# NWS Storm Surge Ensemble Guidance

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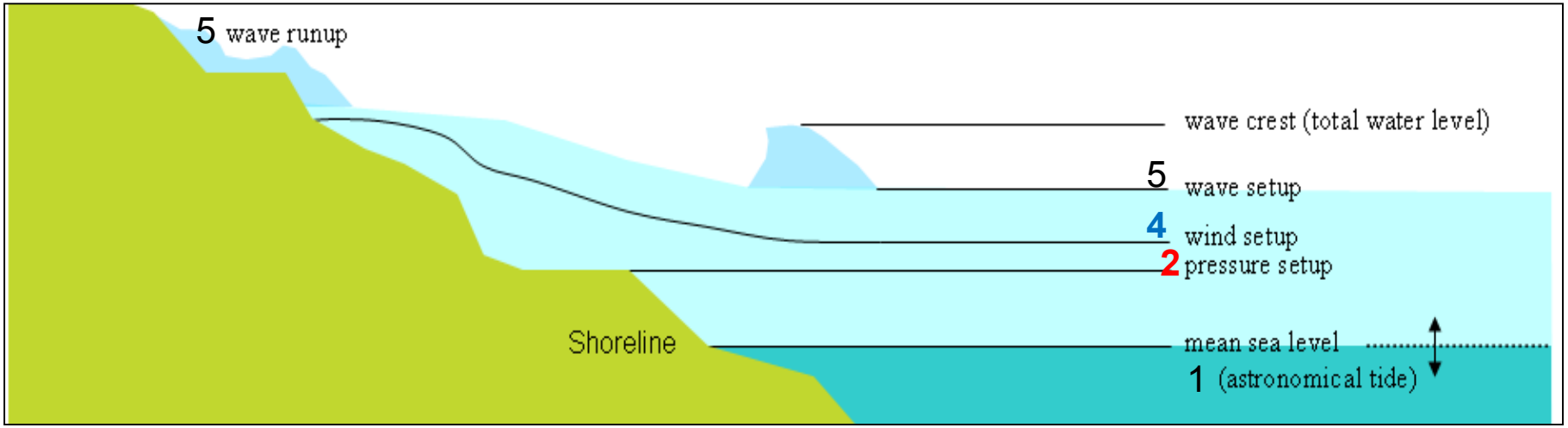
U.S. Nuclear Regulatory Commission
Rockville, MD – April 30, 2019

# What is Storm Surge?

A rising of the sea as a result of atmos. pressure changes and winds associated with a storm.

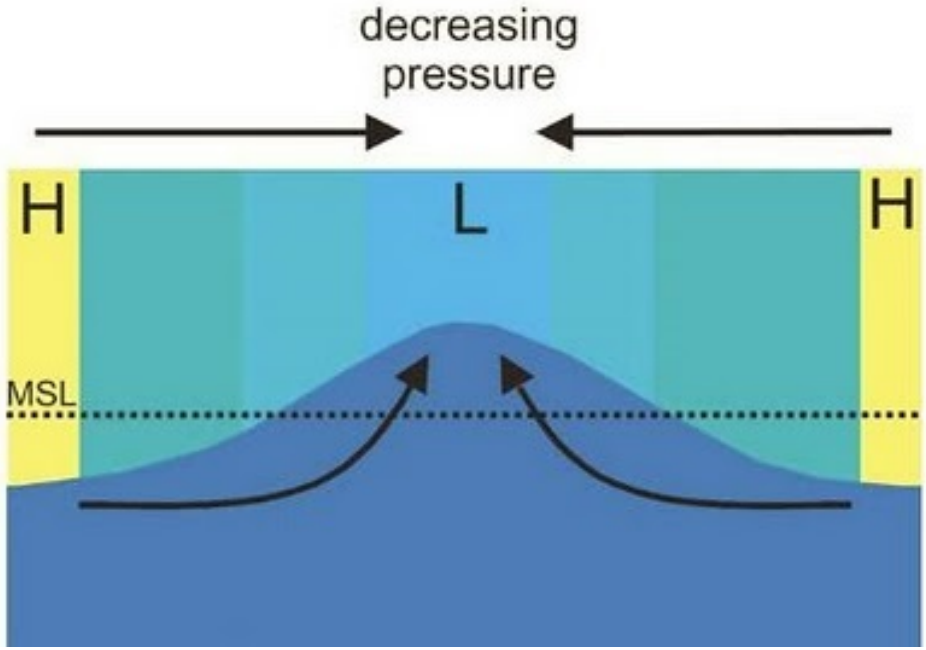
1. **Astronomical Tide**
2. **Pressure setup** – water level change due to lower atmos. pressure
3. **Geostrophic adjustment** – adjustment due to longshore current
4. **Wind setup** – water level change due to the force of the wind
5. **Wave setup** – water level change due to wave setup and run-up
6. **Nonlinear Advection**

**Dissipation terms; Steric setup**

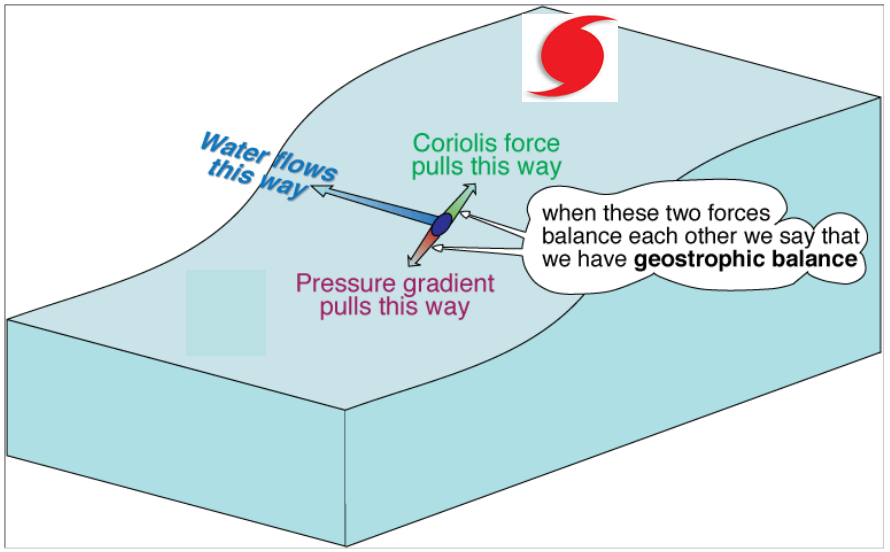


# Pressure Terms

## Pressure Setup




## Geostrophic Adjustment

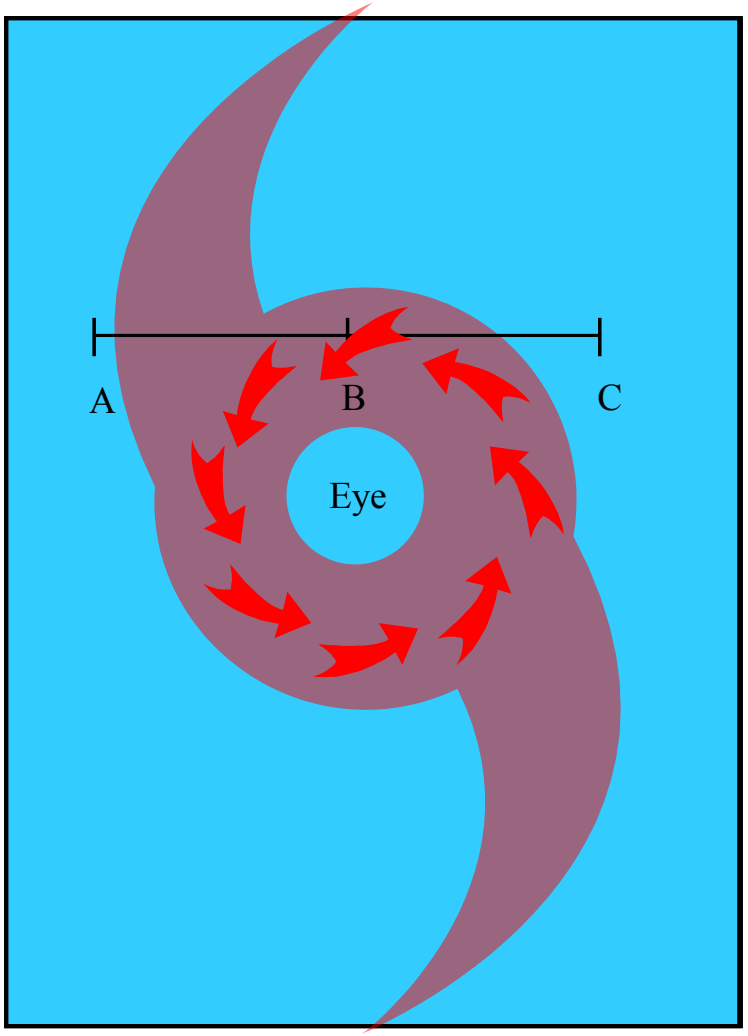



The balance between pressure gradient forces and Coriolis forces on a parcel of water is what we call geostrophic balance.

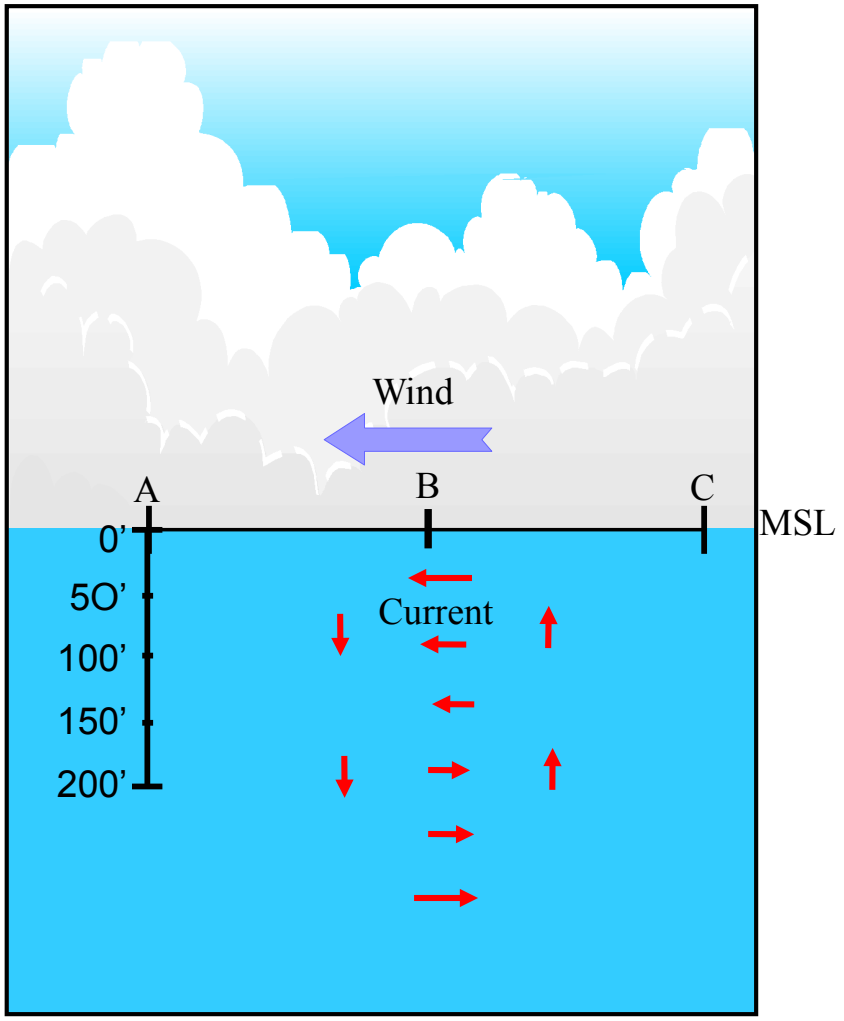
**Slower** and/or **Larger** storms increase the geostrophic adjustment's impact on storm surge.

# Wind Setup

**a. Top view of Sea Surface**

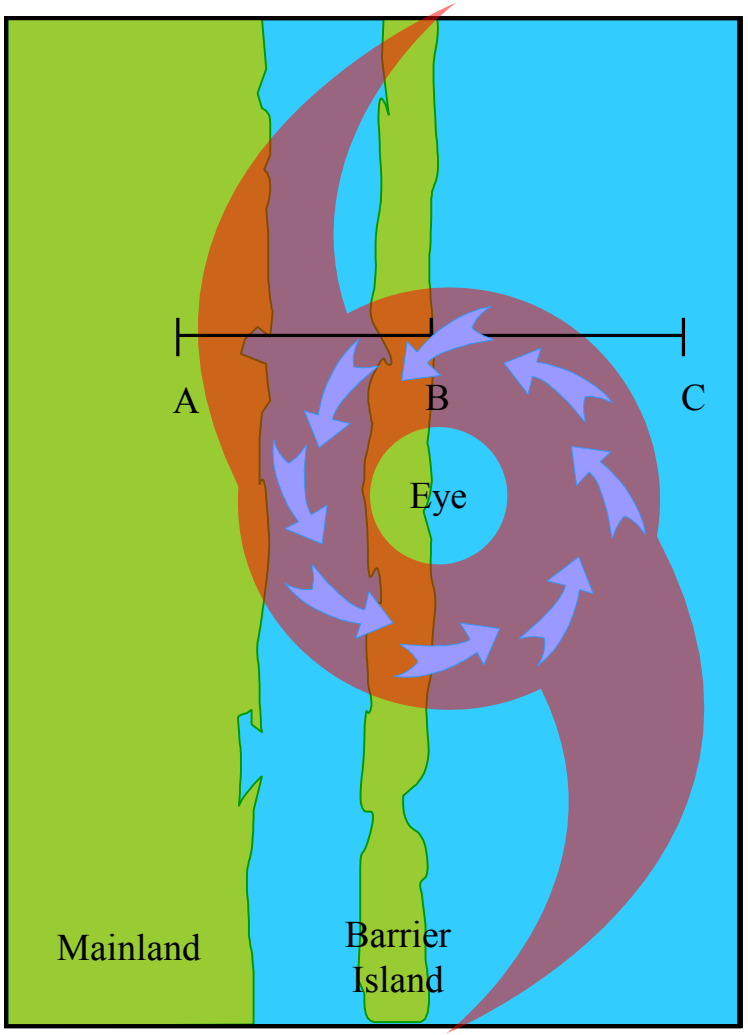



**b. Side view of Cross Section "ABC"**



# Wind Setup

**a. Top view of Sea Surface and Land**

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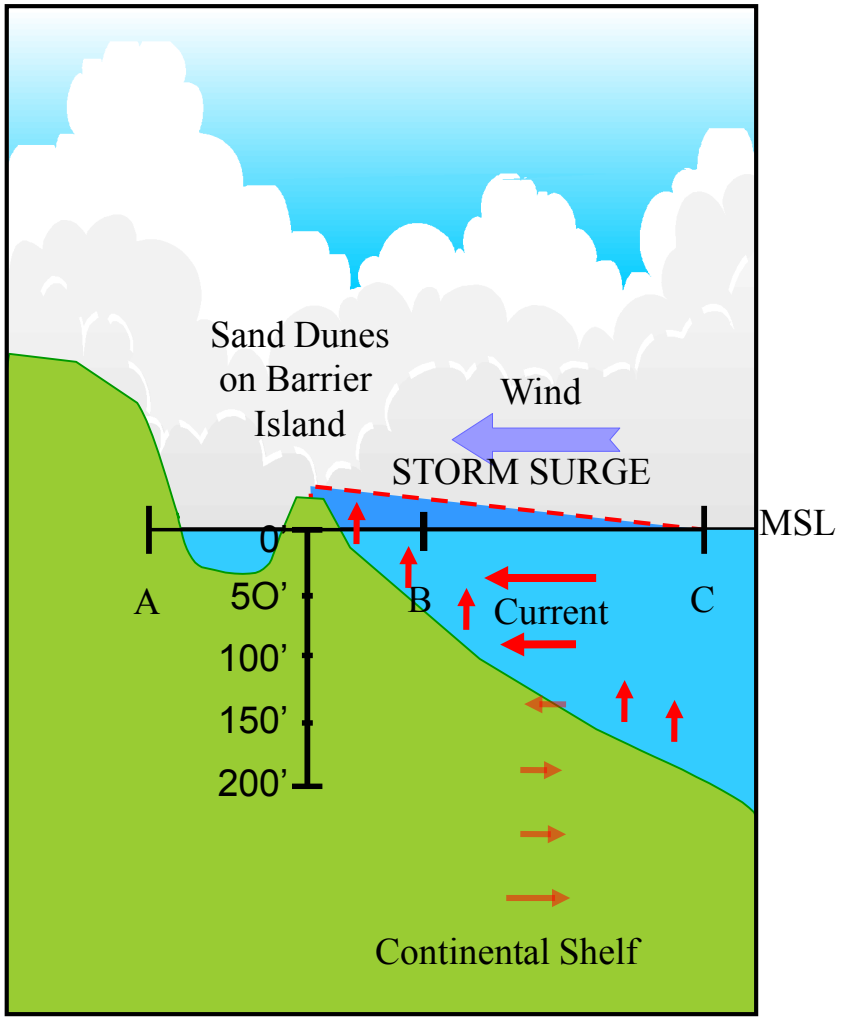
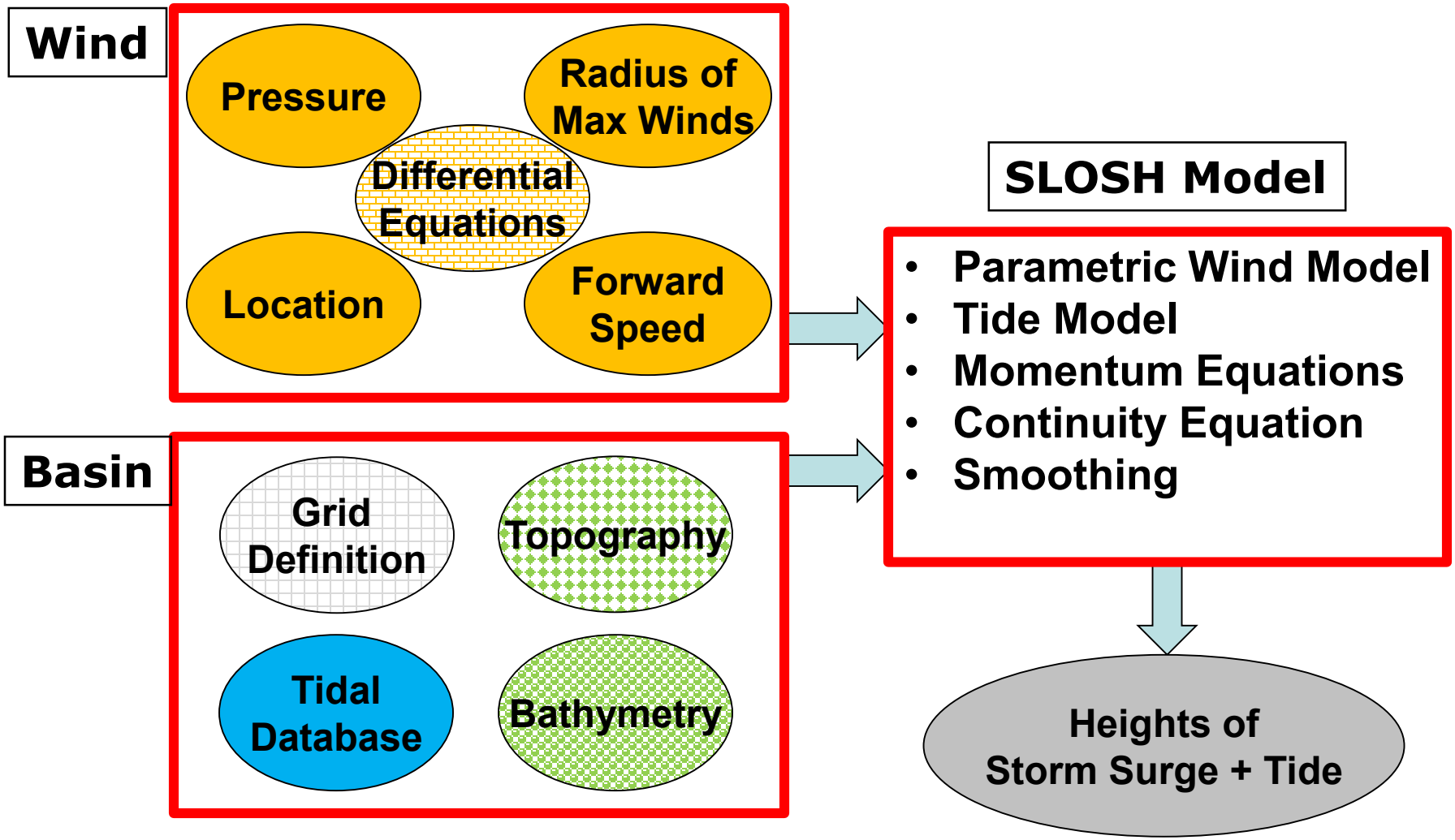
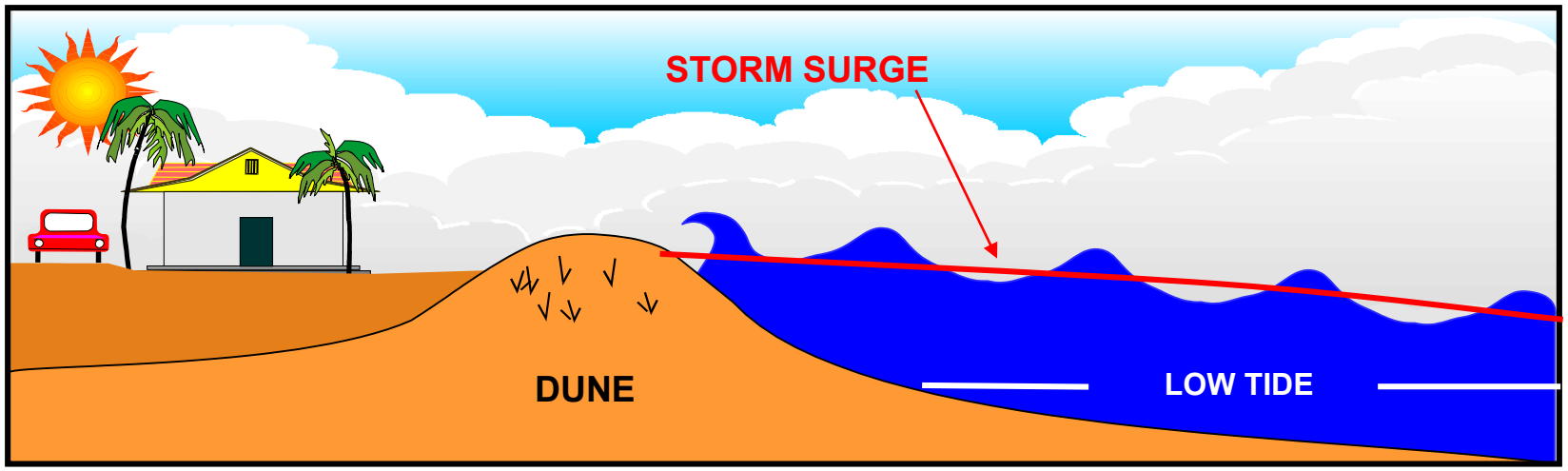


# What is the SLOSH model?

## (Sea Lake and Overland Surges from Hurricanes)



# SLOSH Tide Model



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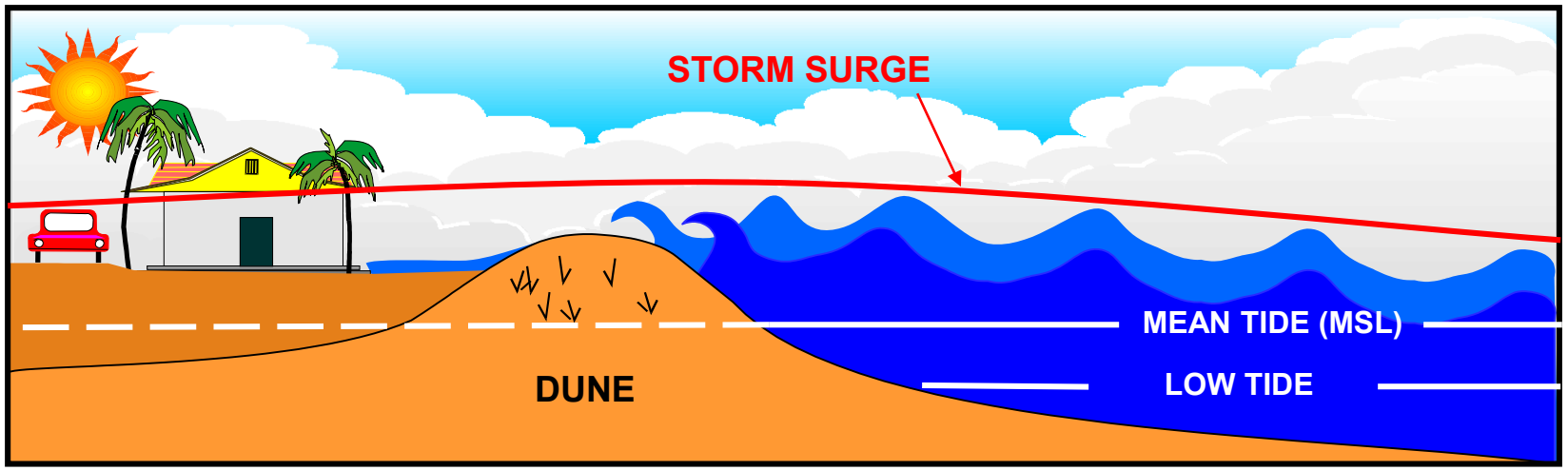

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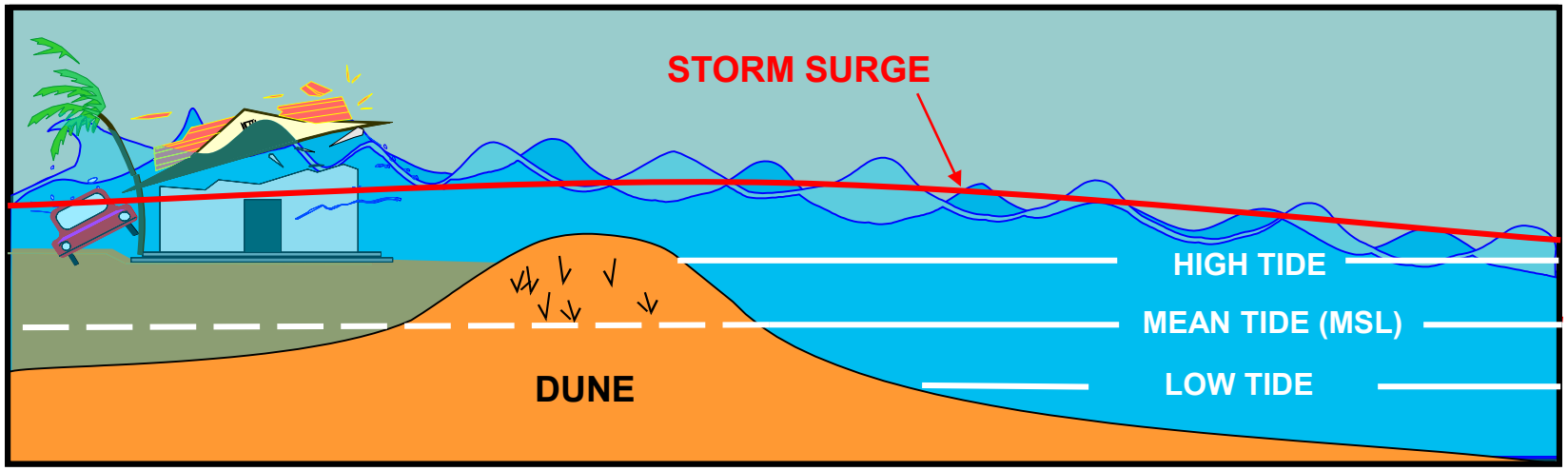



Extract harmonic constituents at every SLOSH grid cell from a tidal model

**V1** – Add after model run (*Tide not considered during inundation step*)

**V2** – Add/Subtract tidal field at each time step (*Wetting / Drying complication*)

$$H(t_0) = Tide(t_0)$$

$$H(t_n) = SLOSH\left(H(t_{n-1})\right) - Tide(t_{n-1}) + Tide(t_n)$$

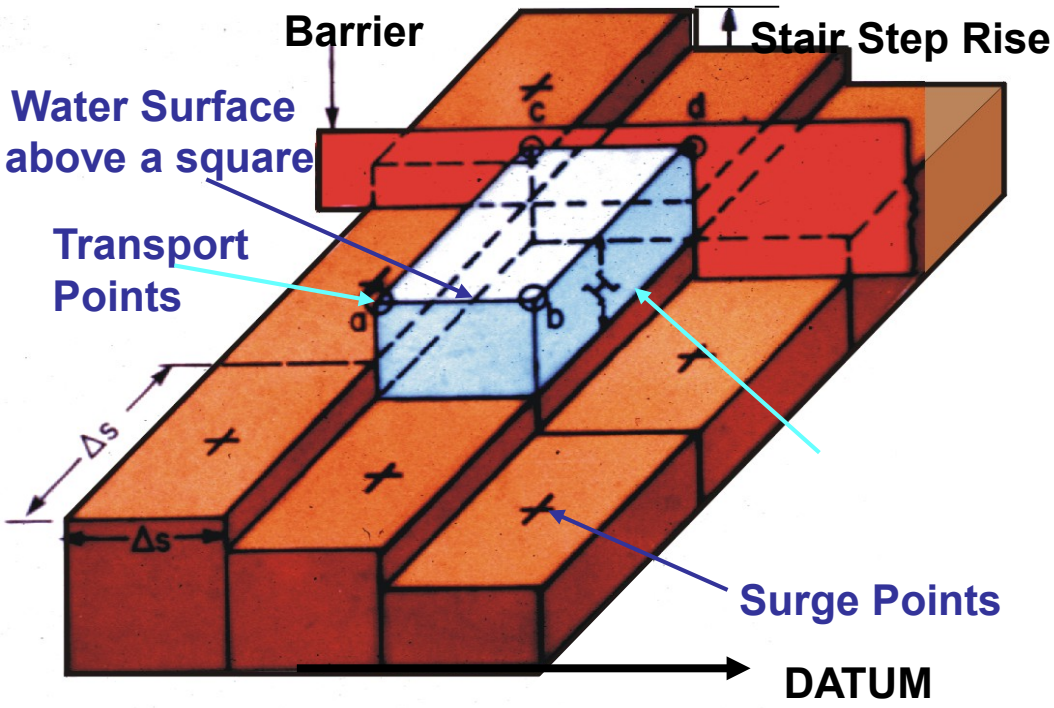
**V3** – Tide as a boundary condition (*Spin-up to initialize transport variables; narrow estuary mouths obstruct the tide*)

# SLOSH Basin

**Tropical** basins maintained by the National Hurricane Program (update cycle approximately 6 years)

Structured, Arakawa B-Grid

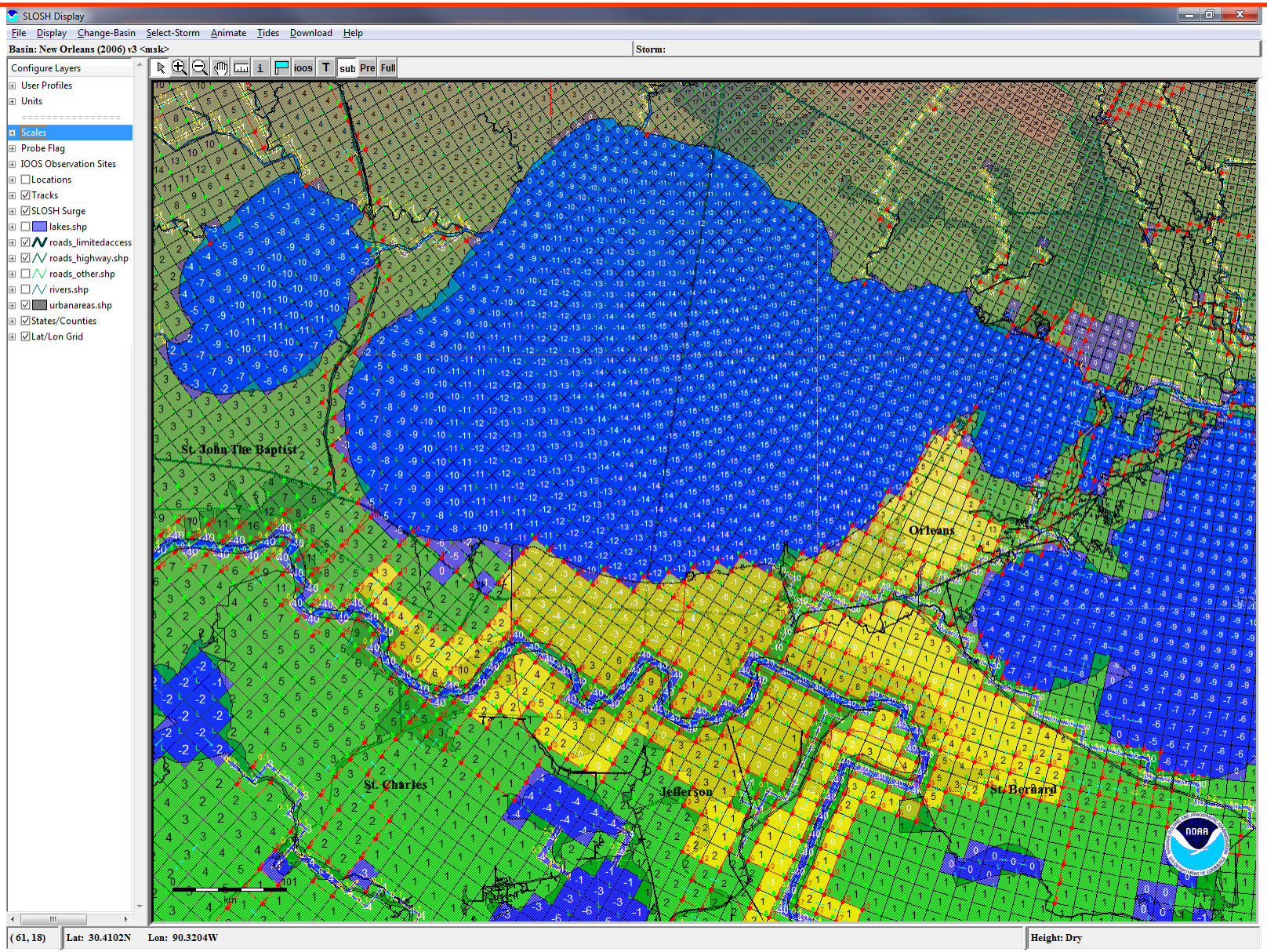
- Heights at the center and transports on the corners
- Finer resolution (**~100 m**) overland, and coarser (**~2 km**) offshore
- Locally orthogonal




Sub-grid elements:

- 1 dimensional flow for rivers and streams
- Barriers
- Cuts between barriers
- Channel flow with chokes and expansions
- Increased friction for trees and mangroves

# SLOSH Basin - Example



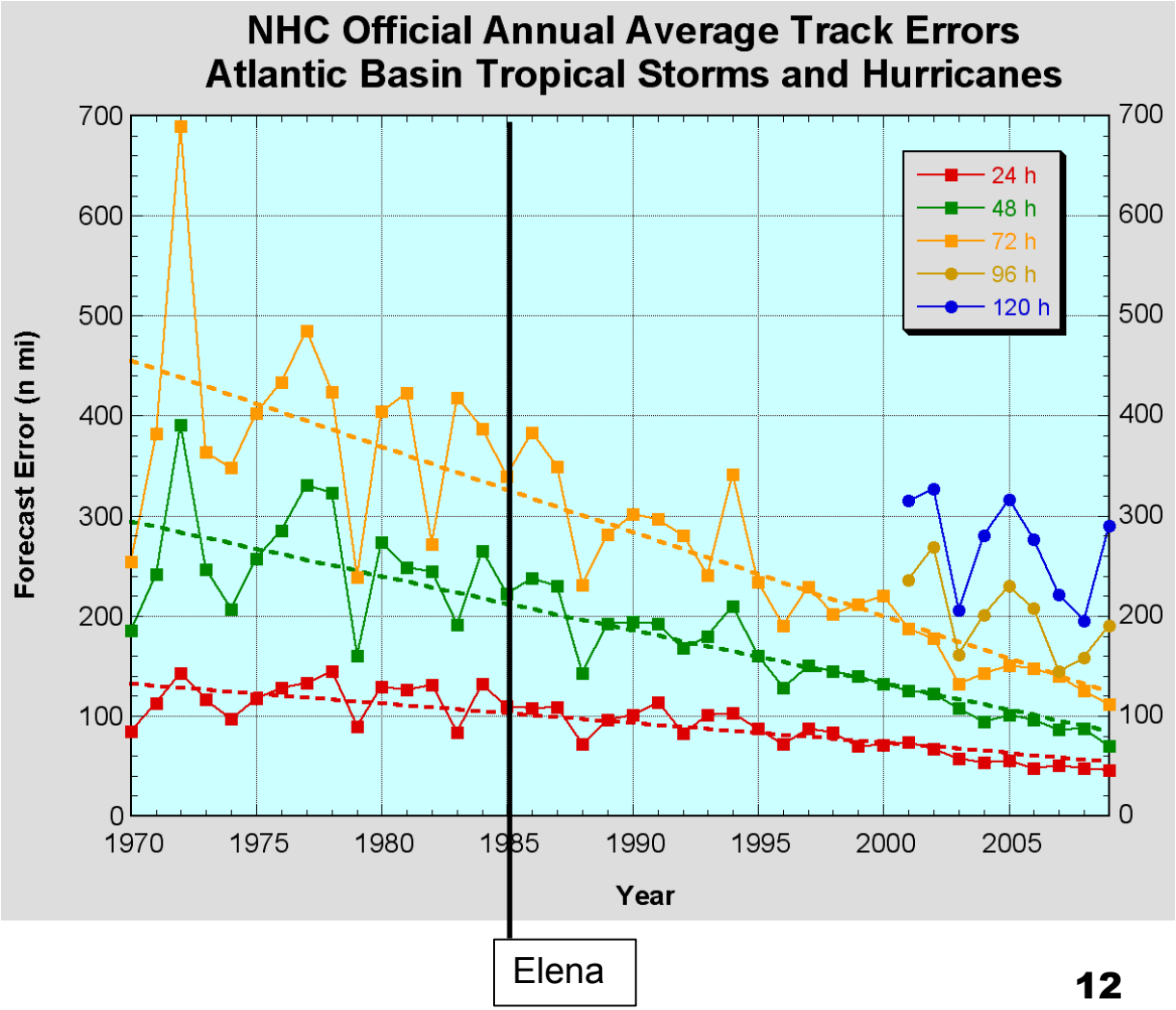
# Why ensembles of model runs?

## Wind input is the Largest Storm Surge Error

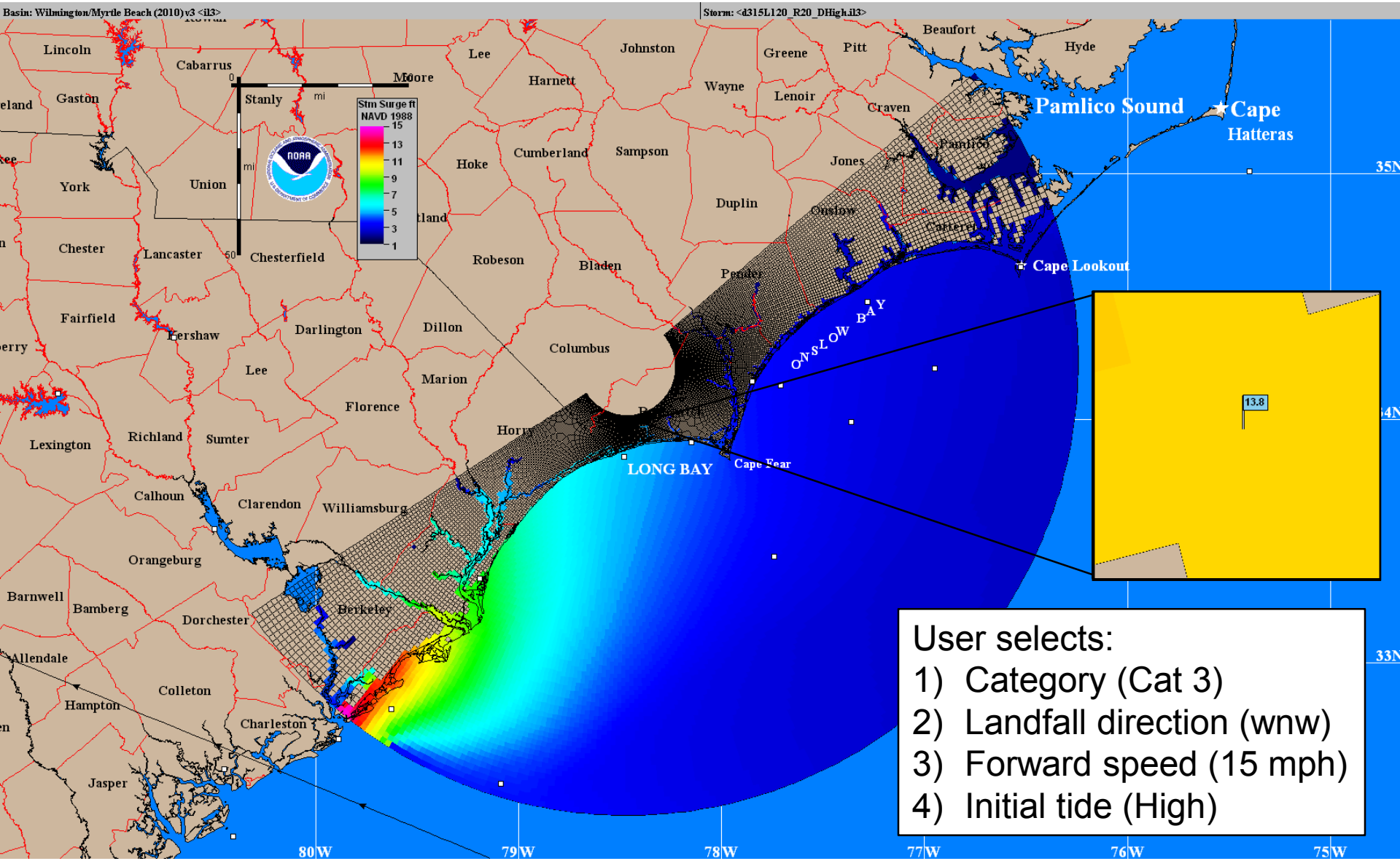
In 1986, due to the uncertainty in the forecast of 1985-Elena

- 100 n mi at 24-h
- 220 n mi at 48-h
- 340 n mi at 72-h

MEOW and MOM products created to represent “potential” Storm Surge risk



# Maximum Envelope Of Water (MEOW)




User selects:

1) Category (Cat 3)
2) Landfall direction (wnw)
3) Forward speed (15 mph)
4) Initial tide (High)

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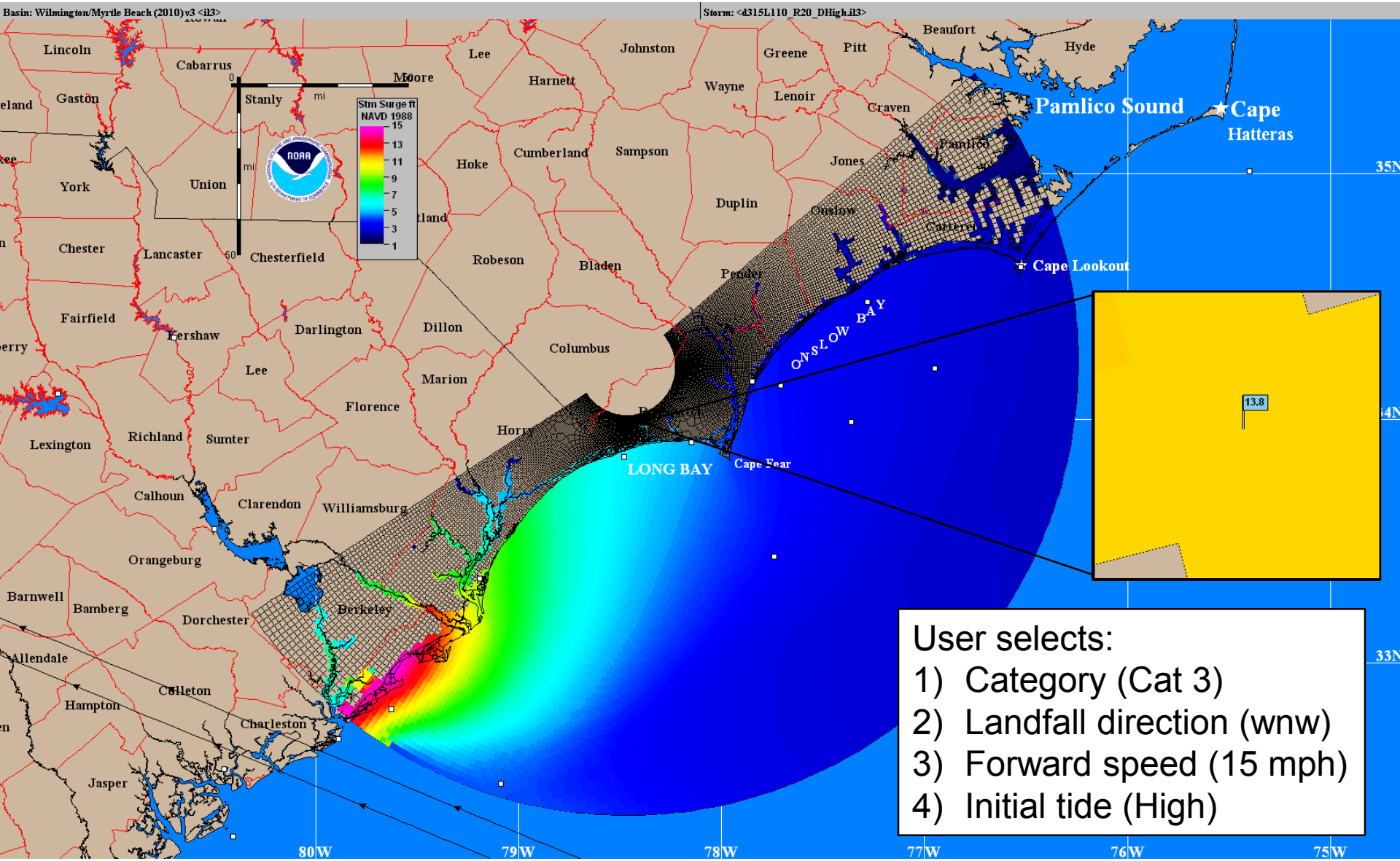


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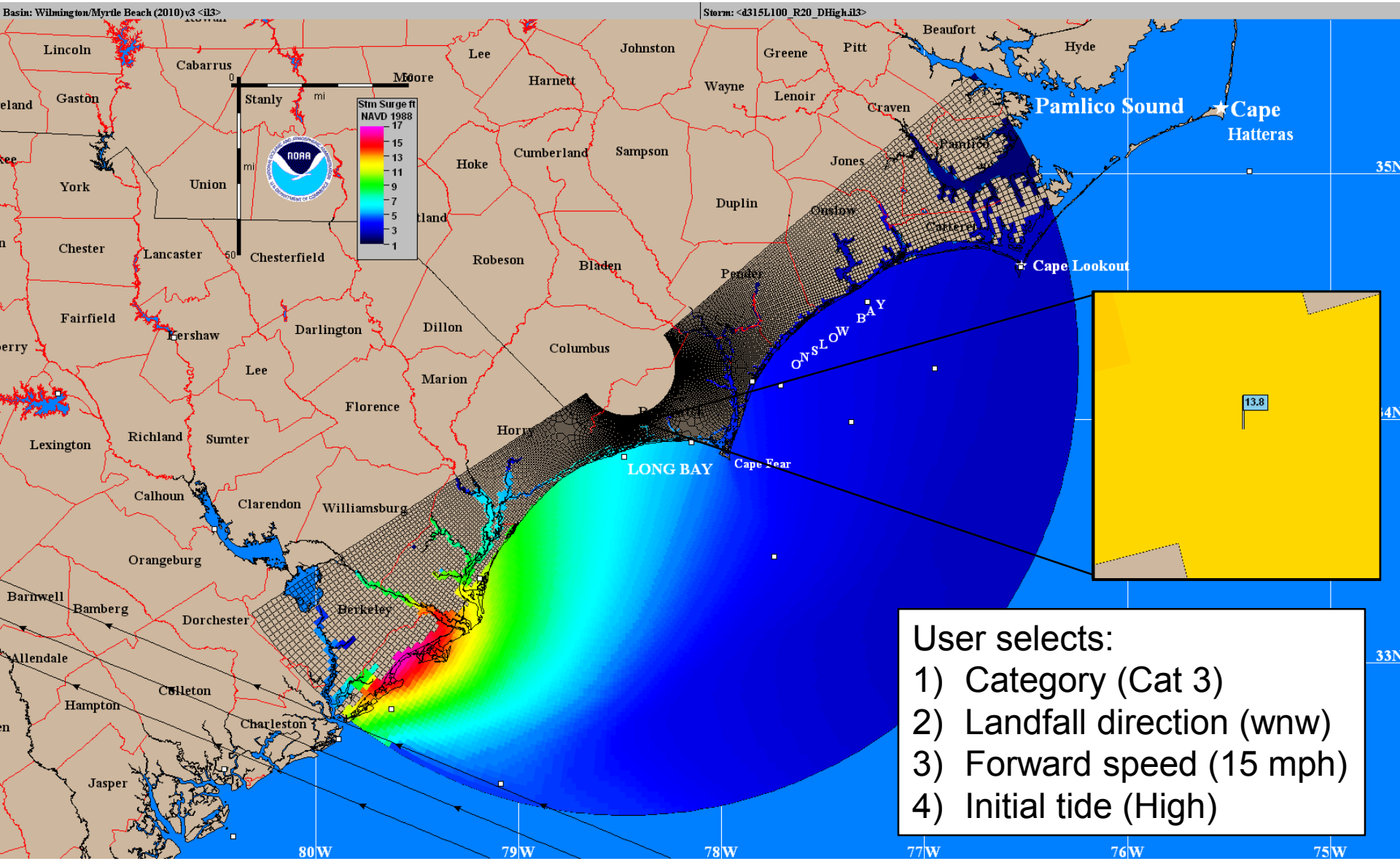


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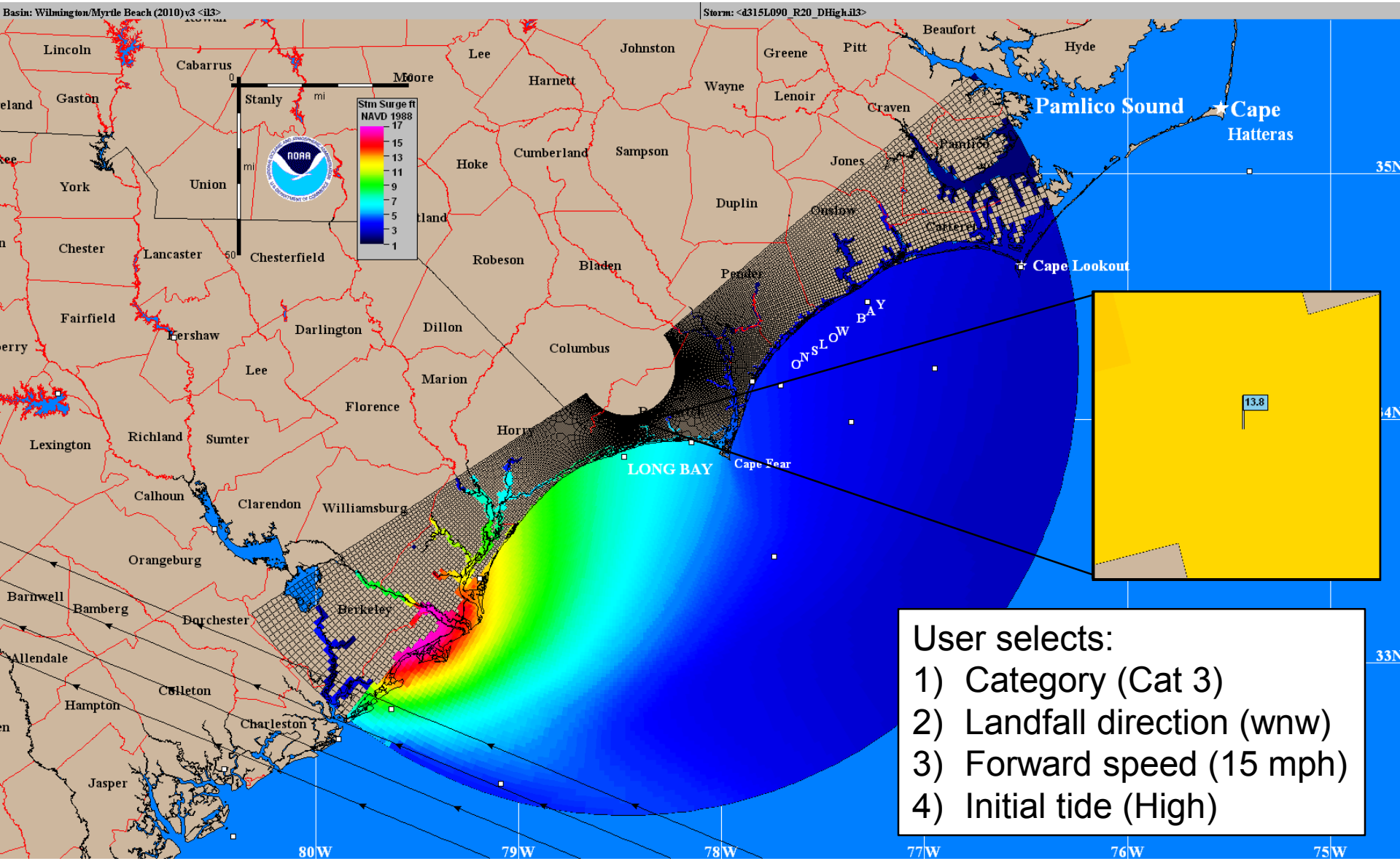


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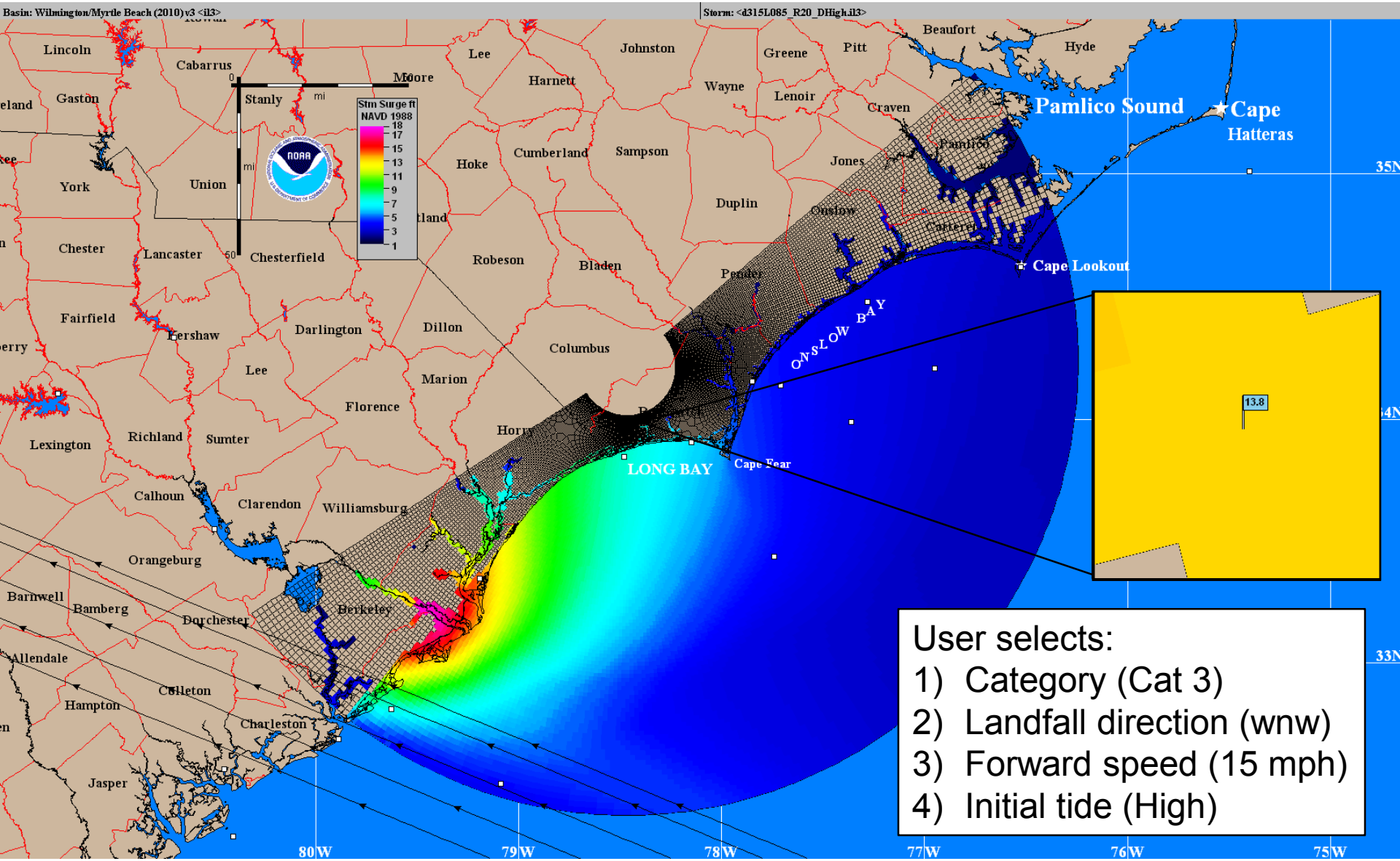


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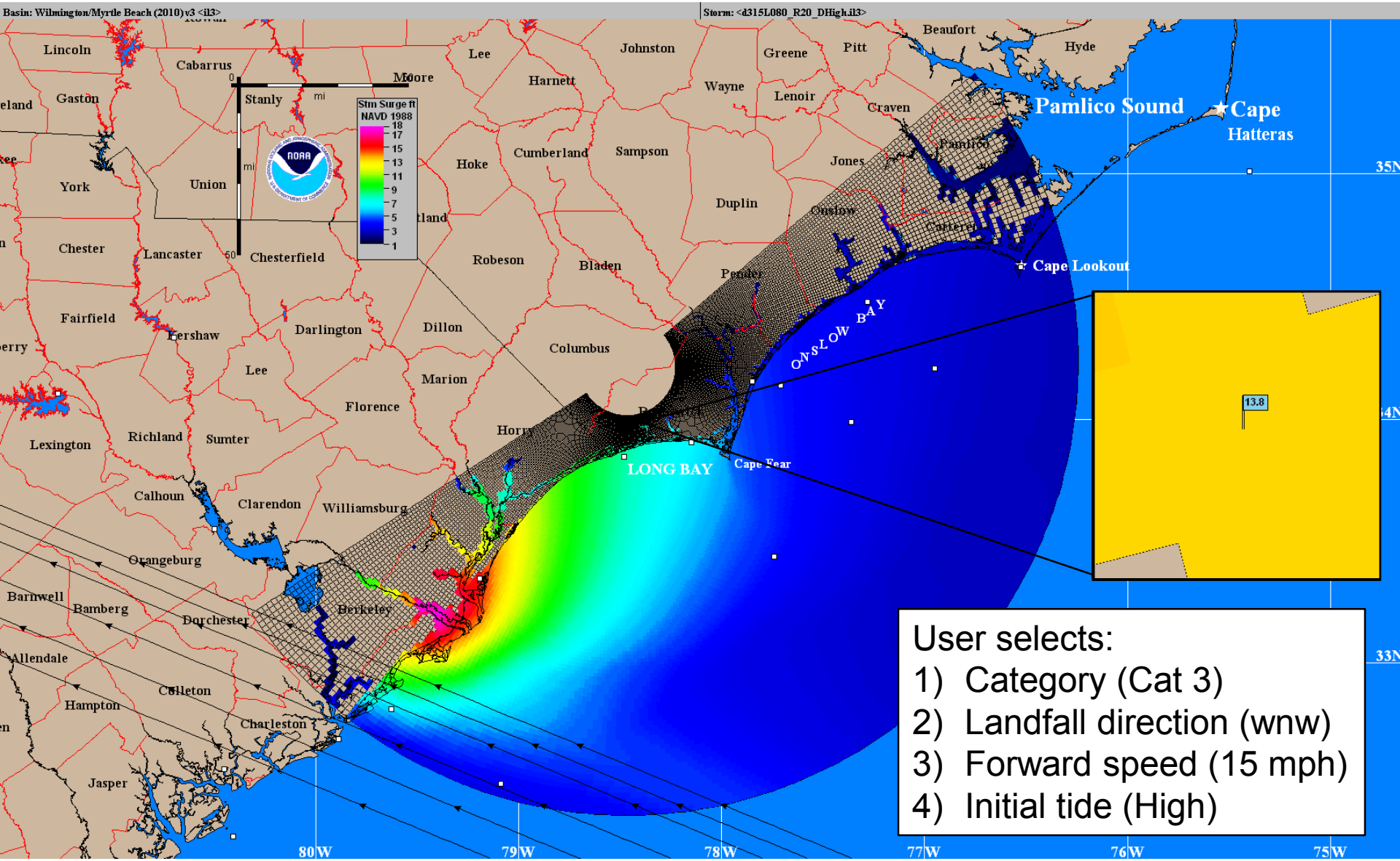


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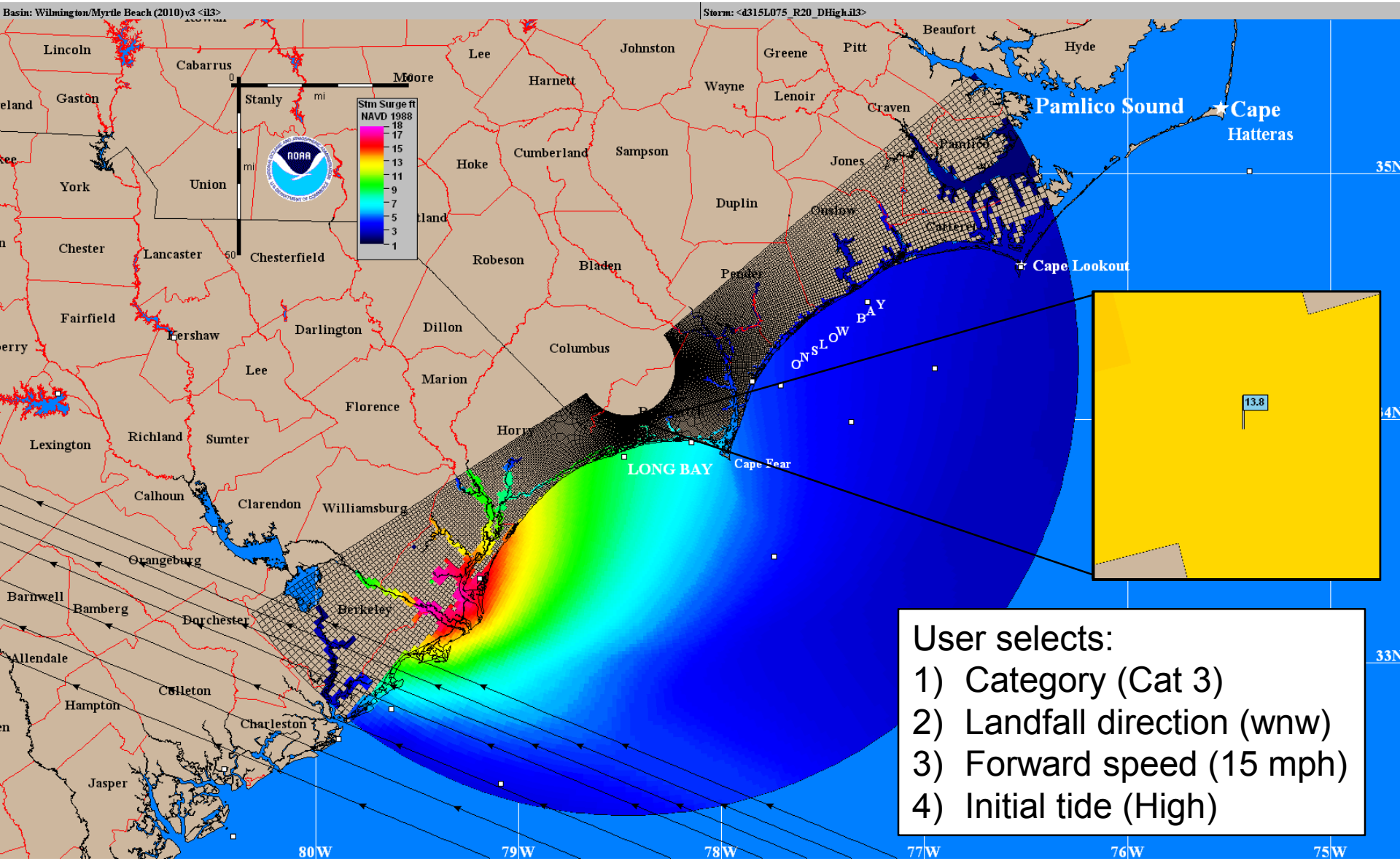


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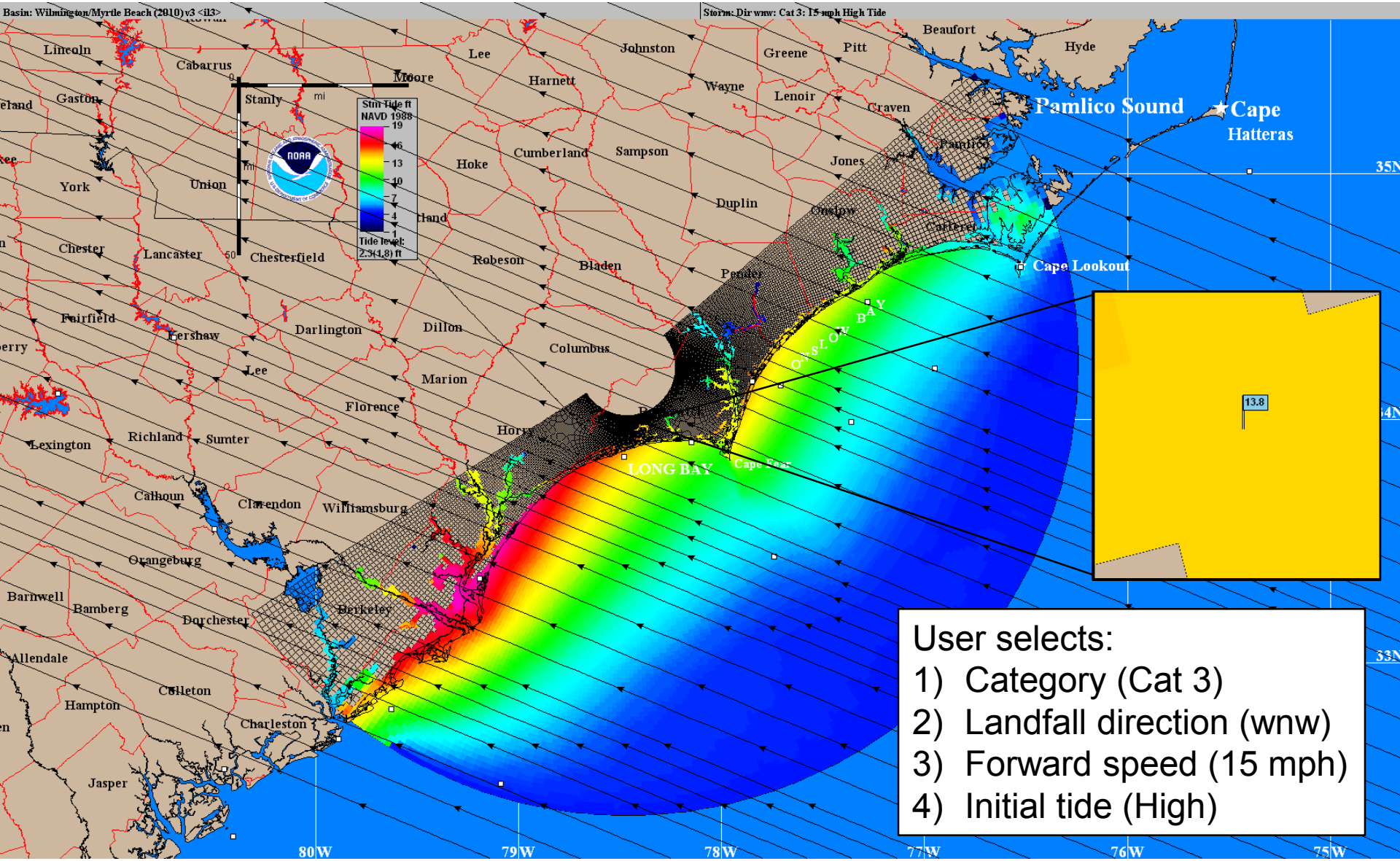


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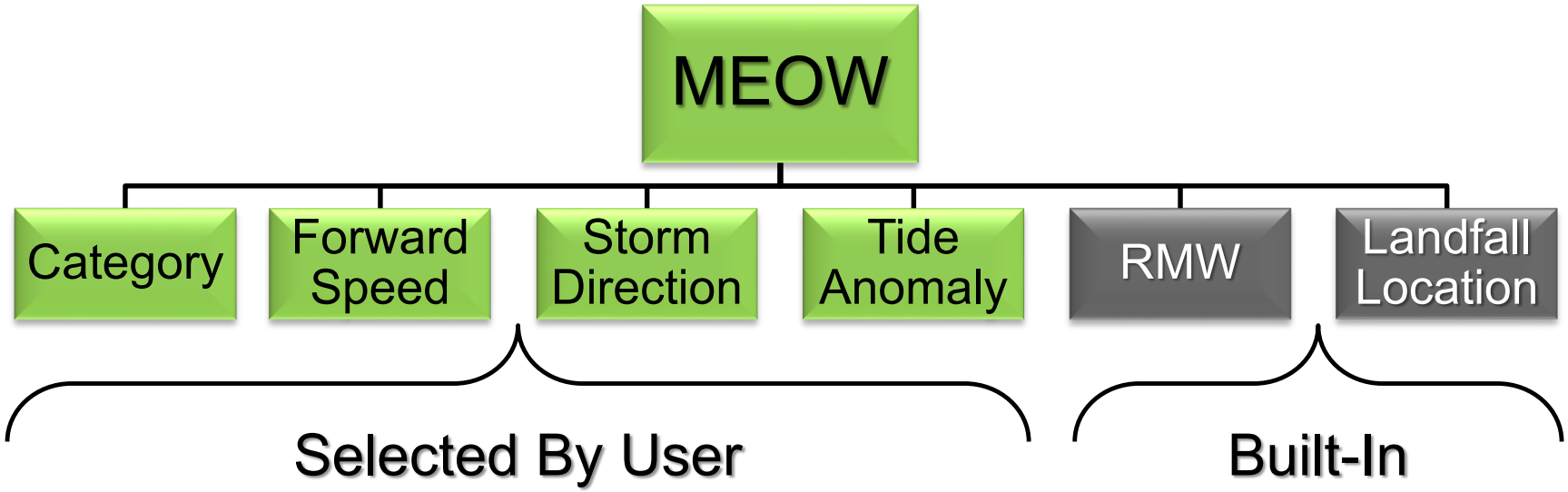
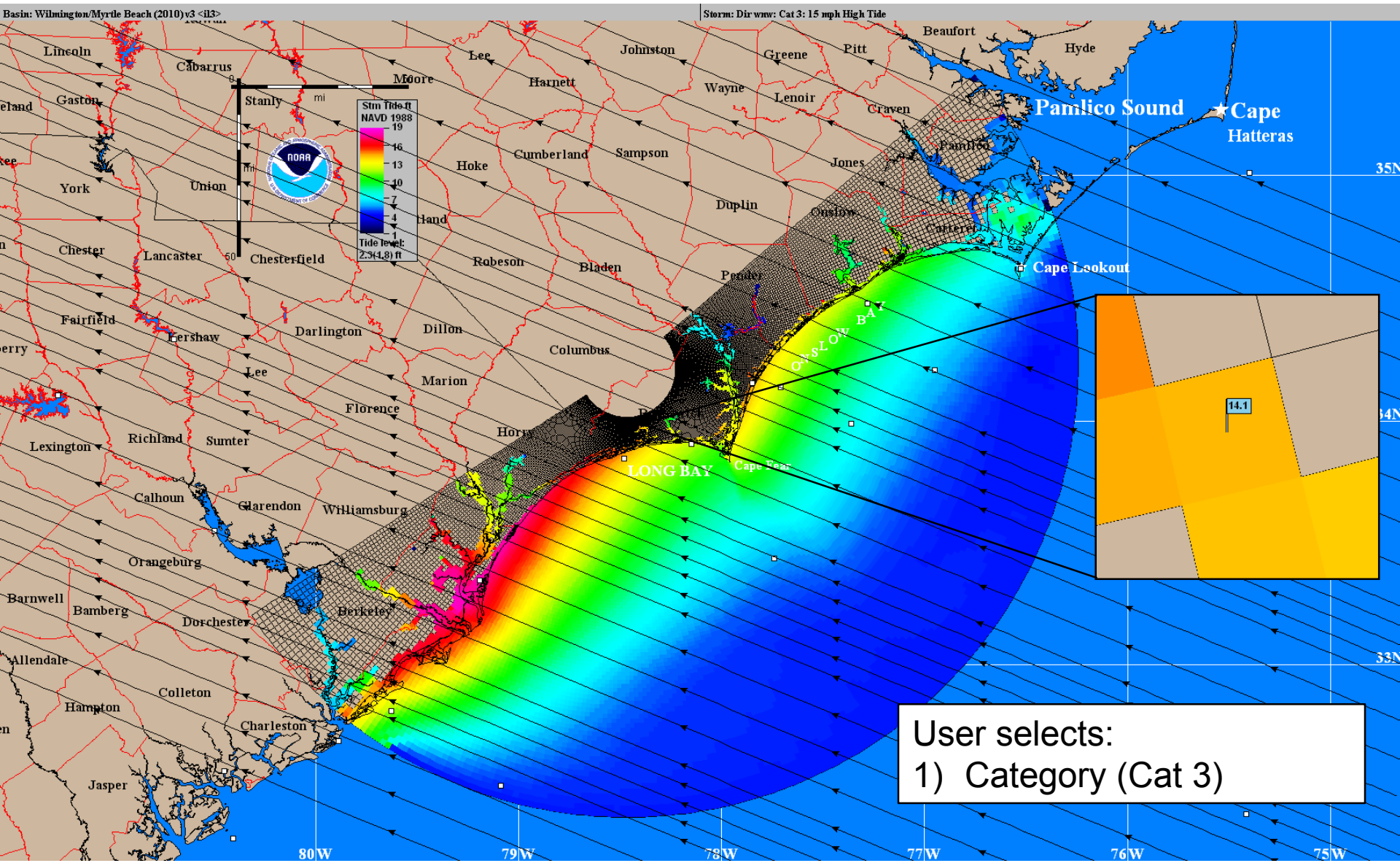
# **M**aximum **E**nvelope **O**f **W**ater (**MEOW**)

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 Of MEOWs (MOM)

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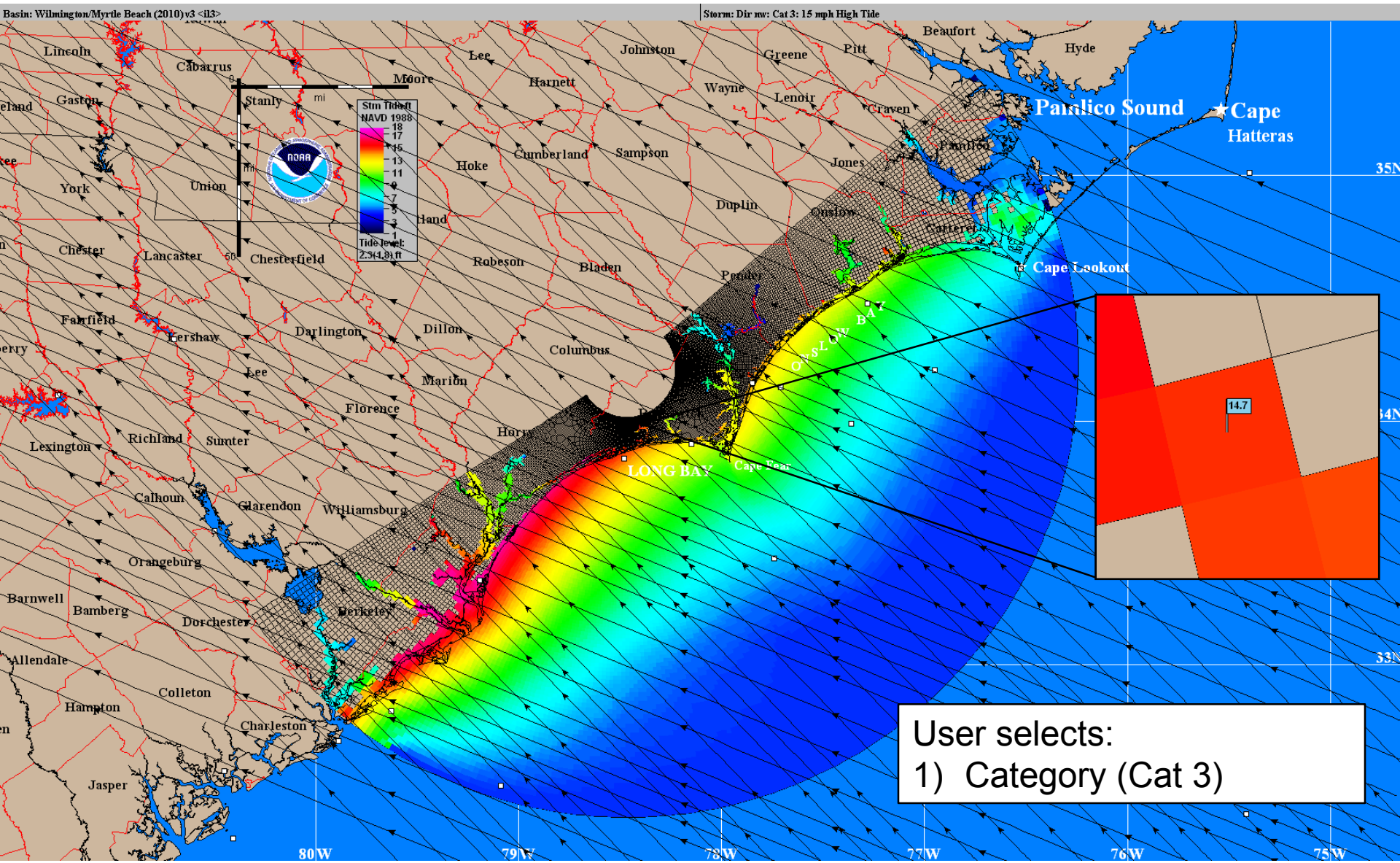


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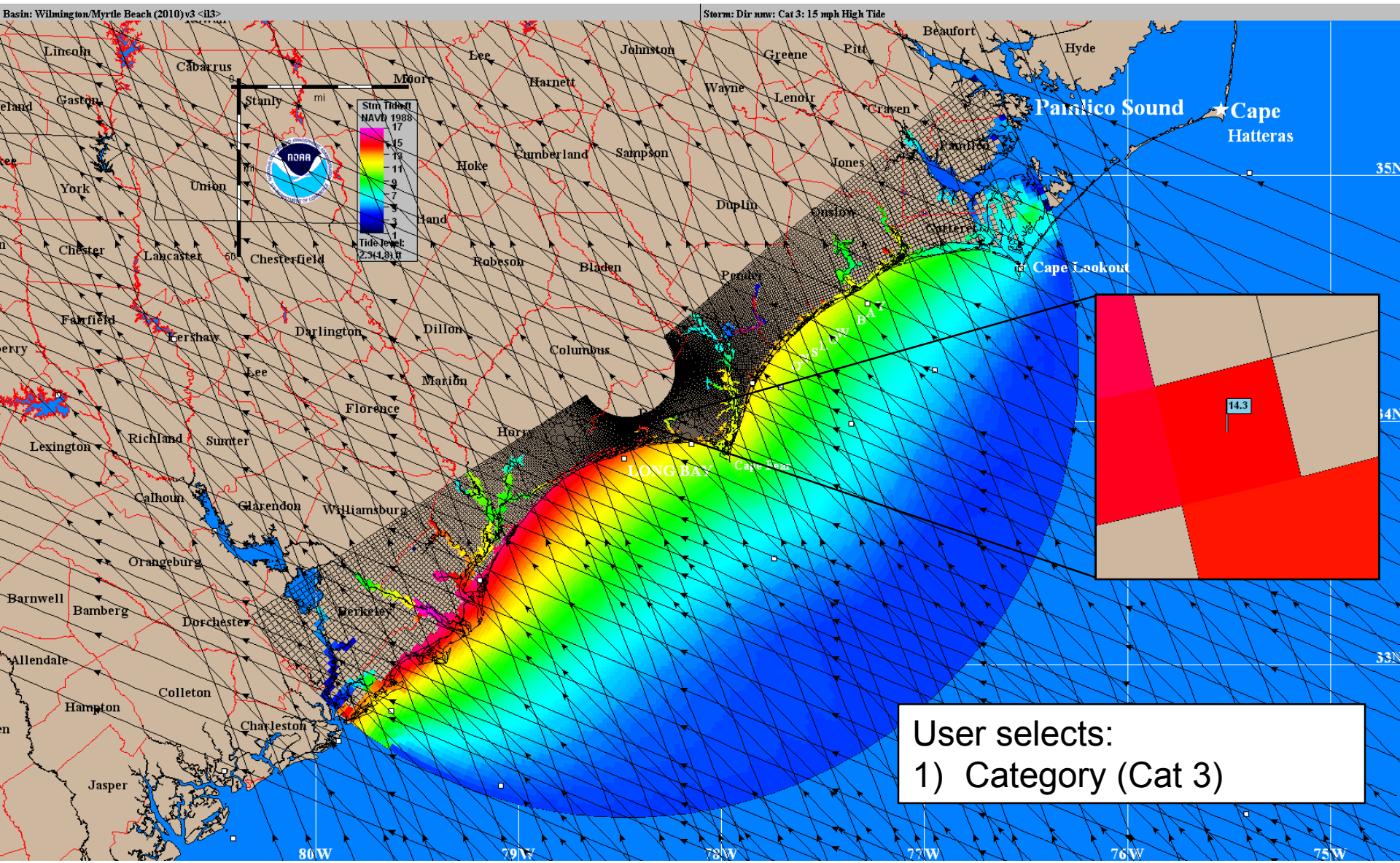


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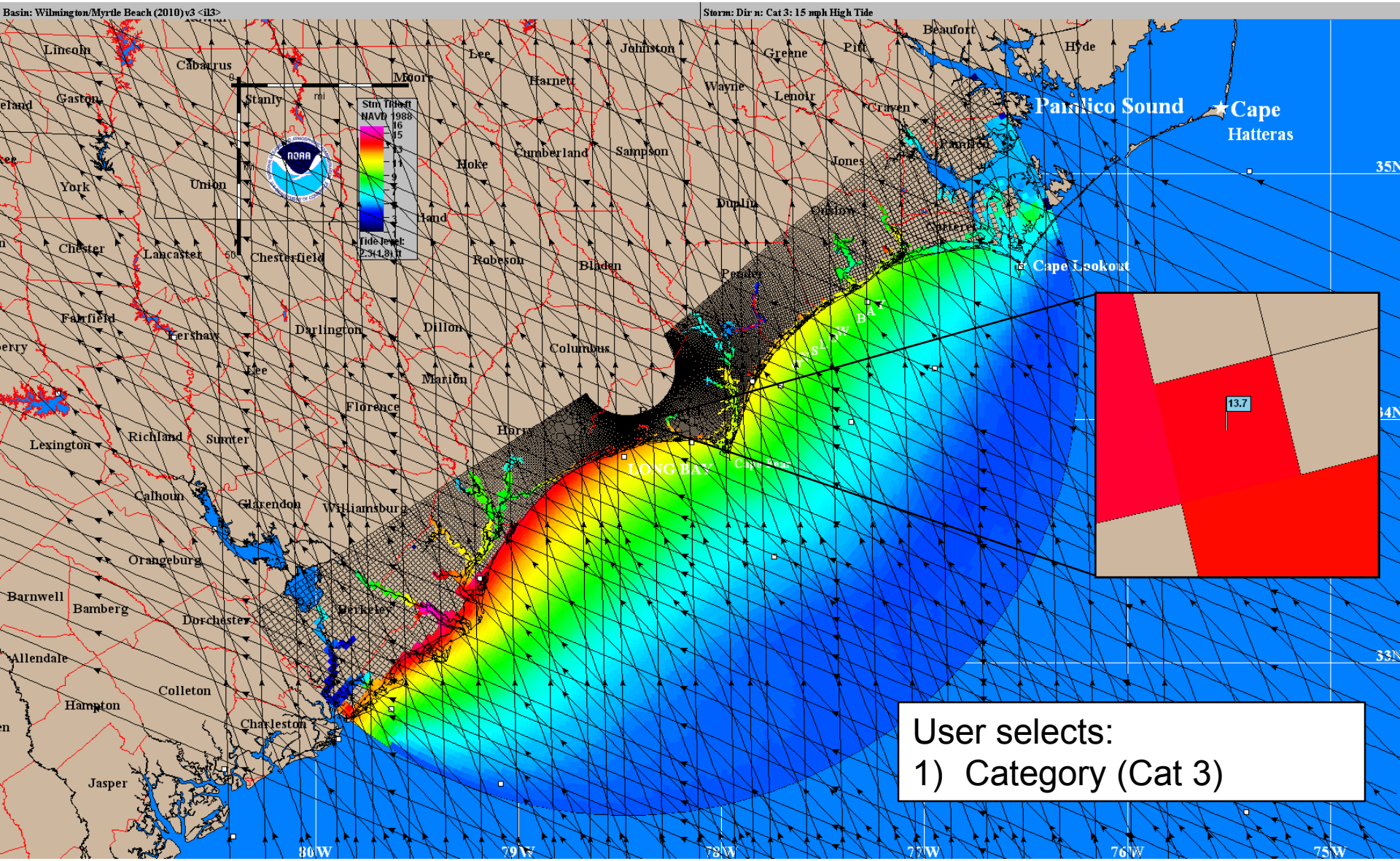


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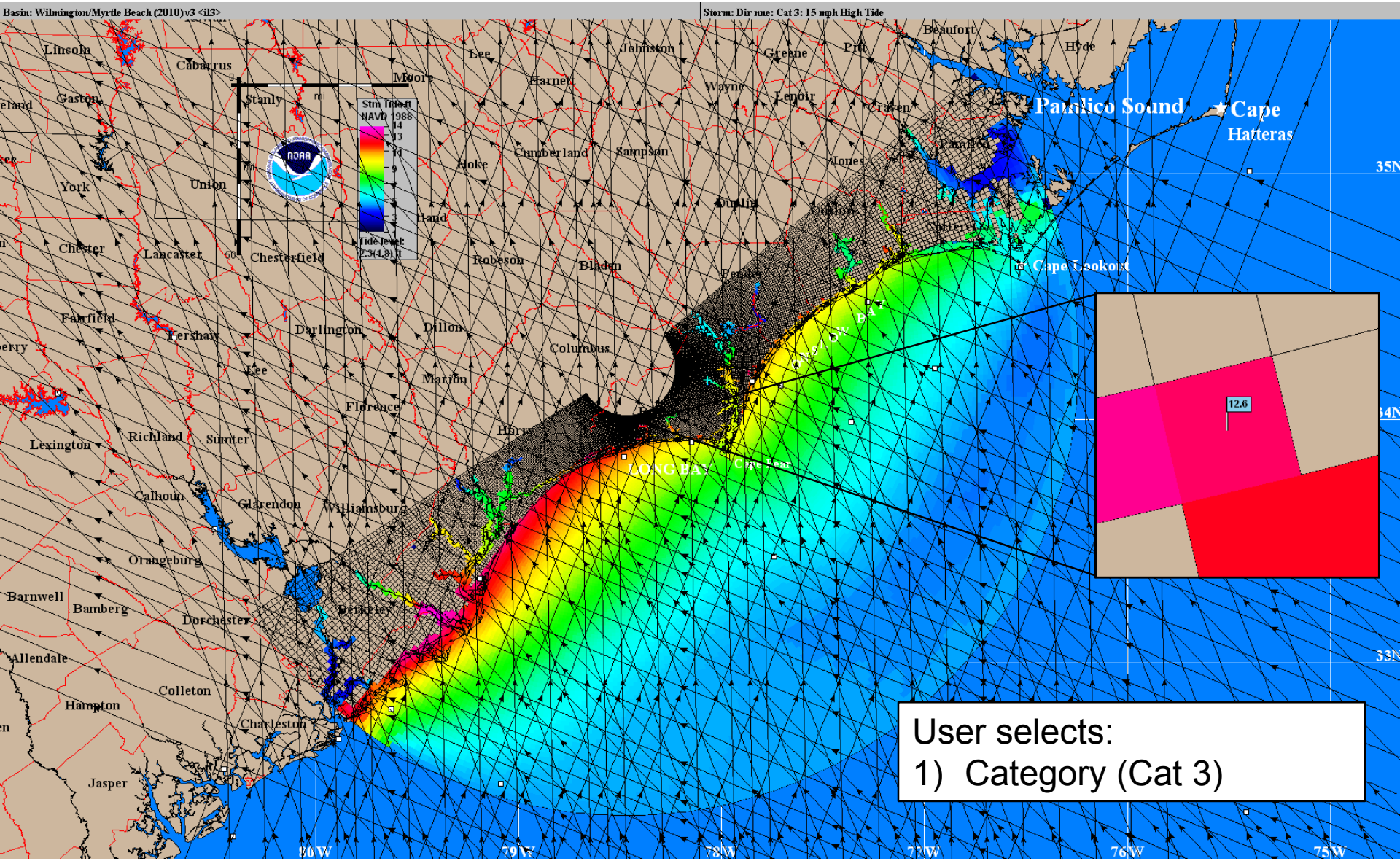


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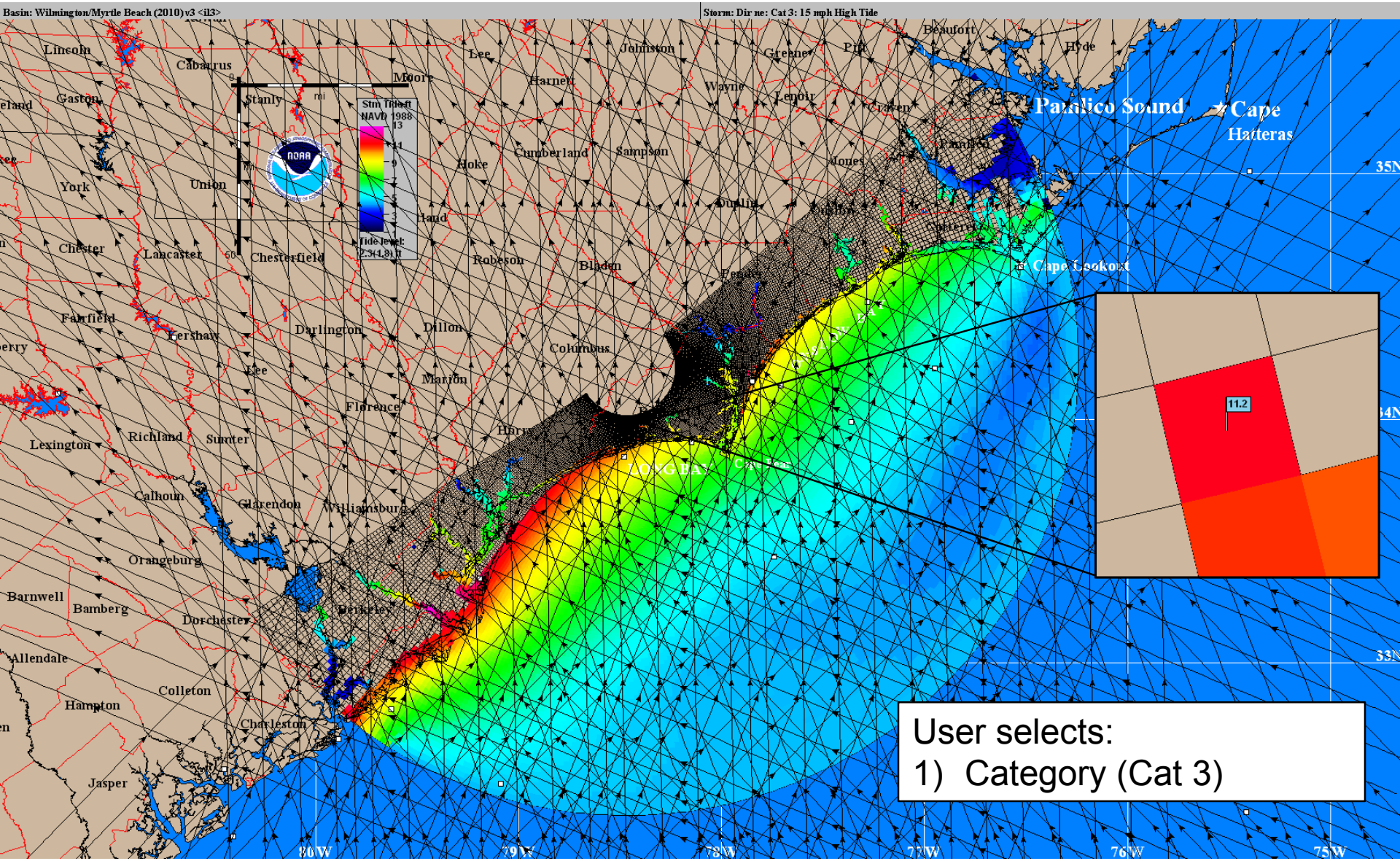


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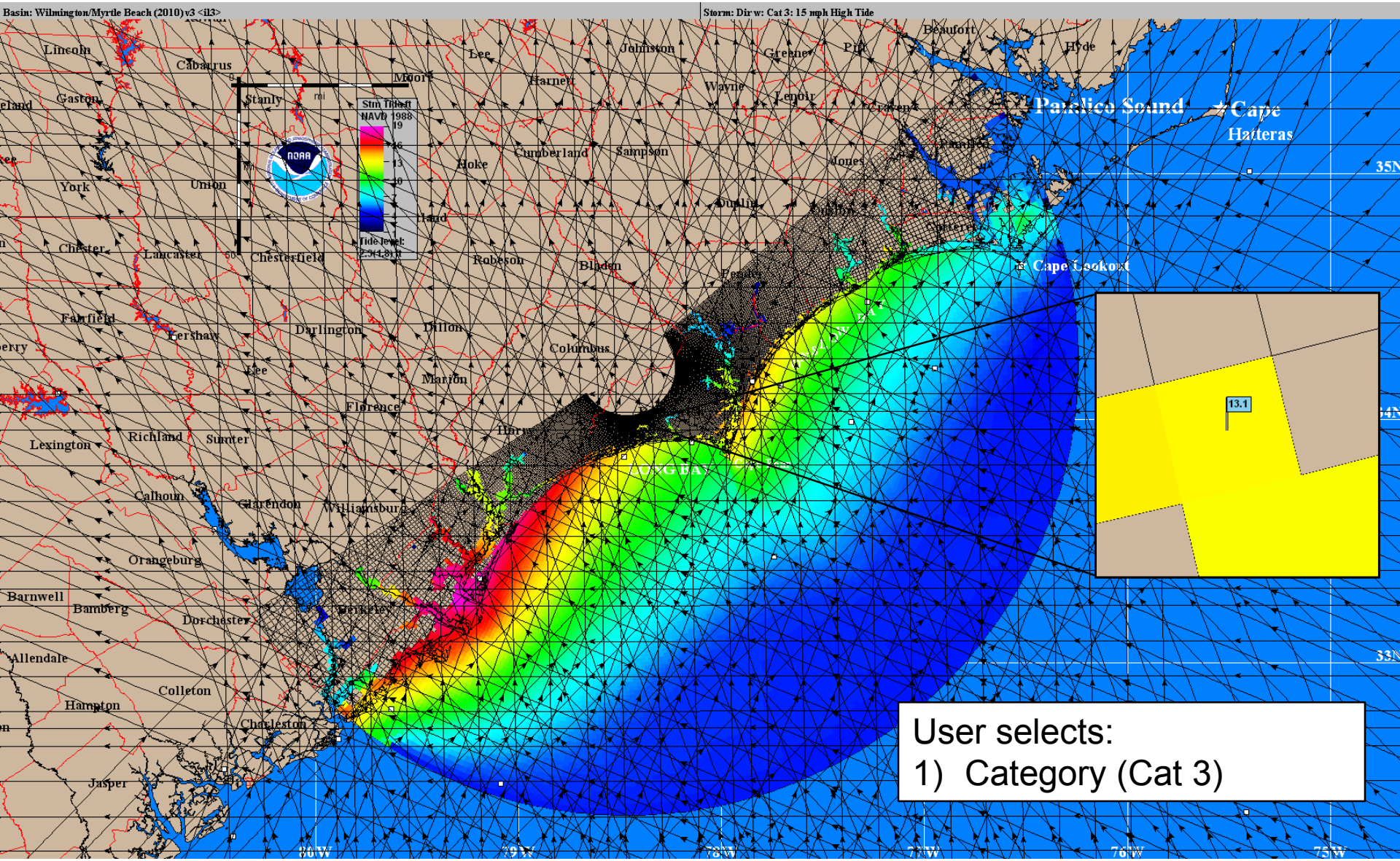


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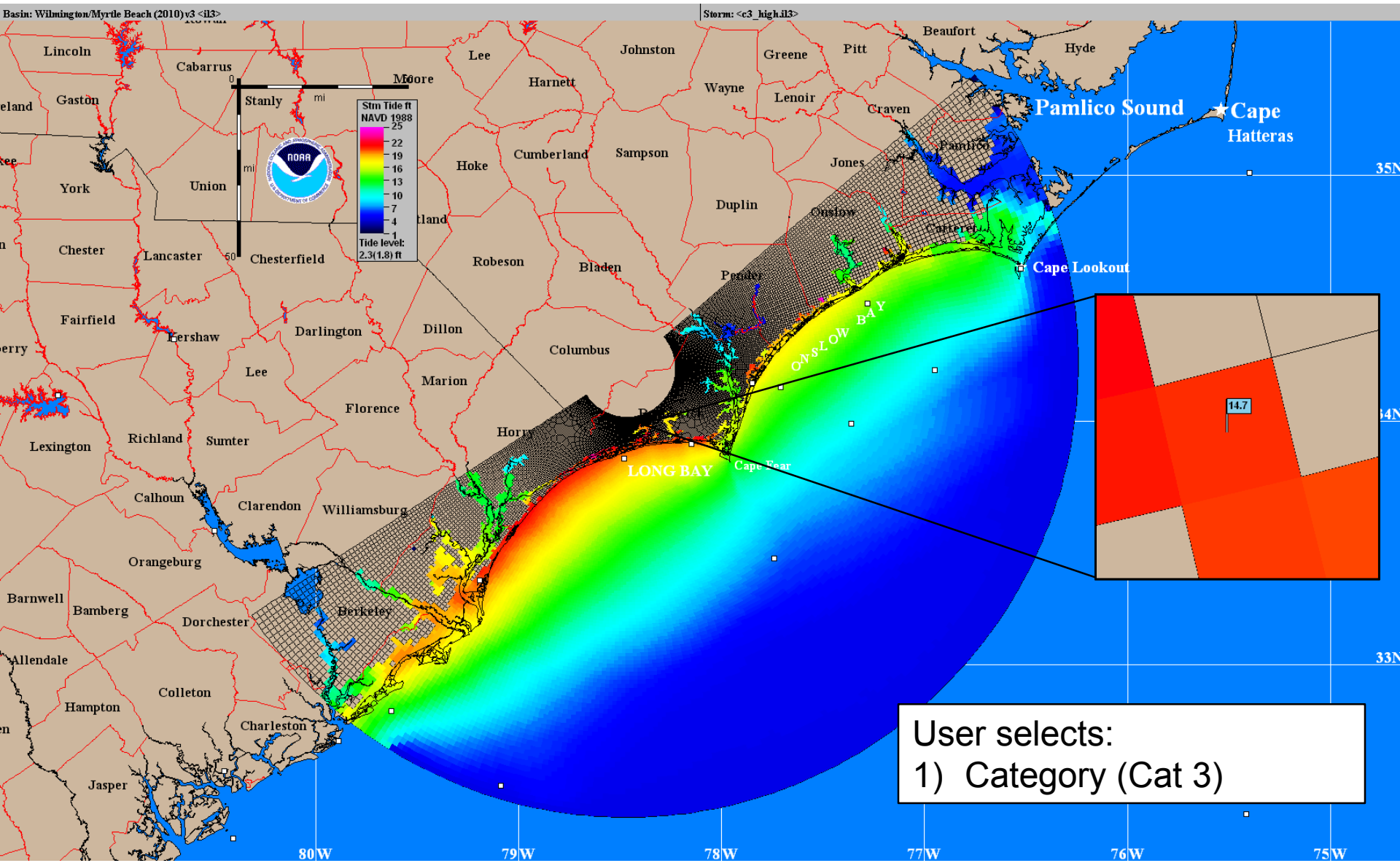


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# U.S. National Hurricane Program

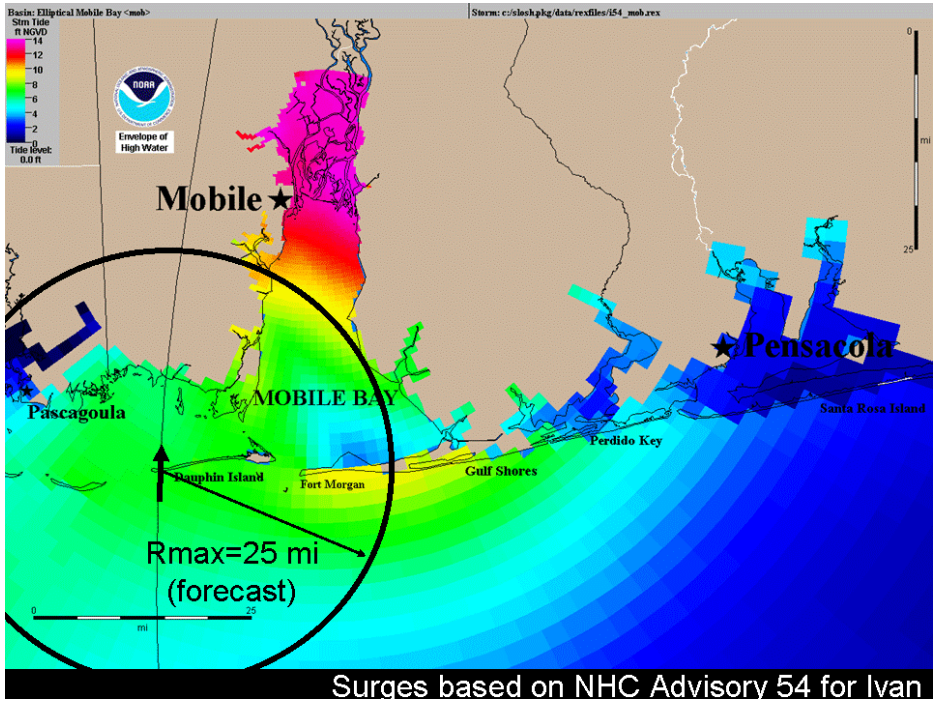
| Step 1 | Step 2 | Step 3 | Step 4 | Step 5 |
|---|---|---|---|---|
| **Basin Build:** Basin grid and data are modified to reflect recent changes NWS (MDL/NHC) | **Stability Test:** Basin undergoes extensive QA/QC process NWS (NHC) | **Simulation Runs:** MEOWs and MOMs are created NWS (NHC) | **Evacuation Plans:** MEOWs and MOMs are combined with infrastructure US Army Corp of Engineers | **Evacuation Decisions:** Plans are triggered based on real-time information Emergency Management |

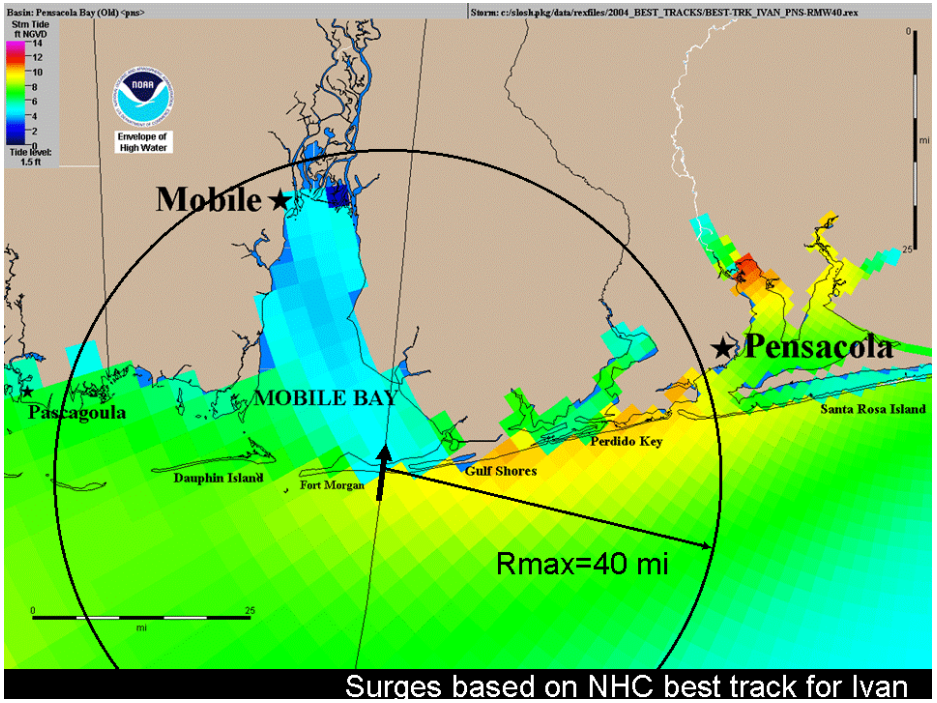
Run from the water, Hide from the wind

SLOSH MOMs and MEOW's form the basis of the water hazard within U.S. evacuation plans

# Why Real-Time Ensembles?

- Short term forecast has considerable uncertainty to it
- Climatological ensemble isn't tailored to the active storm and conditions (tide, initial water anomalies, etc.)

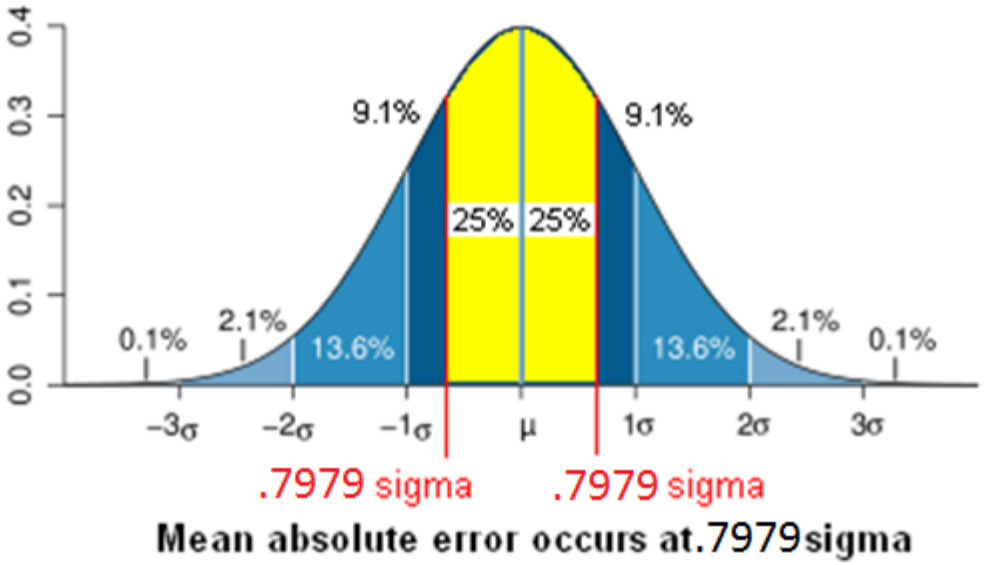


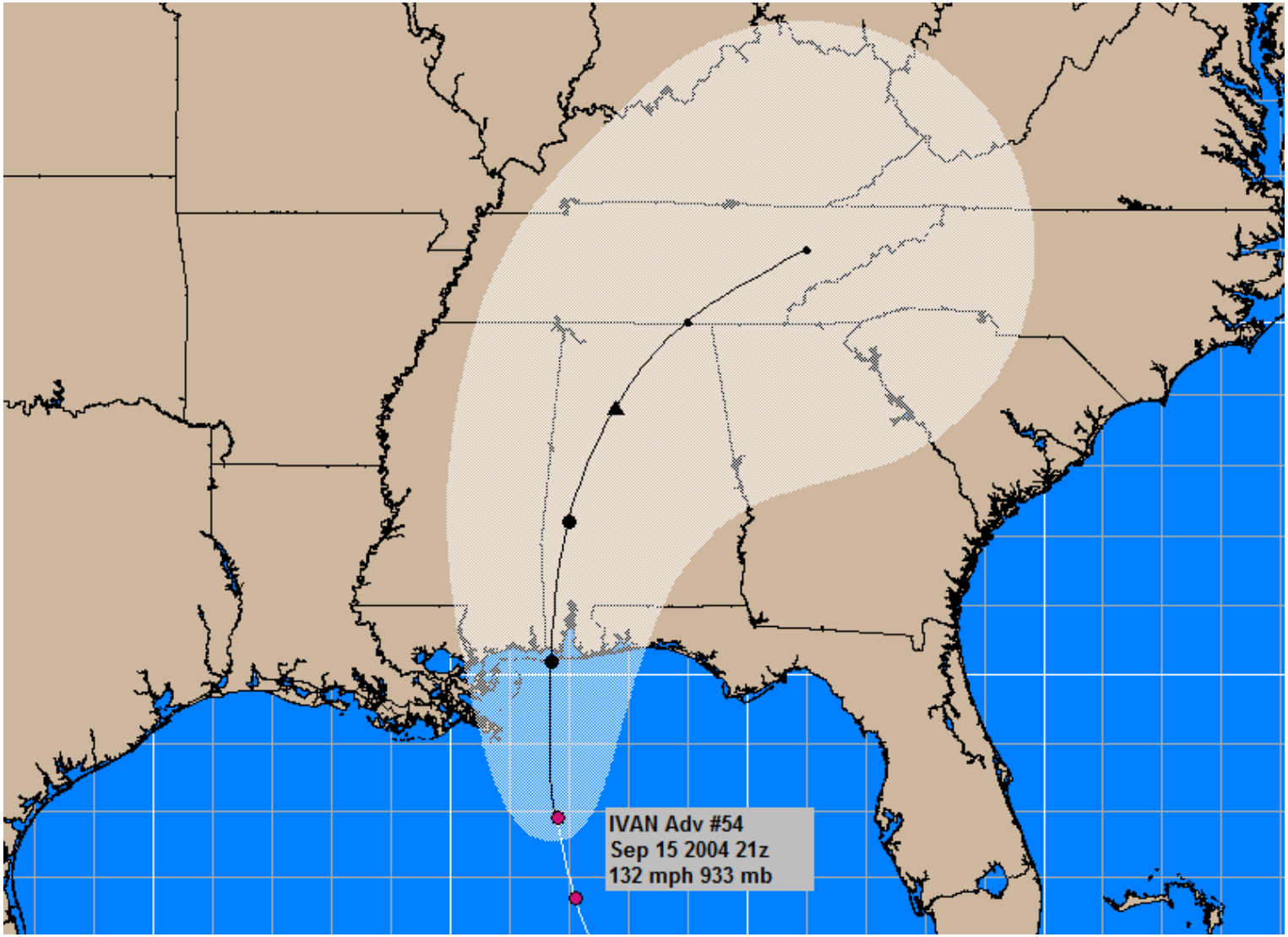

Example: Ivan 2004 – Advisory 54
12-hr before landfall.

# Probabilistic Tropical Storm Surge (P-Surge) Error Distributions

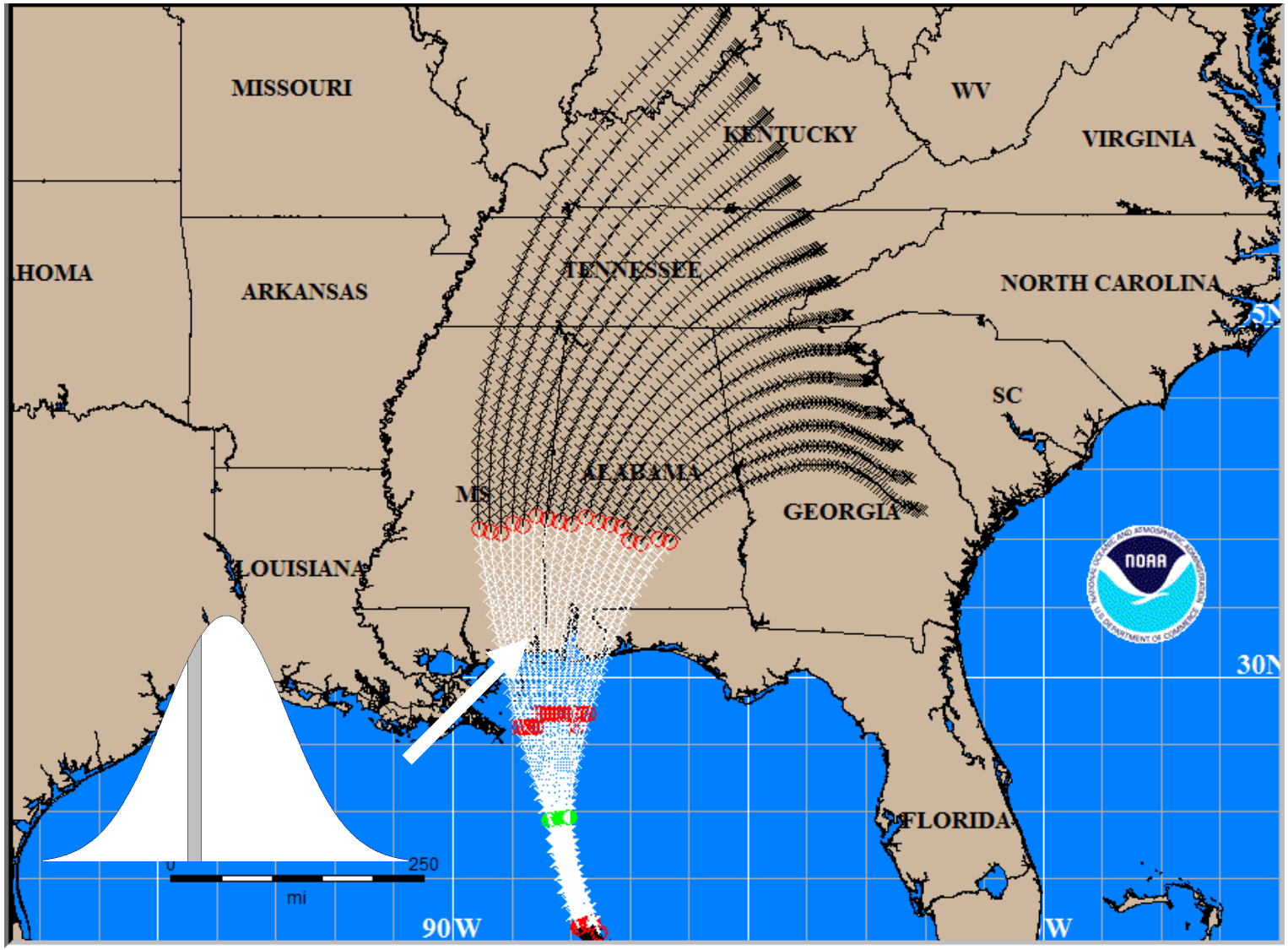
- Error distributions are computed for cross track, along track and intensity by:
  - Assuming a normal distribution
  - Using a 5-year “mean absolute error” and getting the standard deviation (sigma) from:



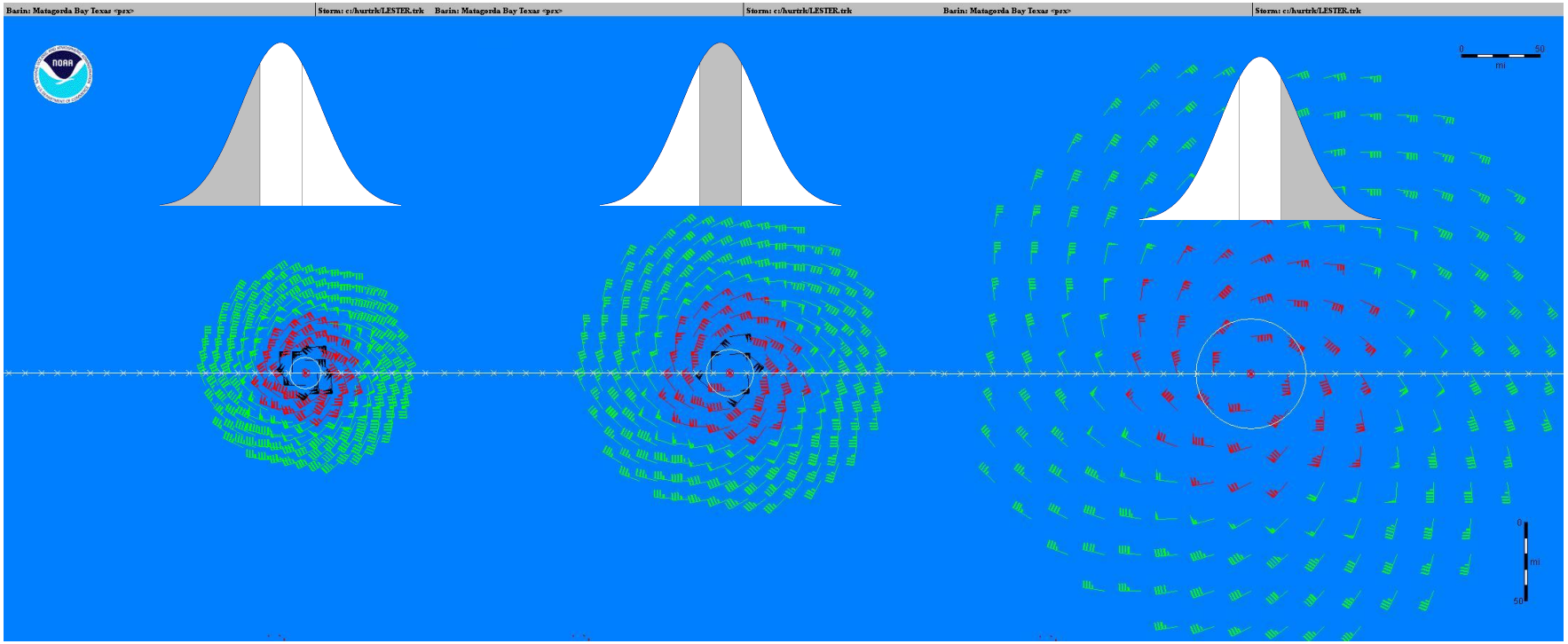
# 2004-Ivan - Advisory 54



# P-Surge - Vary Cross Track



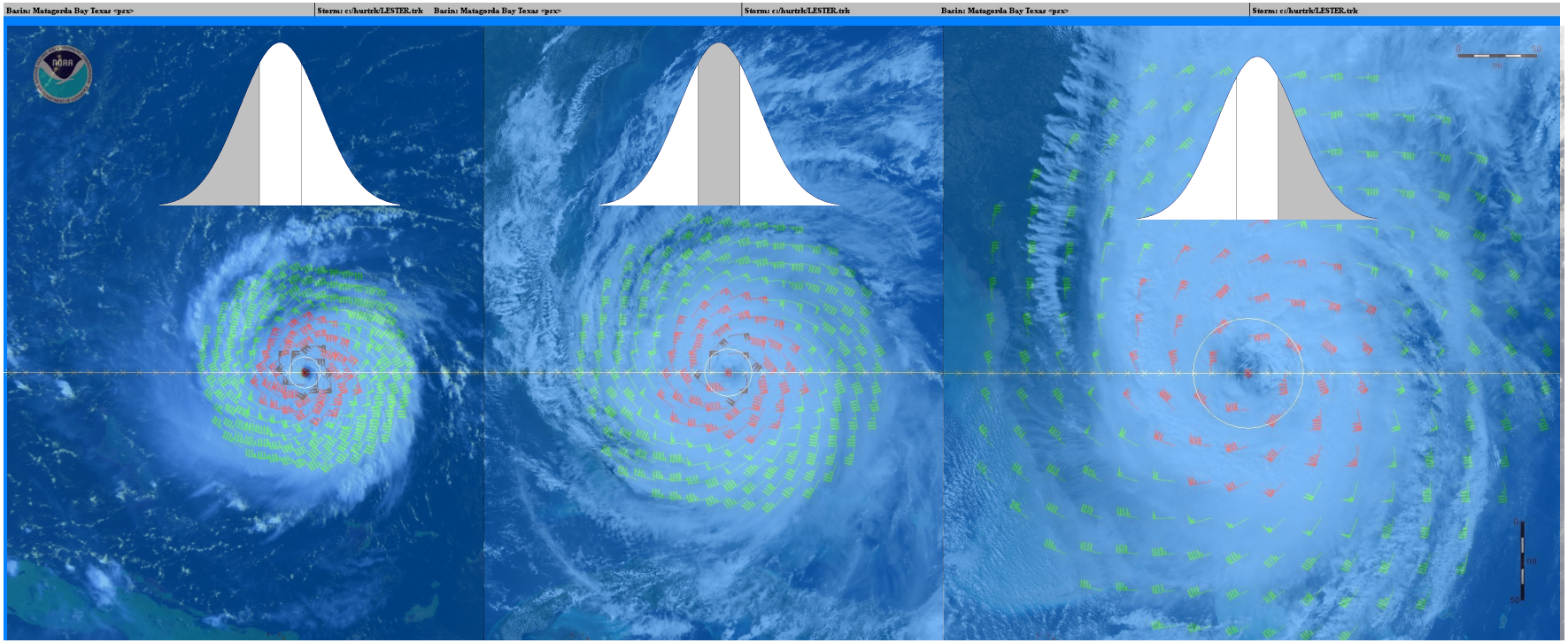
# P-Surge – Vary Other Variables




- Size: Small (30%), Medium (40%), Large (30%)
- Forward Speed (*): Fast (30%), Medium (40%), Slow (30%)
- Intensity: Strong (30%), Medium (40%), Weak (30%)

(*) Changed in 2014 to 7 forward speed samples (14% each)

# P-Surge – Vary Other Variables

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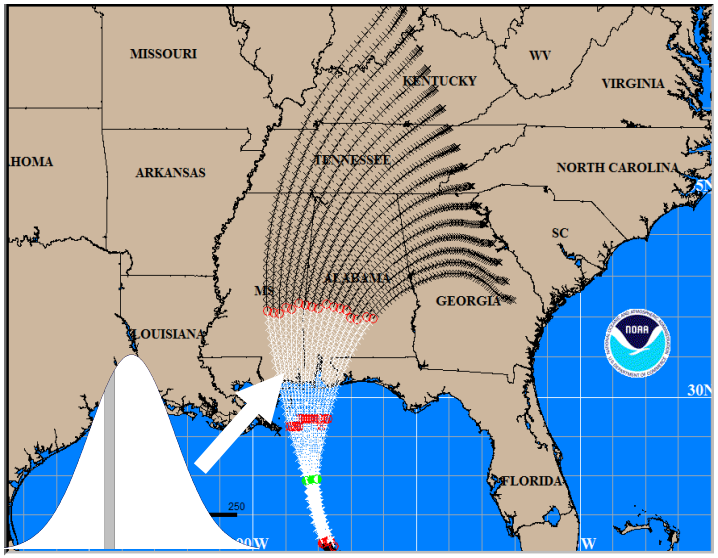
# Probabilistic Tropical Cyclone Storm Surge (P-Surge) - Summary

**Requirements**

- Consistent: Based on the official advisory
- Parametric Wind: Needed for permutations
- Fast: Results 1-hour after forecast release
- 4-day Forecast: Required evacuation time
- Overland: Inundation to 50-foot contour
- Total Water: (surge + tide + wave + river)
- Efficient: Limited resources to run ~630 ensemble members in 5 to 10 basins

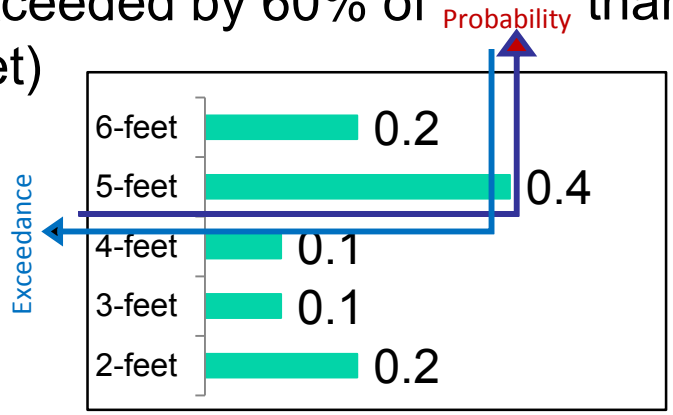



**Solution:** Suite of products derived from an ensemble of SLOSH runs

- Ensemble centered on NHC's official advisory
- Error spaces defined by a normal distribution with 5-yr MAE = 0.8 sigma
- Error spaces sampled via representative storms with dense cross-track sampling

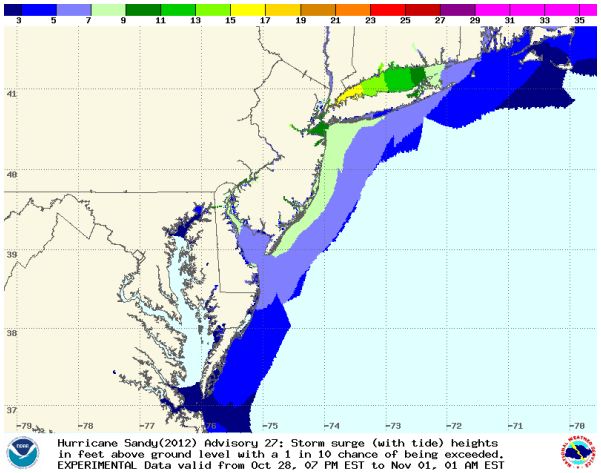
# P-Surge Product Creation

**Exceedance Height**: The surge value which is exceeded by Y% (e.g. height exceeded by 60% of storms is 4 feet)

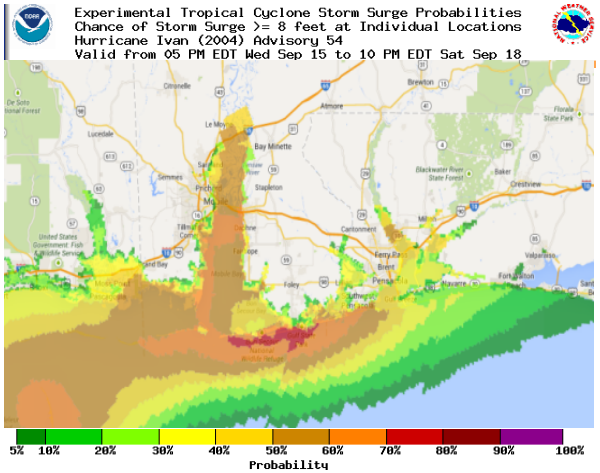



**Probability of Surge:** The probability of storm surge greater than X feet (e.g. probability of > 4 feet is 60%)

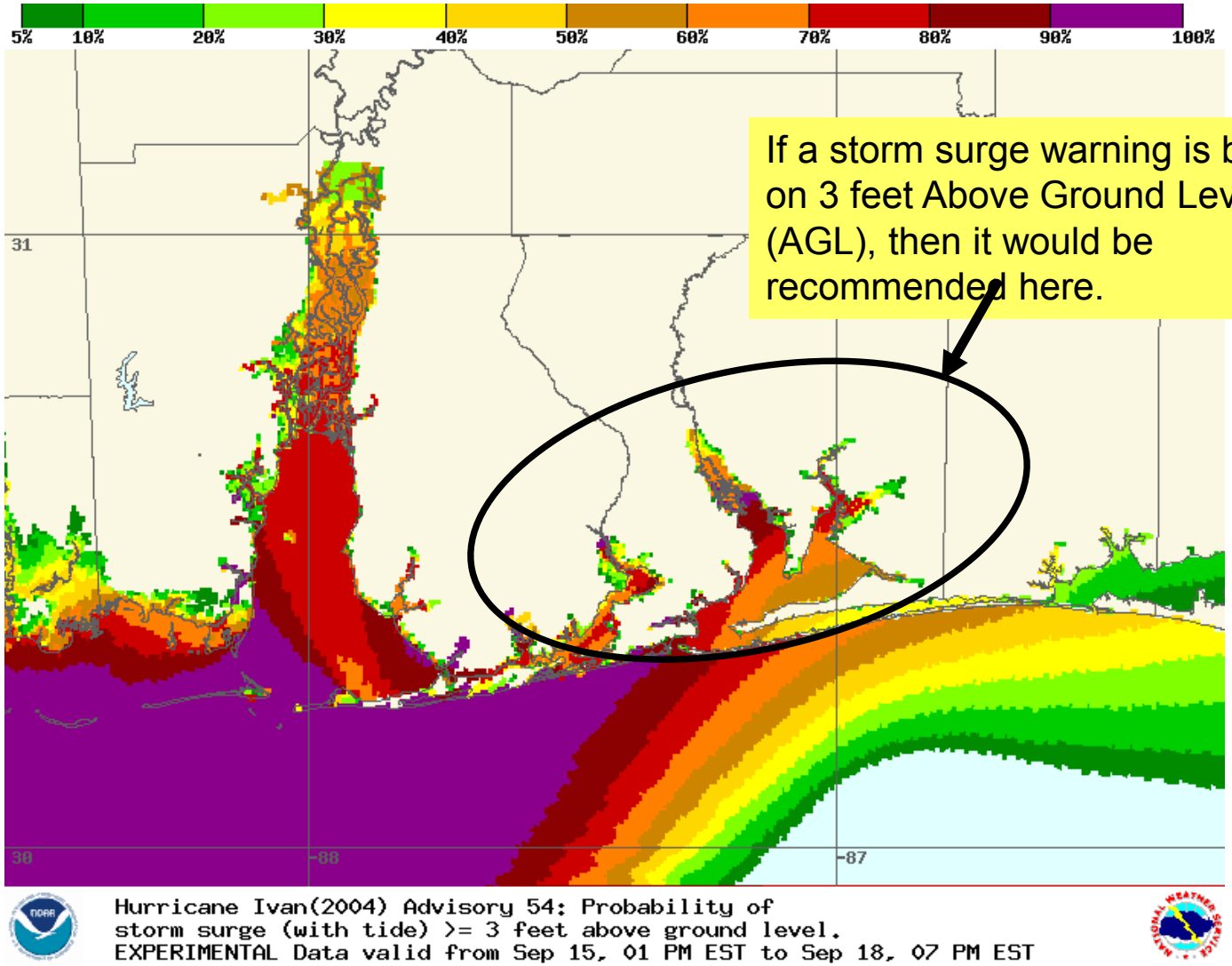
**Use:** Estimate water levels based on a specified risk tolerance



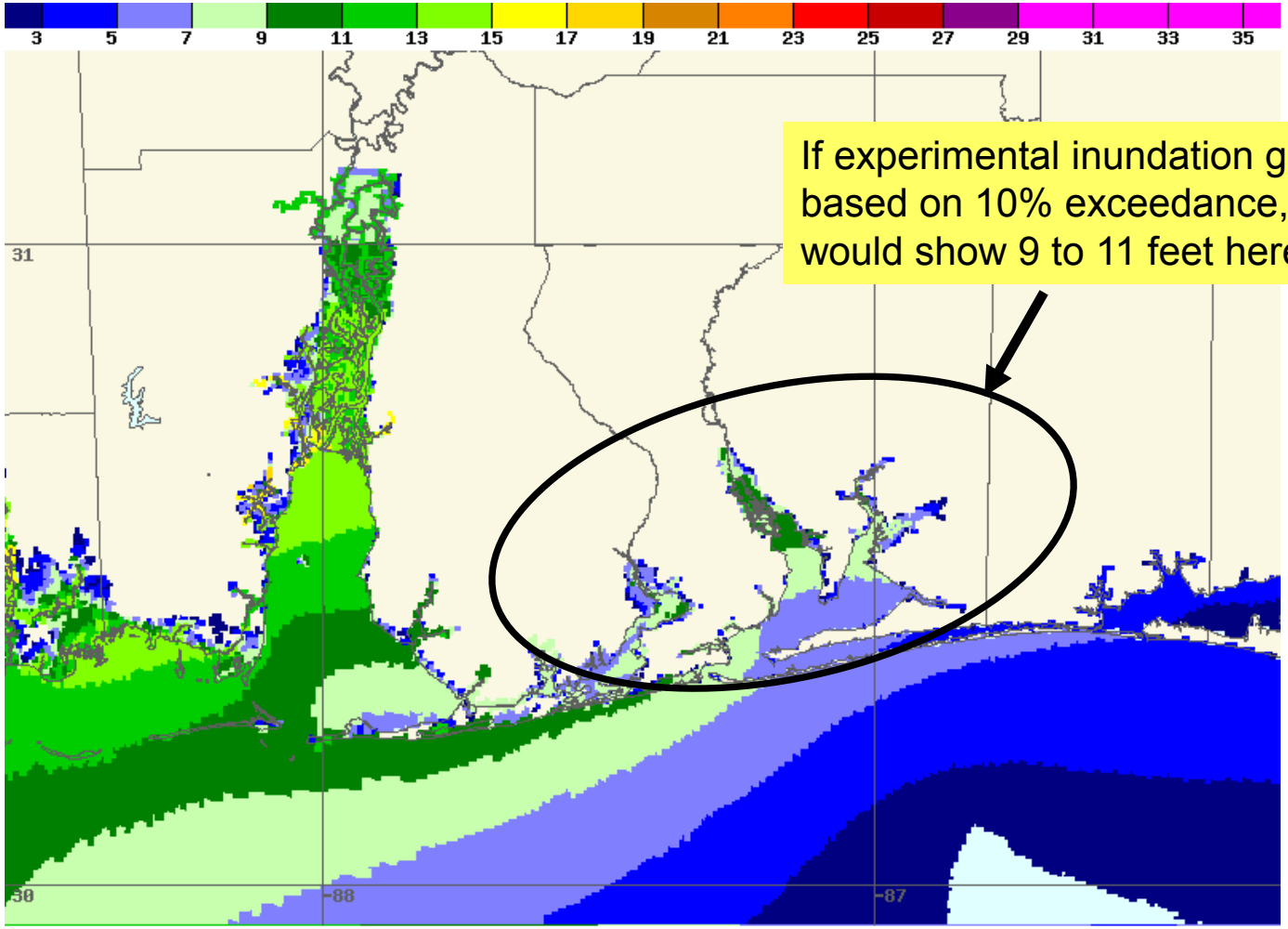

**Use:** Estimate risk at a specific site



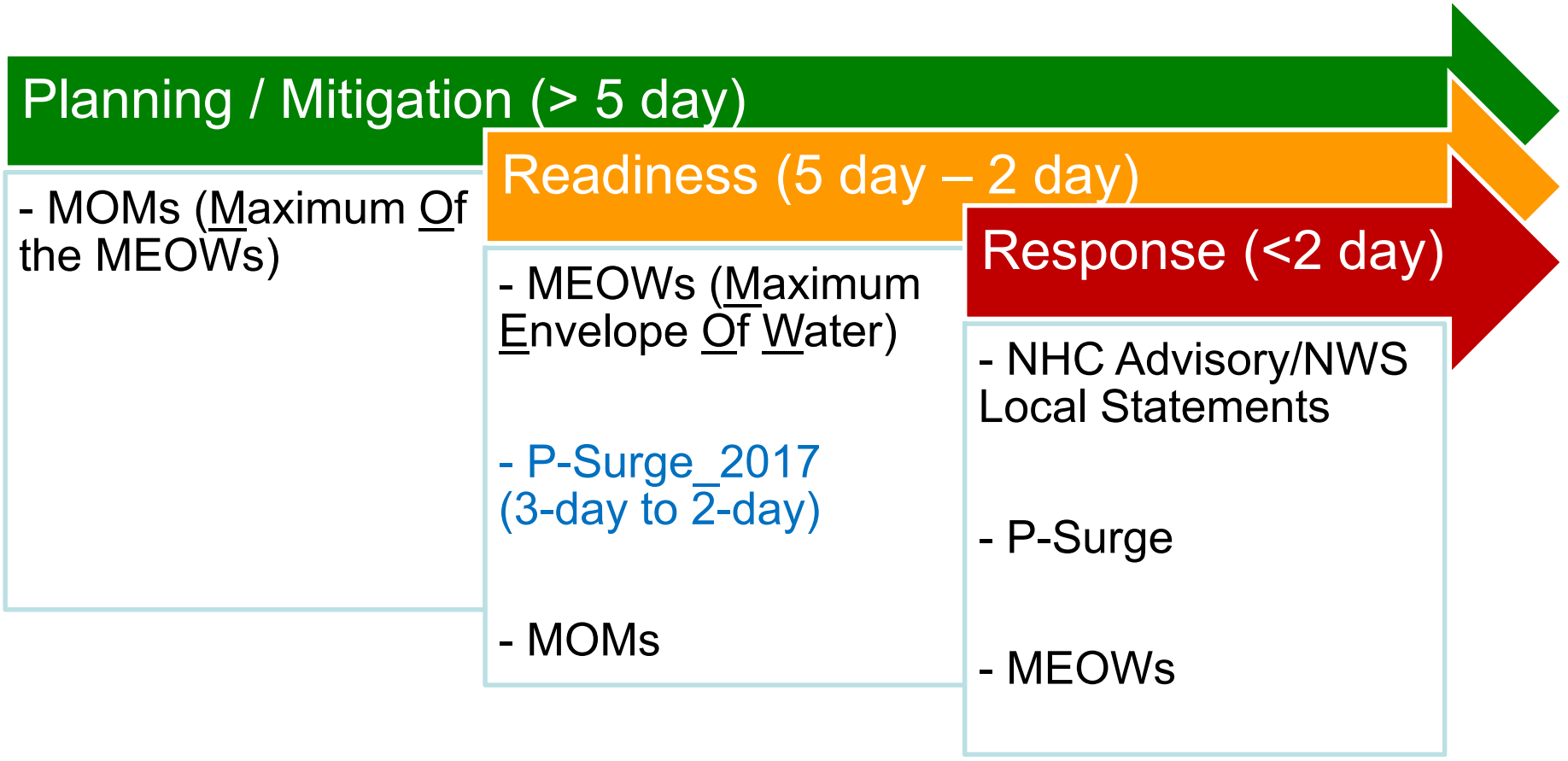
# Storm Surge Warning Guidance
# Probability of Surge + Tide > 3 feet AGL



# Inundation Graphic Guidance
# 10% Exceedance of Surge + Tide AGL



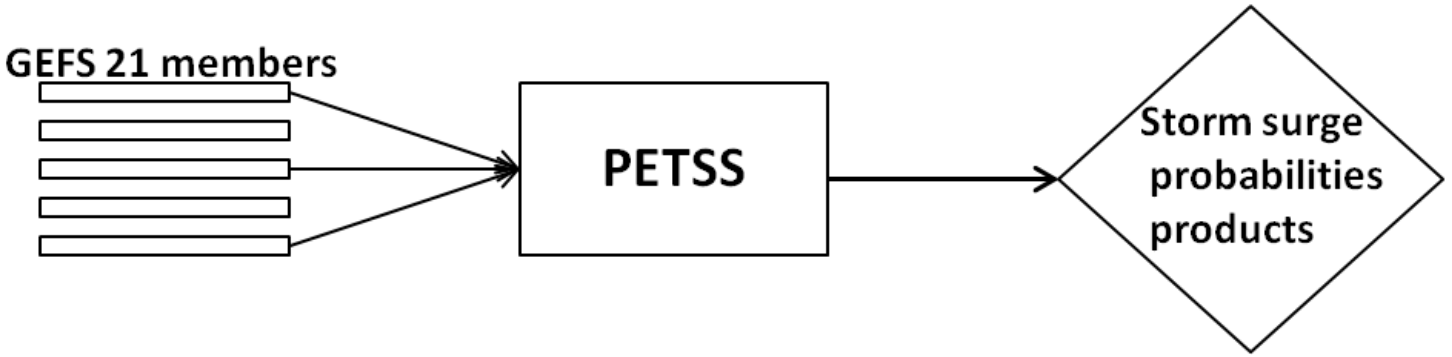
# Tropical Guidance Timeline




(*) These are in days before landfall

# What about Non-Tropical Storms?

- Problem: Extra-Tropical (Nor' Easters) and Post-Tropical (Sandy 2012) storms are not easily parameterized
- Solution: Use atmospheric ensemble models: Probabilistic Extra-Tropical Storm Surge (P-ETSS)

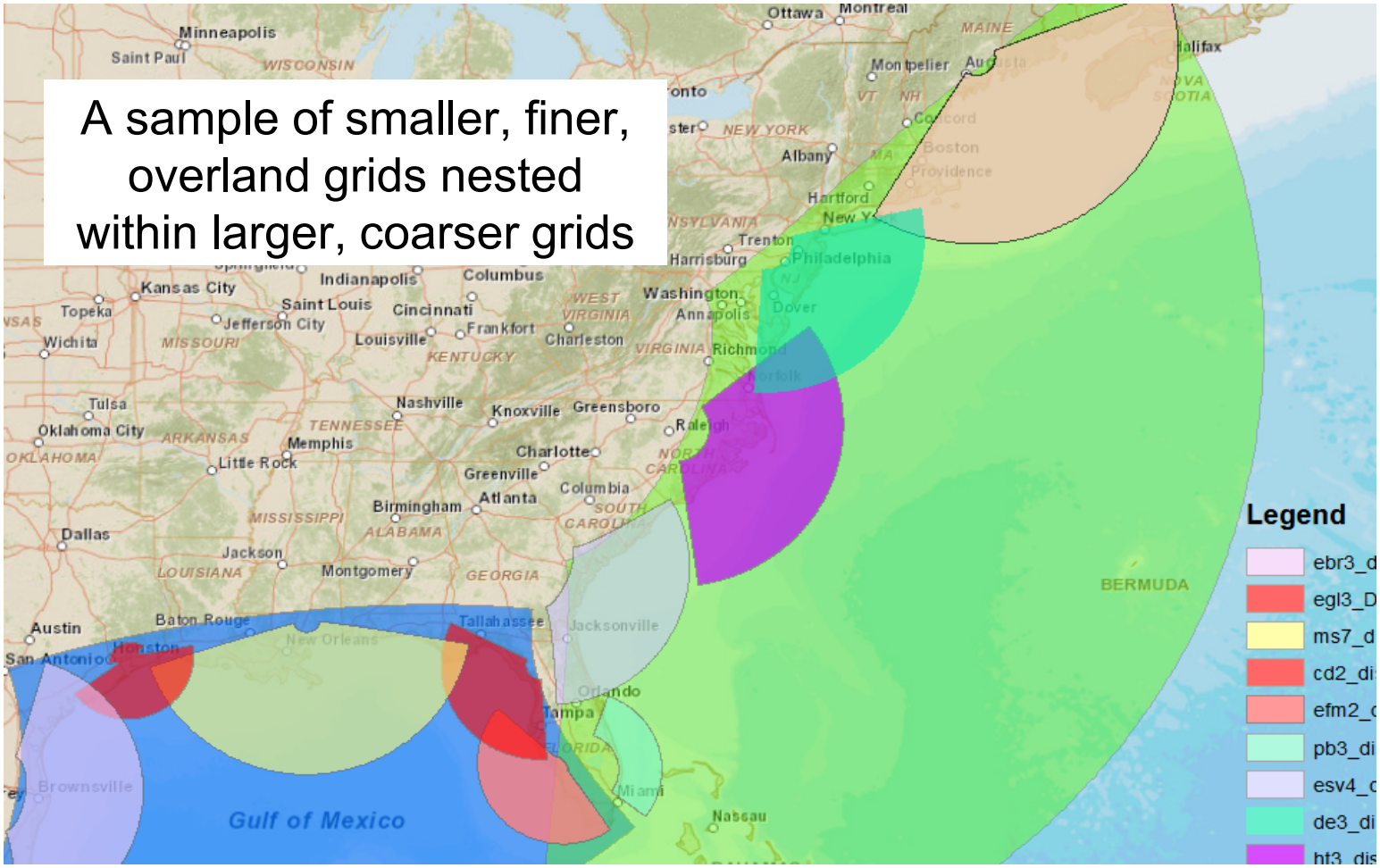



- ❖ 1.0 – Equally weight the ensemble members
- ❖ 1.0 – Use the 21 member Global Ensemble Forecast System (GEFS) as wind forcing
- ❑ Goal – Use the 42 member North American Ensemble Forecast System (NAEFS) as wind forcing

# Non-Tropical Computational Challenge

Problem: Larger (typically Non-Tropical) storms require larger basins to capture the extent of the winds which results in longer run-times

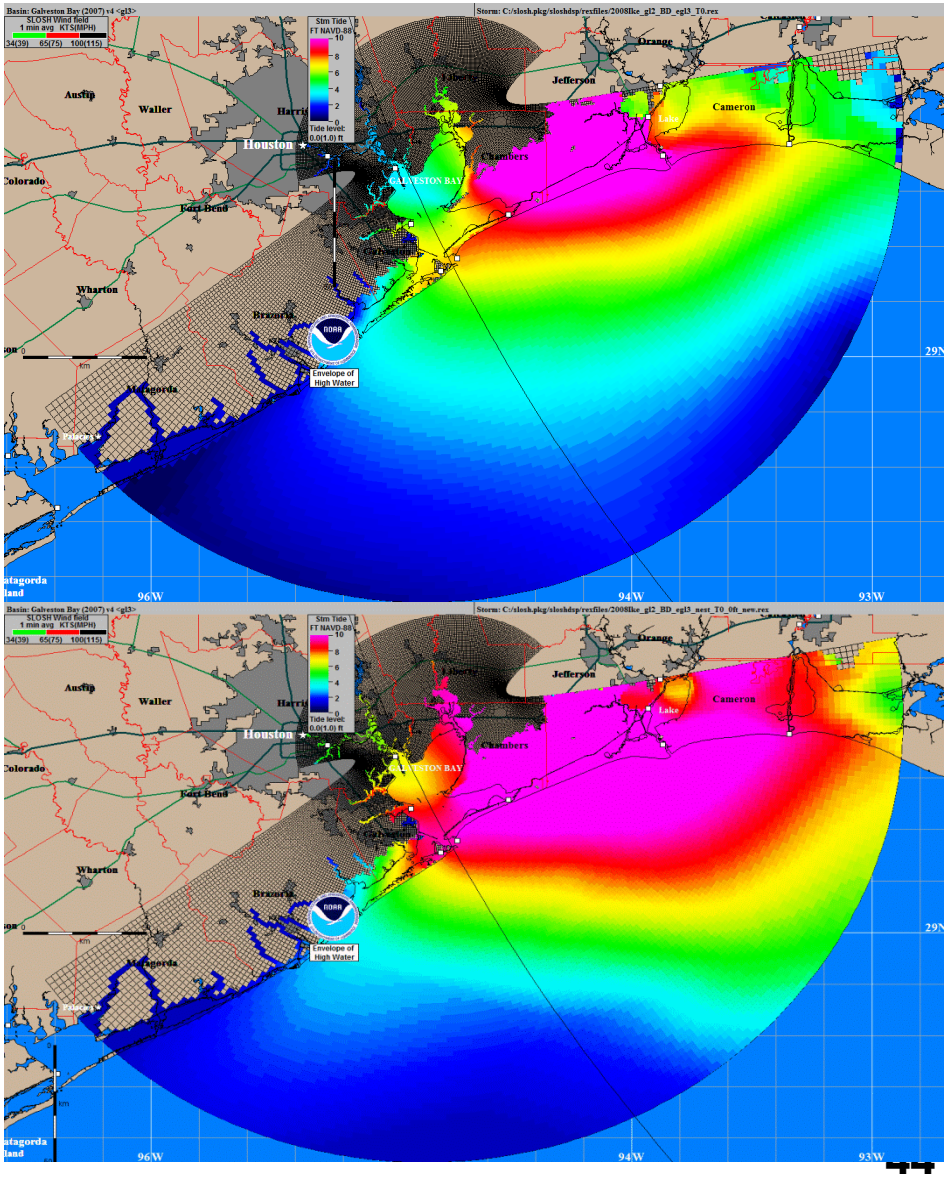
Solution: Nest smaller fine scale grids within the larger coarse grids



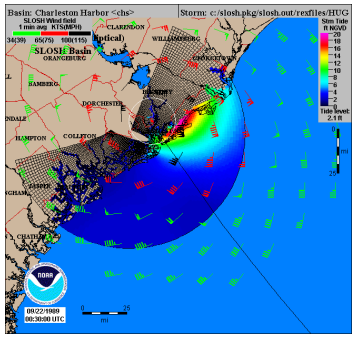
# The Benefit of Nesting

## Hurricane Ike 2008

- Top panel: Modeled in the Galveston basin
- Bottom panel: Modeled by nesting the Galveston basin within the Gulf of Mexico basin
- Better captures fore-runner phenomena



# Thank You
# arthur.taylor@noaa.gov

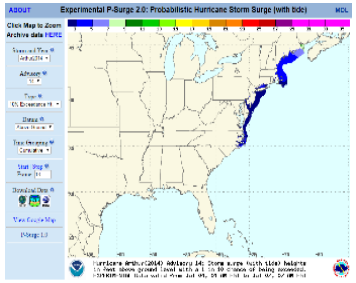



- **SLOSH Display Program**

A GIS for exploring storm surge potential at critical locations and demonstrating the timing of storm surge and winds

https://slosh.nws.noaa.gov/sdp/download.php

(User = Gustav2008 ; Pass = Ike2008)

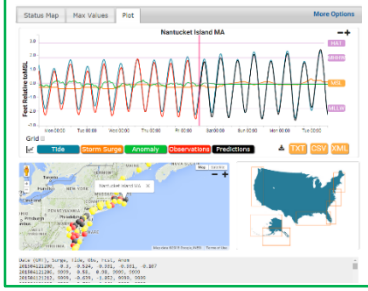



- **Probabilistic Tropical Storm Surge Guidance**

https://slosh.nws.noaa.gov/psurge/

https://slosh.nws.noaa.gov/etsurge2.0/

https://slosh.nws.noaa.gov/petss/




- **Extra-Tropical Storm Surge Guidance**

Deterministic

Probabilistic