# Deterministic, dynamic model forecasts of storm-driven erosion

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MS Defense

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# Committee Members

Dr. Casey Dietrich
Dr. Elizabeth Sciaudone
Dr. Katherine Anarde
Dr. Rick Luettich

# About me

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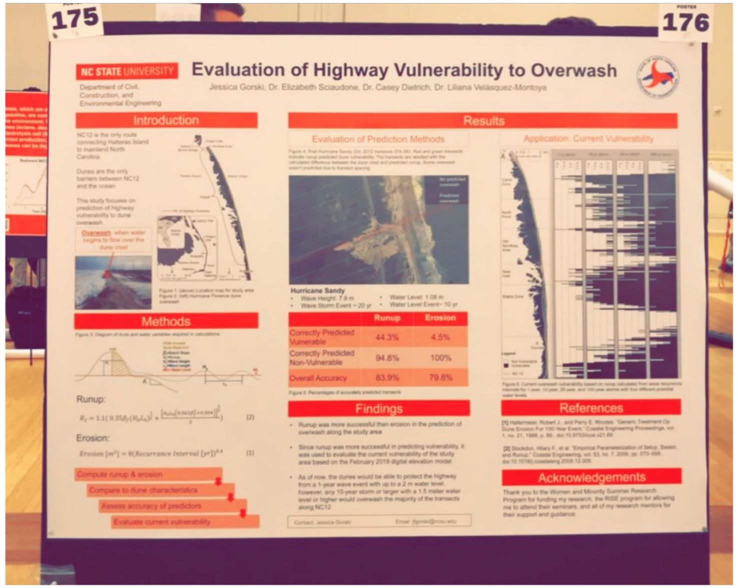
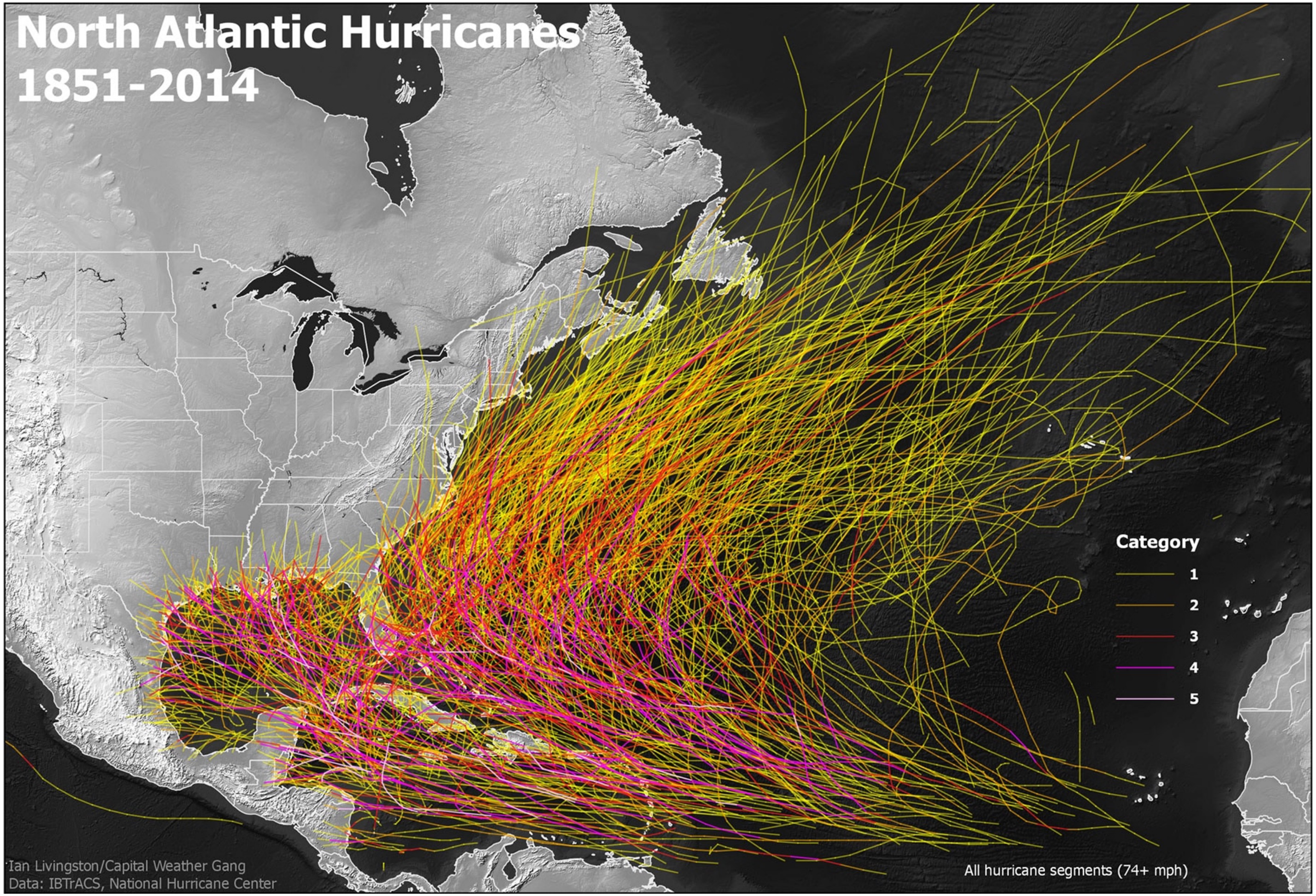
- From Plainville, CT
- North Carolina State University
  - Started coastal undergrad research June 4th, 2019
    - Thanks Beth and Casey!
  - Finished B.S. Civil Engineering in 2021
  - Started M.S. the following fall
- Accepted a job at USGS - St. Petersburg
  - Pending the outcome of this defense
- Hobbies
  - Volleyball
  - Dog walking
  - Travel




# Introduction and Background

# Tropical Cyclones



# Hydrological Hazards

Credit: Max Olson

# Morphological Hazards

NCDOT NC12 Twitter - Hurricane Teddy (2020)

# Motivation

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AP Photo/Wilfredo Lee


Joe Raedle/ Getty Images

# Key Definitions

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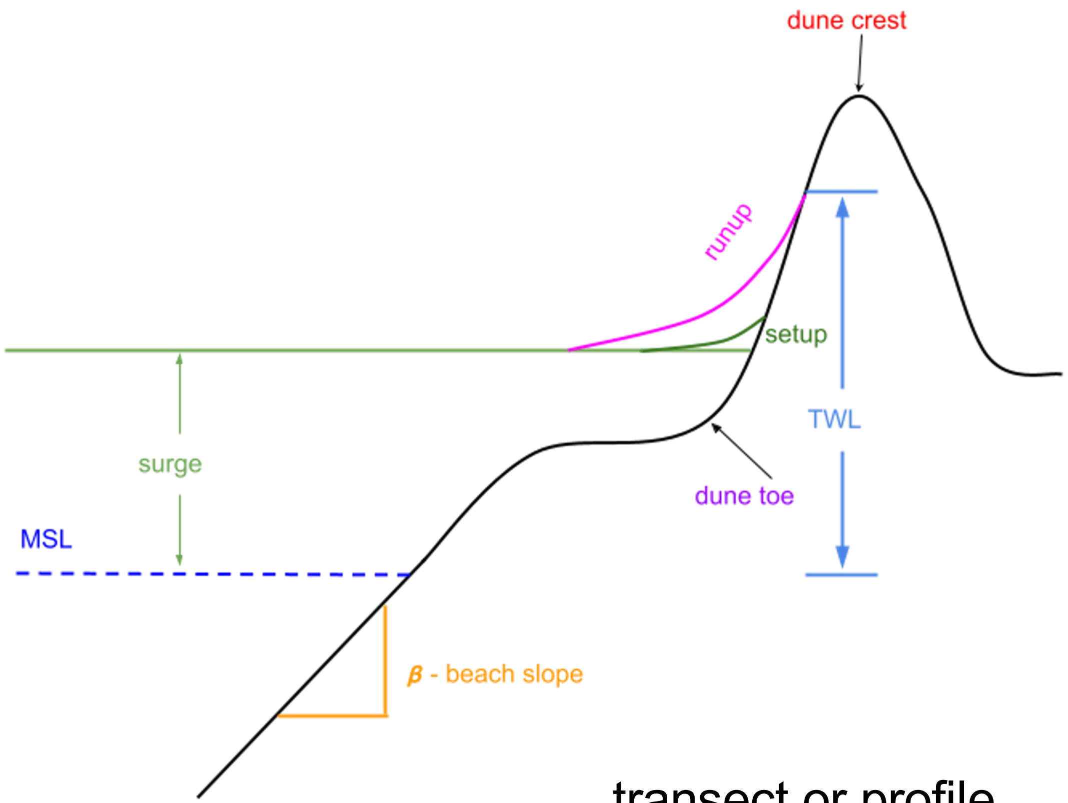
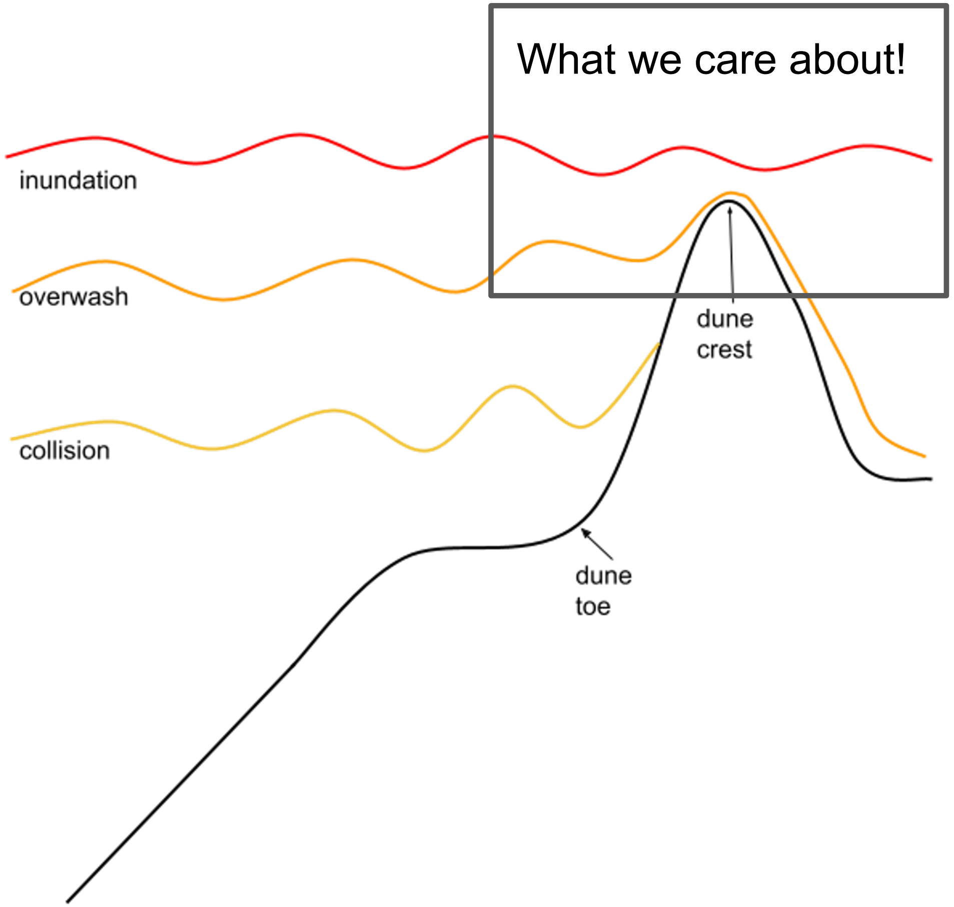
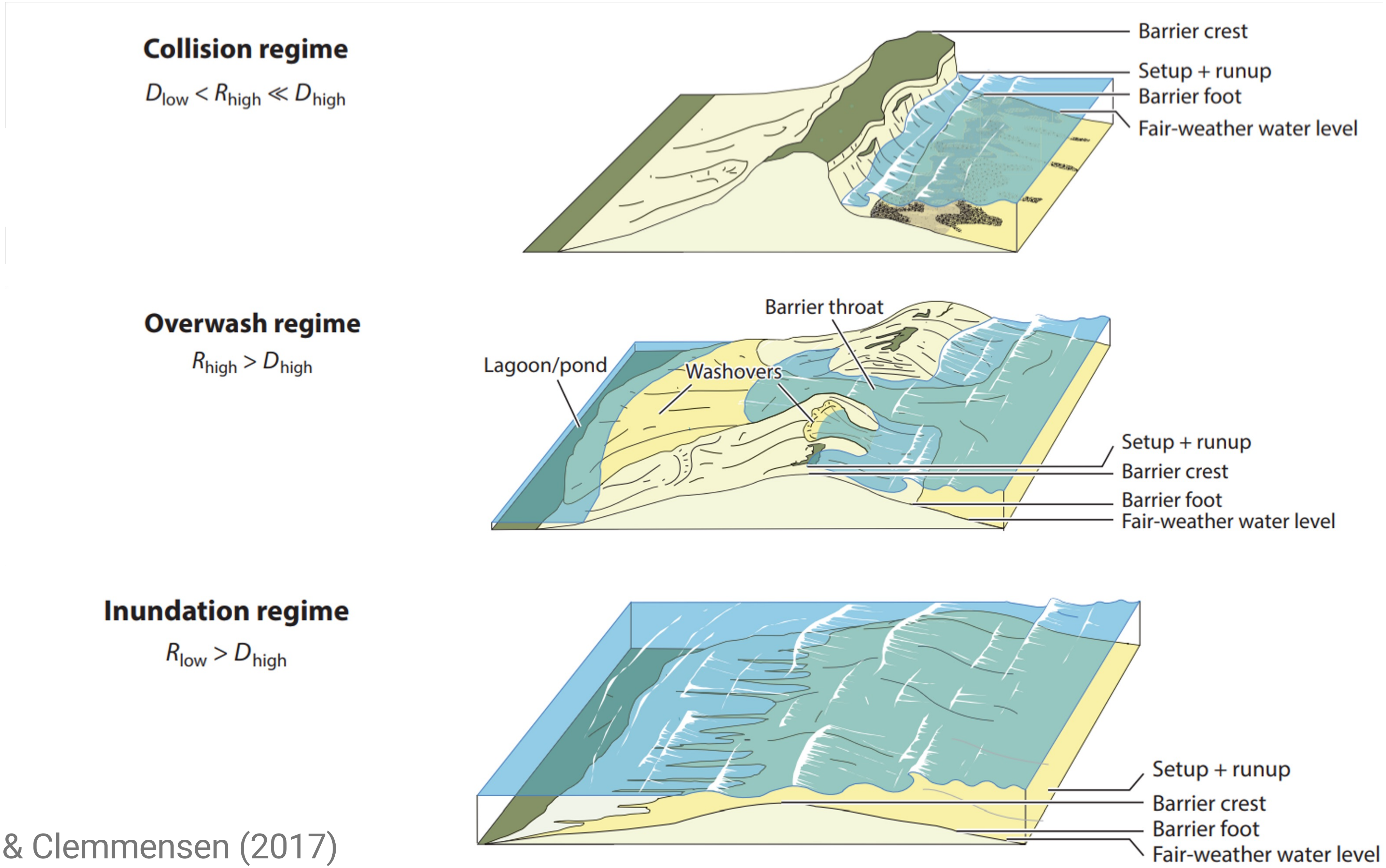



transect or profile



# Sallenger (2000) Impact Regimes






Goslin & Clemmensen (2017)

# Real-time Erosion Forecasts with Impact Regimes

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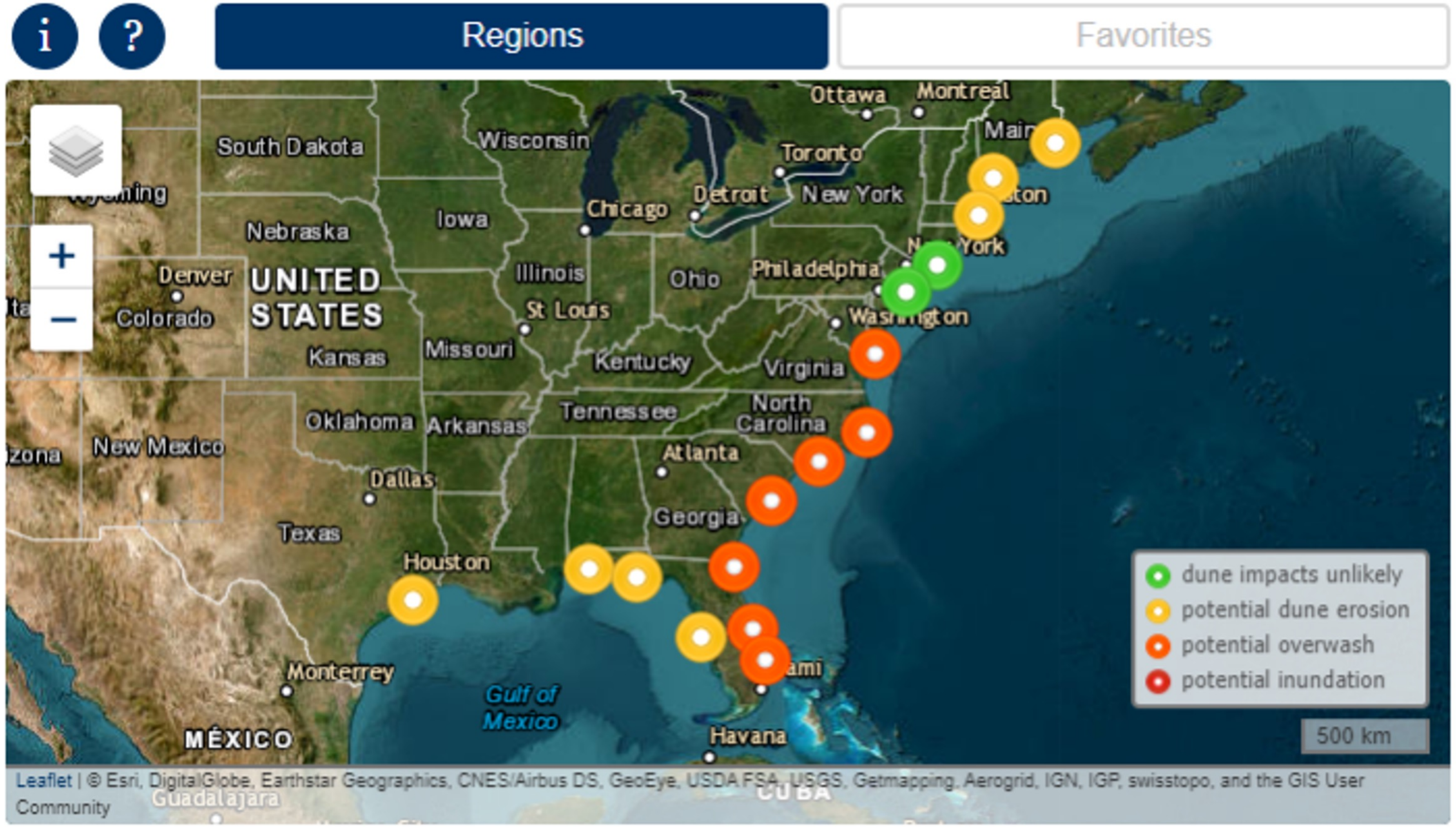


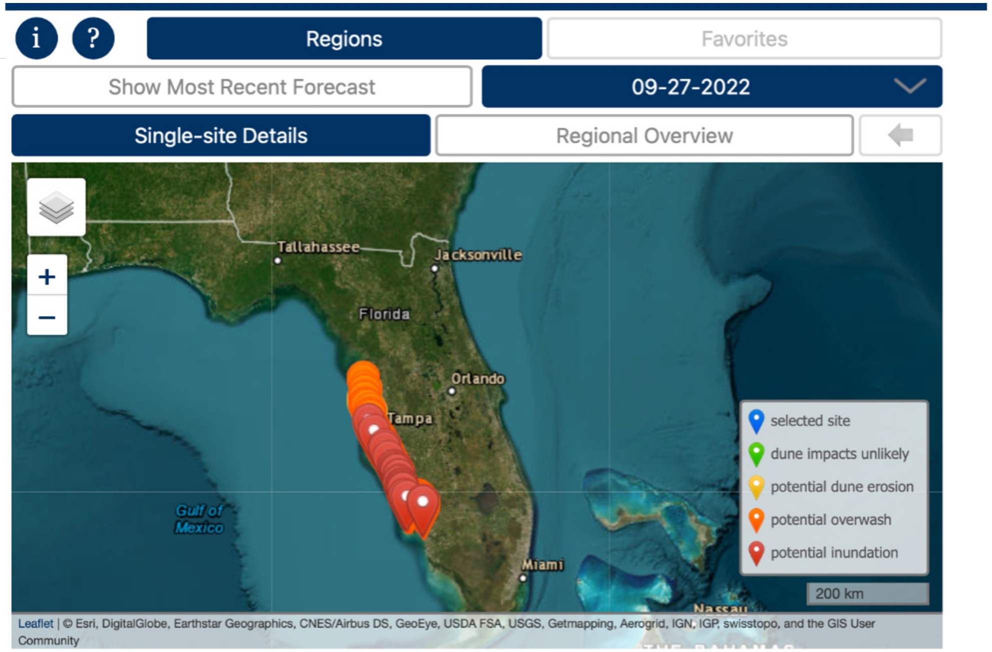


Regional Coastal Change Forecast

Potential Inundation - 30 Site(s)

| Region | Site ID | Forecast Begins [UTC] | Forecast Duration [hours] | Collision Duration [hours] | Overwash Duration [hours] | Inundation Duration [hours] |
|---|---|---|---|---|---|---|
| TBW | 3711 | 09-27-2022 06:00 | 144 | 78 | 55 | 1 |
| TBW | 3741 | 09-27-2022 06:00 | 144 | 49 | 49 | 6 |
| TBW | 3784 | 09-27-2022 06:00 | 144 | 60 | 52 | 12 |
| TBW | 3789 | 09-27-2022 06:00 | 144 | 65 | 51 | 4 |
| TBW | 3814 | 09-27-2022 06:00 | 144 | 62 | 52 | 13 |
| TBW | 3843 | 09-27-2022 06:00 | 144 | 62 | 52 | 14 |
| TBW | 3844 | 09-27-2022 06:00 | 144 | 76 | 54 | 18 |

# Real-time Erosion Forecasts with Impact Regimes

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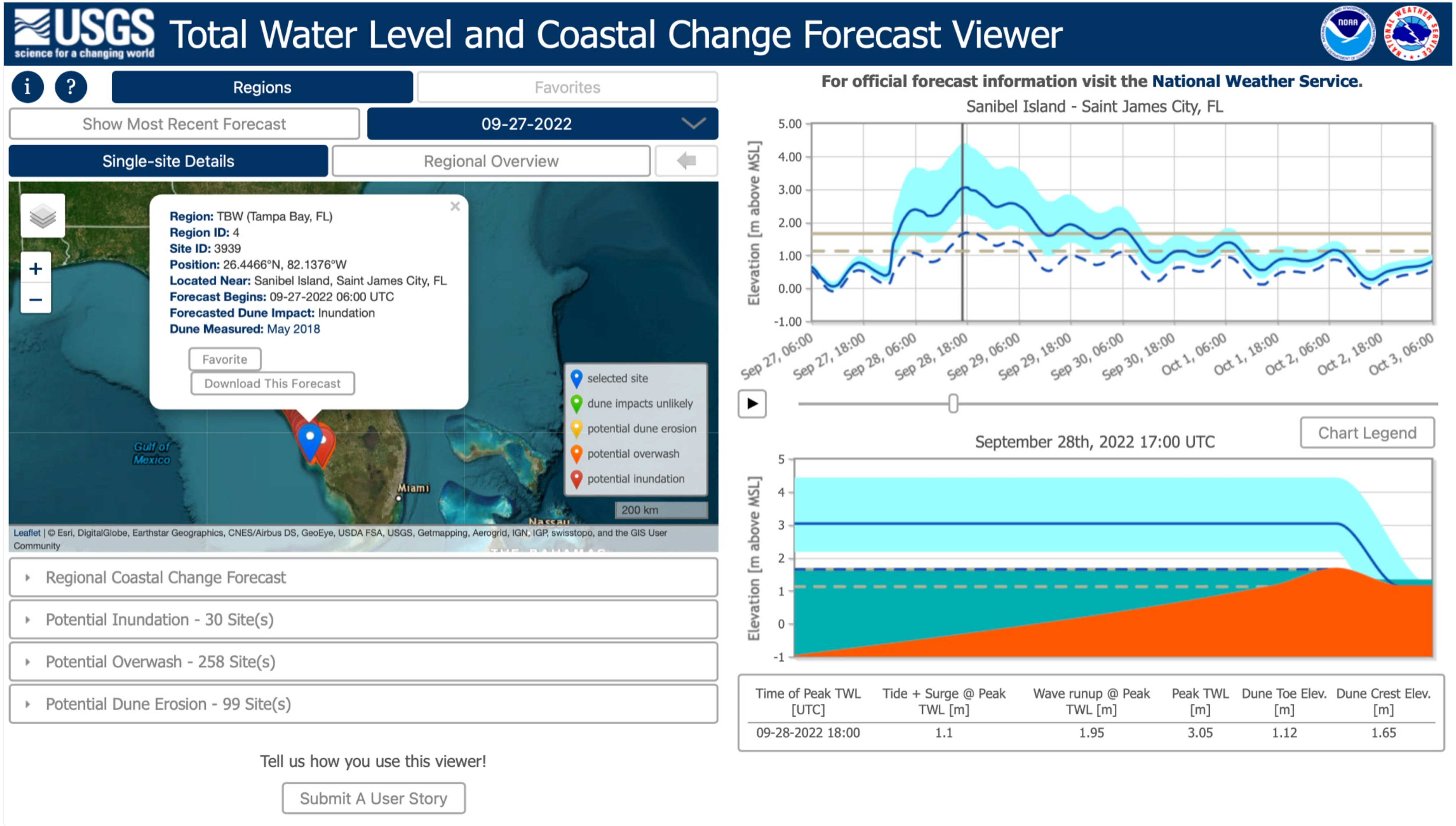


| Time of Peak TWL [UTC] | Tide + Surge @ Peak TWL [m] | Wave runup @ Peak TWL [m] | Peak TWL [m] | Dune Toe Elev. [m] | Dune Crest Elev. [m] |
|---|---|---|---|---|---|
| 09-28-2022 18:00 | 1.1 | 1.95 | 3.05 | 1.12 | 1.65 |

Total Water Level and Coastal Change Forecast Viewer (Stockdon, 2023)

# Erosion Modeling with XBeach

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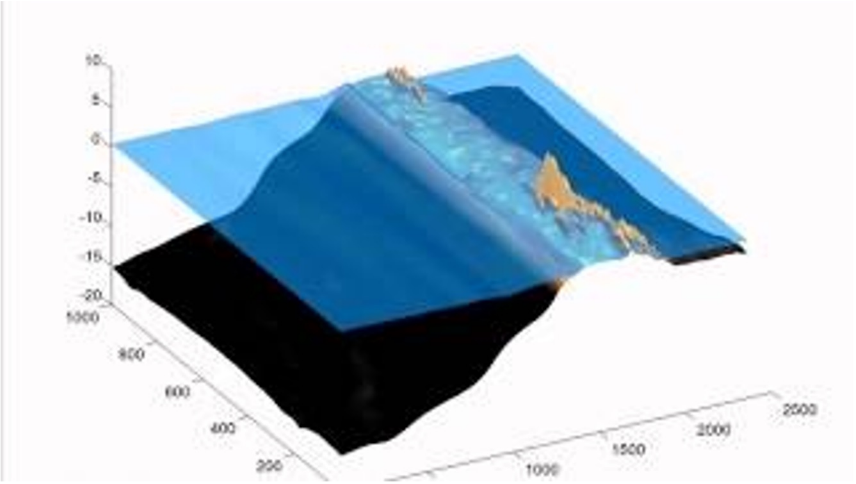
eXtreme Beach (XBeach)

- Morphological model for storm-driven erosion
- 1D or 2D options
- Hydrodynamic and morphodynamic processes (Roelvink 2009)

Requires:

- High-resolution ground surface data
- Computational resources



XBeach-Deltares

# 2D XBeach Modeling- robust, but expensive

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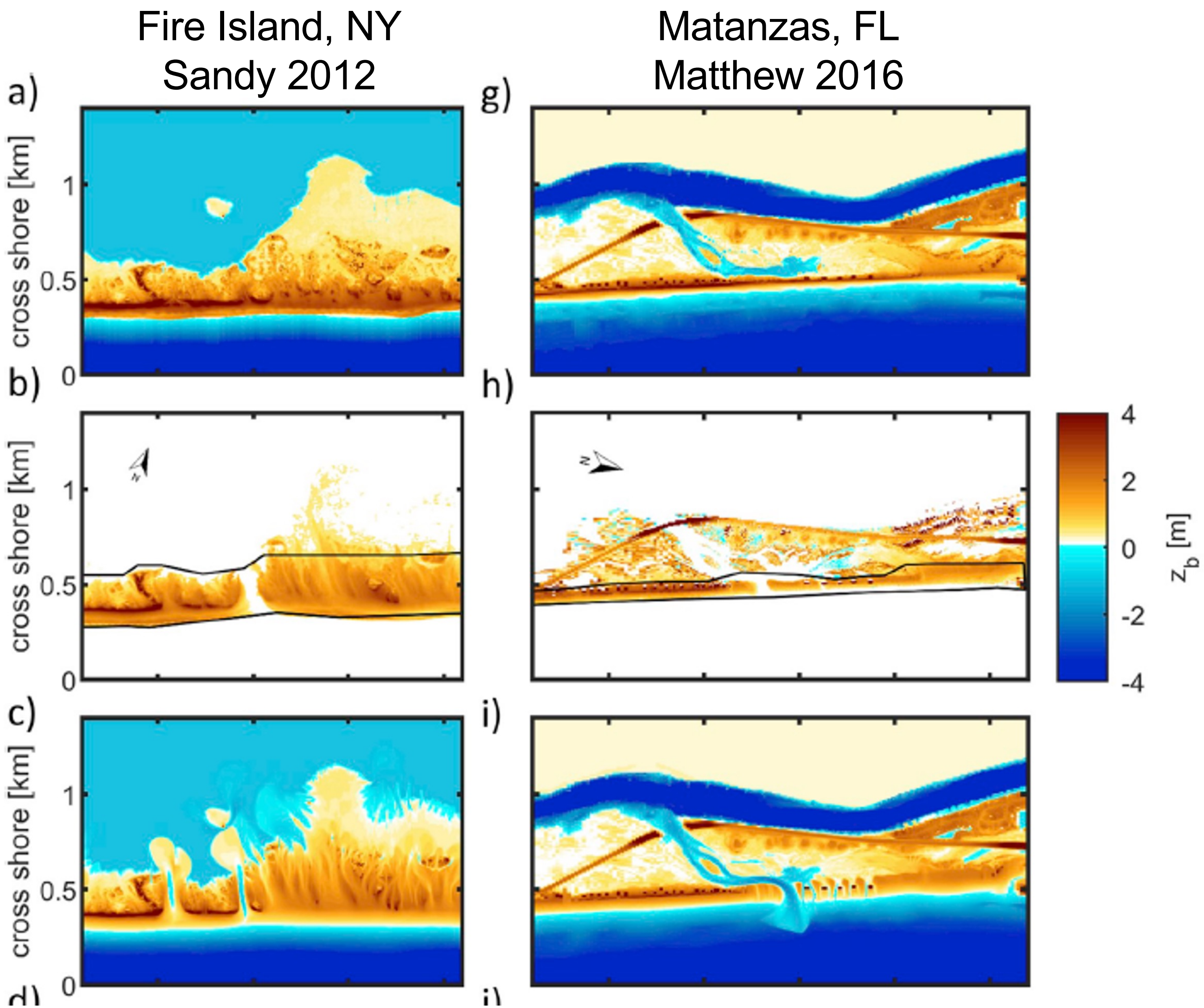
pre-storm

observed

modeled




van der Lugt et al. 2019

# 1D XBeach Modeling - less expensive

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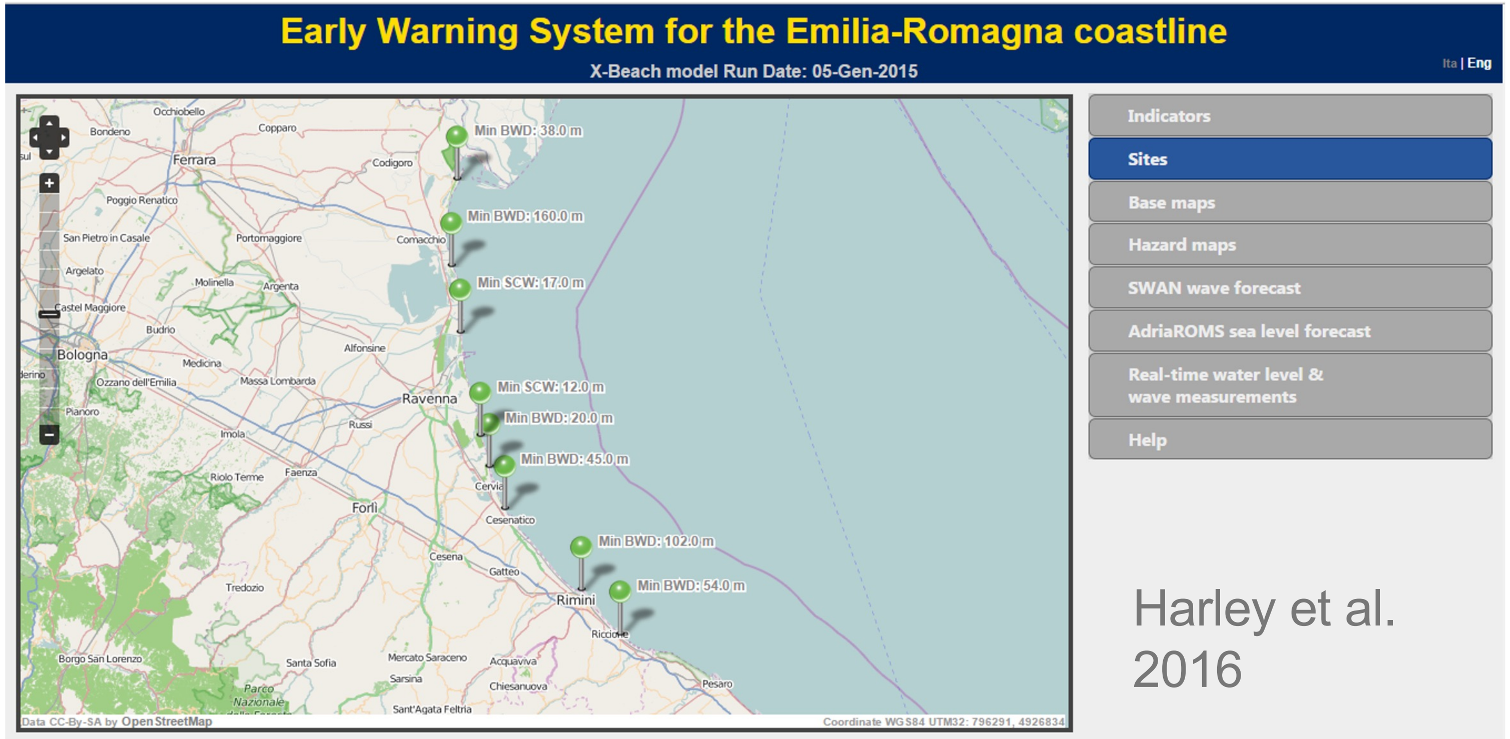
Reduces computational expense

Has been evaluated for forecasting by other studies:

- Harley et al., 2011, 2016
- Vousdoukas et al., 2012
- Baart et al., 2016




Harley et al. 2016

Note: BWD- building waterline distance, SCW - safe corridor width

# Challenges for real-time forecasts

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- Ground Surface information
    - “[Sallenger 2000] simple scale provides an initial estimate of the impact severity but **masks the complexity of the hydrodynamic and sediment-transport processes and feedbacks** that drive the changes” (Sherwood, 2022)
- Model Accuracy
    - “Improvements to the model predictions were observed as **parameters were changed one by one from their default settings**” (Harley 2016)
    - Time consuming, limits versatility
- Model result evaluation
    - “The greatest challenge in assessing the skill of morphological models is often the **lack of accurate and timely data for comparison**. But even when good data are available, **assessing morphological model skill and uncertainty is tricky**.” (Sherwood, 2022)
- Forecast Uncertainty
    - Errors propagate through forecast models  (Baart: 2011, 2016)
- Efficiency:
    - Essential to produce timely predictions of storm-driven erosion

# Research Question

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How accurately and efficiently can a dynamic, deterministic morphological model forecast storm-driven erosion?

# Goal and Objectives

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Use the morphological model XBeach to forecast storm-driven erosion along the U.S. Atlantic and Gulf Coast prior to landfall

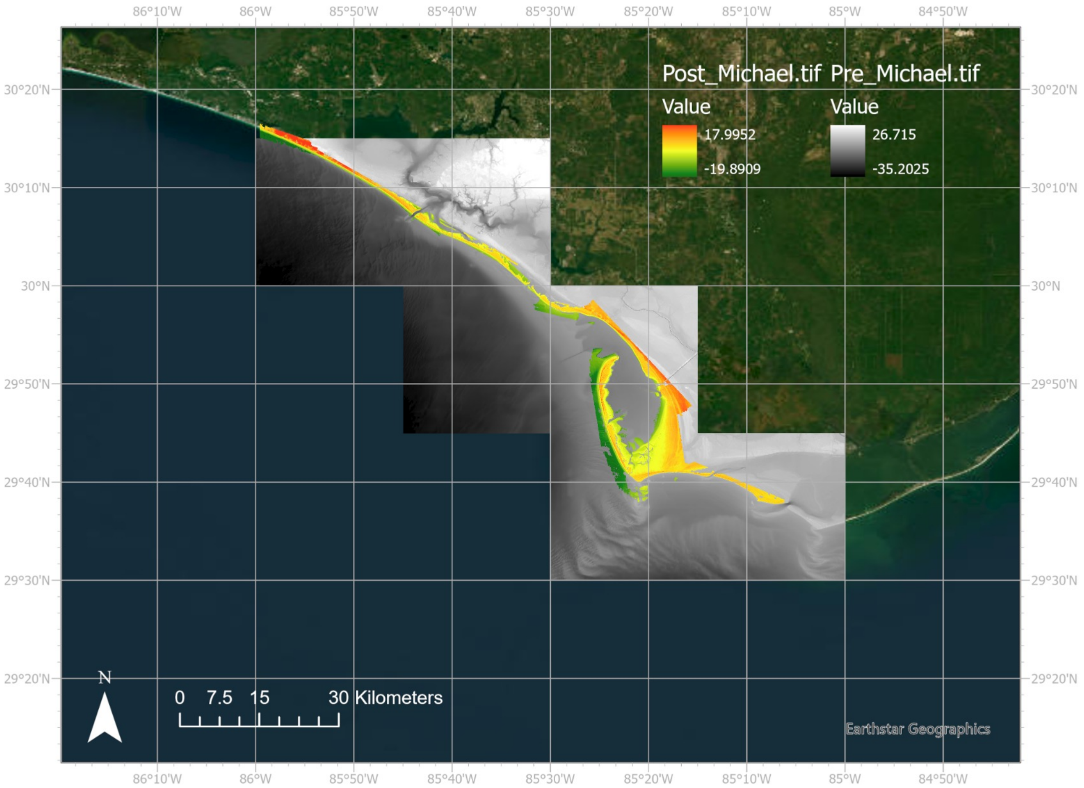
- Demonstrate 1D XBeach is capable of accurately predicting storm-driven erosion for over 4000 km of coastline
- Forecast storm-driven erosion during Ian
- Evaluate and communicate the erosion forecast results
- Verify that the addition of dynamic morphology affects our forecasting capabilities

# Methods

# Storms Selected

Hindcast Validation-

Hurricane Michael (2018)




Forecast Implementation-

Hurricane Ian (2022)

# Hurricane Michael (2018)

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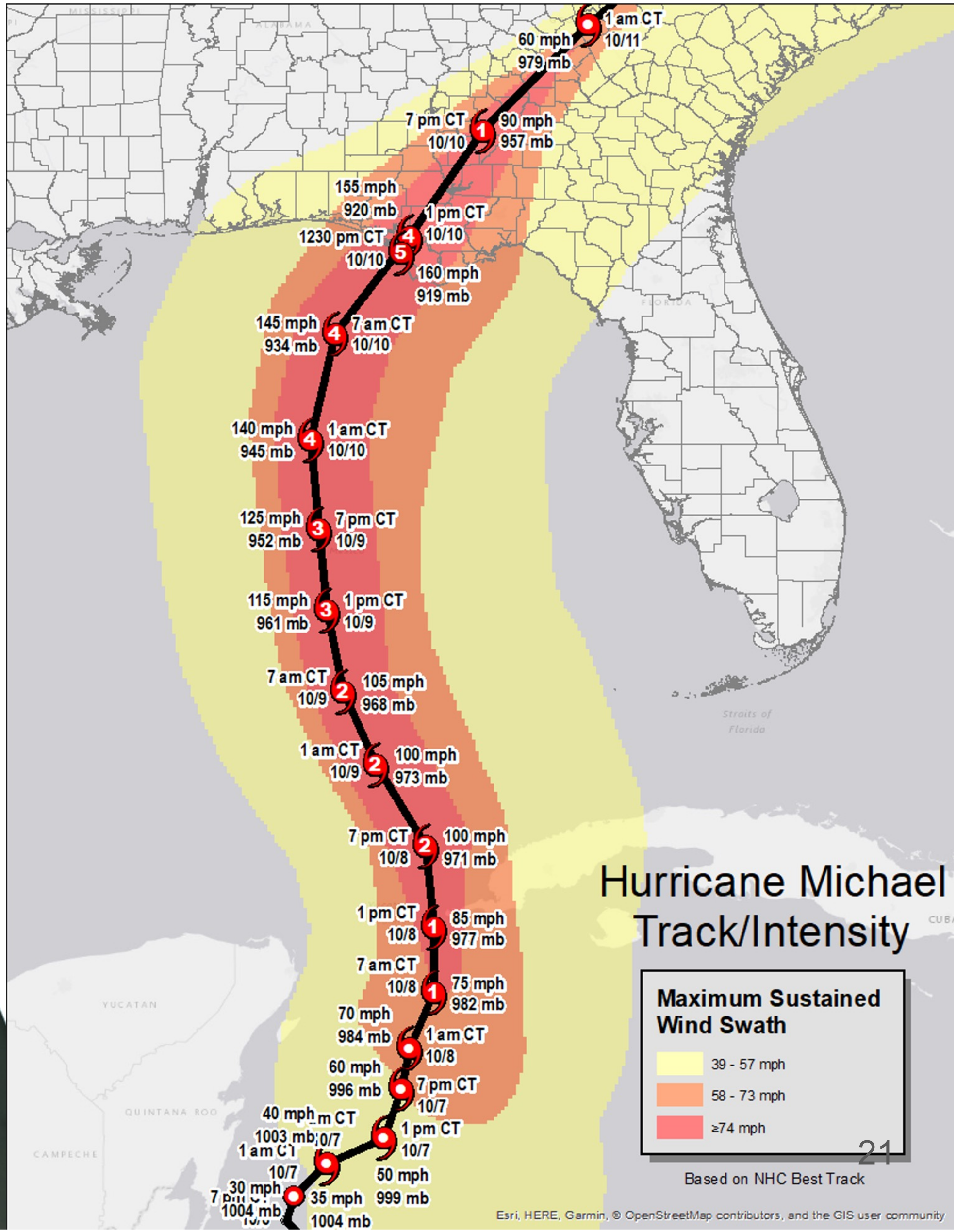
- Category-5
- Landfall near Mexico Beach at 1200 UTC 10 October
- 16 directly related deaths
- $ 25 billion in damages

National Weather Service: Hurricane Michael 2018



# Hurricane Ian (2022)

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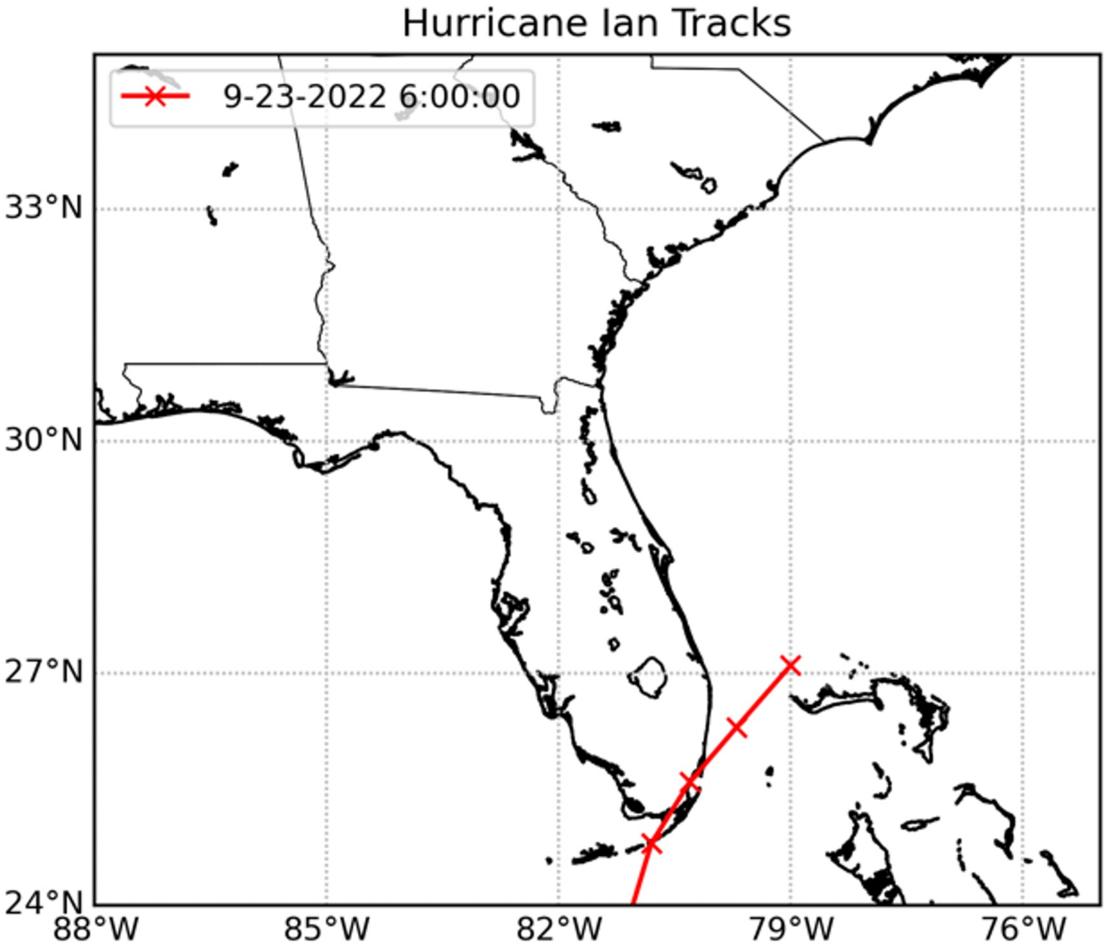
- **3rd costliest storm on record**: $112.9 Billion
- Track originally estimated to make landfall in Tampa
  - Shifted south, made landfall in Fort Myers, moved into Atlantic, made another landfall north of Charleston
  - Adv 15 (~3 days before landfall) vs Adv 23 (~1 days before landfall)




# Modeling Framework

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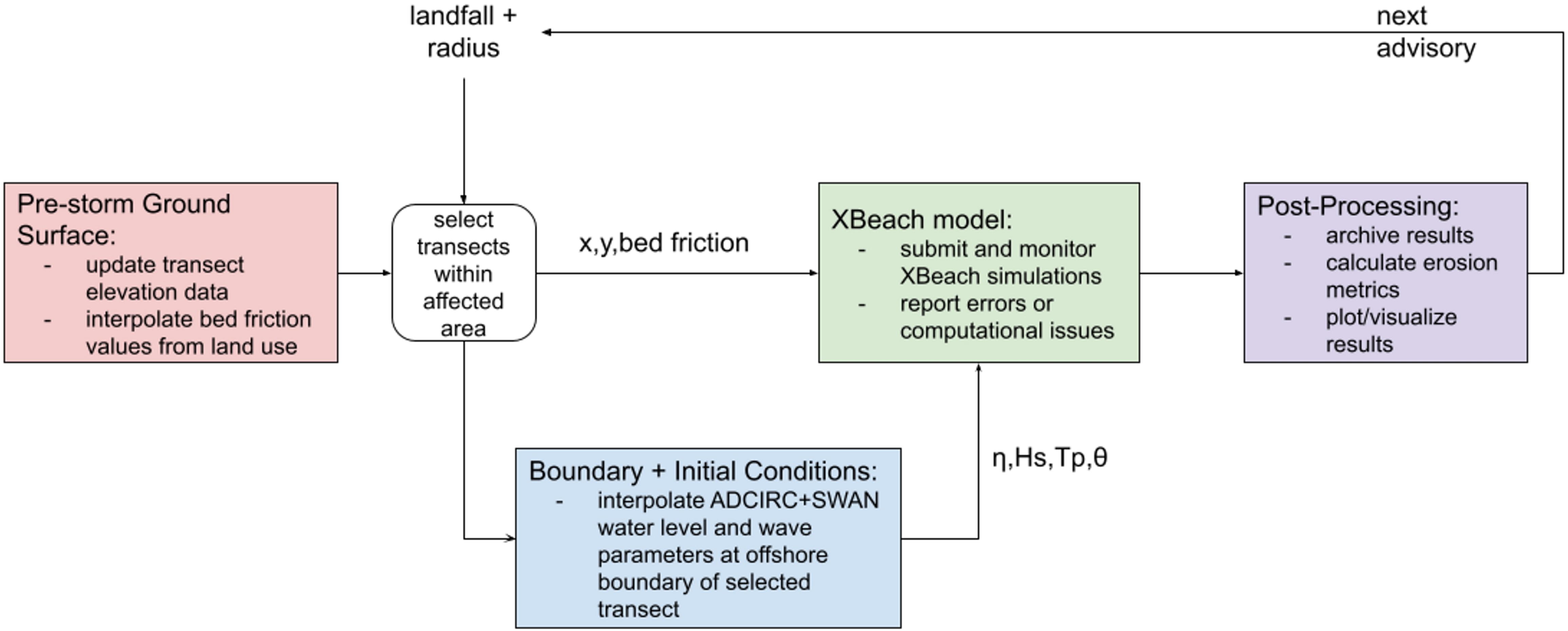

# Modeling Framework

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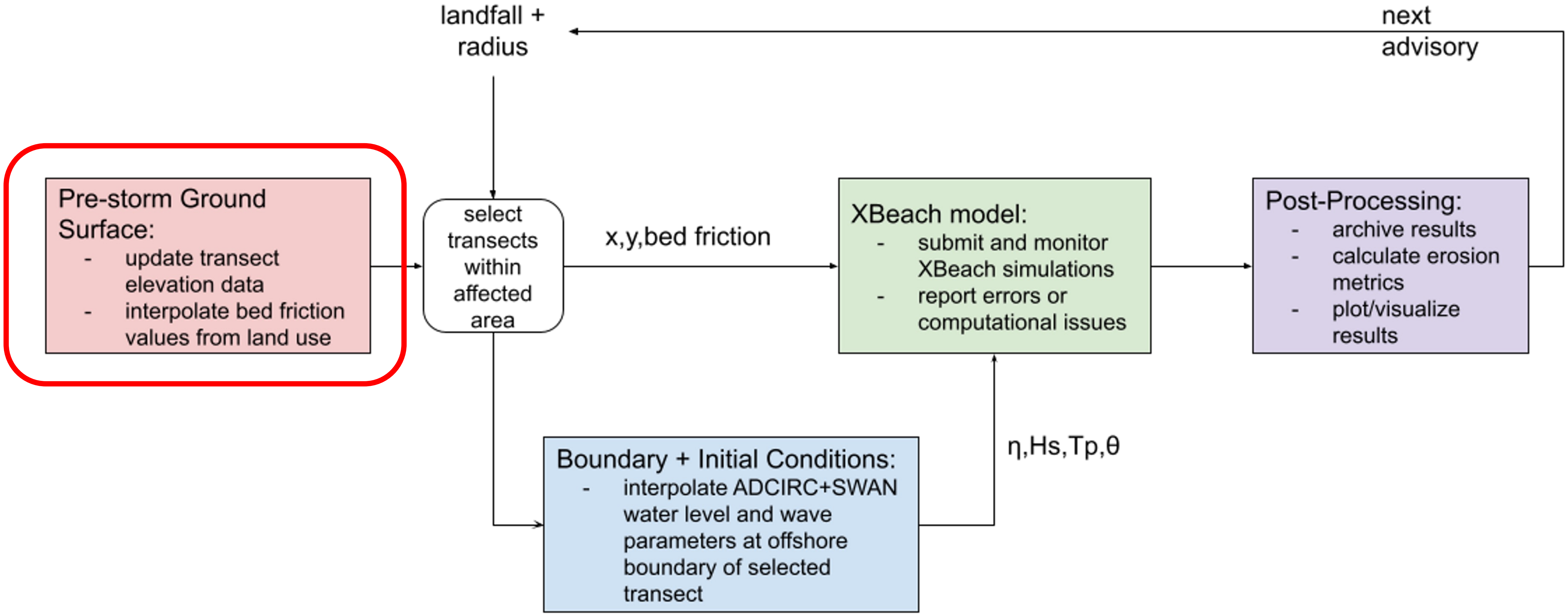

# Start with Mickey & Passeri (2022) transect dataset

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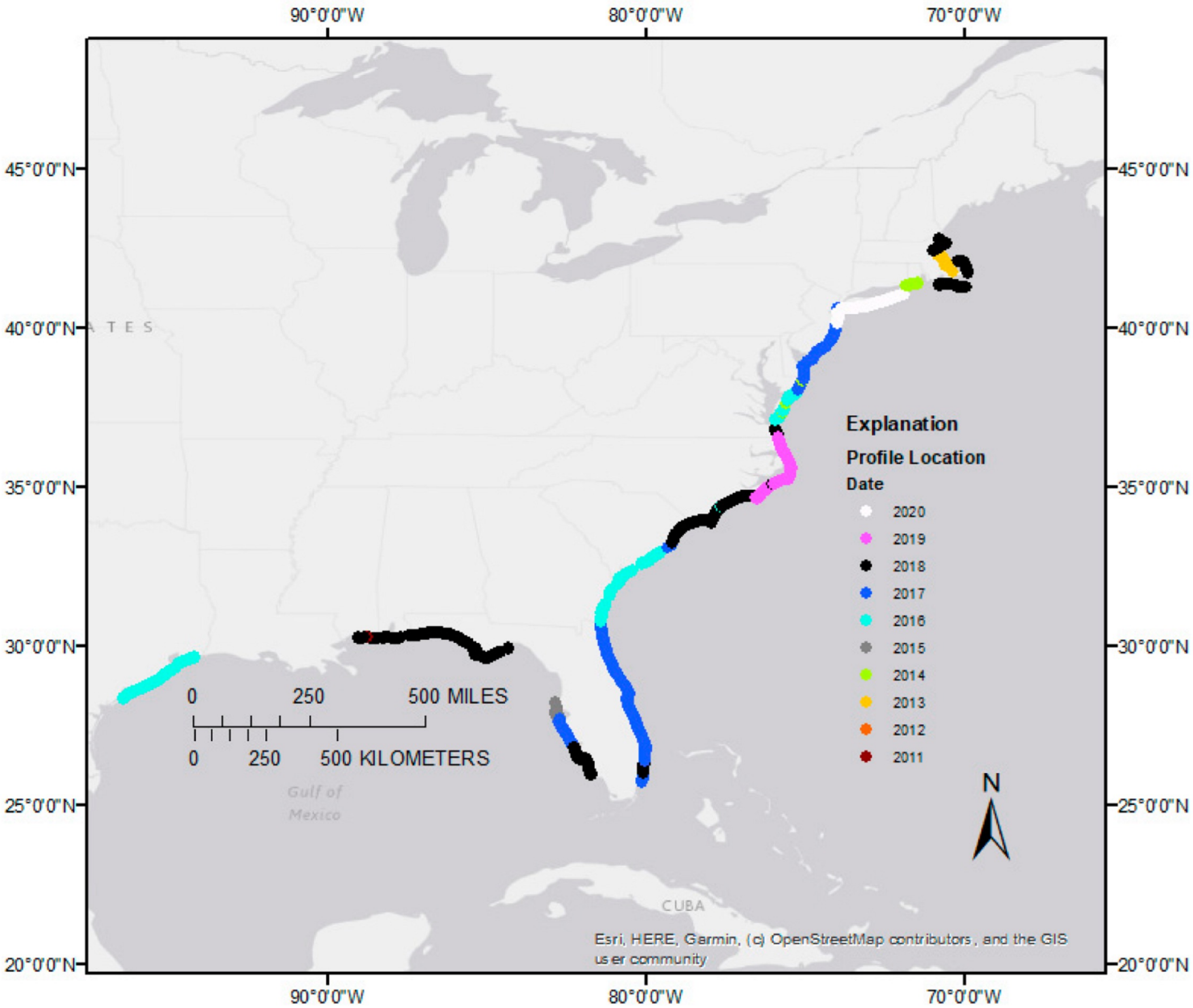

# Update pre-storm elevation data for Michael

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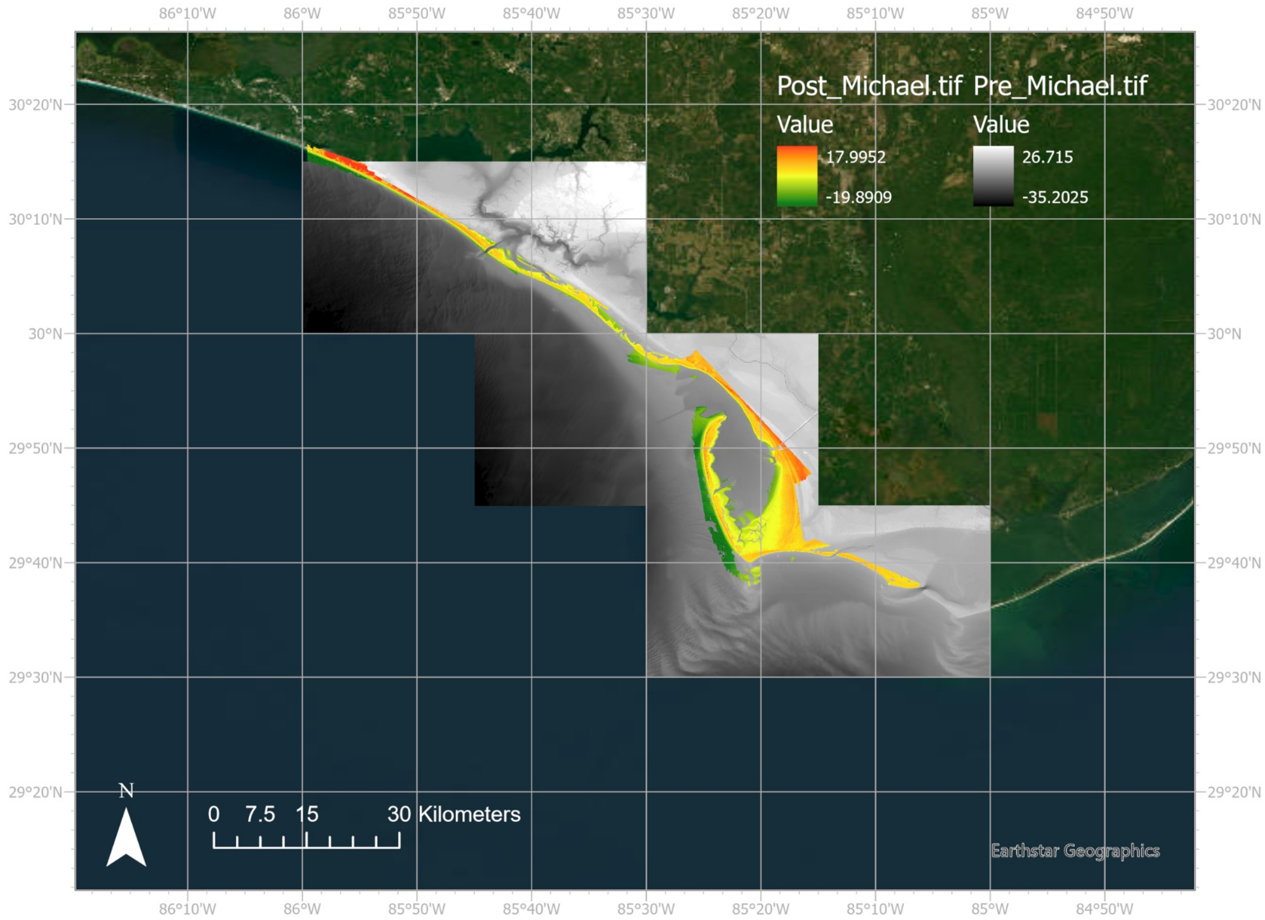
Adjust dune crest and dune toe selection for new topo/bathy



# Add bed friction information from land classes

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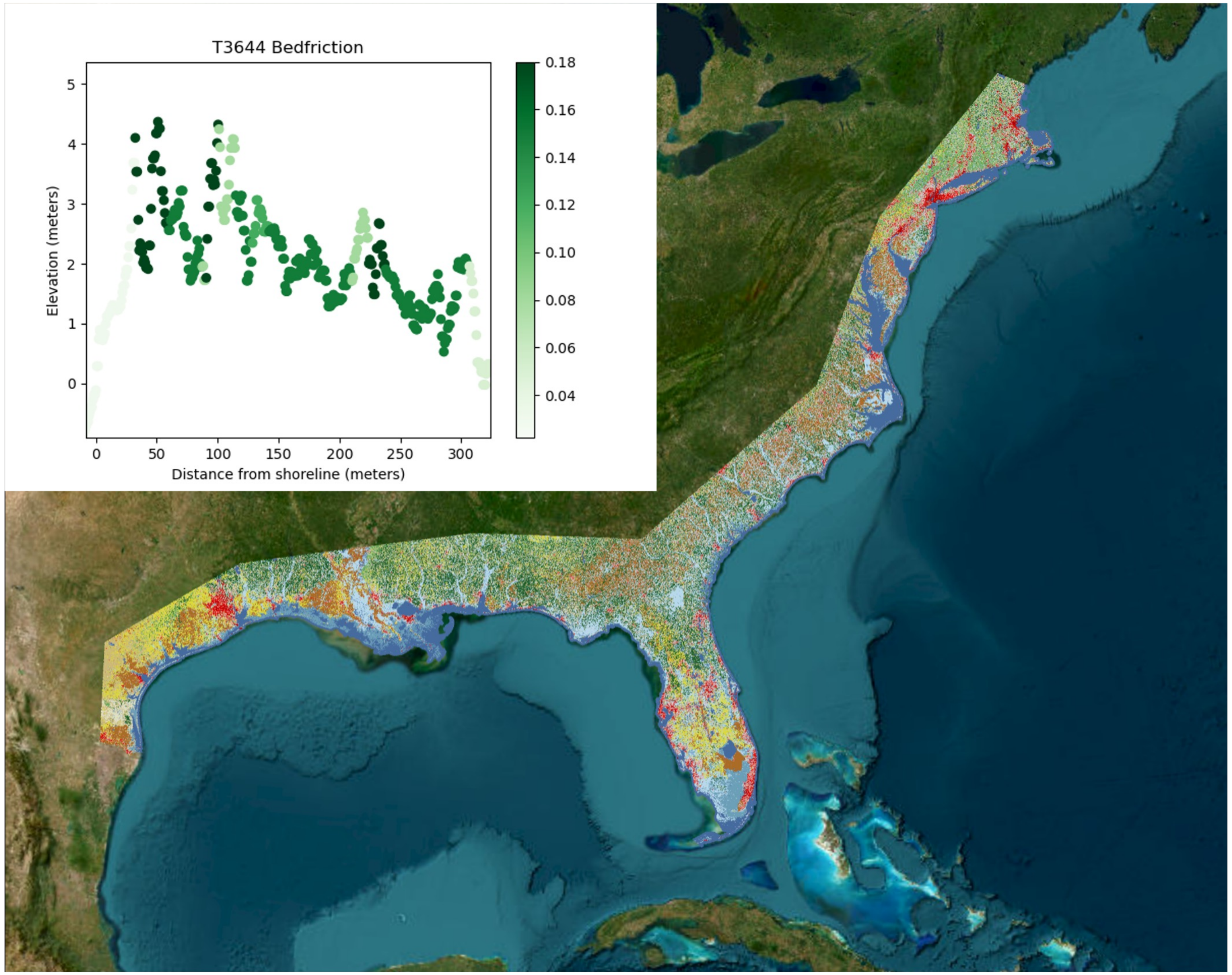
## NLCD2019 30-m resolution

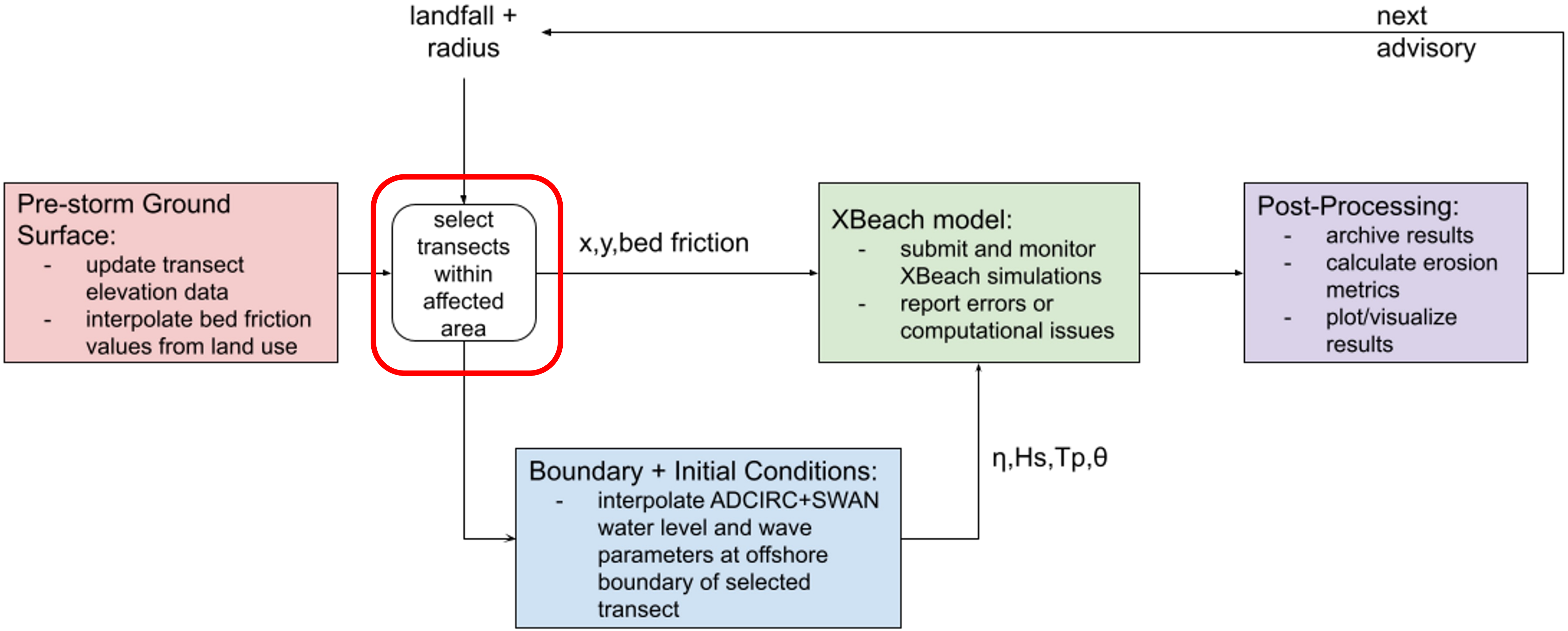
| C-CAP Class | Manning's n | Chezy coefficient |
|---|---|---|
| High Development | 0.12 | 8 |
| Medium Development | 0.12 | 8 |
| Low Development | 0.12 | 8 |
| Open Space Development | 0.035 | 29 |
| Cultivated Crops | 0.1 | 10 |
| Pasture/Hay | 0.05 | 20 |
| Grassland/Herbaceous | 0.035 | 29 |
| Deciduous Forest | 0.16 | 6 |
| Evergreen Forest | 0.18 | 6 |
| Mixed Forest | 0.17 | 6 |
| Scrub/Shrub | 0.08 | 13 |
| Palustrine Forested Wetland | 0.15 | 7 |
| Palustrine Scrub/Shrub Wetland | 0.075 | 13 |
| Palustrine Emergent Wetland | 0.06 | 17 |
| Estuarine Forested Wetland | 0.15 | 7 |
| Estuarine Scrub/Shrub Wetland | 0.07 | 14 |
| Estuarine Emergent Wetland | 0.05 | 20 |
| Unconsolidated Shore | 0.03 | 33 |
| Bare Land | 0.03 | 33 |
| Open Water | 0.022 | 31–71 |
| Palustrine Aquatic Bed | 0.035 | 29 |
| Estuarine Aquatic Bed | 0.03 | 67 |

Passeri et al 2018



# Modeling Framework





# Script implementation and transect selection

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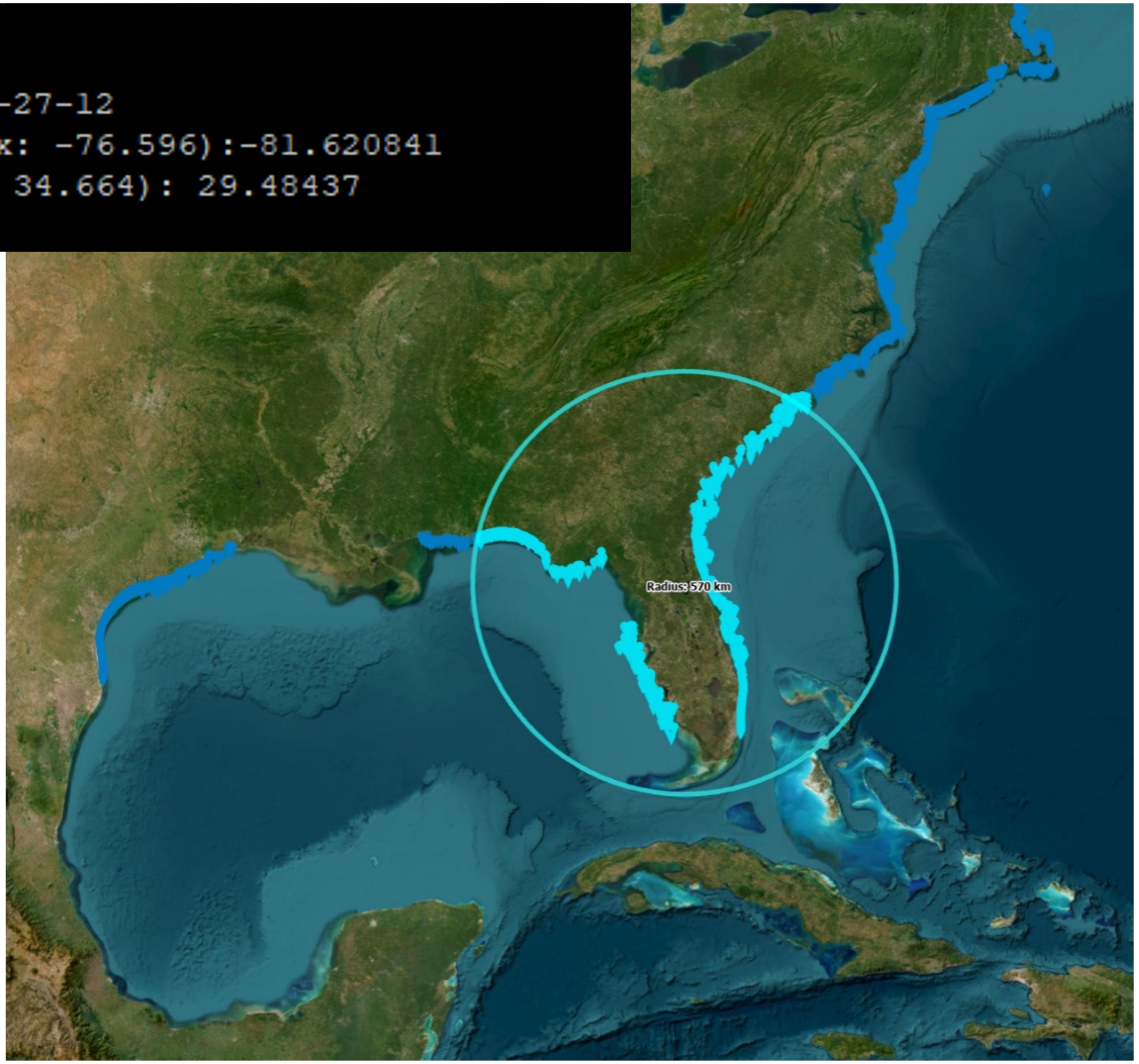
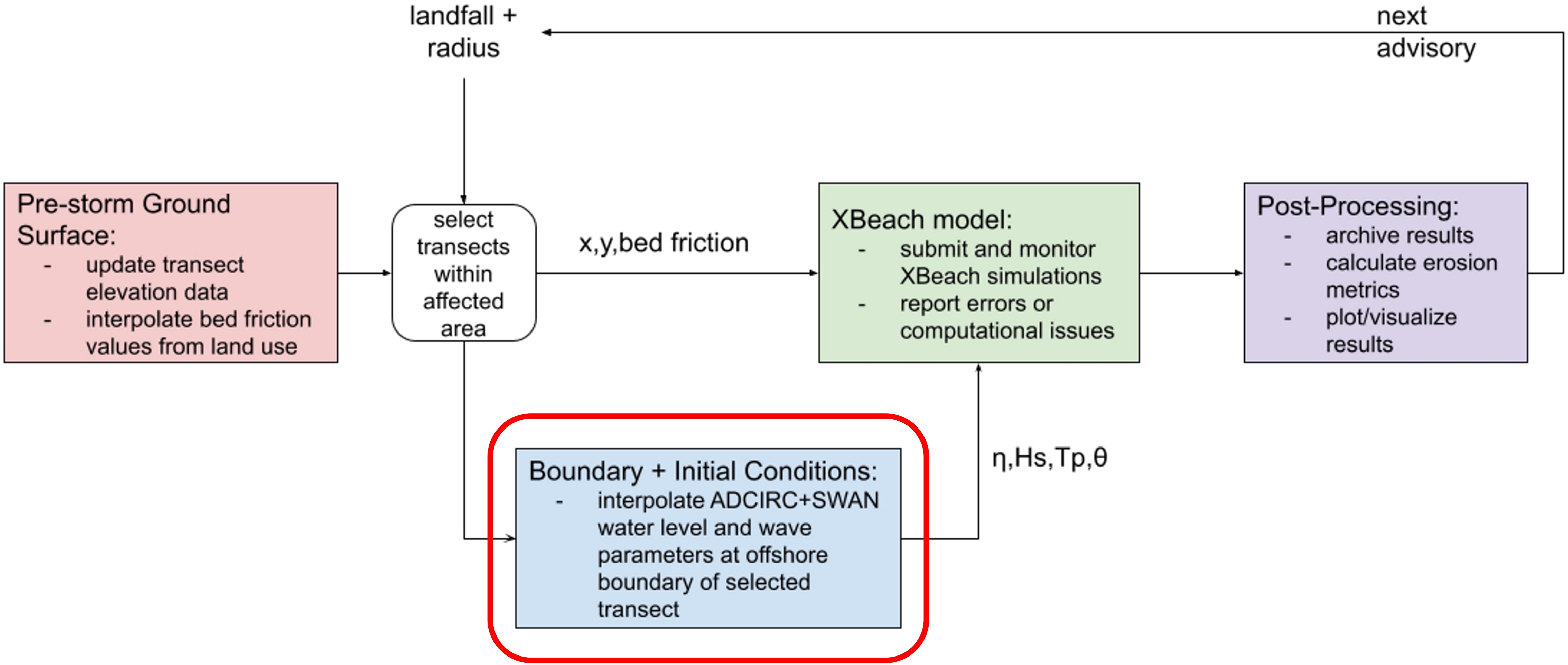
```
[jfgorski@login01 IAN]$ source submit.csh
please enter the storm name (ex: IRENE):IAN
please enter the month, day and time (ex: 9-19-00):9-27-12
please enter the longitutde of the storm landfall (ex: -76.596):-81.620841
please enter the latitude of the storm landfall (ex: 34.664): 29.48437
please enter the radius of interest (kilometers):570
```

- Python script:
  - Asks for user input
  - Selects transects within specified extents
  - Copies prepared transect data to modeling folder
  - Begins boundary condition interpolation



# Modeling Framework





# Boundary Conditions from ADCIRC+SWAN

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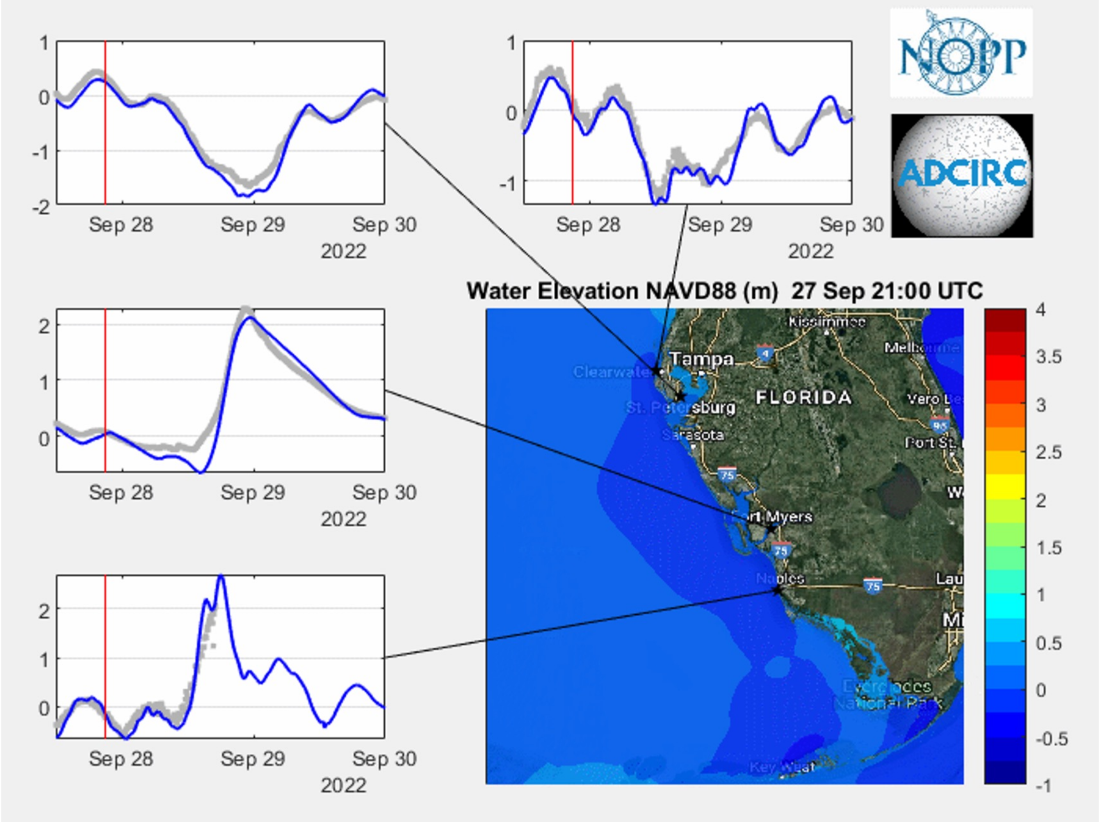
- ADvanced CIRCulation (ADCIRC, Luettich et al. 1992)
  - Ocean circulation model
  - Solves governing shallow water equations
- Simulating WAves Nearshore (SWAN, Booij et al. 1999)
  - Spectral wave model for predicting waves in coastal regions
  - Parameterization for wave evolution
- Can be coupled (Dietrich et al. 2011)




Rick Luettich, NOPP forecasts for Ian

# Interpolation at each offshore origin

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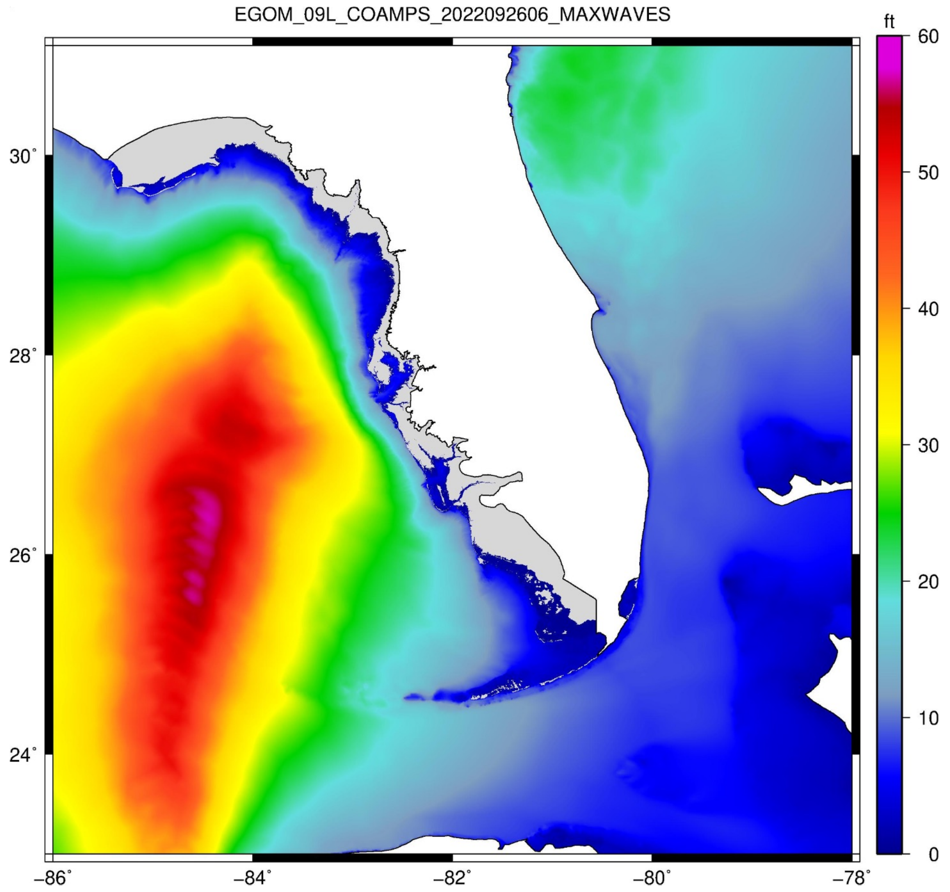
η, Hs, Tp, θ

Time series interpolated from ADCIRC+SWAN:

- Water level ( η )
- Wave height ( Hs )
- Wave period ( Tp )
- Wave direction ( θ )

Start interpolation when Hs > 0.5 m




Credit: Rick Luettich, NOPP

# Modeling Framework

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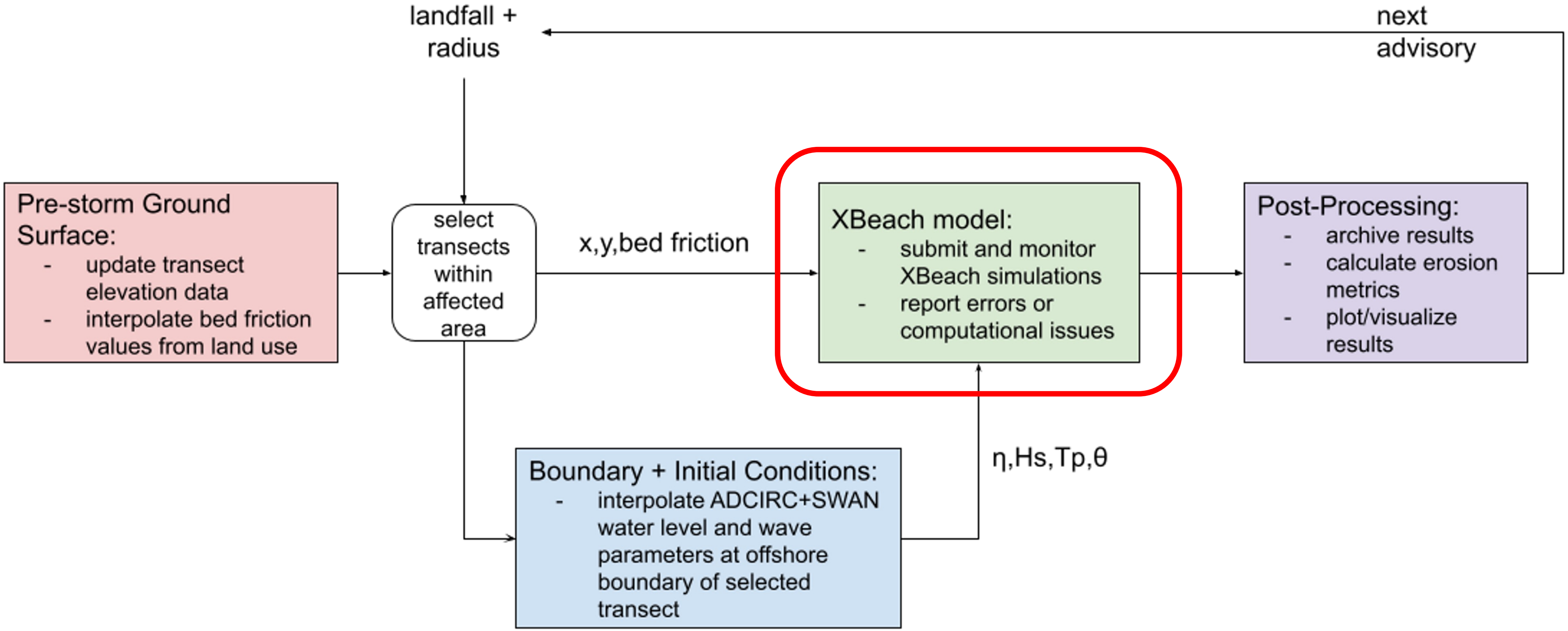

# Tight competition for most jobs submitted…

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Computation restrictions:

- Maximum run time of 1 hour
  - Most finish in 30 min
- 2 cores per simulation

| Name | CPU | Jobs |
|---|---|---|
| Johnathan | 237,101.982 | 240 |
| Tomás | 47,093.592 | 438 |
| Jack | 37,343.814 | 124 |
| Jess | 26,216.571 | 43,706 |
| Casey | 16,014.804 | 61 |
| Thomas | 14,150.552 | 85 |
| Sophia | 12,380.729 | 79 |
| Jenero | 10,887.644 | 73 |

# Parameters selected from a recent study

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Are these parameters applicable elsewhere in our study area?

Estuarine, Coastal and Shelf Science 229 (2019) 106404

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: http://www.elsevier.com/locate/ecss

ELSEVIER

## Morphodynamic modeling of the response of two barrier islands to Atlantic hurricane forcing

Check for updates

Marlies A. van der Lugt [a,*], Ellen Quataert [a], Ap van Dongeren [a,b], Maarten van Ormondt [a], Christopher R. Sherwood [c]

[a] Deltares, Dep. Of Marine & Coastal Systems, Delft, the Netherlands
[b] IHE Delft Institute for Water Education, Delft, the Netherlands
[c] U.S. Geological Survey, Woods Hole Coastal and Marine Science Center, Woods Hole, USA

ARTICLE INFO

*Keywords:*
Barrier islands
Morphodynamic modeling
Hurricanes
XBeach
Vegetation
Uncertainty

ABSTRACT

The accurate prediction of a barrier island response to storms is challenging because of the complex interaction between hydro- and morphodynamic processes that changes at different stages during an event. Assessment of the predictive skill is further complicated because of uncertainty in the hydraulic forcing, initial conditions, and the parameterization of processes. To evaluate these uncertainties, we investigated the morphological change that occurred during two Atlantic hurricane events on two barrier islands at Matanzas (Florida) and Fire Island (New York) with differing topographies and forcing conditions.

We used the morphodynamic model XBeach with hydrodynamic forcing extracted from a regional coupled D-Flow FM/SWAN model. The XBeach model was initialized with a spatially varying roughness map derived from a land cover classification map generated with supervised conditional-random-field classification. The model was supplemented with a dynamic roughness module recognizing that, under extreme conditions, vegetation can be washed away or buried by sediment.

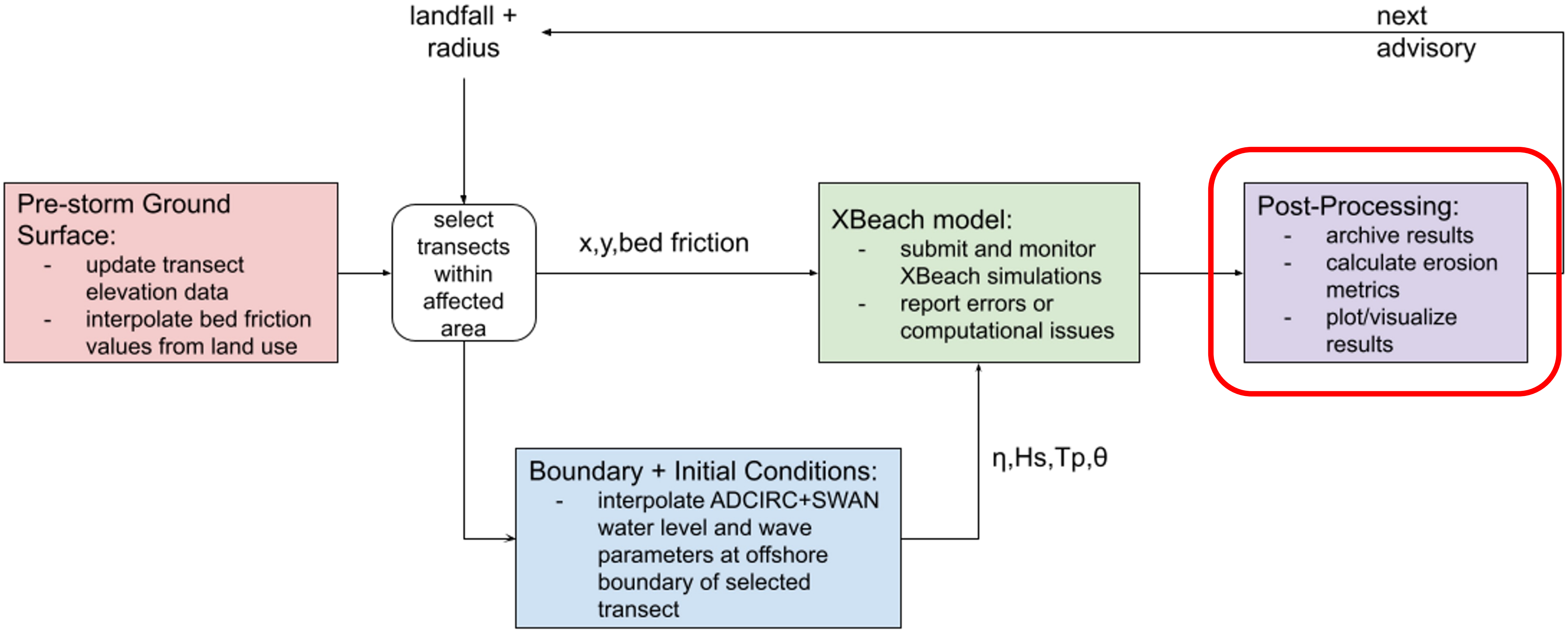
For the Fire Island case, the modeled spatial extent of roughness reduction as a proxy for vegetation removal during the storm was accurate. For both the Fire Island and Matanzas cases, the model predicted erosion and deposition volumes and dune-crest lowering well. The occurrence of breach formation was also predicted by the model, but the exact location of these breaches did not match observations. Variations of 10% in boundary conditions (surge, wave direction, significant wave height, and bay water levels) produced regime shifts in modeled barrier island response. These results not only stress the critical role of boundary conditions in morphodynamic model skill, but also show the limitations of single deterministic model runs in forecasting impact.

### 1. Introduction

Barrier islands are important geological features that provide natural habitats and living and recreation space while protecting mainland coastlines against storm impact (Nordstrom et al., 2000). As sea levels rise (IPCC, 2018), the probability of occurrence of a certain storm surge level increases (Vitousek et al., 2017) as does the risk of damage as coastal areas continue to develop economically (Hallegatte et al., 2013). Therefore, there is a growing need to quantitatively assess the morphological impact by storms on barrier islands. The accurate prediction of a barrier island response to storms is challenging because of the complex interaction of hydro- and morphodynamic processes, which changes markedly as the Sallenger (2000) regime varies during a storm event. In the "collision regime", when the surge level is lower than the dune height, storm waves attack the dune, often causing erosion of dune fronts and depositing sediment in the nearshore. In the "overwash regime", when water levels increase but are still lower than the dune crest, waves start to intermittently overtop the dunes, causing erosion on the landward side of the dunes. When the water level exceeds the dune elevation, water flows over the dunes in the "inundation regime". During the latter two regimes, the combination of waves and water levels may breach the dune front. A proposed additional regime is "storm surge ebb" (Goff et al., 2010; Harter and Figlus, 2017; Lennon, 1991), in which the return flow from the back bay to the sea induced by a seaward sloping water-level gradient drives the formation of scour channels. The processes that occur during these regimes are not only controlled by the

# Modeling Framework





# Post-processing - Erosion Metrics

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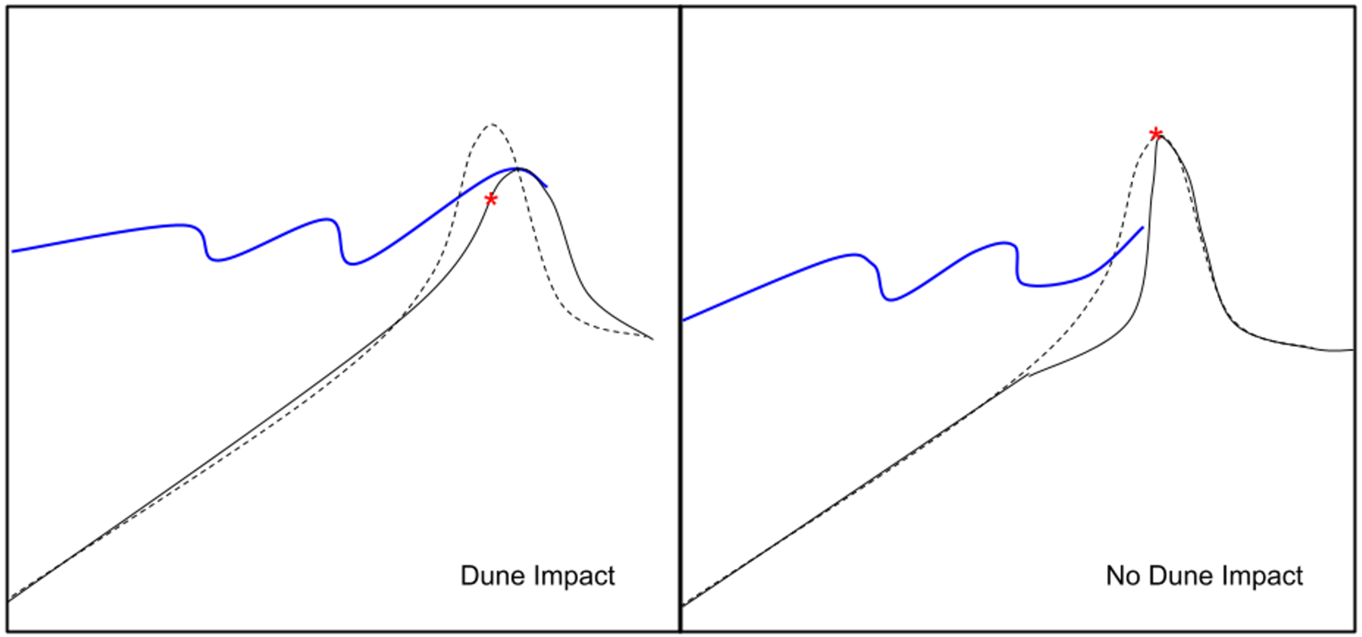
- **Binary dune impact**
  - Impact - overwash/inundation
  - No impact - swash/collision
- Percent volume change
- Dune crest elevation change



# Post-processing - Plotting

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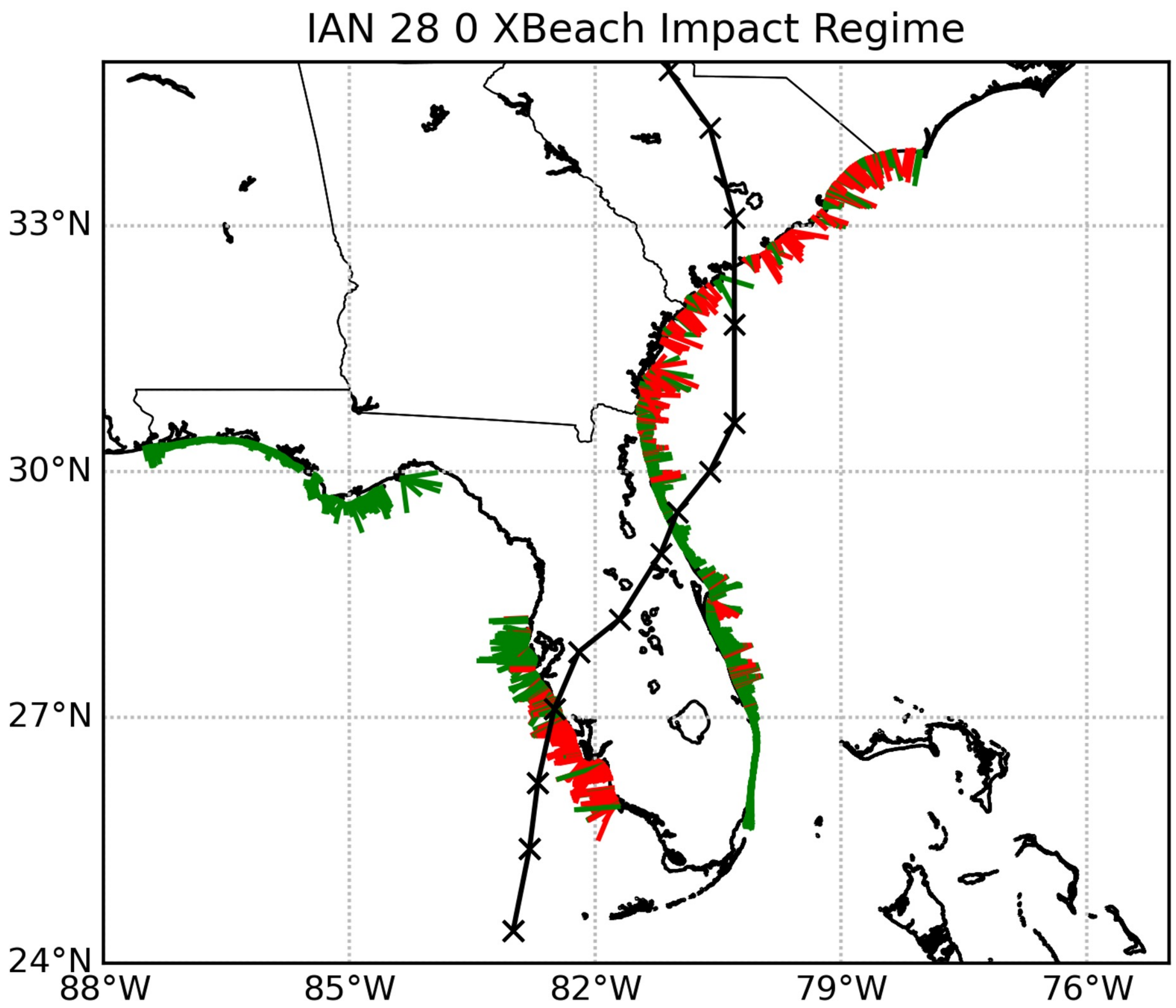
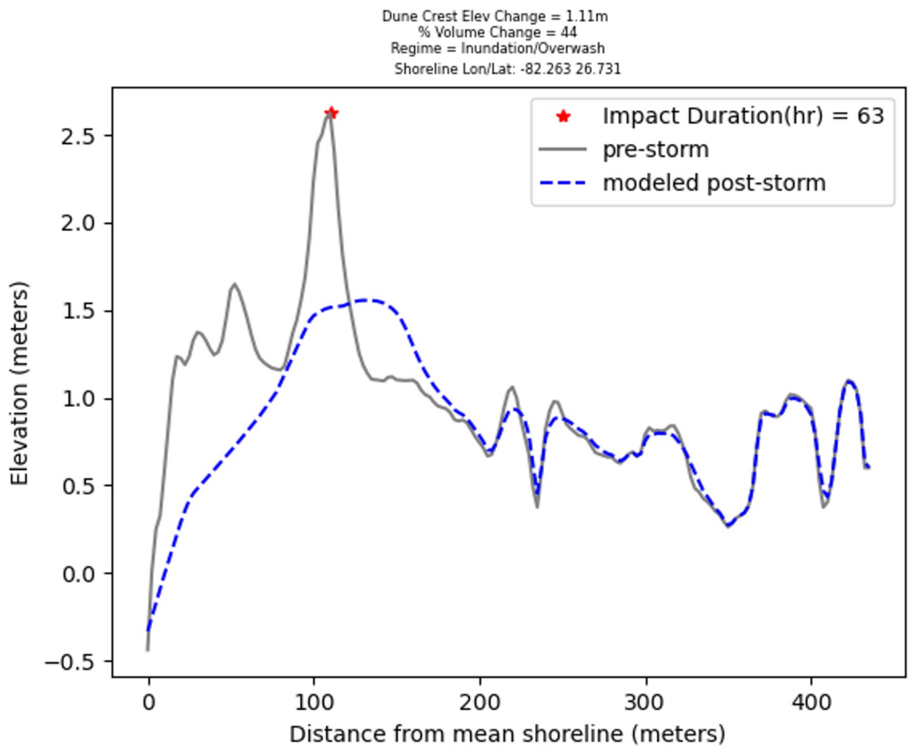


NCSU XBeach Forecasts

# NOPP EROSION MODELING FORECASTS

https://sites.google.com/ncsu.edu/ncsu-xbeach-forecasts/home

4074

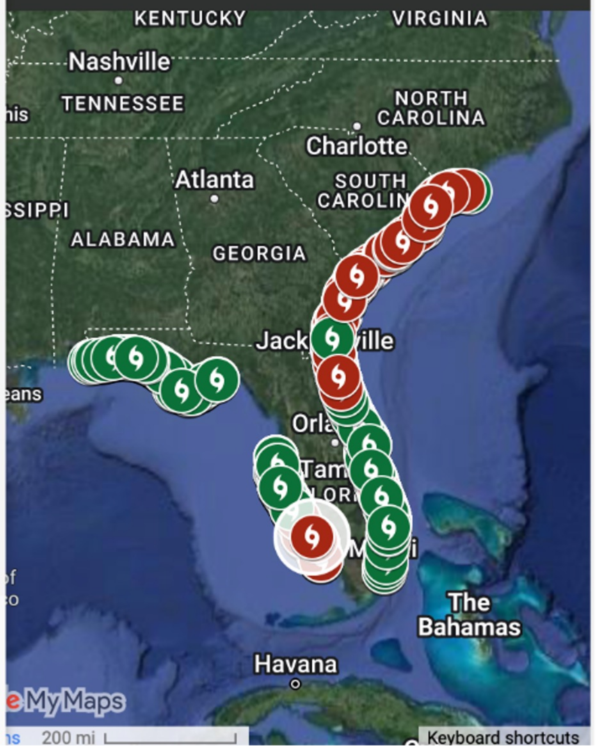
T
4074

lon
-81.956

lat
26.453

Regime
Inundation/Overwash

Link
https://github.com/jessgorski/NOPP-NCSU-Website/blob/main/IAN_9-27-12/T4074_results.png




Welcome!

The map on this page displays the shoreline locations for the most recent set of 1D XBeach simulations.

Modeled results are classified as either:

- swash/collision (green)- water level does not reach the dune crest
- overwash/inundation (red)- water level reaches and/or surpasses the dune crest

The topographic-bathymetric (topo-bathy) profiles were developed by fellow NOPP collaborators [Mickey & Passeri 2022]. Water levels at the crest are determined by XBeach output.

Click on any icon to view the shoreline latitude/longitude, the predicted storm impact regime, and a link to the plotted model results.

# Results

Michael Hindcast

# Michael simulations predict 90% of dune impacts

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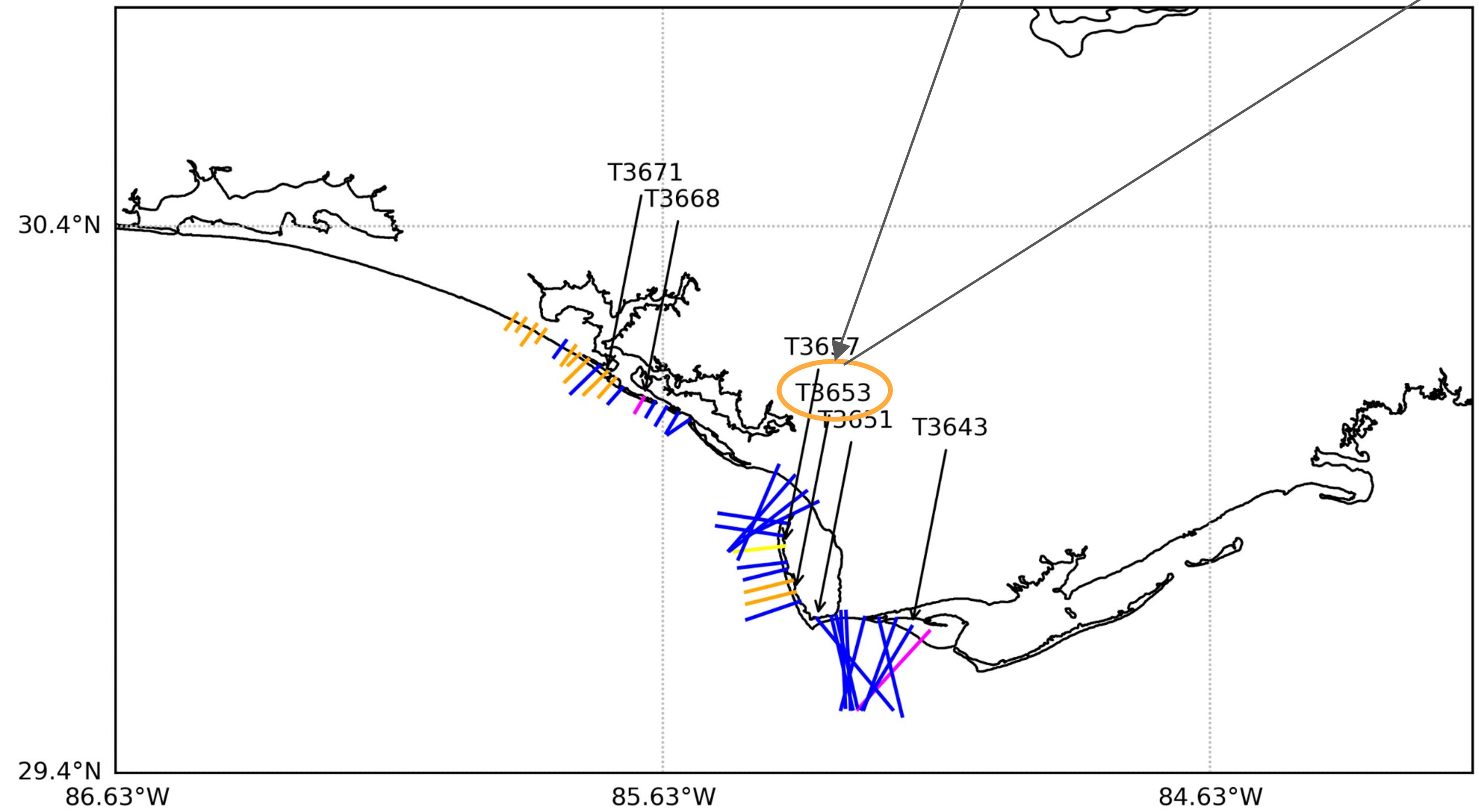
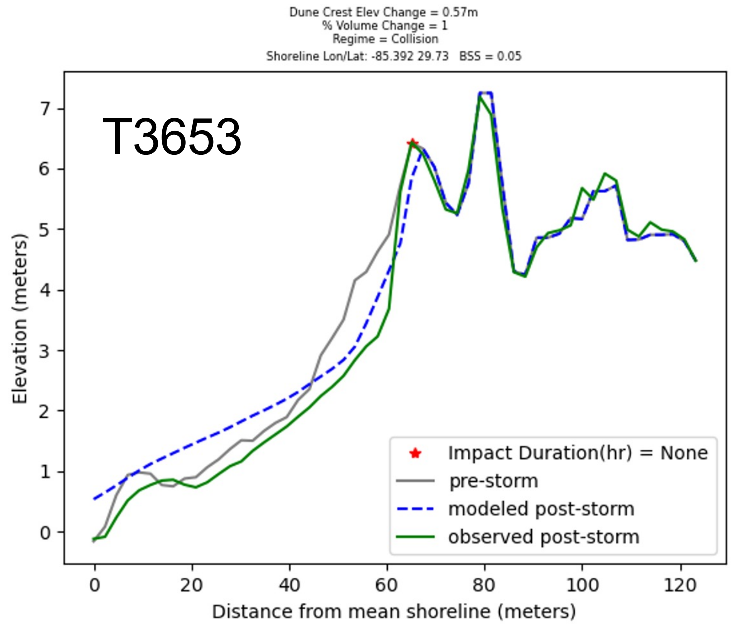
| | | Observed | |
|---|---|---|---|
| | | Impact | No Impact |
| Predicted | Impact | 25 | 2 |
| | No Impact | 1 | 11 |



# Michael simulations predict 90% of dune impacts

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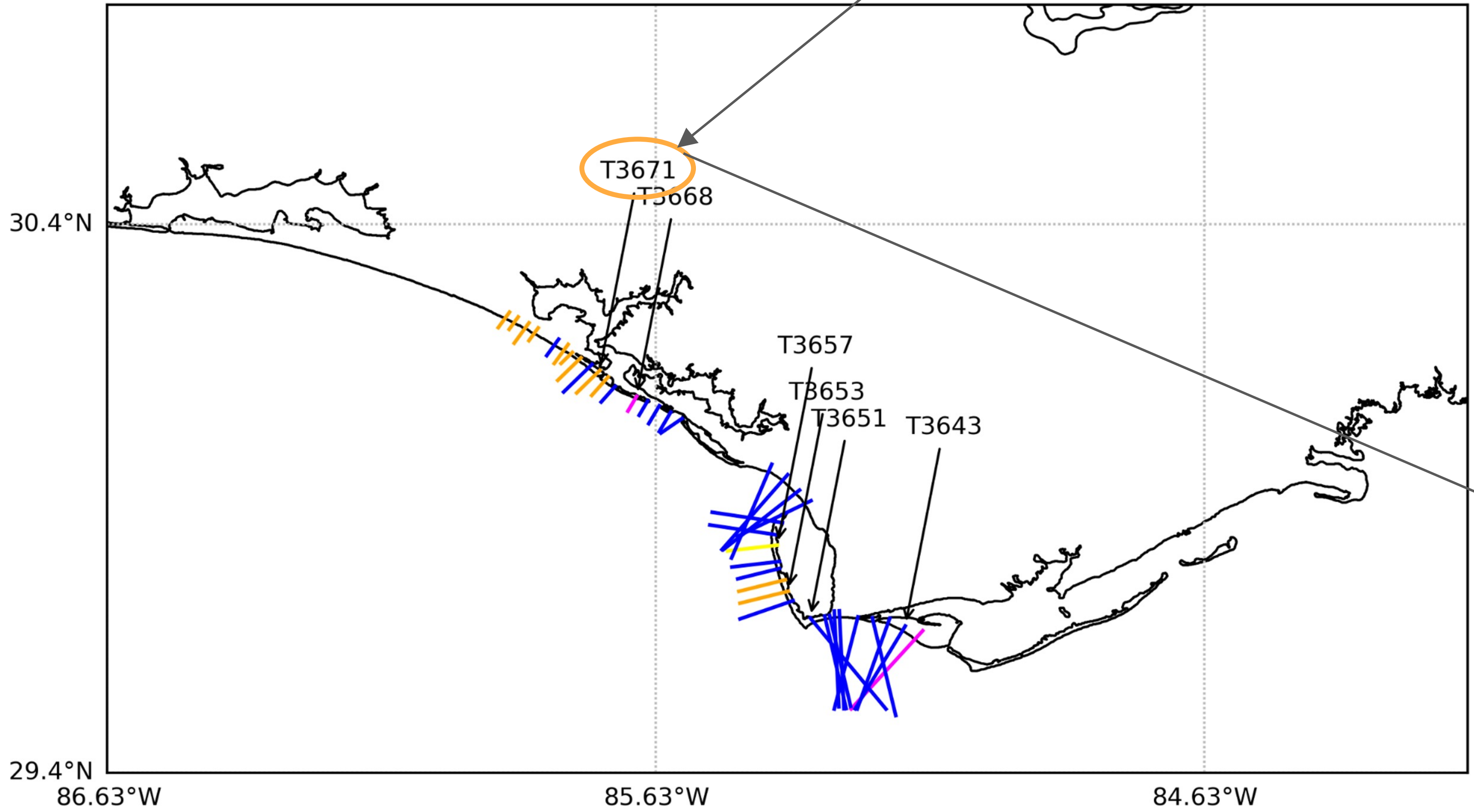


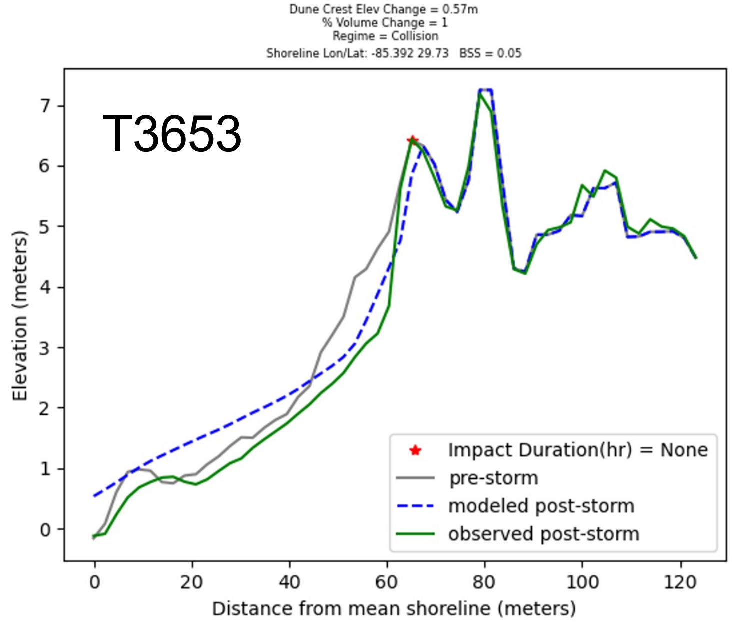


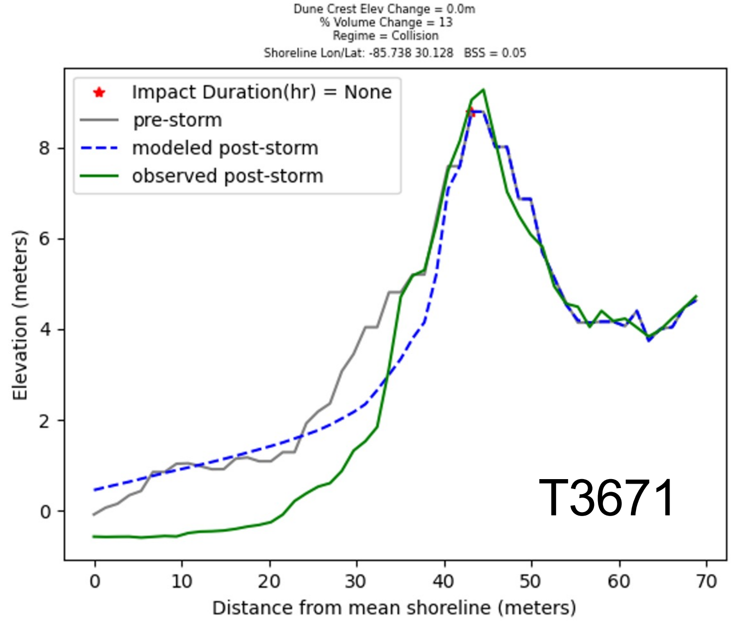

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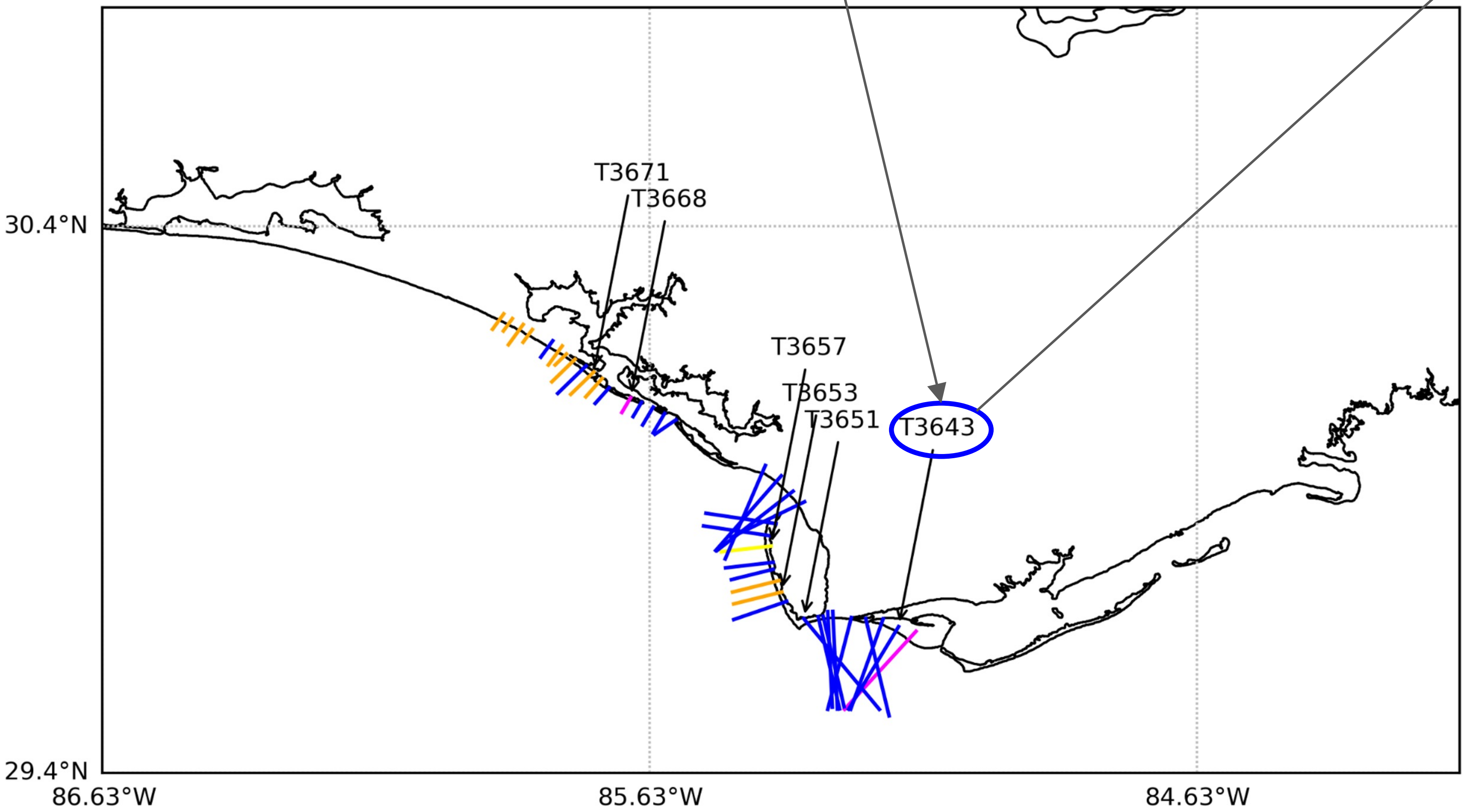


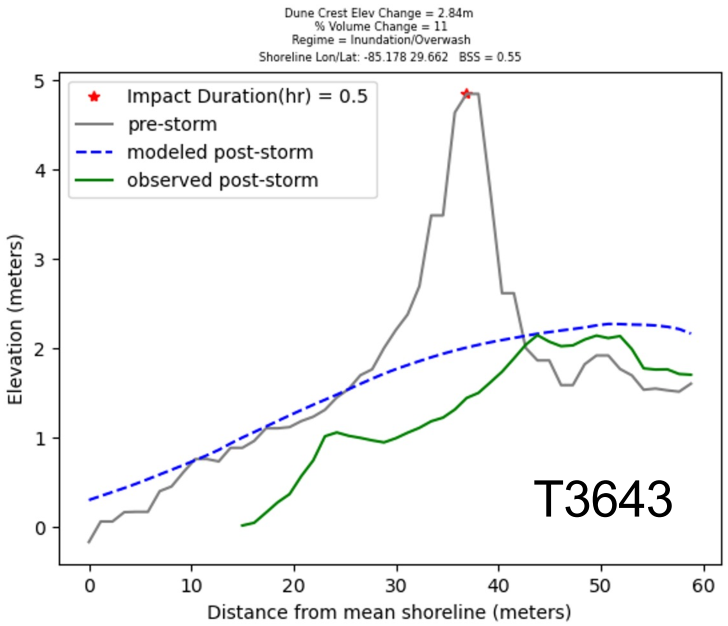

# Michael simulations predict 90% of dune impacts



| | | Observed | |
|---|---|---|---|
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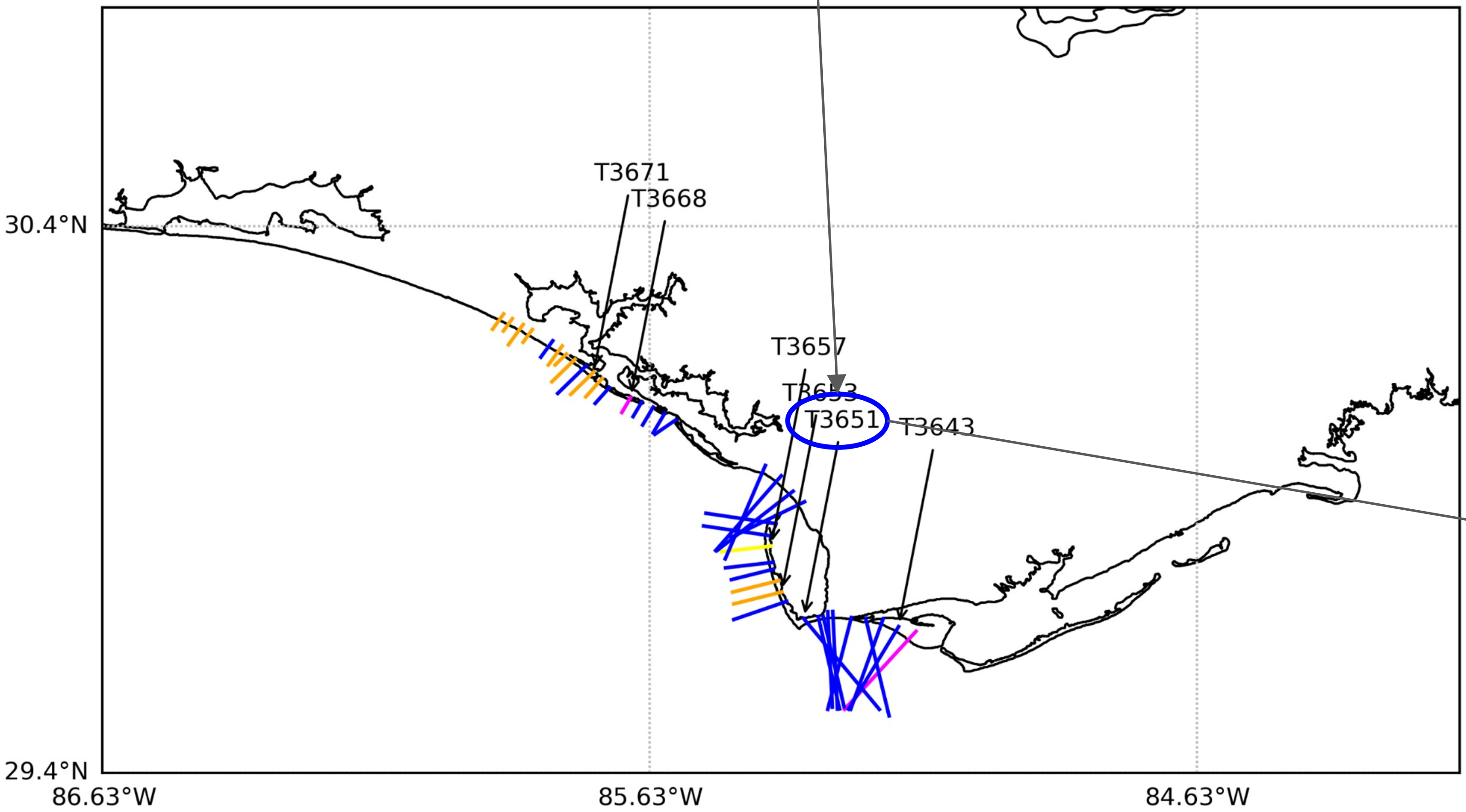
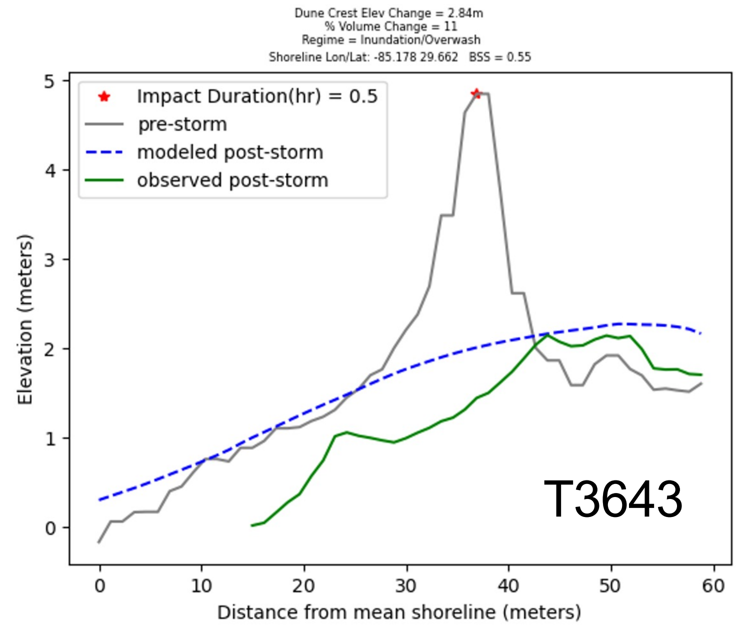
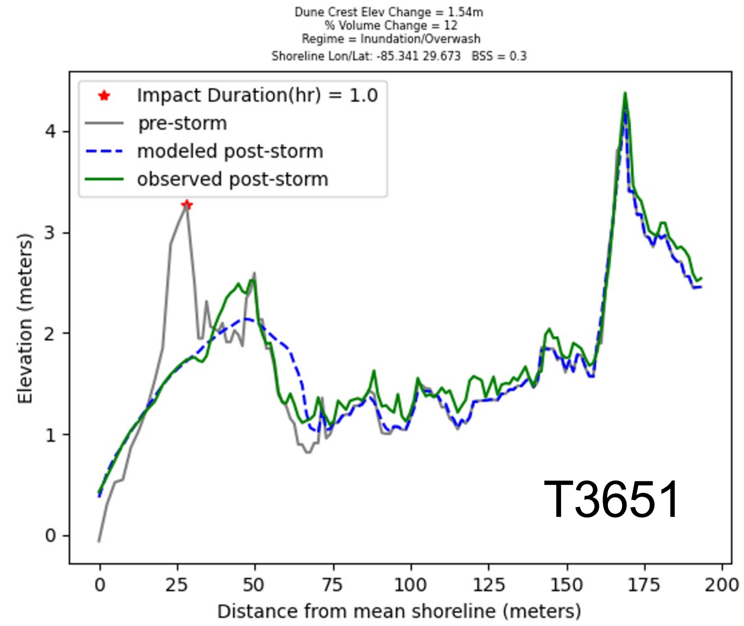
| Predicted | Impact | 25 | 2 |
| | No Impact | 1 | 11 |



# Michael simulations predict 90% of dune impacts

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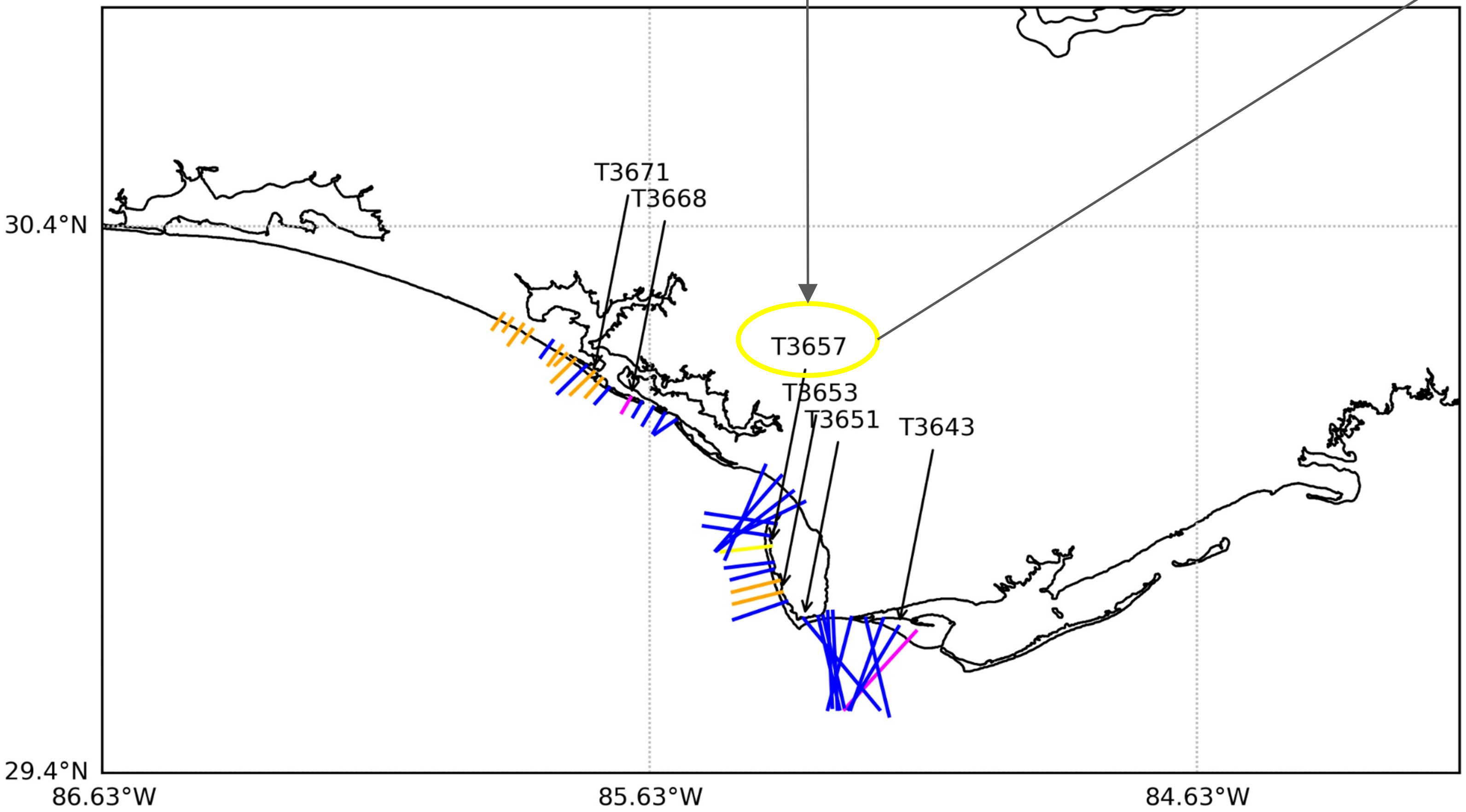
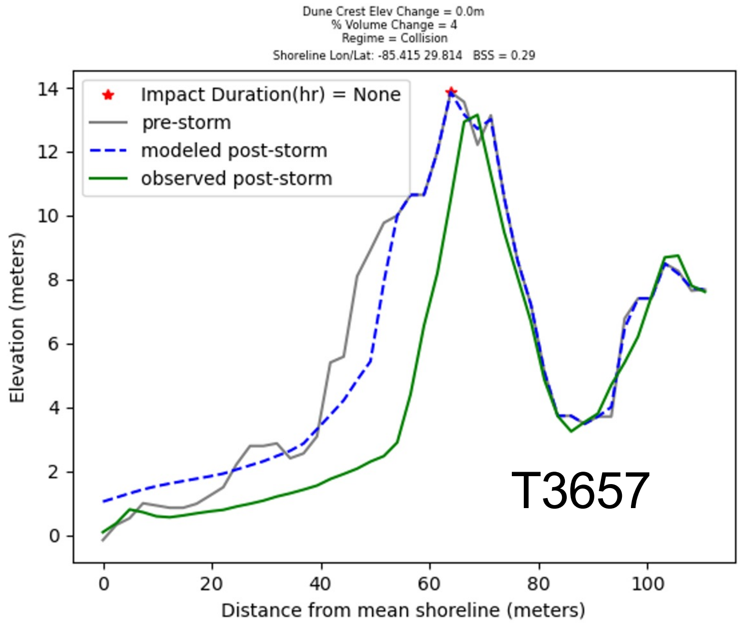
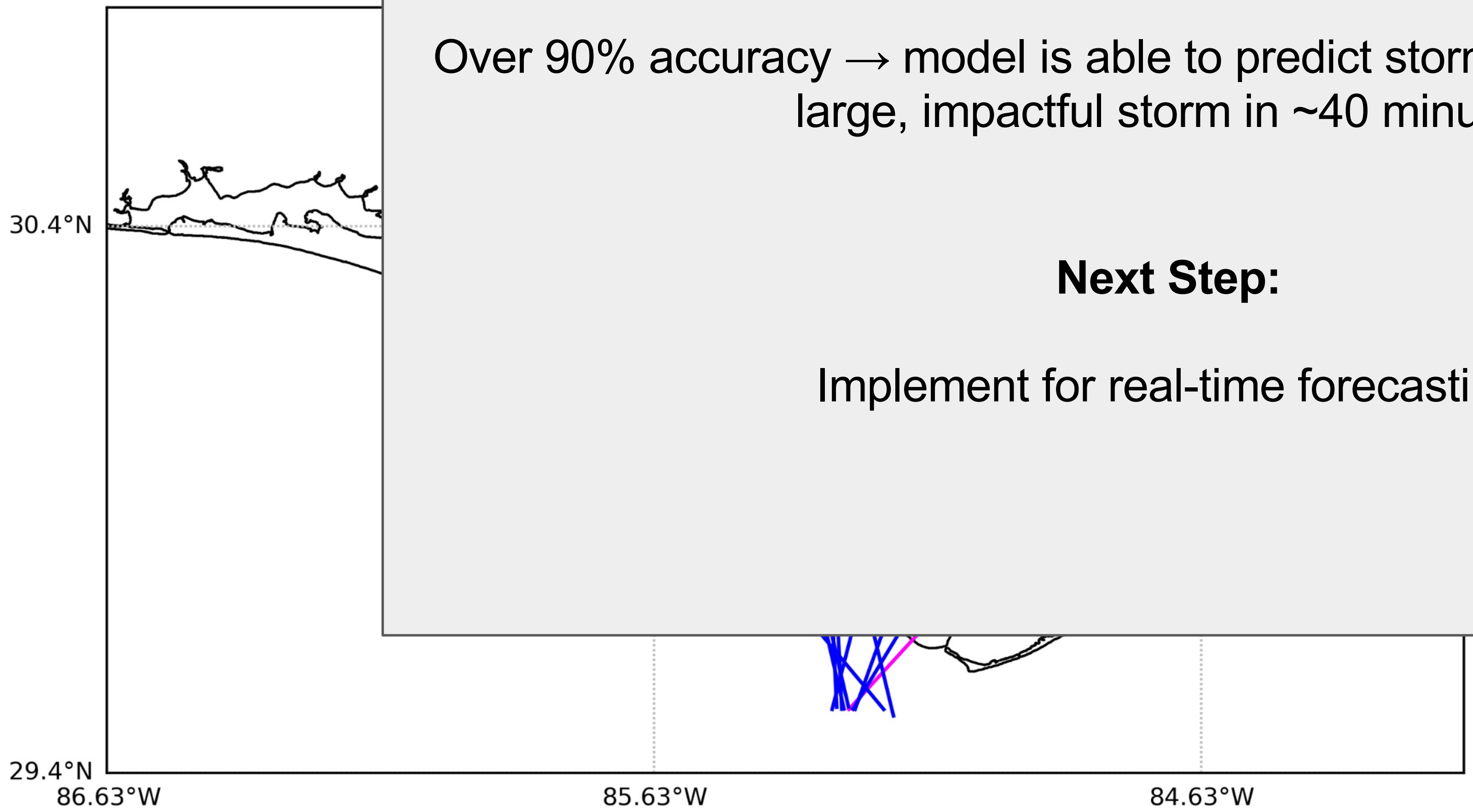
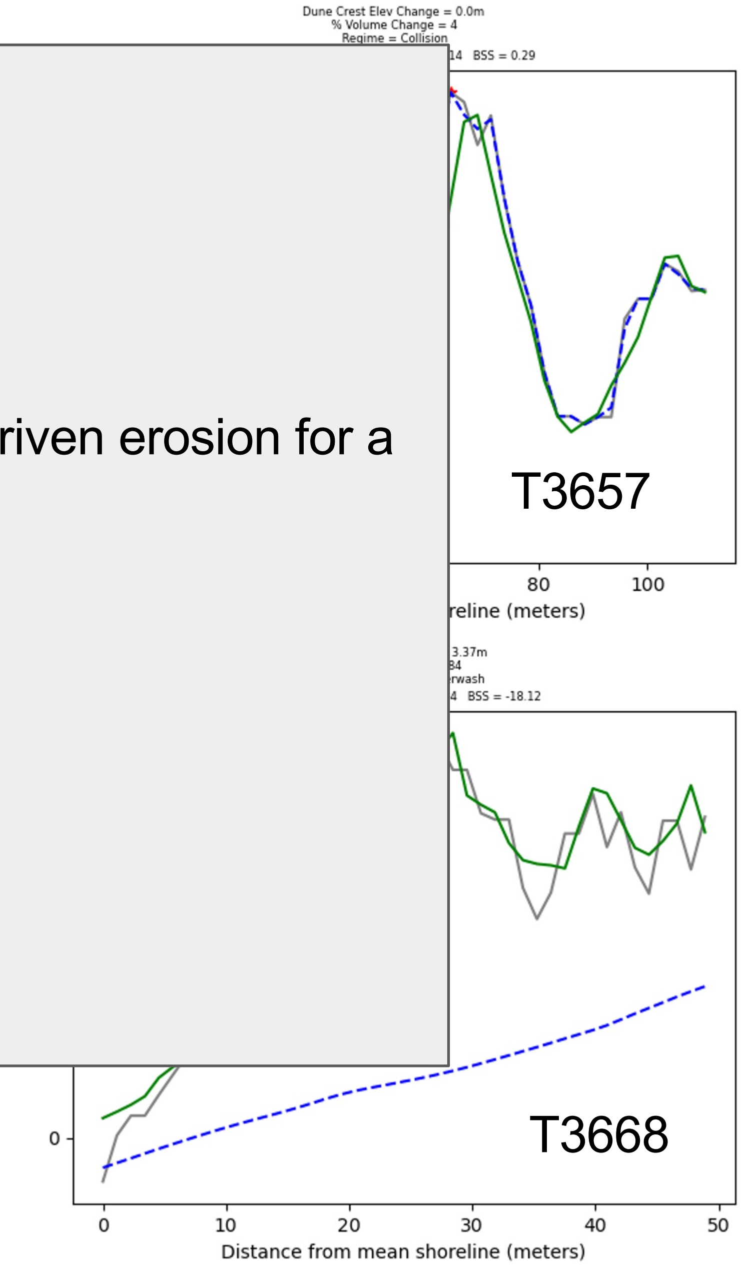
| | | Observed | |
|---|---|---|---|
| | | Impact | No Impact |
| Predicted | Impact | 25 | 2 |
| | No Impact | 1 | 11 |



# Michael simulations predict 90% of dune impacts




**Takeaway:**

Over 90% accuracy → model is able to predict storm-driven erosion for a large, impactful storm in ~40 minutes

**Next Step:**

Implement for real-time forecasting

# Results

Ian Forecast

# Track uncertainties influence erosion forecasts

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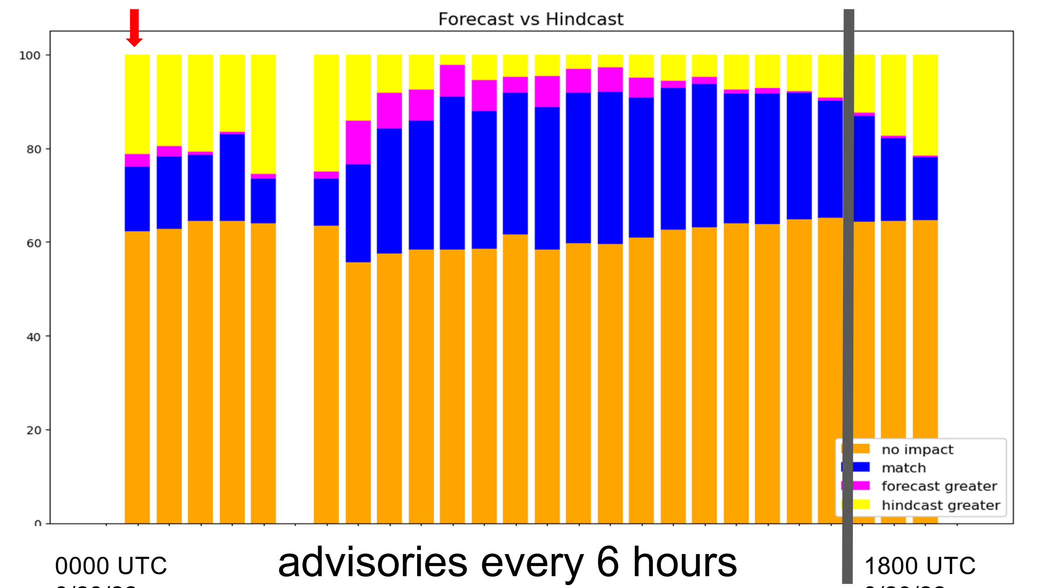
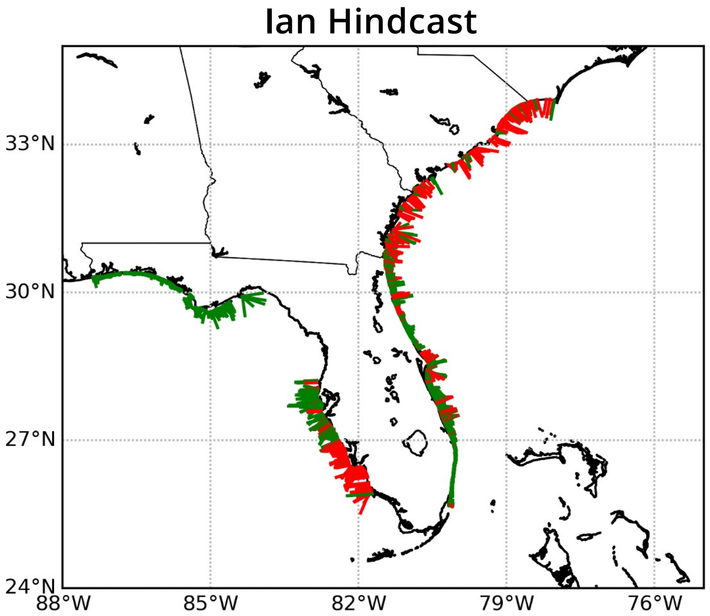
**Blue + Orange = GOOD!**



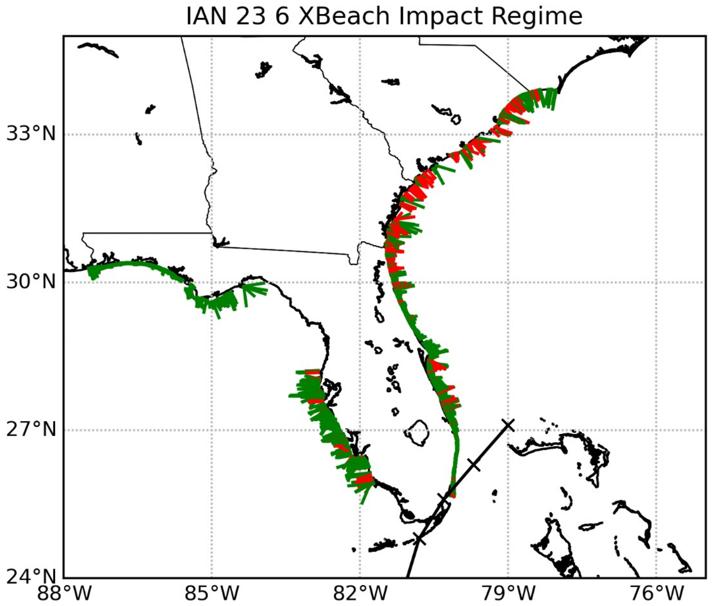

0000 UTC
9/23/22

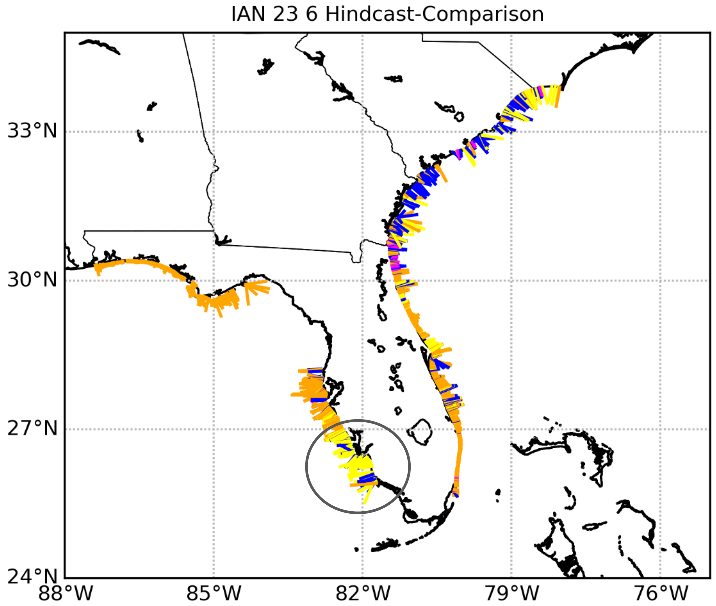
advisories every 6 hours

1800 UTC
9/29/22




VS

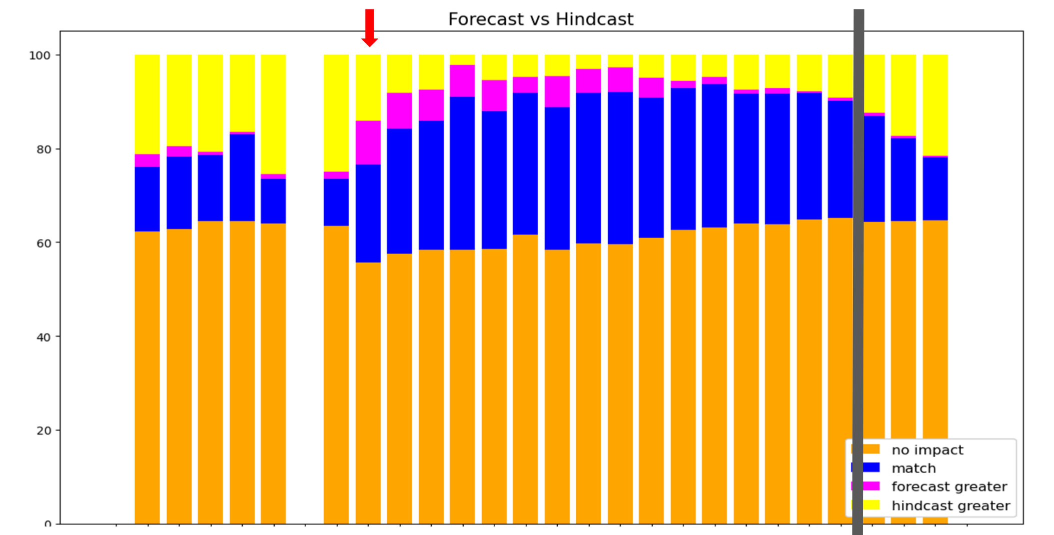


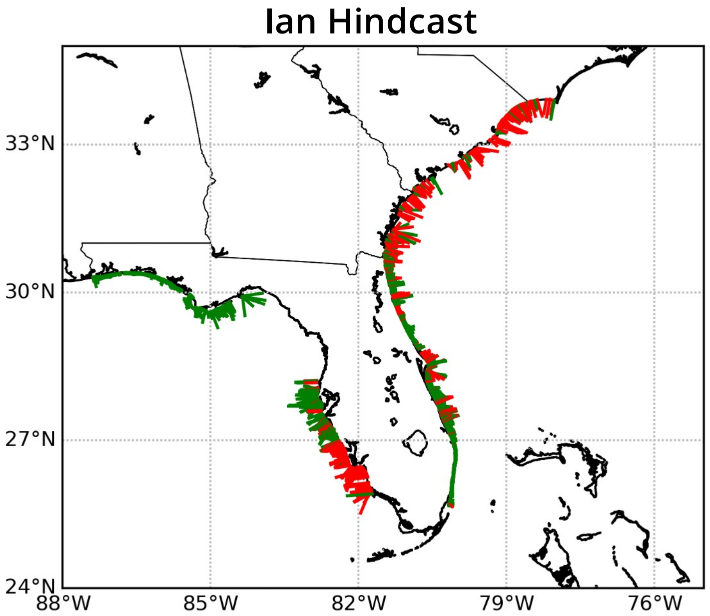
# Track uncertainties influence erosion forecasts



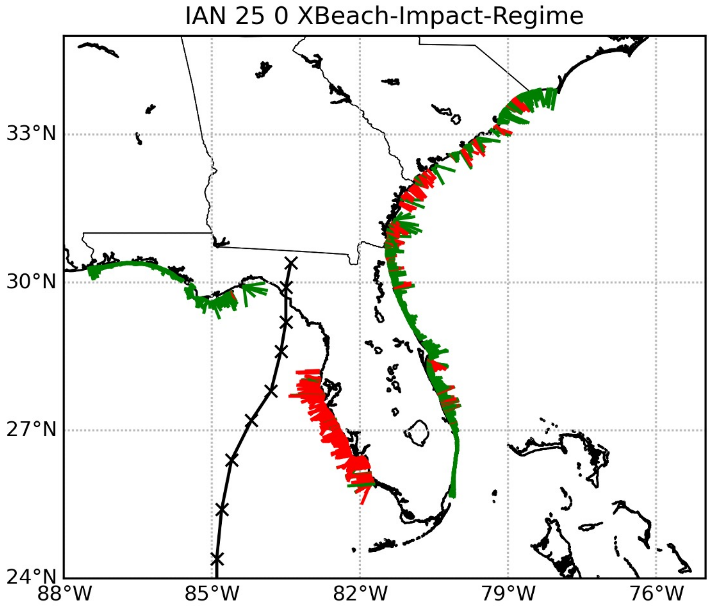
**Blue + Orange = GOOD!**

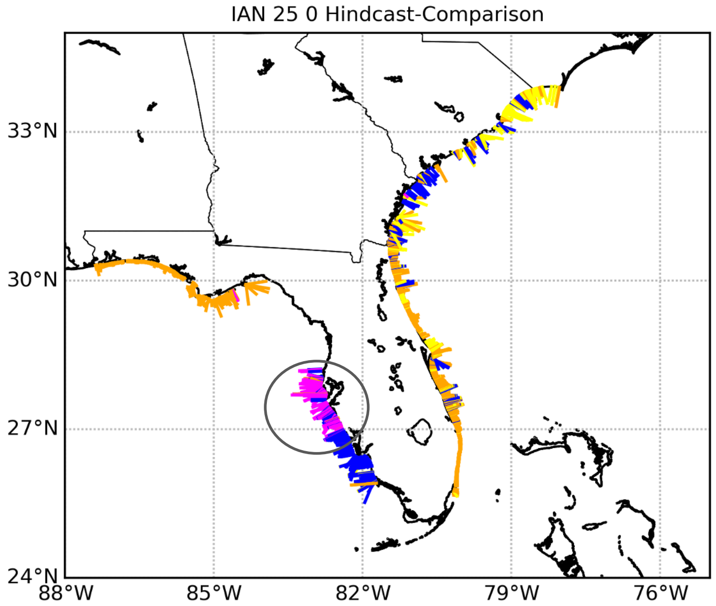



0000 UTC 9/23/22 — advisories every 6 hours — 1800 UTC 9/29/22




VS



# Track uncertainties influence erosion forecasts

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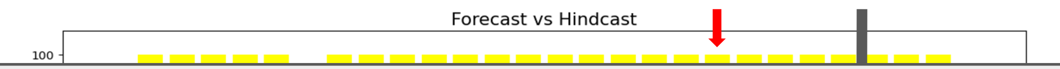
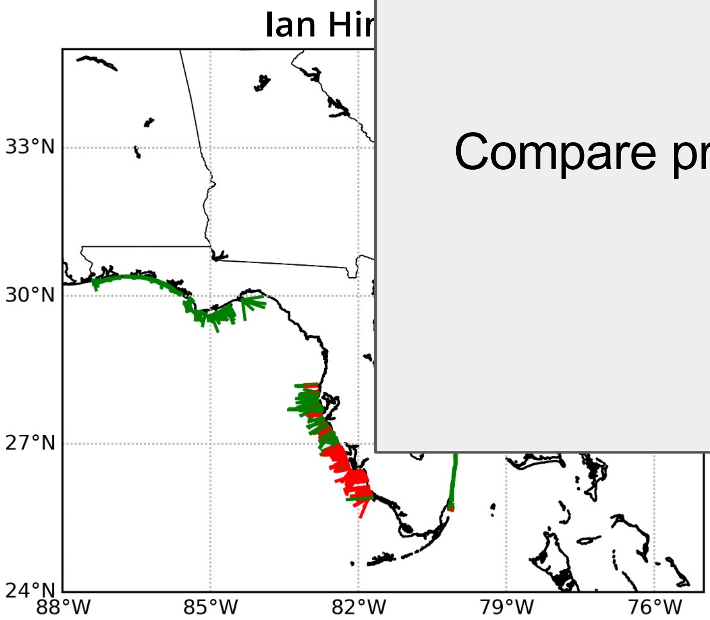


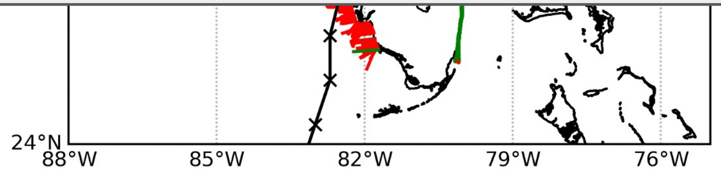

**Takeaway:**

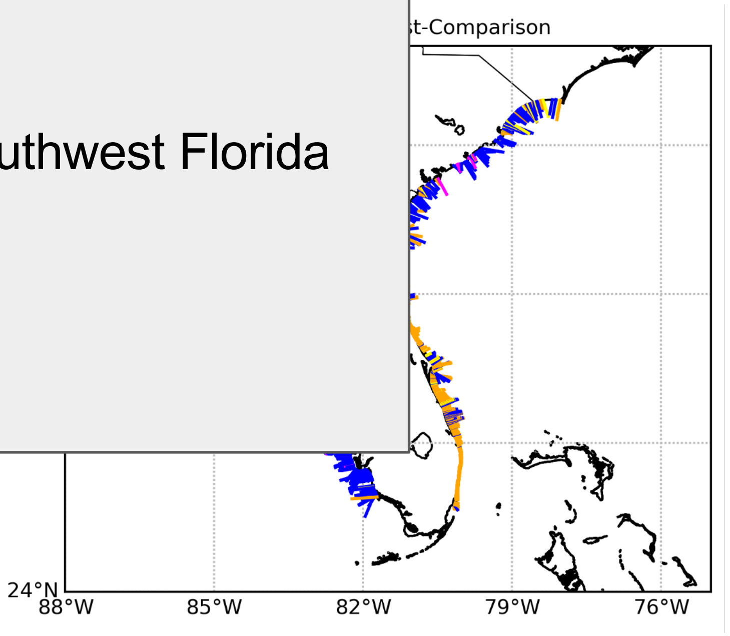
Track uncertainties play a large role in impact prediction accuracy

**Next Step:**

Compare prediction between forecast approaches in southwest Florida



# Southwest Florida Region Qualitative Observations

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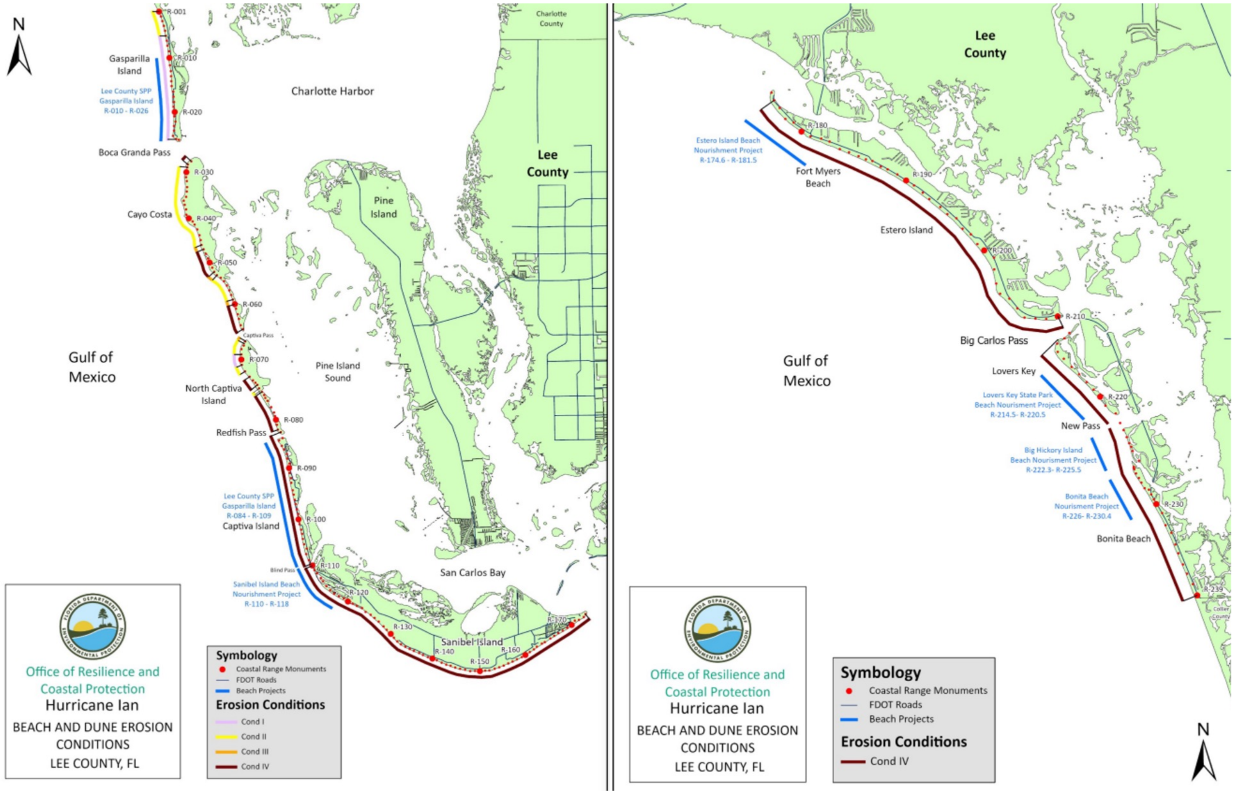
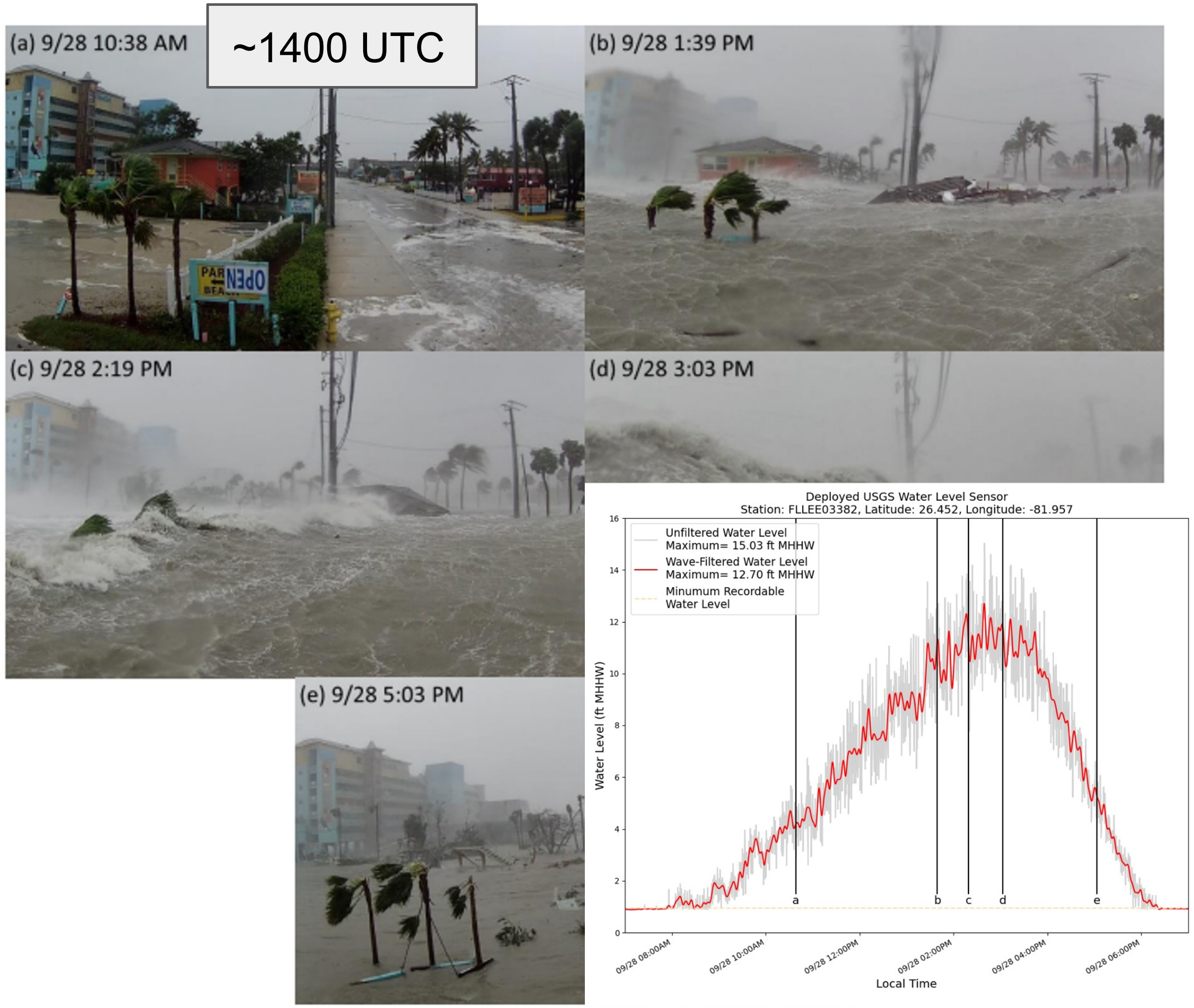



[Credit: Florida Department of Environmental Protection Hurricane Ian & Hurricane Nicole Preliminary Post-Storm Beach Conditions and Coastal Impact Report]



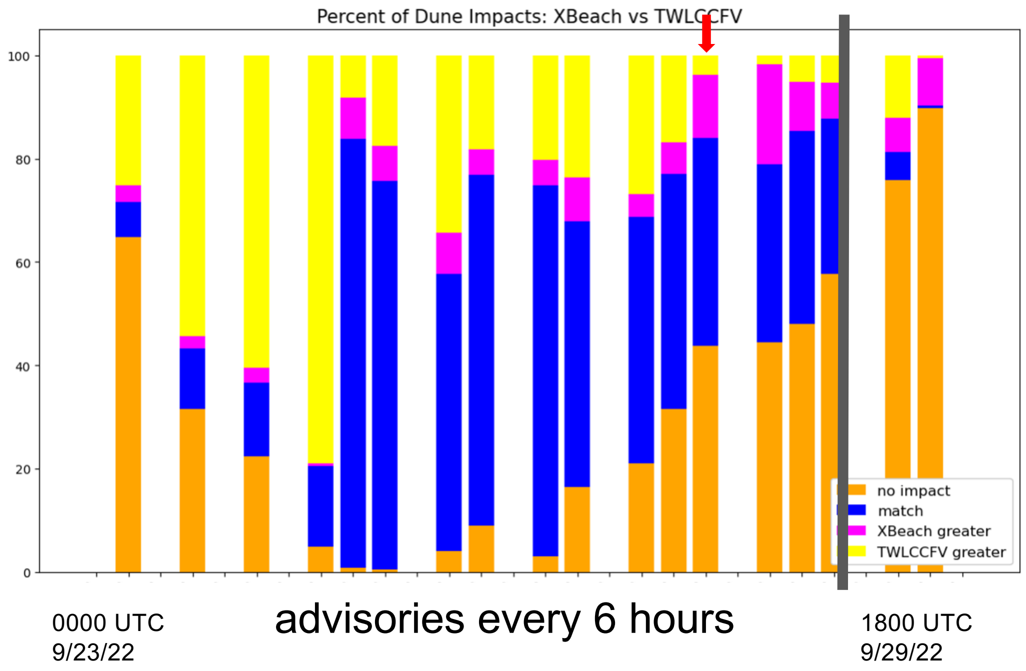

Fort Myers, local time [Credit: Max Olson- NHC Tropical Cyclone Report: Hurricane Ian (2023)]

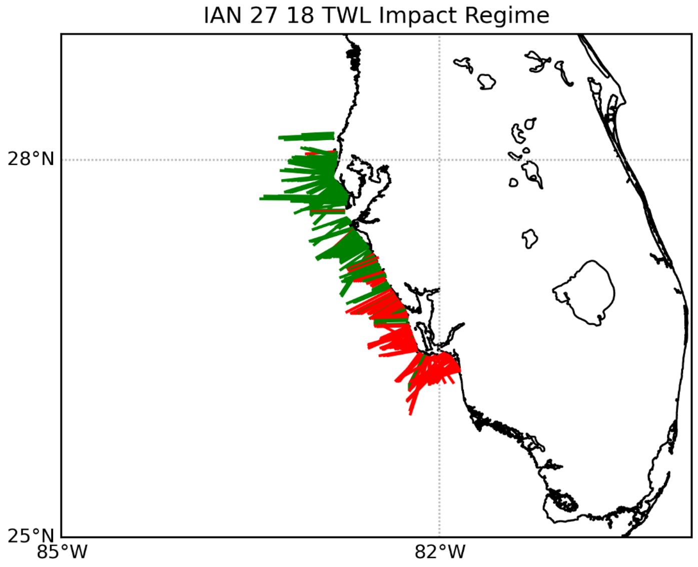
# XBeach vs TWLCCFV



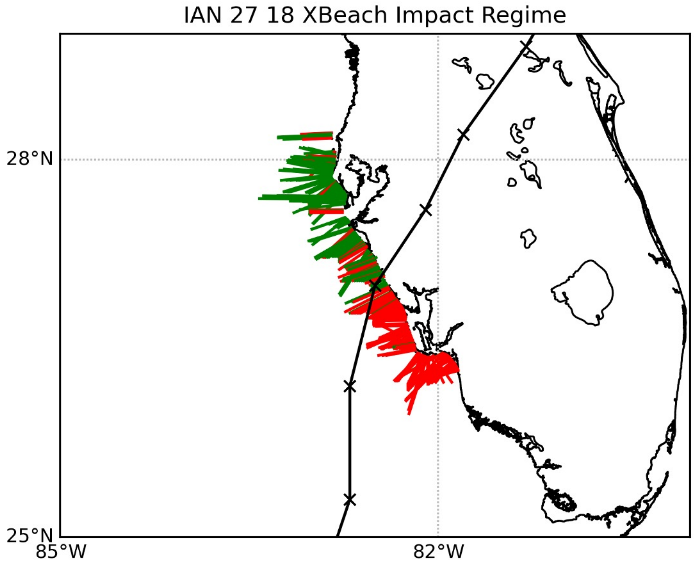
> 80% agreement near landfall

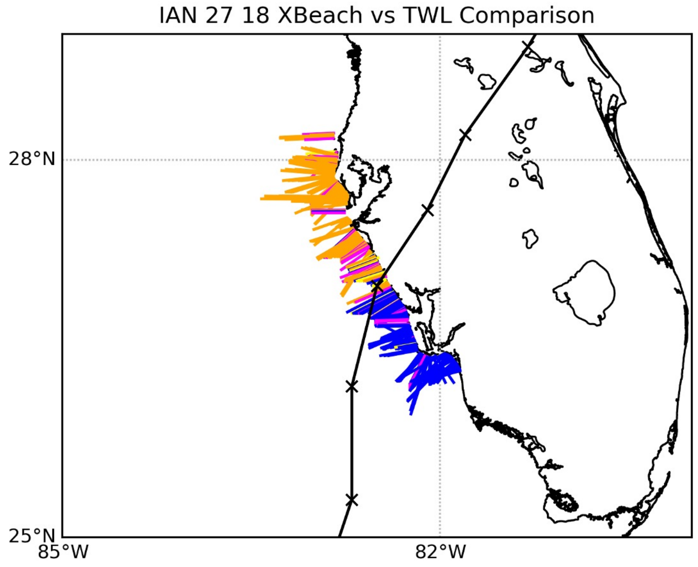
most disagreements near the eye



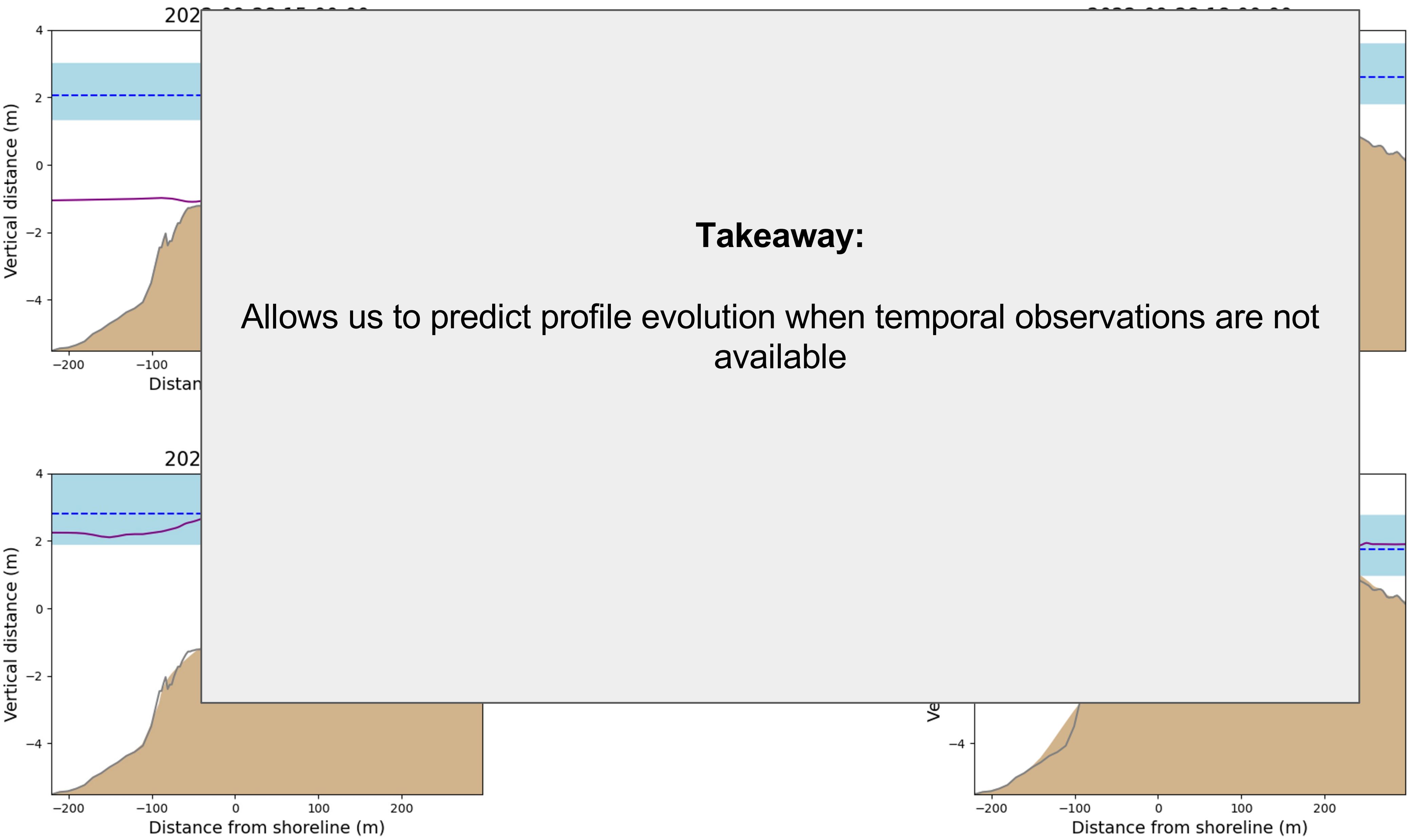

vs



# Longer duration of dune impact with dynamic bed






**Takeaway:**

Allows us to predict profile evolution when temporal observations are not available

# Main Takeaways

- Modeling framework is **efficient** and reasonably **accurate**
- Track uncertainties heavily influence erosion predictions
- Binary dune impact classification captures coastal vulnerability
- Dynamic ground surface **improves our understanding of profile evolution** during an extreme event

# Future Work

- XBeach sensitivity testing
  - Transect length sensitivity
- Remove back ‘wall’ boundary condition
  - Additional parameter calibration to prevent over-erosion
- Fully-automate modeling process
  - Replace user-specified selection method
- Trigger more robust 2D modeling
  - Use 1D profiles to initiate 2D domains

# Thank you!