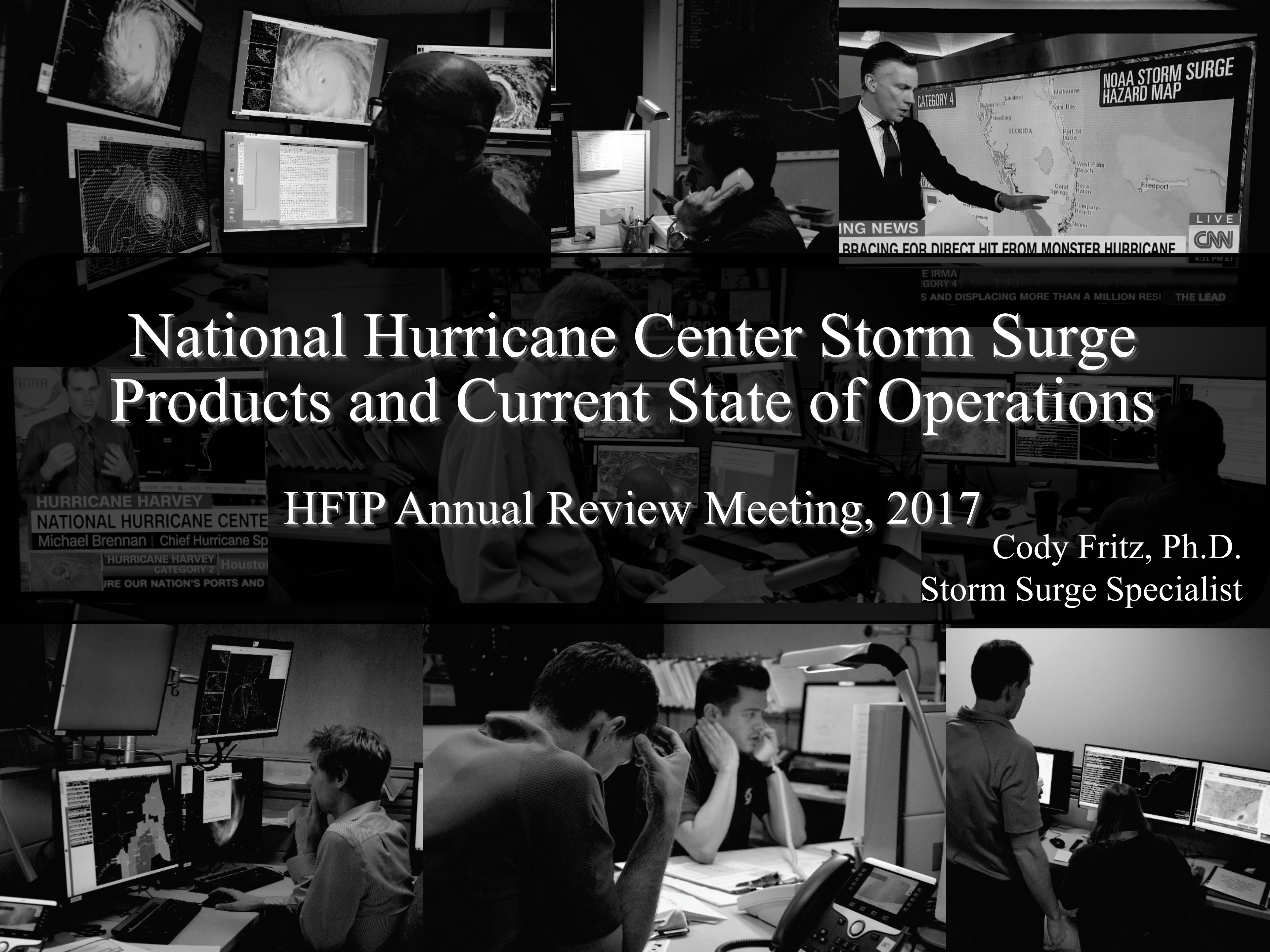
# National Hurricane Center Storm Surge Products and Current State of Operations

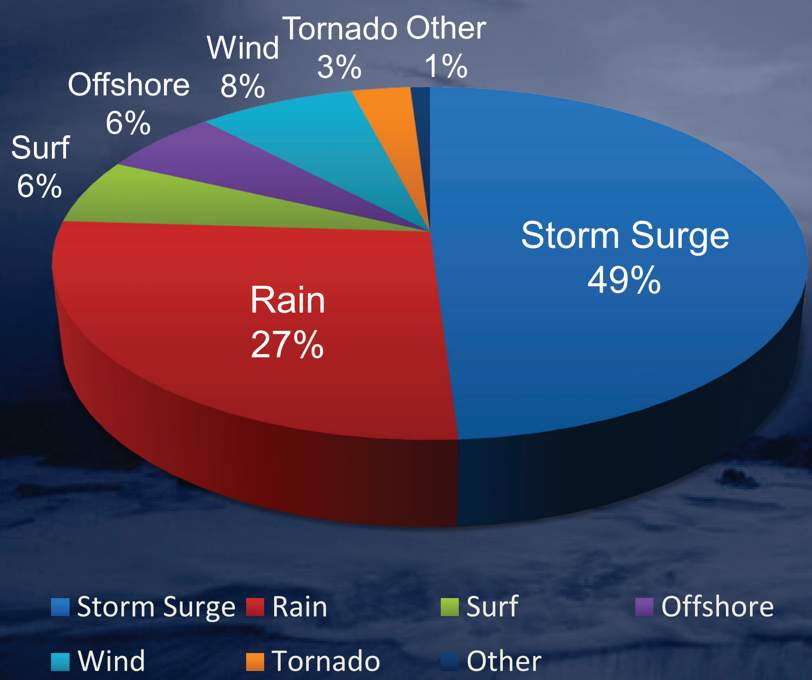
## HFIP Annual Review Meeting, 2017

Cody Fritz, Ph.D.
Storm Surge Specialist



# Atlantic Tropical Cyclone Deaths

## 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.

# National Hurricane Center Mission

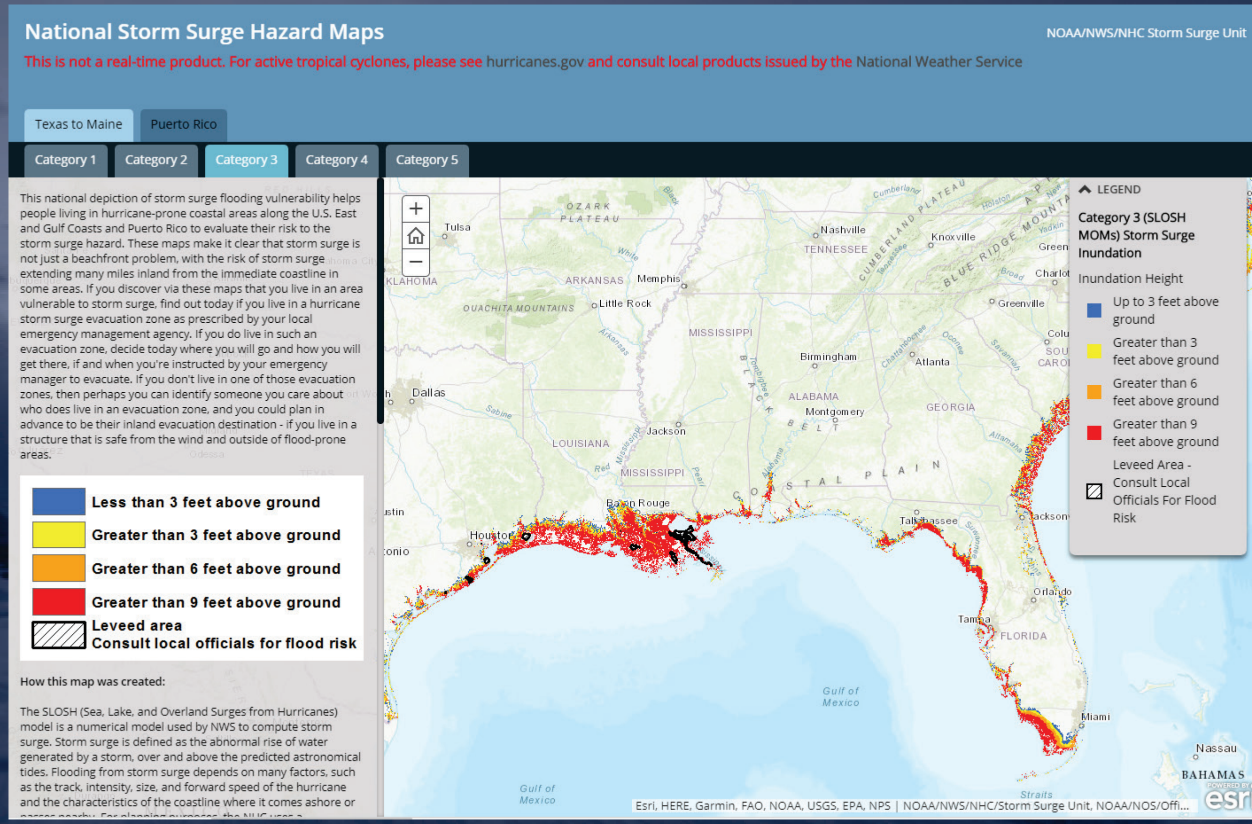
- Support coastal community preparedness and resiliency through storm surge vulnerability and risk analysis
  - Drives U.S. evacuation zones and planning

- Increase awareness through outreach and education

- Provide accurate real-time storm surge forecasts during tropical cyclone events
  - Lead National Weather Service official forecast process
  - Provide briefings and decision support

# National Storm Surge Risk

- Roughly 22 million people in U.S. are vulnerable to storm surge flooding
- About 10,000 miles of evacuation route becomes inundated or cut off
- Nearly 16 million housing units vulnerable to surge




http://noaa.maps.arcgis.com/home/item.html?id=b1a20ab5eec149058bafc059635a82ee

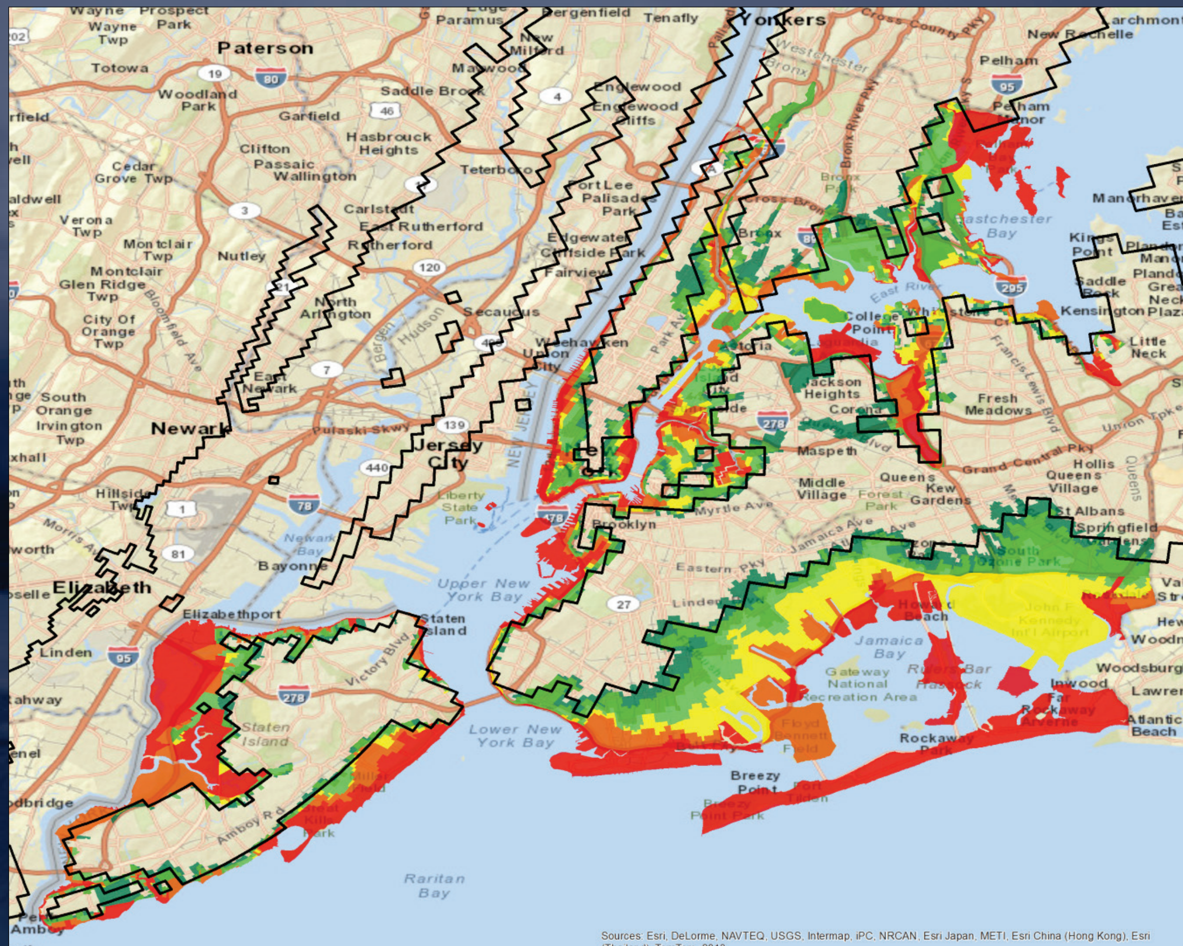
Zachry, B. C., W. J. Booth, J. R. Rhome, and T. M. Sharon, 2015: A National View of Storm Surge Risk and Inundation. J Wea. Climate Soc., 7(2), 109-117

# Evacuations:
# Where the Rubber Meets the Road

## NYC Evacua[illegible]Tide Anomaly

- Zone 1
- Zone 2
- Zone 3
- Zone 4
- Zone 5
- Zone 6

| 2010 Population | |
|---|---|
| Zone 1 | 370,000 |
| Zone 1+2 | 620,000 |
| Zone 1+2+3 | 1,020,000 |
| Zone 1+2+3+4 | 1,470,000 |
| Zone 1+2+3+4+5 | 2,230,000 |
| Zone 1+2+3+4+5+6 | 2,990,000 |



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UNITED STATES DEPARTMENT OF COMMERCE
WEATHER BUREAU
Washington 25, D C

July 20, 1955 0.5

CIRCULAR LETTER NO. 36-55
(To All First Order Stations)

Subject: Inclusion of High Water Information in Hurricane Advisories and Warnings and in Local Bulletins

Reference: Weather Bureau Manual III-B-5007 N (2 and 3) and MAL No. 49 55 dated July 8, 1955

The reference instructions provide that tropical storm and hurricane advisories and warnings will include statements as to high water expected when a storm is near the coast or passing inland. Similar information will be included in alert messages whenever practicable. Multiple Address Letter No. 49-55 instructs station officials regarding issue of local bulletins and warnings based on the information contained in formal advisories, warnings, and alerts, including information on high water.

Central Office Memorandum of June 17, 1955 (R-3.4) transmitted two recent papers on "Hurricane Surge" to all first order stations. Each of these studies contains case histories of tropical storms and hurricanes and associated rises in water levels at coastal points affected as the storms moved inland. Additional studies of this nature aimed at developing further aids for use in storm tide forecasting are planned. Results of these studies will be distributed to appropriate stations when completed. Arrangements are also in process to make tide gage reports from coastal stations available to hurricane centers and local Weather Bureau offices for forecast purposes.

As soon as a tropical storm or hurricane is expected to produce rises in water levels along our coasts, hurricane forecast centers will include in the advisories or warnings an indication of the height of water above normal tide likely to occur during the period for which the advice is applicable. The forecasts can be based on the principles described and the case histories given in the above-mentioned papers and on such other aids as are available to the forecaster. It will be desirable to specify rises of water according to a range of heights expected along the coastal sections to be effected, including the time at which the peak water level anomalies are expected to occur. It is preferable that the range of expected water heights above normal tides be given in feet if techniques in use at hurricane centers permit this to be done; otherwise, somewhat descriptive terms may be used. Examples of advices containing water height information follow:

Hurricane (moving north) expected to cross coastline slightly south of Wilmington, N. C.

(1) Water rises given in feet: Hurricane will cause dangerously high water ranging from at least 8 feet above normal in Wilmington area to 4 feet as far northward as Hatteras. Highest values will occur as storm approaches

File: 656.4 CL 36-55 (Inclusion of High Water Information in Hurricane Advisories and Warnings and in Local Bulletins)

Washington, D.C. 7-20-55

LIBRARY WEATHER BUREAU

# Where We Started

COASTAL STORM SURGE FLOODING OF UP TO 20 FEET...WITH A FEW SPOTS TO NEAR 25 FEET...ABOVE NORMAL TIDES ALONG WITH LARGE AND DANGEROUS BATTERING WAVES...CAN BE EXPECTED NEAR AND TO THE EAST OF WHERE THE CENTER OF IKE MAKES LANDFALL. THE SURGE EXTENDS A GREATER THAN USUAL DISTANCE FROM THE CENTER DUE TO THE LARGE SIZE OF THE CYCLONE. WATER LEVELS HAVE ALREADY RISEN BY MORE THAN 5 FEET ALONG MUCH OF THE NORTHWESTERN GULF COAST.

# SLOSH-Based Probabilistic Storm Surge Guidance (P-Surge 2.6)

# Basic Operational Model Requirements

- Provide probabilistic storm surge model forecasts that fully samples the meteorological forecast uncertainty
  - Deterministic simulations and small ensemble runs do not meet this criteria at medium-to-long range lead times
- Probabilistic storm surge model forecast must run on NWS operational supercomputer WCOSS in under 1 wall clock hour using less than ~1000 CPUs (current computing standard)
- Model output resolution must be ~2.5 km for ingest into AWIPS II and CAVE (current resolution standard)
  - Fundamental program for NOAA/NWS operational weather forecasting
  - High-resolution model output must be re-sampled to meet this requirement

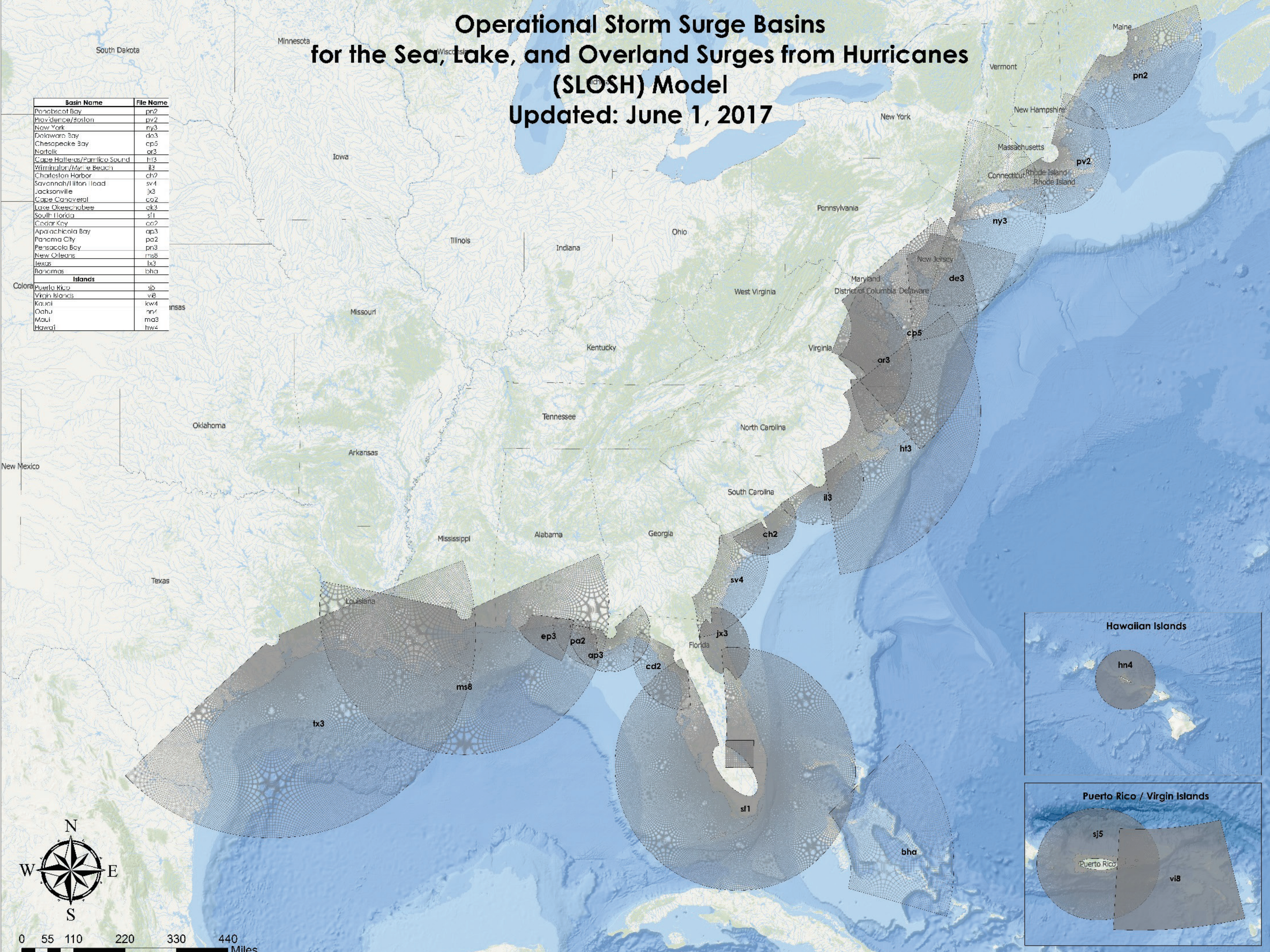
# NWS/NHC Operational Model: SLOSH

- Computationally efficient surge model that has provided the foundation for reliable NWS storm surge forecasts for decades
- SLOSH does include:
  - Wetting and drying
  - Sub-grid scale water features, topographic obstructions, levees, etc.
  - Overtopping of barrier systems, levees, and roads
  - Captures shelf waves and coastal trapped waves
  - New grid resolutions of 250-500 m in critical areas
  - Astronomical tide and initial water level anomaly
- SLOSH does not include:
  - Wave setup or wave run-up
    - Operational version coupled to SWAN
    - Experimental version coupled to 2nd Gen (Parametric) Wave Model
  - River flow, rainfall, and inland freshwater flooding
    - Part of the long-term strategic plan

# Operational Storm Surge Basins for the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) Model

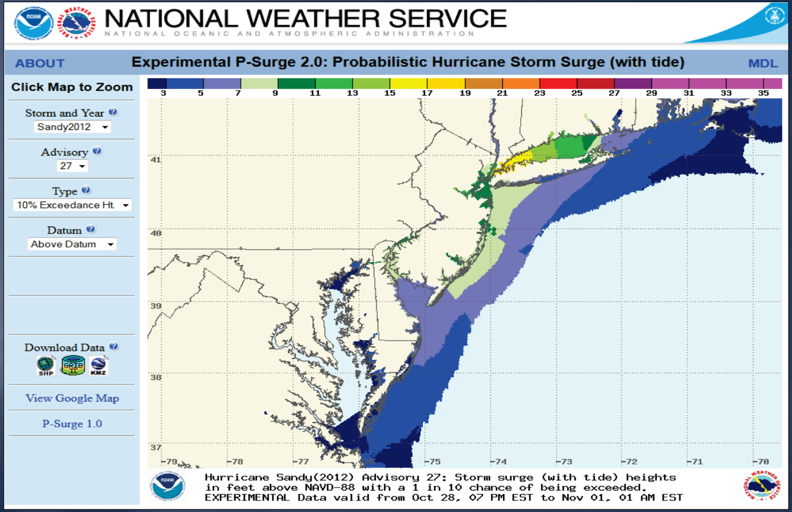
## Updated: June 1, 2017

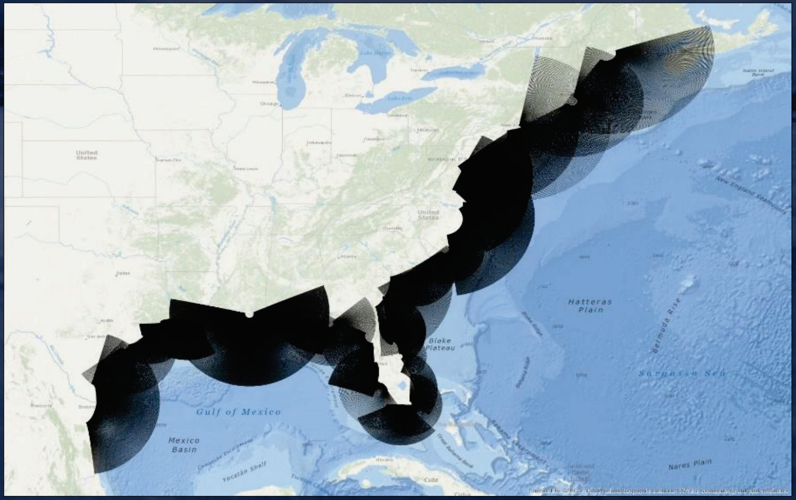
| Basin Name | File Name |
|---|---|
| Penobscot Bay | pn2 |
| Providence/Boston | pv2 |
| New York | ny3 |
| Delaware Bay | de3 |
| Chesapeake Bay | cp5 |
| Norfolk | or3 |
| Cape Hatteras/Pamlico Sound | ht3 |
| Wilmington/Myrtle Beach | il3 |
| Charleston Harbor | ch2 |
| Savannah/Hilton Head | sv4 |
| Jacksonville | jx3 |
| Cape Canaveral | co2 |
| Lake Okeechobee | ok3 |
| South Florida | sf1 |
| Cedar Key | cd2 |
| Apalachicola Bay | ap3 |
| Panama City | pa2 |
| Pensacola Bay | pn3 |
| New Orleans | ms8 |
| Texas | tx3 |
| Bahamas | bha |
| **Islands** | |
| Puerto Rico | sj5 |
| Virgin Islands | vi8 |
| Kauai | kw4 |
| Oahu | hn4 |
| Maui | ma3 |
| Hawaii | hw4 |



# P-Surge 2.6

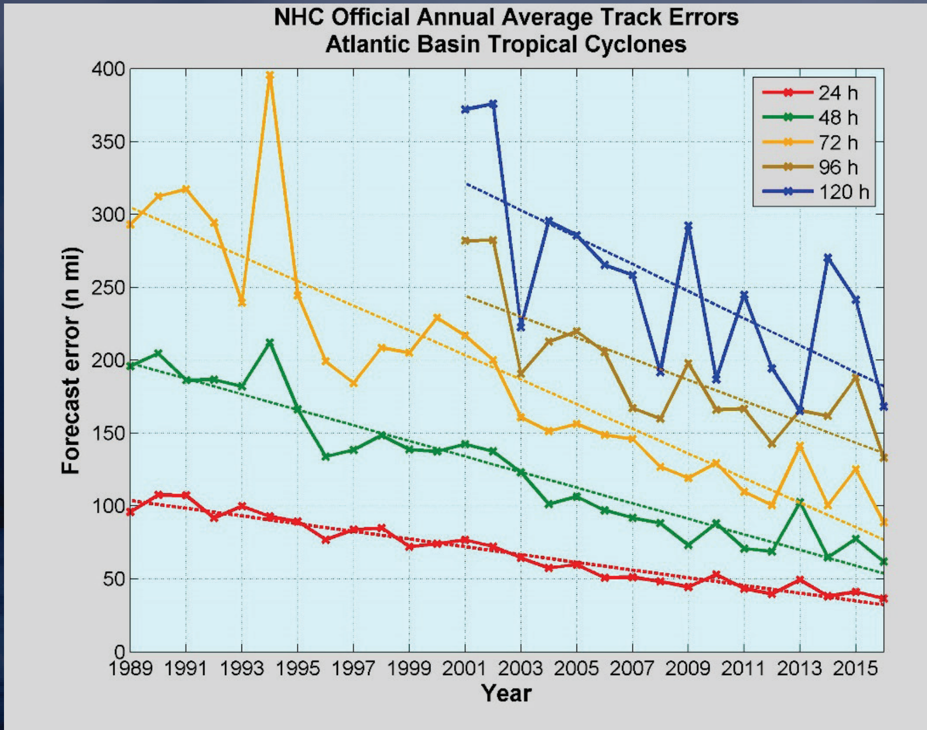
- Fundamental data used to create NWS/NHC storm surge products
- Real-time probability products based on the NHC official advisory information
- Accounts for meteorological uncertainty in:
  - Track (cross- and along-track)
  - Intensity (Vmax)
  - Size (Rmax)
- Uncertainties in track and intensity are based on the 5-year average NHC historical forecast errors
- Simulate astronomical tide using 2015 ADCIRC tidal database



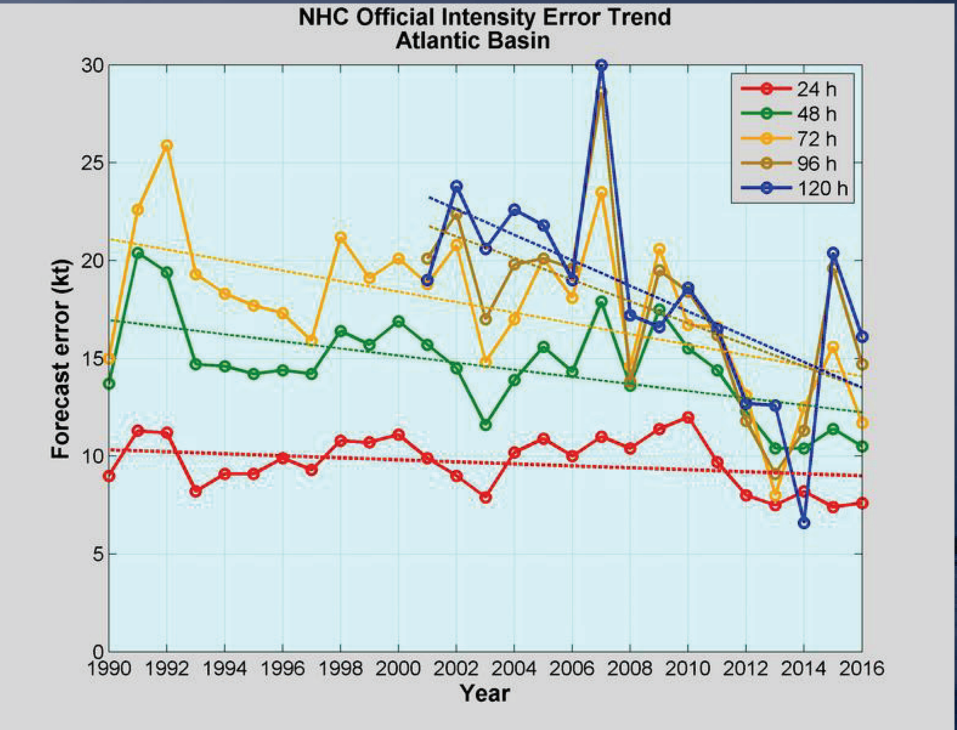
# NHC Track and Intensity Forecast Errors

## Track Errors (1989-2016)




2010-2016 Average Error:
24-hr: 42.9 nautical miles
48-hr: 74.1 nautical miles

## Intensity Errors (1990-2016)

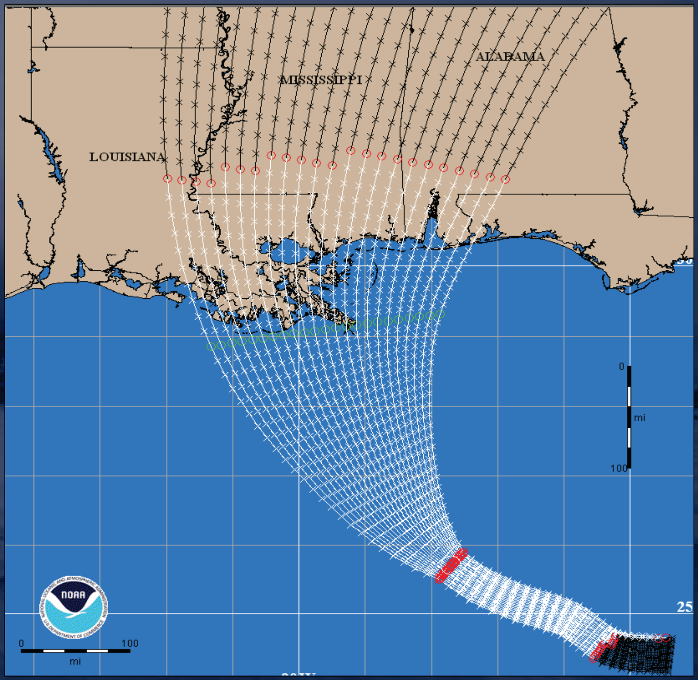



2010-2016 Average Error:
24-hr: 8.9 knots
48-hr: 12.6 knots

# Sampling the Meteorological Uncertainty

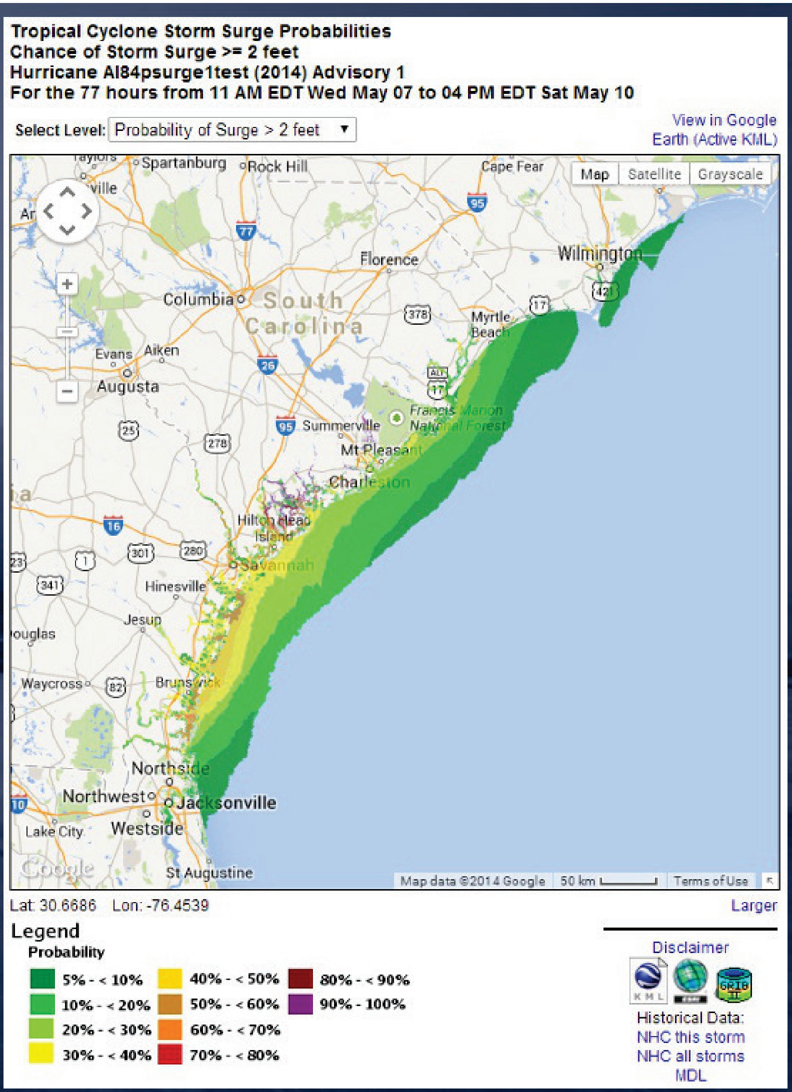
- Samples error distributions in discrete pieces to create a representative set of hypothetical storms
  - Ensemble centered on NHC official advisory
  - Error spaces are based on normal distributions
- Meteorological perturbations in P-Surge 2.6:
  - Variable number of cross-track
  - 7 variations in storm speed
  - 3 variations in storm size
  - 3 variations in storm intensity
- About 500-1000 unique storm scenarios
- Total number of simulations increases when applied to various SLOSH basins
- Future modeling development will explore ways to improve reliability scores

Hurricane Katrina (2005)
Advisory 23



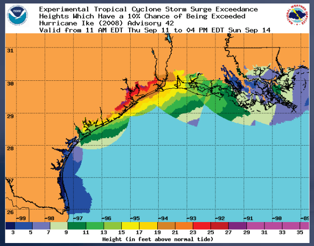
# P-Surge 2.6 Products

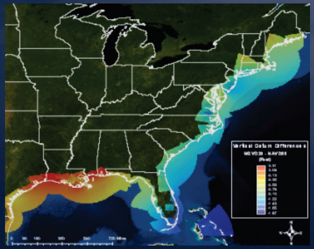
- Probability product
  - Probability of surge greater than 1-20 ft
  - Available as above ground level and above NAVD88
- Exceedance product
  - Storm surge height exceeded by 10-90% of storms
  - Available as above ground level and above NAVD88
  - Cumulative and incremental probabilities
- Output sent over SBN to NHC and WFOs
- Viewer/data available on MDL website
- GIS shapefiles on NHC website

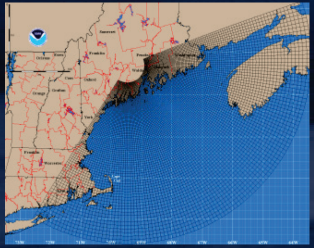


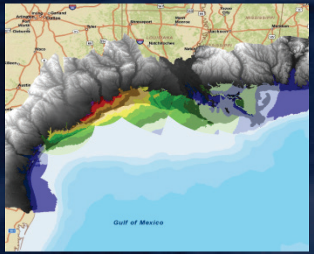
# Potential Storm Surge Flooding Map

# NHC Potential Storm Surge Flooding Map



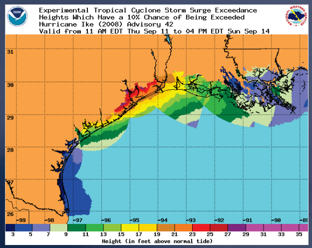



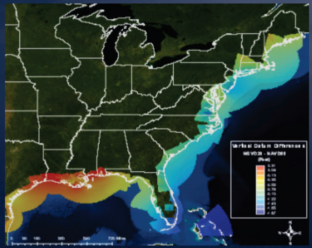


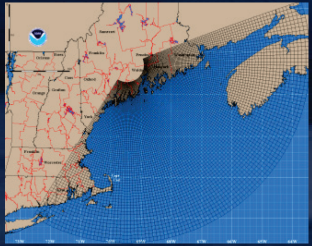


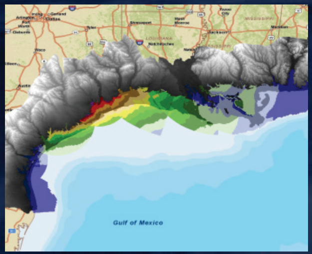
- Which product will drive the flooding map?
  - P-Surge 2.6 (includes tides)
  - 10% Exceedance (a reasonable worst-case scenario)
- SLOSH Grids
  - Latest SLOSH basins updated to NAVD88
- Topography/Digital Elevation Models (DEMs)
  - NOAA OCM Sea-level rise DEM
    - Resampled to smoother resolution (~100 m)
  - DEM gaps augmented with USGS 3DEP
- Processing
  - Locally using ArcGIS for Server and Desktop
  - Working toward leveraging NWS integrated dissemination program (IDP)

# NHC Potential Storm Surge Flooding Map



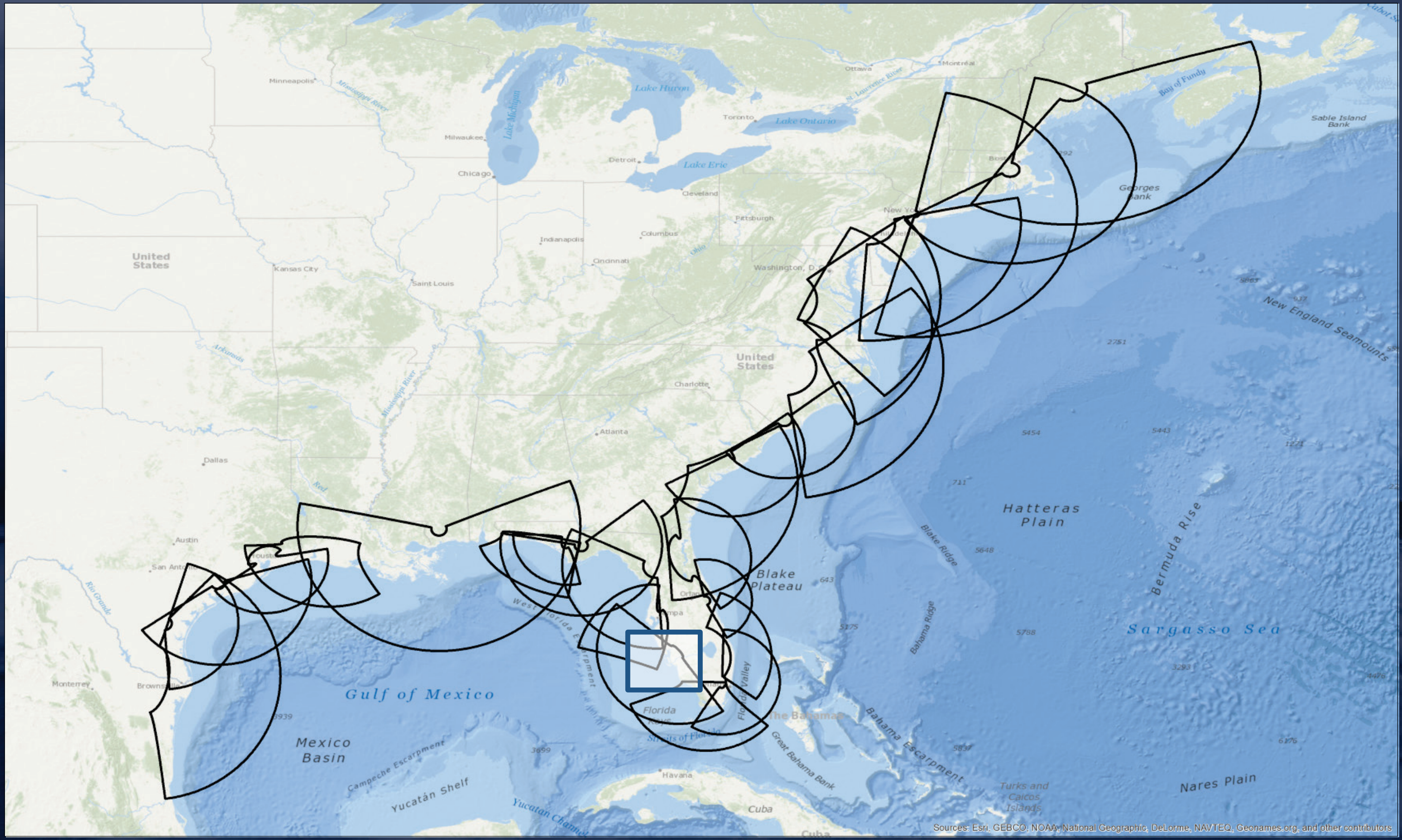








- What it does account for:
  - Flooding due to storm surge from the ocean, including adjoining tidal rivers, sounds, and bays
  - Normal astronomical tides
  - Land elevation, coastline, wetlands, etc.
  - Uncertainties in the landfall location, forward speed, angle of approach to the coast, intensity, and wind field of the cyclone
- What it does NOT account for:
  - Wave action
  - Freshwater flooding from rainfall
  - Riverine discharge
  - Flooding resulting from levee failures
  - For mapped leveed areas, flooding inside levee systems and overtopping of levees

# The Process

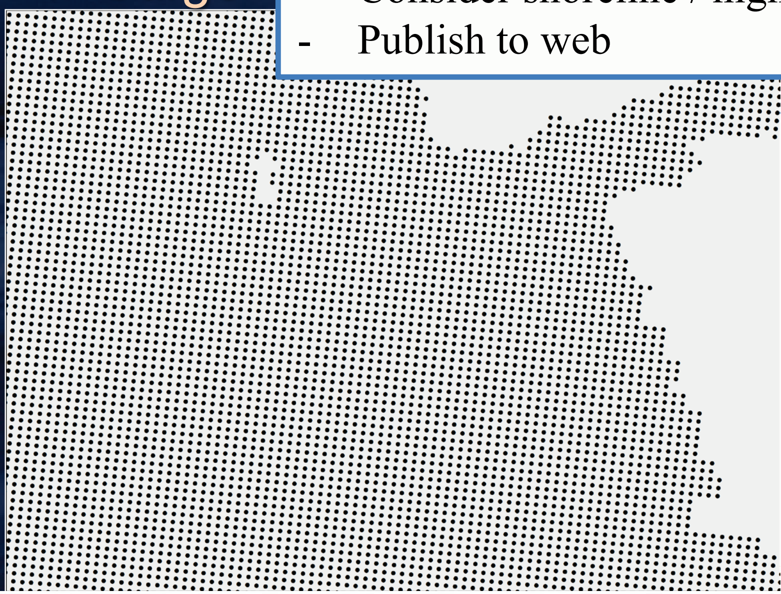


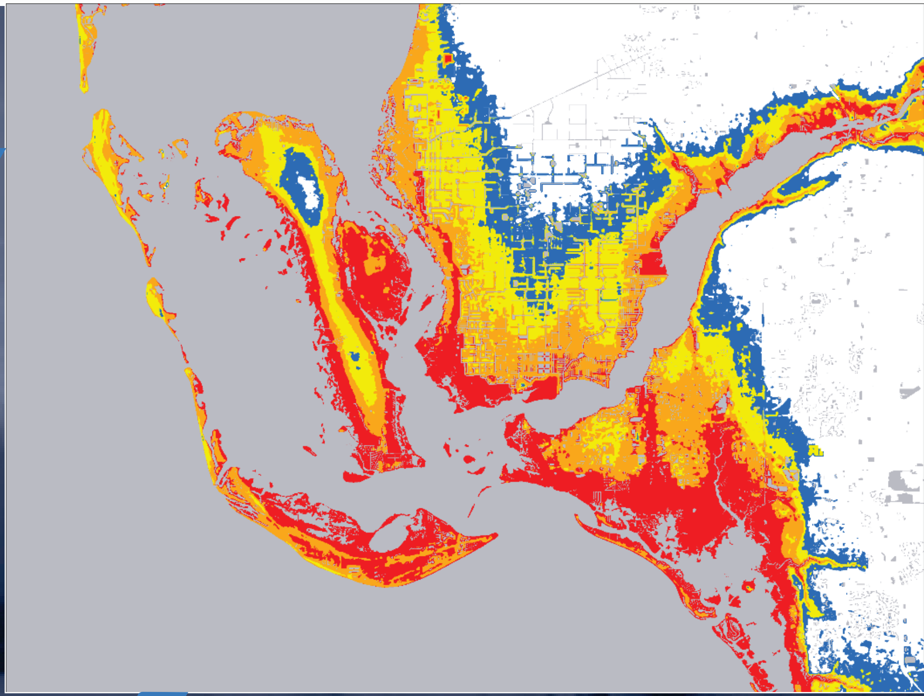
United States
Gulf of Mexico
Mexico Basin
Hatteras Plain
Blake Plateau
Sargasso Sea
Bermuda Rise
Nares Plain
New England Seamounts
Florida
Cuba
Yucatán Shelf
Sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, NAVTEQ, Geonames.org, and other contributors

# Potential Storm Surge Flooding Map

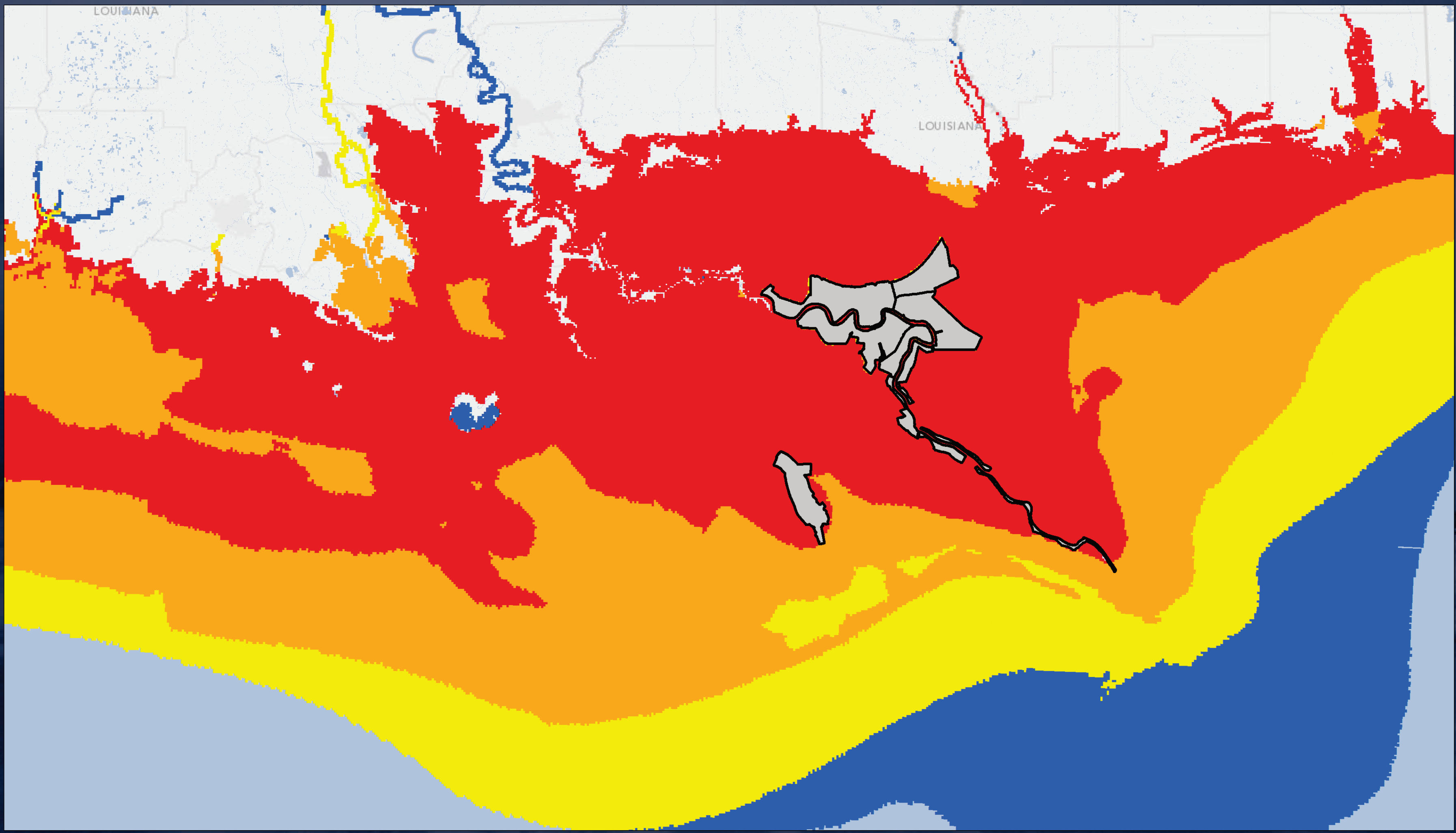
Geoprocessing
- Merge P-Surge output
- DEM smoothing
- Processing with elevation data
- Interpolation
- Consider shoreline / high tide
- Publish to web

P-Surge



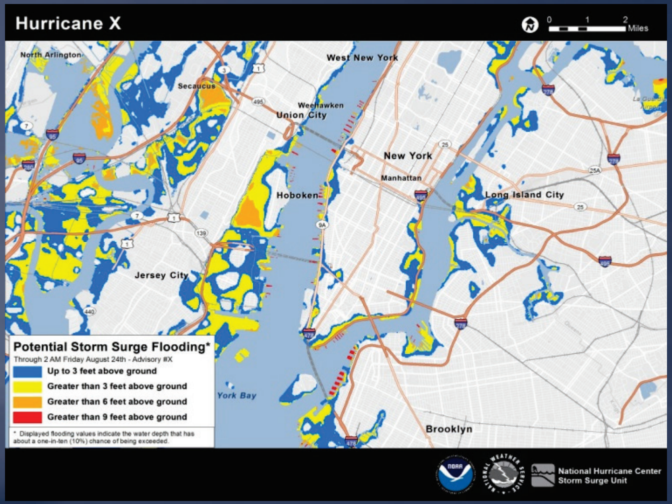


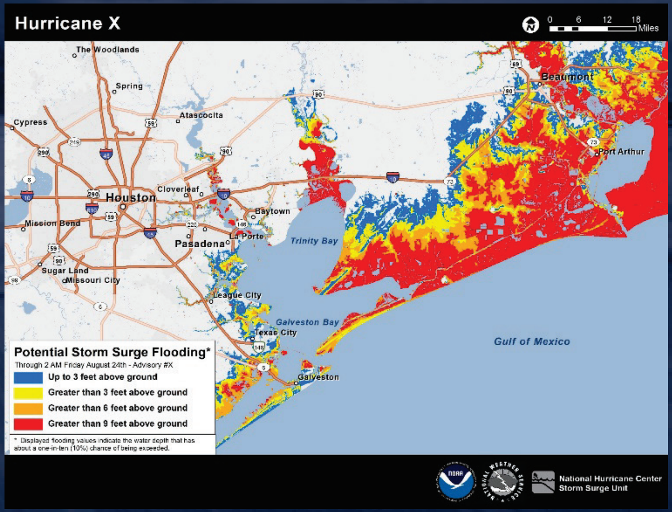
# From Datum to Inundation



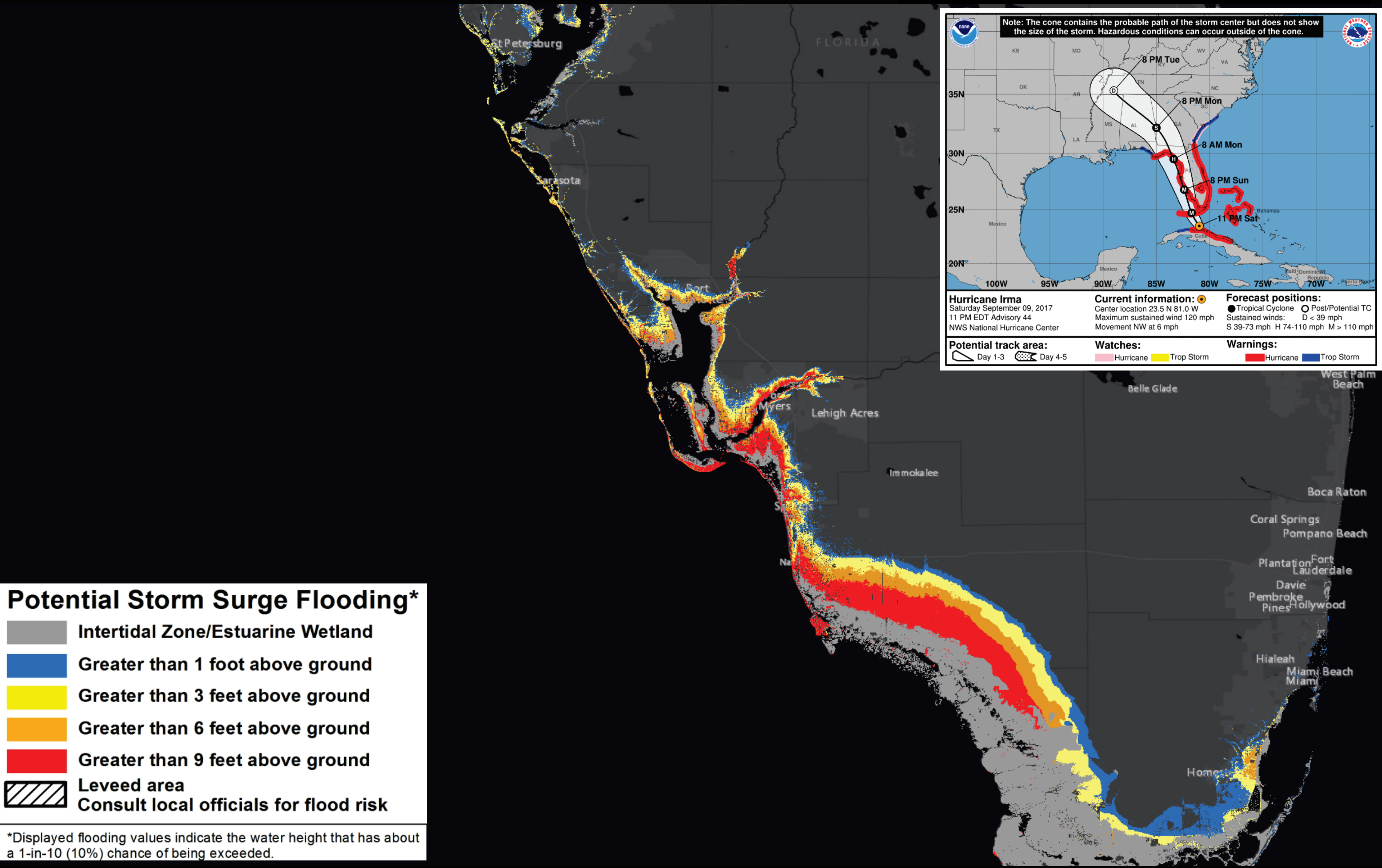
# Potential Storm Surge Flooding Map

- Provides a quantitative risk assessment for decision makers
- Shows height above ground that the water could reach, depicting a reasonable worst-case scenario at any individual location
- Shows inundation levels that have a 10% chance of being exceeded
- First map issued at the same time as the initial hurricane watch or in some cases, with a tropical storm watch
- Available about 60 to 90 minutes following the advisory release



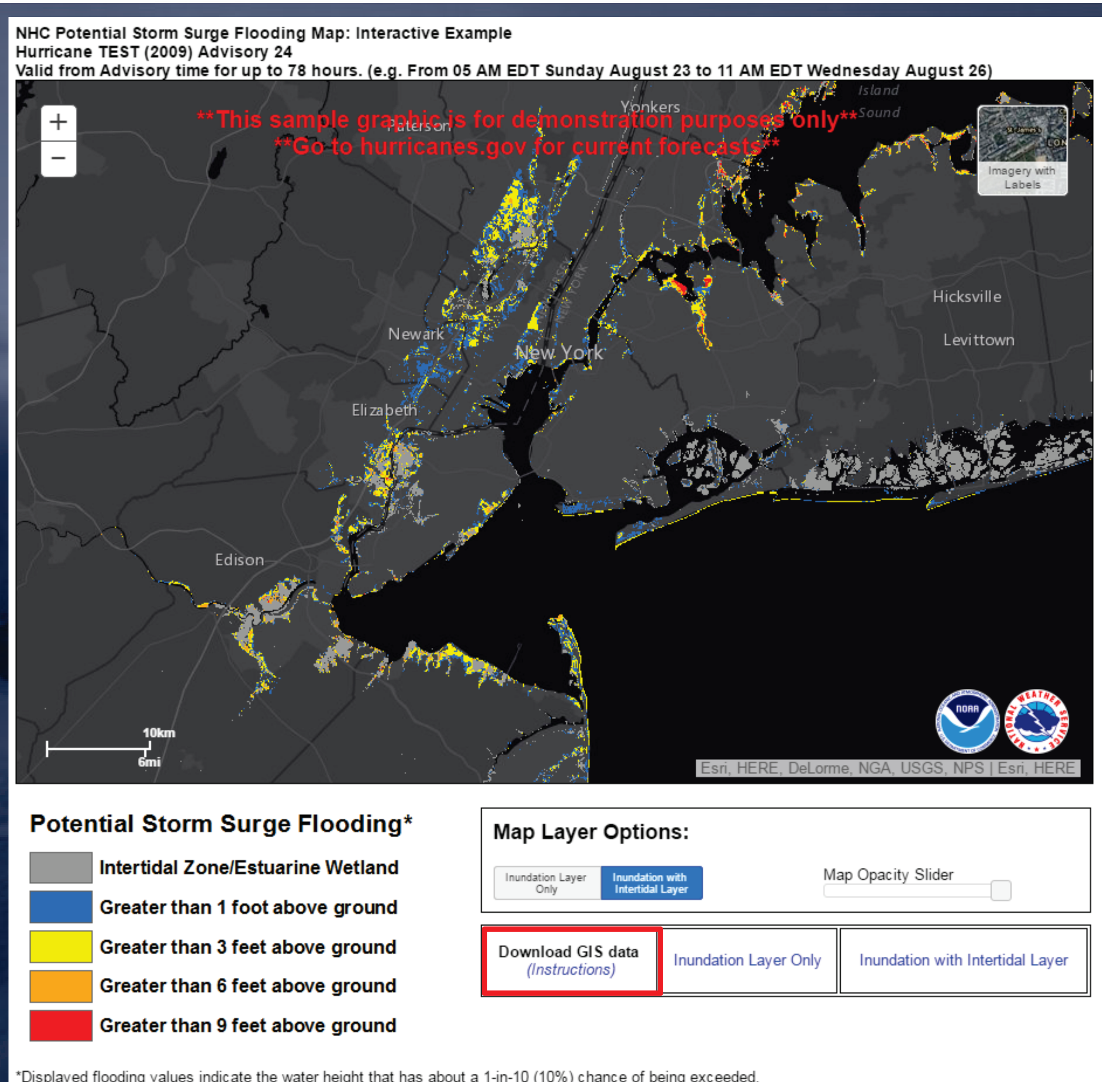
# Hurricane Irma Advisory 44




National Hurricane Center
Storm Surge Unit

# Viewable in Interactive Map Interface

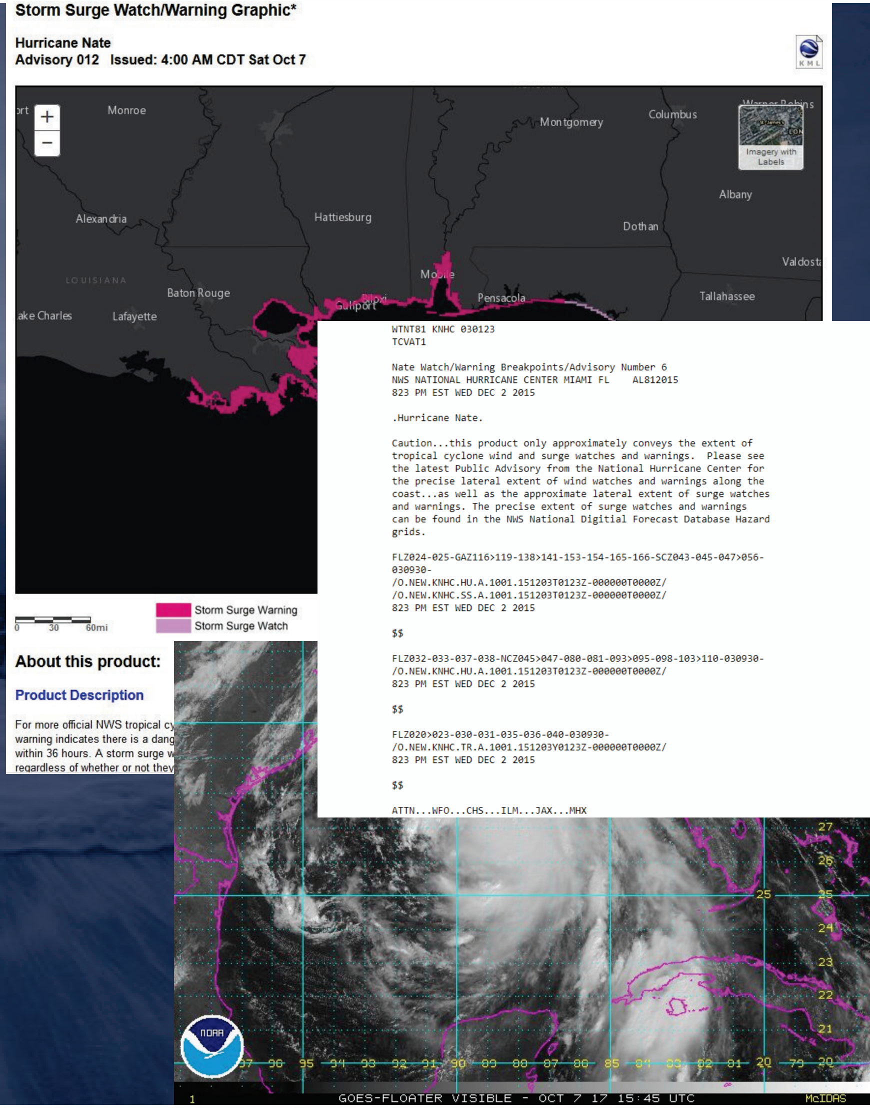
## http://www.nhc.noaa.gov/surge/inundation/



# Storm Surge Watch & Warning

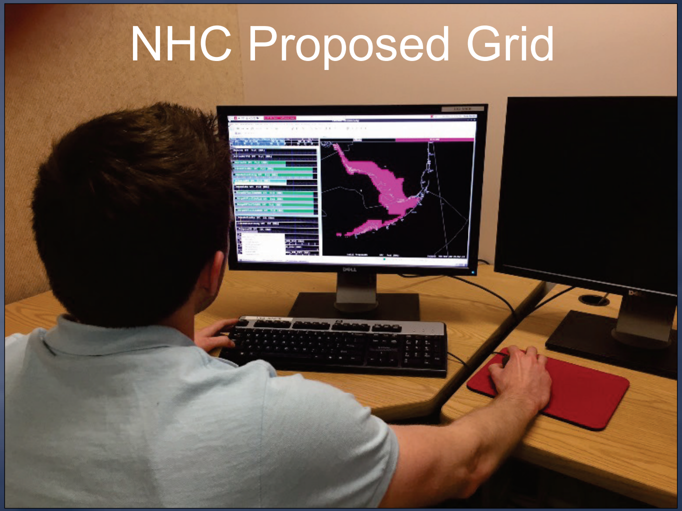
# Storm Surge Watch & Warning

- Intended to enhance public response to instructions from local officials, and, ultimately, to help guide EM decisions
- Highlights areas that have a significant risk of life-threatening inundation from surge (current threshold is 3 ft above ground)
- Issued 48 hours before possibility of life-threatening surge, or other hazards that would hinder evacuations
- Represents collaboration of NHC's Hurricane Specialists, Storm surge experts, and local NWS WFOs
- Included in NHC and WFO issued TCV

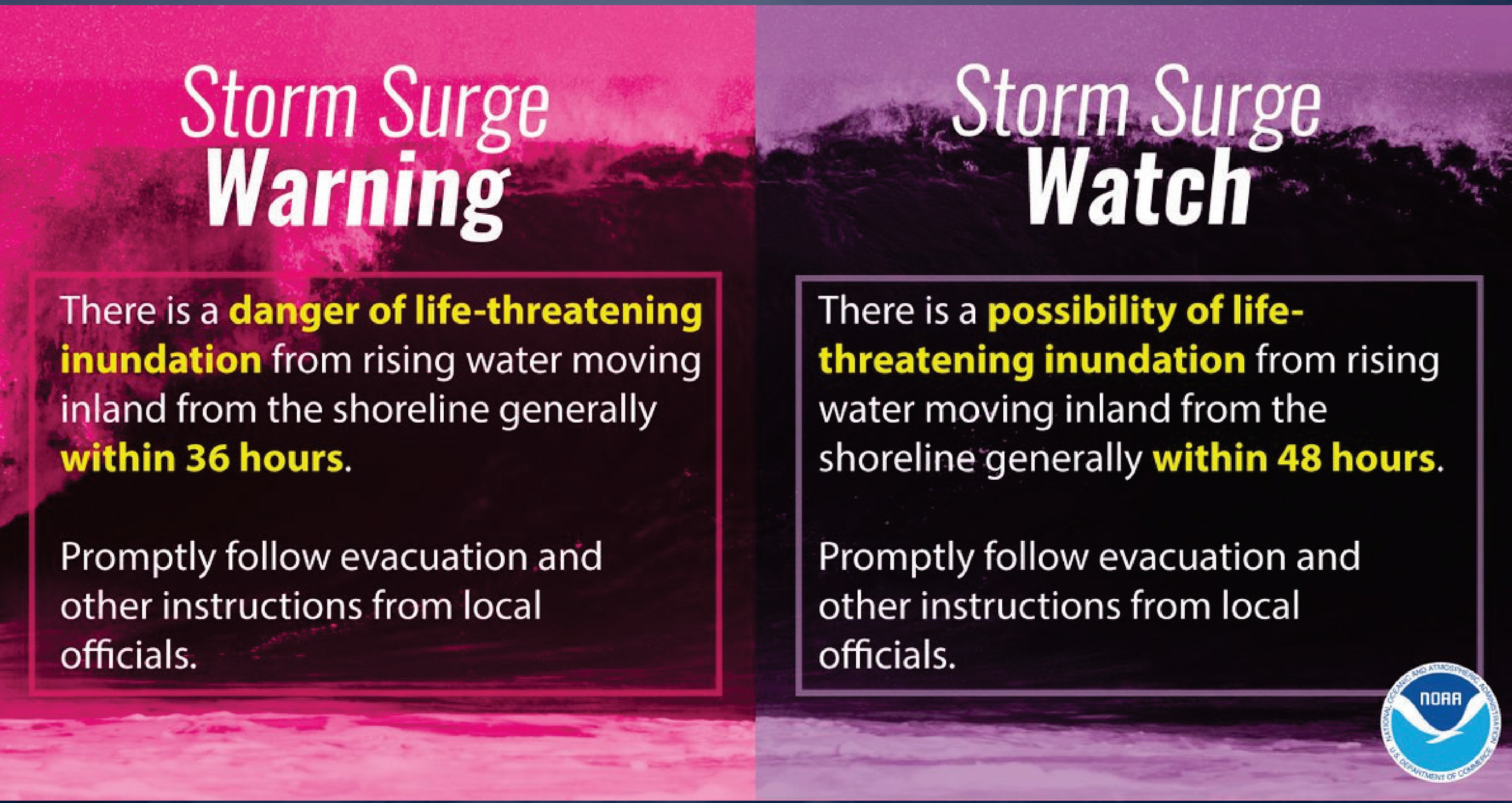


# Storm Surge Watch / Warning
# NHC-WFO Collaboration Process

- **Step 1:** NHC generates proposed grid based on pre-determined watch / warning inundation criteria and SSU/HSU expertise
- **Step 2:** Collaborate with impacted local WFOs to refine the watch / warning grid based on local knowledge and experience
- **Step 3:** NHC finalizes collaborated storm surge watch / warning



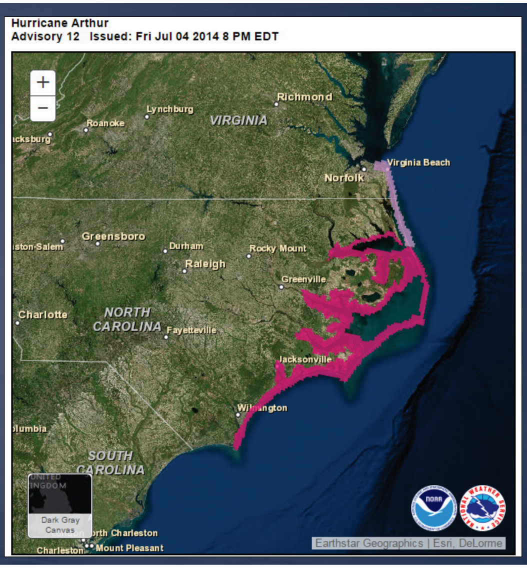

# Definitions



# A Tale of Two Maps

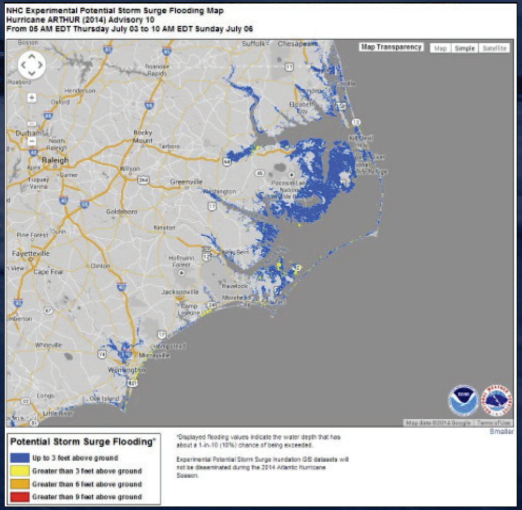
## Storm Surge Watch / Warning

- Highlights the areas that have a significant risk of life-threatening surge, but does not provide any quantitative inundation levels
- Although driven by automated guidance, W/W areas also based on subjective factors such as forecaster confidence, continuity with previous issuances, wind trigger, smoothing, isolated areas, etc.




## Potential Storm Surge Flooding Map

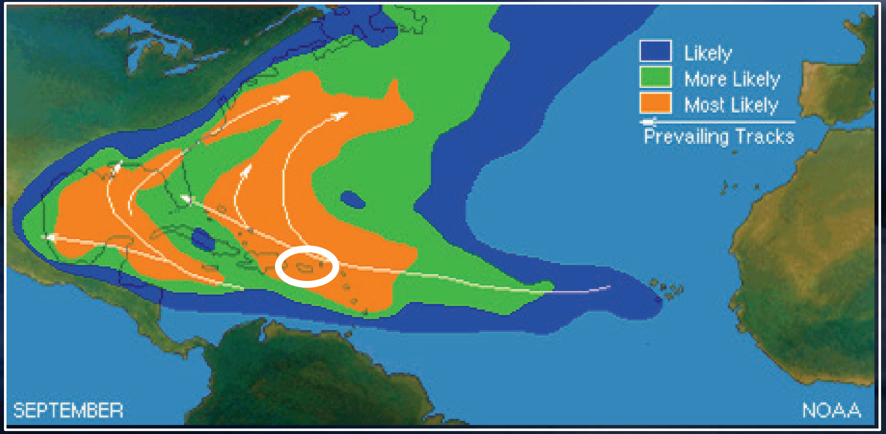
- Automated guidance on where inundation from surge could occur and the height above ground the water could reach
- Based solely on the latest NHC forecast and historical error characteristics. No guaranteed continuity from cycle to cycle, or consistency with W/W graphic



# OCONUS Storm Surge Activities

# NOAA/IOOS Modeling Testbed

To extend the present **operational surge forecasting** capability from mild-sloped coastal areas such as the US East and Gulf of Mexico coasts to **steep-sloped areas** such as Caribbean and Pacific islands, and study the **contribution of waves**. Identify models or techniques to transition to NOAA's **National Hurricane Center** and **local WFOs**.




www.nhc.noaa.gov/climo


www.caricoos.org

# Effects of Waves on Total Water Level Rise

- Waves can be a significant contributor to the total water level rise and cause substantial damage to property
- Waves-effects can be grouped into two main categories:
  - Wave setup
  - Wave runup
- Not all wave models can resolve both wave setup and wave runup
- Waves are not <u>as</u> important in all regions (bathymetric profile)

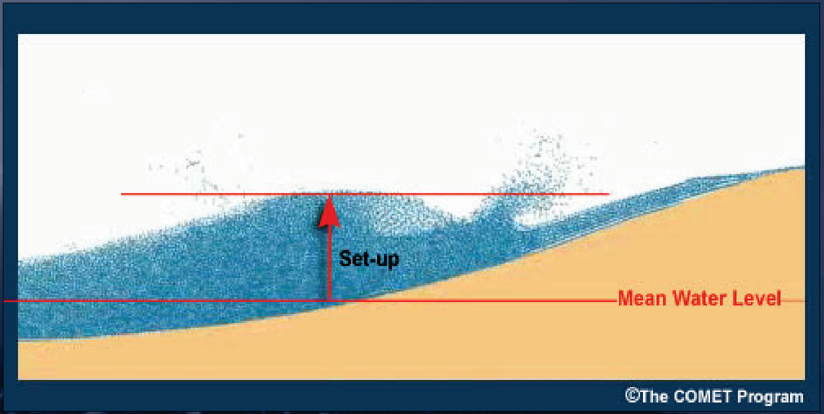
# Wave Setup

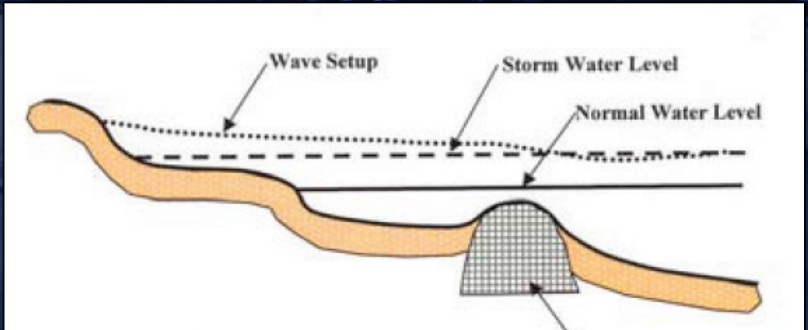
- Increase in the mean water level due to momentum transfer to the water column by breaking waves
- Can account for over 50% of total water level rise in some locations
- Affected by the incident wave properties, bathymetry, etc.
- Numerous empirical methods exist to estimate wave setup

## Steady-State Solution

$$\frac{\partial \overline{\eta}}{\partial x} = \frac{1}{\rho g (h + \overline{\eta})} \left( -\frac{\partial S_{xx}}{\partial x} + \tau_b \right)$$

$$S_{xx} = \overline{\int_{-h}^{\eta} (p + \rho u^2) dz}$$

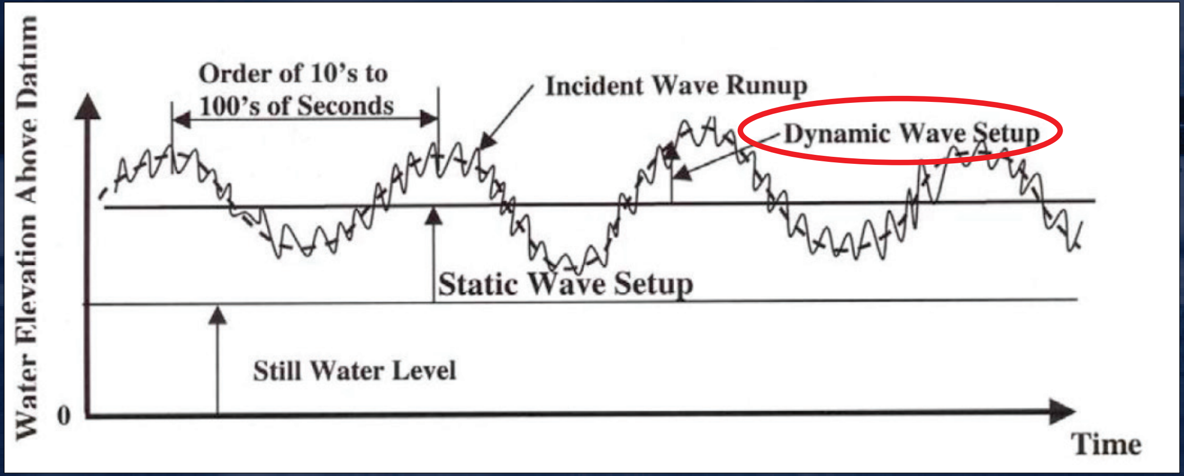


FEMA 2003

# Wave Setup

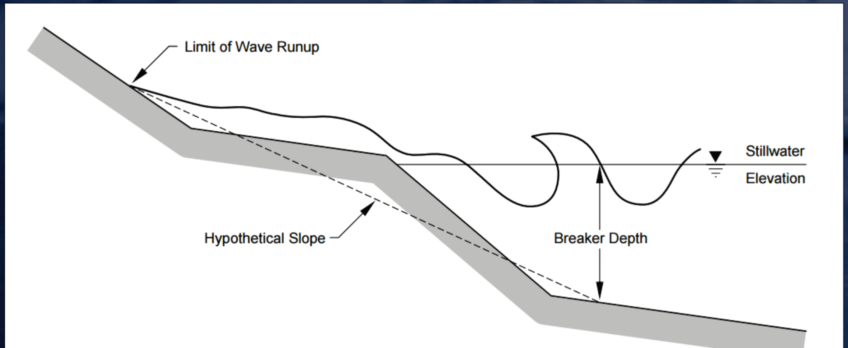
- Wave setup is comprised of two components:
  - Static/mean: transfer of breaking wave momentum to the water column (averaged over a time period)
  - Dynamic/fluctuating: nonlinear transfer of energy and momentum (wave groups/infragravity waves)




FEMA 2003

# Wave Runup

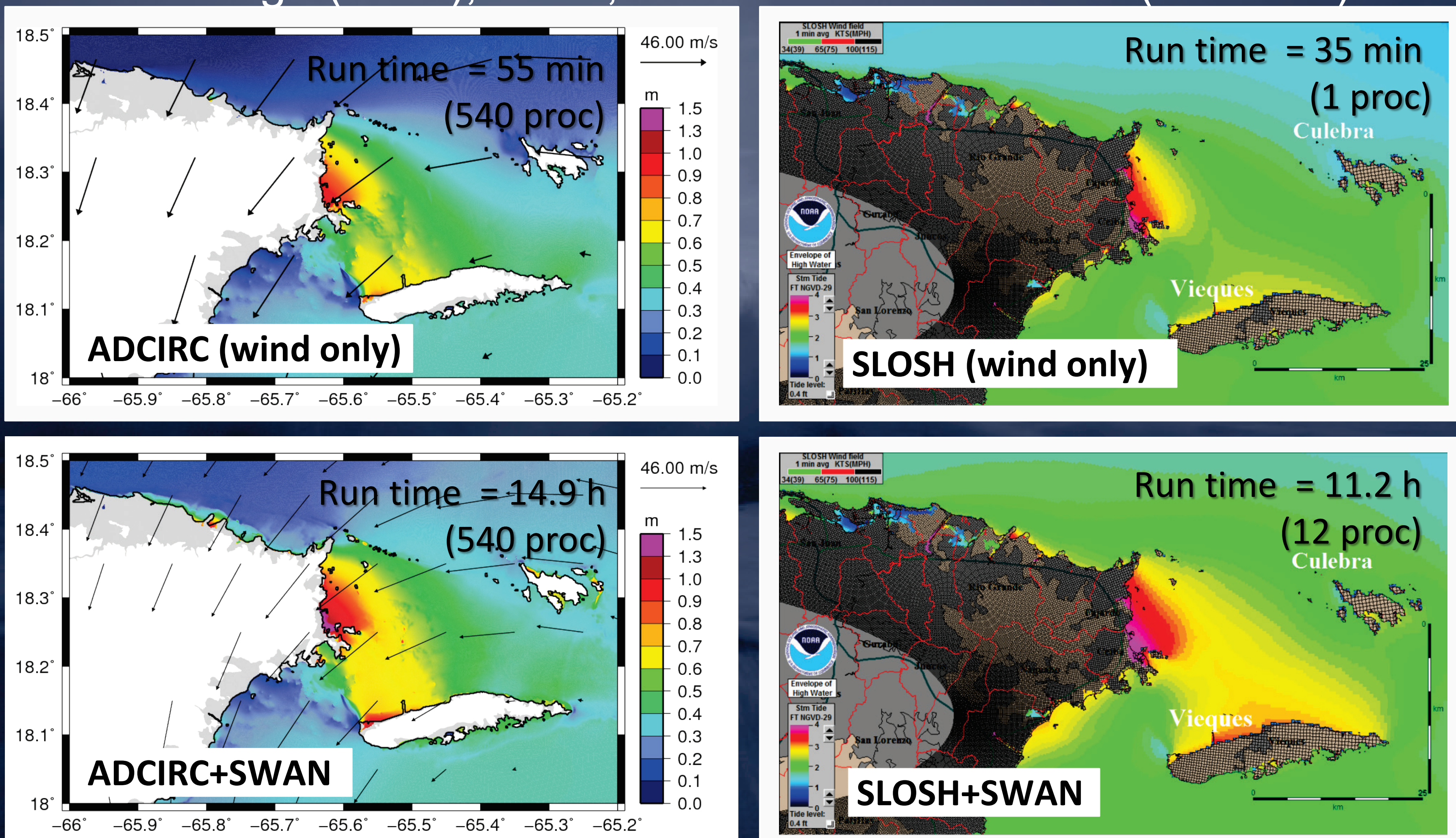
- Maximum vertical extent of wave uprush (swash zone) above the still water level (tide and surge)
- Extremely complex phenomenon that is difficult to model
  - Function of the local water level, incident wave conditions and beach characteristics (slope, permeability, reflectively, roughness, etc.)
  - Individual wave crests and slowly varying wave groups (infragravity waves) can penetrate well beyond the still-water inundation
- Important to coastal engineering, structural analysis and vulnerability, and beach/buff erosion, etc.



FEMA 2003

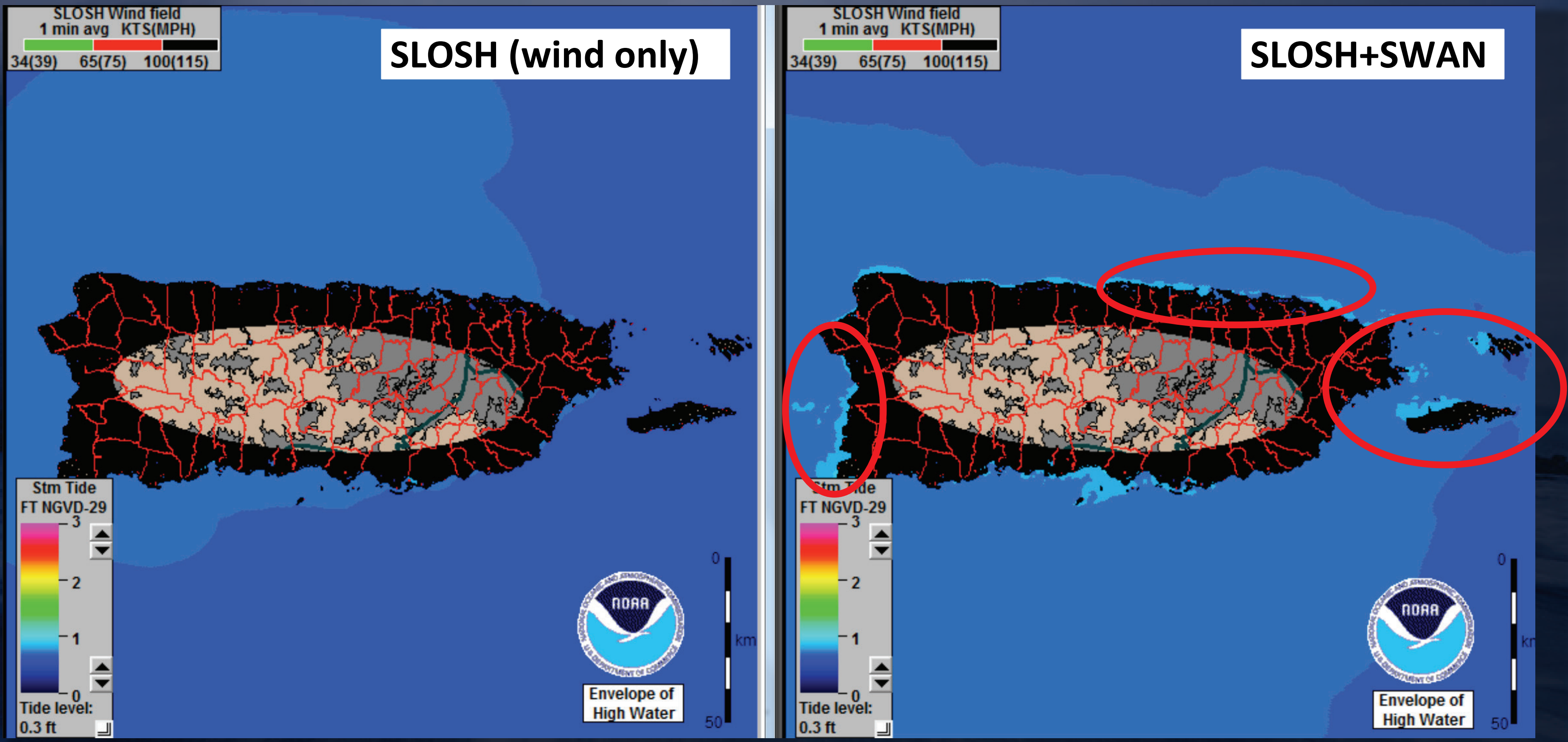
# Computational Efficiency is Key

## H. George (1998), Cat 4, landfall NE Puerto Rico (48 h sim)



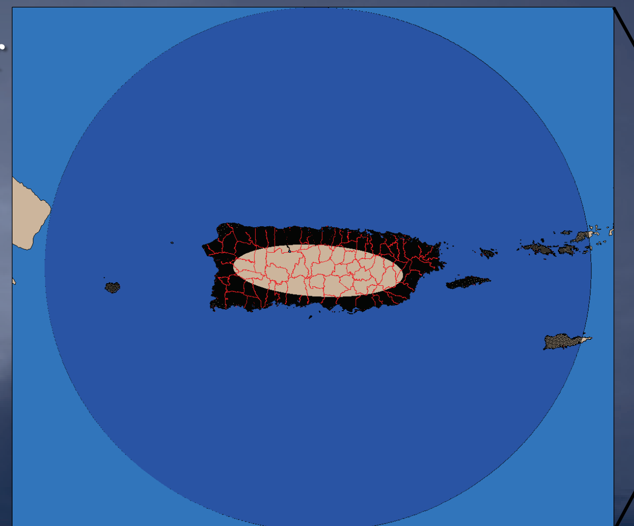
# SLOSH+SWAN Wave Impacts

## Post-Tropical Cyclone Sandy (2012)

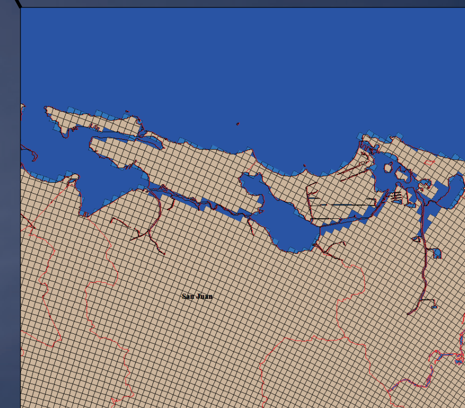


# Expanding SLOSH to OCONUS: Puerto Rico

- Same process, procedures, and quality control as employed for traditional (i.e. non-wave) MOMs/MEOWs
- Accounts for thousands of possible storm scenarios:
  - Track / landfall location
  - Storm size (RMW)
  - Forward speed
  - Intensity
  - Tide anomaly
- Scenarios based on climatological analysis
- Enables HES and other NHP activities

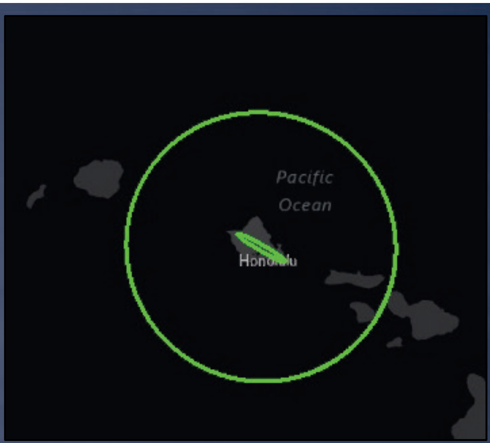


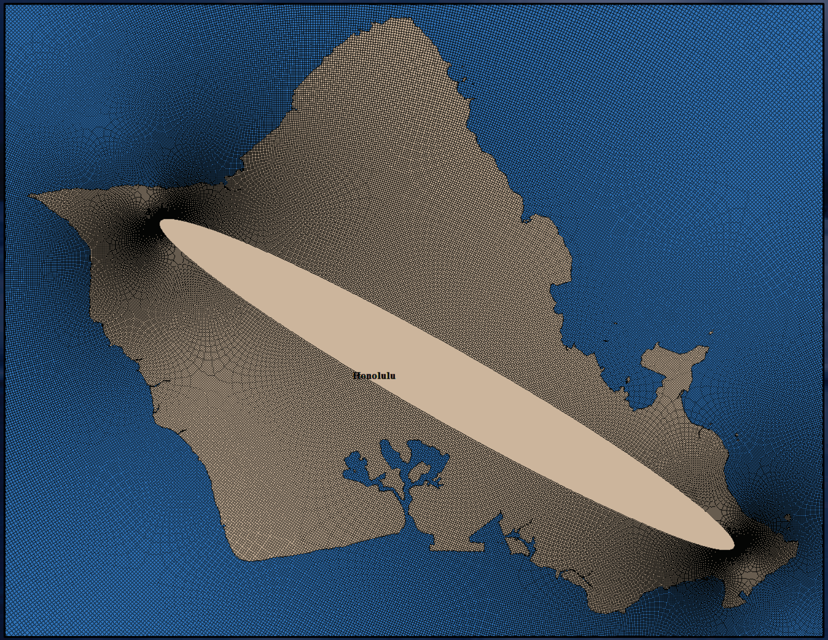
San Juan, PR

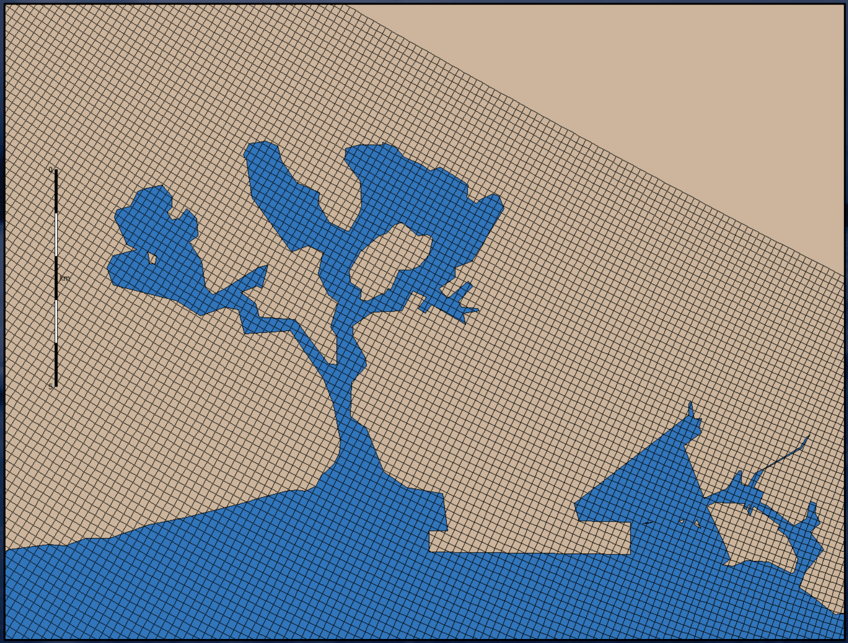


# Expanding SLOSH to OCONUS: Oahu

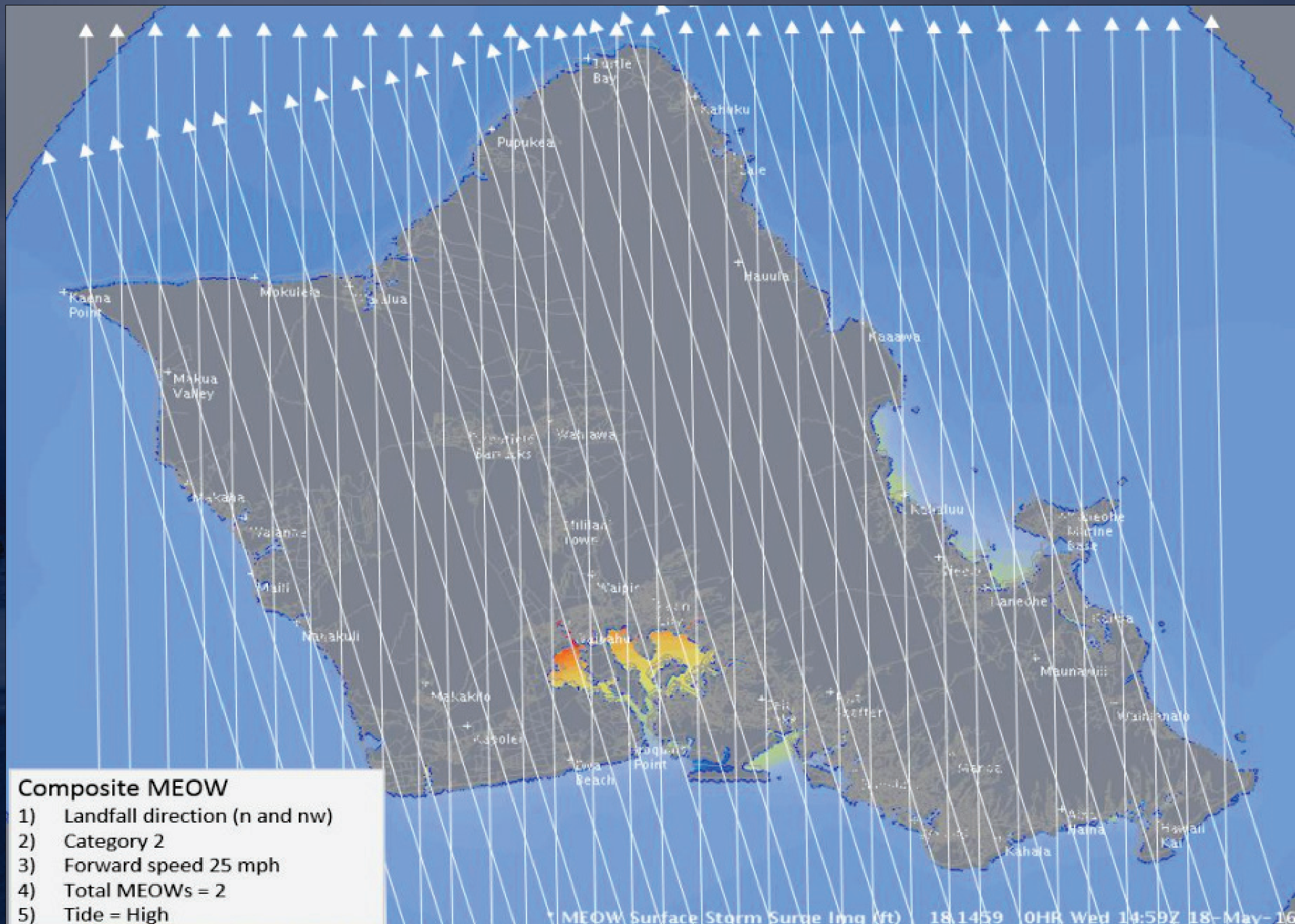
- Leverage NOAA testbed work in Puerto Rico
- SLOSH+SWAN storm surge modeling
- High-resolution SLOSH grid with 420k cells
  - Hyperbolic SLOSH grid configuration
  - Average shoreline resolution Oahu ≈ 140 m



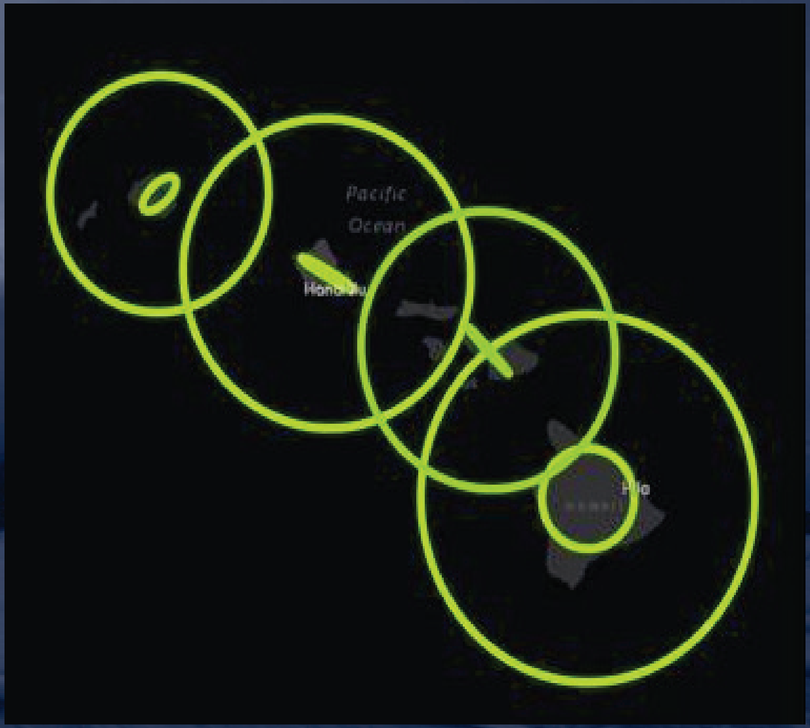
# Expanding SLOSH to OCONUS: Oahu



# Hawaii SLOSH+SWAN Basins

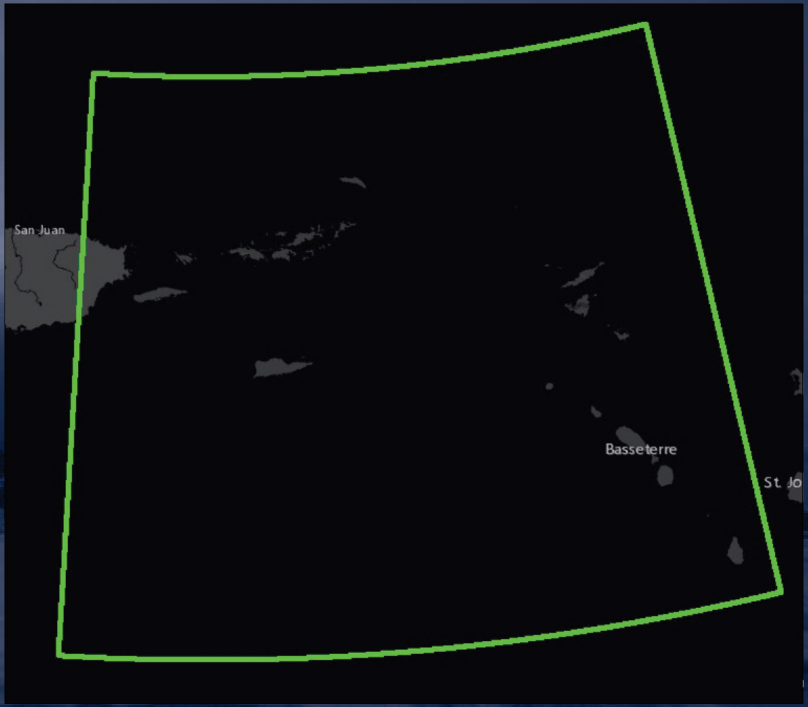
- Expand SLOSH+SWAN code to remaining Islands for complete coverage
  - Kauai
  - Hawaii
  - Maui

- Enable planning and mitigation capabilities and operational forecasting for all Hawaiian Islands



# Virgin Islands SLOSH+SWAN Basin

- Increased size and resolution
  - More than 2x resolution of current
  - 1,098,900 cells (999x1100)
  - Uniform grid spacing of ~350m
- Other improvements
  - Referenced vertically to Virgin Islands Vertical Datum (VIVD09)
  - DEM derived from 2013 NOAA Topographic Lidar



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