



Quantifying the historical intensity of Hurricane Helene & Milton using a data-driven vulnerability model

2025 FSBPA Conference

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Coastal Engineering Research Group

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Collaborators



Ian J Day Stevens

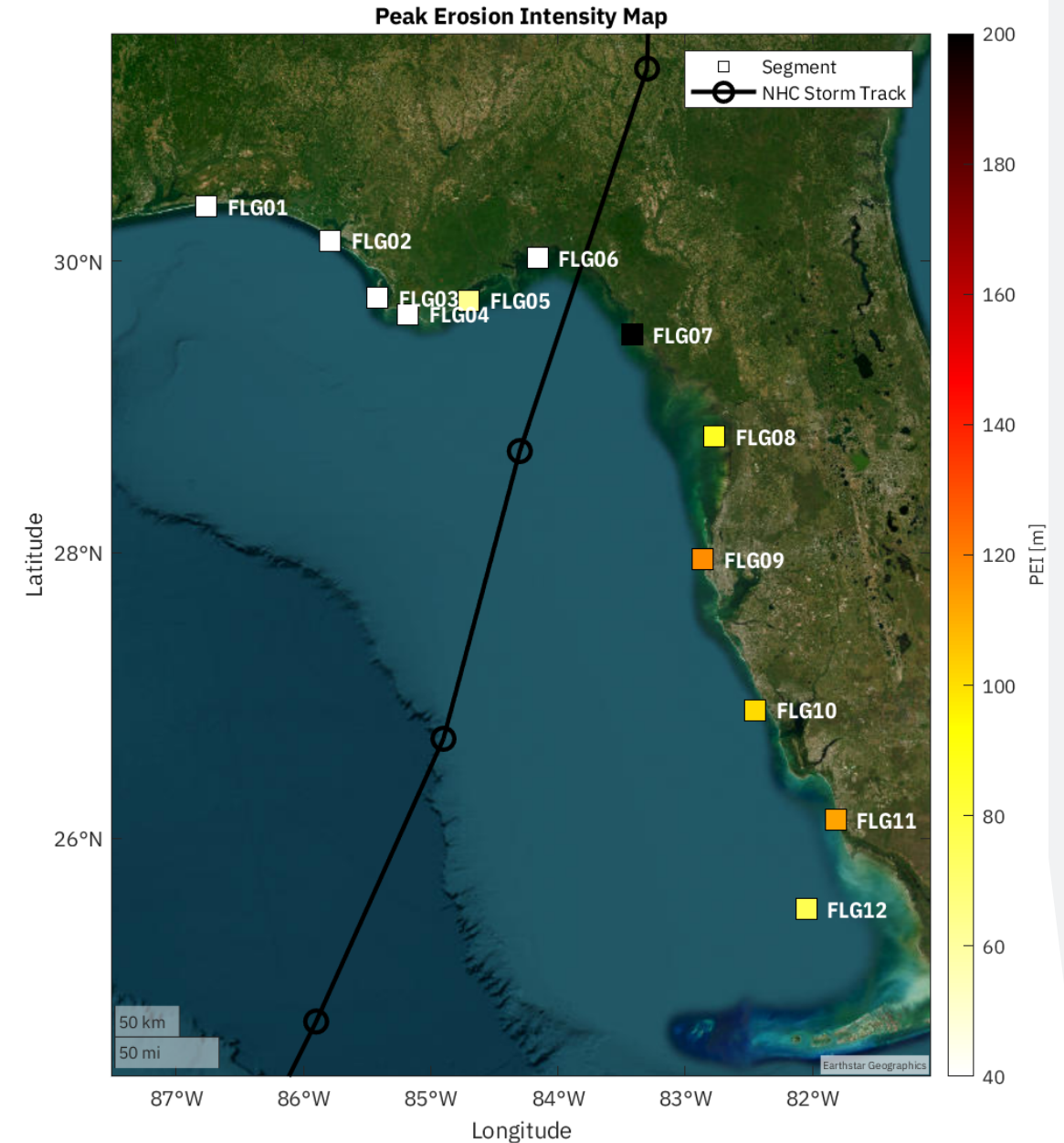
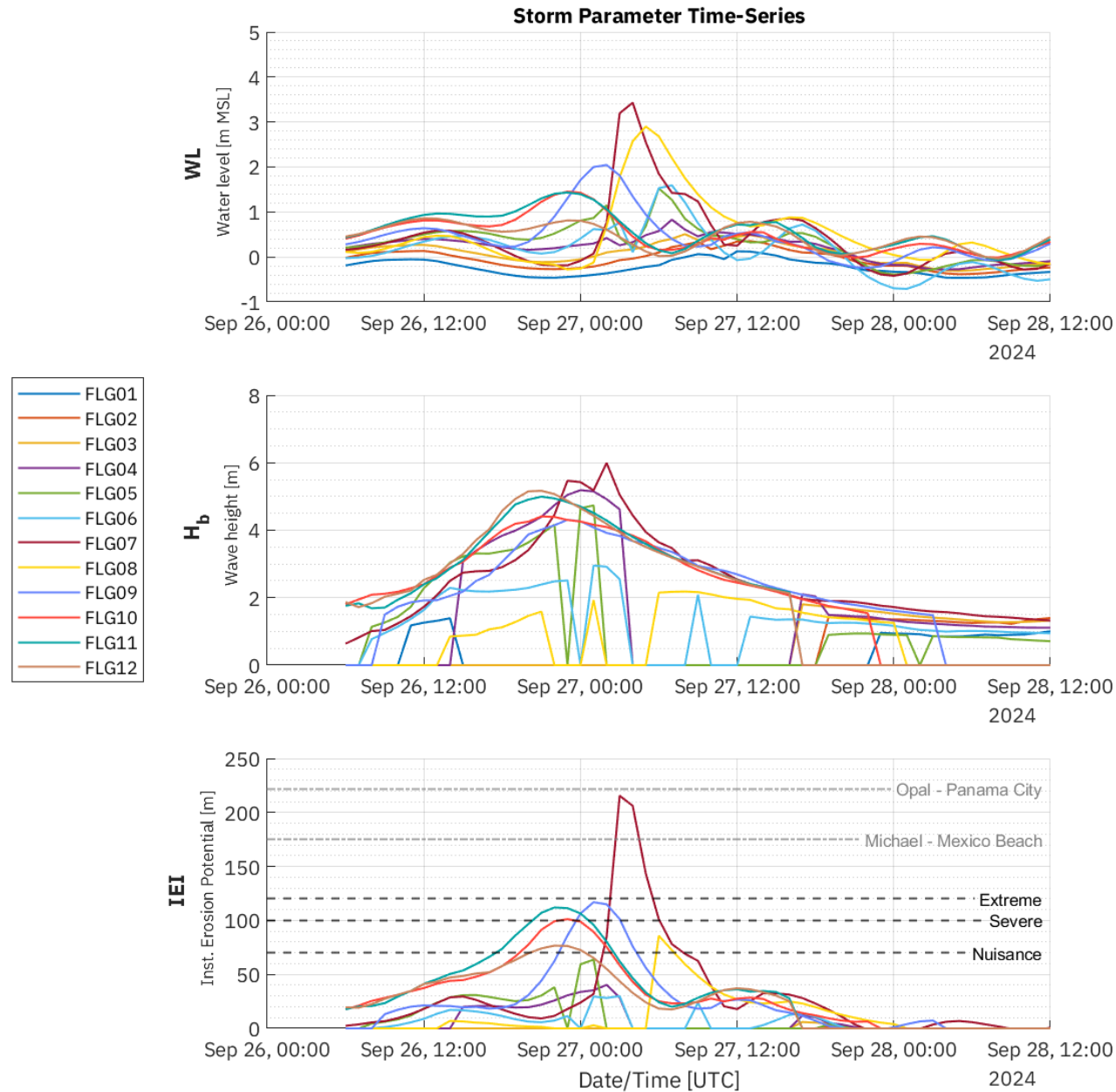


Pouya Darestani Farahani Stevens

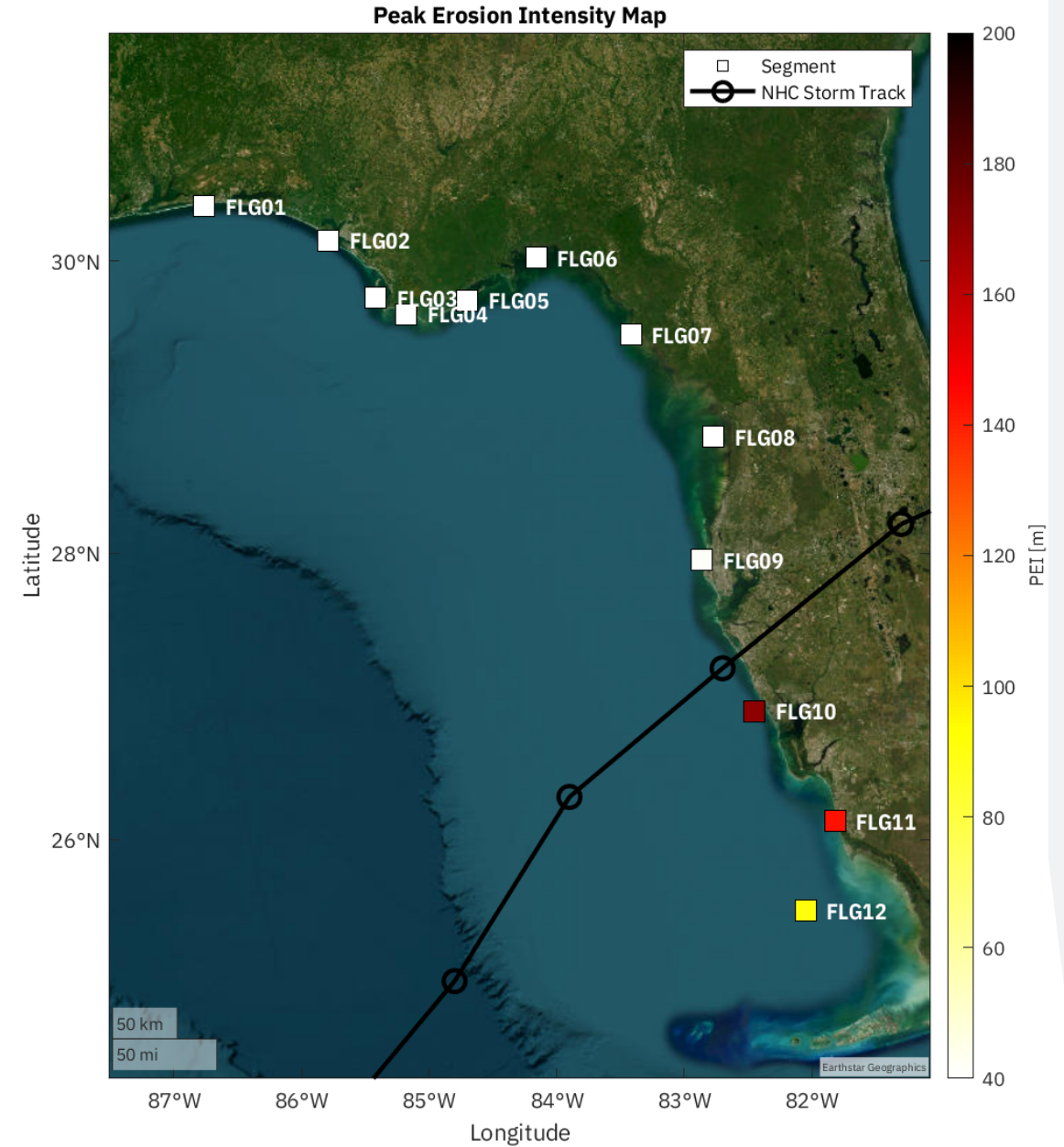
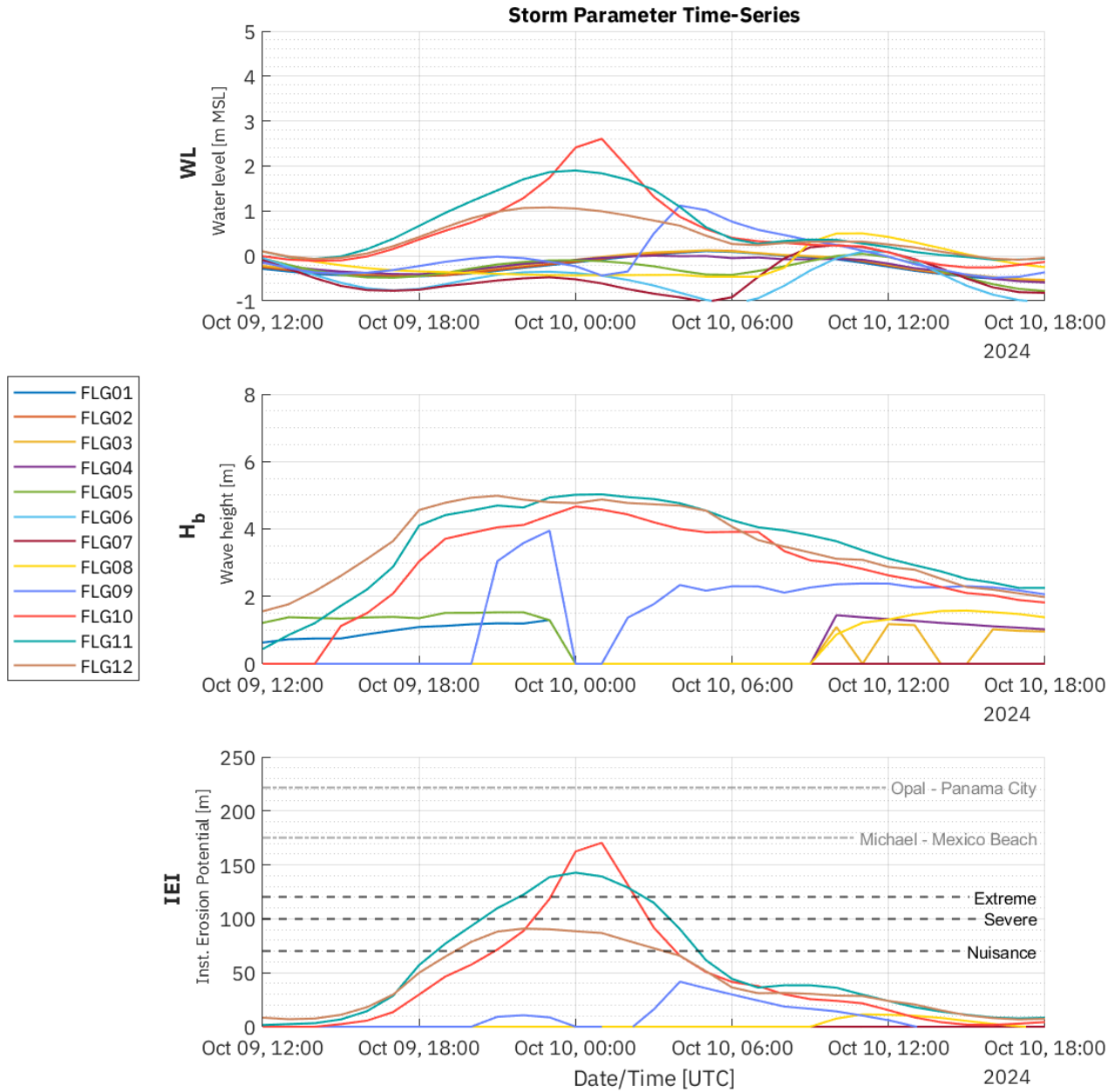


Jon K Miller Stevens

Hourly Storm Intensity Hurricane Helene Gulf Coast



Hourly Storm Intensity Hurricane Milton Gulf Coast



Motivation

- Why...?

Model

- Parameterization of Storm Intensity and Beach Resilience
- Physically Informed Probabilistic Fragility Model
- Trained on 34-year observational record

Hurricanes Helene & Milton

- Statewide Forecasts, error estimates
- Comparison with notable storms
- Explore variation between Anna Maria Island and Longboat Key

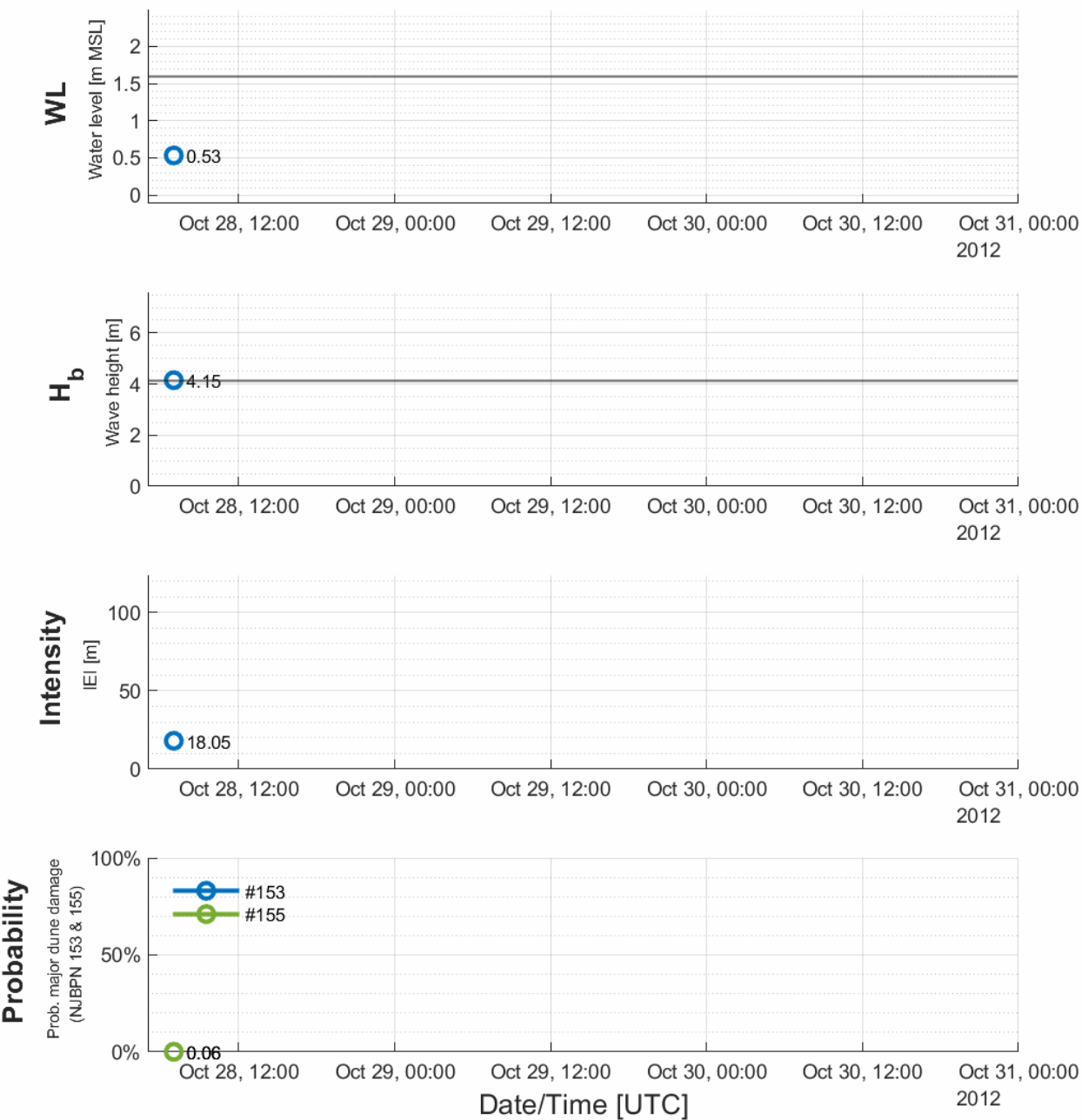


Motivation

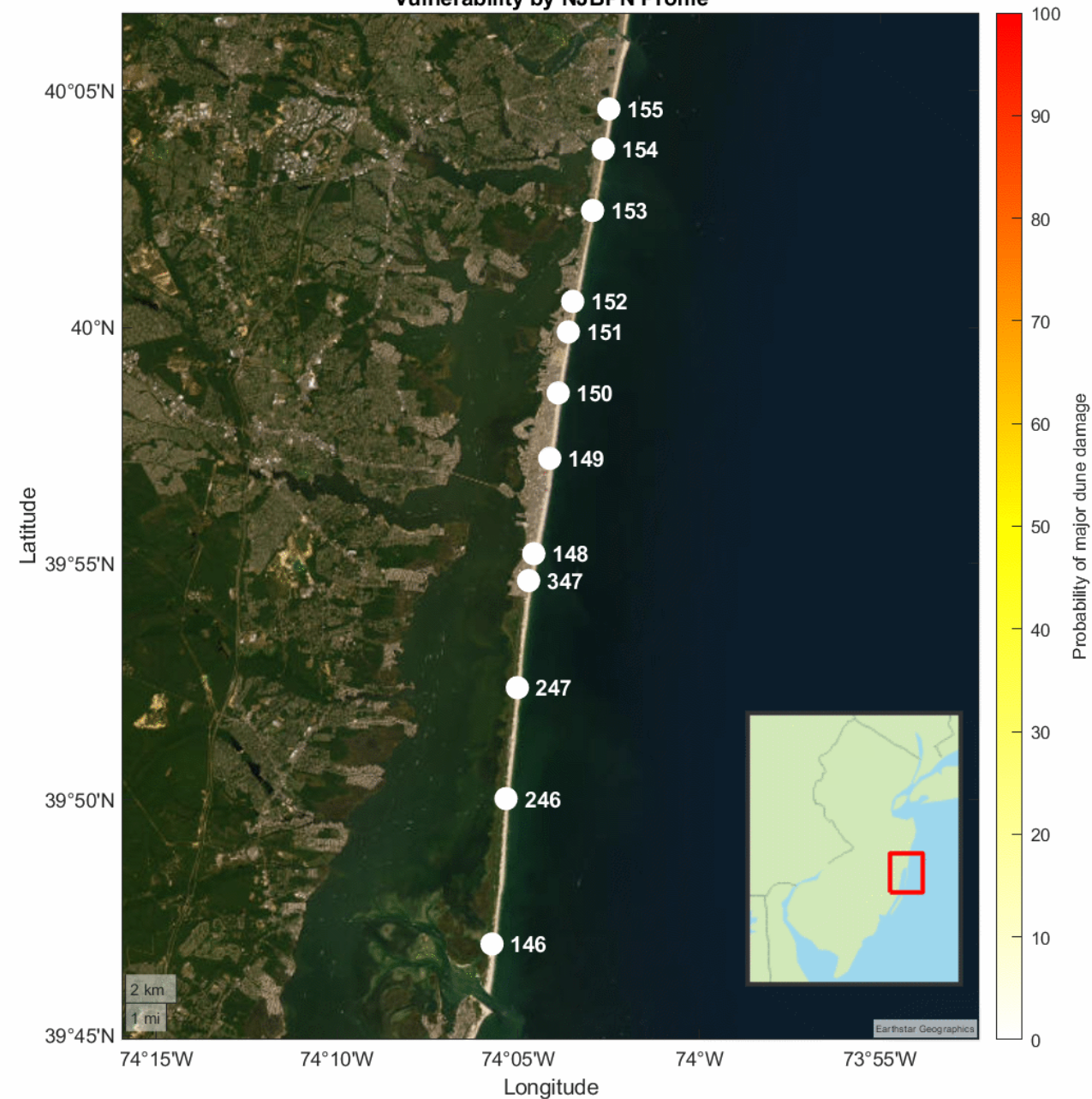


Hourly Storm Vulnerability NJ Shoreline Segment 5

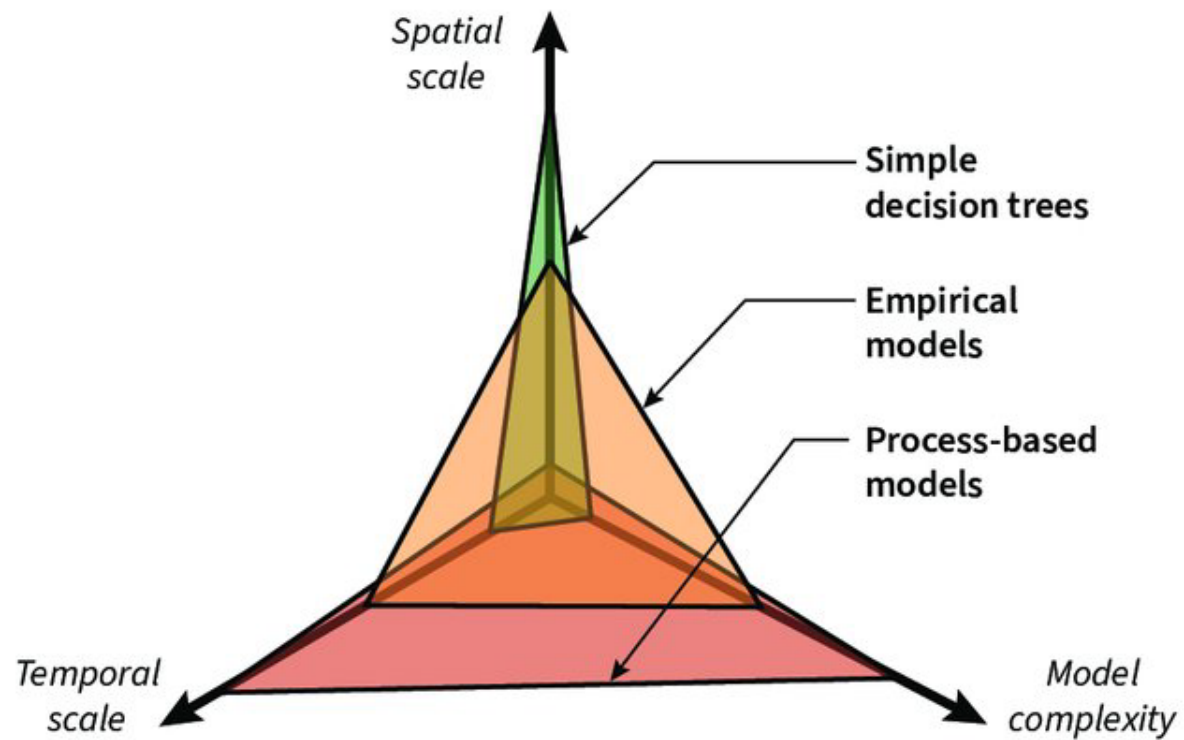
Storm Parameter Time-Series



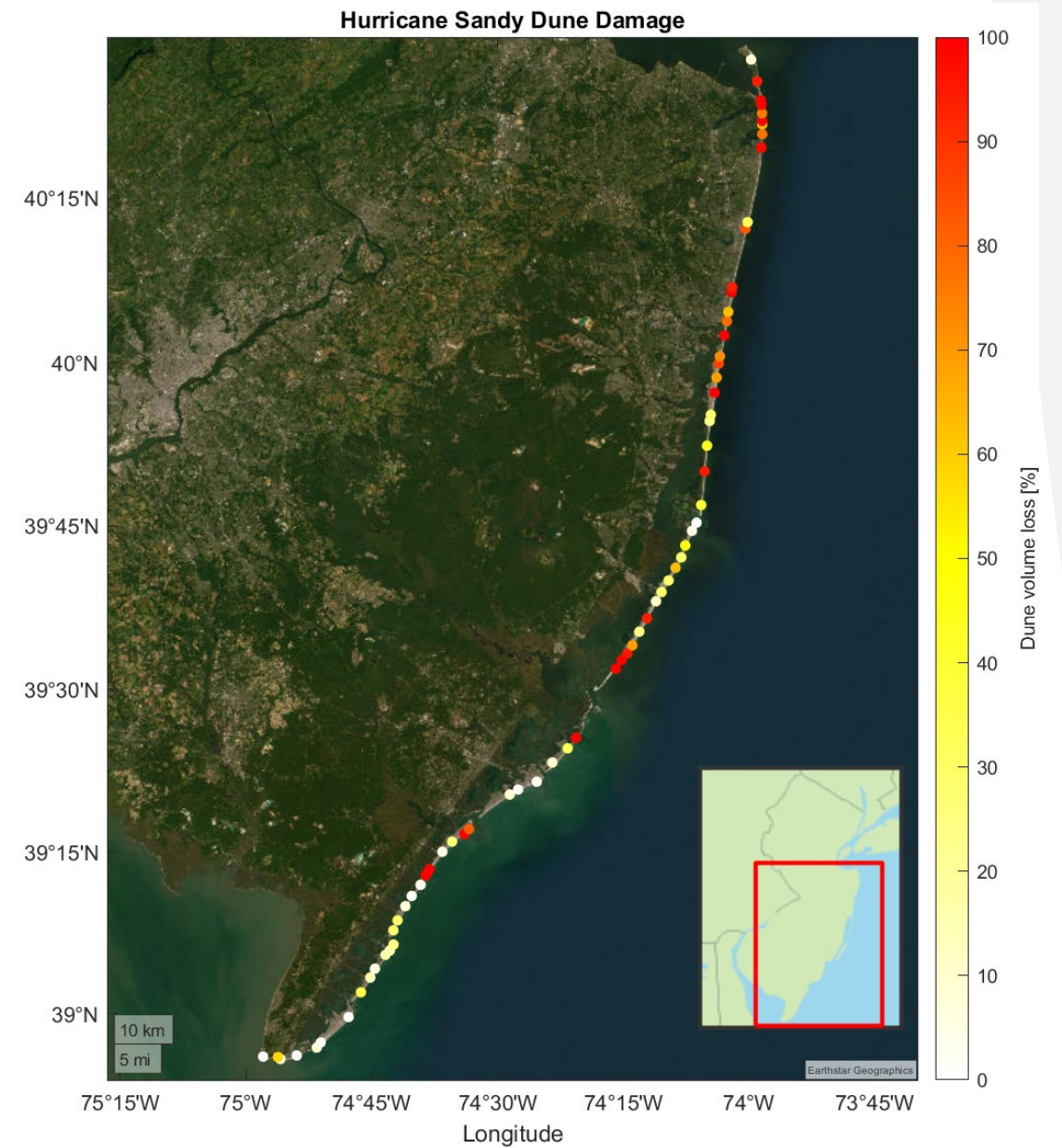
Vulnerability by NJBNP Profile



Motivation



Leaman (2022)



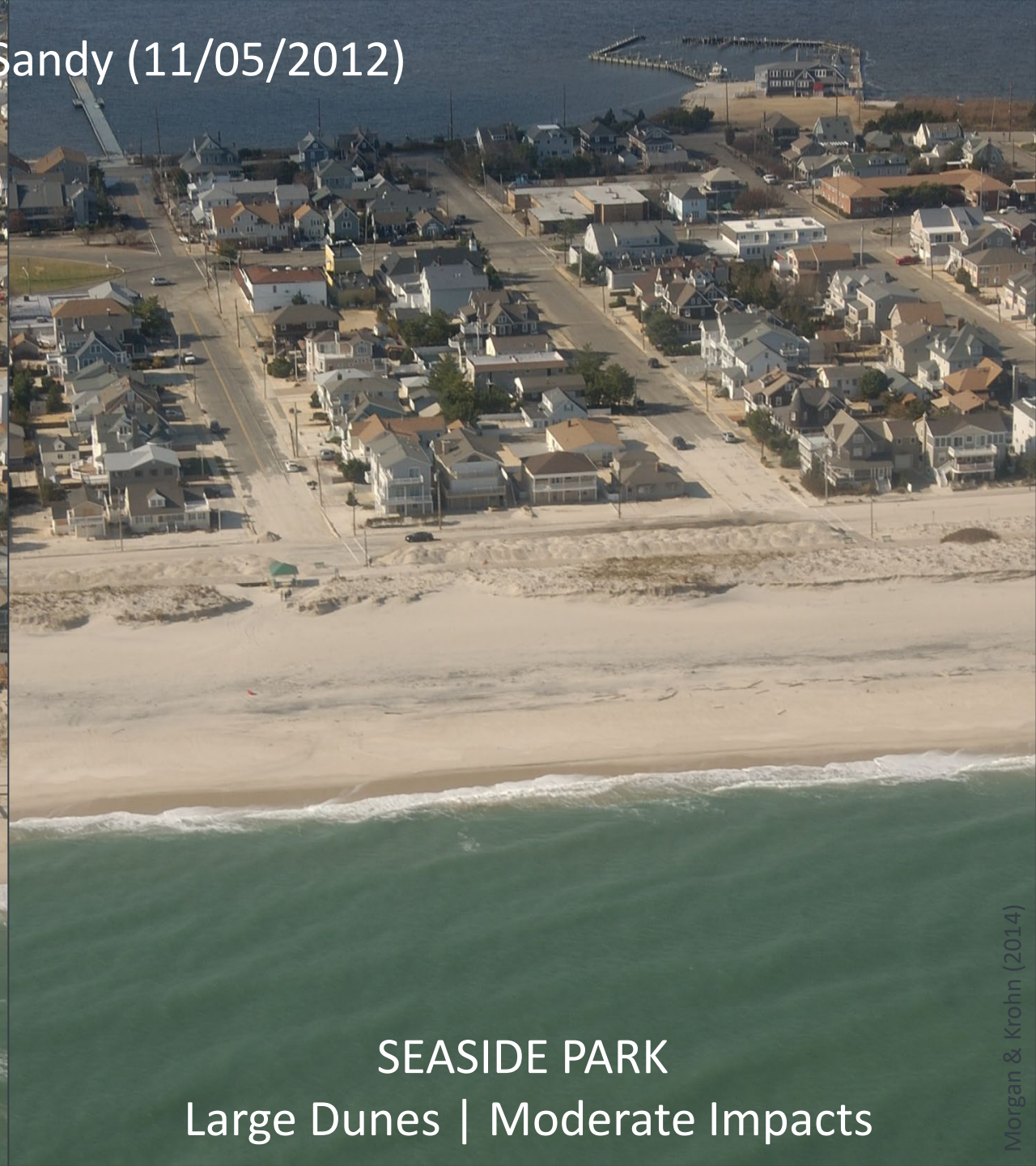
NETHERLANDS



Post-Hurricane Sandy (11/05/2012)



ORTLEY BEACH
Small Dunes | Major Impacts



SEASIDE PARK
Large Dunes | Moderate Impacts

Winter Storm Orlena (2021)



Jersey Shore beaches were torn apart by winter storm; N.J. urges feds for emergency aid

Updated: Feb. 09, 2021, 12:30 p.m. | Published: Feb. 09, 2021, 12:30 p.m.



Hurricane Milton: At least 14 deaths co monster storm slams into Florida

The dangerous storm spawned a tornado outbreak ahead of landfall. Millions w
hurric

Hurricane Helene Smashes Florida, Southeast U.S.

Helene hit Florida as a Category 4 hurricane Thursday, bringing deadly storm surges and flooding to much of the Southeast U.S.

By Alan Kronenberg | Sept. 27, 2024, at 4:13 p.m.

Save Comment f X in ...



The New York Times

Hurricane Michael Leaves Trail of Destruction as It Slams Florida's Panhandle

BBC

Home News Sport Business Innovation Culture Arts Travel Earth Video Live

Hurricane Irma: Storm hits west coast of Florida

11 September 2017

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U.S. NEWS

Tropical Storm Debby hits Florida with floods, threat of record rain in Georgia and the Carolinas



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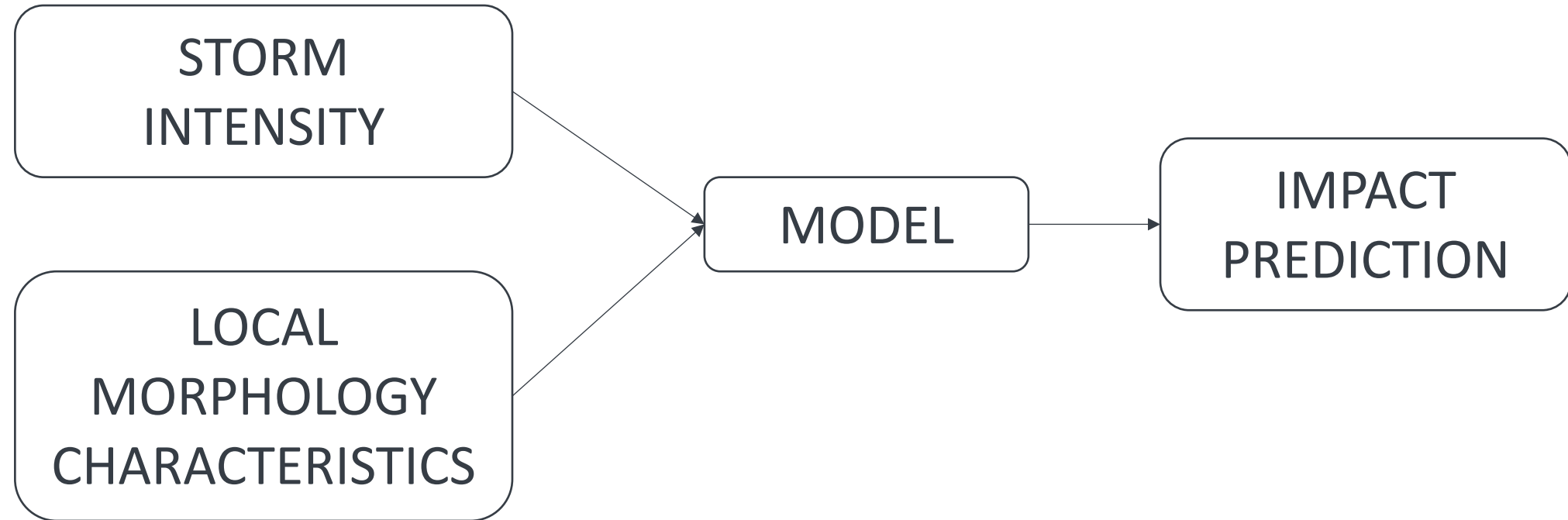
REPORT

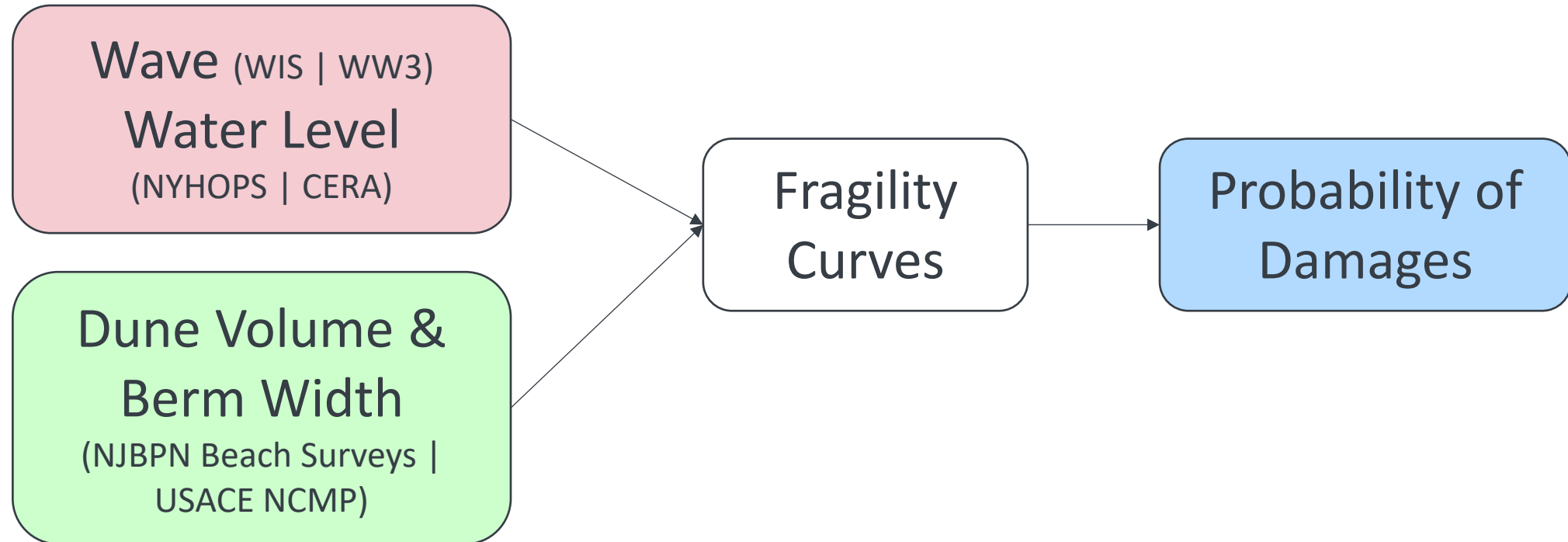
U.S. NEWS

Ian was one of the most lethal hurricanes in decades. Many of the deaths were preventable.

The model

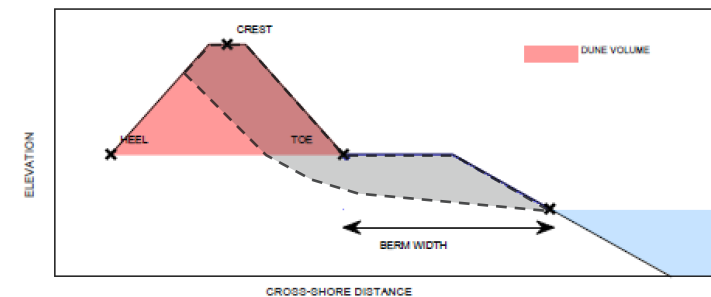
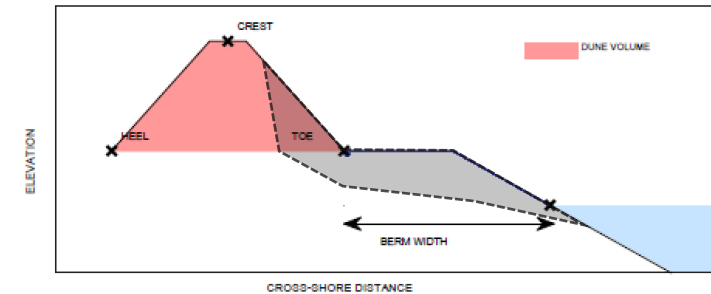
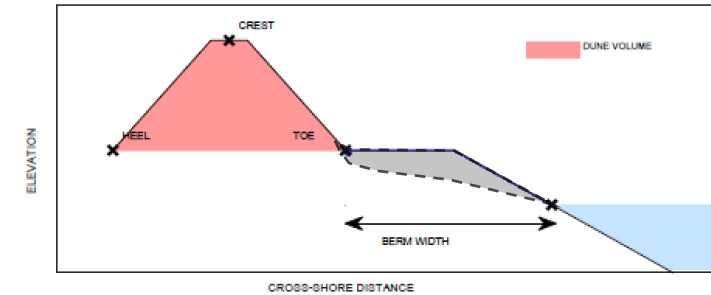




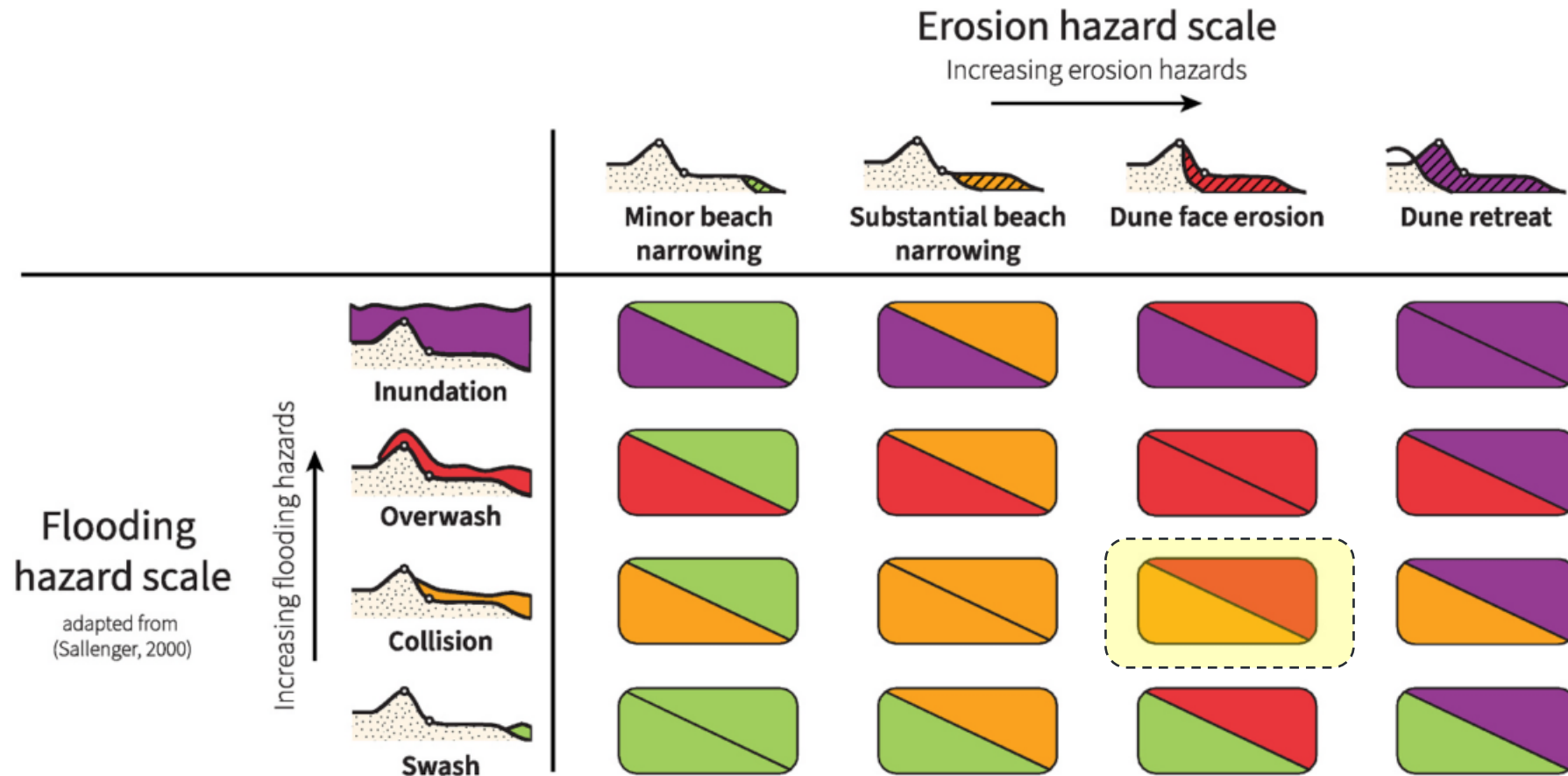


Damage Class apply to the Dune Erosion only

Class	Volume loss (% of pre-storm dune volume)	Interpretation
Minimal	< 5%	No measurable impacts
Moderate	5% to 40%	Visually apparent erosion/scarping
Major	> 40%	Overwash likely; <i>Onset of damages upland</i>

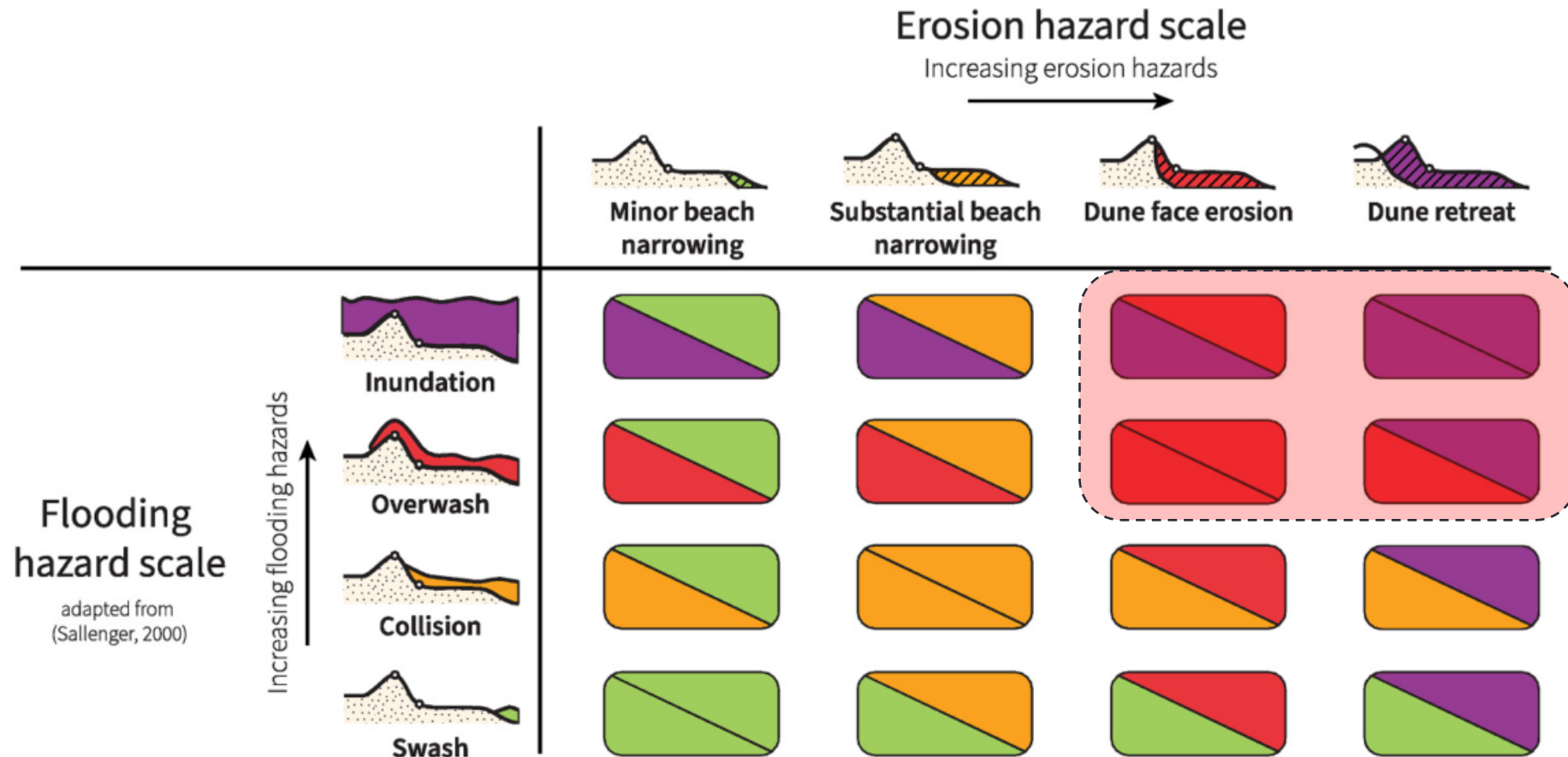


Storm Hazard Matrix



Leaman, et al. (2022)

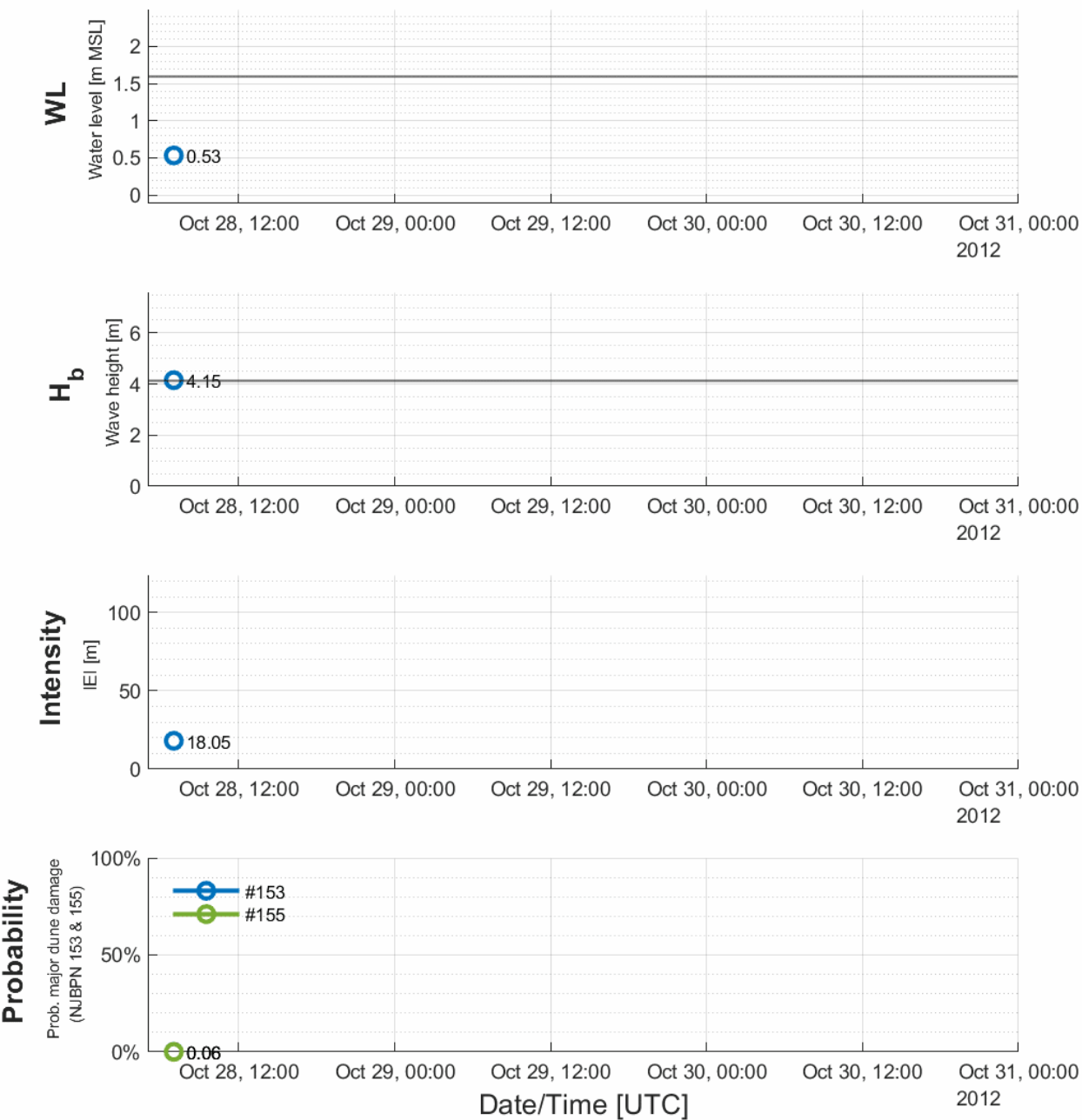
Storm Hazard Matrix



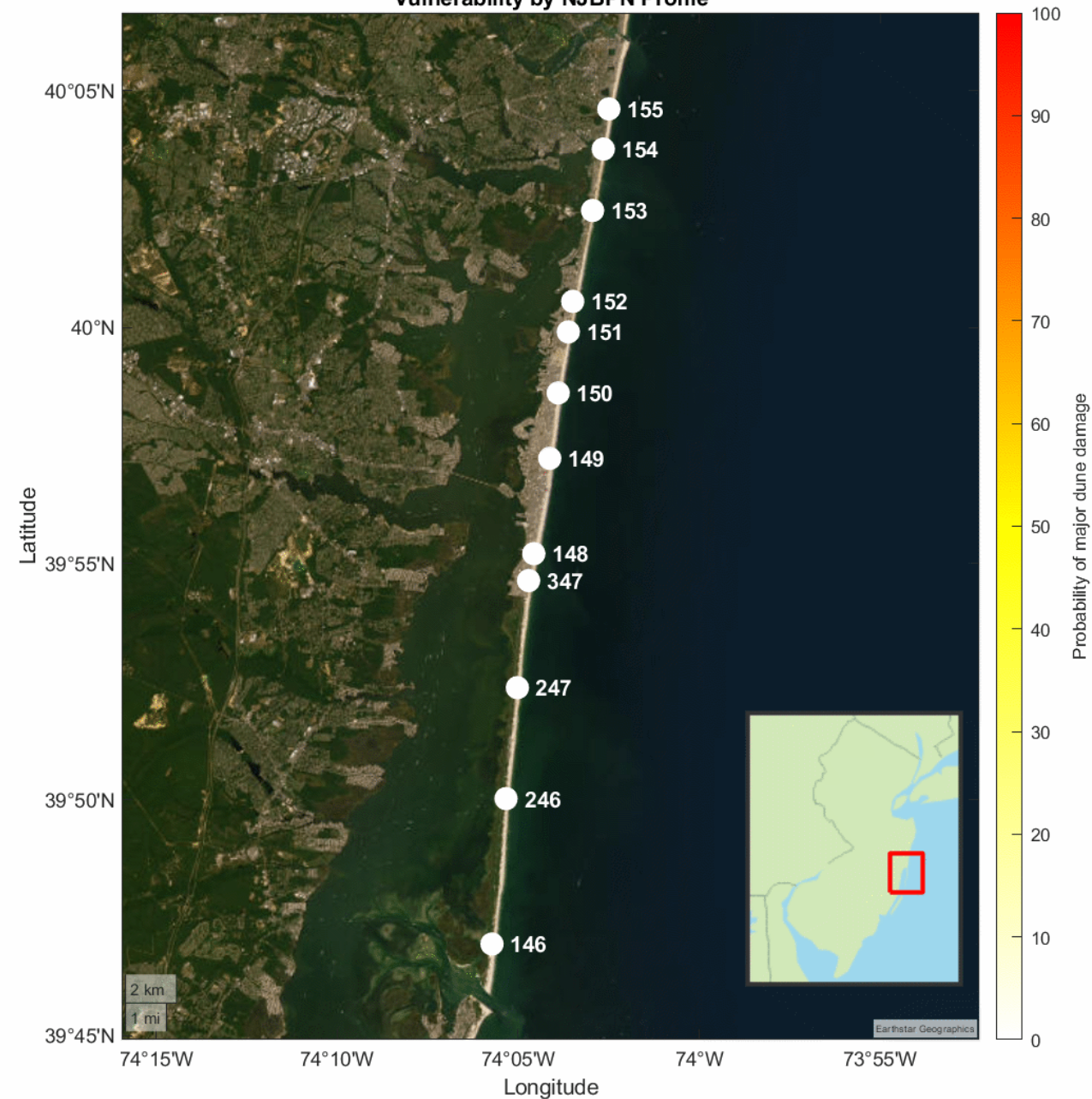
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Hourly Storm Vulnerability NJ Shoreline Segment 5

Storm Parameter Time-Series

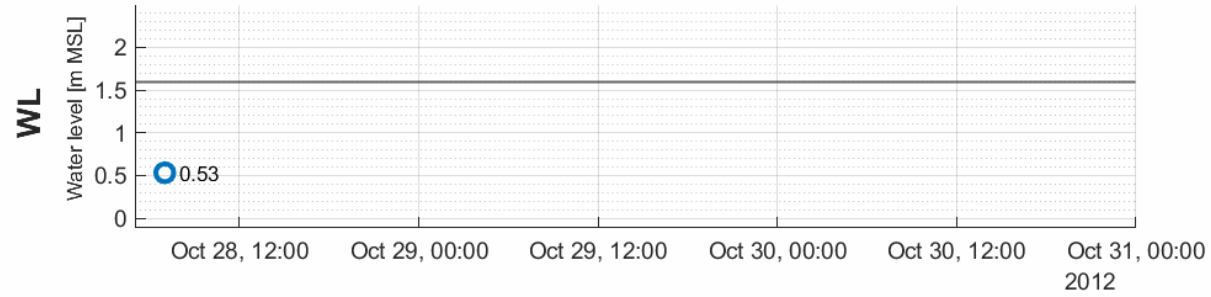


Vulnerability by NJBNP Profile



Hourly Storm Vulnerability NJ Shoreline Segment 5

Storm Parameter Time-Series



Instantaneous Erosion
Intensity (IEI)

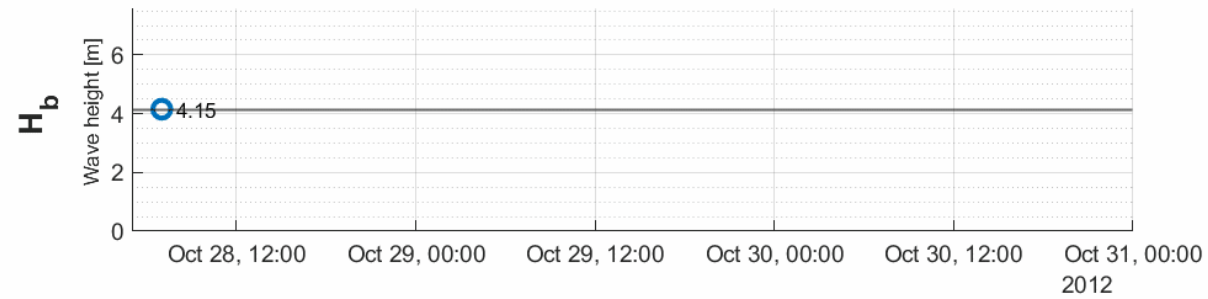
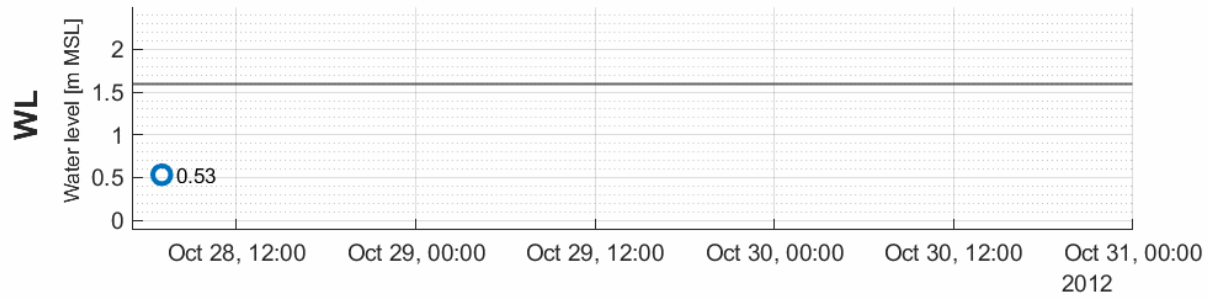
$$IEI(t_i) = W_* \left[\frac{0.068H_b(t_i) + S(t_i)}{B + 1.28H_b(t_i)} \right]$$

Lemke and Miller (2020)



Hourly Storm Vulnerability NJ Shoreline Segment 5

Storm Parameter Time-Series



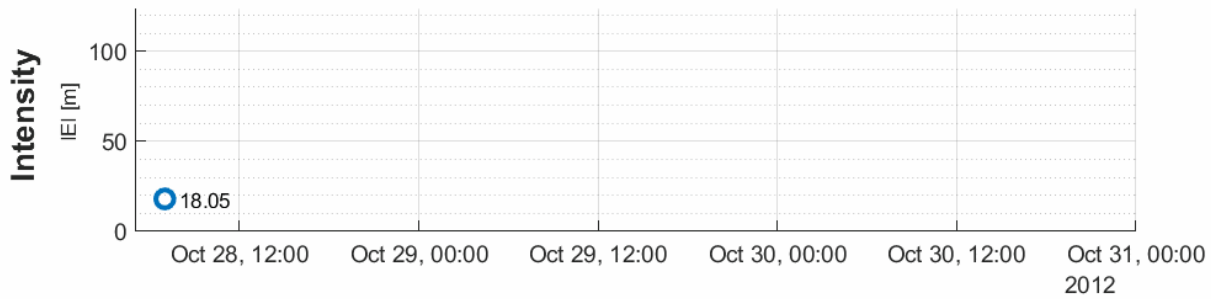
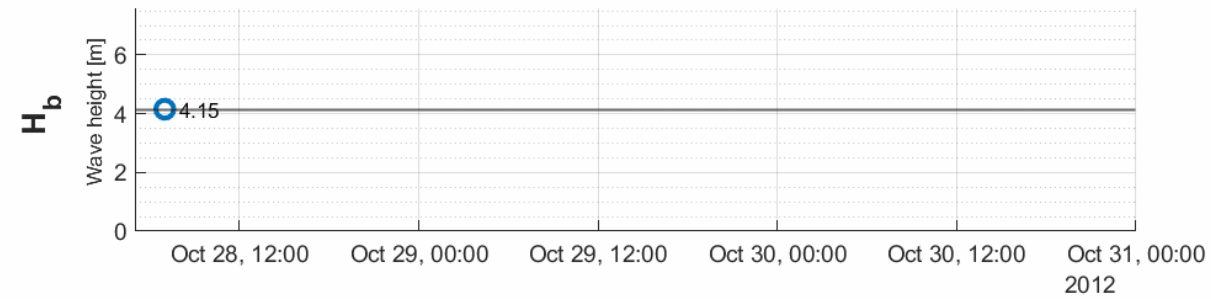
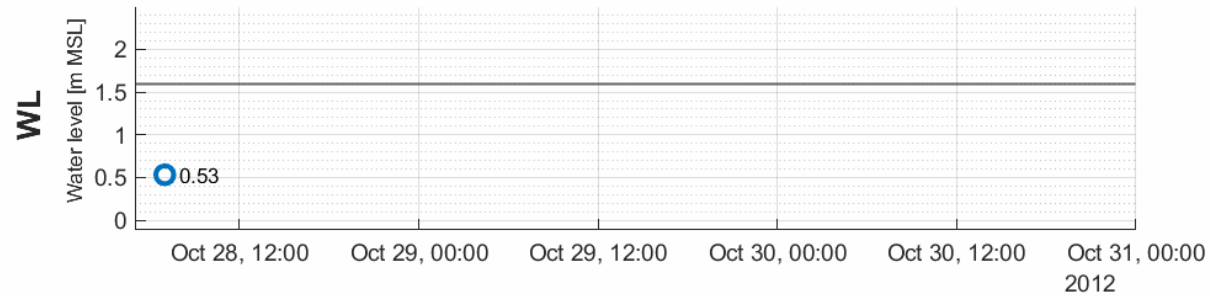
Instantaneous Erosion
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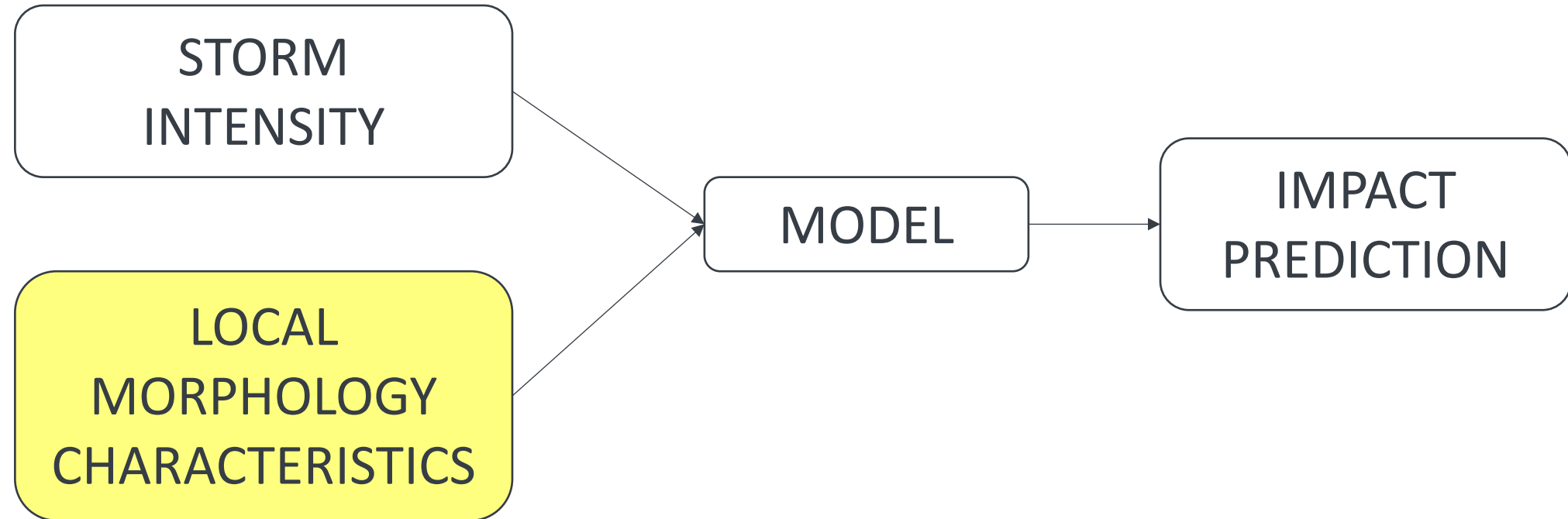
Storm Parameter Time-Series



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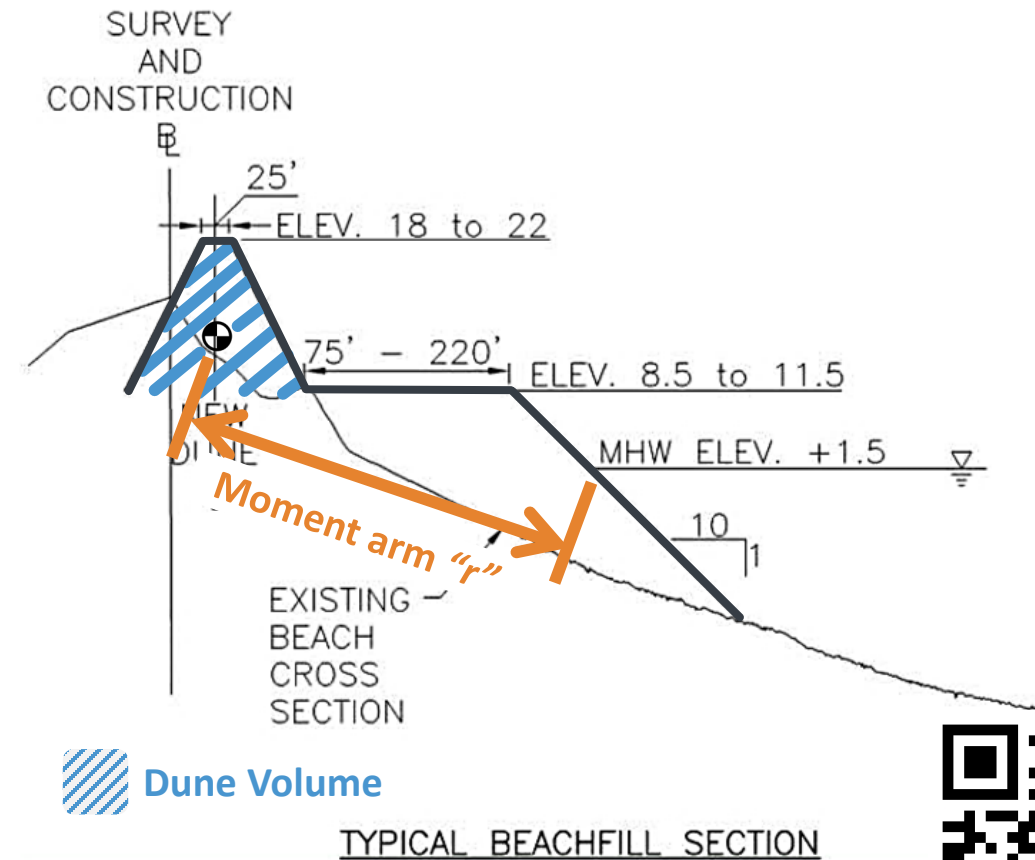




Dune Engineering Demand Parameter (EDP)

$$EDP = \frac{\text{Storm Intensity}}{\text{Dune Resilience } (R_f)}$$

$$EDP = \frac{\text{Peak Storm Intensity}^4}{\text{Dune Vol} \times r^2}$$

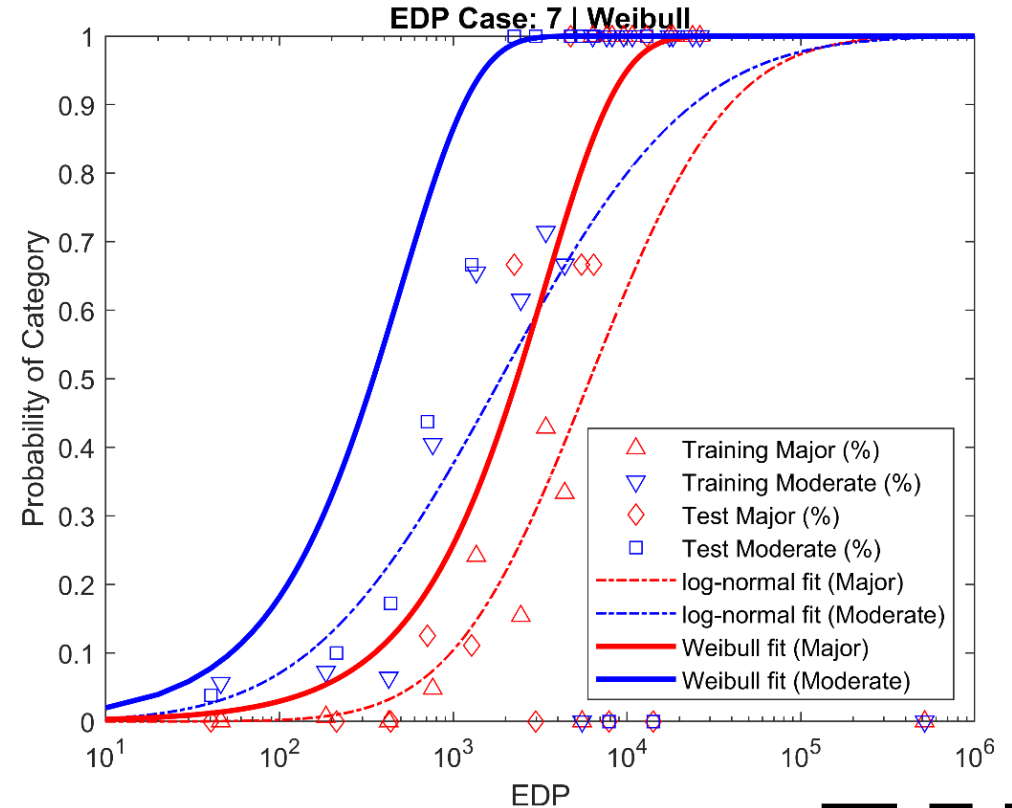


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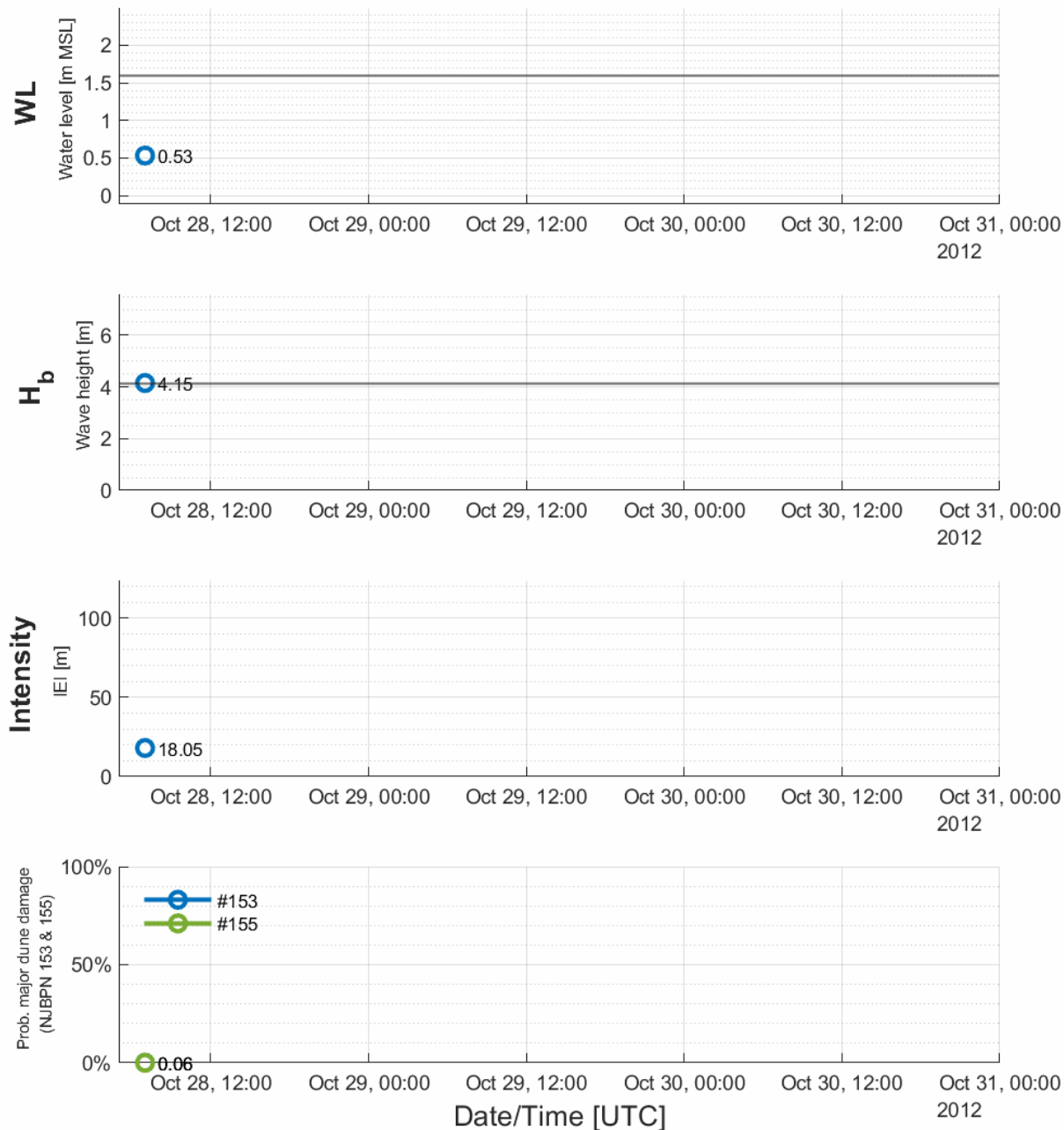
$$EDP = \frac{\text{Peak Storm Intensity}^4}{\text{Dune Vol} \times r^2}$$

$$P(\text{Class}) = 1 - \exp\left(\frac{-EDP}{1697}\right)^{1.35}$$



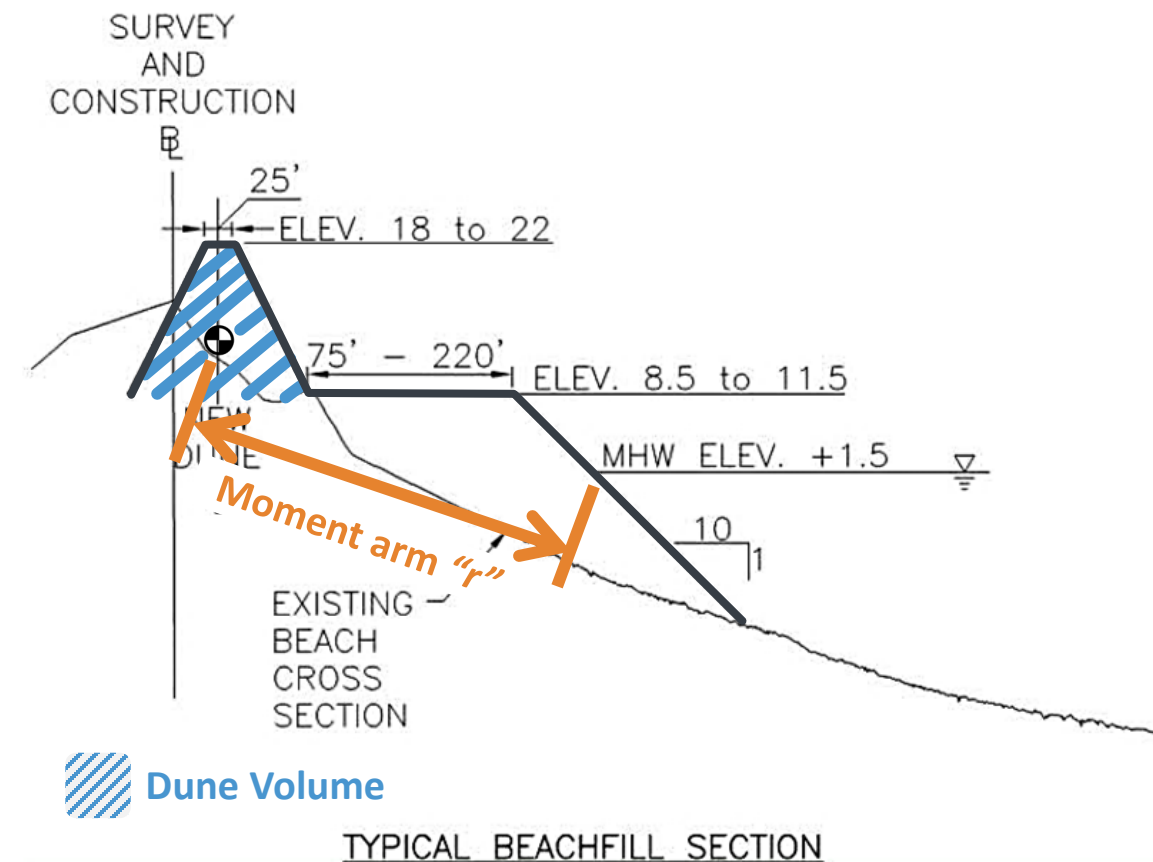
Hourly Storm Vulnerability NJ Shoreline Segment 5

Storm Parameter Time-Series



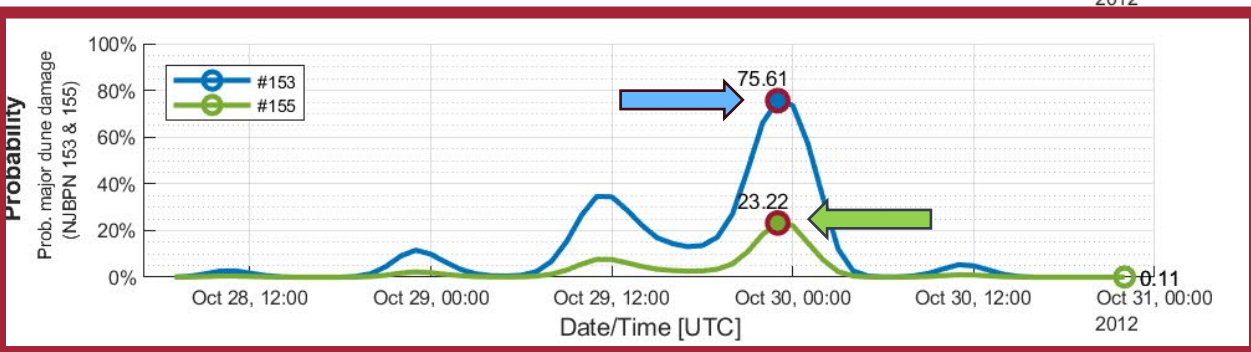
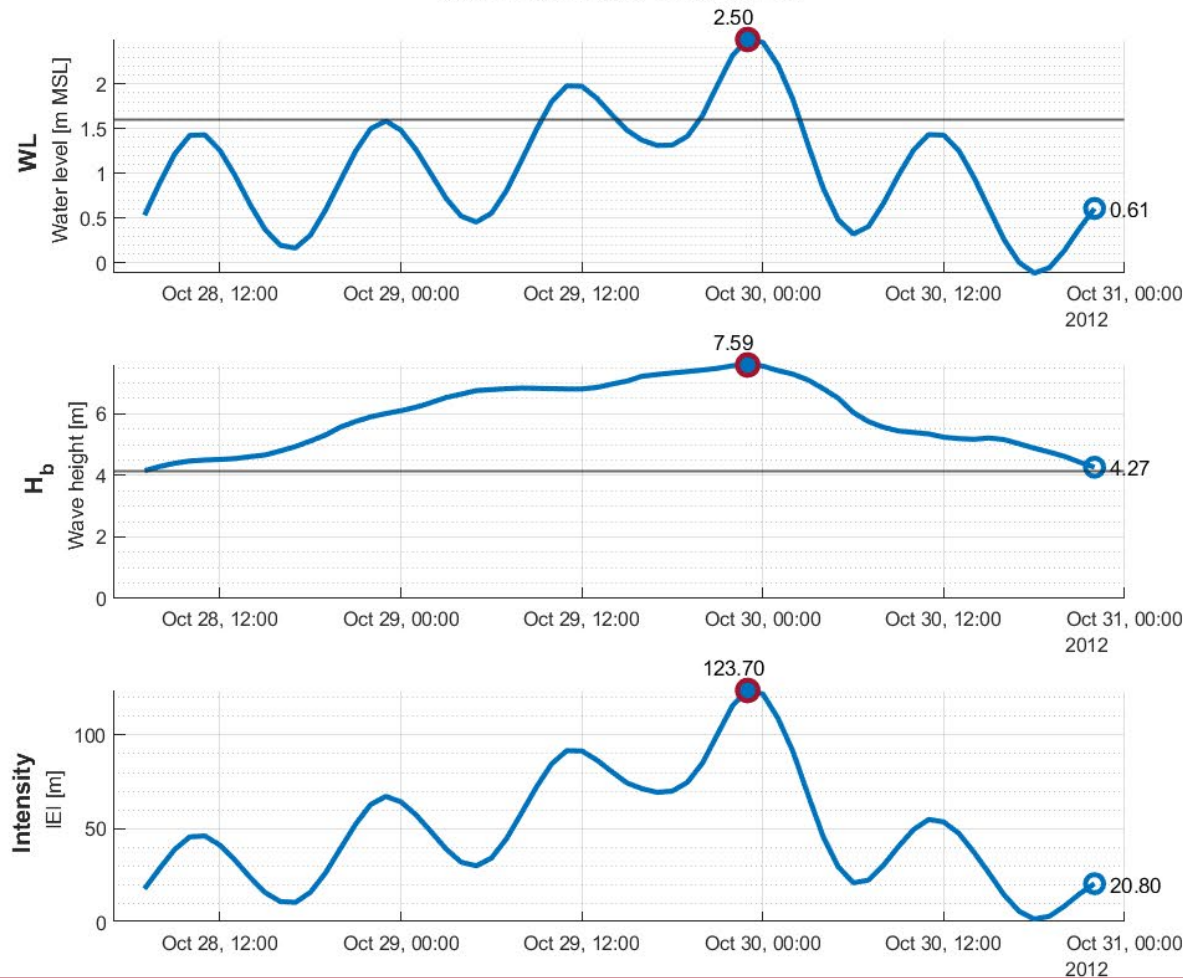
Engineering Demand Parameter (EDP)

$$EDP = \frac{PEI^4}{Dune\ Vol \times r^2}$$

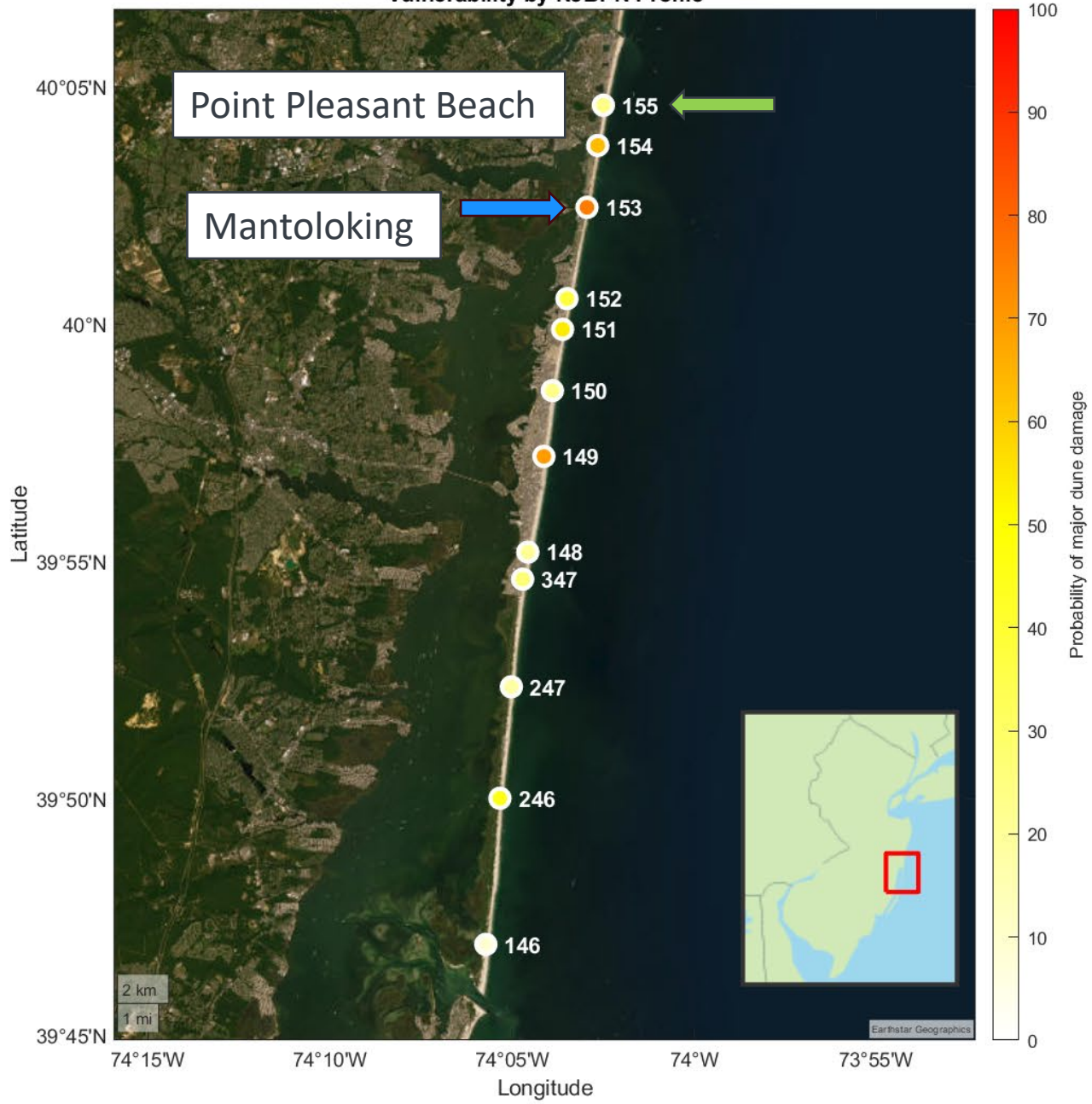


Hourly Storm Vulnerability NJ Shoreline Segment 5

Storm Parameter Time-Series

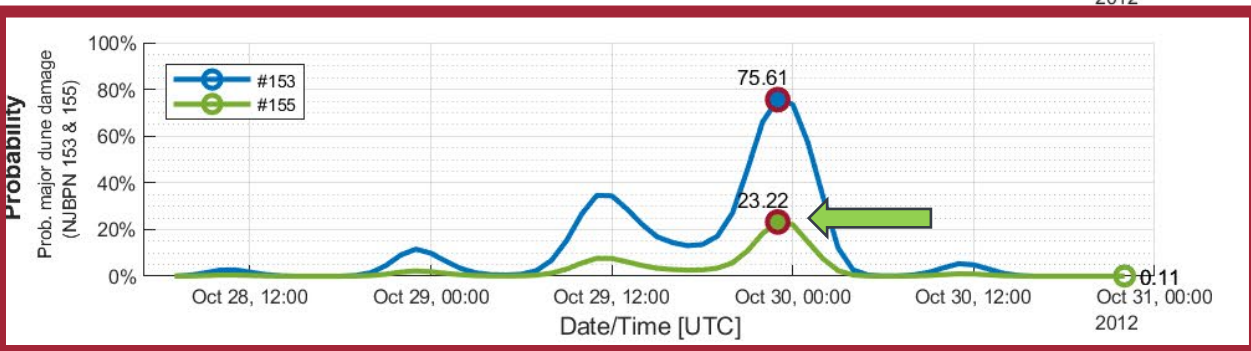
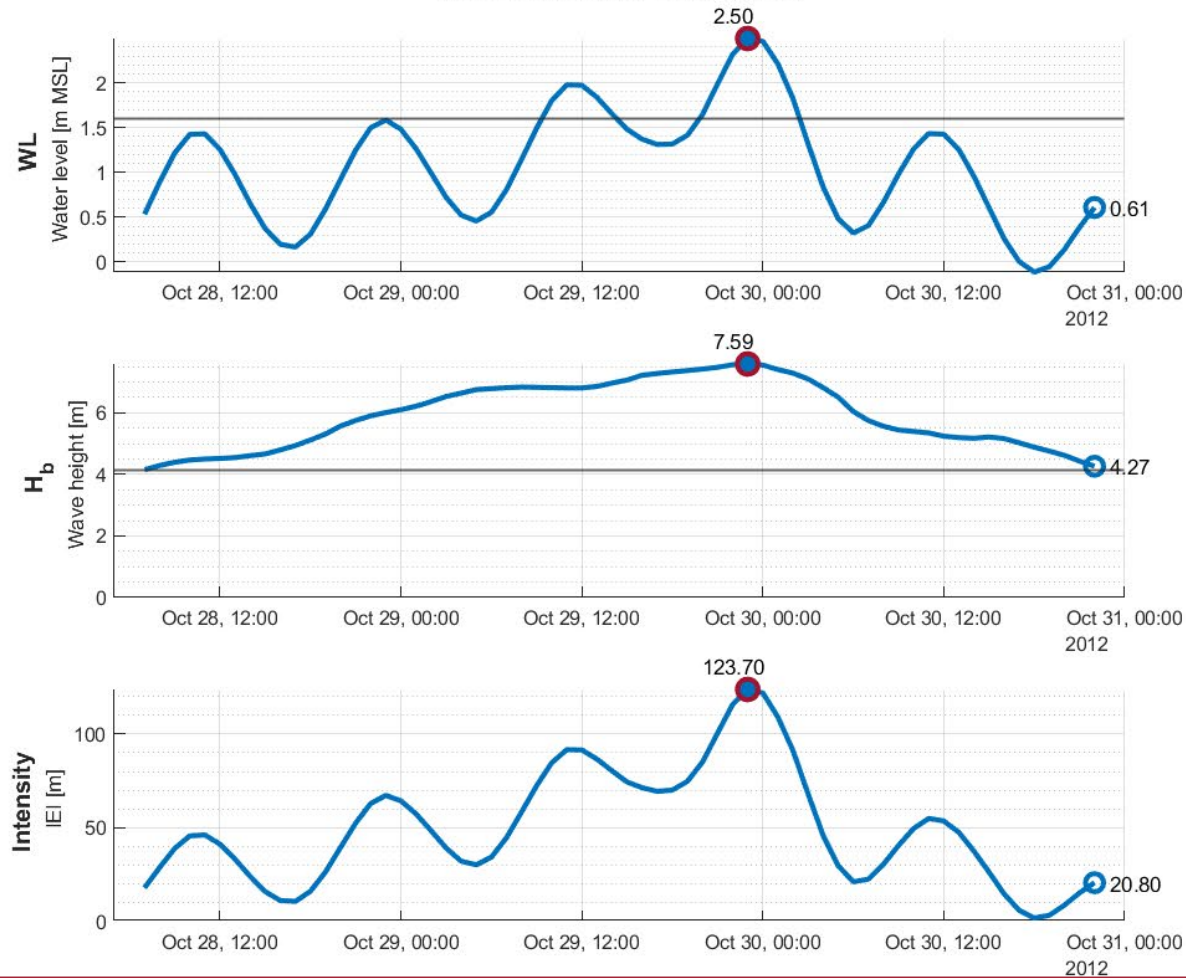


Vulnerability by NJBPN Profile

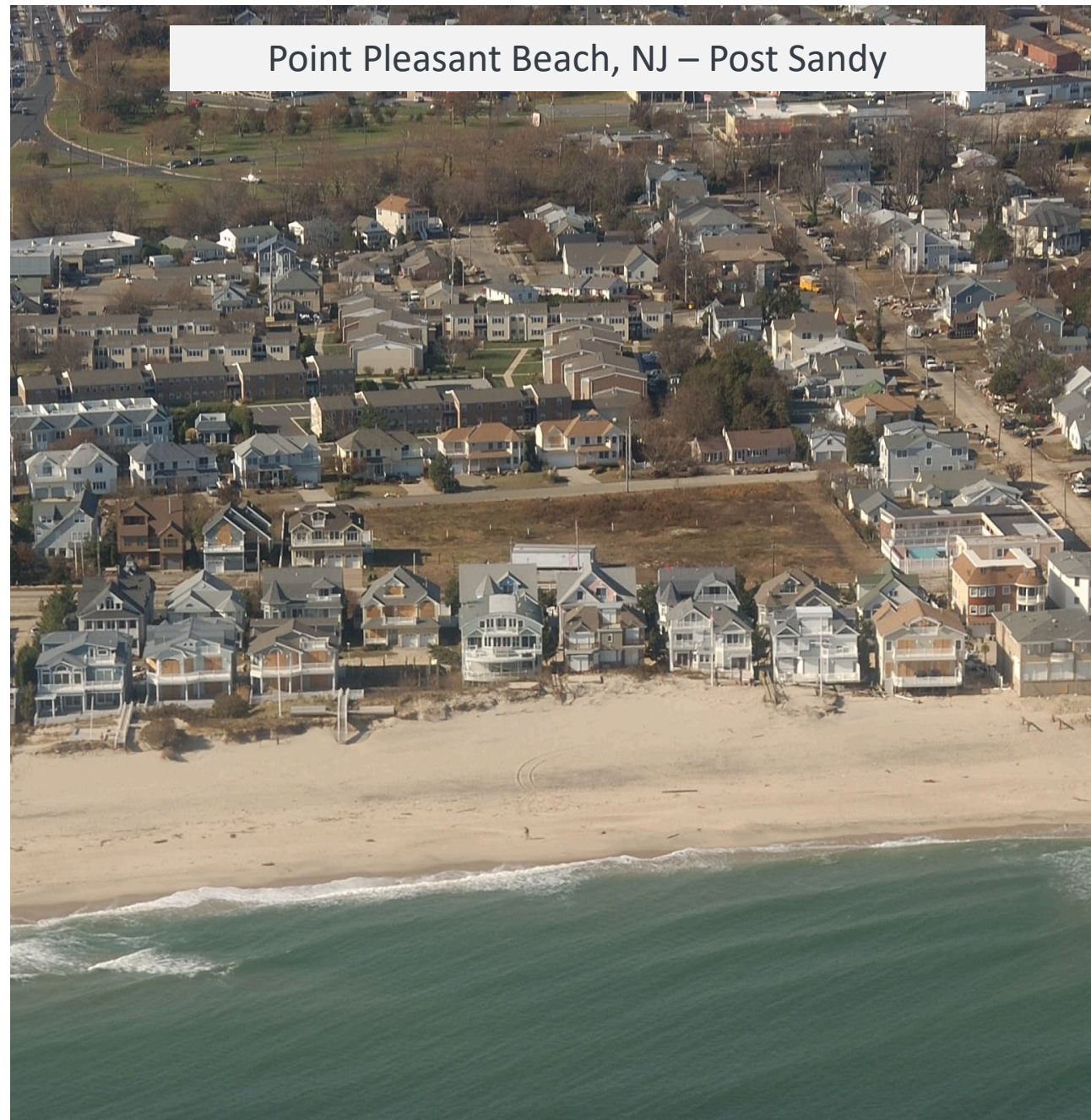


Hourly Storm Vulnerability NJ Shoreline Segment 5

Storm Parameter Time-Series

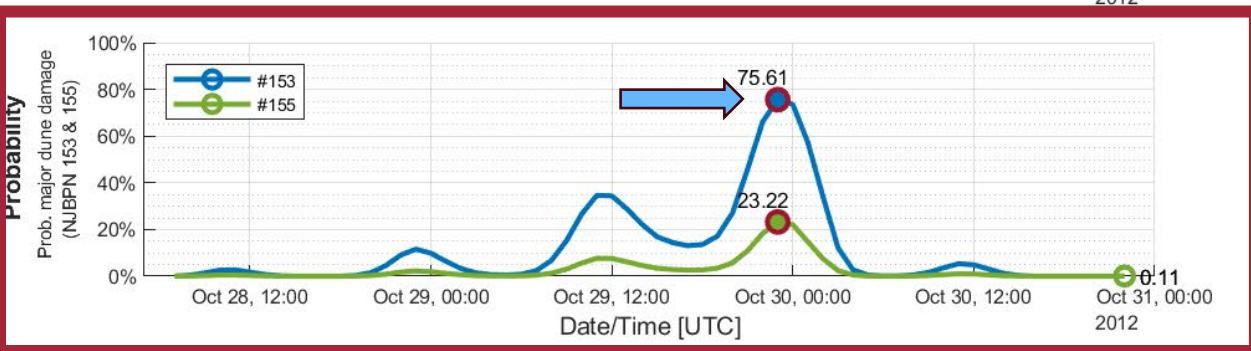
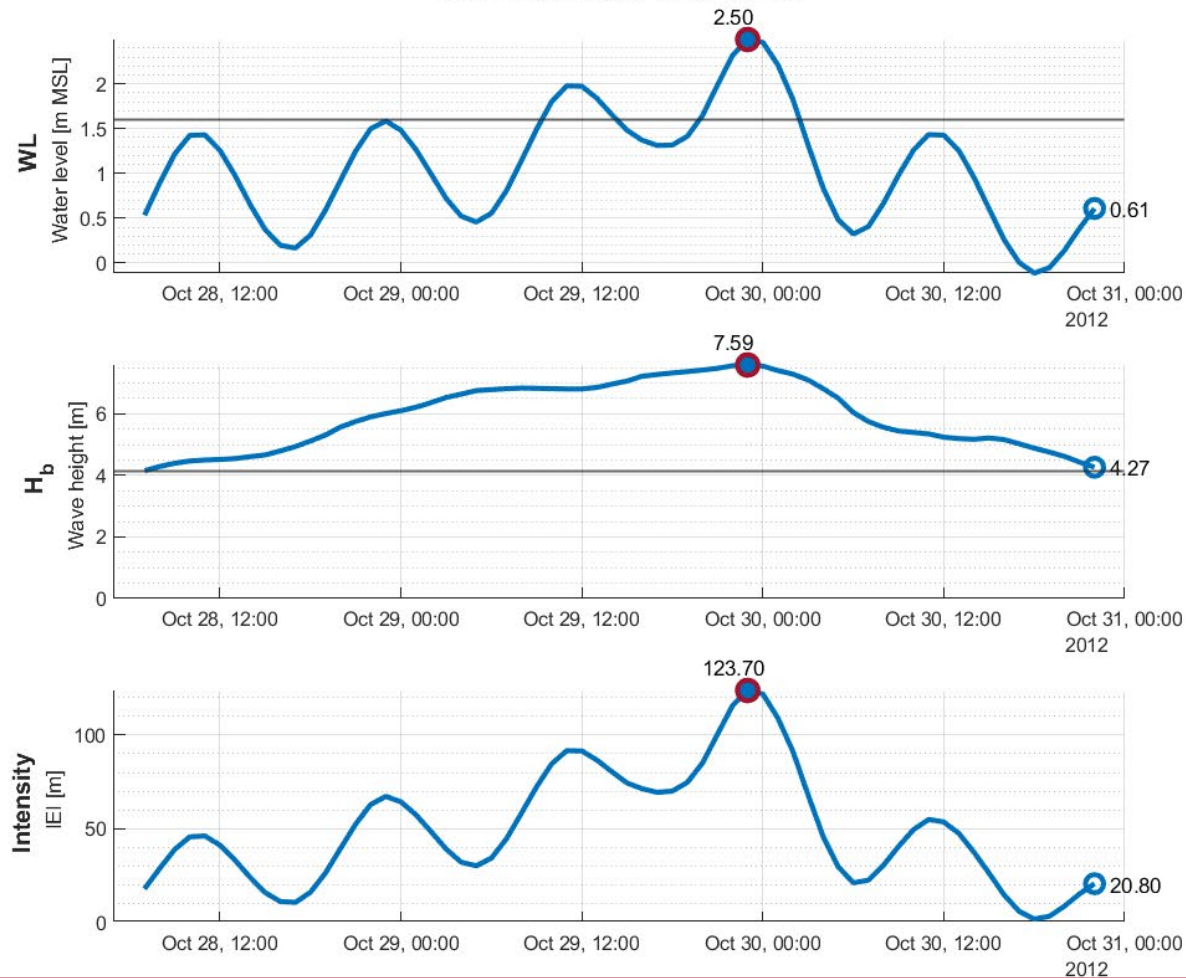


Point Pleasant Beach, NJ – Post Sandy

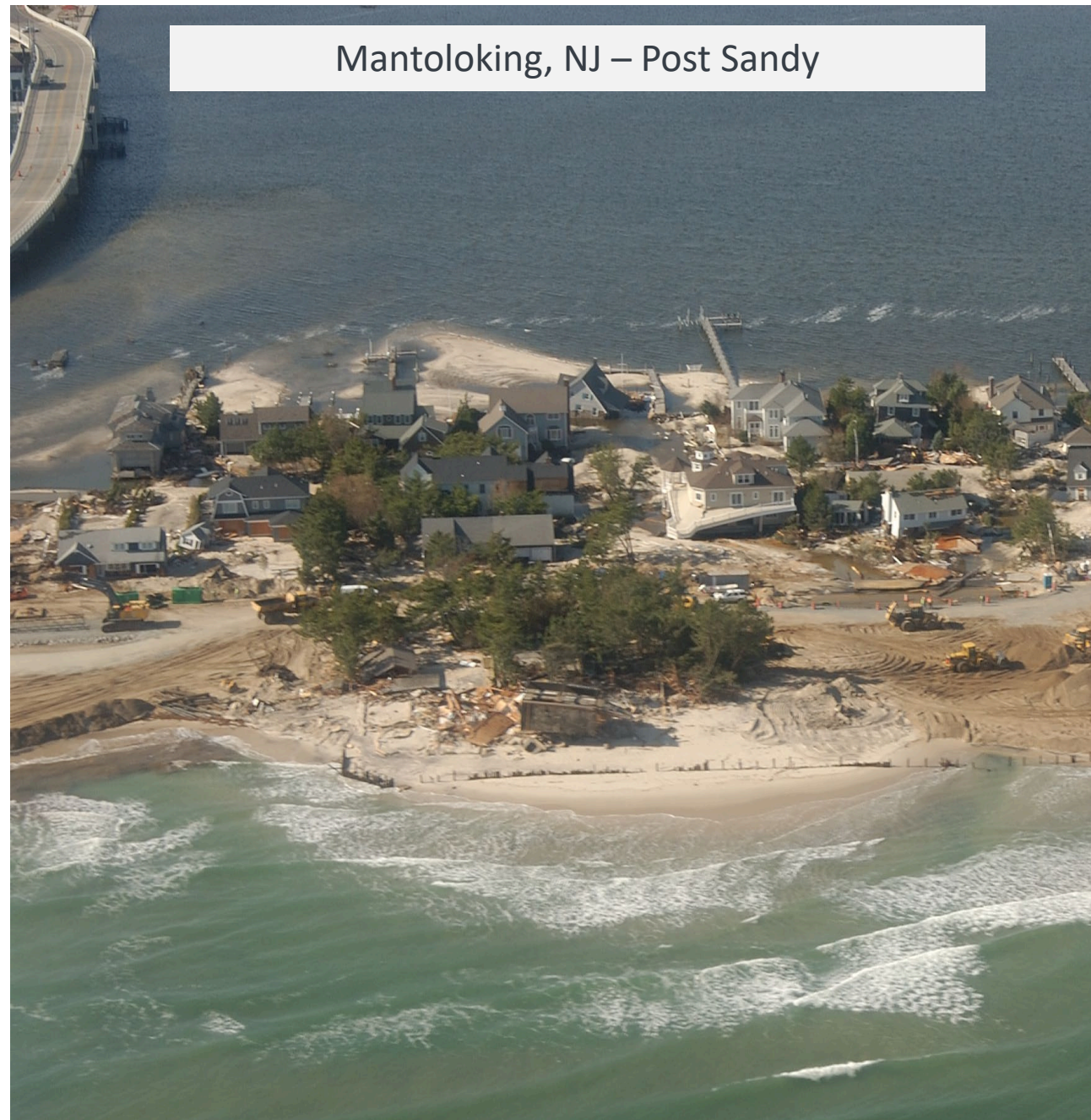


Hourly Storm Vulnerability
NJ Shoreline Segment 5

Storm Parameter Time-Series

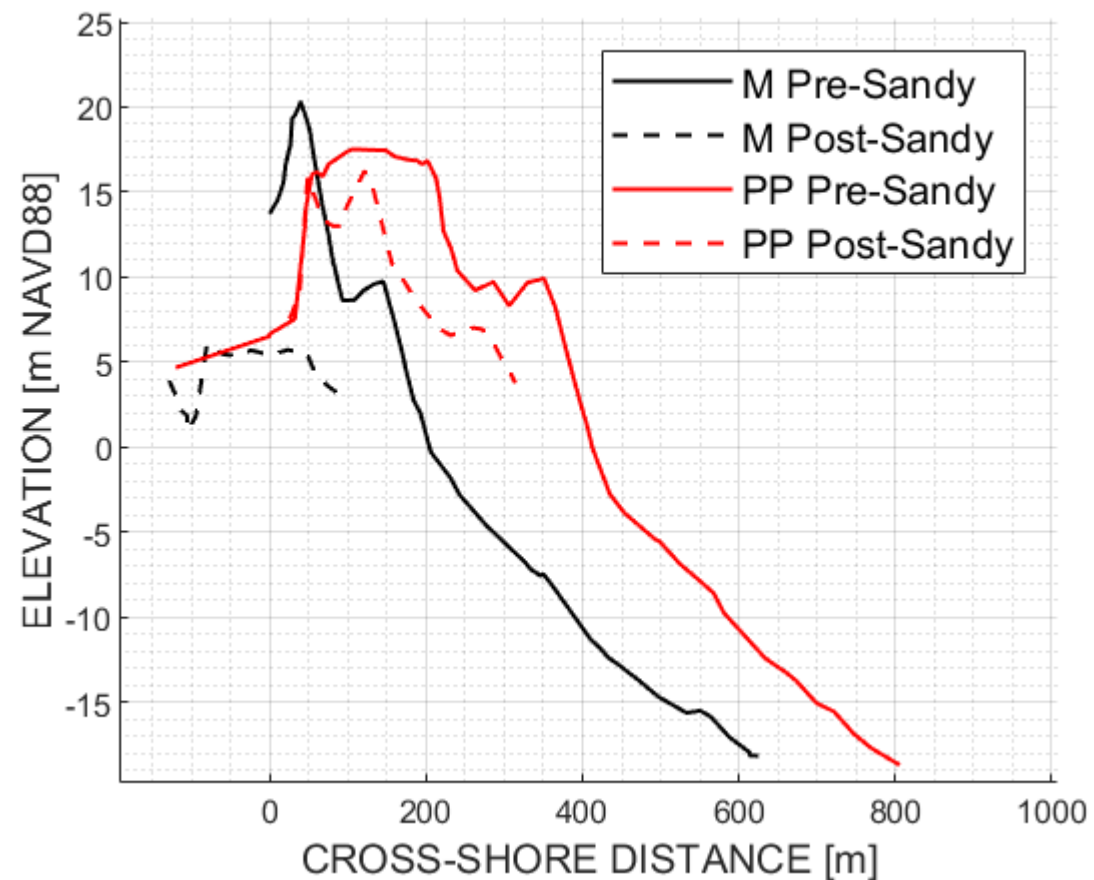
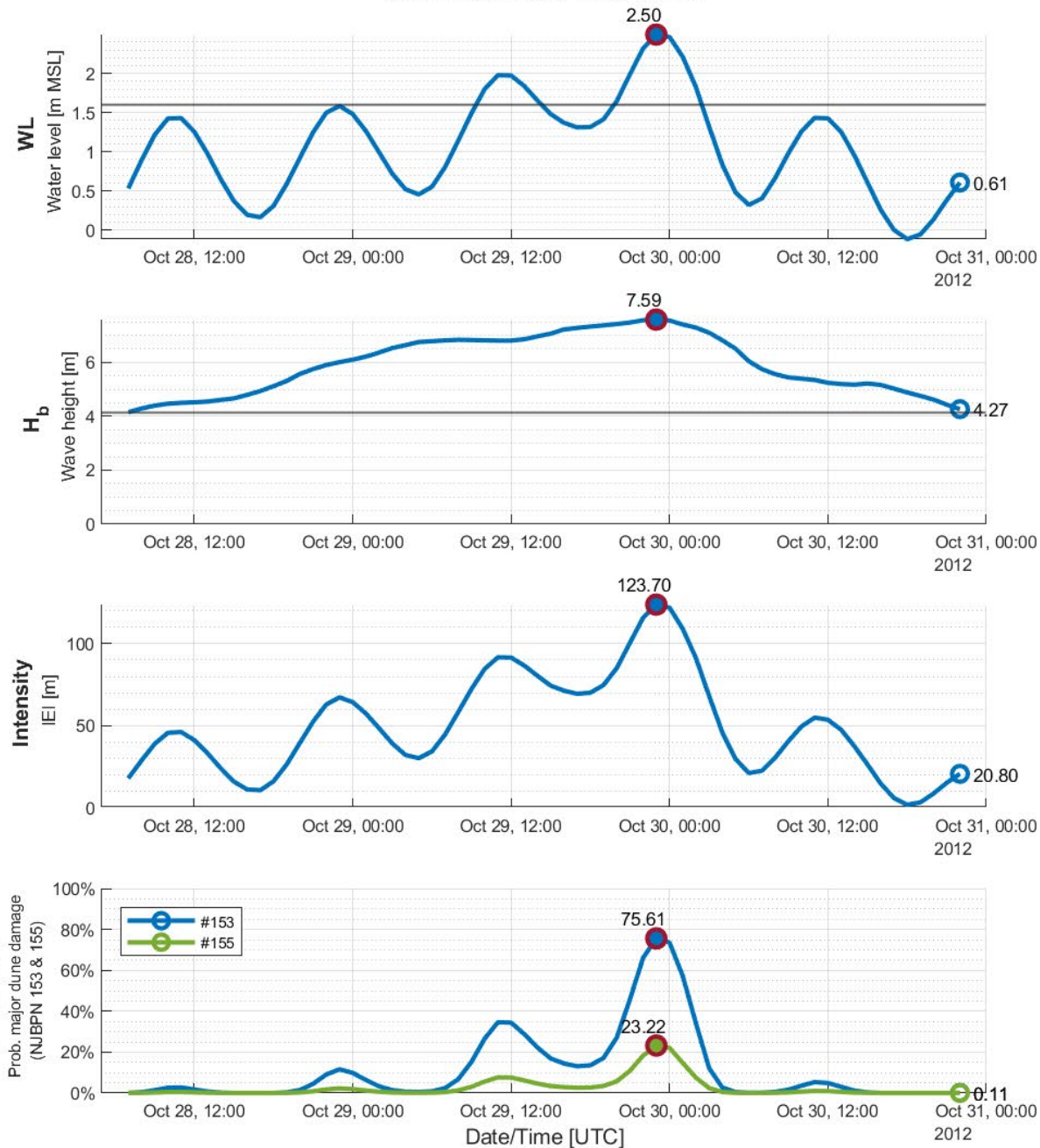


Mantoloking, NJ – Post Sandy



Hourly Storm Vulnerability NJ Shoreline Segment 5

Storm Parameter Time-Series



Model Sensitivity & Parameter Isolation

Hurricane Sandy (2012)

- Change in vulnerability as a function of dune volume

Winter Storm Orlena (2021)

- Change in vulnerability as a function of berm width

Winter Storm Izzy (2022)

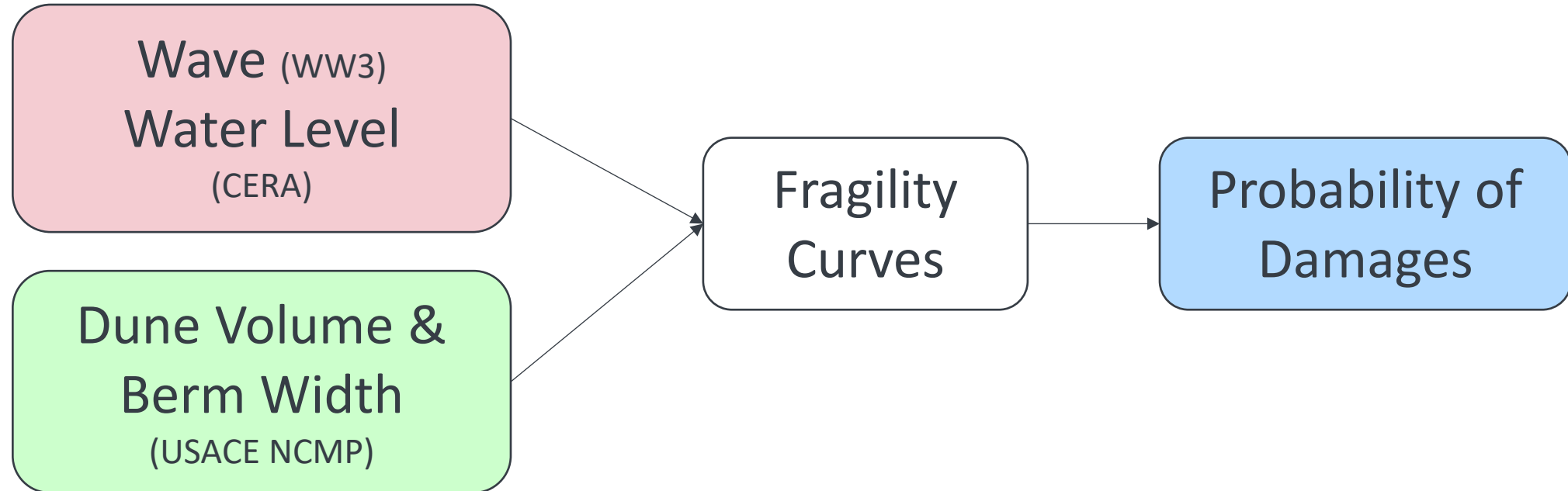
- Captures spatial variation in storm intensity



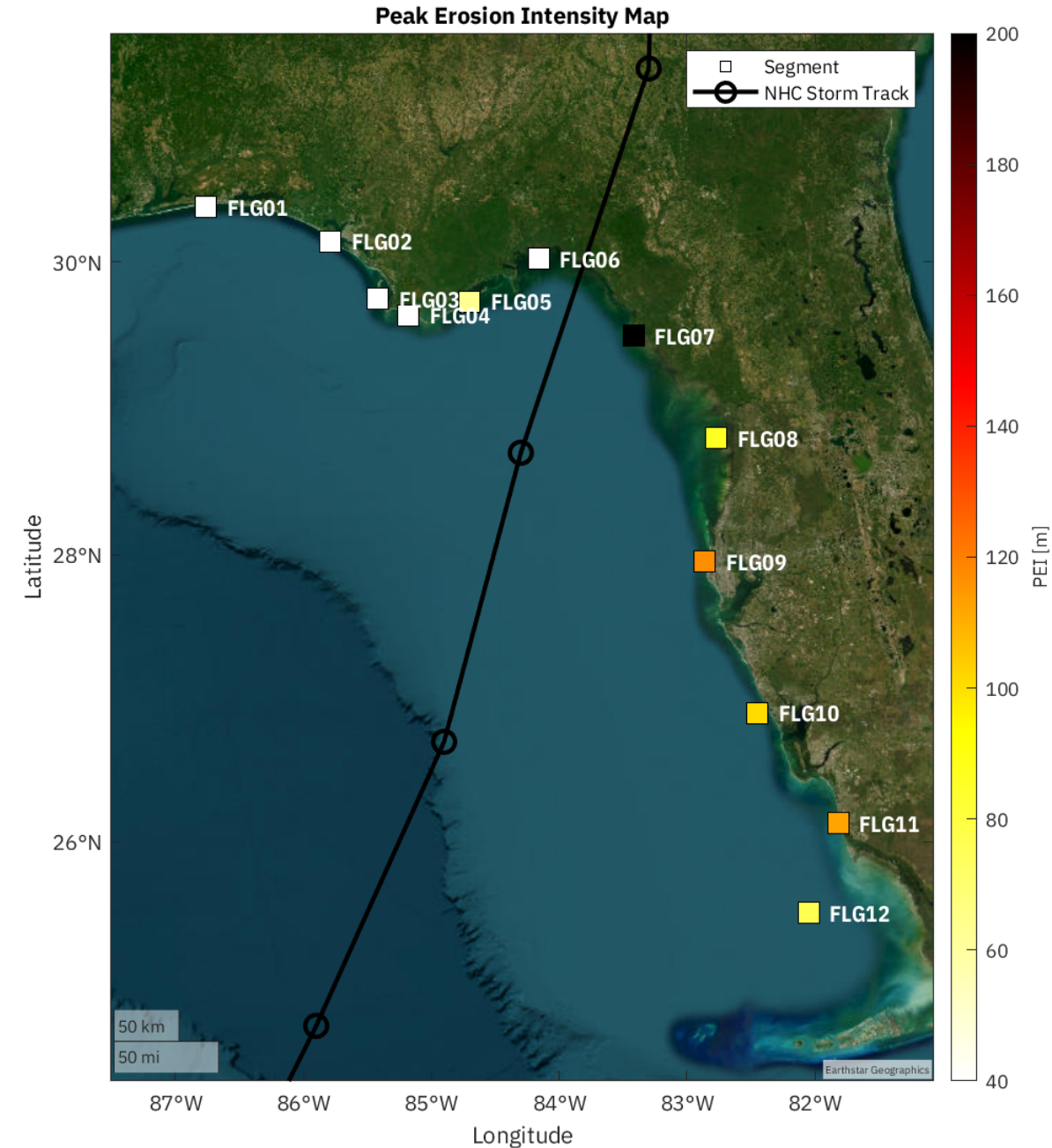
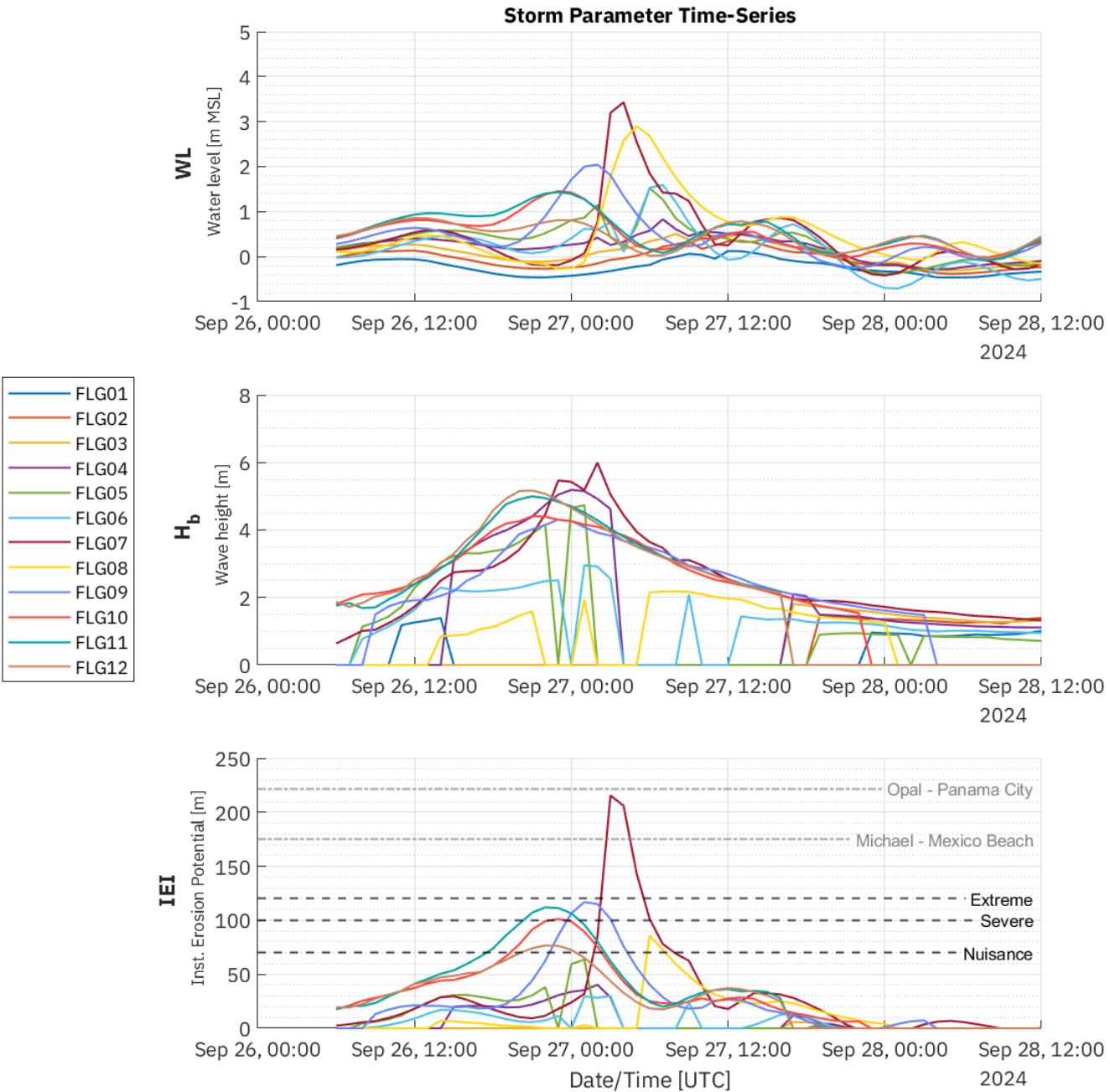
Combining Storm Intensity with Dune Volume and Berm Width as a modified moment of inertia is an efficient way to characterize the capacity of a dune (Day et al, 2023)

Hurricane Helene & Milton

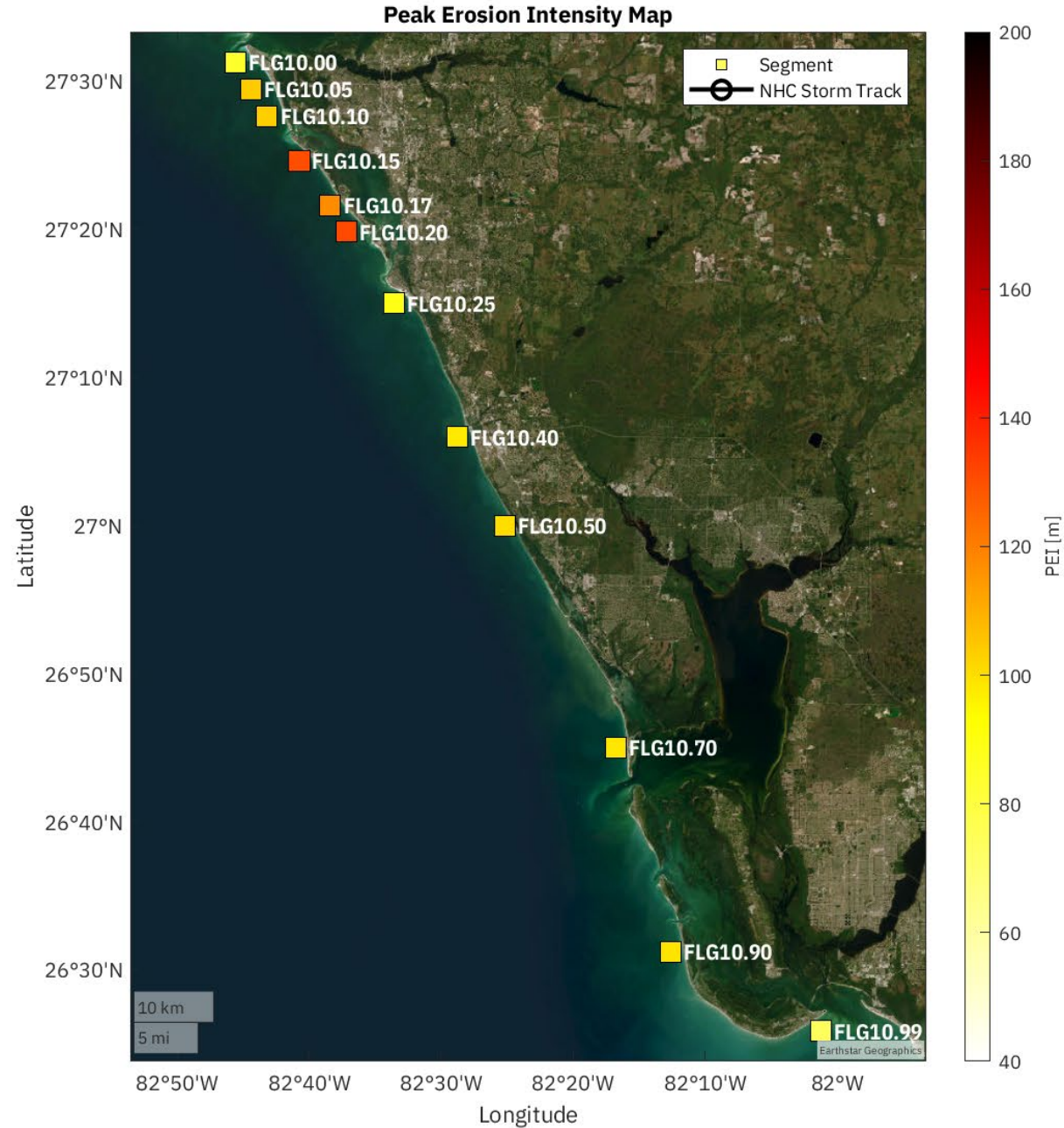
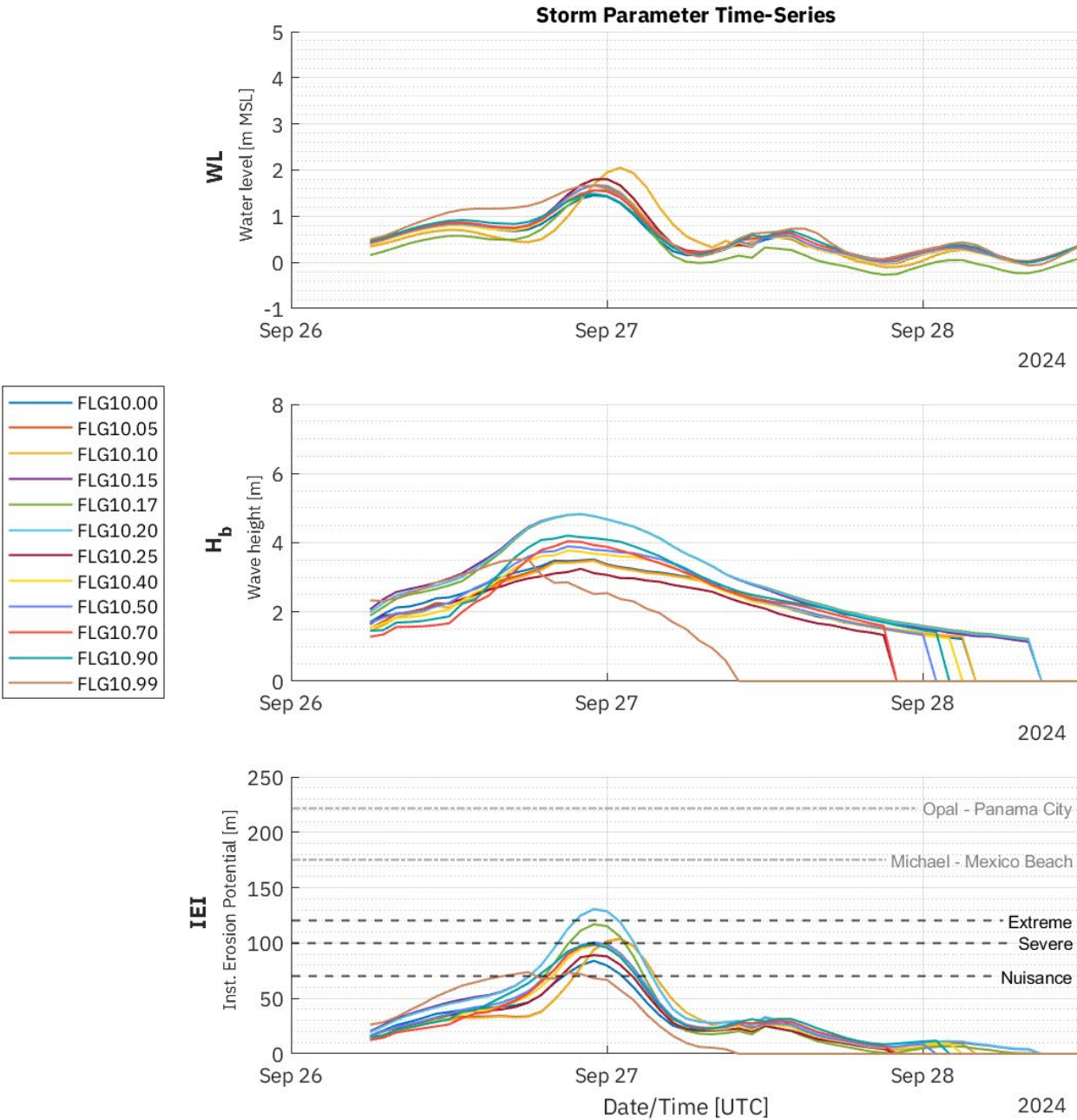




Hourly Storm Intensity Hurricane Helene Gulf Coast

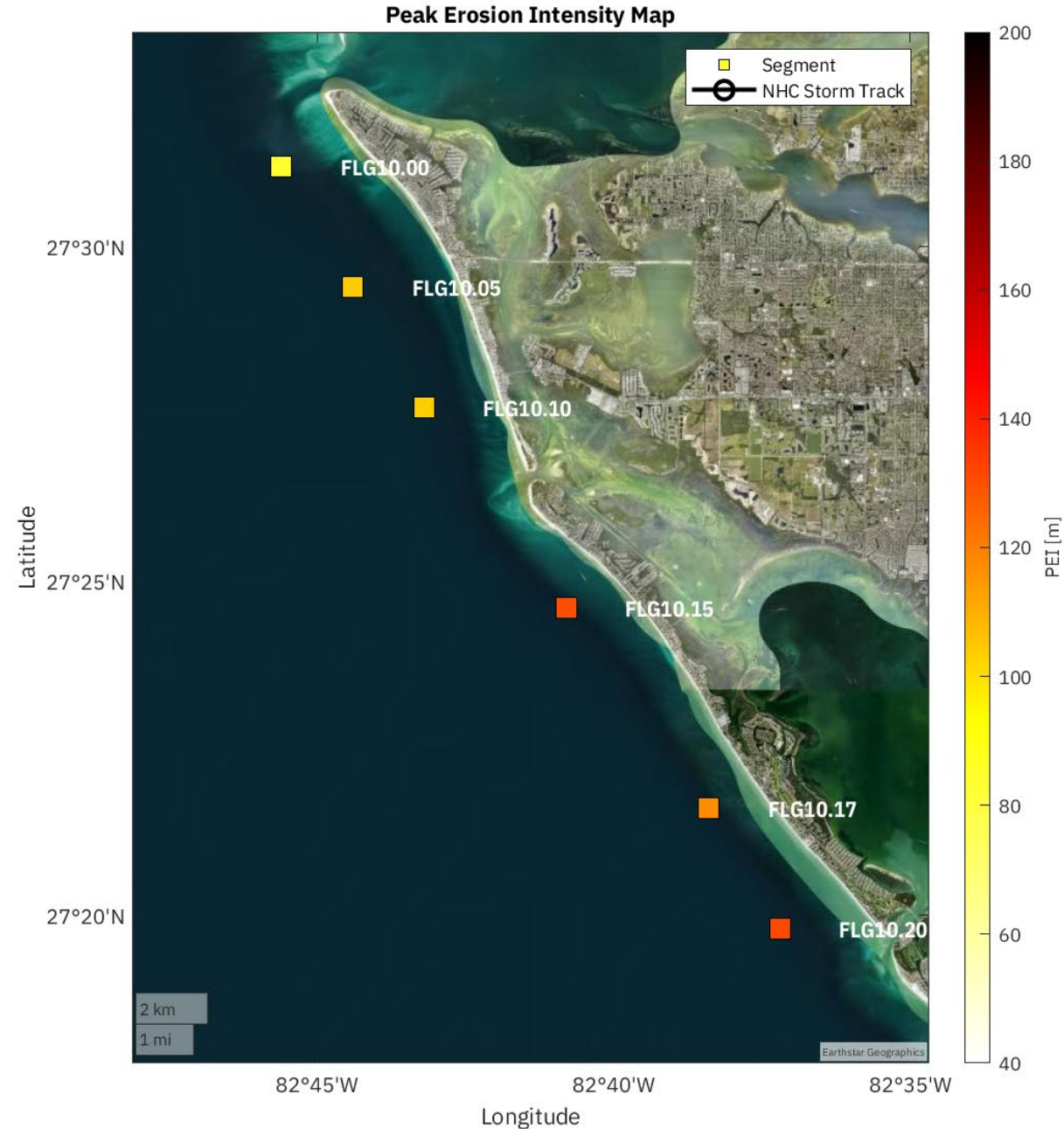
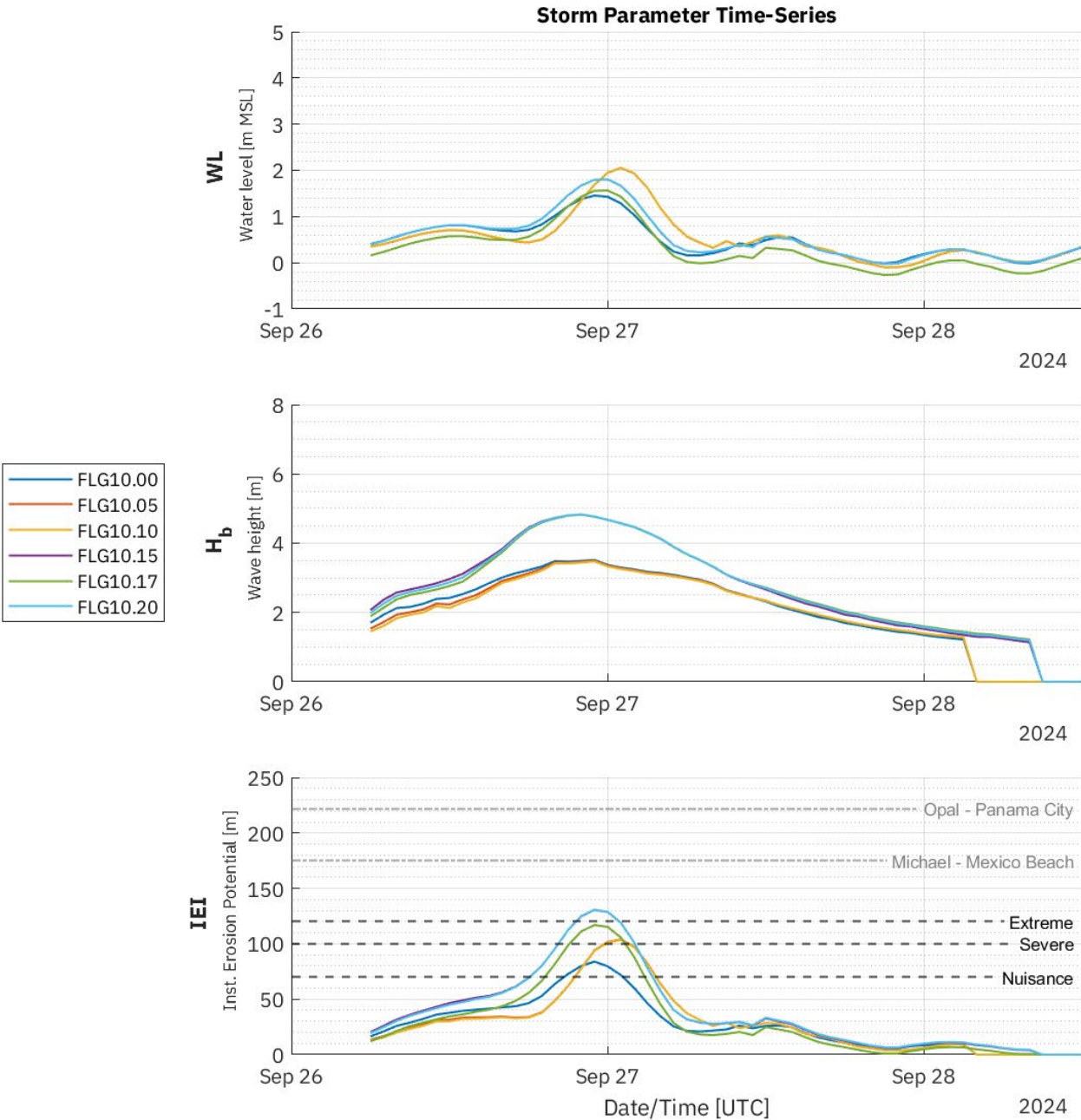


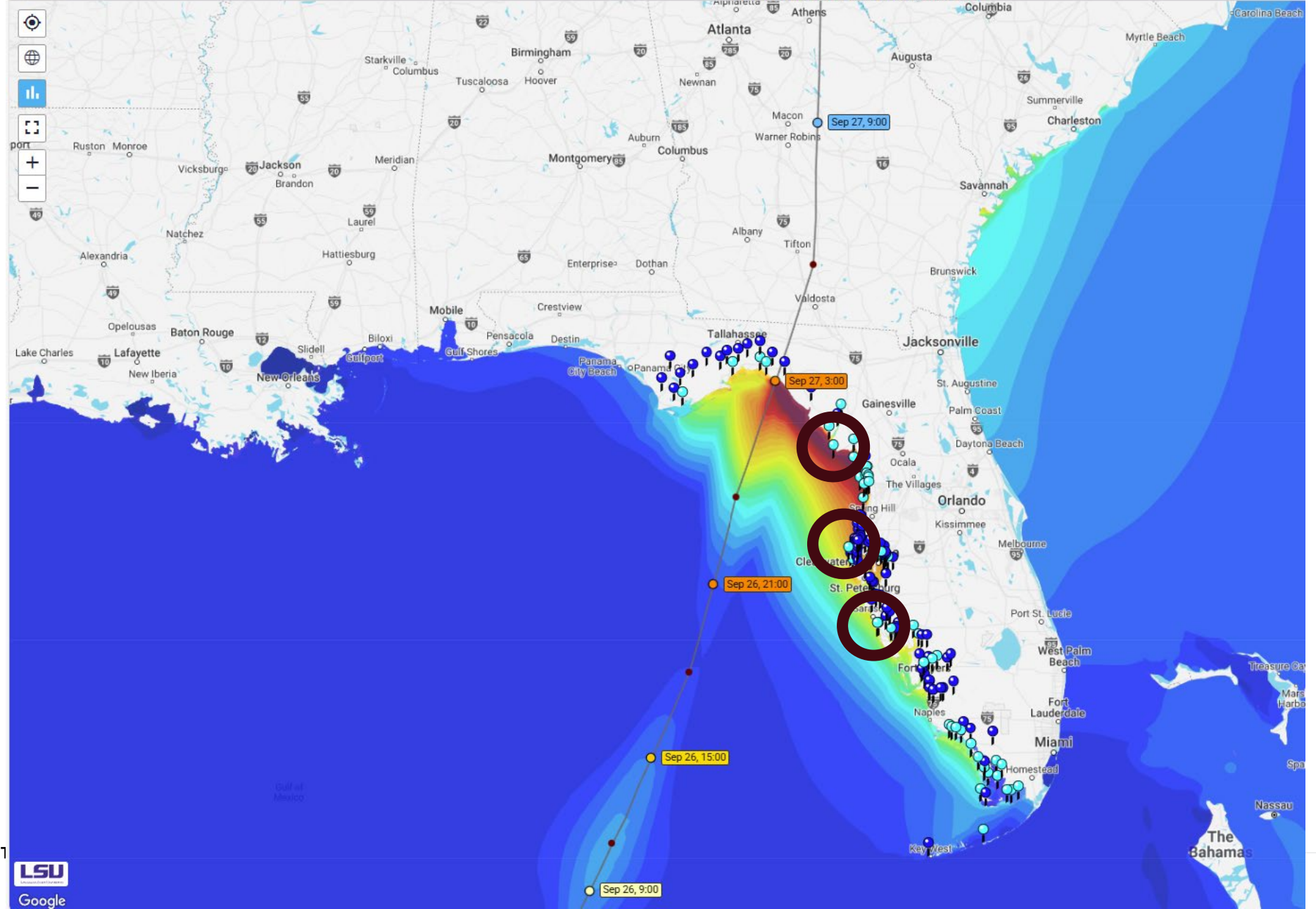
Hourly Storm Intensity Hurricane Helene Segment FLG10



Hourly Storm Intensity

Hurricane Helene Anna Maria to Longboat Key

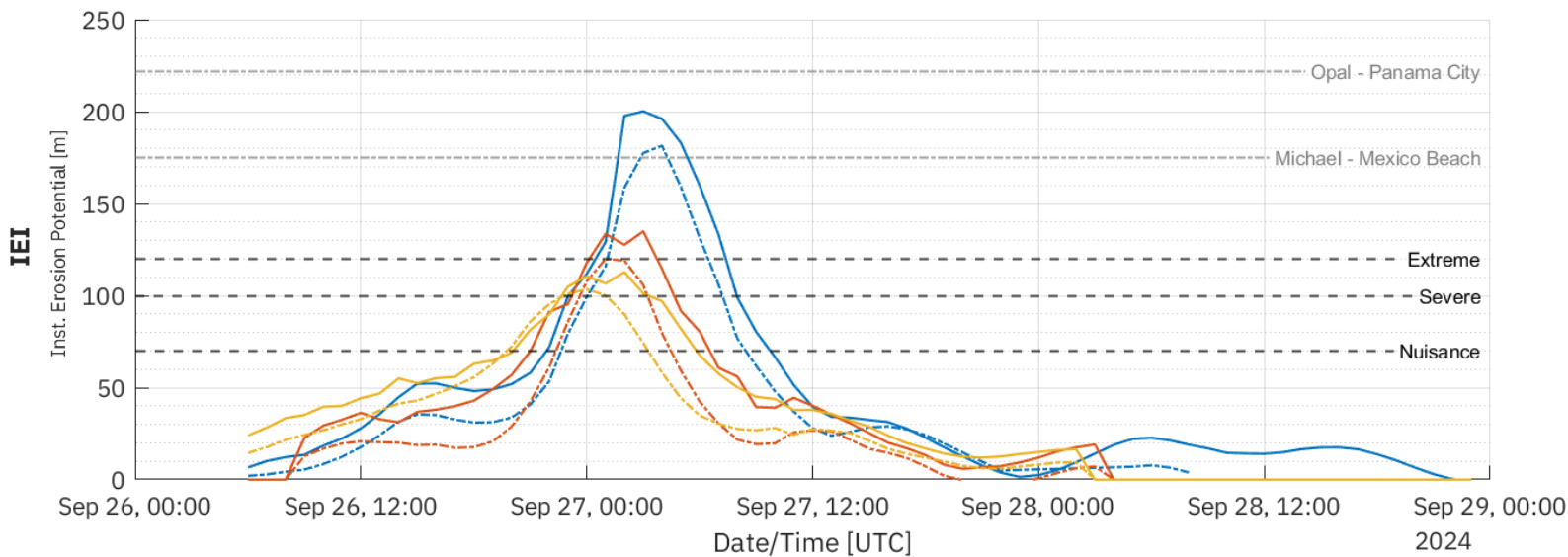
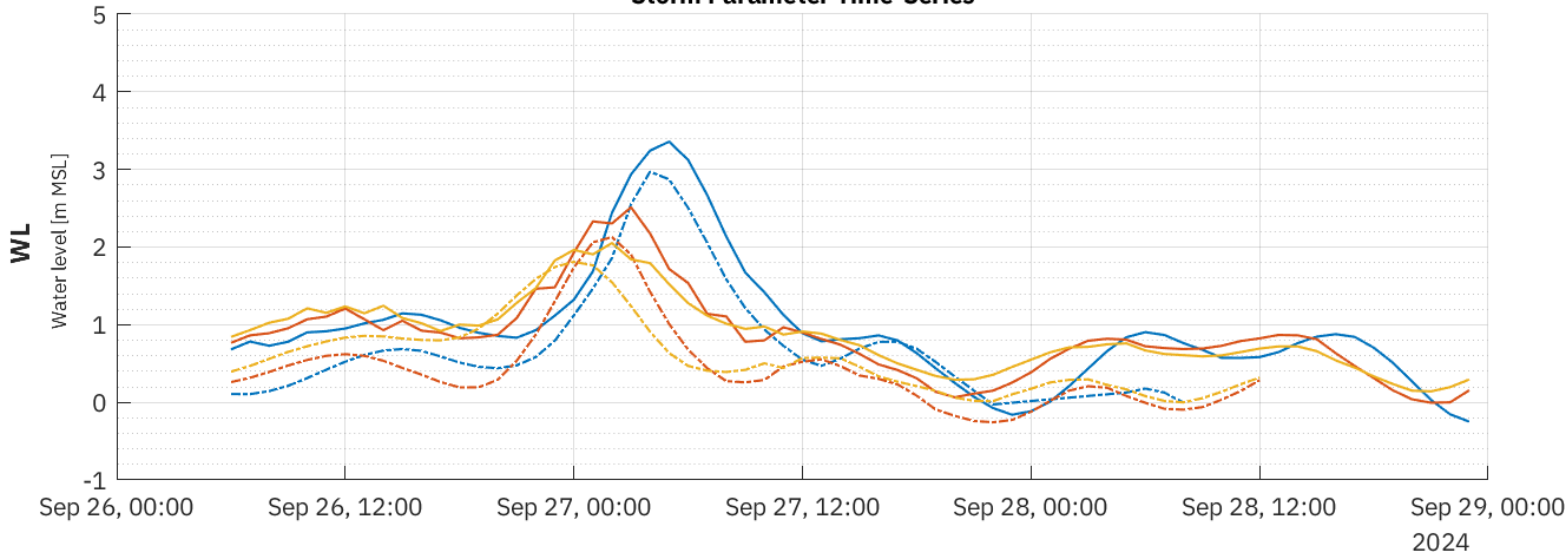




Hourly Storm Intensity

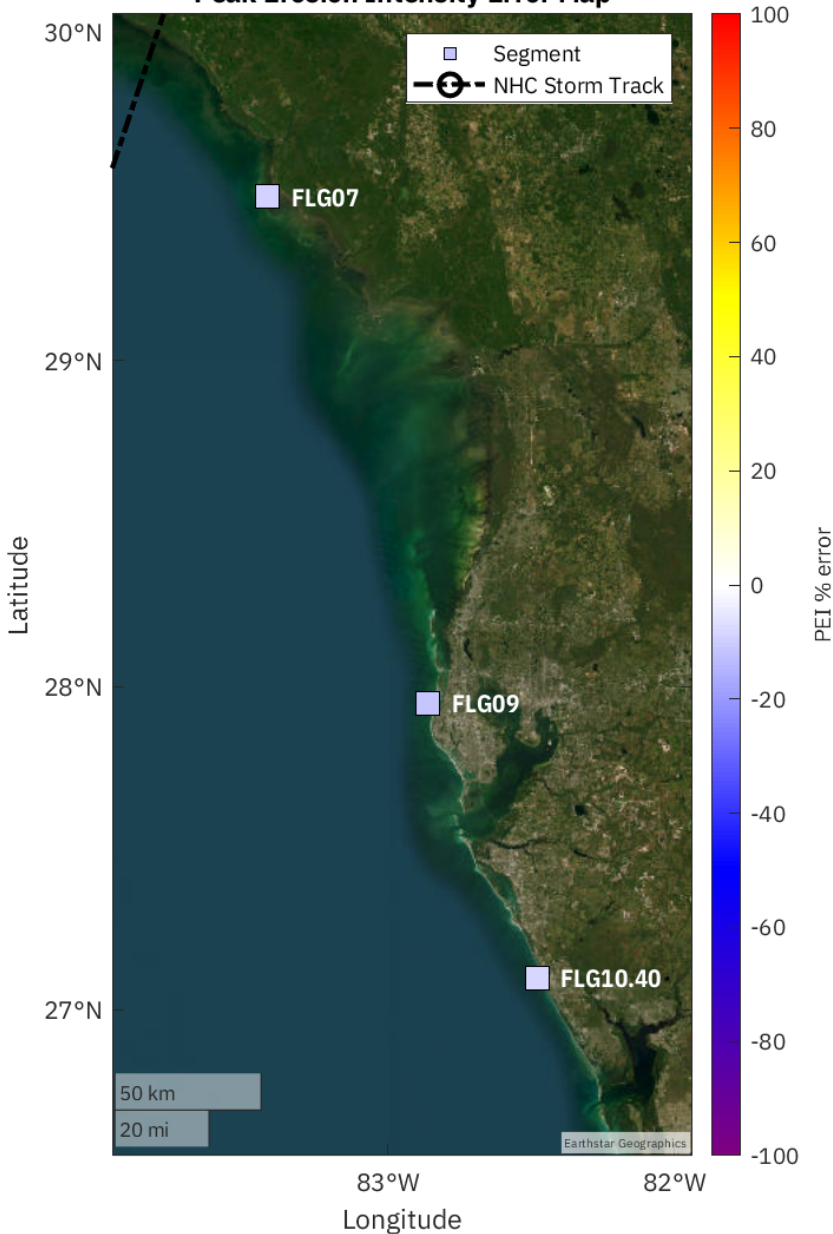
Hurricane Helene Forecast Error

Storm Parameter Time-Series



--- FLG07 Forecast --- FLG09 Forecast --- FLG10.40 Forecast
— FLG07 Observed — FLG09 Observed — FLG10.40 Observed

Peak Erosion Intensity Error Map



What about beach state?

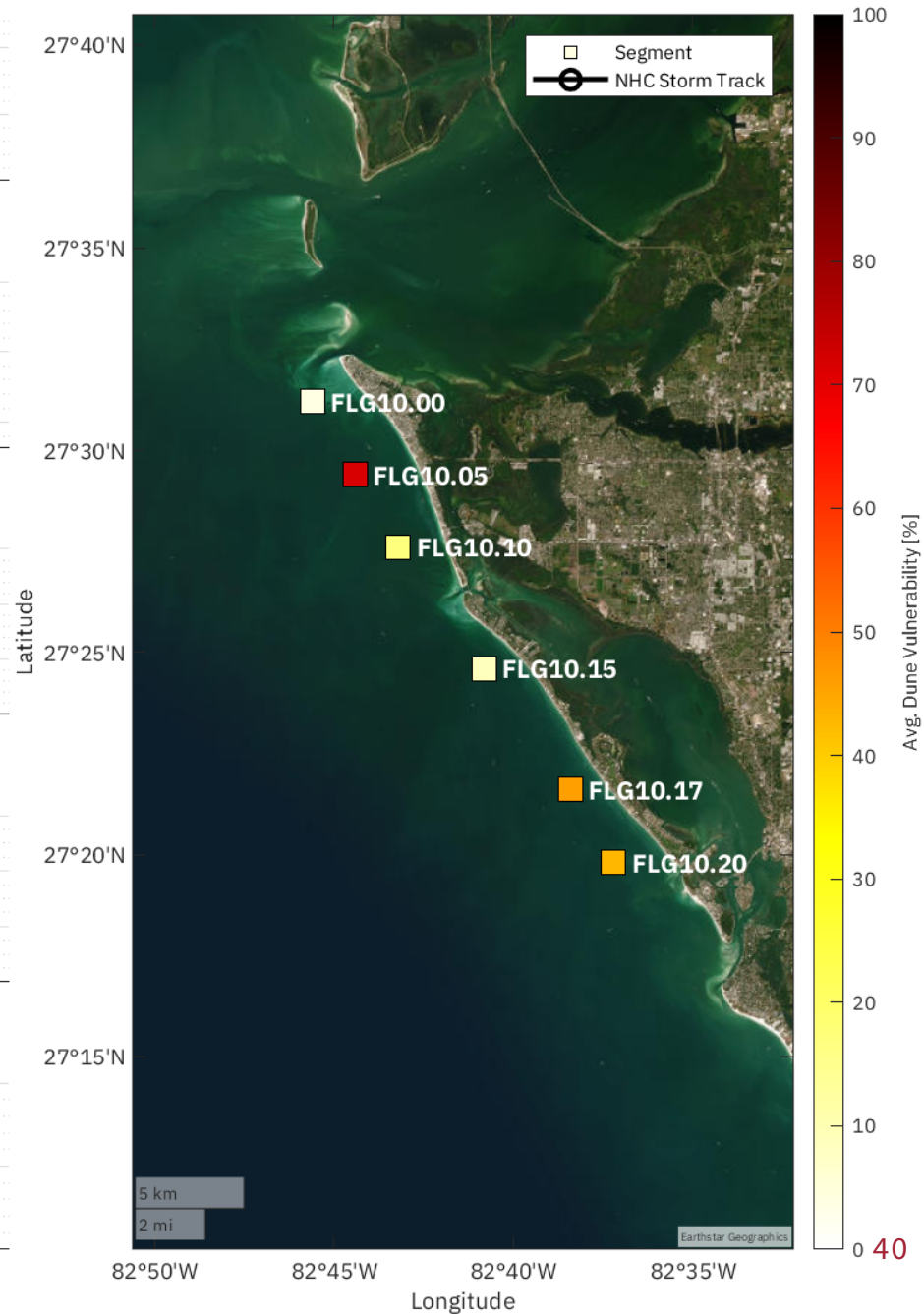
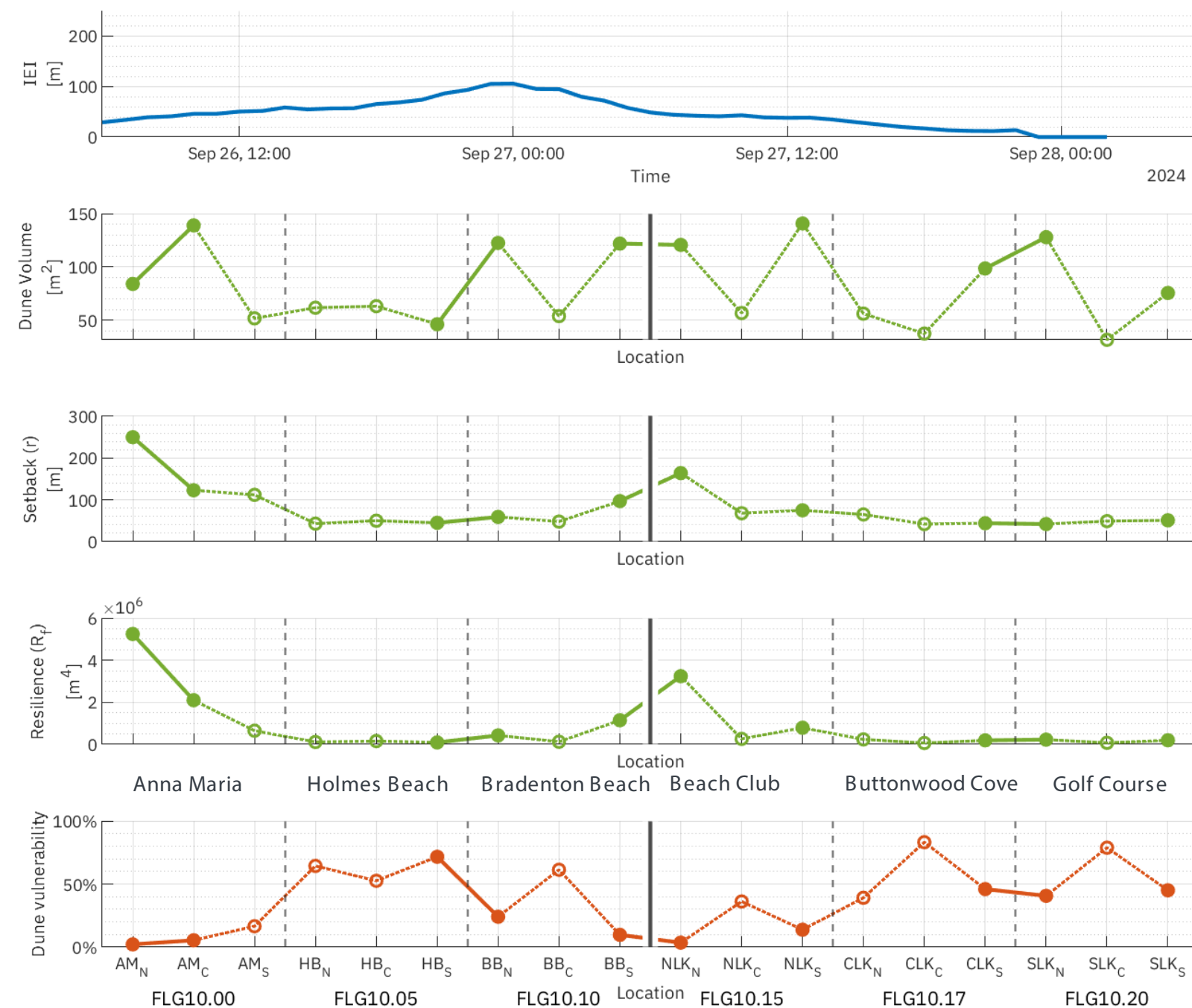
- Extracted (3) profiles across each segment
- 18 transects in total
- In 9 profiles, we could not identify a dune
- Elevation from 2022 USACE NCMP

[2022 USACE NCMP Topobathy Lidar DEM: Gulf Coast \(FL\) | InPort](#)



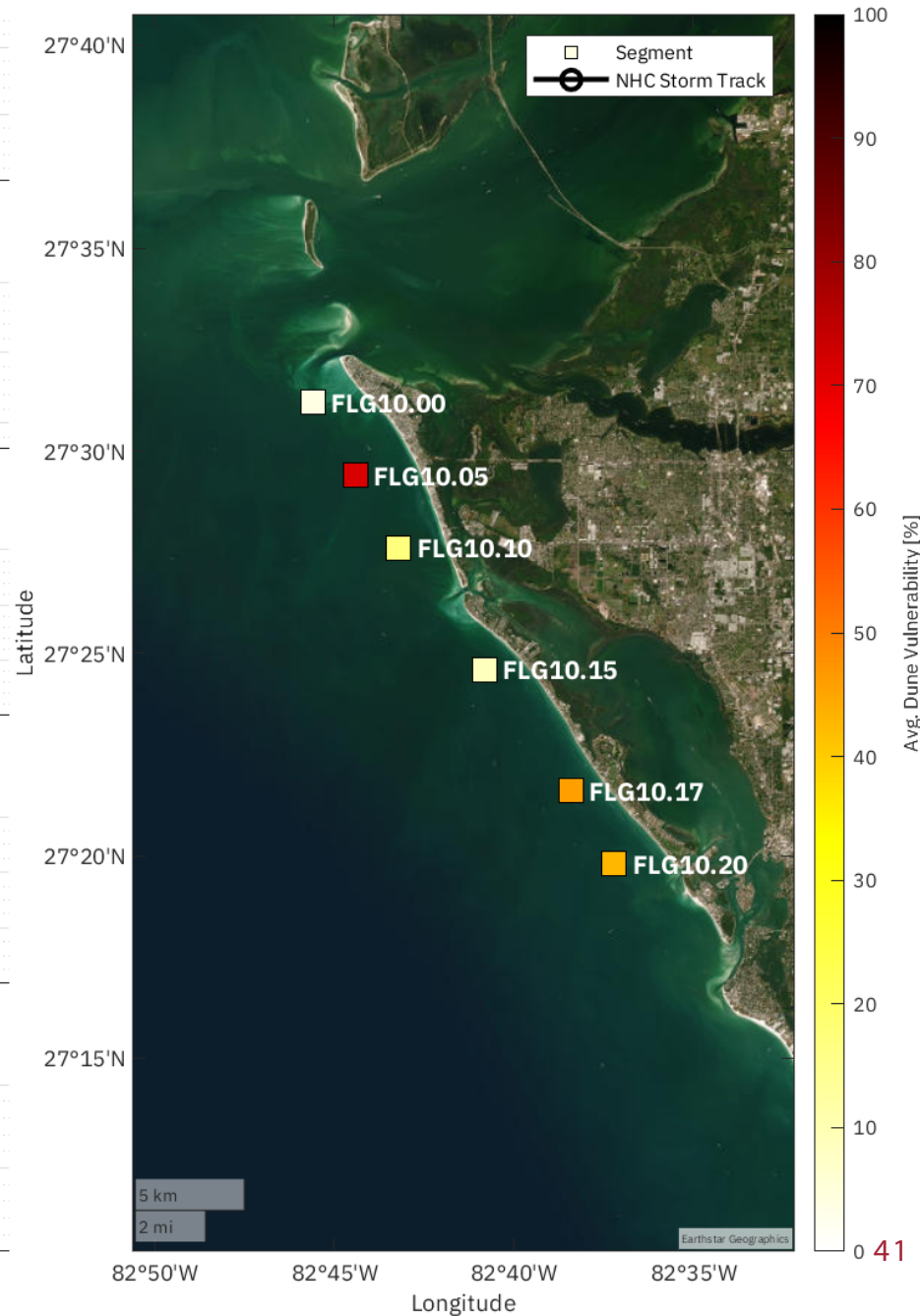
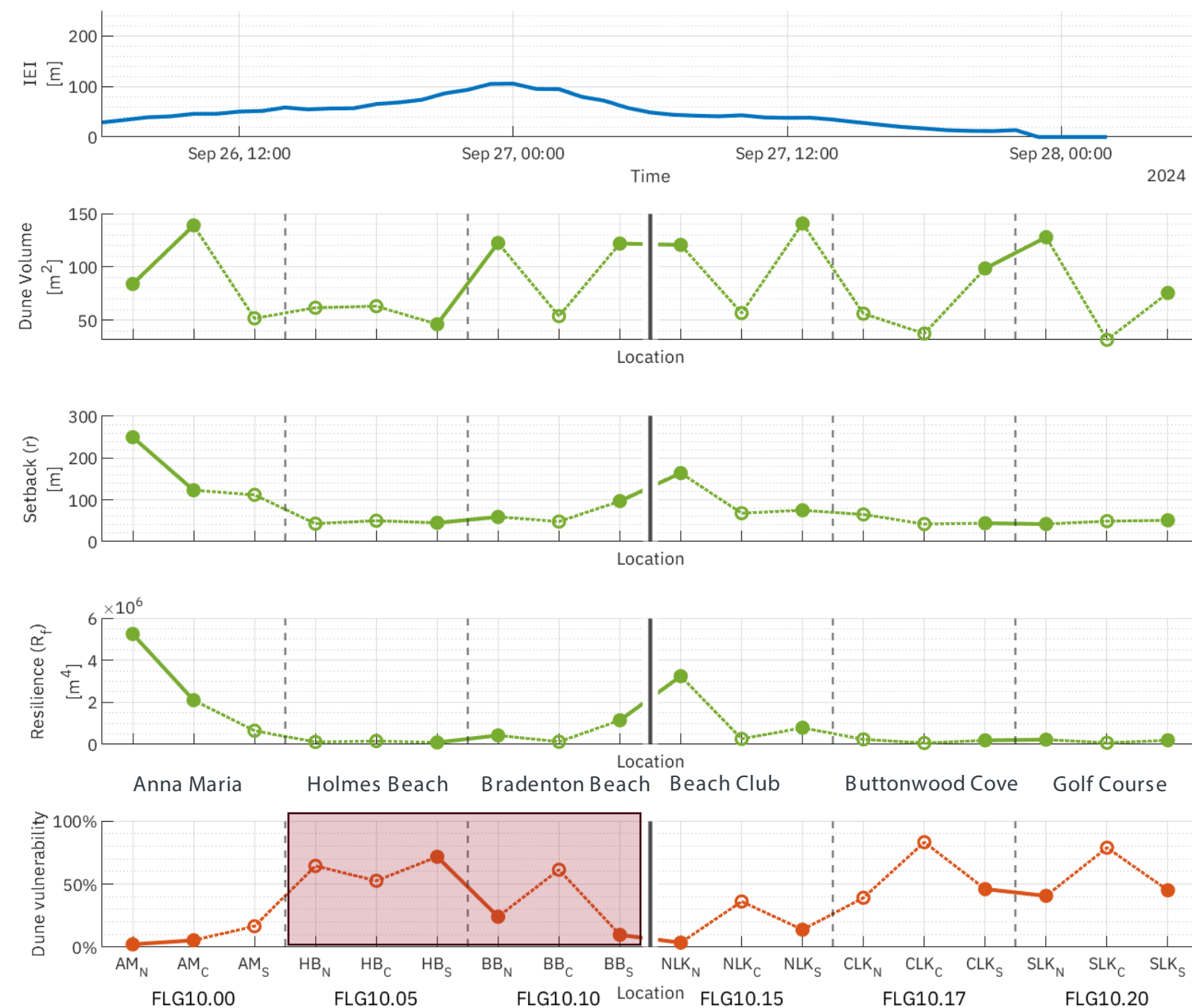
Storm Intensity, Beach Resilience, and Vulnerability

Hurricane Helene



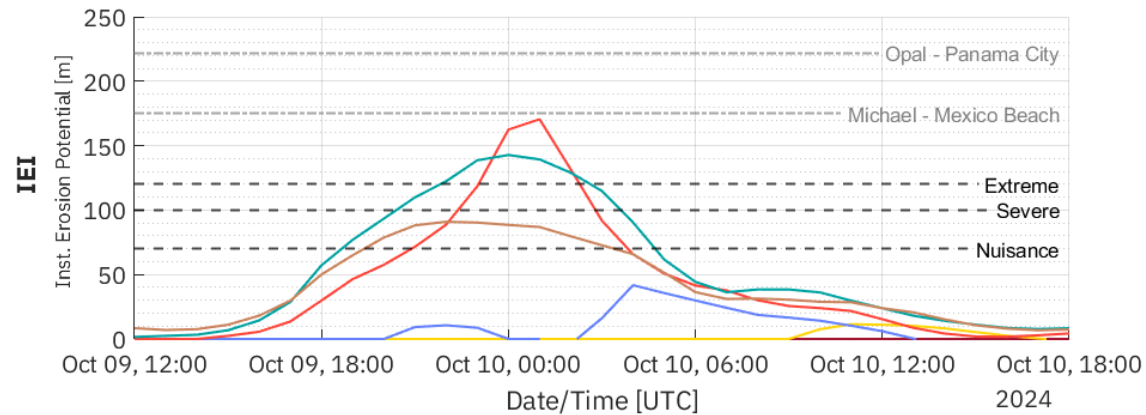
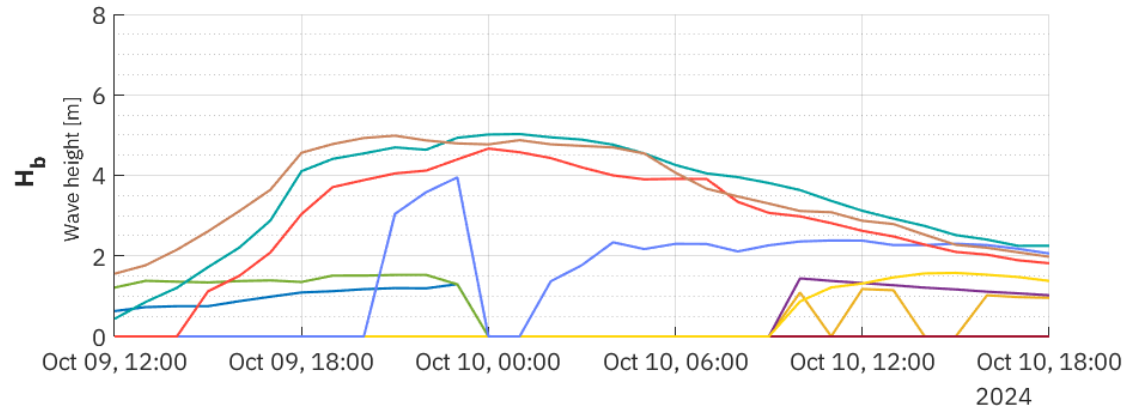
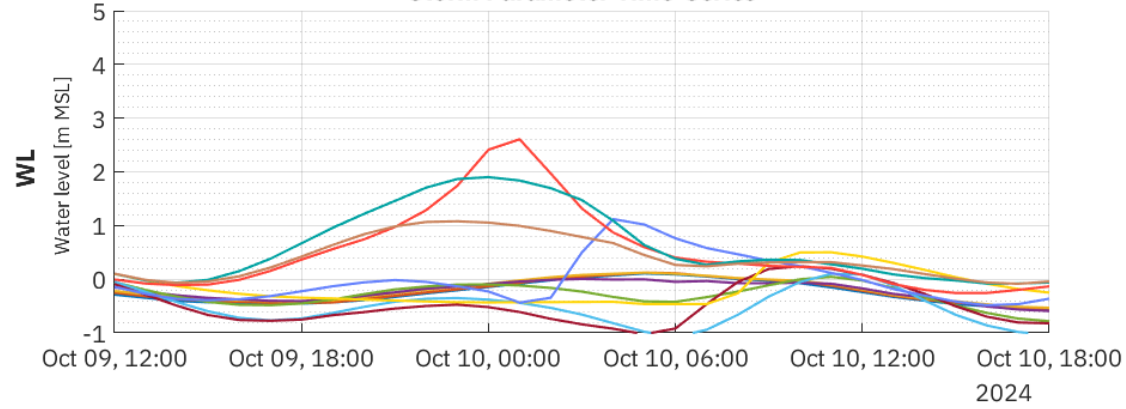
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Hurricane Helene

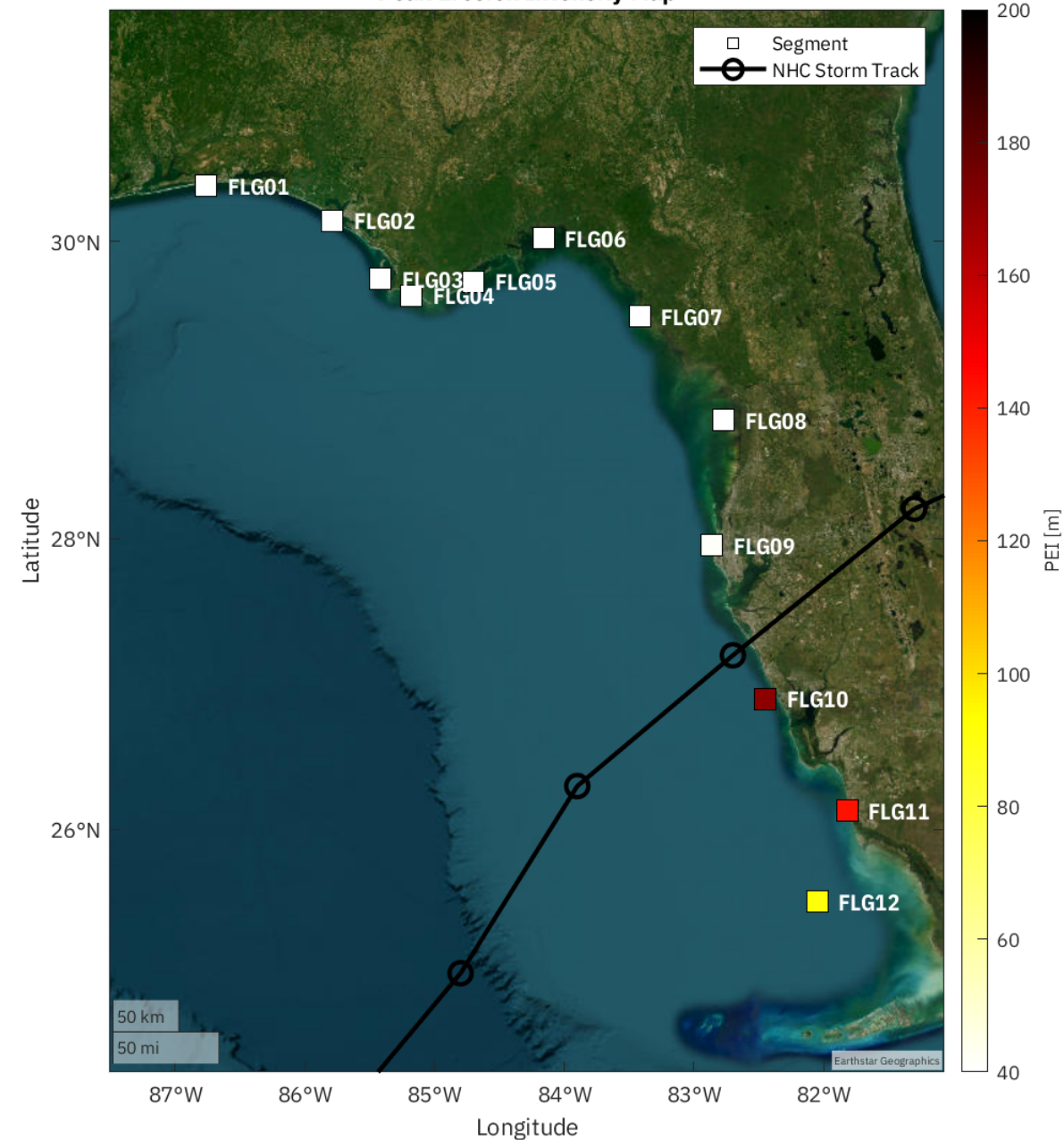


Hourly Storm Intensity Hurricane Milton Gulf Coast

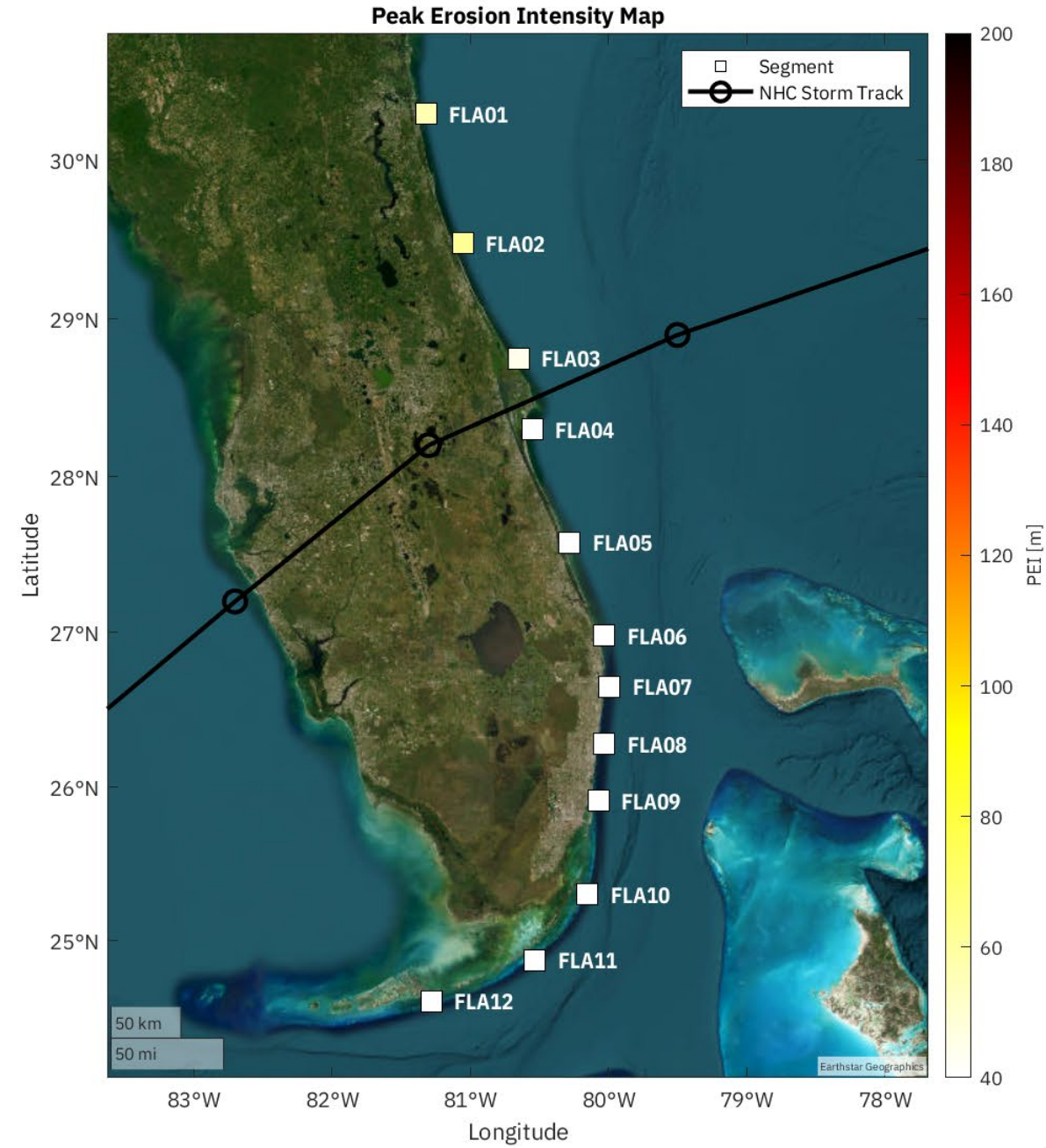
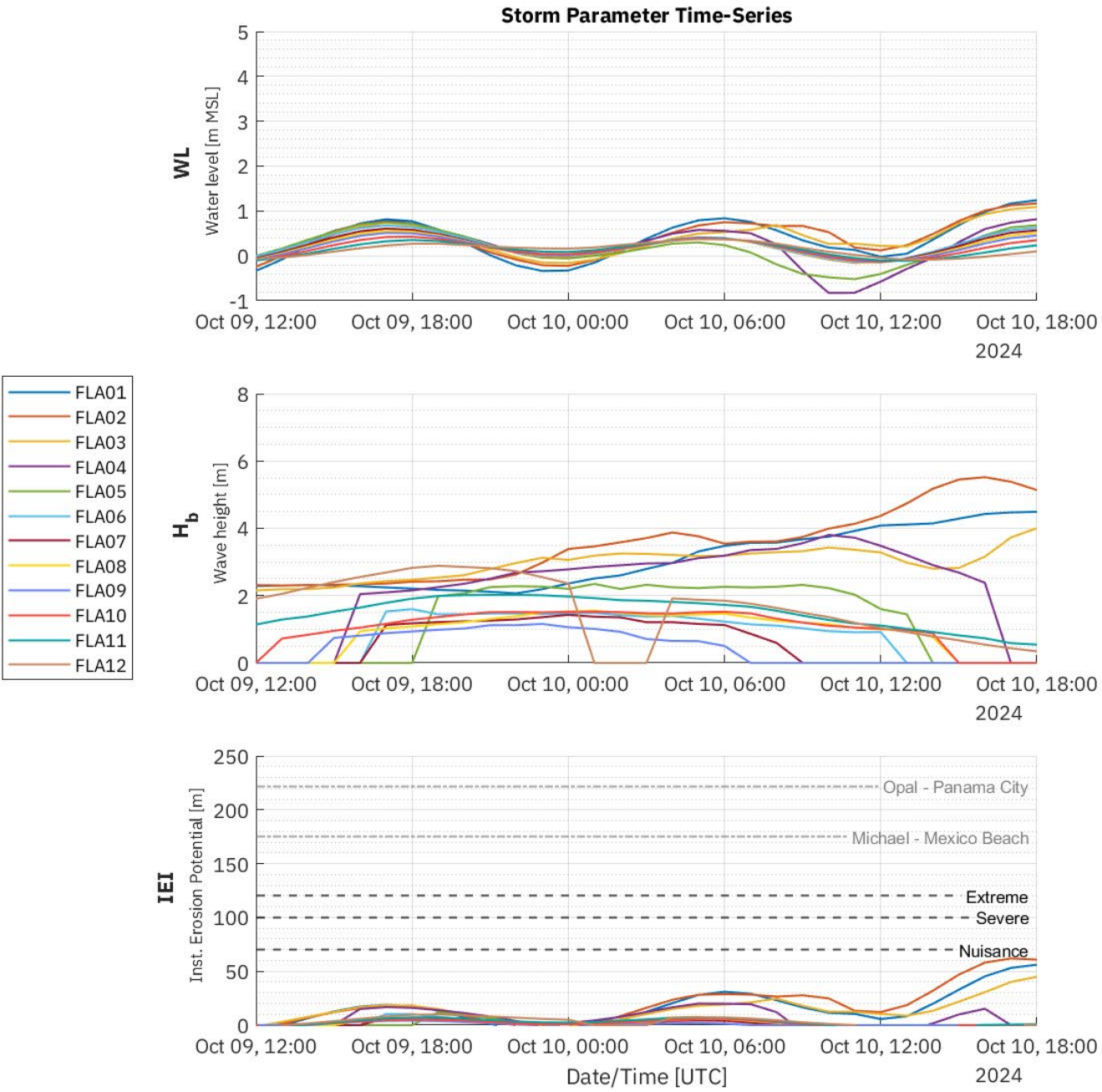
Storm Parameter Time-Series



Peak Erosion Intensity Map

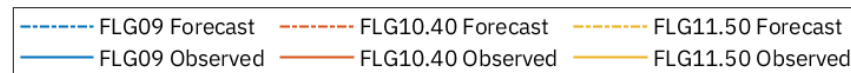
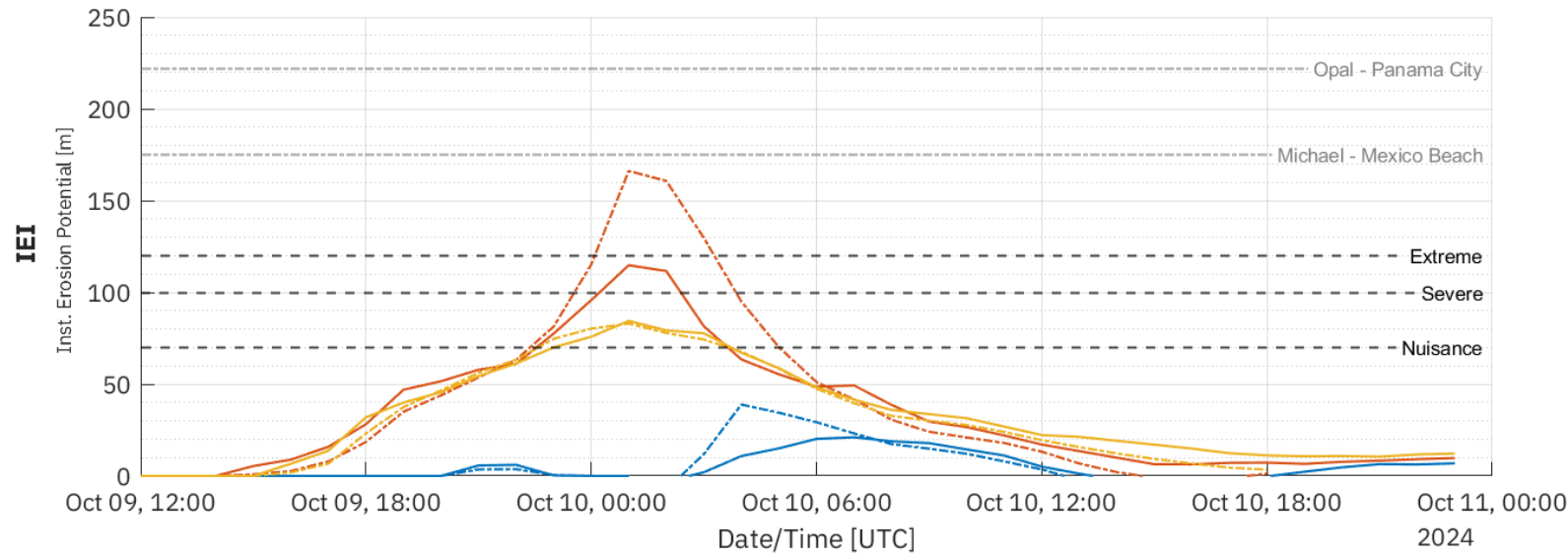
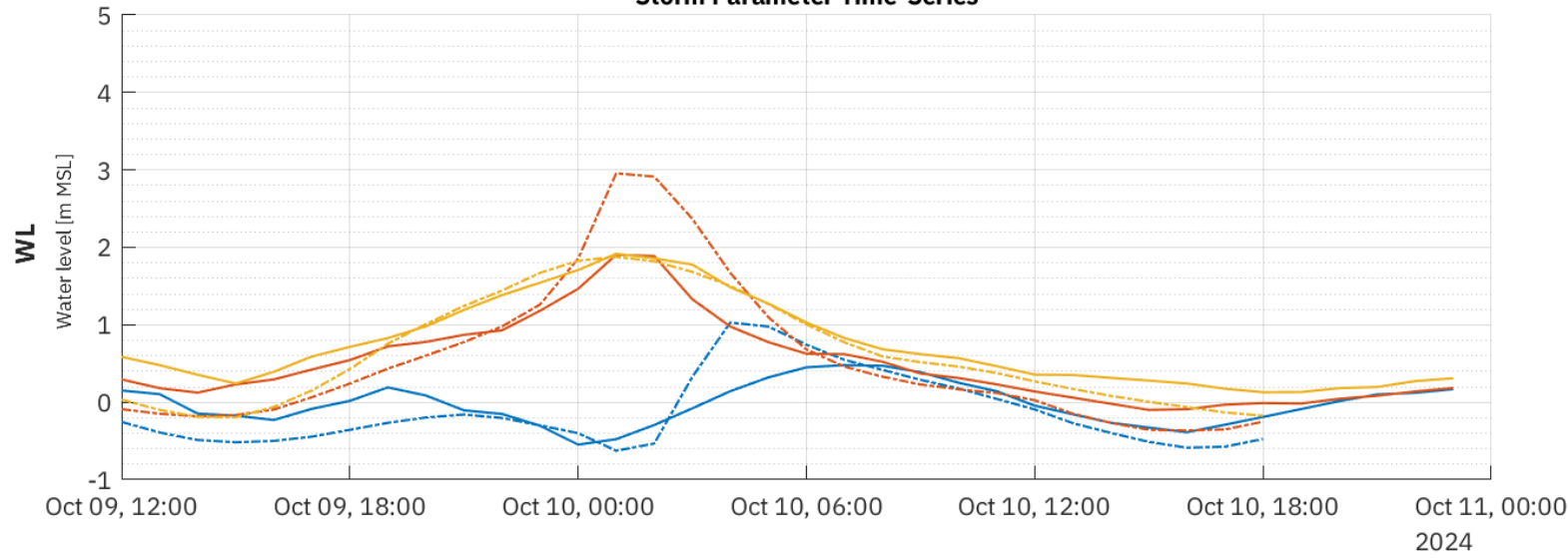


Hourly Storm Intensity
Hurricane Milton Atlantic Coast

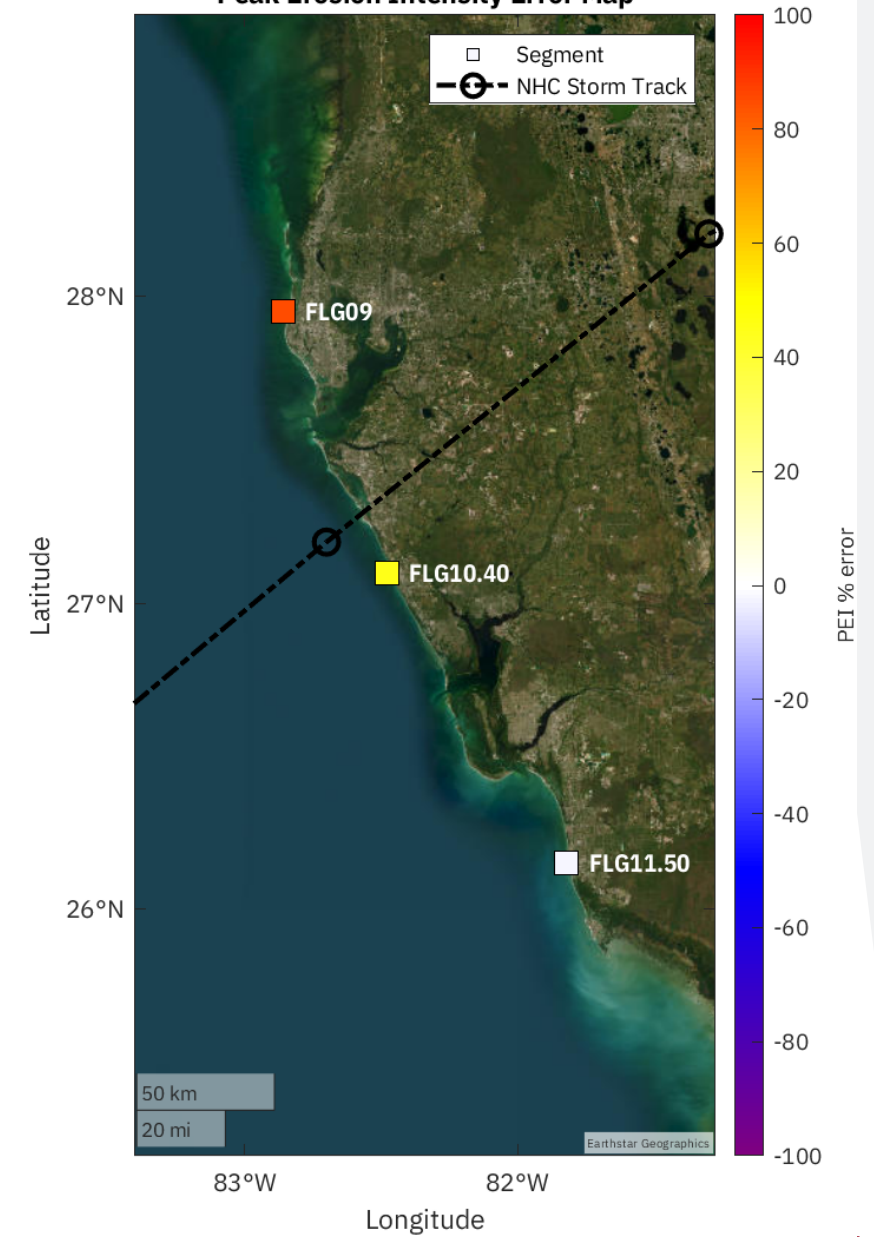


Hourly Storm Intensity Hurricane Milton Forecast Error

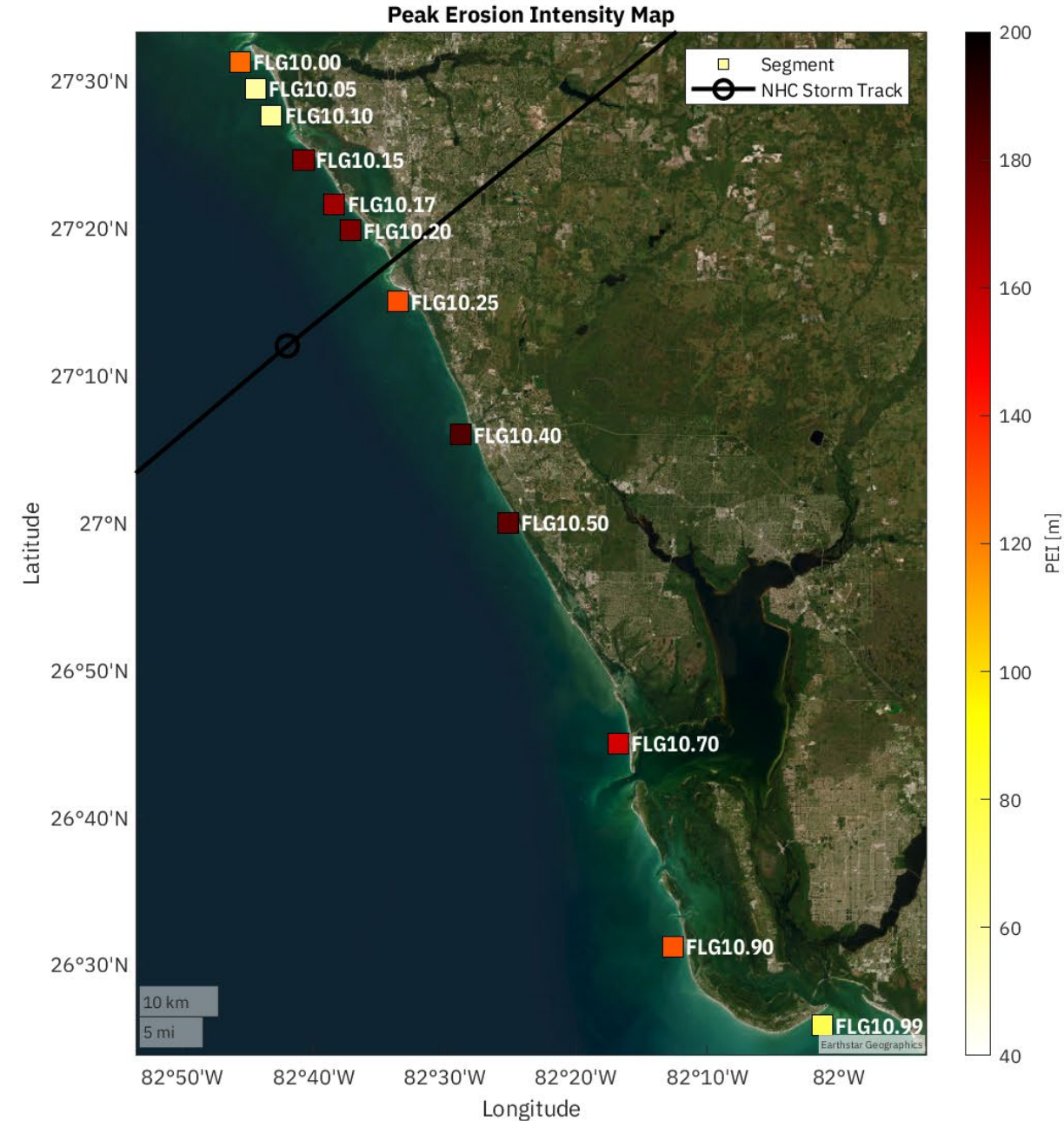
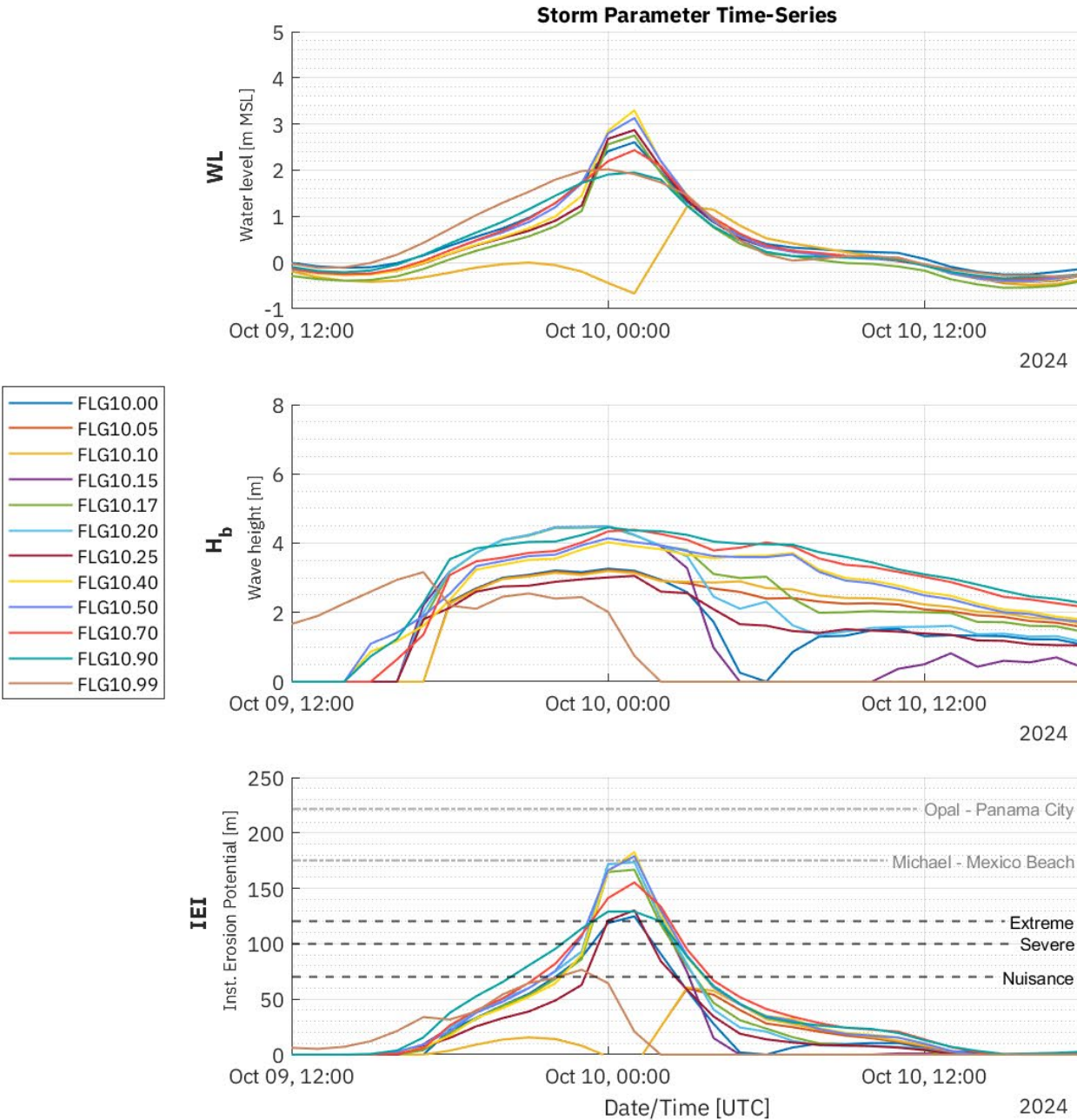
Storm Parameter Time-Series



Peak Erosion Intensity Error Map

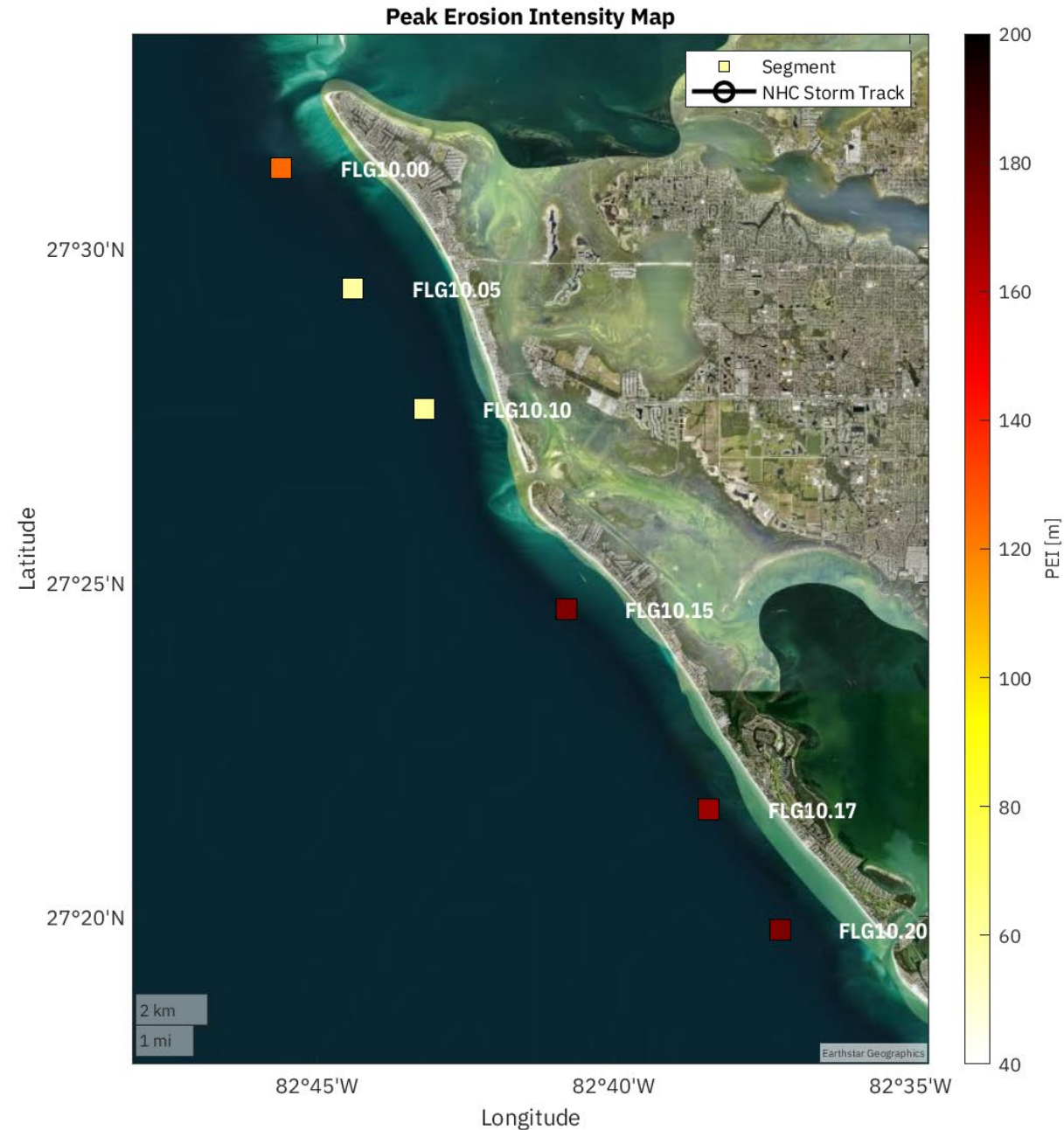
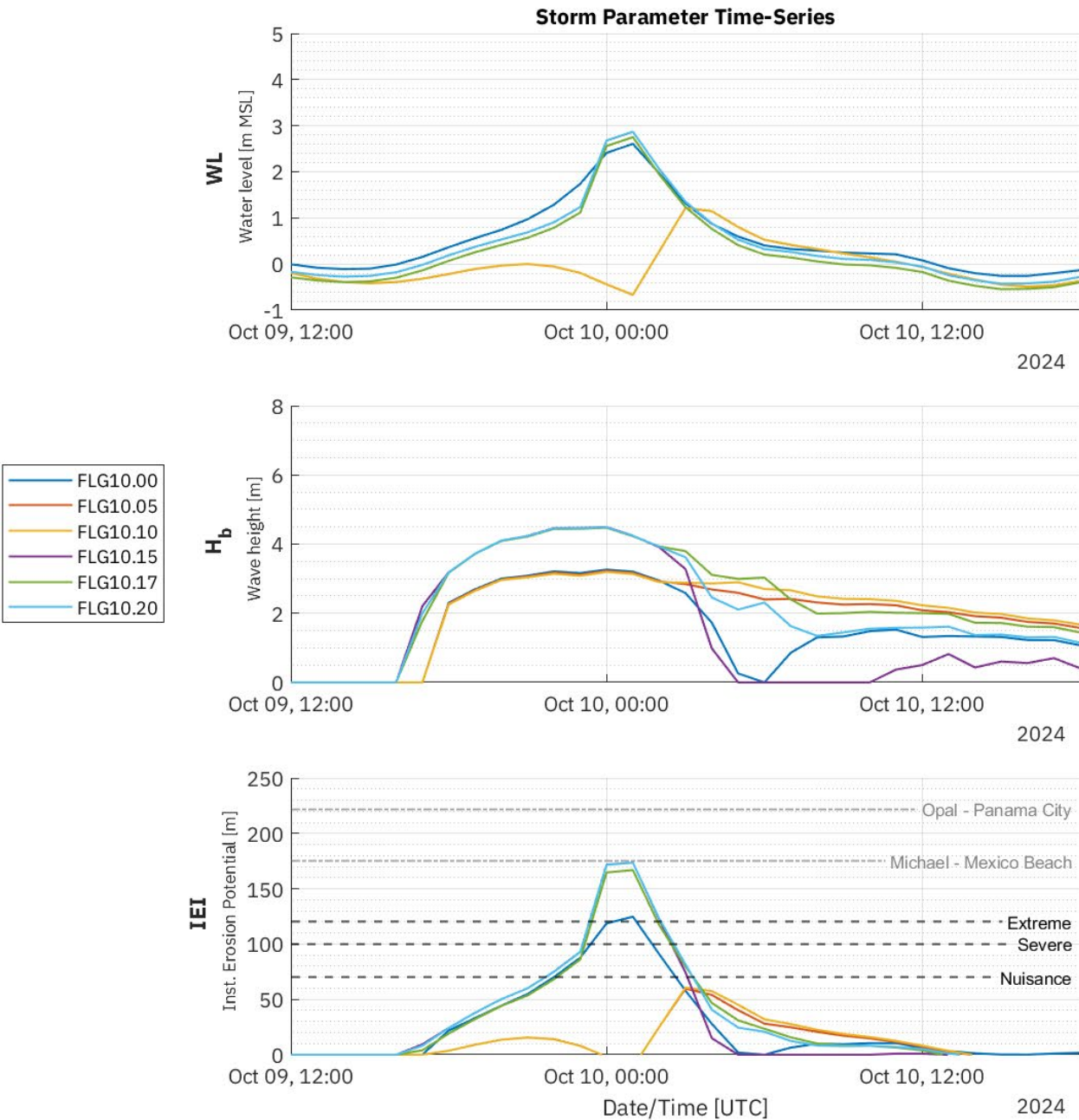


Hourly Storm Intensity Hurricane Milton Segment FLG10

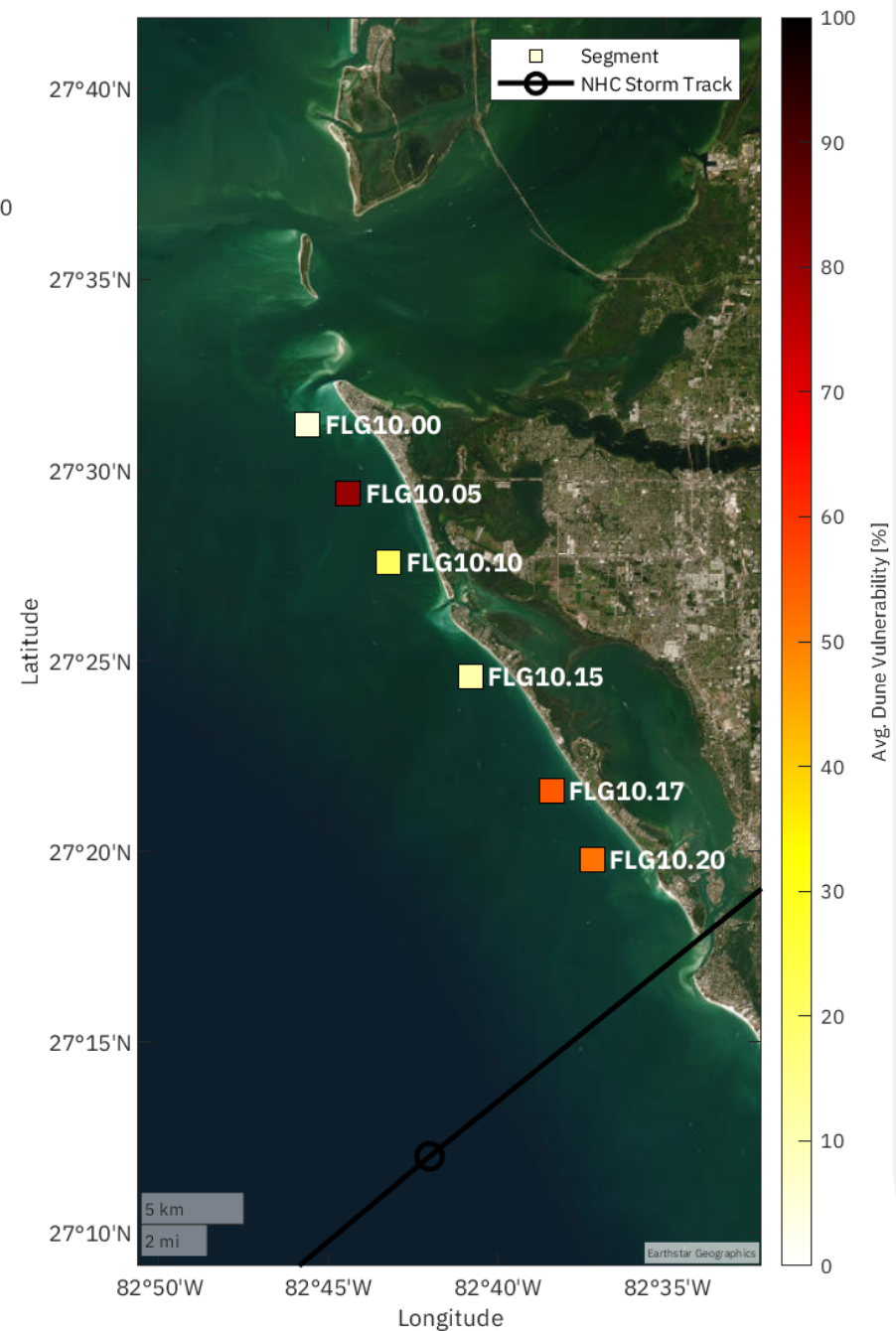
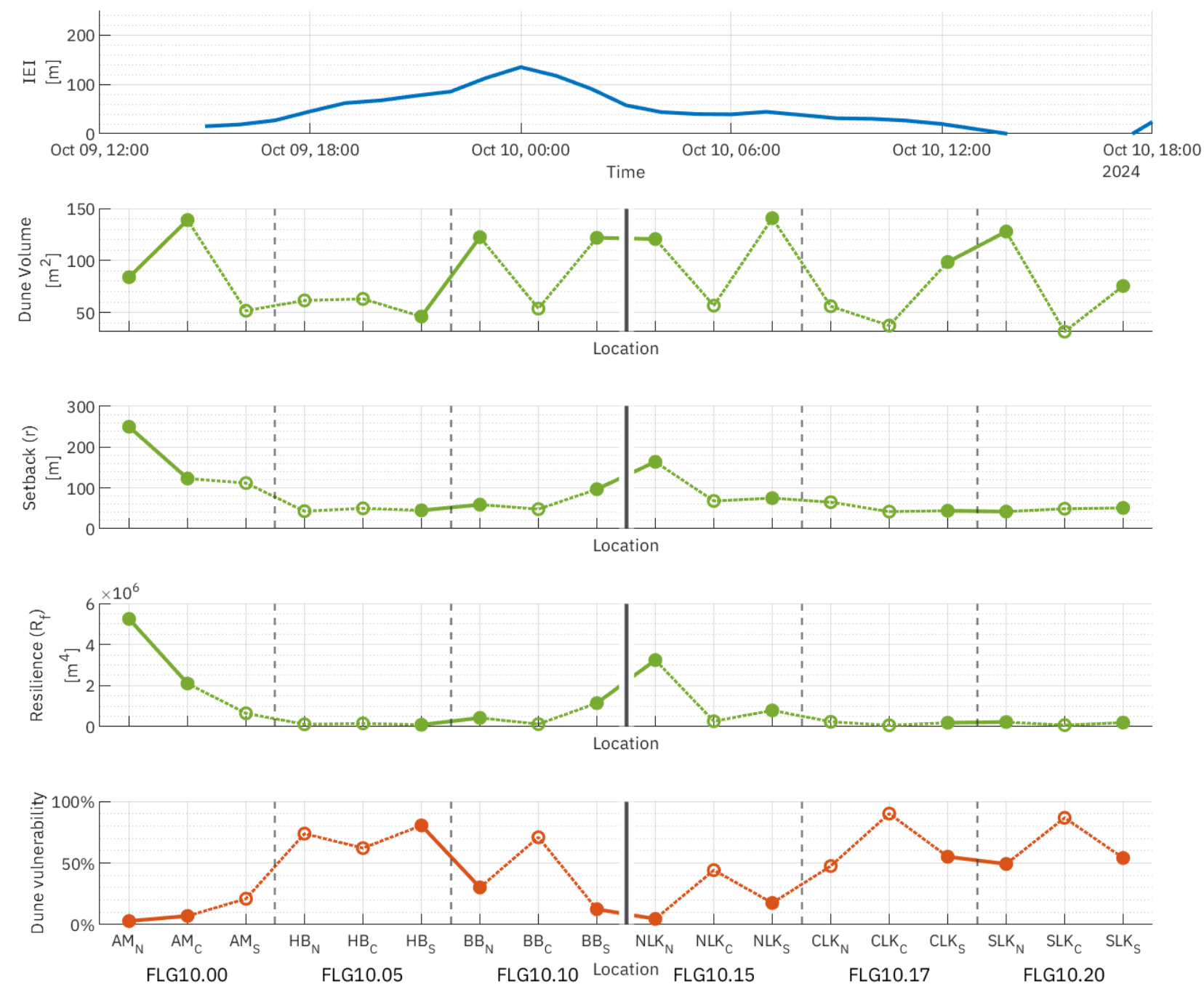


Hourly Storm Intensity

Hurricane Milton Anna Maria to Longboat Key



Storm Intensity, Beach Resilience, and Vulnerability Hurricane Milton



Takeaways

- Storm intensity perspective:
 - Helene – near Cedar Key compares to Hurricane Opal; forecast generally underestimated
 - Milton – near Manasota Key compares with Hurricane Michael; forecasts generally overestimated
- For the area of interest (e.g., Holmes Beach & Longboat Key) both storms appear to have similar
 - Provides an interesting case study; is the damage due to Helene or cumulative impacts?
- Suggestions welcome & collaborators are welcome
 - areas of interest or notable differences in outcomes
- We anticipate running forecasts for Florida for any event modeled by CERA for 2025 season. If interested:

mjanssen@stevens.edu or jmiller@stevens.edu



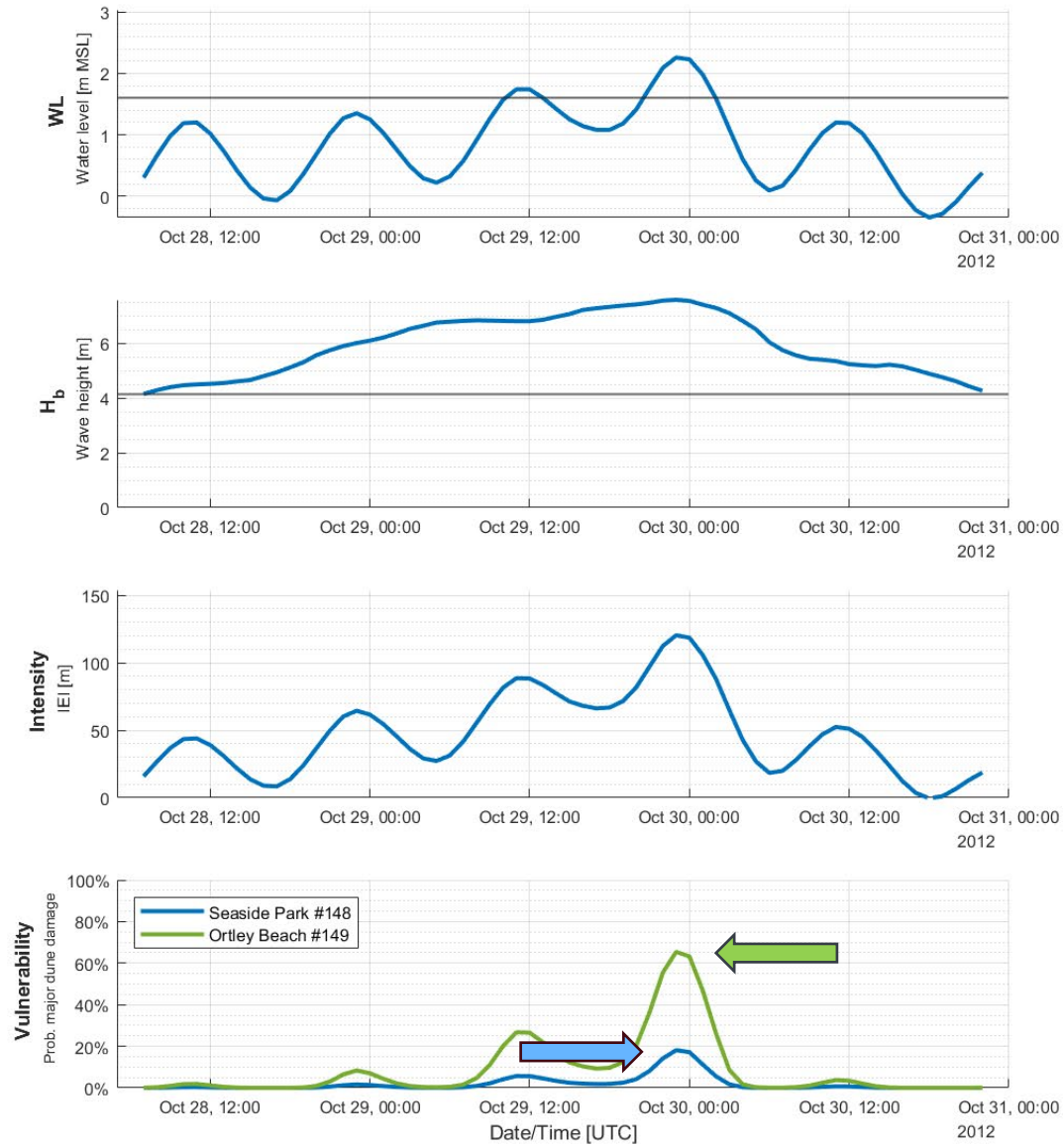


Storm Intensity Class	IEI Range	Approximate Return Period (Current Climate)	Likely Dune Volume Loss (order of magnitude)	Likely Storm Hazard Matrix Impact scale (Leaman et al., 2021)
Extreme	$120 \leq \text{IEI}$	$> 50\text{-yr}$	$> 40\%$	Overwash; Inundation; Dune Retreat
Severe	$100 \leq \text{IEI} < 120$	27-yr to 50-yr	$\leq 40\%$	Dune Face Erosion
Nuisance	$70 \leq \text{IEI} < 100$	6-yr to 27-yr	$\sim 10\%$	Collision, Dune Face Erosion
Insignificant	$\text{IEI} < 70$	$< 6\text{-yr}$	None	Swash, Minor Beach narrowing

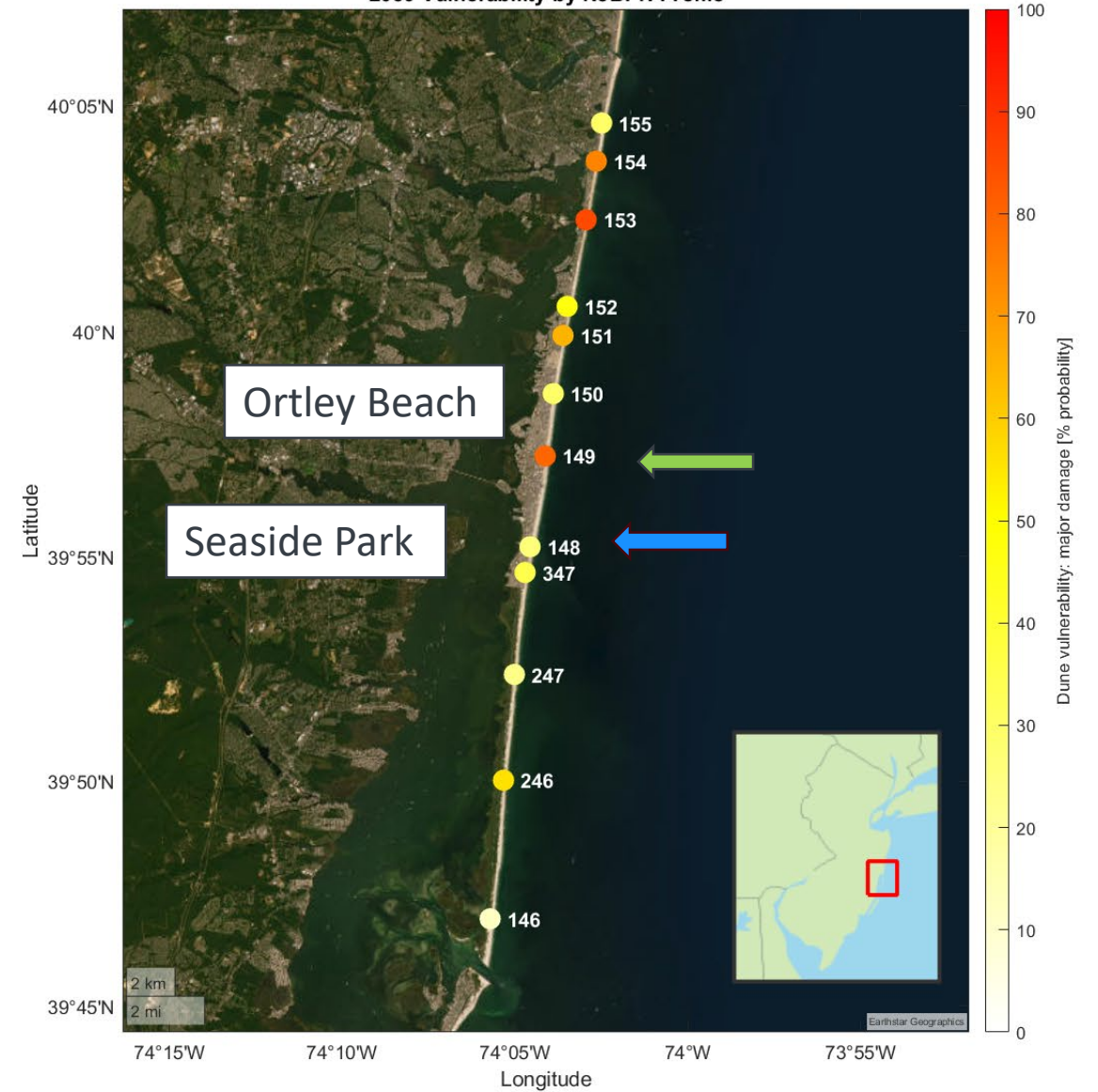


Hourly dune vulnerability for Hurricane Sandy with SSP2-4.5 SLR NJ Shoreline Segment 5

Storm Parameter Time-Series

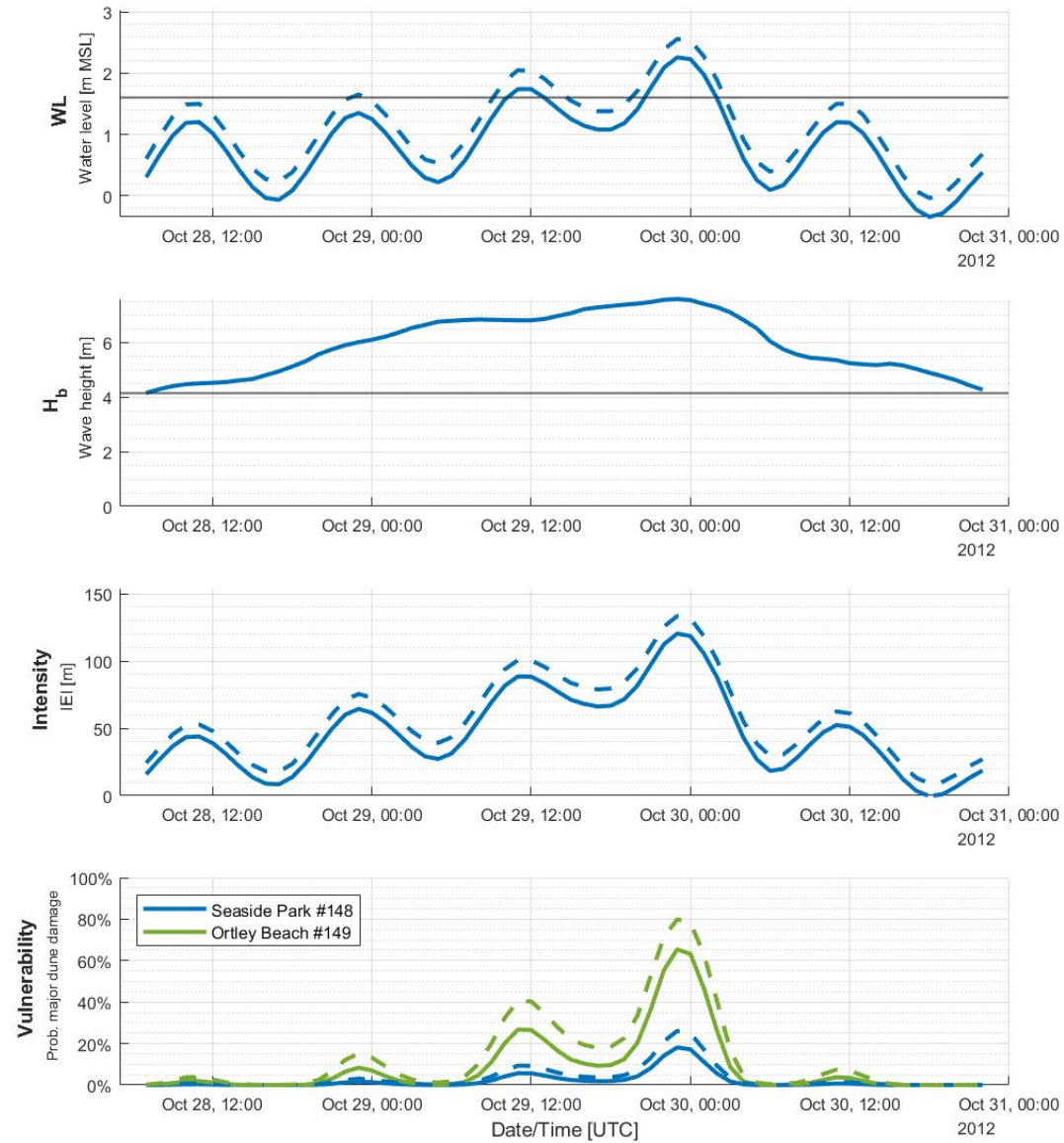


2050 Vulnerability by NJBPN Profile

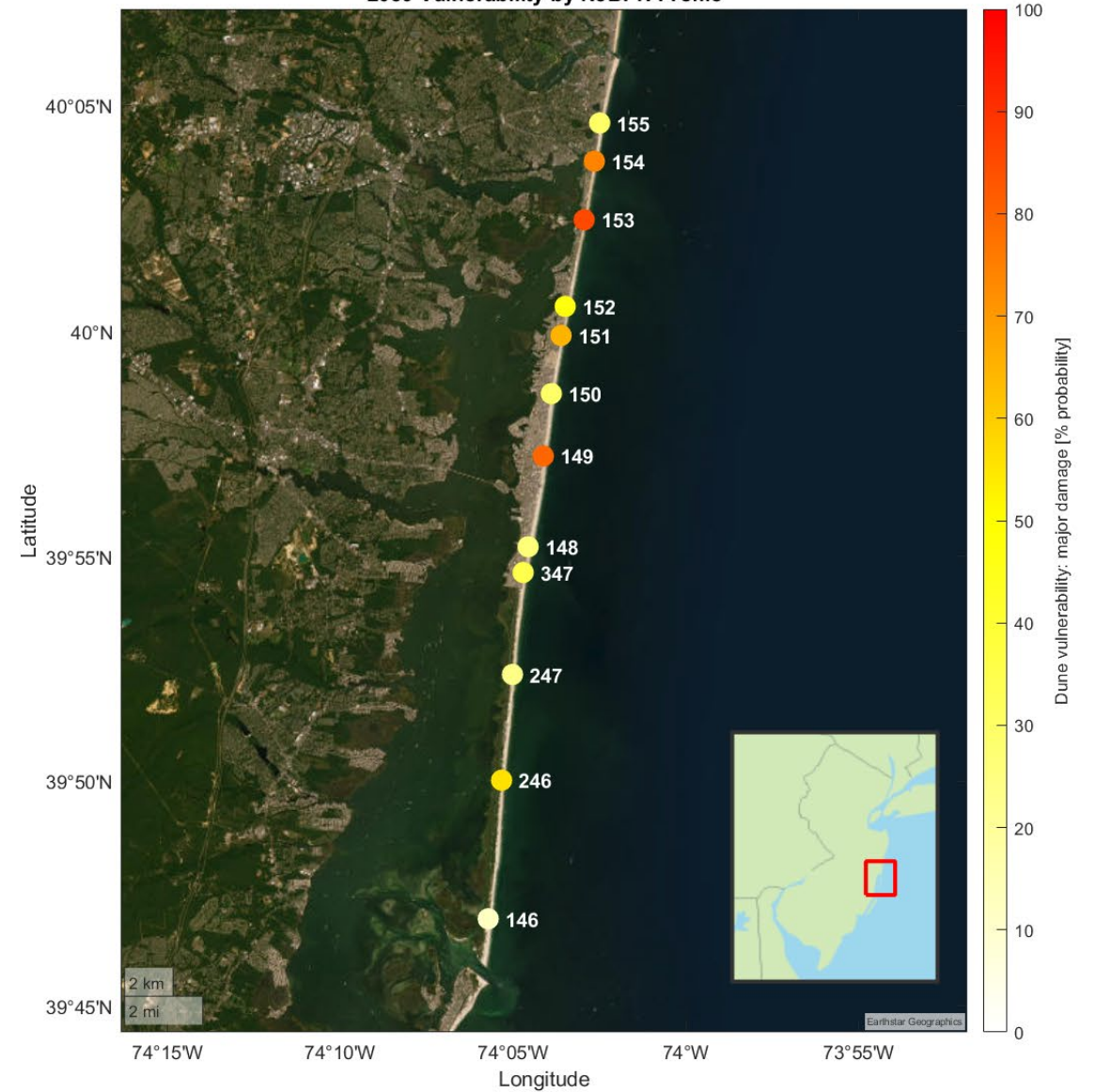


Hourly dune vulnerability for Hurricane Sandy with SSP2-4.5 SLR NJ Shoreline Segment 5

Storm Parameter Time-Series

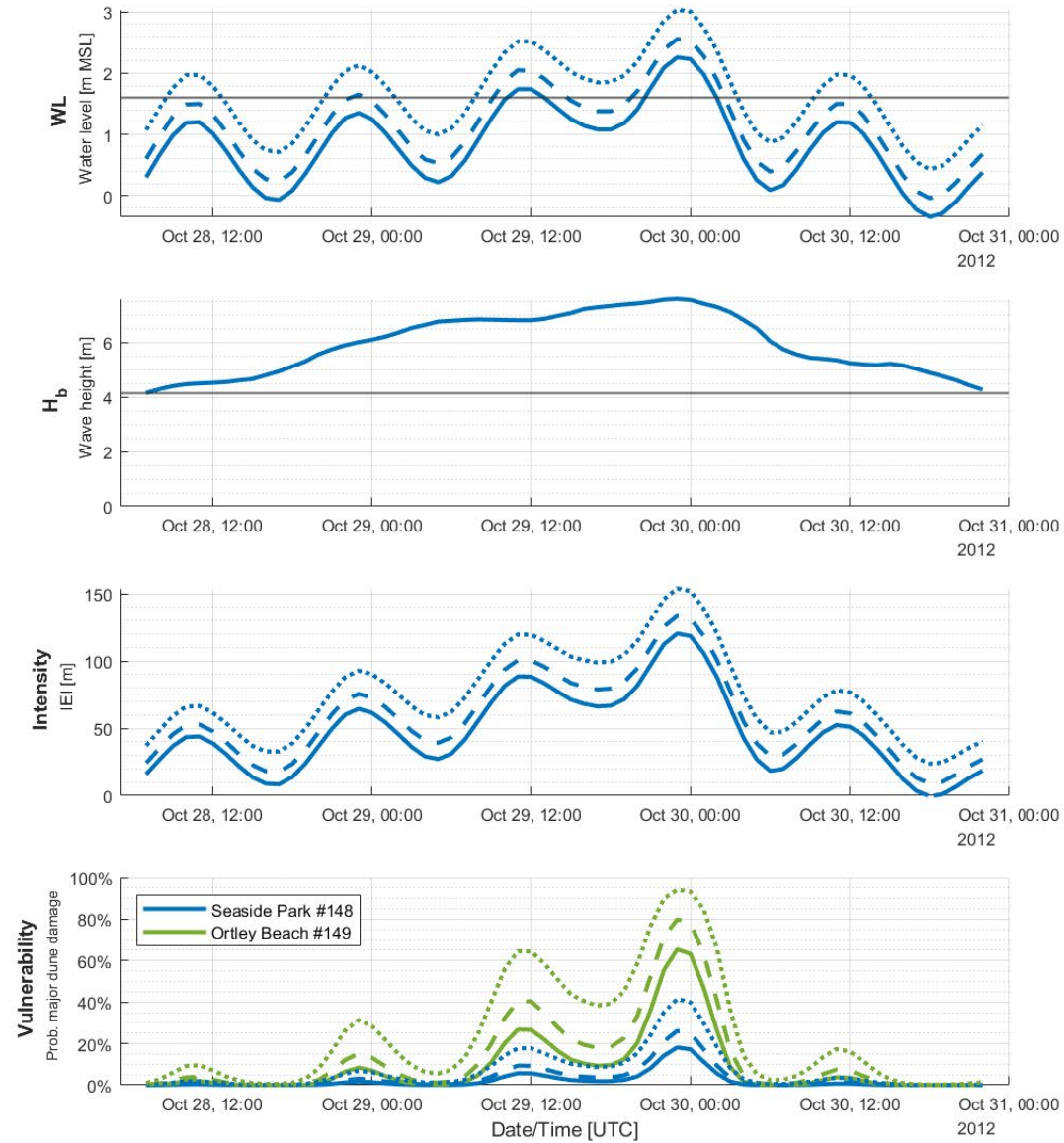


2050 Vulnerability by NJBPN Profile



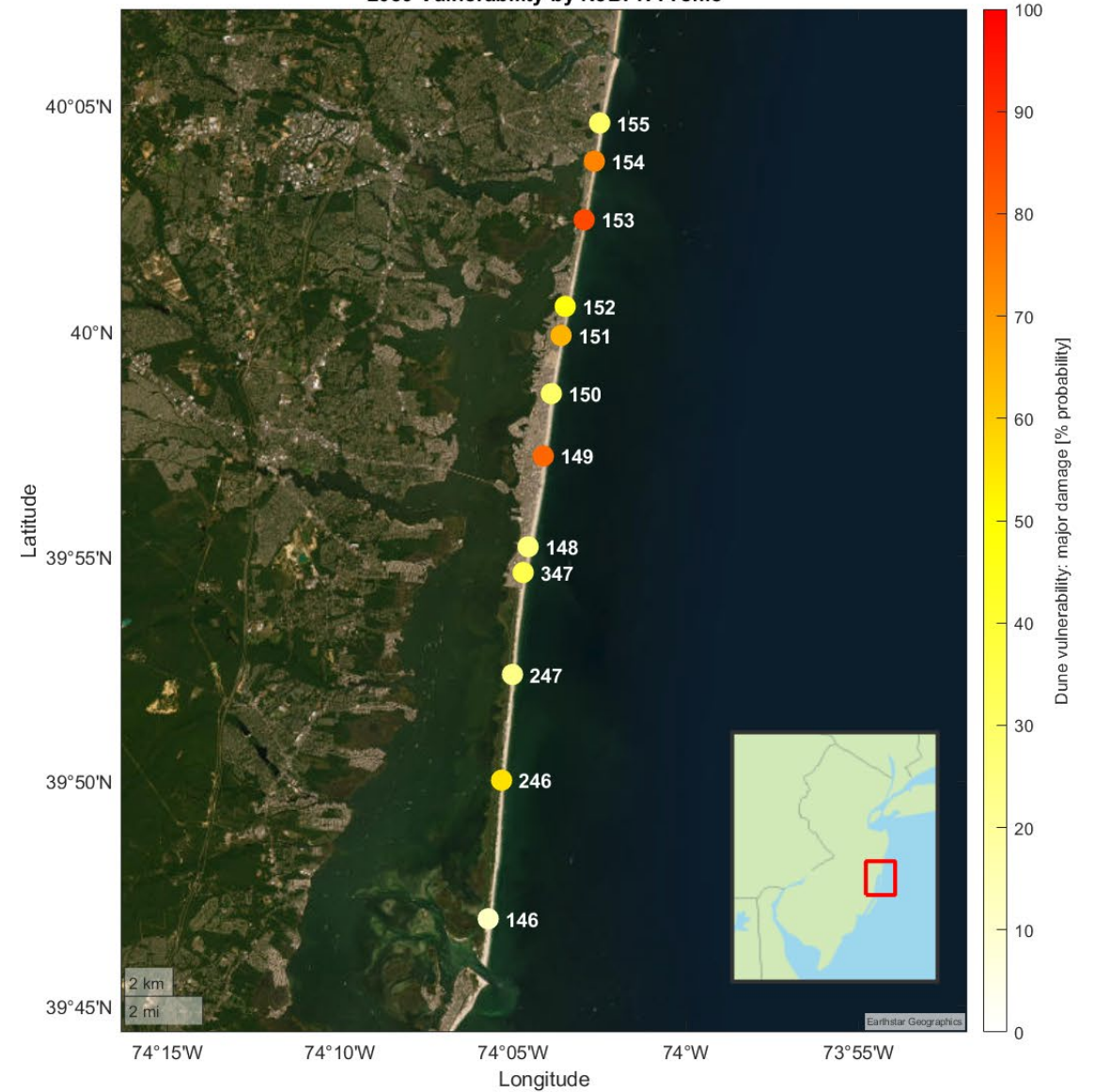
Hourly dune vulnerability for Hurricane Sandy with SSP2-4.5 SLR NJ Shoreline Segment 5

Storm Parameter Time-Series



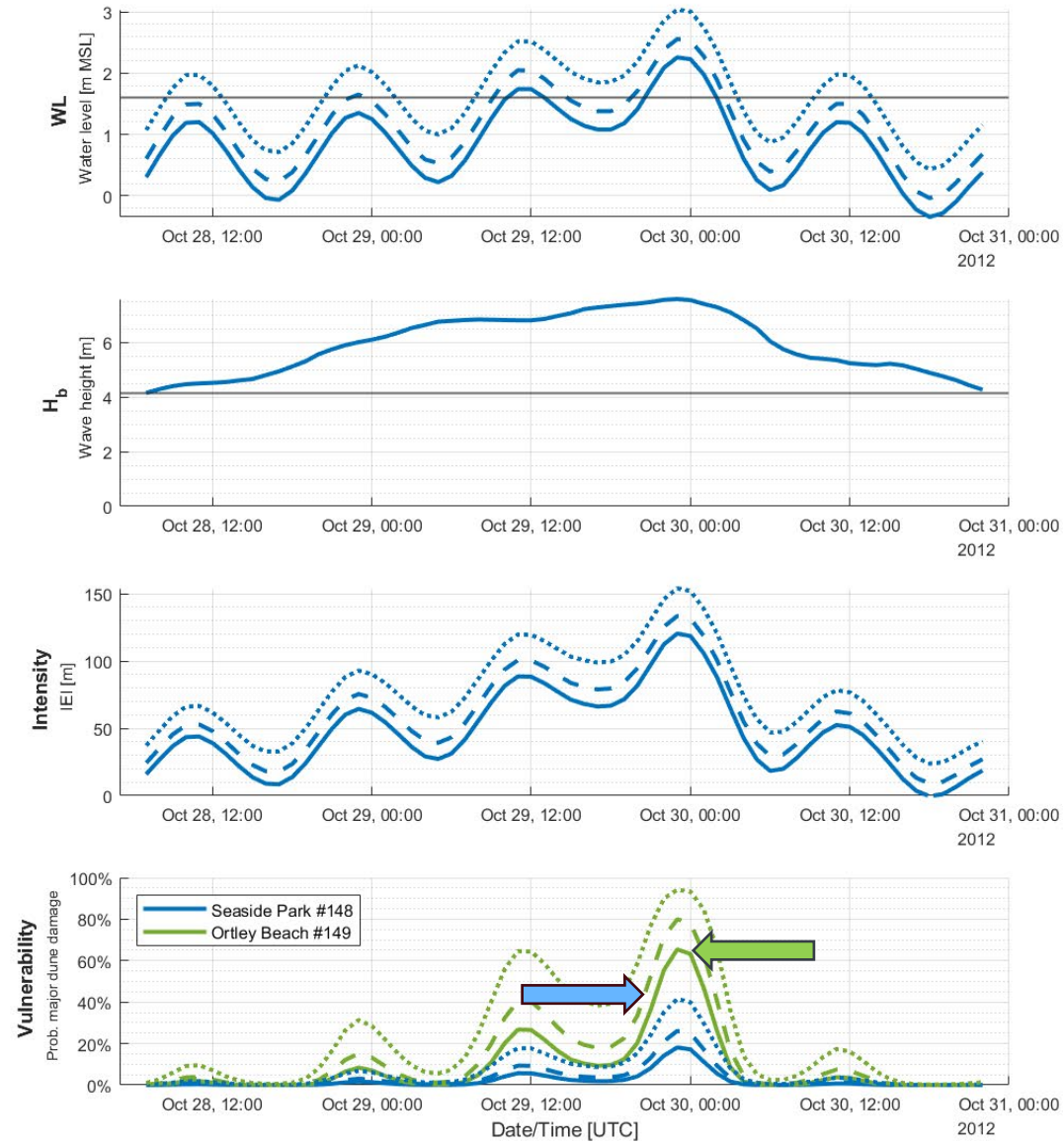
— Baseline — 2050 2100

2050 Vulnerability by NJBPN Profile



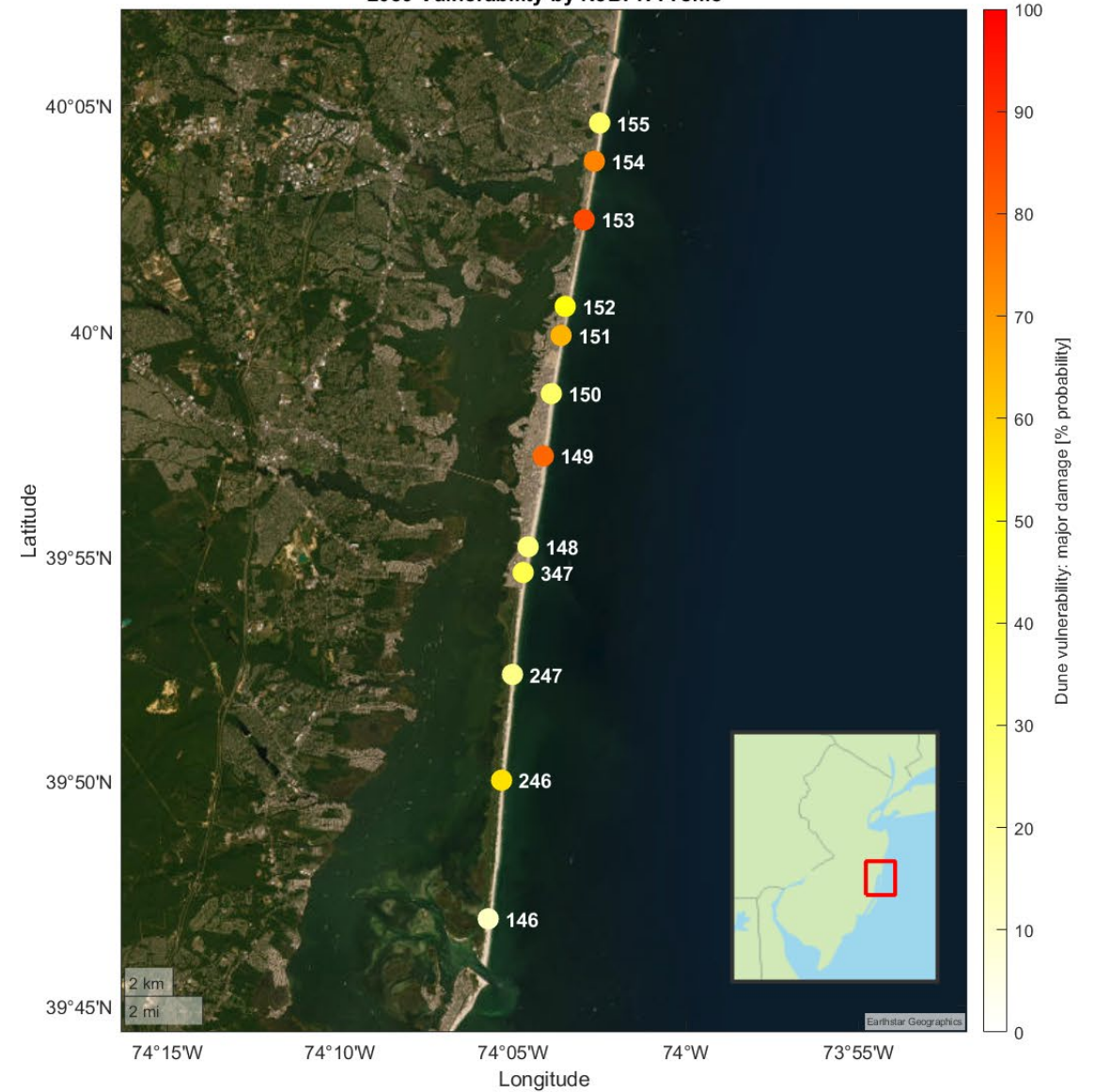
Hourly dune vulnerability for Hurricane Sandy with SSP2-4.5 SLR NJ Shoreline Segment 5

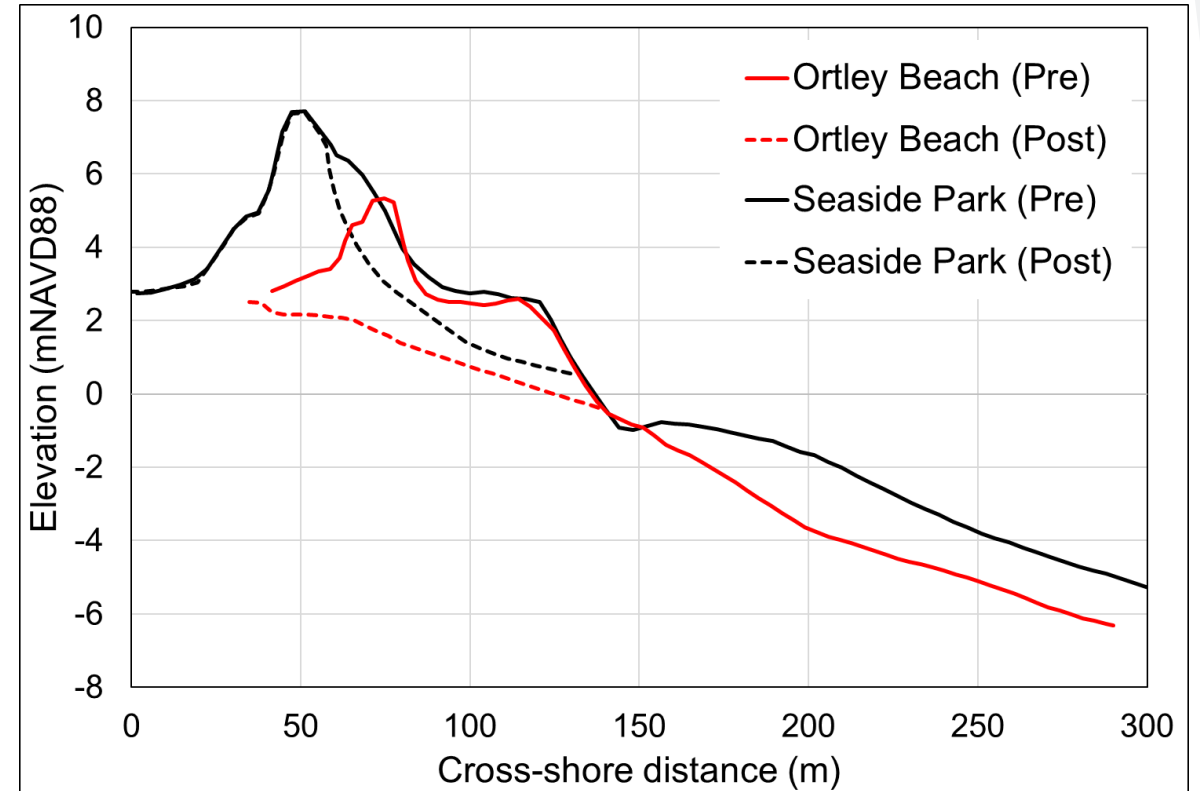
Storm Parameter Time-Series



— Baseline — 2050 2100

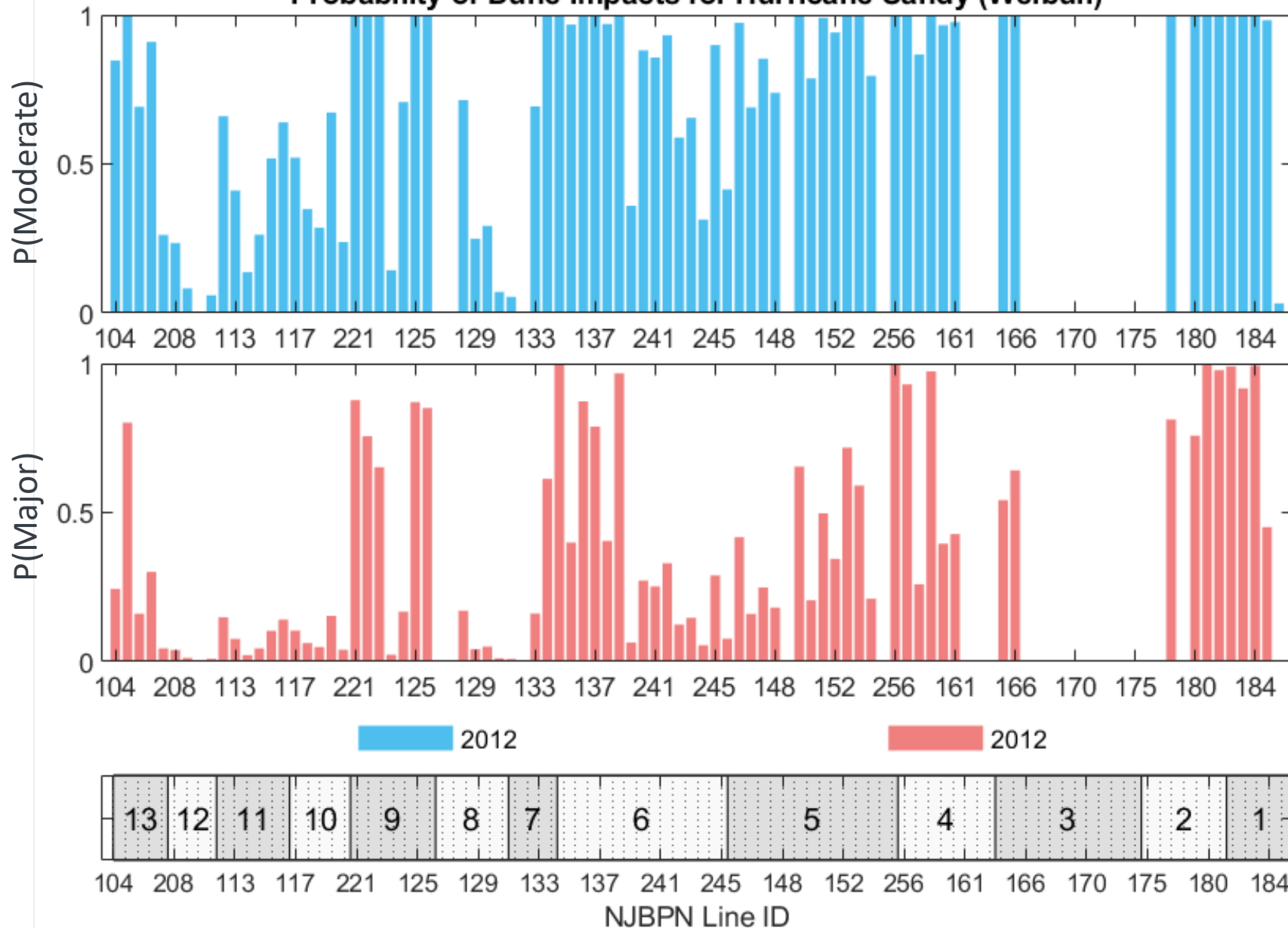
2050 Vulnerability by NJBPN Profile



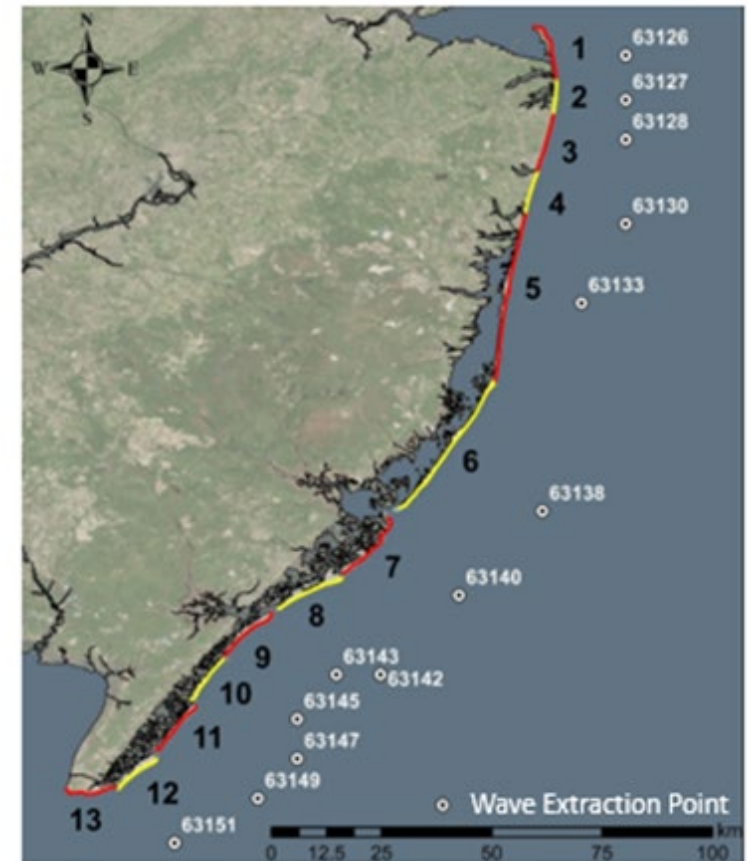


Reproduced from the New Jersey Beach Profile Network (NJBPN)
Coastal Research Center, Stockton University

Probability of Dune Impacts for Hurricane Sandy (Weibull)

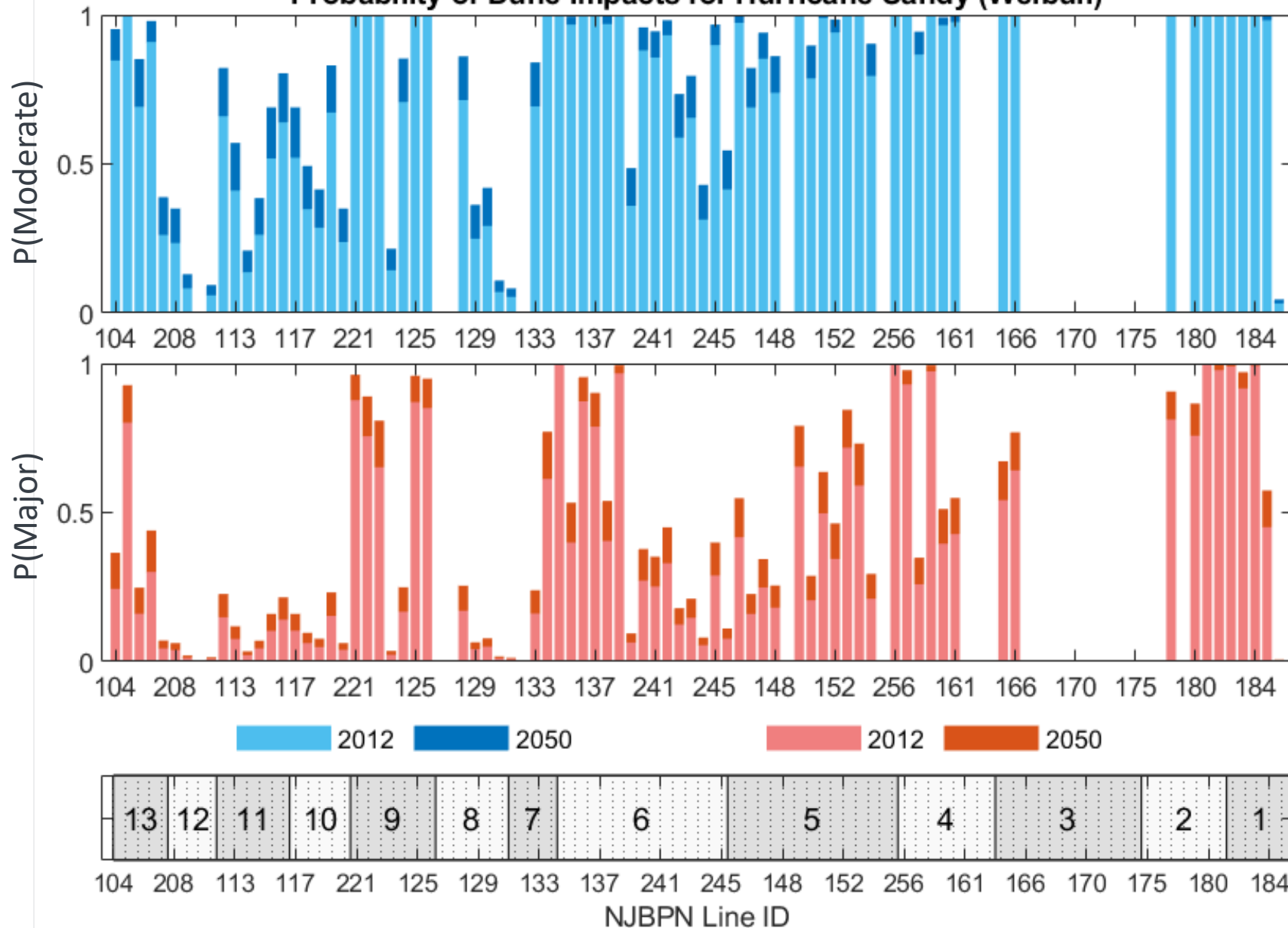


SSP1-1.9 (Low Emissions)

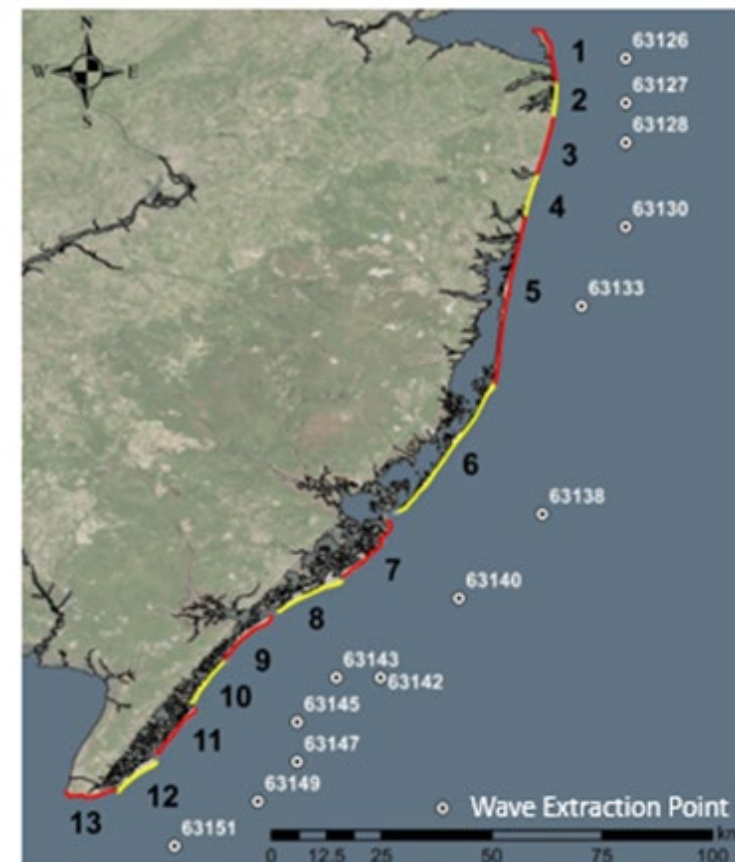


Dune Damage Classifications
 Moderate: Dune Volume Loss 5% - 40%
 Major: Dune Volume Loss > 40%

Probability of Dune Impacts for Hurricane Sandy (Weibull)

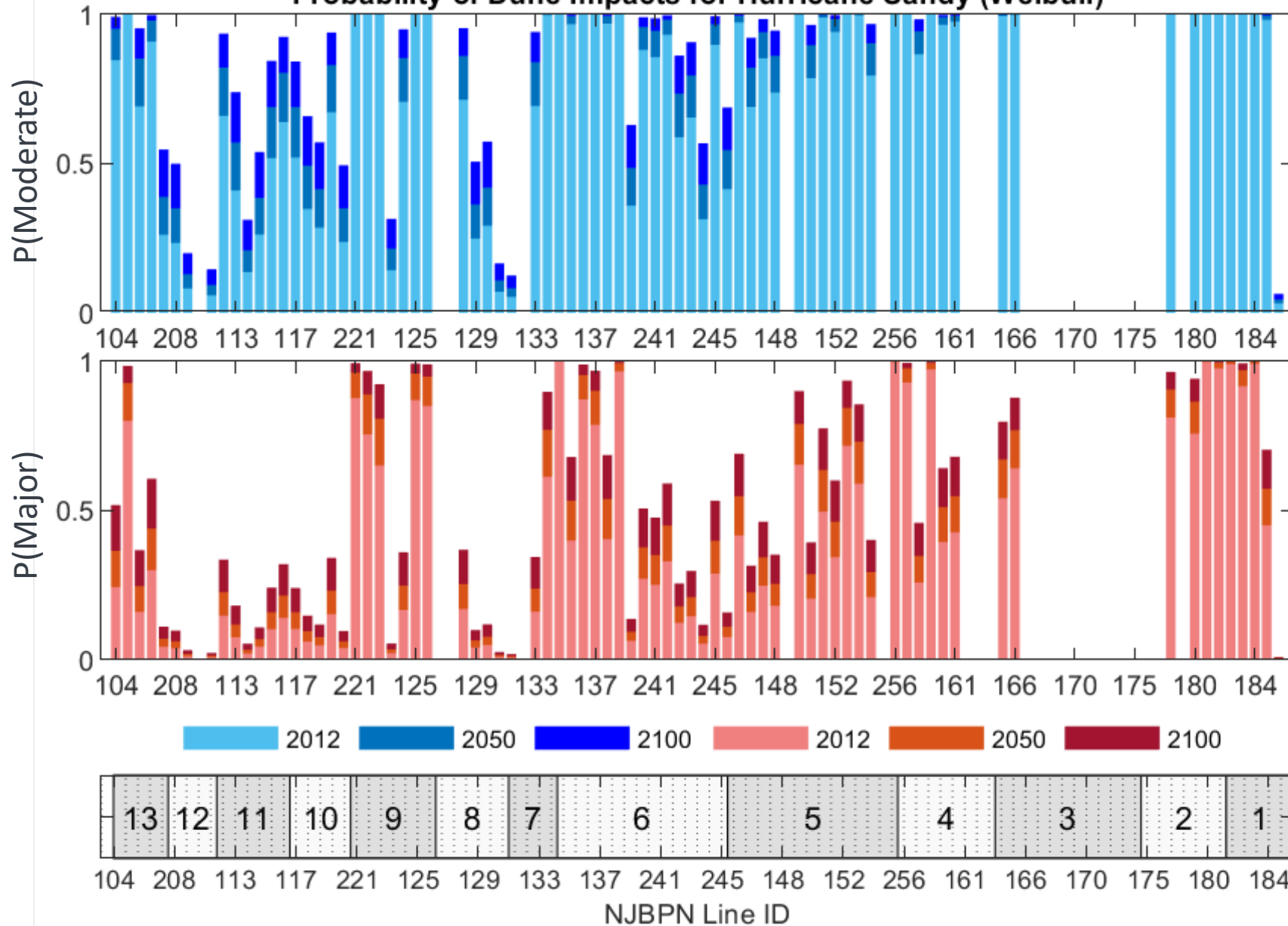


SSP1-1.9 (Low Emissions)

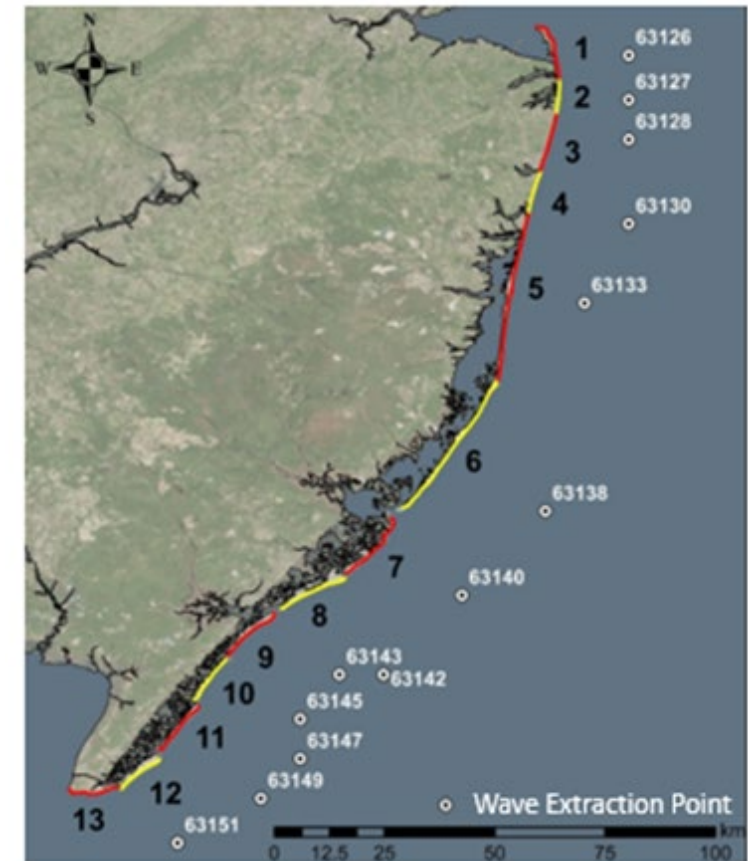


Dune Damage Classifications
 Moderate: Dune Volume Loss 5% - 40%
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Probability of Dune Impacts for Hurricane Sandy (Weibull)

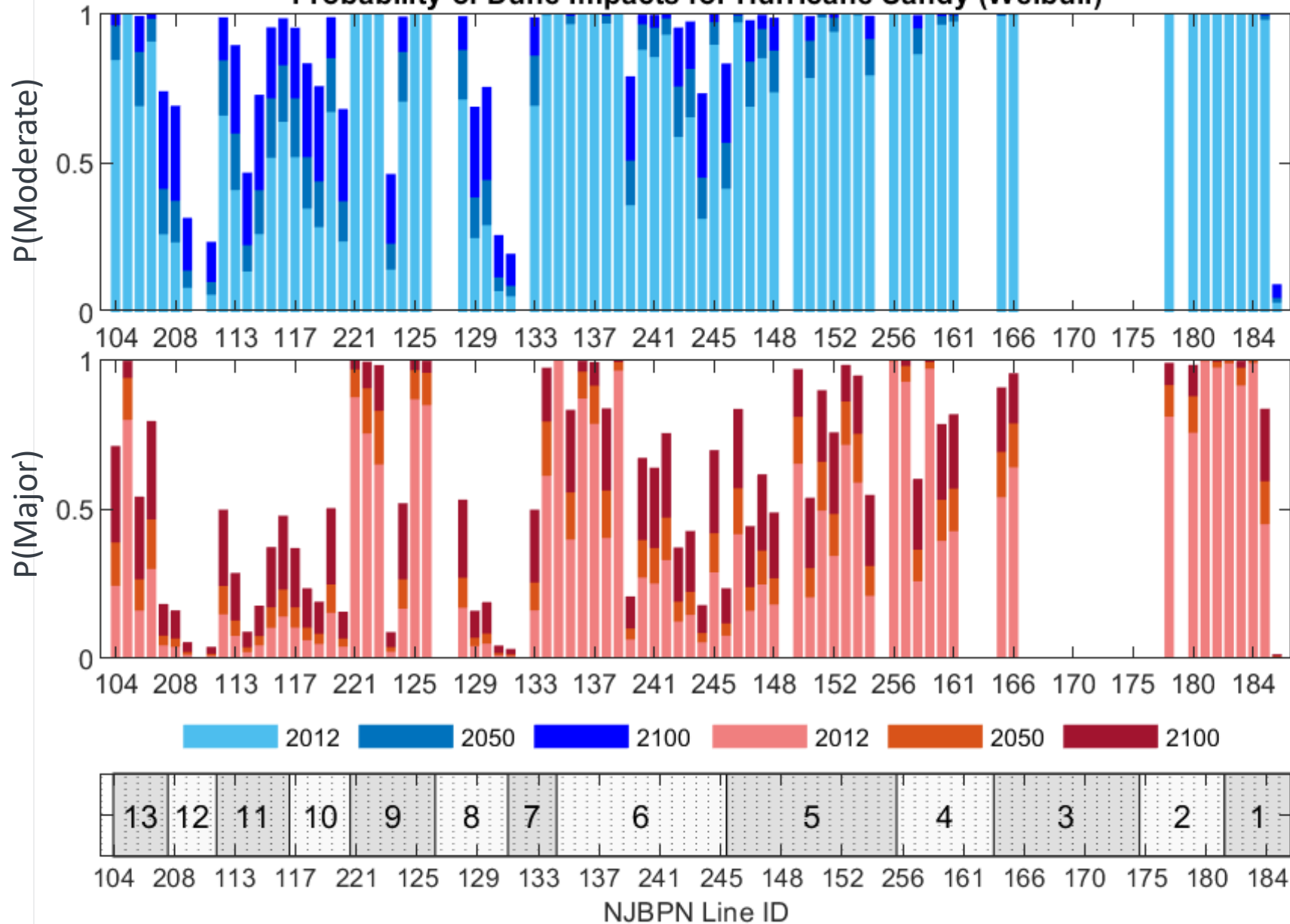


SSP1-1.9 (Low Emissions)

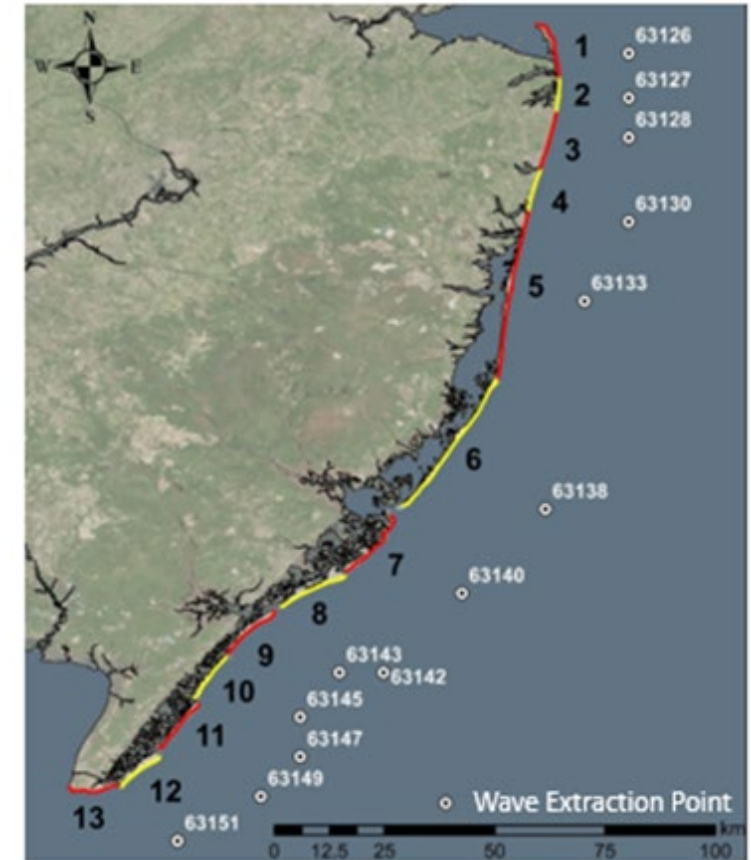


Dune Damage Classifications
 Moderate: Dune Volume Loss 5% - 40%
 Major: Dune Volume Loss > 40%

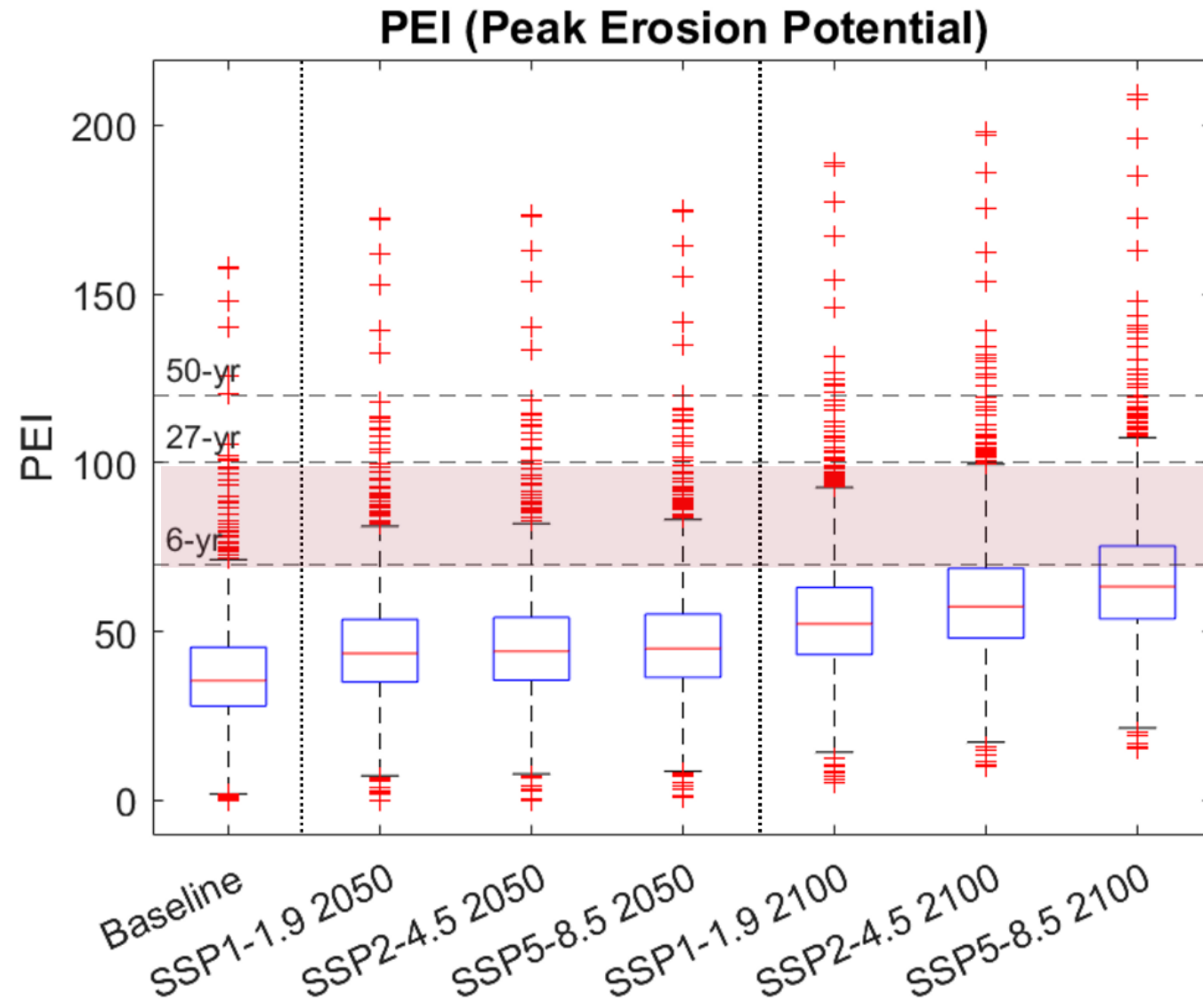
Probability of Dune Impacts for Hurricane Sandy (Weibull)



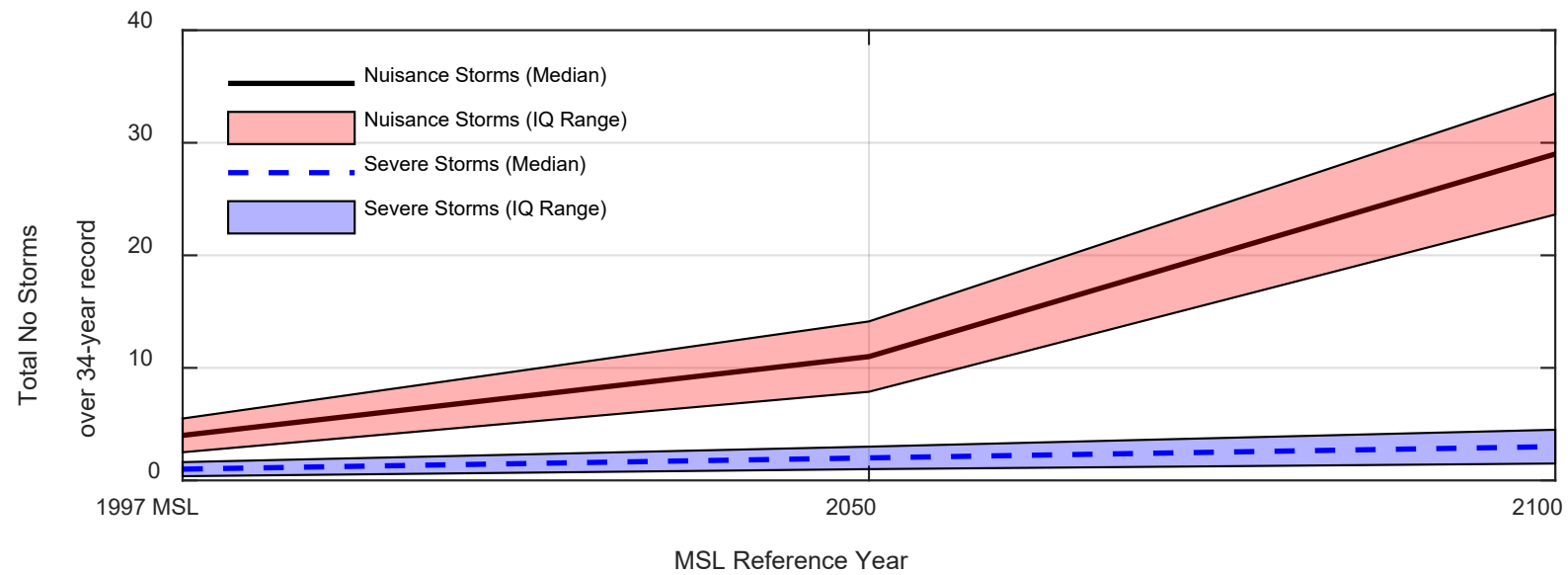
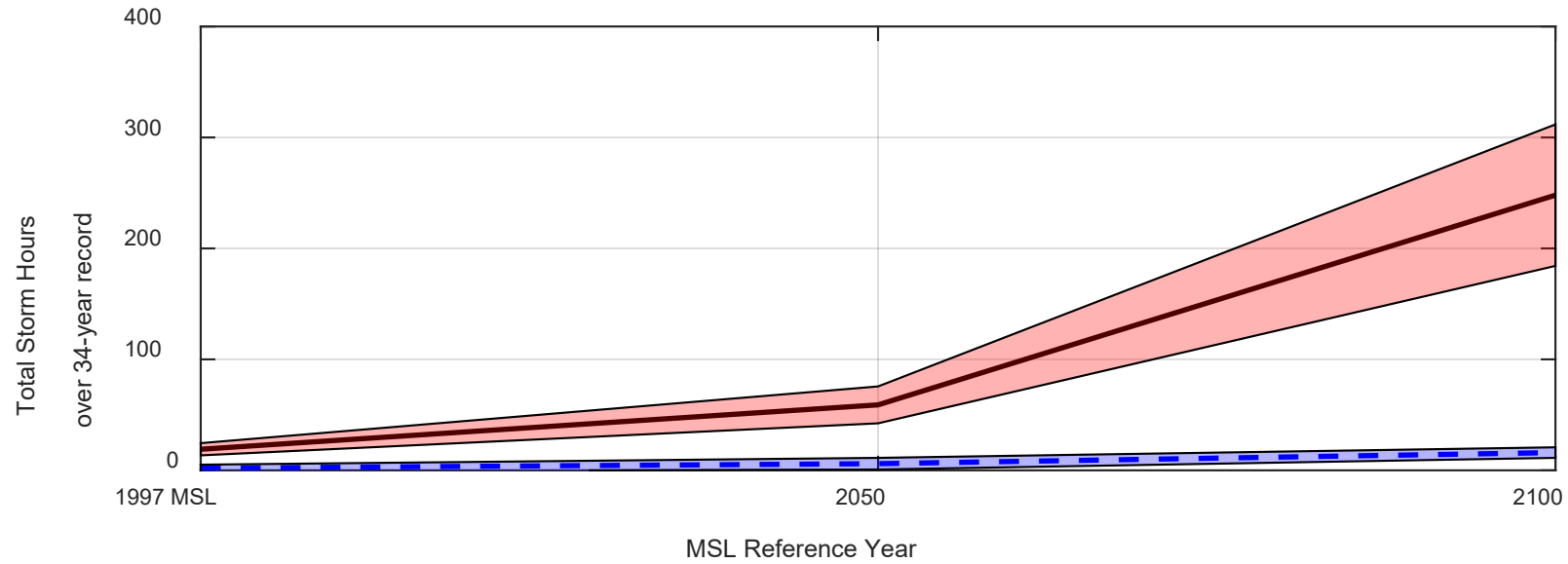
SSP5-8.5 (High Emissions)



Dune Damage Classifications
 Moderate: Dune Volume Loss 5% - 40%
 Major: Dune Volume Loss > 40%

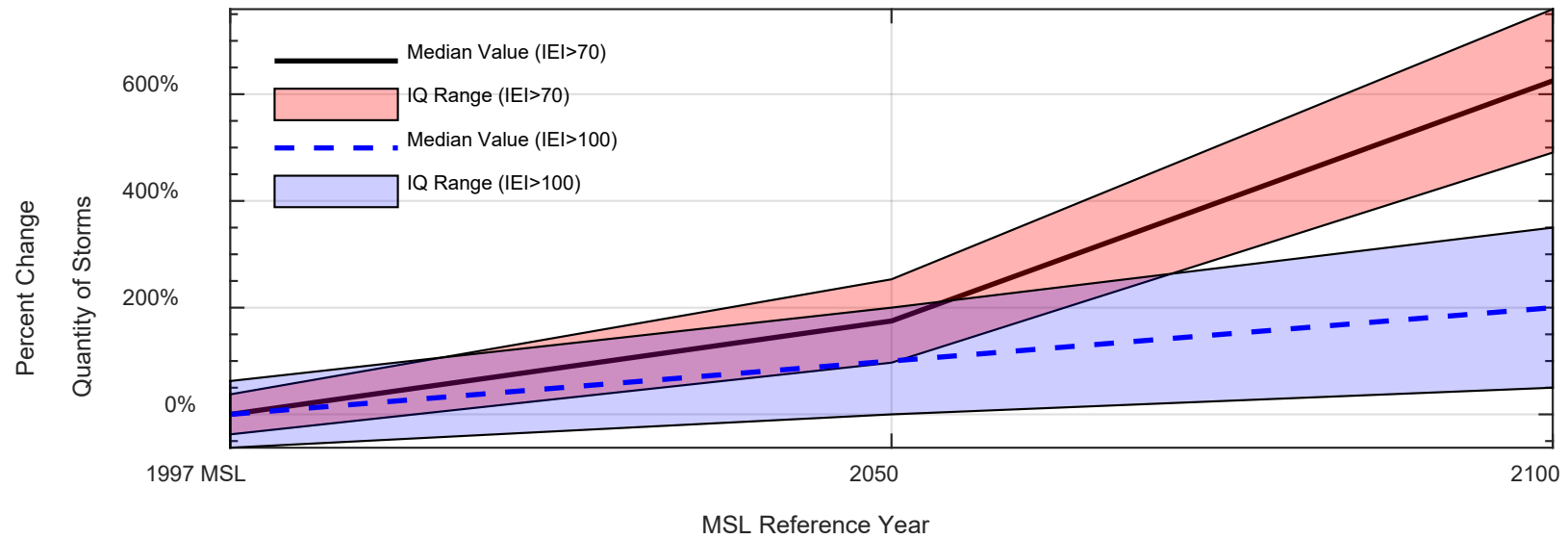
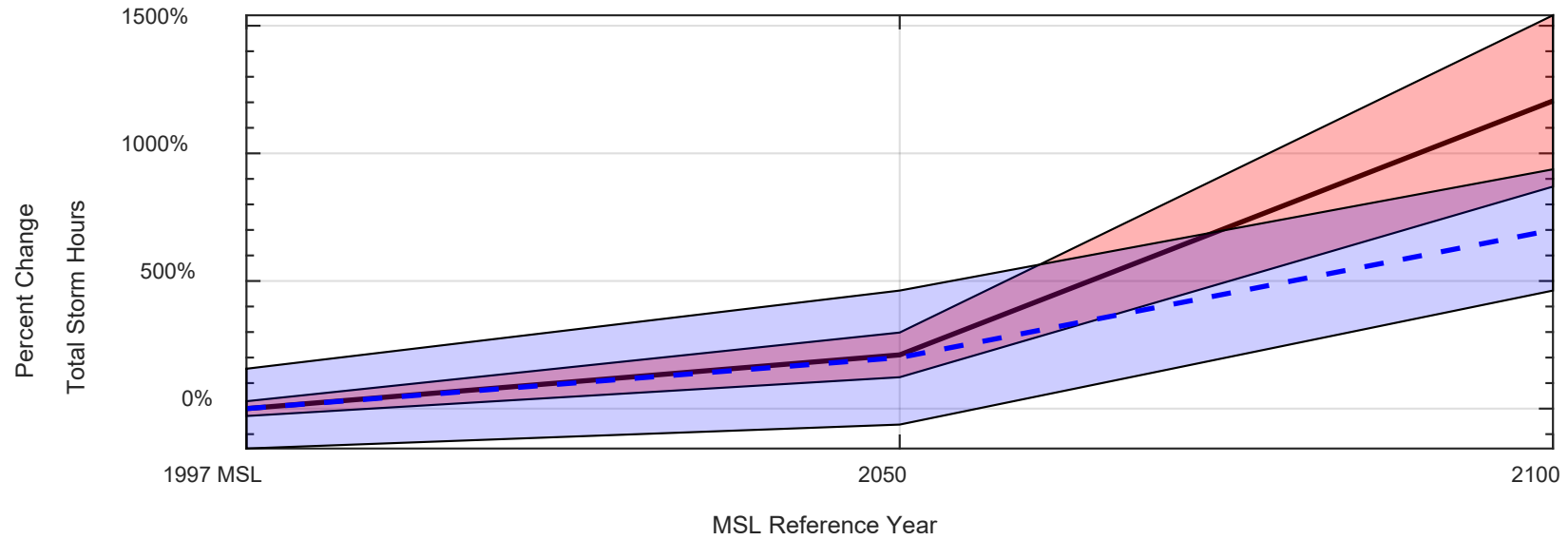


Variation in Storm Climate Across NJ under SSP2-4.5

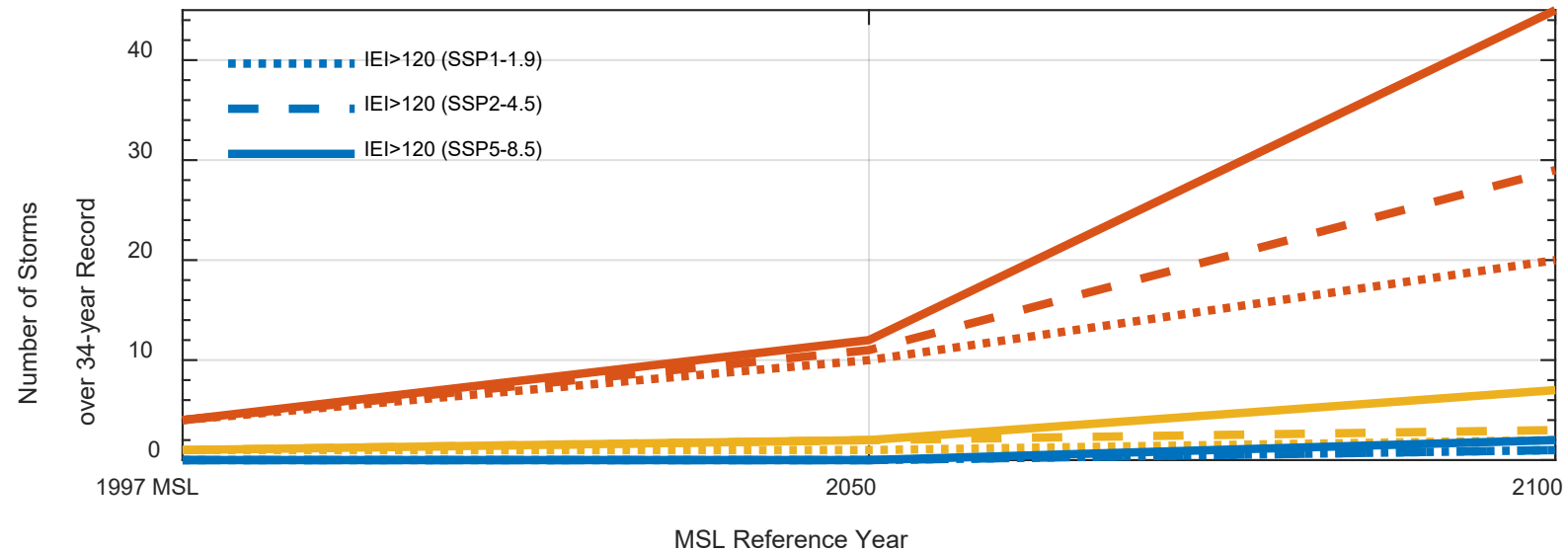
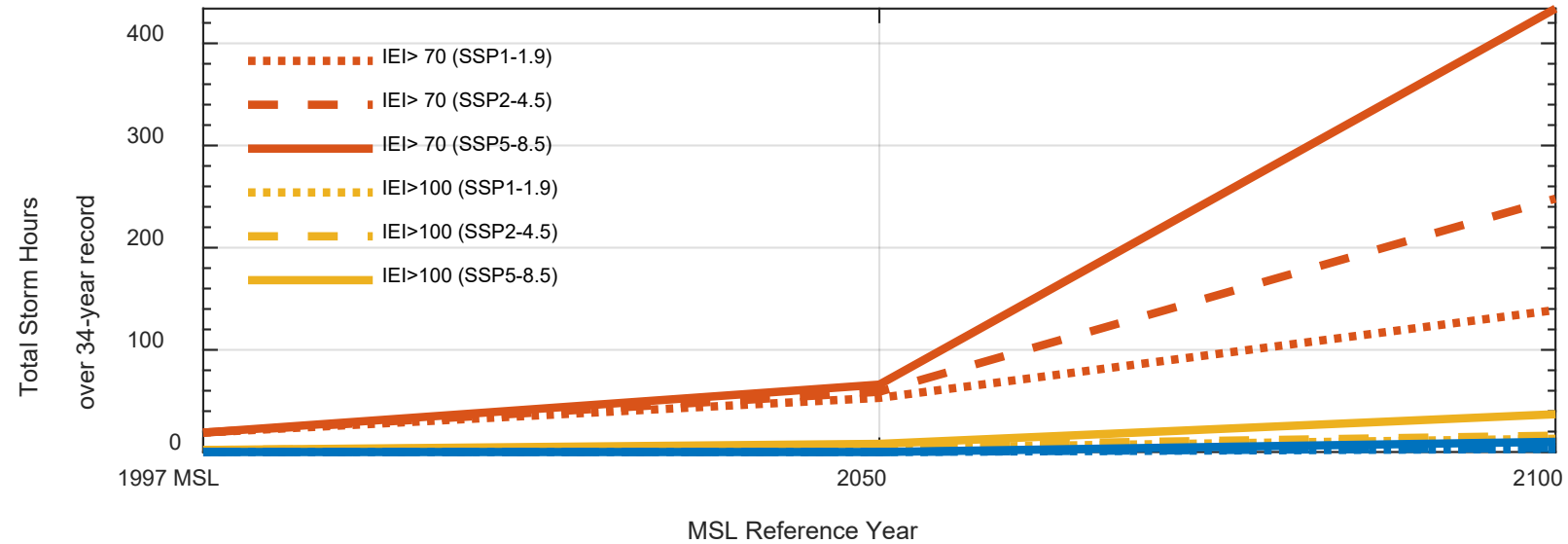


	Baseline	SSP1-1.9 2050	SSP2-4.5 2050	SSP5-8.5 2050	SSP1-1.9 2100	SSP2-4.5 2100	SSP5-8.5 2100
Nuisance Storm Class (IEI > 70)							
Hours	19	53	59	66	139	248	434
Storms	4	10	11	12	20	29	45
Severe Storm Class (IEI > 100)							
Hours	2	4	6	8	13	16	37
Storms	1	1	2	2	2	3	7
Extreme Storm Class (IEI > 120)							
Hours	0	0	0	0	3	4	10
Storms	0	0	0	0	1	1	2

Variation in Storm Climate Across NJ under SSP2-4.5



SLR Effect on Storm Intensity

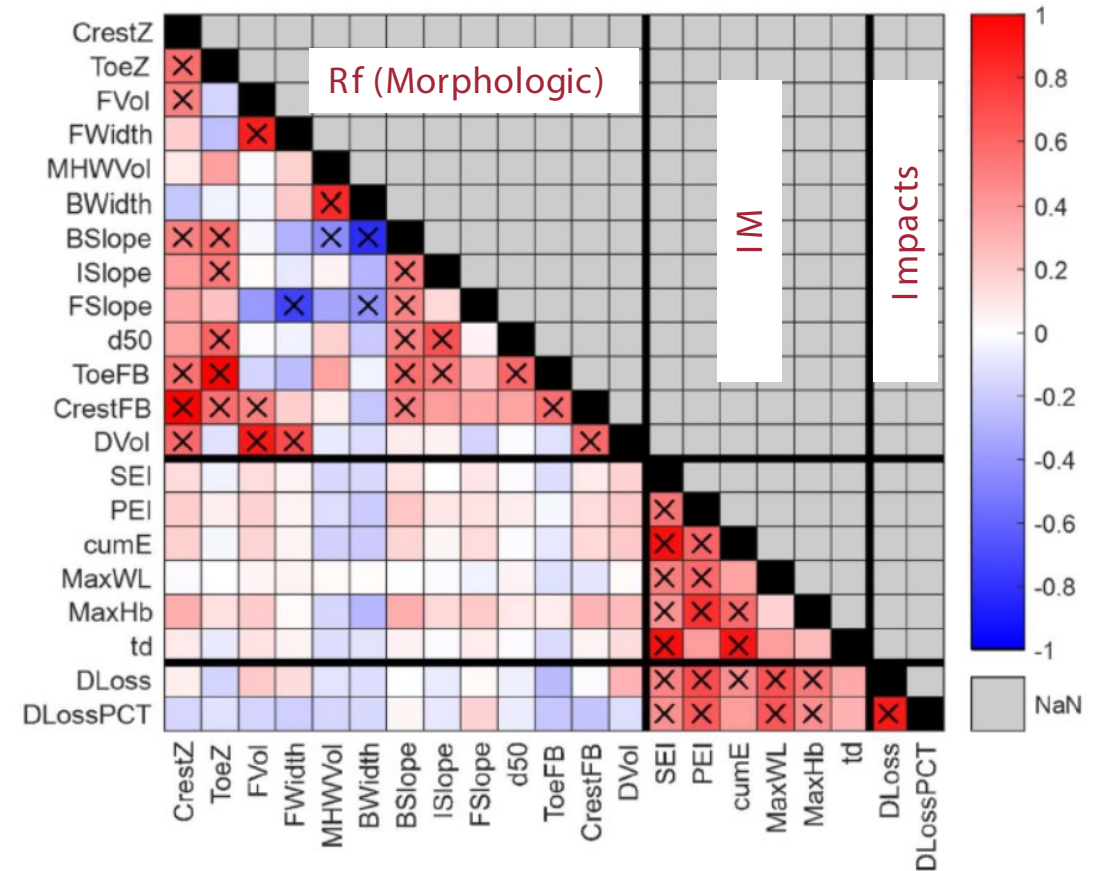


The Engineering Demand Parameter (EDP)

$$P\left(C \left| \frac{IM}{R_f} = EDP \right. \right) = 1 - \exp\left(\frac{-EDP}{\lambda}\right)^\kappa$$

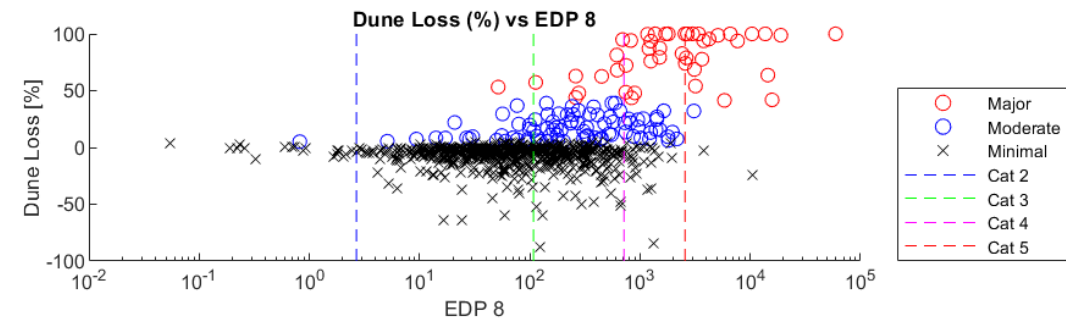
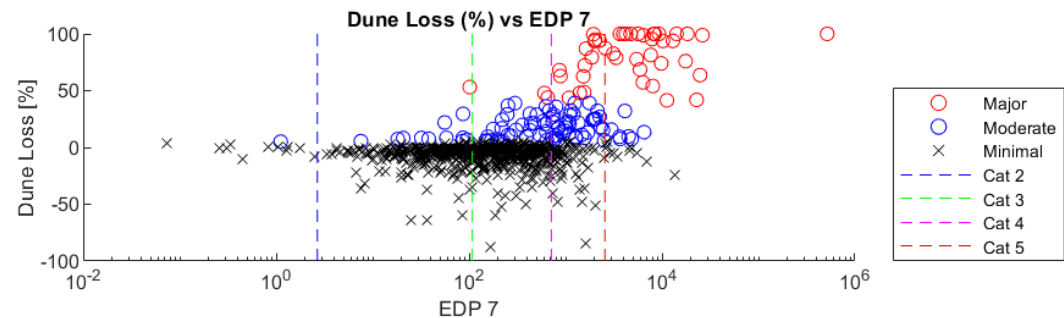
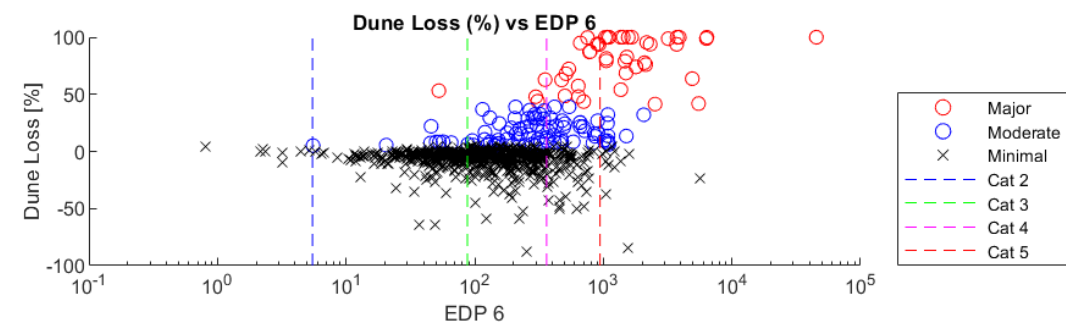
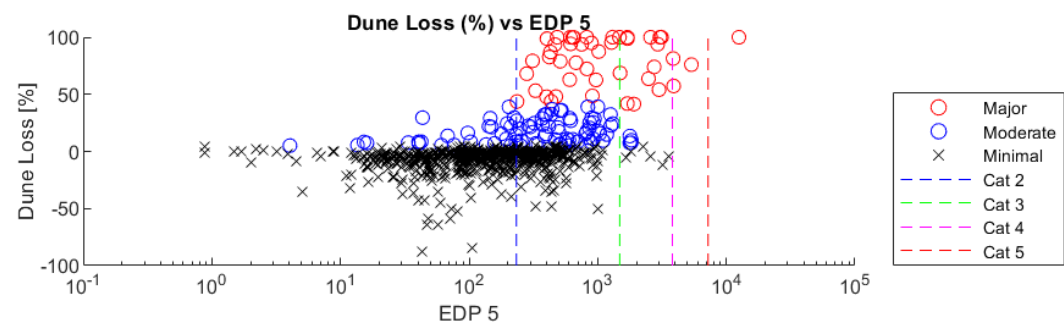
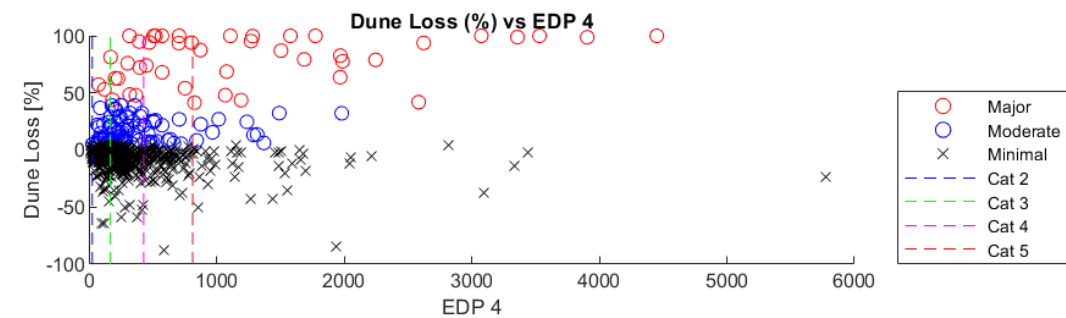
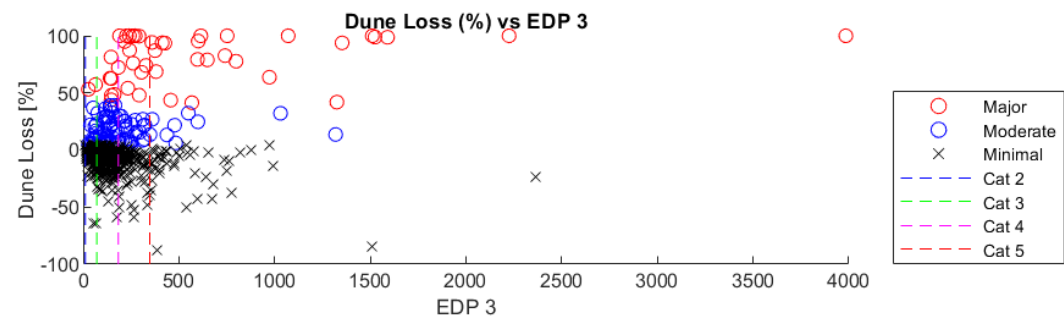
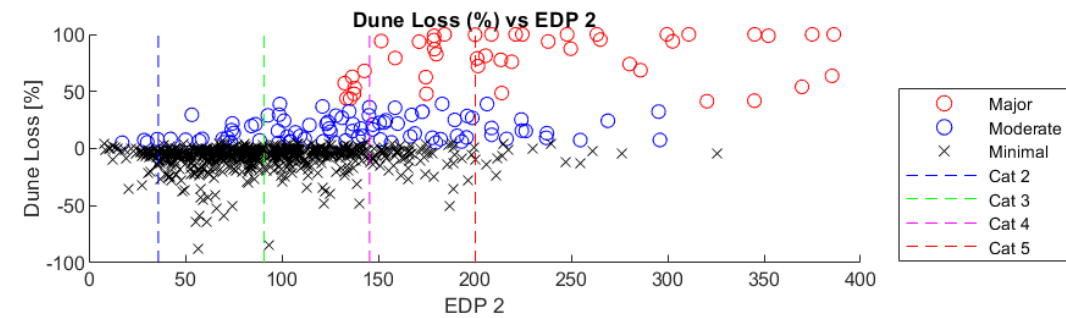
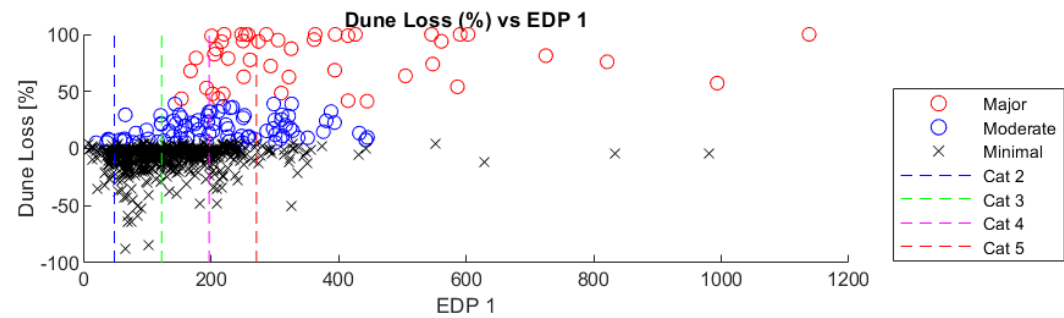
$$EDP = \frac{IM}{R_f} = \frac{IM^i}{R_{fa}^j, R_{fb}^k \dots R_{fn}^m}$$

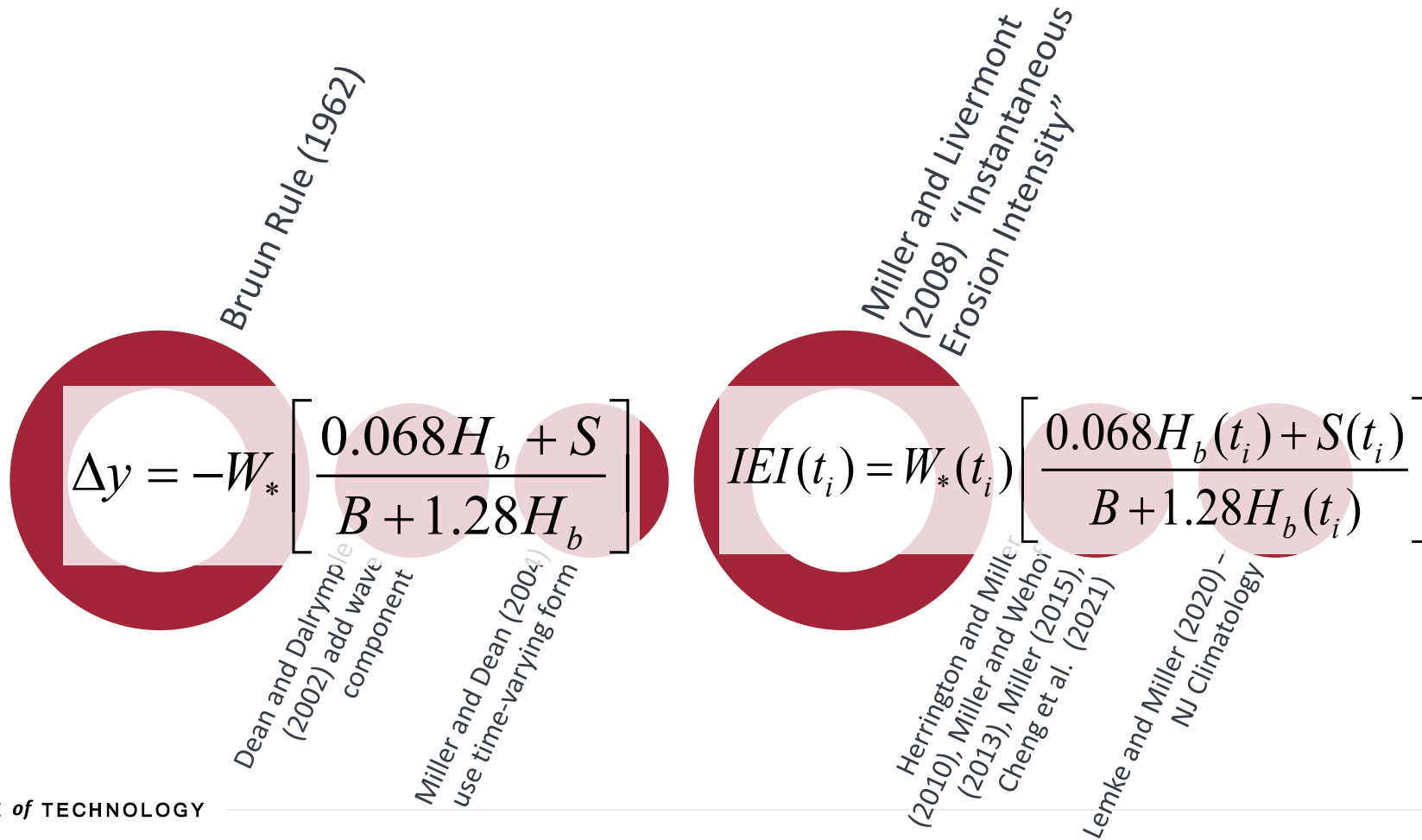
- Eliminate highly correlated parameters
- Emphasize easily measurable parameters



Lemke (2021)







New Jersey SEI Climatology (Lemke and Miller, 2020)

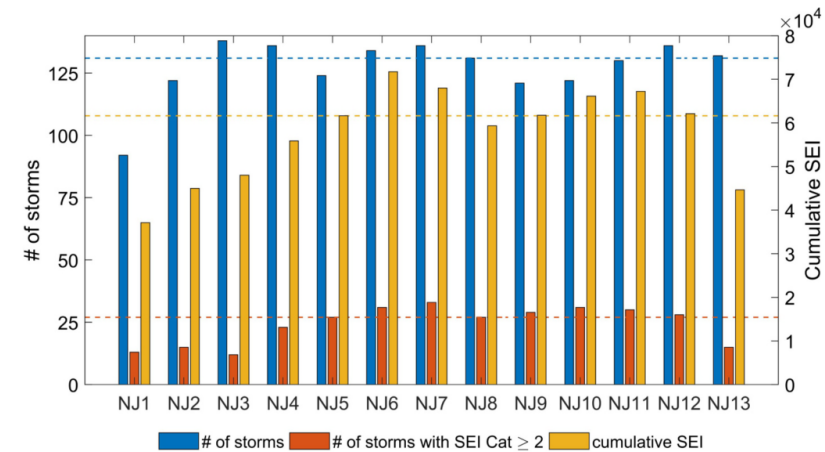
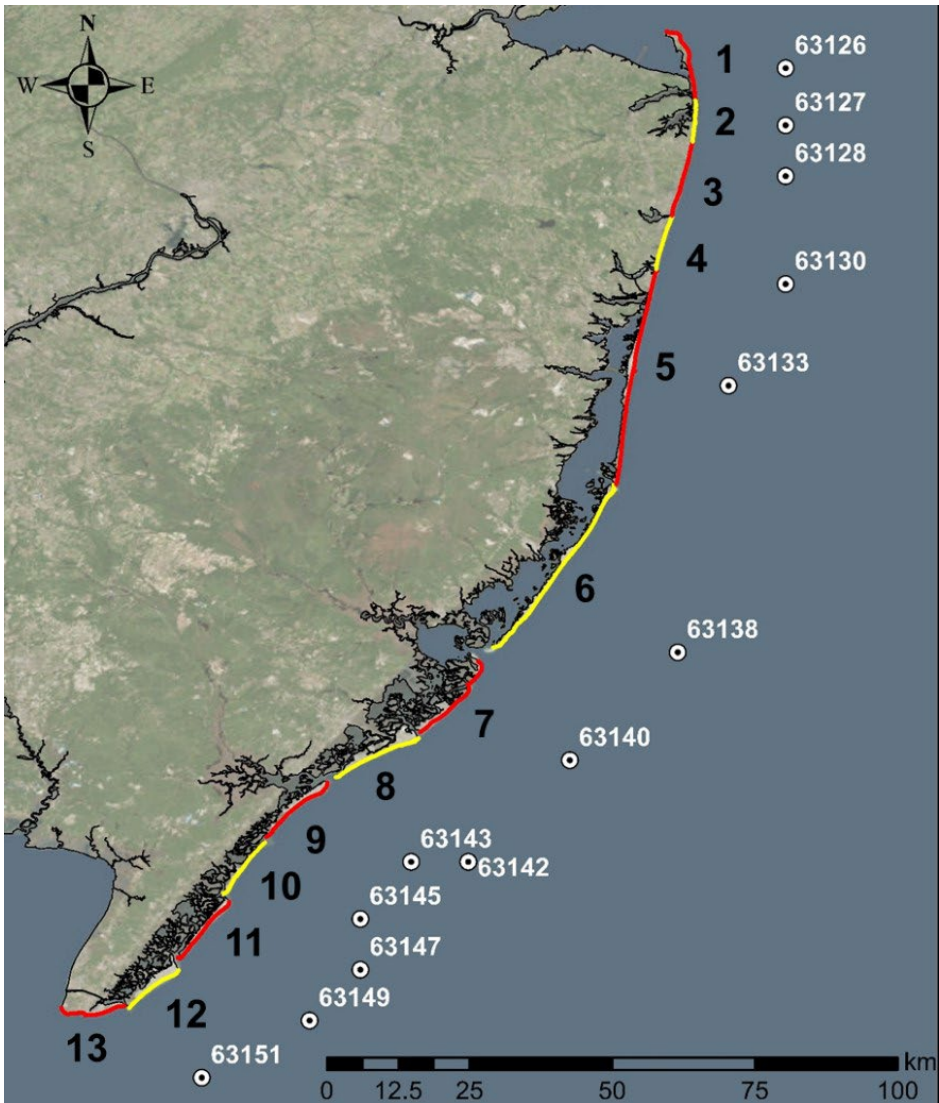
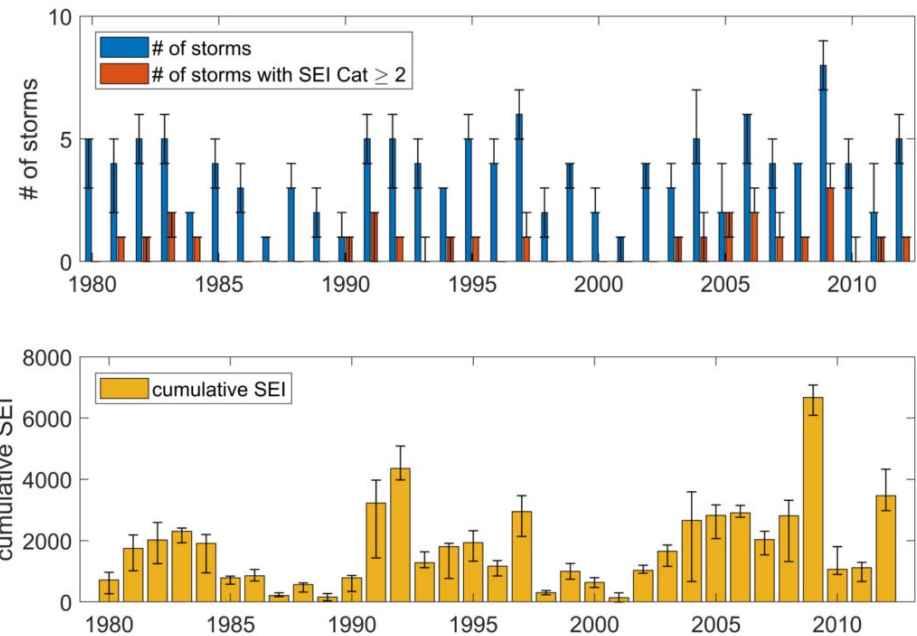


Fig. 7. Totals for three parameters, summed over the 34-year record, with median values presented as horizontal dotted lines.



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- Barone, D.A., McKenna, K.K., Farrell, S.C., 2014. Hurricane Sandy: Beach-dune performance at New Jersey Beach Profile Network sites 82.
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- Janssen, M.S. and J.K. Miller, 2022. The Dune Engineering Demand Parameter and Applications to Forecasting Dune Impacts, *Journal of Marine Science and Engineering*, 10(2), 234.
- Lemke, L. and J.K. Miller, 2020. Evaluation of storms through the lens of erosion potential along the New Jersey, USA coast, *Coastal Engineering*, 158.
- Lemke, L. and J.K. Miller, 2021. Role of Storm Erosion Potential and Beach Morphology in Controlling Dune Erosion, *Journal of Marine Science and Engineering*, 9(12), 1428.
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- Overbeck, J.R., J.W. Long and H.F. Stockdon, 2017. Testing model parameters for wave-induced dune erosion using observations from Hurricane Sandy, *Geophysical Research Letters*, 44(2), 937-945.
- Walling, K., T.O. Herrington and J.K. Miller, 2016. Hurricane Sandy damage comparison: Oceanfront houses protected by a beach and dune system with vs. without a rock seawall, *Shore & Beach*, 84(3), 35-41.



Storm Erosion Climatology [1980 – 2013] (Lemke and Miller, 2020)

Detrend climatology to eliminate the effects of local sea level rise during the duration of the 34-year period of study

Baseline Storm Erosion Climatology [1997]

Add 2050 GMSL projections
(IPCC, 2023)

Add VLM contributions

2050 Storm Erosion Climatology

SSP1-1.9

SSP2-4.5

SSP5-8.5

Add 2100 GMSL projections
(IPCC, 2023)

Add VLM contributions

2100 Storm Erosion Climatology

SSP1-1.9

SSP2-4.5

SSP5-8.5

Global Sea Level Rise from IPCC

Three SSP scenarios outlined in the IPCC's Assessment Report 6 listed with the projected global sea level rise with respect to 1995 – 2014 GMSL and global surface temperature difference with respect to 1850 – 1900 levels

IPCC Scenario	SLR 2050 (m)	SLR 2100 (m)	Degrees warming 2100 (°C)	Notes
SSP1-1.9 "Low"	0.18 (0.15 – 0.23)	0.38 (0.28–0.55)	1.4 (1.0 – 1.8)	Sustainable pathway with low greenhouse gas and CO2 emissions declining to net zero around 2050 then remaining at levels of net negative CO2 emissions
SSP2-4.5 "Middle"	0.20 (0.17 – 0.26)	0.56 (0.44–0.76)	2.7 (2.1 – 3.5)	Intermediate greenhouse gas and CO2 emissions which remain at their currently level until approximately 2050 before declining
SSP5-8.5 "High"	0.23 (0.20 – 0.29)	0.77 (0.63–1.01)	4.4 (3.3 – 5.7)	Very high greenhouse gas and CO2 emissions with no decline



Local Sea Level Rise

Technical Report NOS CO-OPS 065

Estimating Vertical Land Motion from Long-Term Tide Gauge Records

Estimated vertical land movement from long-term tide gauges via NOAA

Station	Record Length	MSL trend (mm/yr)	Est. VLM (mm/yr)
Sandy Hook 8531680	75	3.90 (3.65 – 4.15)	-2.27 (-2.34 – -2.20)
Atlantic City 8534720	96	3.99 (3.81 – 4.17)	-2.17 (-2.28 – -2.06)
Cape May 8536110	42	4.06 (3.32 – 4.80)	-2.10 (-2.35 – -1.85)

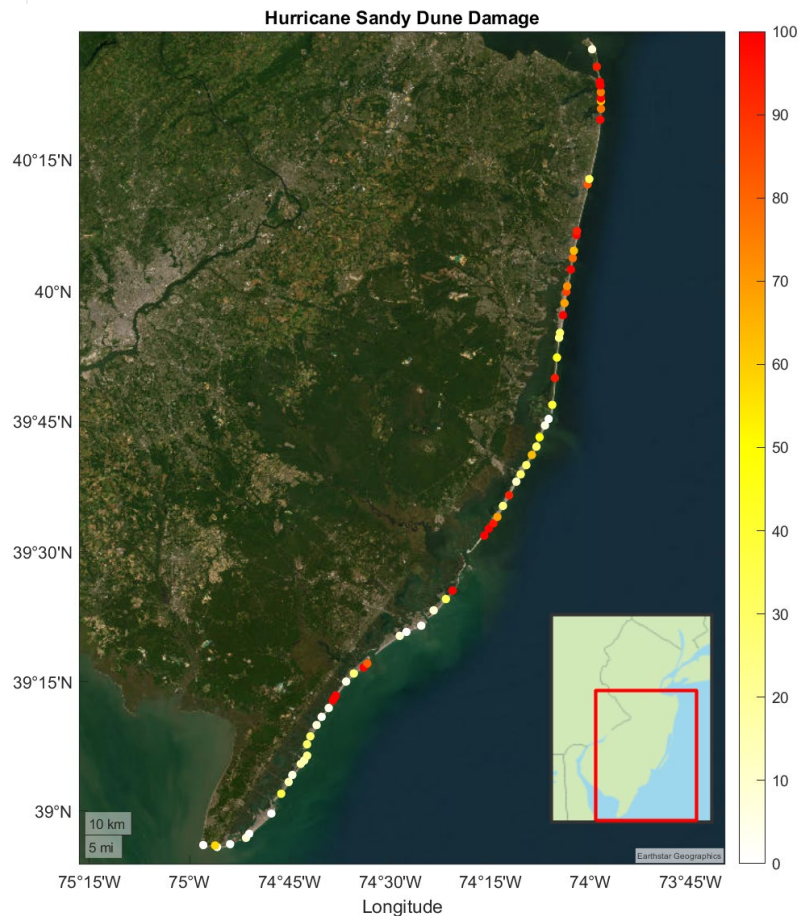
Increases in local sea level (m) by shoreline segment relative to 1995-2014 mean sea level using the IPCC's global sea level rise projections as a baseline

Segment	WL Station	SSP1-1.9 "Low" (m)	SSP2-4.5 "Middle" (m)	SSP5-8.5 "High" (m)
2050				
NJ 1 – NJ 5	Sandy Hook	0.282	0.302	0.332
NJ 6 – NJ 9	Atlantic City	0.278	0.298	0.328
NJ 10 – NJ 13	Cape May	0.275	0.295	0.325
2100				
NJ 1 – NJ 5	Sandy Hook	0.596	0.776	0.986
NJ 6 – NJ 9	Atlantic City	0.586	0.766	0.976
NJ 10 – NJ 13	Cape May	0.580	0.760	0.970

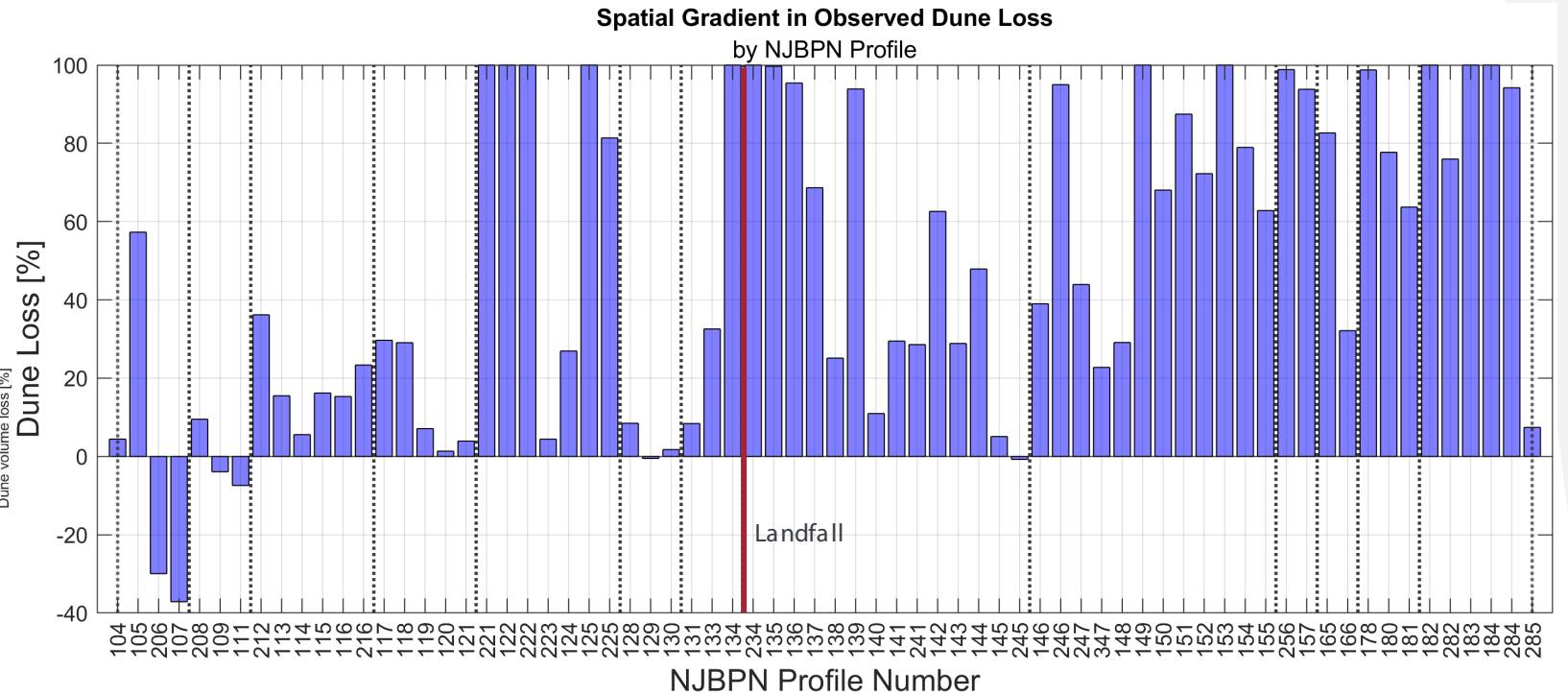


Observed Impacts of Hurricane Sandy

Spatial Variation



Measured Dune Losses based on NJBPN



NJBPN

Stockton University Coastal Research Center

Well-documented impacts and drivers

Storm Intensity spatial gradient

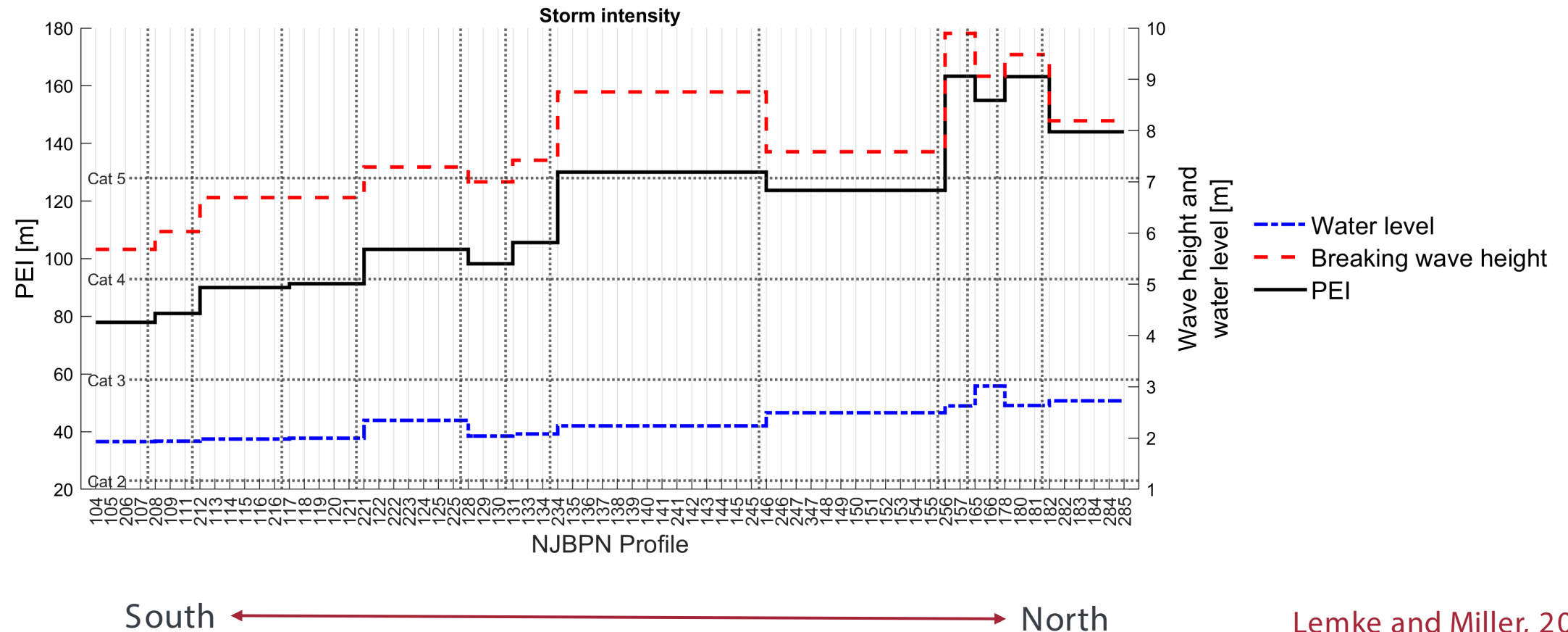
Correlations between beach state and damage

- Barone, D.A., McKenna, K.K., Farrell, S.C., 2014. Hurricane Sandy: Beach-dune performance at New Jersey Beach Profile Network sites 82.
- Overbeck, J.R., Long, J.W., Stockdon, H.F., 2017. Testing model parameters for wave-induced dune erosion using observations from Hurricane Sandy. *Geophysical Research Letters* 44, 937–945.
- Walling, K., T.O. Herrington and J.K. Miller, 2016. Hurricane Sandy damage comparison: Oceanfront houses protected by a beach and dune system with vs. without a rock seawall, *Shore & Beach*, 84(3), 35-41.



Storm Intensity – Hurricane Sandy

Spatial Variation

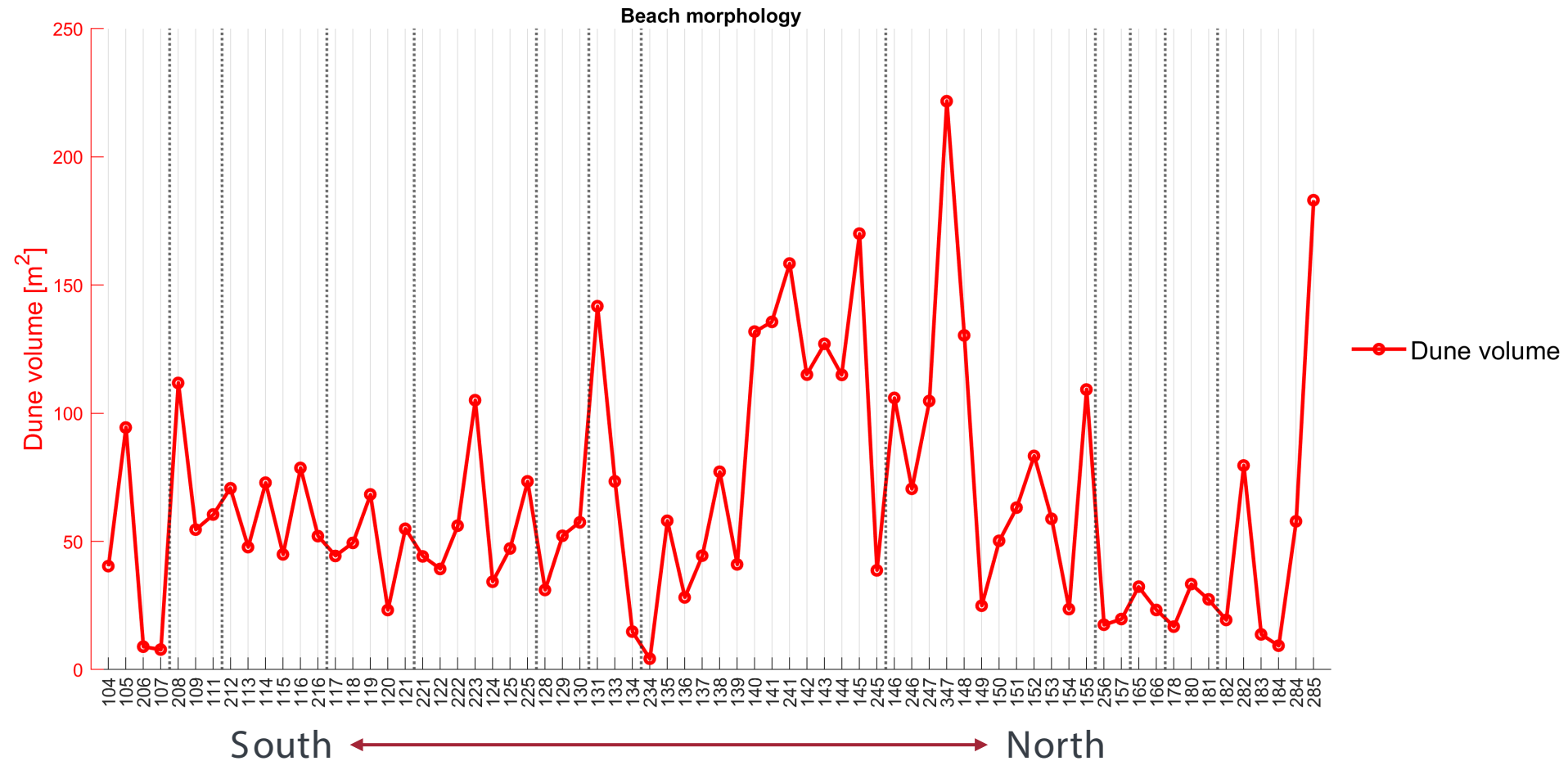


Lemke and Miller, 2020

Beach profile parameters

Spatial Variation

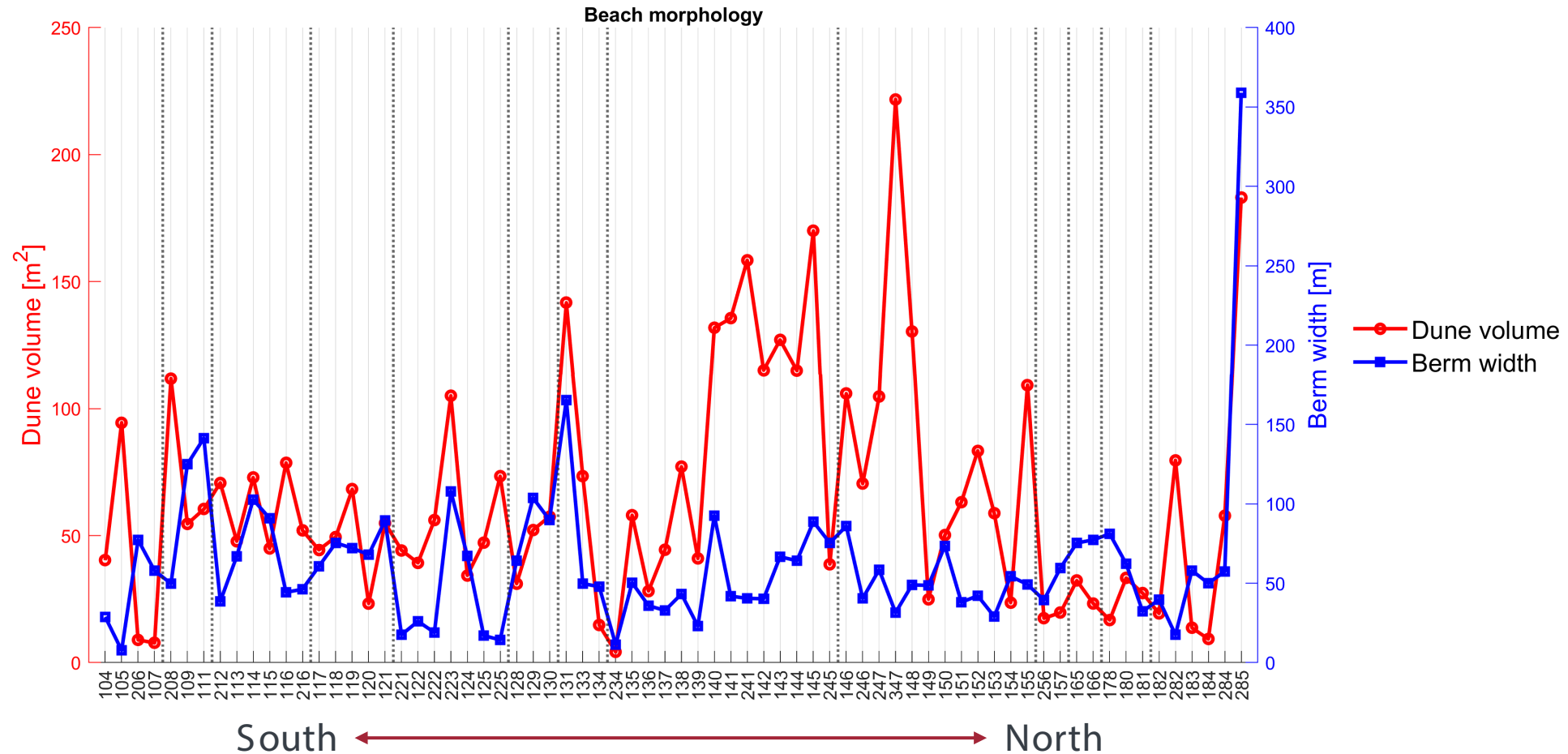
Farrell et al. 2013; Lemke and Miller 2021



Beach profile parameters – pre-Sandy

Spatial Variation

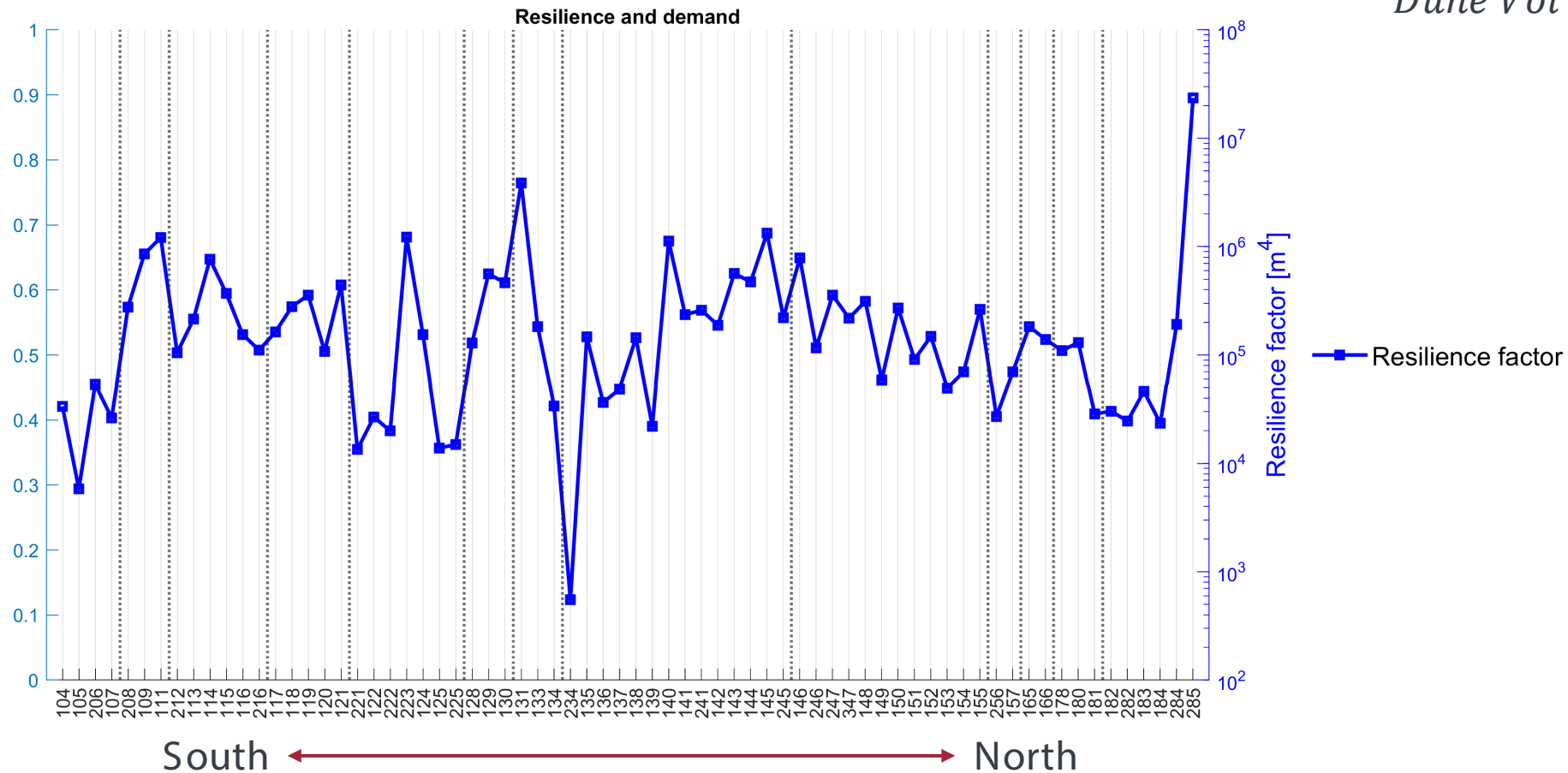
Farrell et al. 2013; Lemke and Miller 2021



Resilience and demand – Sandy

Spatial Variation

$$\text{Resilience Factor} = \text{Dune Vol} \times \text{Berm Width}^2$$

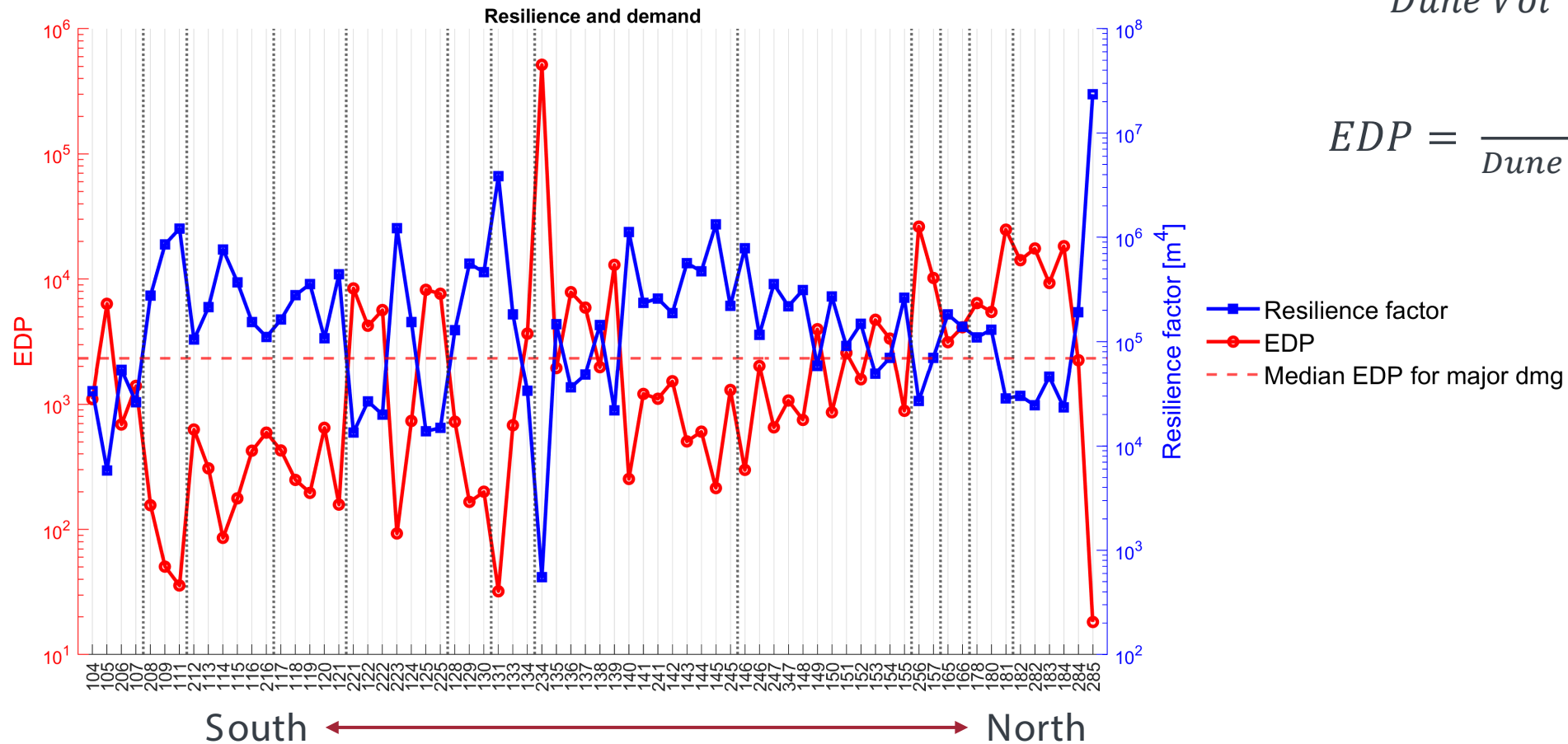


Resilience and demand – Sandy

Spatial Variation

$$\text{Resilience Factor} = \text{Dune Vol} \times \text{Berm Width}^2$$

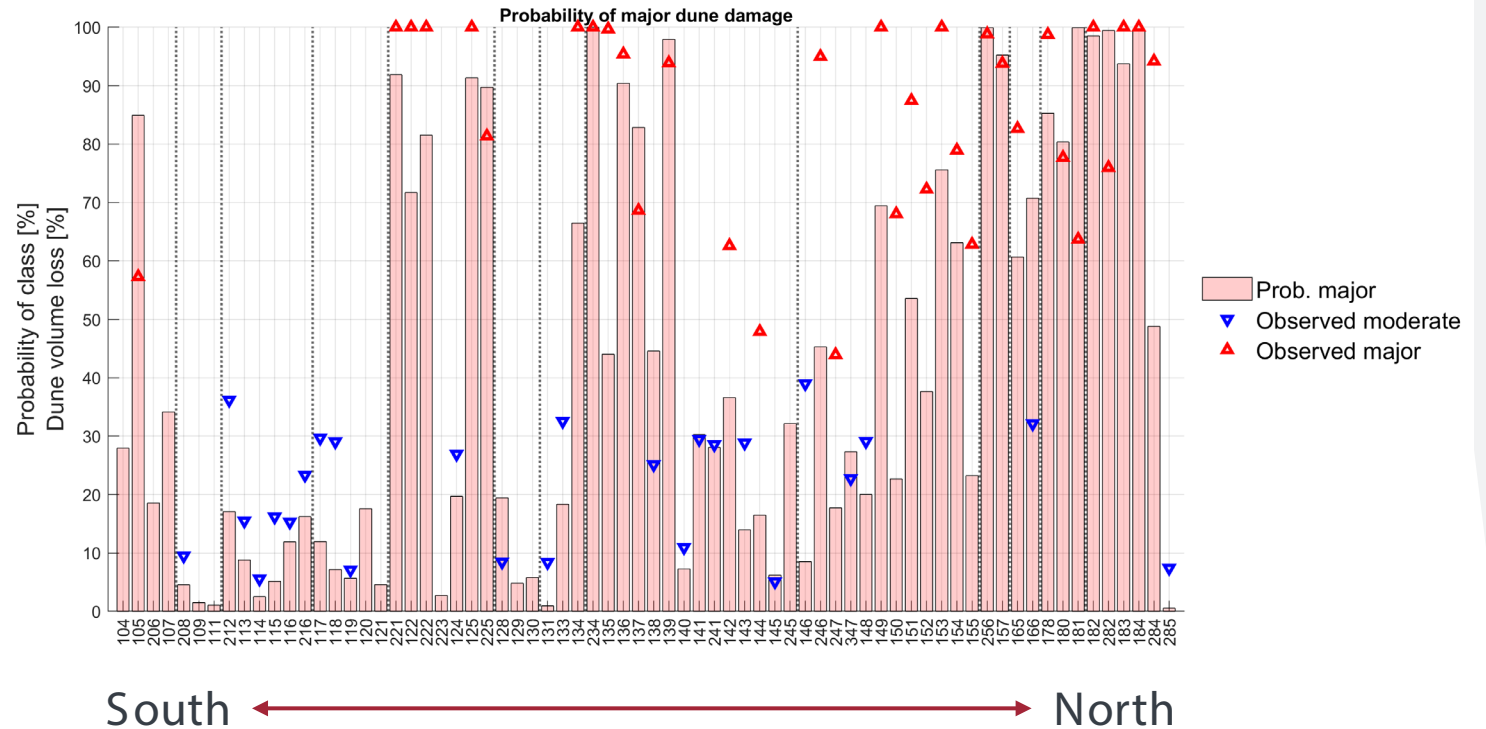
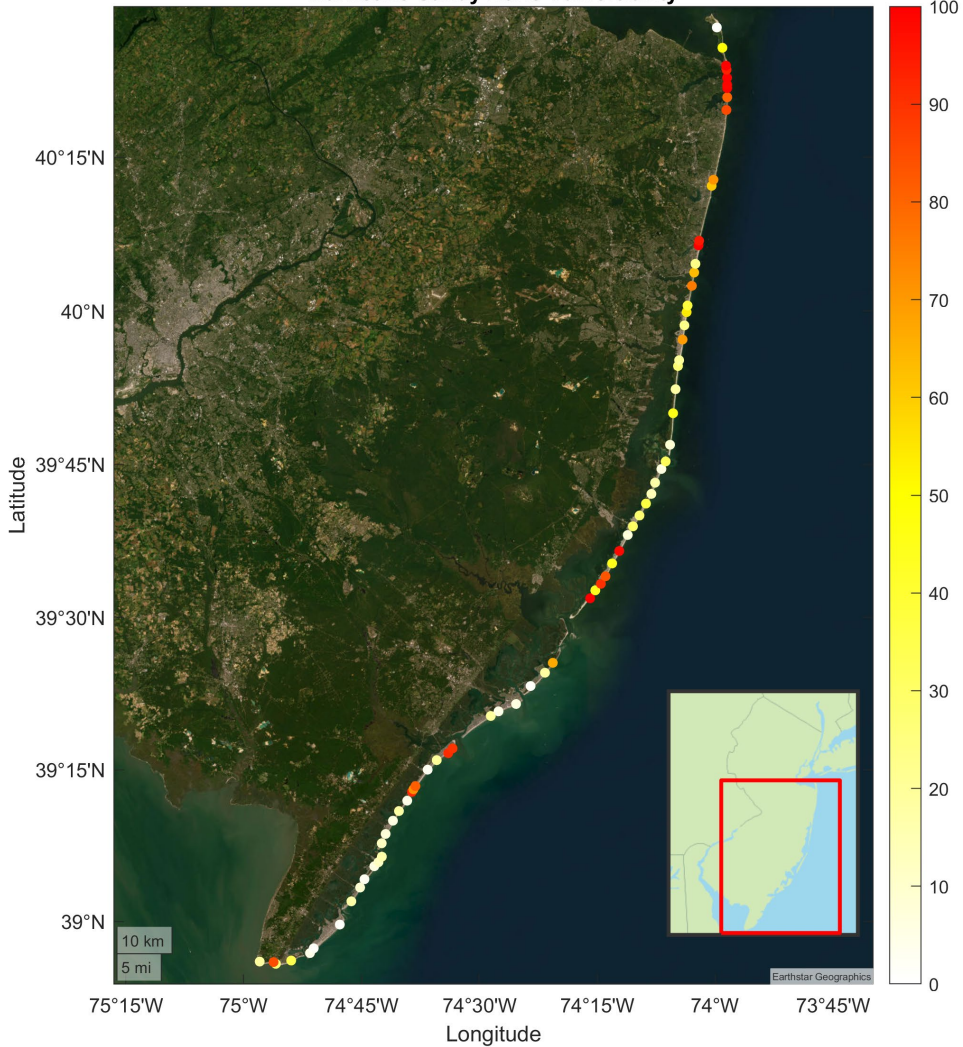
$$EDP = \frac{PEI^4}{\text{Dune Vol} \times \text{Berm Width}^2}$$



Predicted Impacts of Hurricane Sandy

Spatial Variation

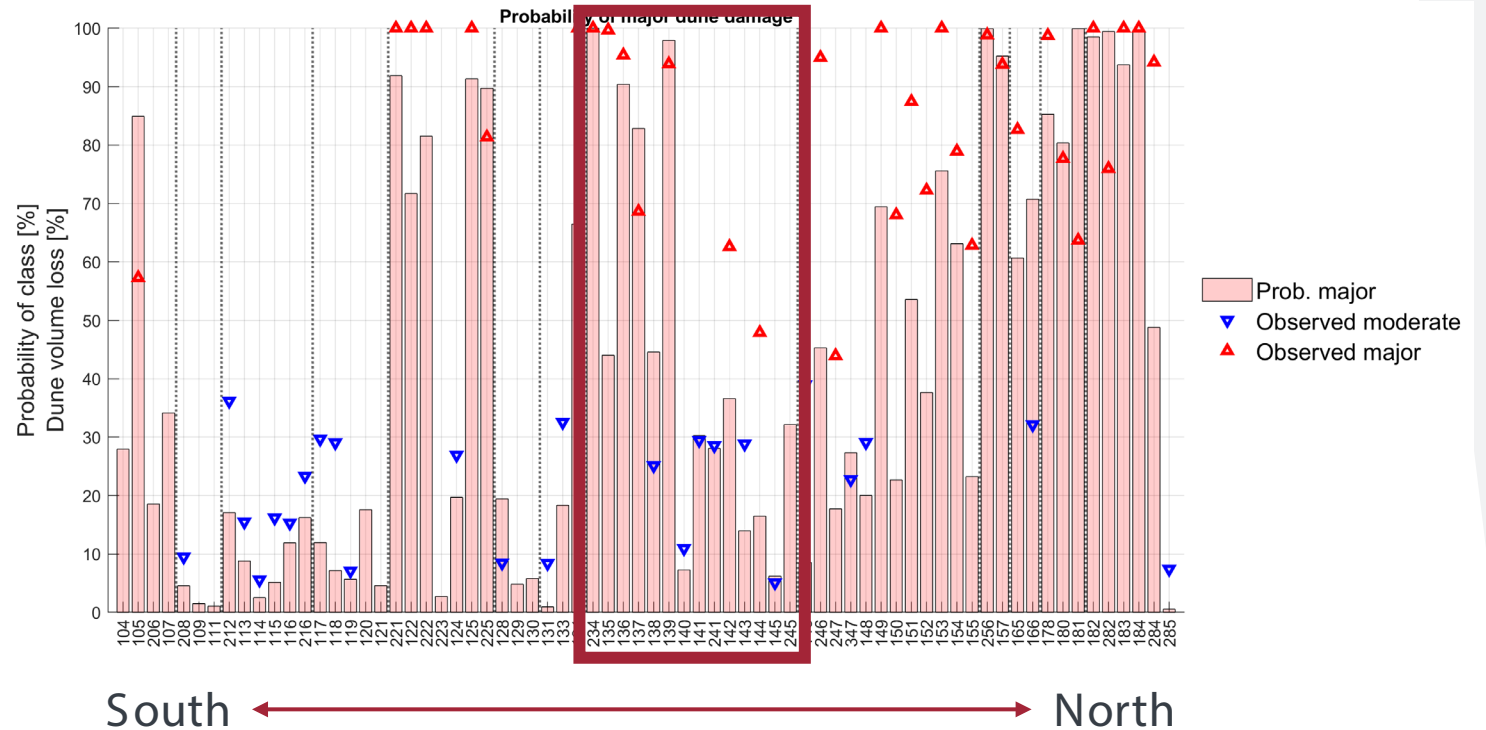
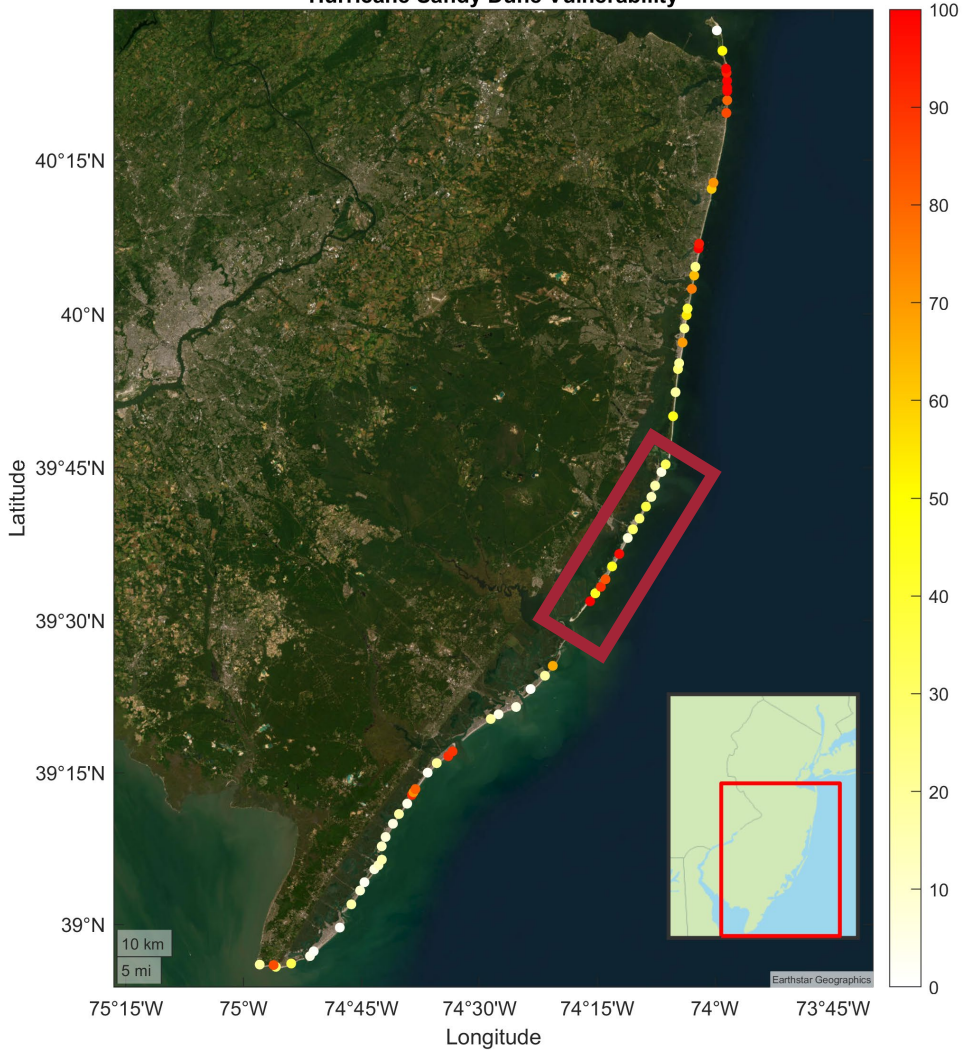
Hurricane Sandy Dune Vulnerability



Driving parameter isolation – beach resilience

Spatial Variation

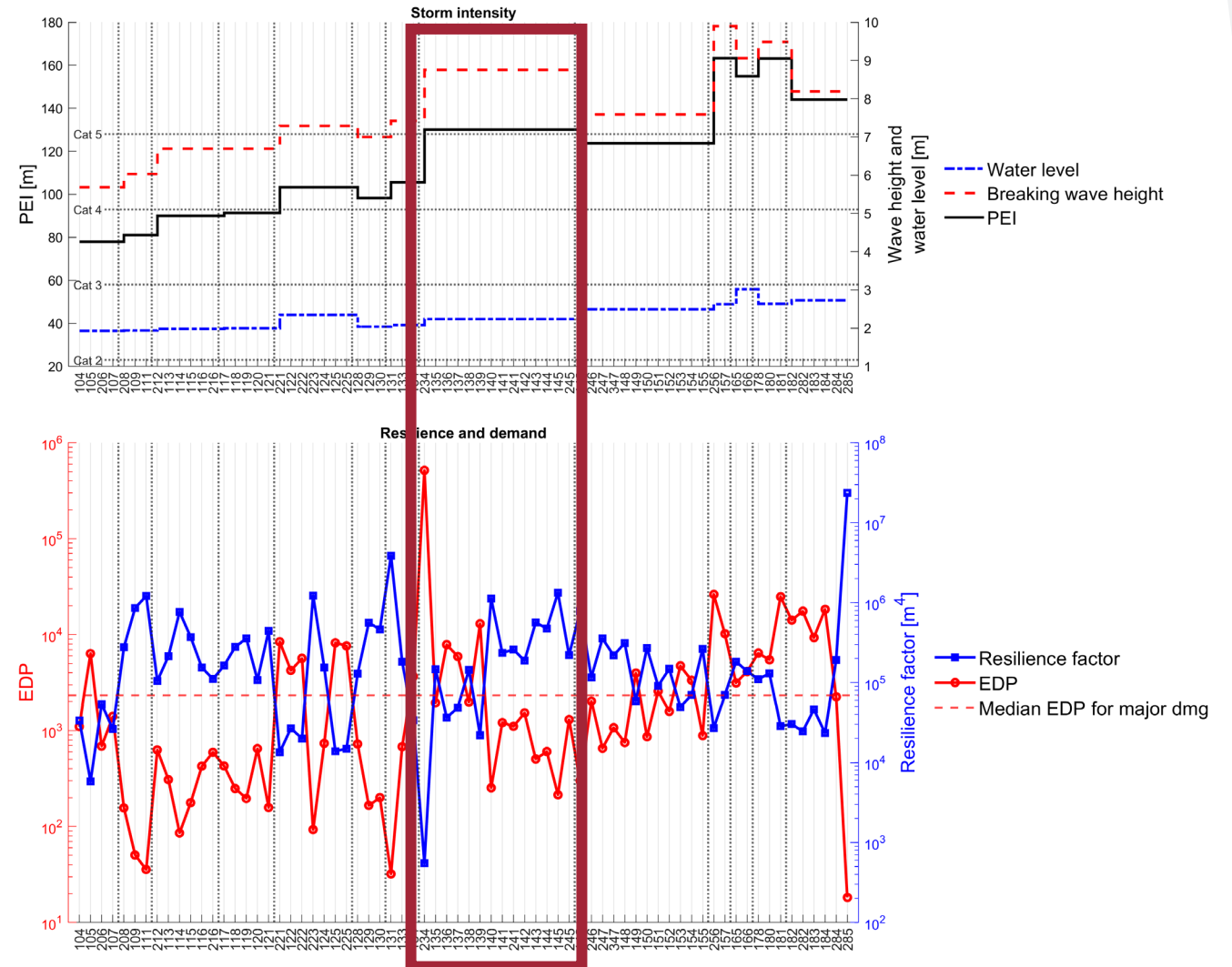
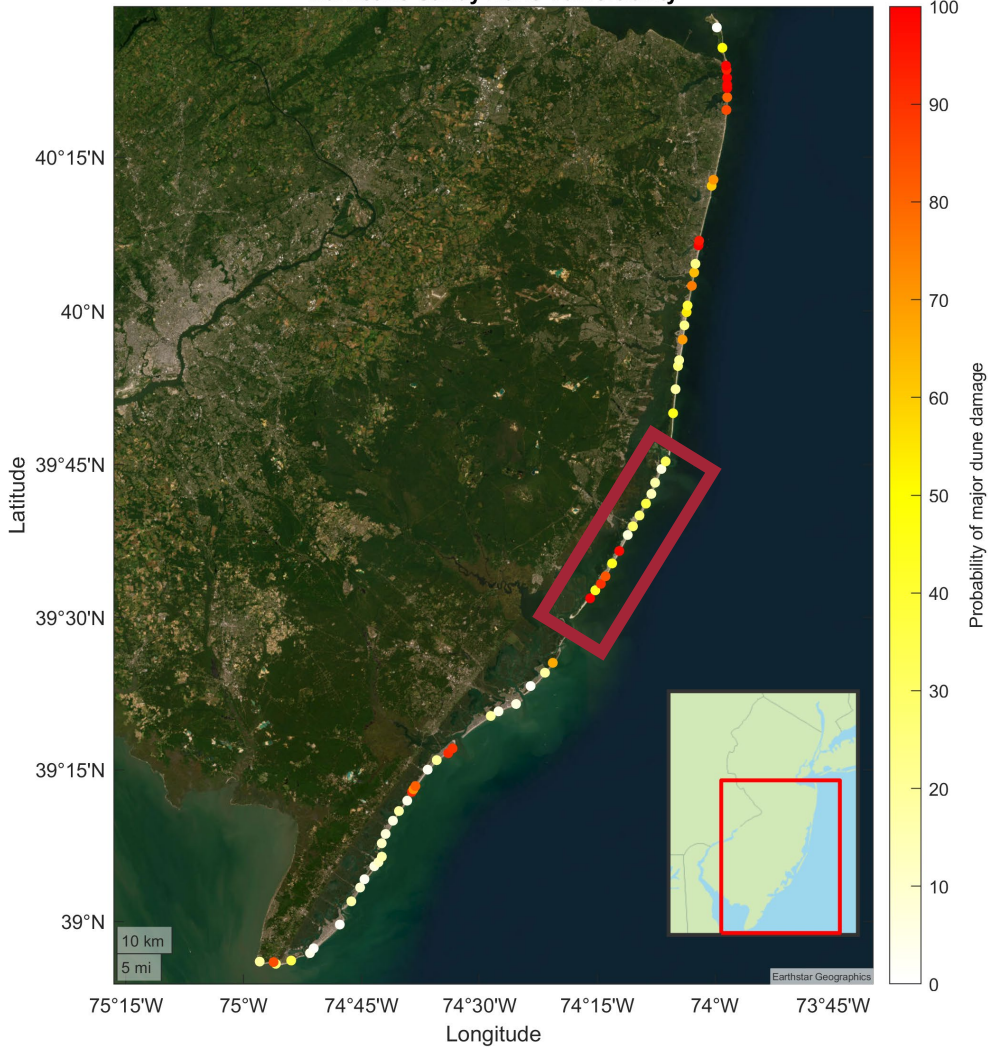
Hurricane Sandy Dune Vulnerability



Driving parameter isolation – beach resilience

Spatial Variation

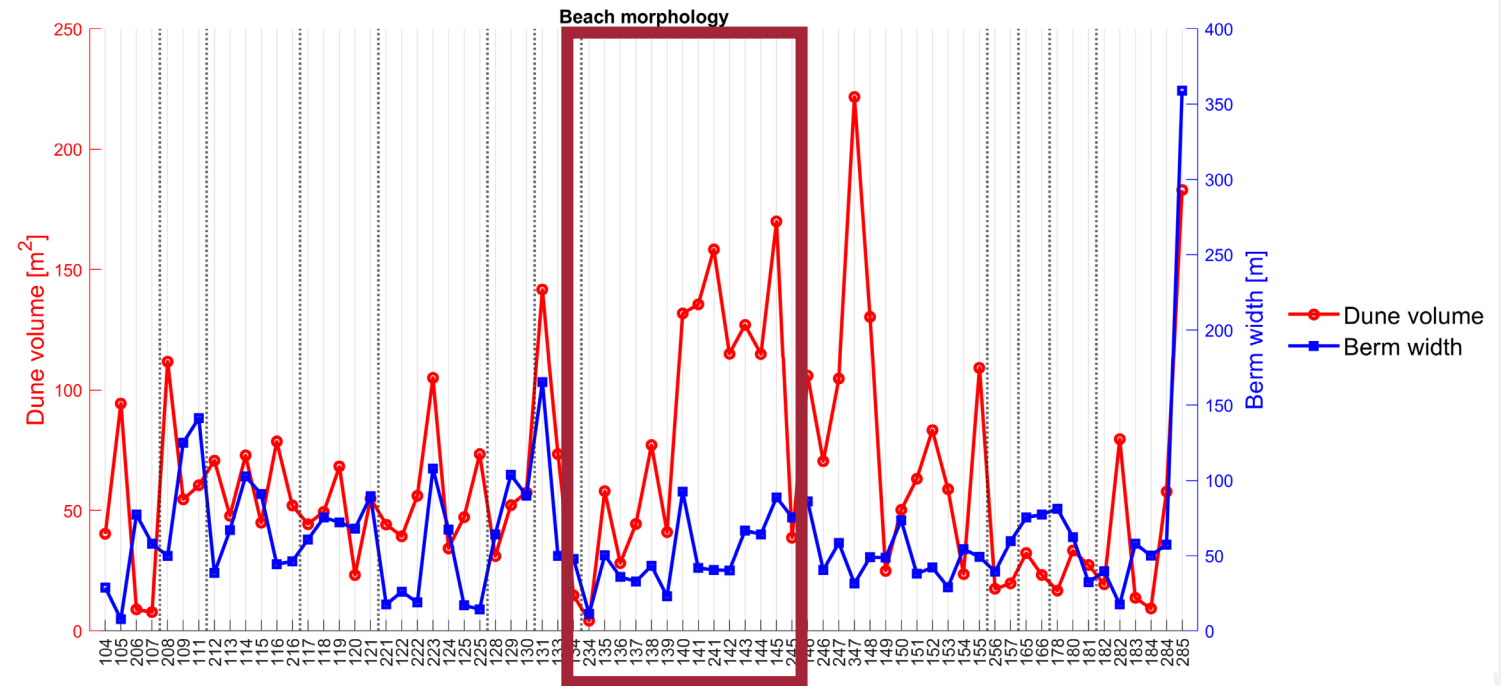
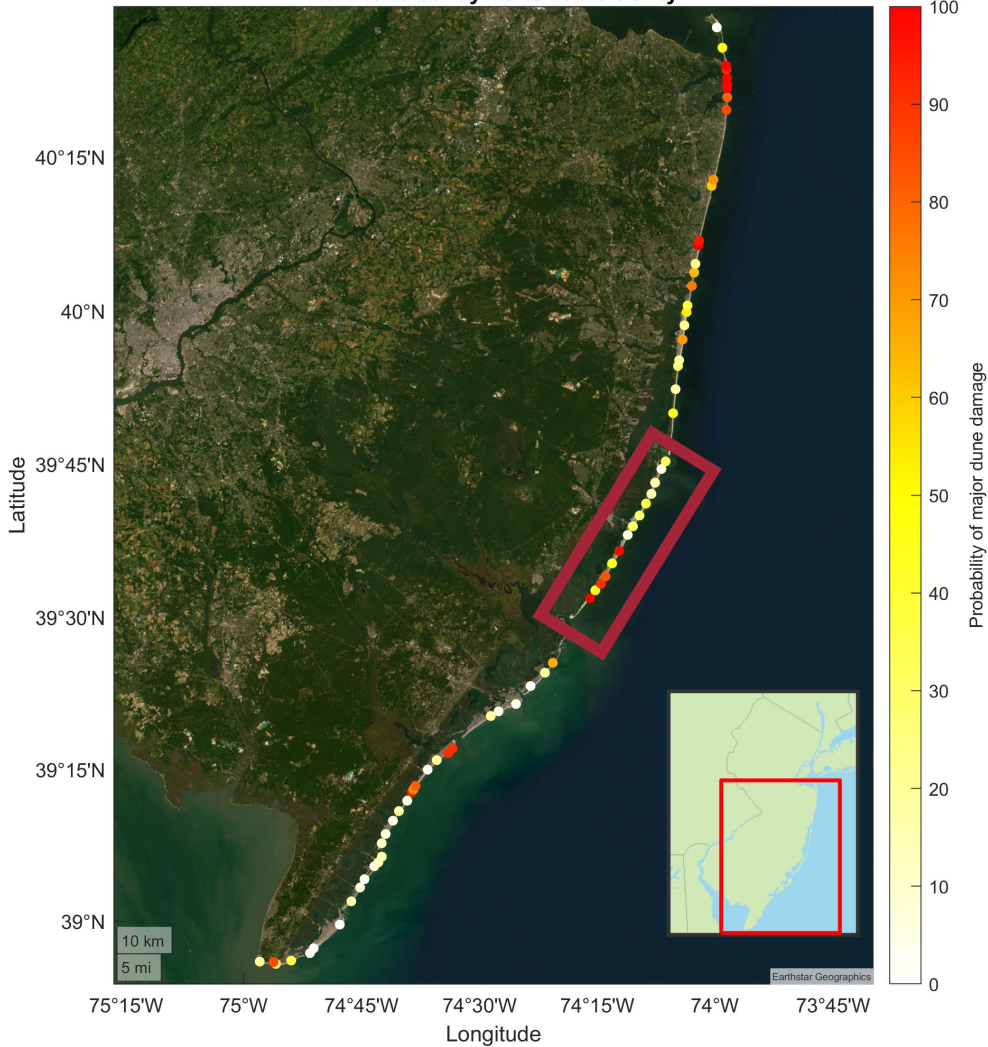
Hurricane Sandy Dune Vulnerability



Driving parameter isolation – beach resilience

Spatial Variation

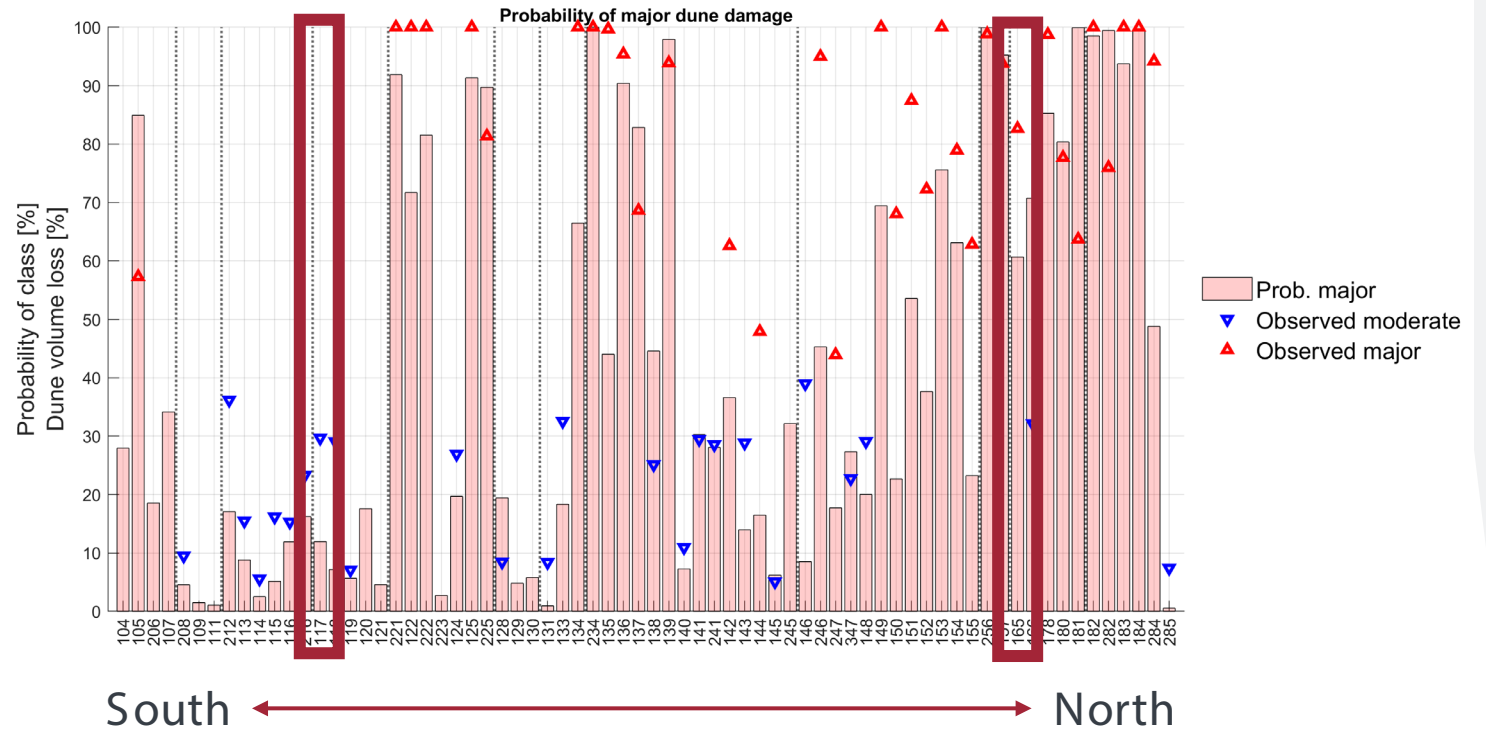
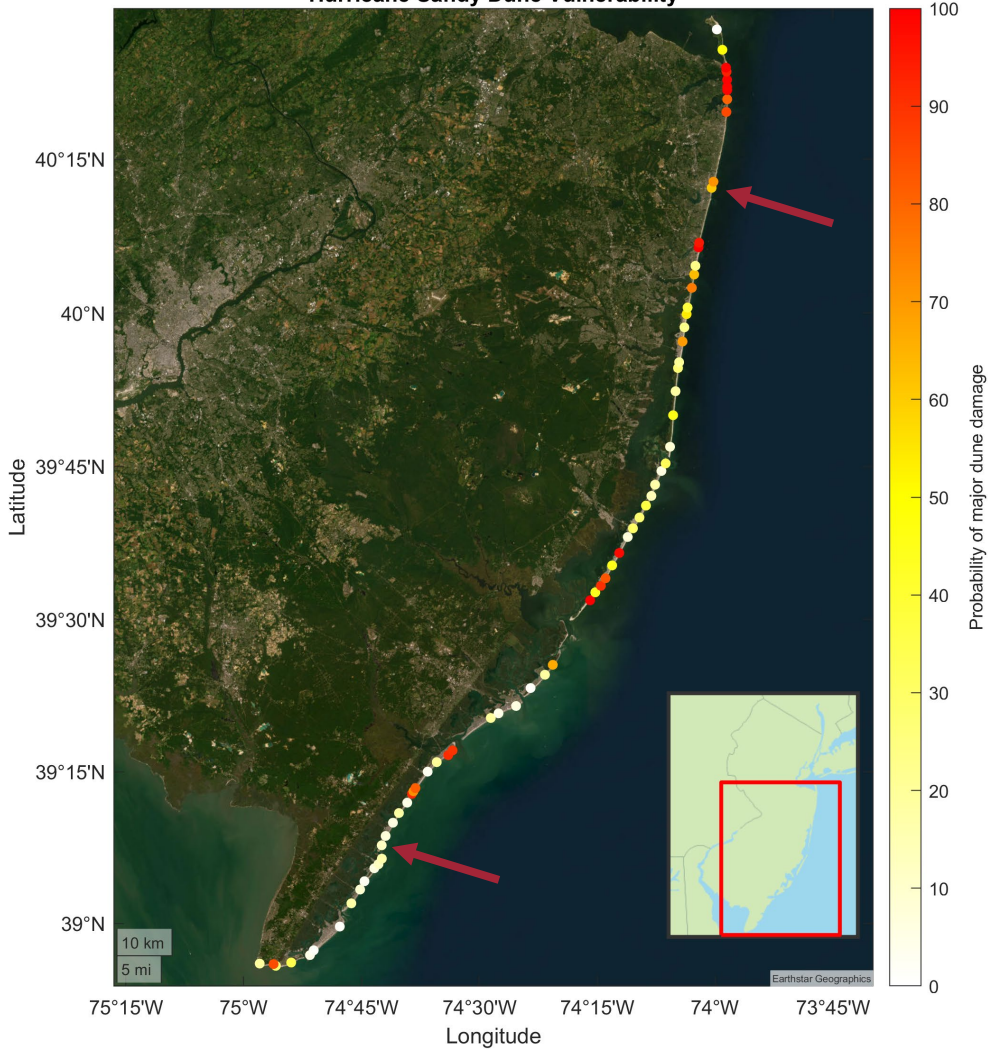
Hurricane Sandy Dune Vulnerability



Driving parameter isolation – storm intensity

Spatial Variation

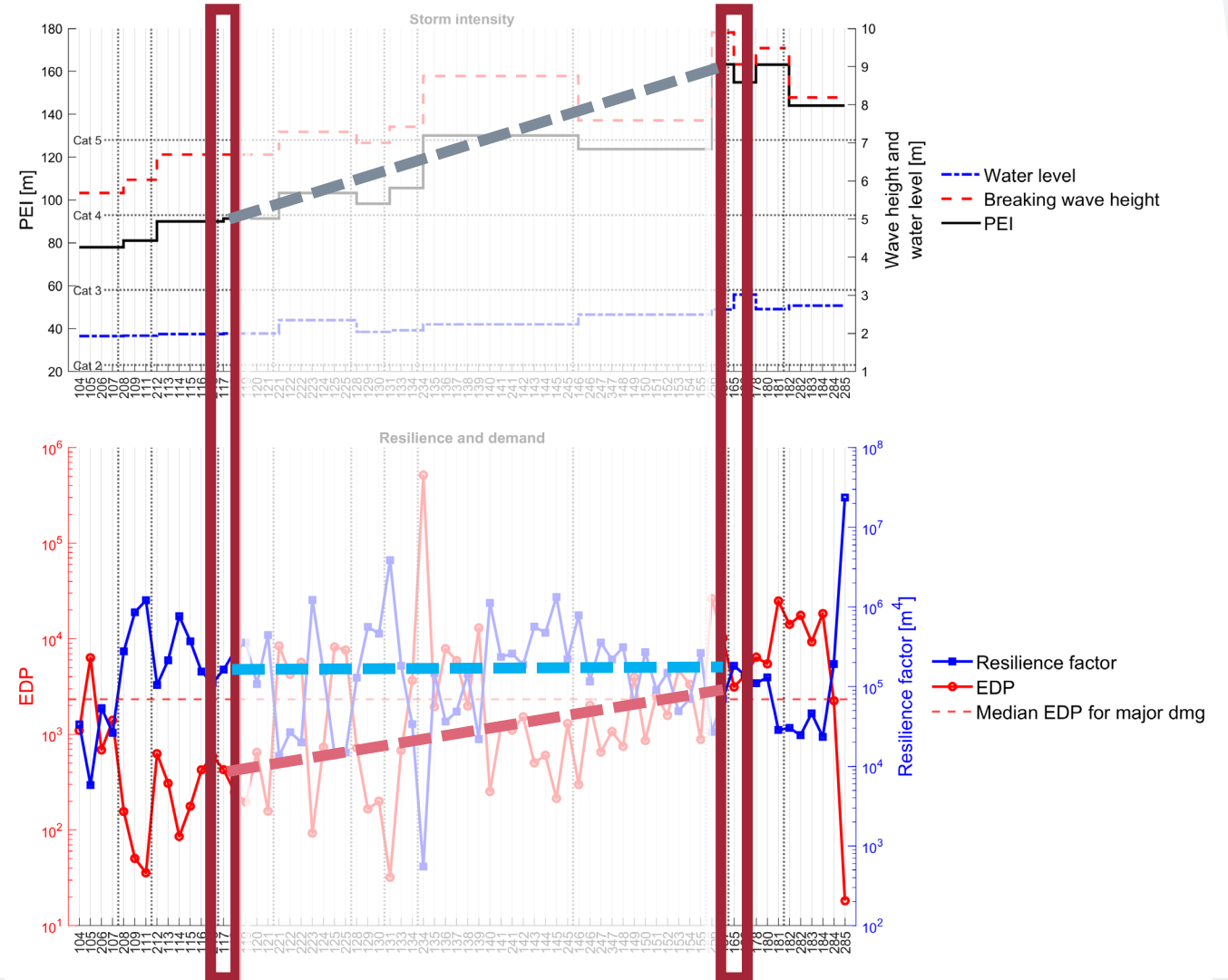
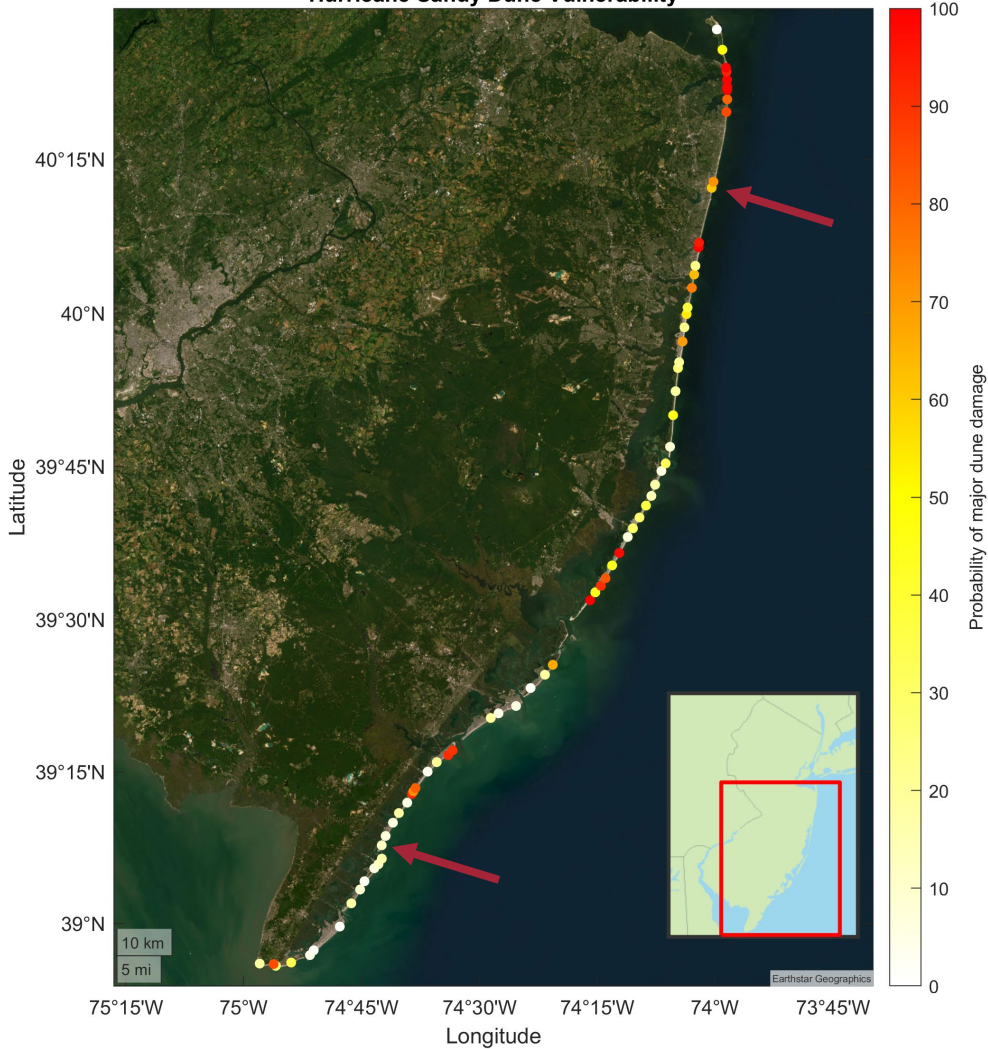
Hurricane Sandy Dune Vulnerability



Driving parameter isolation – storm intensity

Spatial Variation

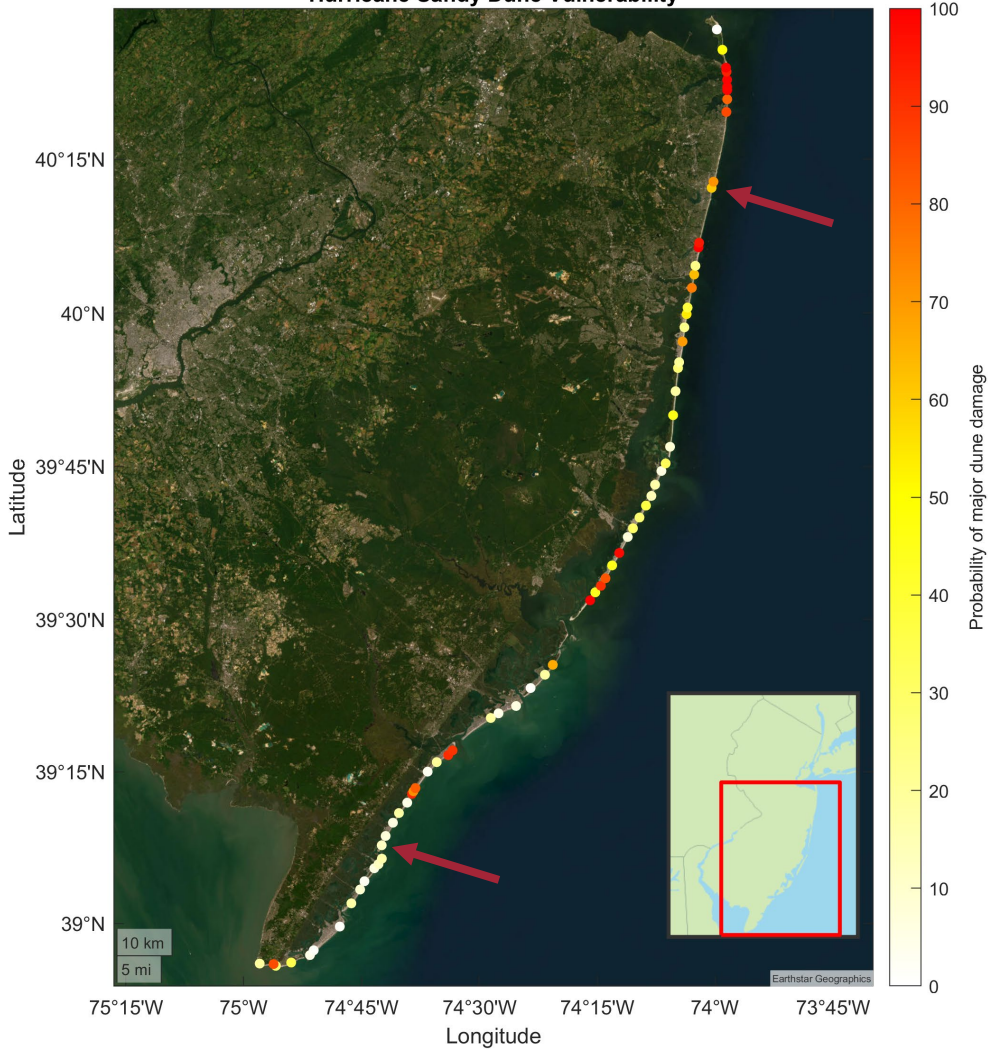
Hurricane Sandy Dune Vulnerability



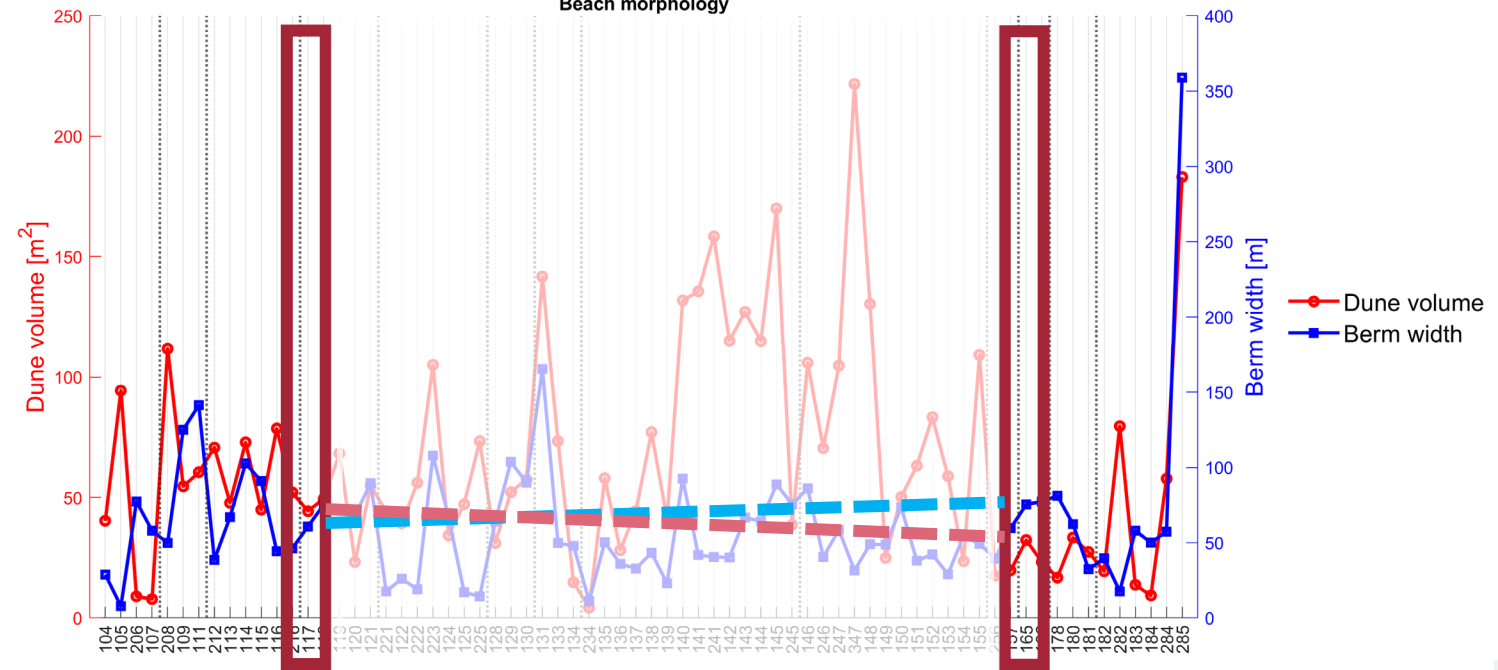
Driving parameter isolation – storm intensity

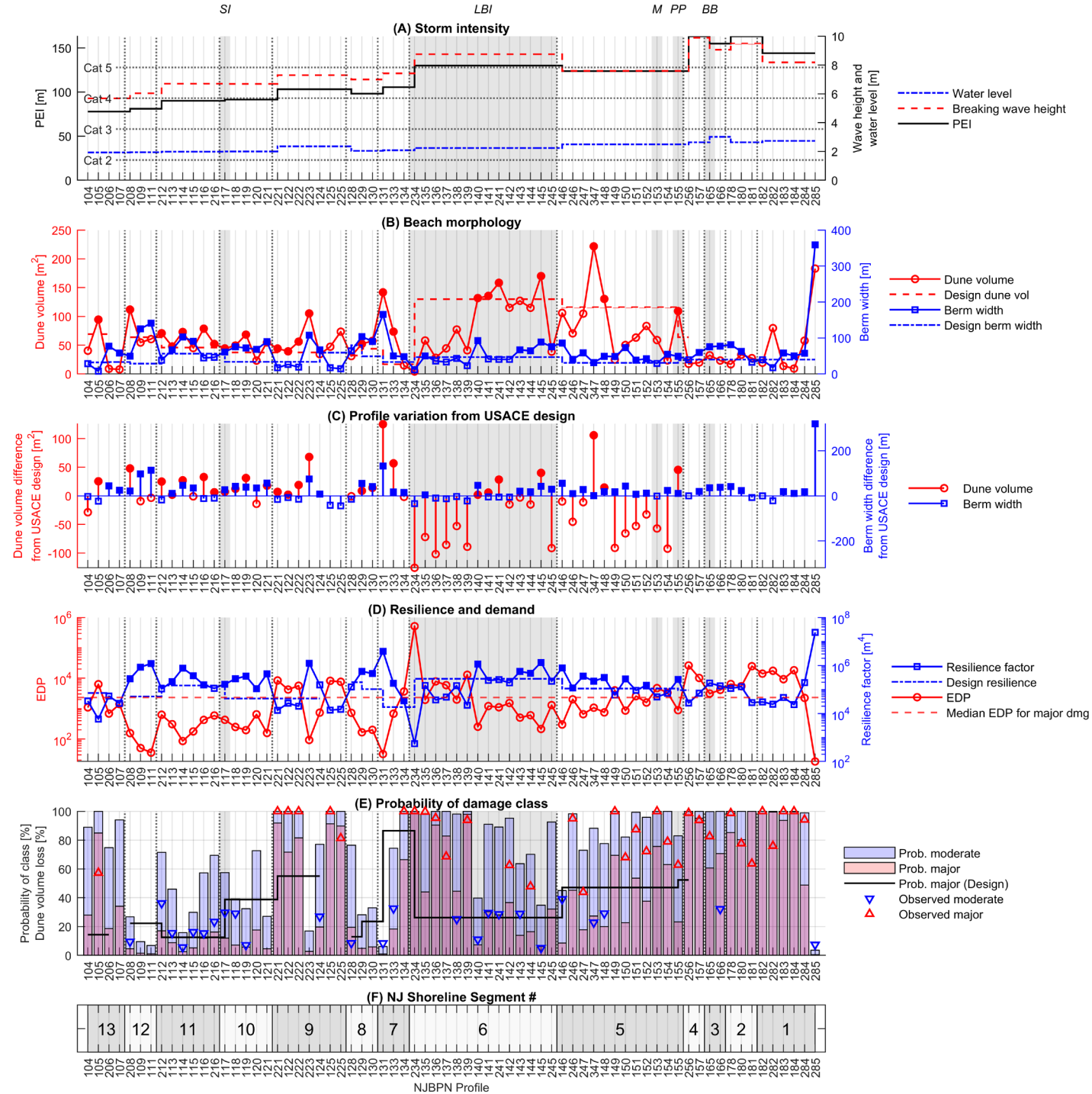
Spatial Variation

Hurricane Sandy Dune Vulnerability



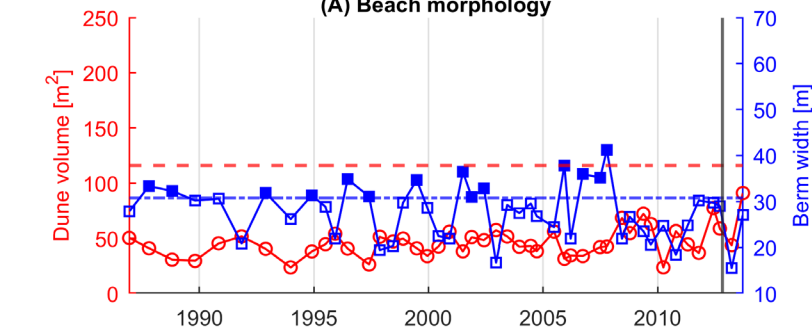
Beach morphology





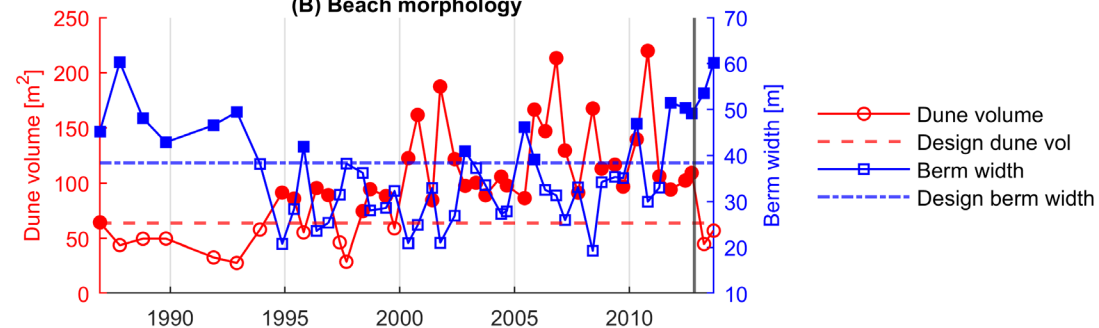
NJBPN profile 153

(A) Beach morphology

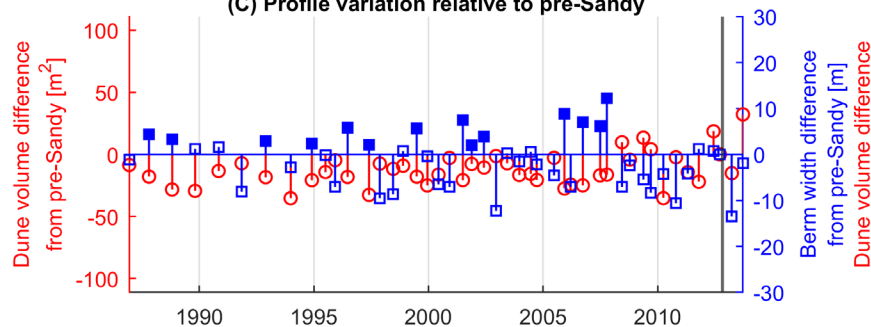


NJBPN profile 155

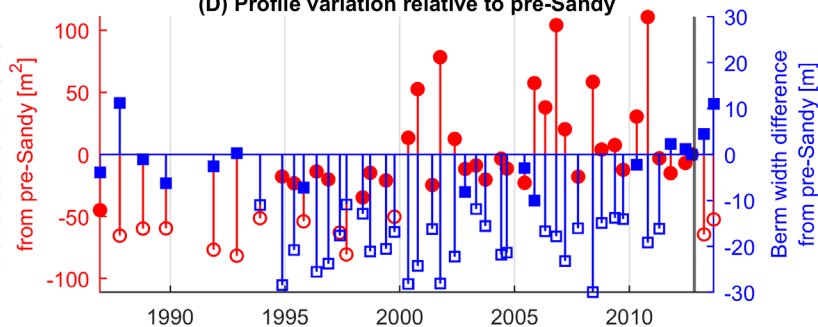
(B) Beach morphology



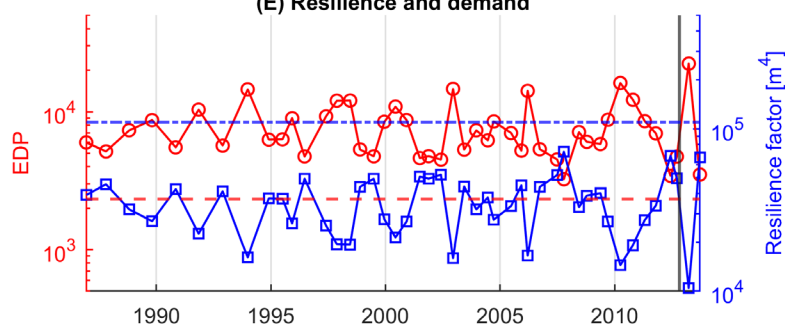
(C) Profile variation relative to pre-Sandy



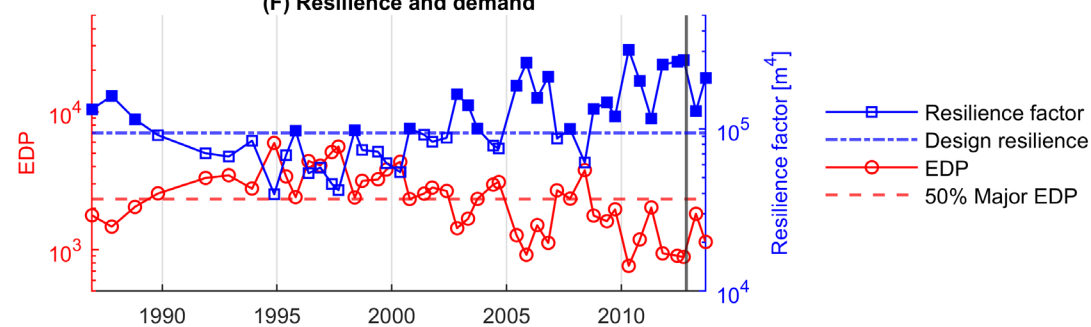
(D) Profile variation relative to pre-Sandy



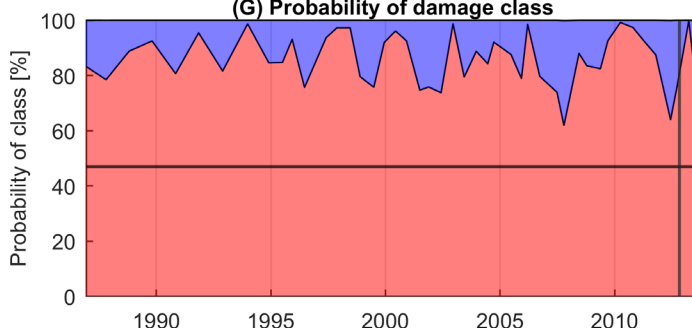
(E) Resilience and demand



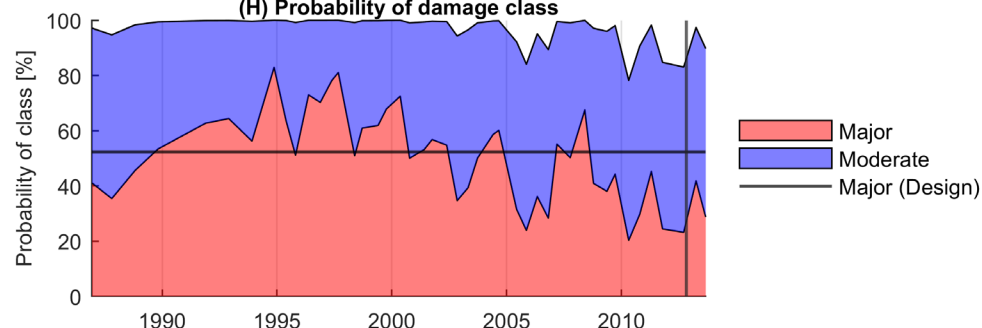
(F) Resilience and demand



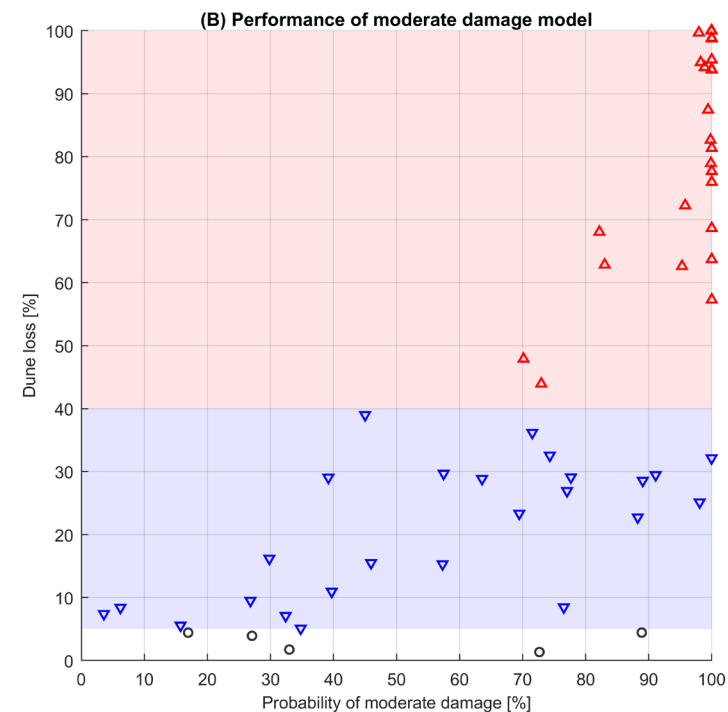
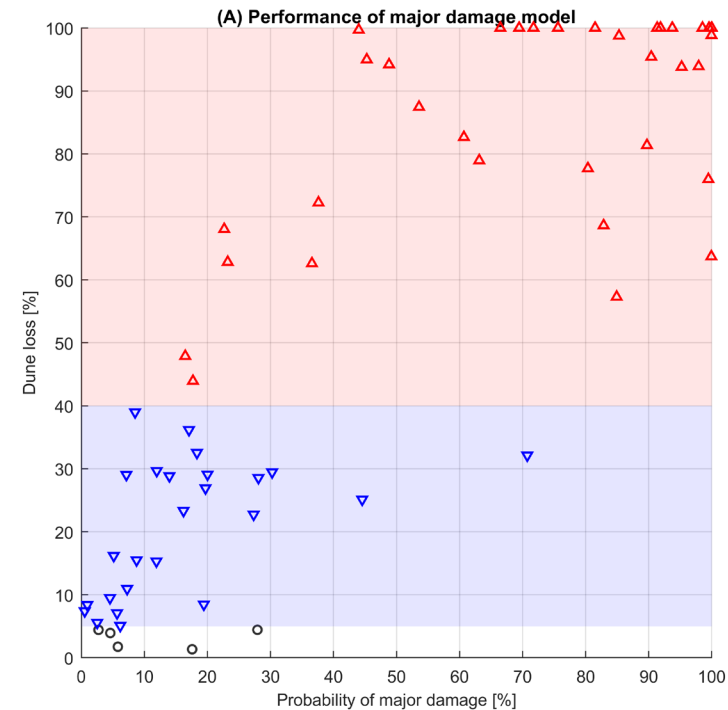
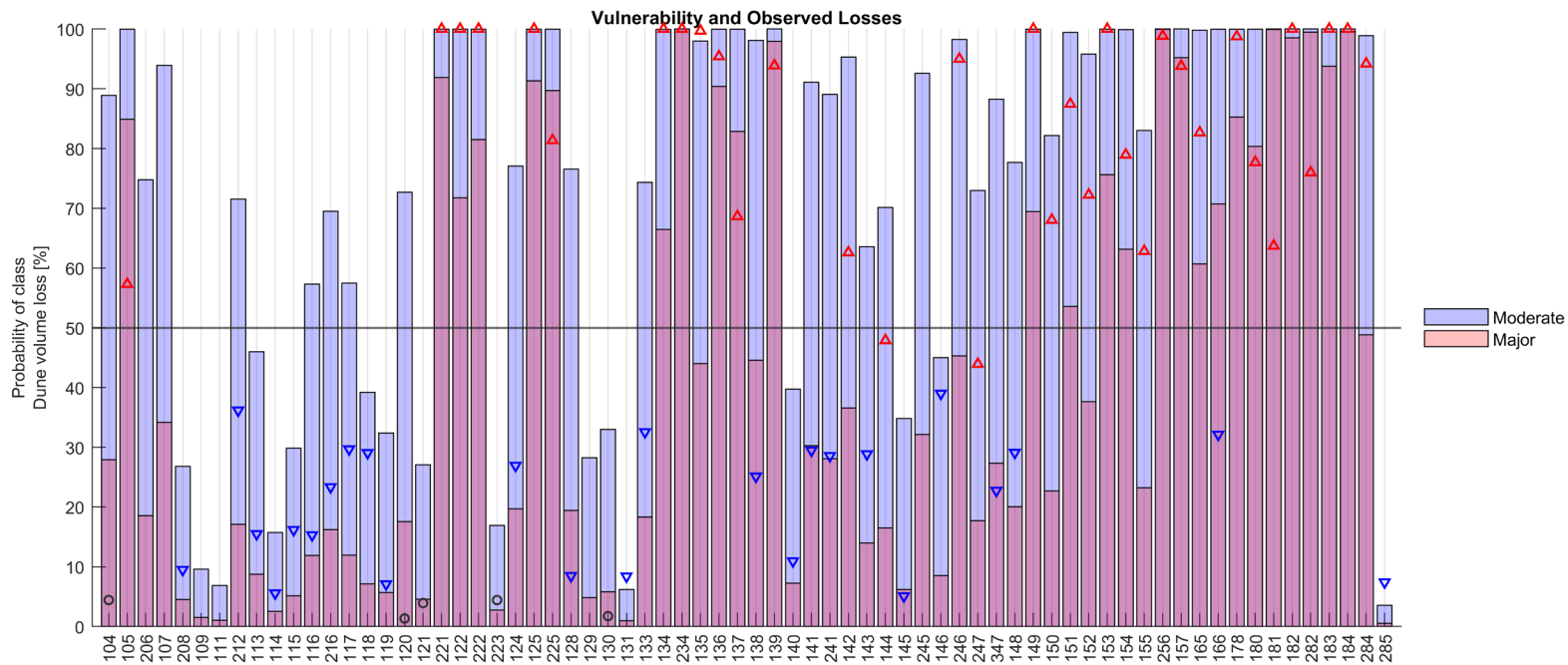
(G) Probability of damage class



(H) Probability of damage class



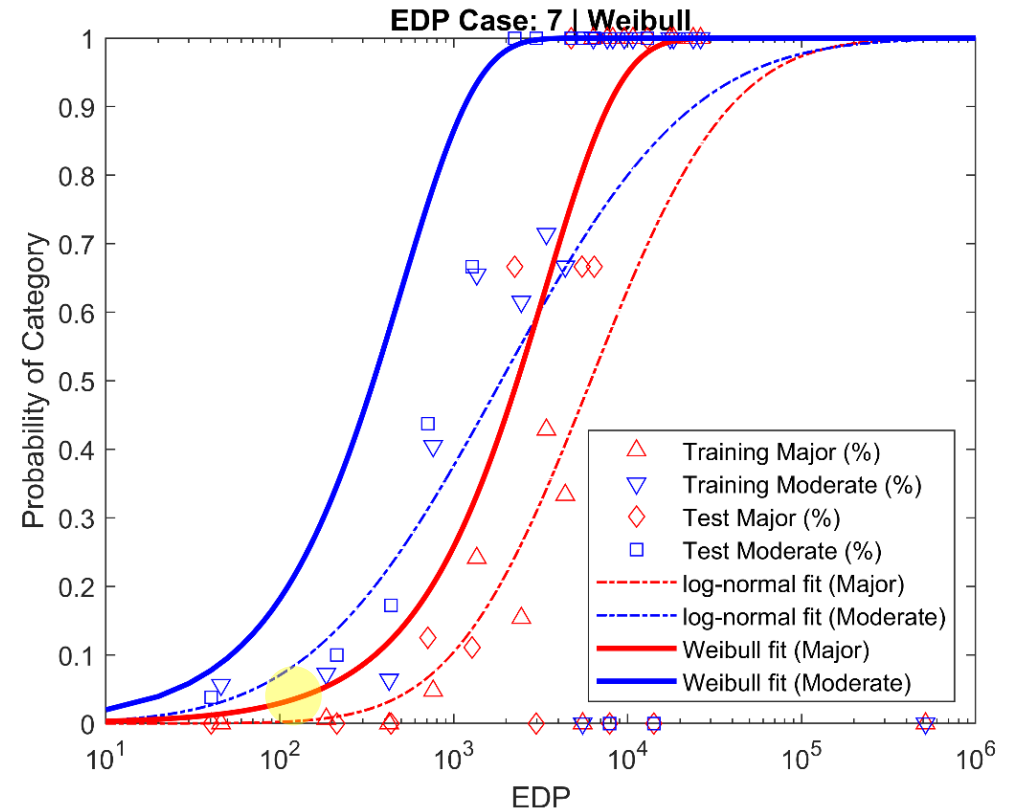
Survey Date



The EDP Fragility Curve

$$P\left(C \left| \frac{IM}{R_f} = EDP \right. \right) = 1 - \exp\left(\frac{-EDP}{\lambda}\right)^\kappa$$

- IM = Storm Intensity Measure
- R_f = Beach Resilience (e.g., beach width)
- Fit Coefficients:
 - κ (1.14 | 1.32)
 - λ (570 | 4428)



Janssen and Miller (2022), The Engineering Demand Parameter and Applications to Forecasting Dune Impacts

In final form...

$$EDP = \frac{PEI^4}{Dune\ Vol \times Berm\ Width^2}$$

