Storm Surge Decision Support

Experiences and Lessons Learned

Arthur A. Taylor
Storm Surge Team Lead
NOAA/NWS/OSTI/MDL

ESCAP/WMO Typhoon Committee Roving Seminar
Hanoi, Vietnam – November 15, 2016

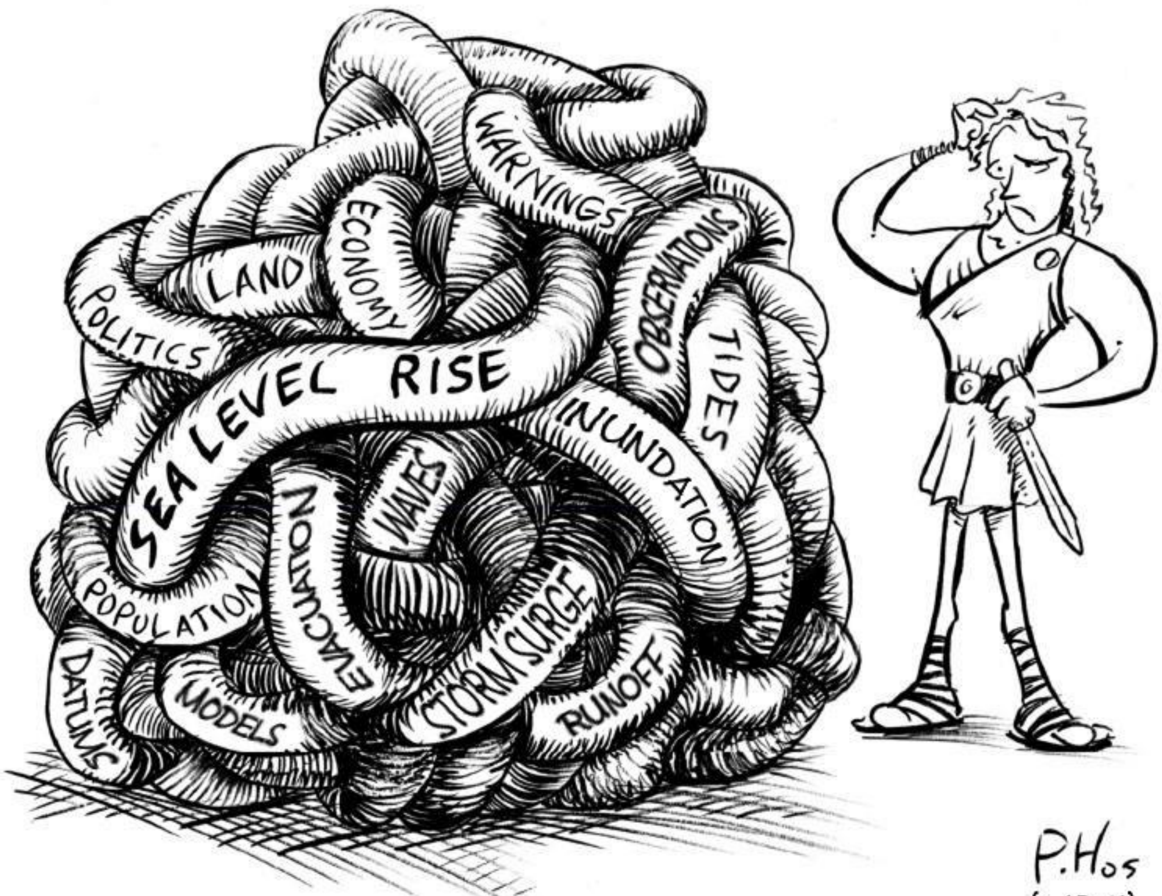
Overview

- **Part 1 – Stakeholders** *(who)*
- **Part 2 – Models and Products** *(what)*
- **Part 3 – Basins** *(where)*
- **Part 4 – Operational Timeline** *(when)*
- **Part 5 – Raising Awareness** *(why)*

Part 1:

Stakeholders

It's Complicated: Don't Go it Alone



A Wicked Problem

Stakeholders

- Federal
  - National Oceanic and Atmospheric Administration (NOAA)
    - National Weather Service (NWS)
    - National Ocean Service (NOS)
  - Army Corps of Engineers (ACE)
  - Federal Emergency Management Agency (FEMA)
  - US Geological Service (USGS)
- State and Local

Lesson Learned

- Stakeholder:
  - *Identification.* Must be proactive and thorough, particularly at the local level.
  - *Coordination.* Must be formal and continuous.
  - *Communication.* Must be formal, continuous, and clear; training is essential, particularly for those new to storm surge.

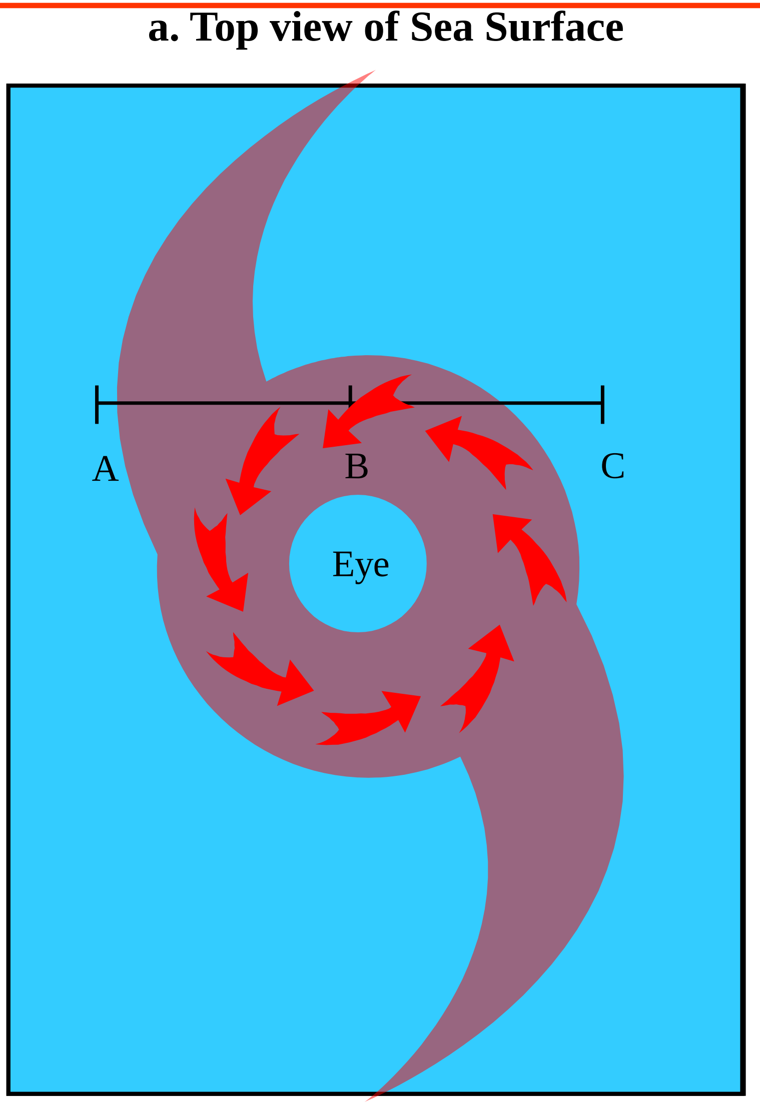
Storm Surge Fast Draw

https://youtu.be/bBa9bVYKLP0

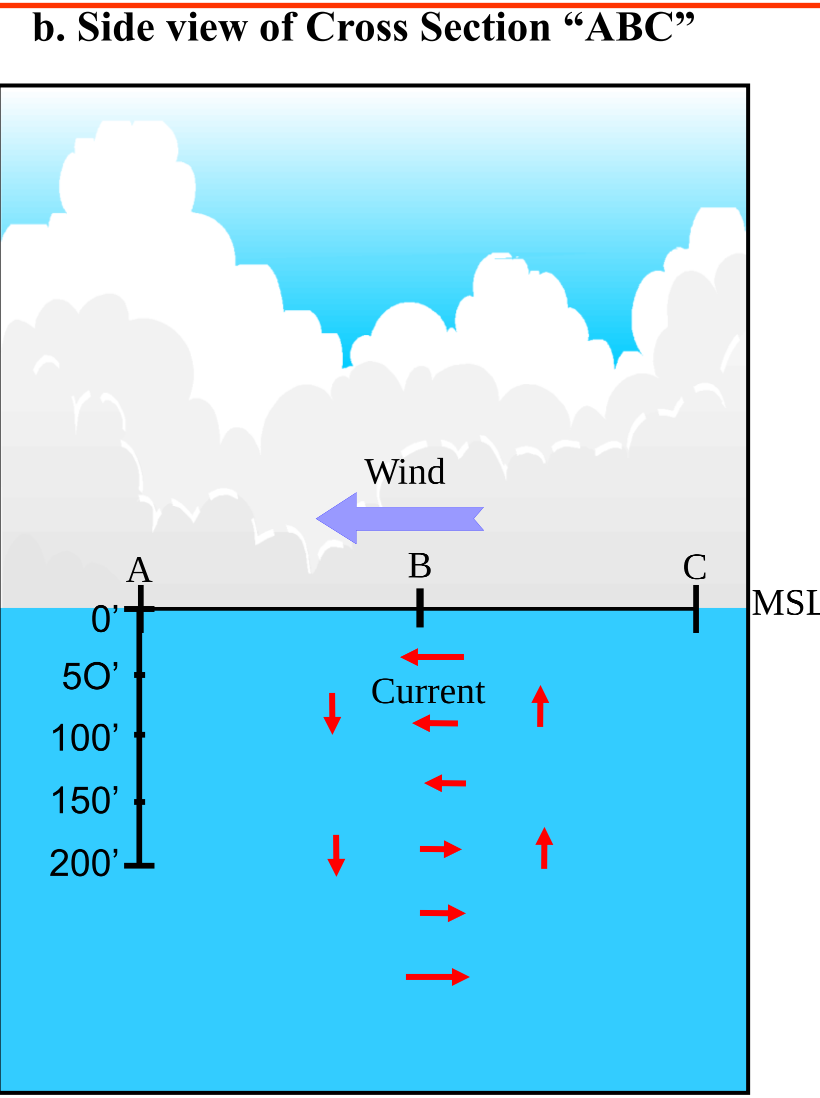
Part 2:

Models and Products

Deep Water



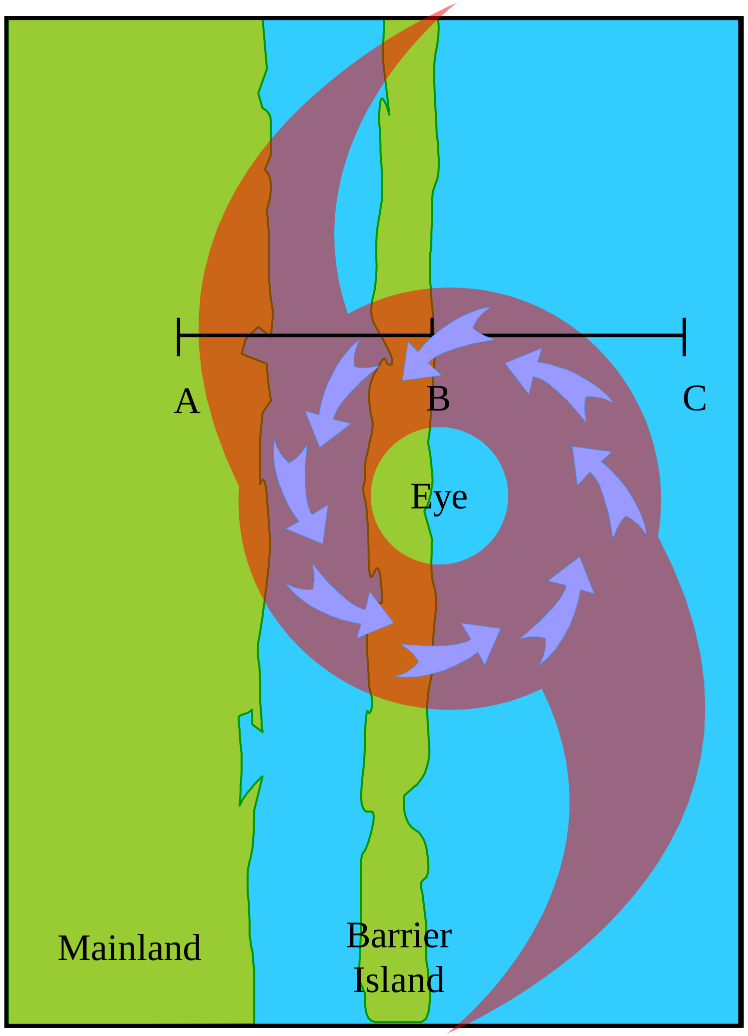
a. Top view of Sea Surface
A
B
C
Eye



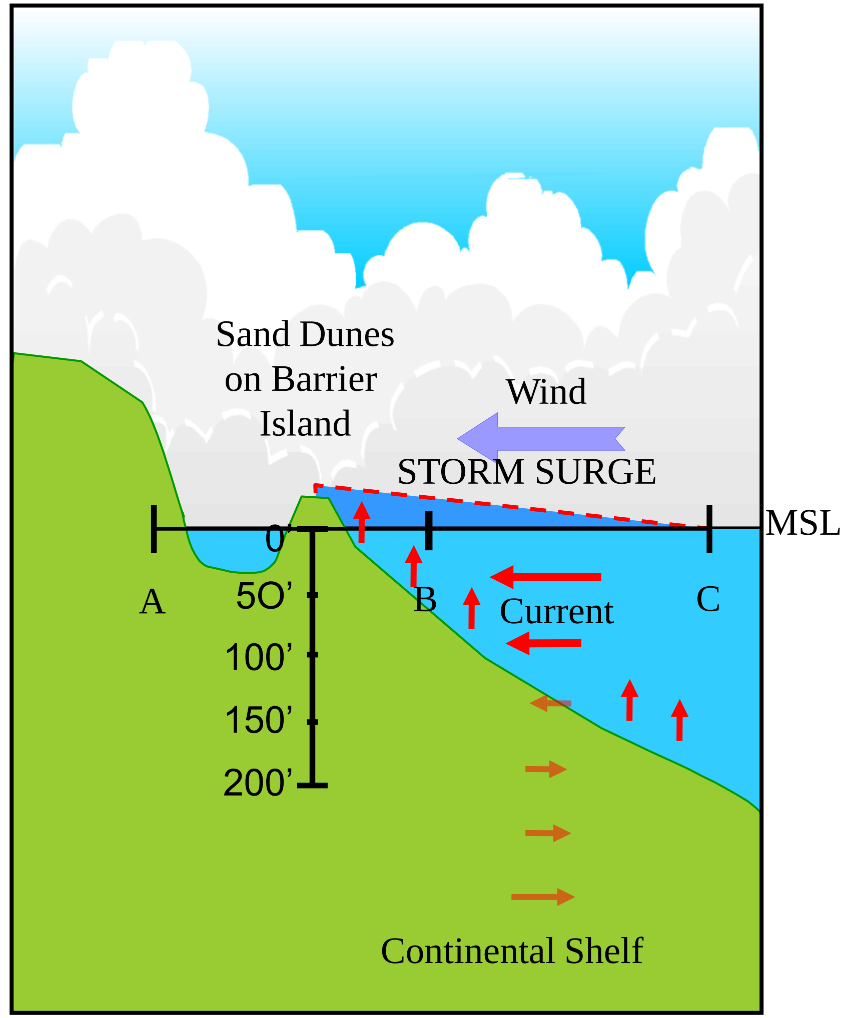
b. Side view of Cross Section "ABC"
Wind
A
B
C
MSL
0'
5O'
100'
150'
200'
Current

Landfall

a. Top view of Sea Surface and Land



b. Side view of Cross Section "ABC"

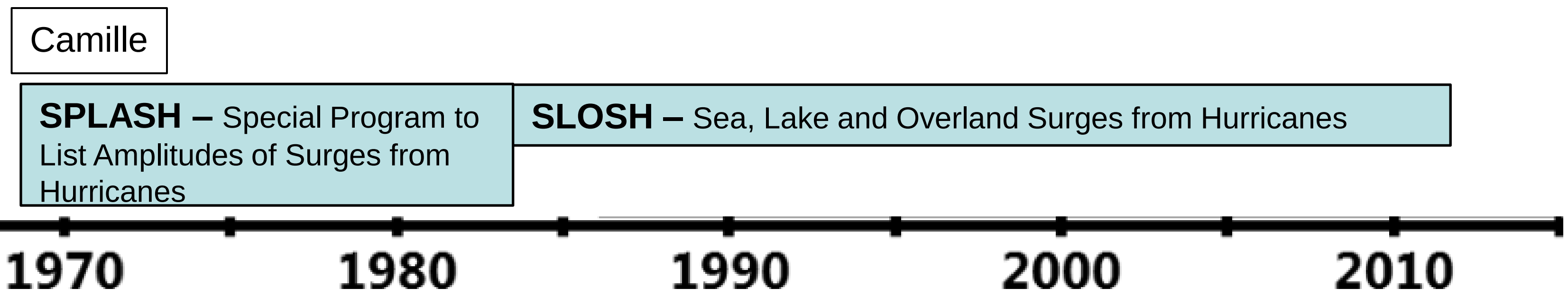


Fundamental Surge Components

1. **Wind setup** – Increase in water level due to the force of the wind on the water
2. **Geostrophic adjustment** – Adjustment due to longshore current
3. **Pressure setup** – Increase in water level due to lower atmospheric pressure
4. **Tide**
5. **Wave setup** – Increase due to breaking waves (wave setup and run-up)
6. **Steric setup** – Increase due to water temperature
7. **Nonlinear advection**
8. **Dissipation terms**

SLOSH: Sea Lake and Overland Surges from Hurricanes

- A computationally efficient finite differencing model that predicts **overland** flooding from storm surge
- Parametric wind model
  - Utilizes "forecastable" hurricane parameters of position, delta pressure and radius of maximum winds
  - Solves a differential equation for wind speed and direction incorporating forward speed into the asymmetry
  - Universal (not "calibrated" to location)
- Structured (Arakawa B) Grid with finer resolution overland
- Sub-grid elements to model rivers and streams, Barriers, Cuts, Channel Flow and Increased friction for trees and mangrove



SLOSH Equations

$$\frac{\partial U}{\partial t} = -g(D+h)\left[B_r \frac{\partial (h-h_0)}{\partial x} - B_t \frac{\partial (h-h_0)}{\partial y}\right] + f(A_r V + A_t U) + C_r x_t - C_t y_t$$

$$\frac{\partial V}{\partial t} = -g(D+h)\left[B_r \frac{\partial (h-h_0)}{\partial y} + B_t \frac{\partial (h-h_0)}{\partial x}\right] + f(A_r U - A_t V) + C_r y_t + C_i x_t$$

$$\frac{\partial h}{\partial t} = -\frac{\partial U}{\partial x} - \frac{\partial V}{\partial y}$$

Where U and V are the **components of transport**, g is the gravitational constant, D is the depth of quiescent water relative to datum, h is the height of water above datum, h_0 is the hydrostatic water height, f is the Coriolis parameter, x_t and y_t are the components of surface stress, and A_r, A_t, B_r, B_t, C_r, and C_t are the bottom stress terms [Jelesnianskiet al. 1992].

The **surface stress**, $\vec{t}$, is an important term in the equations of motion. Generally, the **wind stress** per unit mass on the sea surface is expressed as:

$$\vec{t}_{(x,y,t)} = C_D \frac{\rho_a}{\rho_w} \left|\vec{W}_{(x,y,t)}\right| \vec{W}_{(x,y,t)}$$

Where C_D is the drag coefficient, ρ_w and ρ_a are the densities of water and air, the W is the vector wind. The z coordinate of the stress term is $z = z_s$ where z_s is the distance above the sea surface (typically 10 m) and where wind sources retained at the surface utilize a constant pressure to be converted to z_s[Jelesnianski et al. 1992].

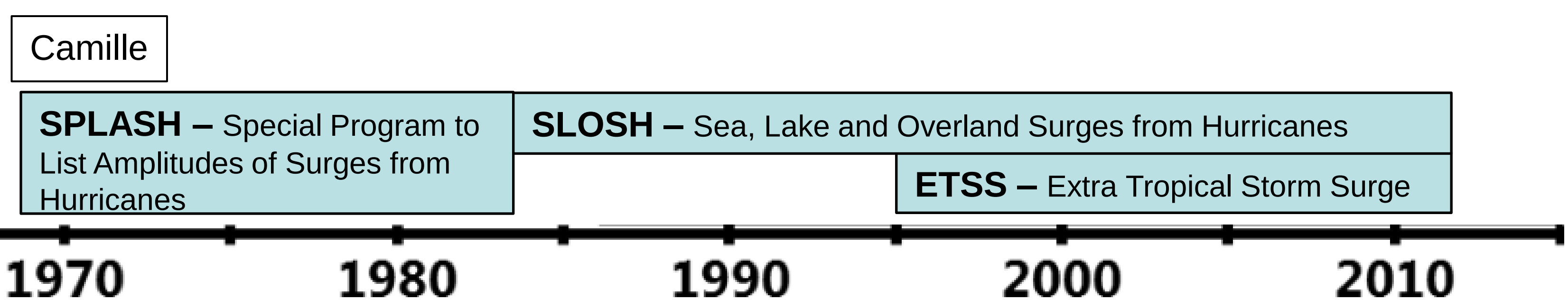
SLOSH Winds

- Parametric wind model
  - Utilizes “forecastable” hurricane parameters (Does have errors)
  - Solves a differential equation for wind speed and direction
  - Forward speed is incorporated into asymmetry
  - Tested on many past hurricanes
  - Universal (not “calibrated” to location)

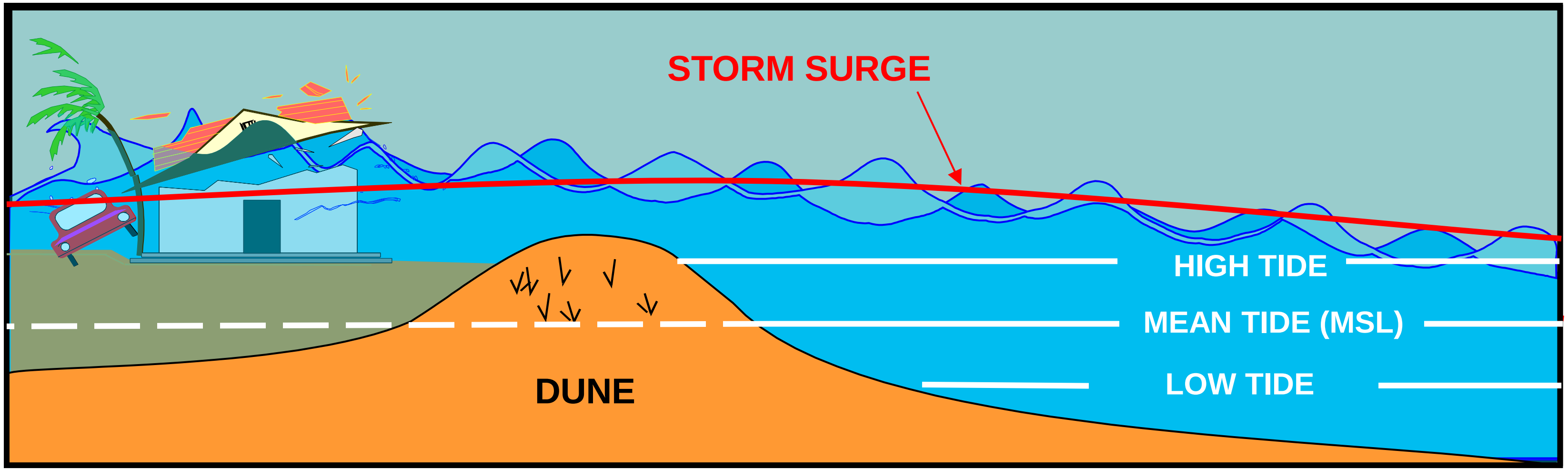
- Inputs
  - Track => NHC advisory
  - Current Rmax => estimated from available obs
  - Current DelP => NHC Advisory
  - Forecast Rmax, DelP => estimated by NHC's storm surge specialists

Extra-**T**ropical **S**torm **S**urge (ETSS)

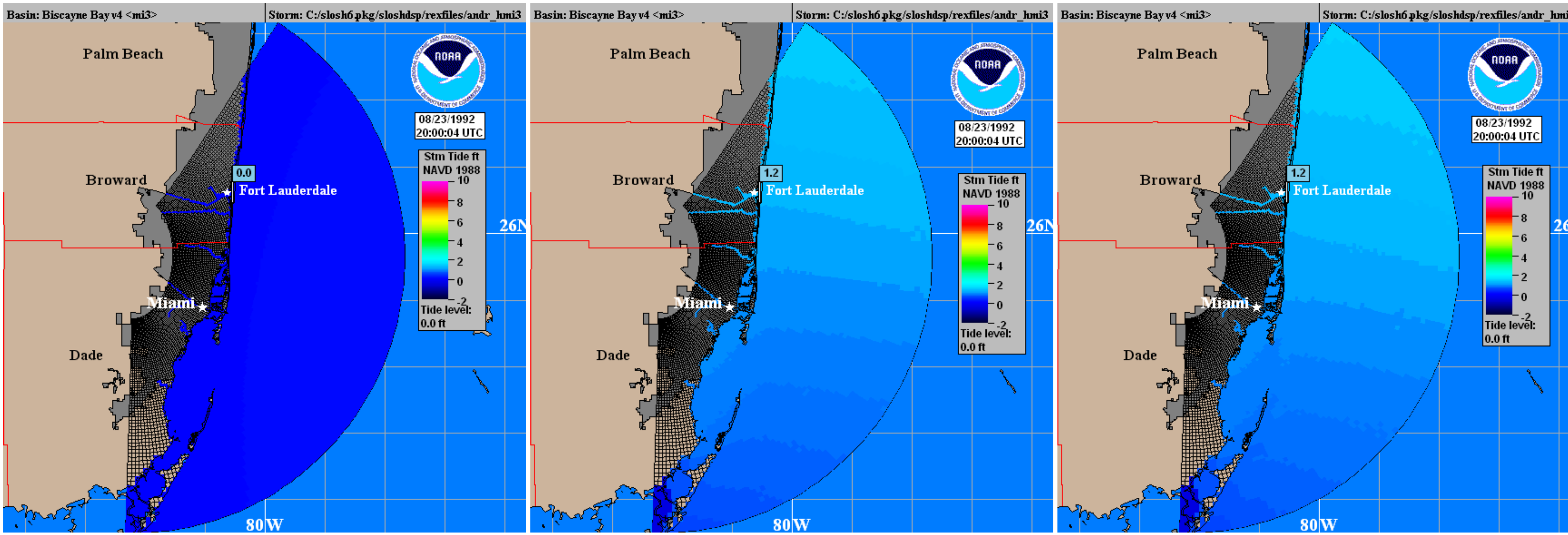
- Modification of SLOSH to use 0.5 degree Global Forecast System (GFS) winds and pressure as input
- Intended for large extra-tropical storms rather than hurricanes (aka tropical storms)
- Does not include Waves and River Flow
- It's been applied to
  - Bering, Beaufort, Chukchi Seas, AK (Oct 2015)
  - Gulf of Alaska (Apr 2008); West Coast (Feb 2011)
  - East Coast (Feb 2009); Gulf of Mexico (Jan 2011)



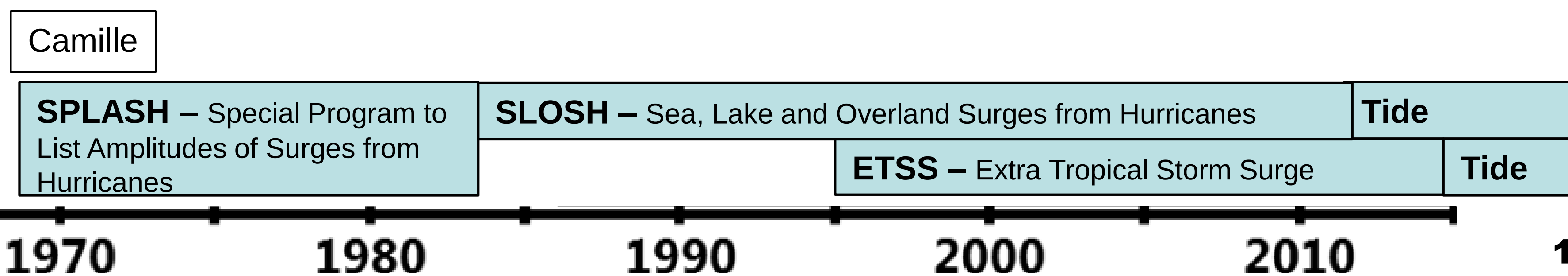
Storm Tide = Storm Surge + Tide



SLOSH + Tides



Extract harmonic constituents at every SLOSH grid cell from a global or higher resolution model



SLOSH + Tides

- Version 1 - Addition after model run
  - **Issue:** Tide not considered during inundation step
  - **Issue:** Extrapolated tidal values overland
- Version 2 - Addition and subtraction of tidal field at each time step

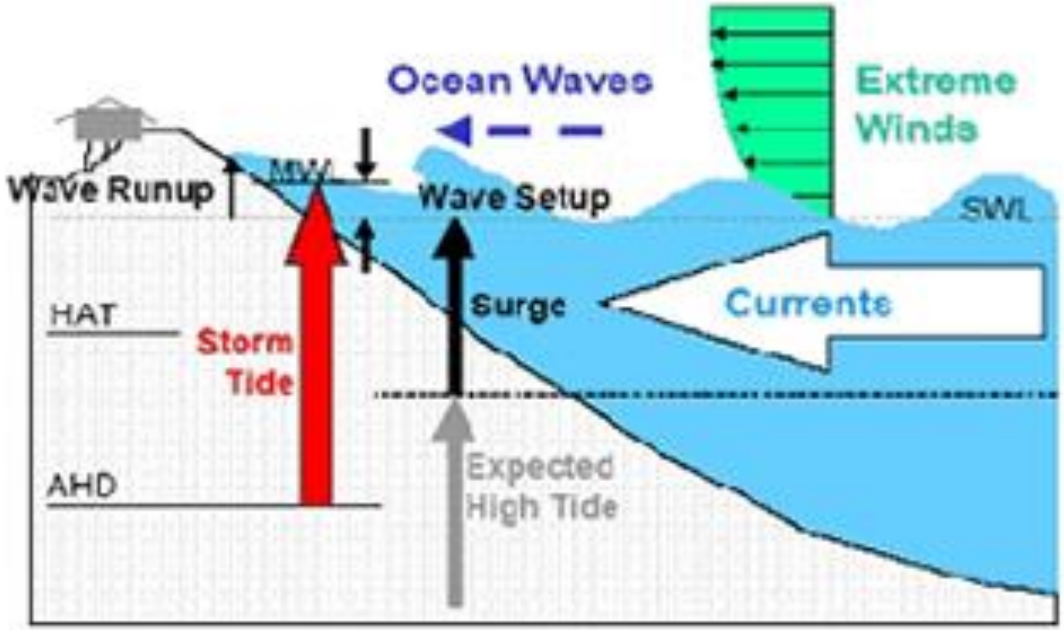
$$H(t_0) = Tide(t_0)$$
$$H(t_n) = SLOSH\left(H(t_{n-1})\right) - Tide(t_{n-1}) + Tide(t_n)$$

  - **Issue:** Wetting/Drying impacts computation
  - **Issue:** Extrapolated tidal values overland
- Version 3 – Tide as a boundary condition
  - **Issue:** Getting tide through narrow mouths into estuaries
  - **Issue:** Spin up time required to initialize transport variables

Tropical and Extra-Tropical Storm Surge Products

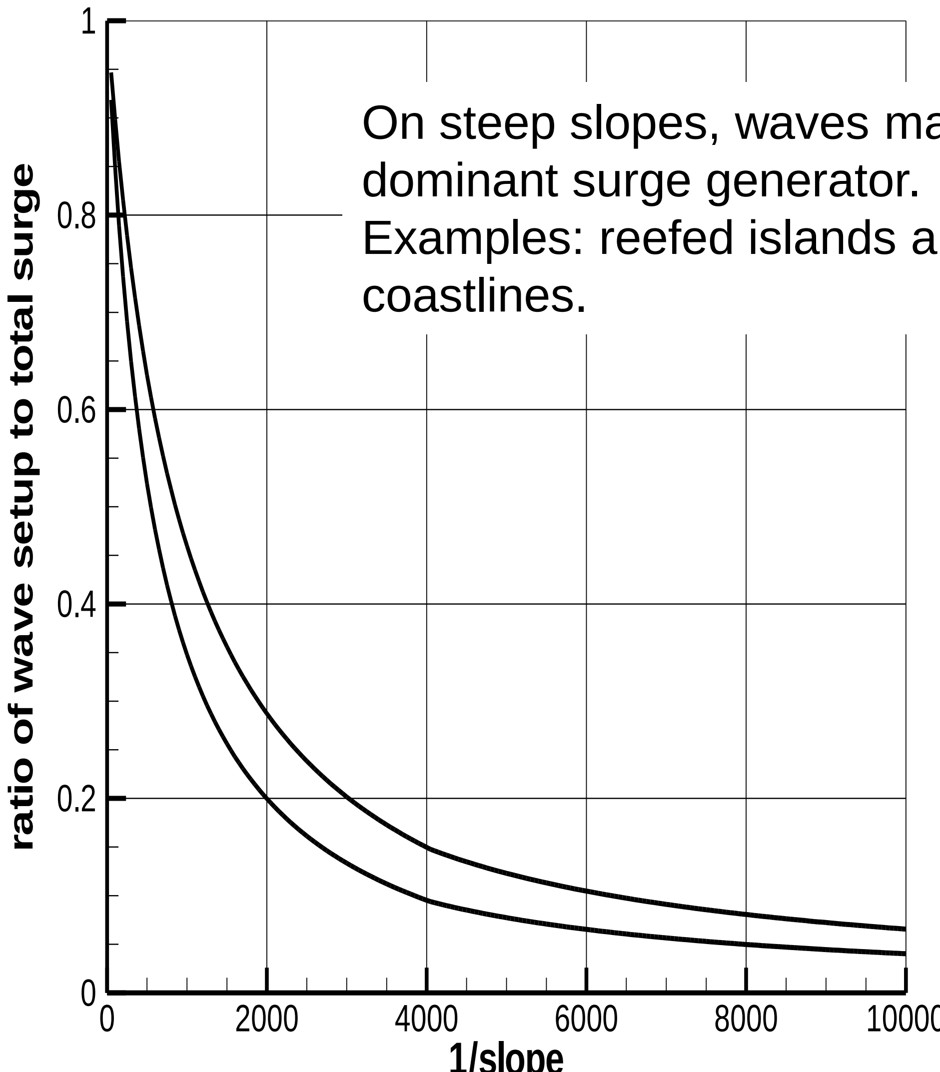
Tropical	Extra-Tropical
Storm Surge to Coastline	
SPLASH (1972 – 1984)	ETSS (1995 – 2014) ESTOFS (2012 –) ETSS 1.5 (2014 – 2015)
Overland Storm Surge	
SLOSH (1984 –) ------------------------------------ P-Surge 1.0 (2008 – 2013) MEOW/MOM (1986 –)	ETSS 2.0 (May 2015) ------------------------------------ No Real-Time Ensemble No Climate Ensemble
Overland Storm Surge + Gridded Tide	
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

Total Water Level



Storm surge + Tides + Waves + Freshwater

Waves – Relative Contribution



On steep slopes, waves may be the dominant surge generator.
Examples: reefed islands and many rocky coastlines.

Resio (2012)

Wave Runup

Wave Setup

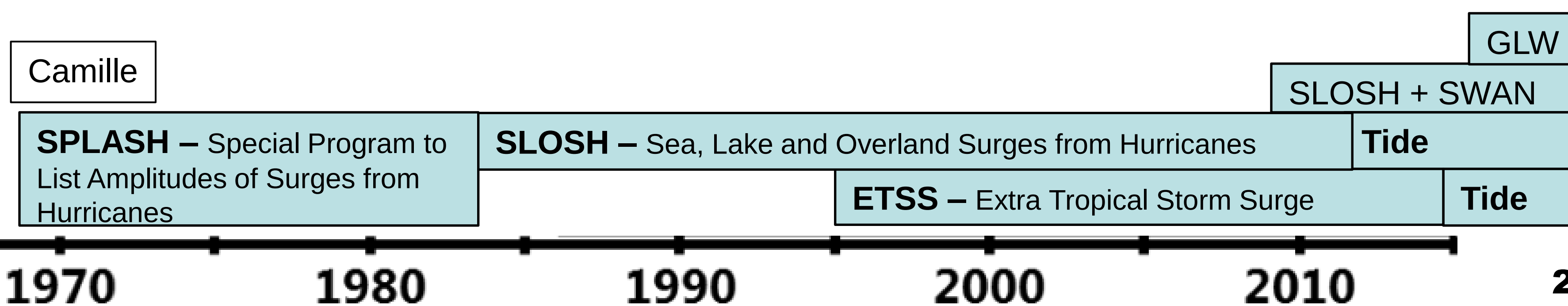
SLOSH + Waves (SWAN, GLW)

SLOSH + SWAN coupling (Example of R2O)

- Developed by Don Slinn (University of FL) in 2009
- Worked on by Cristina Forbes (NHC)
- Used for Puerto Rico potential storm surge inundation

Real Time Application?

- SWAN (3rd gen. wave model) takes too long
- Great Lakes Waves (GLW) a recently retired 2nd gen. wave model
- Dongming Yang is working to couple GLW to SLOSH



SLOSH
Room for Improvement

Surge Component

- ❑ Constant bottom friction term
- ❑ Constant wind drag coefficient in air
- ❑ Constant eddy stress coefficient in water
- ❑ Coriolis term is generally omitted for lakes and inland inundation but retained for large amplitude surges if inundation covers a large area
- ❑ **6. Steric setup** – Increase due to water temperature
- ❑ **7. Nonlinear advection term**
- ❑ **8. Dissipation term**

Other

- ❑ **River** – Allow river boundary condition
- ❑ **Initialization** – Initialize based on observations
- ❑ **Computation (runtime)** – Use multiple CPU's

Requirements

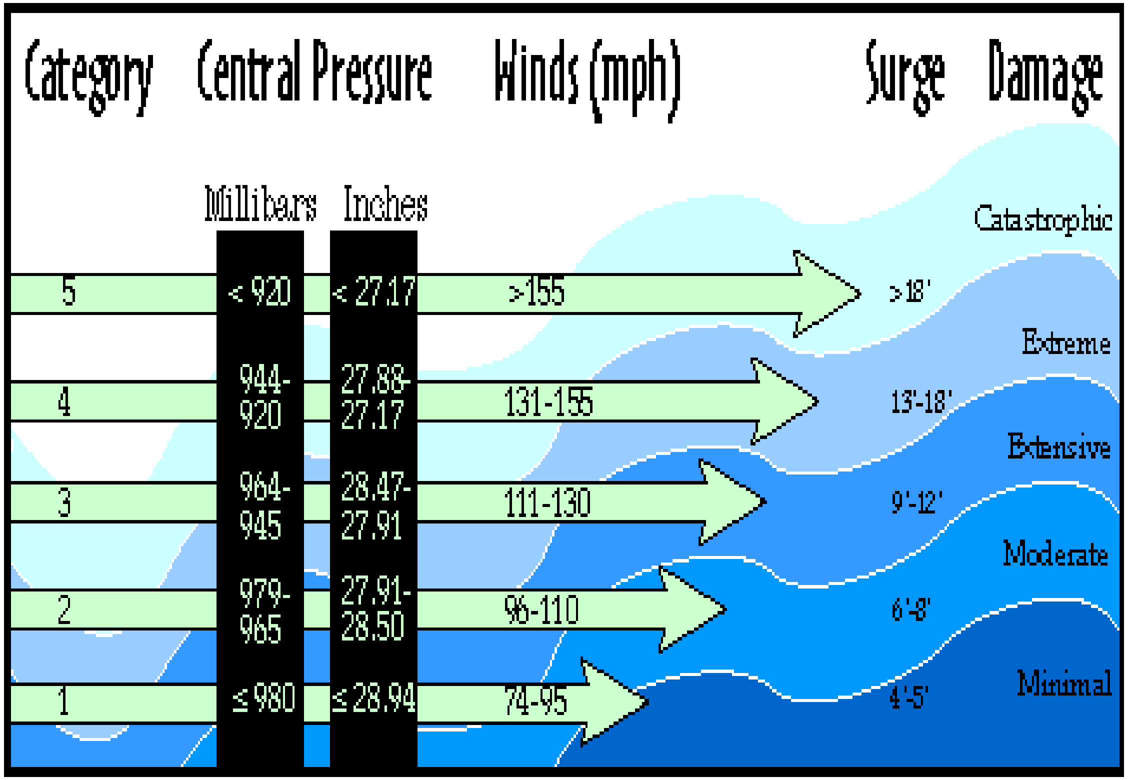
- 1 hour post forecast release
- Inundation to the 50’ contour line (populated areas, evacuation routes, sensitive infrastructure)
- 96-hour evacuation window for some cities
- Communication via preferred platforms
- Total Water Level (surge + tide + wave + river)

Lesson Learned

- Available resources drive development as much as, if not more than, requirements:
  - Dedicated Personnel
  - Computational Resources

Lesson Learned - Surge is **NOT** directly correlated with intensity

No more surge in the Saffir-Simpson Scale!



KATRINA (3)

IKE (2)

CHARLEY (4)

Lesson Learned

- **Ike 2008**: Communicate Above Ground Level (AGL) to public and Above Datum to scientists

- Best numerical model still needs good inputs:
  - Bathymetry and Topography
  - Wind forcing
  - Observations

Part 3:

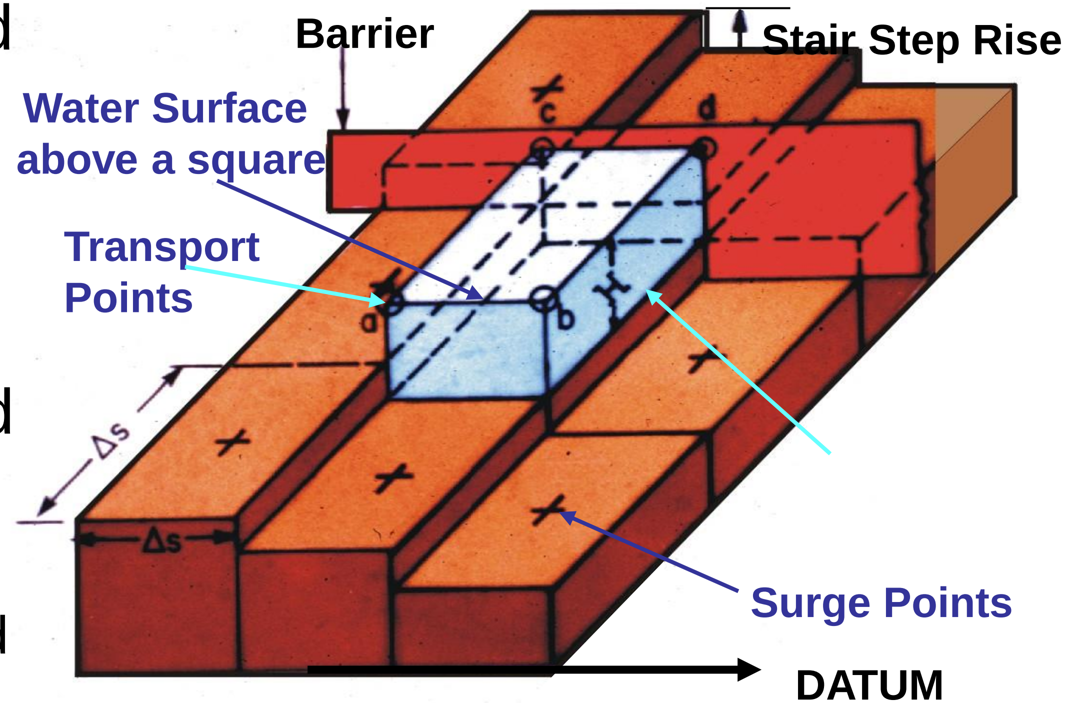
Basins

SLOSH Basin

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

Structured, Arakawa B-Grid

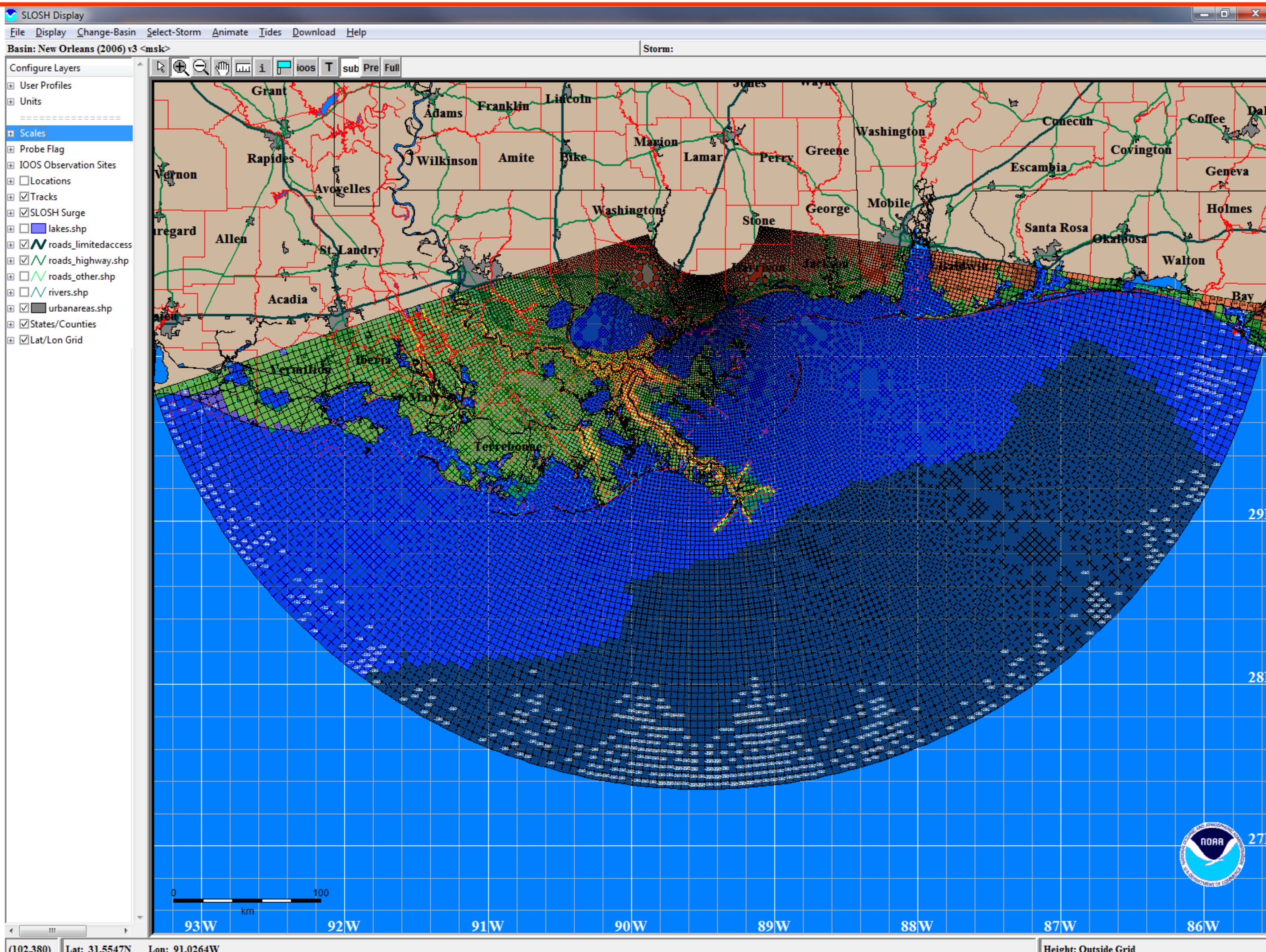
- Heights at the center and transports on the corners
- Finer resolution overland, and coarser offshore
- Locally orthogonal



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



SLOSH Display
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Storm:
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roads_other.shp
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Coffee
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Wilkinson
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Pike
Marion
Lamar
Perry
Greene
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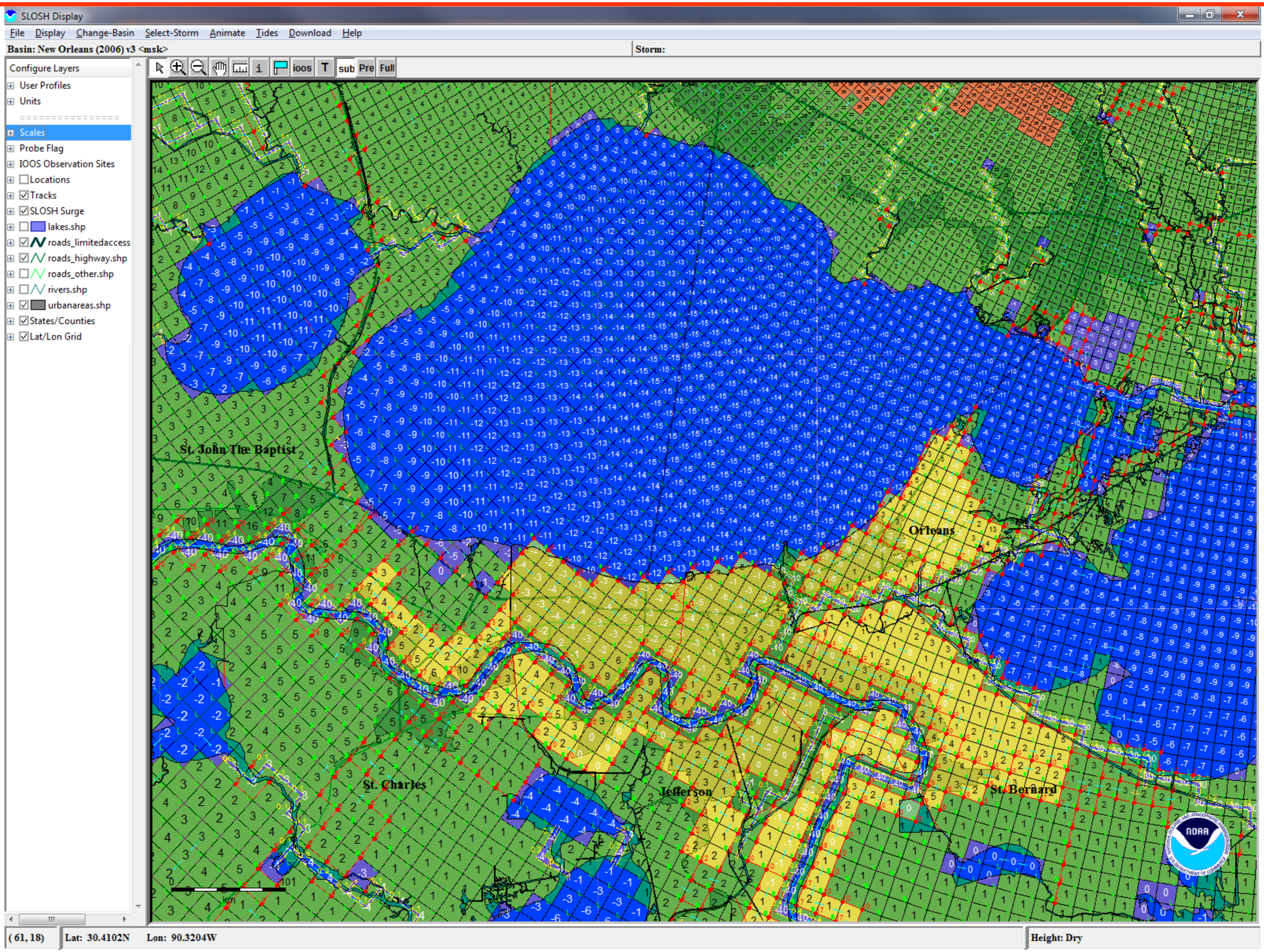
Geneva
Avoyelles
Escambia
Washington
George
Mobile
Holmes
Stone
Santa Rosa
Okaloosa
Walton
Allen
St Landry
Acadia
Bay
Vermilion
Iberia
Terrebonne
29N
28N
27N
0
100
km
93W
92W
91W
90W
89W
88W
87W
86W
(102,380)
Lat: 31.5547N
Lon: 91.0264W
Height: Outside Grid

SLOSH Basin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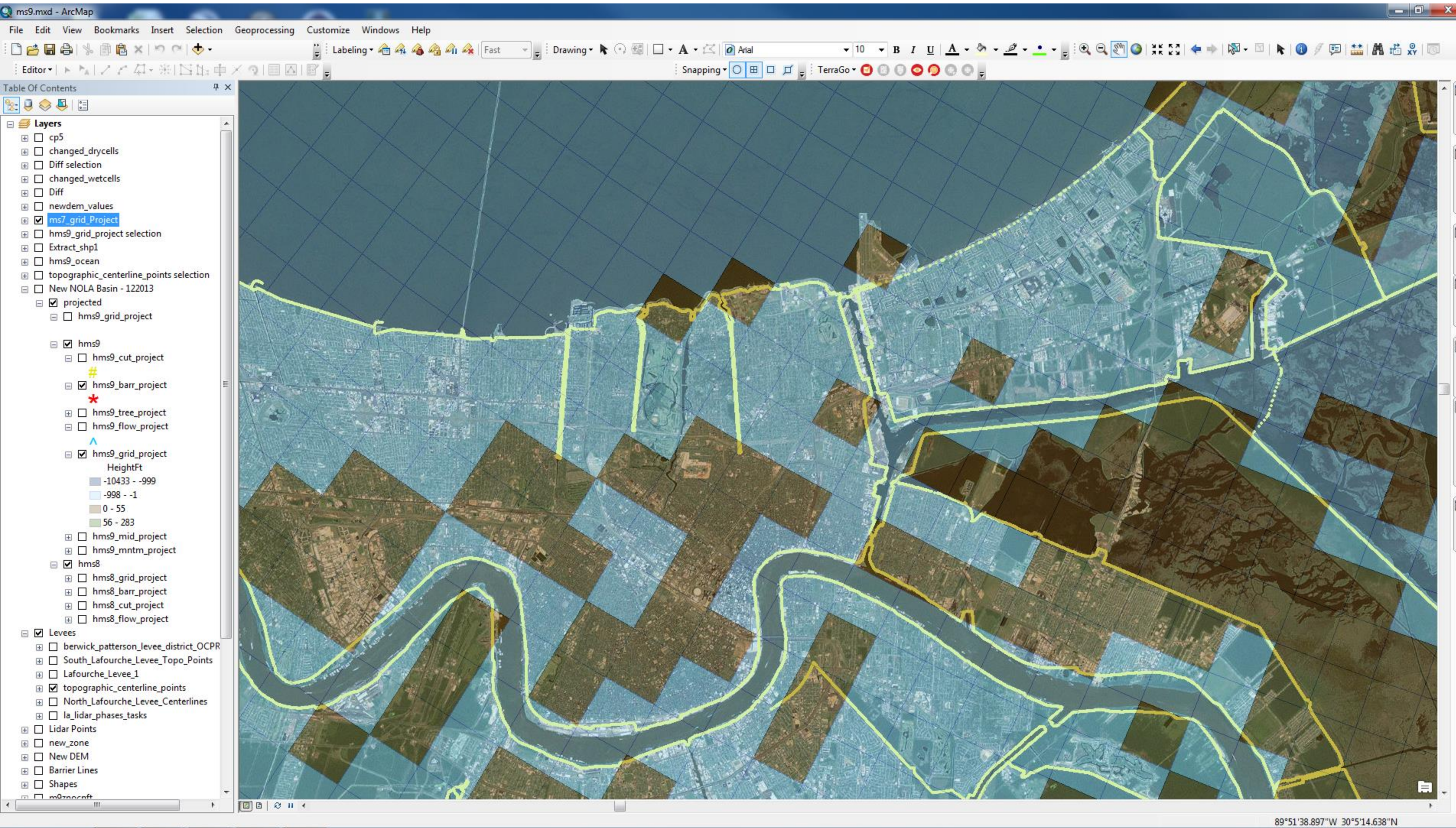
roads_highway.shp
roads_other.shp
rivers.shp
urbanareas.shp
States/Counties
Lat/Lon Grid
ioos T sub Pre Full
St. John The Baptist
Orleans
St. Charles
Jefferson
St. Bernard
(61, 18)
Lat: 30.4102N Lon: 90.3204W
Height: Dry

SLOSH Basin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ArcToolbox
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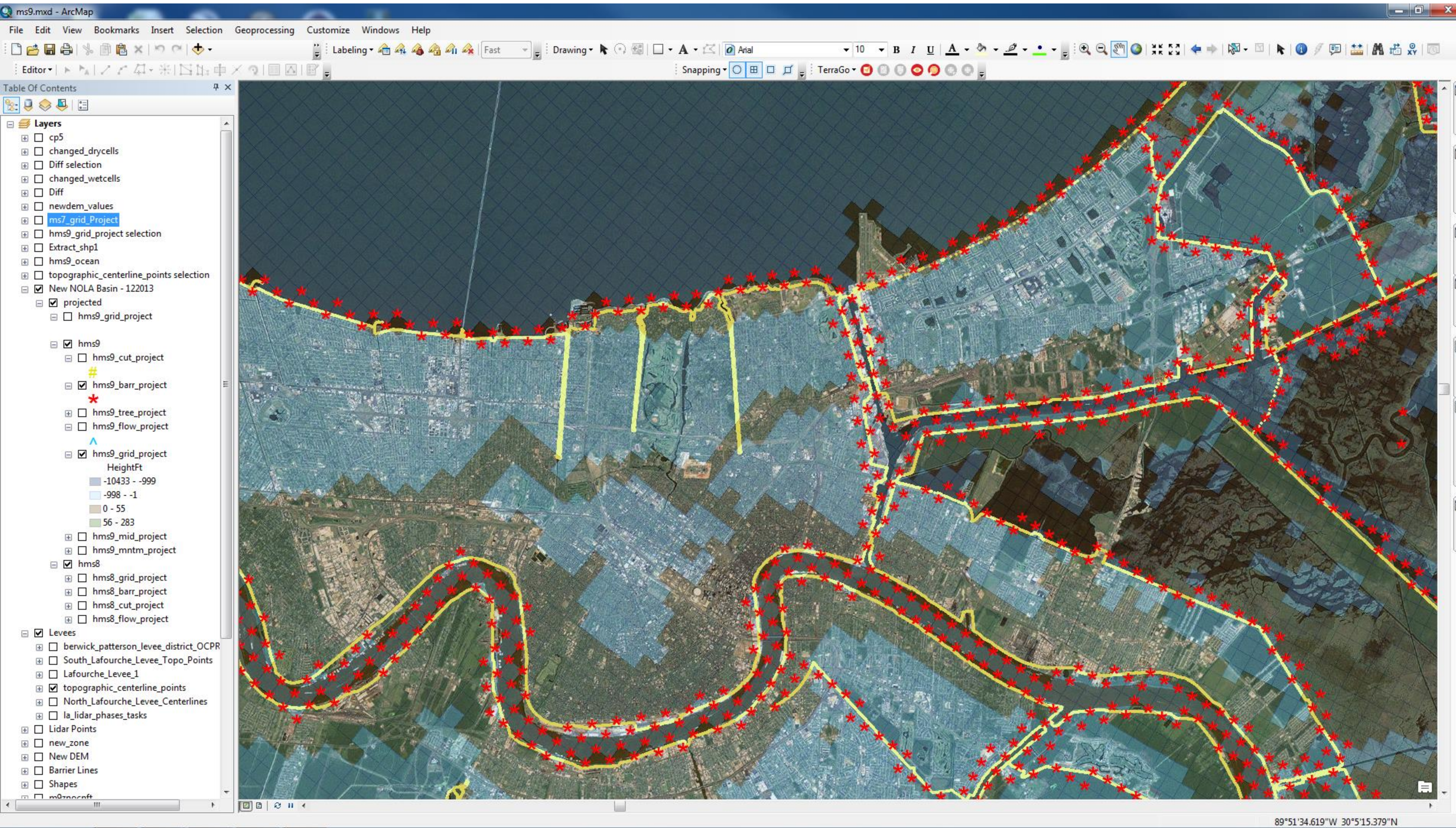
SLOSH Basin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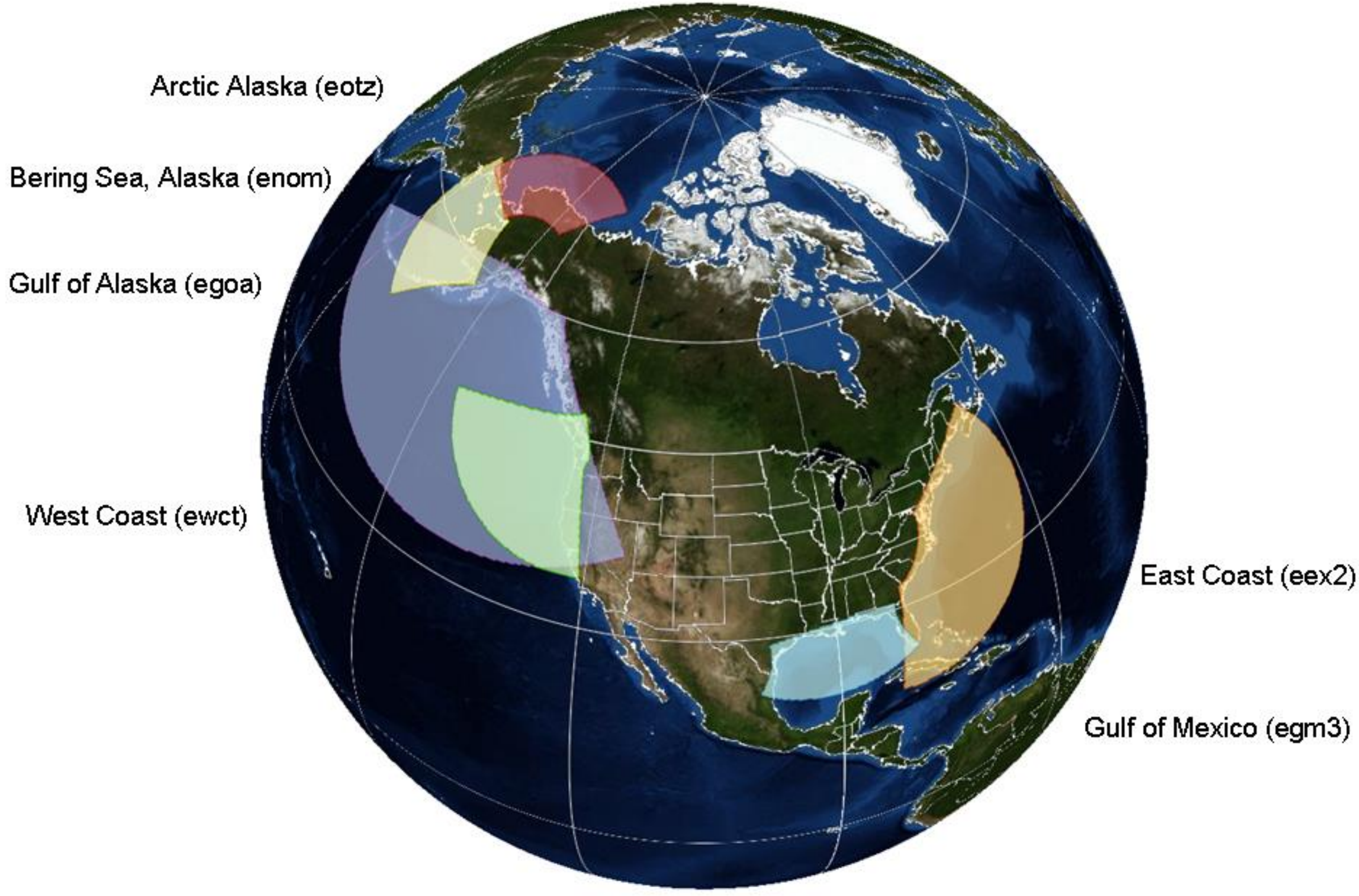
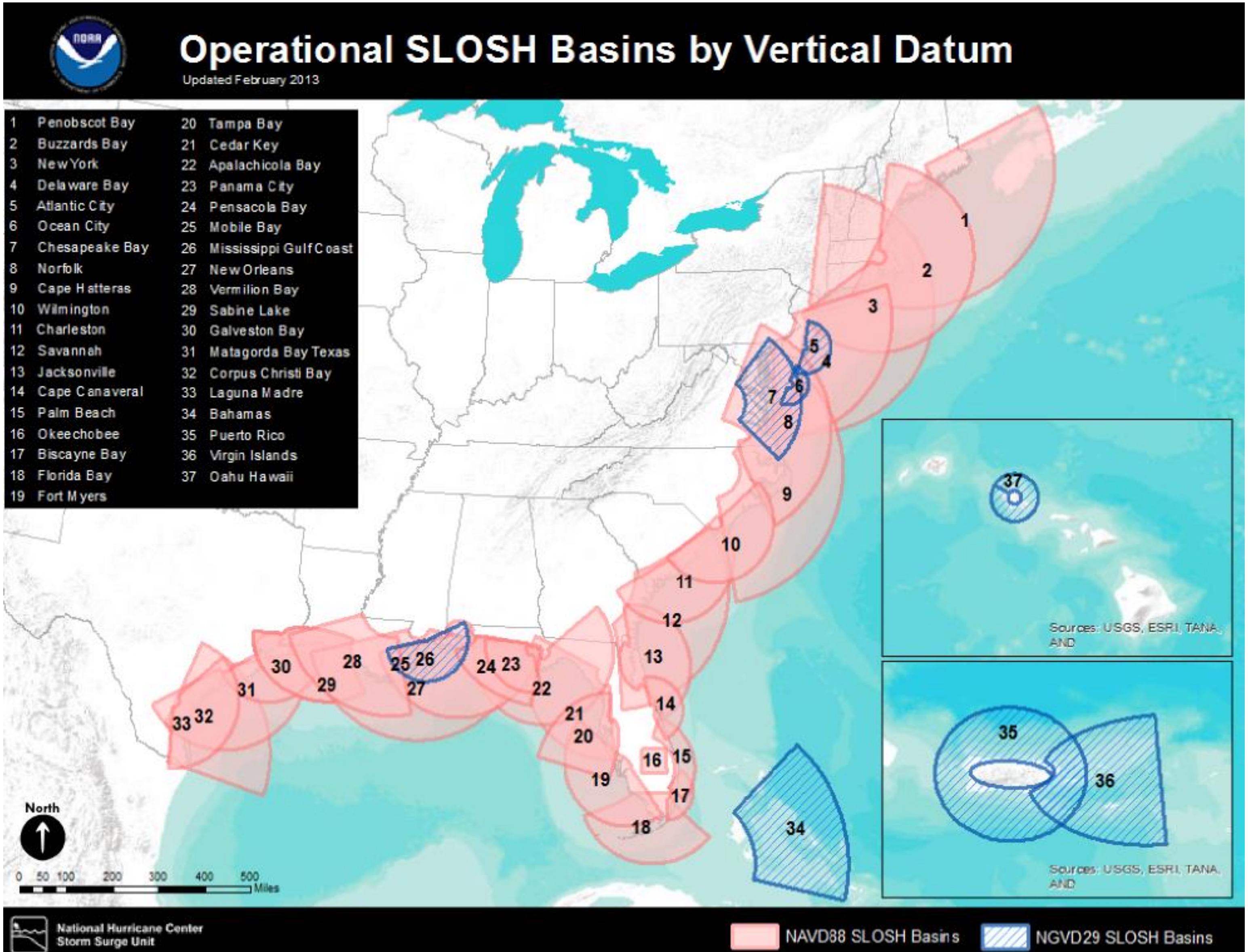
Catalog
89°51'34.619"W 30°5'15.379"N

Extra Tropical Basins



East and Gulf Coasts



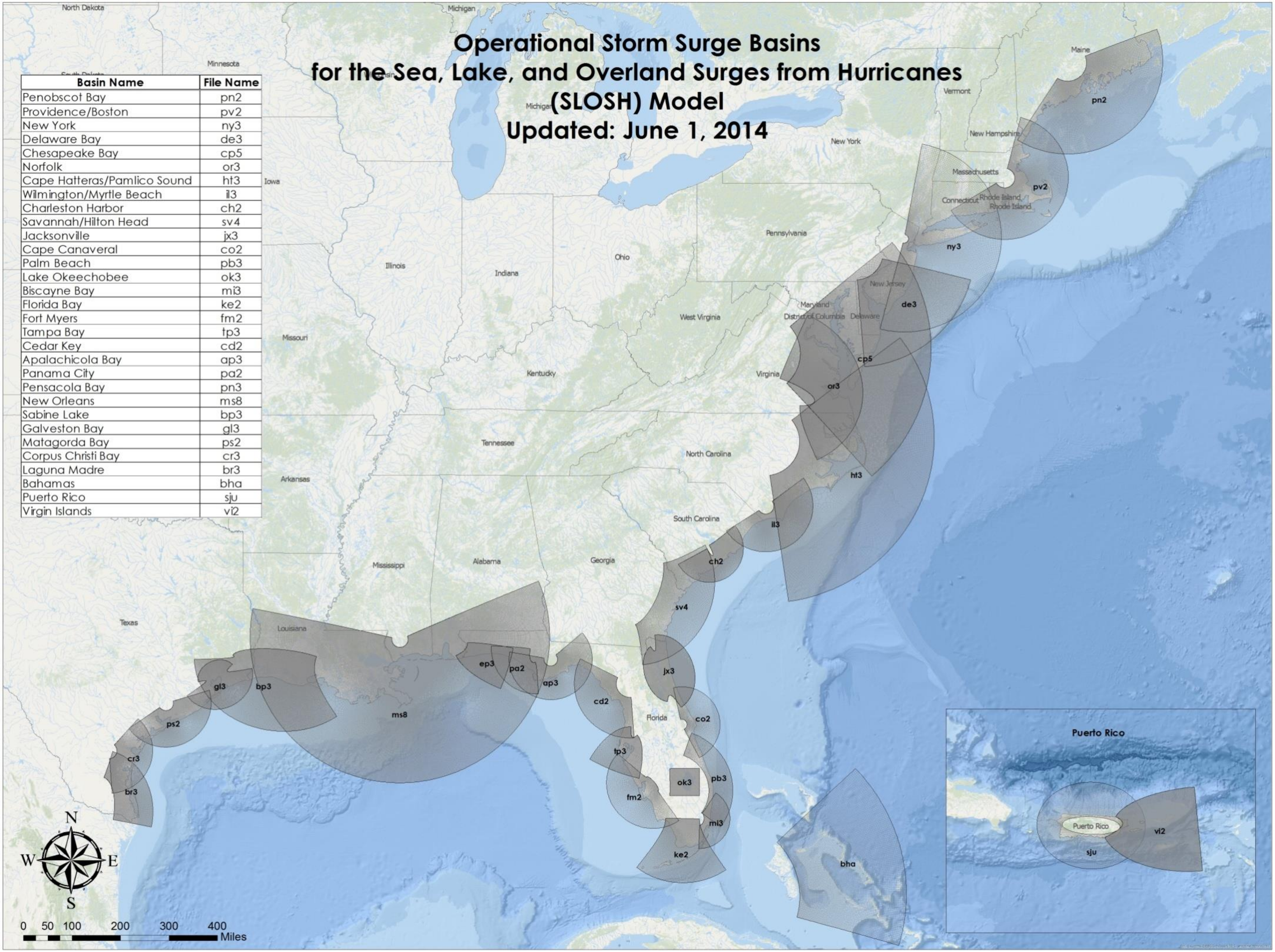
Lesson Learned

- Basins need a maintenance path
- Basins need to be 2.5 times the size of the storm as evidenced by Hurricane Ike.
  - Super basins lead to run time issues
  - Nested approach developed by Huiqing Liu

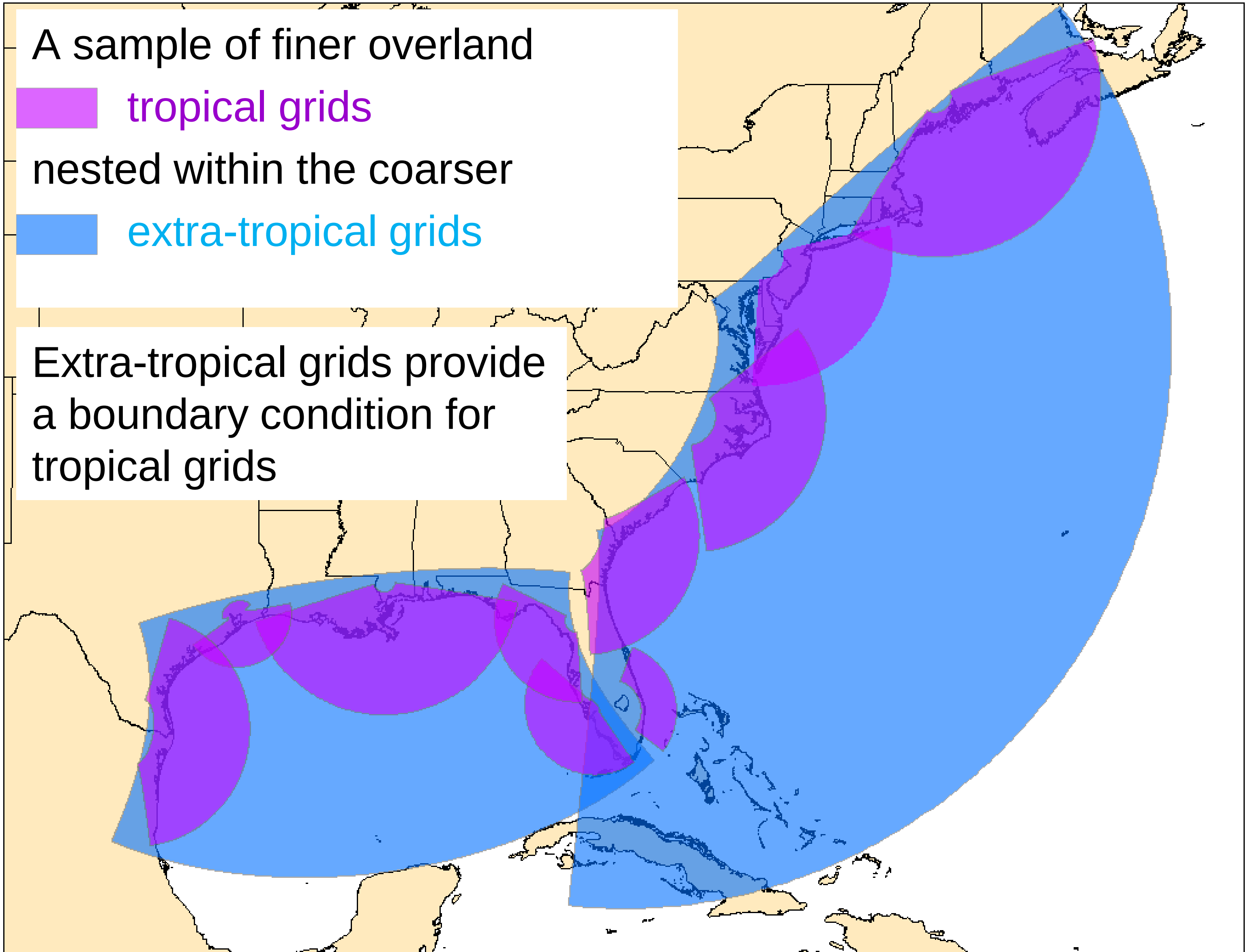
Operational Storm Surge Basins for the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) Model

Updated: June 1, 2014

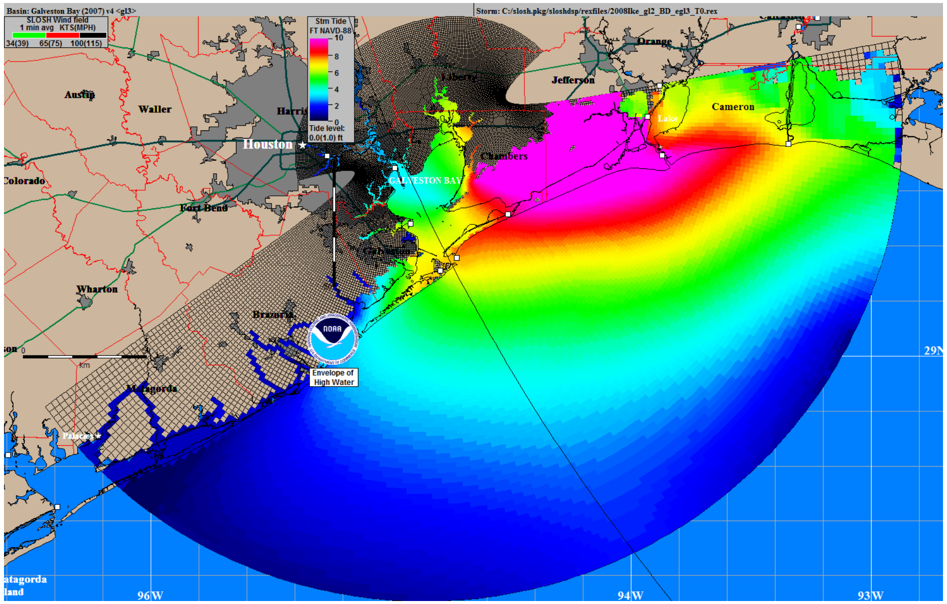
Basin Name	File Name
Penobscot Bay	pn2
Providence/Boston	pv2
New York	ny3
Delaware Bay	de3
Chesapeake Bay	cp5
Norfolk	or3
Cape Hatteras/Pamlico Sound	ht3
Wilmington/Myrtle Beach	il3
Charleston Harbor	ch2
Savannah/Hilton Head	sv4
Jacksonville	jx3
Cape Canaveral	co2
Palm Beach	pb3
Lake Okeechobee	ok3
Biscayne Bay	mi3
Florida Bay	ke2
Fort Myers	fm2
Tampa Bay	tp3
Cedar Key	cd2
Apalachicola Bay	ap3
Panama City	pa2
Pensacola Bay	pn3
New Orleans	ms8
Sabine Lake	bp3
Galveston Bay	gl3
Matagorda Bay	ps2
Corpus Christi Bay	cr3
Laguna Madre	br3
Bahamas	bha
Puerto Rico	sju
Virgin Islands	vi2



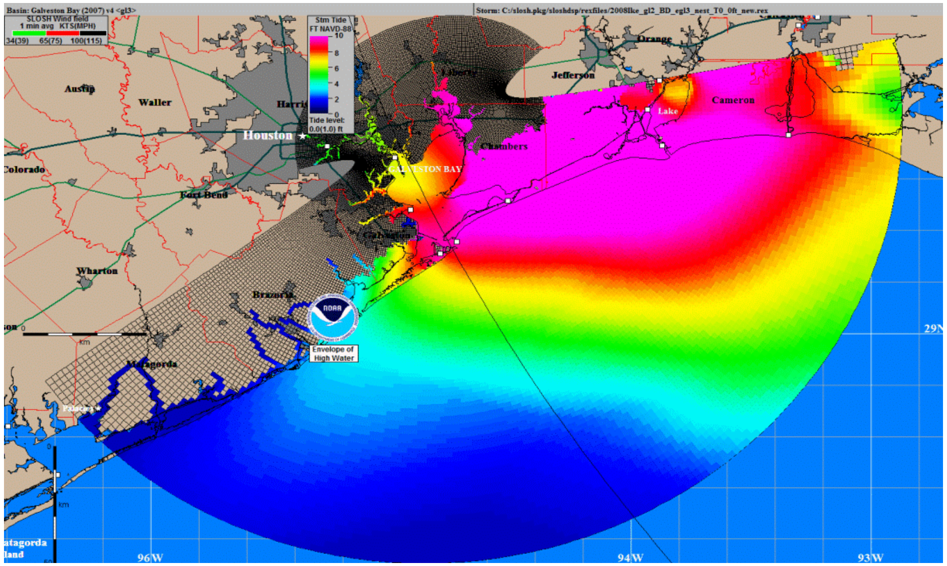
East Coast and Gulf of Mexico



Hurricane Ike

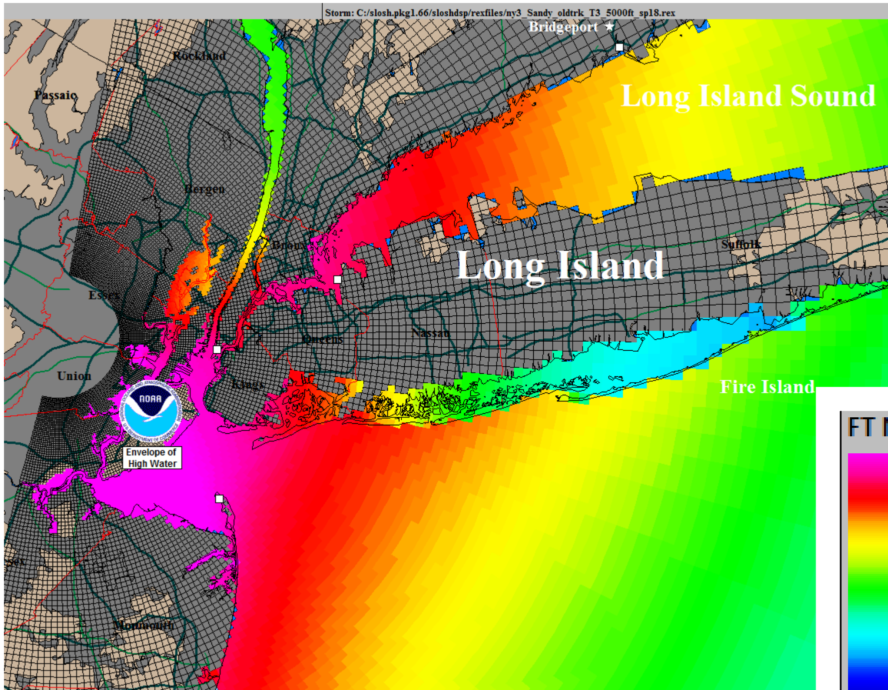


Ike2008 modeled in SLOSH's Galveston basin

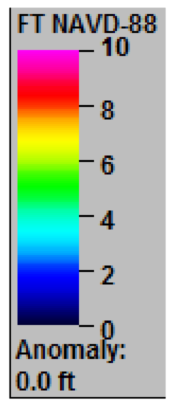


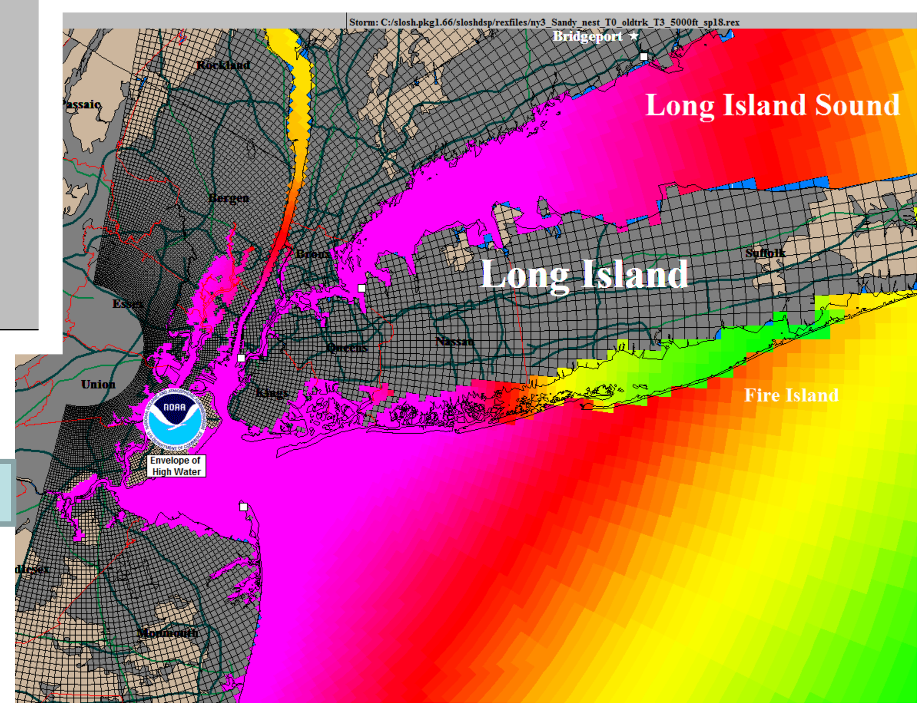
Ike2008 modeled by nesting SLOSH's Galveston basin within SLOSH's Gulf of Mexico basin; better-captures fore-runner phenomena

Hurricane Sandy



Maximum Storm Tide
<u>without nesting</u>





Maximum Storm Tide
<u>with nesting</u>

Part 4:

Operational Timeline

Operational Timeline

Planning / Mitigation (>120 hr)

- MOMs (Maximum Of the MEOWs)

Readiness (48hr – 120hr)

- MEOWs (Maximum Envelope Of Water)
- MOMs

Response (<48hr)

- NHC Advisory/NWS Local Statements
- Probabilistic Storm Surge (P-Surge)
- MEOWs

Part 5:

Raising Awareness

Hurricane Katrina (2005)

Hurricane Sandy (2012)

Hurricane Ike (2008)


© Imaginechina / Splash News


TOMI ELEGANCE

Lesson Learned

- While the threat posed by storm surge is well-understood in academic and professional circles, more needs to be done to educate at risk populations.

Education Needed

Education Needed

Education Needed

Education Needed

Education Needed

Education Needed

Public Service Announcement

https://vimeo.com/13463438

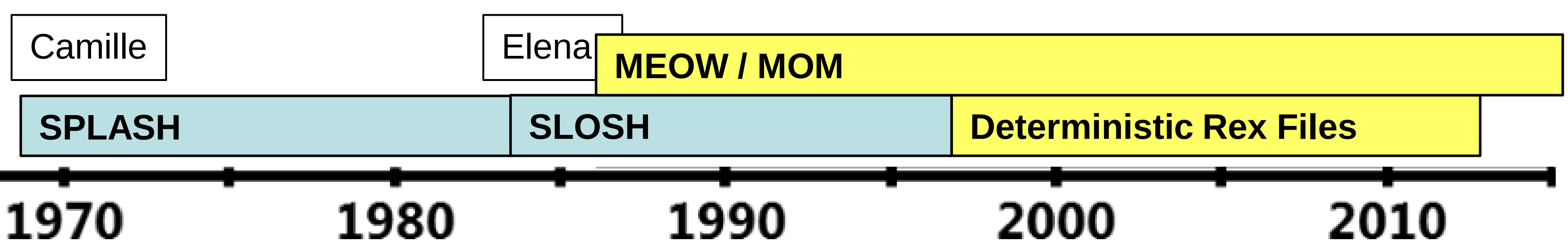
Communication: SLOSH Display Program (SDP)

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)



Questions?

(Arthur.Taylor@noaa.gov)