NWS Storm Surge Ensemble Guidance

Arthur A. Taylor (Team Lead)
Huiqing Liu, Tatiana Gonzalez, Kwangmin Kang

NWS Meteorological Development Laboratory
Decision Support Branch

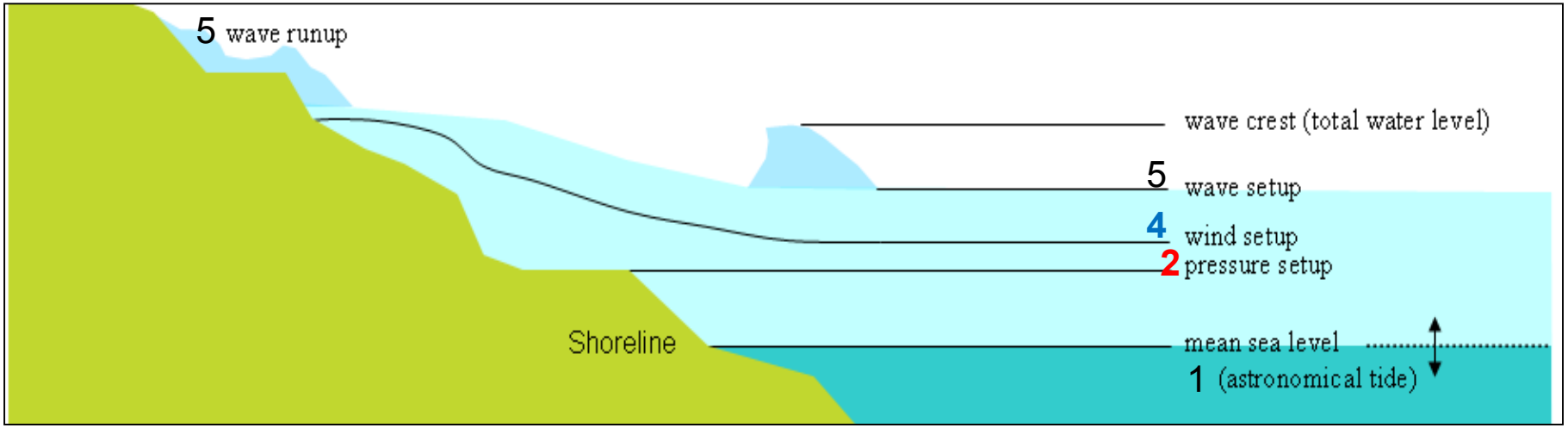
U.S. Nuclear Regulatory Commission
Rockville, MD – April 30, 2019

What is Storm Surge?

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

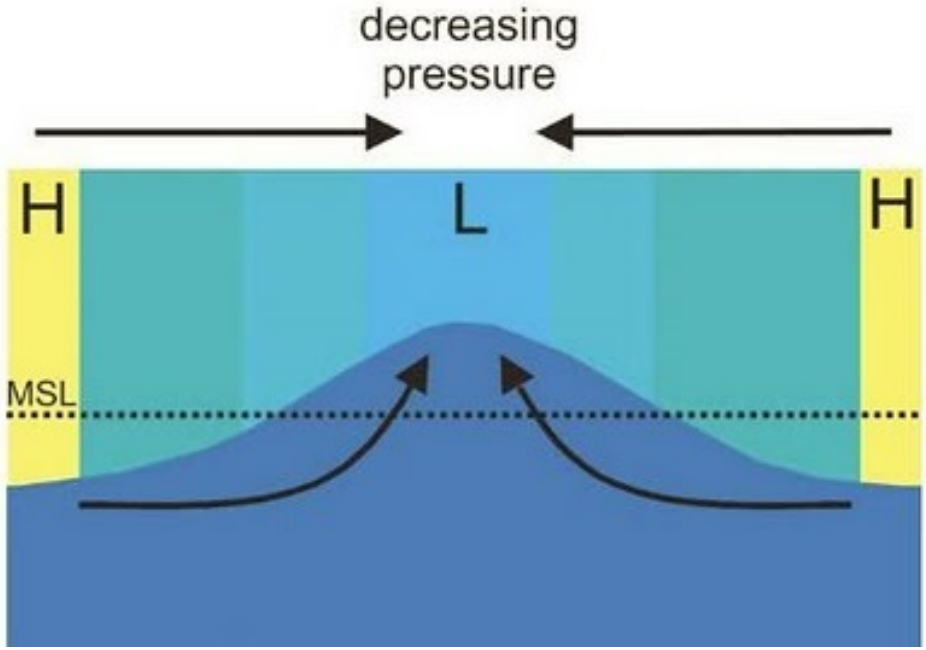
1. **Astronomical Tide**
2. **Pressure setup** – water level change due to lower atmos. pressure
3. **Geostrophic adjustment** – adjustment due to longshore current
4. **Wind setup** – water level change due to the force of the wind
5. **Wave setup** – water level change due to wave setup and run-up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

Dissipation terms; Steric setup

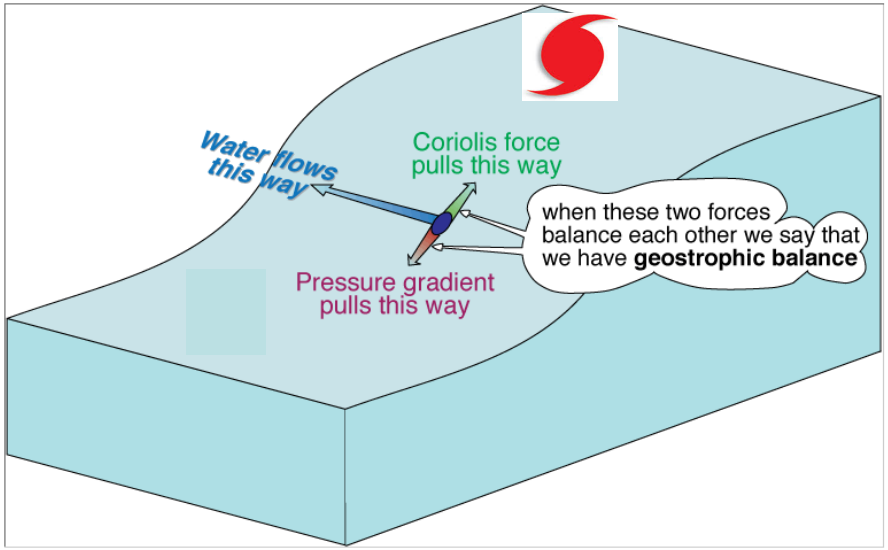


Pressure Terms

Pressure Setup



Geostrophic Adjustment

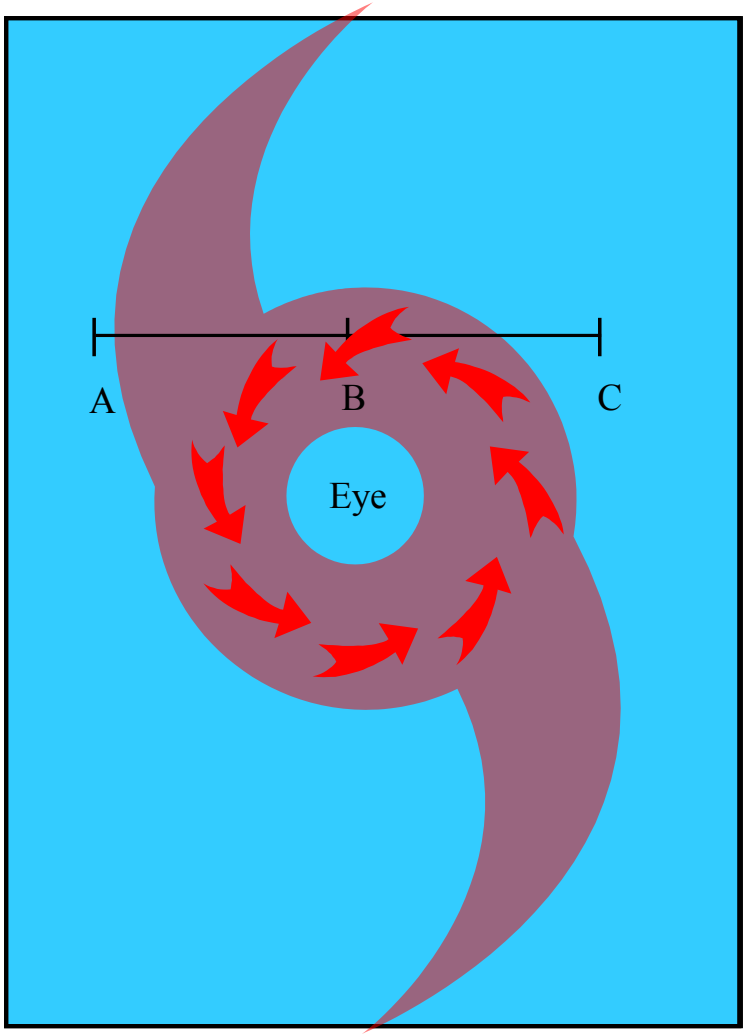


The balance between pressure gradient forces and Coriolis forces on a parcel of water is what we call geostrophic balance.

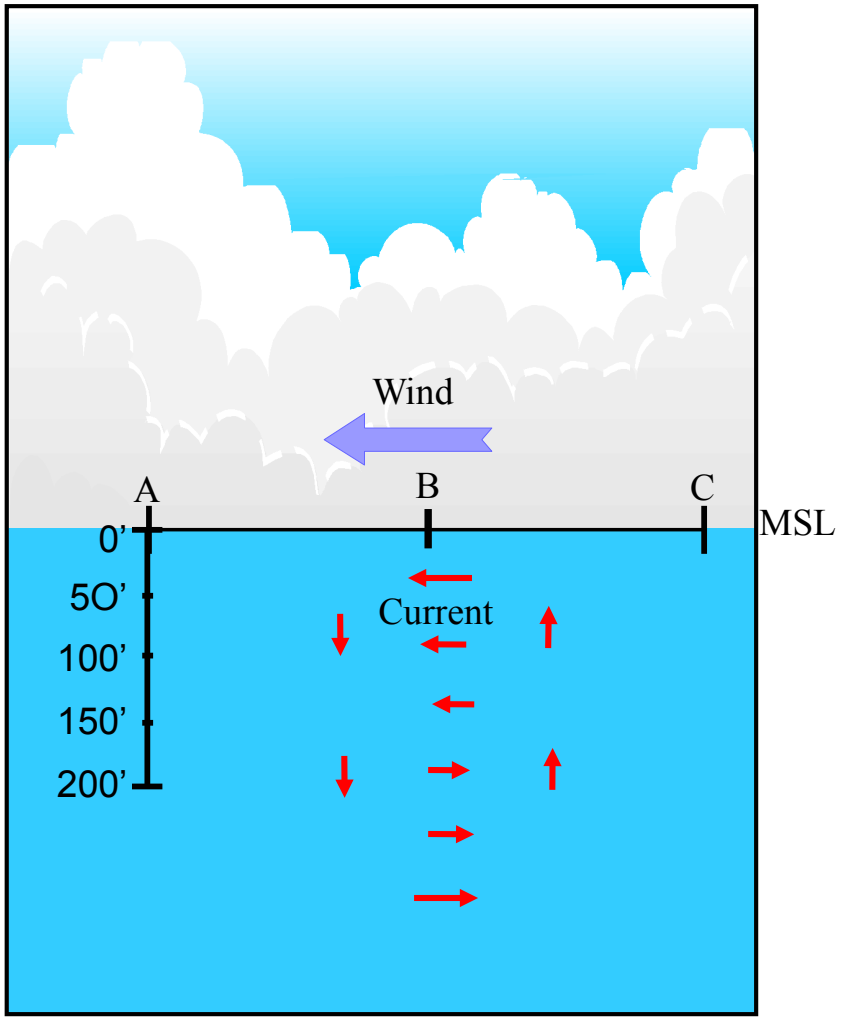
Slower and/or **Larger** storms increase the geostrophic adjustment's impact on storm surge.

Wind Setup

a. Top view of Sea Surface

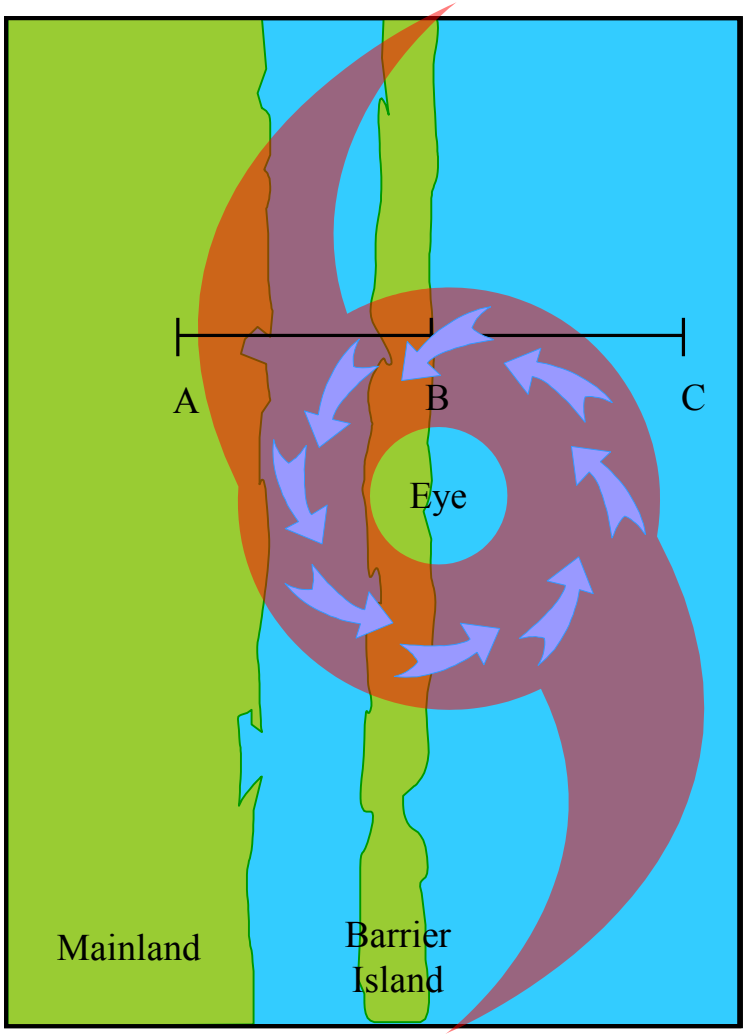


b. Side view of Cross Section "ABC"

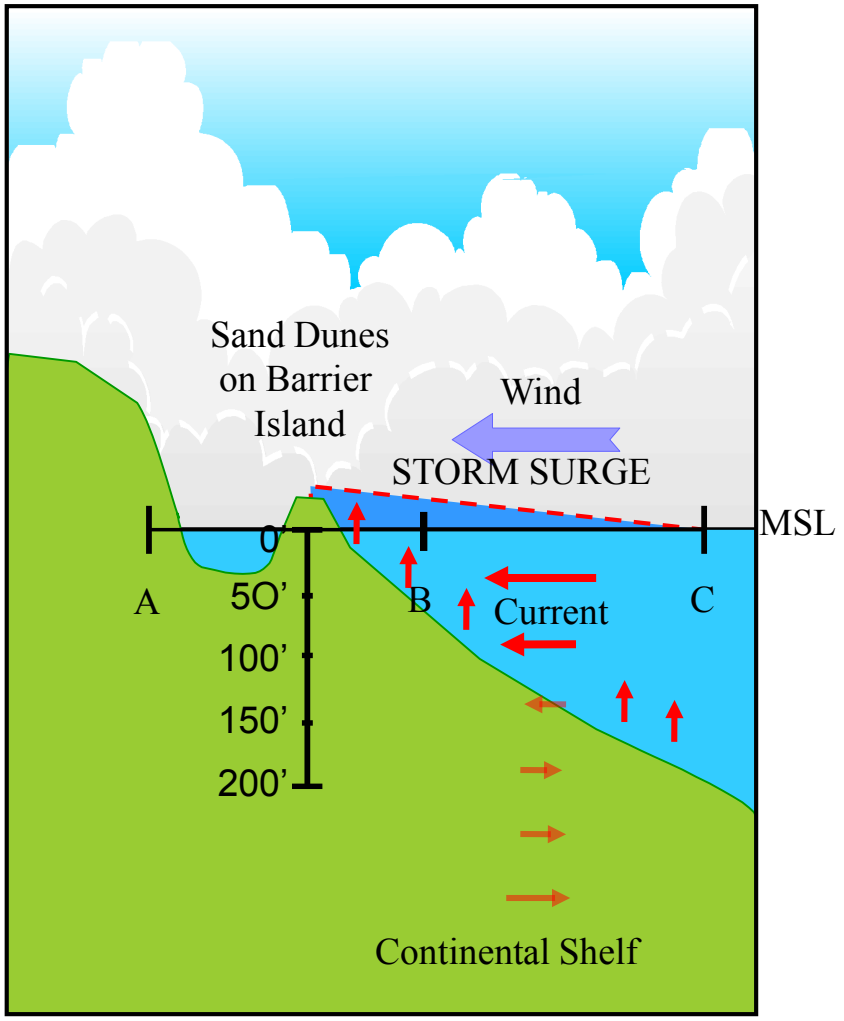


Wind Setup

a. Top view of Sea Surface and Land

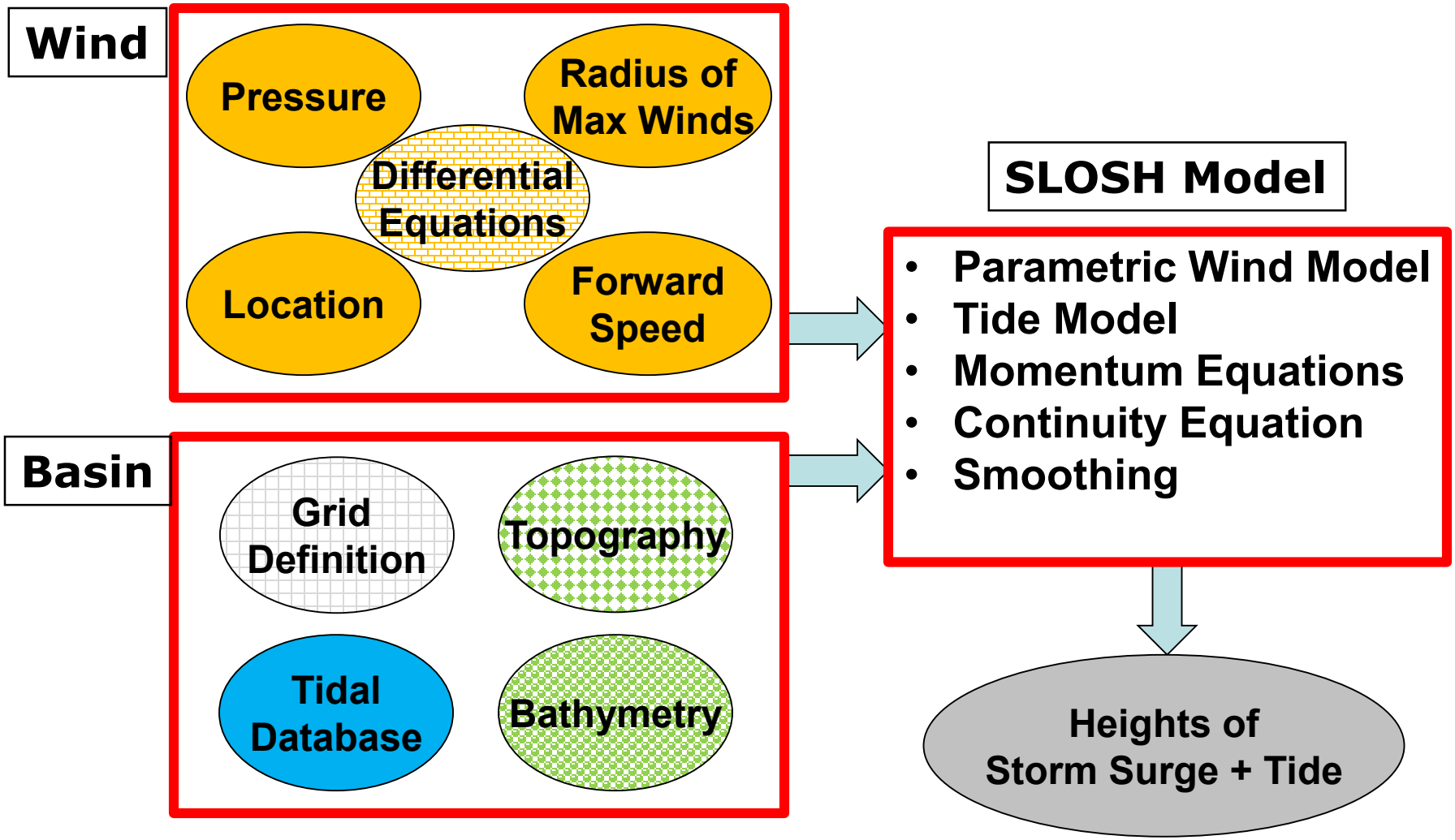


b. Side view of Cross Section "ABC"

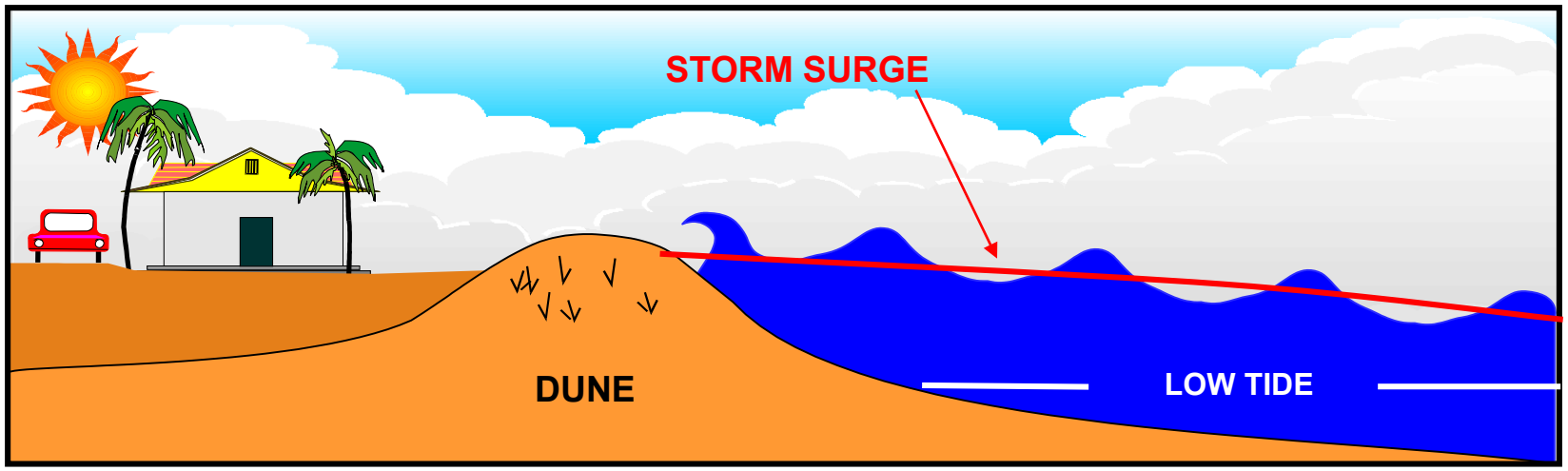


What is the SLOSH model?

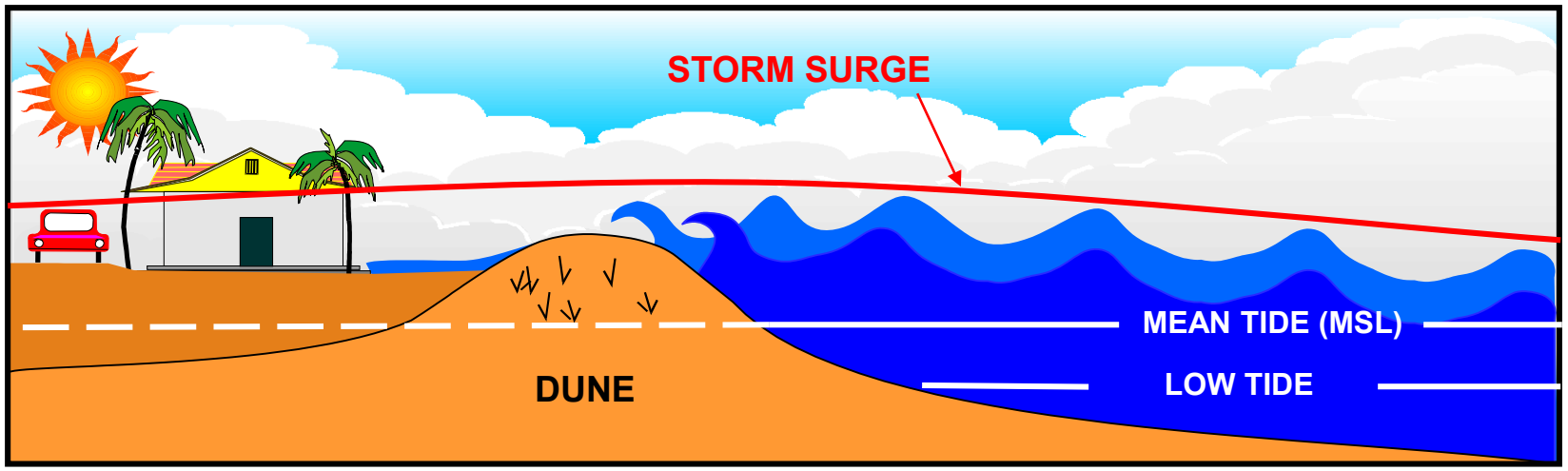
(Sea Lake and Overland Surges from Hurricanes)



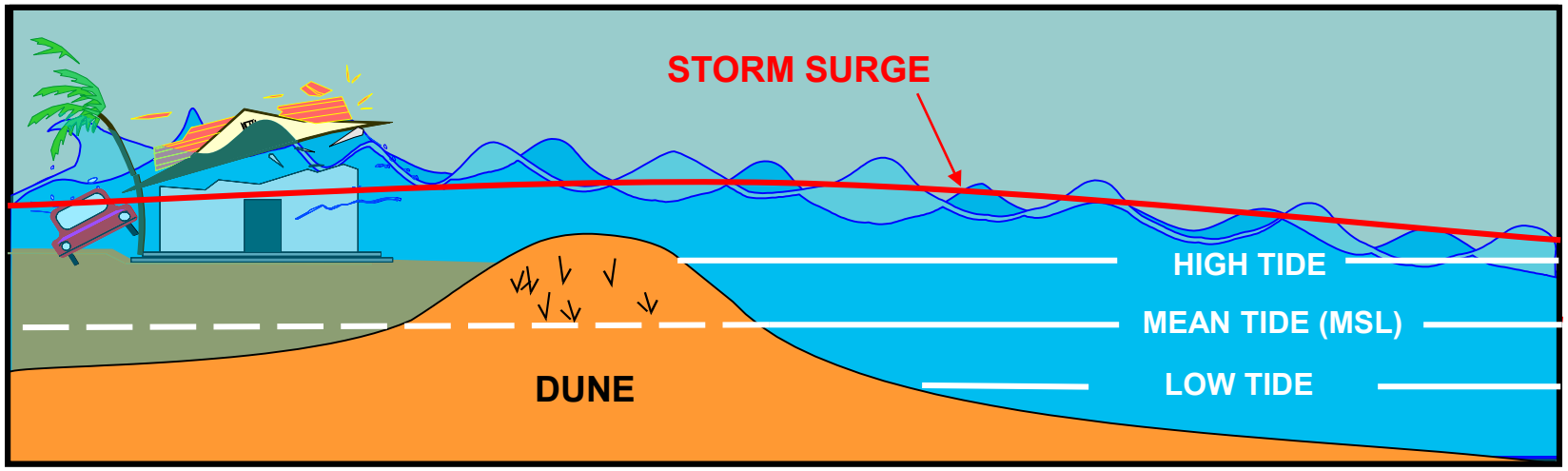
SLOSH Tide Model



SLOSH Tide Model



SLOSH Tide Model



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*)

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

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

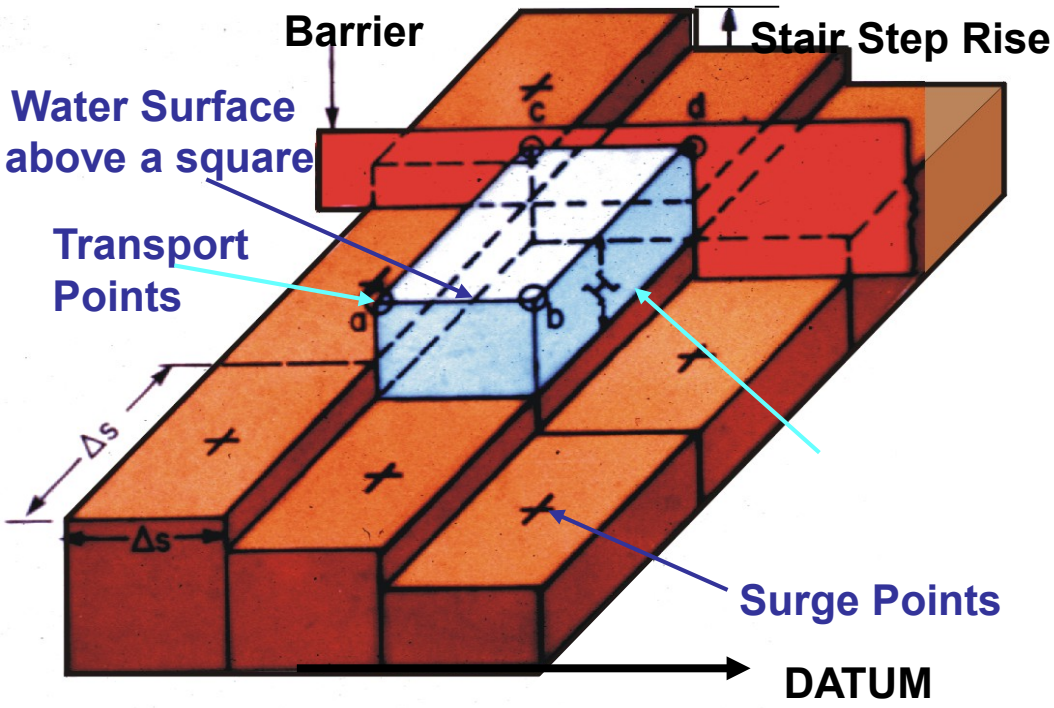
V3 – Tide as a boundary condition (*Spin-up to initialize transport variables; narrow estuary mouths obstruct the tide*)

SLOSH Basin

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

Structured, Arakawa B-Grid

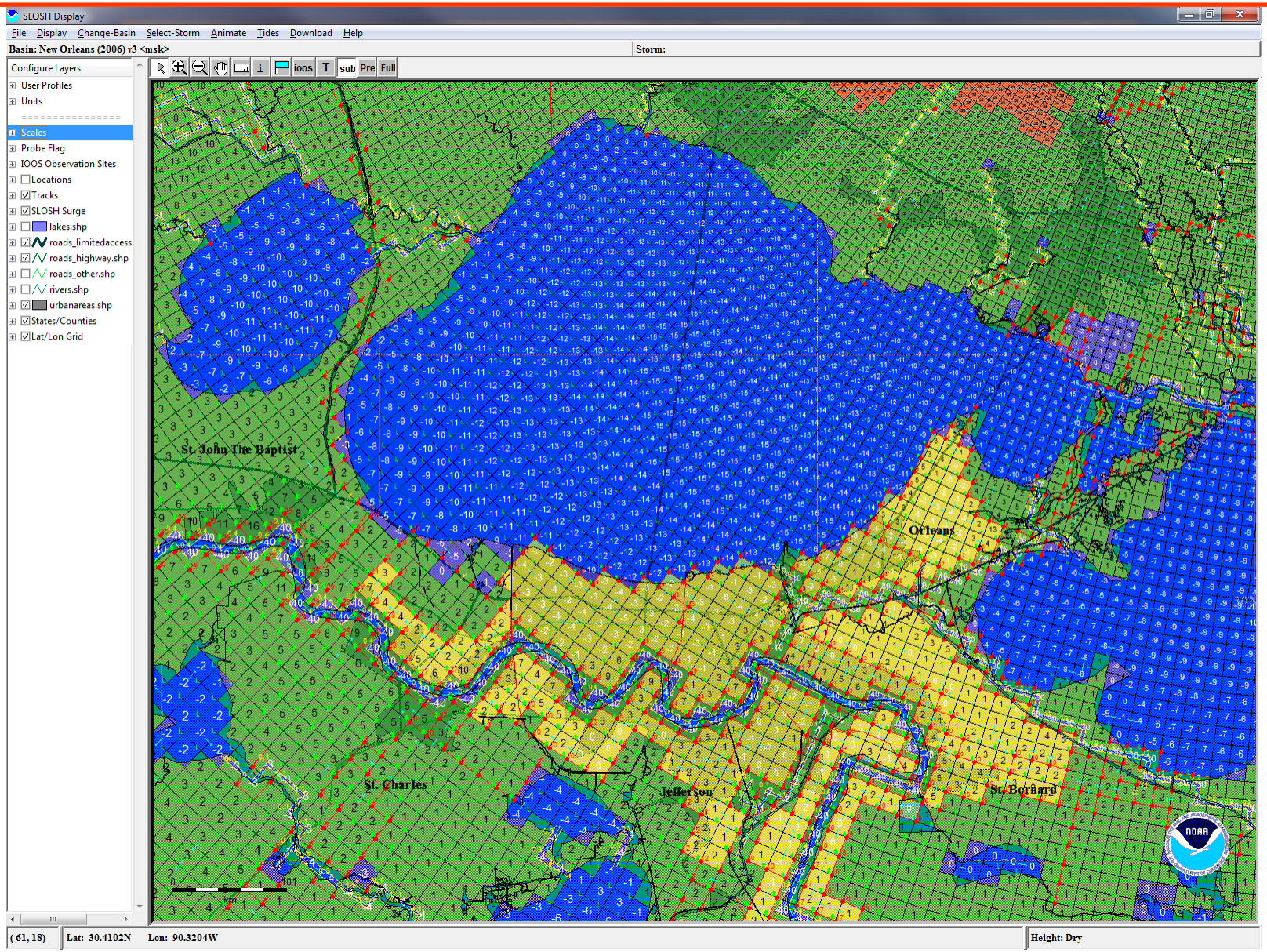
- Heights at the center and transports on the corners
- Finer resolution (**~100 m**) overland, and coarser (**~2 km**) offshore
- Locally orthogonal



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



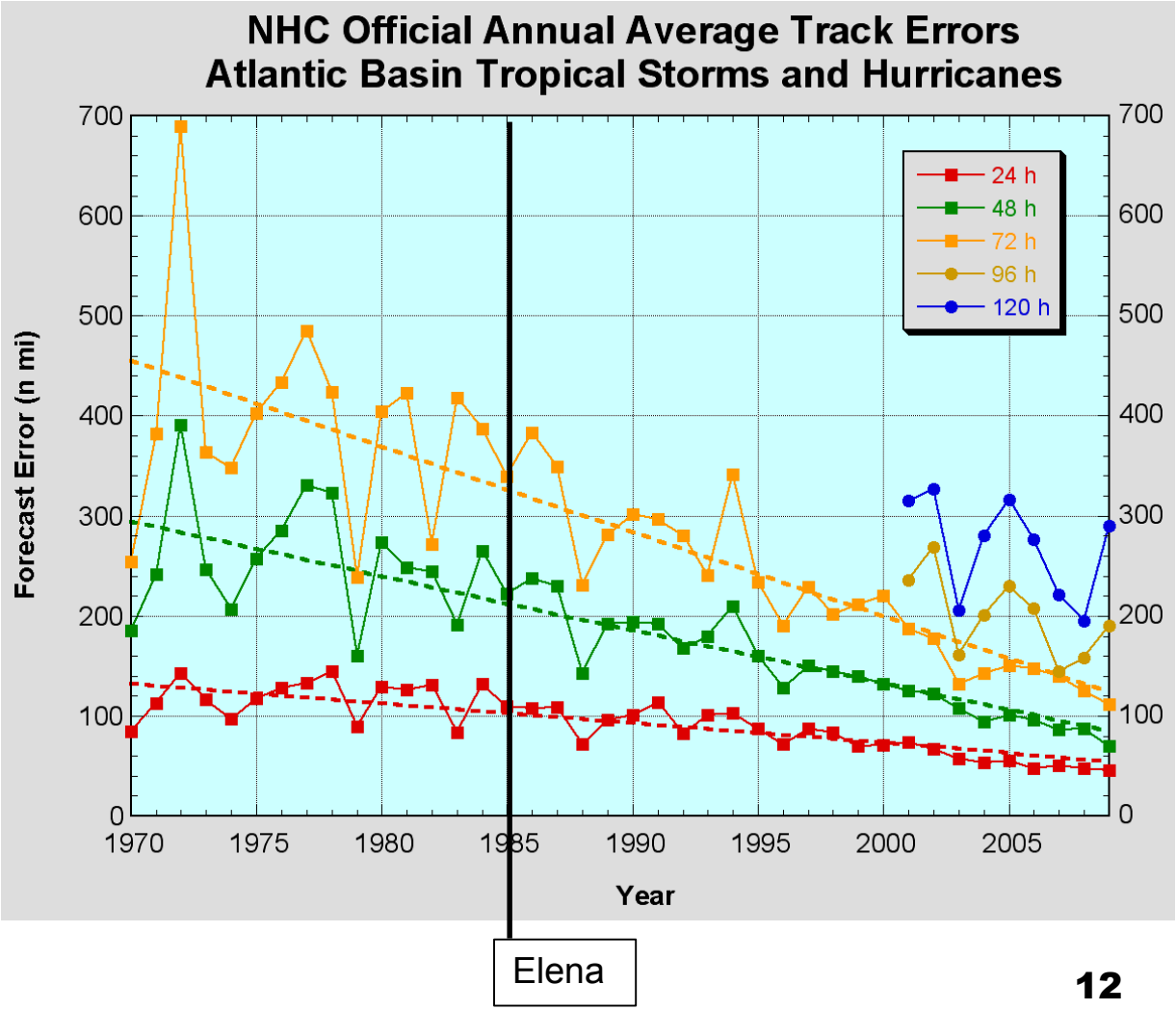
Why ensembles of model runs?

Wind input is the Largest Storm Surge Error

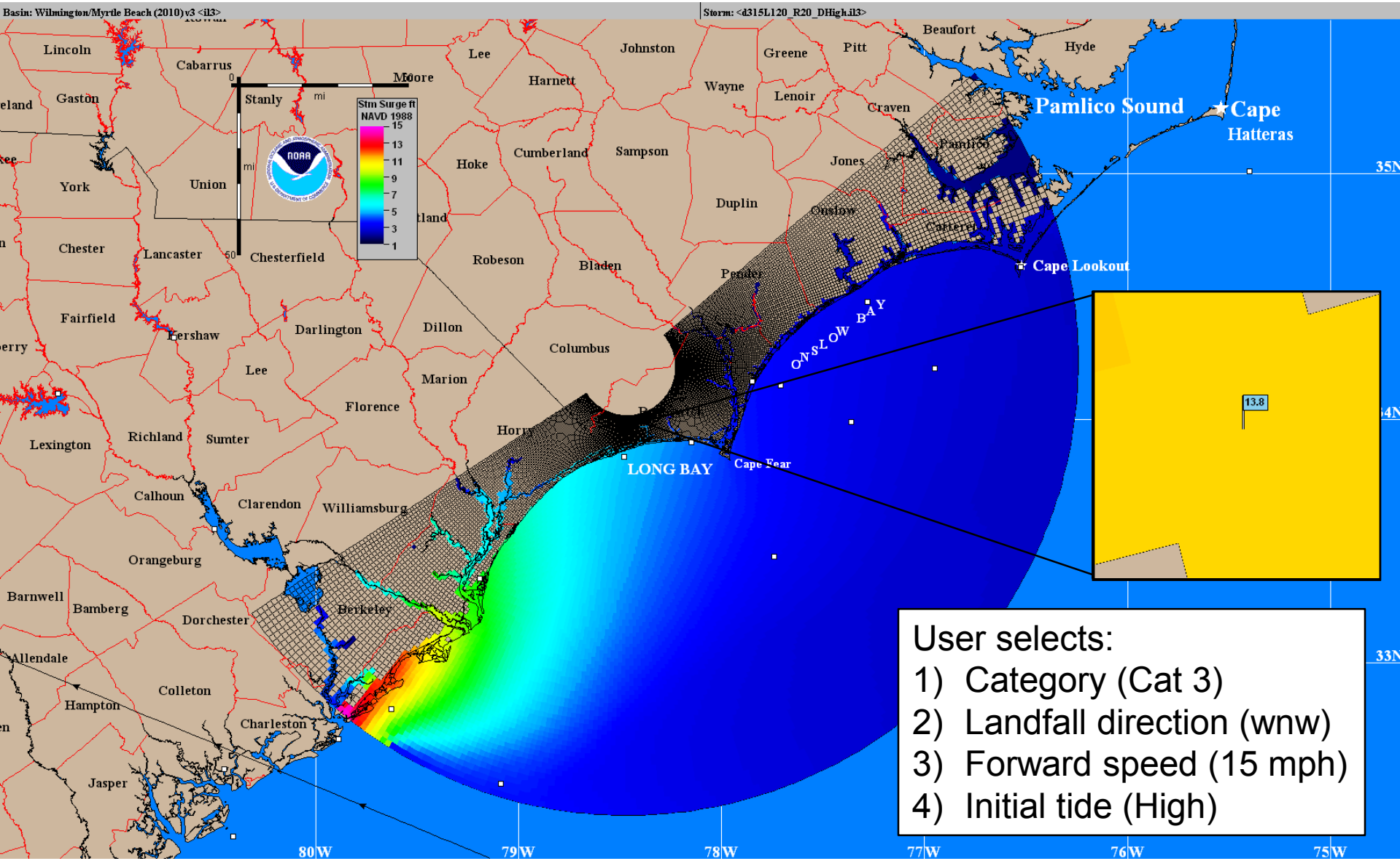
In 1986, due to the uncertainty in the forecast of 1985-Elena

- 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



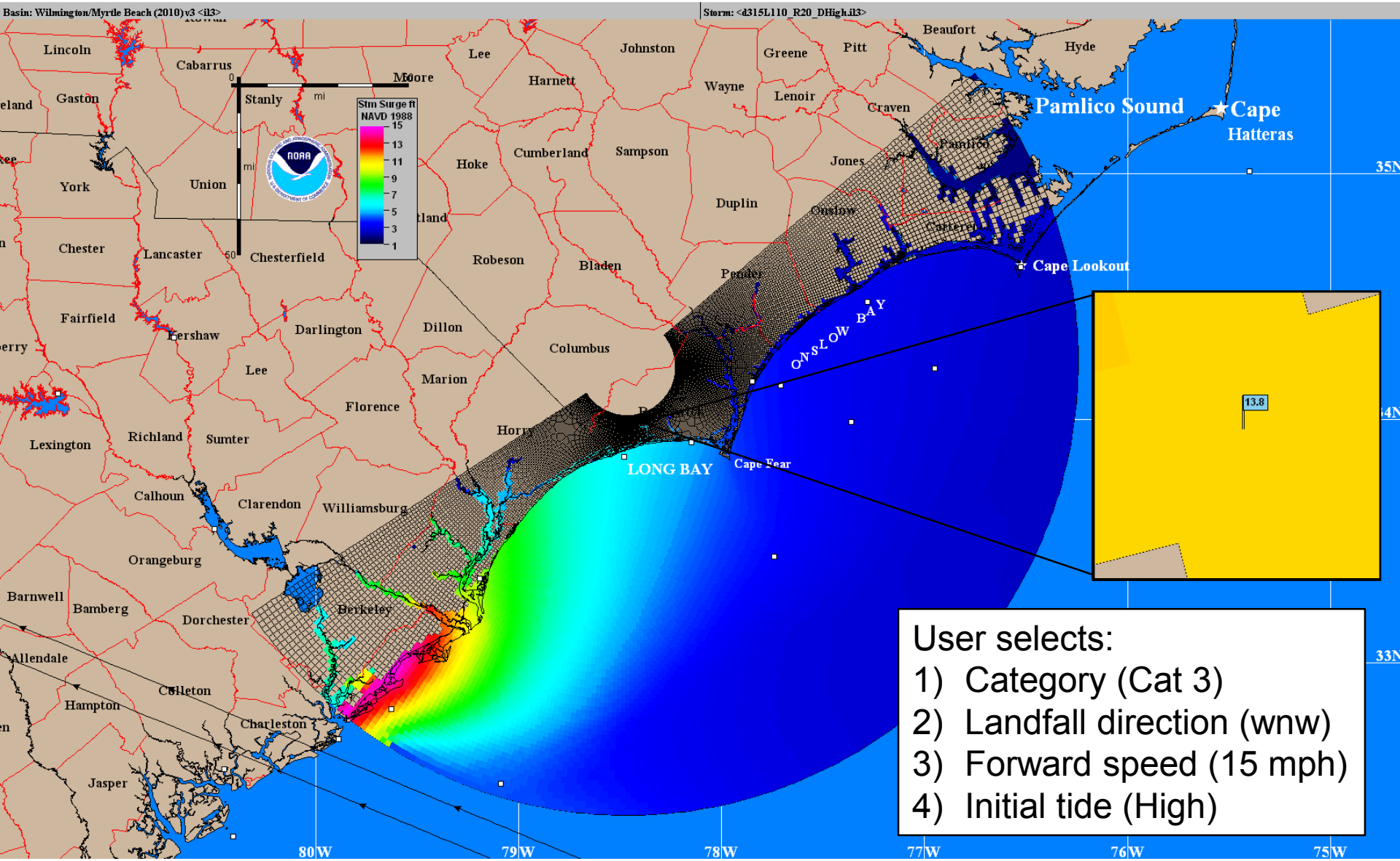
Maximum Envelope Of Water (MEOW)



User selects:

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

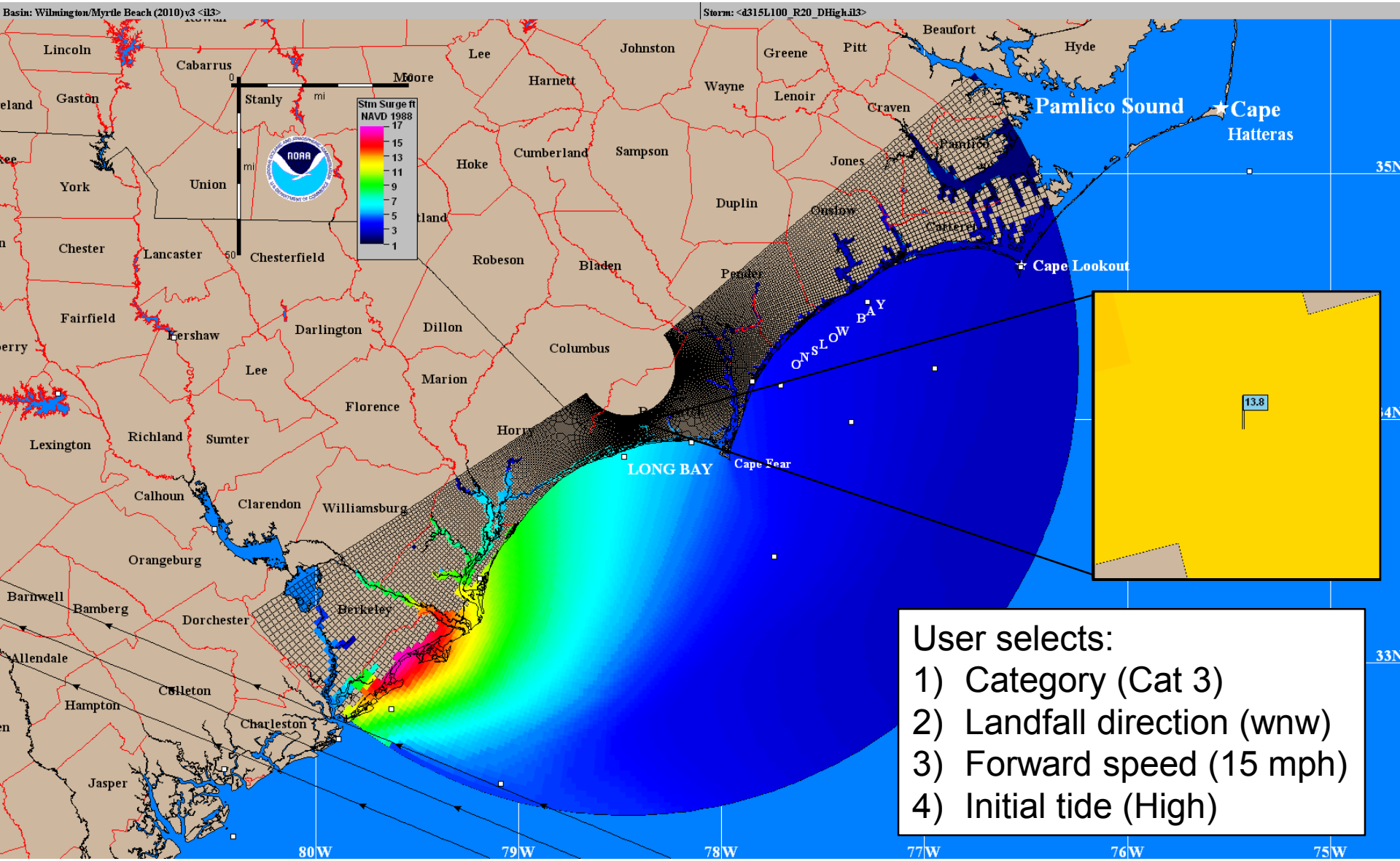
Maximum Envelope Of Water (MEOW)



User selects:

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

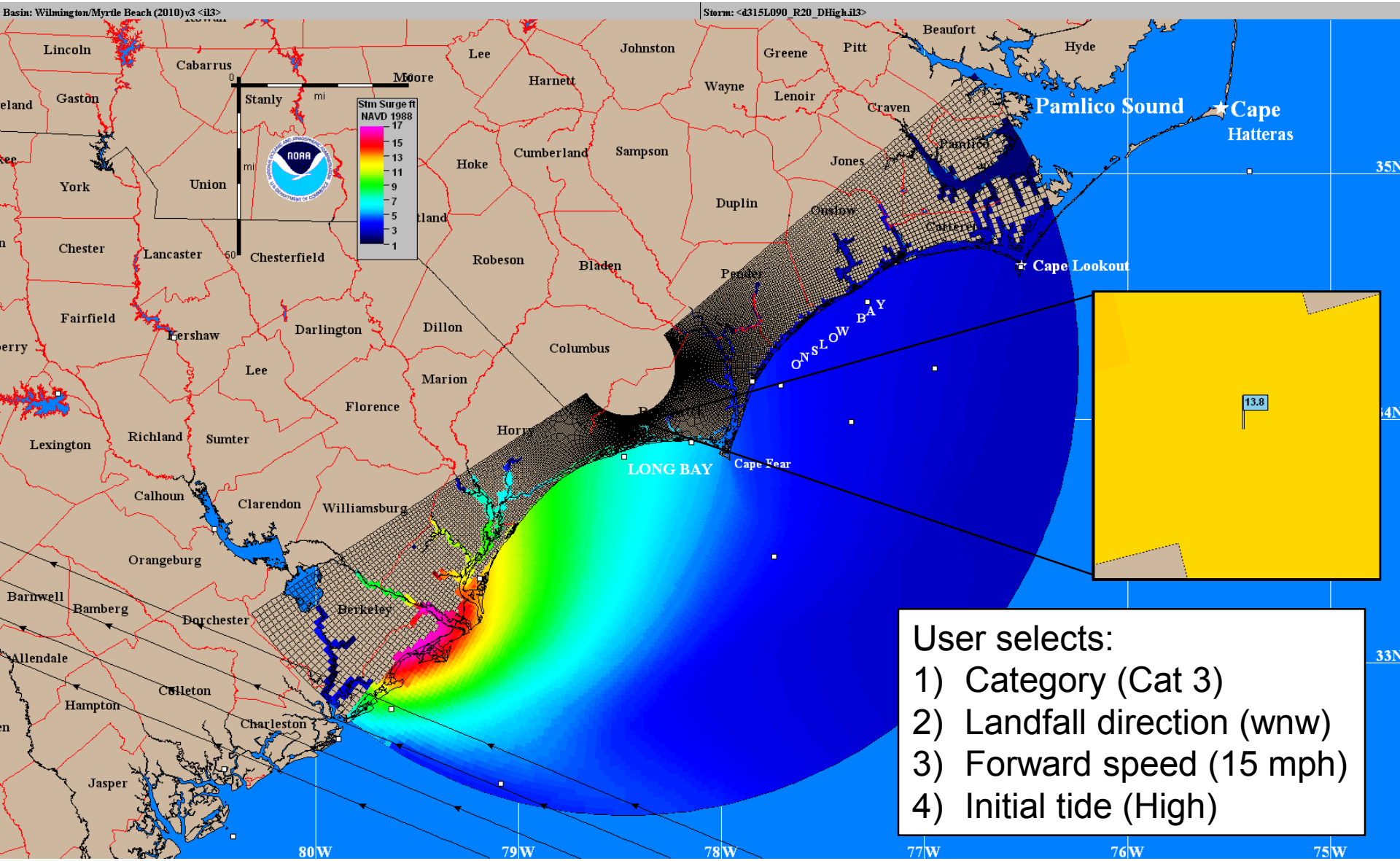
Maximum Envelope Of Water (MEOW)



User selects:

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

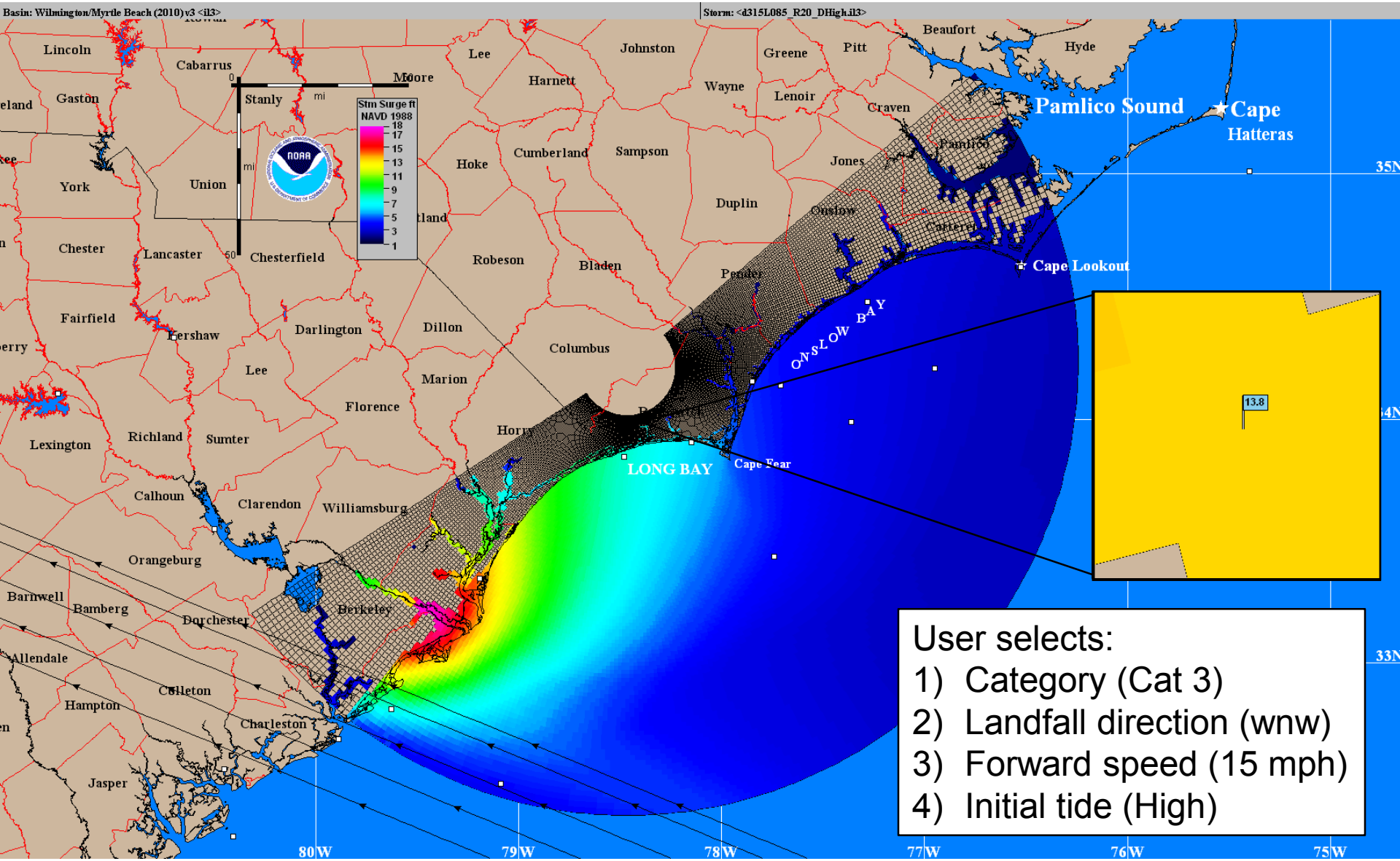
Maximum Envelope Of Water (MEOW)



User selects:

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

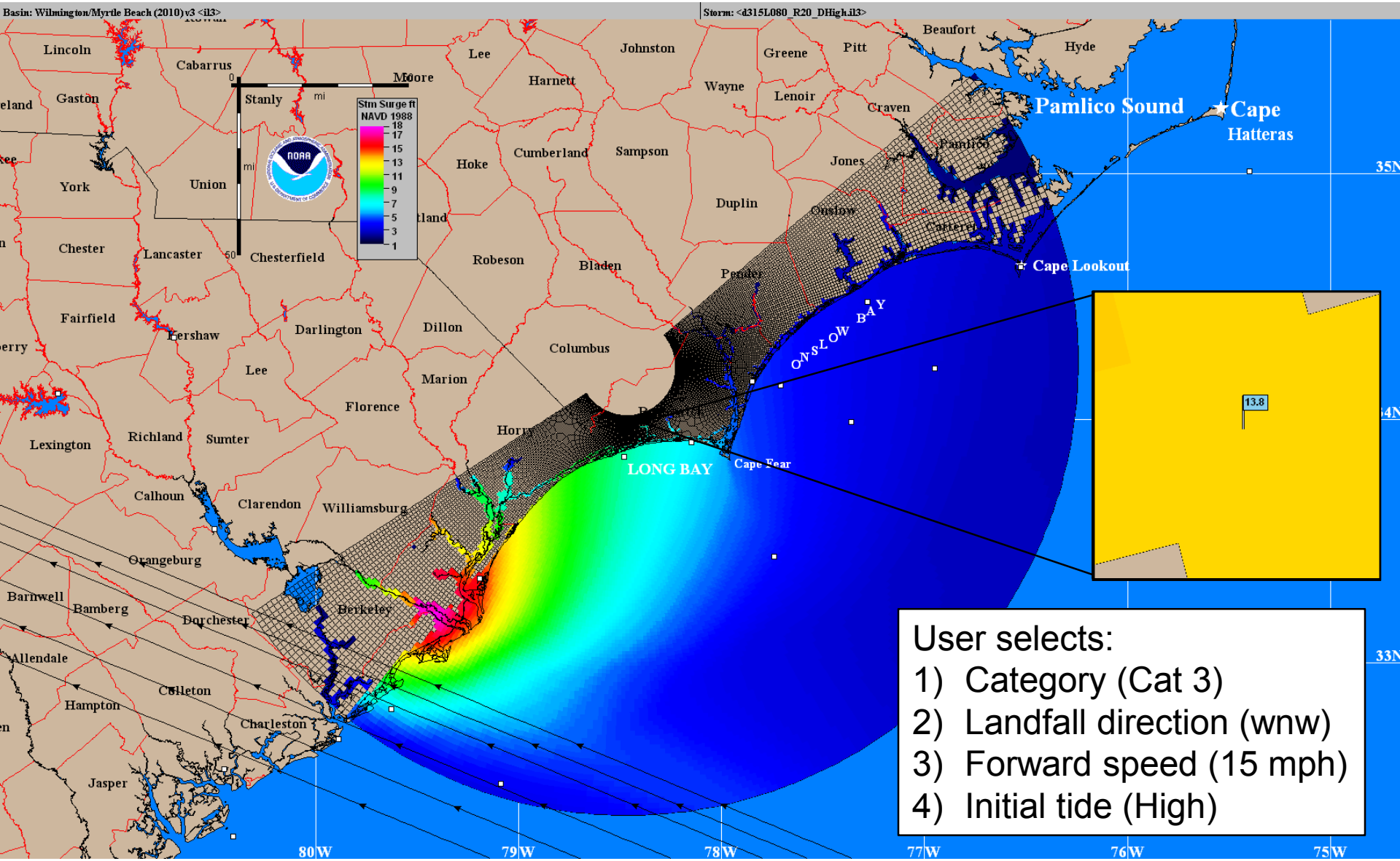
Maximum Envelope Of Water (MEOW)



User selects:

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

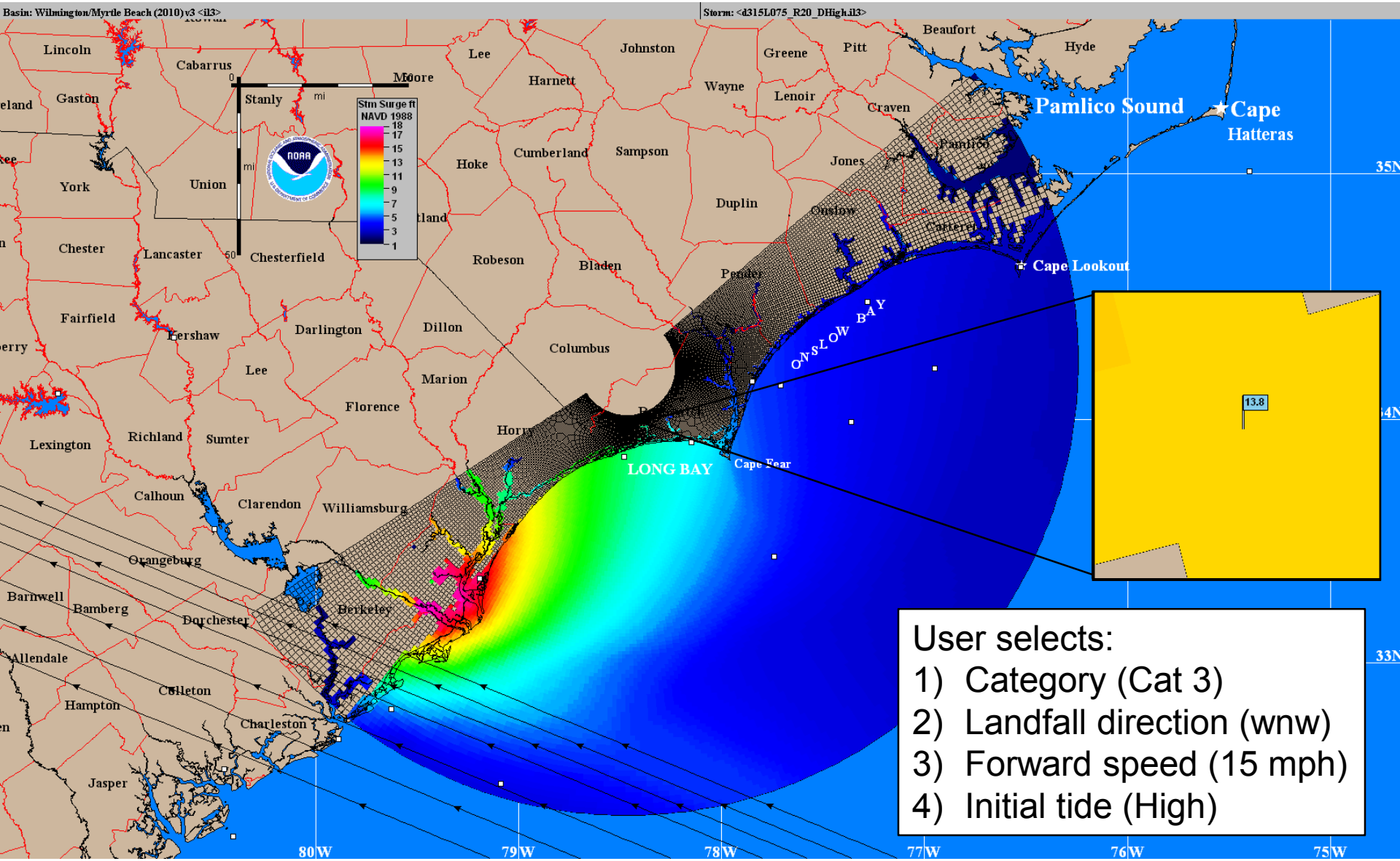
Maximum Envelope Of Water (MEOW)



User selects:

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

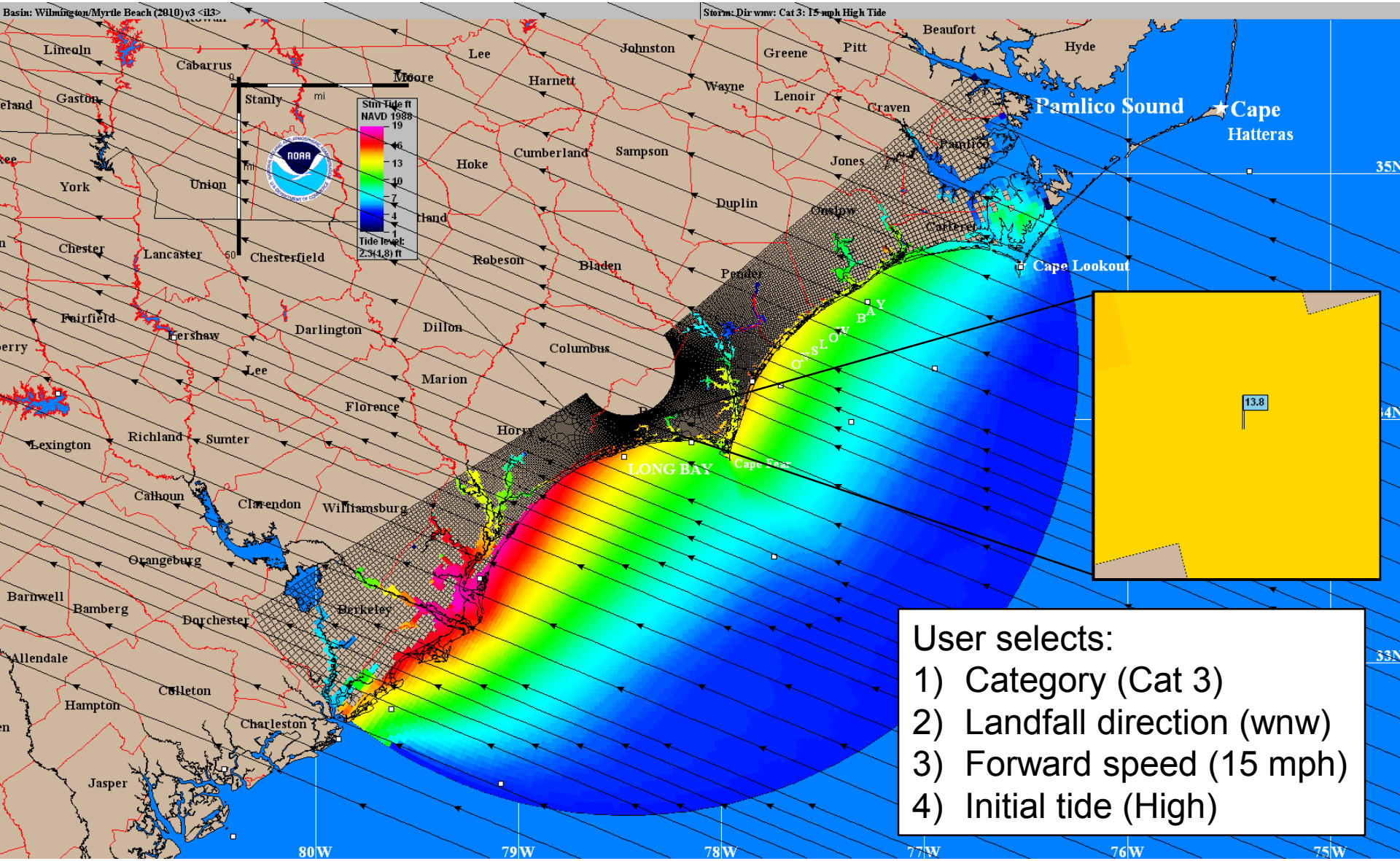
Maximum Envelope Of Water (MEOW)



User selects:

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

Maximum Envelope Of Water (MEOW)



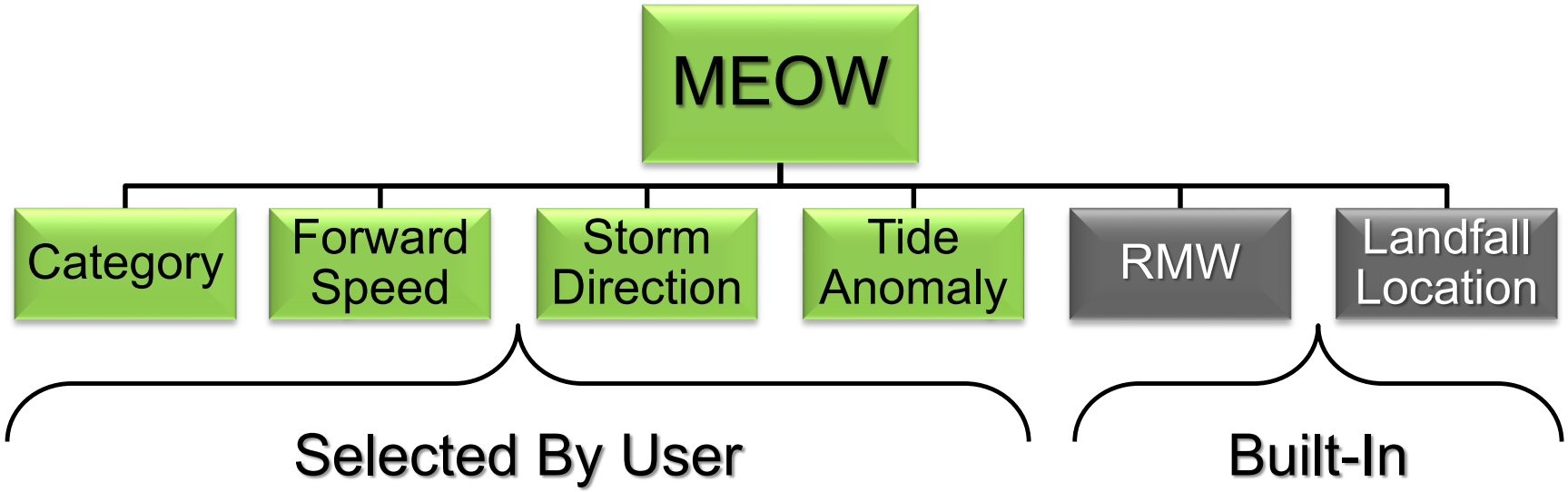
User selects:

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

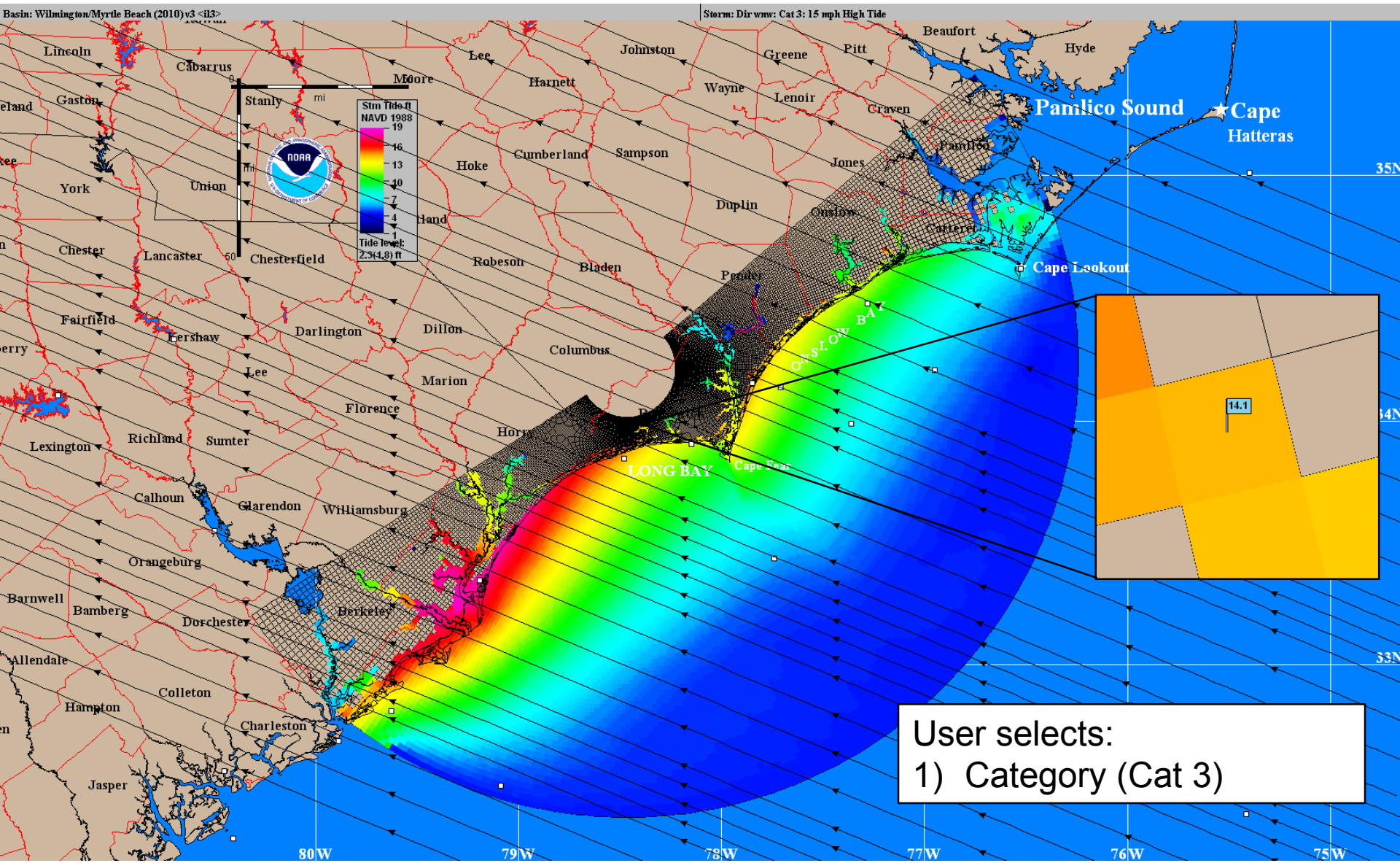
Maximum **E**nvelope **O**f **W**ater (**MEOW**)

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

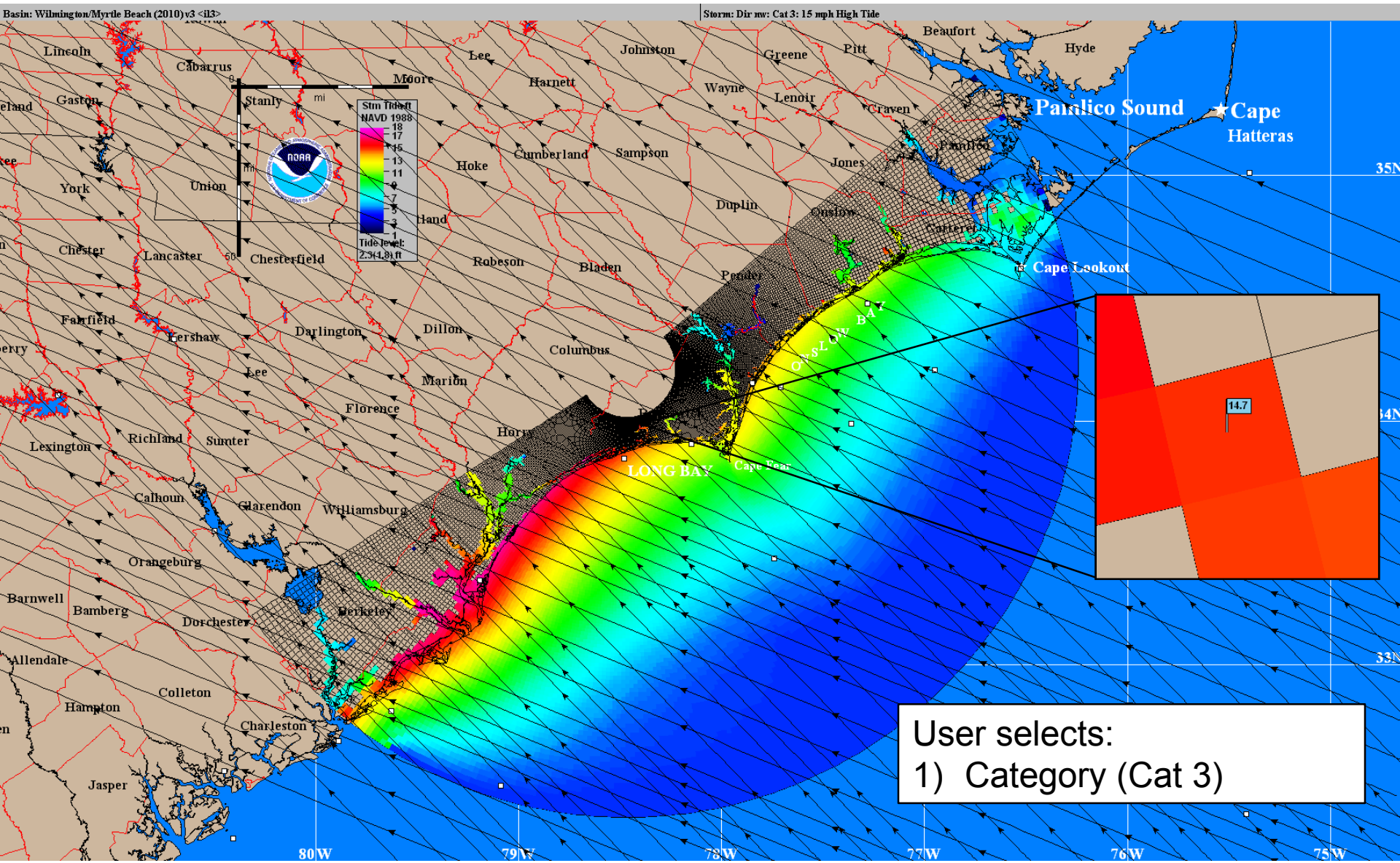


Maximum Of MEOWs (MOM)



User selects:
1) Category (Cat 3)

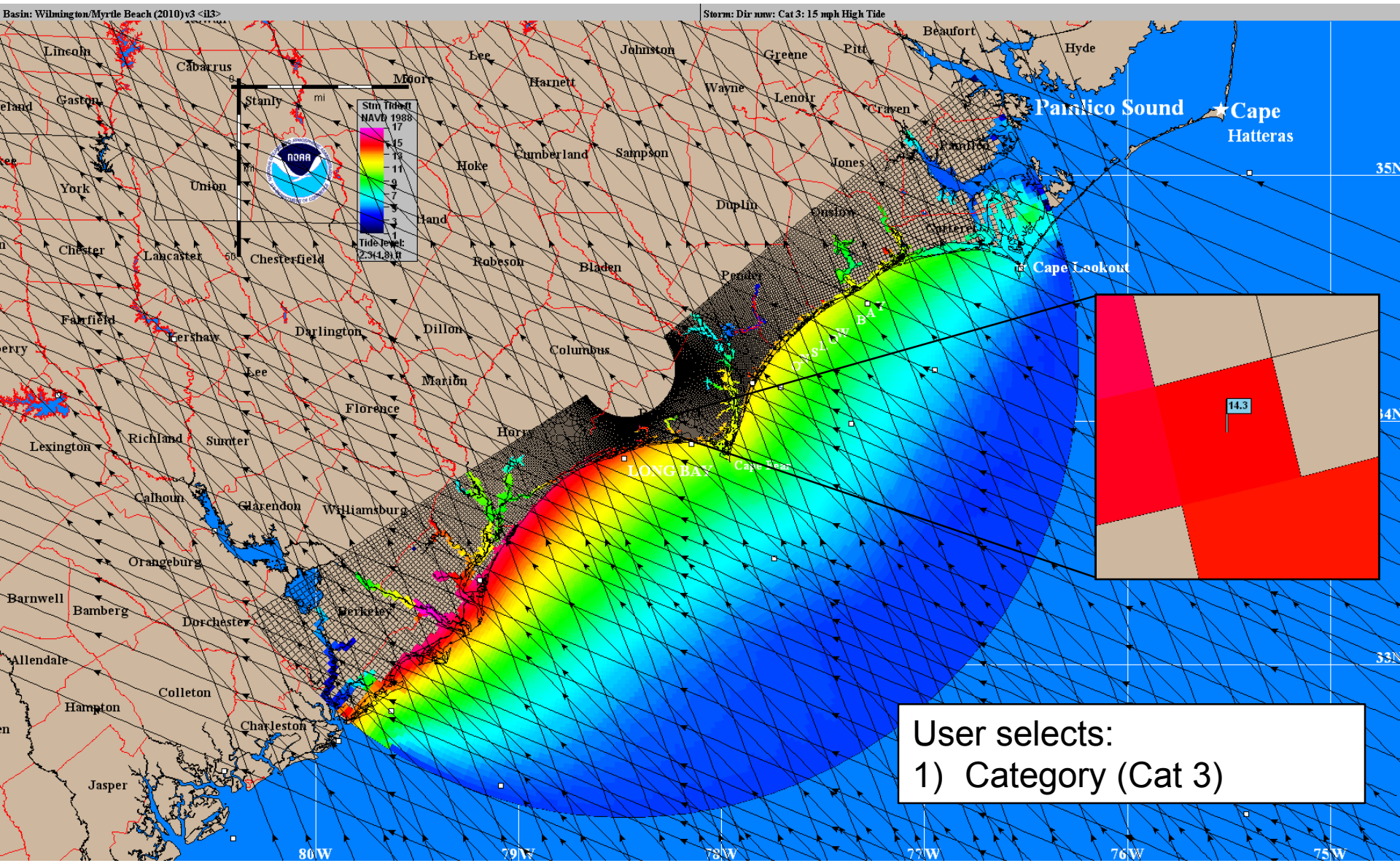
Maximum Of MEOWs (MOM)



User selects:

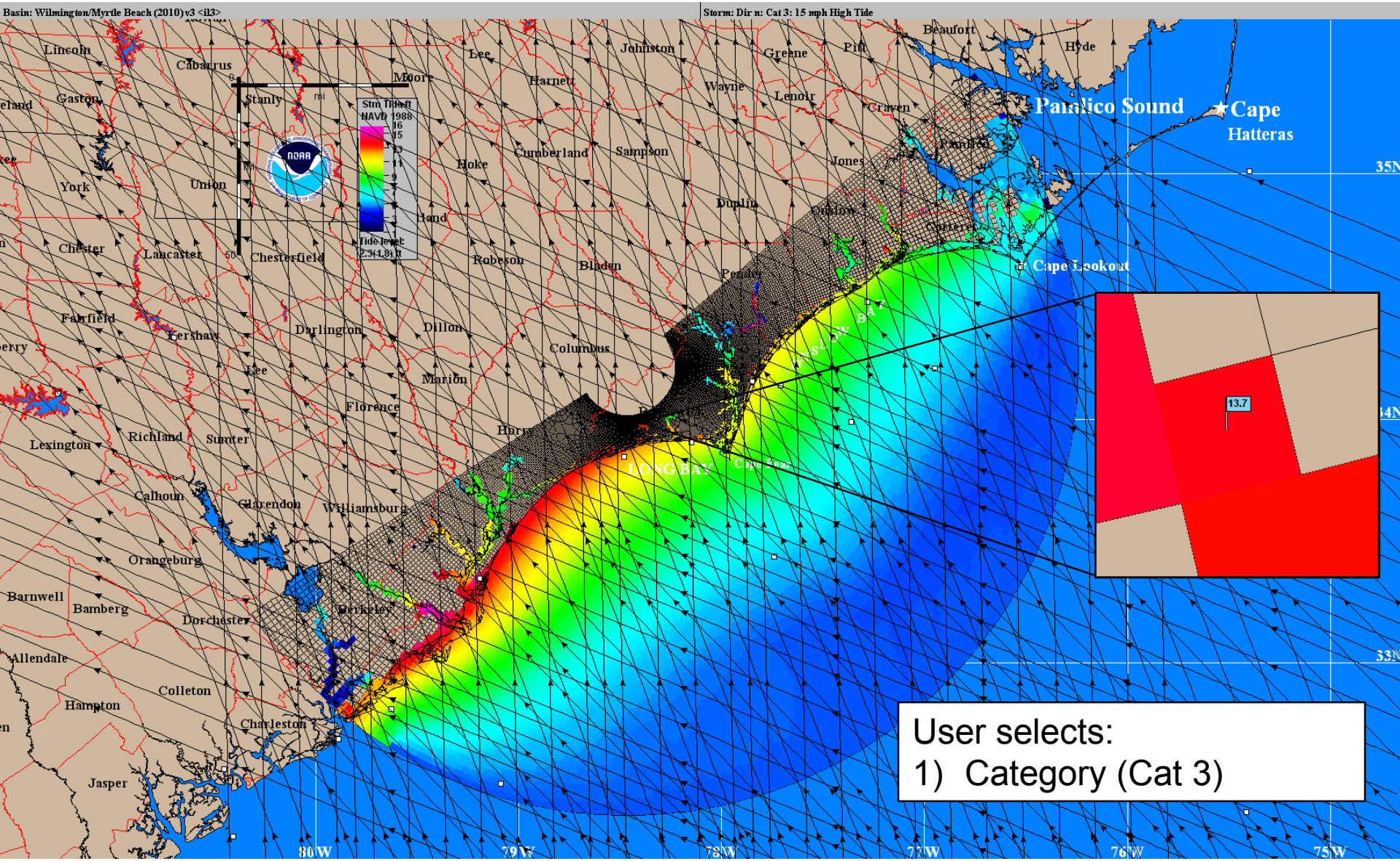
1) Category (Cat 3)

Maximum Of MEOWs (MOM)



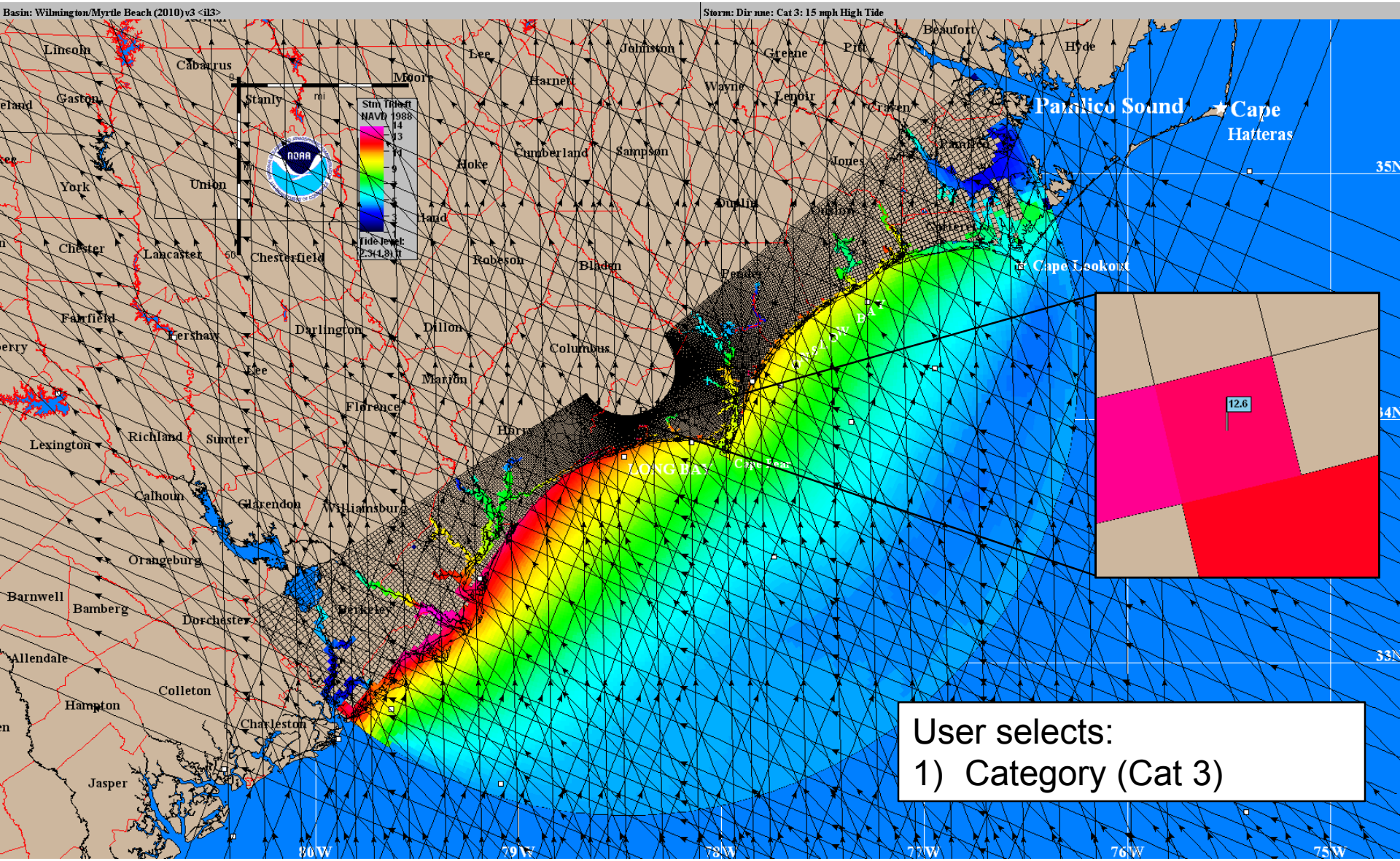
User selects:
1) Category (Cat 3)

Maximum **O**f **M**EOWs (**MOM**)



User selects:
1) Category (Cat 3)

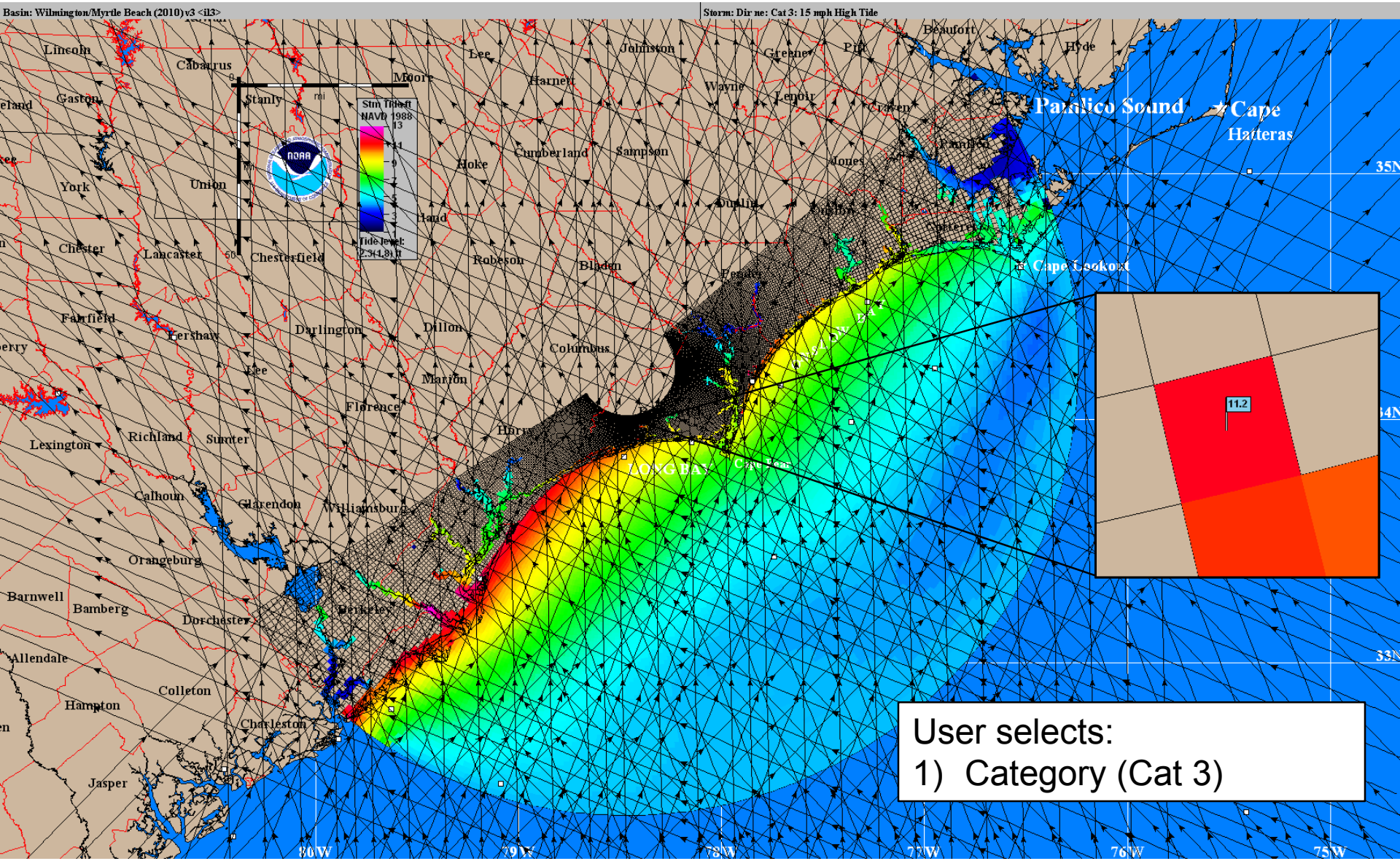
Maximum Of MEOWs (**MOM**)



User selects:

1) Category (Cat 3)

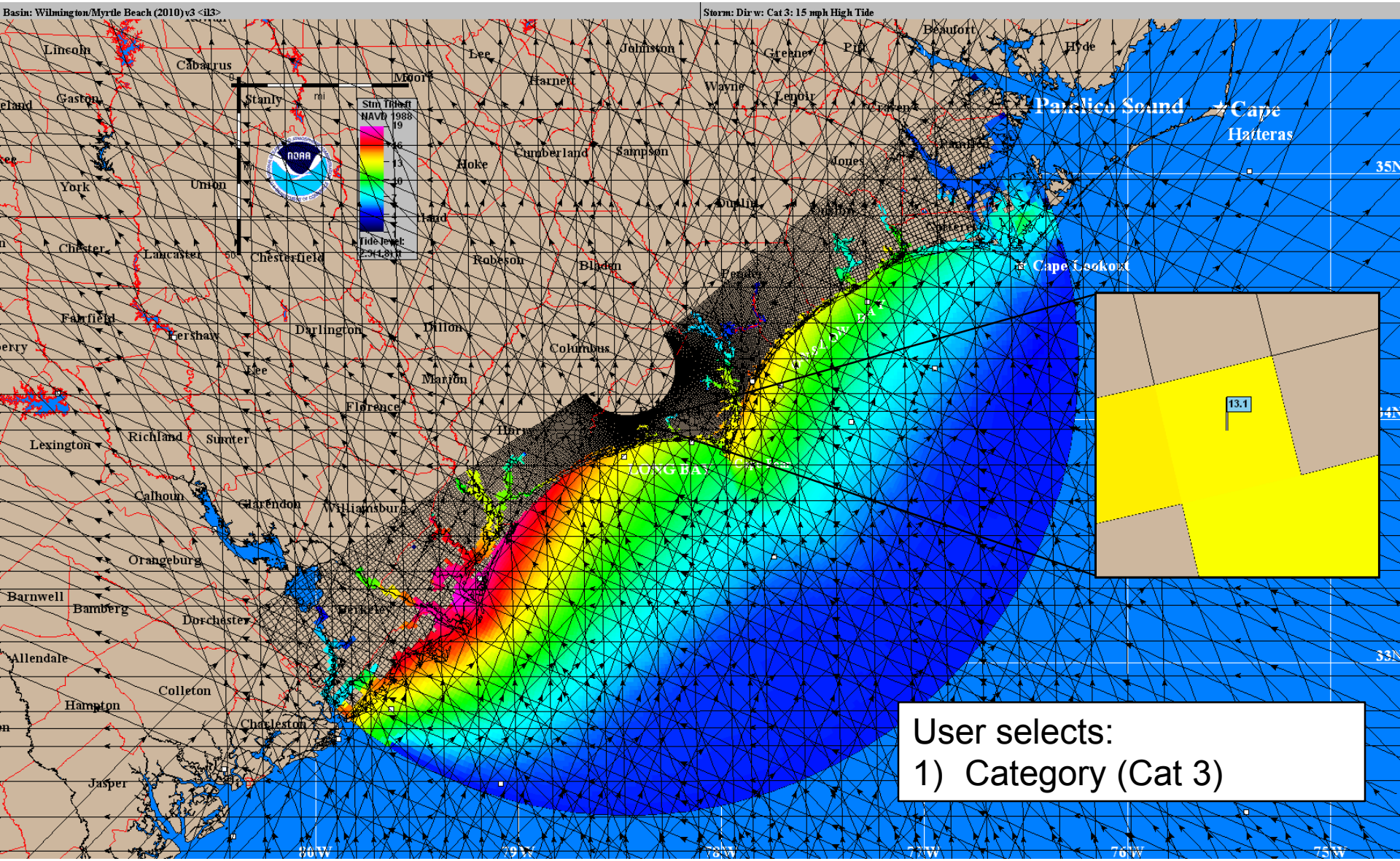
Maximum Of MEOWs (MOM)



User selects:

1) Category (Cat 3)

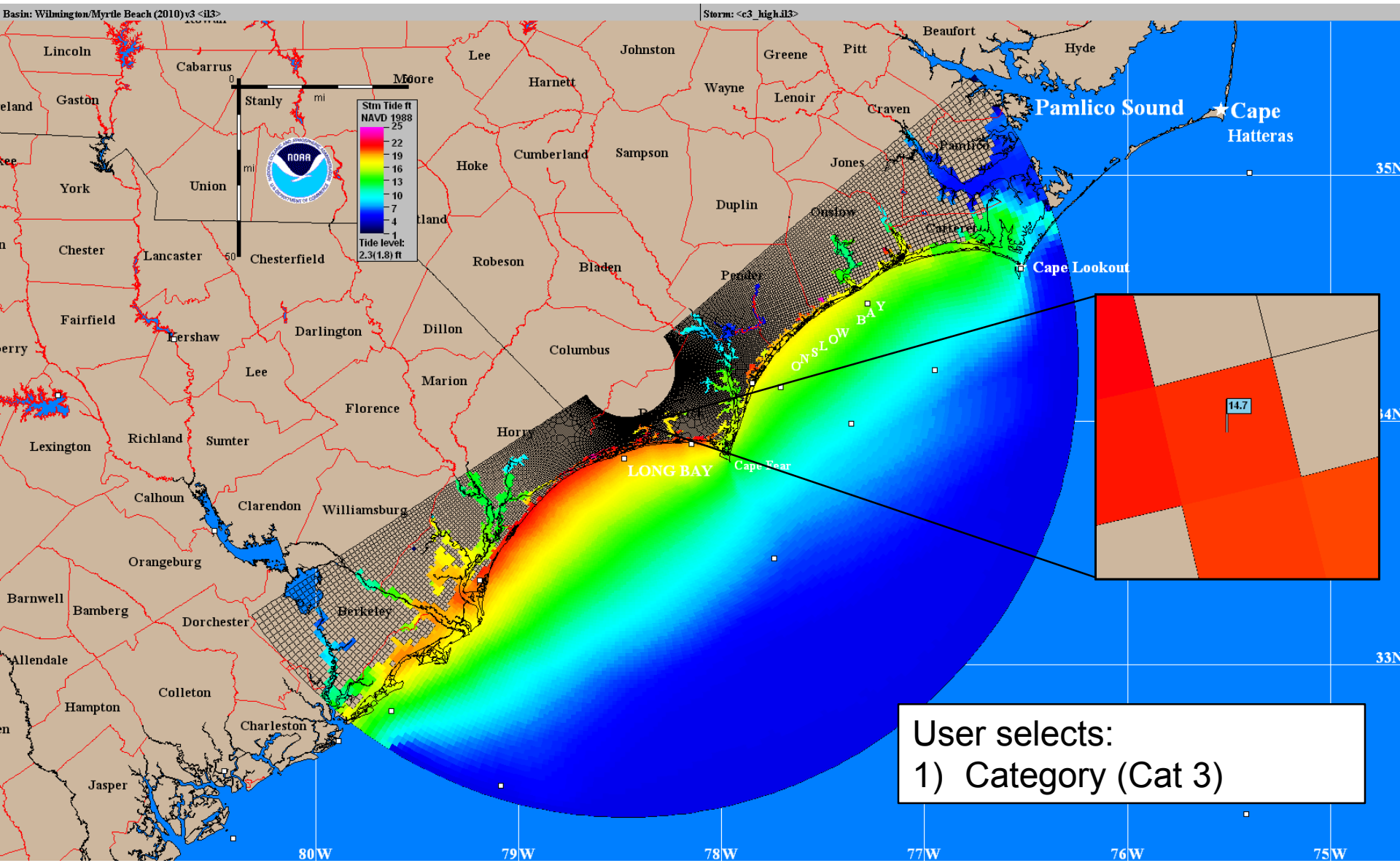
Maximum Of MEOWs (MOM)



User selects:

1) Category (Cat 3)

Maximum Of MEOWs (MOM)



User selects:
1) Category (Cat 3)

U.S. National Hurricane Program

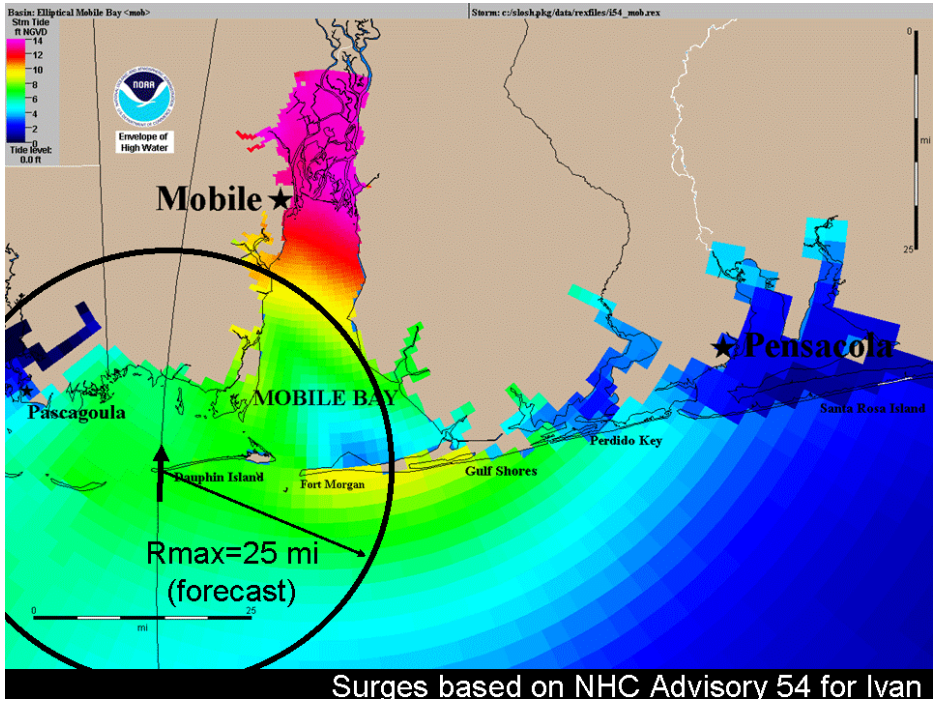
Step 1	Step 2	Step 3	Step 4	Step 5
Basin Build: Basin grid and data are modified to reflect recent changes NWS (MDL/NHC)	**Stability Test:** Basin undergoes extensive QA/QC process NWS (NHC)	**Simulation Runs:** MEOWs and MOMs are created NWS (NHC)	**Evacuation Plans:** MEOWs and MOMs are combined with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

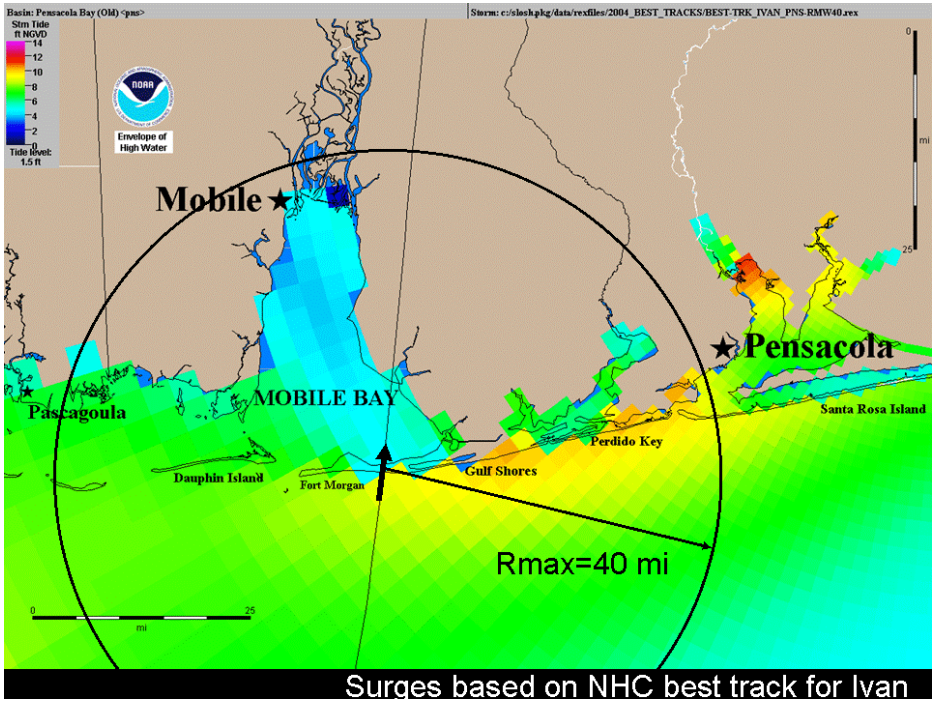
Run from the water, Hide from the wind

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.)

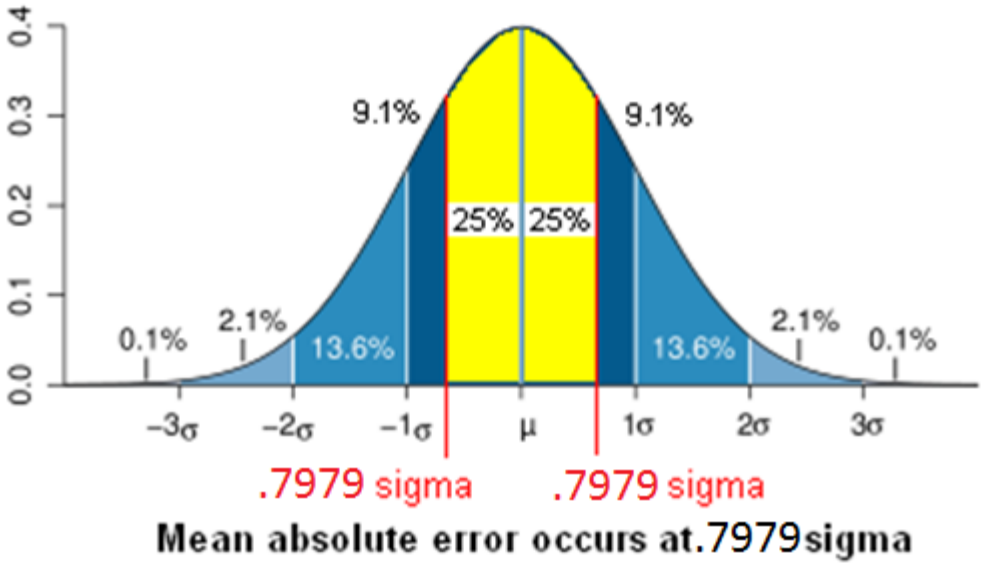




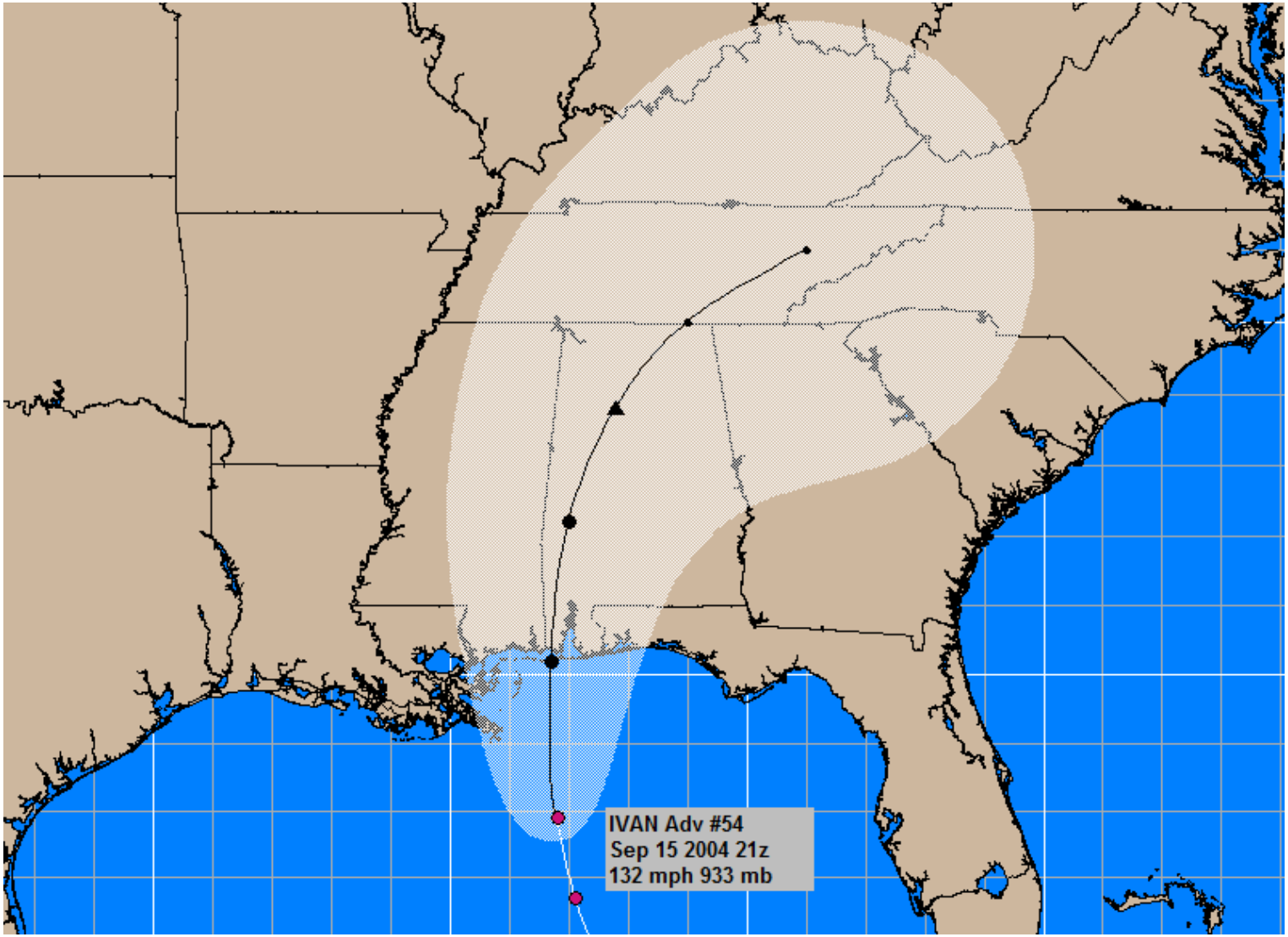
Example: Ivan 2004 – Advisory 54
12-hr before landfall.

Probabilistic Tropical Storm Surge (P-Surge) Error Distributions

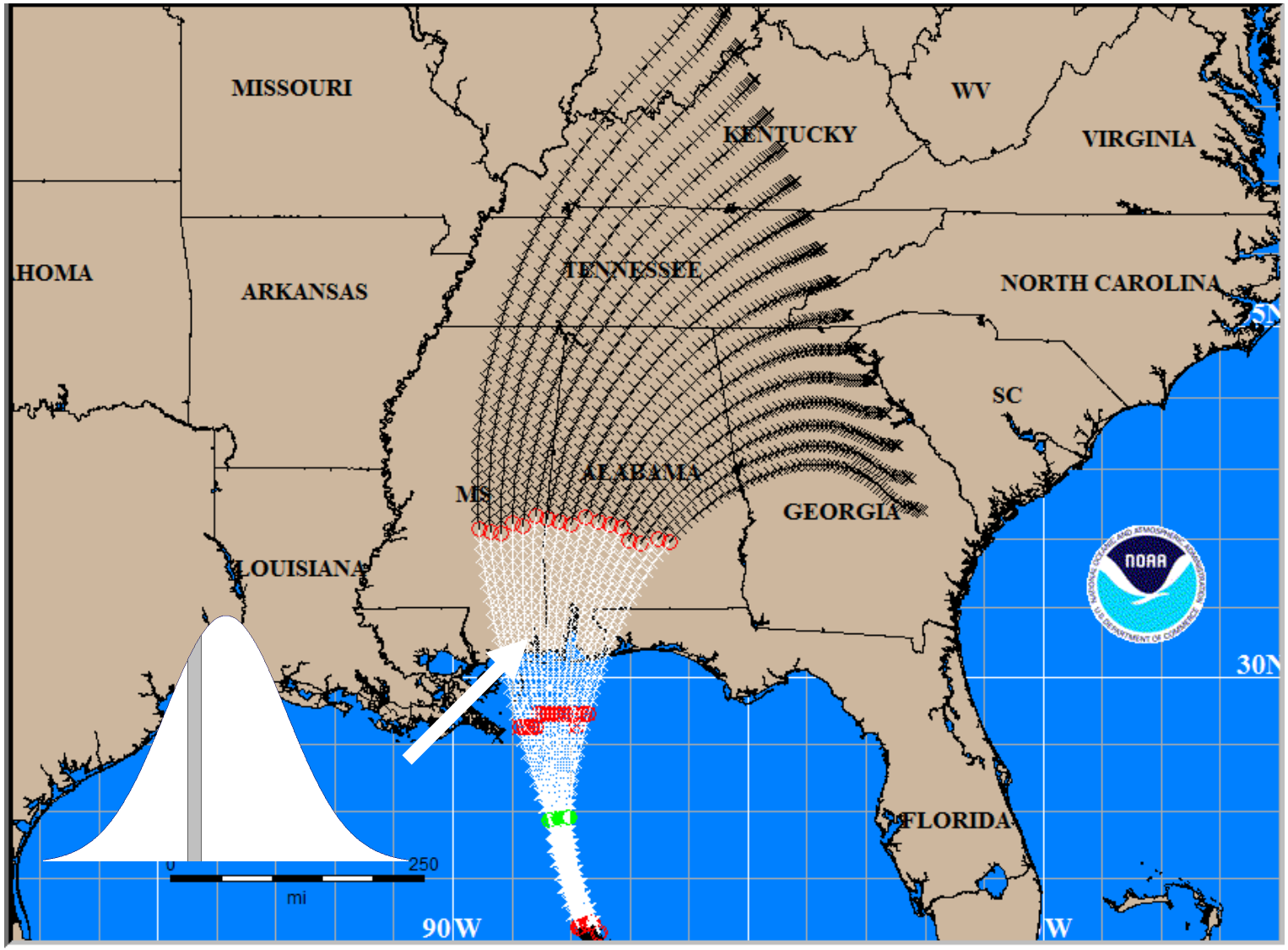
- Error distributions are computed for cross track, along track and intensity by:
  - Assuming a normal distribution
  - Using a 5-year “mean absolute error” and getting the standard deviation (sigma) from:



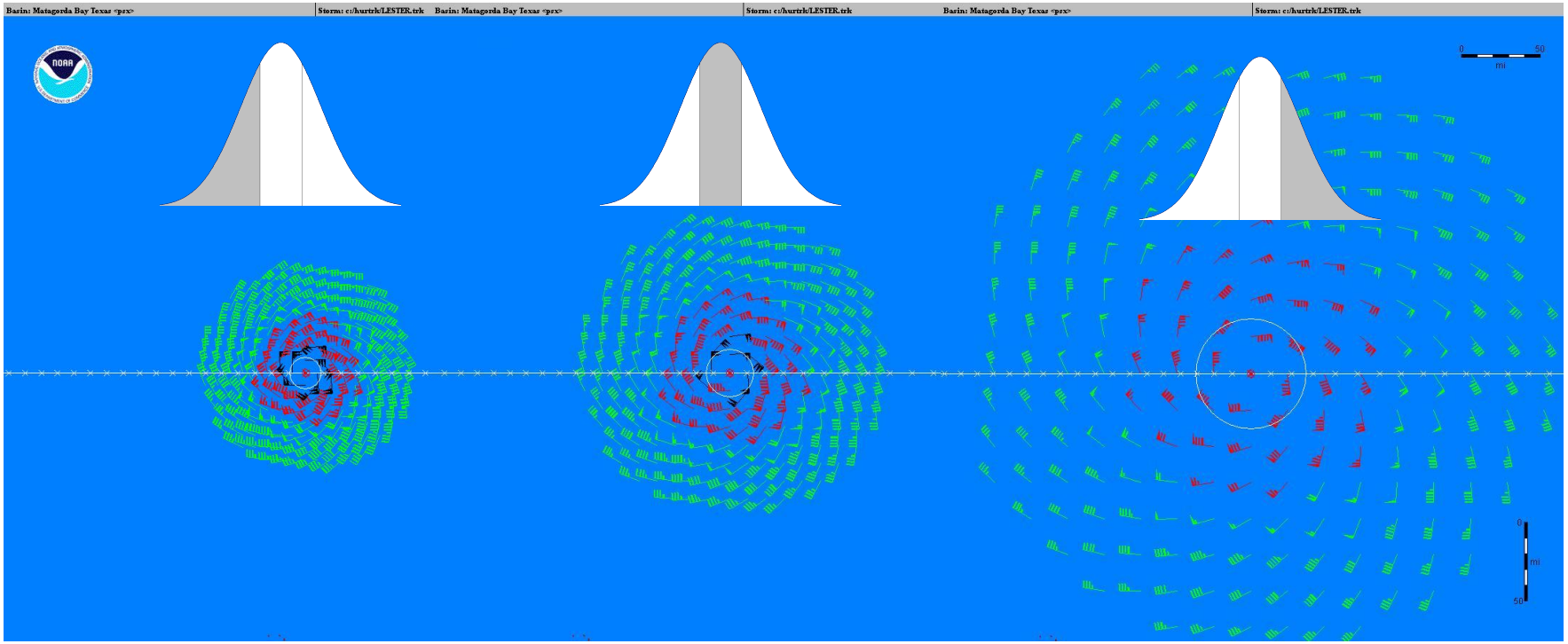
2004-Ivan - Advisory 54



P-Surge - Vary Cross Track



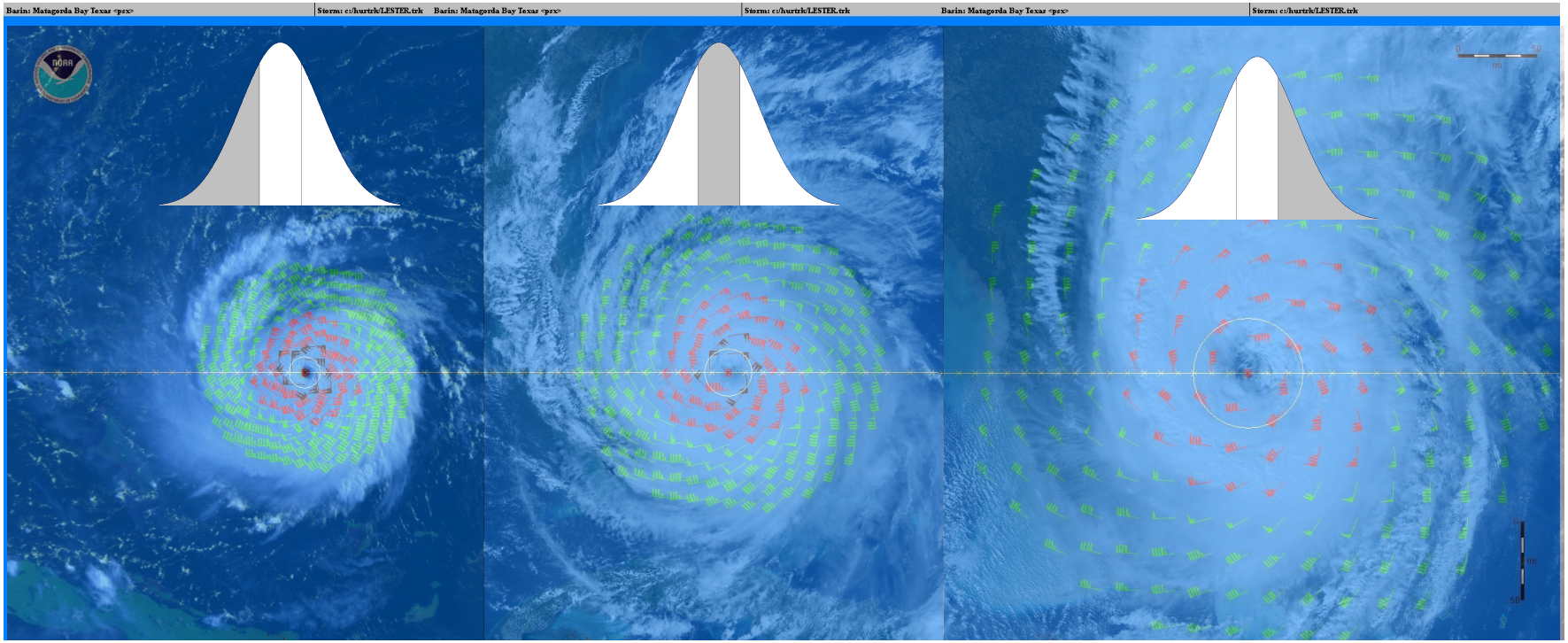
P-Surge – Vary Other Variables



- 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



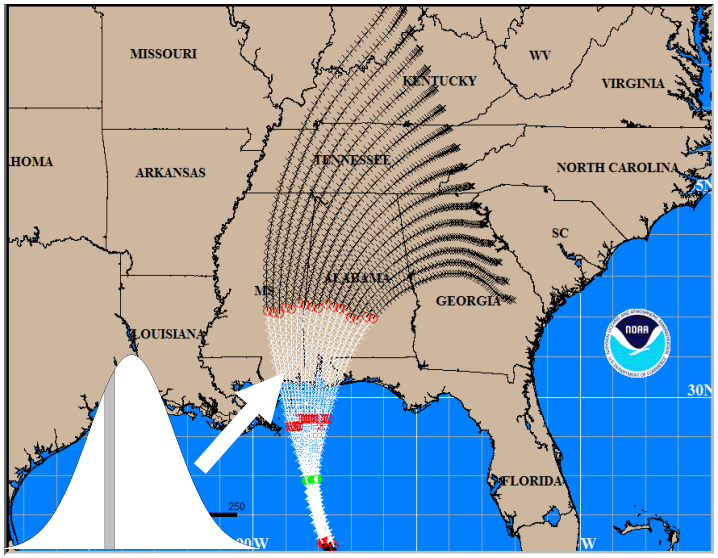
- Size: Small (30%), Medium (40%), Large (30%)
- Forward Speed (*): Fast (30%), Medium (40%), Slow (30%)
- Intensity: Strong (30%), Medium (40%), Weak (30%)

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

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

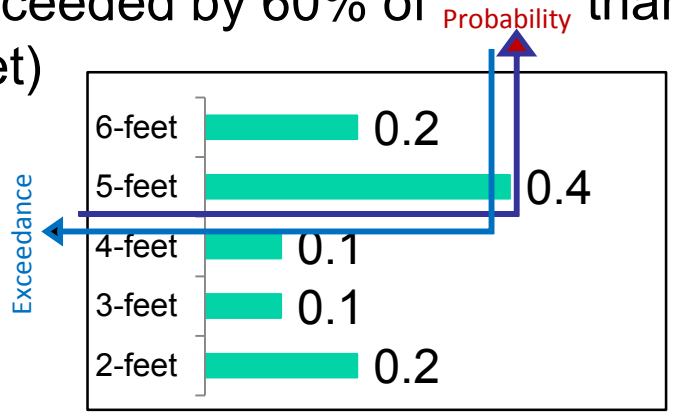


Solution: Suite of products derived from an ensemble of SLOSH runs

- 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

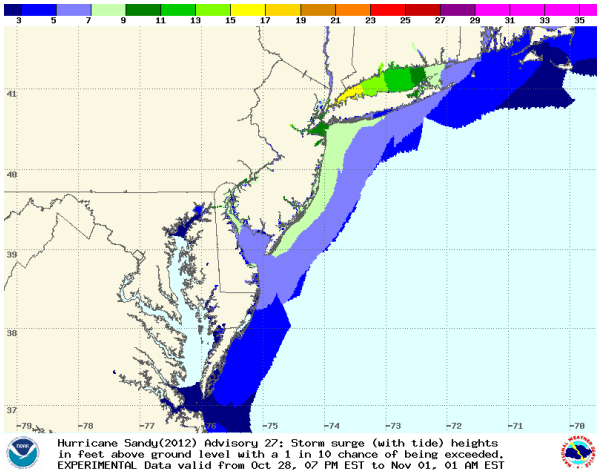
P-Surge Product Creation

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

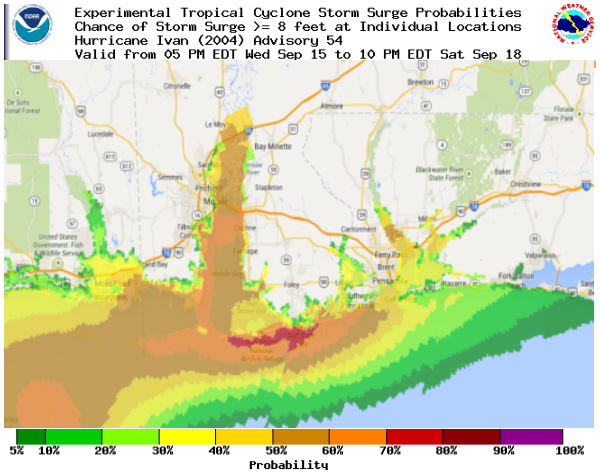


Probability of Surge: The probability of storm surge greater than X feet (e.g. probability of > 4 feet is 60%)

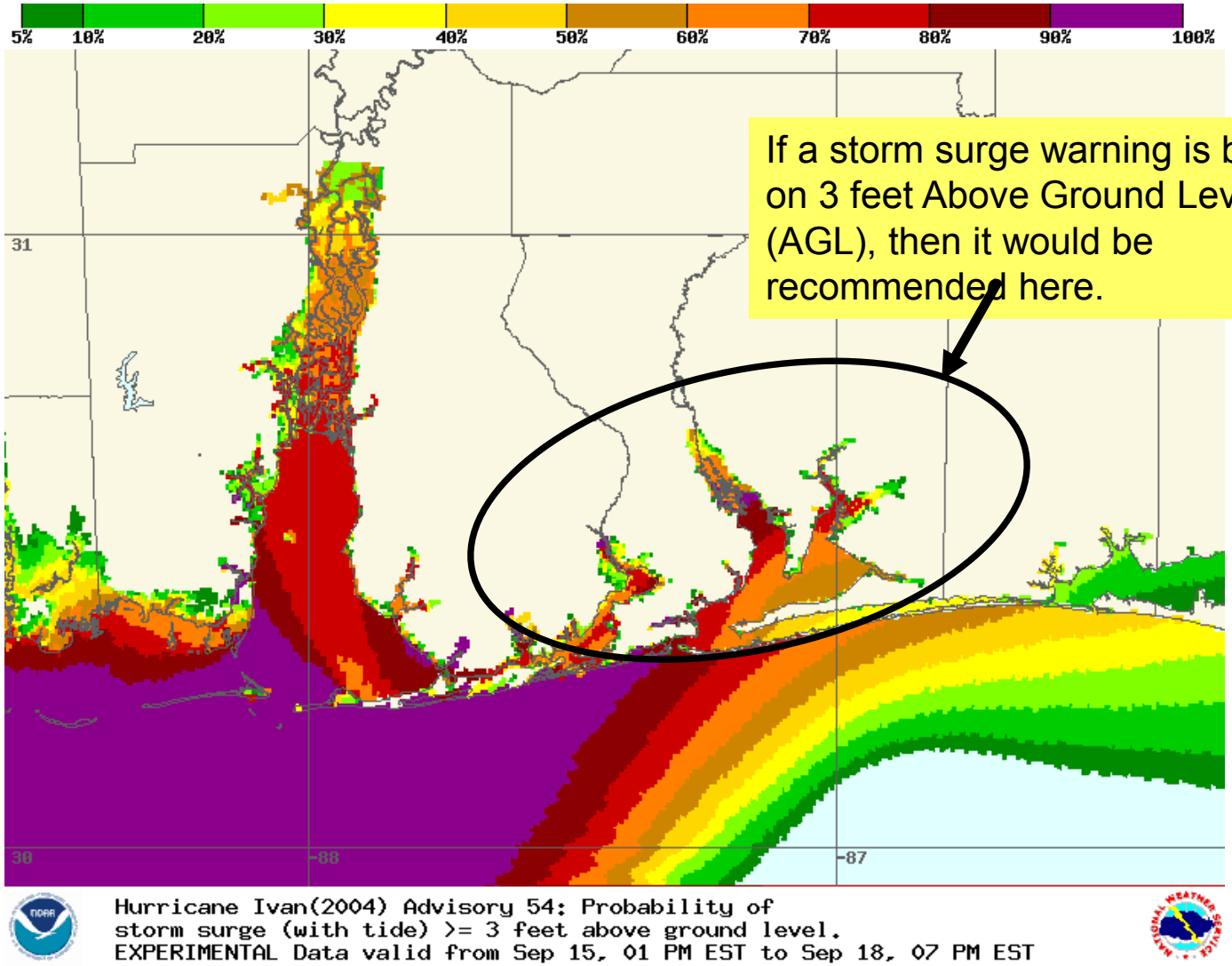
Use: Estimate water levels based on a specified risk tolerance



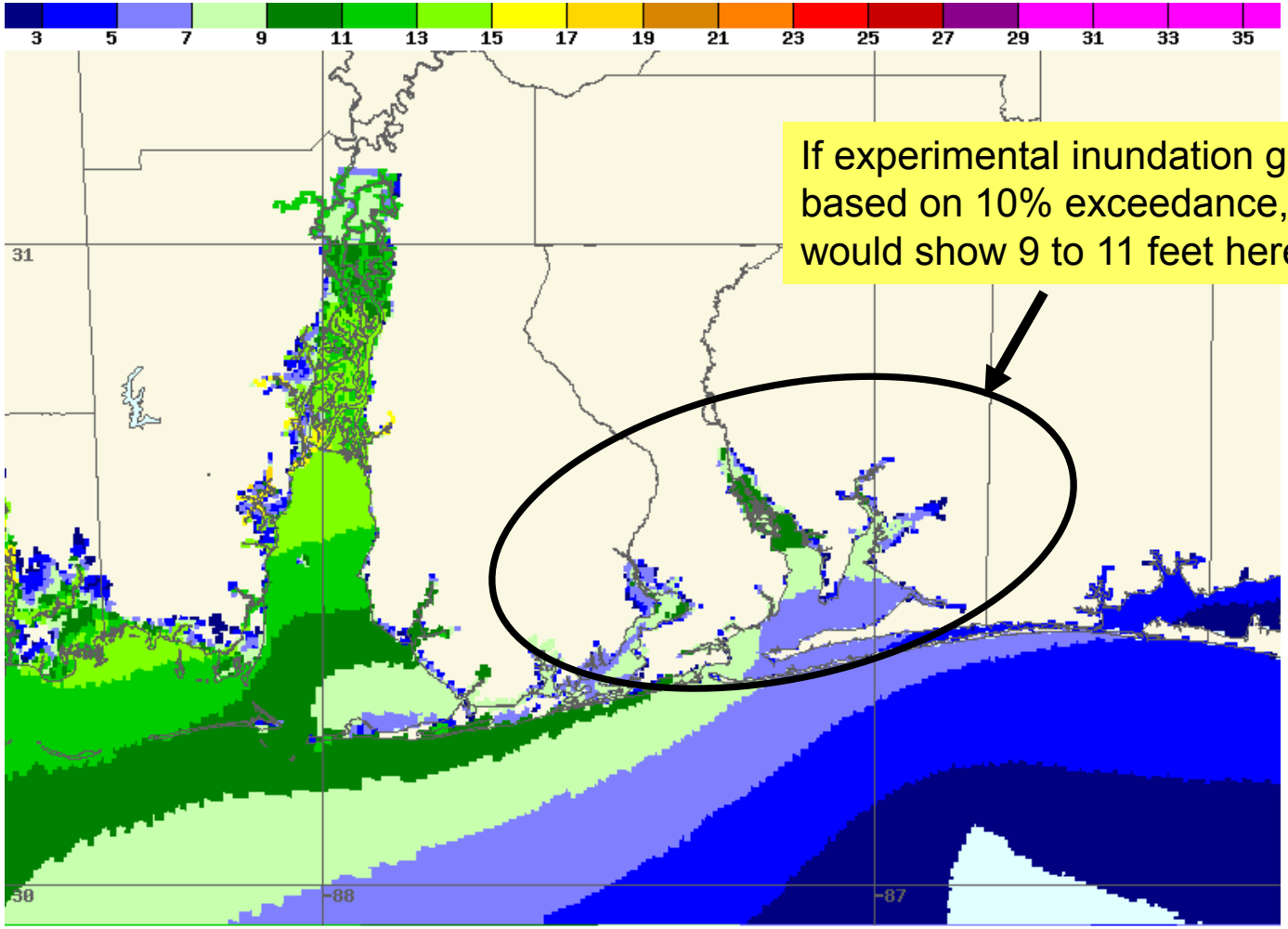
Use: Estimate risk at a specific site



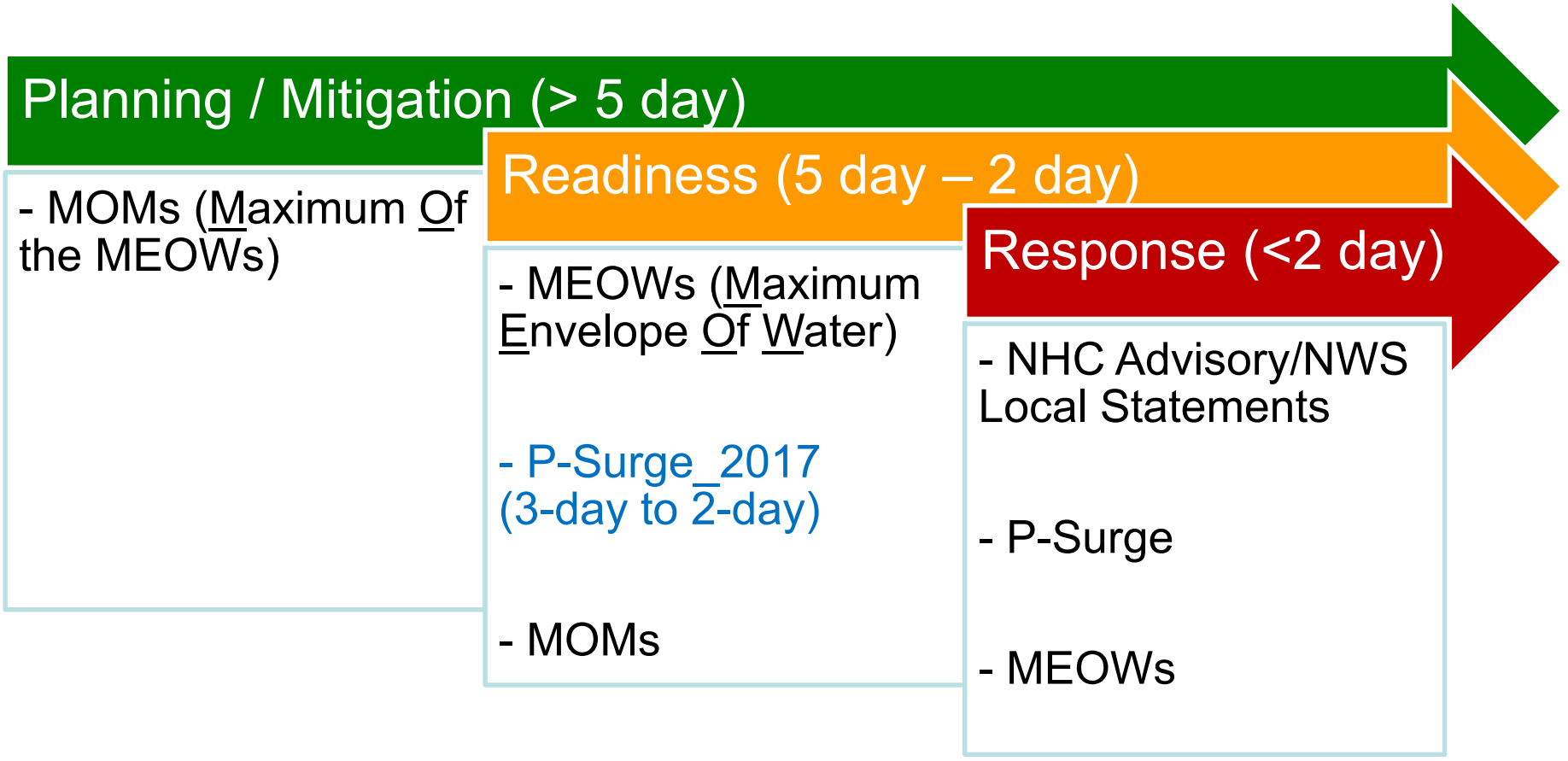
Storm Surge Warning Guidance
Probability of Surge + Tide > 3 feet AGL



Inundation Graphic Guidance
10% Exceedance of Surge + Tide AGL



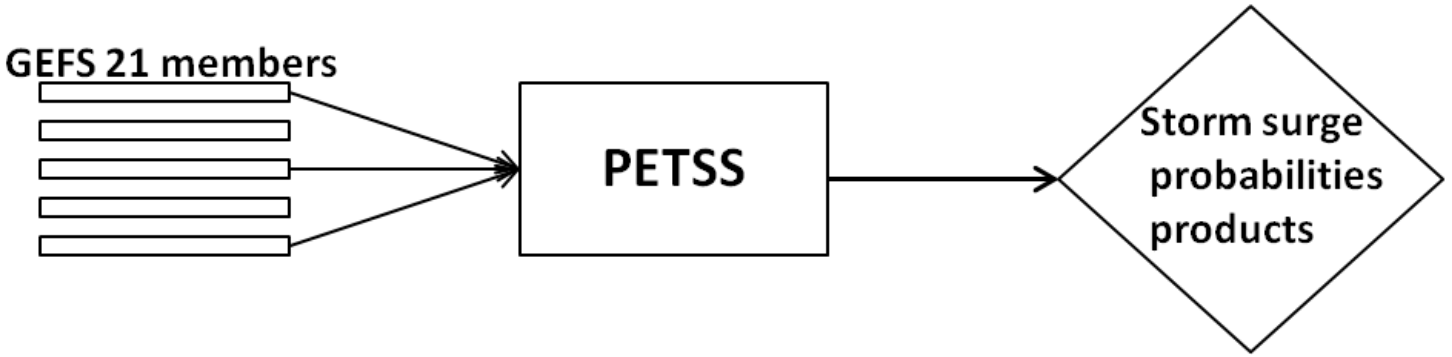
Tropical Guidance Timeline



(*) 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)

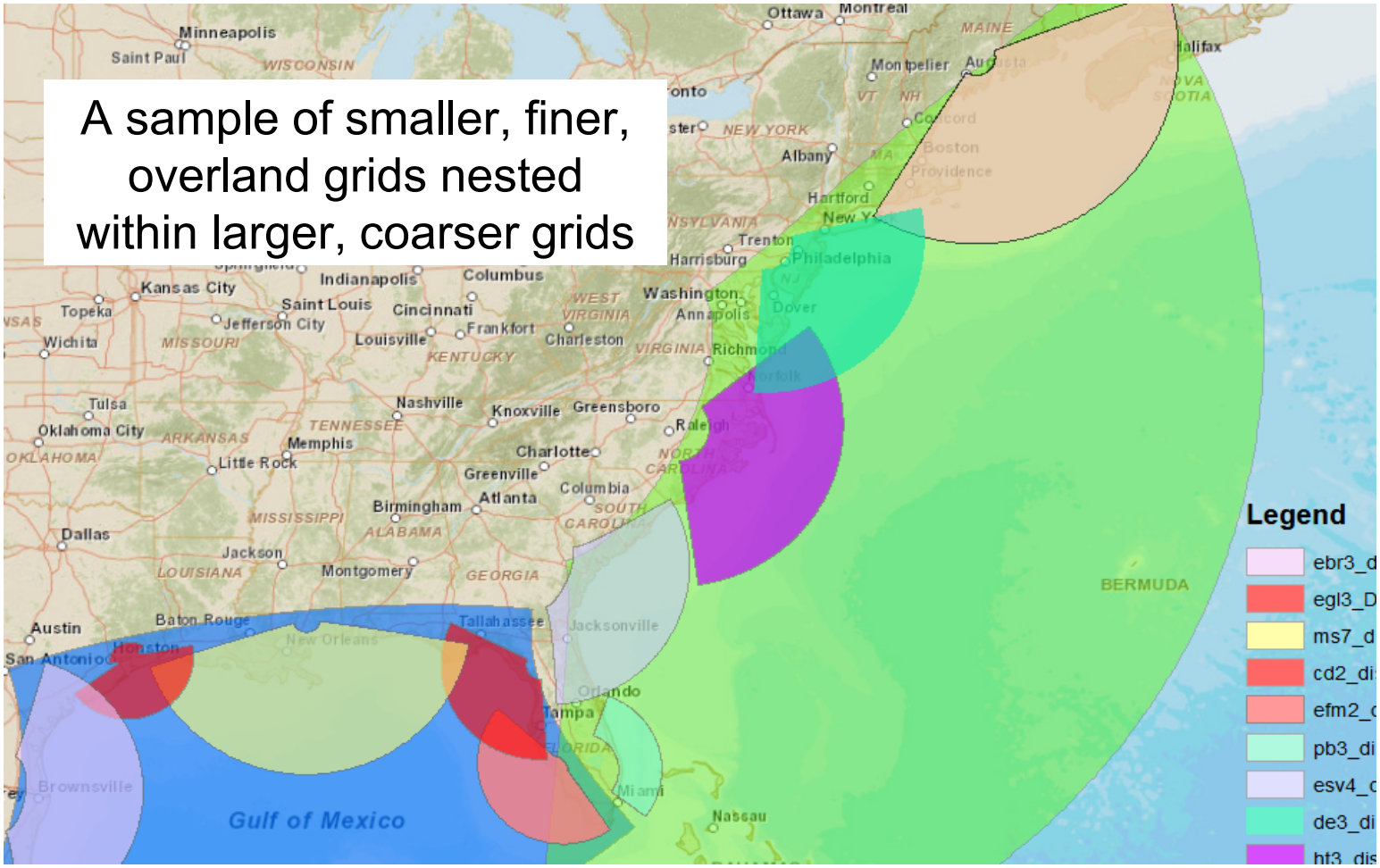


- ❖ 1.0 – Equally weight the ensemble members
- ❖ 1.0 – Use the 21 member Global Ensemble Forecast System (GEFS) as wind forcing
- ❑ Goal – Use the 42 member North American Ensemble Forecast System (NAEFS) as wind forcing

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

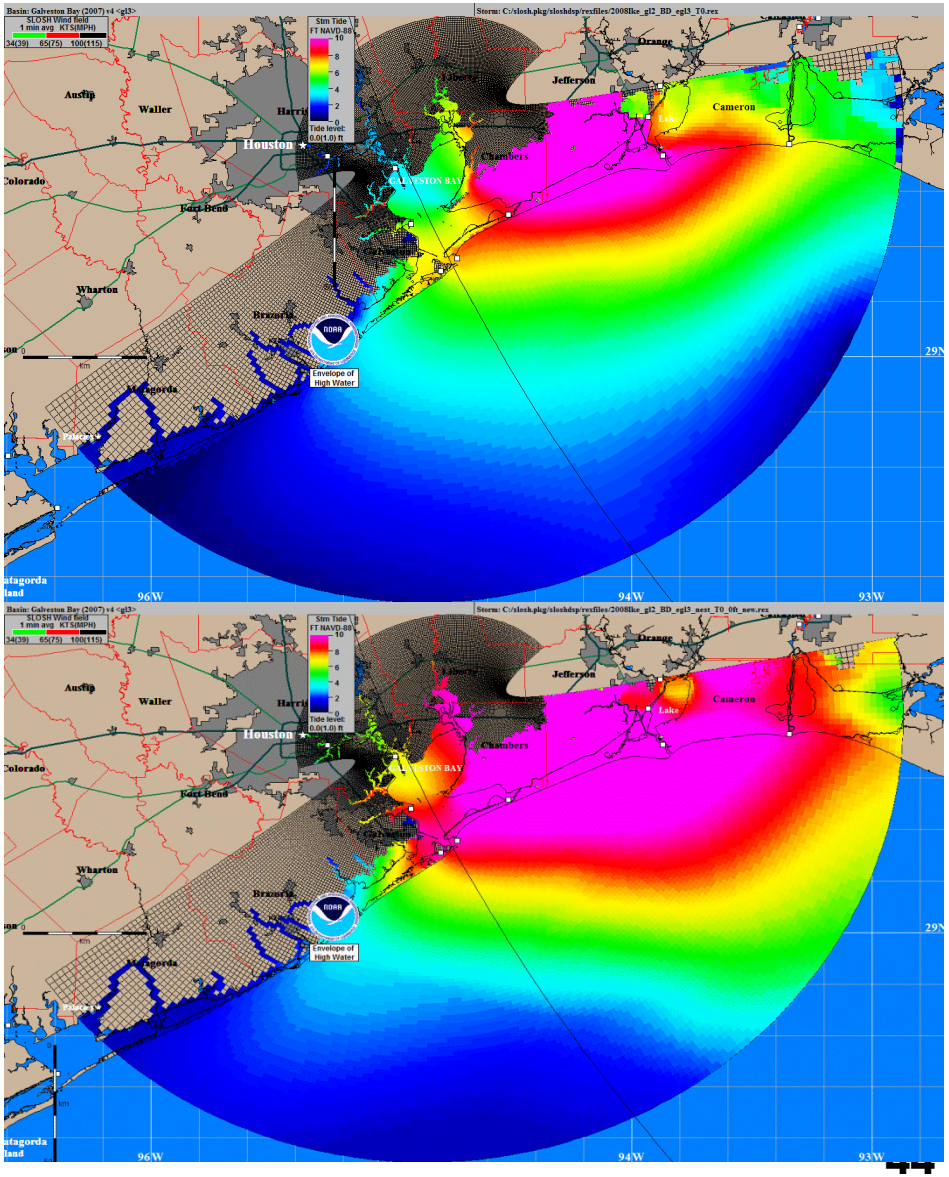
Solution: Nest smaller fine scale grids within the larger coarse grids



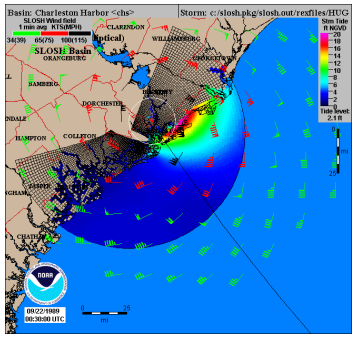
The Benefit of Nesting

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

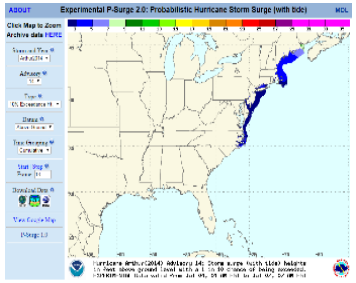


- **SLOSH Display Program**

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)

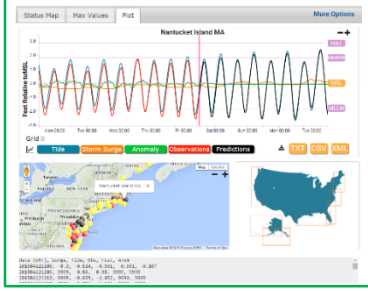


- **Probabilistic Tropical Storm Surge Guidance**

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