Development and Applications of an Ocean, Infragravity Wave, Morphological, and Structural Response Coupled Nearshore Prediction System

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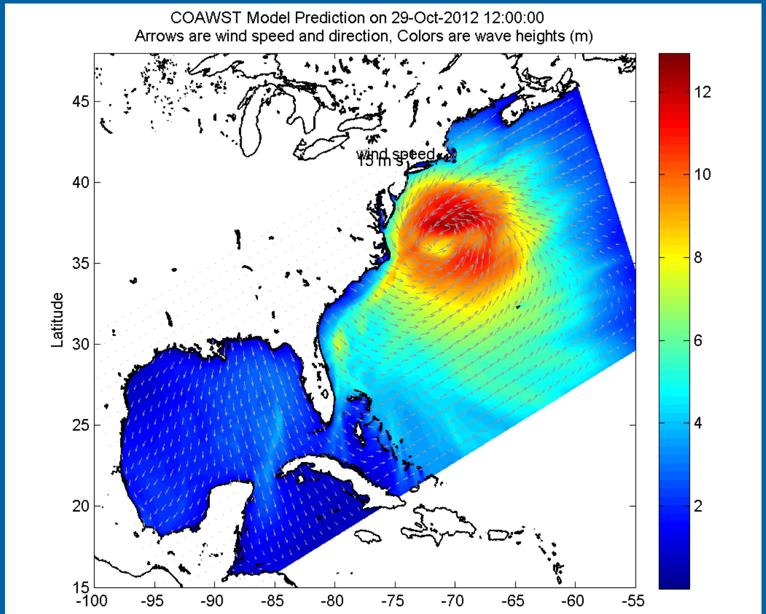
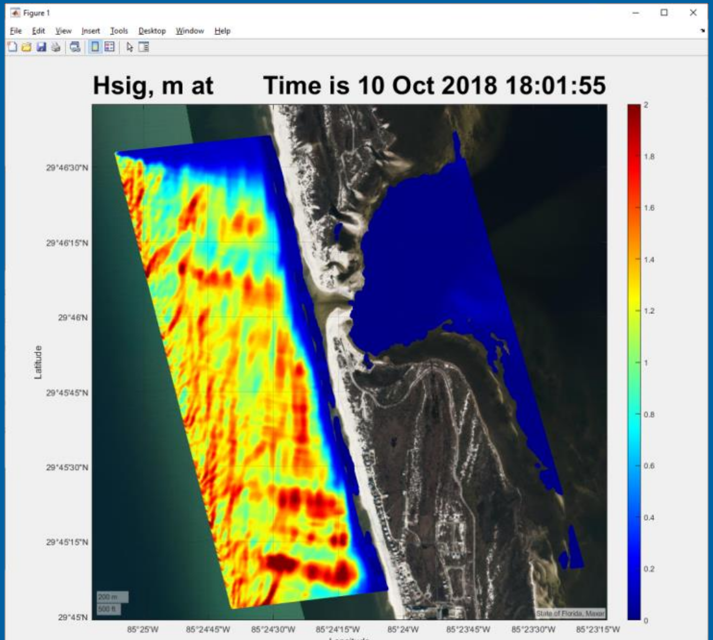
Regional Scale (km's)



Hurricane Sandy, 2012

Coastal Scale (m's)



Hurricane Michael, Oct 2018

Funding Support from: ONR N0001421IP00066
NOPP Hurricane Coastal Impacts (NHCI) Project

USGS science for a changing world

U.S. Department of the Interior
U.S. Geological Survey

Outline

COAWST modeling system overview

Model Coupling – physics fields exchanged

InWave infragravity wave model

Sediment Model components

Hurricane Michael

Coastal erosion impacts

Structure damage assessments

USGS

NOPP Hurricane Coastal Impacts (NHCI) Project
www.nopp.org

NOPP:

The National Oceanographic Partnership Program (NOPP) is a collaboration of Federal agencies which facilitates partnerships between Federal agencies, academia, industry, and others in the ocean scientific community to advance ocean science research and education

Task 0) Provide hindcasts and forecasts of hurricane track and intensity predictions for CONUS landing hurricanes

Task 1) Build and update Digital Elevation Models (DEM)

Task 2) Satellite remote sensing for ground-truthing DEMs and geophysical measurements during the storms

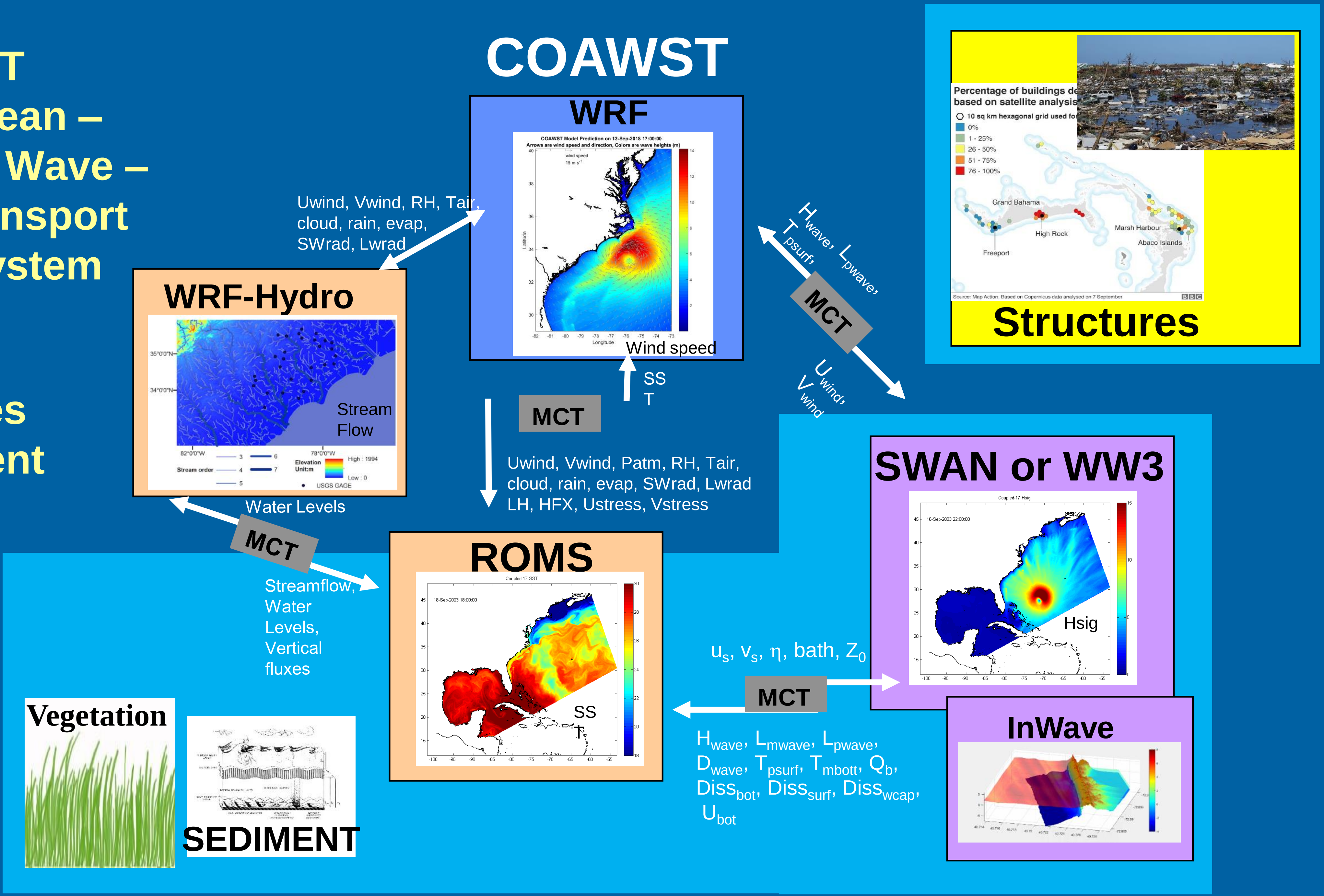
Task 3) In situ measurements of waves, currents, and water levels prior to and during landfall.

Task 4) Forecasting of wave, surge, sediment transport, structure interaction and damage

COAWST
Coupled Ocean – Atmosphere – Wave – Sediment Transport Modeling System

+

Structures Assessment



USGS

WAV 2 OCN

Hwave	height
Lmwave	length mean
Lpwave	length peak
Dwave	direction
Tpsurf	period surface
Tmbot	period bottom
Qb	percent breaking
Dissbot	Bottom dissipation
Disssurf	Breaking dissipation
Disswcap	Whitecap dissipation
Ubot	Bottom orbital velocity

USGS

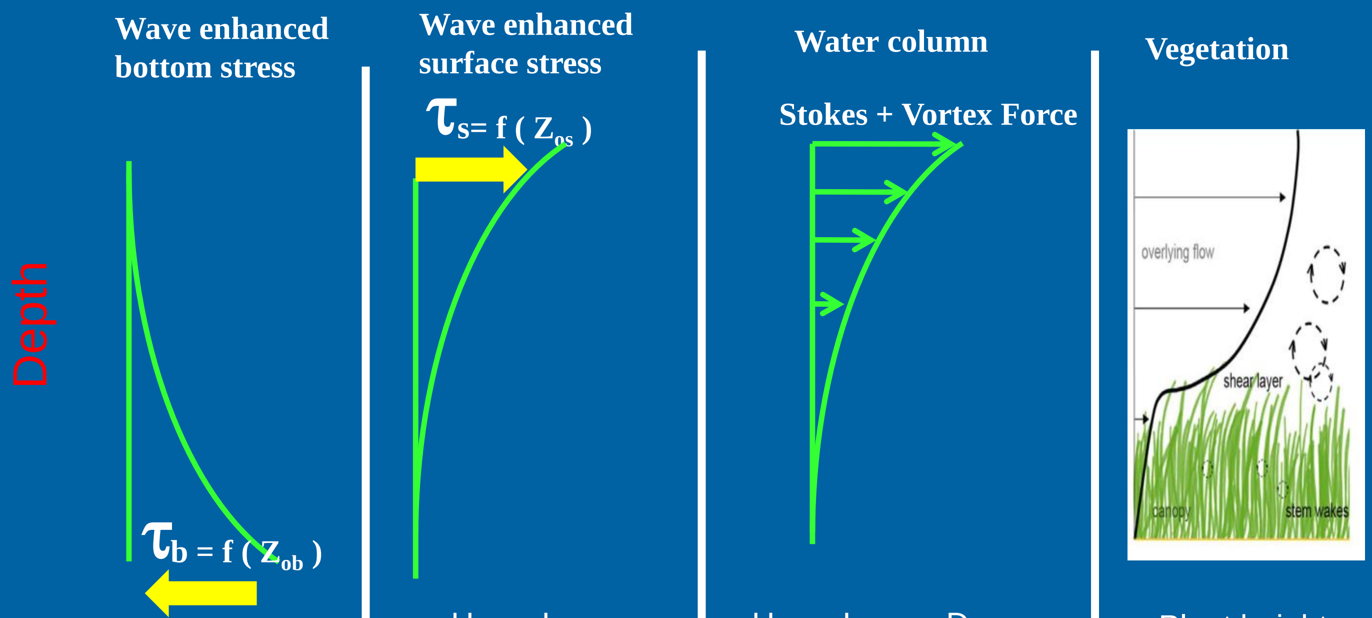
Receiving component updated physics.

Warner, J.C., Sherwood, C.R., Signell, R.P., Harris, C.K., and Arango, H.G., (2008) “Development of a three-dimensional, regional, coupled wave, current, and sediment-transport model.” *Computers and Geosciences*, 34, 1284-1306.

Olabarrieta, M., Warner, J.C., and Armstrong, B. (2012). “Ocean-atmosphere dynamics during Hurricane Ida and Nor'Ida: an atmosphere-ocean-wave coupled modeling system application.” *Ocean Modelling*, 43-44, pp 112-137.

Kumar, N., Voulgaris, G., Warner, J.C., and M., Olabarrieta (2012). Implementation of a vortex force formalism in a coupled modeling system for inner-shelf and surf-zone applications. *Ocean Modelling*, 47, 65-95.

Beudin, A., Kalra, T. S., Ganju, N. K., and Warner, J.C. (2016). Development of a coupled wave-flow-vegetation interaction module. Computers and Geosciences, http://dx.doi.org/10.1016/j.cageo.2016.12.010



H_{wave}, L_{mwave}, D_{wave}, T_{mbott}, U_{bot}

H_{wave}, L_{pwave}, D_{wave}, T_{psurf},

H_{wave}, L_{mwave}, D_{wave}, T_{psurf}, Q_b, $Diss_{bot}$, $Diss_{surf}$, $Diss_{wcap}$,

Plant height, density, stem thickness, diameter

OCN 2 WAV

u_s	current eastward
v_s	current northward
η	water level
bath	bathymetry (morphology)
Z_0	bottom roughness f(sed)

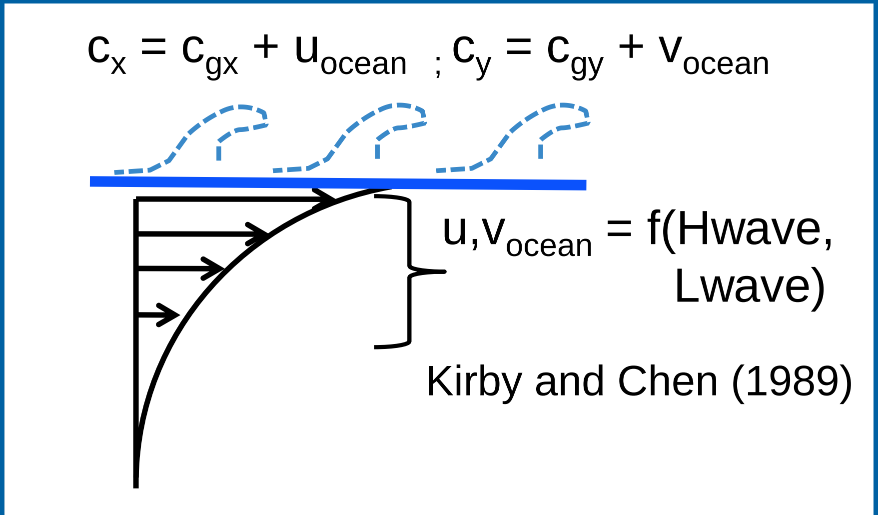
1) **Generation**

wind speed forcing is modified by ocean currents

$U_{wind} - u_{ocean}$; $V_{wind} - v_{ocean}$

2) **Propagation in geographic space**

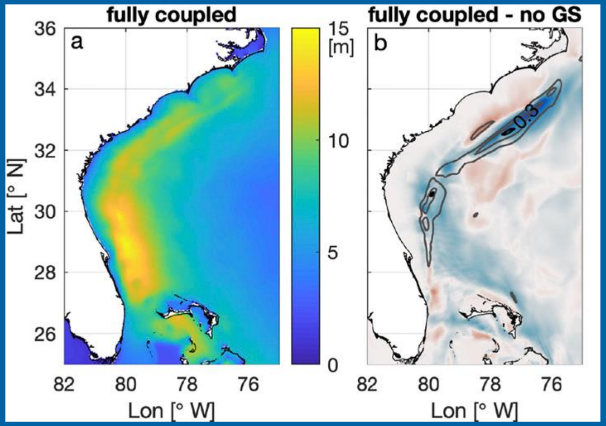
wave celerity is modified by ocean currents



3) **Propagation in theta space**

change of wave direction (refraction) due to η, bathy, and currents:

Hegermiller, C.A., J.C. Warner, M. Olabarrieta, and C.R. Sherwood, 2019: Wave–Current Interaction between Hurricane Matthew Wave Fields and the Gulf Stream. J. Phys. Oceanogr., 49, 2883–2900



Variation in H Matthew wave heights due to Gulf Stream

USGS

InWave – nearshore infragravity wave model

Wave action balance transport equation in Cartesian coordinate system

$$\frac{\partial(A)}{\partial t} + \frac{\partial\left(C_{g,x}A\right)}{\partial x} + \frac{\partial\left(C_{g,y}A\right)}{\partial y} + \frac{\partial\left(C_{g,\theta}A\right)}{\partial \theta} = -\frac{D_w}{\sigma}$$

$$C_{g,x} = C_g \cos\theta + U$$

$$C_{g,y} = C_g \sin\theta + V$$

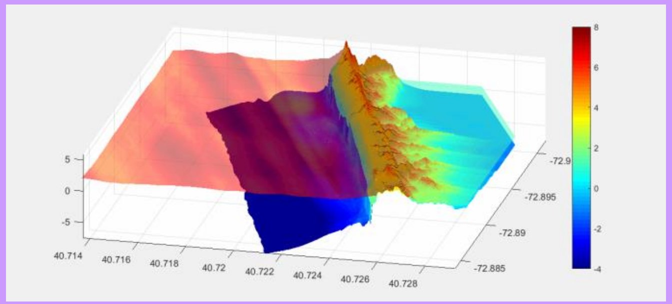
$$C_{g,\theta} = \frac{\sigma}{\sinh(2kh)}\left(\frac{\partial h}{\partial x}\sin\theta - \frac{\partial h}{\partial y}\cos\theta\right) + \cos\theta\left(\frac{\partial U}{\partial x}\sin\theta - \frac{\partial U}{\partial y}\cos\theta\right) + \sin\theta\left(\frac{\partial V}{\partial x}\sin\theta - \frac{\partial V}{\partial y}\cos\theta\right)$$

Wave dispersion relation + Doppler relation

$$\sigma = \sqrt{gk\tanh(kh)}$$

$$w = \sigma + \vec{k}\cdot\vec{u}$$

$$C = \frac{gk\tanh(kh)}{\sinh(2kh)} \qquad C_g = 0.5C\left(1 + \frac{2kh}{\sinh(2kh)}\right)$$



Eikonal equation

$$\frac{\partial k_x}{\partial t} = -\frac{\partial(w)}{\partial x} \qquad \frac{\partial k_y}{\partial t} = -\frac{\partial(w)}{\partial y} \qquad |\vec{k}| = k_x^2 + k_y^2$$

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Convert Wave: A → Hwave, Dwave

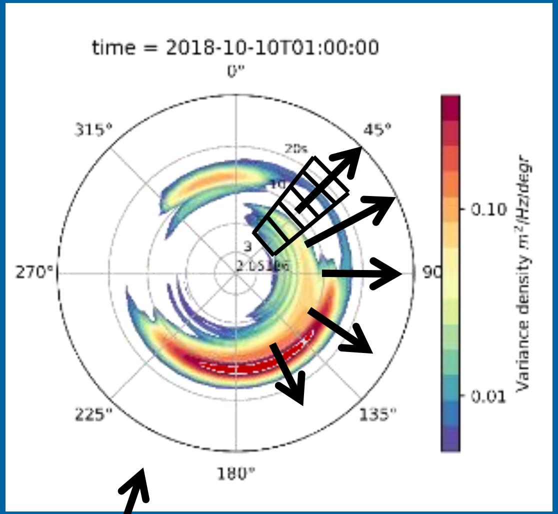
k → Lwave

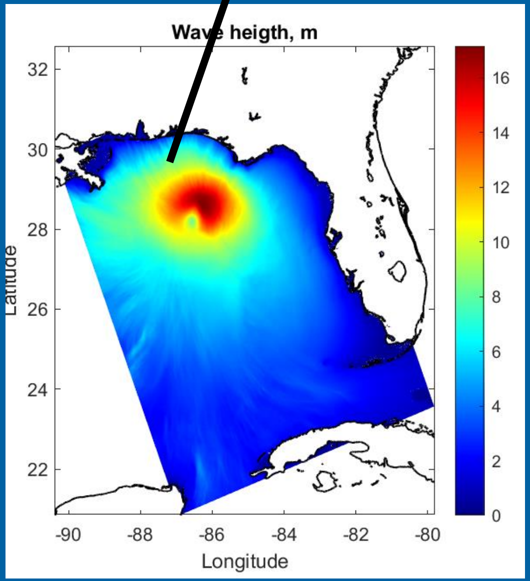
ROMS

Vortex Force
3D
hydrodynamics

InWave wave group bc's

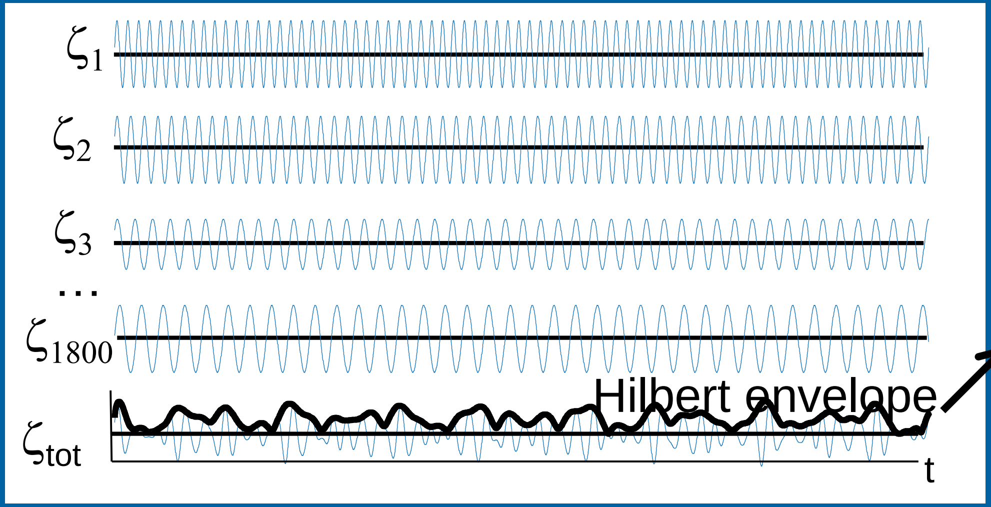
2D spectra



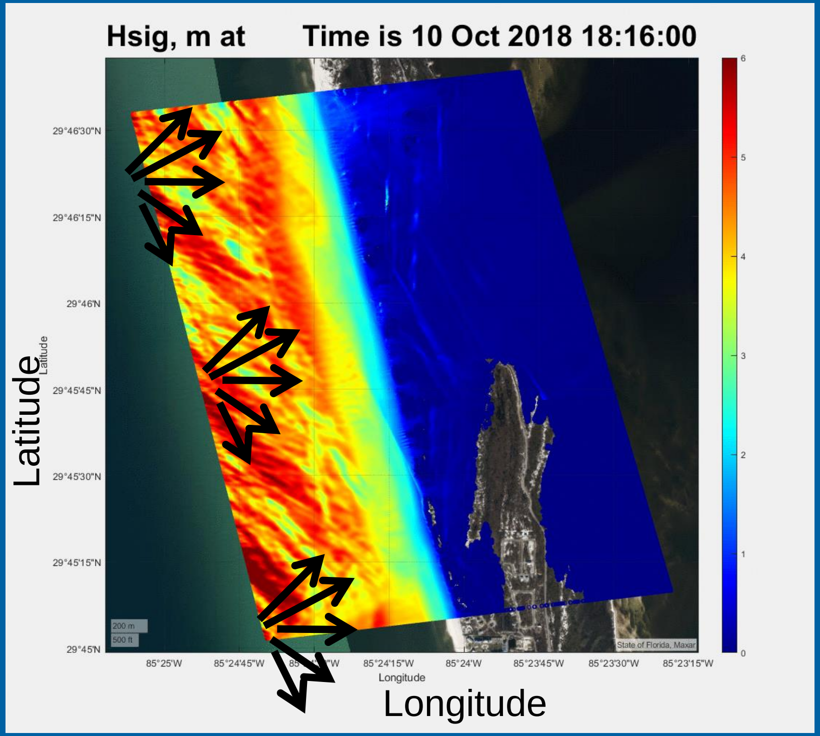


For each direction:

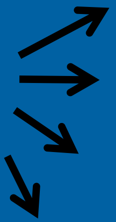
- compute water level time series for each freq.
- ζ = amp * sin(2πf t + phase + k L)
- 3600 s time series
- 1800 freqs
- sum them up, take Hilbert envelope



Impose BC's at every point along the open boundary.



Repeat for other directions.
Use ~ 15 degree directional bins.



WaveAction = ρ g $(2\eta)^2$ T / (16 π)

Adding this feature to WW3 !
(w3updtmd.ftn)

Sediment and Nearshore Processes

Vortex Force
Wave energy dissipation transferred from WAV to OCN model to drive ocean momentum.
Kumar et al, 2010

Vertical turbulent mixing

Generic Length Scale (GLS) by Umlauf and Burchard (2003), as implemented by Warner et al (2005).

Surface tke flux from wave breaking

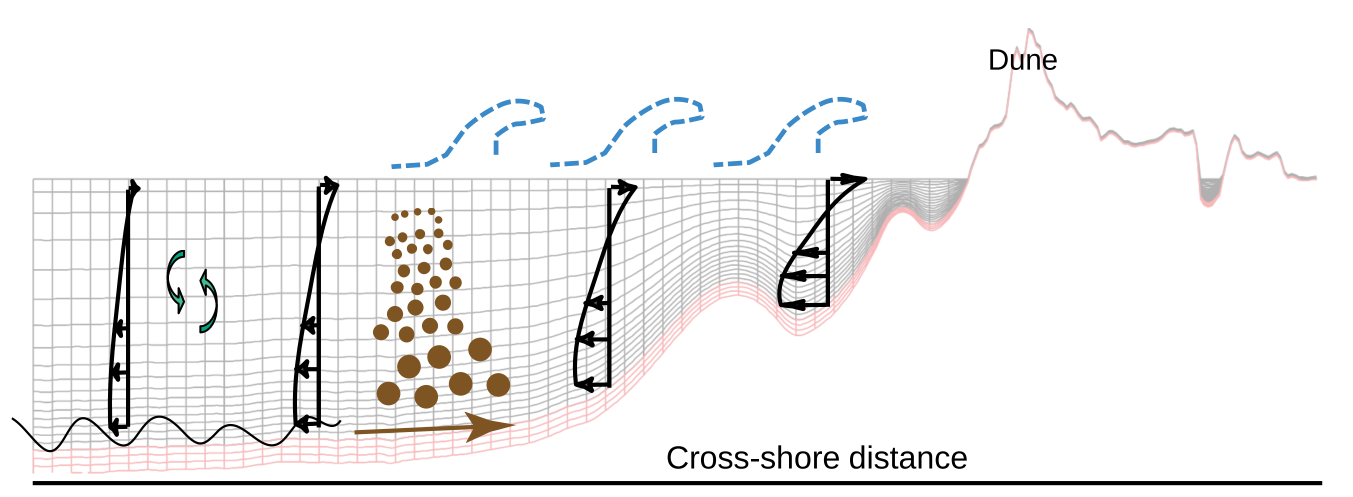
- Vertical tke flux from surface wave breaking
- surface flux boundary conditions to GLS

Roller model

Transfers non-breaking wave momentum flux landward
Reniers et al., 2004.

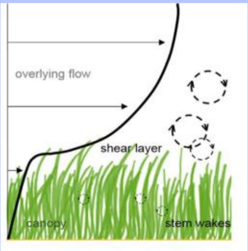
Wetting / Drying

- User defined Dcrit establishes minimum depth criteria.
- Flux onto a dry (or wet) cell is always permitted.



Vegetation

Momentum loss throughout vertical height of plant layer
Beudin,et al., 2016

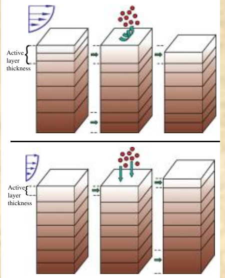


Wave-current bottom boundary layer

- Enhanced bottom stress from oscillatory wave motion
- Enhanced bed stress for currents and Erate
- Compute sand ripple dimensions

Dune slumping

- Dune slope slumping criteria
- Bed slope transport

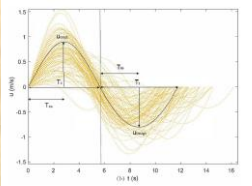


Bed model

- 3D underlies hydro grid
- constant number of bed layers
- erosion: material removed from top layer
- deposition: material is added to top layer
- layers are merged or separated based on user criteria

Bedload Transport

- Meyer-Peter Muller (1948)
- Soulsby and Damgaard (2005)
- Van der A et al. (2013)
  wave asymmetry based mobility



Suspended-Sediment Transport

- Tracer advection w/ Sources/Sinks.
- Flux resuspension
- WENO settling algorithm (no CFL)
- Multiple sediment classes: settling velocity, density, erosion rate, bed porosity, grain diameter, and critical stress for erosion.

Morphology

- Update seafloor elevation as sediment is transported and bed model evolves.
- Update of this bed elevation is critical to provide feedback to the circulation.
- Transfer elevations to WAV model critical.
- Implemented Implicit vertical advection for stability
- Implemented 5th order bed update elevation scheme

Hurricane Michael 2018

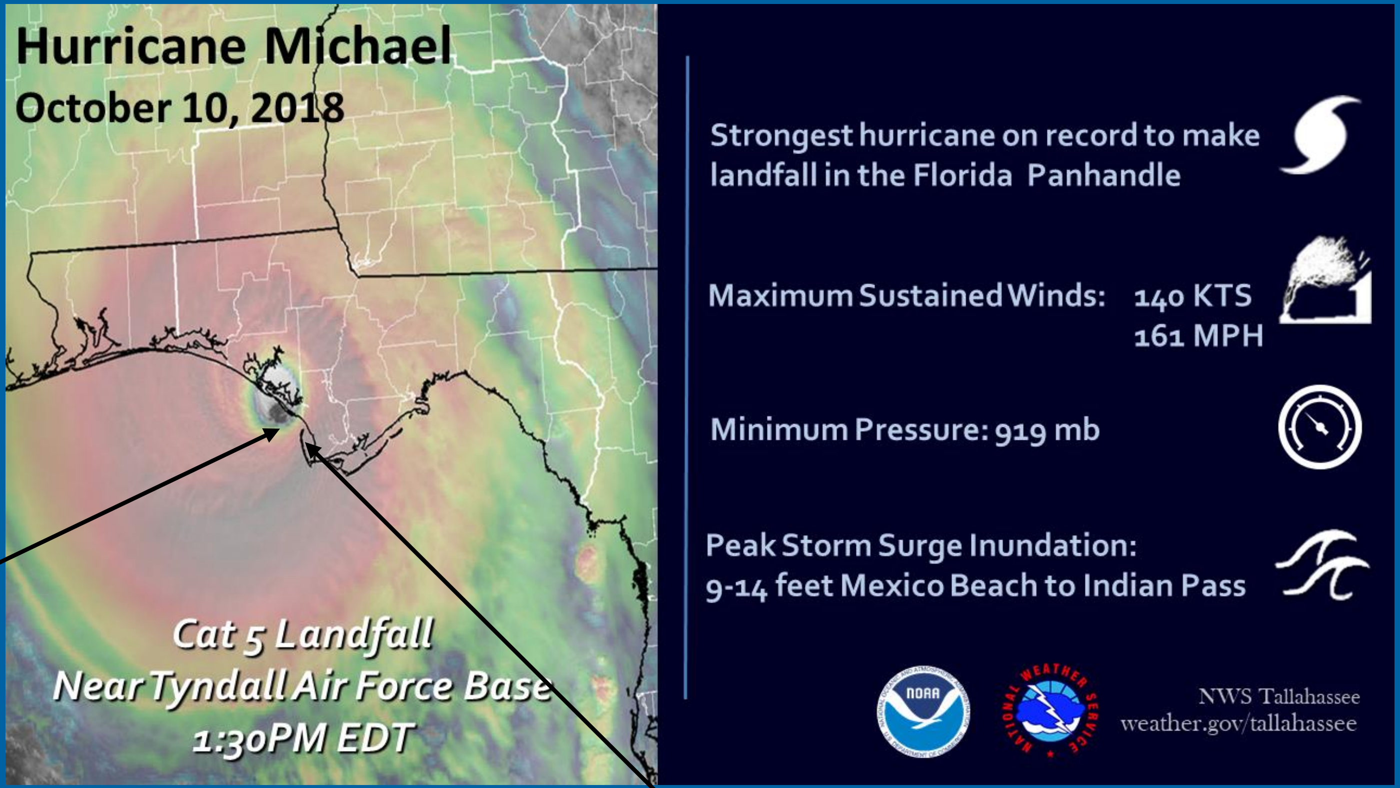
https://www.weather.gov/tae/HurricaneMichael2018

Structure Impacts

Figure 10. Aerial image of the devastation caused by Michael in Mexico Beach, Florida. Image courtesy of the NOAA National Geodetic Survey and the NWS Weather Forecast Office in Tallahassee, Florida.

Mexico Beach

Beven, Berg, and Hagen, NHC TC Report AL142018_Michael 2018.



Cape San Blas

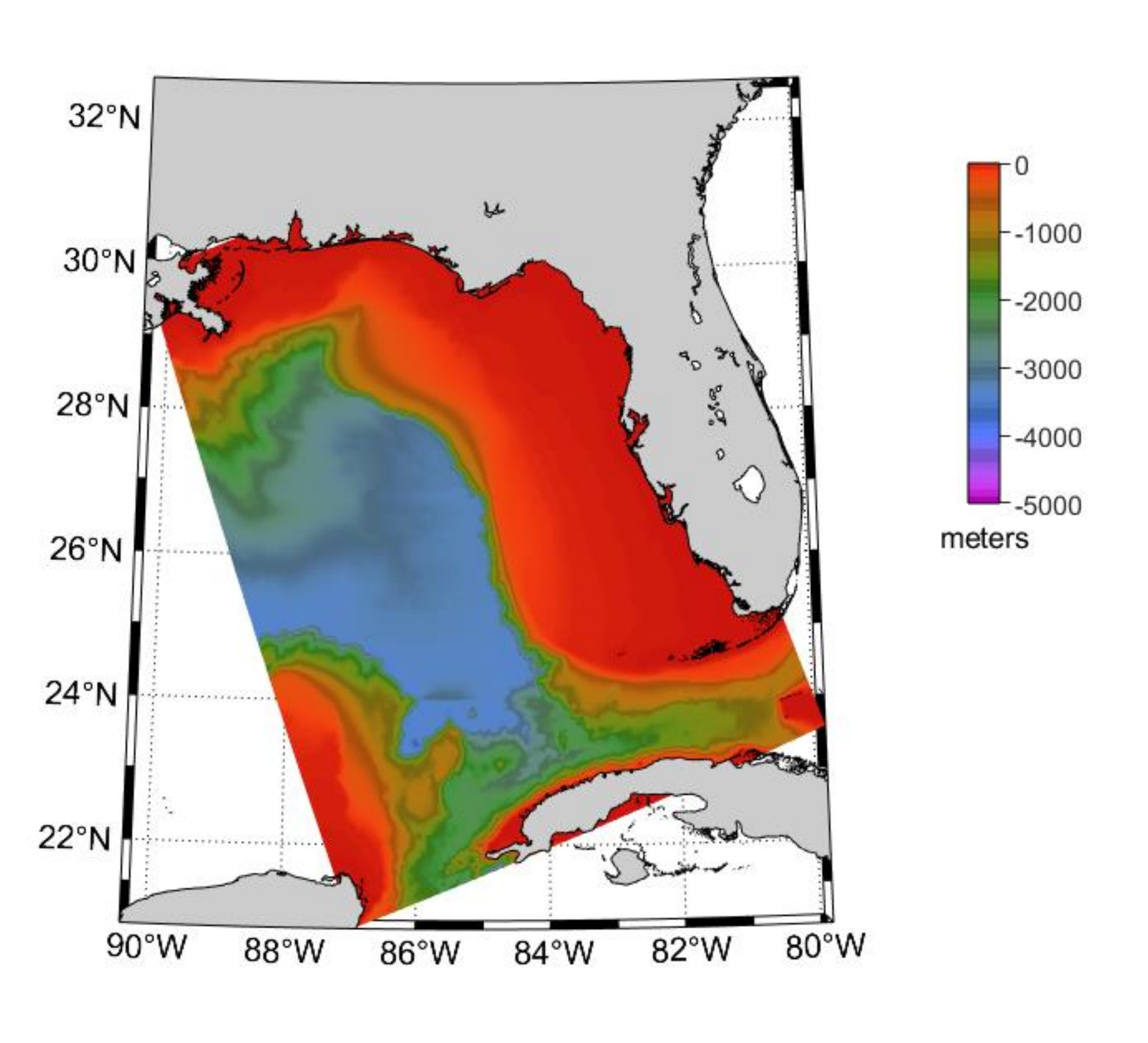
Geomorphic Impacts

https://www.usgs.gov/media/images/and-after-photos-show-hurricane-michaels-destructive-power-2

GoM Regional grids:
ROMS + SWAN simulation

<u>L1 Grid</u>

- 15 vertical layers
- Approx. 950 m horizontal resolution
- Init and boundary conditions from coarser grid covering all GoM and USEast coast.
- COMAPS-TC atmospheric forcings of 10m winds, atm pressure
-Tides TPOX 8.0
-Bathy GEBCO19
-Simulated Oct 7-11, 2018



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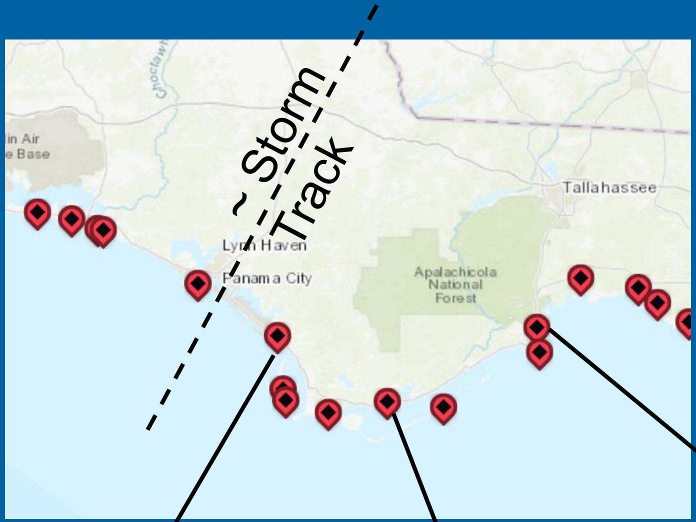
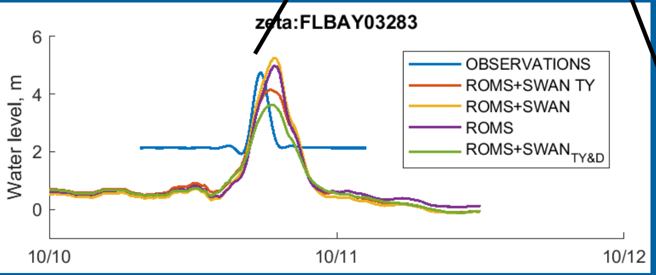
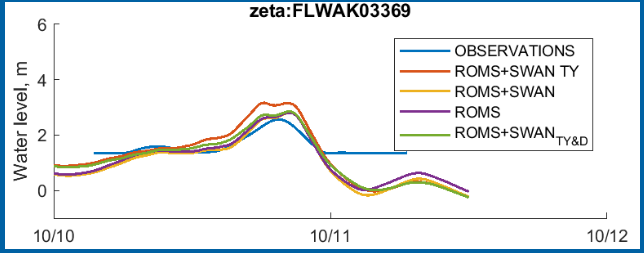
Water Level and Wave results



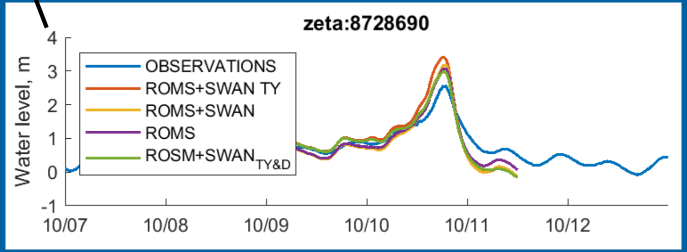
Water Levels



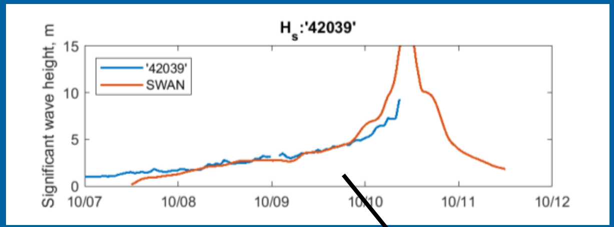
- FLBAY03283 (Mexico Beach)

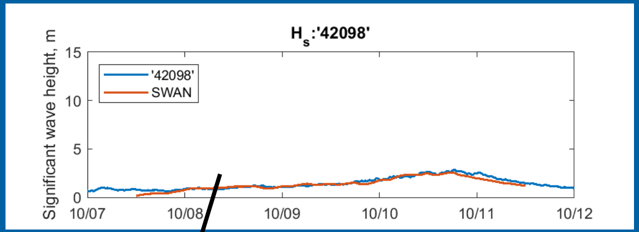


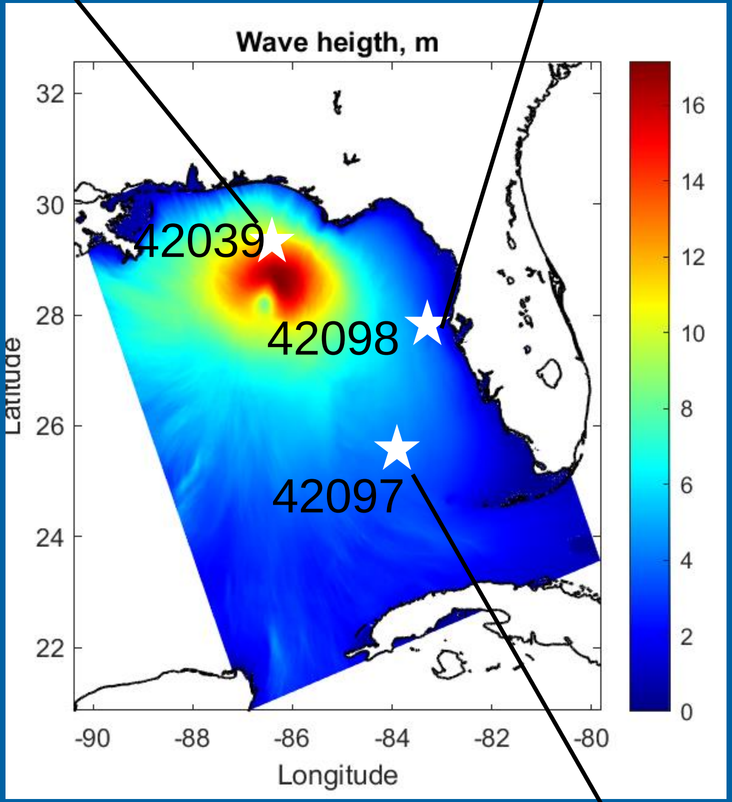
- FLWAK03369



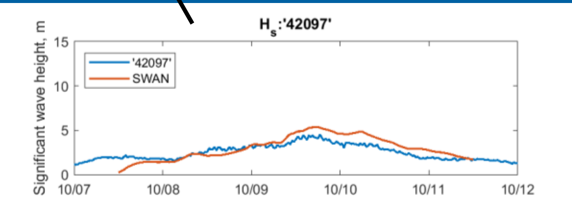
- Apalochicola 8728690







Wave Heights



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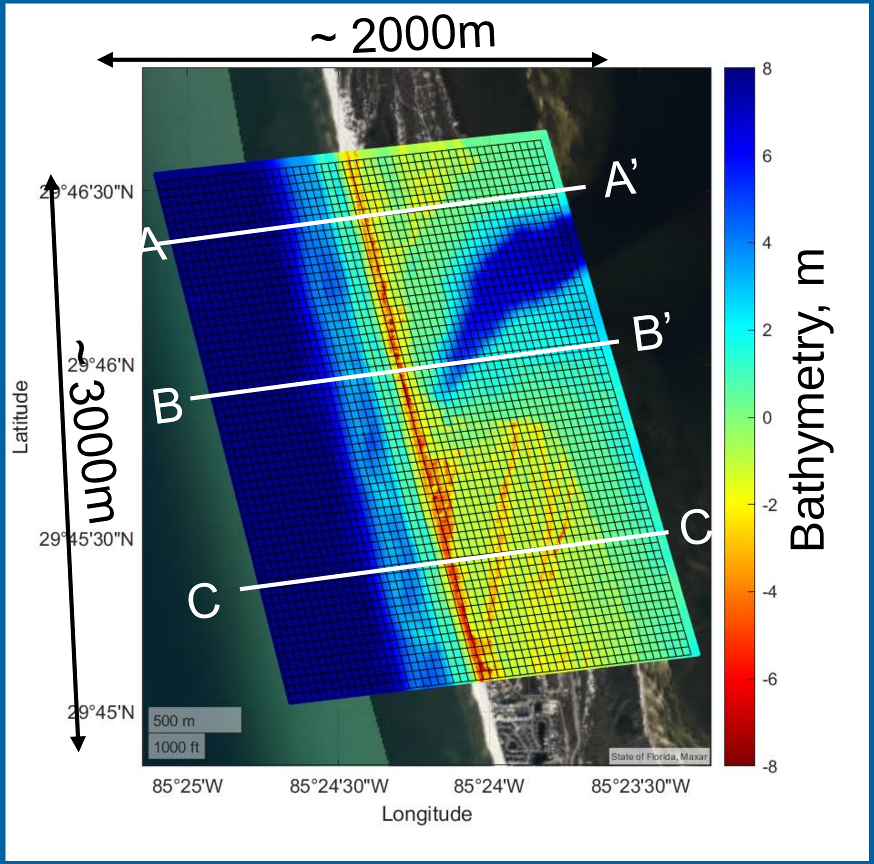
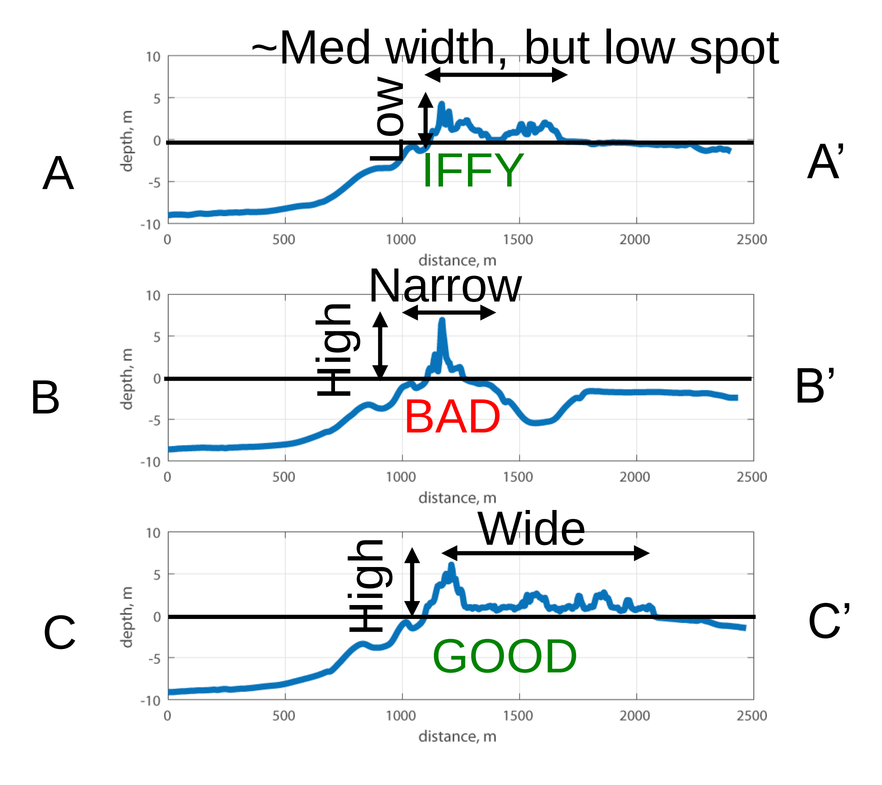
Cape San Blas nearshore grid



'ncei19_n30X00_w085X50_2019v1_pre_michael.tif'

Grid
550 cells 'x' , dx ~ 4m
650 cells 'y' , dy ~ 5m

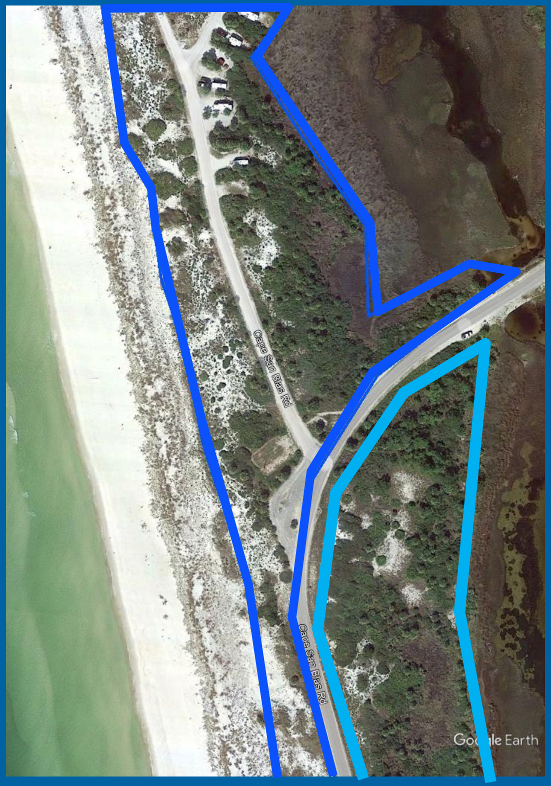
Cross-shore Profiles



Vegetation map

Areas defined as ‘vegetated’

Zoom in of vegetated area.



Parameters for Cape San Blas

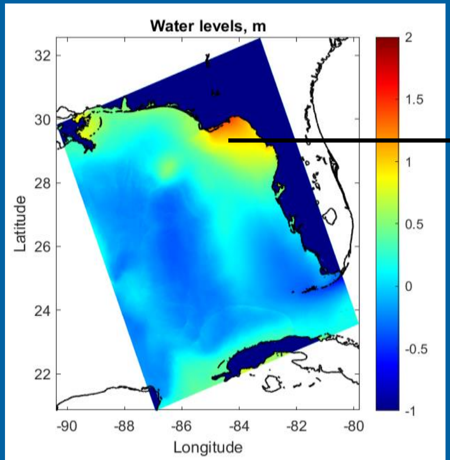
plant density	10 stems/m^2
plant diameter	0.03 m
plant thickness	0.005m
plant height	1.0m

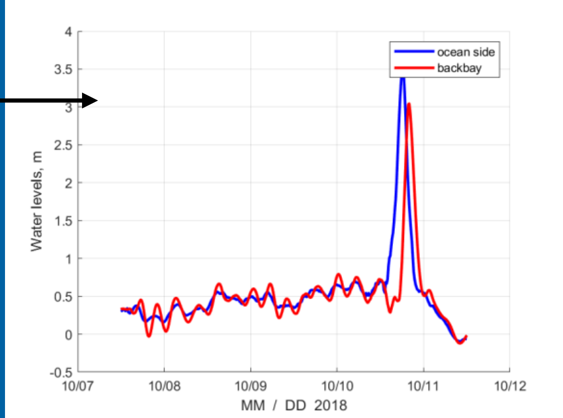
USGS

Very approximate vegetation cover for now.

Cape San Blas- forcings

Water levels

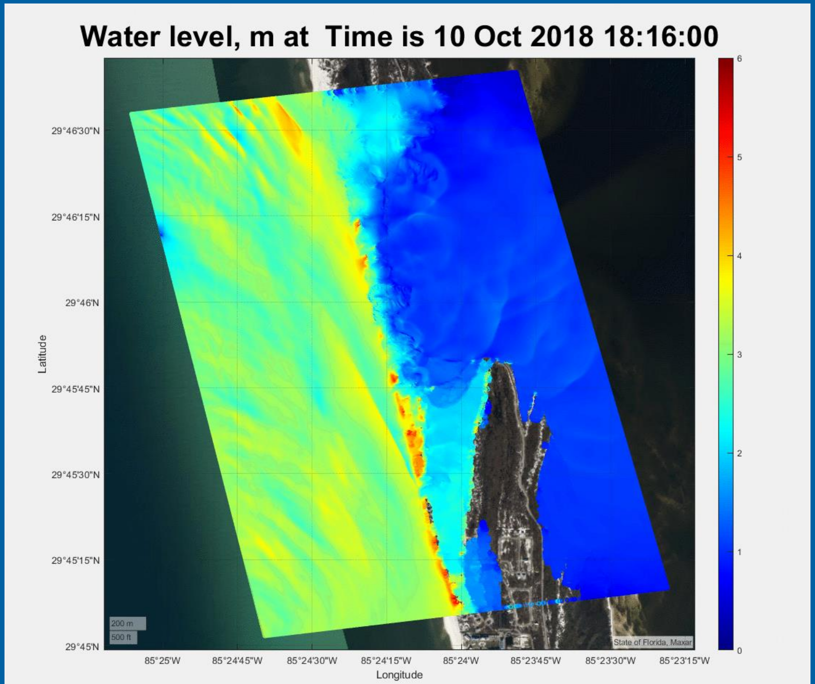




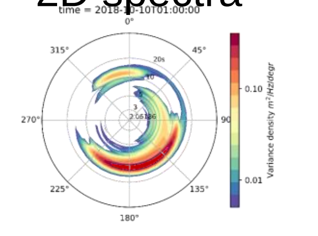
Extract data from coarser grid

Water levels

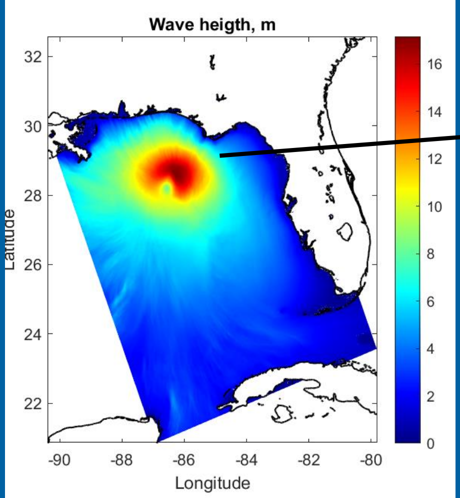
Simulated the storm event from Oct 10, 2018 to Oct 11, 2018



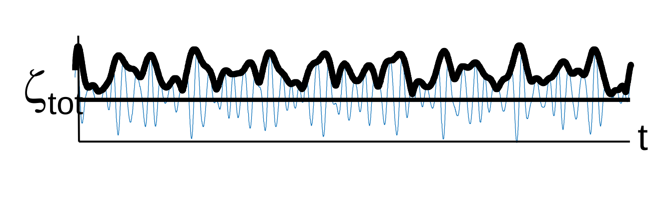
2D spectra



Waves

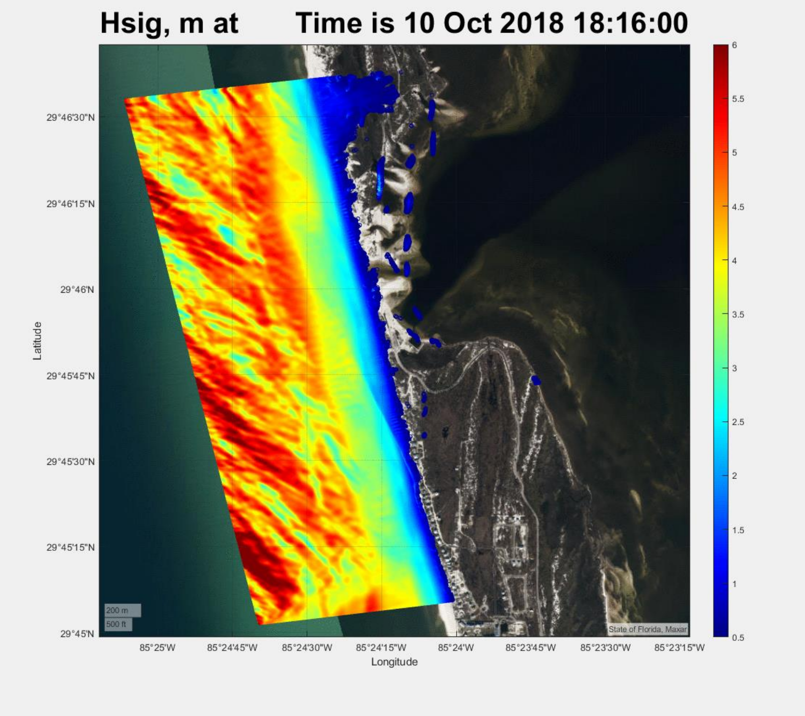


Extract data from coarser grid



Hilbert envelope over reconstructed water level time series.

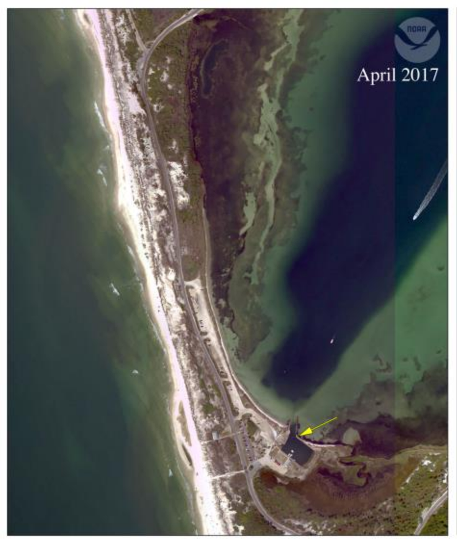
wave action density (wave group envelope)

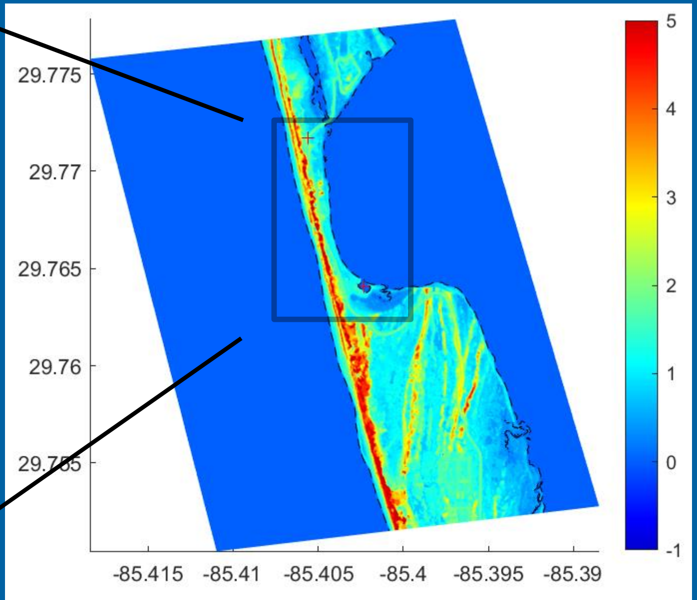


Cape San Blas breach

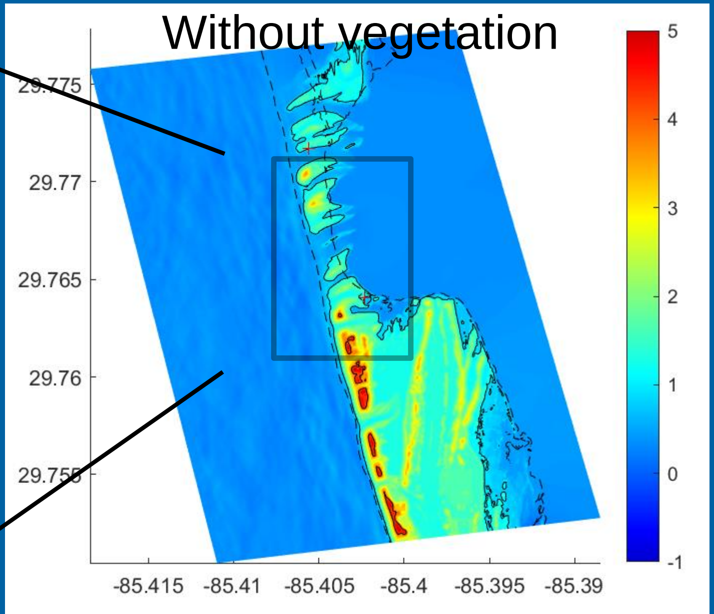
Elevations of water level and dunes, near mid tide.

before storm

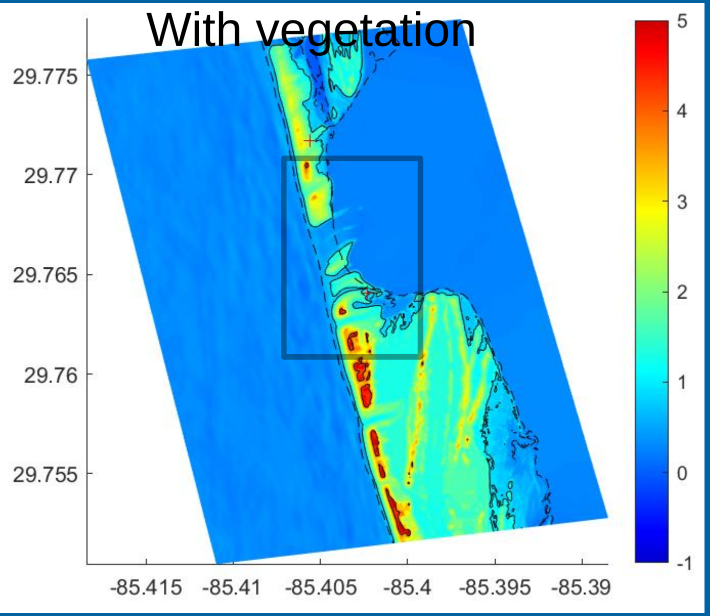




after storm



Excessive dune erosion and many breaches.



Limited erosion and breaches.

USGS

Damage to Structures – Objective

Buildings

STEER
STRUCTURAL EXTREME EVENTS RECONNAISSANCE

Surge

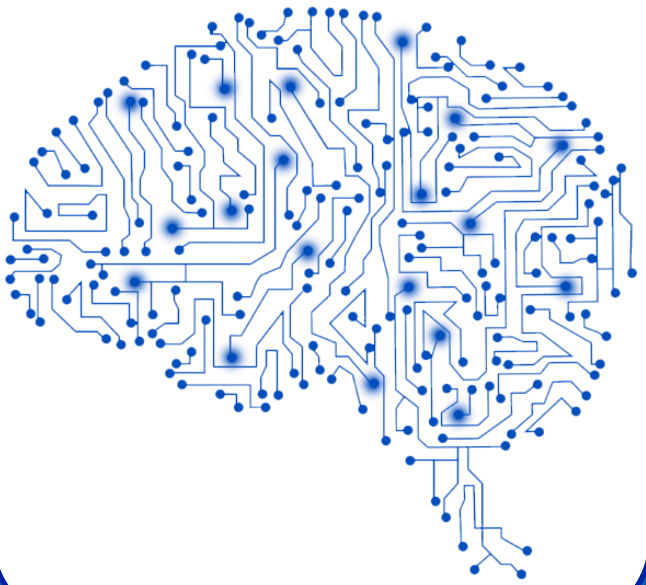
U.S. DEPARTMENT OF HOMELAND SECURITY
FEMA

Wind

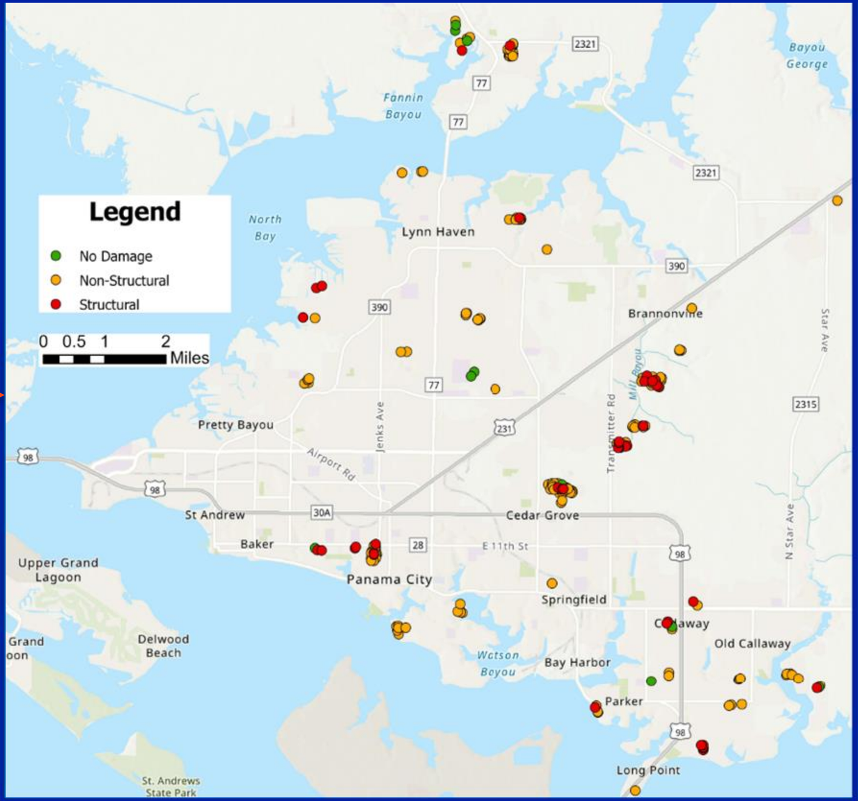
NATIONAL WEATHER SERVICE
National Hurricane Center

ARA

Machine Learning



Damage State Predictions



Damage to Structures – Results

Prediction Model

- Random Forest algorithm
- Trained on reconnaissance data

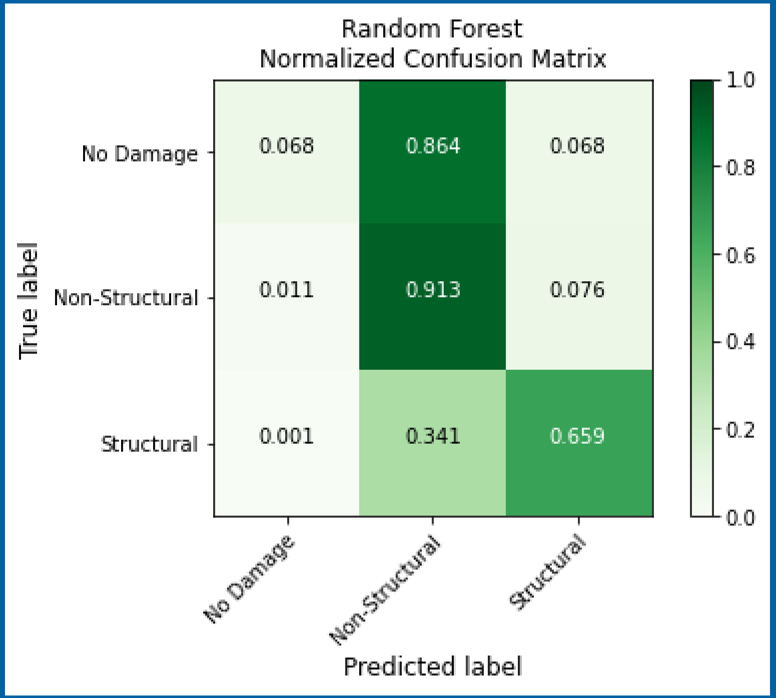
Important Input Features

- Design wind speed exceedance
- Age
- Distance to coastline
- Surge depth
- Wall structural type
- Roof structural type
- Number of stories
- Roof shape
- Wall cladding material

	Extent of failure in:		
Damage State	Roof/Wall Cover	Roof/Wall Substrate	Roof/Wall Structure
No Damage	0%	None	None
Non-Structural	> 0% and ≤ 50%	≤ 3 panels	None
Structural	> 50%	> 3 panels	Any

Hurricane Michael Case Study Performance

- Accuracy = 79%
- Over-conservative
  - Predicts No Damage as Non-Structural Damage
  - Very few “No Damage” samples in available data



Conclusions

NOPP Hurricanes Project is pulling together many needed resources to address predictions of landfall hurricanes.

Continuing to develop an Ocean-Atmosphere-Wave-SedimentTransport Modeling System to couple coastal storm processes.

Application of Hurricane Michael with larger scale grids simulated the wave, current, and water levels and provide boundary forcings for smaller scale models.

Cape San Blas smaller scale application (~ 4m grid spacing) simulated dune overtopping and barrier island breaching.

Inclusion of small/local scale (O~m) land use/cover features of vegetation resulted in more accurate simulation of breaching.

Developing a machine learning framework to predict categorical damage states to buildings in hurricane impact areas.

USGS