

STORM SURGE

An Introduction to Storm Surge and Storm Surge Forecasting

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National Hurricane Center
Storm Surge Unit

WMO RA-IV Workshop on Hurricane Forecasting and Warnings
April 29th, 2021



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



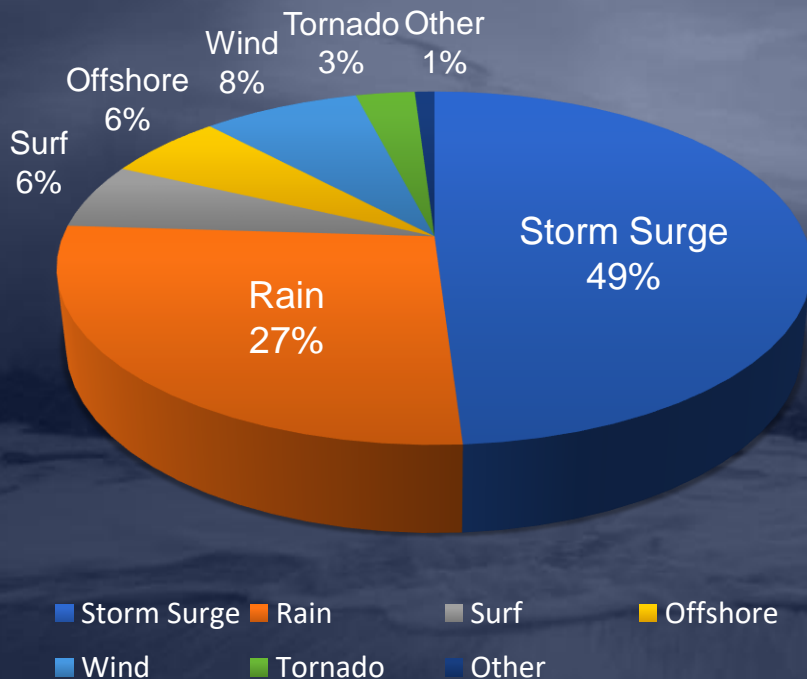
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The Danger of Storm Surge

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



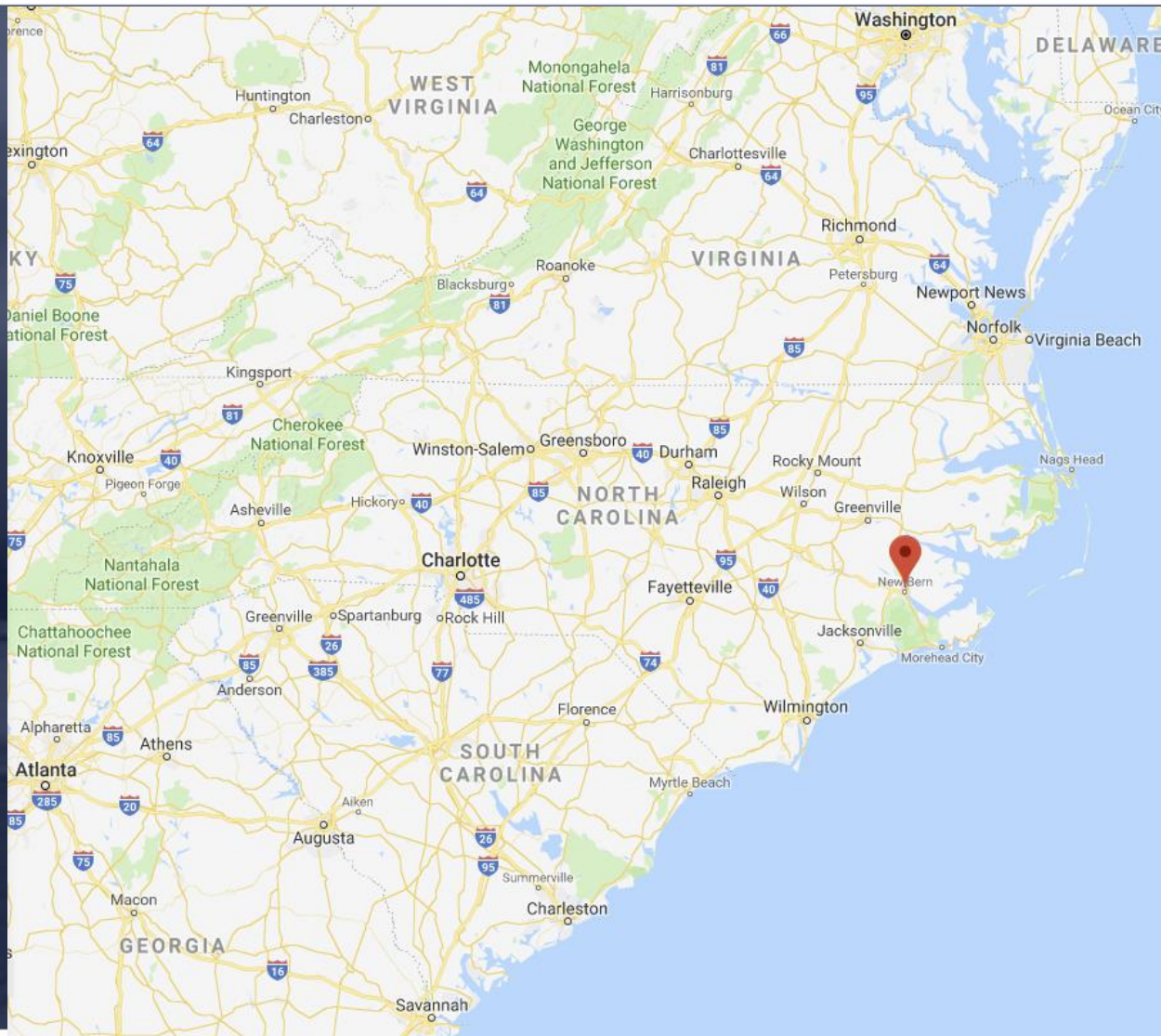
Myth or Fact?

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



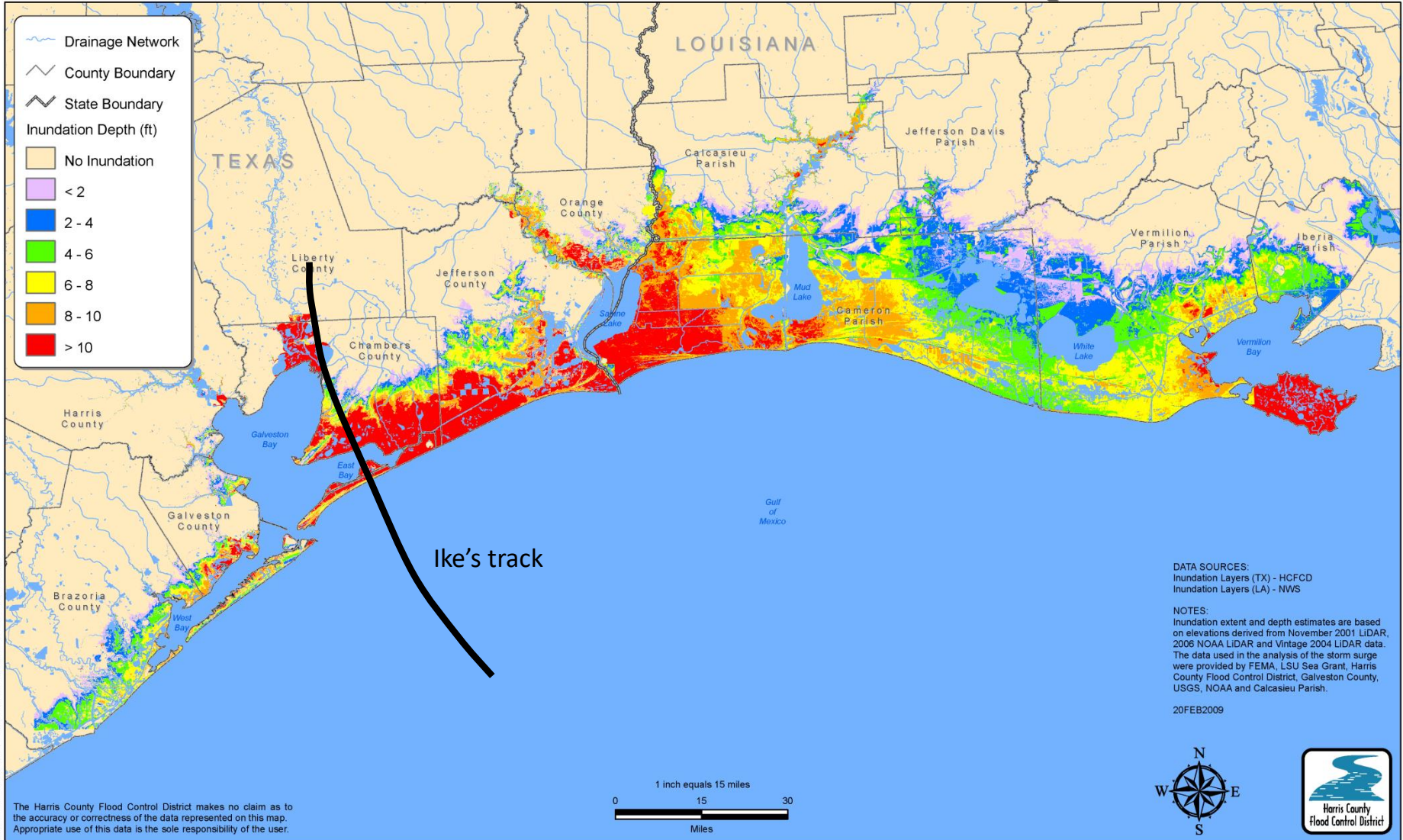
New Bern, NC – Hurricane Florence

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nest



Hurricane Ike Inundation Depth



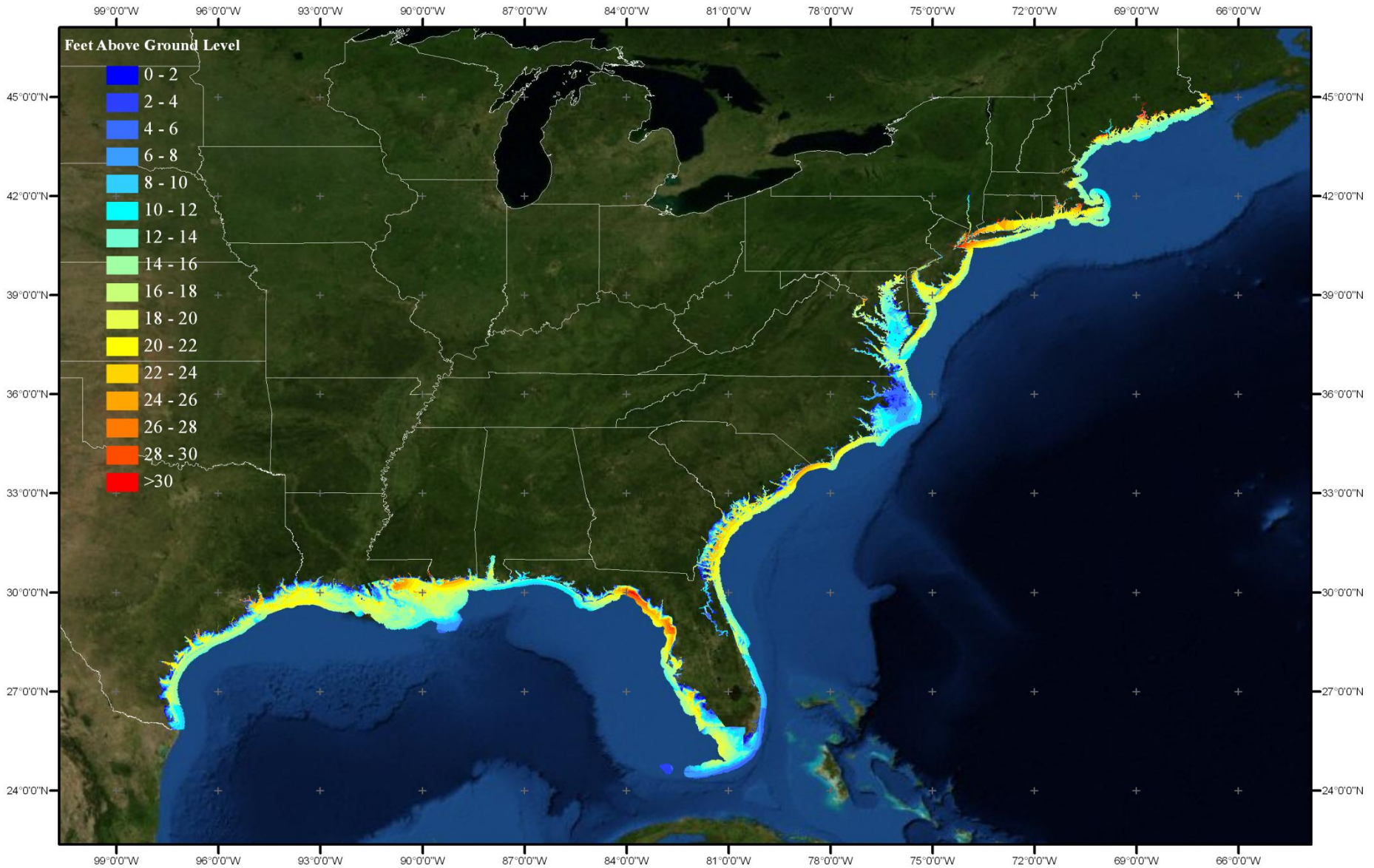
S:\Open\GIS\Swort_direct\Ike\Inundation\Mapa\ke_inund_elevationdepth_11x17.pdf



**Are some areas more vulnerable to
storm surge than others?**

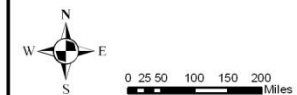


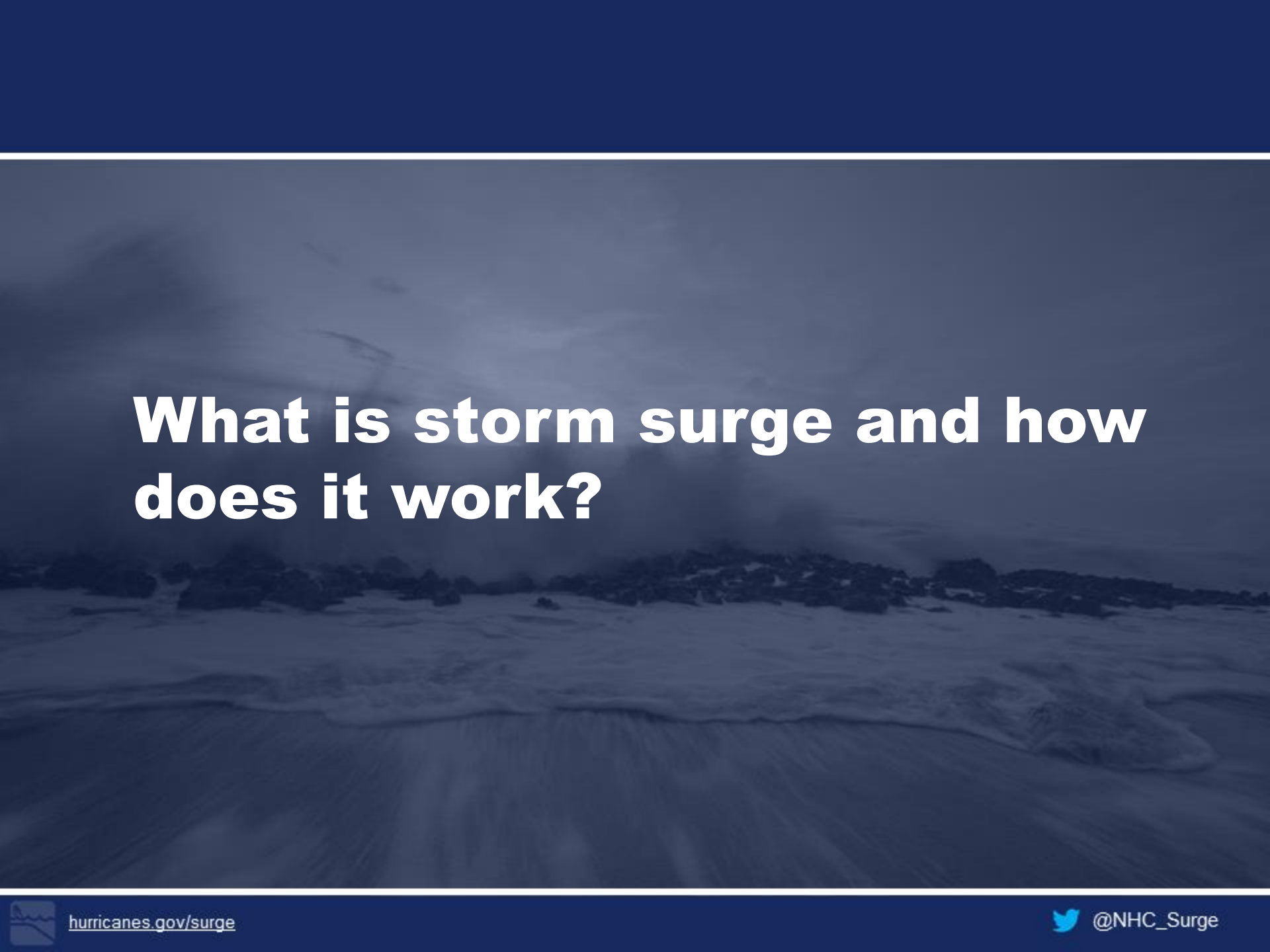
Storm Surge Vulnerability: Category 4 Hurricane



Data Source:
NWS/NHC/Storm Surge Unit

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

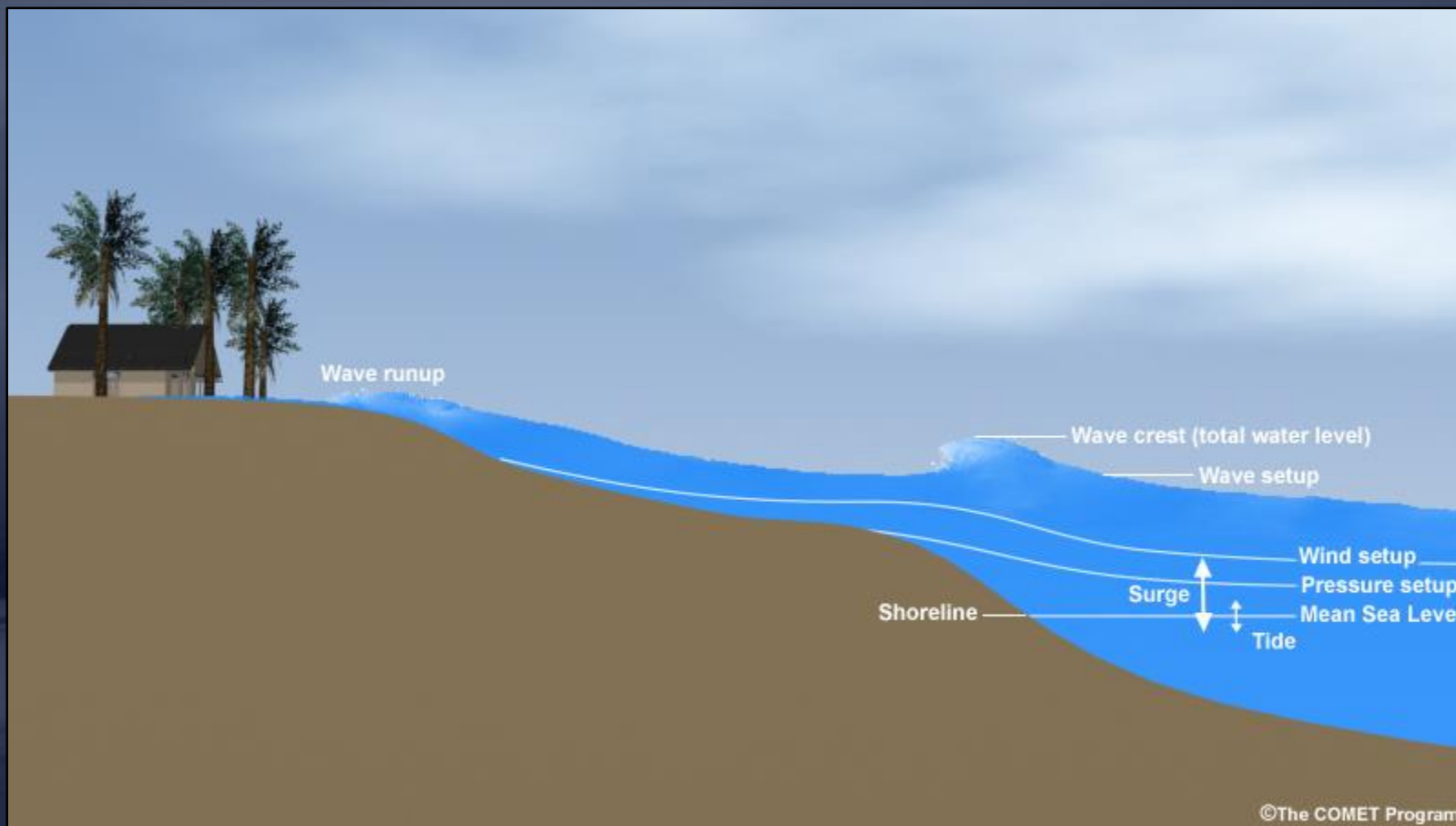




What is storm surge and how does it work?



Total Water



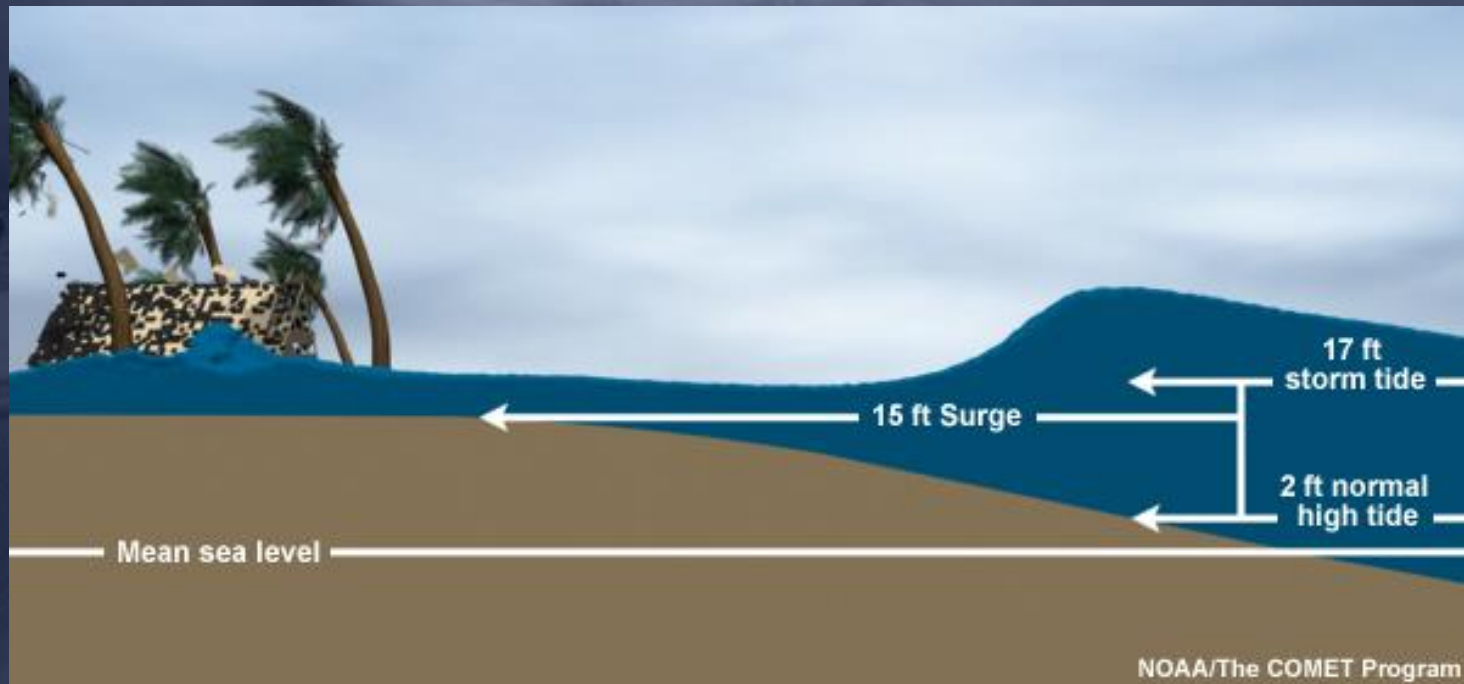
Total water level = Storm surge + Tides + Wave setup + Freshwater



What are Storm Surge and Storm Tide?

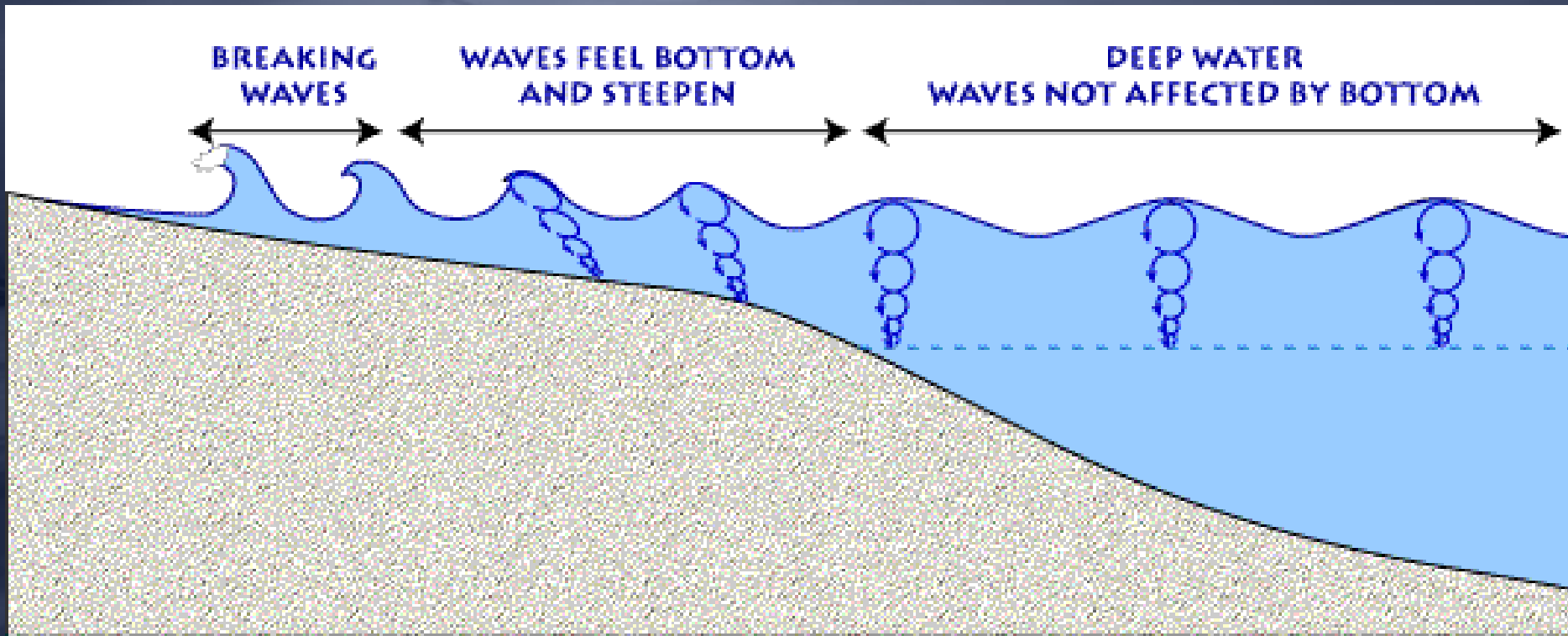
STORM SURGE is an abnormal rise of water generated by a storm, over and above the predicted astronomical tide.

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

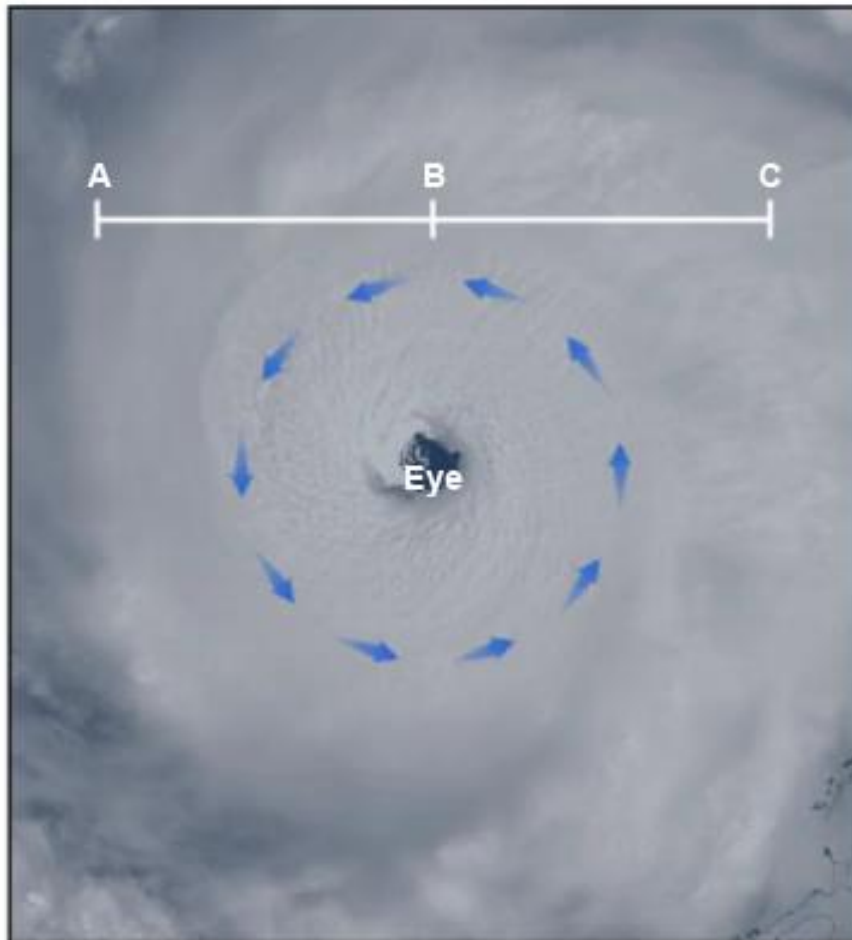
Freshwater Input



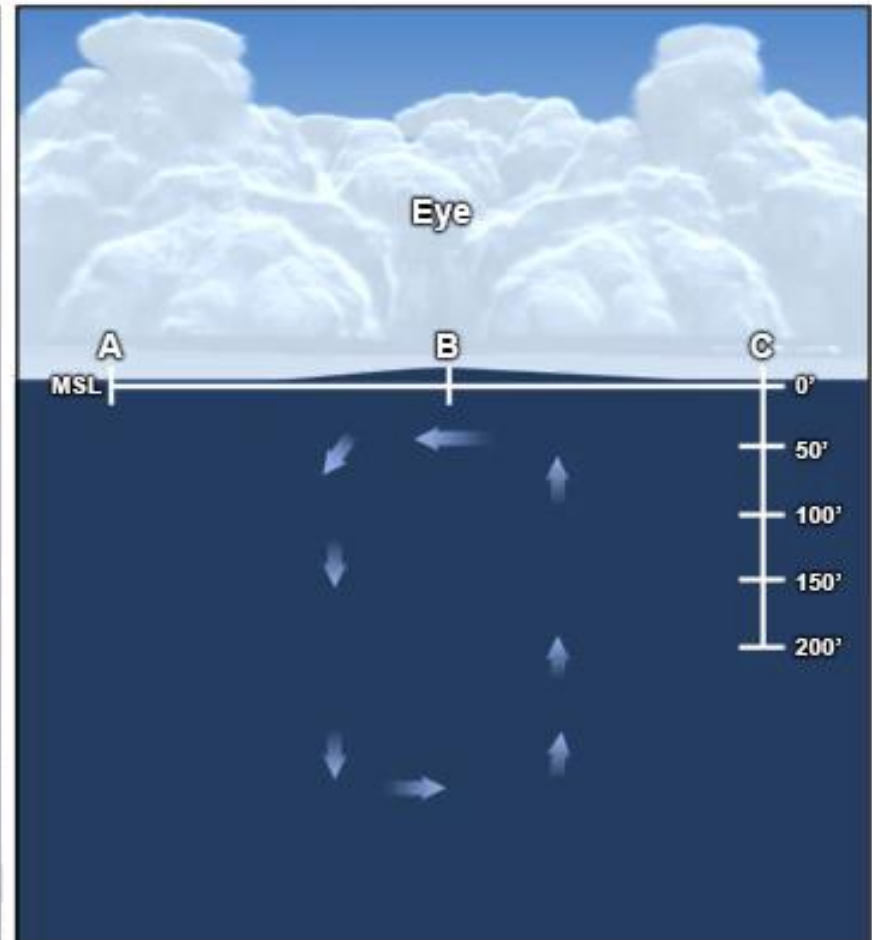
- River input, esp. into bays and sounds
 - Mississippi River discharges 200,000 – 700,000 cubic feet per second
- Rivers

From Deep Water to Shallow Water

Top View of Sea Surface

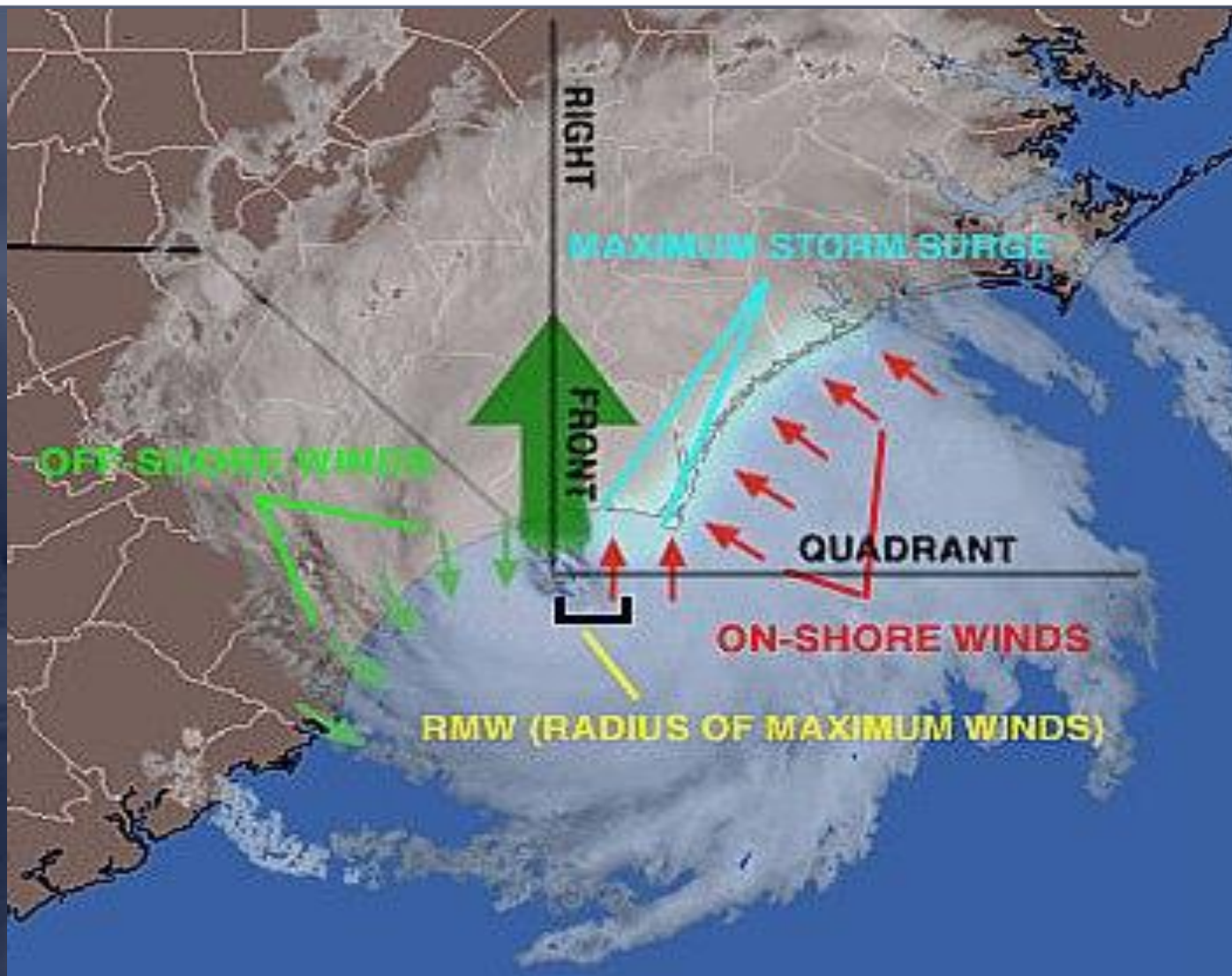


Side View of Cross Section "ABC"



©The COMET Program

Understanding Surge



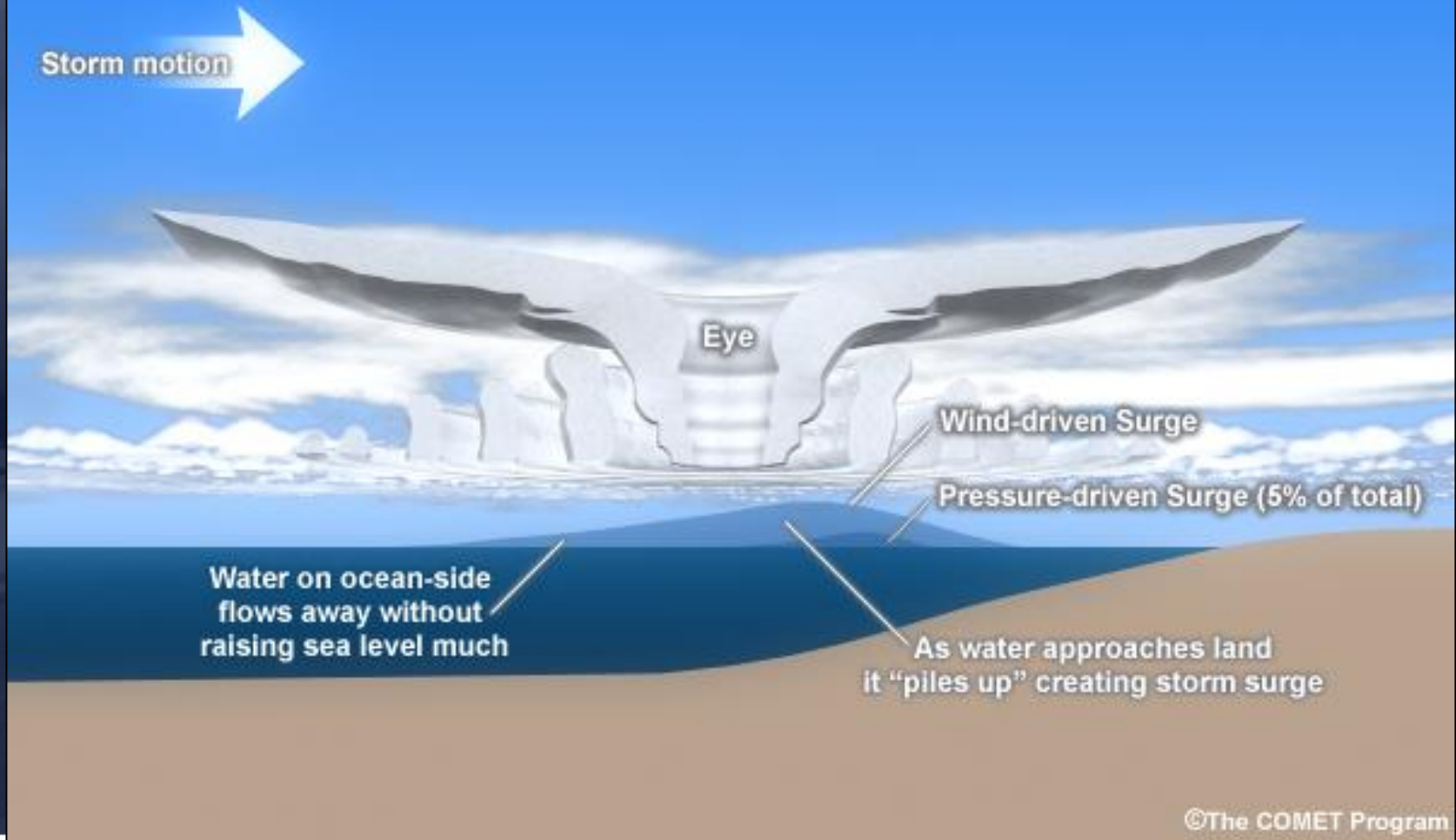


What are the factors that affect storm surge?



Effects of Low Pressure

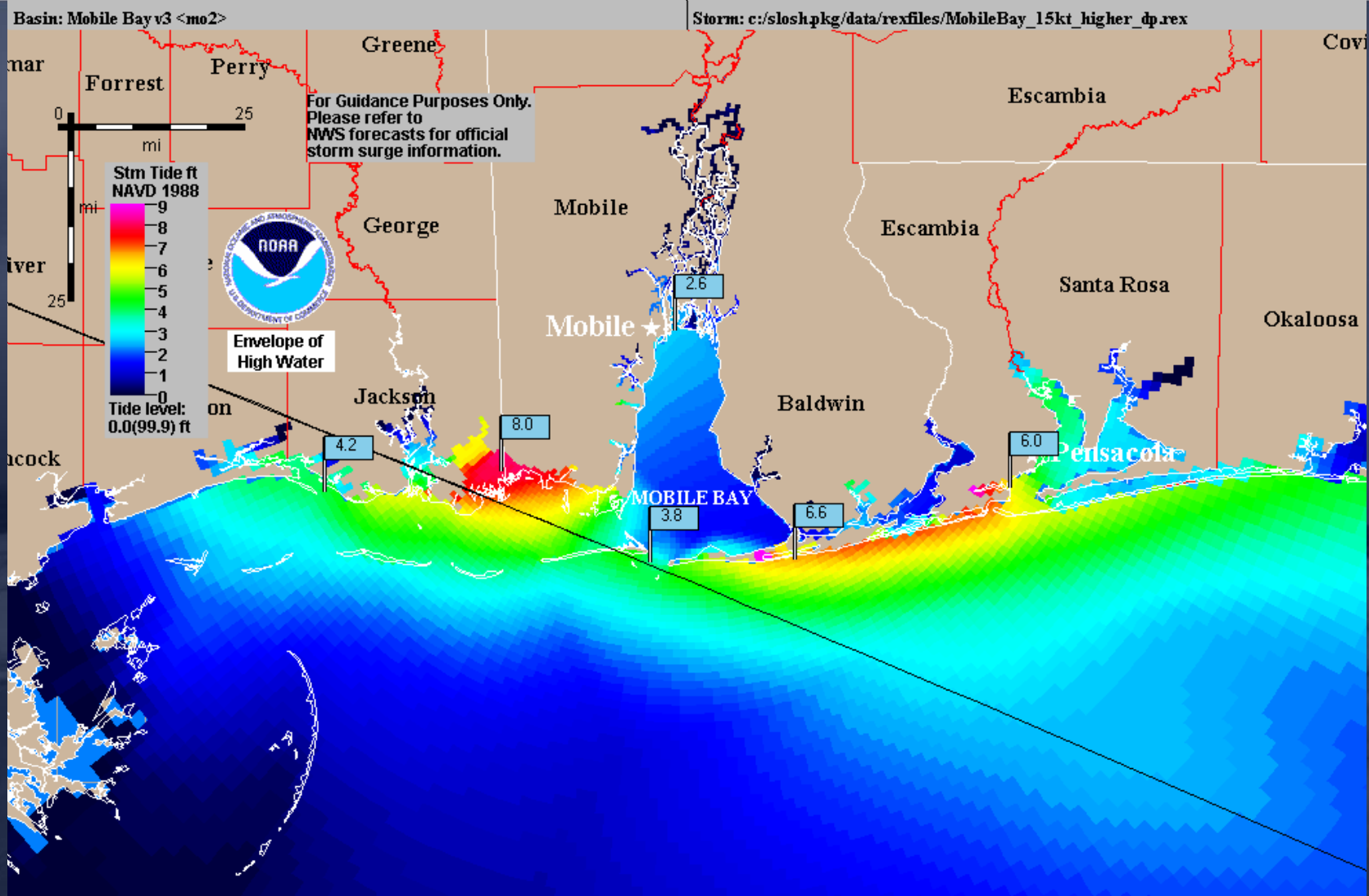
Wind and Pressure Components of Hurricane Storm Surge



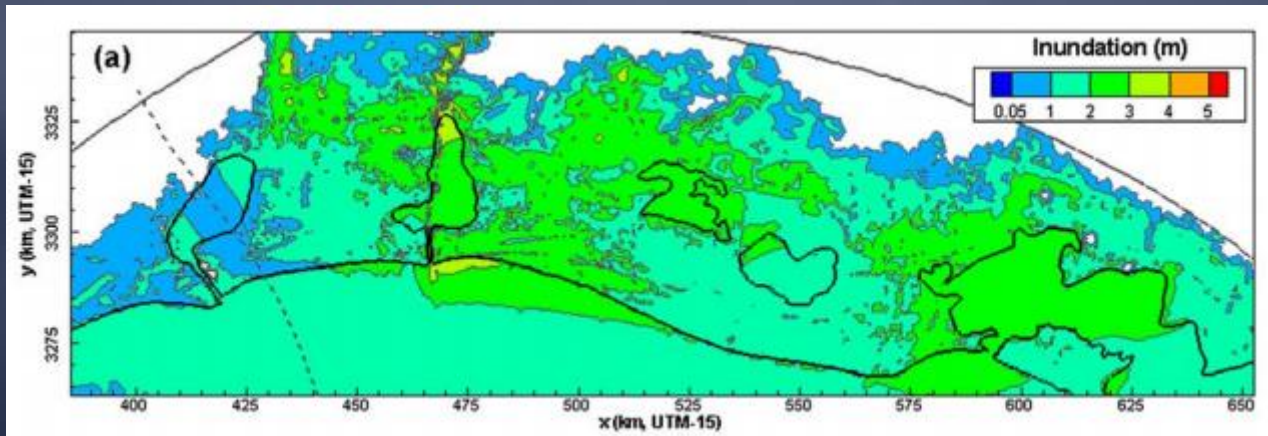
©The COMET Program

Intensity (Wind Speed)

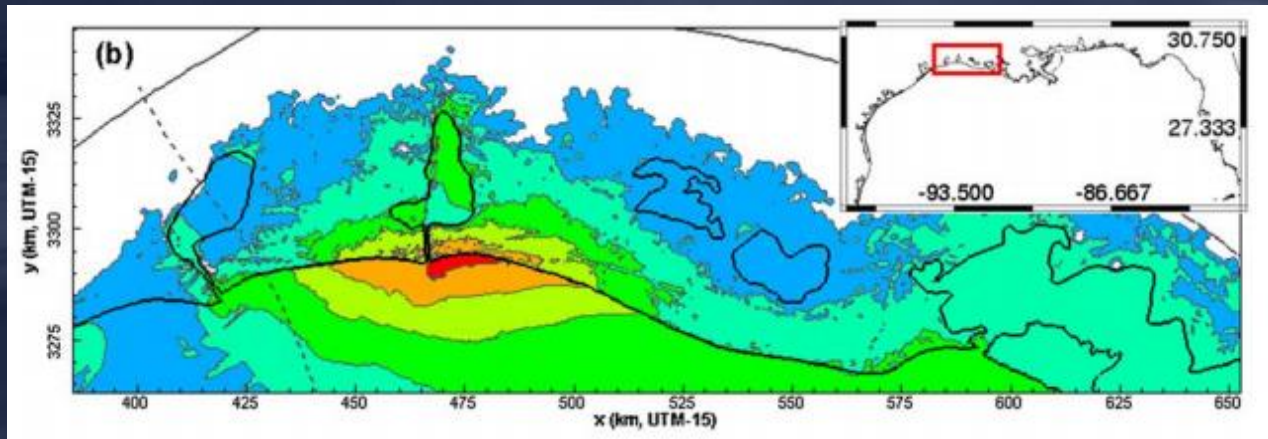
15 mph stronger



Forward Speed



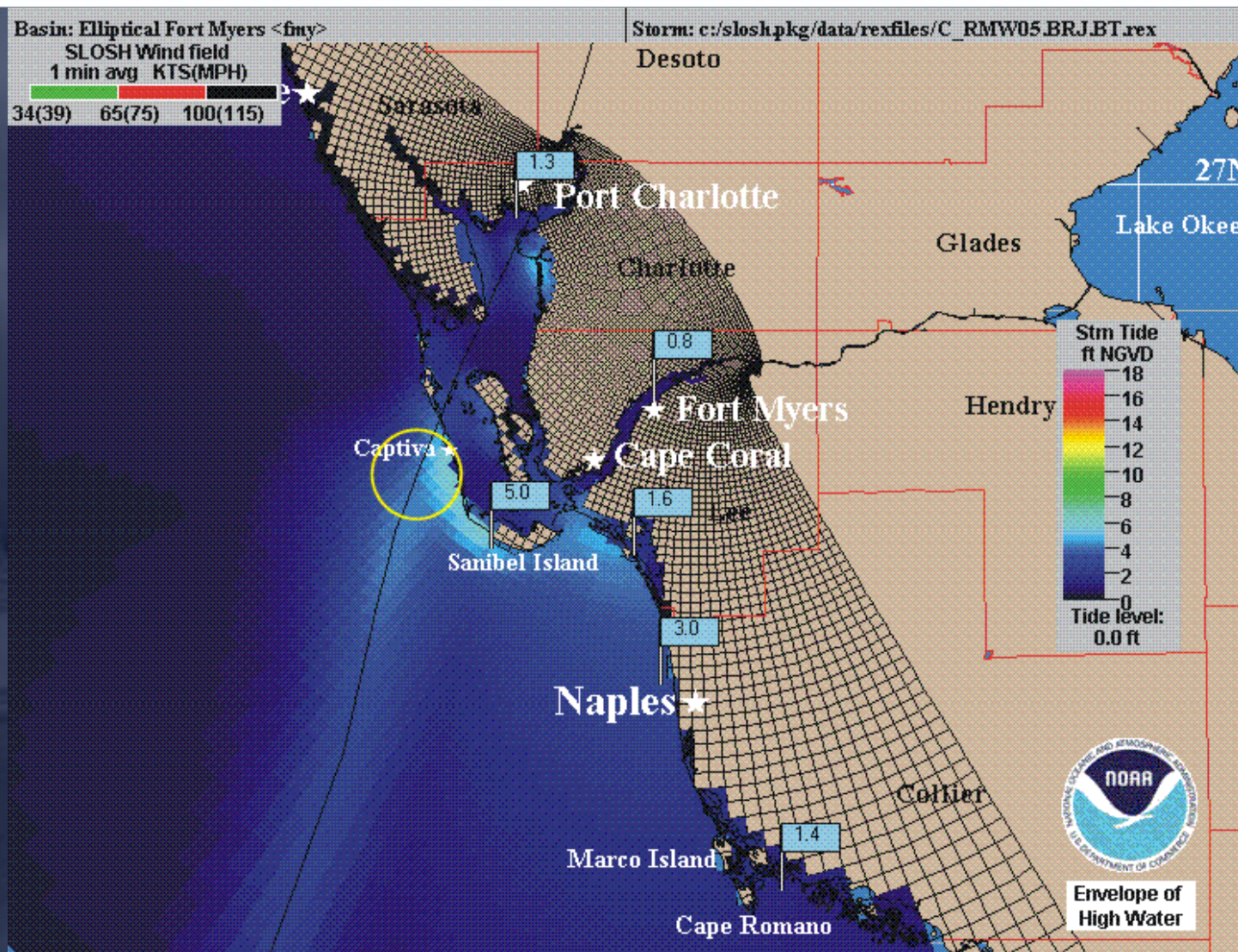
- Slow Speed (5 mph)**
 - More inland penetration



- 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)



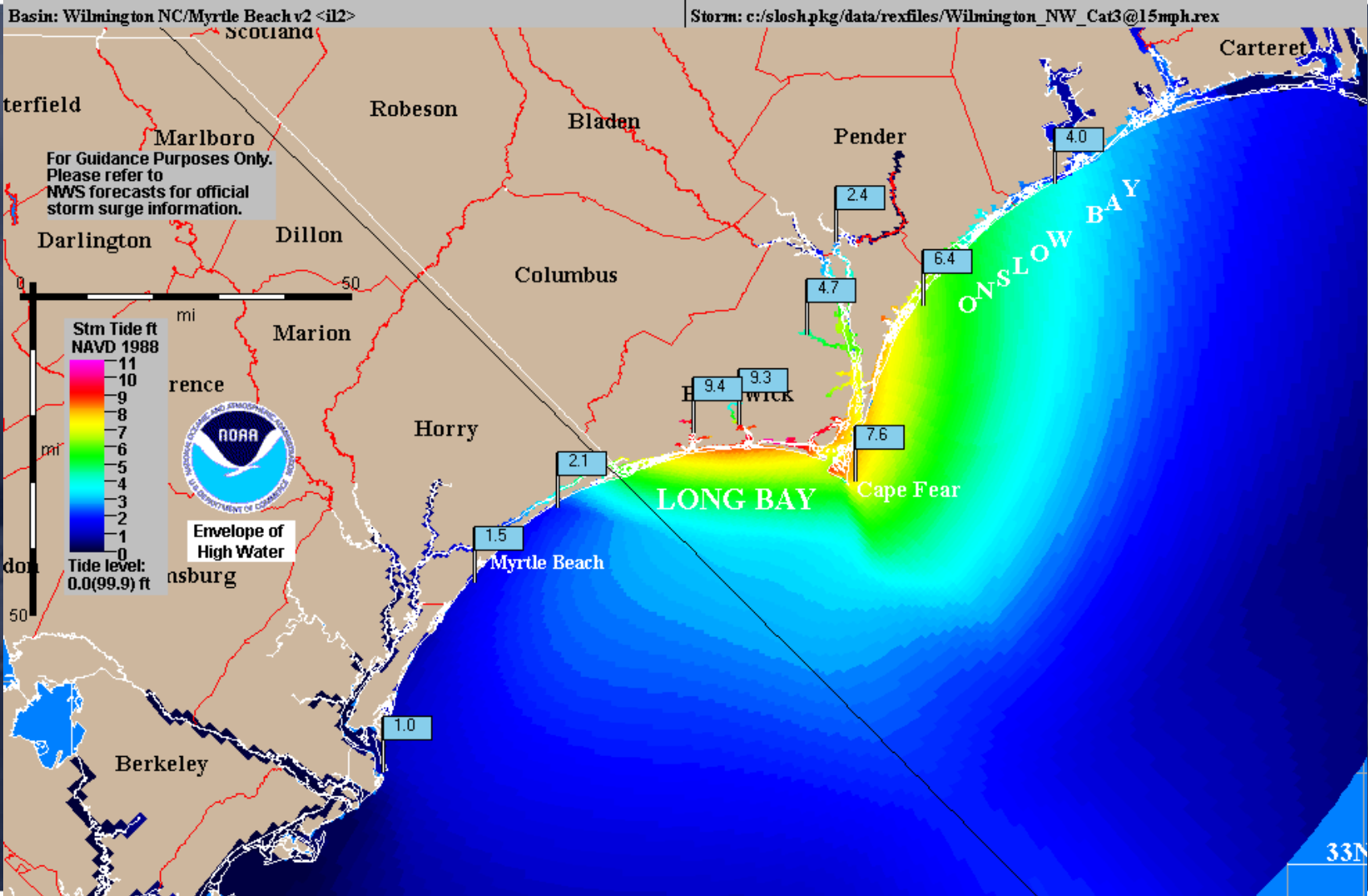
Size (Radius of Max Winds)



©The COMET Program

Angle of Approach

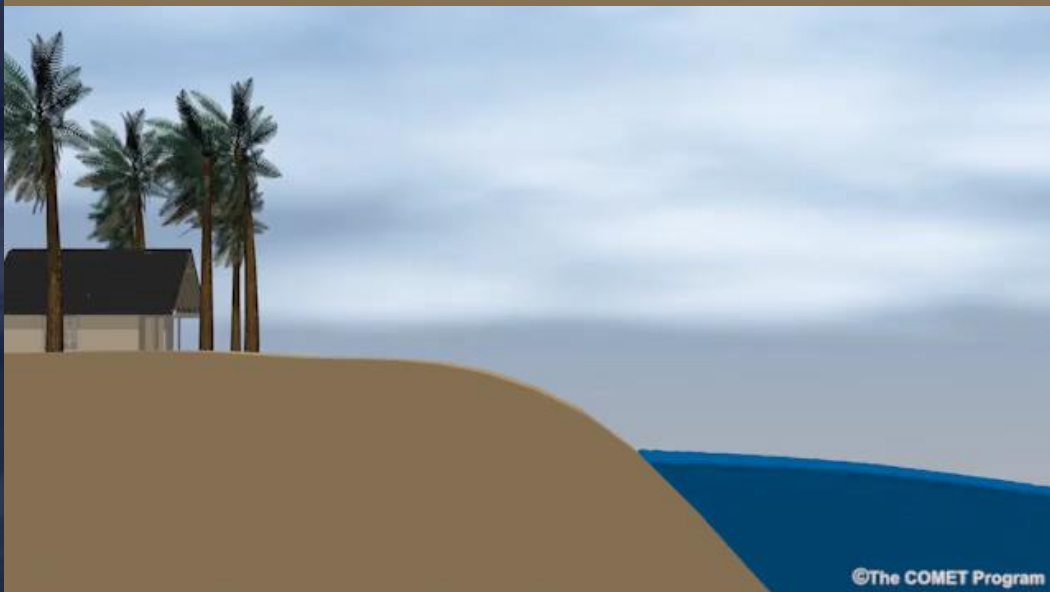
NNW Motion



Width and Slope of Shelf



Wide shelf/gentle slope

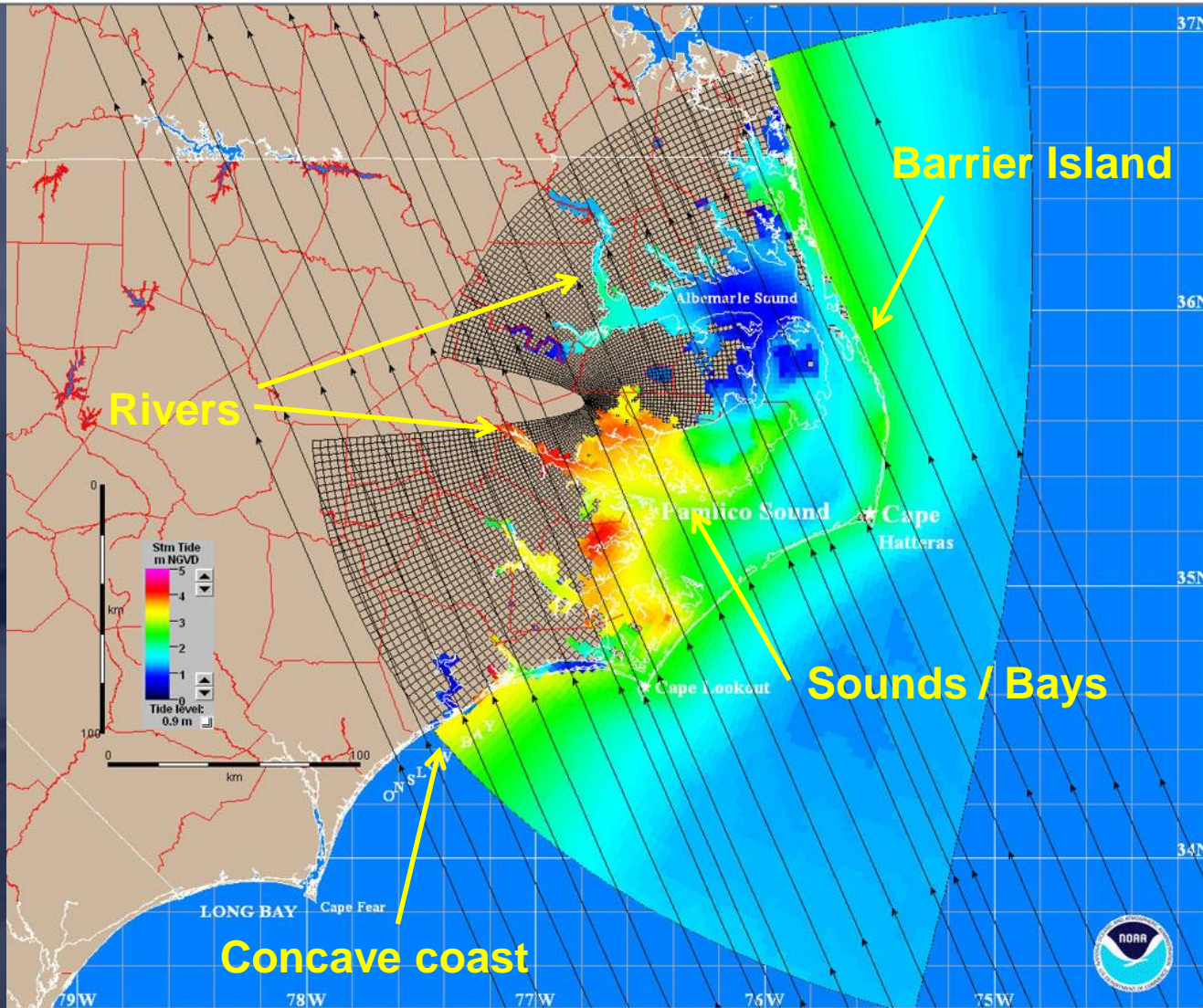


Narrow shelf/sharp slope

©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**



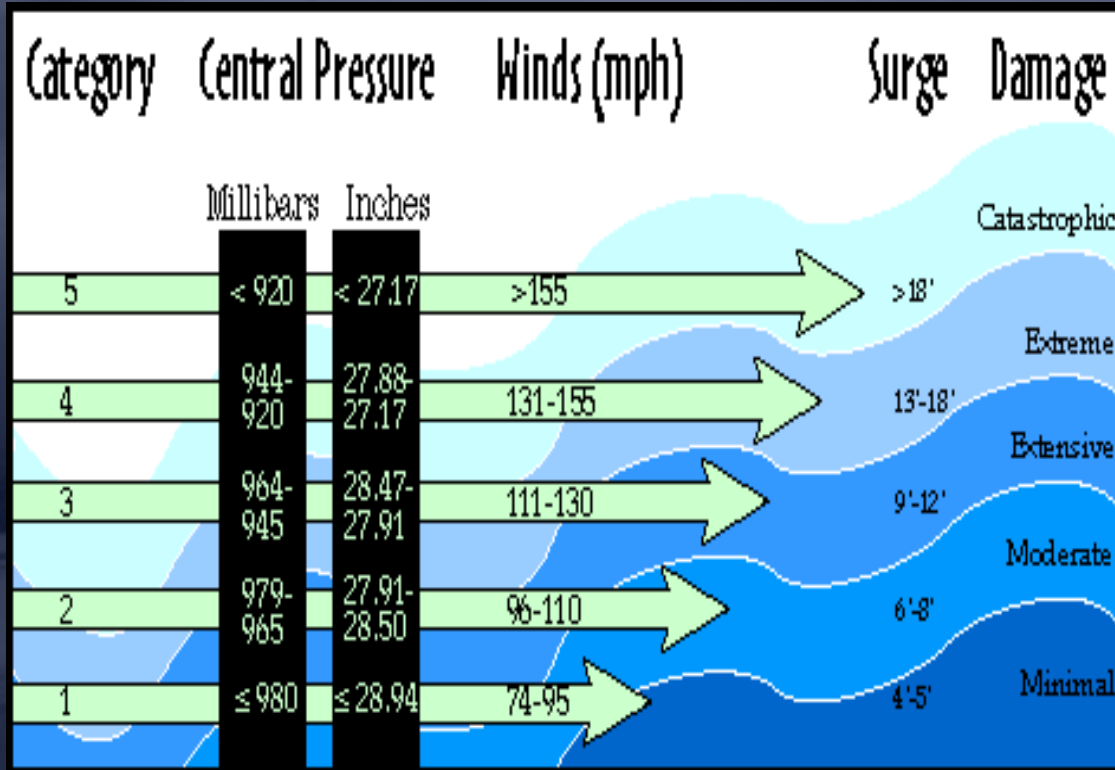
Myth or Fact?

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)

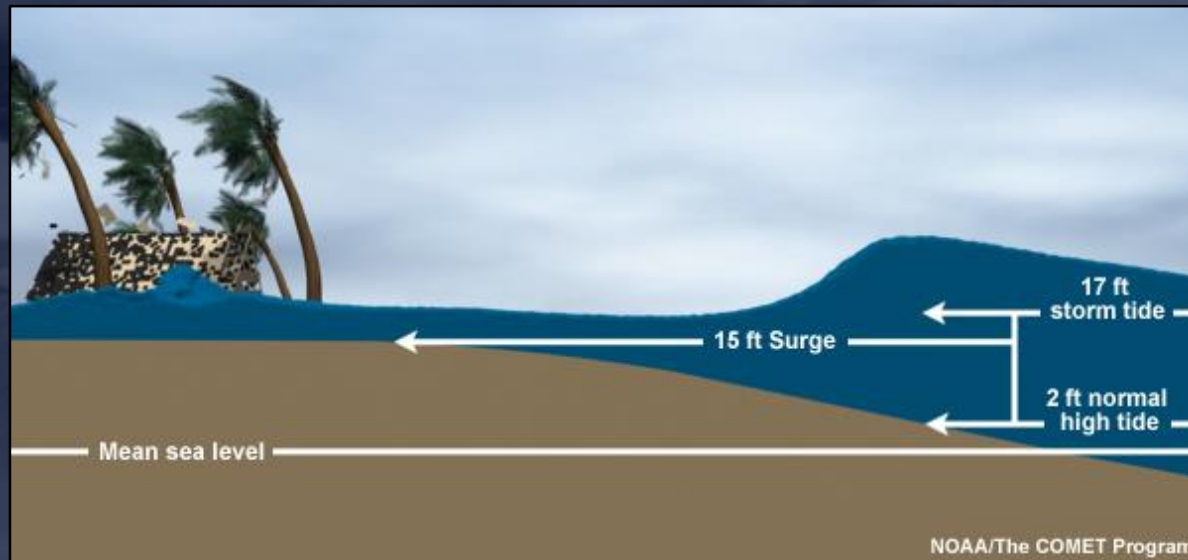
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SLOSH

- **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)

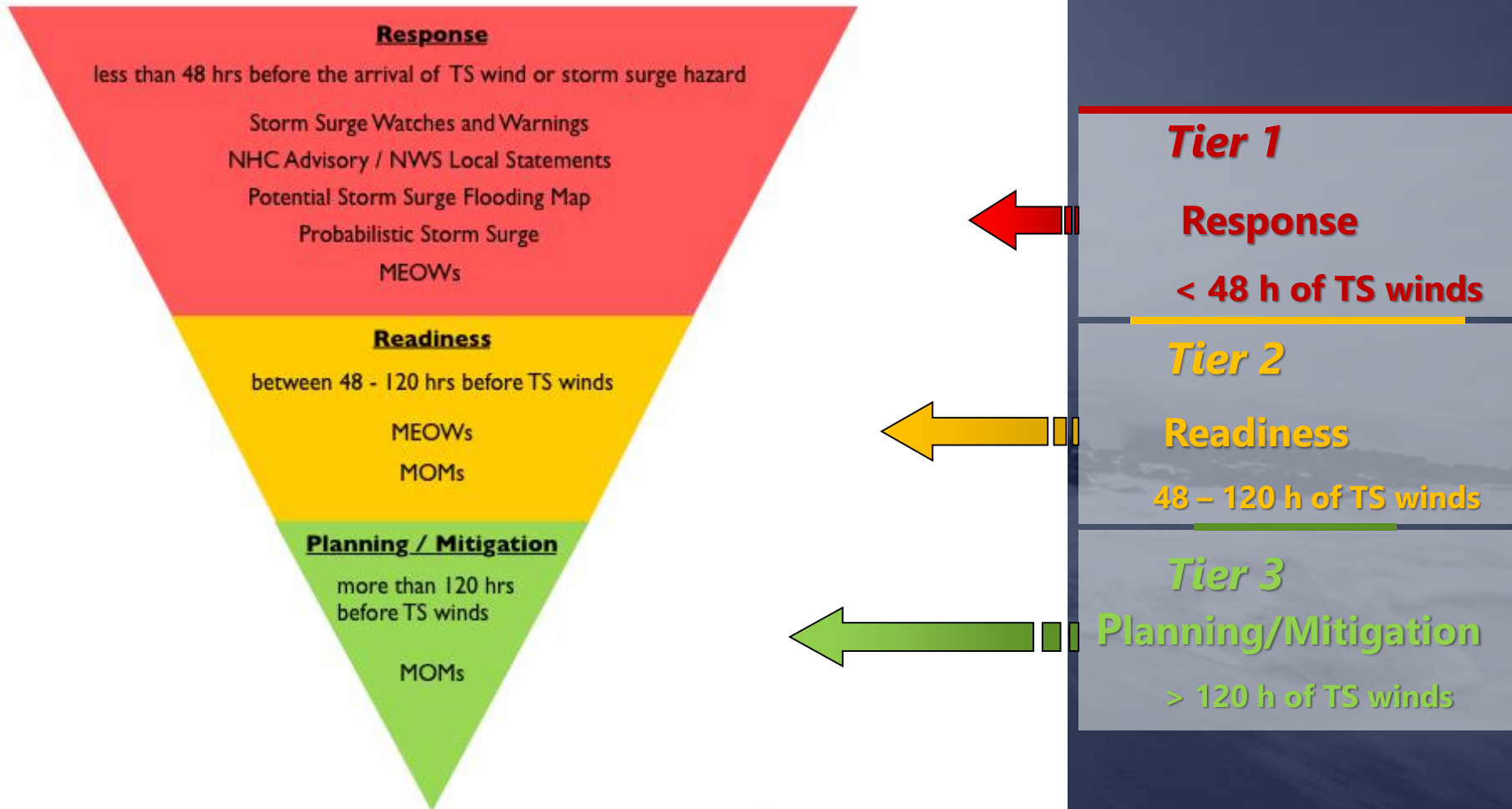
Potential Storm Surge Flooding Graphic

Storm Surge Watch/Warning

Storm Surge Guidance Timeframe

NHC Storm Surge Product Decision Support Wedge

Decision Support Wedge Based on the Arrival of Tropical-Storm-Force Winds



NHC / The COMET Program



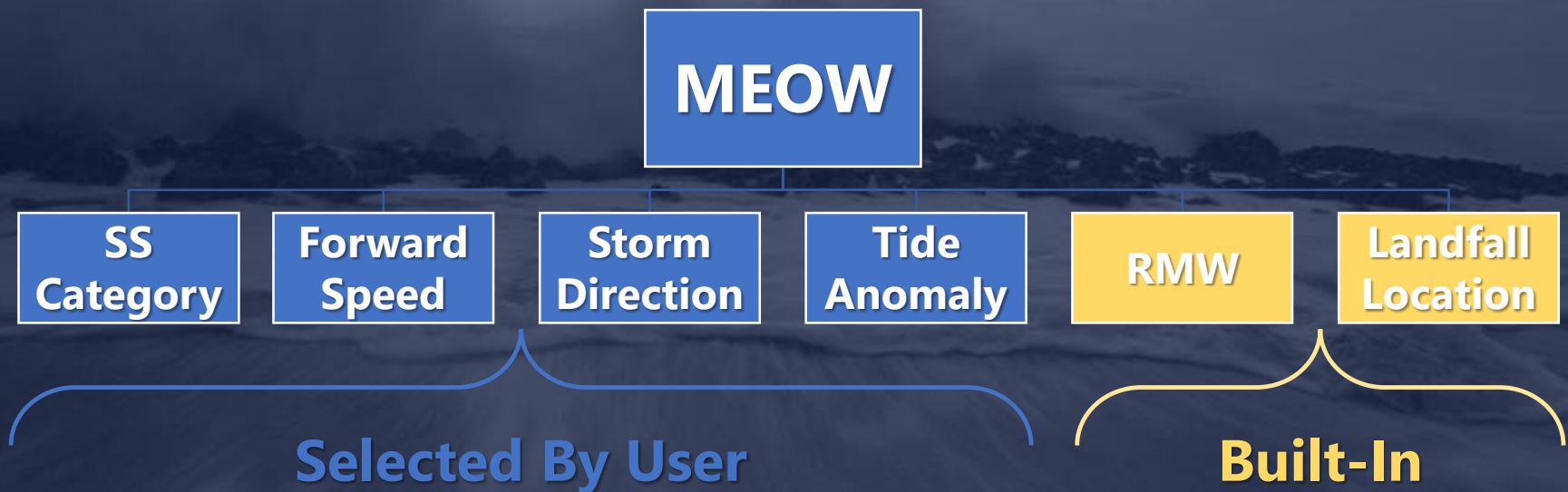
MEOW

Maximum Envelope Of Water

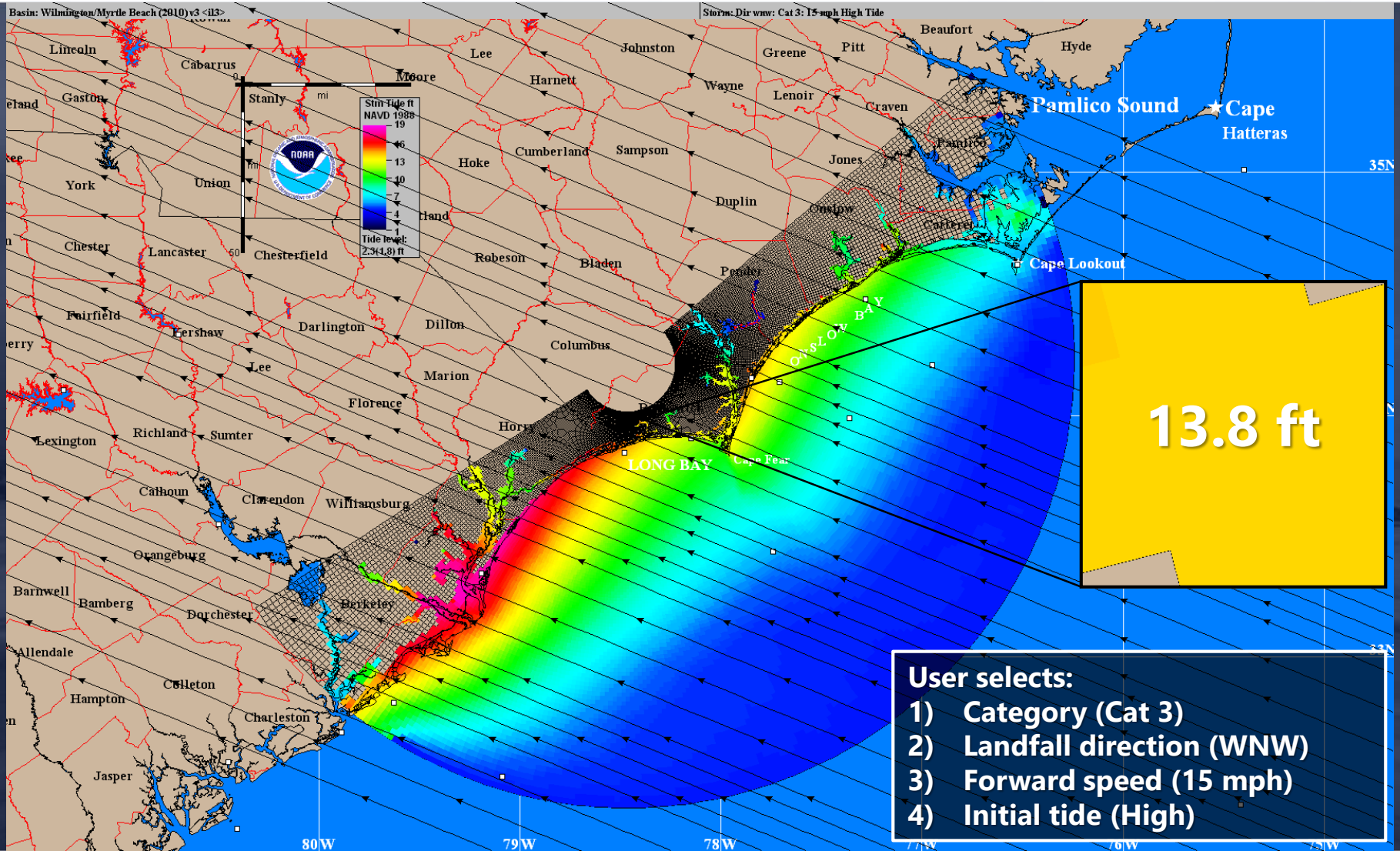


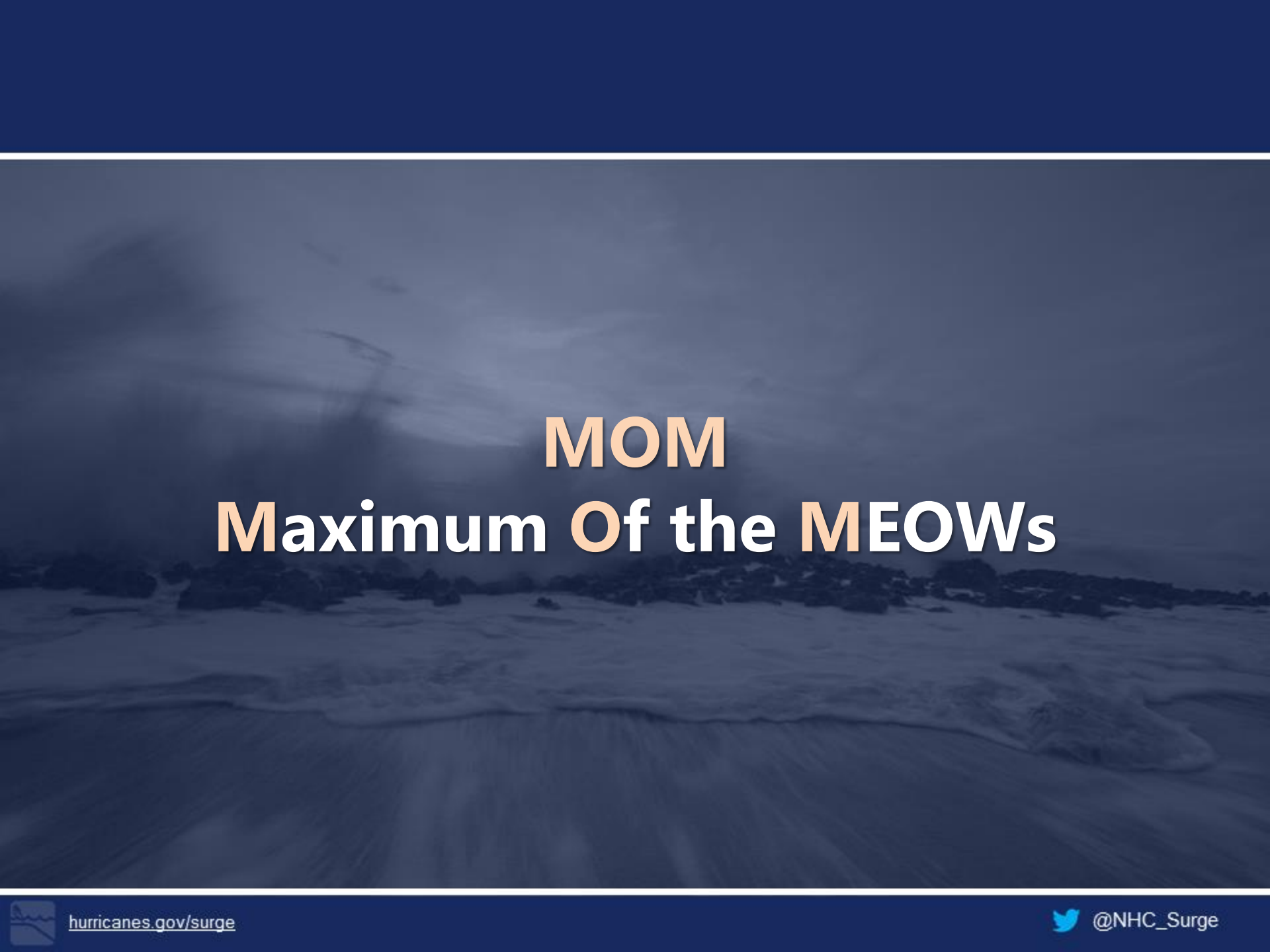
Maximum Envelope of Water (MEOW)

- Composite of the maximum storm surge for all surge simulations for a given set of parameters (by basin)
- Used as guidance for planning and operations



Maximum Envelope of Water (MEOW)

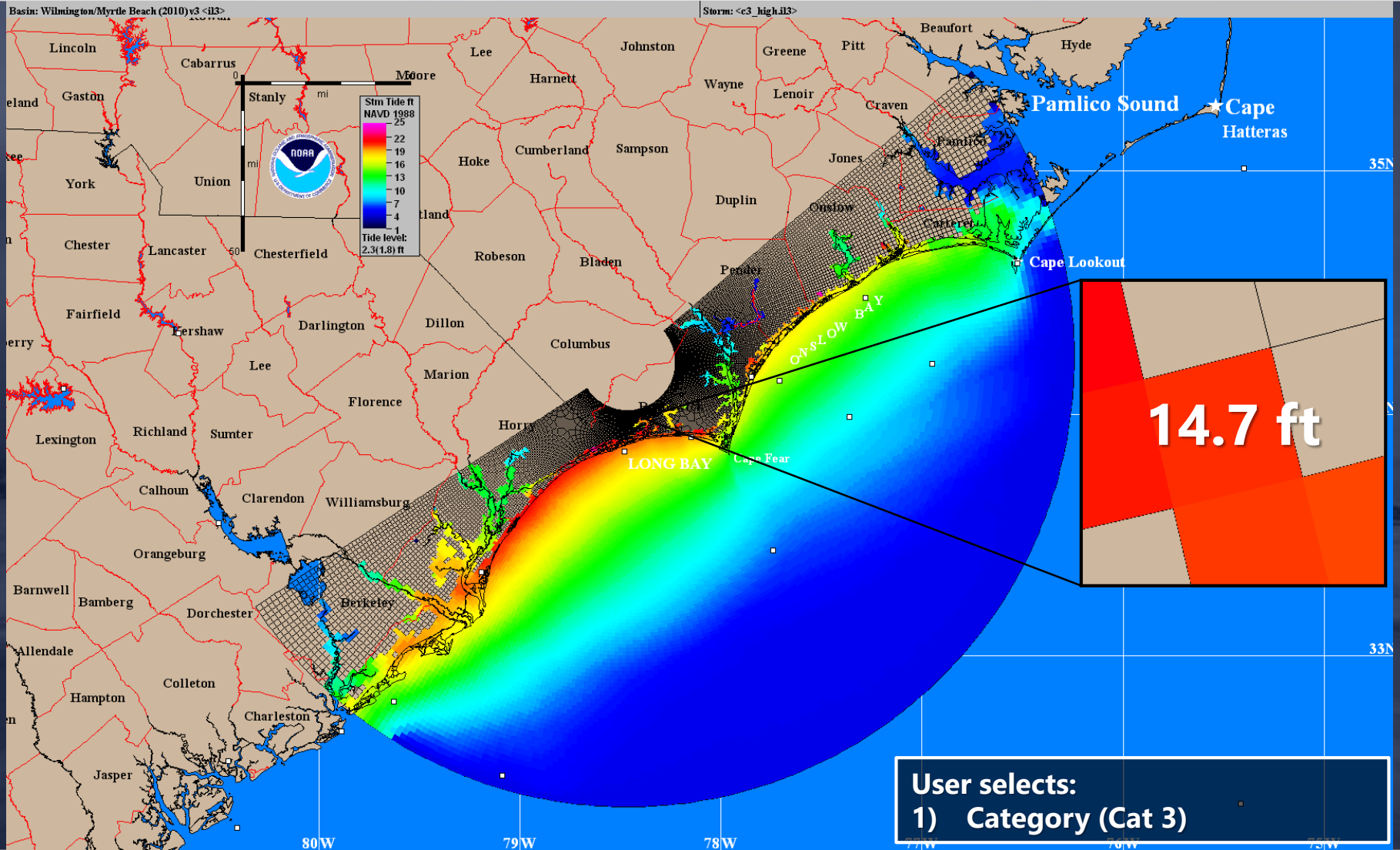




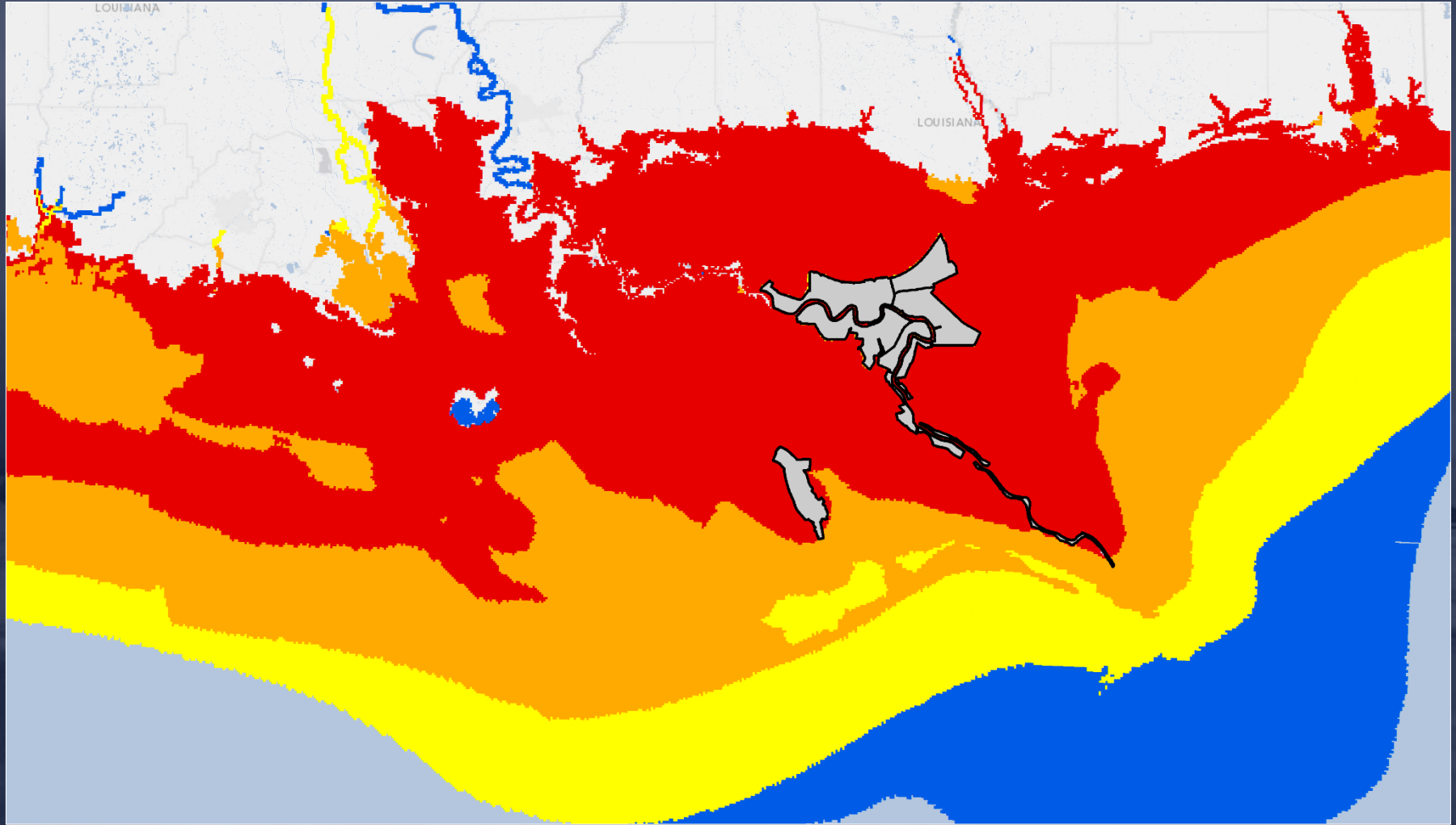
MOM
Maximum Of the MEOWs



Maximum of the MEOWs (MOMs)



Storm Surge Inundation



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

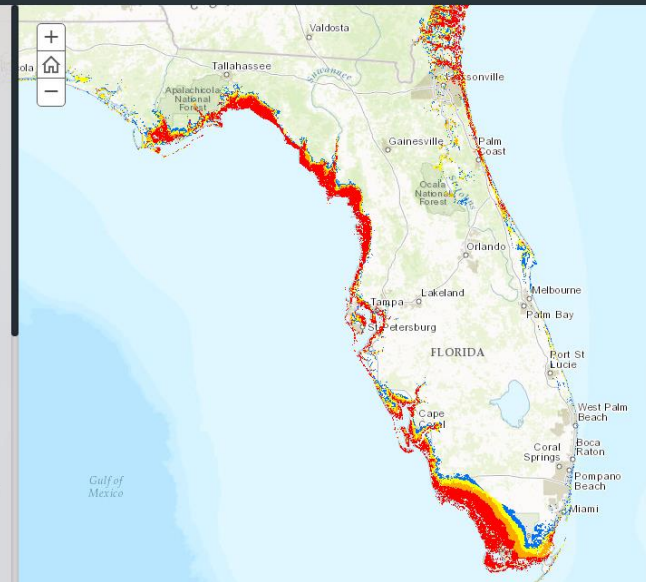
Category 1 Category 2 Category 3 Category 4 Category 5

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.

	Less than 3 feet above ground
	Greater than 3 feet above ground
	Greater than 6 feet above ground
	Greater than 9 feet above ground
	Leveed area
	Consult local officials for flood risk

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

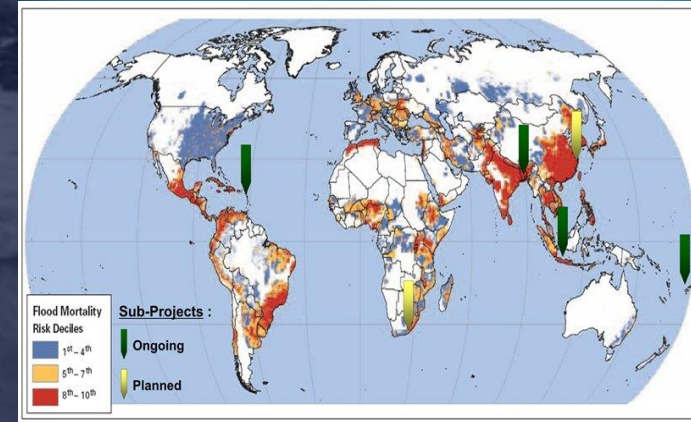
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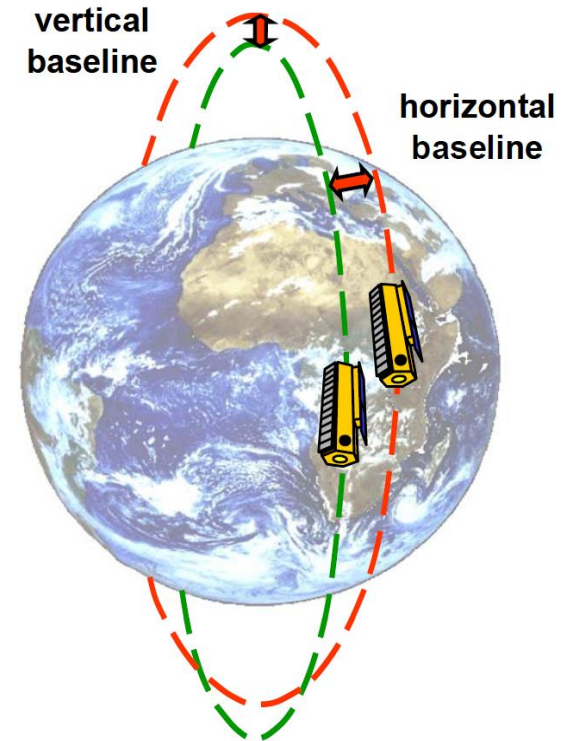
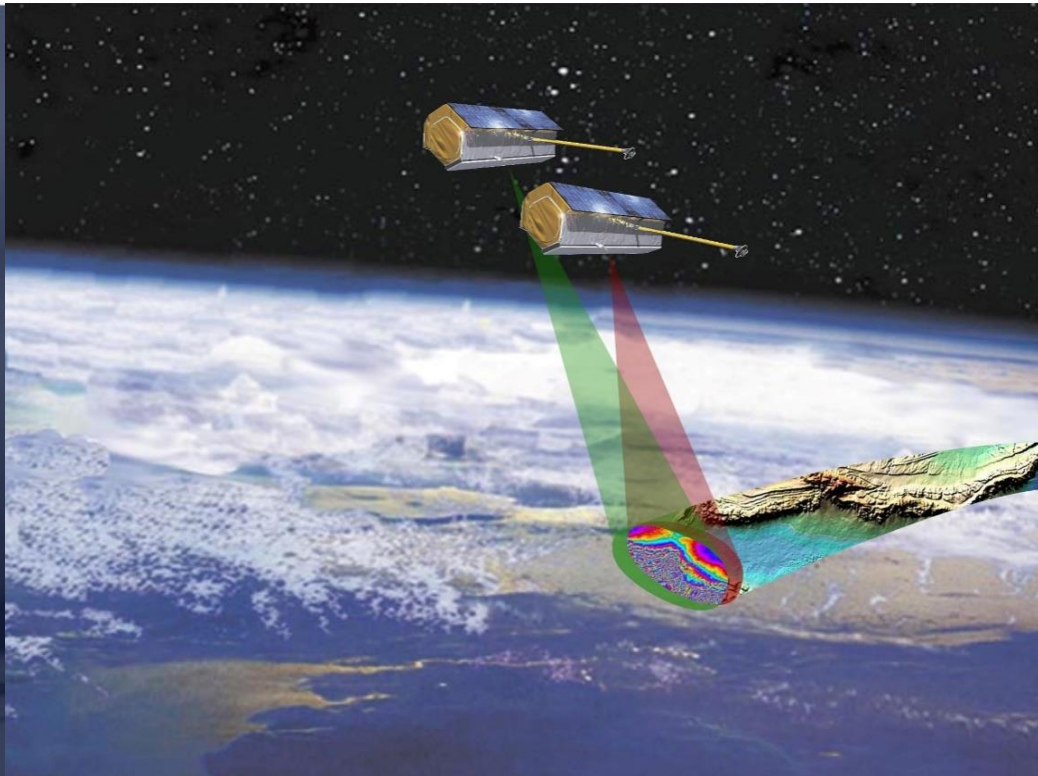


History of CIFDP-C

- 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*



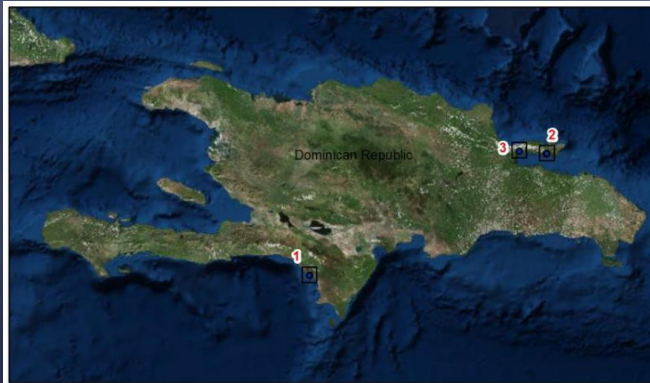
TanDEM-X



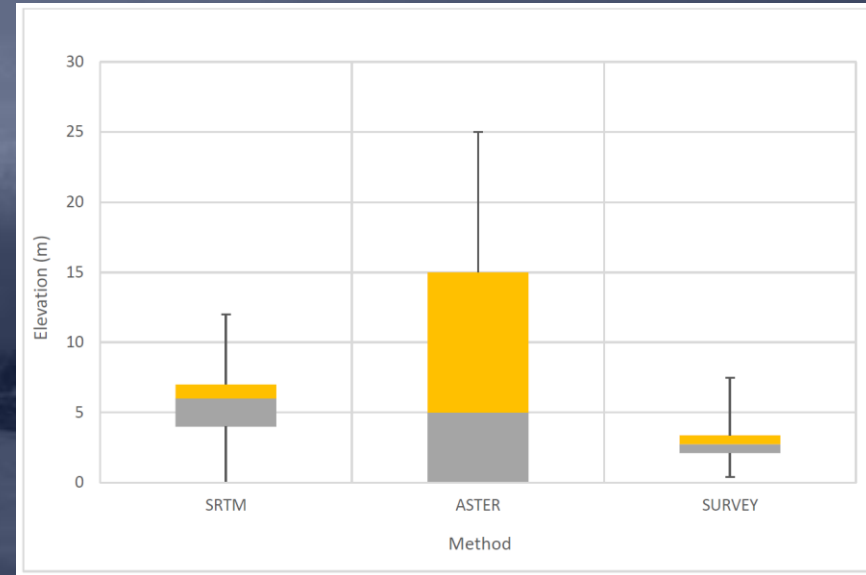
Requirements	Specification	DTED-2	TanDEM-X DEM
Relative Vertical Accuracy	90 % linear point-to-point error over a 1° by 1° cell	12 m (slope < 20 %) 15 m (slope > 20 %)	2 m (slope < 20 %) 4 m (slope > 20 %)
Absolute Vertical Accuracy	90 % linear error	18 m	10 m
Relative Horizontal Accuracy	90 % circular 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)

FIU Surveyed Areas in Dominican Republic

Survey Locations

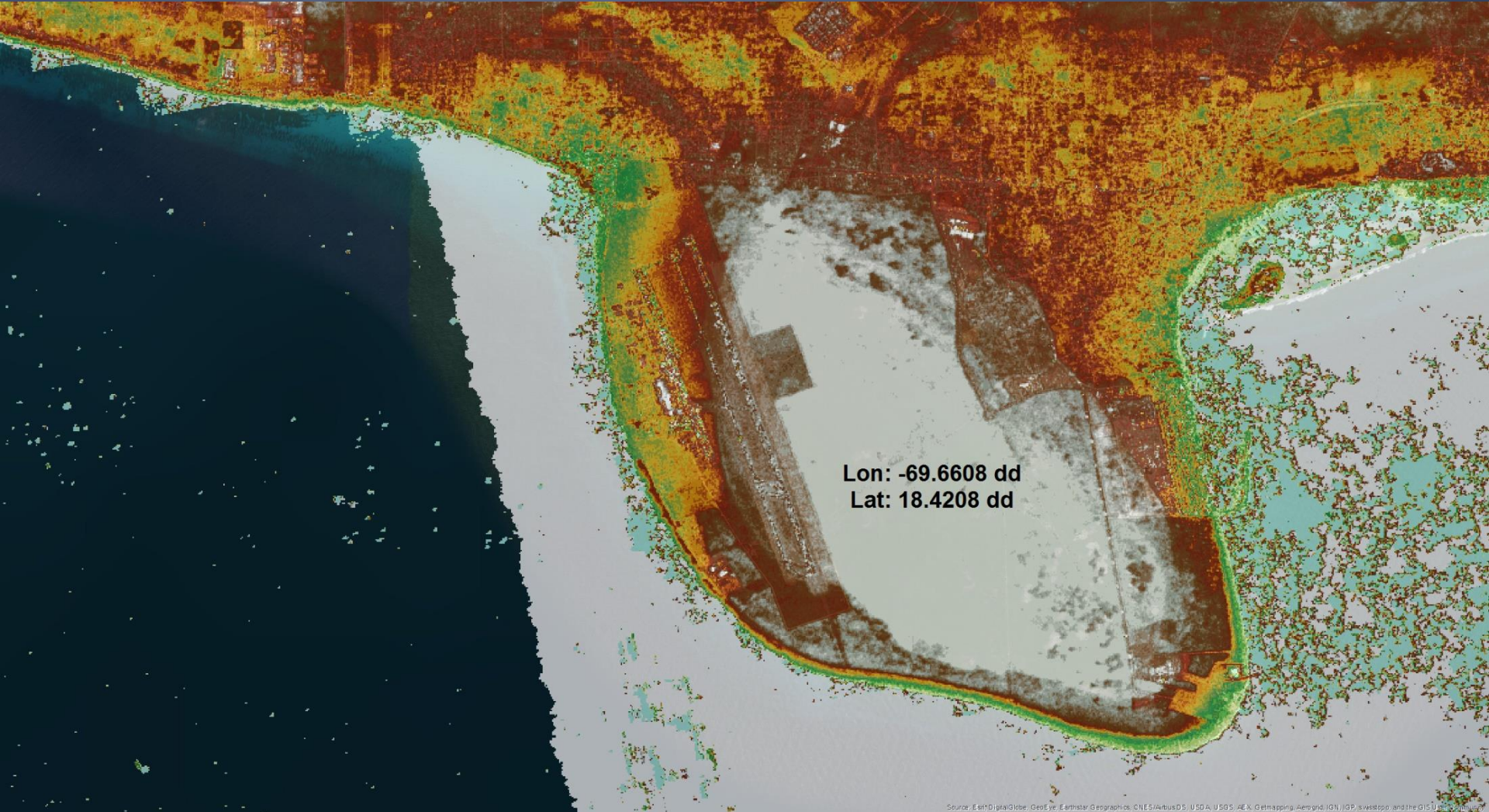


Verification Boxplots



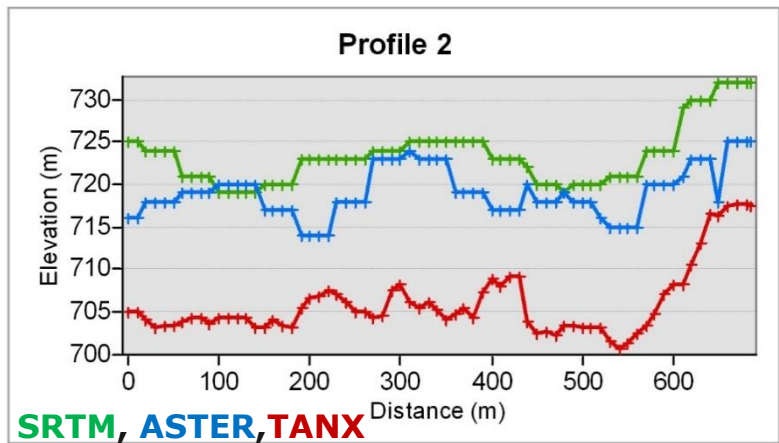
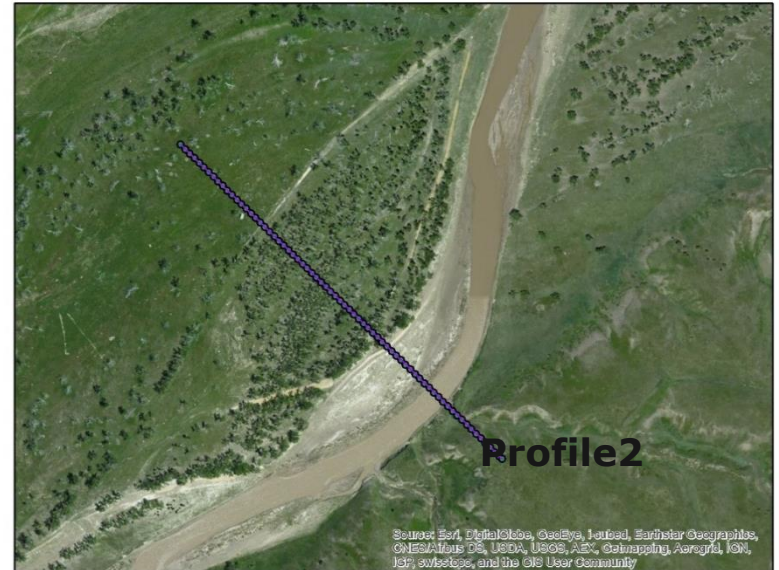
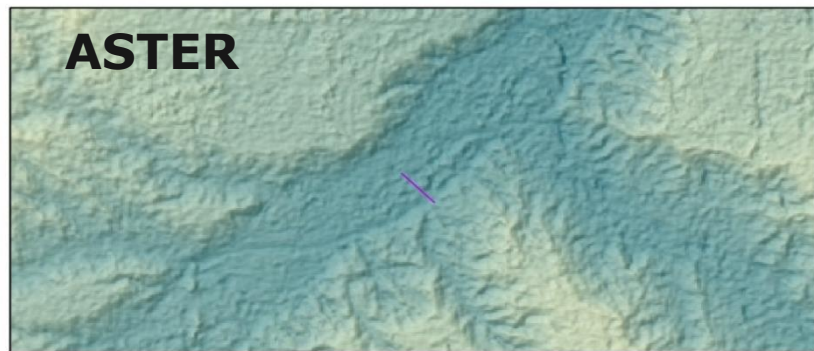
Gray area represents the 25th to 50th percentiles;
yellow 50th to 75th

Raw TanDEM-X: Santo Domingo Airport



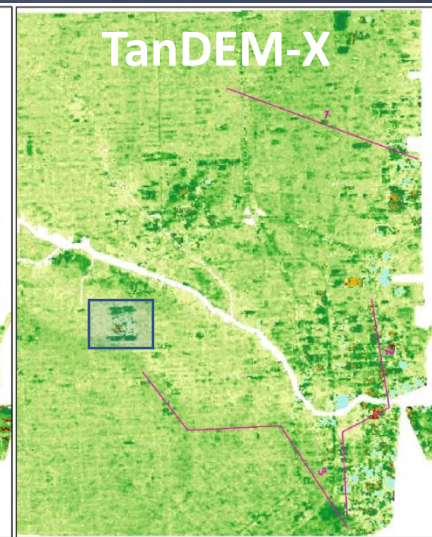
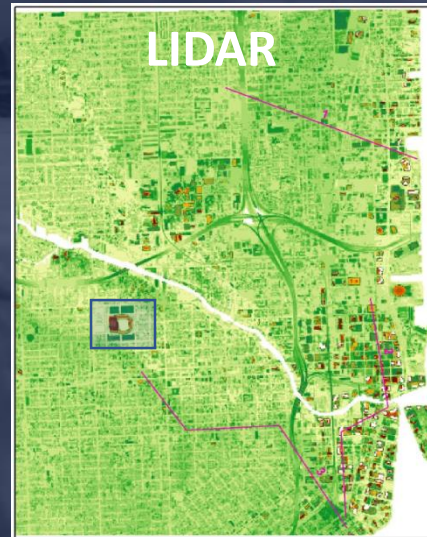
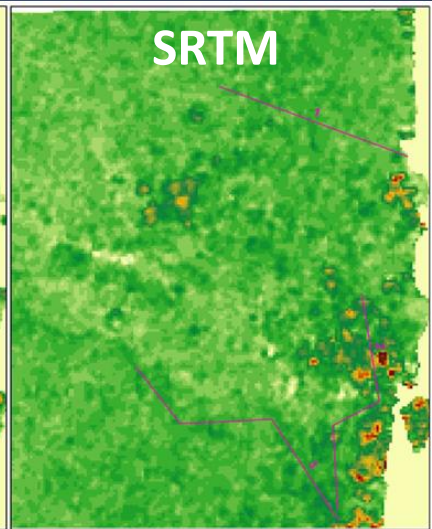
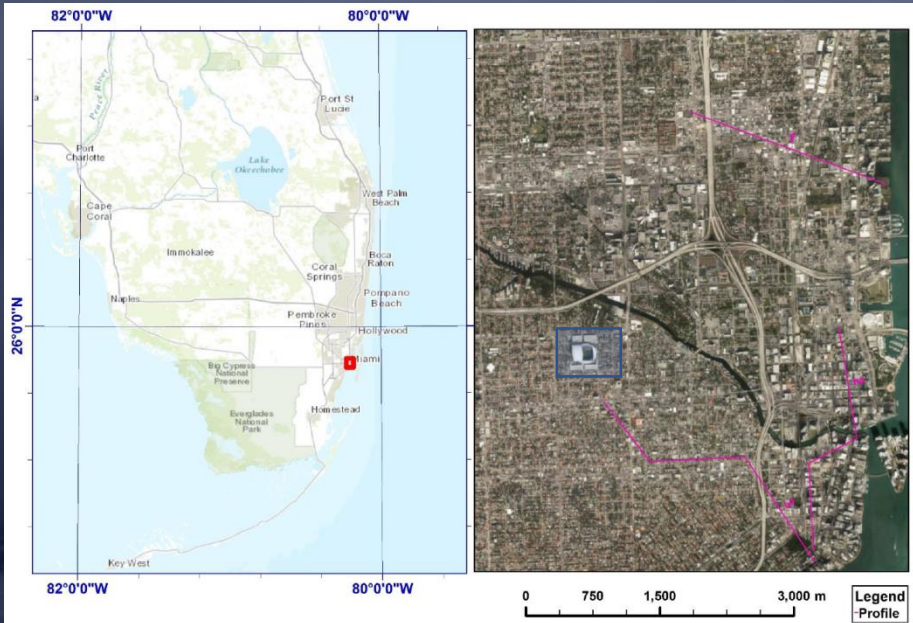
Source: EarthDigitalGlobe, GeoEye, Earthstar Geographics, CNES/AirbusDS, USDA, USGS, AeroGRID, IGN, IGP, Swirestop, and the GIS User Community

Accuracy Comparison

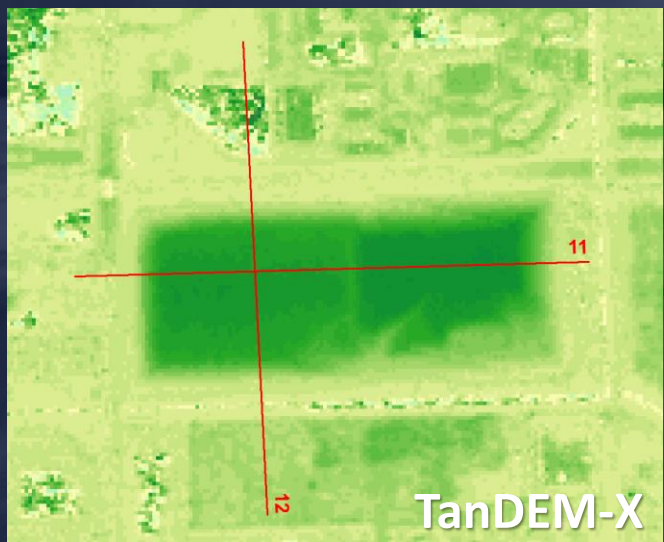
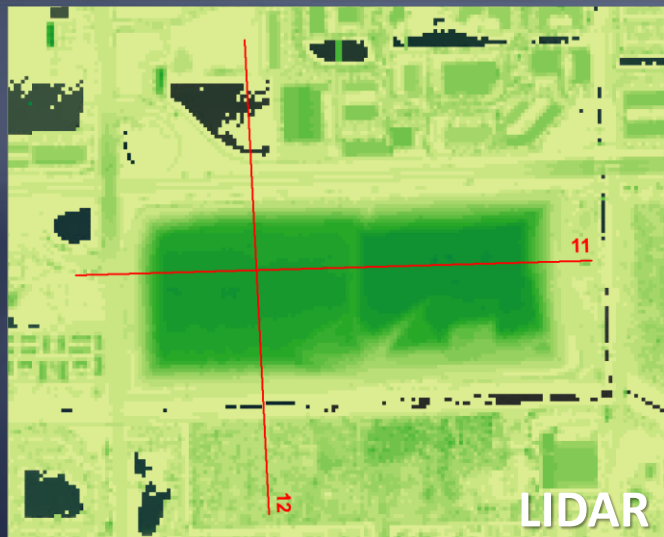


Topography Data Comparison: Miami, FL

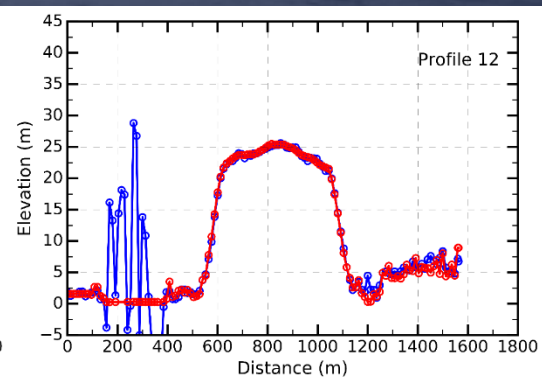
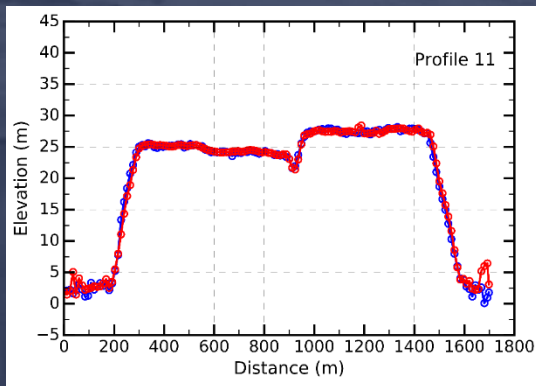
Downtown Miami, FL



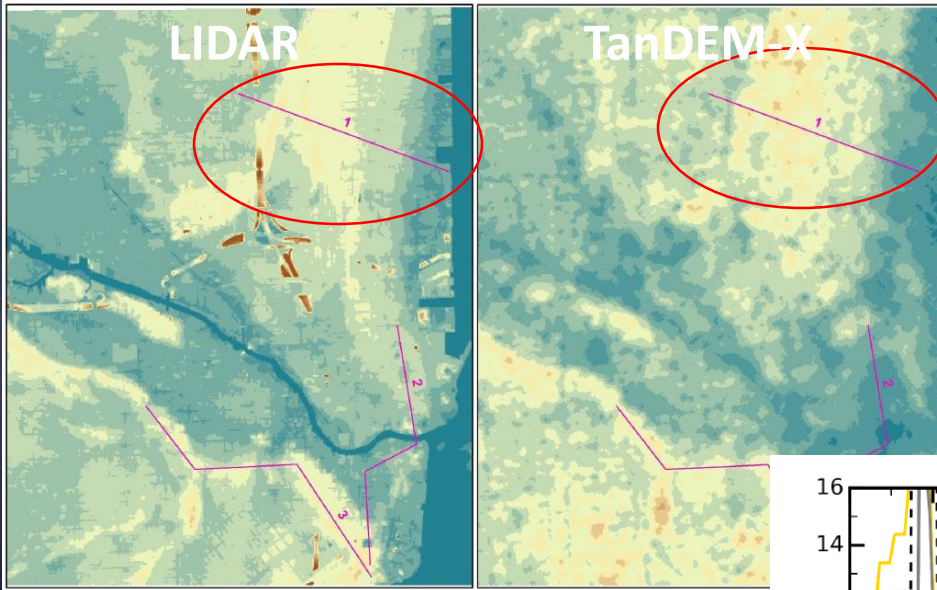
Topography Data Validation: Miami, FL



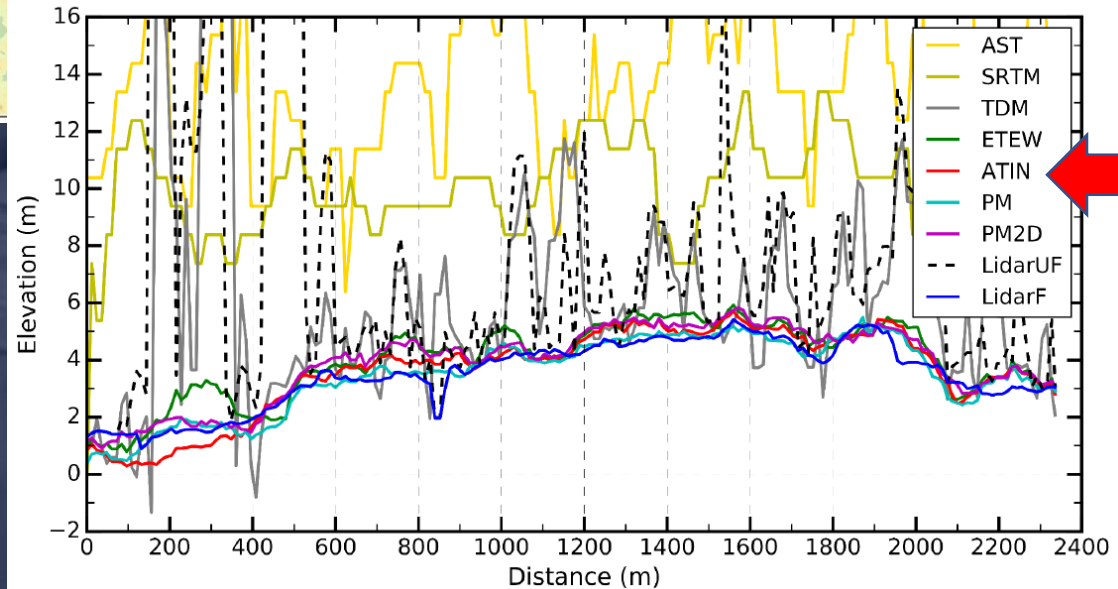
Trash Mound



Topography Data Comparison: Miami, FL

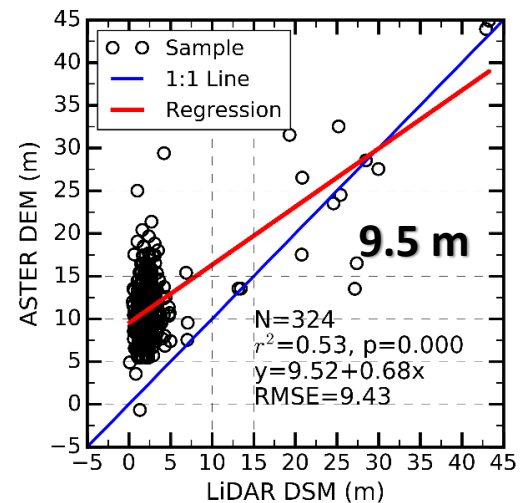
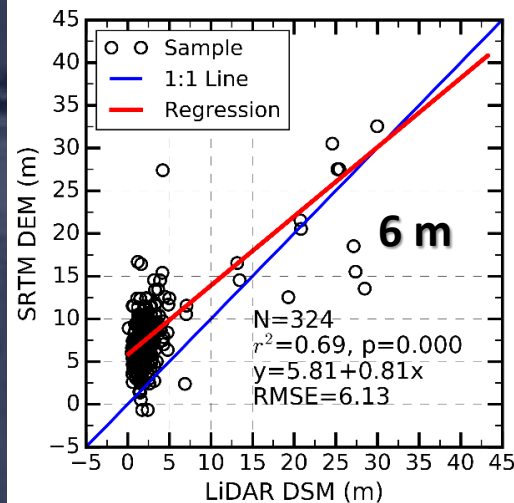
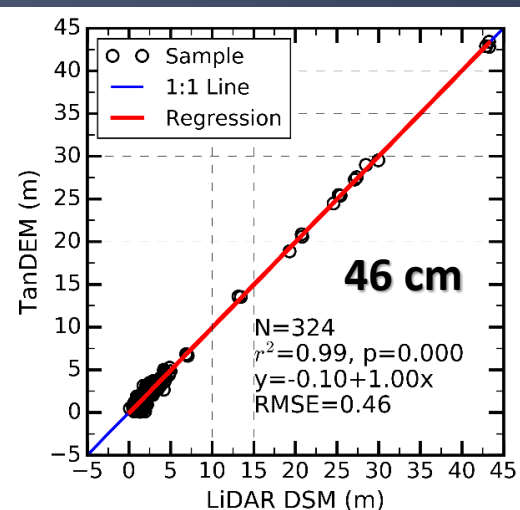
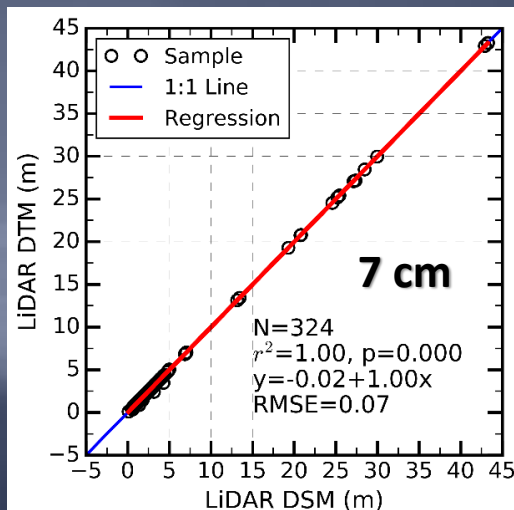
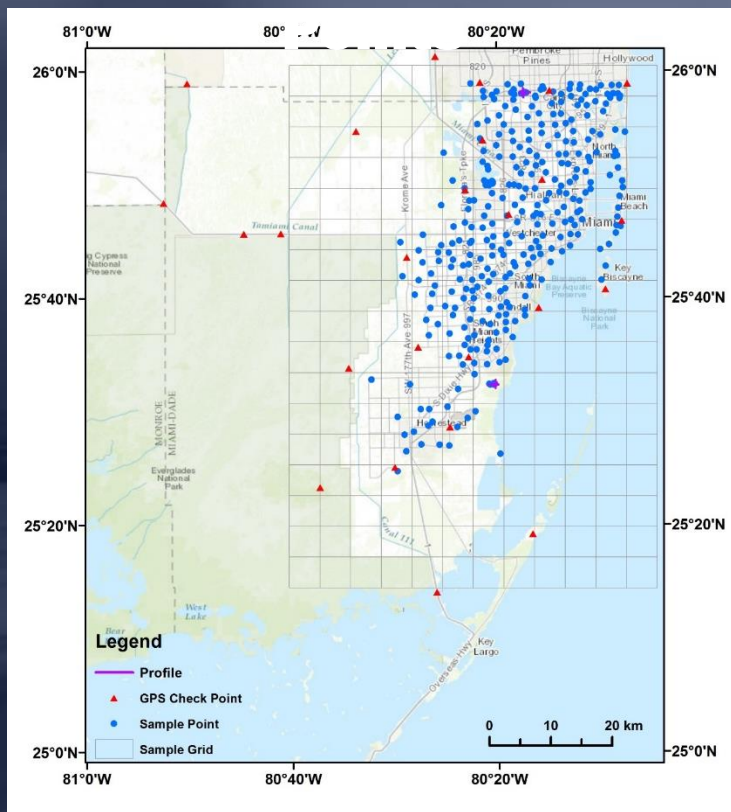


Filtering Methods to create DTM



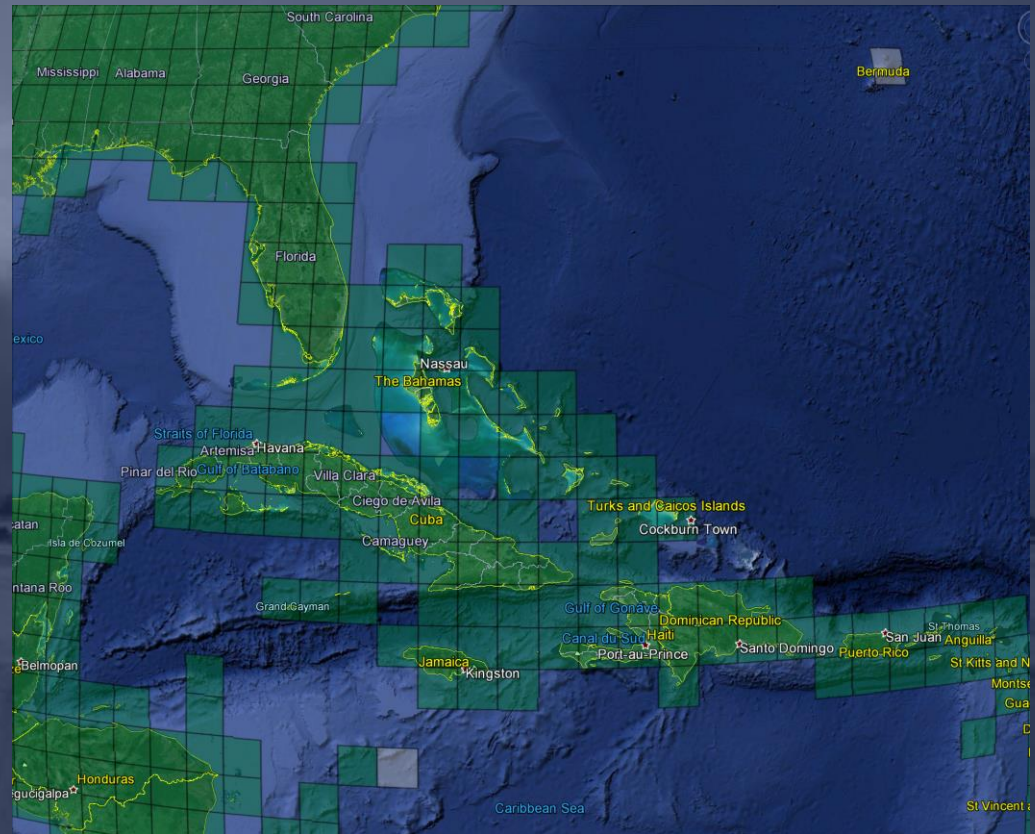
TanDEM-X Verification Results

Verification Sample

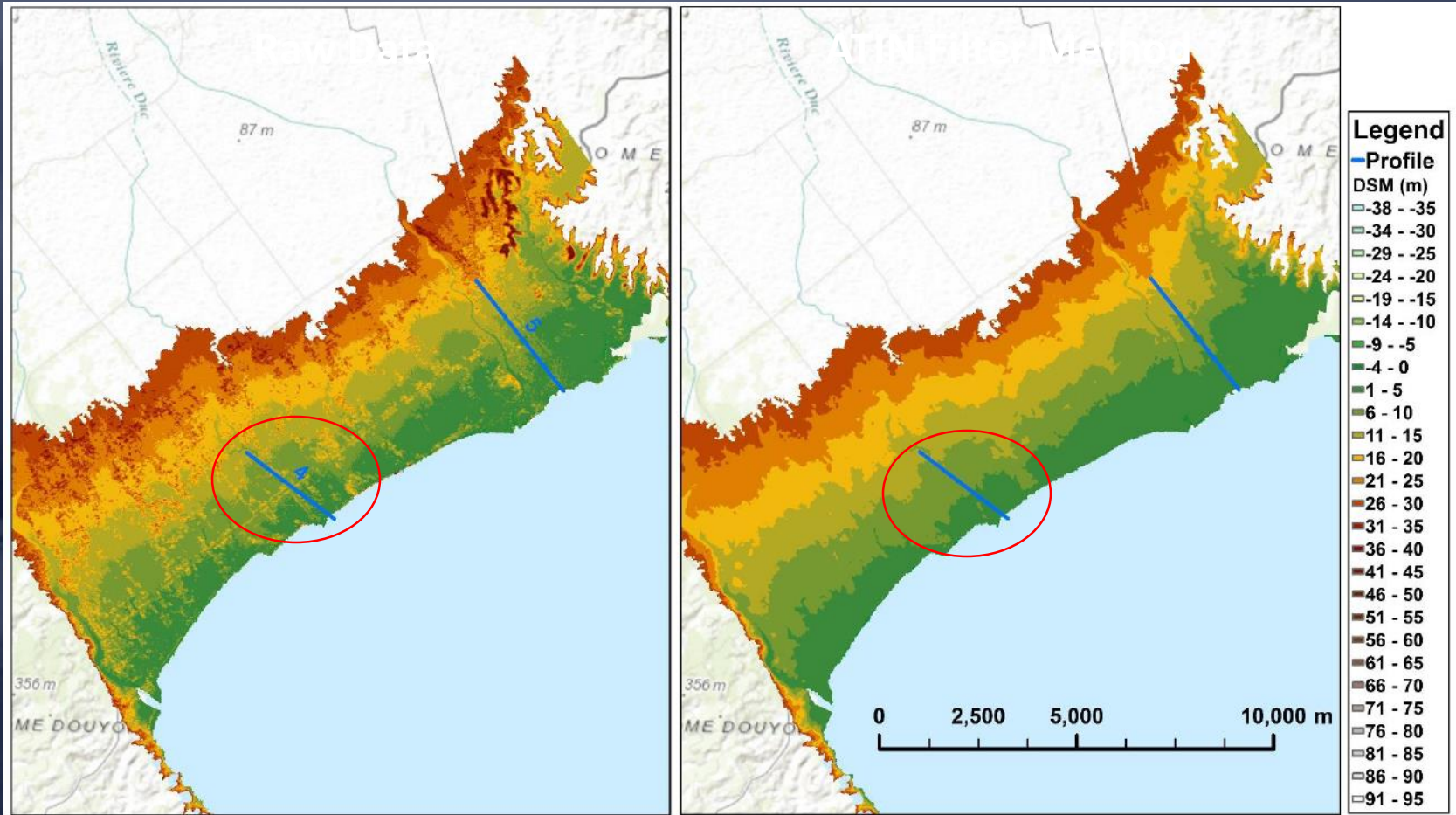


Data Availability

- **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**

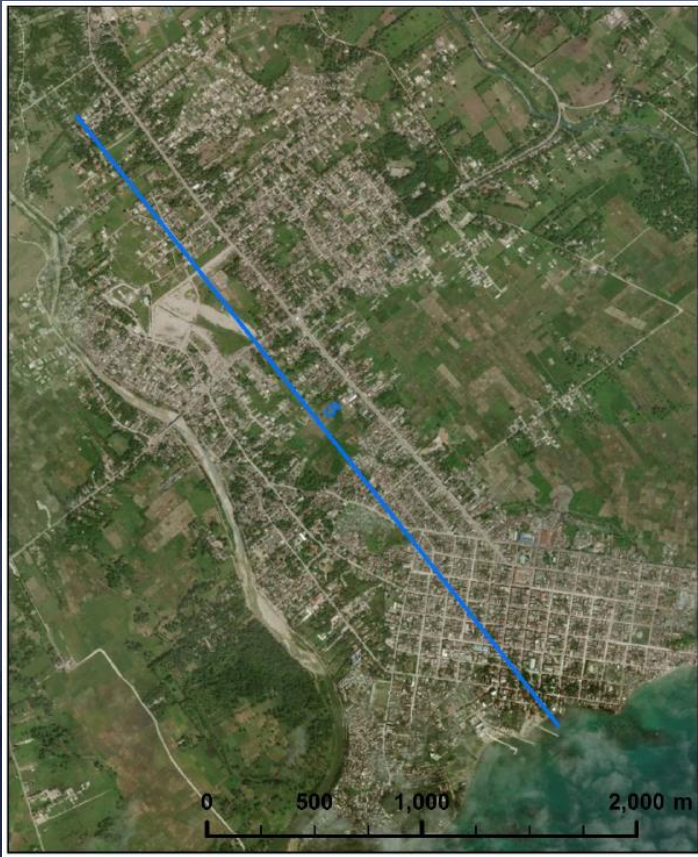


DTM Comparison: Torbeck, Haiti

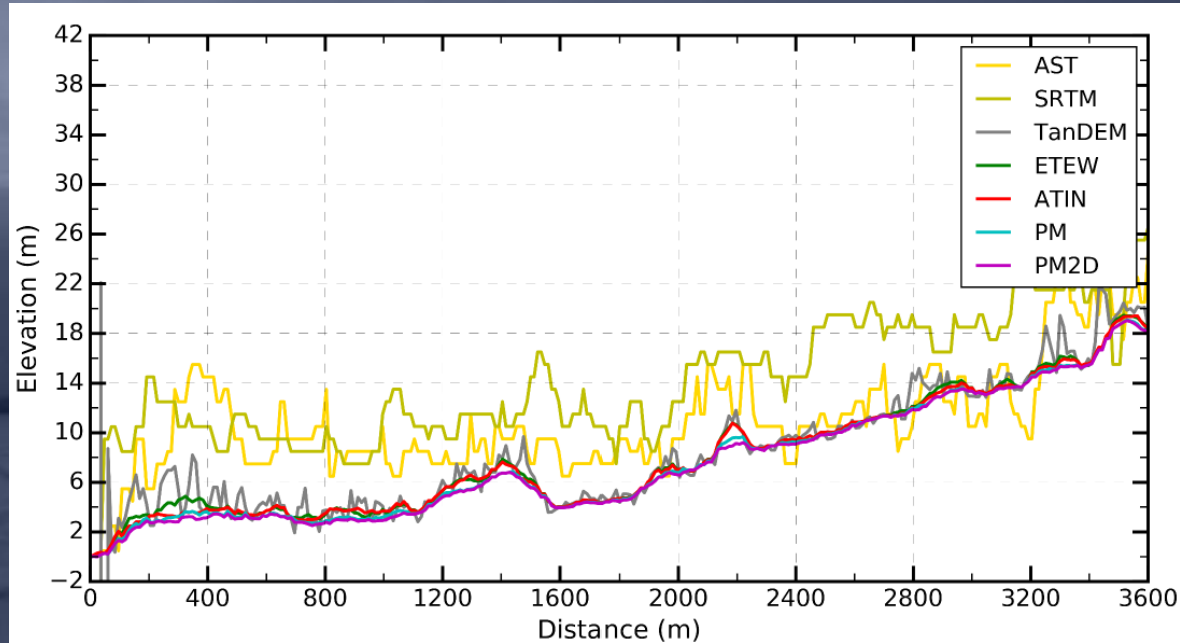


DTM Comparison: Torbeck, Haiti

Profile Location

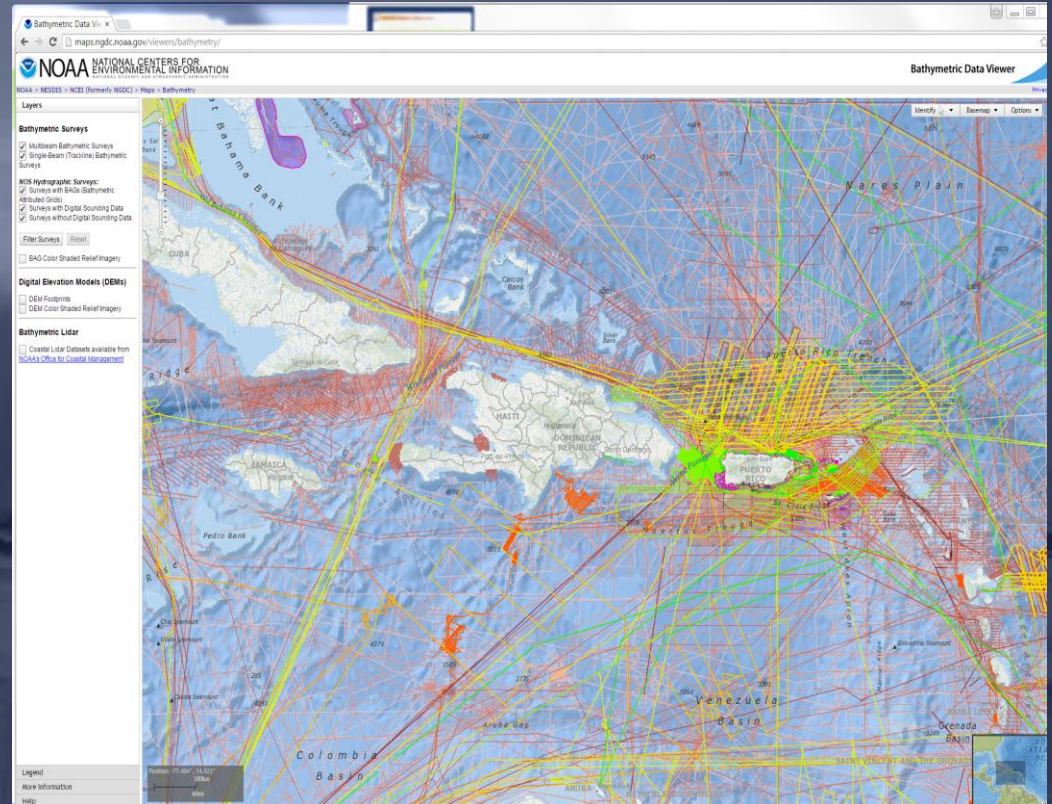


DTM Comparison: ASTER, SRTM, TanDEM-X



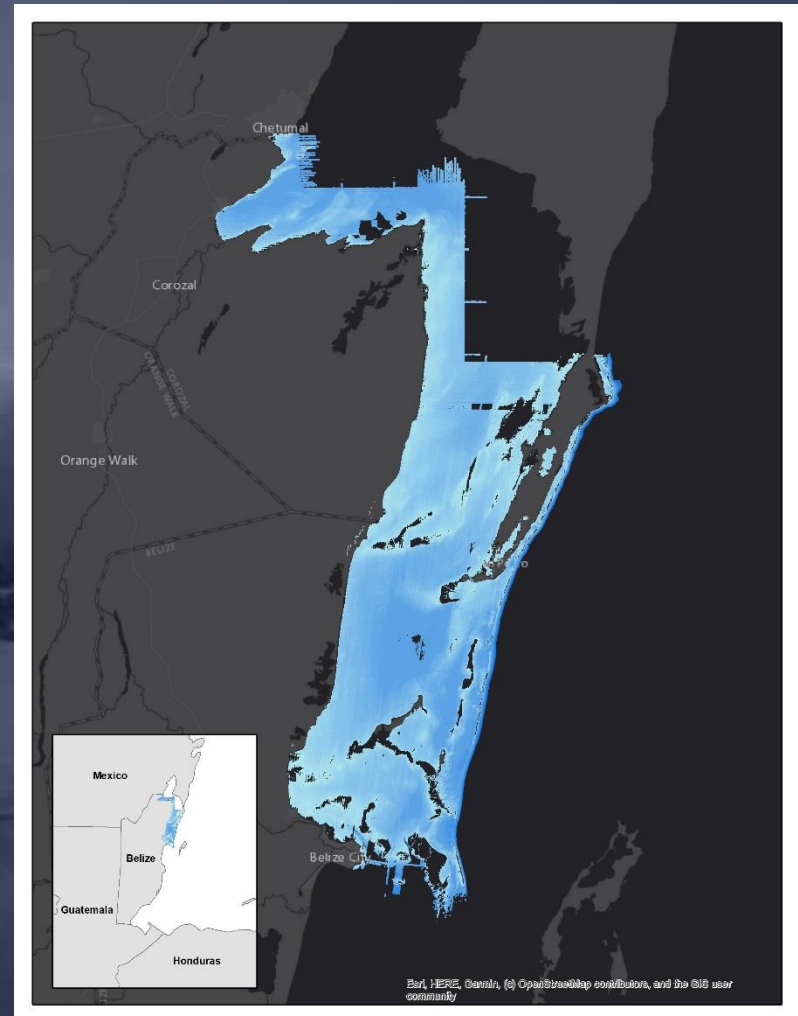
Bathymetric Data

- **NOAA single and multi-beam sounding surveys**
- **NOAA Tsunami program**
- **CIFDP-C NCT data collection**
- **IOC bathymetry**



Bathymetric Data

- **Working with U.K. and FIU to test enhanced extraction of near-shore bathymetry via synthetic aperture radar (SAR)**
- **Working with DOD to potentially test new remotely sensed approaches**

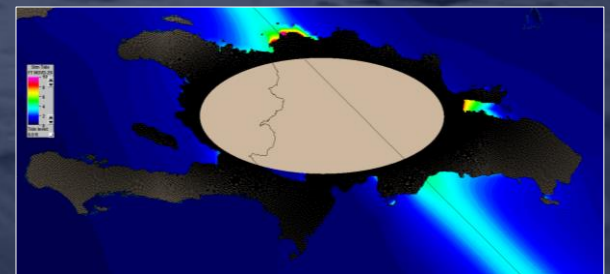
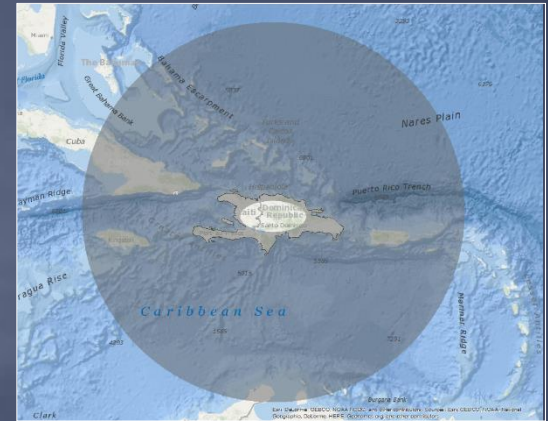


SLOSH + Waves Development



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

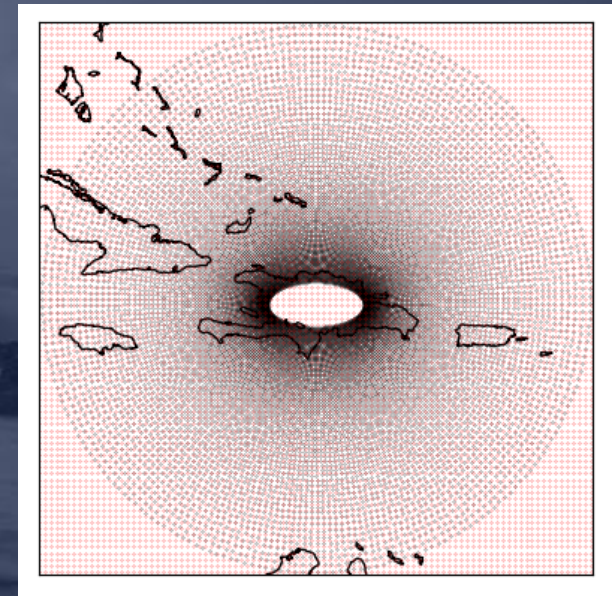
- **An efficient parametric wave model to couple with SLOSH**
- **Parametric models that reduce full solution space $\mathbf{N}(t,x,y,\sigma,\theta)$, to e.g. $\mathbf{M}(t,x,y)$ (Schwab et al. 1984).**

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

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

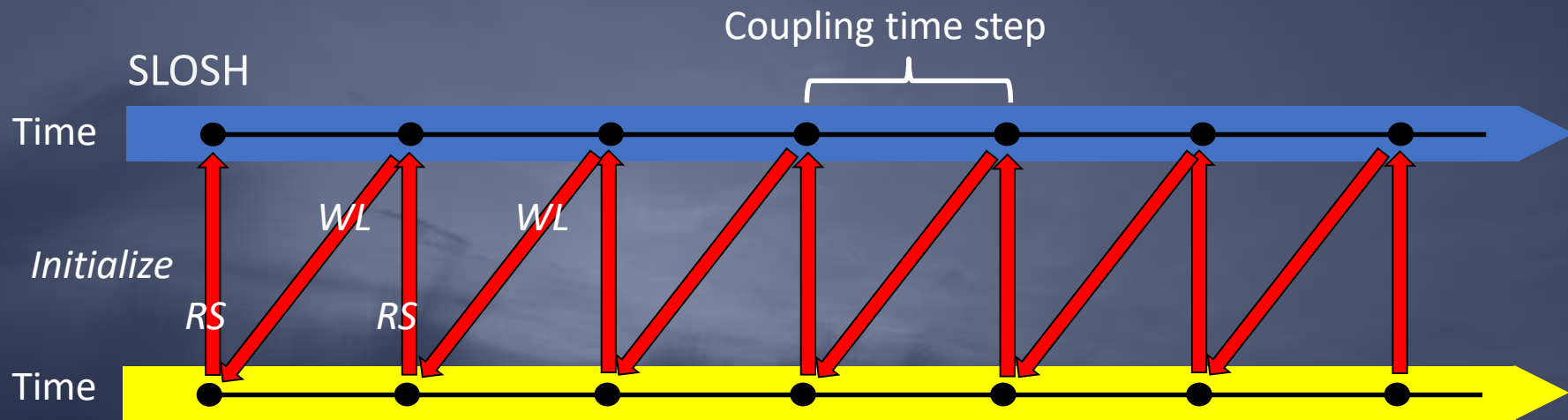
$$\sigma^2 = 6.23 \times 10^{-6} \left(\frac{f_p U}{g} \right)^{-10/3} \frac{U^4}{g^2}$$

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



SLOSH basin and wave model grid mesh

Wave Model Coupling to SLOSH

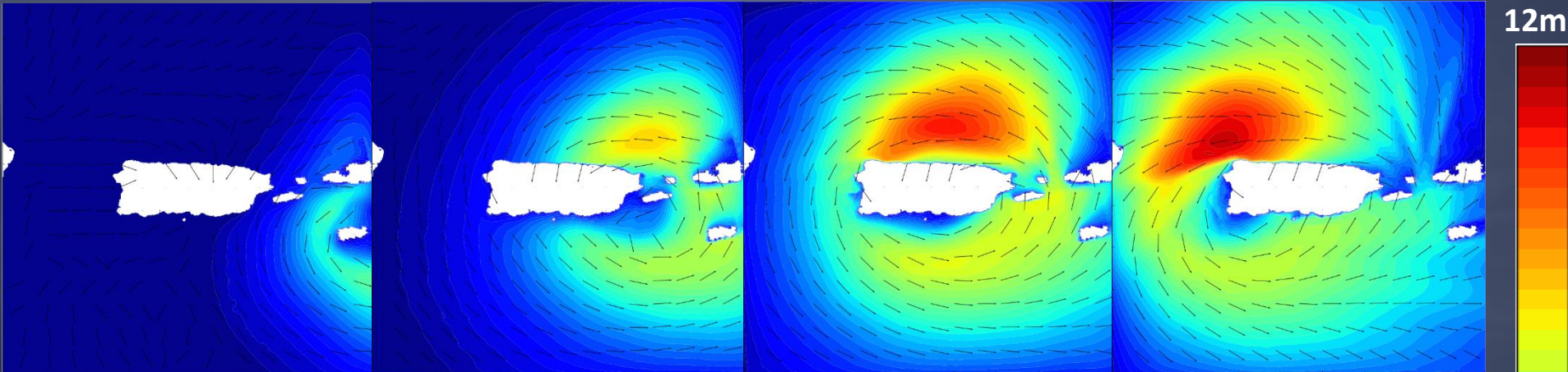


Parametric Wave Model

- **SLOSH is driver, with parametric wave model as a subroutine**
- **Compiled into single, efficient executable**
- **To be used for computation of MEOW surge/inundation envelopes**

Wave Height Comparison (Hurricane Georges, 1998)

SWAN Model



$t = 40$ hr

$t = 45$ hr

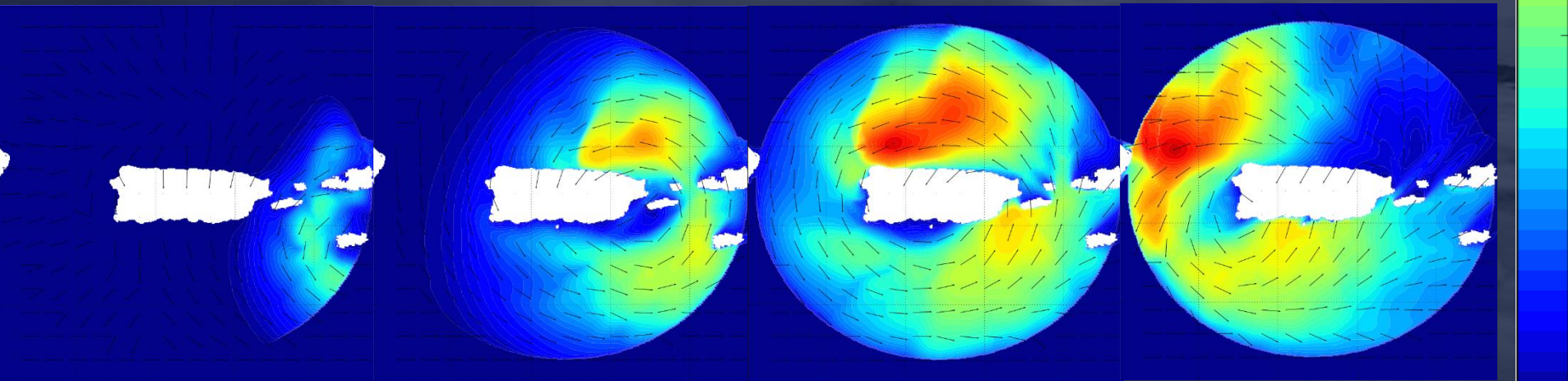
$t = 50$ hr

$t = 55$ hr

12m

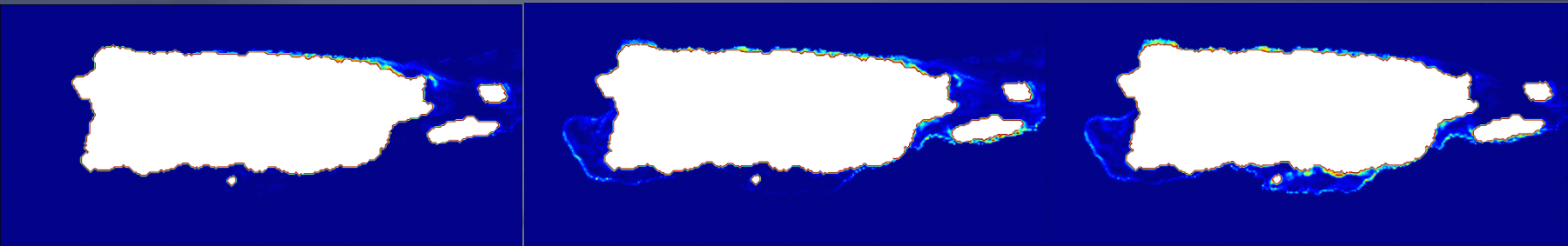
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Parametric Wave Model



Wave Radiation Stress Comparison

SWAN Model

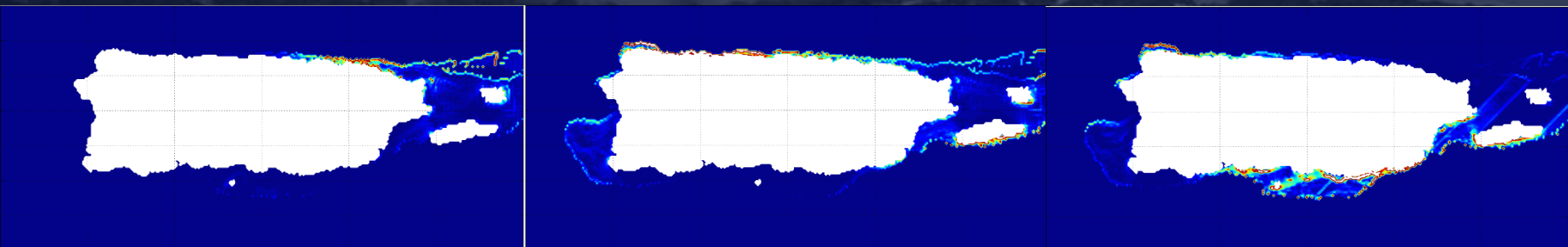


$t = 45 \text{ hr}$

$t = 50 \text{ hr}$

$t = 55 \text{ hr}$

Parametric Wave Model

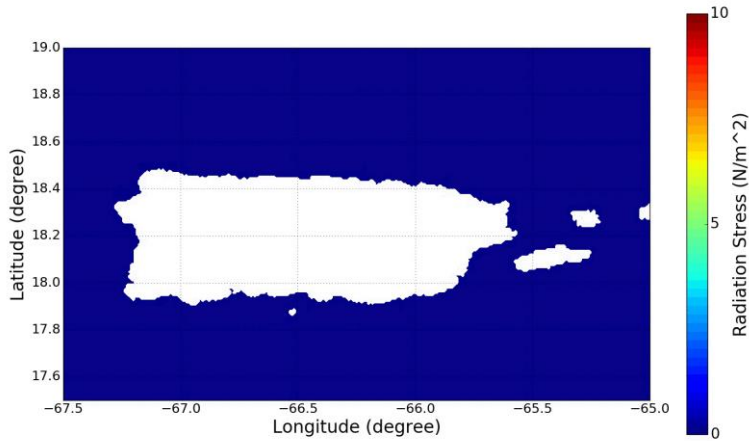


10 N/m

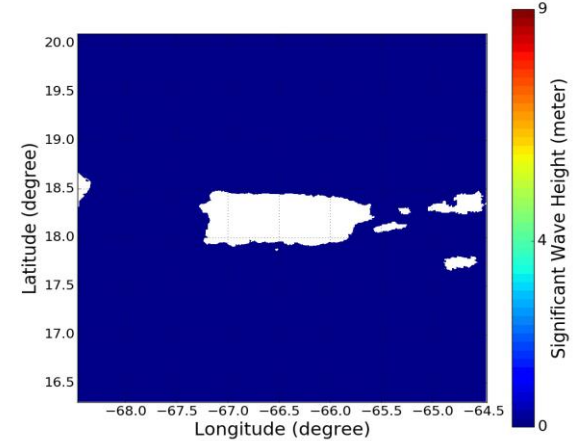


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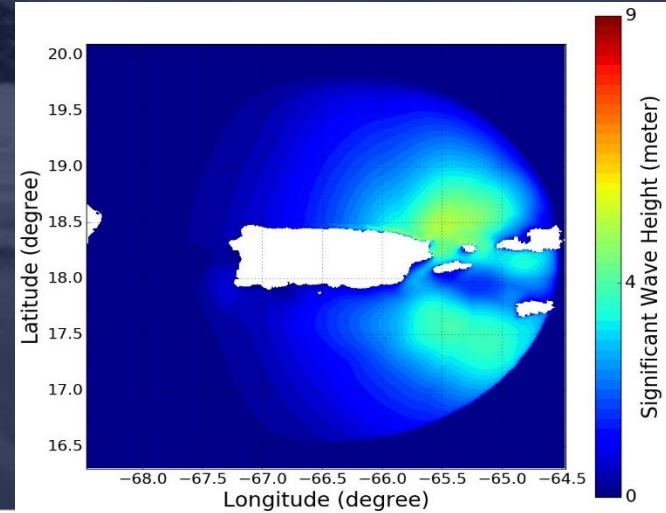
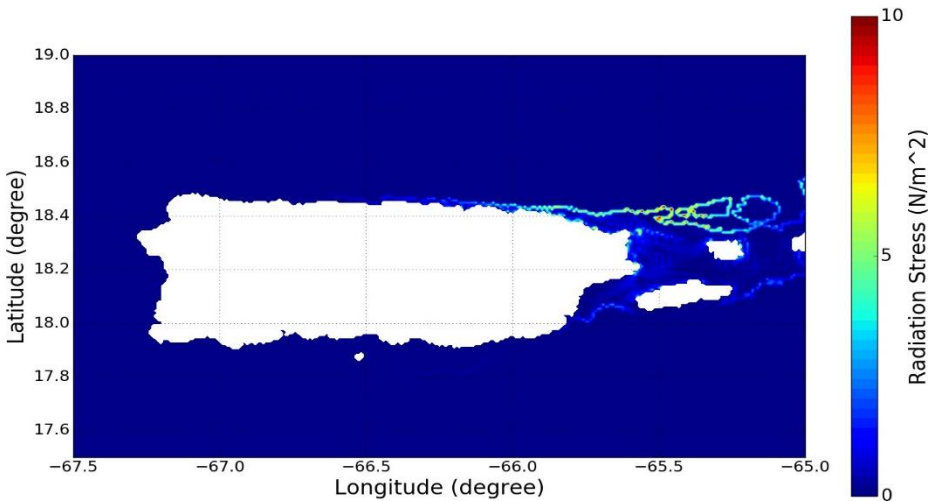
Coupled SLOSH + Waves



Wave Radiation Stress



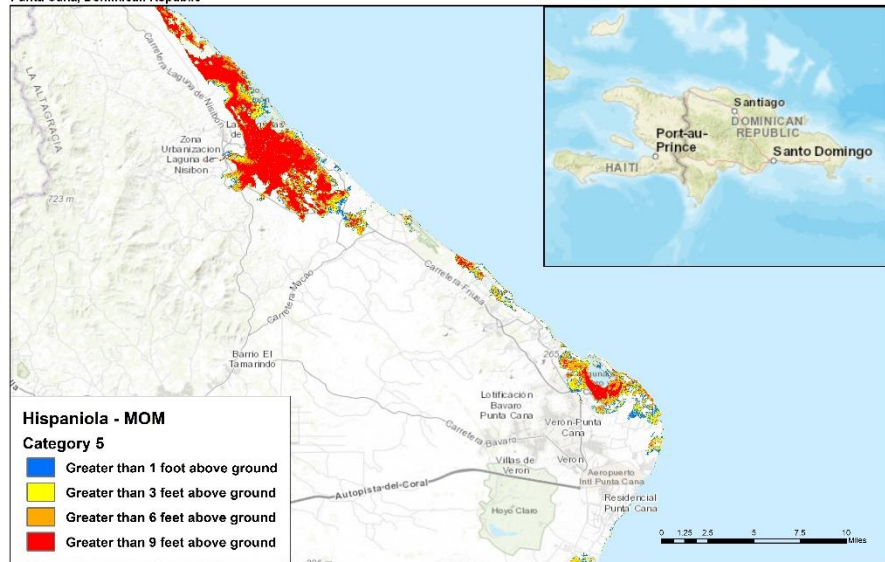
Significant Wave Height



Final Deliverable: High-Resolution Inundation Mapping

Storm Surge Hazard Mapping

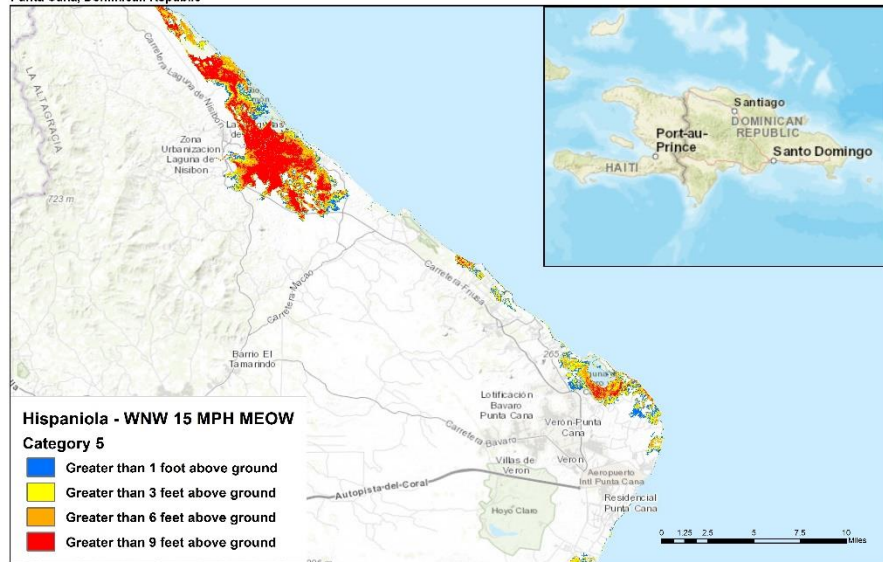
National Hurricane Center
Punta Cana, Dominican Republic



Service Layer Credits: Sources: Esri, HERE, DeLorme, Intermap, iroventiv P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GEBCO, IGN, Metastat, Swisstopo, SIA, USGS, NOAA, Swisstopo, Mapbox, OpenStreetMap contributors, and the GIS User Community

Storm Surge Hazard Mapping

National Hurricane Center
Punta Cana, Dominican Republic



Service Layer Credits: Sources: Esri, HERE, DeLorme, Intermap, iroventiv P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GEBCO, IGN, Metastat, Swisstopo, SIA, USGS, NOAA, Swisstopo, Mapbox, OpenStreetMap contributors, and the GIS User Community

Bahamas Storm Surge Project Phases

Phase 0
2019-2020

Phase 1
2021

Phase 2
2022

Phase 3
2023

Phase 4
2024

Project Scoping and Preparation:

Stakeholder meetings & workshop (Barbados)

WRN/Storm Surge dual track established

Project Planning and Design:

Initial project design/setup

Establish definitive National Agreement

Data acquisition and processing

System Development & Validation:

Final bathy/topo processing

Final SLOSH model configuration and testing.

Develop specialized training needs & requirements

Postprocessing and Distribution:

MOMs/MEOW creation, QA/QC, post-processing, inundation mapping

Transmit GIS data and HVX integration

Test/evaluate for hurricane season

System Integration and Training:

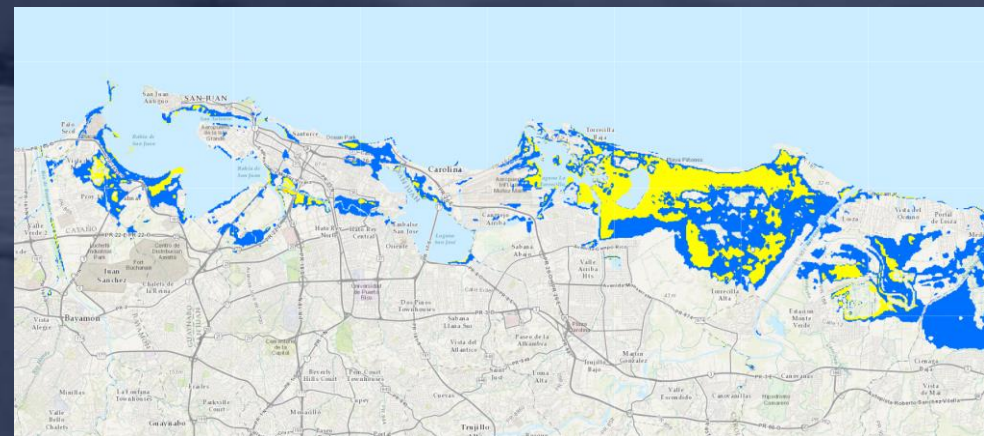
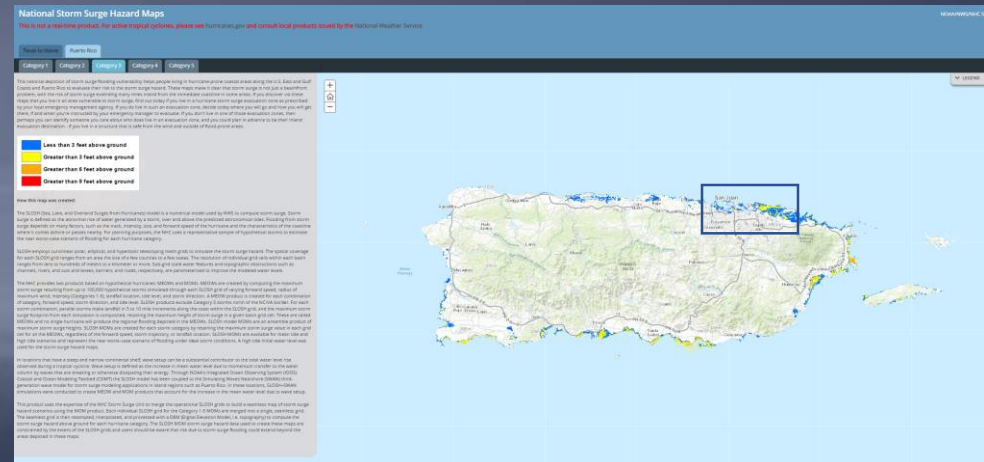
System implementation, project evaluation, specialized training workshop

Fully deploy for hurricane season

Project evaluation and recommended application to region (RA-IV)

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



Introduction to Tropical Cyclone Storm Surge

Produced by The COMET[®] Program

Begin

- Printable Lesson
- Download
- Quiz
- User Survey
- Media Gallery

MetEd Home
COMET Home

The screenshot shows a 3D rendering of a tropical cyclone's eye and surrounding clouds over the ocean. A navigation menu is overlaid on the right side.



Storm Surge and Datums

Produced by The COMET[®] Program

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- Download
- Quiz
- User Survey
- Media Gallery

MetEd Home
COMET Home

The screenshot displays a map of a coastal region with a legend for 'Potential Storm Surge Flooding'. The legend categories are: Up to 2 feet aboveground (blue), Greater than 2 feet aboveground (yellow), Greater than 3 feet aboveground (orange), and Greater than 4 feet aboveground (red). A navigation menu is overlaid on the right side.



Storm Surge Forecasting



Shallow Water Waves

2012 Update

Produced by The COMET[®] Program

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- User Survey
- Contributors
- Technical Notes
- Media Gallery
- Bibliography

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The screenshot features a photograph of a large ocean wave. A navigation menu is overlaid on the right side.



Nearshore wave modeling

Produced by The COMET[®] Program

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- Tech Notes
- User Survey
- Quiz
- Contributors
- Print Version

The screenshot shows a 3D rendering of waves crashing on a beach. A navigation menu is overlaid on the right side.

