

STORM SURGE

An Introduction to Storm Surge and Storm Surge Forecasting

Presented By: Cody Fritz

National Hurricane Center
Storm Surge Unit

WMO RA-IV Workshop on Hurricane Forecasting and Warnings
March 03, 2022



OUTLINE

- Introduction to Storm Surge
 - Who is vulnerable?
 - What is Storm Surge?
 - What factors affect Storm Surge?
- Forecasting Storm Surge and Storm Surge Products
 - SLOSH
 - Ensemble Guidance
- CIFDP-C Demonstration Project



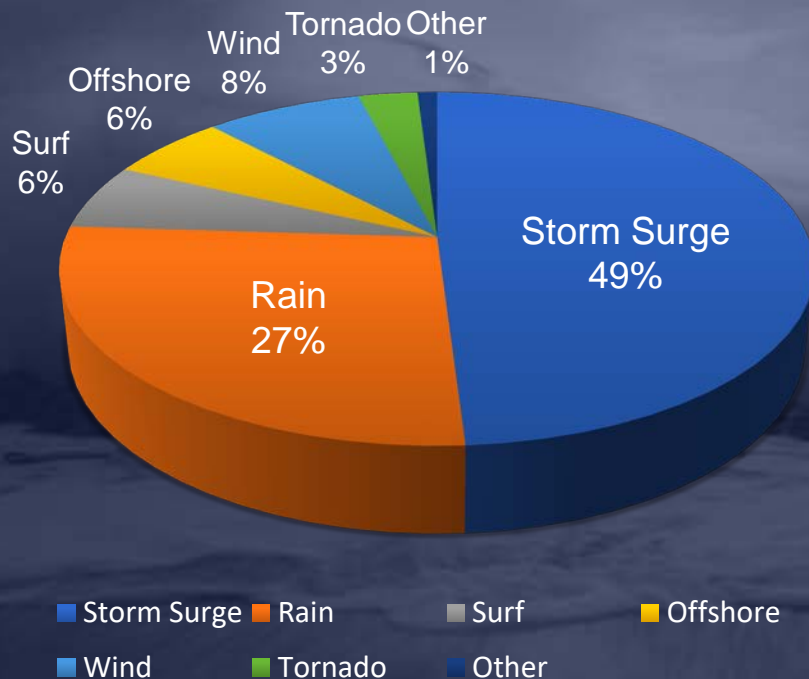
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The Danger of Storm Surge

2,544 Fatalities From 1963–2012



- Almost 50% the deaths are due to storm surge
- Over 80% of deaths are due to water
- Wind causes less than 10% of deaths

Edward N. Rappaport, 2014: Fatalities in the United States from Atlantic Tropical Cyclones: New Data and Interpretation. Bull. Amer. Meteor. Soc., 95, 341–346.

Hurricane Ike (2008) - Bolivar Peninsula, Texas

20 deaths

\$29.5 billion



House of David and Kimberly King



Waveland, Mississippi



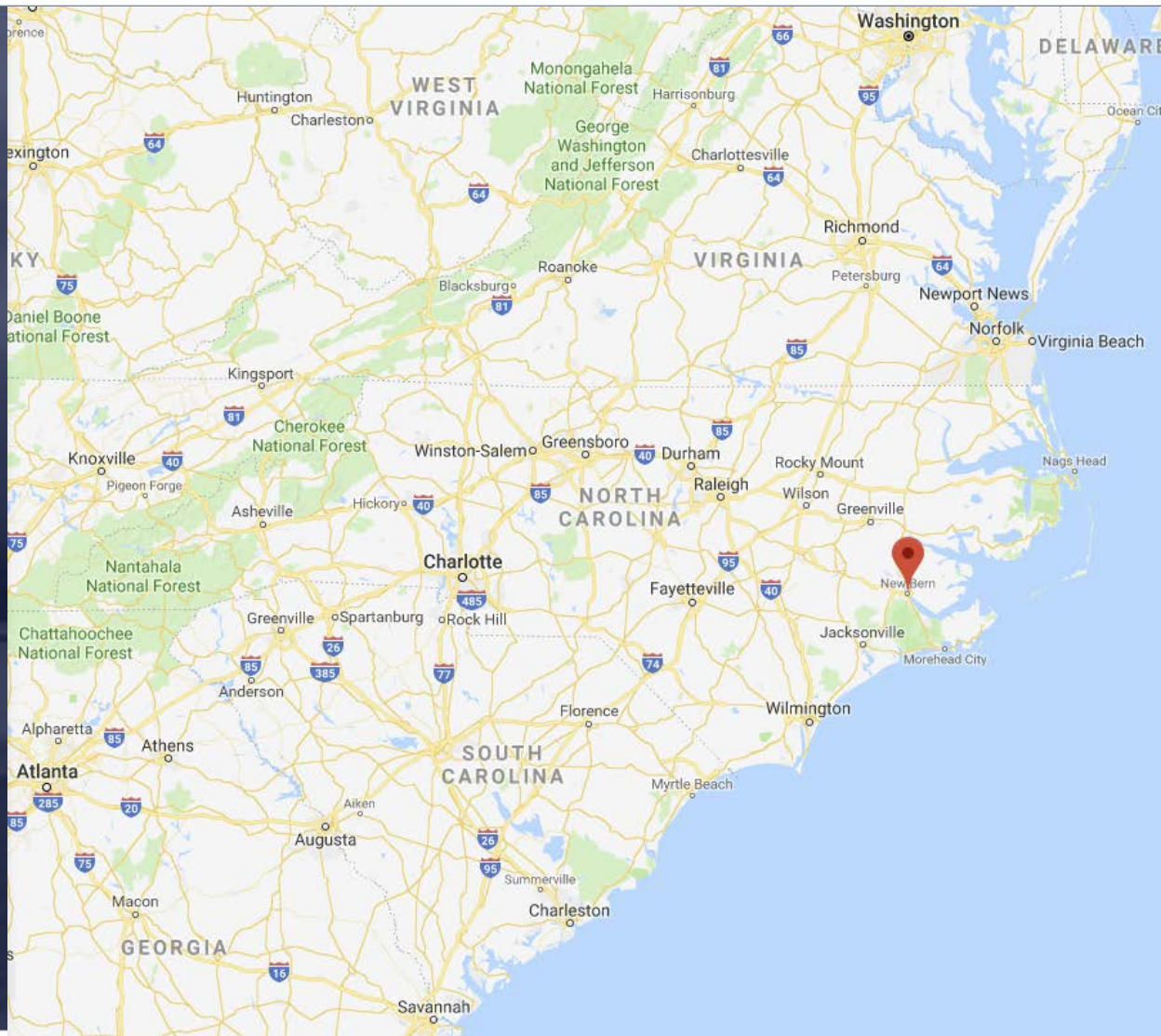
Myth or Fact?

I live miles from the beach, so storm surge is not my problem.

Myth



New Bern, NC – Hurricane Florence



New Bern, NC – Hurricane Florence



1:23:47 PM

nest



hurricanes.gov/surge



@NHC_Surge

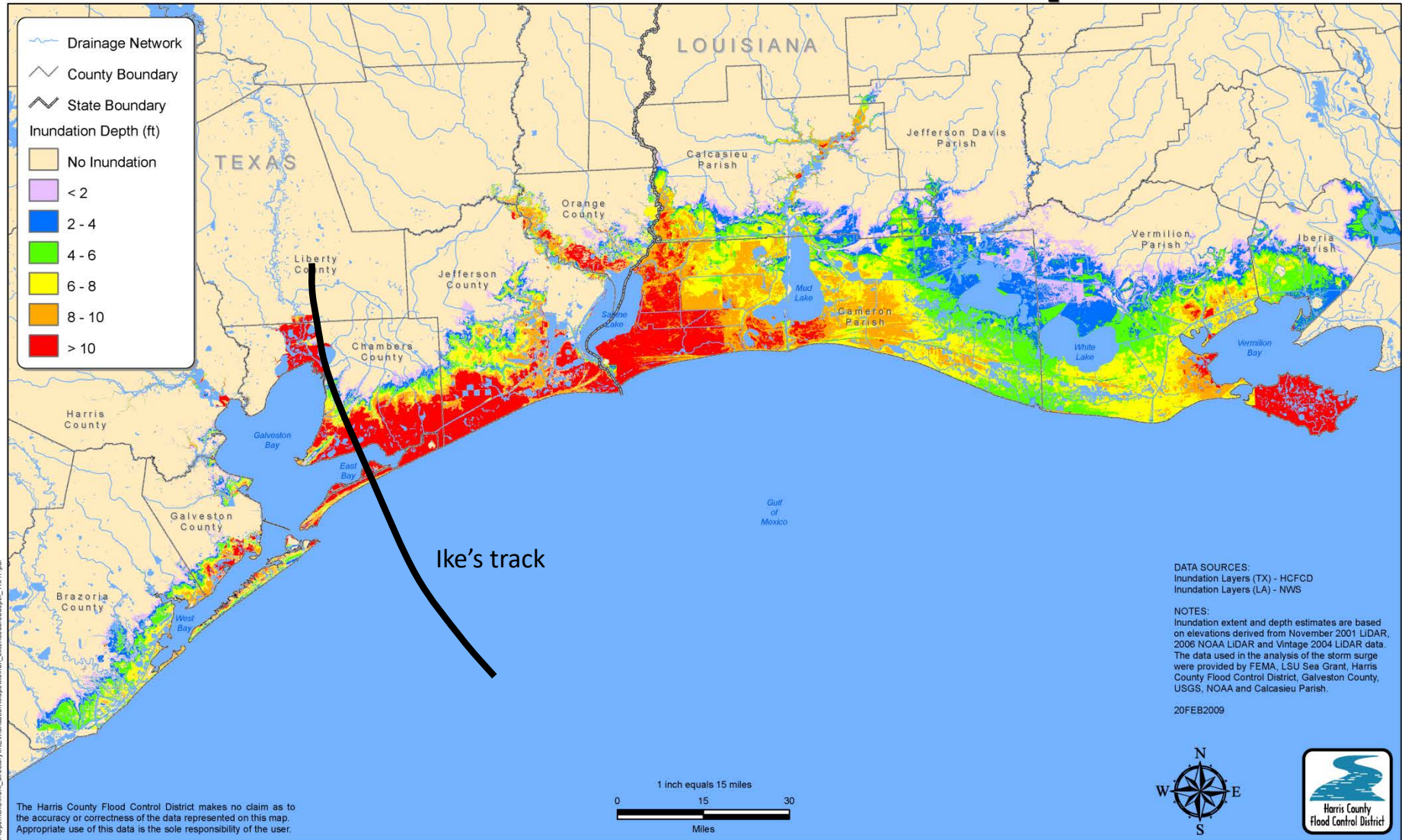
New Bern, NC – Hurricane Florence

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Hurricane Ike Inundation Depth



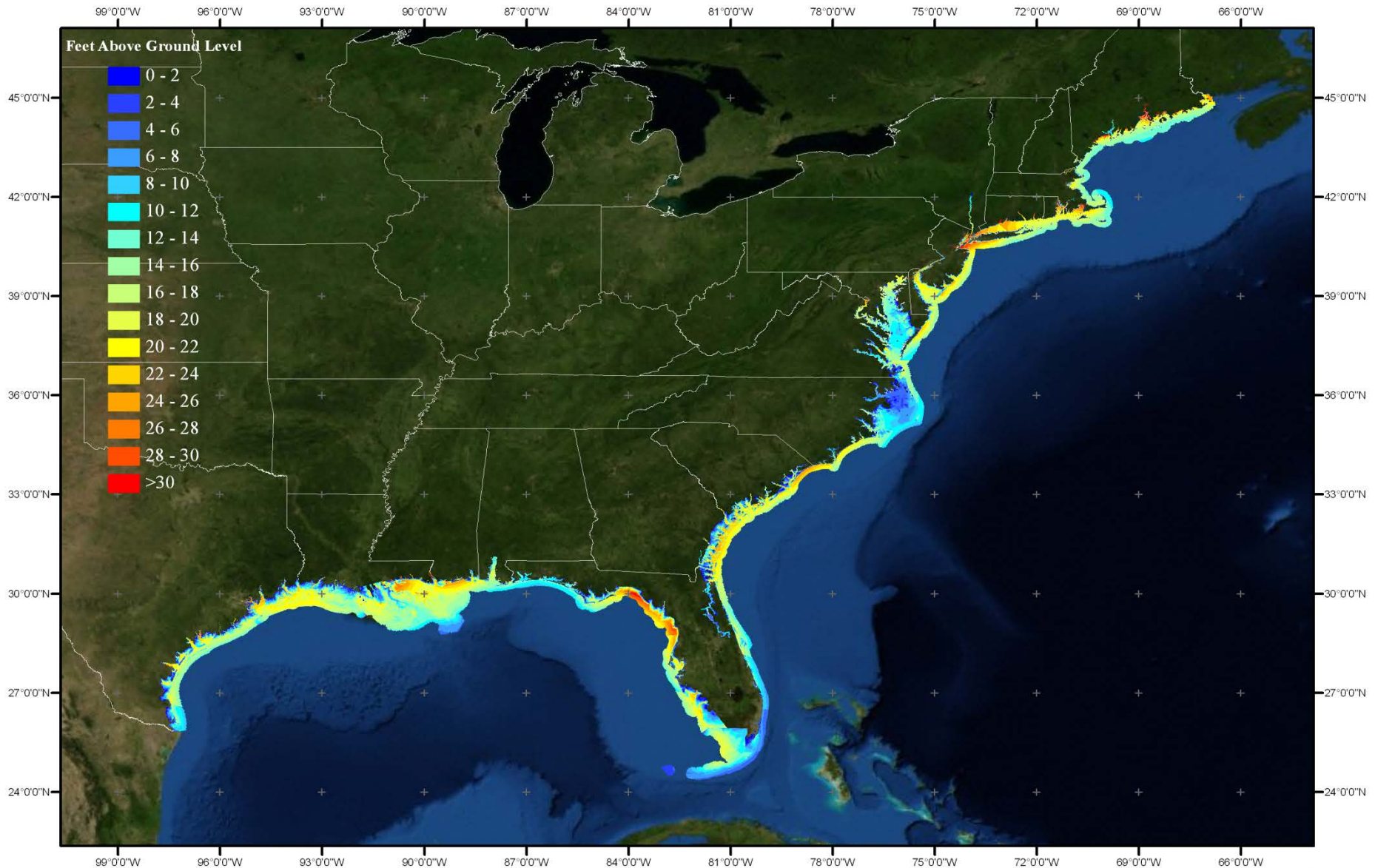
S:\OpenGIS\Short_directory\HCFCD\Inundation\Map\ike inundation\inundationdepth_11x17.pdf



Are some areas more vulnerable to
storm surge than others?

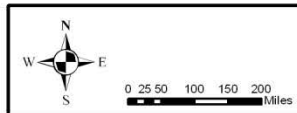


Storm Surge Vulnerability: Category 4 Hurricane



Data Source:
NWS/NHC/Storm Surge Unit

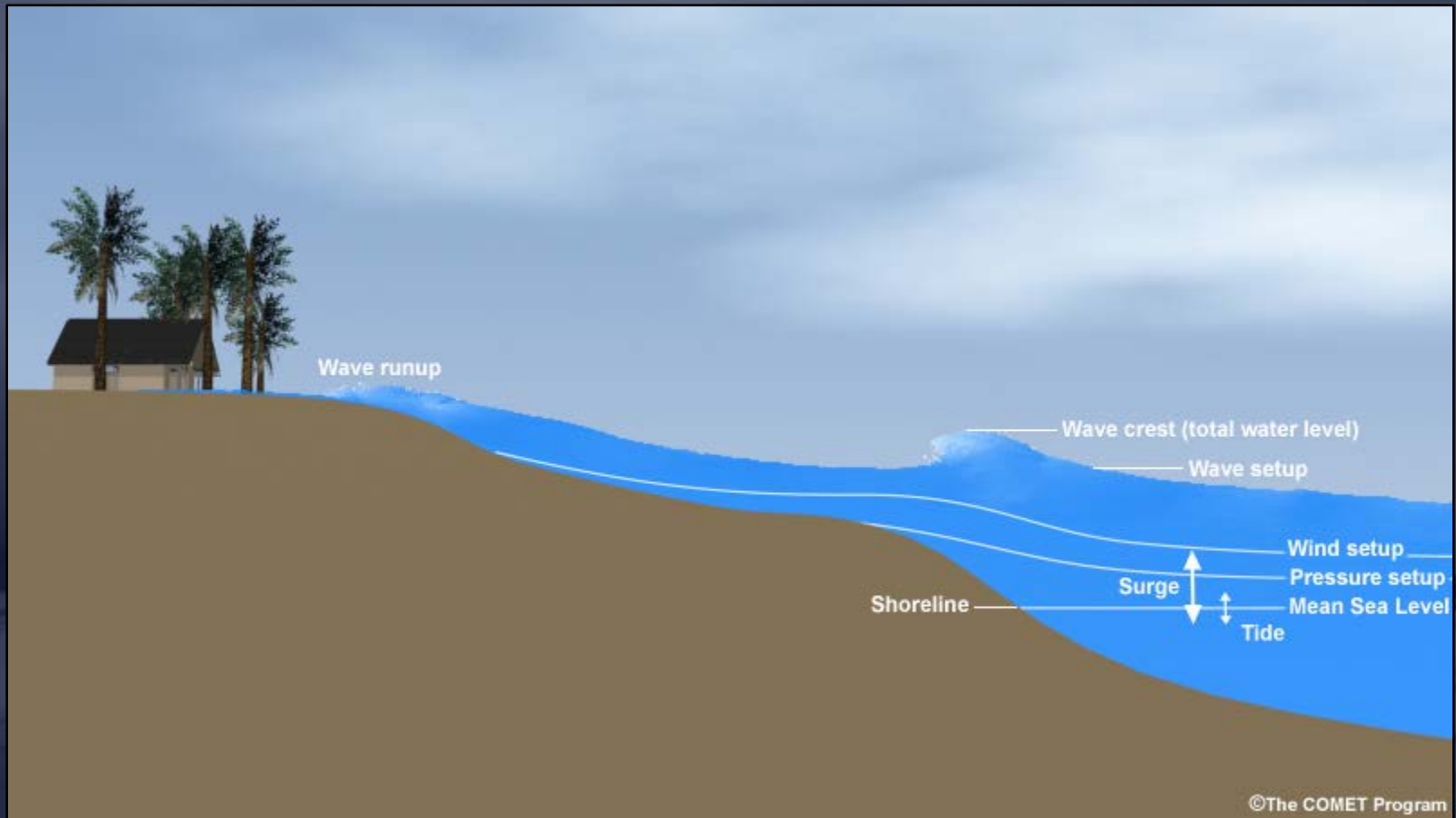
FOR EDUCATIONAL PURPOSES ONLY
NOT TO BE USED TO MAKE LIFE OR DEATH DECISIONS



What is storm surge and how does it work?



Total Water

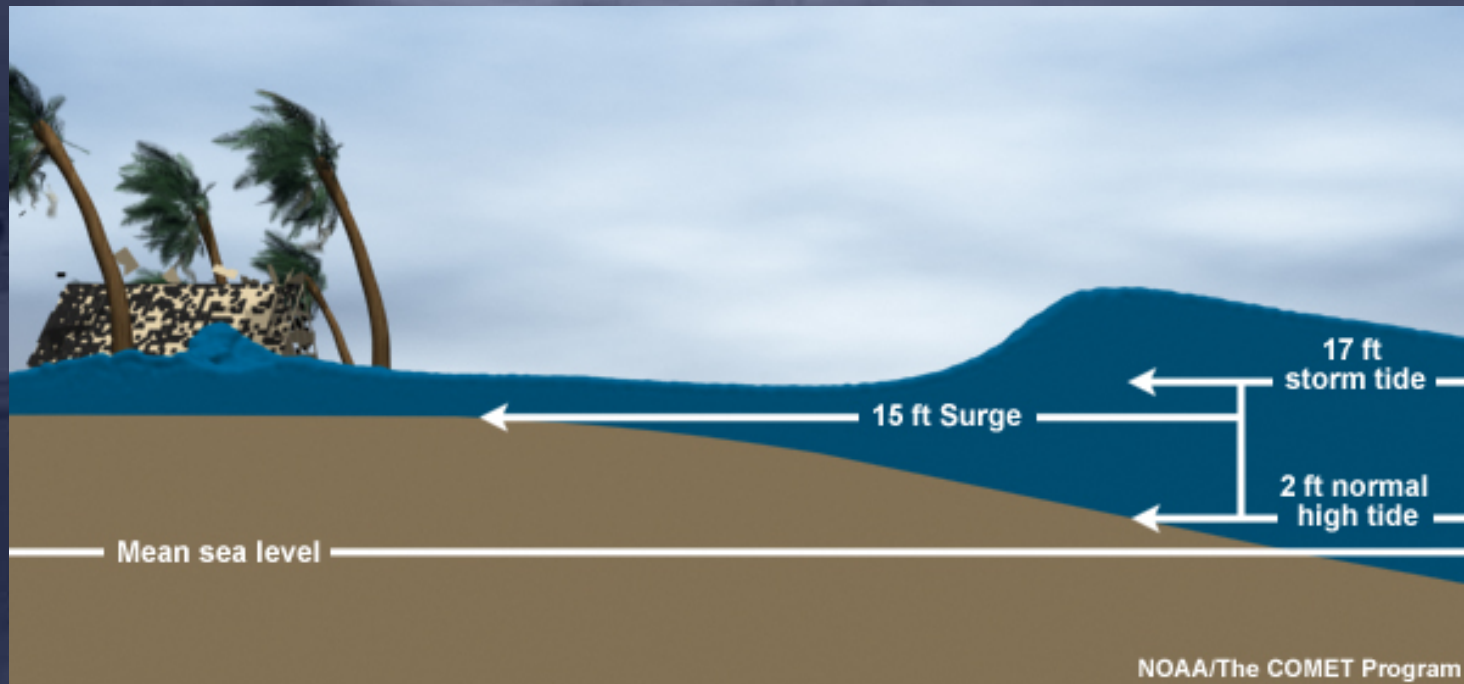


Total water level = Storm surge + Tides + Wave setup
+ Freshwater

What are Storm Surge and Storm Tide?

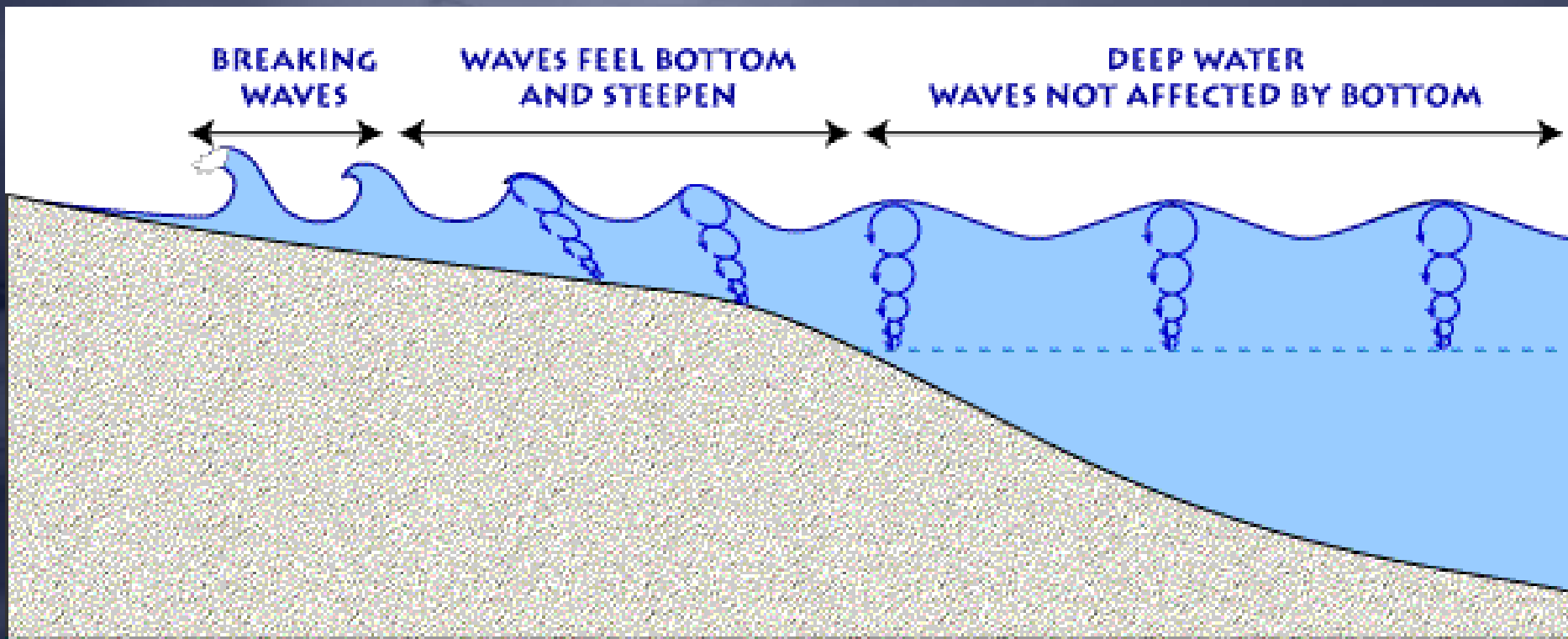
STORM SURGE is an abnormal rise of water generated by a storm, over and above the predicted astronomical tide.

STORM TIDE is the water level rise during a storm due to the combination of storm surge and the astronomical tide



What about Waves?

Breaking waves also contribute to the total water level through wave runup/setup



Wave Runup and Setup

Wave Setup

Wave
Runup

Wave
Setup

Mean Water Level

©The COMET Program

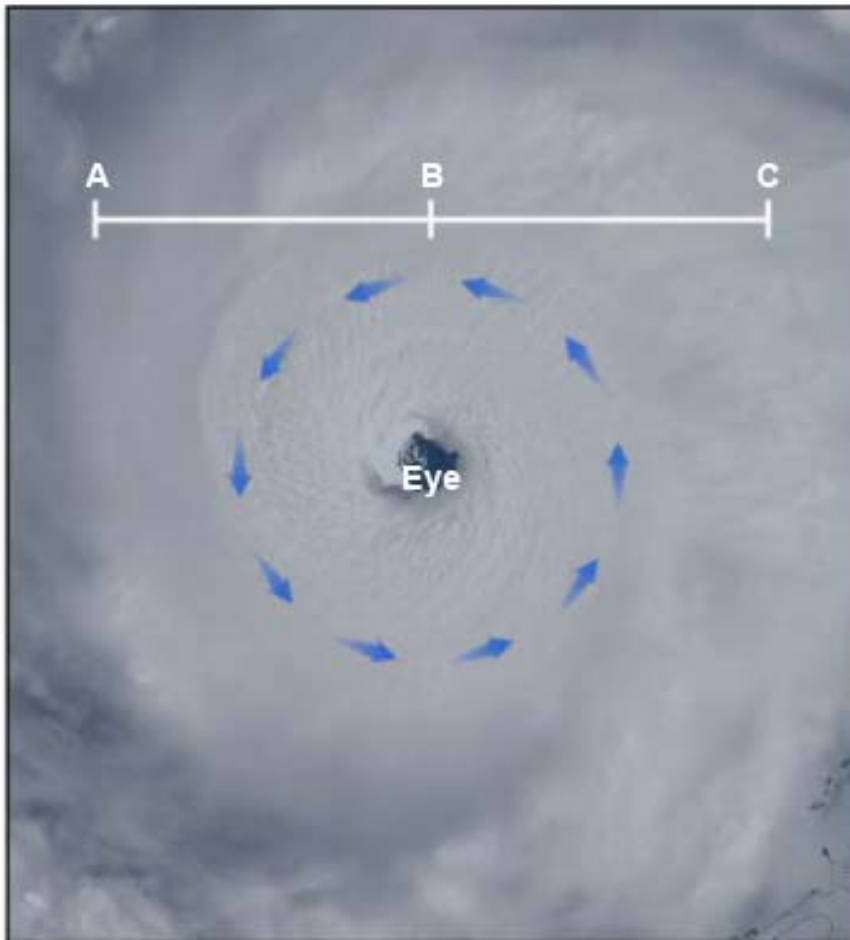
Freshwater Input



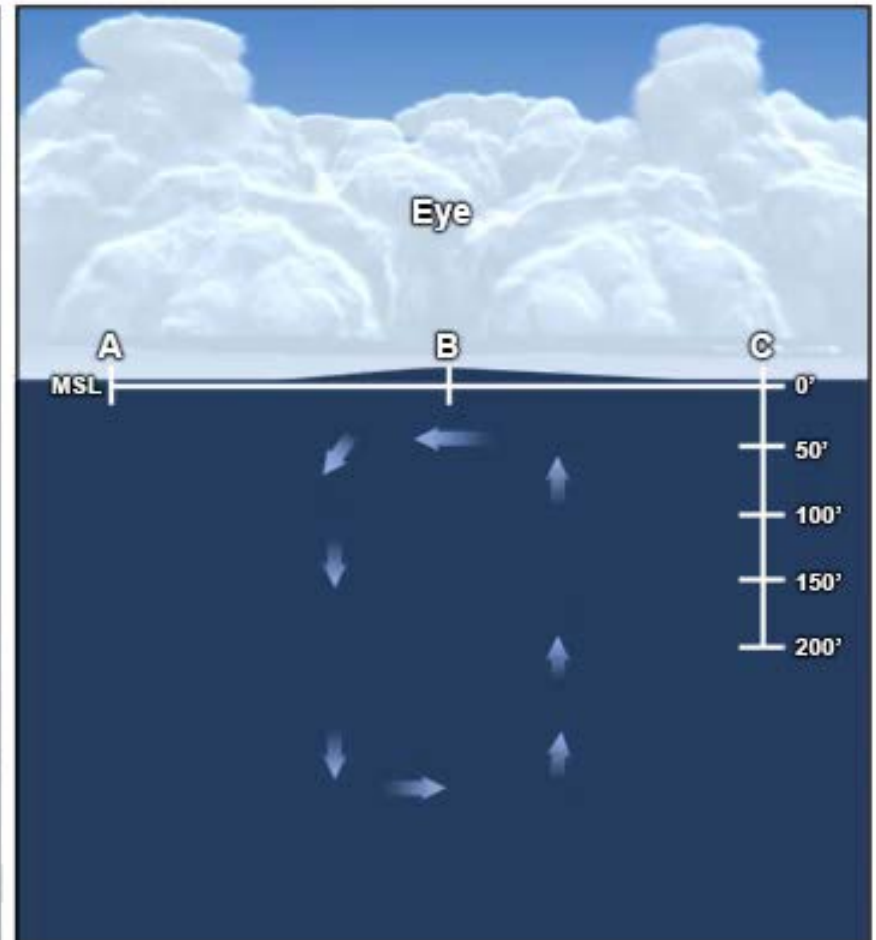
- River input, esp. into bays and sounds
 - Mississippi River discharges 200,000 – 700,000 cubic feet per second
- Rivers

From Deep Water to Shallow Water

Top View of Sea Surface

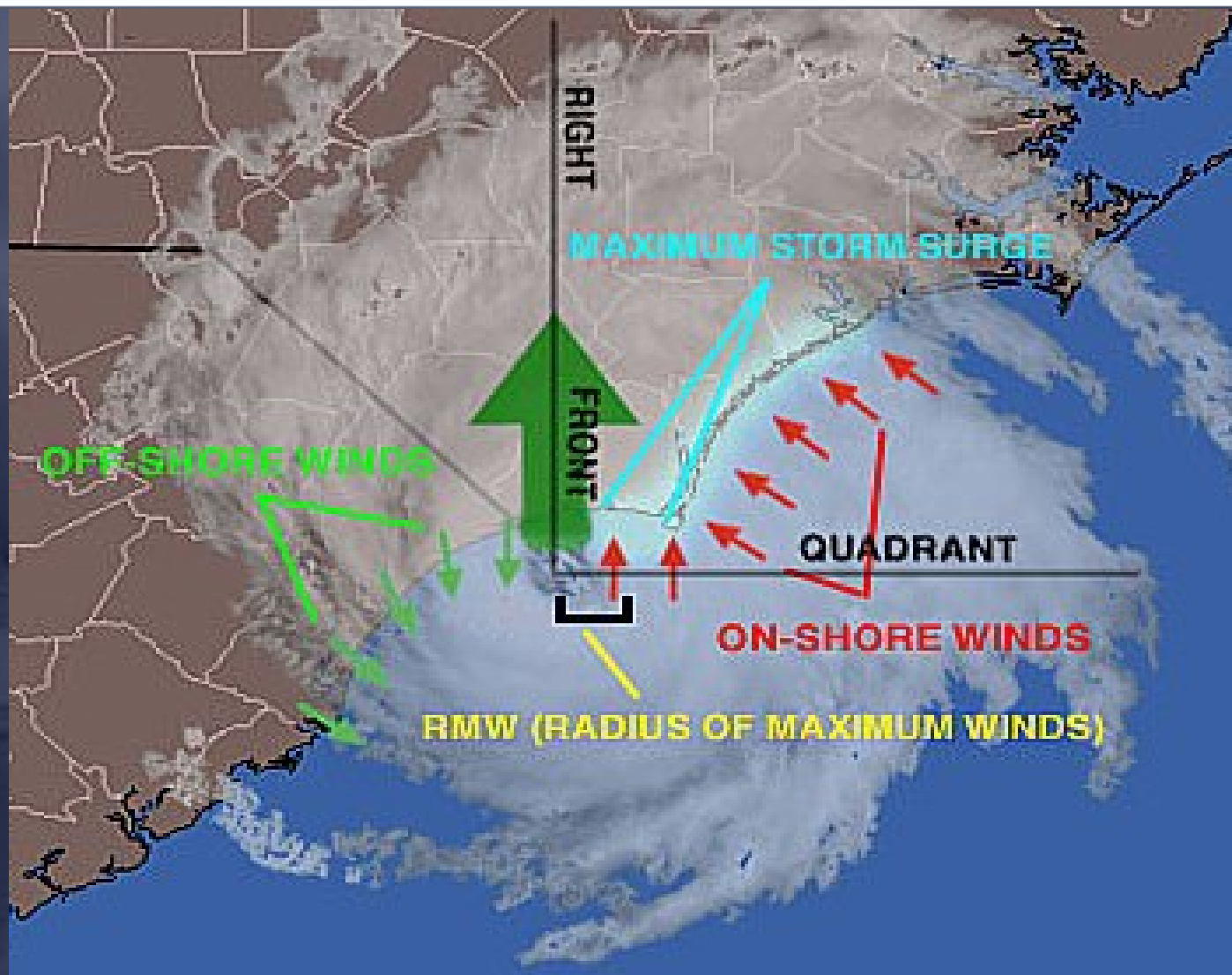


Side View of Cross Section "ABC"



©The COMET Program

Understanding Surge



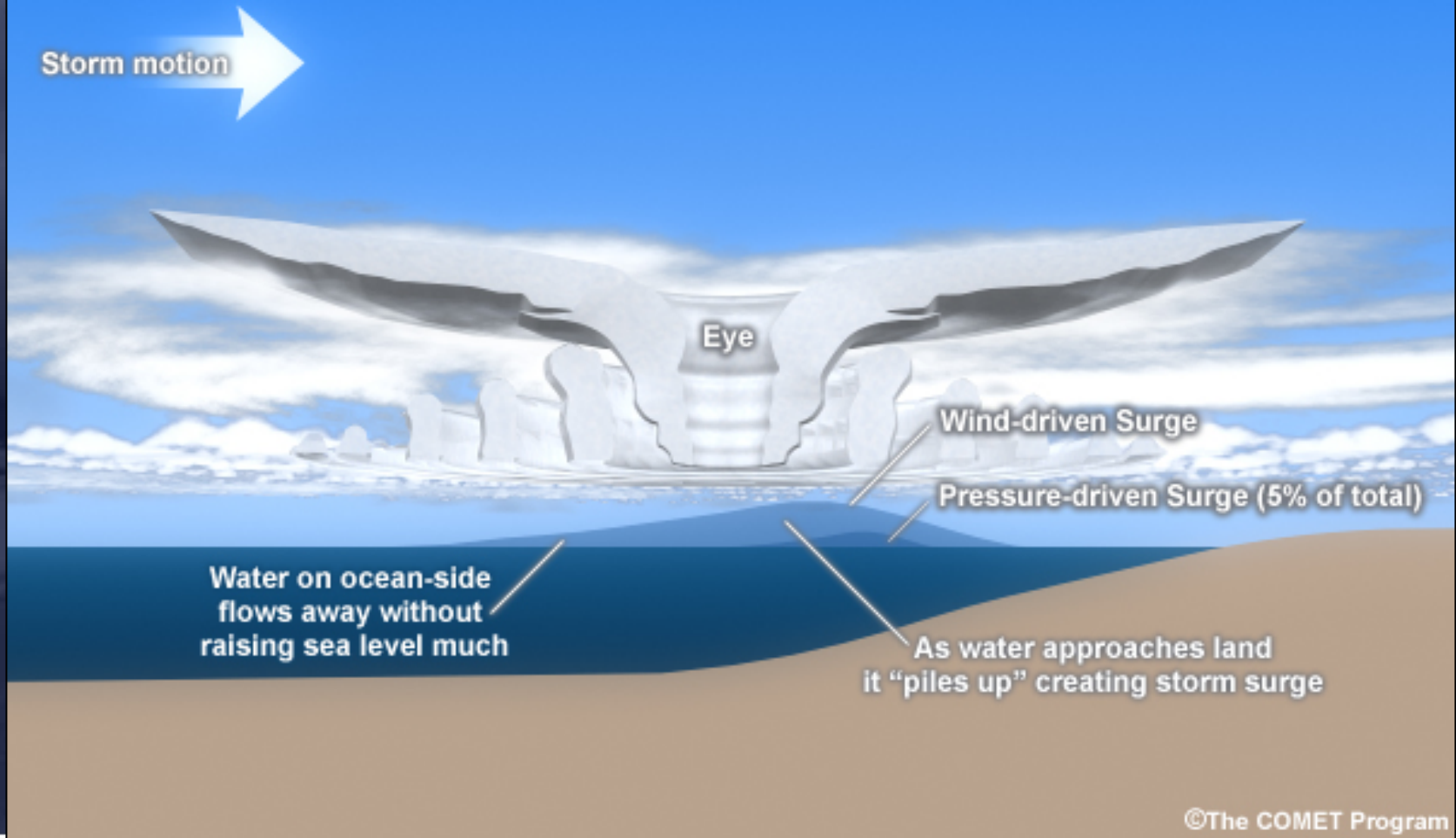


What are the factors that affect
storm surge?

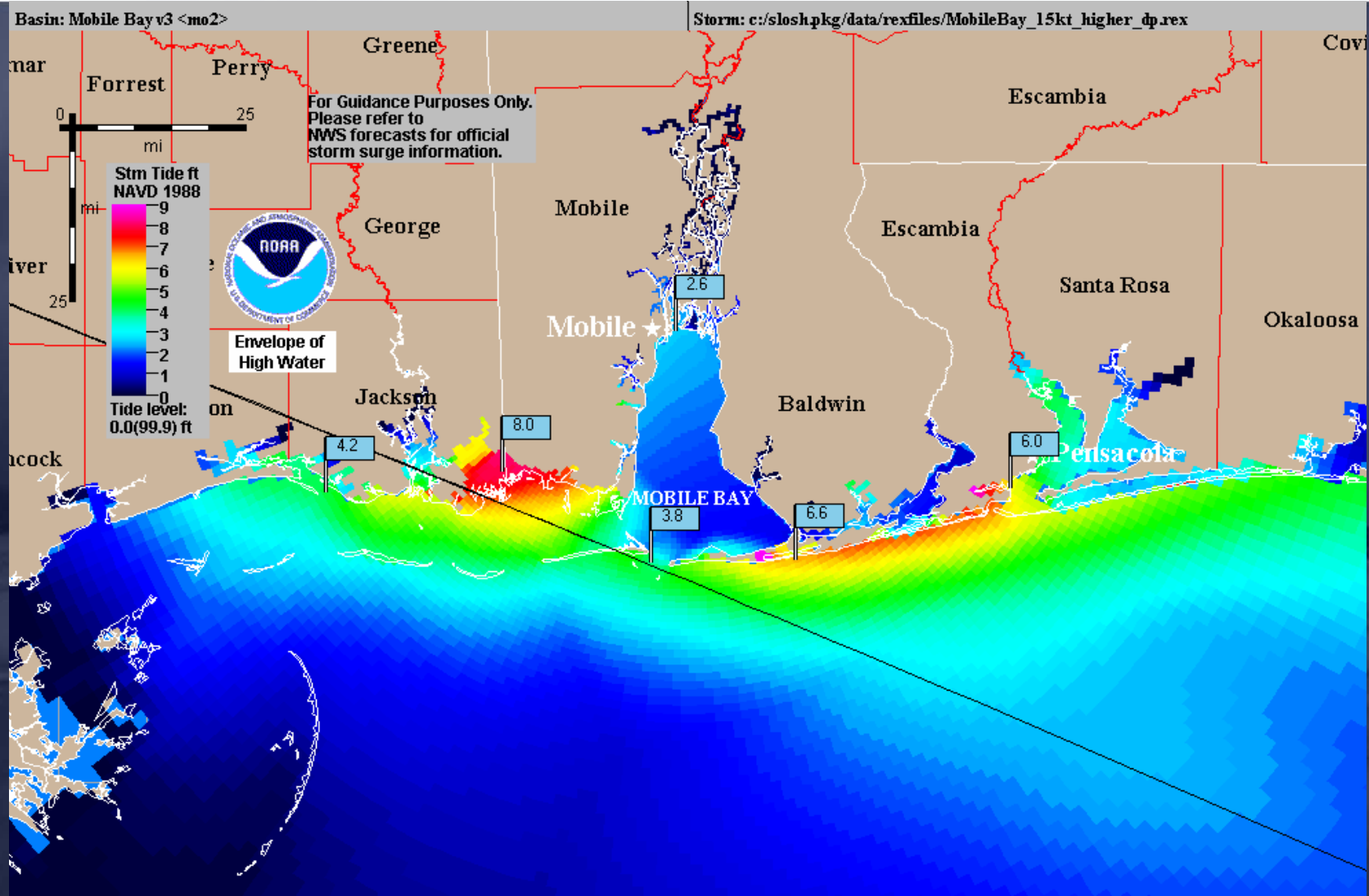


Effects of Low Pressure

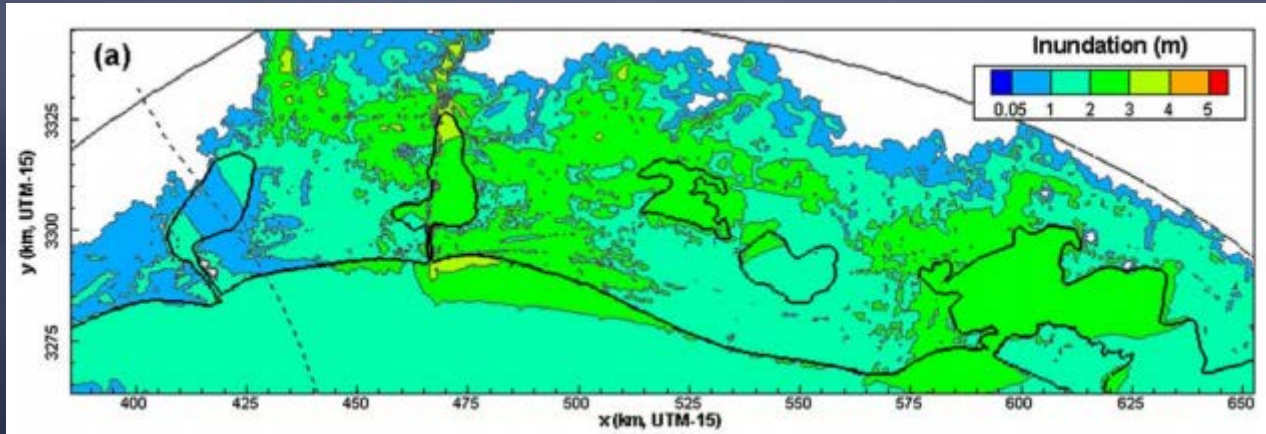
Wind and Pressure Components of Hurricane Storm Surge



15 mph stronger

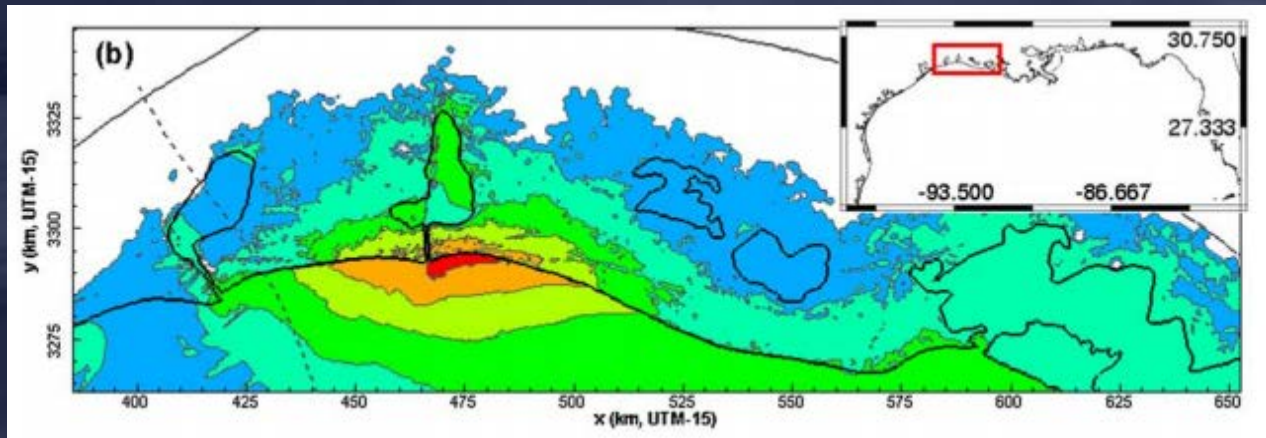


Forward Speed



Slow Speed (5 mph)

- More inland penetration

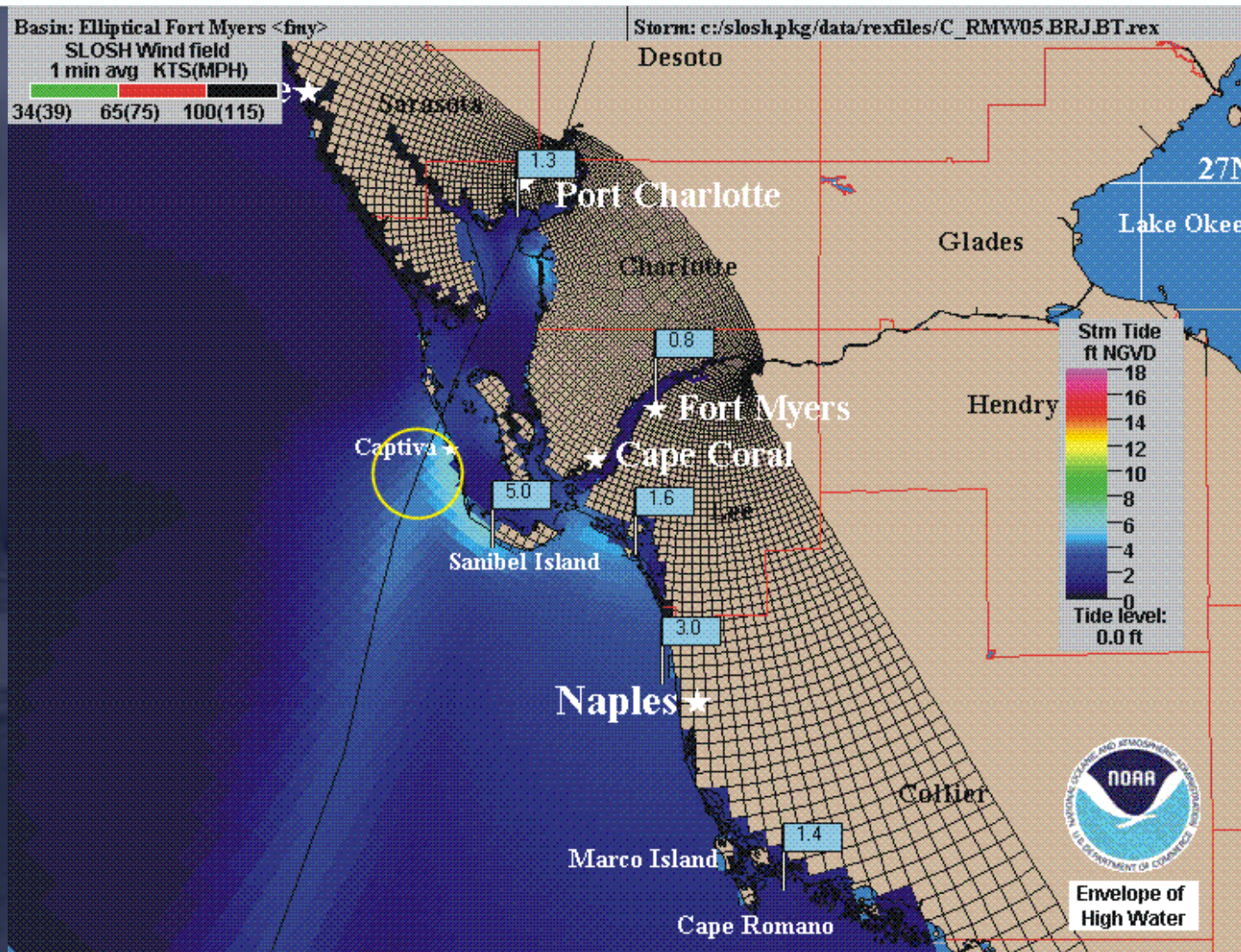


Fast Speed (25 mph)

- Higher maximum

Rego, J. L., and C. Li (2009). Forward speed of a hurricane. *Geophysical Research Letters*, 36.

Size (Radius of Max Winds)



Size (Radius of Max Winds)

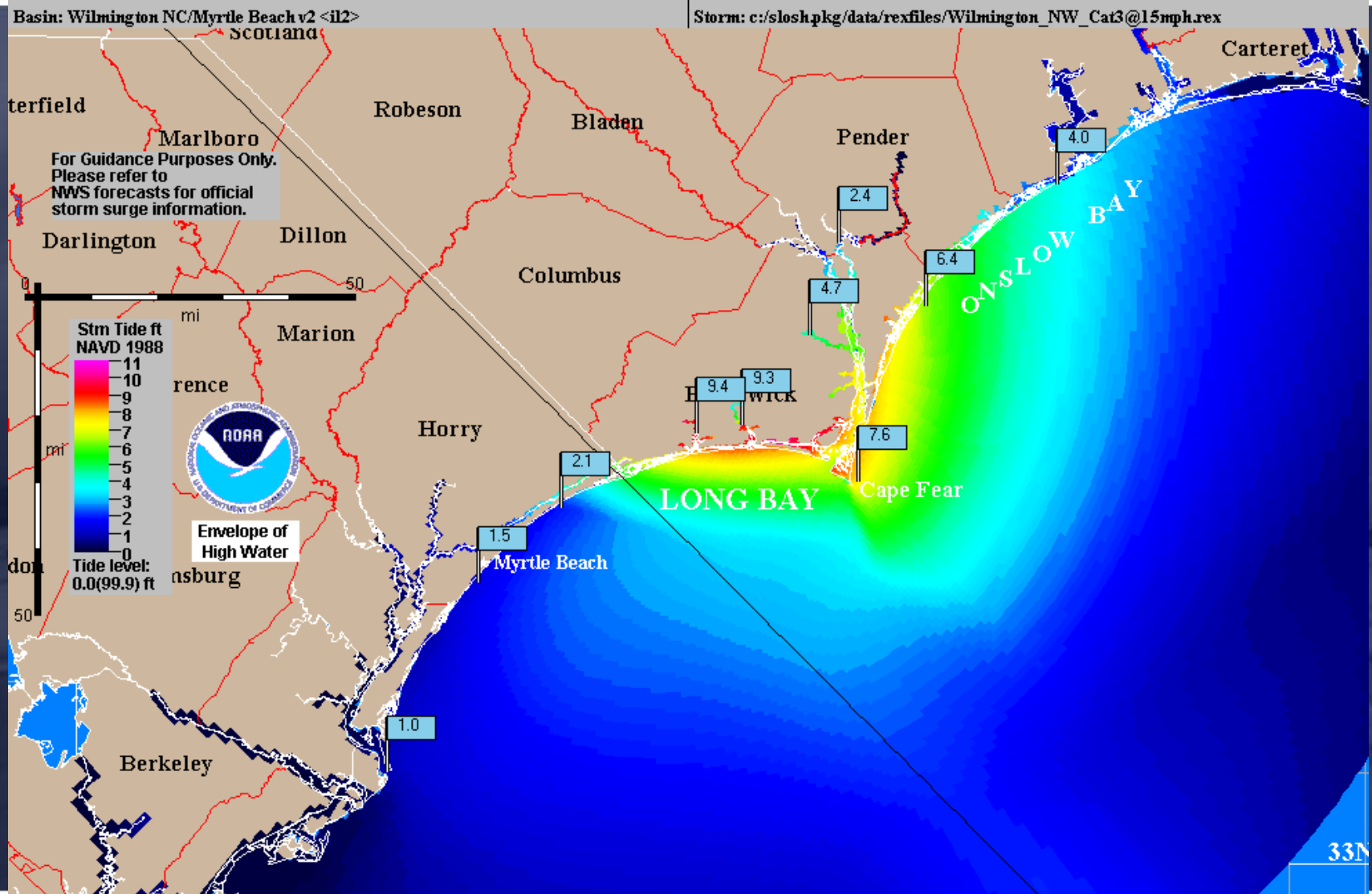


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Angle of Approach

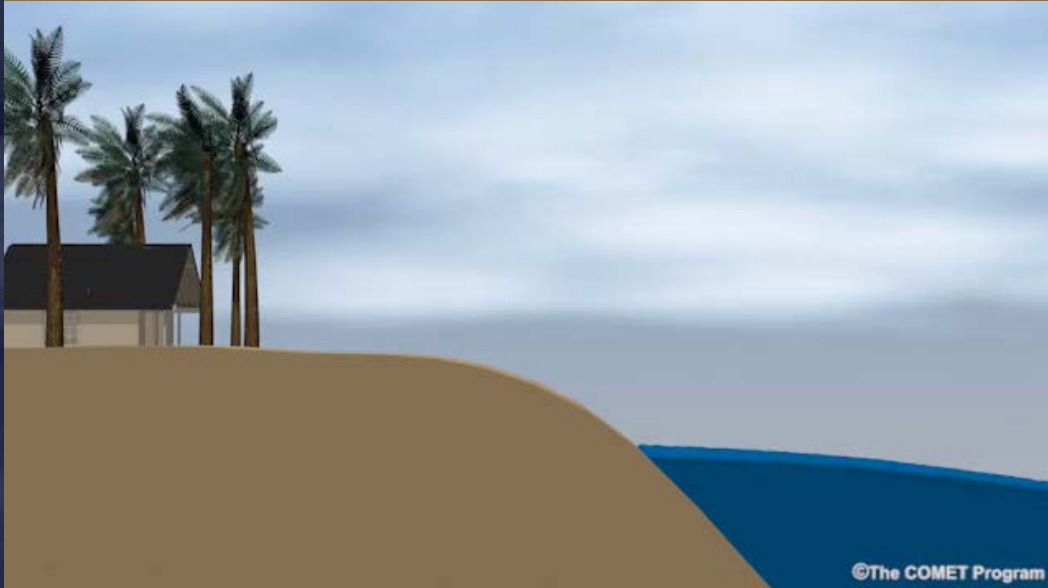
NNW Motion



Width and Slope of Shelf



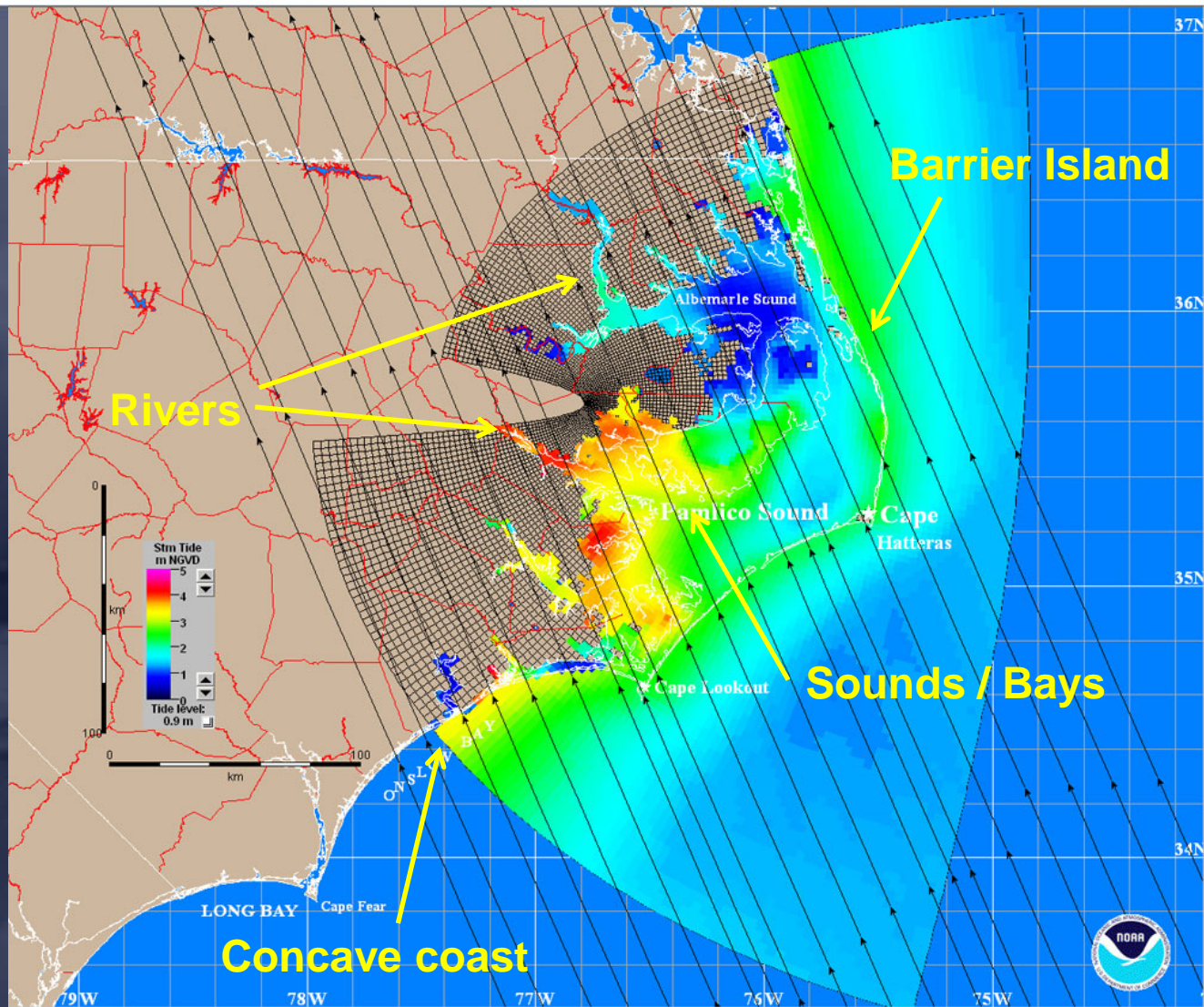
Wide shelf/gentle slope



Narrow shelf/sharp slope

©The COMET Program

Local Features



Factors Affecting Storm Surge

- Central Pressure
- Intensity (wind speed)
- Forward Speed
- Size - Radius of Maximum Winds (RMW)
- Angle of Approach
- Width and Slope of Shelf
- Local features – concavity of coastlines, bays, rivers, headlands, or islands



Hurricane Laura

- Laura Actual Track
- - - Simulated Track Shifted West

How Might Storm Surge Inundation Have Been Different Had Hurricane Laura Made Landfall 20 Miles Farther West?

- 3 to 5 feet lower
- 1 to 3 feet lower
- No Significant Difference
- 1 to 3 feet higher
- 3 to 5 feet higher
- 5 to 10 feet higher
- 10 to 15 feet higher
- Inundation not mapped for levee area

Louisiana

Texas

Sources: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

hurricanes.gov/surge  @NHC_Surge

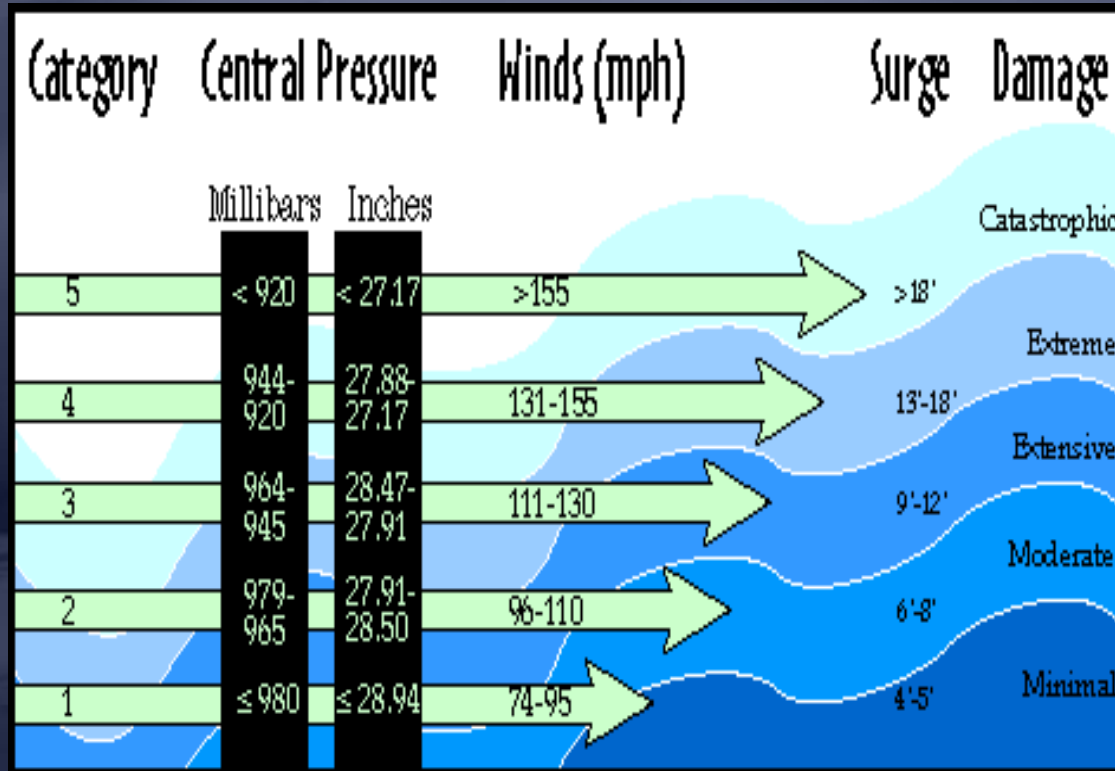
Myth or Fact?

Category 4 hurricanes always produce more storm surge than Category 1 hurricanes?

Myth



No More Surge in the Saffir-Simpson Scale!



← **KATRINA (3)**
← **IKE (2)**
← **SANDY (1)**
ISAAC (1)
← **CHARLEY (4)**

No Such Thing as “Just a Tropical Storm”



Louisiana State Rd. 23 near Myrtle Grove
Tropical Storm Lee (2011)

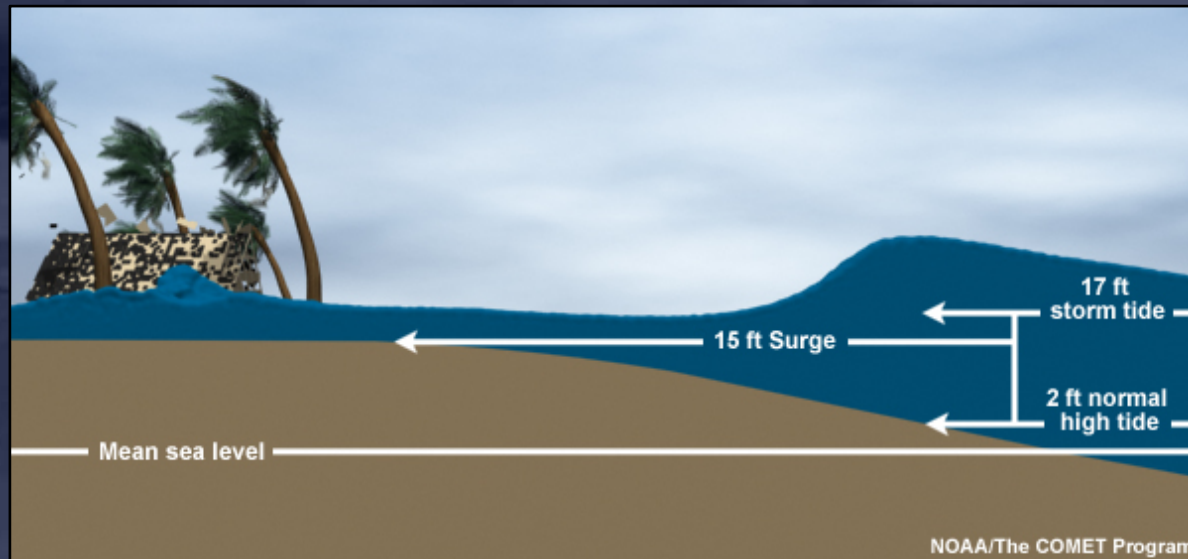
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SLOSH

- **Sea, Lake, and Overland Surges from Hurricanes**
- A computerized numerical **model** developed by the National Weather Service (NWS) **to estimate storm surge heights** (and winds) resulting from historical, hypothetical, or predicted hurricanes



SLOSH

Strengths and Limitations

- SLOSH **does include**:
 - Flow through barriers/gaps/passes
 - Deep passes between bodies of water
 - Inland inundation (wet/dry cell)
 - Overtopping of barrier systems, levees, and roads
 - Coastal reflection (coastally trapped Kelvin waves)
 - Astronomical tide
 - Wave setup in U.S. island states and territories
- SLOSH **does not include**:
 - Wave run-up (efforts underway)
 - Normal river flow and rain



Storm Surge Products

Pre-Computed

Available outside US

MEOWs

Maximum Envelopes Of Water

MOMs

Maximum Of the MEOWs

Real-Time

Not Available
outside US

Probabilistic Storm Surge (P-Surge)
Potential Storm Surge Flooding Graphic
Storm Surge Watch/Warning

National SLOSH MOM and Risk Analysis

- About 7.4 million people vulnerable to storm surge
- Roughly 4,600 miles of evacuation route becomes inundated or cut off
- Almost 3.9 million housing units vulnerable to surge

National Storm Surge Hazard Maps

This is not a real-time product. For active tropical cyclones, please see hurricanes.gov and consult local products issued by the National Weather Service

Texas to Maine

Puerto Rico

Category 1

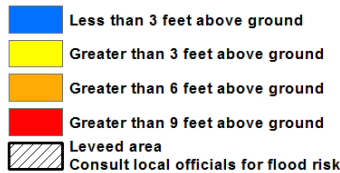
Category 2

Category 3

Category 4

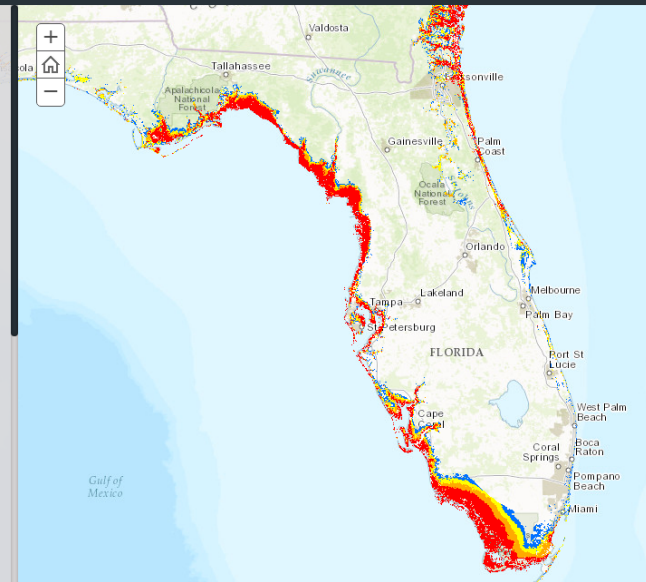
Category 5

This national depiction of storm surge flooding vulnerability helps people living in hurricane-prone coastal areas along the U.S. East and Gulf Coasts and Puerto Rico to evaluate their risk to the storm surge hazard. These maps make it clear that storm surge is not just a beachfront problem, with the risk of storm surge extending many miles inland from the immediate coastline in some areas. If you discover via these maps that you live in an area vulnerable to storm surge, find out today if you live in a hurricane storm surge evacuation zone as prescribed by your local emergency management agency. If you do live in such an evacuation zone, decide today where you will go and how you will get there, if and when you're instructed by your emergency manager to evacuate. If you don't live in one of those evacuation zones, then perhaps you can identify someone you care about who does live in an evacuation zone, and you could plan in advance to be their inland evacuation destination - if you live in a structure that is safe from the wind and outside of flood-prone areas.



How this map was created:

The SLOSH (Sea, Lake, and Overland Surges from Hurricanes) model is a numerical model used by NWS to compute storm surge. Storm surge is defined as the abnormal rise of water generated by a storm, over and above the predicted astronomical tides. Flooding from storm surge depends on many factors, such as the track, intensity, size, and forward speed of the hurricane and the characteristics of the coastline where it comes ashore or passes nearby. For planning purposes, the NHC uses a representative sample of hypothetical storms to estimate the near worst-case scenario of flooding for each hurricane category.



Zachry, B. C., W. J. Booth, J. R. Rhome, and T. M. Sharon, 2015: A National View of Storm Surge Risk and Inundation. J. Wea. Climate Soc., 7(2), 109-117

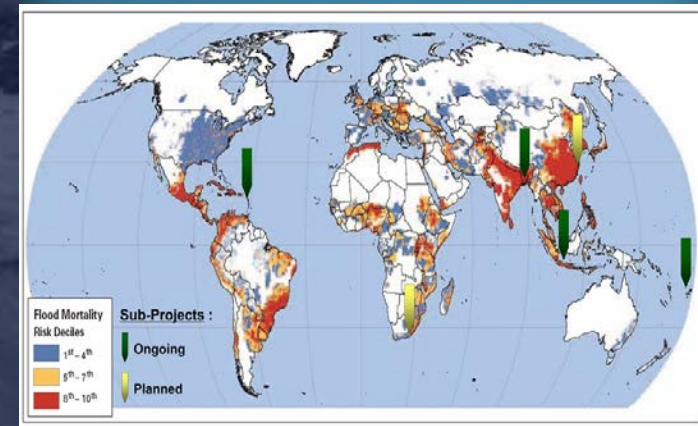
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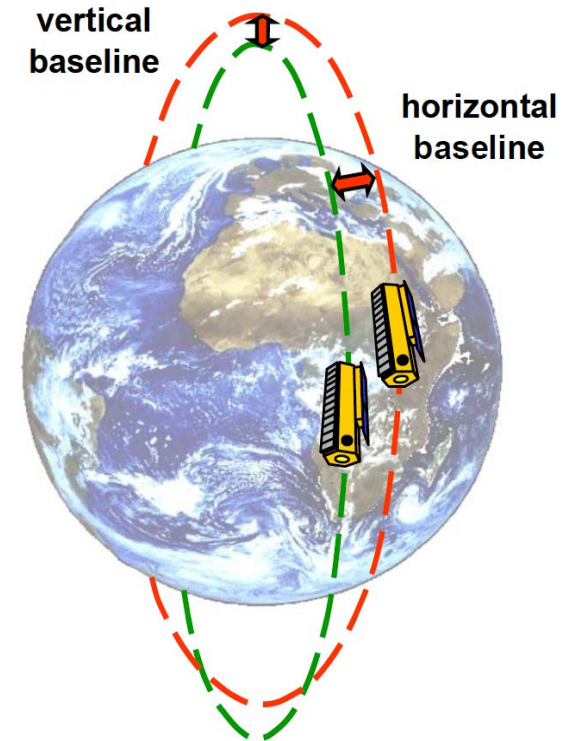
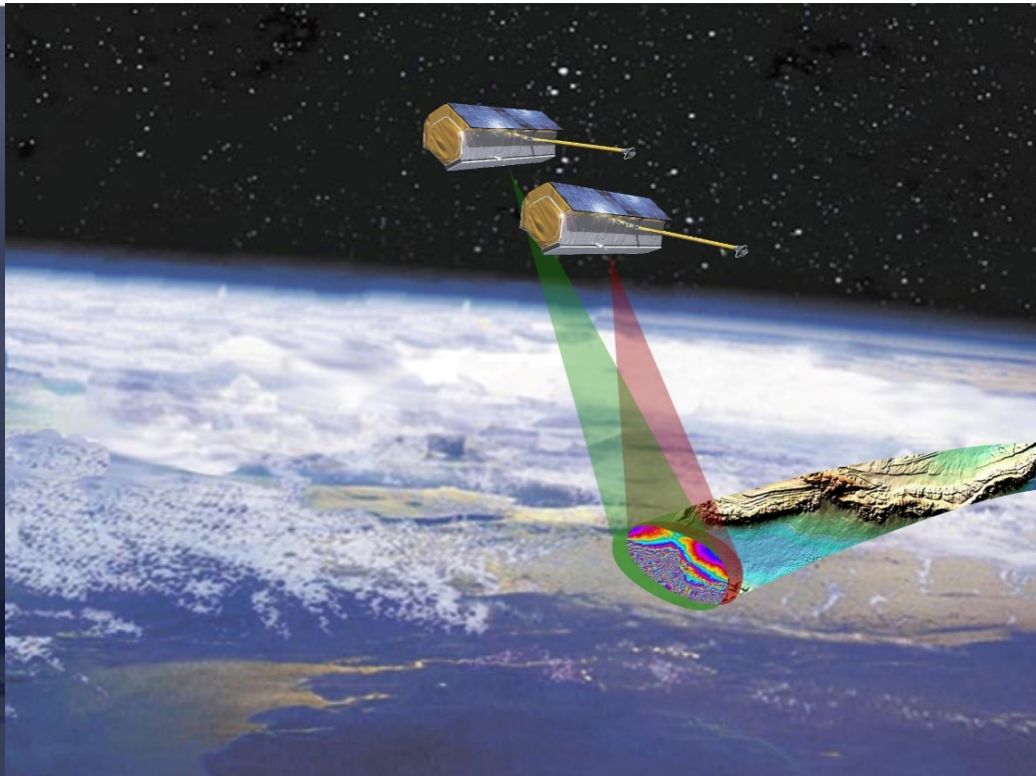


History of CIFDP-C

- At the 5th meeting of the CIFDP Program Steering Group (May 2014, Geneva), the previous Sub-Project for Dominican Republic (CIFDP-DR) was re-scoped for a Caribbean/regional approach and denoted CIFDP-C
- CIFDP-C was initially demonstrated and tested for the Dominican Republic and Haiti
- RSMC Miami provided the leading technical contribution, in collaboration with the PSG and other partners, which ensured the maximum synergies of regional and national efforts *and introduced a new direction to provide storm surge information to all other Caribbean countries*



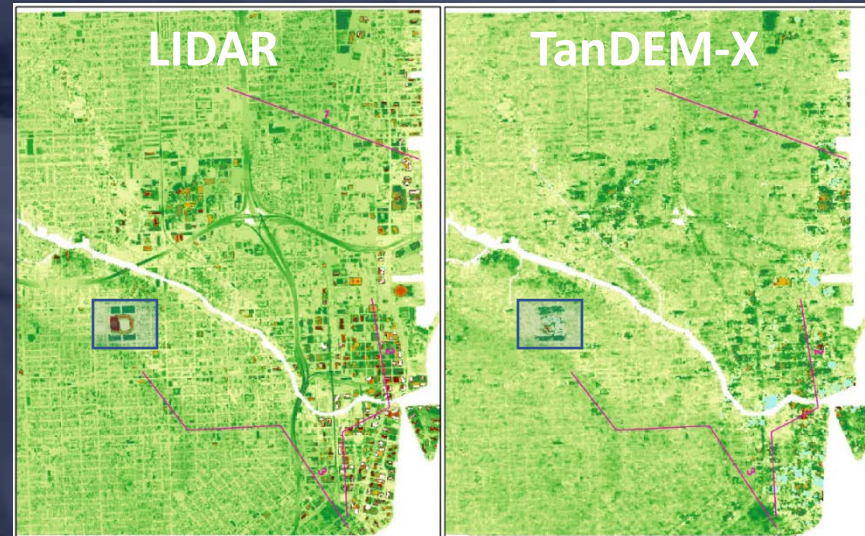
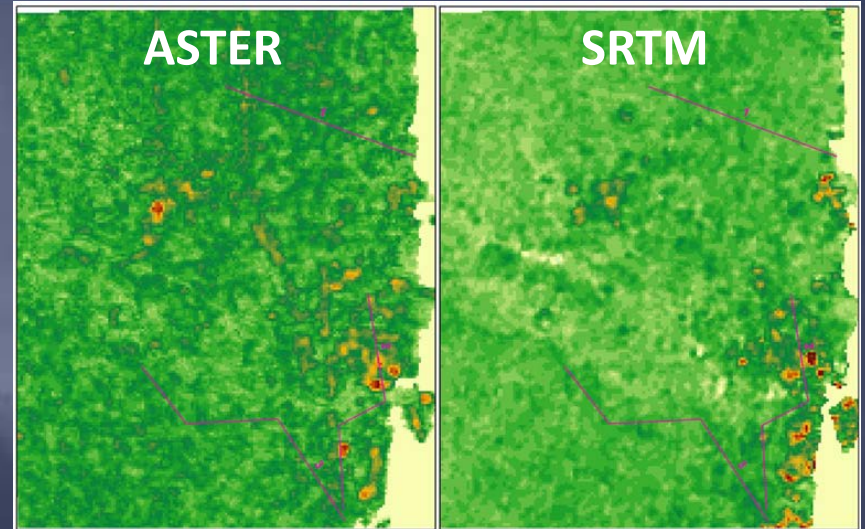
TanDEM-X



Requirements	Specification	DTED-2	TanDEM-X DEM
Relative Vertical Accuracy	90 % linear point-to-point error over a 1° by 1° cell	12 m (slope < 20 %) 15 m (slope > 20 %)	2 m (slope < 20 %) 4 m (slope > 20 %)
Absolute Vertical Accuracy	90 % linear error	18 m	10 m
Relative Horizontal Accuracy	90 % circular error	15 m	3 m
Absolute Horizontal Accuracy	90 % circular error	23 m	10 m
Spatial Resolution	Independent pixels	30 m (1 arc sec @ equator)	12 m (0,4 arc sec @ equator)

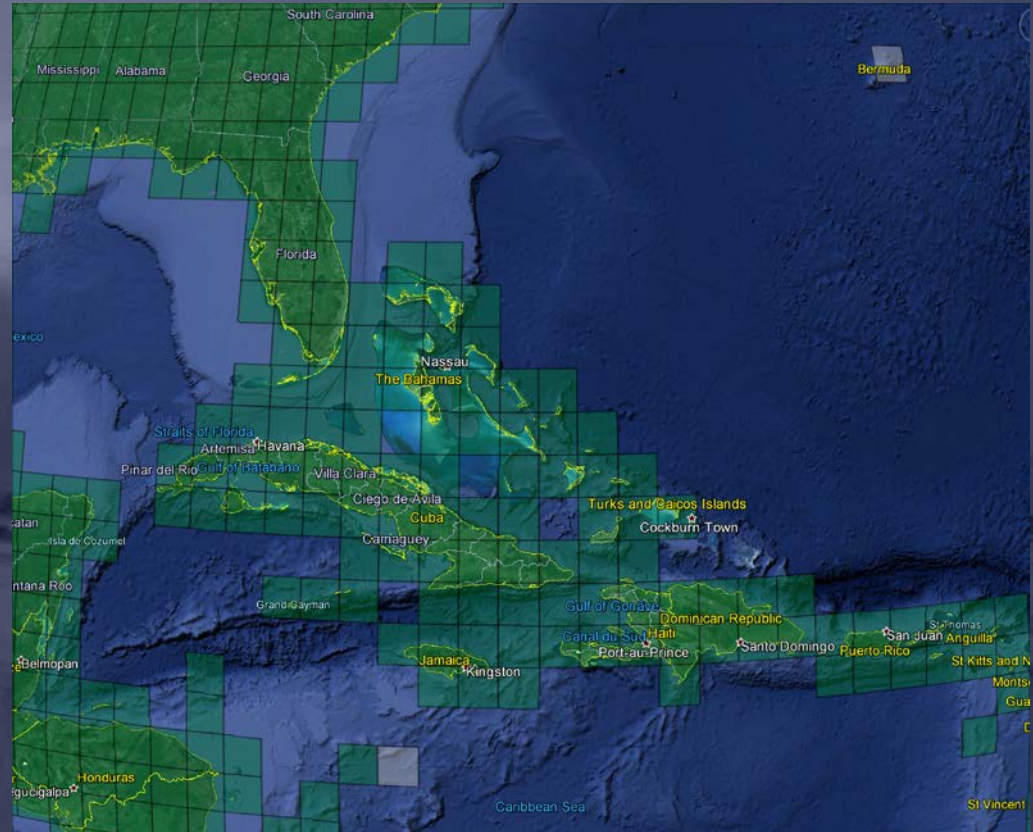
Topography Data Comparison: Miami, FL

Downtown Miami, FL



Data Availability

- Availability 2015
- Established an agreement with U.S. DOD for cost savings for CIFDP-C
- TANDEM-X DEMs not sharable per licensing agreement but final modeling results are



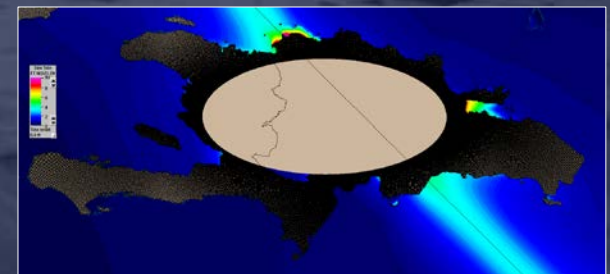
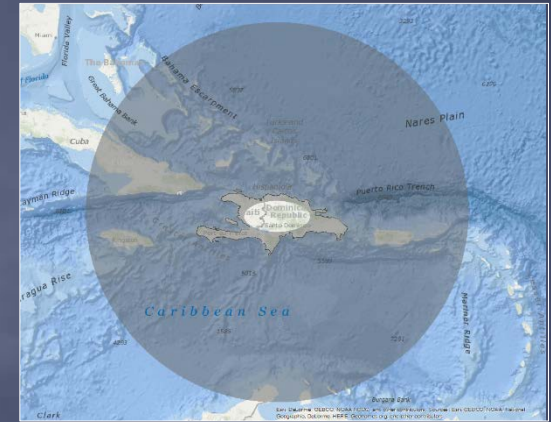
A dark, moody photograph of a stormy ocean with white-capped waves crashing against a rocky shore under a heavy, grey sky. The image is dimly lit, emphasizing the power and scale of the weather system.

SLOSH + Waves Development



Coastal Inundation Forecasting Demonstration Project

- Implement a coupled storm surge and wave modeling system
 - SLOSH hydrodynamic model
 - Wave model recommended by IOOS modeling testbed (parametric)
- Develop products for planning, preparedness, and forecasting
 - SLOSH MOMs and MEOWs
- Provide specialized training programs on how to use the storm surge products for planning and preparedness



2nd Gen (Parametric) Wave Model

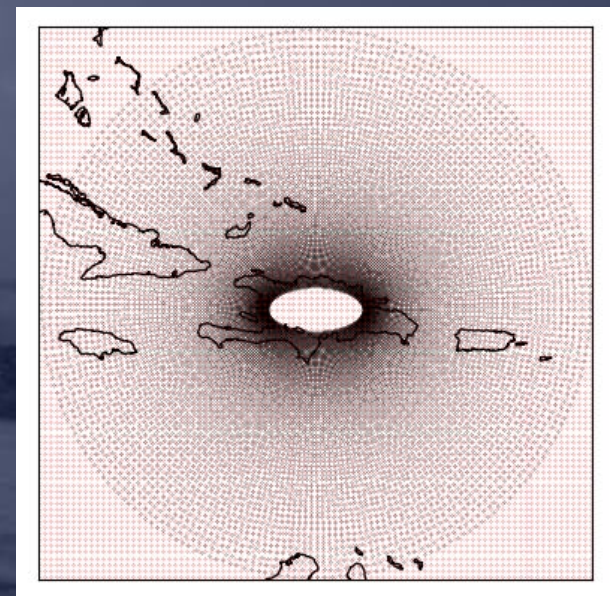
- An efficient parametric wave model to couple with SLOSH
- Parametric models that reduce full solution space $N(t,x,y,\sigma,\theta)$, to e.g. $M(t,x,y)$ (Schwab et al. 1984).

$$\frac{\partial \vec{M}}{\partial t} + \vec{v} \cdot \nabla_{x,y} \vec{M} = \vec{\tau}_w$$

$$\vec{\tau}_w = 0.028 \rho_a D_f |\vec{U} - 0.83 C_p| (\vec{U} - 0.83 C_p)$$

$$\sigma^2 = 6.23 \times 10^{-6} \left(\frac{f_p U}{g} \right)^{-10/3} \frac{U^4}{g^2}$$

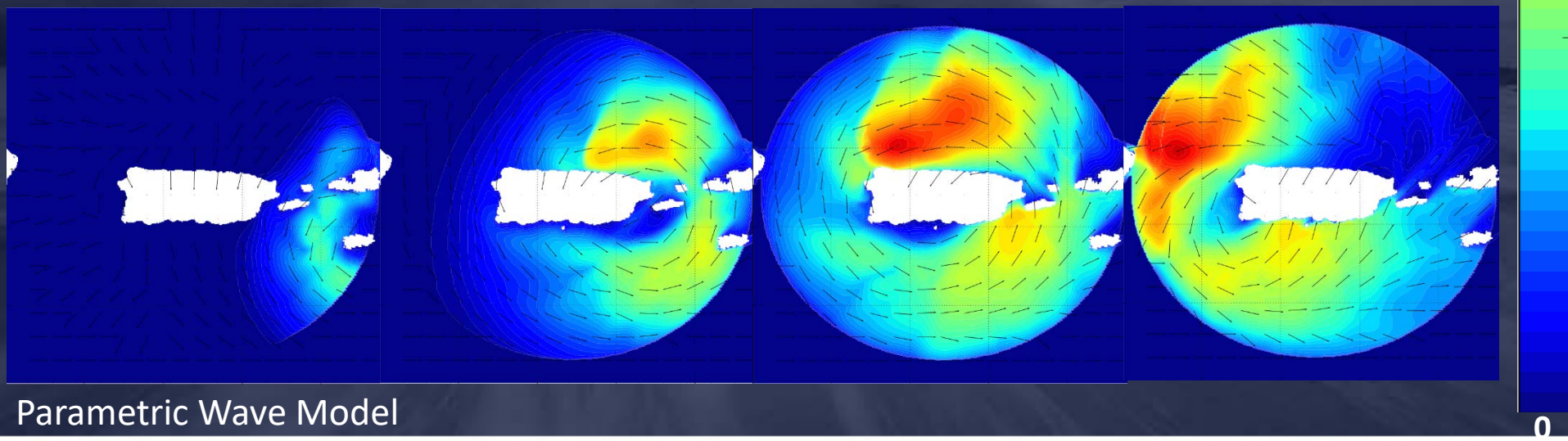
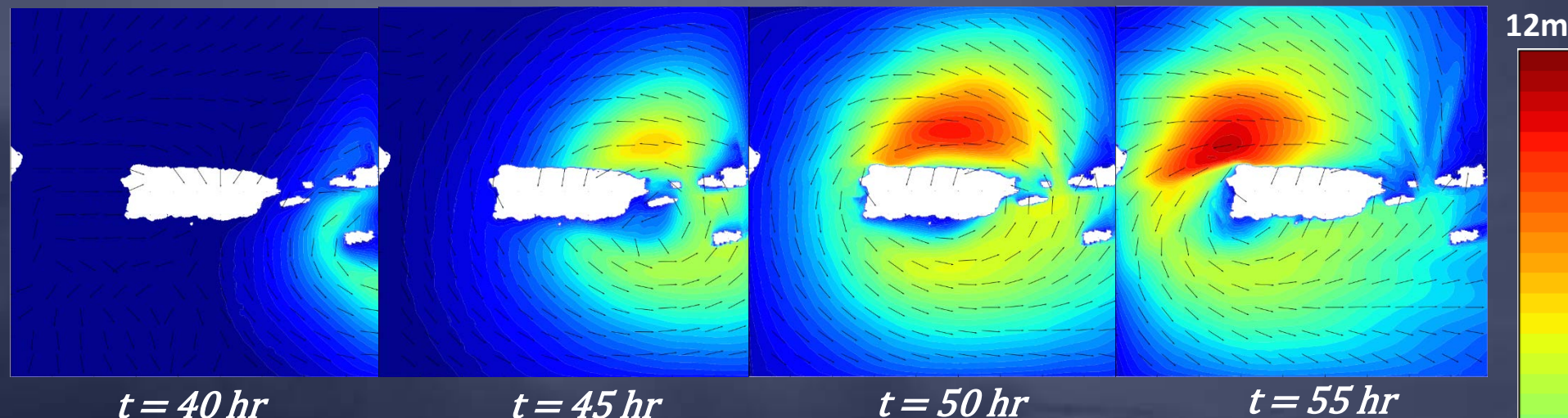
- Simplified physics, but significantly cheaper than SWAN or WW3
- More suitable to couple with SLOSH



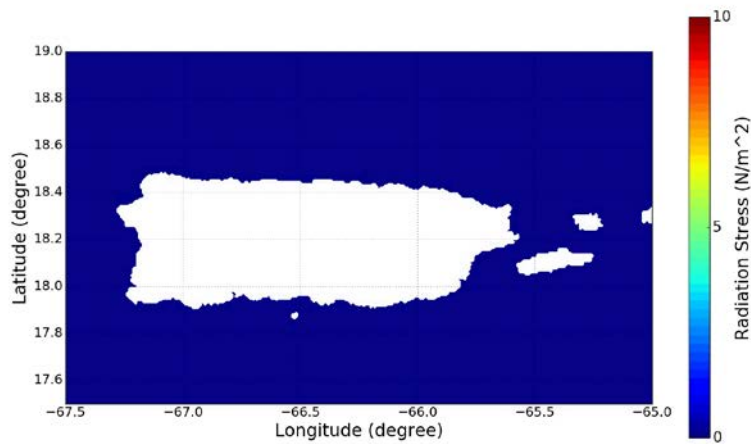
SLOSH basin and wave model grid mesh

Wave Height Comparison (Hurricane Georges, 1998)

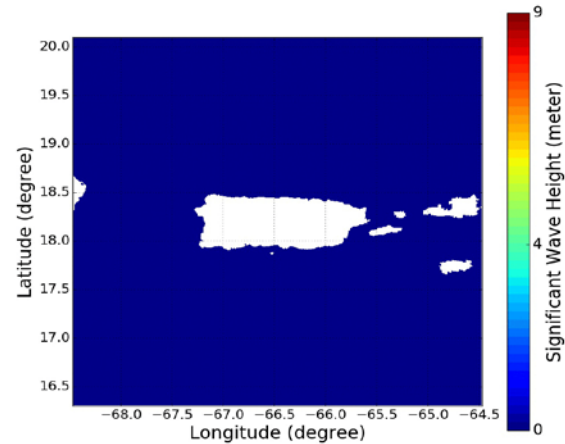
SWAN Model



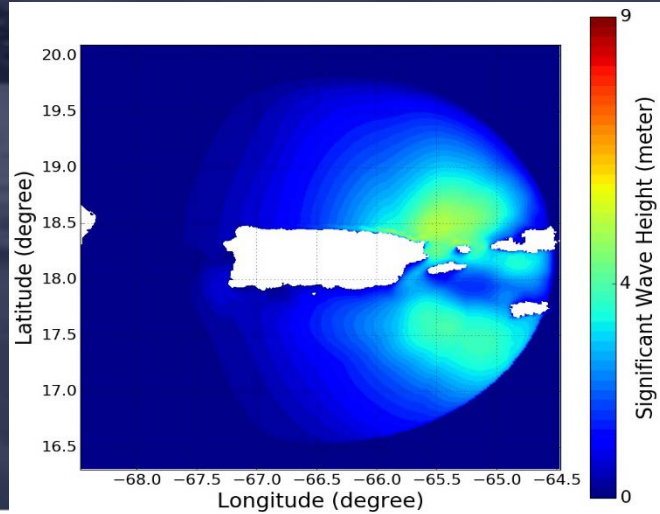
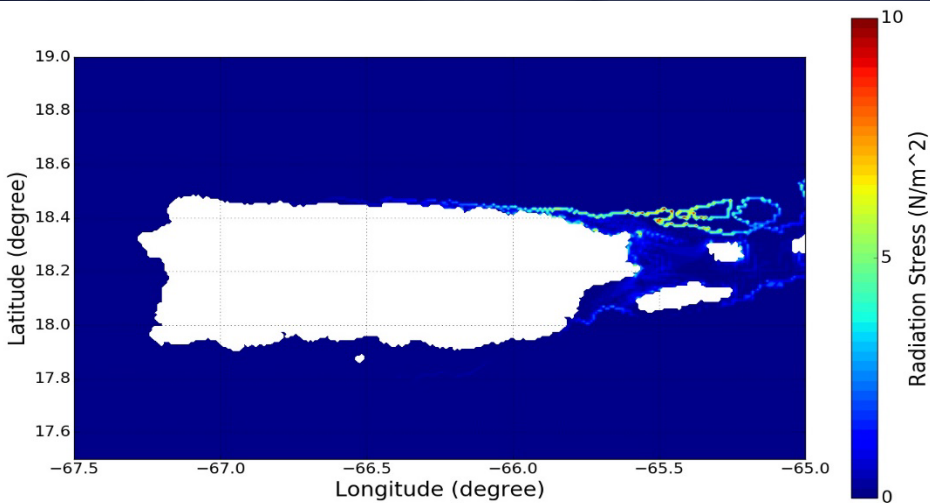
Coupled SLOSH + Waves



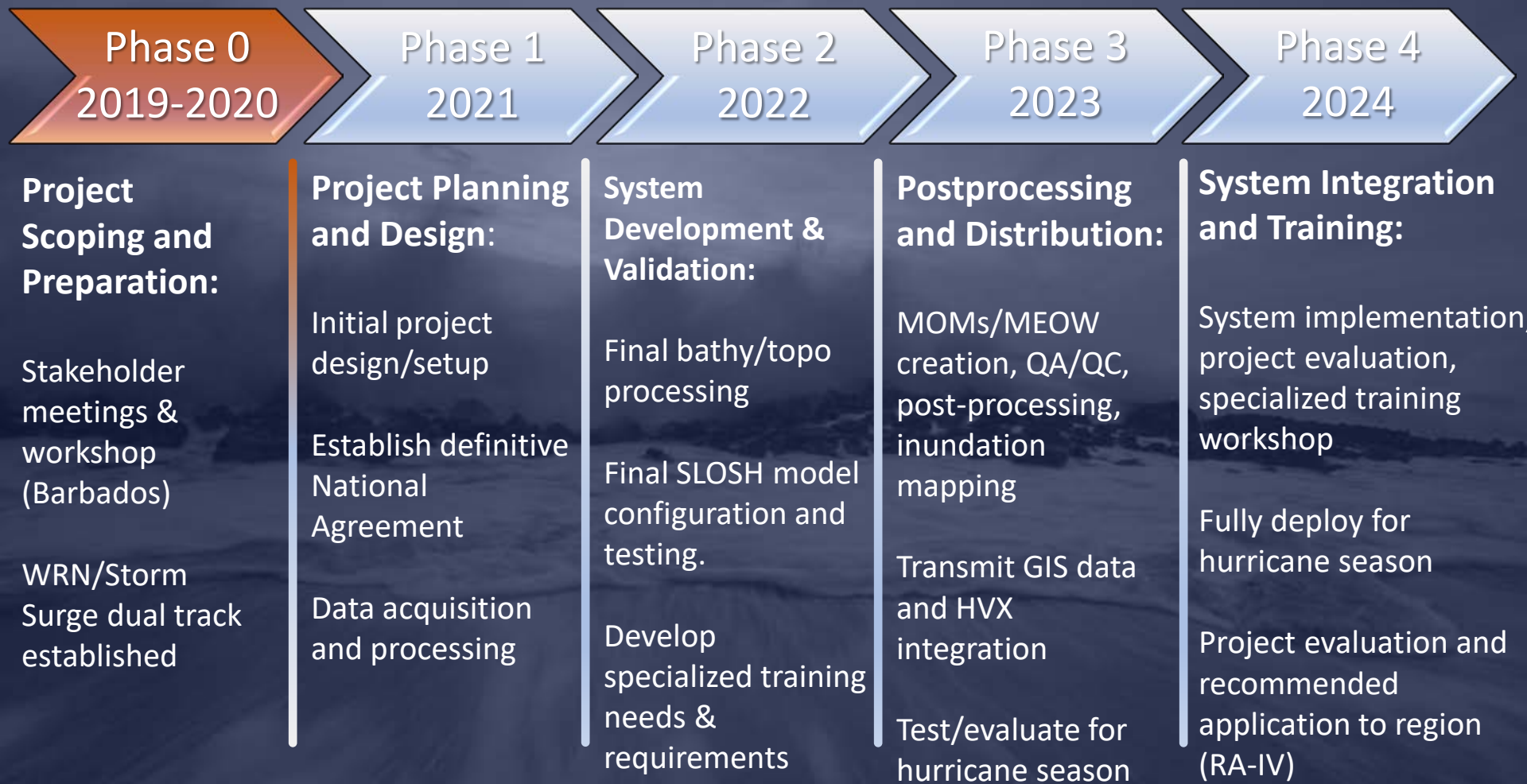
Wave Radiation Stress



Significant Wave Height

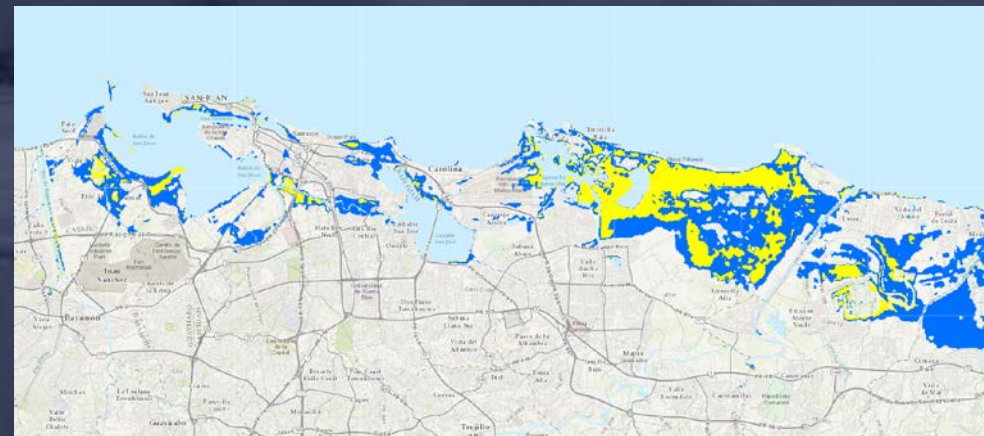
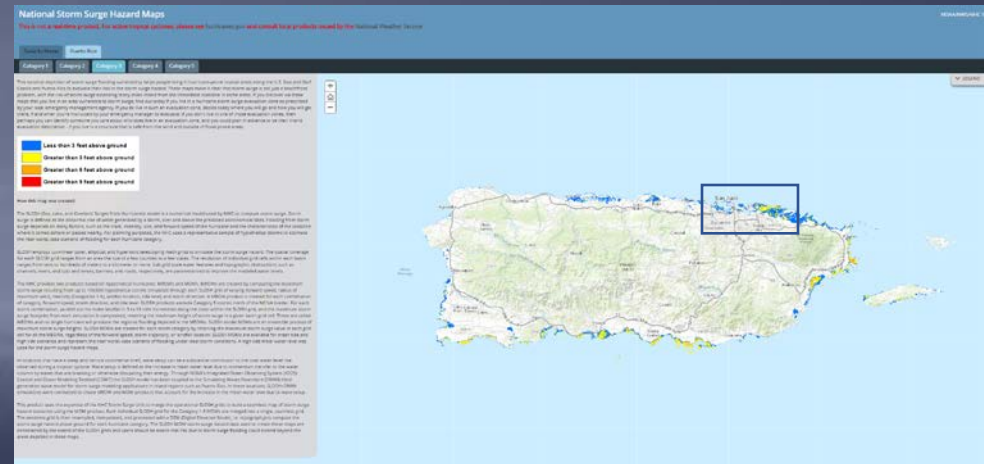


Bahamas Storm Surge Project Phases



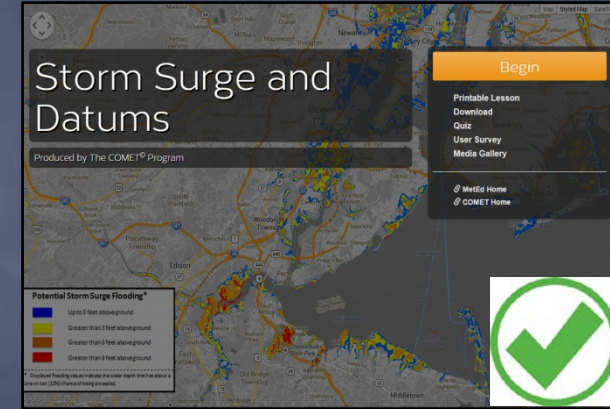
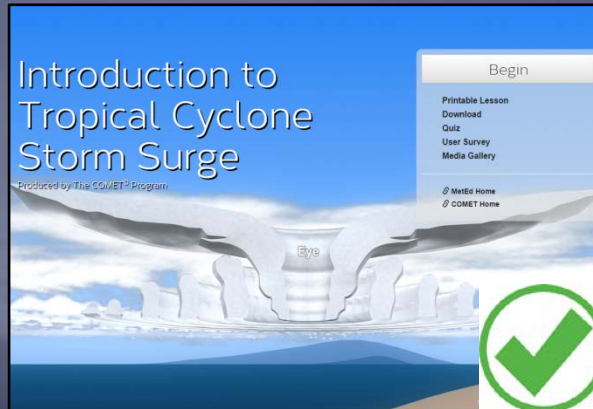
Dissemination and Data Availability

- MEOWs: GIS files provided to the Government of the Bahamas
- NHC will host the CIFDP-C MOMs on an online web portal for high-resolution inundation mapping
 - Provide GIS data
 - Map services



Existing Forecaster and Civil Defense Training Modules

Tropical Cyclone Forecast Uncertainty



Storm Surge Forecasting

