Implementation of a Coupled Storm Surge plus Waves Modeling System at the National Hurricane Center

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Outline

SLOSH+SWAN (SWOSH) Coupled Model

(Sea, Lake, and Overland Surges from Hurricanes + Simulating WAves Nearshore)

- IOOS Testbed 1
- IOOS Testbed 2
- MEOWs/MOMs

Validation Results in Puerto Rico

- Hurricane Georges (1998)
- Hurricane Irene (2011)
- Tropical Storm Erika (2015)

IOOS/SURA Testbed

(Integrated Ocean Observing System/Southeastern Universities Research Association)

Testbed 1: June 1, 2010 - May 31, 2012

- SLOSH+SWAN (SWOSH) coupled model developed by Don Slinn at University of Florida.
- Delivered to NHC in 2011.
- Original code was configured for elliptical basins (egl3), Gulf of Mexico (egm2, egm3) and Sabine Lake (ebp3) and the polar basin Providence/Boston (pv2).
- NHC needed to assess whether coupled model system could use existing infrastructure to create and visualize products.

Inclusion of Wave Forcing in SLOSH

Prof. Don Slinn, University of Florida, Department of Civil and Coastal Engineering

$$\frac{\partial \zeta}{\partial t} = -\frac{\partial U}{\partial x} - \frac{\partial V}{\partial y} - \frac{\partial \boxed{U_{mass\ flux}}}{\partial x} - \frac{\partial \boxed{V_{mass\ flux}}}{\partial y}$$

Continuity Eqn (2-16)

$$\frac{\partial U}{\partial t} = -g(h+\zeta)\left[B_r \frac{\partial(\zeta-\zeta_0)}{\partial x} + B_i \frac{\partial(\zeta-\zeta_0)}{\partial y}\right] + f(A_r V + A_i U)$$
$$+ C_r(\tau_x + \tau_{wx}) - C_i(\tau_y + \tau_{wy}) - \frac{U}{(h+\zeta)}\left[\frac{\partial \boxed{U_{mass\ flux}}}{\partial x} + \frac{\partial \boxed{V_{mass\ flux}}}{\partial y}\right]$$

U Transport Eqn (2-17)

$$\frac{\partial V}{\partial t} = -g(h+\zeta)\left[B_r \frac{\partial(\zeta-\zeta_0)}{\partial y} + B_i \frac{\partial(\zeta-\zeta_0)}{\partial x}\right] + f(A_r U + A_i V)$$
$$+ C_r(\tau_y + \tau_{wy}) + C_i(\tau_x + \tau_{wx}) - \frac{V}{(h+\zeta)}\left[\frac{\partial \boxed{V_{mass\ flux}}}{\partial x} + \frac{\partial \boxed{U_{mass\ flux}}}{\partial y}\right]$$

V Transport Eqn (2-18)

τ_{wx}, – real wave radiation stress per unit mass component

τ_{wy} – imaginary wave radiation stress per unit mass component

$U_{mass\ flux}$ – real component of horizontal transport due to mass transport

$V_{mass\ flux}$ – imaginary component of horizontal transport due to mass transport

Smith (2006)

MEOWs / MOMs

(Maximum Envelopes of Water / Maximum of MEOWs)

- Hypothetical tracks that take into account the climatology of the region were generated for Puerto Rico at NHC
- 8 directions (WSW, W, WNW, NW, NNW, N, NNE, NE)
- 2 RMWs (20, 35 nm)
- 3 storm motions (5, 15, 25 mph)
- 5 Wind speed intensity categories (1, 2, 3, 4, 5)
- 21 landfall locations, spaced 10 miles apart
- 2 initial water level/datums (Zero, High Tide)
- Total number of synthetic storms = 10,080
- MEOWs composited by category, direction, datum, forward speed
- MOMs composited by category and initial water level (or datum)

IOOS/SURA Testbed

(Integrated Ocean Observing System/Southeastern Universities Research Association)

Post Testbed 1:

- Code was modified for Puerto Rico basin (hsj2).
- Preliminary MEOWs/MOMs were created with hsj2 to see if it would be possible to use the NHC operational infrastructure.
- In partnership with the University of Miami-RSMAS, TeraGrid/Xsede supercomputer resources were used to create MEOWs/MOMs with hsj2.
- Test was successful. MEOWs and MOMs were generated for SLOSH wind-only and SLOSH wind-plus-waves simulations and were visualized in the SLOSH Display.

IOOS/SURA Testbed

Testbed 2: October, 2013 - September 2015

SLOSH code was modified to:

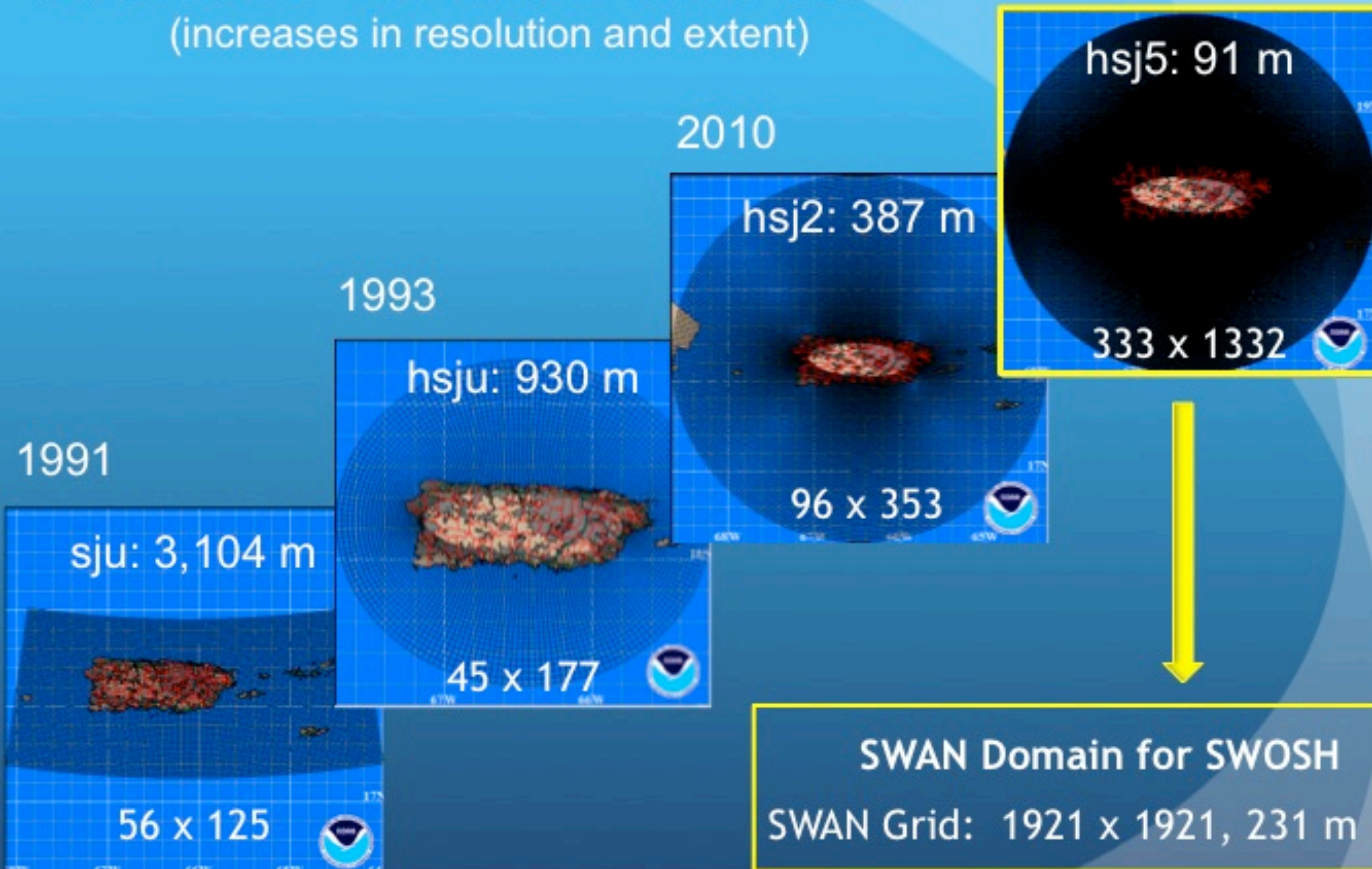
- Allow basins larger than 400x400 grid points,
- Implement new horizontal datum,
- Make hardwired parameters flexible.

Basin development

- Various high-resolution grids were developed and tested,
- Code that generates the GIS shapefiles was modified to produce GRS80 horizontal datum instead of Clarke ellipsoid,
- Code modifications were transitioned to NOAA/MDL for inclusion in master svn codebase.

Evolution of Puerto Rico Basin

(increases in resolution and extent)



SWAN Domain for SWOSH

SWAN Grid: 1921 x 1921, 231 m

Puerto Rico Basin

Sources of Bathymetry and Topography Data

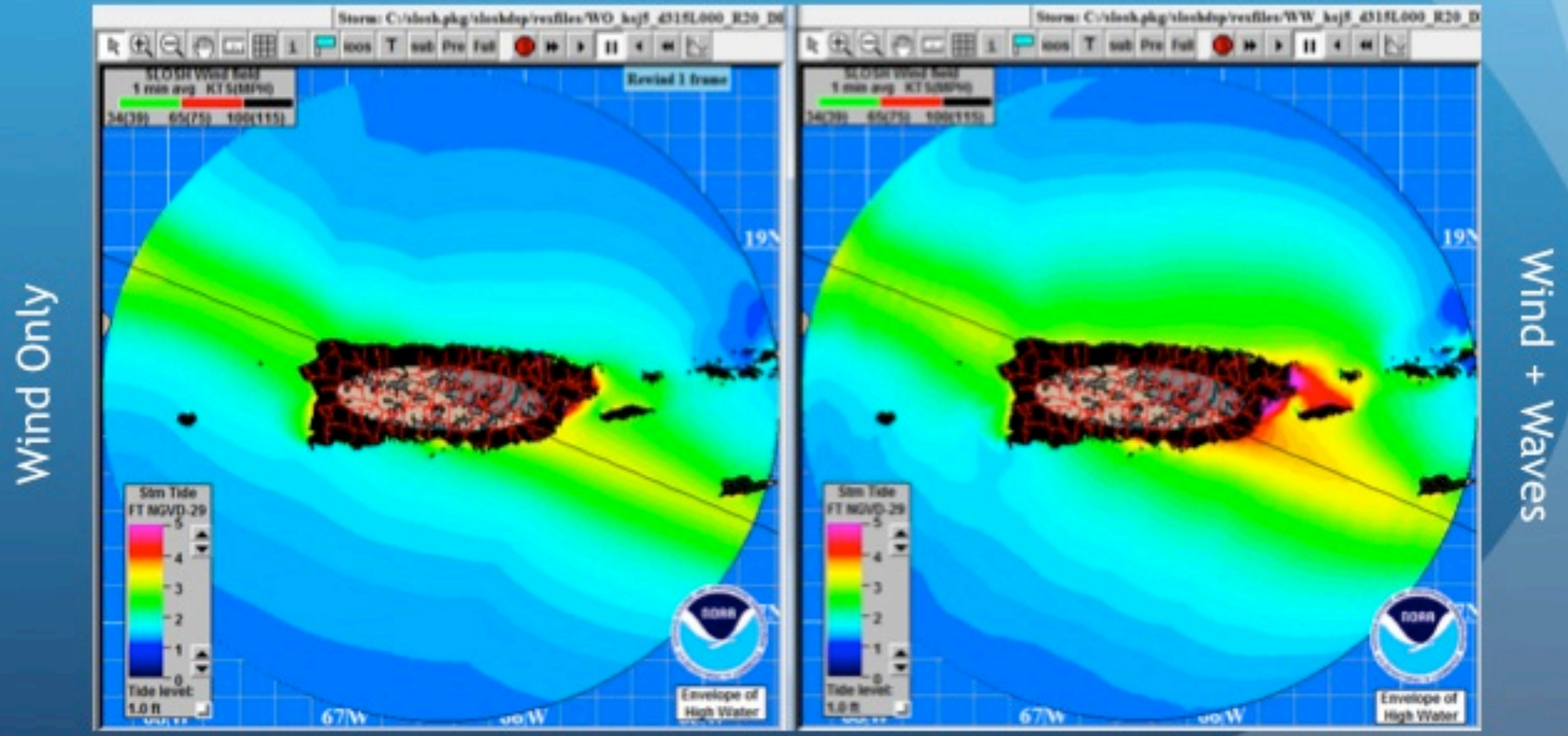
Bathymetry		
NOAA National Geophysical Data Center (NGDC)	ETOPO Bedrock Horizontal Datum World Geodetic System of 1984 (WGS 84) Vertical Datum Sea Level Vertical Units Meters Grid Format Multiple: tiff, xyz	Cell Size 1 arc-minute
USCRM		3 arc-seconds (90 m cell size)
NOS Nav Charts	For channels	Variable Res

Topography				
Combined DEM from CSC	2004 US Army Corps of Engineers (USACE)	Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX) Puerto Rico Lidar	January 10 - February 8, 2004	Vertical Accuracy 18.6 cm RMS Error
	FEMA ADCIRC Composite DEM for Puerto Rico			
	NOAA National Geophysical Data Center (NGDC) Tsunami Inundation DEMs	Guayama Ponce Fajardo San Juan Arecibo	20070622	1/3 arc-sec MHW DEM
		Mayaguez	20060505	1/3 arc-sec MHW DEM
NED Data		Islands around PR	20140605	30 m

MEOWs / MOMs

- 10,080 simulations of hypothetical storms were run on the Jet supercomputing cluster to produce the MEOWs/MOMs.
- Example MEOW track – SLOSH vs. SWOSH

Cat 3, 15 mph, RMW=20 miles

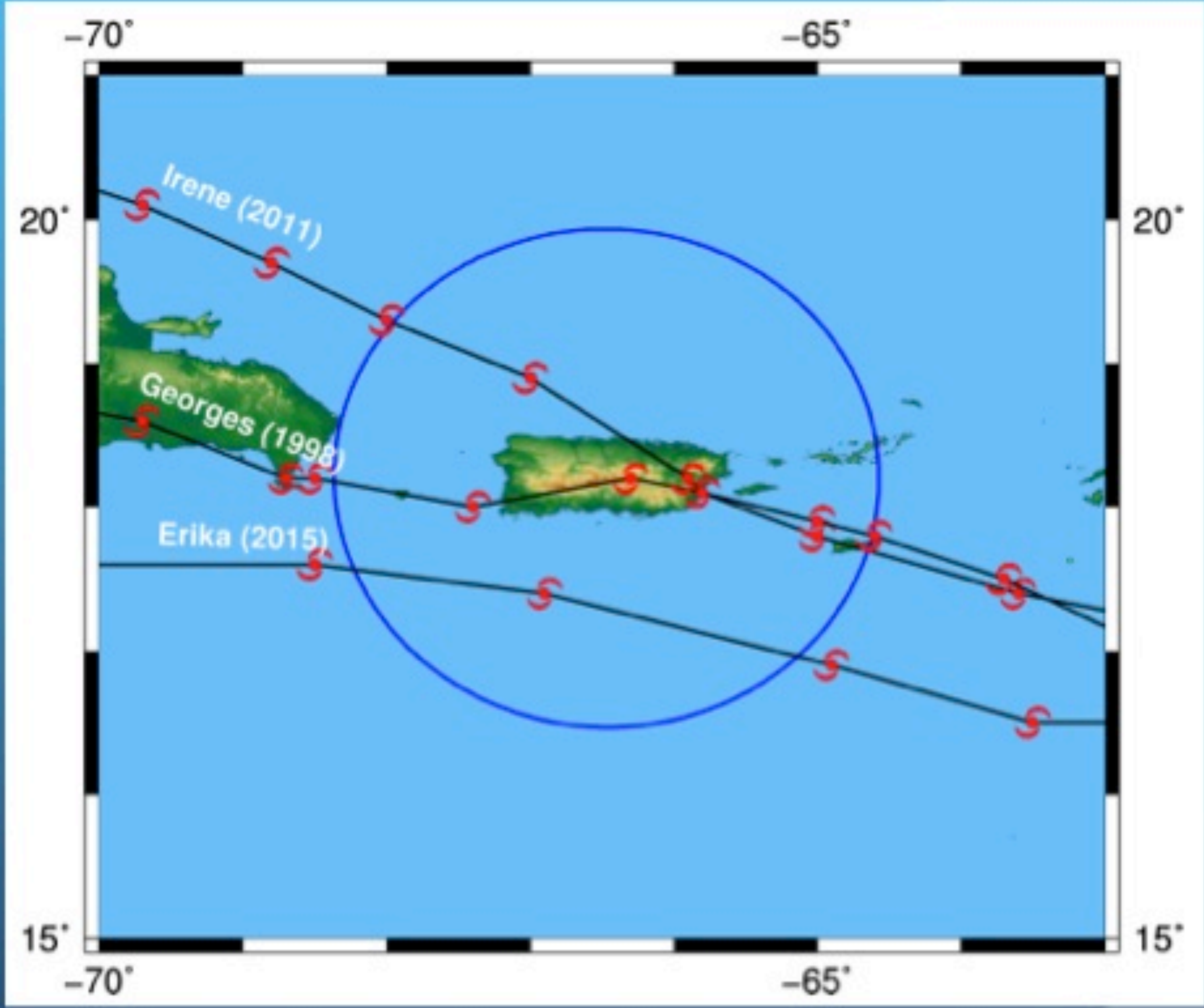


MEOWs/MOMs

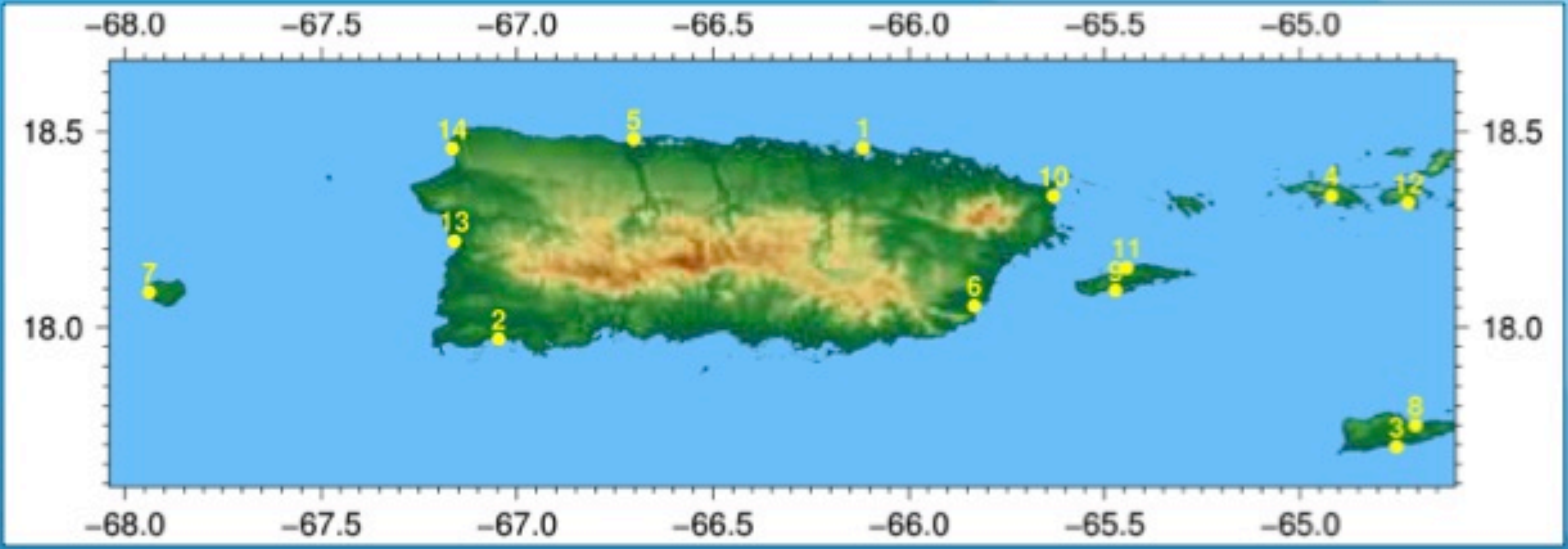
- MEOWs/MOMs are considered by NHC as the best approach for determining the vulnerability of an area to account for the forecast uncertainty and form the basins for the development of the nation's evacuation zones.
- MEOWs/MOMs were delivered to NOAA's Meteorological Development Laboratory (MDL) in May 2015 for distribution.

SWOSH Validation

Tropical Cyclone Tracks

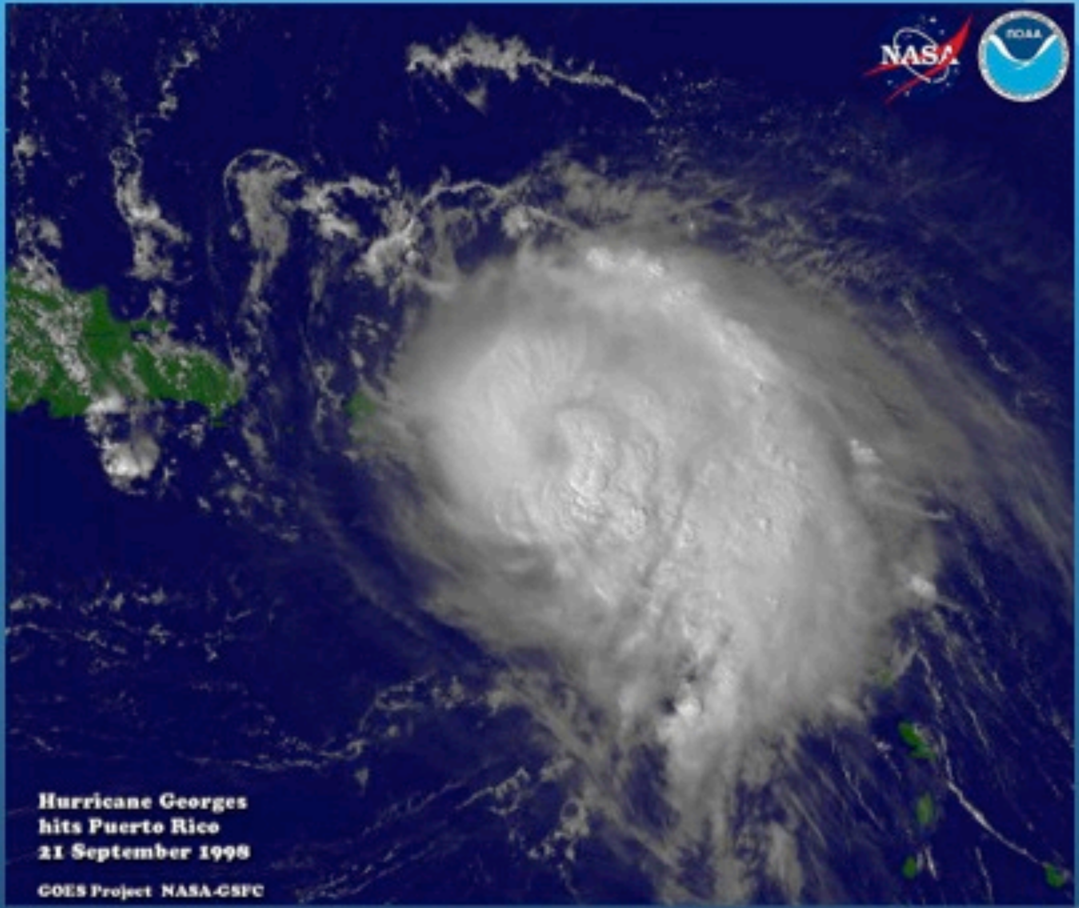


Verification Stations



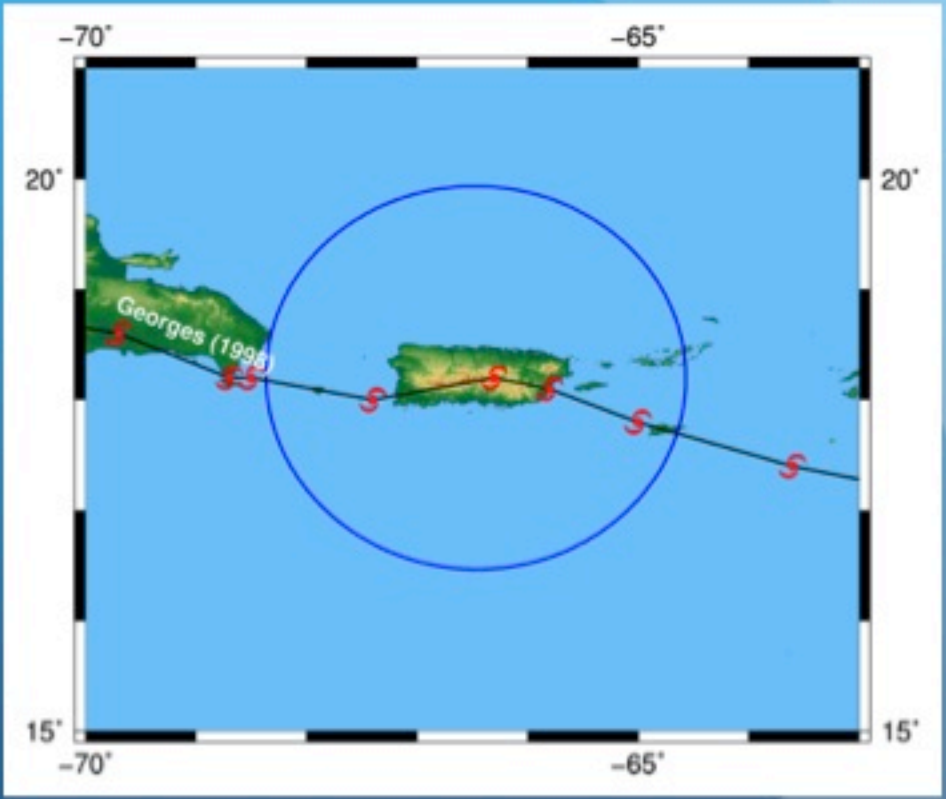
NOAA Stations				
N	Stn ID	Station Name	Lon (deg)	Lat (deg)
1	9755371	San Juan, PR	-66.1164	18.4589
2	9759110	Magueyes Island, PR	-67.0464	17.9701
3	9751401	Lime Tree Bay, VI	-64.7538	17.6947
4	9751639	Charlotte Amalie, VI	-64.9200	18.3358
5	9757809	Arecibo, PR	-66.7024	18.4805
6	9754228	Yabucoa Harbor, PR	-65.8330	18.0551
7	9759938	Mona Island, PR	-67.9385	18.0899
8	9751364	Christiansted H, St Croix, VI	-64.7050	17.7500
9	9752695	Esperanza, Vieques Island, PR	-65.4714	18.0939
10	9753216	Fajardo, PR	-65.6311	18.3352
11	9752619	Isabel Segunda, Viequez Is., PR	-65.4438	18.1525
12	9751381	Lameshur Bay, St John, VI	-64.7242	18.3182
13	9759394	Mayaguez, PR	-67.1600	18.2200
14	9759412	Aguadilla, PR	-67.1646	18.4566

Hurricane Georges (1998)

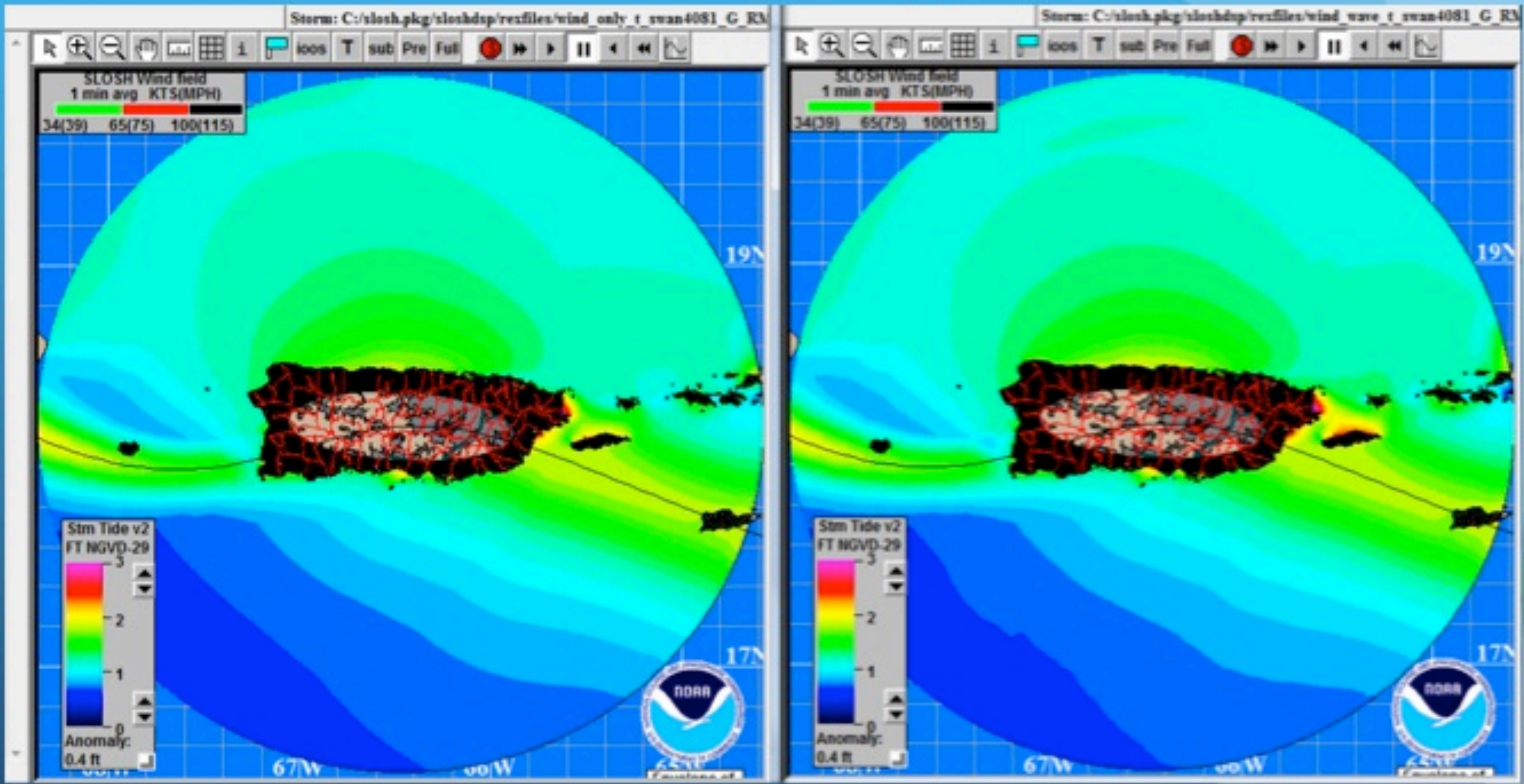


Hurricane Georges (1998)

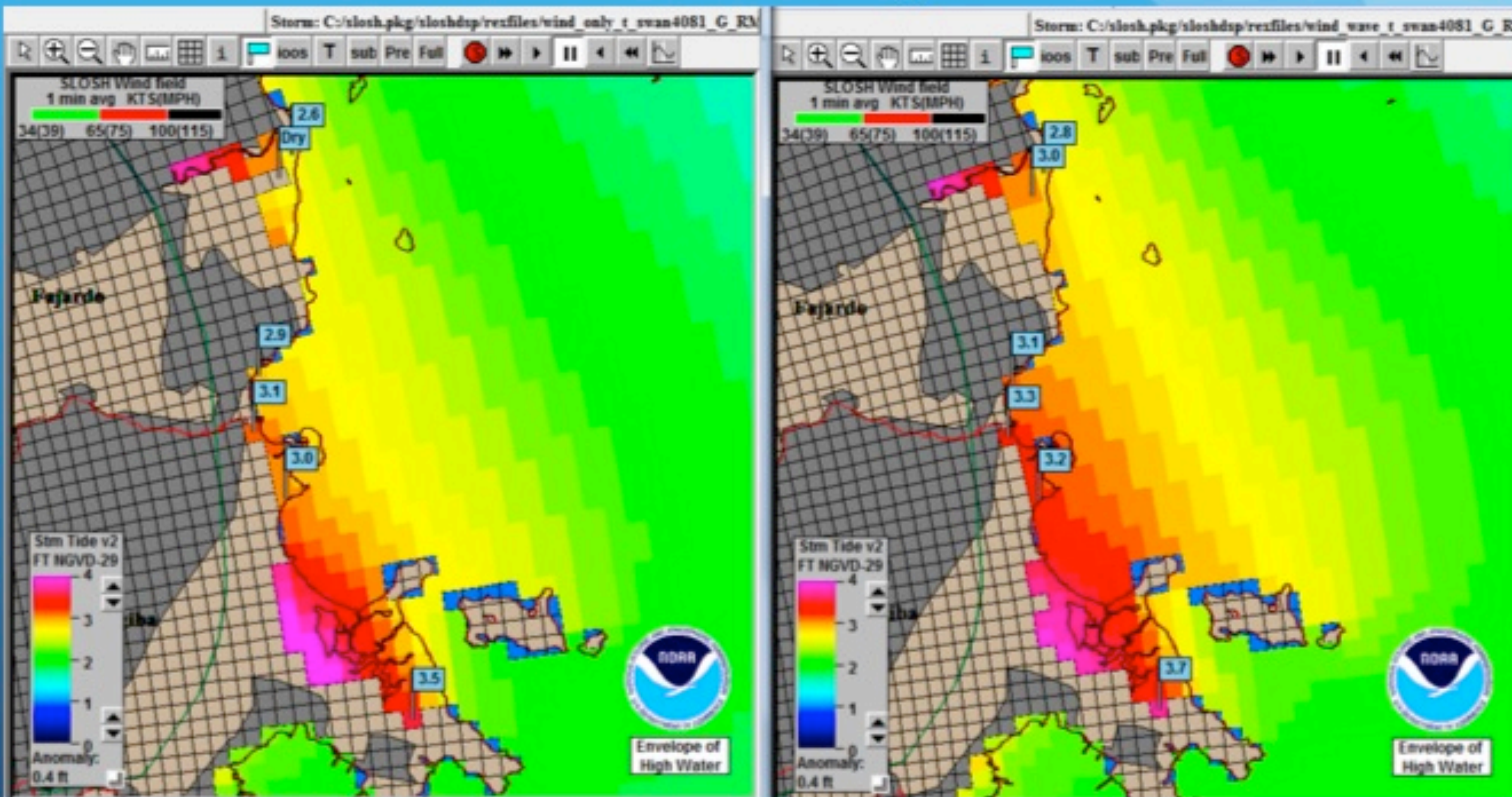
- Genesis: Cape Verde storm formed from large African wave on Sept 17, 1998
- Peak Winds: 155 mph (250 kph) Cat 4, wide wind field - 300 mi (490 km) TS force winds
- Lowest Pressure: 937 mb
- Lives Lost: 604 (most in Hispanola)
- Damage Est: $14.1 billion
- Landfall (PR): Sept. 21 as Cat 3 with 129 mph (208 kph) gusts, 3 tornadoes, crossed entire island (weakened to Cat 1 over mountains, reintensified to Cat 1), 8 deaths, $2.8 billion in damage, catastrophic damage to electrical system, roads, crops
- Storm Surge: 10 ft (3 m) at Fajardo along northeast coast
- Waves: Reports of 20 ft (6 m) at landfall in PR and 13.1 ft (4m) by a ship nearby.
- Peak Rainfall: 240 inches (6,096) mm, mountain flooding, river overflows



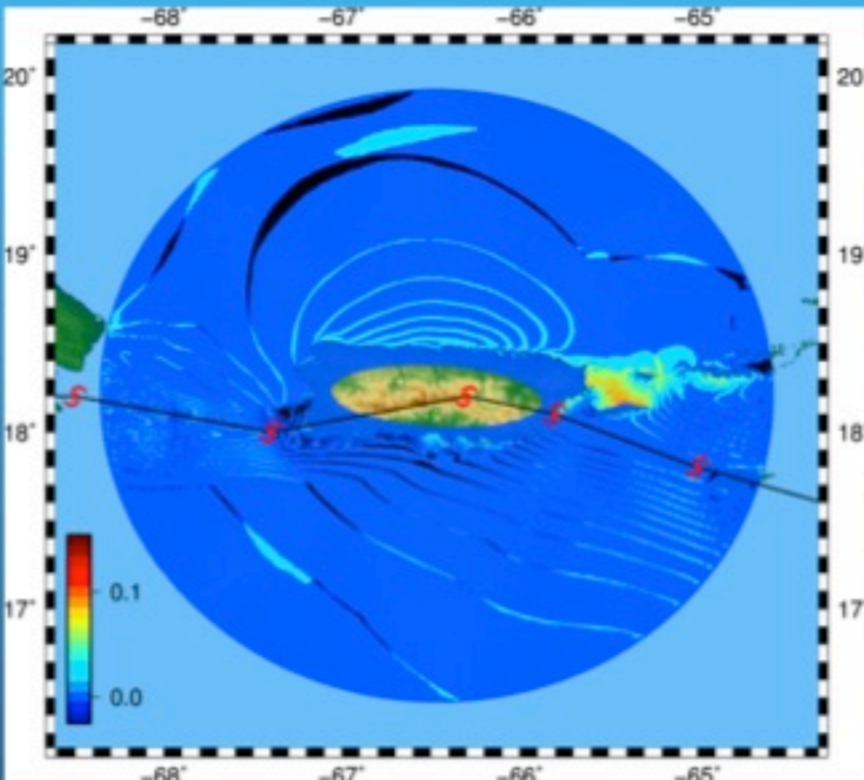
Max Water Level
SLOSH vs. SWOSH
Hurricane Georges



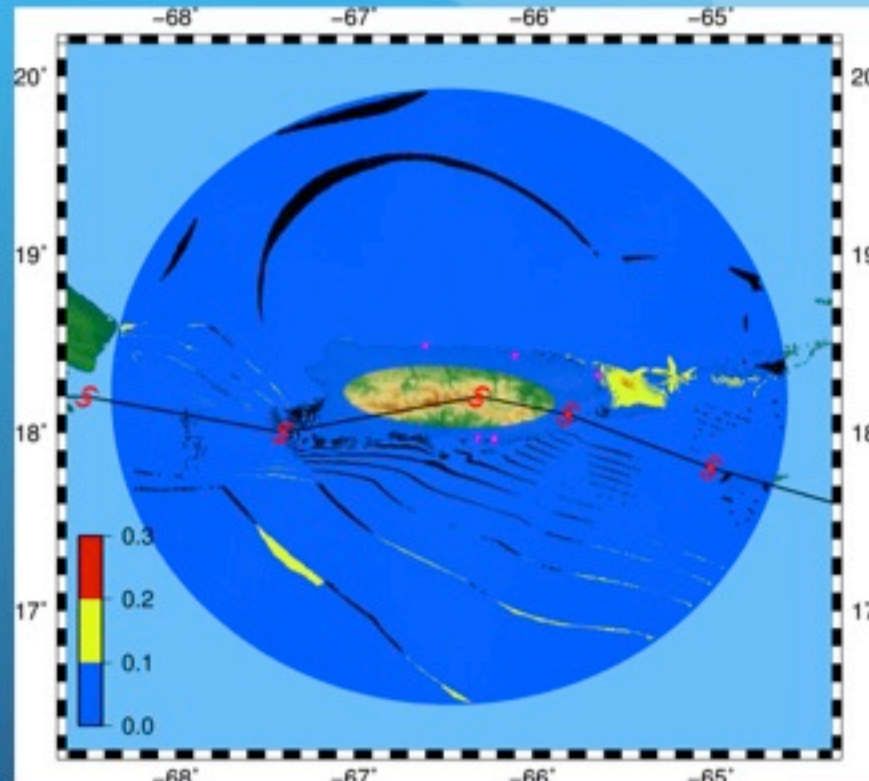
Max Water Level SLOSH vs. SWOSH Hurricane Georges



Differences in Max Water Level
SLOSH vs. SWOSH
Hurricane Georges

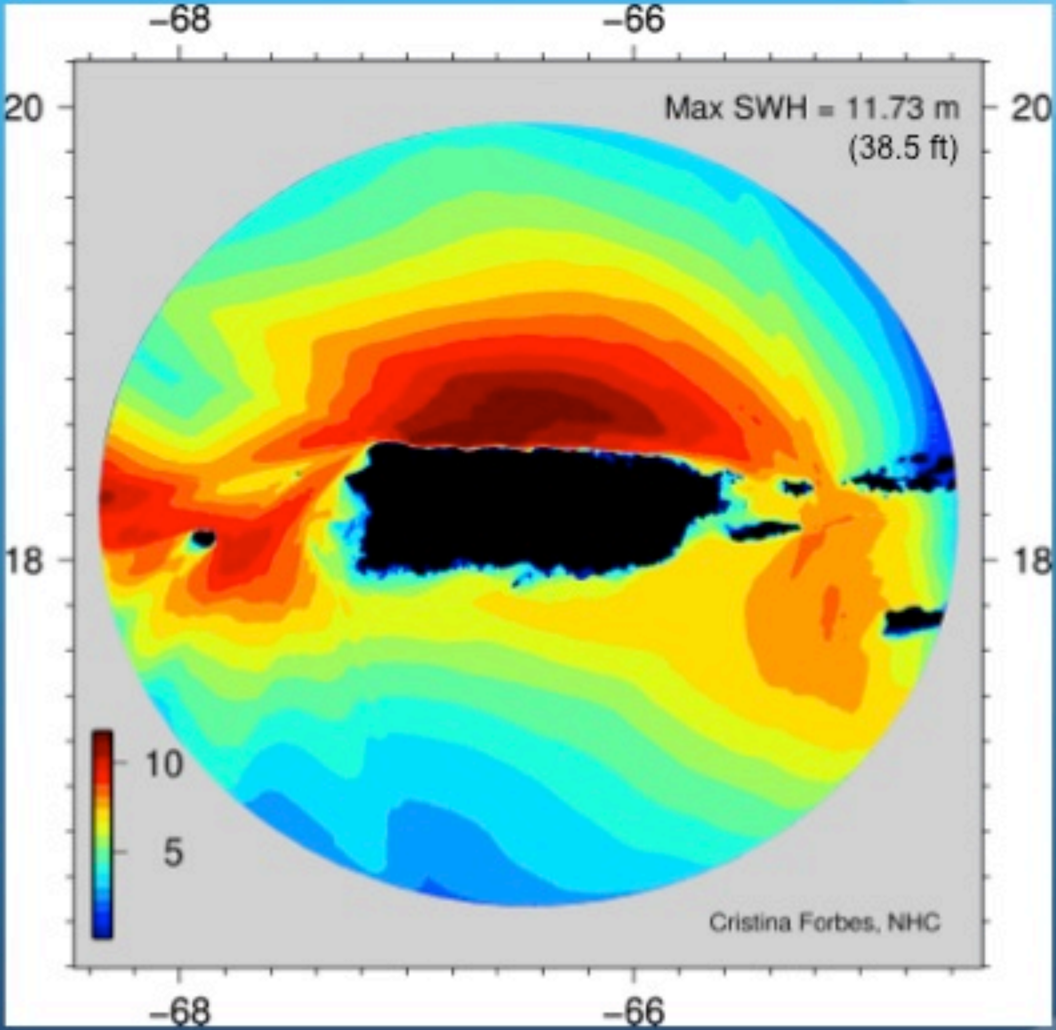


Difference in Water Level
Max = 0.91 m

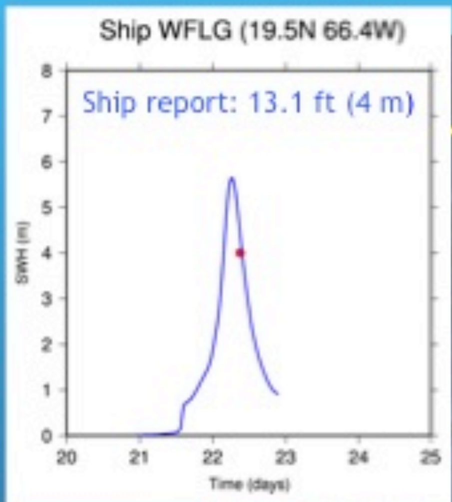


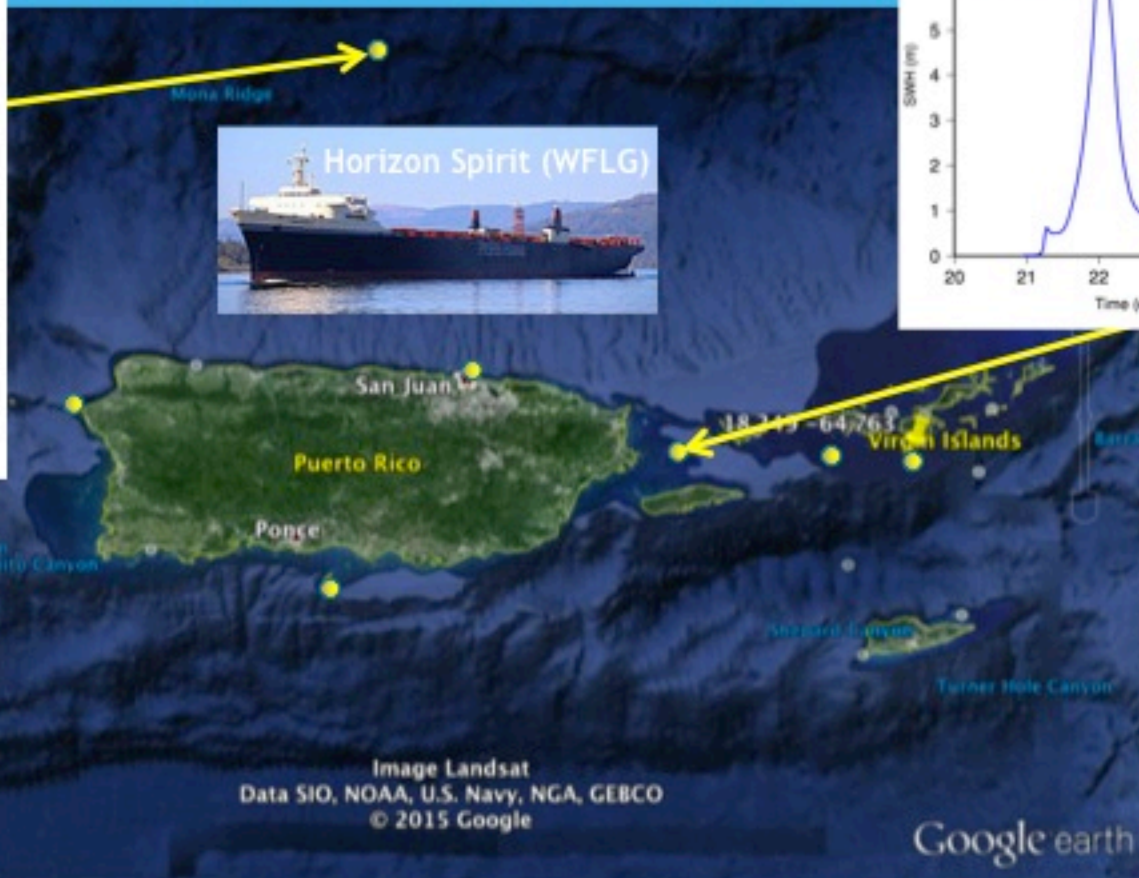
Percentage Difference in Water Level
Max = 100% (pink dots)
10-20% increase from waves

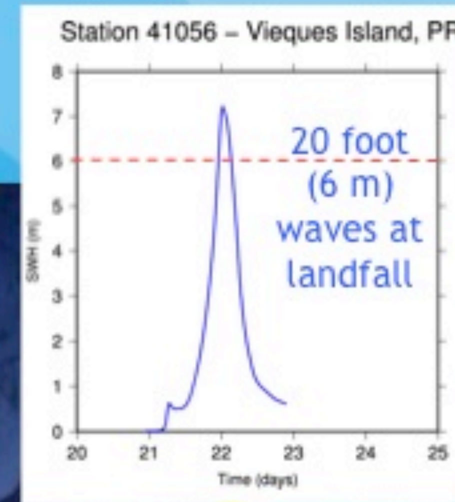
SWAN Max Significant Wave Height Hurricane Georges



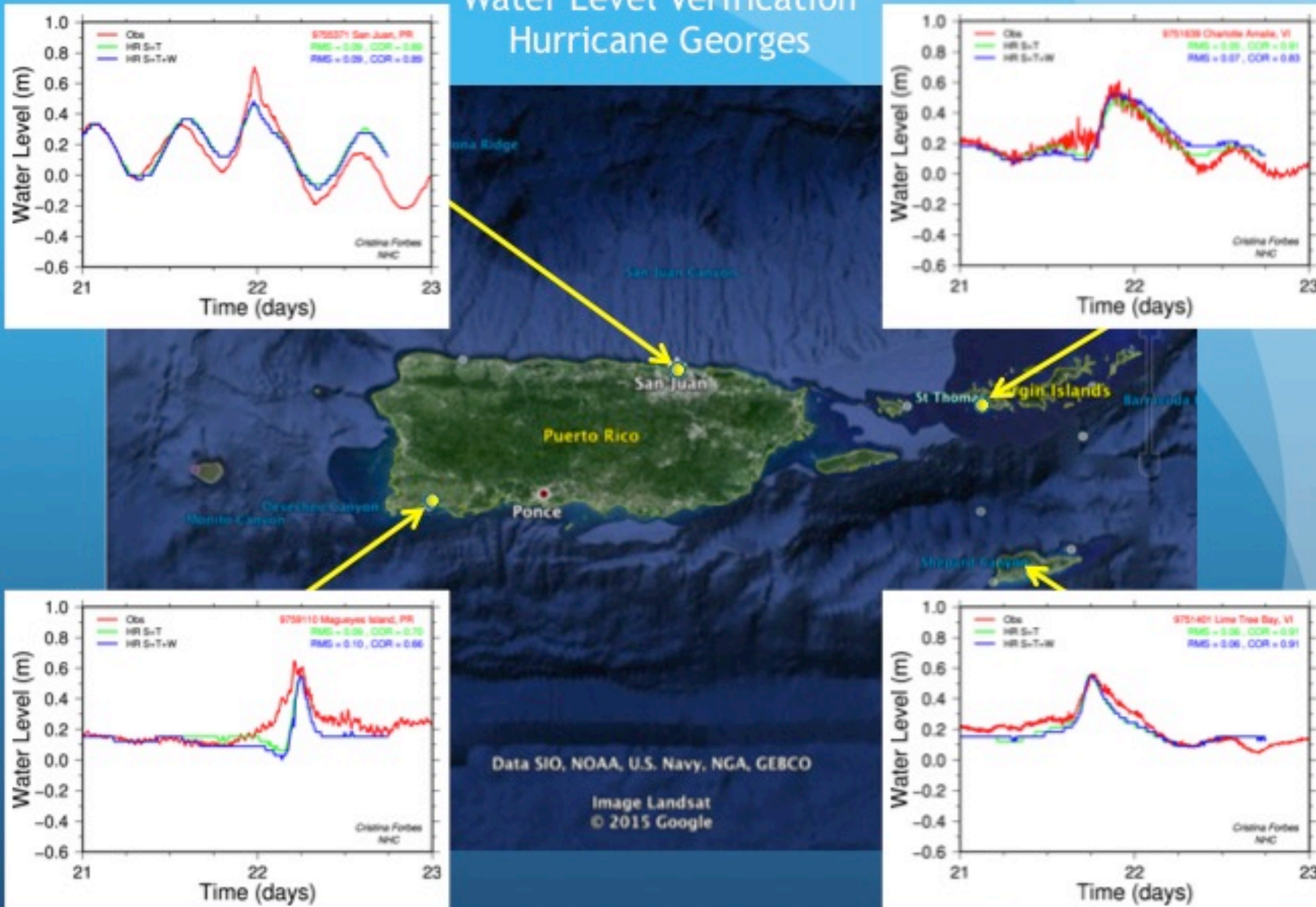
Significant Wave Height Verification
Hurricane Georges





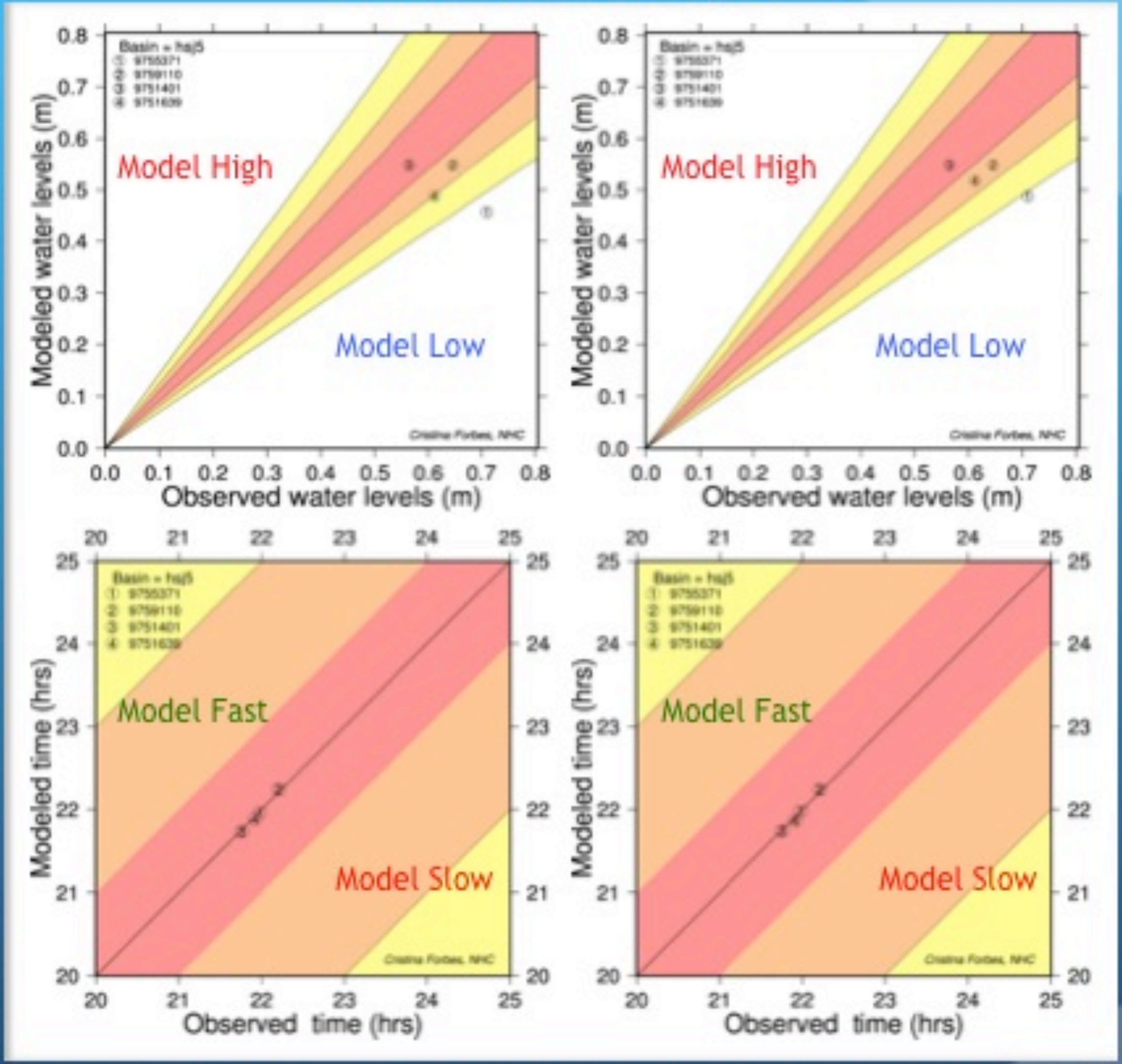


Water Level Verification
Hurricane Georges



Error Cones
SLOSH vs. SWOSH
Hurricane Georges

Wind Only



Wind + Waves

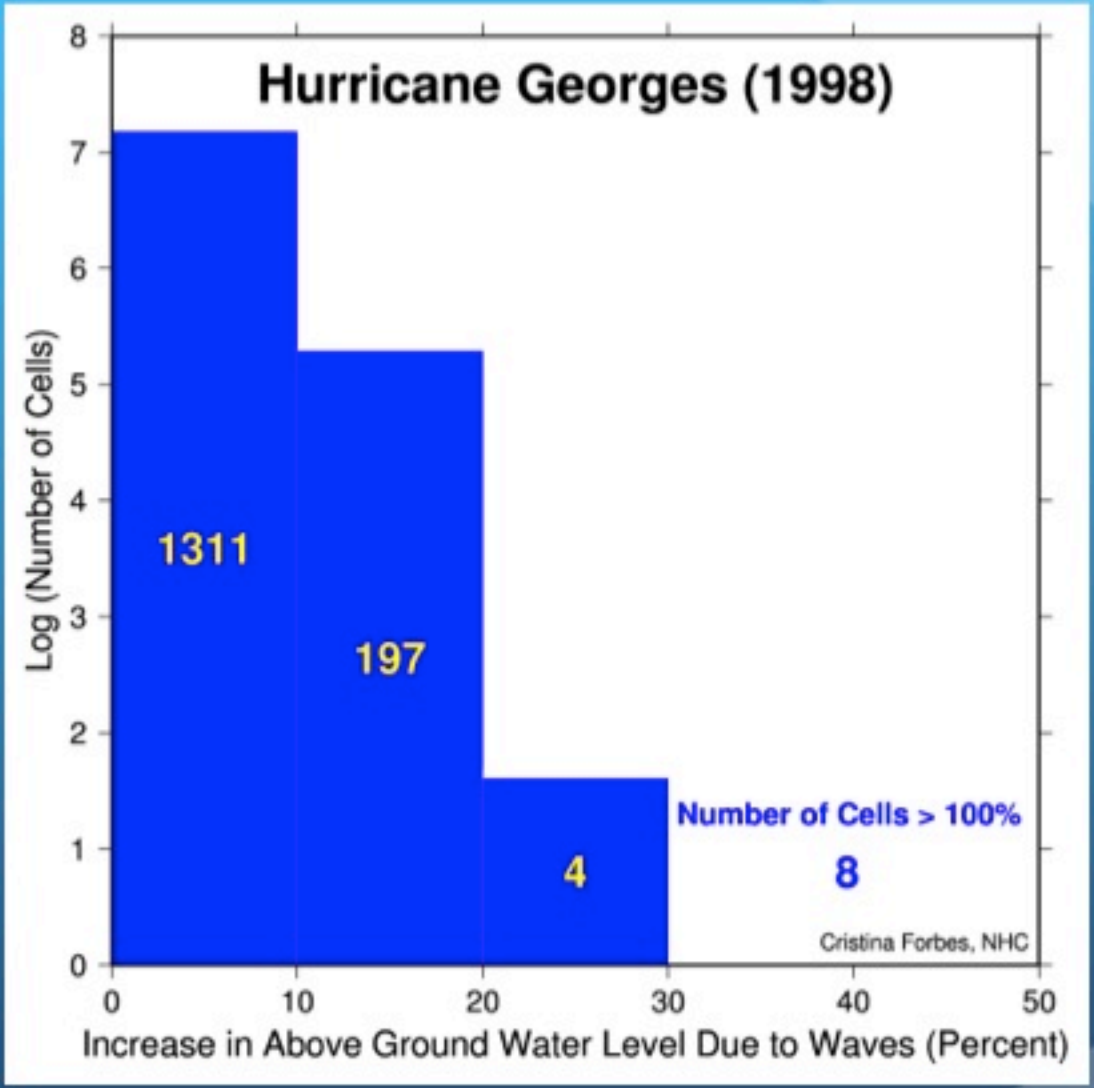
Summary
SLOSH vs. SWOSH
Hurricane Georges

Hurricane Georges (1998) IWL=.4										
Stn ID	Time of Max Elev (day)			Max Elev (m)			RMS		CORR	
	Obs	SL	SW	Obs	SL	SW	SL	SW	SL	SW
9755371	21.9833	21.96	21.98	.710	.457	.488	.09	.09	.89	.89
9759110	22.2083	22.24	22.24	.646	.549	.549	.09	.10	.70	.66
9751401	21.7583	21.74	21.74	.565	.549	.549	.06	.06	.91	.91
9751639	21.9125	21.89	21.87	.612	.488	.518	.05	.07	.91	.83

7% increase
at San Juan, PR

RMSE = 5 to 10 cm
CORR = .66 to .91

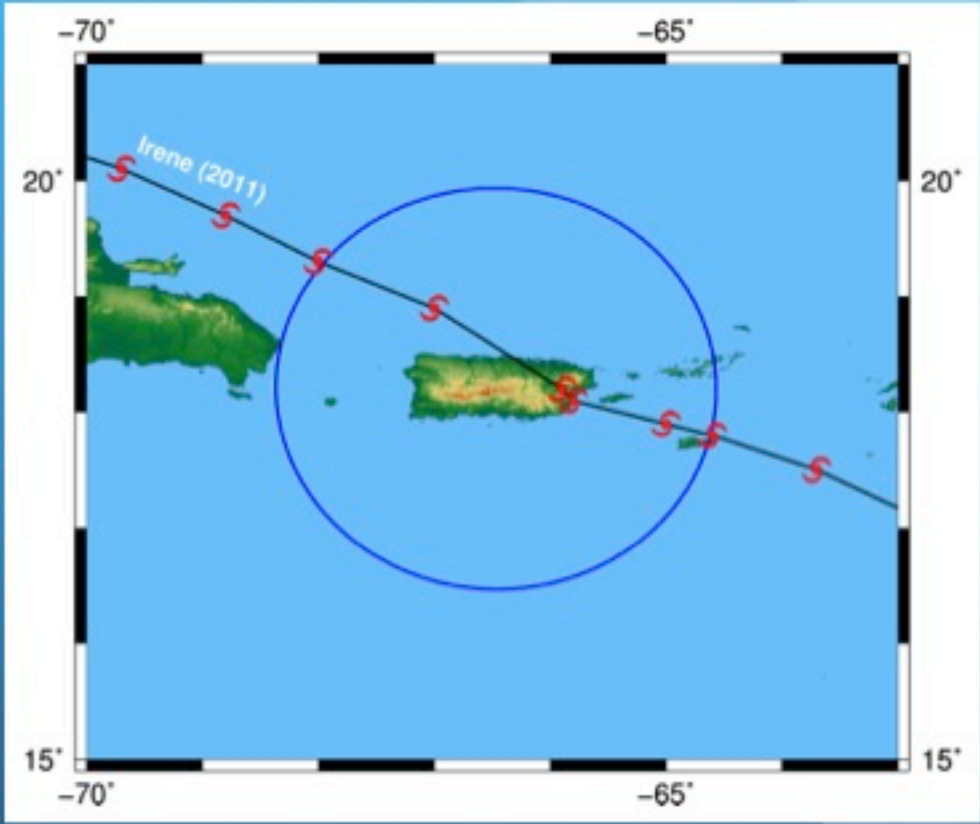
Impact of Waves



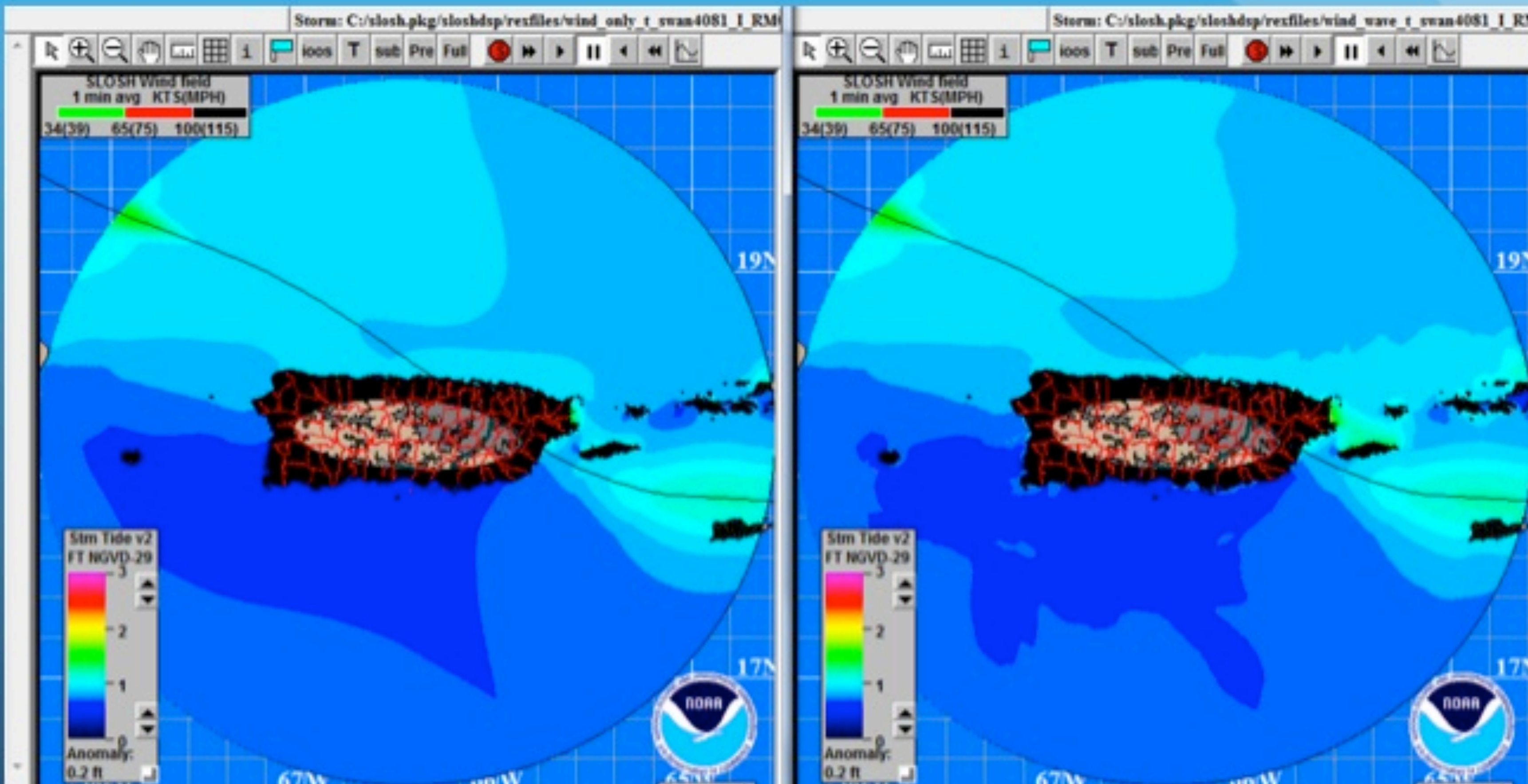
Hurricane Irene (2011)

Hurricane Irene (2011)

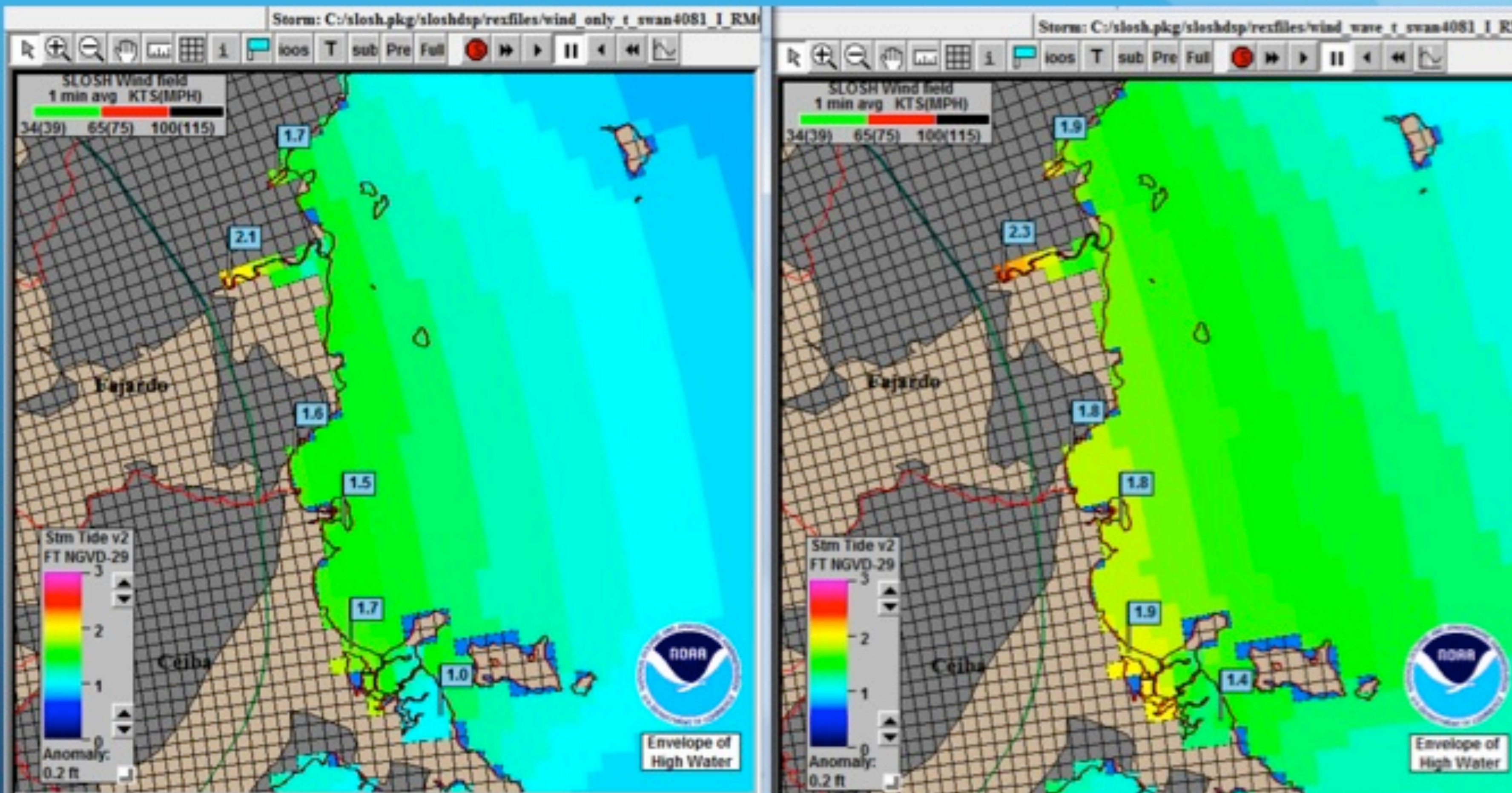
- Genesis: Hurricane recon aircraft, investigating tropical wave east of Lesser Antilles, found small low-level circulation center SW of large convective burst on Aug. 20, 2011
- Peak Winds: 120 mph (195 kph) Cat 3 in the Bahamas
- Lowest Pressure: 940 mb
- Lives Lost: 49
- Damage Est: $17.45 billion
- Landfall (PR): Aug. 21 with 70 mph (110 kph) winds, strengthened to Cat 1 as it traversed the island
- Storm Surge: 1.62 ft (0.5 m) in Esperanza, Vieques
- Storm Tide: 2.58 ft in Fajardo (0.8 m)
- Waves: 12.5 ft (3.8 m) in San Juan and St. John buoys
- Peak Rainfall: 22.09 inches (561 mm) in Gurabo



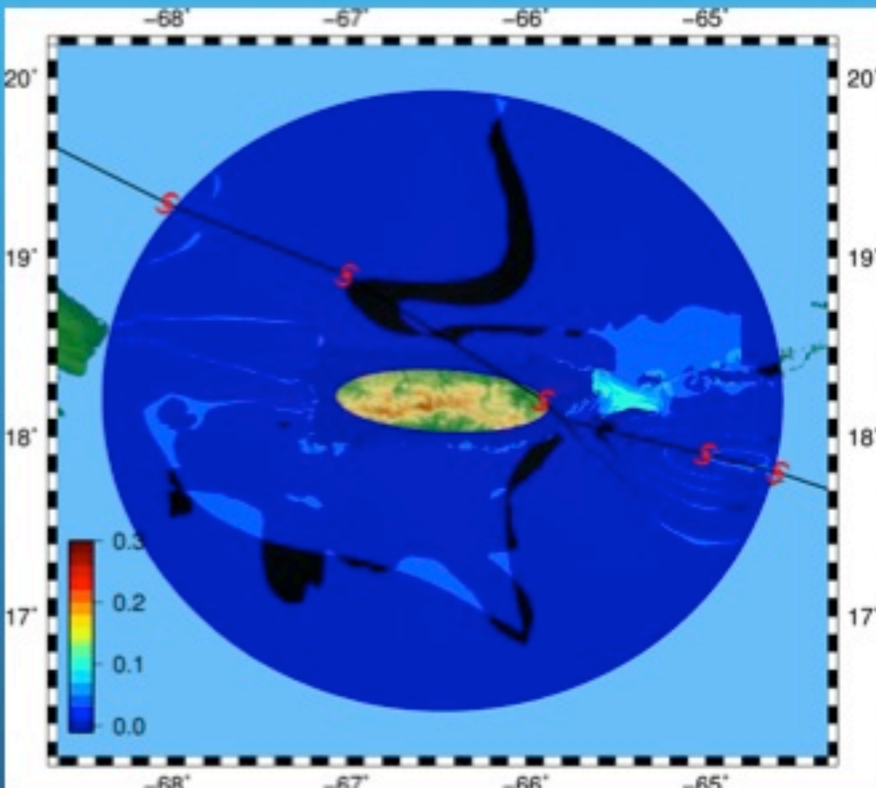
Max Water Level
SLOSH vs. SWOSH
Hurricane Irene



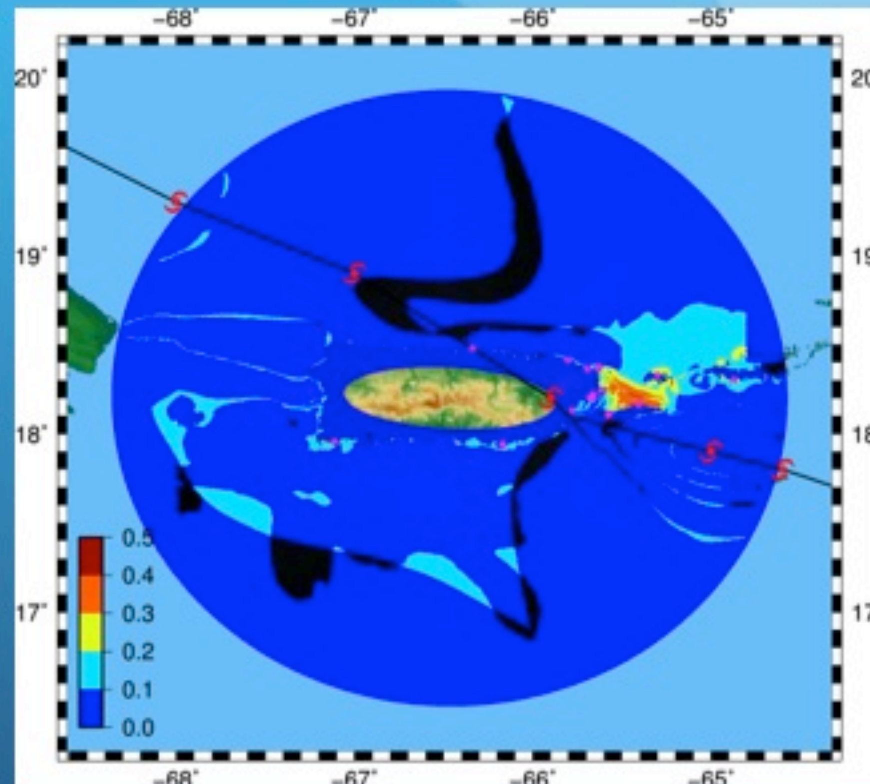
Max Water Level
SLOSH vs. SWOSH
Hurricane Irene



Differences in Max Water Level
SLOSH vs. SWOSH
Hurricane Irene

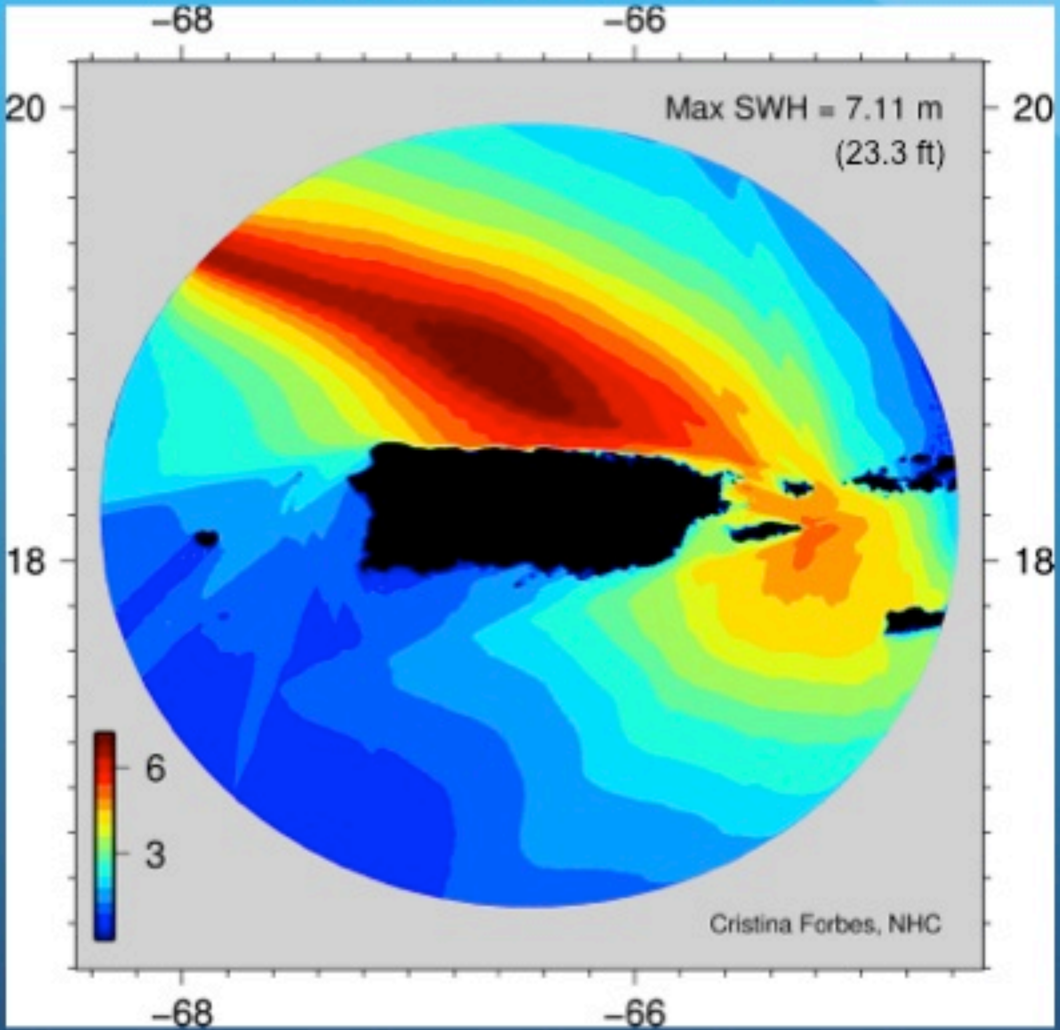


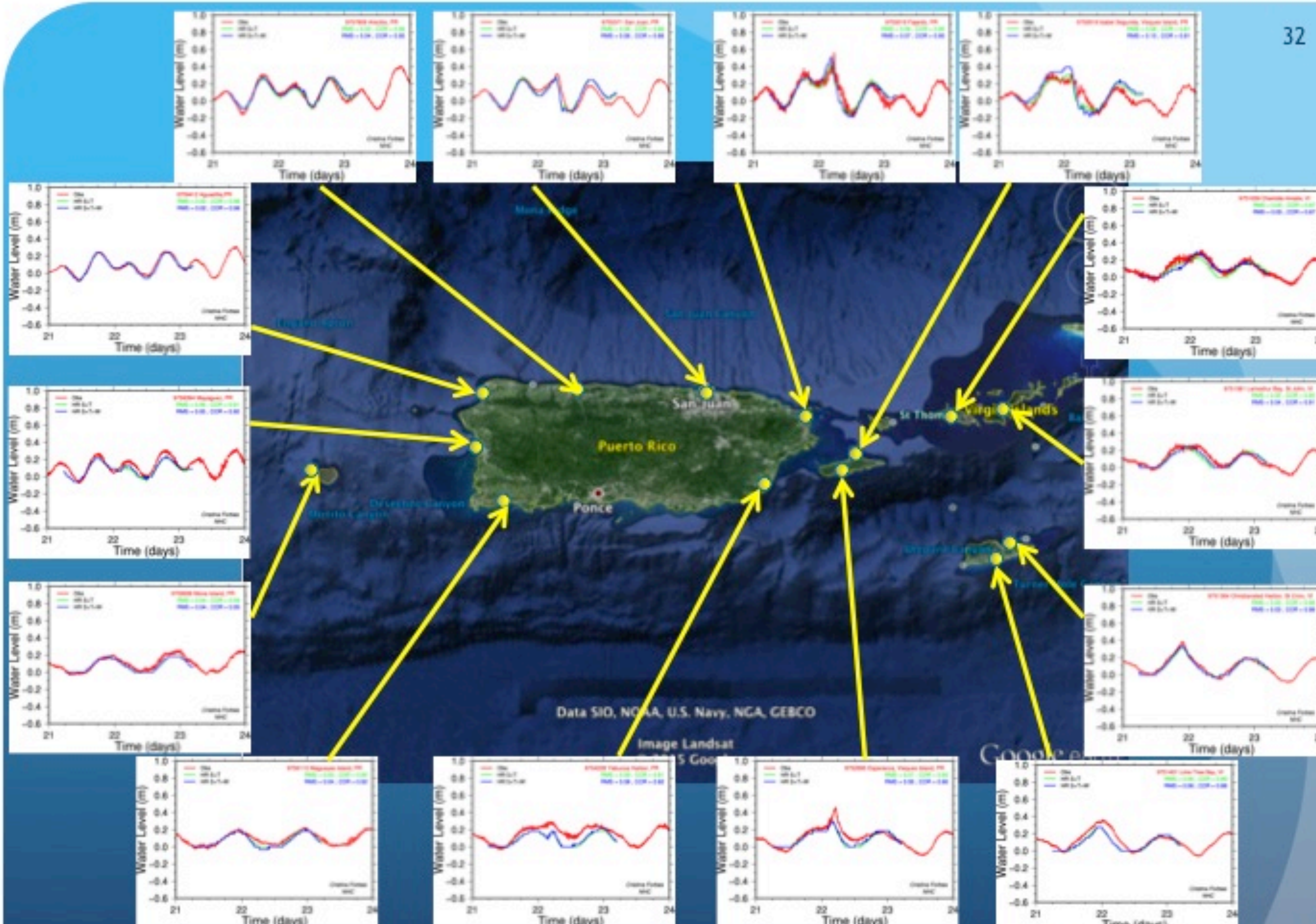
Difference in Water Level
Max = 0.73 m



Percentage Difference in Water Level
Max = 100% (pink dots)
10-40% increase from waves

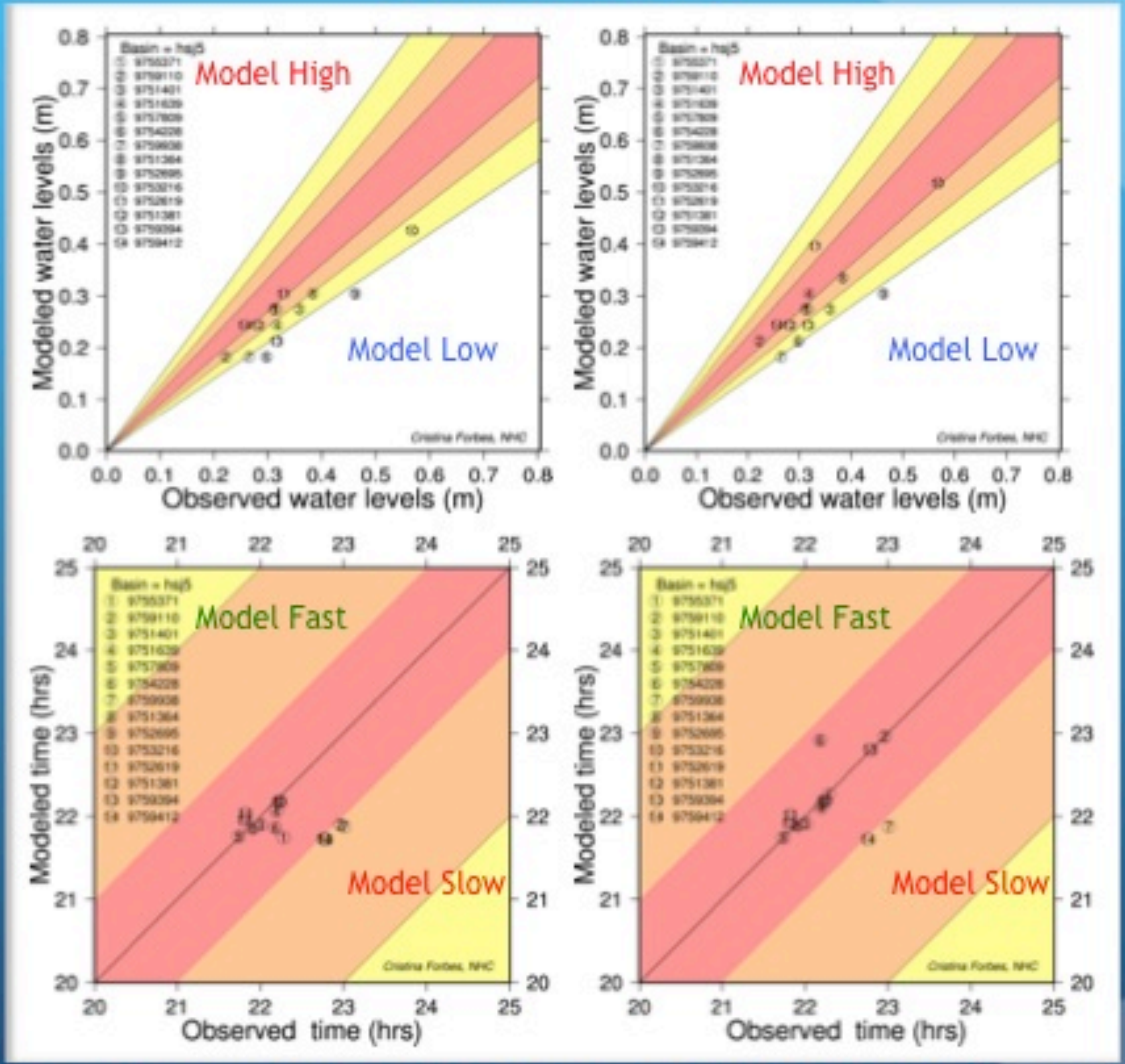
SWAN Max Significant Wave Height Hurricane Irene




Puerto Rico
San Juan
Ponce
Virgin Islands
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat
Water Level (m)
Time (days)

Error Cones
SLOSH vs. SWOSH
Hurricane Irene

Wind Only



Wind + Waves

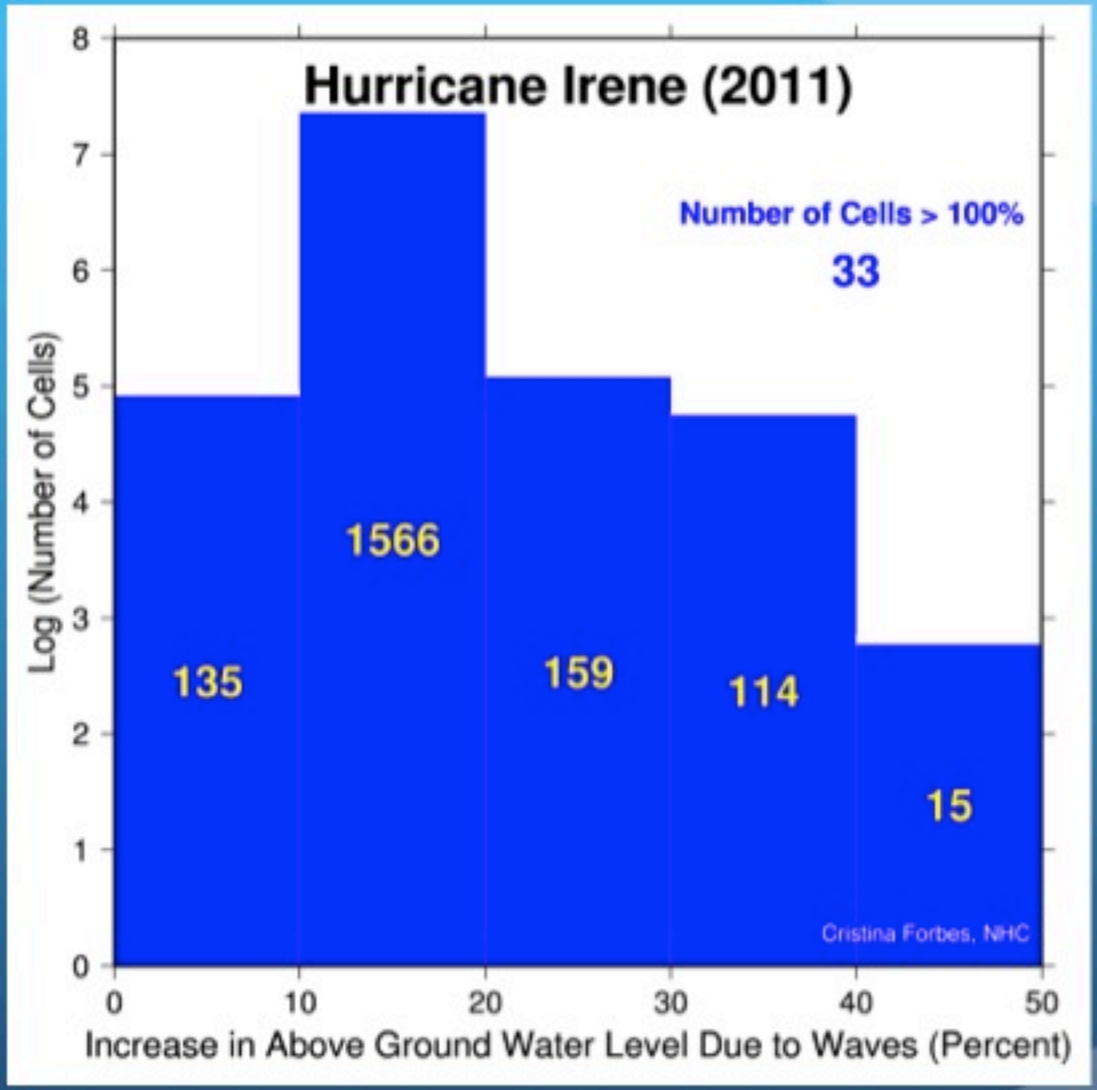
Summary
SLOSH vs. SWOSH
Hurricane Irene

Hurricane Irene (2011) IWL=.7										
Stn ID	Time of Max Elev (day)			Max Elev (m)			RMS		CORR	
	Obs	SL	SW	Obs	SL	SW	SL	SW	SL	SW
9755371	22.28	21.74	22.26	.316	.274	.274	.06	.06	.88	.86
9759110	22.96	21.90	22.96	.223	.183	.213	.03	.04	.95	.92
9751401	22.01	21.90	21.92	.359	.274	.274	.06	.06	.89	.88
9751639	22.19	22.06	22.10	.318	.244	.305	.05	.05	.87	.87
9757809	22.74	21.76	21.74	.312	.274	.274	.03	.04	.96	.95
9754228	23.18	21.86	22.92	.298	.183	.213	.09	.08	.81	.82
9759938	23.01	21.87	21.87	.265	.183	.183	.04	.04	.94	.95
9751364	21.91	21.85	21.88	.384	.305	.335	.03	.03	.98	.98
9752695	22.21	22.17	22.17	.463	.305	.305	.07	.06	.83	.86
9753216	22.23	22.18	22.19	.567	.427	.518	.06	.07	.90	.90
9752619	21.82	22.03	22.02	.330	.305	.396	.08	.10	.81	.81
9751381	28.81	21.96	21.92	.281	.244	.244	.05	.04	.85	.91
9759394	22.79	21.72	22.81	.316	.213	.244	.06	.05	.91	.92
9759412	22.76	21.73	21.72	.257	.244	.244	.02	.02	.98	.98

RMSE=2 to 10 cm
CORR=.81 to .98

30% increase at Isabel Segunda

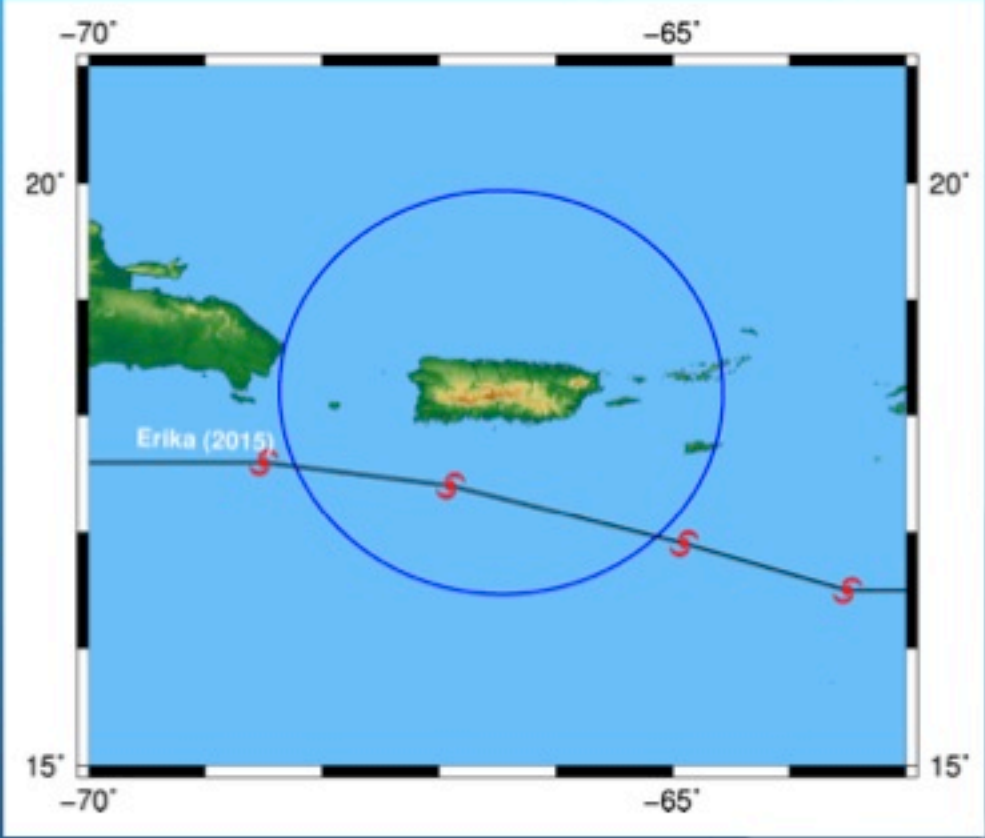
Impact of Waves



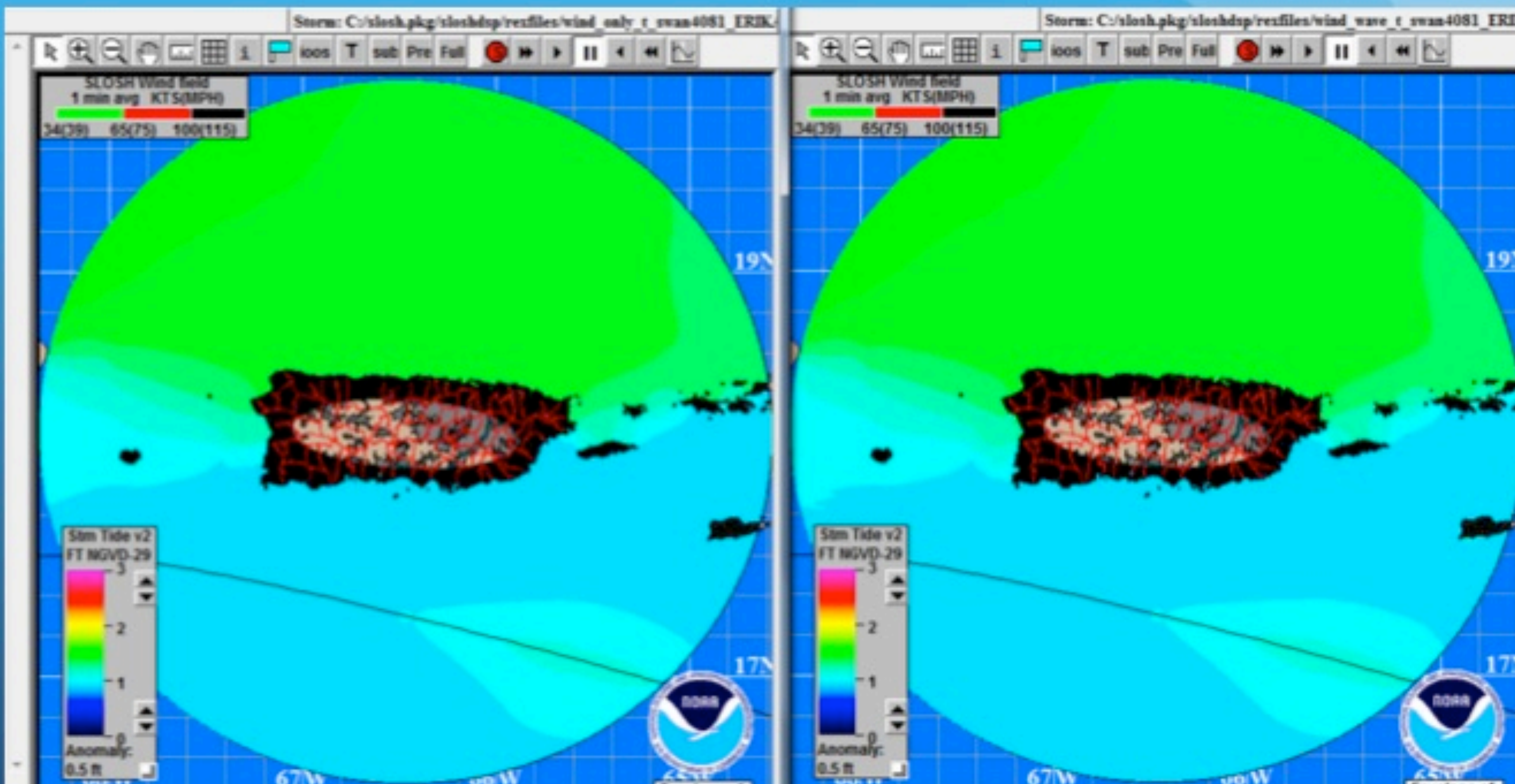
Tropical Storm Erika (2015)

Tropical Storm Erika (2015)

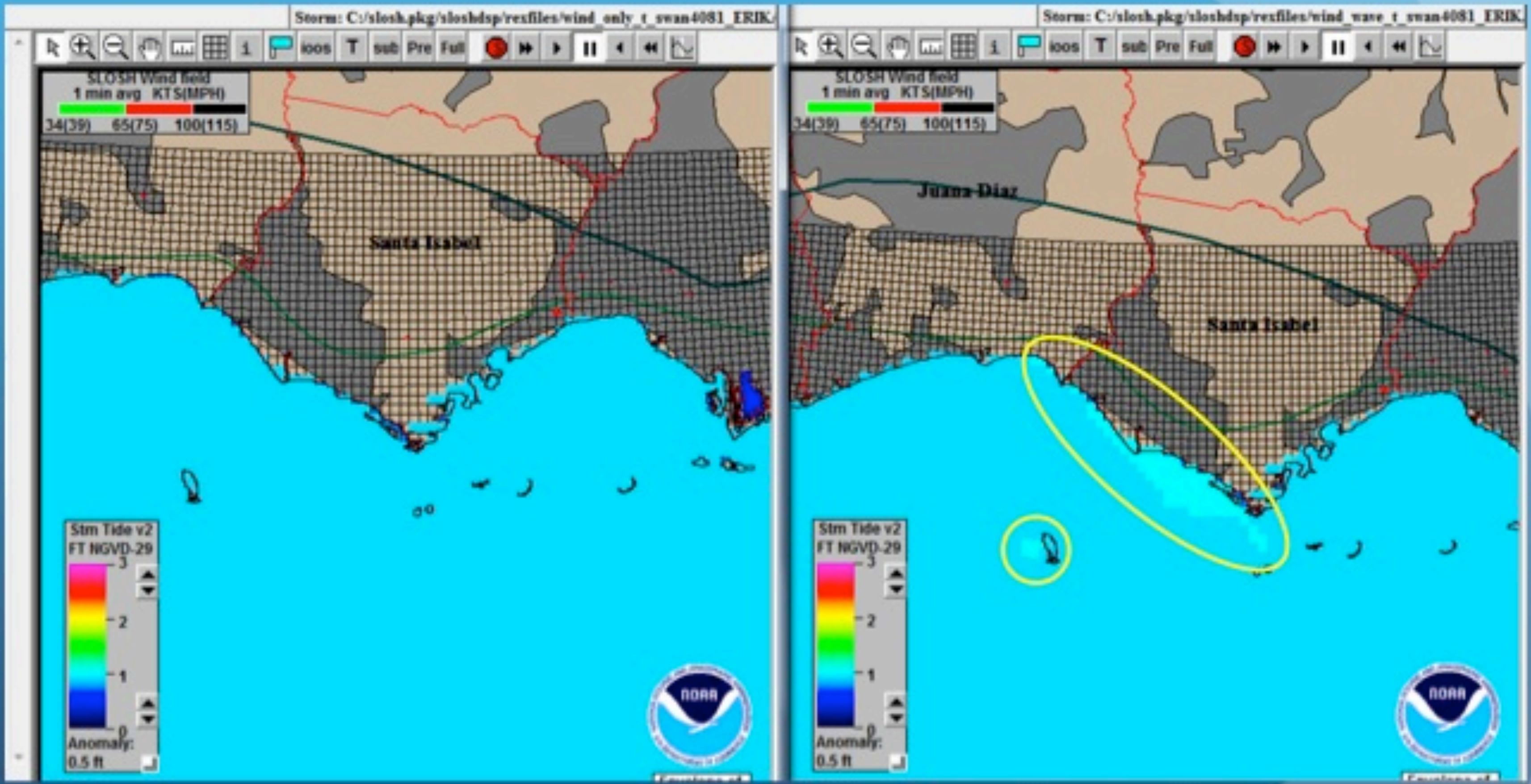
- Genesis: Developed from westward-moving tropical wave east of Lesser Antilles. Slow to intensify, disorganized due to wind shear, moved rapidly westward. Designated as a tropical storm when a well-defined circulation revealed by ASCAT (radar scatterometer) pass early on Aug 25, 2015.
- Peak Winds: 50 mph (85 kph)
- Lowest Pressure: 1003 mb
- Lives Lost: 36
- Damage Est: $511.7 million
- Landfall (PR): None – passed south of island
- Storm Tide: 1.6 ft (0.49 m)
- Waves: 15.1 ft (4.6 m) in St. John. VI
- Peak Rainfall: 7.67 inches (195 mm) southeast, in Cavey Mountain Range



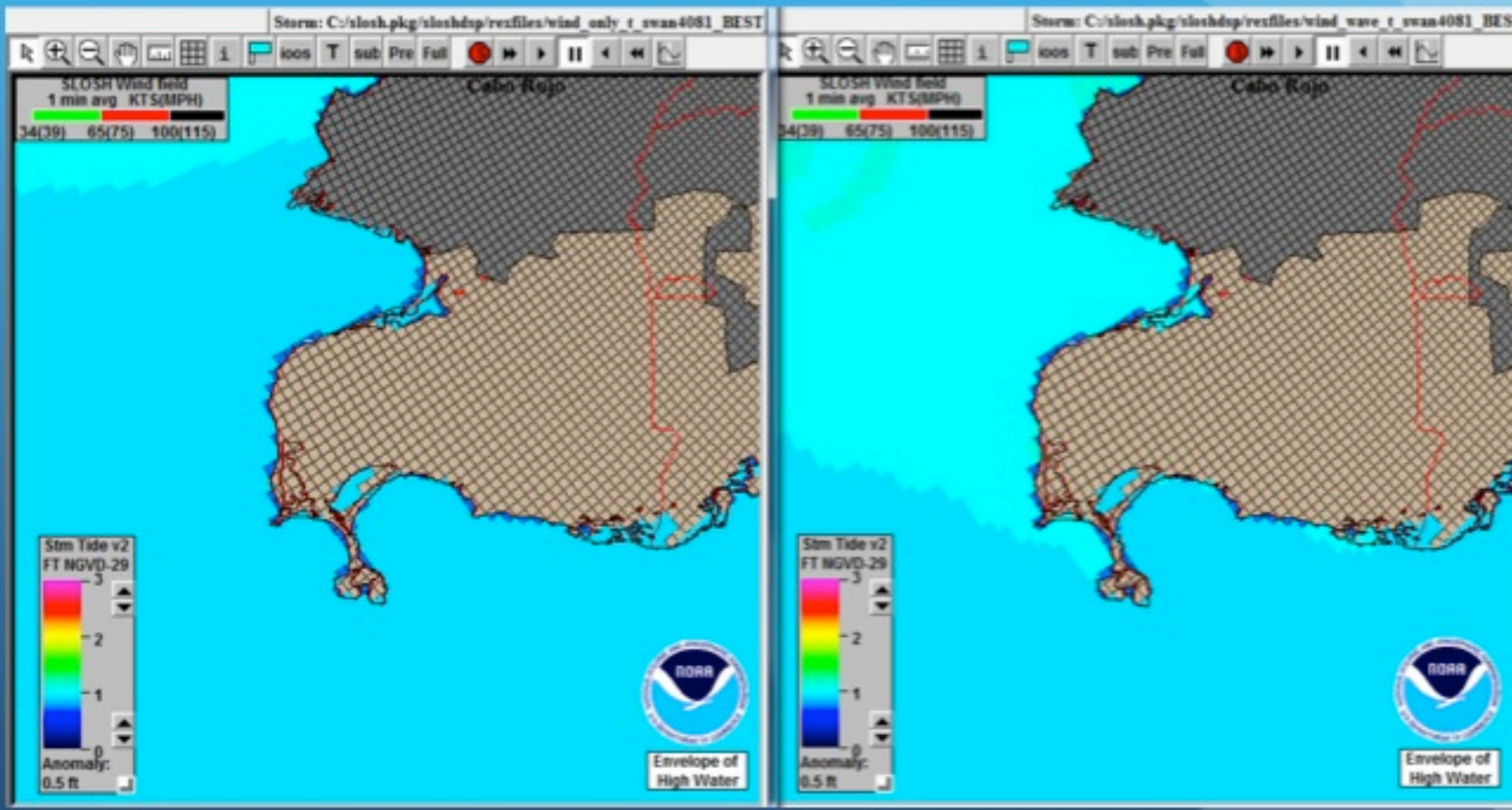
Max Water Level
SLOSH vs. SWOSH
TS Erika



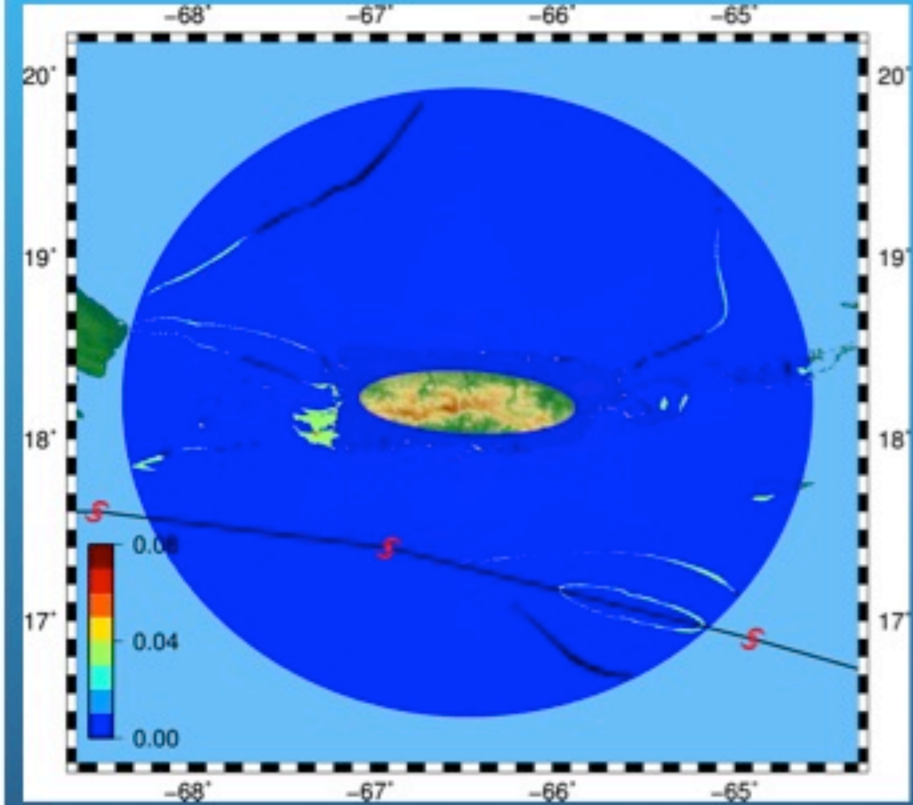
Max Water Level
SLOSH vs. SWOSH
TS Erika



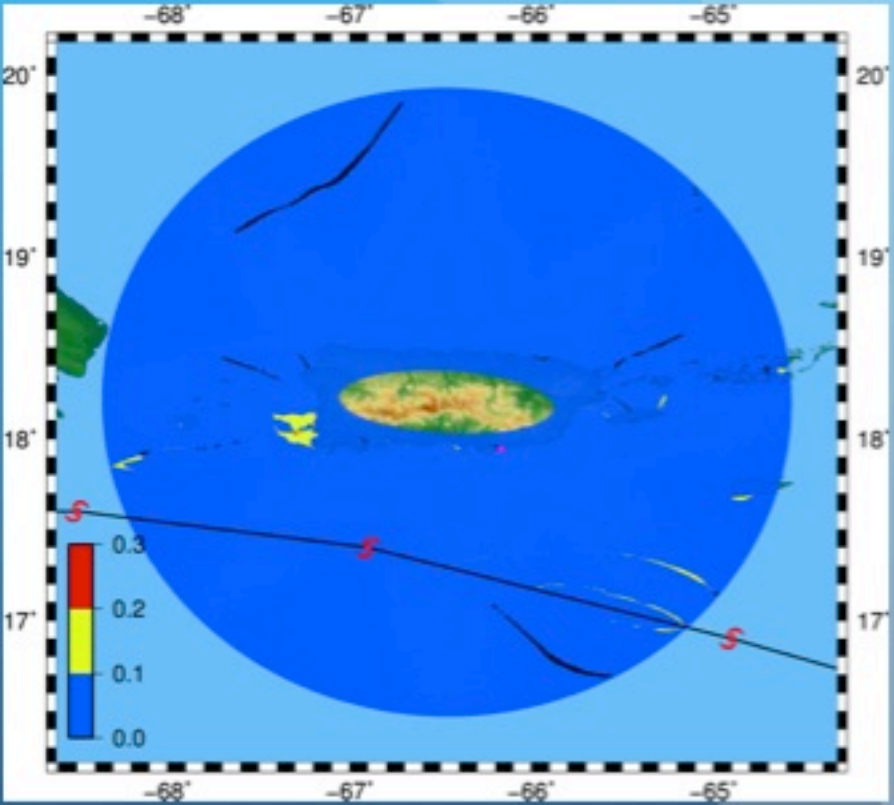
Max Water Level SLOSH vs. SWOSH TS Erika



Differences in Max Water Level SLOSH vs. SWOSH TS Erika

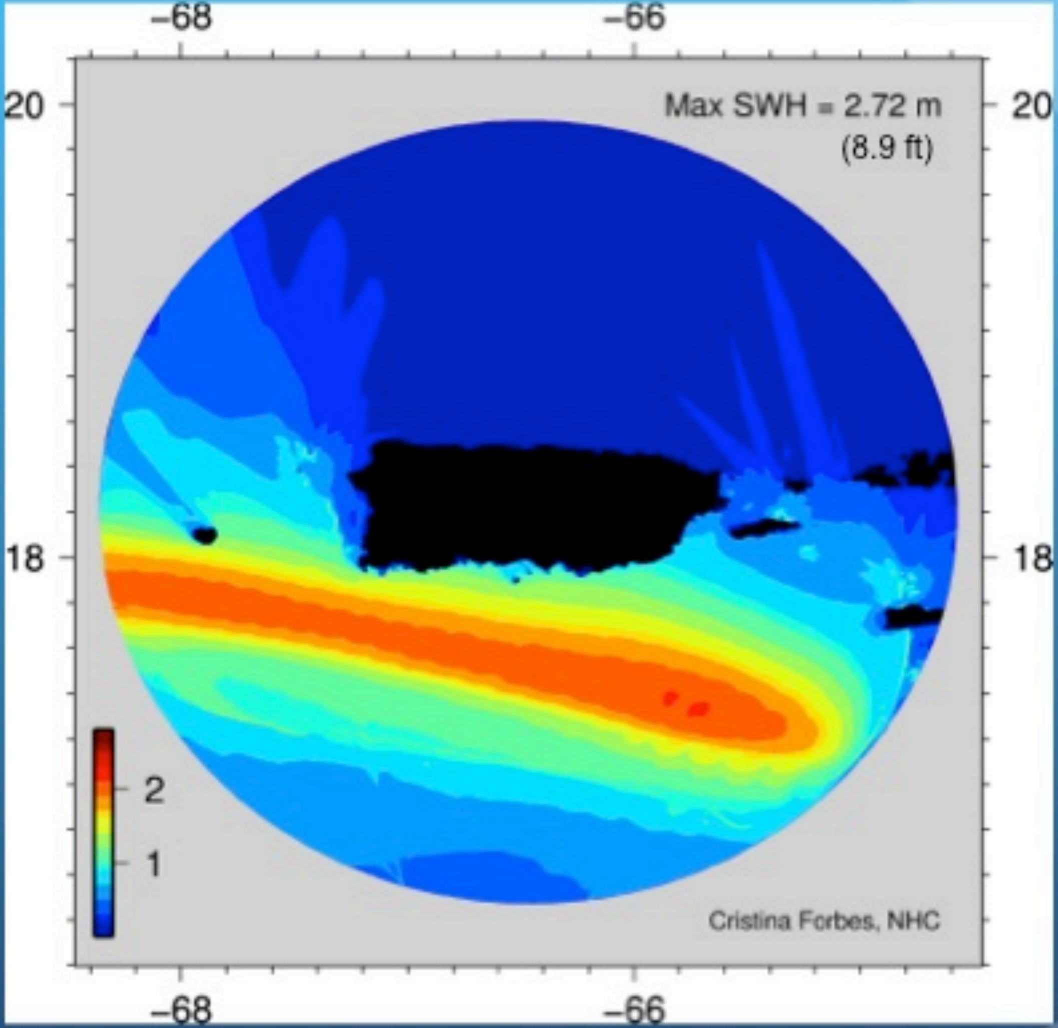


Difference in Water Level
Max = 0.33 m

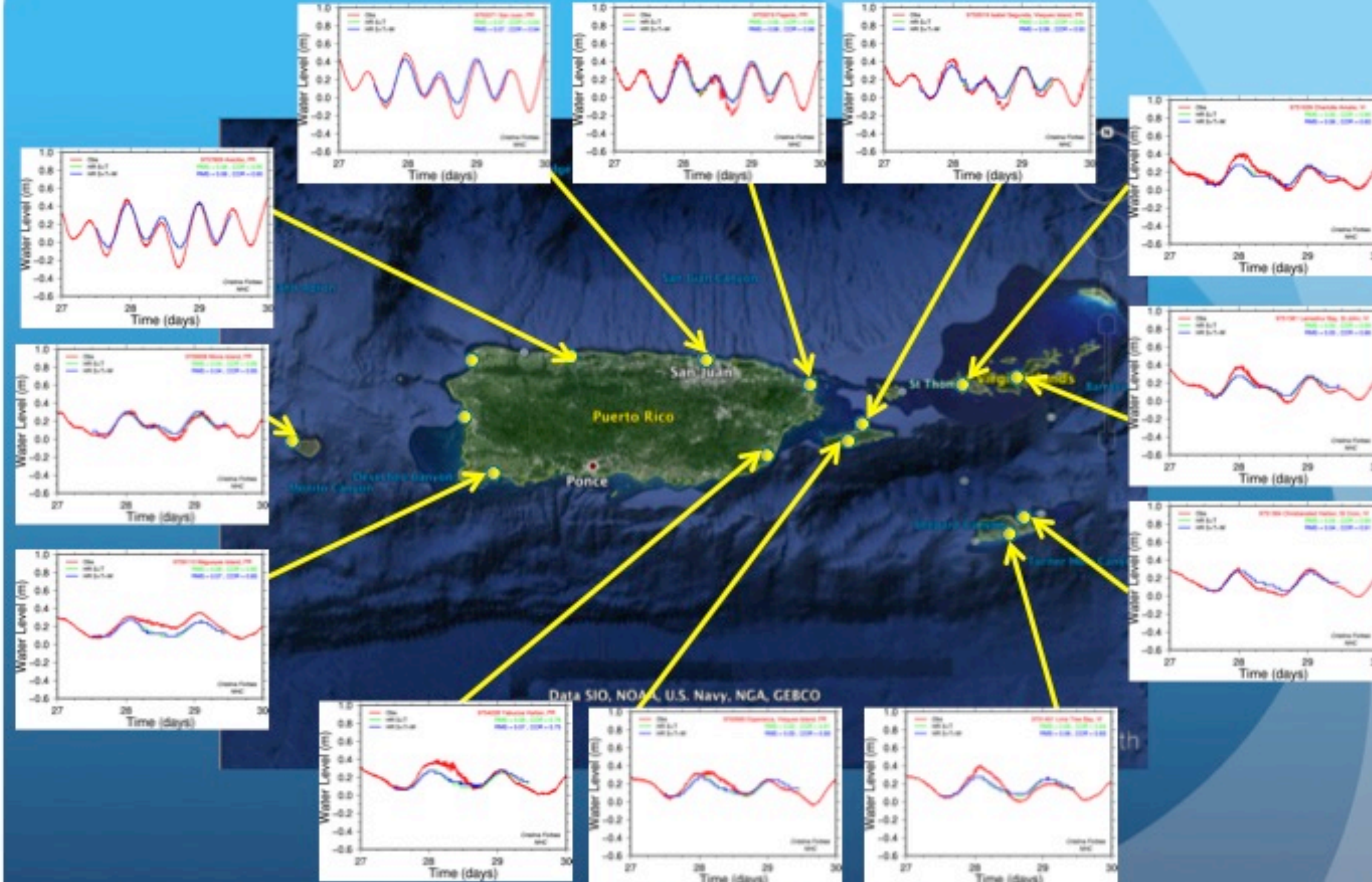


Percentage Difference in Water Level
Max = 100% (pink dots)
10-20% increase from waves

SWAN Max Significant Wave Height TS Erika

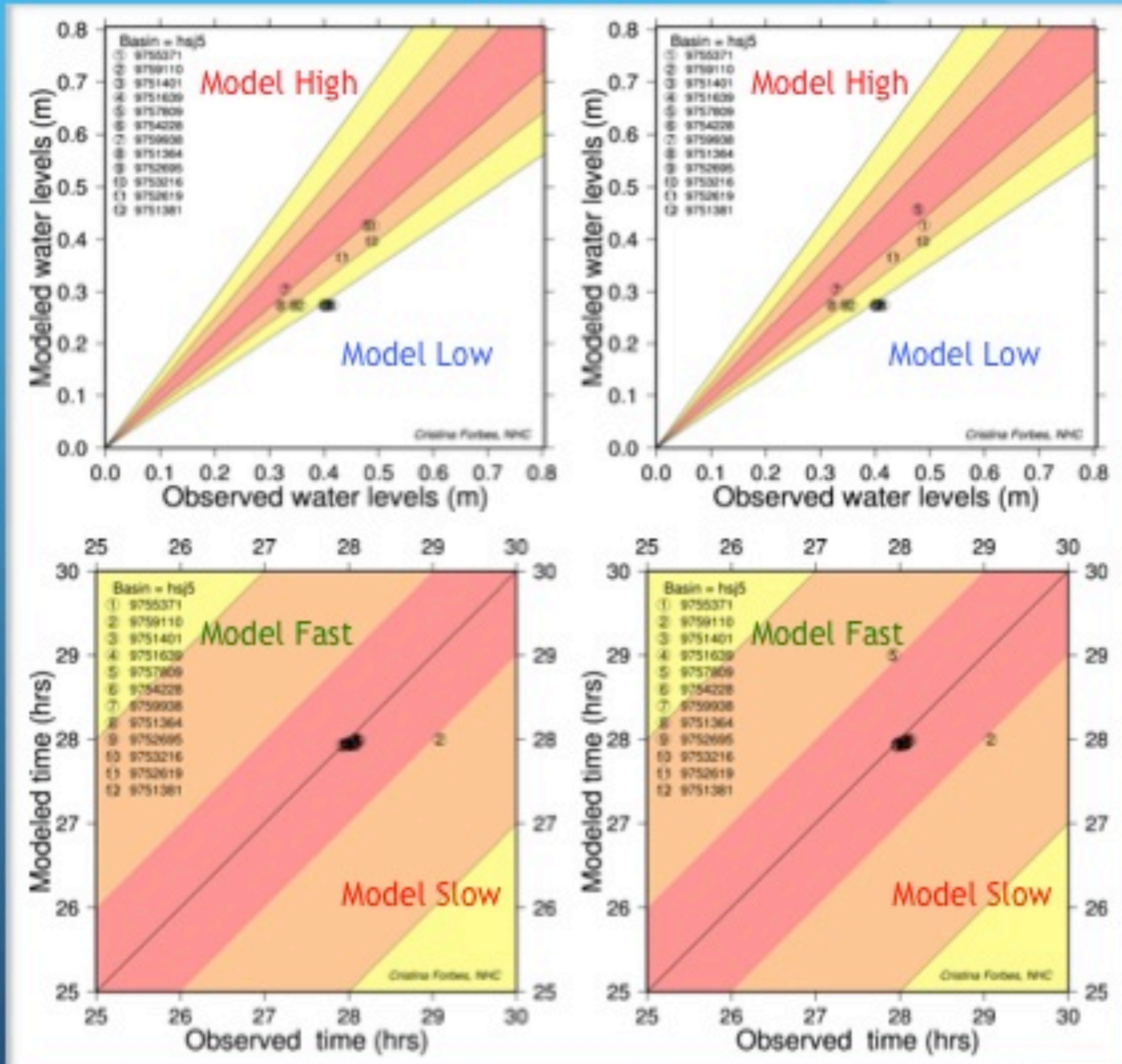


Water Level Verification - SLOSH vs. SWOSH - TS Erika



Error Cones
SLOSH vs. SWOSH
TS Erika

Wind Only



Wind + Waves

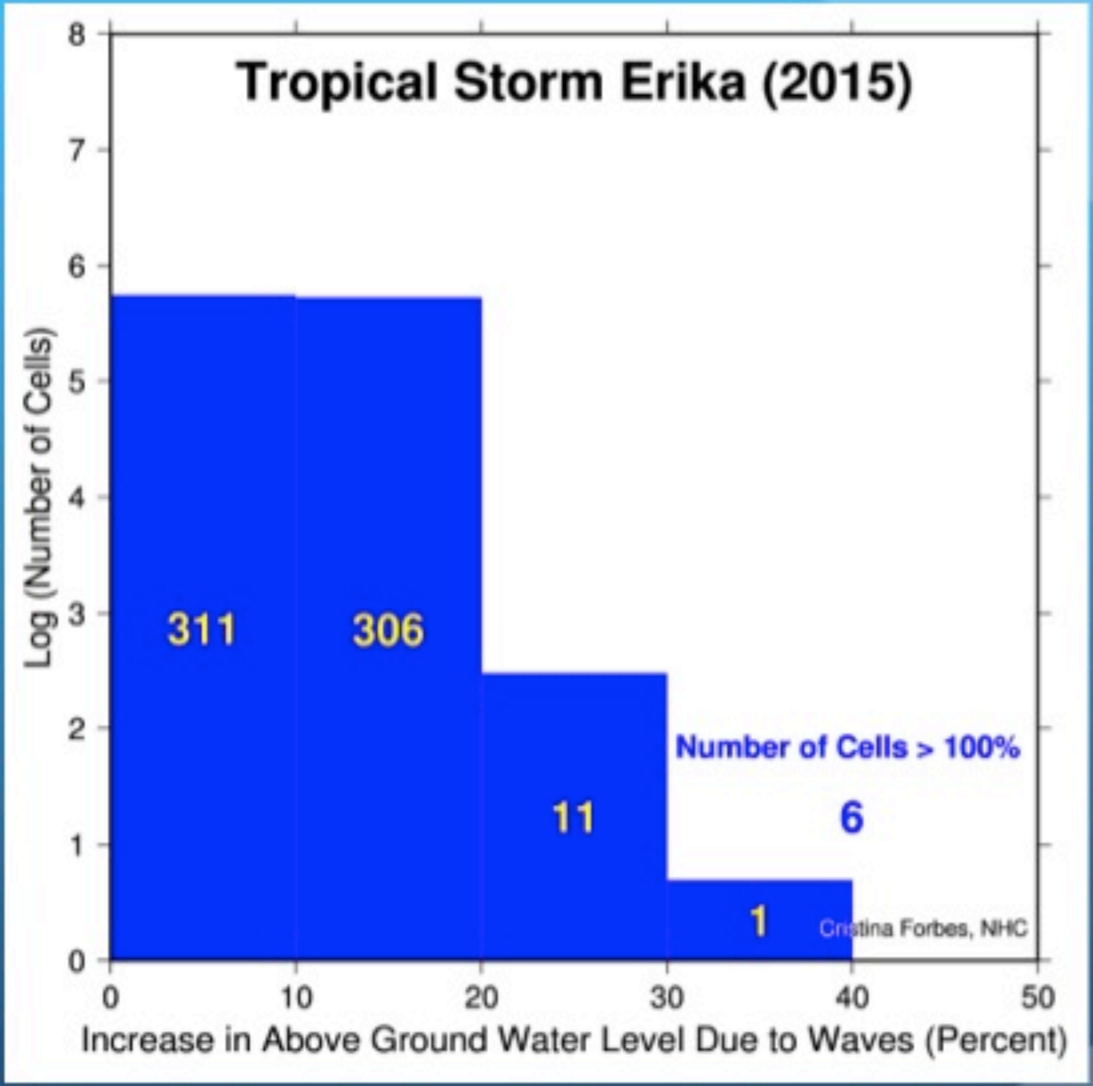
Summary
SLOSH vs. SWOSH
TS Erika

Hurricane Erika (2015) IWL=.5										
Stn ID	Time of Max Elev (day)			Max Elev (m)			RMS		CORR	
	Obs	SL	SW	Obs	SL	SW	SL	SW	SL	SW
9755371	27.97	27.94	27.93	.490	.427	.427	.07	.07	.94	.94
9759110	29.08	28	28	.357	.274	.274	.08	.07	.85	.85
9751401	28.09	27.98	27.98	.406	.274	.274	.06	.06	.84	.83
9751639	28.05	27.94	27.94	.415	.274	.274	.06	.06	.86	.83
9757809	27.92	27.93	29	.479	.427	.457	.08	.08	.95	.95
9754228	28.13	27.99	27.99	.400	.274	.274	.08	.07	.76	.75
9759938	28.08	27.99	27.99	.329	.305	.305	.04	.04	.95	.95
9751364	27.99	27.94	27.94	.321	.274	.274	.04	.04	.90	.91
9752695	28.09	27.98	27.99	.345	.274	.274	.05	.05	.81	.80
9753216	27.97	27.94	27.94	.487	.396	.396	.06	.06	.95	.96
9752619	28.02	27.96	27.97	.433	.366	.366	.05	.06	.94	.93
9751381	28.05	27.94	27.94	.403	.274	.274	.05	.05	.89	.86

RMSE=4 to 8 cm
CORR=.75 to .96

7% increase at Arecibo, PR

Impact of Waves



Summary

- SLOSH + SWAN coupled model was implemented at NHC.
- Puerto Rico MEOW/MOM composites were completed and delivered to NOAA/MDL for archival and distribution.
- Validation of the SWOSH model was performed with Hurricane Georges (1998), Hurricane Irene (2011) and Tropical Storm Erika (2015).
- This analysis will provide a platform for future modeling and forecasting improvements which will support evacuation planning in locations where waves are important.

Future Work

- Validations of SWOSH with other storms will be performed.
- Validations of SWAN-predicted significant wave height, direction and period against observations will be conducted.
- Sensitivity studies with different SWAN input parameters will be carried out to determine the optimum parameters to use for SWOSH.
- Inclusion of boundary conditions in will be considered for implementation and validation.

Thank you!