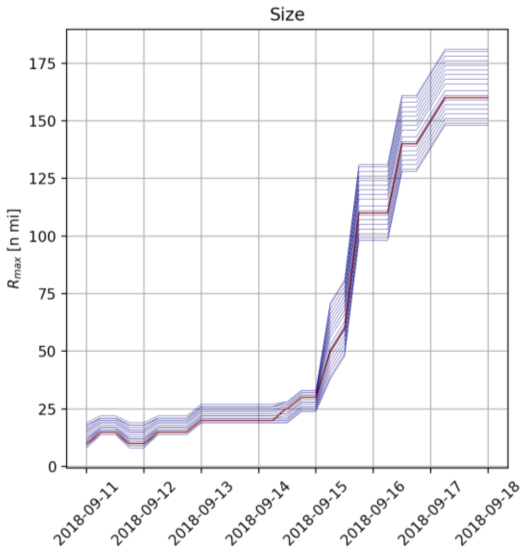


PARAMETRIC VORTEX MODEL COMPARISON - WATER LEVELS

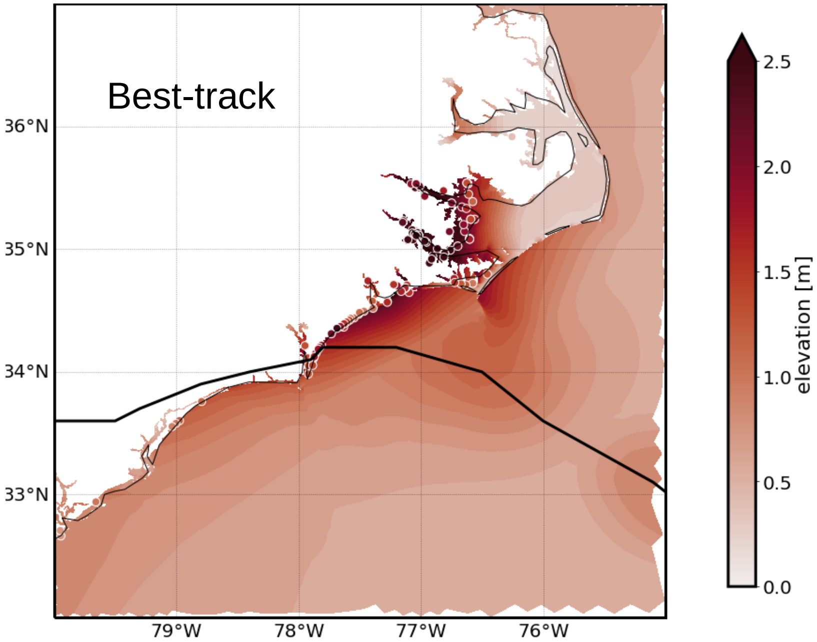
BEST-TRACK PERTURBATION - 19 ENSEMBLES

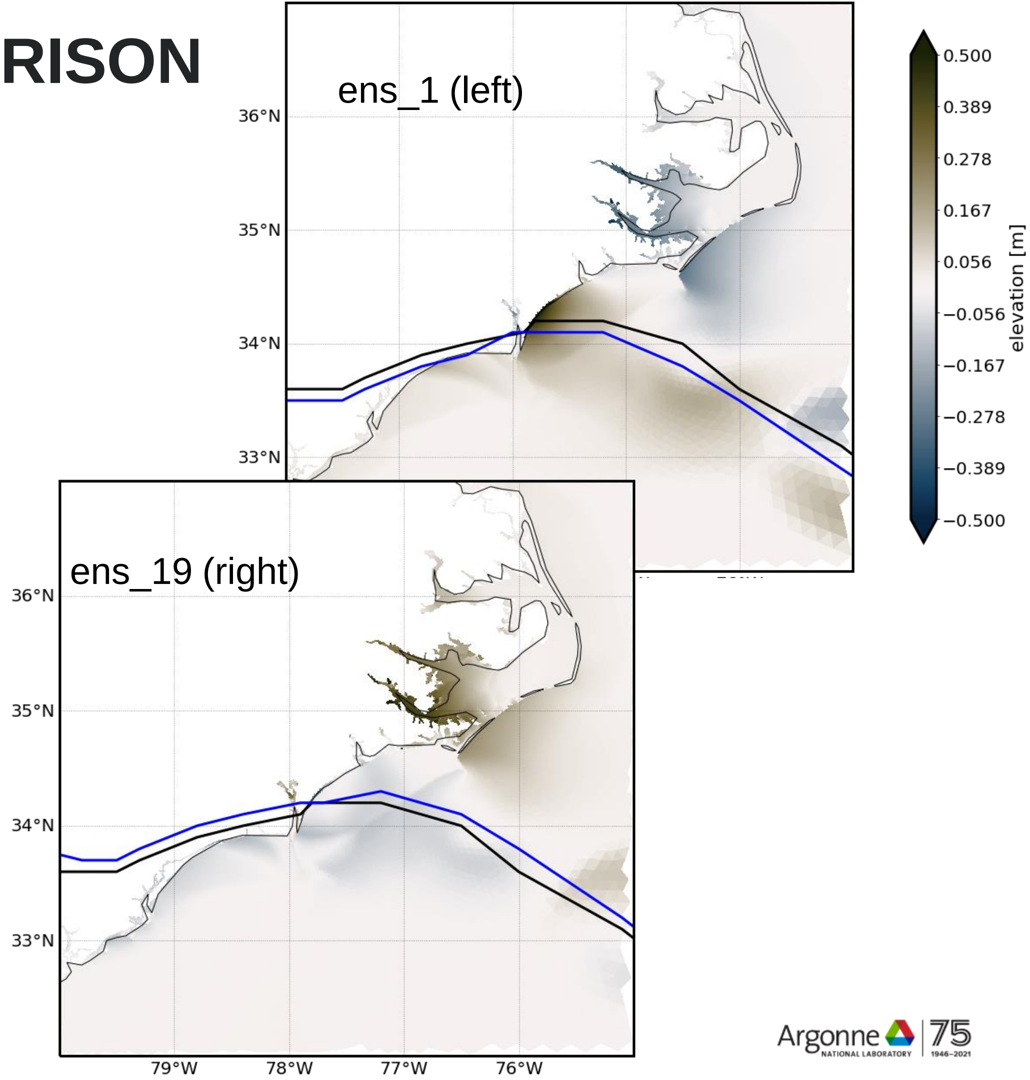




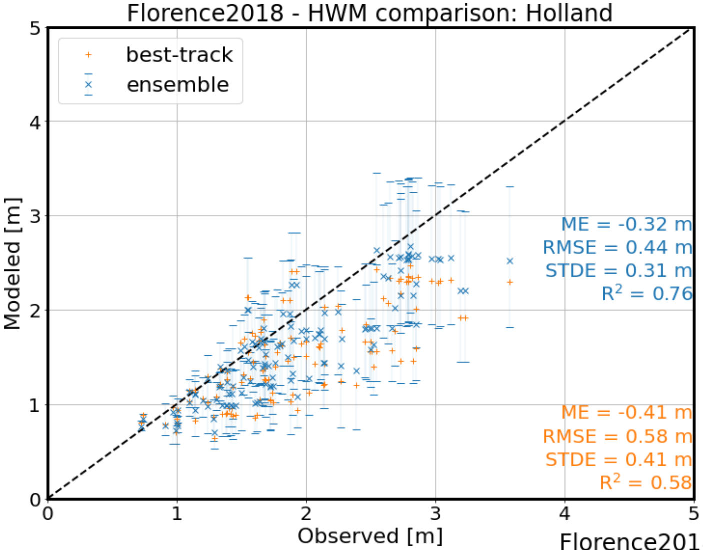


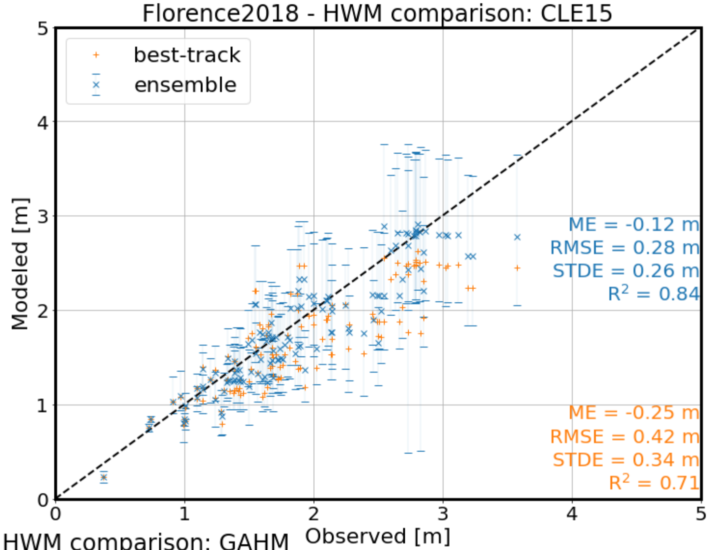
GAHM ENSEMBLE COMPARISON

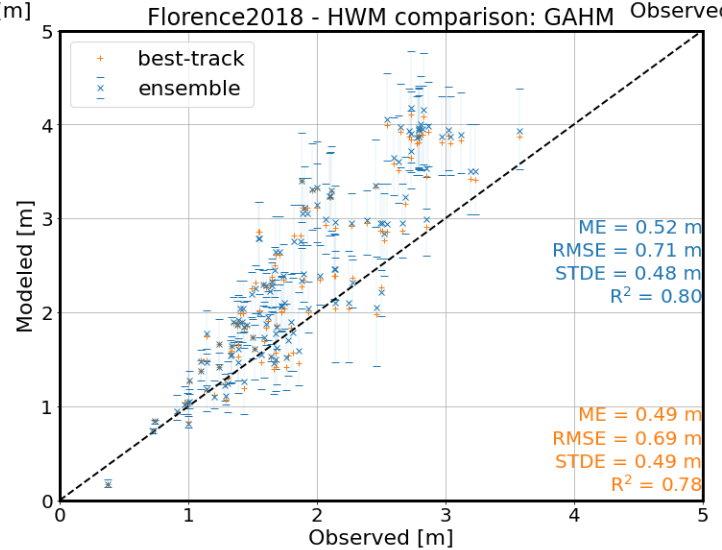


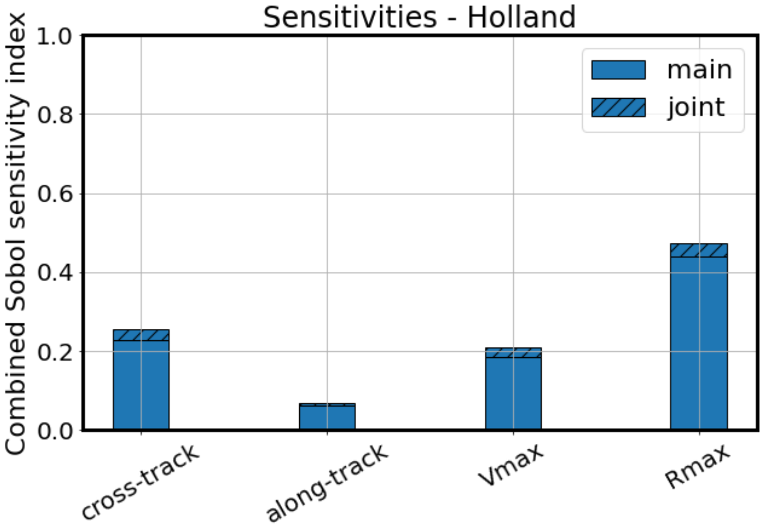


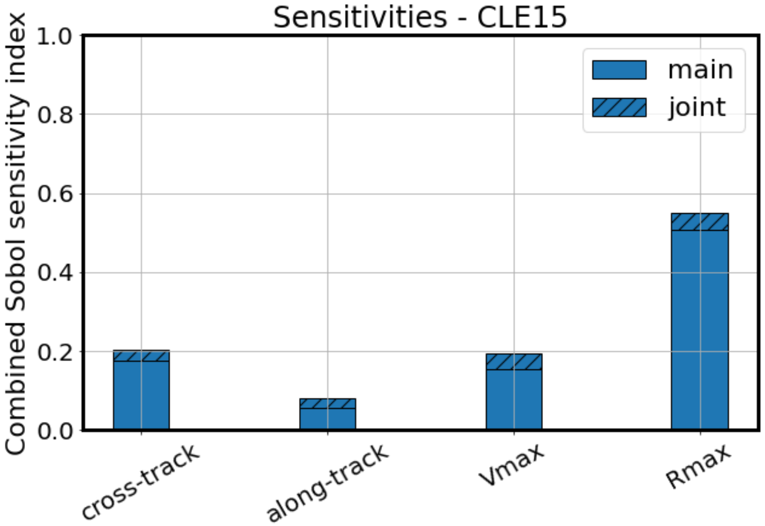
HIGH-WATER MARK COMPARISONS - ENSEMBLE MEAN IMPROVES STATS





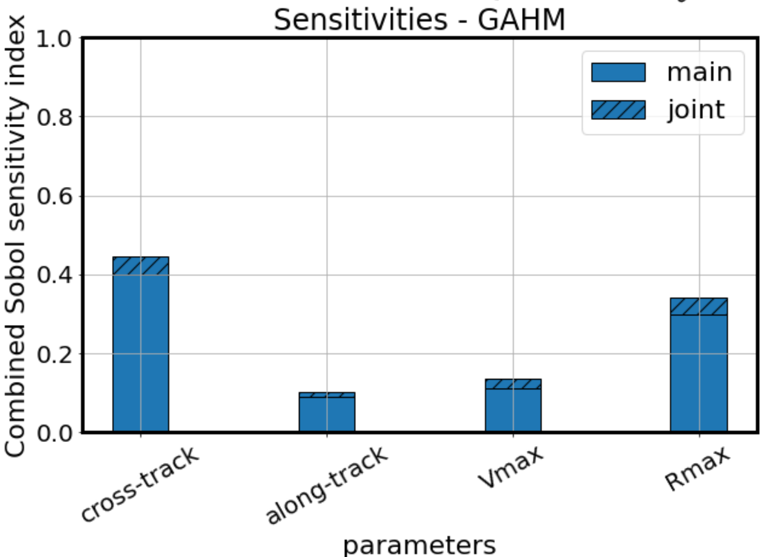




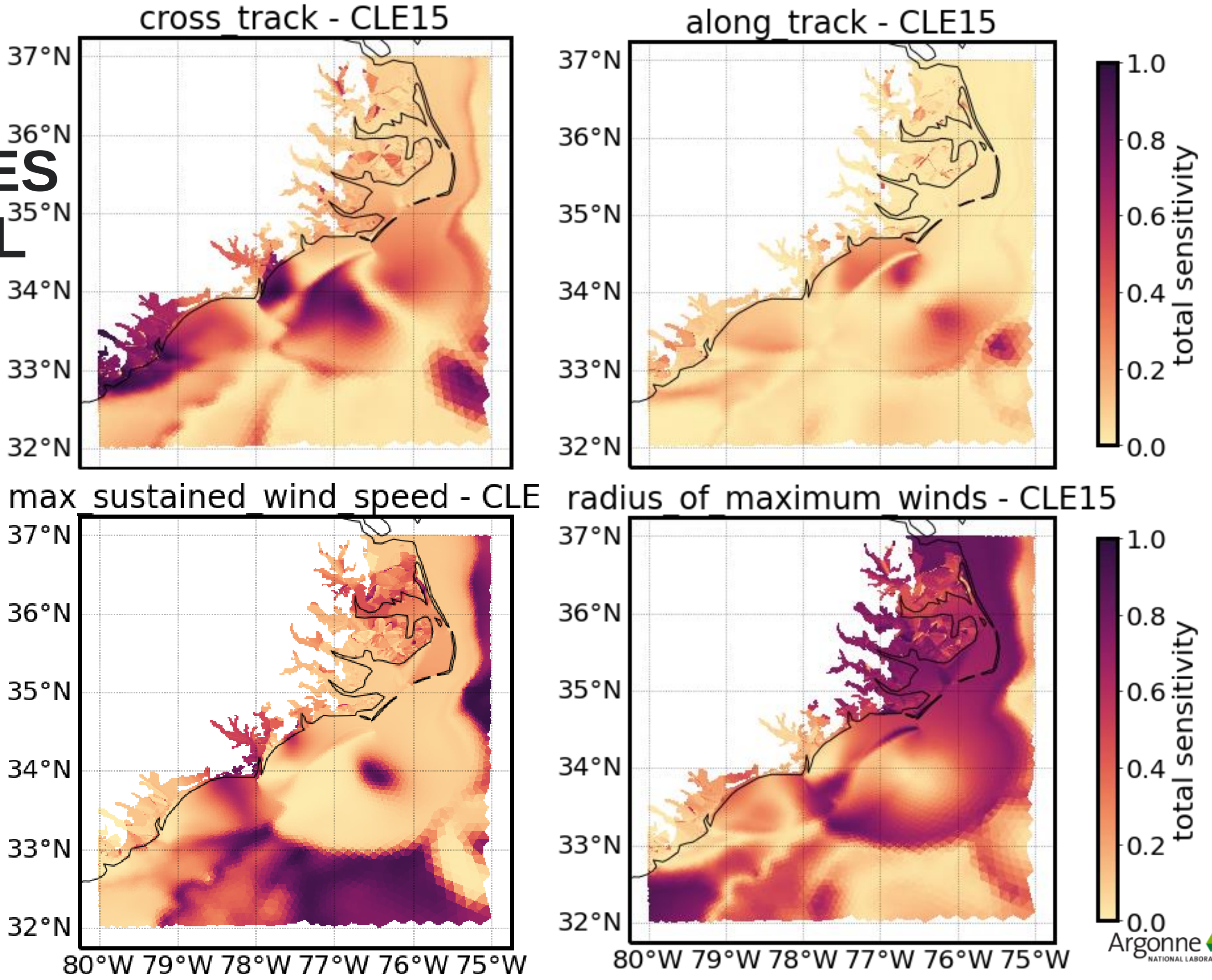


OVERALL SENSITIVITIES

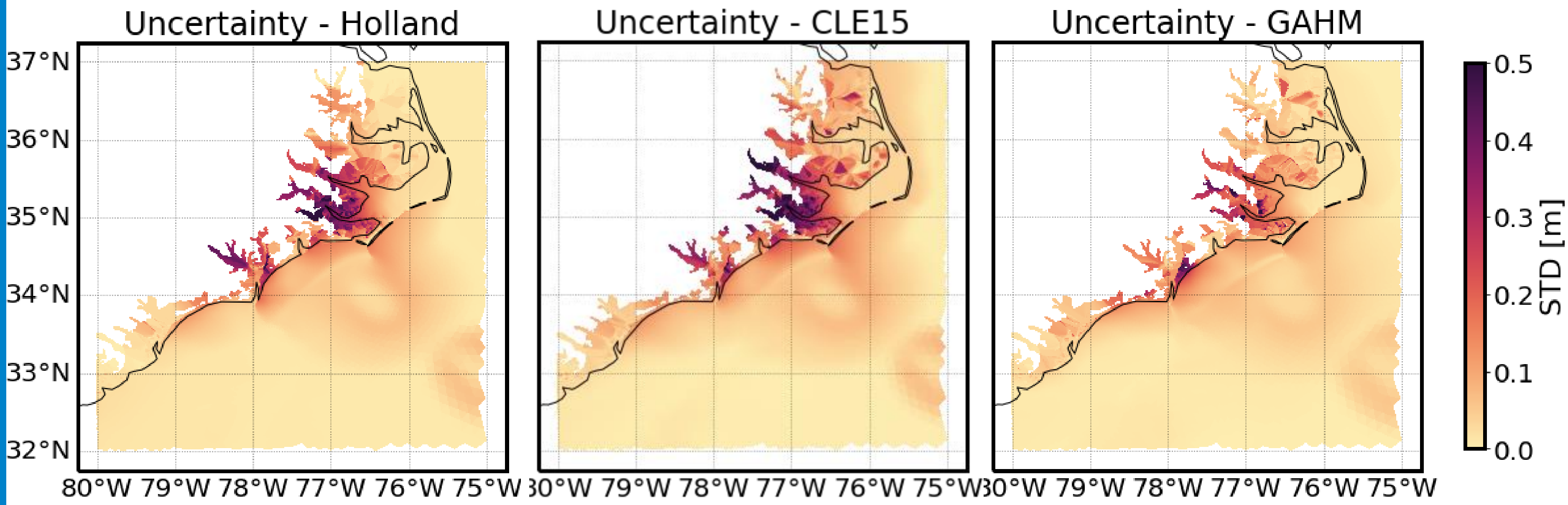
- Rmax important, GAHM different behavior



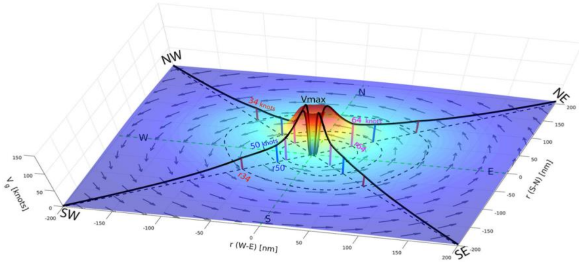
CLE15 SENSITIVITIES GEOSPATIAL



[PRIOR] GEOSPATIAL UNCERTAINTY



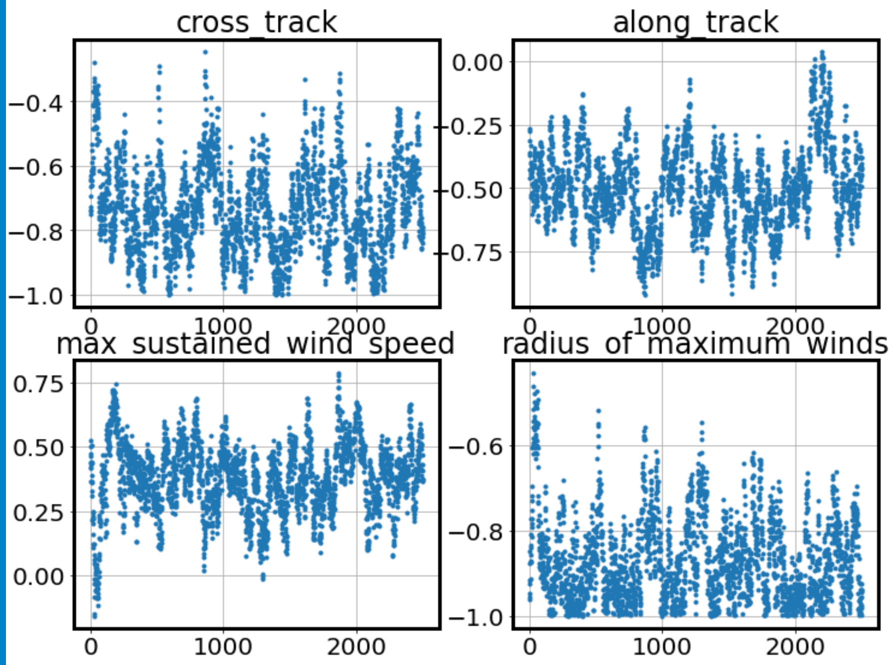
Similar patterns between all models, GAHM less uncertain than Holland & CLE15 as more constrained by r34/r50/r64



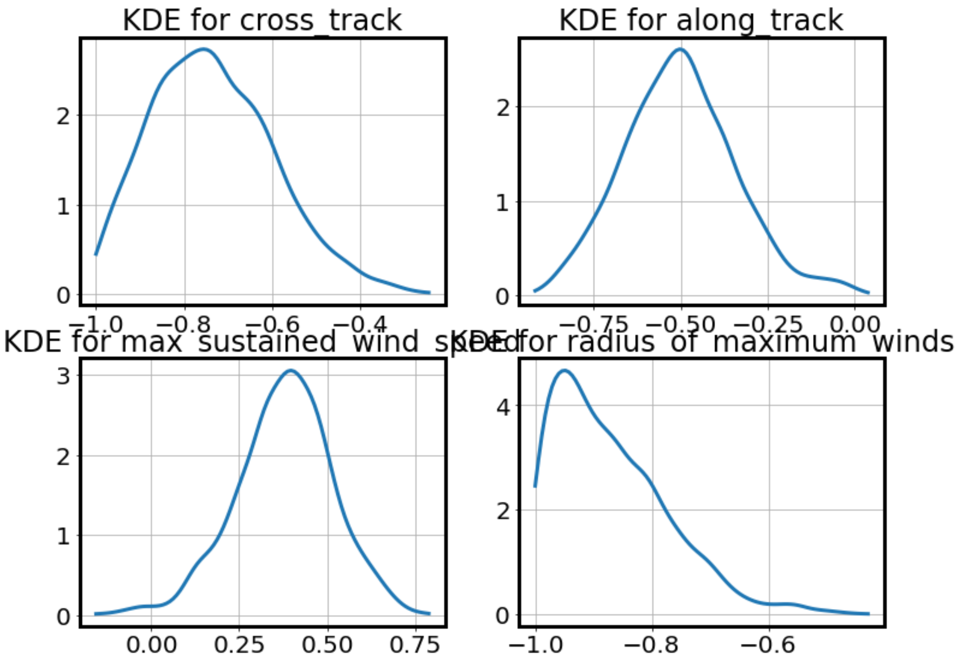
BAYESION INFERENCE TO CONSTRAIN INPUT AND OUTPUT DISTRIBUTION

CLE15

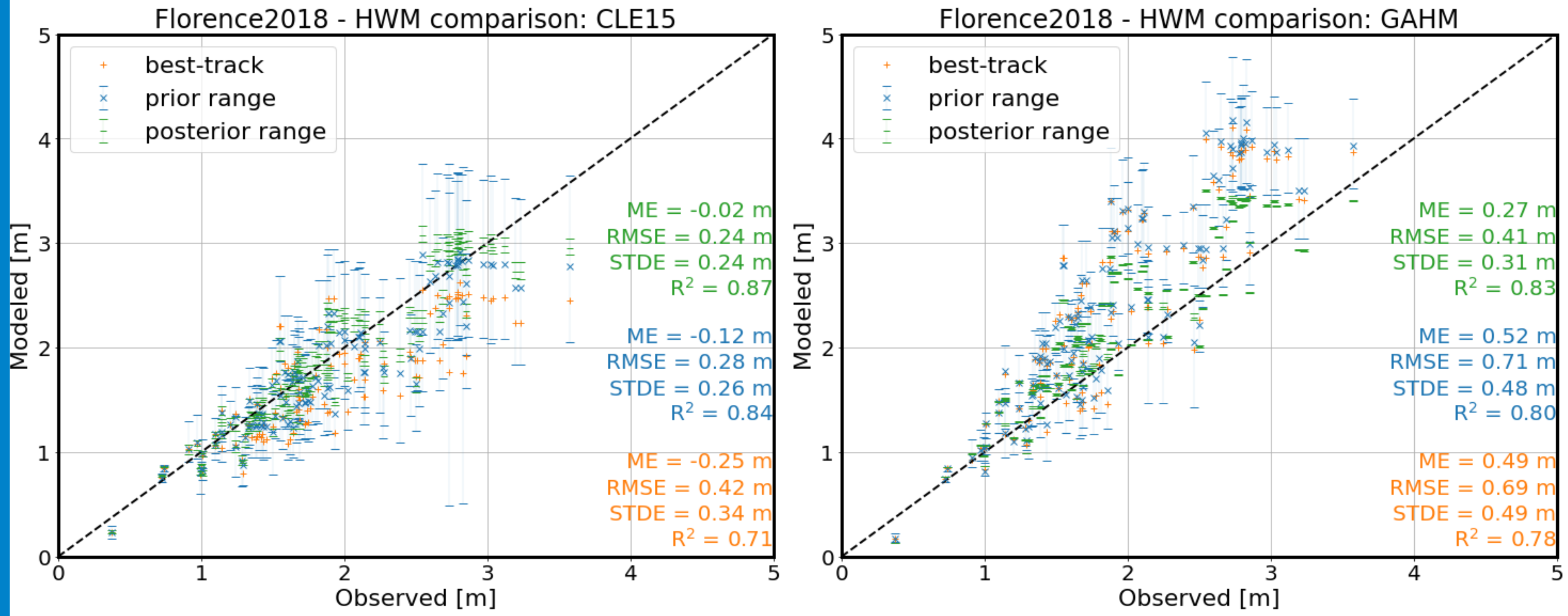
Markov Chain



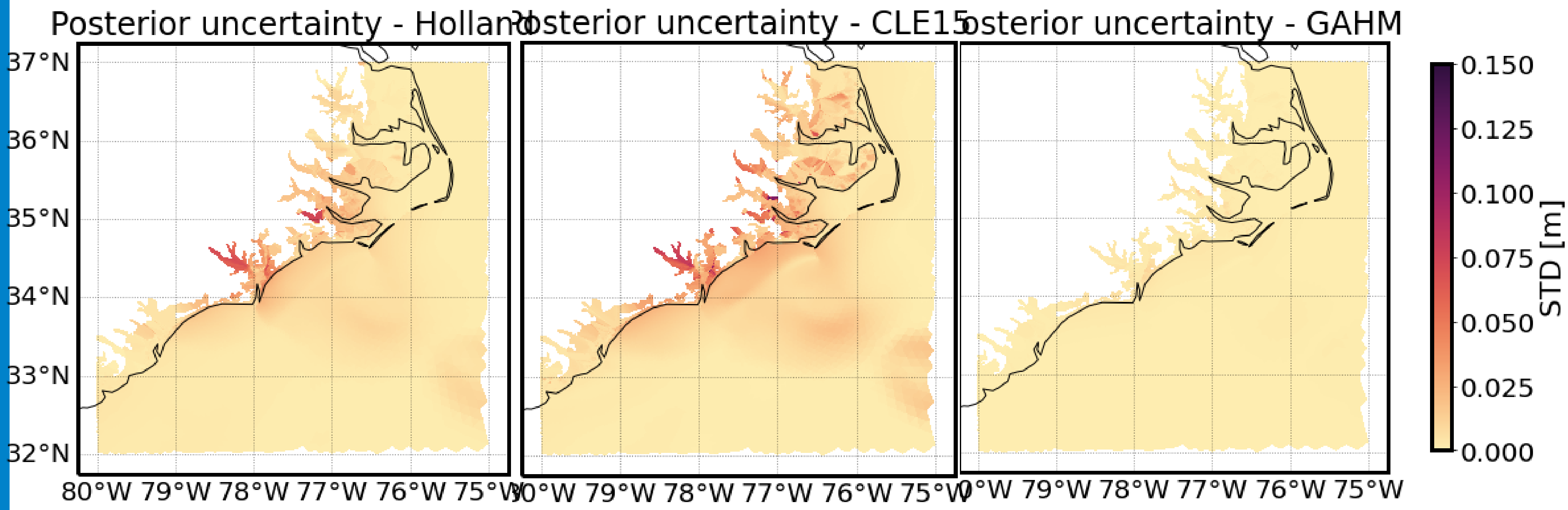
PDF



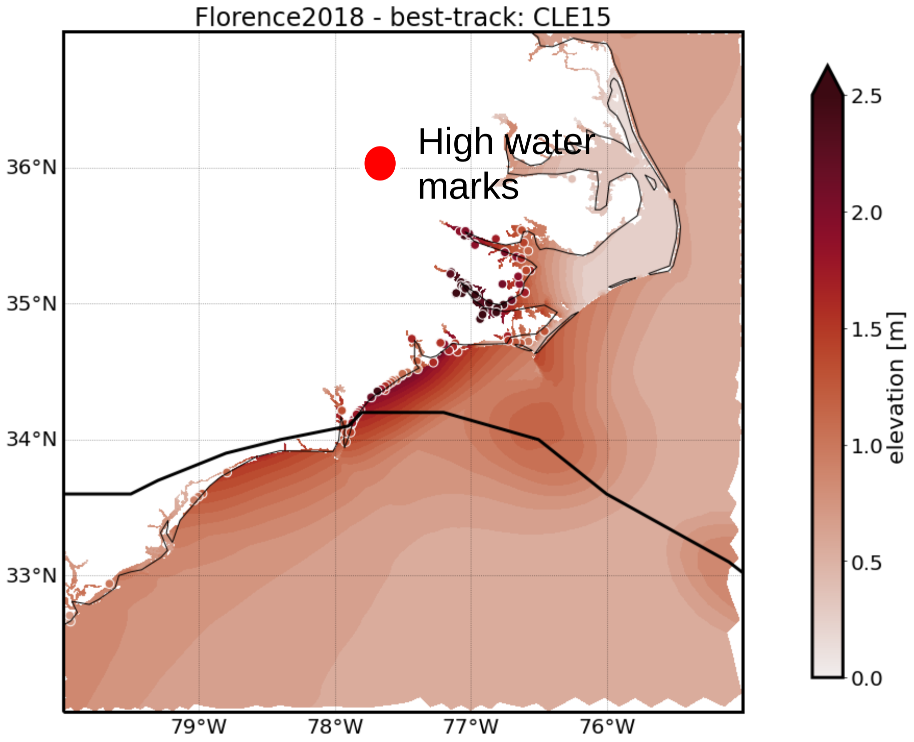
HIGH-WATER MARK COMPARISONS
- POSTERIOR RANGE SMALLER AND REDUCES ERROR

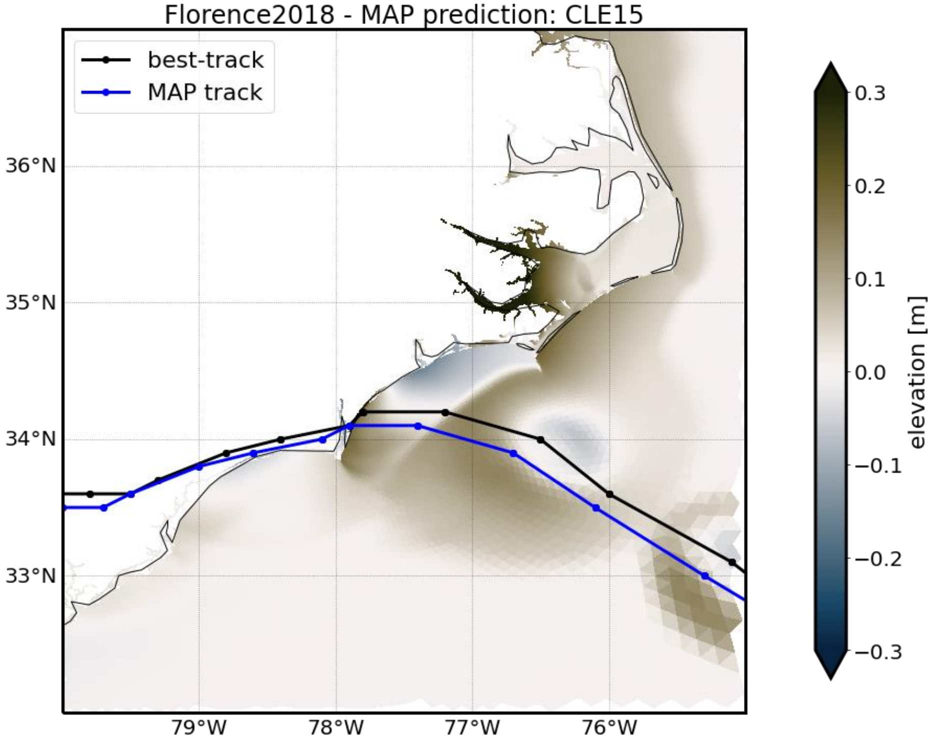


[POSTERIOR] GEOSPATIAL UNCERTAINTY



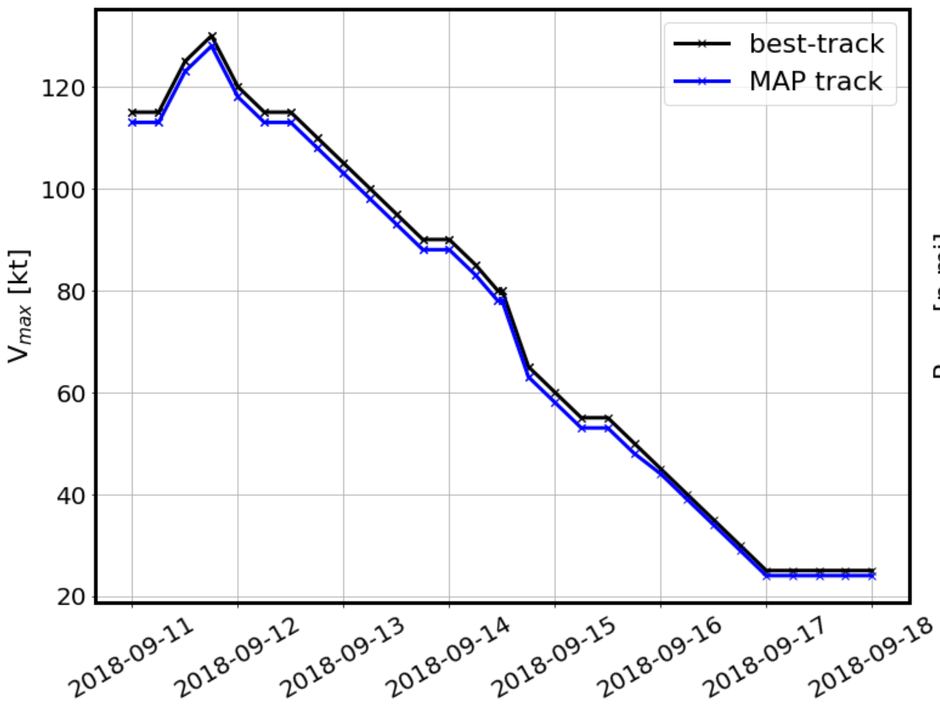
- GAHM has much smaller uncertainty (MCMC may not have converged correctly)
- CLE15 has the most but reduced to less than 0.15 m

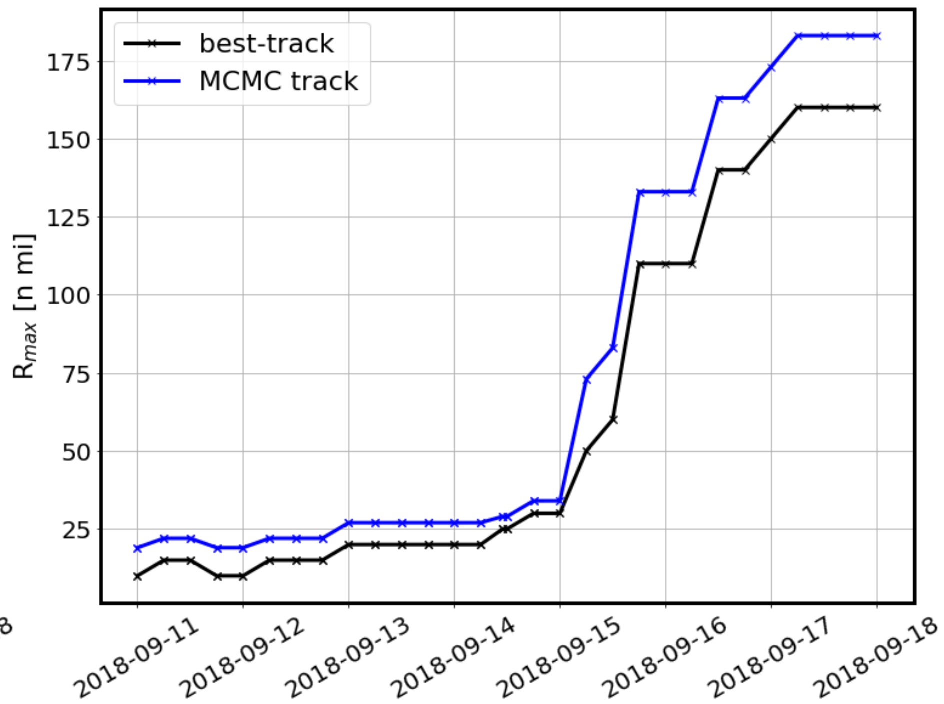




ORIGINAL BEST-TRACK AND MAXIMUM A POSTERIORI PREDICTION COMPARISON - WATER LEVELS [CLE15]

Main effect is to increase storm size as most sensitive parameter





Summary

1) Dimensionally-reduced NN surrogate model trained on qMC model ensemble with cross-validation technique
2) Sensitivities and uncertainty computed from surrogate model
3) Observations used to constrain the likely ensemble range and update input TC error parameters through MCMC
4) For Florence, CLE15 produces smallest errors, most sensitive to Rmax. Uncertainty up to 0.5 m a priori, reduced to <0.15 m with HWM constraints. Suggests a larger Rmax with track to left.

Ongoing/Future work:

- Test more storms
- Alternative method(s) for Rmax/r34/r50/r64 perturbation
- Perturbing hydrodynamic model parameters e.g., bottom friction