Ensemble Storm Surge Modeling

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Storm Surge Team Lead

NOAA/NWS/OSTI/MDL

Vulnerability

- Coastal areas are at increasing risk from sea-level rise and storm surge
  - Sea-level rise and storm surge place many U.S. coastal areas at increasing risk of erosion and flooding. Energy and transportation infrastructure and other property in coastal areas are very likely to be adversely affected (Global Climate Change Impacts in the U.S. 2009)
- Rising sea-level provides a higher "base" for future surge/inundation events thus producing an increasing threat to:
  - Coastal communities
  - Ecosystems (wetlands, critical species, habitat loss, etc)
  - Transportation systems (highway systems, ports, rail)
  - Economic viability (tourism, transport of goods, natural resources)
  - Energy

SLOSH Model

Input

Output

Pressure

Radius of Max Winds

Tidal Database

Location

Topography

Direction

Forward Speed

Bathymetry

Heights of Storm Surge + Tide

Camille

SPLASH	SLOSH	Tide

1970   1980   1990   2000   2010

3

Real Time Guidance
Deterministic Rex Files
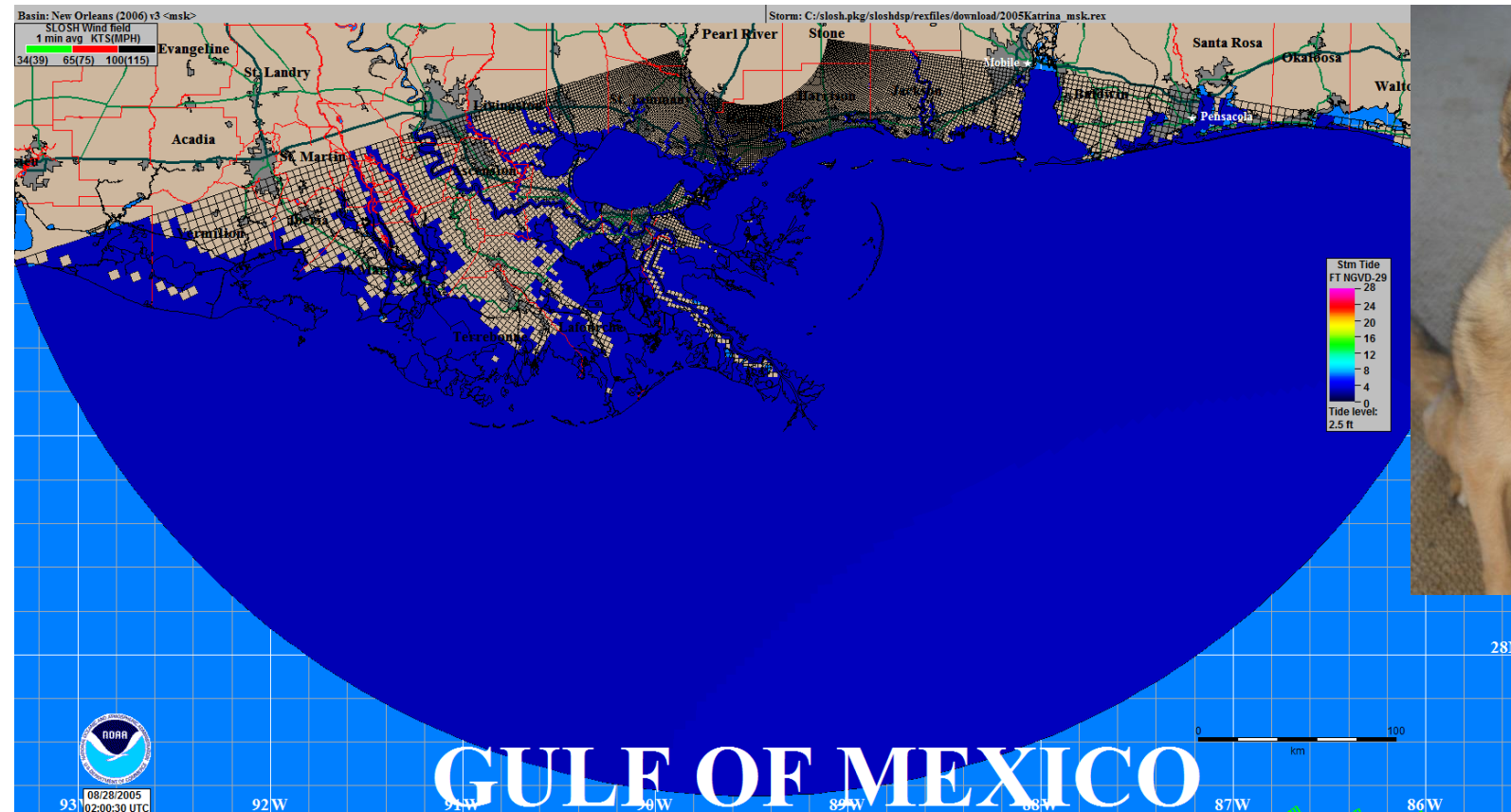
Largest Storm Surge Error?
Wind Input

NHC Official Annual Average Track Errors
Atlantic Basin Tropical Storms and Hurricanes
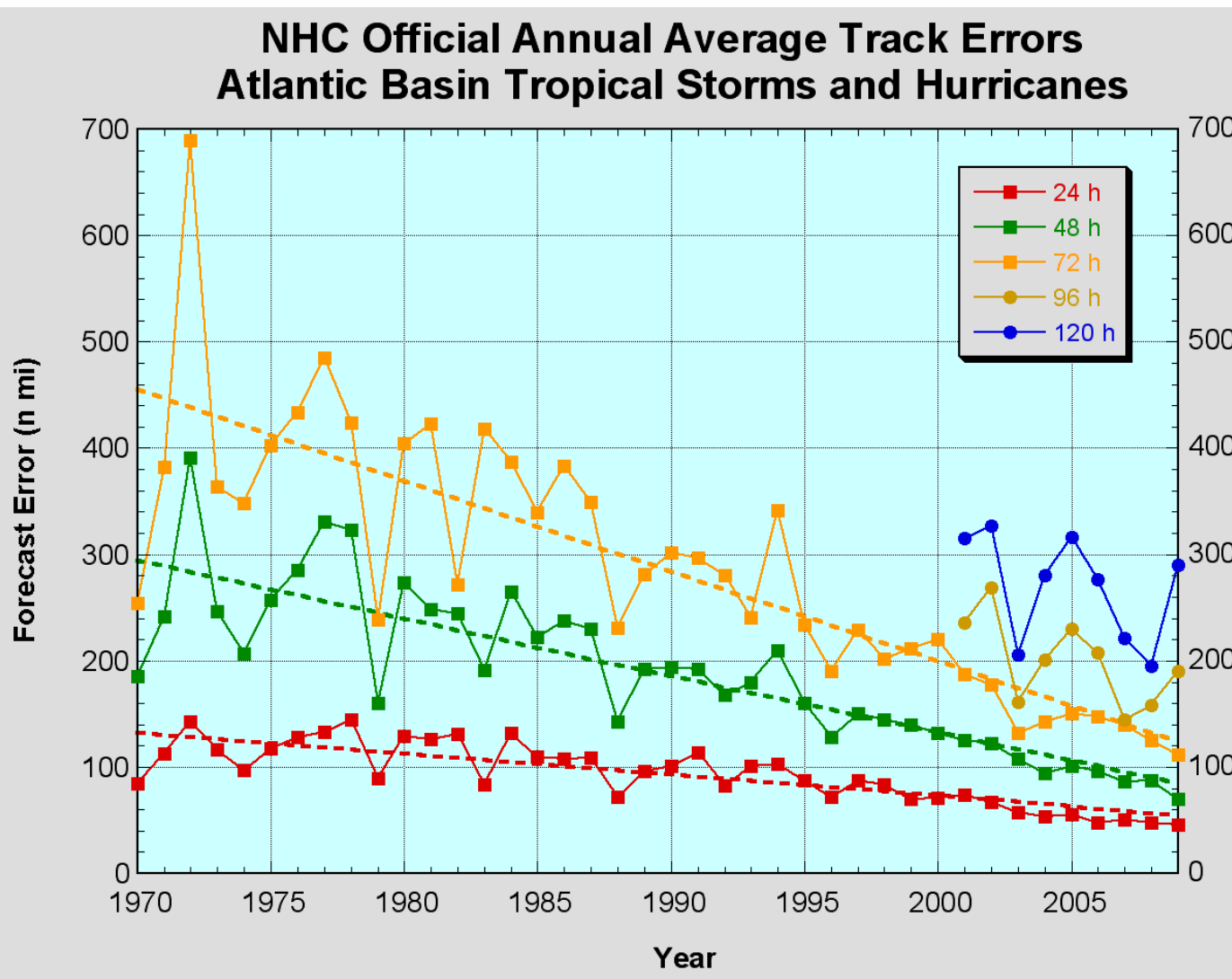
Climatological Ensembles (aka MEOWs and MOMs)

NHC Official Annual Average Track Errors
Atlantic Basin Tropical Storms and Hurricanes

Legend:
- 24 h
- 48 h
- 72 h
- 96 h
- 120 h
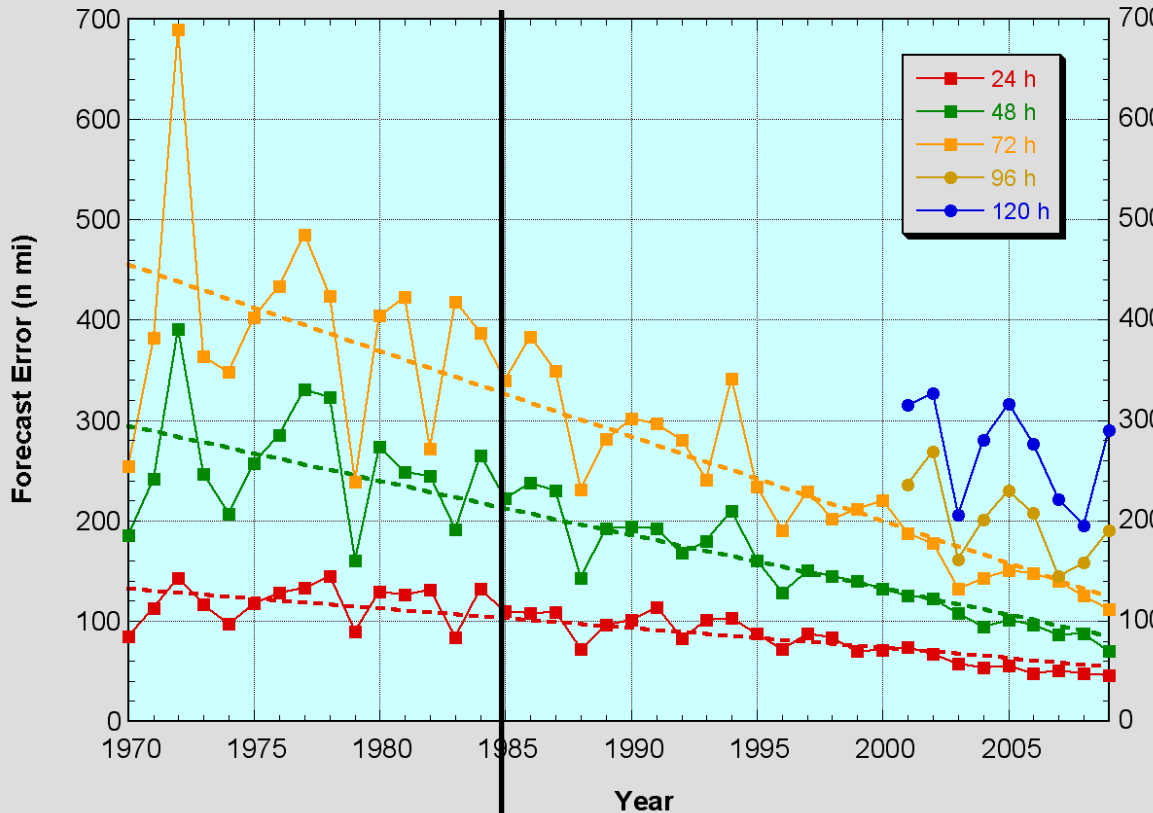
In 1986, due to the uncertainty in the forecast of 1985-Elena:

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

MDL developed MEOW and MOM products to represent the "potential" Storm Surge risk.
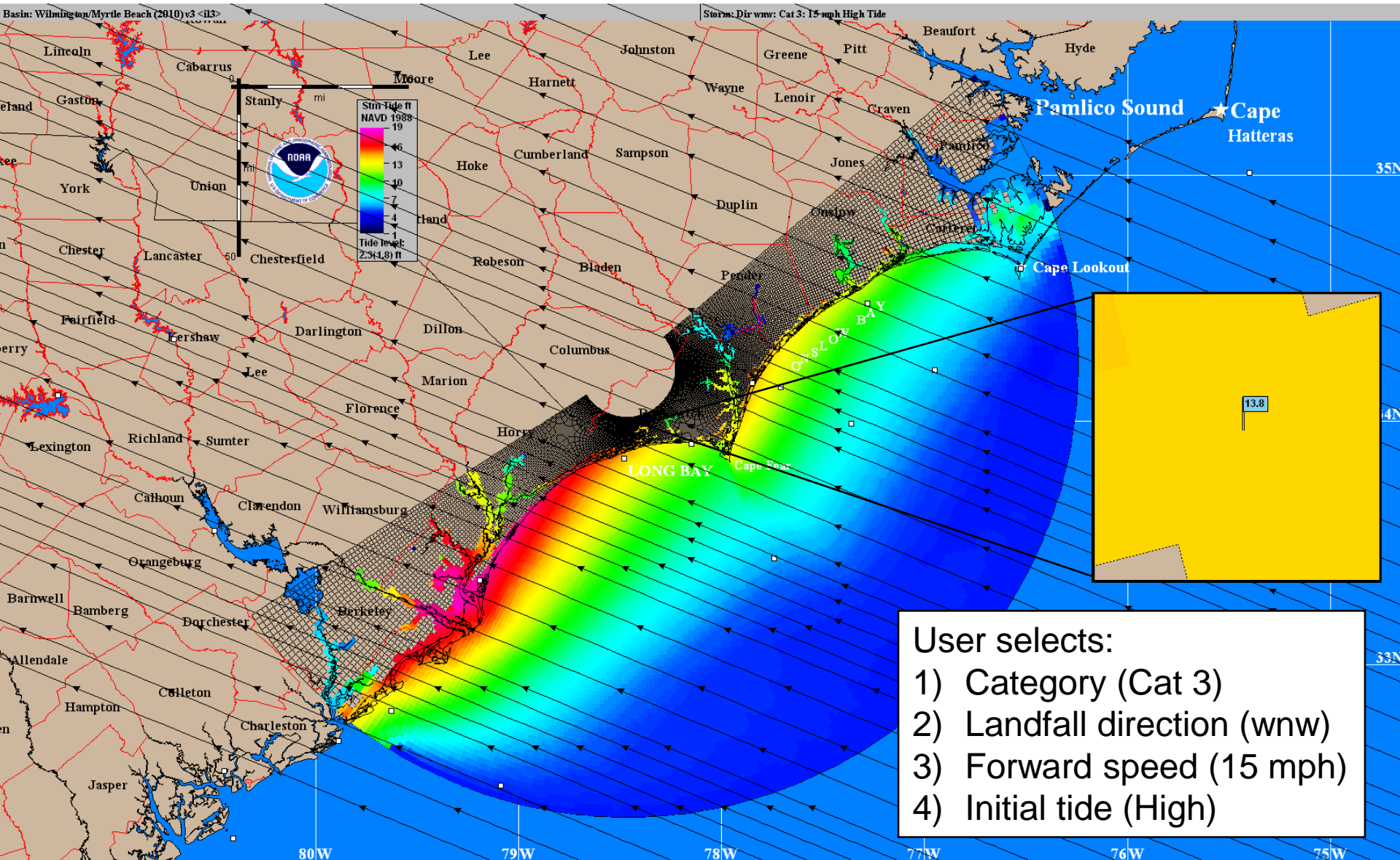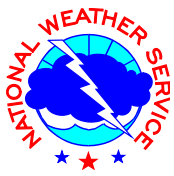
Camille

Elena

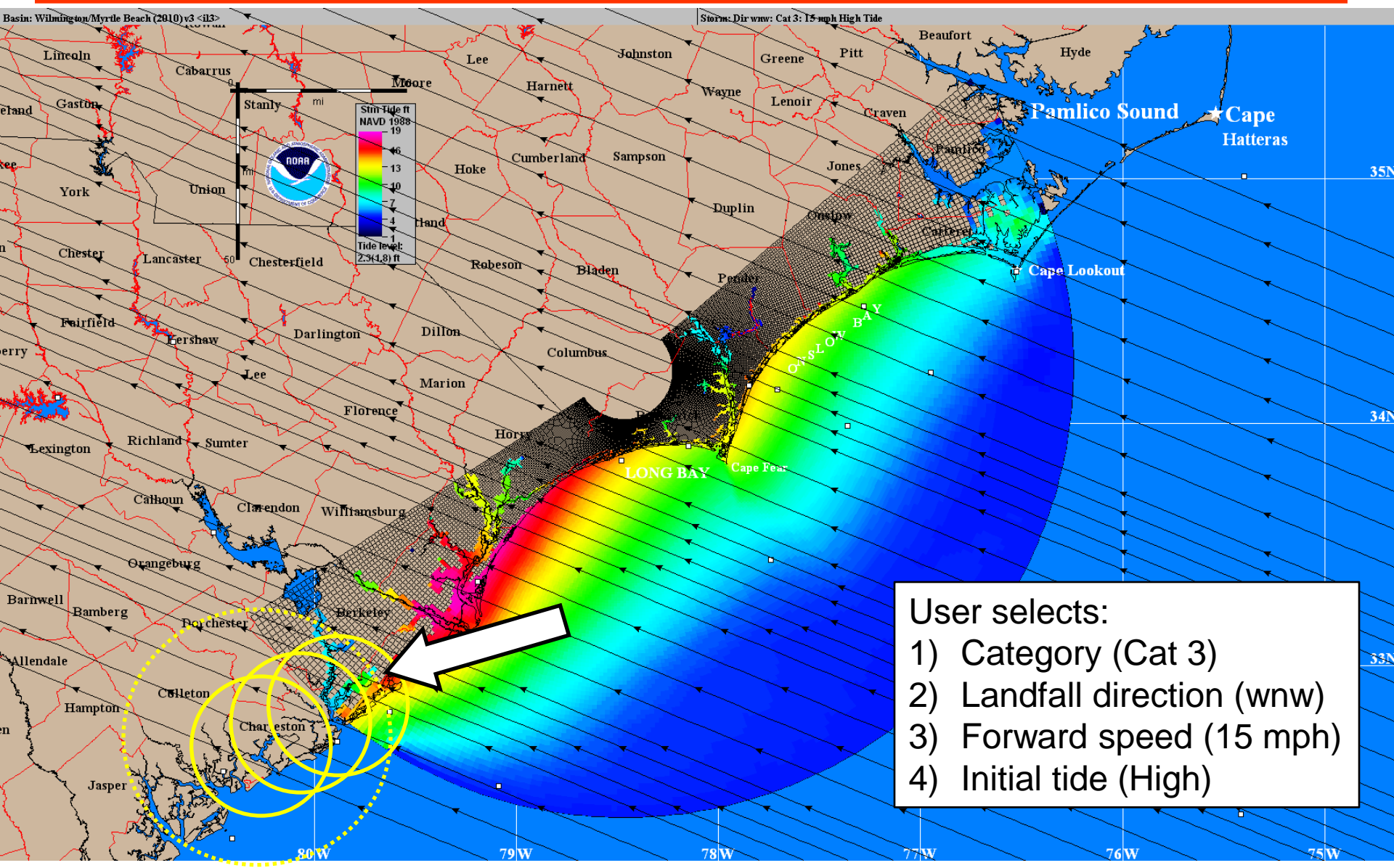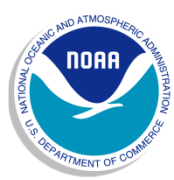SPLASH   SLOSH   Deterministic Rex Files

1970   1980   1990   2000   2010

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

Basin: Wilmington/Myrtle Beach (2010) v3 <il3>

Storm: Dir wnw: Cat 3: 15 mph High Tide

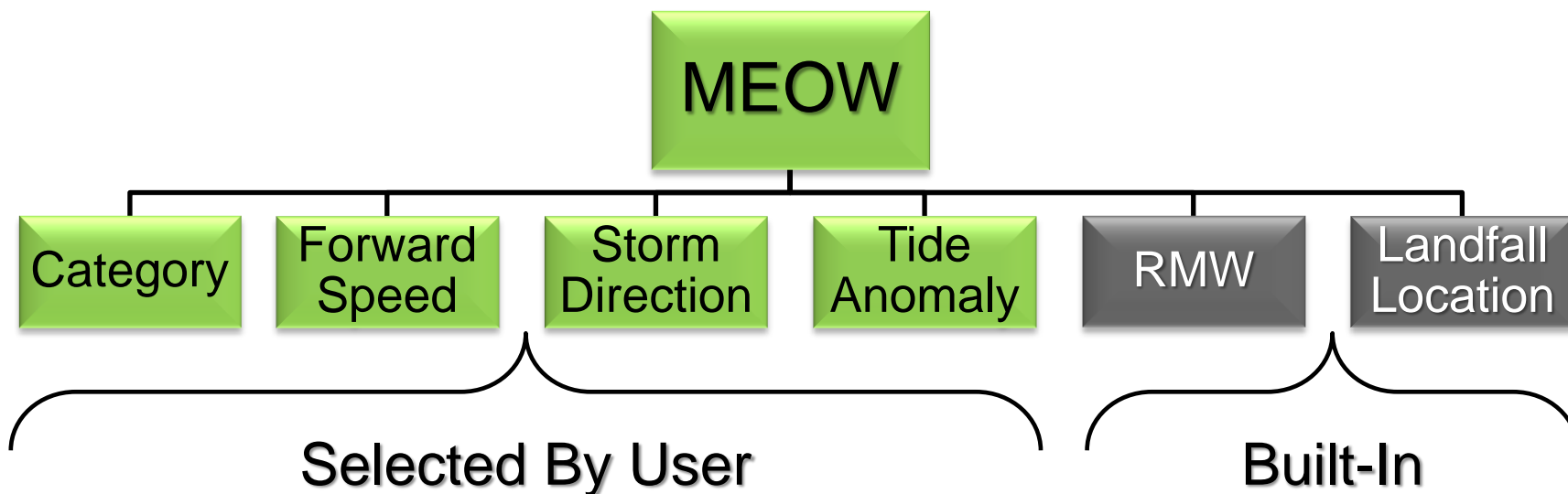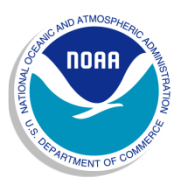Stm Tide ft
NAVD 1988

19
16
13
10
7
4
1

Tide level:
2.3(1.8) ft

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**)

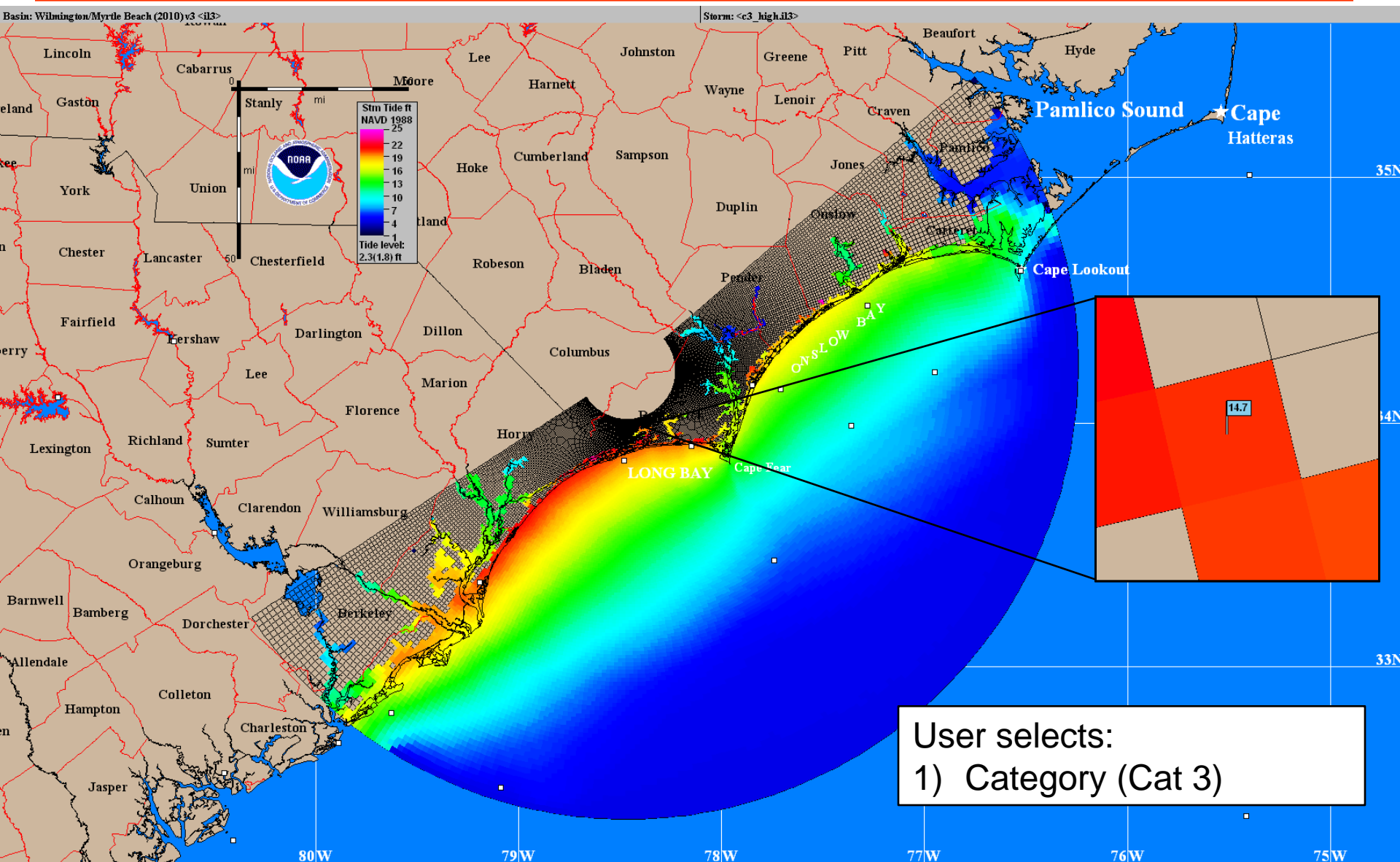Composite of the maximum storm surge for all surge simulations for a given set of parameters (by basin)

Used as guidance for planning and operations

```
                          MEOW

  Category   Forward    Storm     Tide      RMW    Landfall
             Speed    Direction  Anomaly            Location

        Selected By User                      Built-In
```

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

User selects:
1) Category (Cat 3)

Storm Surge Vulnerability: Category 4 Hurricane

Feet Above Ground Level

- 0 - 2
- 2 - 4
- 4 - 6
- 6 - 8
- 8 - 10
- 10 - 12
- 12 - 14
- 14 - 16
- 16 - 18
- 18 - 20
- 20 - 22
- 22 - 24
- 24 - 26
- 26 - 28
- 28 - 30
- >30
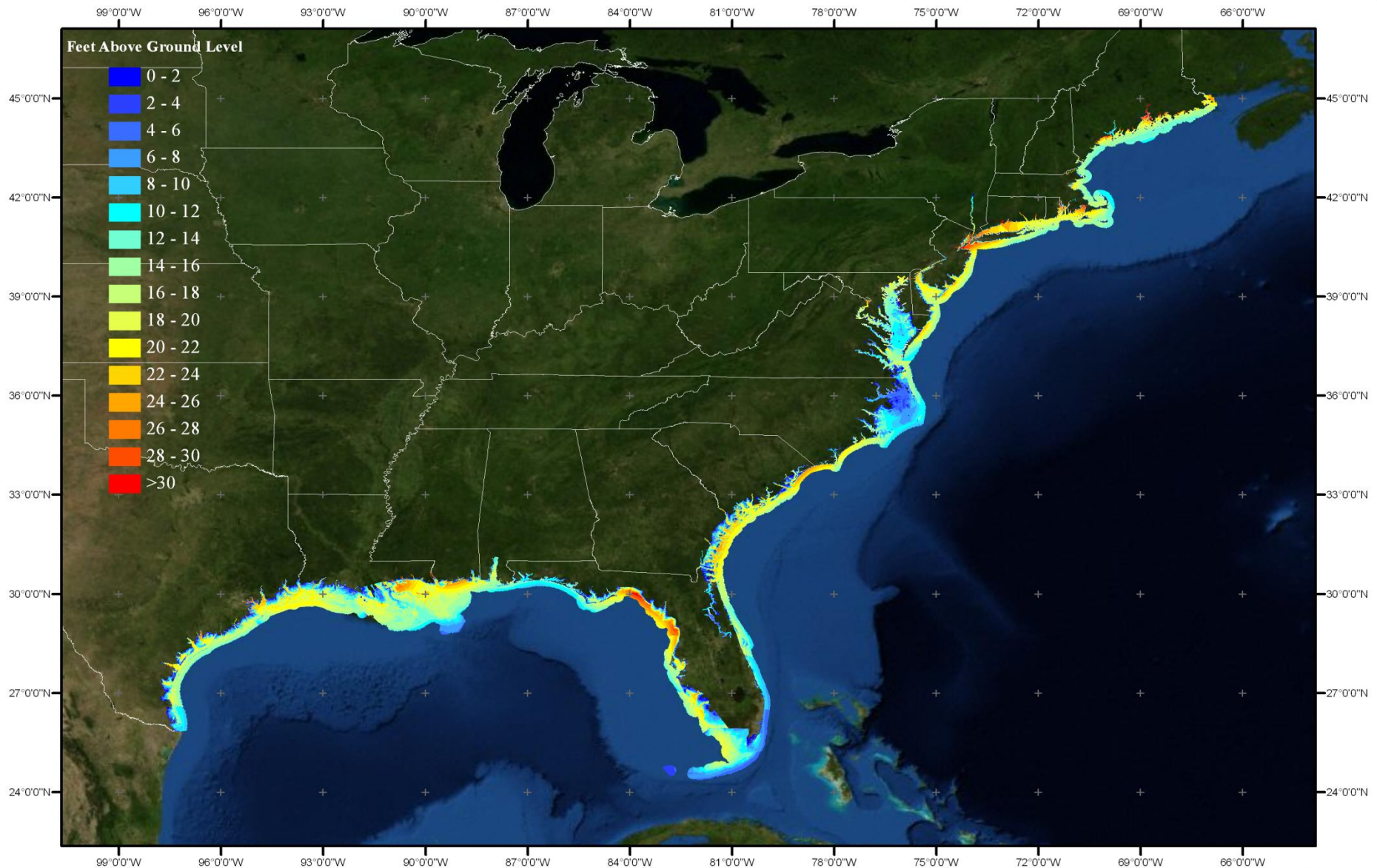
Data Source:
NWS/NHC/Storm Surge Unit

FOR EDUCATIONAL PURPOSES ONLY
NOT TO BE USED TO MAKE LIFE OR DEATH DECISIONS
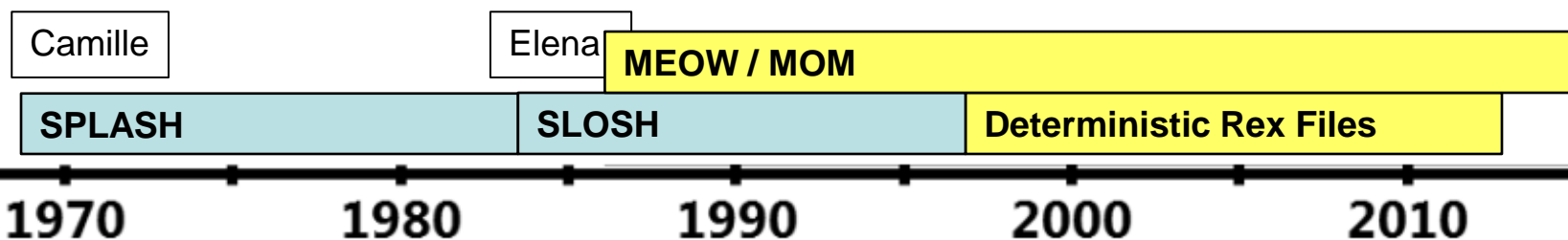
0 25 50 100 150 200
Miles
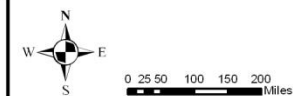
Communication
SLOSH Display Program (SDP)

The SLOSH Display Program is a Geographic Information System provided by NOAA to

1. Display **MEOWs and MOMs**
2. Animate **Deterministic Rex Files** (real-time and historic)
3. Determine vulnerability of critical locations
4. **Educate** Emergency Management and others

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

(User = Gustav2008 ; Pass = Ike2008)

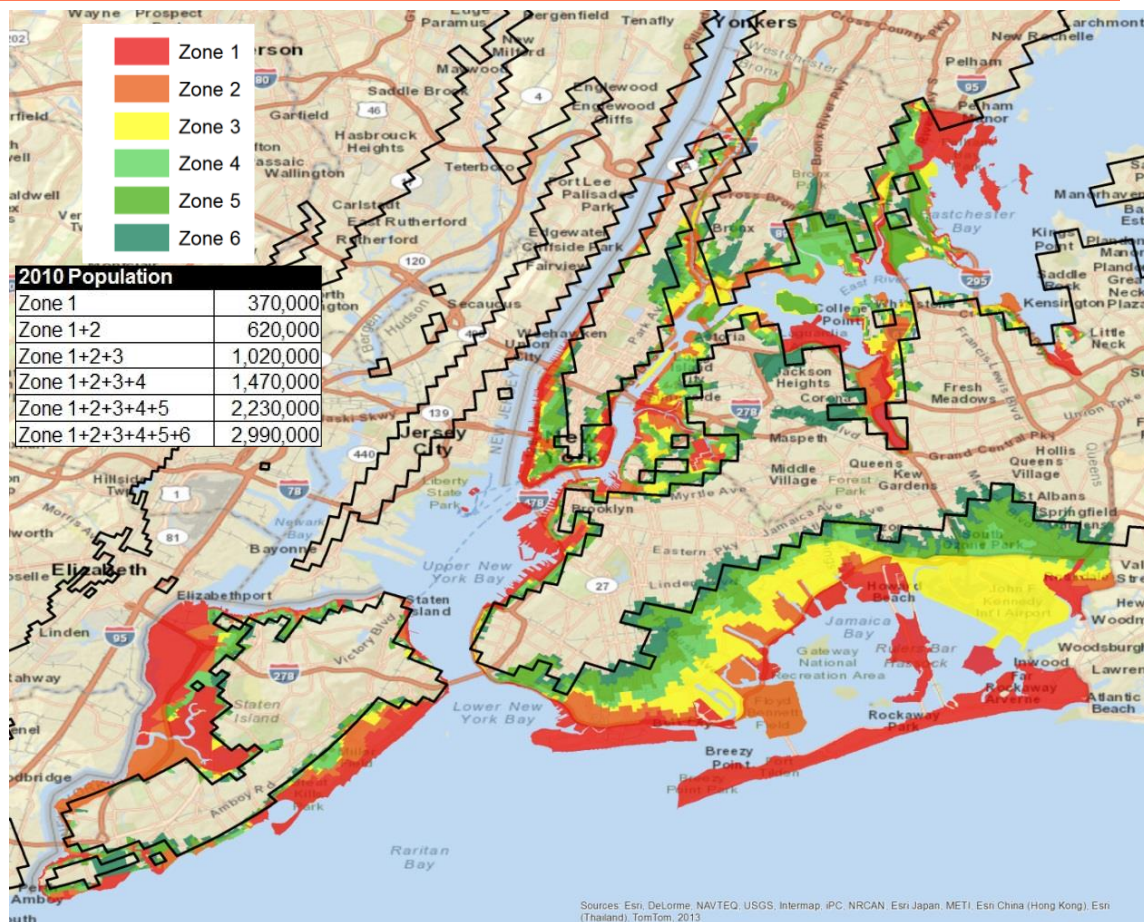| Camille		Elena	MEOW / MOM	
SPLASH		SLOSH	Deterministic Rex Files	

1970   1980   1990   2000   2010

U.S. Evacuation Plans
Run from the water, Hide from the wind

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

Risk = Hazard * Vulnerability

Legend:
- 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

Sources: Esri, DeLorme, NAVTEQ, USGS, Intermap, iPC, NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), TomTom, 2013

Camille

Elena

MEOW / MOM ➜ Evacuation Zones

SPLASH

SLOSH

Deterministic Rex Files

1970   1980   1990   2000   2010

Evacuation Planning Timeline

Build Basin	QA QC Basin	Simulation Study	Risk Analysis
Update basin to reflect recent changes	Extensive QA/QC process to validate stability	Run thousands of simulations to create MEOWs and MOMs	Make evacuation plans by combing hazard (MEOW/MOM) and infrastructure analyses
(4 to 6 months)	(4 to 6 months)	(6 months)	(~ 1 year)
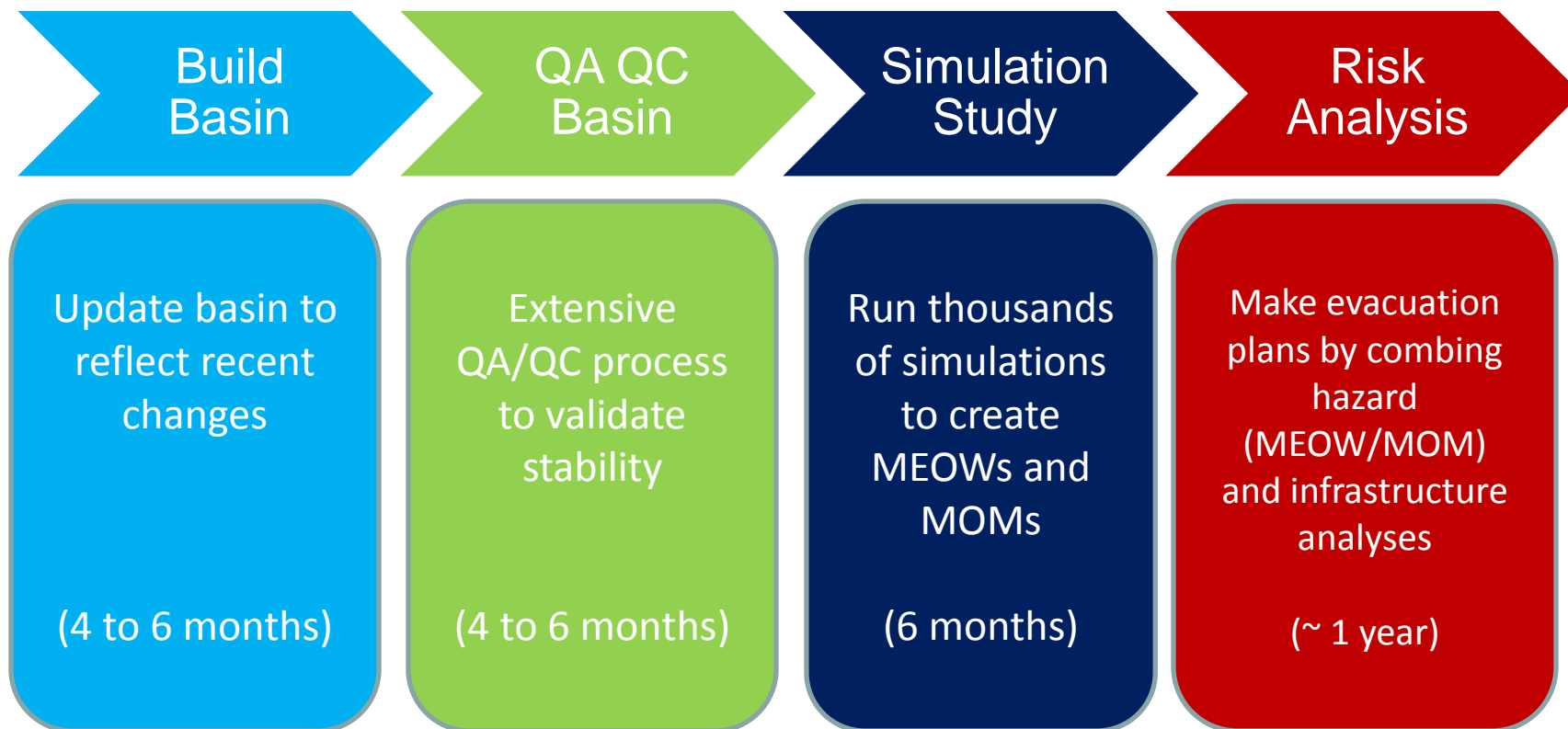
- From start to finish, updating a SLOSH basin can be **1 to 2 years** depending on complexity of updates, availability of data, and size of basin

- Evacuation study update can take **3 years** or more

MEOWs and MOMs
Based on SLOSH + SWAN
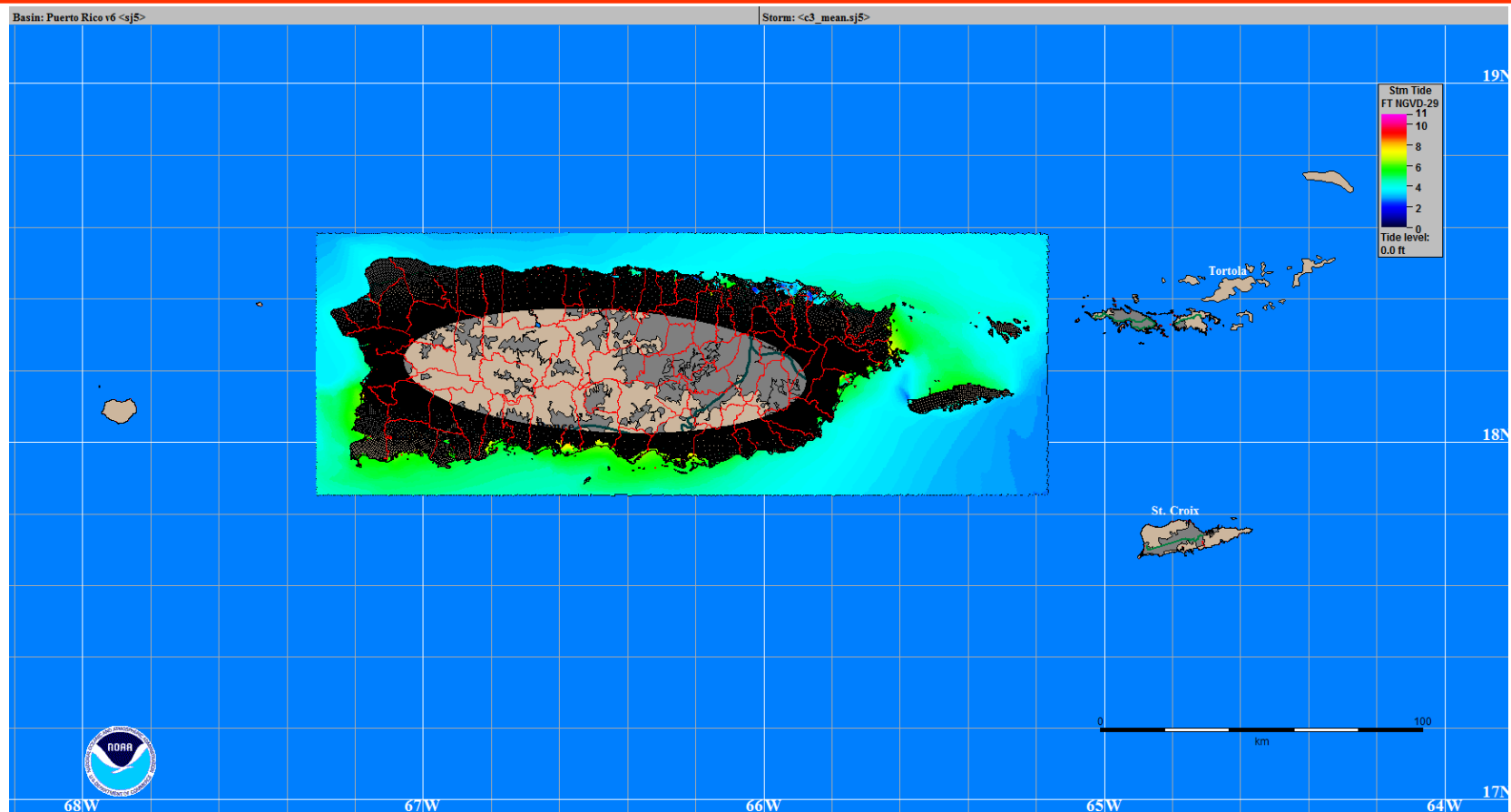
Primary Guidance Timeline

Planning / Mitigation (>120 hr)

- **MOMs** (Maximum Of the MEOWs)

Readiness (48hr – 120hr)
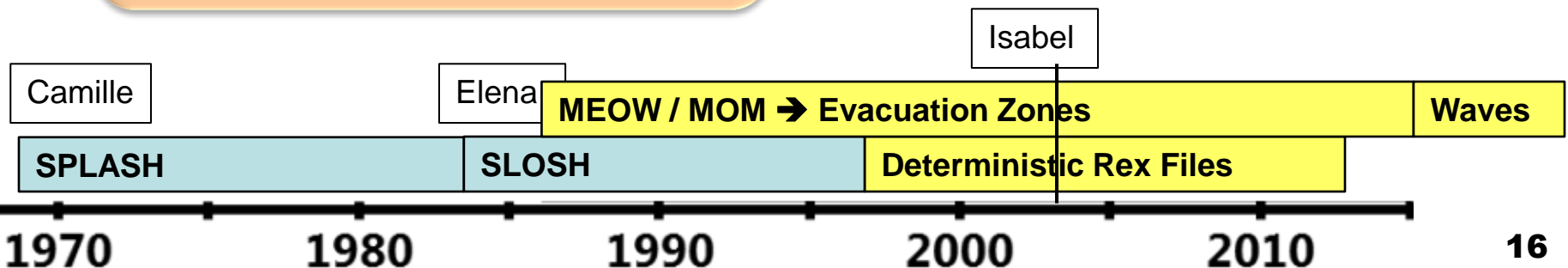
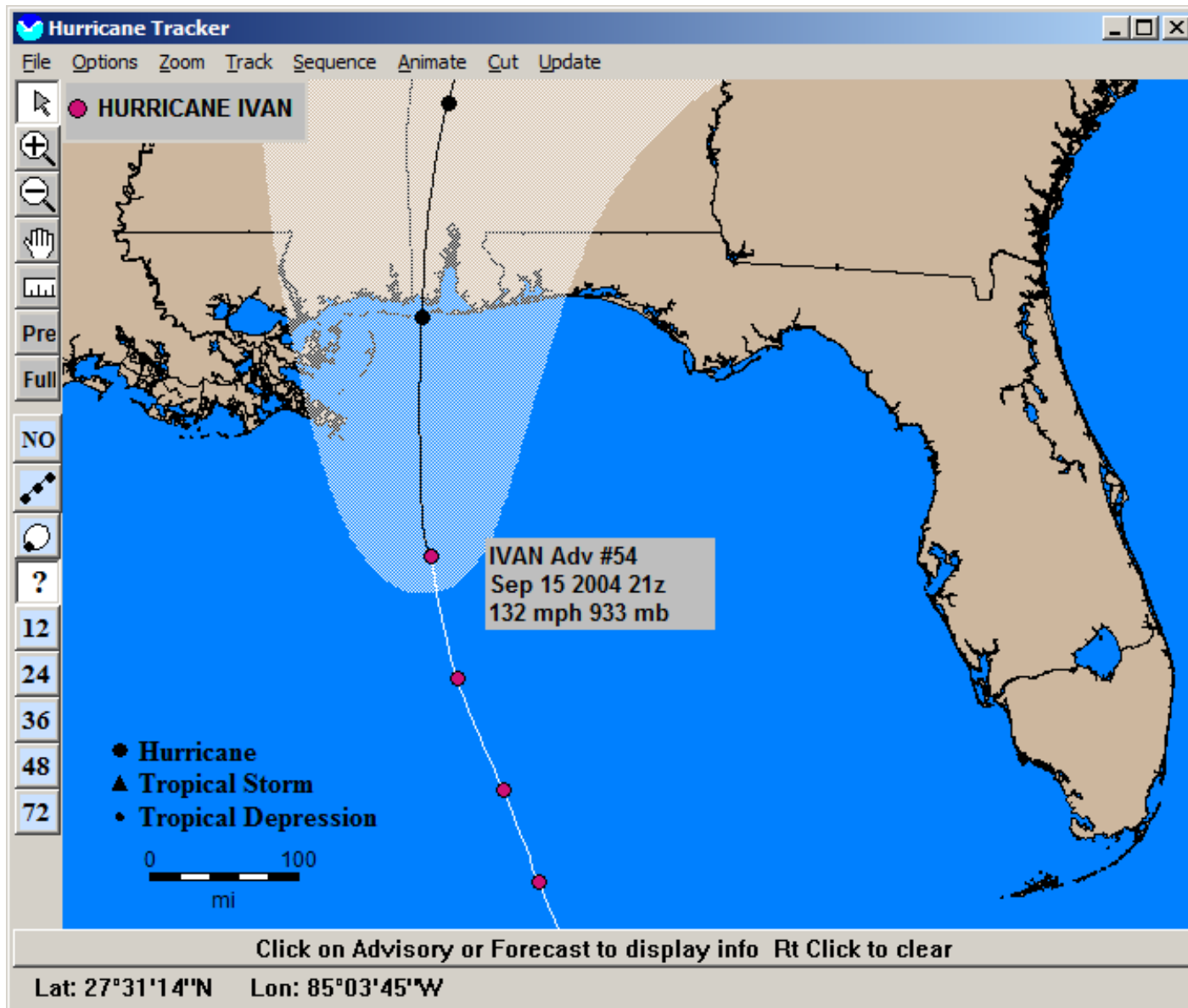- **MEOWs** (Maximum Envelope Of Water)
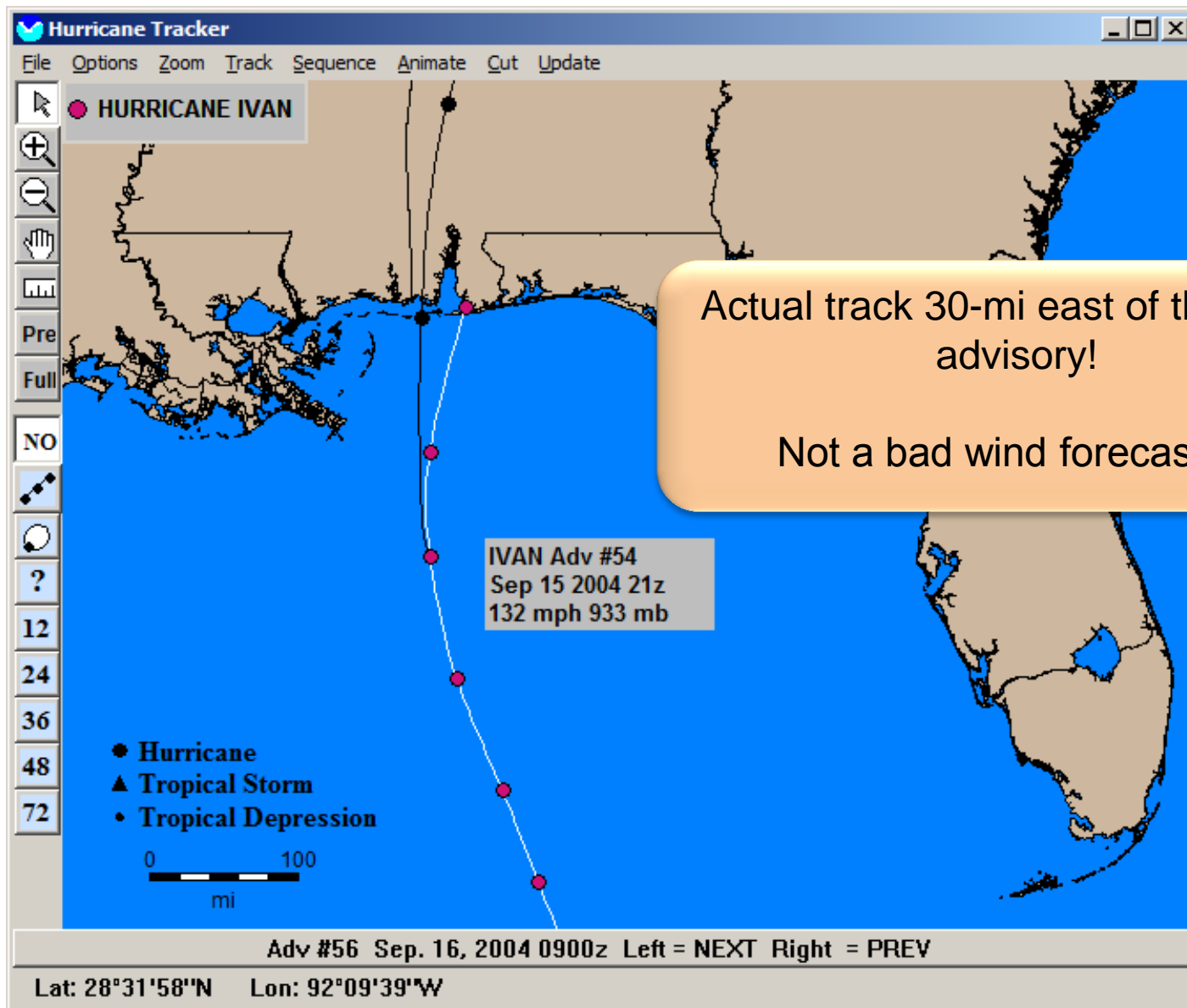
- MOMs

Response (<48hr)

- **Deterministic** Rex Files

- MEOWs

Isabel-2003
Caused us to reconsider
Deterministic Rex Files

Isabel

Camille

Elena

MEOW / MOM ➜ Evacuation Zones

Waves

SPLASH

SLOSH

Deterministic Rex Files

1970   1980   1990   2000   2010

Advisory 54 for Ivan 2004

Hurricane Tracker

File Options Zoom Track Sequence Animate Cut Update

● **HURRICANE IVAN**

IVAN Adv #54
Sep 15 2004 21z
132 mph 933 mb

● Hurricane
▲ Tropical Storm
• Tropical Depression

0   100
mi

Pre
Full
NO
12
24
36
48
72

Click on Advisory or Forecast to display info Rt Click to clear

Lat: 27°31'14"N   Lon: 85°03'45"W

Advisory 54 for Ivan 2004

Actual track 30-mi east of the 12-hr advisory!

Not a bad wind forecast …

18

Largest Storm Surge Error?
Wind Input

Impact of the "fairly good" wind forecast …

Rmax=25 mi (forecast)

Surges based on NHC Advisory 54 for Ivan

Rmax=40 mi

Surges based on NHC best track for Ivan
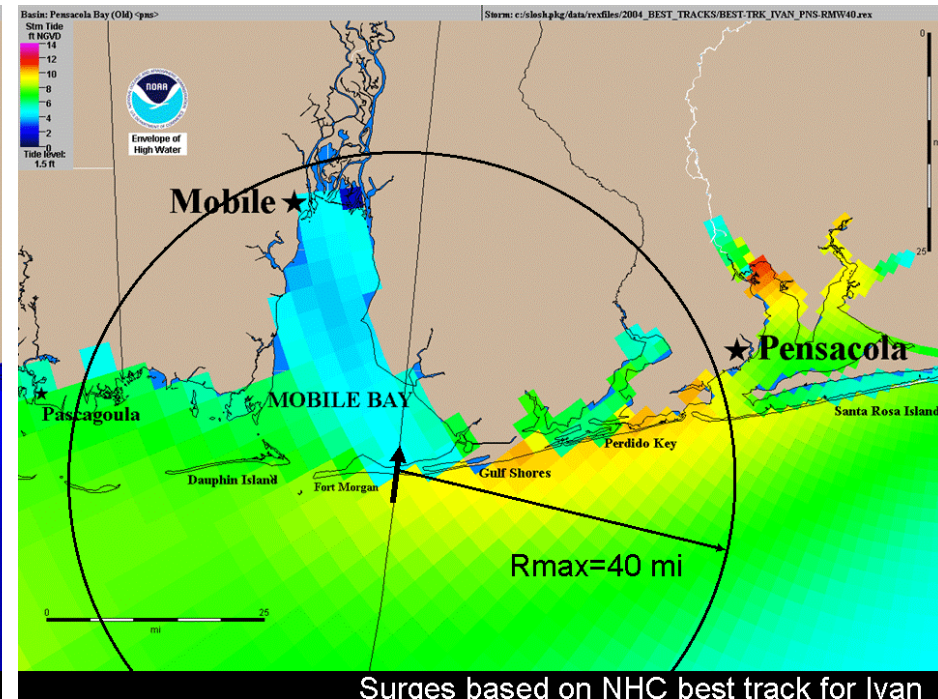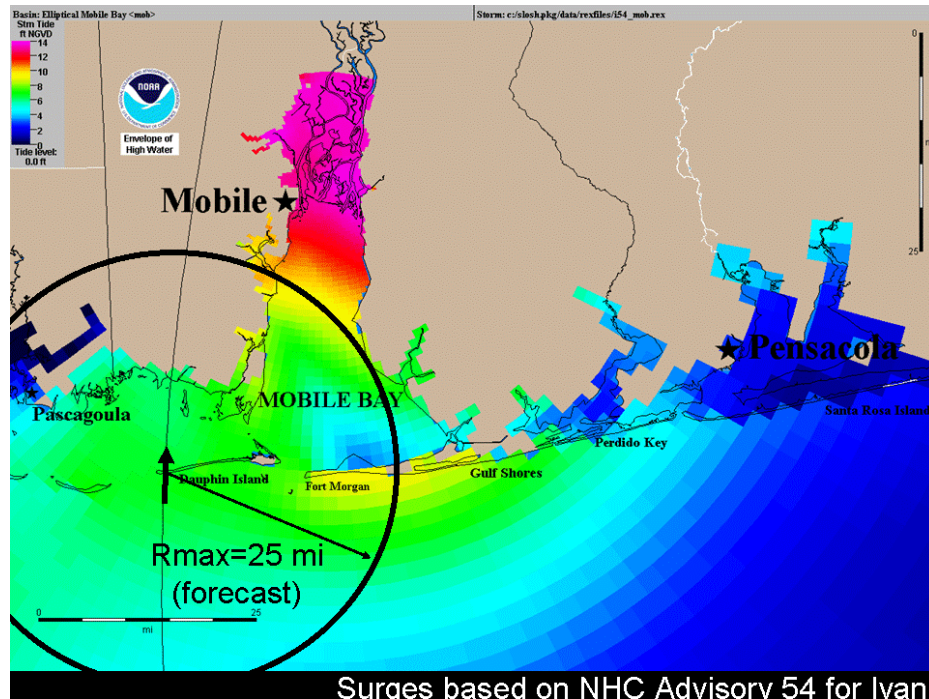
What is P-Surge?

Probabilistic tropical cyclone inundation guidance derived from a **real-time ensemble** of model runs.

- Centered on NHC's advisory
- Error spaces (except size) defined by an assumed normal error distribution with 5-yr MAE = 0.7979 sigma
- Error spaces sampled via representative storm
- Produced within 1 hour of the advisory release

Uses SLOSH as the hydrodynamic core due to it:

- ✓ utilizing a parametric wind model for forcing
- ✓ computing inundation from surge and tide
- ✓ having national coverage (in the US)
- ✓ being efficient (100s of runs with relatively few CPU)
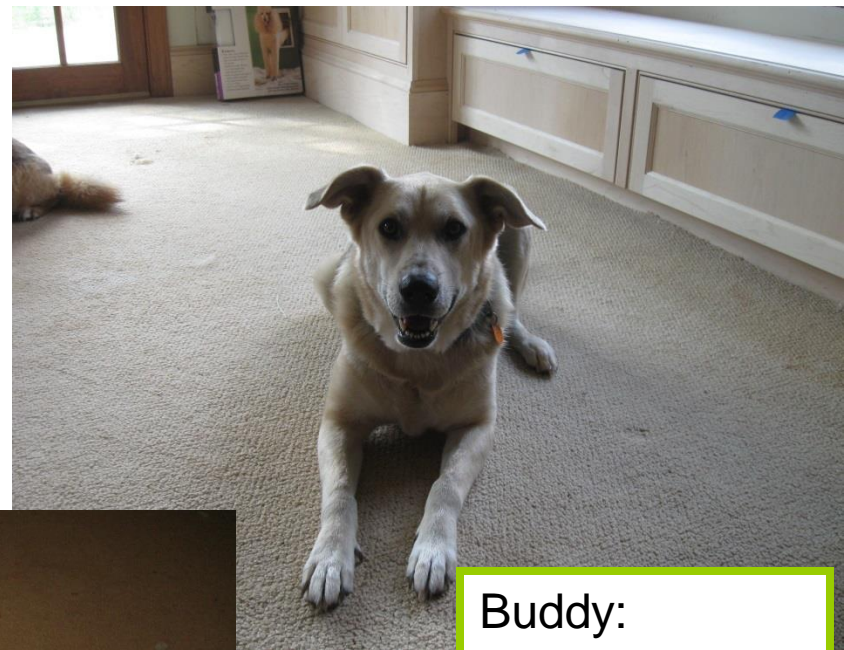- ✓ being maintained as part of hurricane evacuation studies

P-Surge - Vary Cross Track
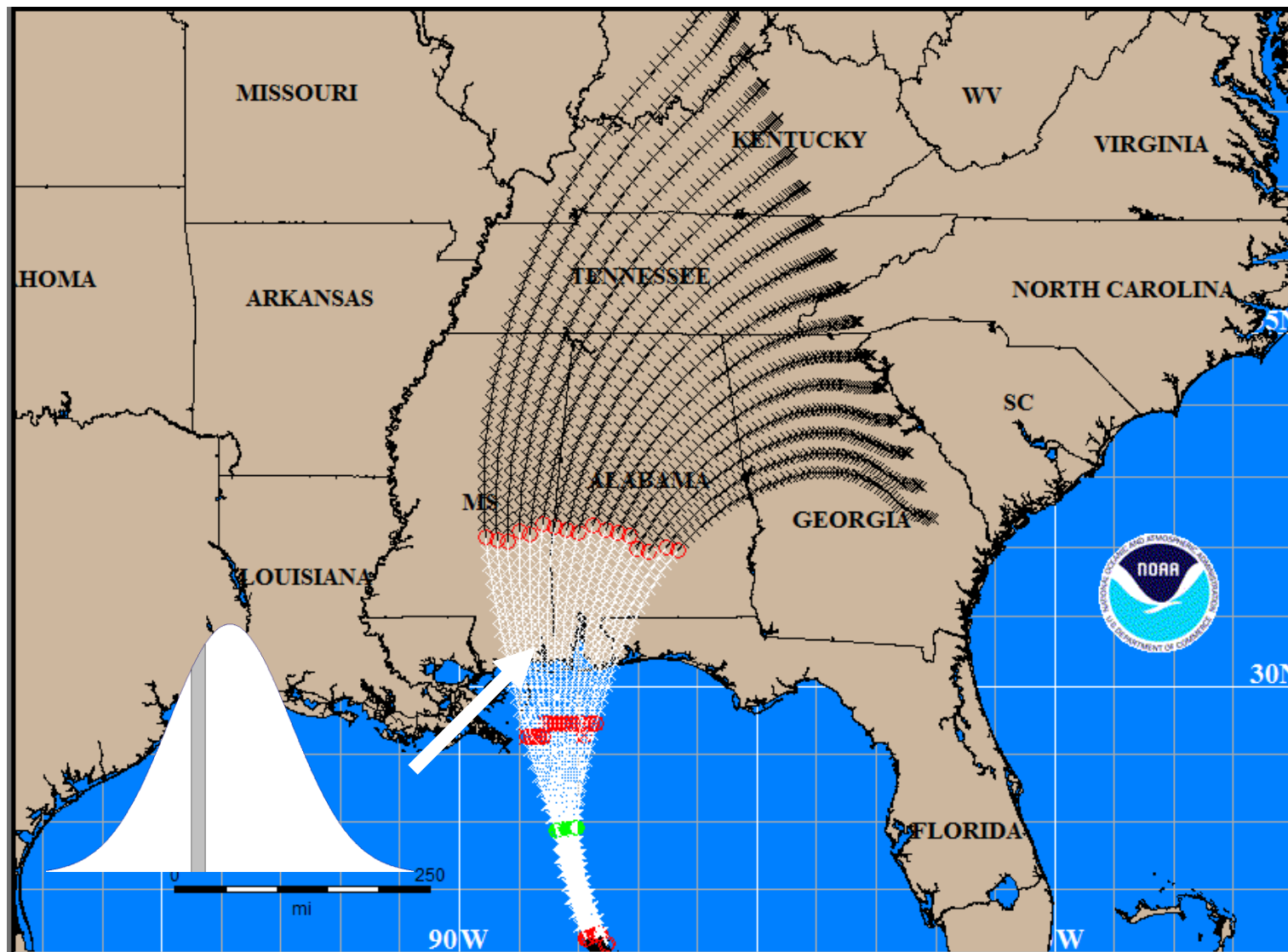
Adventure:
Small,
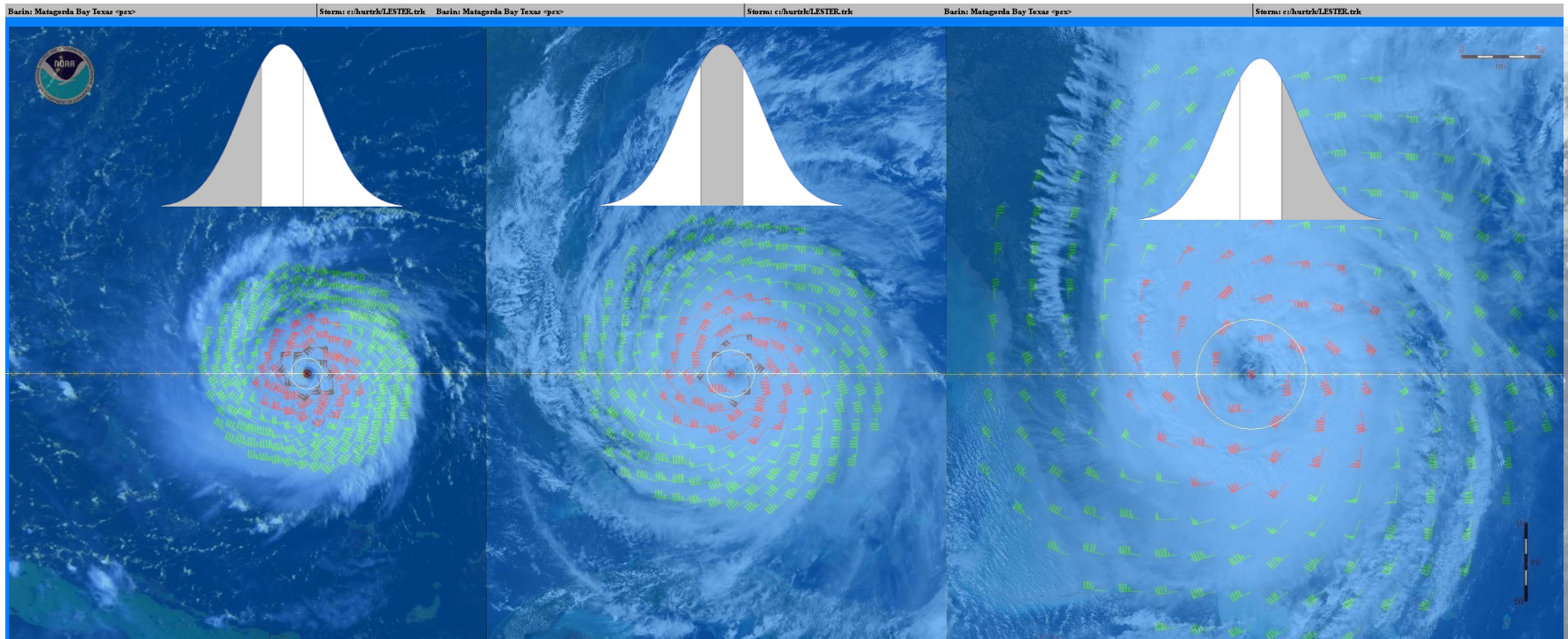Medium Intensity,
Slower

Buddy:
Large,
Intense,
Medium speed

Sandy:
Medium Size,
Laid Back,
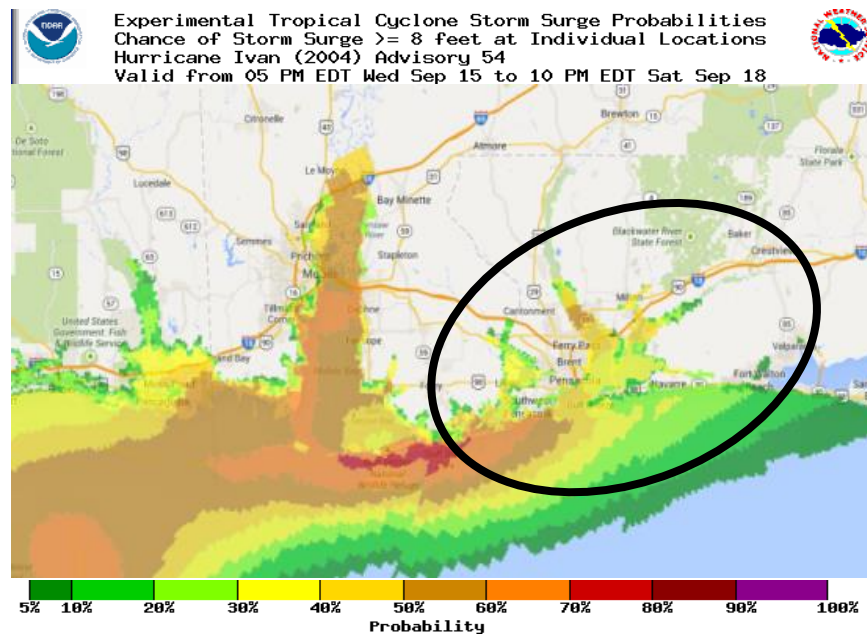Fast

P-Surge – Vary Other Variables

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

P-Surge – Products

Probability

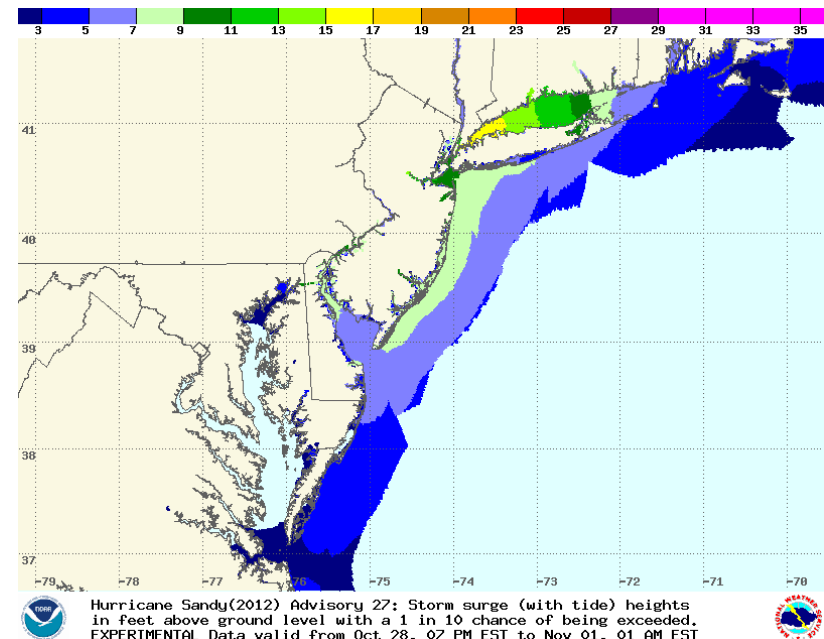Probability (in %) of water above a threshold.

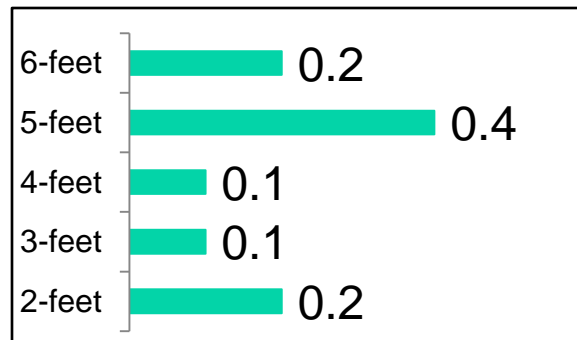➢ Estimate the risk to a specific site

Exceedance

Water level (in feet) exceeded by a given percent of the storms.

➢ Estimate water levels based on a specified risk tolerance

P-Surge – Example Product Generation

Example of water levels and weights in a grid cell

Water Level	Weight
6-feet	0.2
5-feet	0.4
4-feet	0.1
3-feet	0.1
2-feet	0.2

Probability

Probability of > 4 feet of water?

➢ 60%

Exceedance

Water level exceeded by 70% of storms?

➢ 3 feet

Storm: Ivan2004 Adv54 | Type: Prob. of surge > 8 feet | Zoom Level: Full

Experimental Tropical Cyclone Storm Surge Probabilities
Chance of Storm Surge >= 8 feet at Individual Locations
Hurricane Ivan (2004) Advisory 54
Valid from 05 PM EDT Wed Sep 15 to 10 PM EDT Sat Sep 18
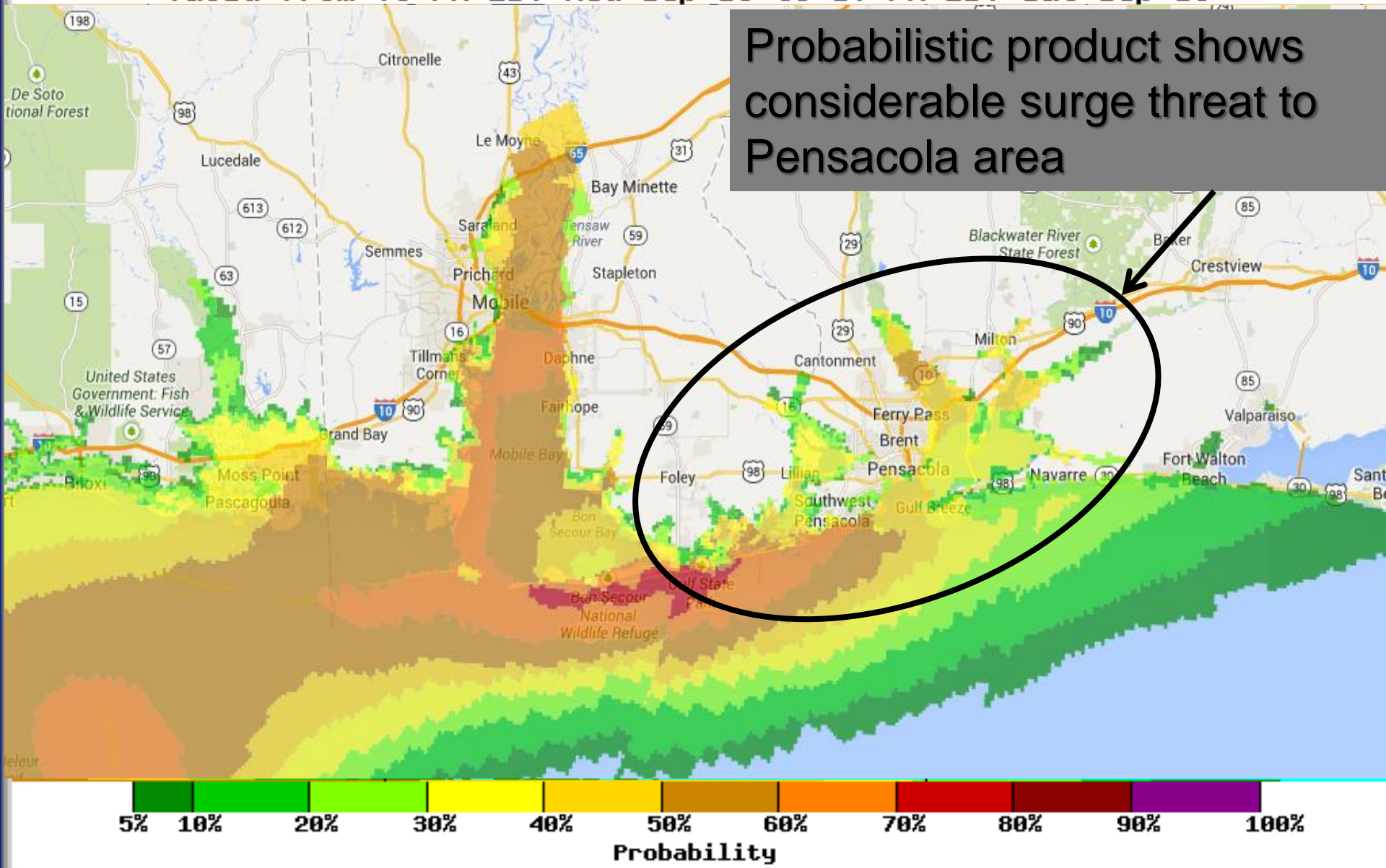
Probabilistic product shows considerable surge threat to Pensacola area

Probability: 5% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%

Primary Guidance Timeline

Planning / Mitigation (>120 hr)

Readiness (48hr – 120hr)

Response (<48hr)

- **MOMs** (Maximum Of the MEOWs)

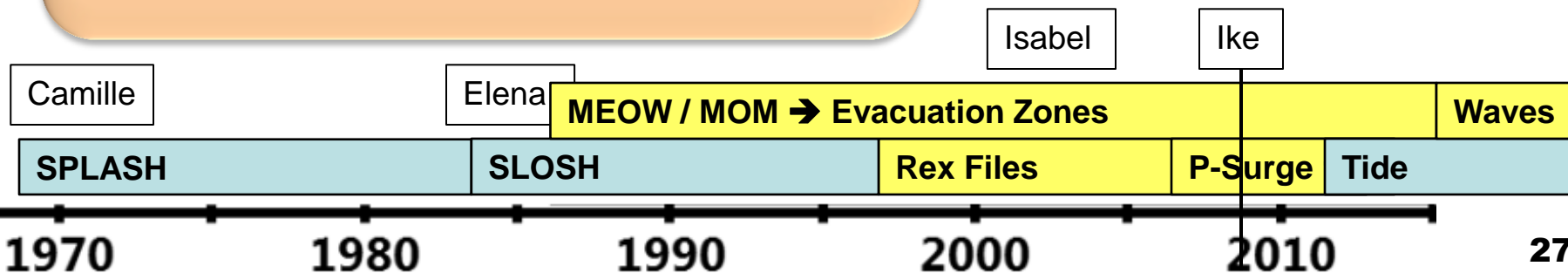- **MEOWs** (Maximum Envelope Of Water)
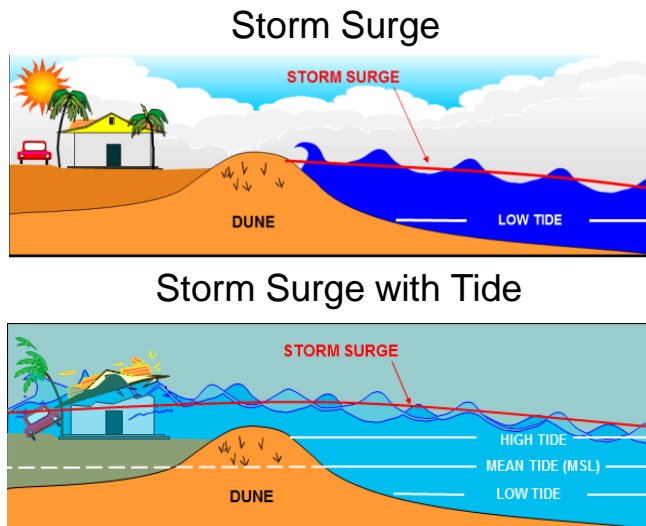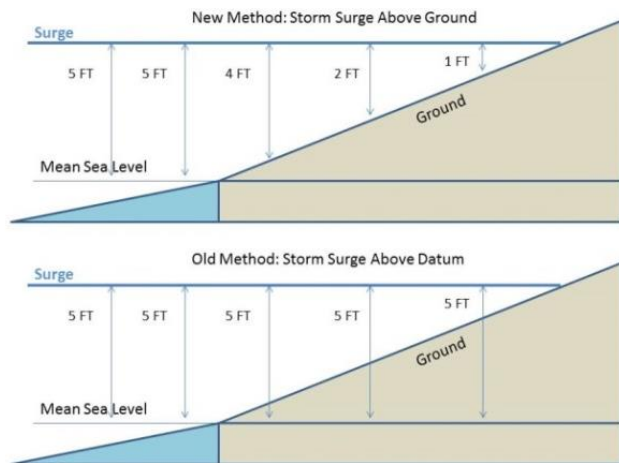
- MOMs

- **P-Surge 1.0** results

- Deterministic Rex Files, MEOWs

1. Ike-2008 caused us to reconsider above datum versus Above Ground Level
2. 2012 – SLOSH added tides
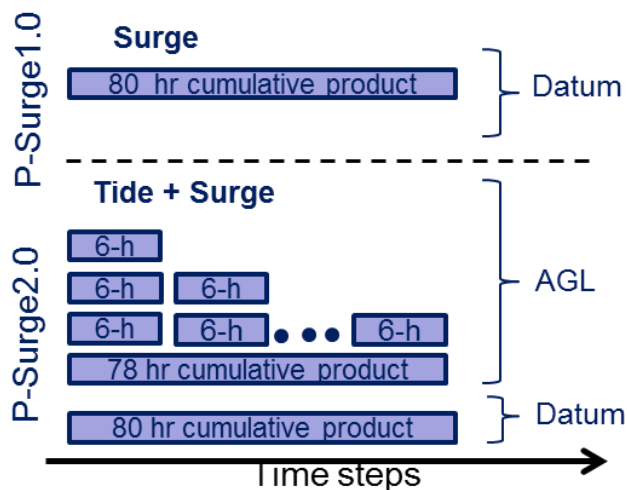3. 2013 – Retiring Rex files meant we needed a time component

Isabel

Ike

Camille

Elena

MEOW / MOM ➔ Evacuation Zones

Waves

SPLASH

SLOSH

Rex Files

P-Surge

Tide

1970   1980   1990   2000   2010

In 2015
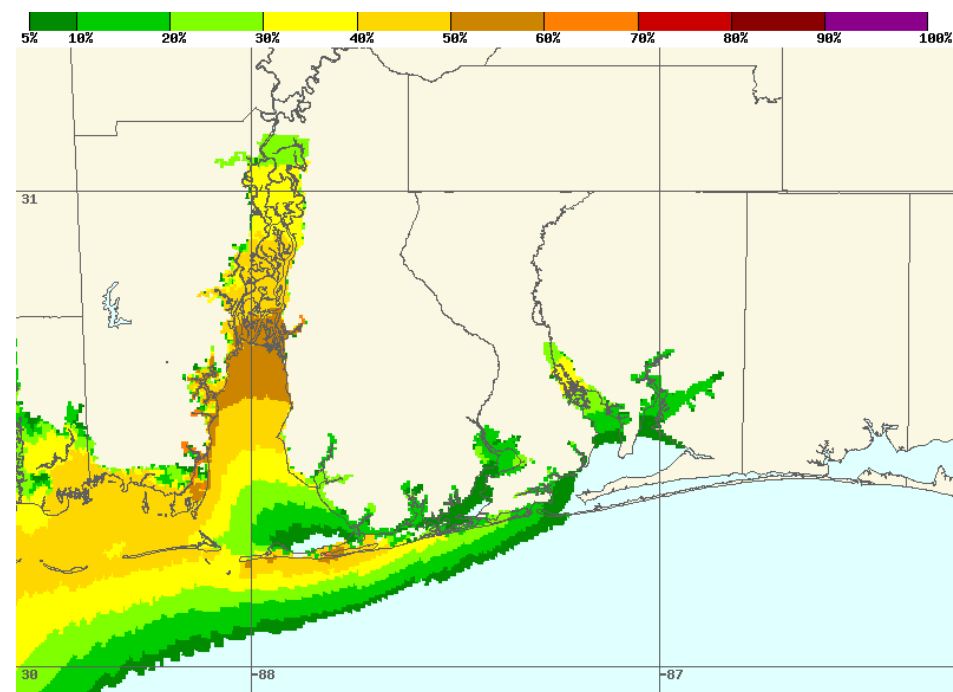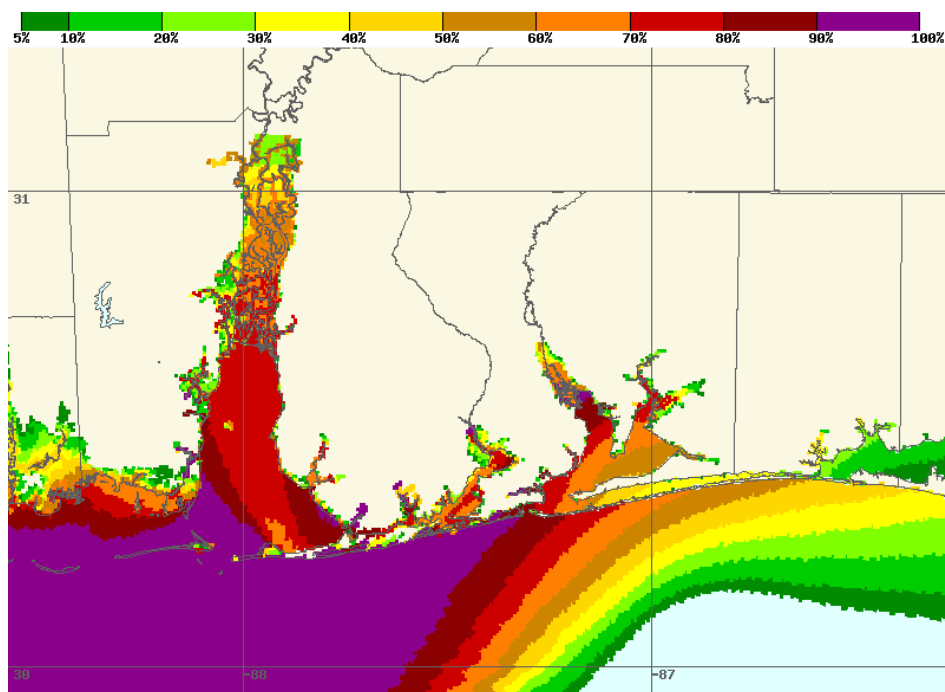Added 1-hr exceedance products

Used by:
1) NWPS
2) Coastal RFCs

Storm Surge Warning Guidance
P-Surge 2.0 - Ivan-2004 Adv54

Prob. of Surge + Tide > 3 feet
Above Ground Level
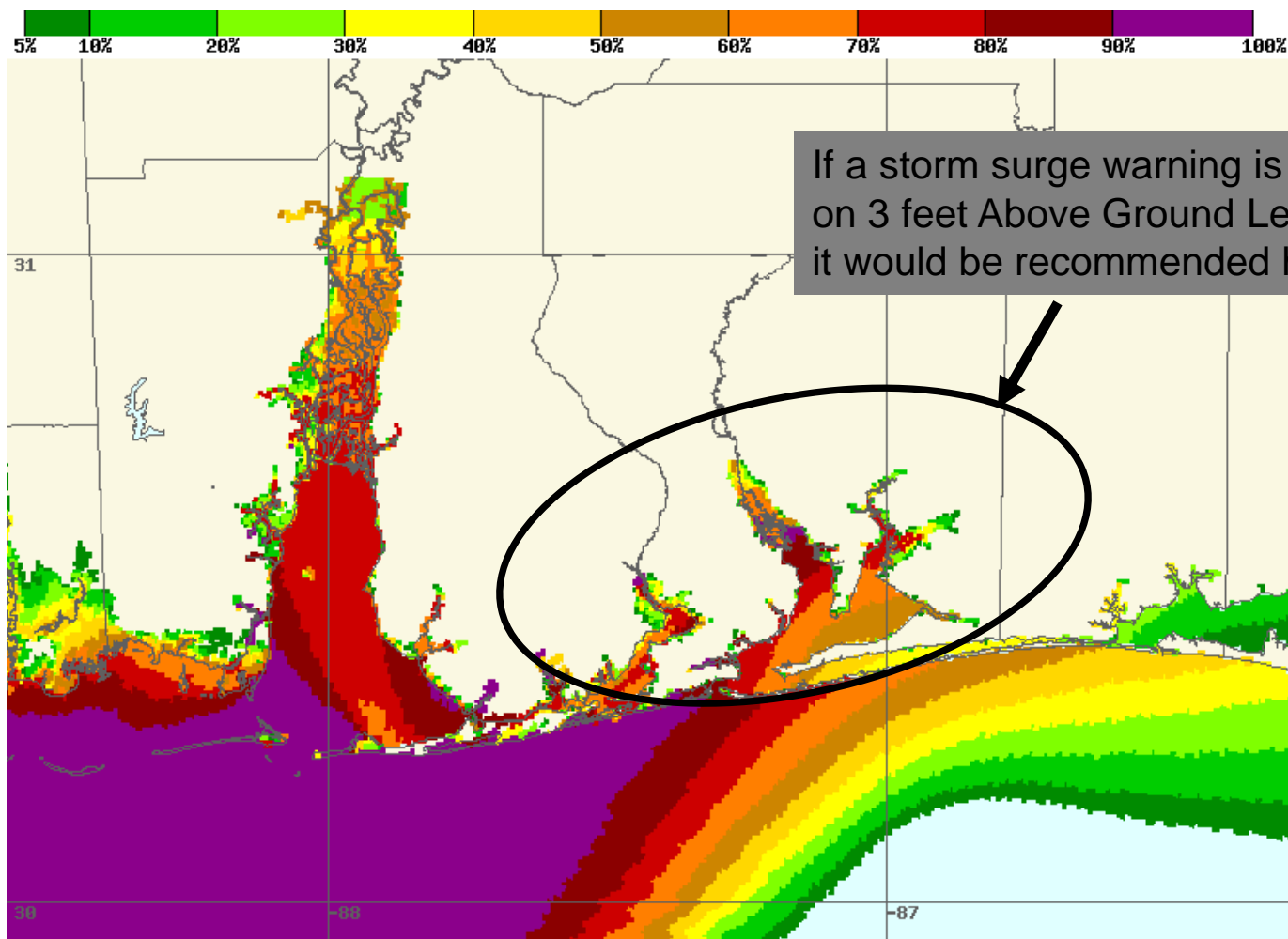
Prob. of Surge + Tide > 8 feet
Above NAVD-88

Hurricane Ivan(2004) Advisory 54: Probability of
storm surge (with tide) >= 3 feet above ground level.
EXPERIMENTAL Data valid from Sep 15, 01 PM EST to Sep 18, 07 PM EST

Hurricane Ivan(2004) Advisory 54: Probability of
storm surge (with tide) >= 8 feet above NAVD-88.
EXPERIMENTAL Data valid from Sep 15, 01 PM EST to Sep 18, 07 PM EST

Ivan-2004 Adv54 P-Surge 2.0
Probability of Surge + Tide > 3 feet AGL

If a storm surge warning is based on 3 feet Above Ground Level, then it would be recommended here.

Hurricane Ivan(2004) Advisory 54: Probability of storm surge (with tide) >= 3 feet above ground level. EXPERIMENTAL Data valid from Sep 15, 01 PM EST to Sep 18, 07 PM EST
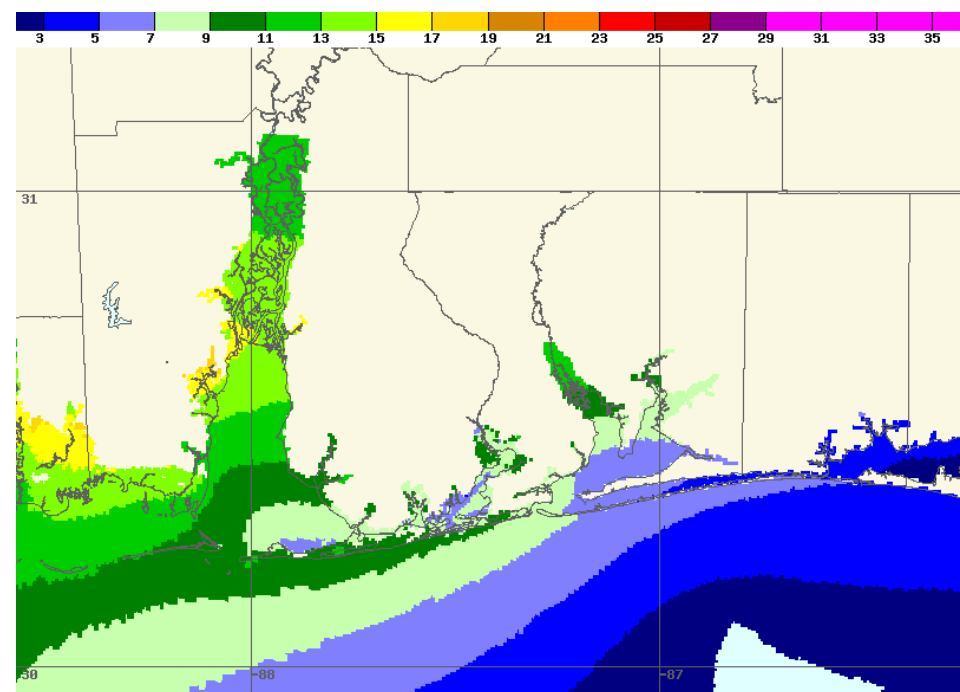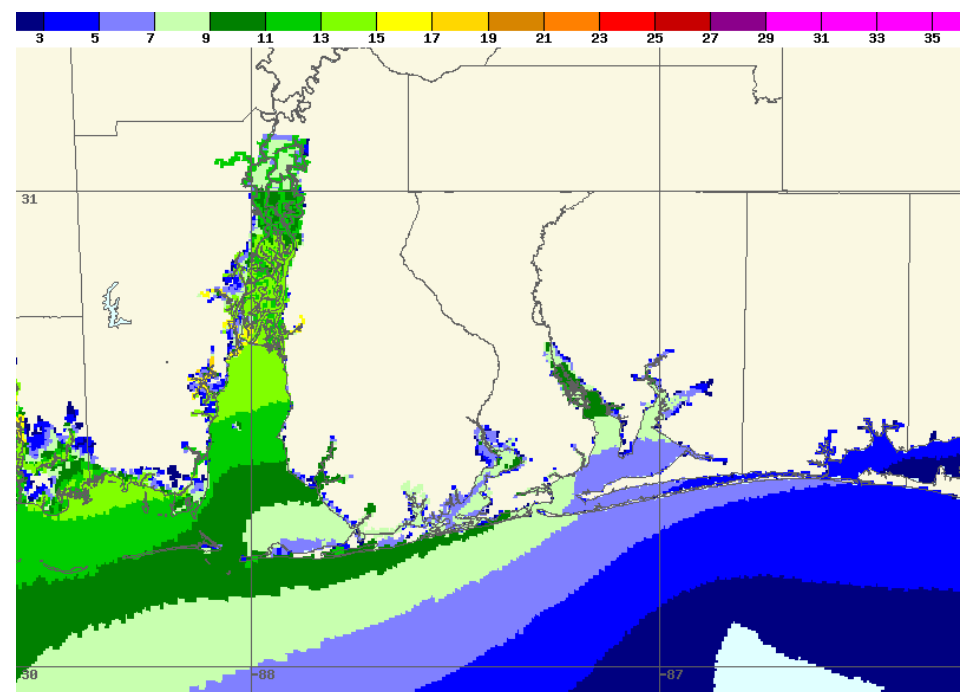
Inundation Mapping Guidance
P-Surge 2.0 - Ivan-2004 Adv54

Surge + Tide Above Ground Level
With a 10% chance of being exceeded

Surge + Tide Above NAVD-88
With a 10% chance of being exceeded

Hurricane Ivan(2004) Advisory 54: Storm surge (with tide) heights in feet above ground level with a 1 in 10 chance of being exceeded. EXPERIMENTAL Data valid from Sep 15, 01 PM EST to Sep 18, 07 PM EST

Hurricane Ivan(2004) Advisory 54: Storm surge (with tide) heights in feet above NAVD-88 with a 1 in 10 chance of being exceeded. EXPERIMENTAL Data valid from Sep 15, 01 PM EST to Sep 18, 07 PM EST

Ivan-2004 Adv54 P-Surge 2.0
Surge + Tide AGL with a 10% chance of exceeded

If experimental inundation graphic based on 10% exceedance, it would show 9 to 11 feet here.

Hurricane Ivan(2004) Advisory 54: Storm surge (with tide) heights in feet above ground level with a 1 in 10 chance of being exceeded. EXPERIMENTAL Data valid from Sep 15, 01 PM EST to Sep 18, 07 PM EST
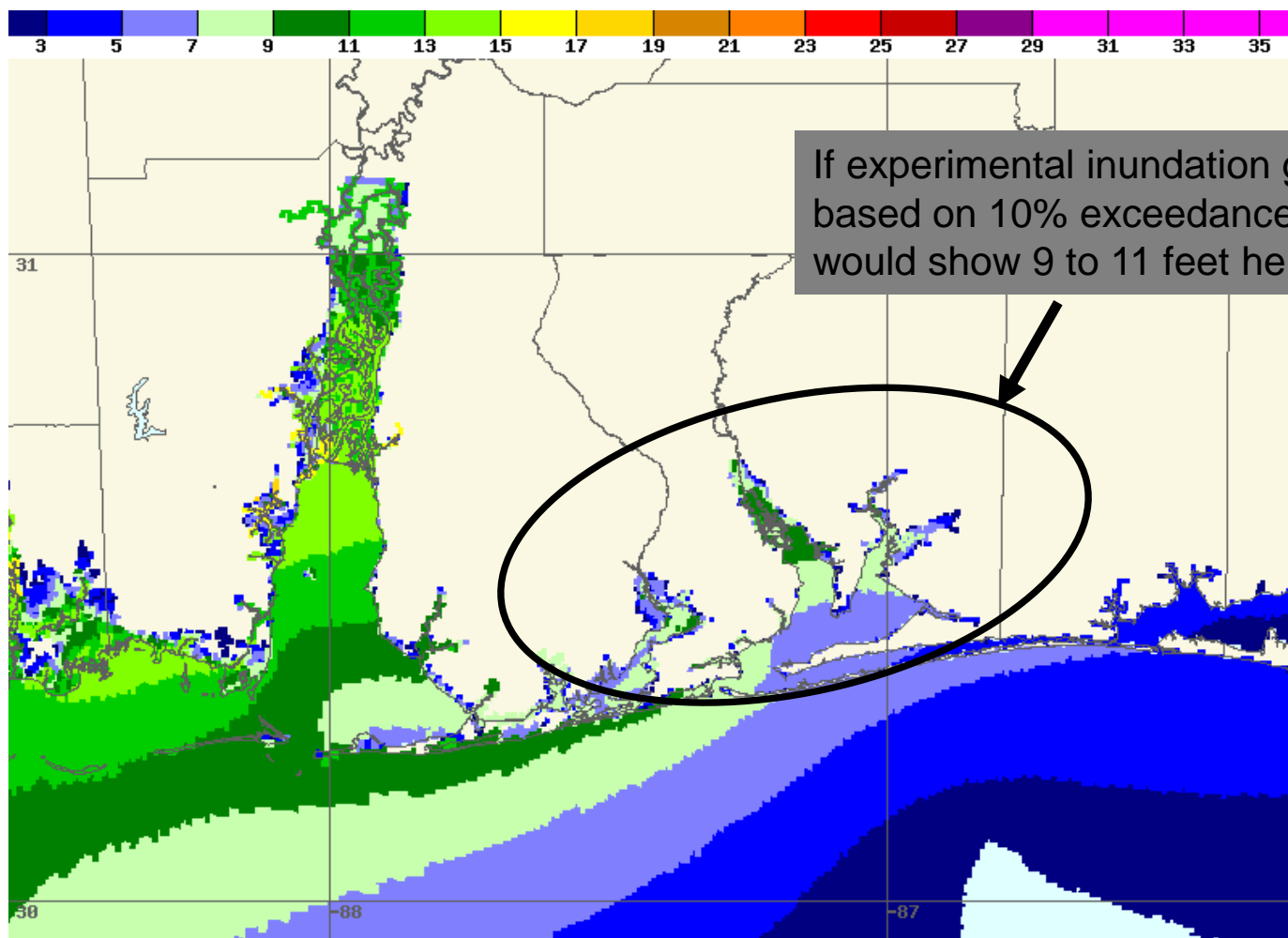
RFC and NWPS Model Guidance
P-Surge 2.0 – Sandy-2012 Adv27

Surge + Tide Above Ground Level
With a 10% chance of being exceeded
6-hour increments
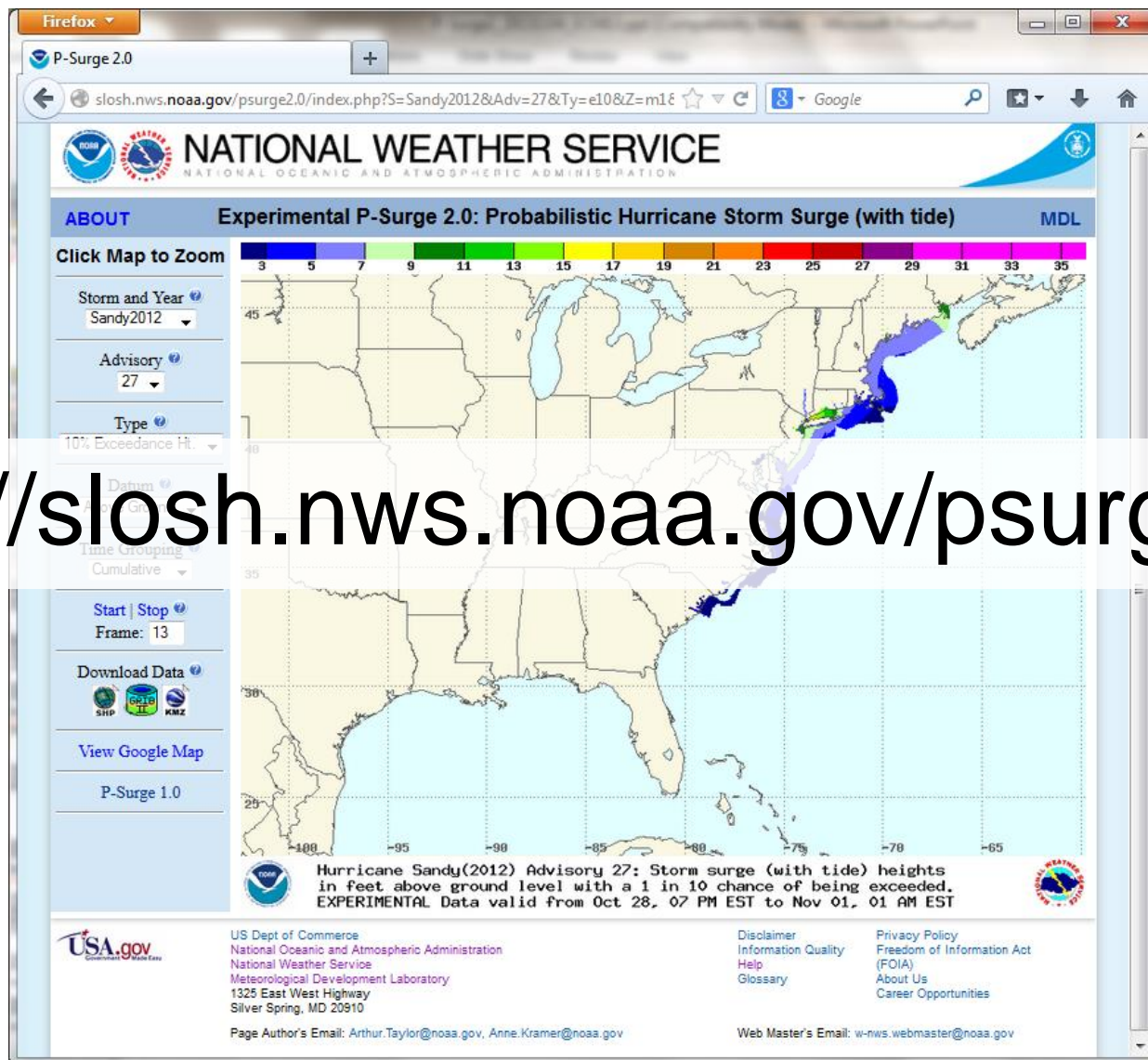

Tide signal

Hurricane Sandy(2012) Advisory 27: Storm surge (with tide) heights in feet above ground level with a 1 in 10 chance of being exceeded. EXPERIMENTAL Data valid from Oct 28, 07 PM EST to Oct 29, 01 AM EST

33
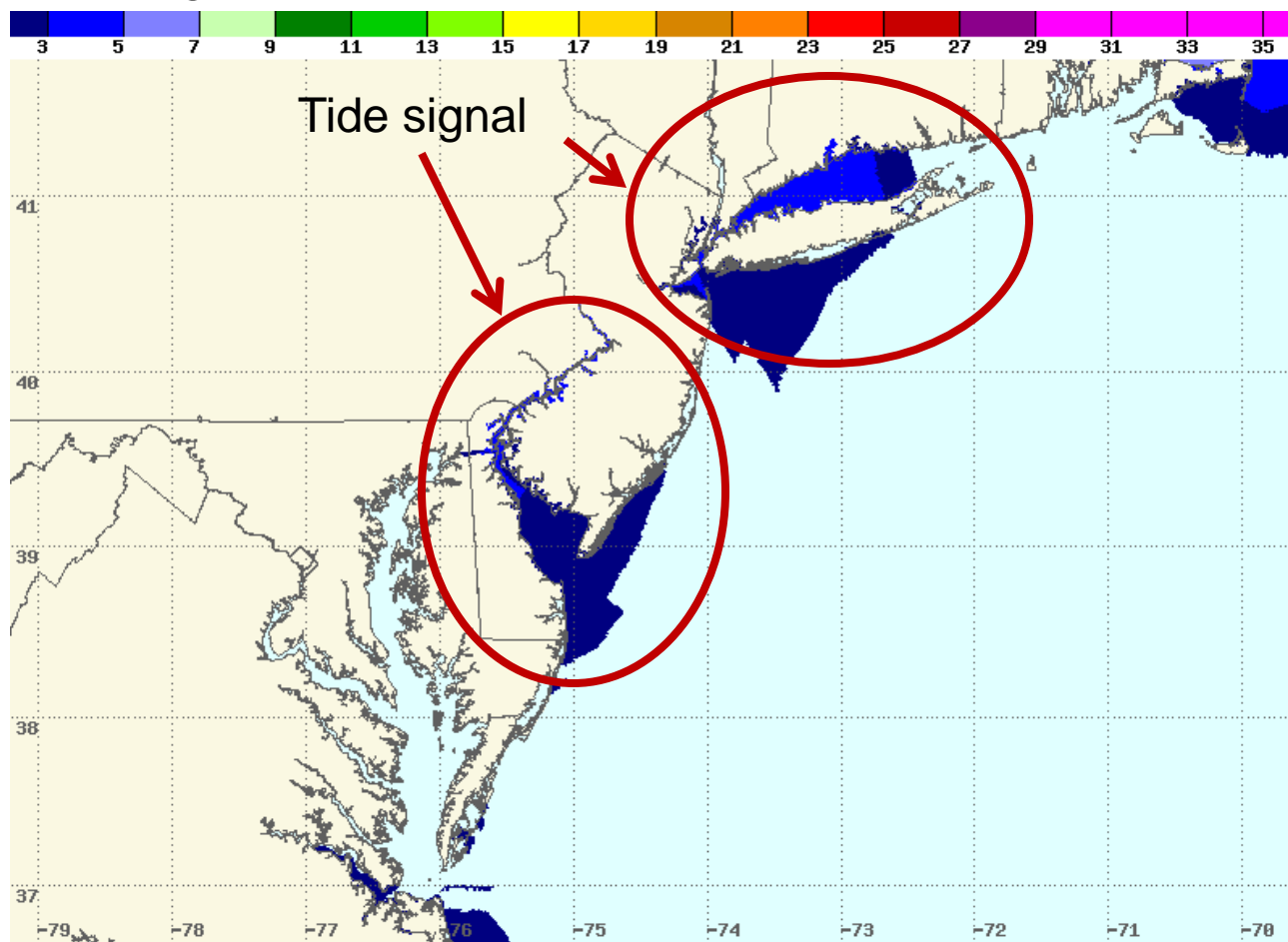
RFC and NWPS Model Guidance
P-Surge 2.5 – Sandy-2012 Adv27

Surge + Tide Above NAVD-88
With a 10% chance of being exceeded
1-hour increments

Tide signal

Hurricane Sandy(2012) Advisory 27: Storm surge (with tide) heights in feet above NAVD-88 with a 1 in 10 chance of being exceeded. EXPERIMENTAL Data valid from Oct 28, 07 PM EST to Oct 28, 08 PM EST

P-Surge 2.0

http://slosh.nws.noaa.gov/psurge2.0

Primary Guidance Timeline

Planning / Mitigation (>120 hr)
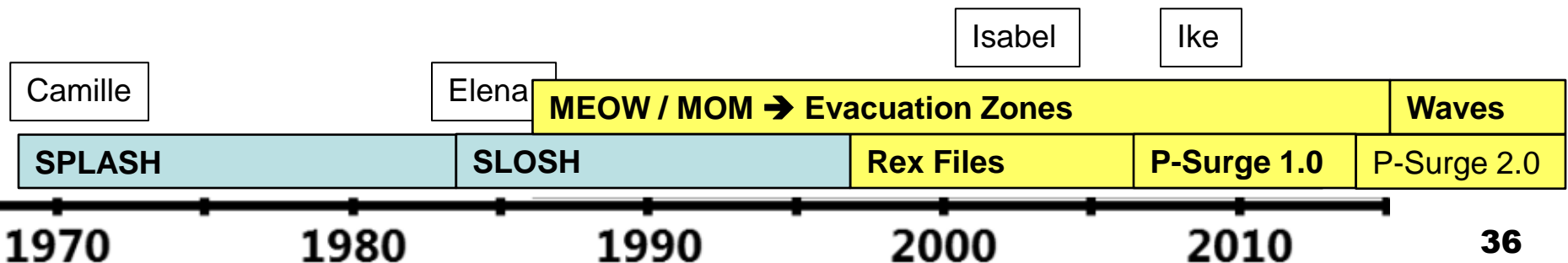
- **MOMs** (Maximum Of the MEOWs)

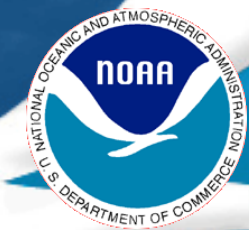**Readiness (48hr – 120hr)**

- **MEOWs** (Maximum Envelope Of Water)

- MOMs
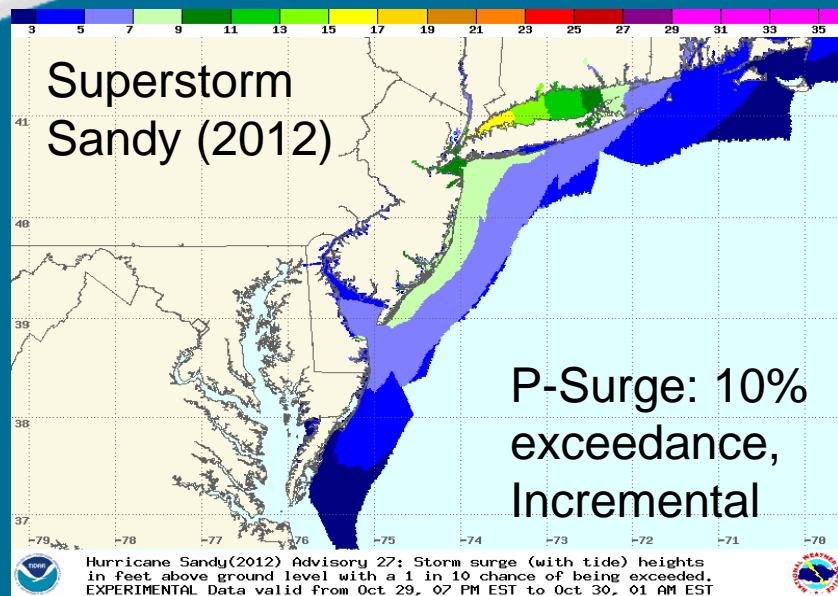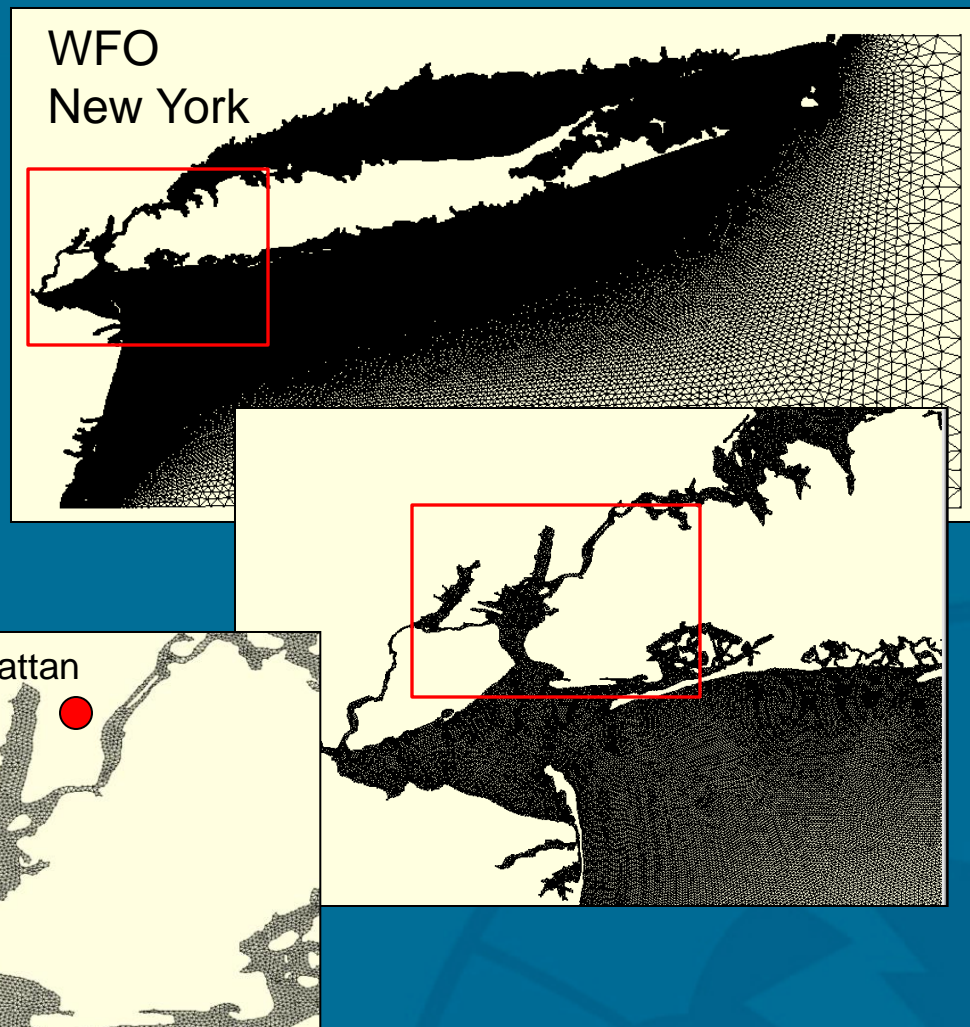
Response (<48hr)

- **P-Surge 2.0** results

- MEOWs

Camille

Elena

Isabel

Ike

MEOW / MOM ➔ Evacuation Zones

Waves

SPLASH

SLOSH

Rex Files

P-Surge 1.0

P-Surge 2.0

1970   1980   1990   2000   2010

National Wave Prediction System Tropical: P-Surge coupling

Superstorm Sandy (2012)

P-Surge: 10% exceedance, Incremental

Hurricane Sandy(2012) Advisory 27: Storm surge (with tide) heights in feet above ground level with a 1 in 10 chance of being exceeded. EXPERIMENTAL Data valid from Oct 29, 07 PM EST to Oct 30, 01 AM EST

WFO New York

Manhattan

- NWPS forced with TCMWindTool winds

- Water levels from time-dependent P-Surge

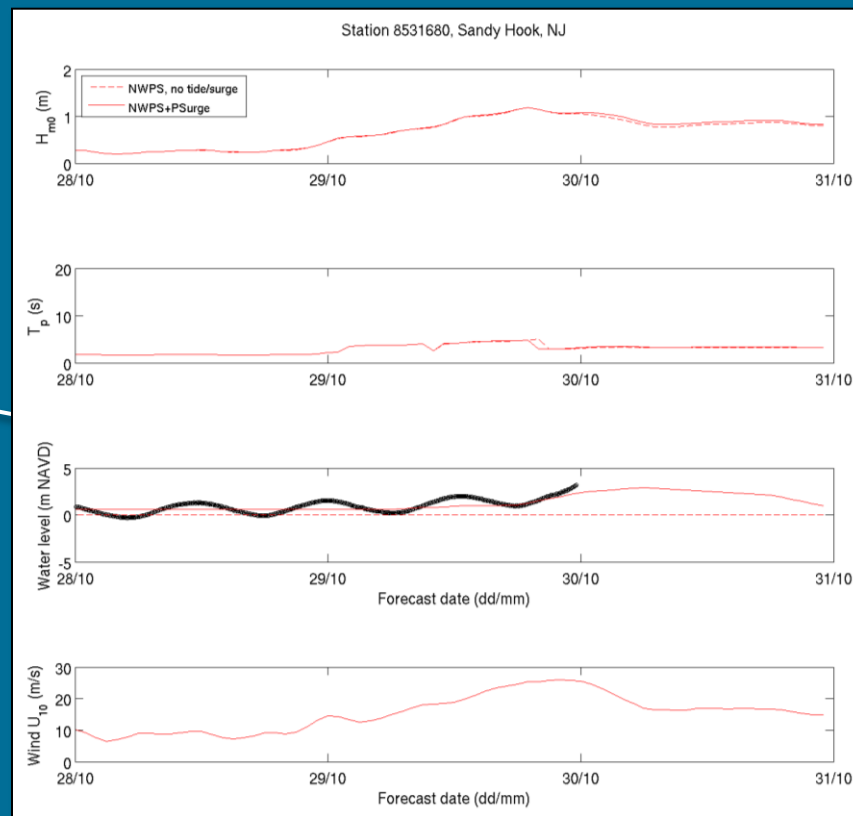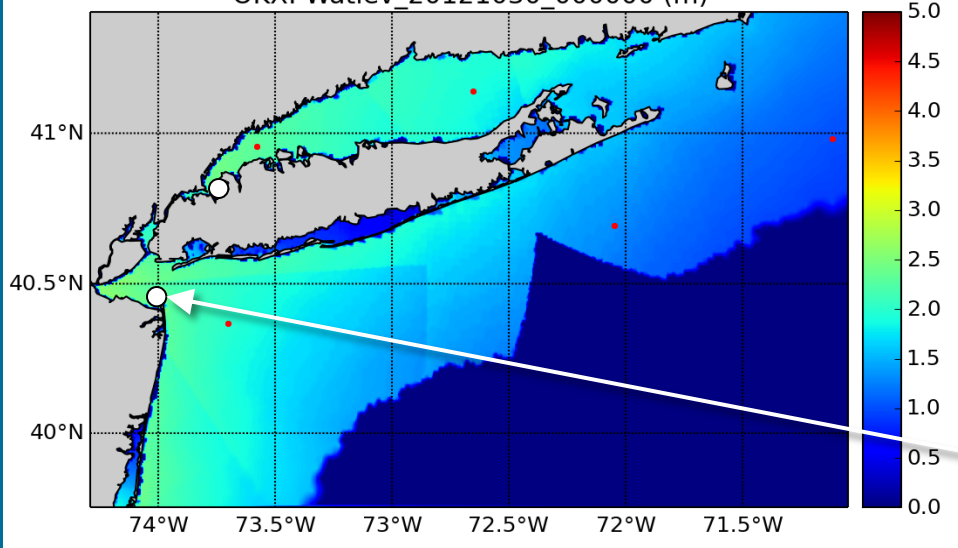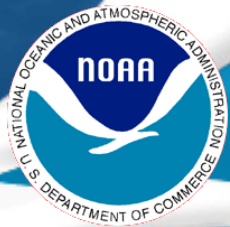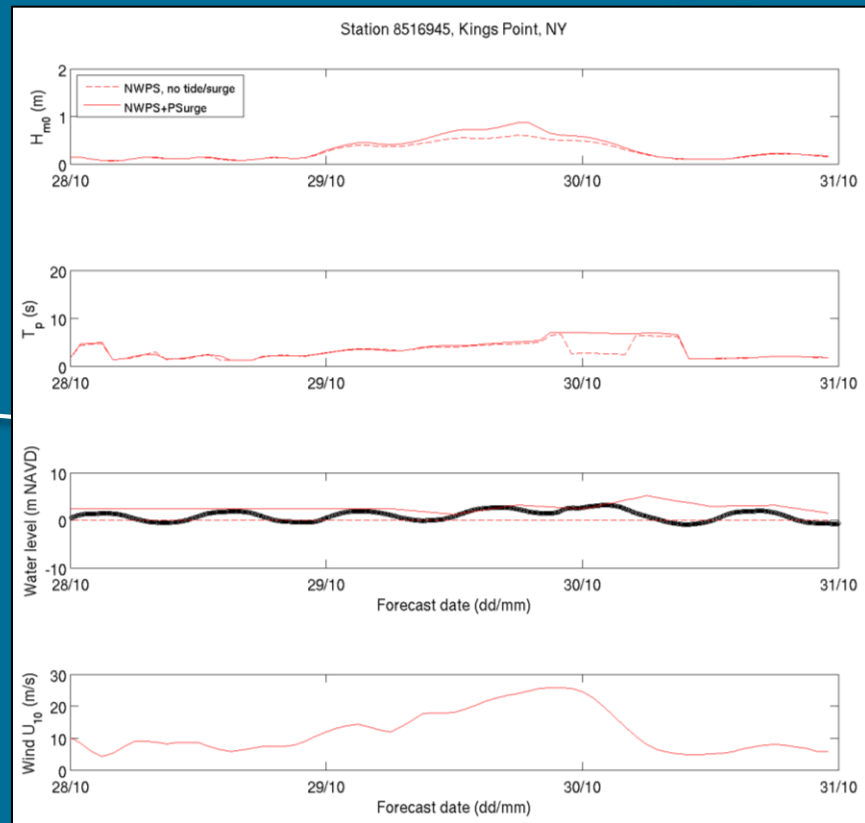# P-Surge versus CO-OPS observations

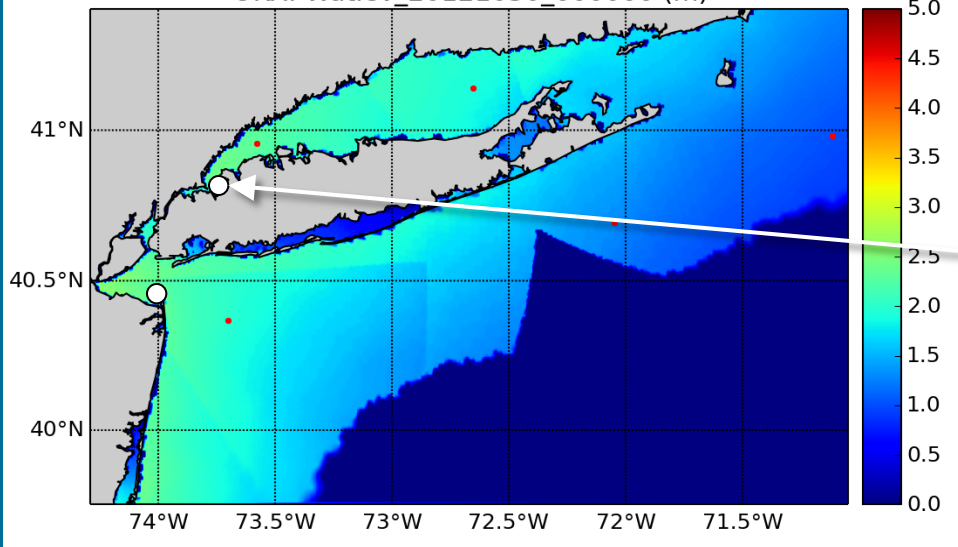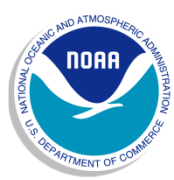P-Surge 10% exceedance (incremental)

OKX: Watlev_20121030_000000 (m)

Station 8531680, Sandy Hook, NJ

P-Surge versus CO-OPS observations

P-Surge 10% exceedance (incremental)

OKX: Watlev_20121030_000000 (m)

Station 8516945, Kings Point, NY

Tropical Storm Surge
Ensemble Modeling Questions
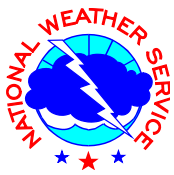
How should MOMS/MEOWs deal with Tide?

- Currently set initial value to high tide
- Over-estimate but works (except in the Gulf of Maine)

How should P-Surge deal with "double landfall storms (e.g. Dennis 1999)?

Can P-Surge use forecasted confidence for an advisory instead of the 5 year mean absolute error?

How should river boundary conditions be handled?

Tropical Inundation Graphic + Watch Warning

Hurricane Ike Inundation Depth

Tropical and Extra-Tropical Storm Surge Products

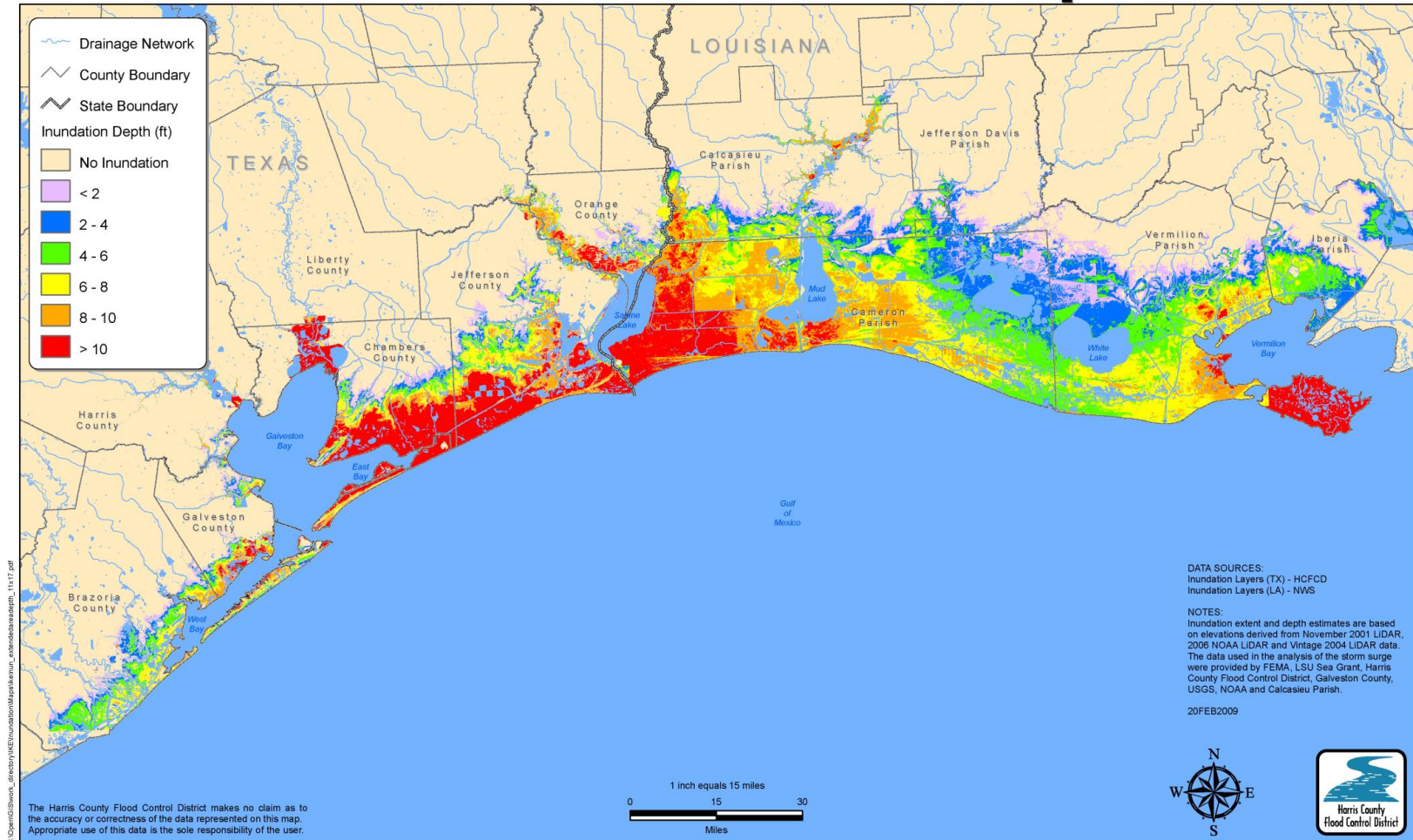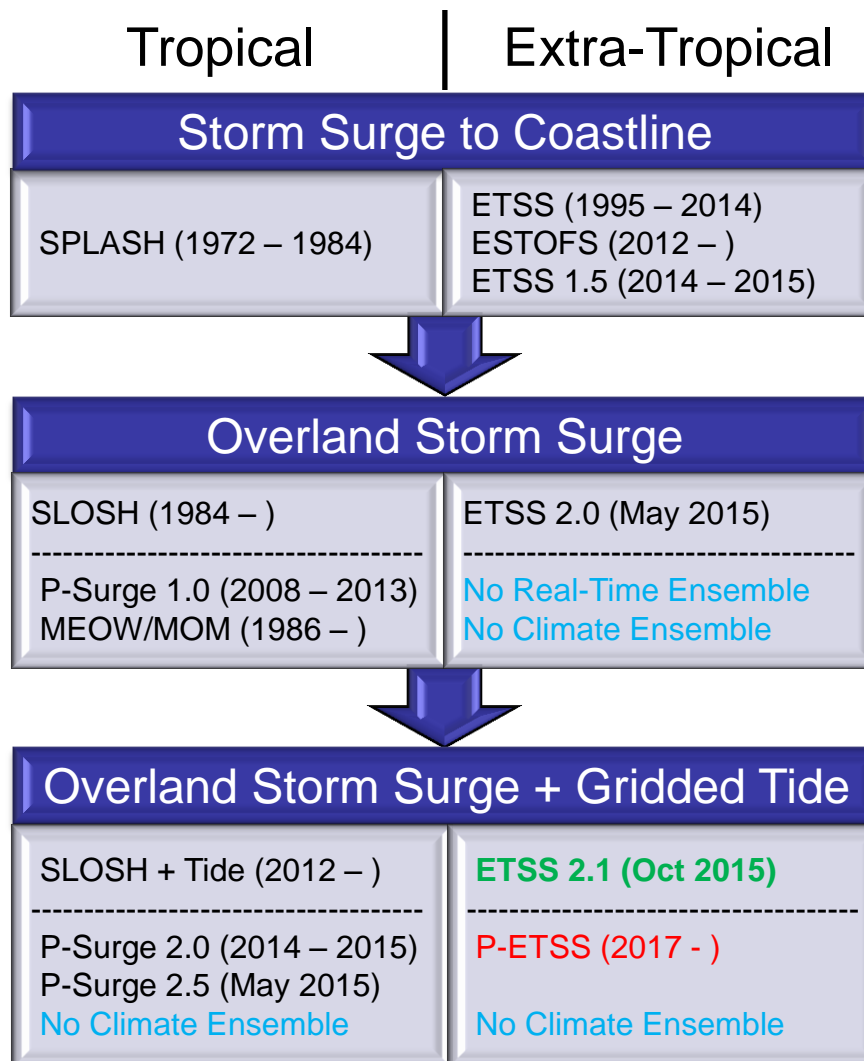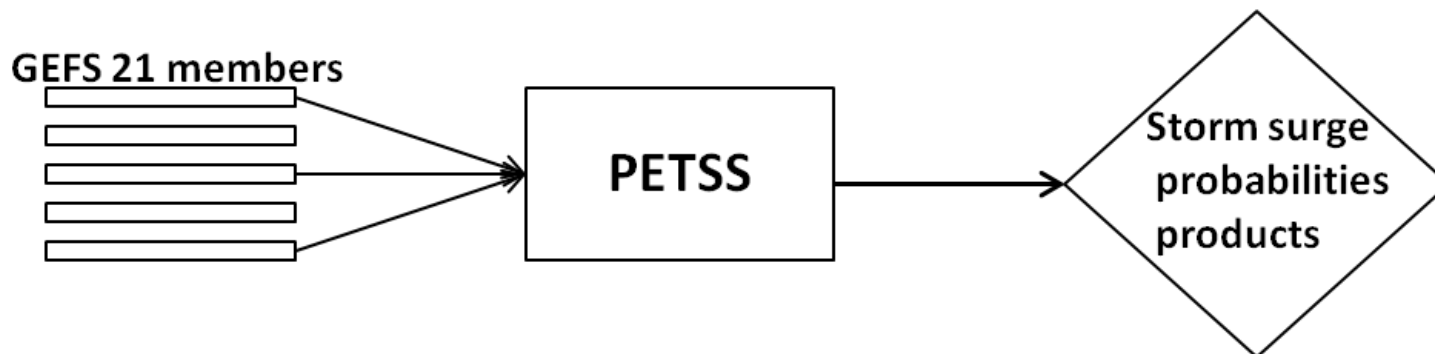Tropical | Extra-Tropical

Storm Surge to Coastline

Tropical	Extra-Tropical
SPLASH (1972 – 1984)	ETSS (1995 – 2014) ESTOFS (2012 –) ETSS 1.5 (2014 – 2015)

Overland Storm Surge

Tropical	Extra-Tropical
SLOSH (1984 –) ------------------------------------- P-Surge 1.0 (2008 – 2013) MEOW/MOM (1986 –)	ETSS 2.0 (May 2015) ------------------------------------- No Real-Time Ensemble No Climate Ensemble

Overland Storm Surge + Gridded Tide

Tropical	Extra-Tropical
SLOSH + Tide (2012 –) ------------------------------------- P-Surge 2.0 (2014 – 2015) P-Surge 2.5 (May 2015) No Climate Ensemble	ETSS 2.1 (Oct 2015) ------------------------------------- P-ETSS (2017 -) No Climate Ensemble

Probabilistic Extra-Tropical Storm Surge (P-ETSS)

- Use the 21 member Global Ensemble Forecast System to drive the ETSS model

- Tropical Storm Colin-2016 highlighted importance for Tropical program

- Guidance for Tropical Inundation graphic for parts of Hermine-2016 and Matthew-2016

- Implementation - 2017

P-ETSS Questions?

How should P-ETSS weight the ensemble members?

- P-Surge error spaces are defined by climatological error statistics
- Initially P-ETSS equally weights them, but could attempt to "measure" the relation to an ensemble mean

Can a parametric wind model be embedded in the Gridded wind field?

Can hypothetical Extra-Tropical storms be developed?

Questions?

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