Research concentrations at MSU-Stennis and as a consultant

- Statistical schemes
- Tropical cyclones
- Storm surge
- Commercialization activities
- Deepwater Horizon oil spill
- Model validation
- Mesoscale meteorology/sea breeze
- Wave Glider® Field Program
- CONsortium for oil spill exposure pathways in COastal River-Dominated Ecosystems (CONCORDE)
- Knowledge transferred as commercial products to Barons and WorldWinds

Storm surge applications in the geosciences

Pat Fitzpatrick and Yee Lau
Mississippi State University

Storm surge is an abnormal rise of water associated with a cyclone, not including tidal influences

Low pressure system can be a baroclinic cyclone, tropical cyclone, or a hybrid of the two.

Fundamental surge components

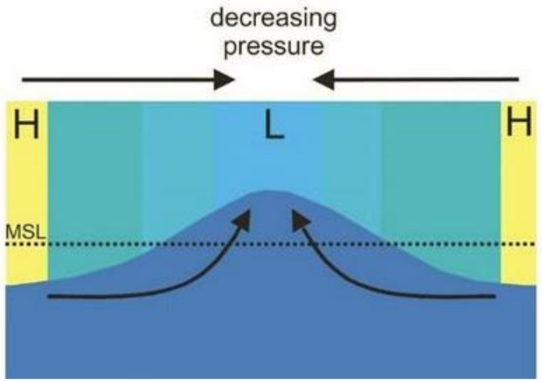
- Pressure setup - *increase in water level due to lower atmospheric pressure in storm interior.* A slight surface bulge occurs within the storm, greatest at the storm's center, decreasing at the storm's periphery. For every 10-mb pressure drop, water expands 4.0 inches.
  - *Effect is a constant*

- Wind setup - *increase in water level due to the force of the wind on the water.* As the transported water reaches shallow coastlines, bottom friction slows their motion, causing water to pile up. Further enhanced near land boundaries.
  - *Depends on bathymetry, size, and intensity. MOST IMPORTANT IN TERMS OF MAGNITUDE FOR SHALLOW WATER BATHYMETRIES!*

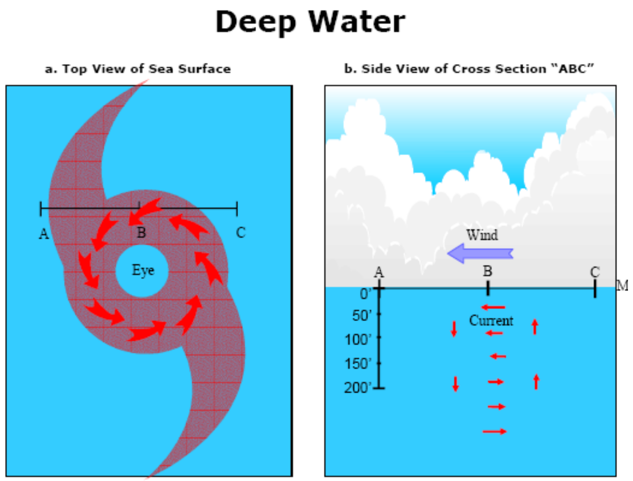
- Geostrophic adjustment – *water levels adjust to a developing longshore current.*
  - *Impact increases for slow-moving tropical cyclones*
  - *Impact increases for larger tropical cyclones*
  - *Causes a storm surge "forerunner"*
  - *Generally second in importance; *may* be most important in deep water bathymetries*

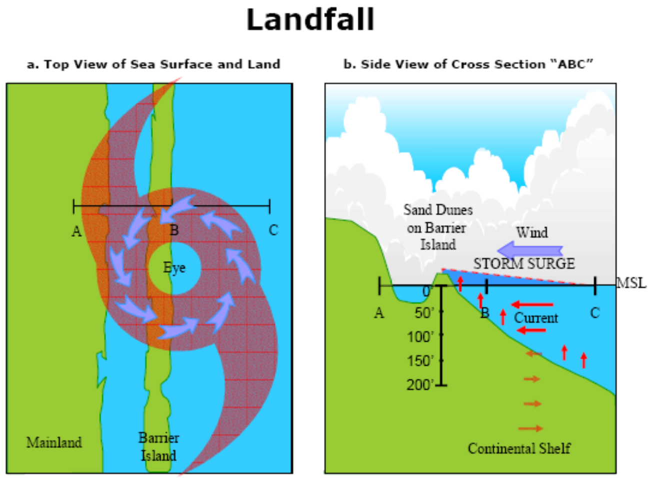
- Wave setup - *increase due to onshore waves.* Incoming water from wave breaking exceeds retreating water after wave runup.
  - *Impact minor in shallow bathymetry (0.5-1 ft); may contribute up to 3 ft surge in deep bathymetry (still the subject of debate)*

Pressure setup

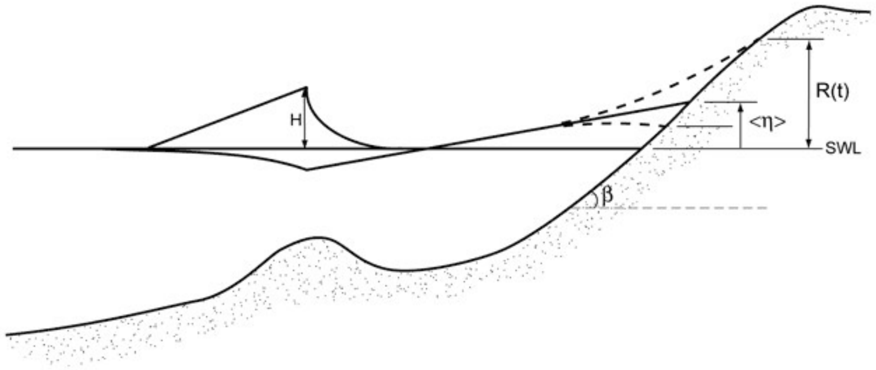


Wind setup

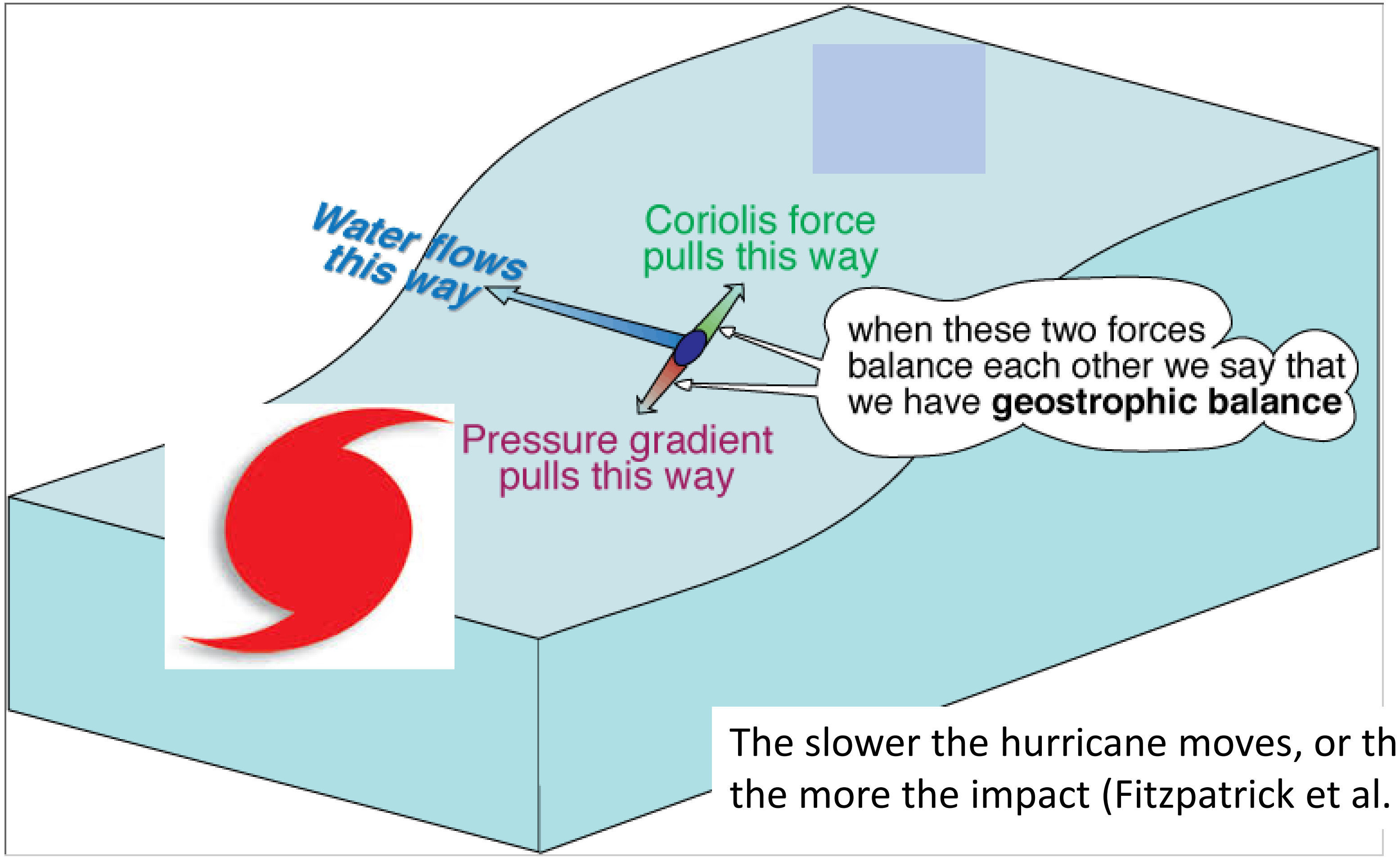




Wave setup



Geostrophic adjustment (creates surge "forerunner")



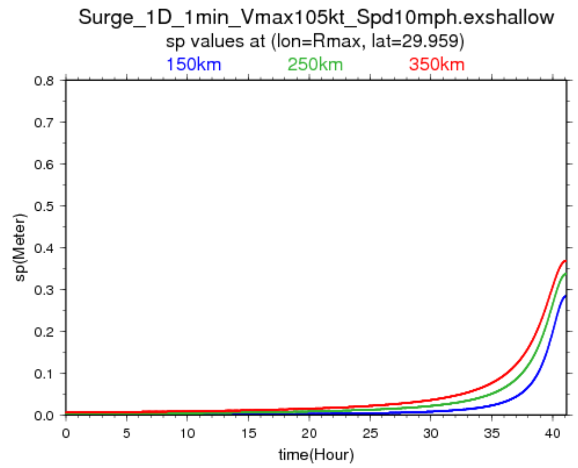
The slower the hurricane moves, or the larger the hurricane, the more the impact (Fitzpatrick et al. 2012)

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

http://www.seos-project.eu/modules/oceancurrents/oceancurrents-c06-s02-p01.html

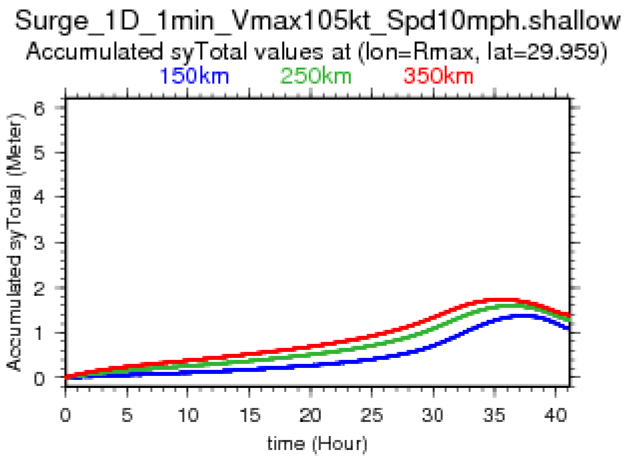
Pressure effect

(peaks at landfall)



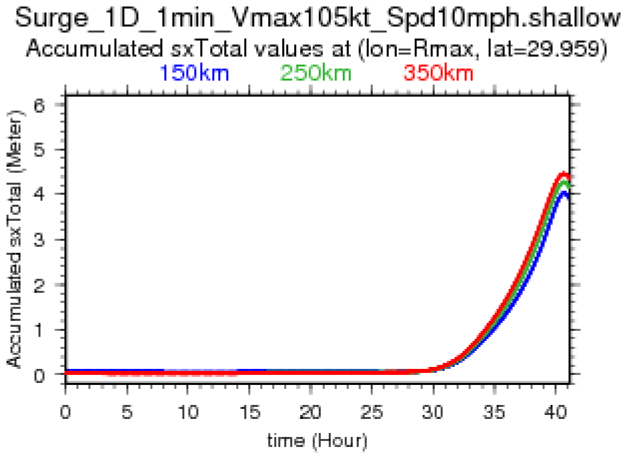
Surge forerunner

(peaks before landfall)



Wind effect

(peaks at landfall)



Time series example for Cat 3 in shallow bathymetry for small, average, and large hurricane moving 10 mph

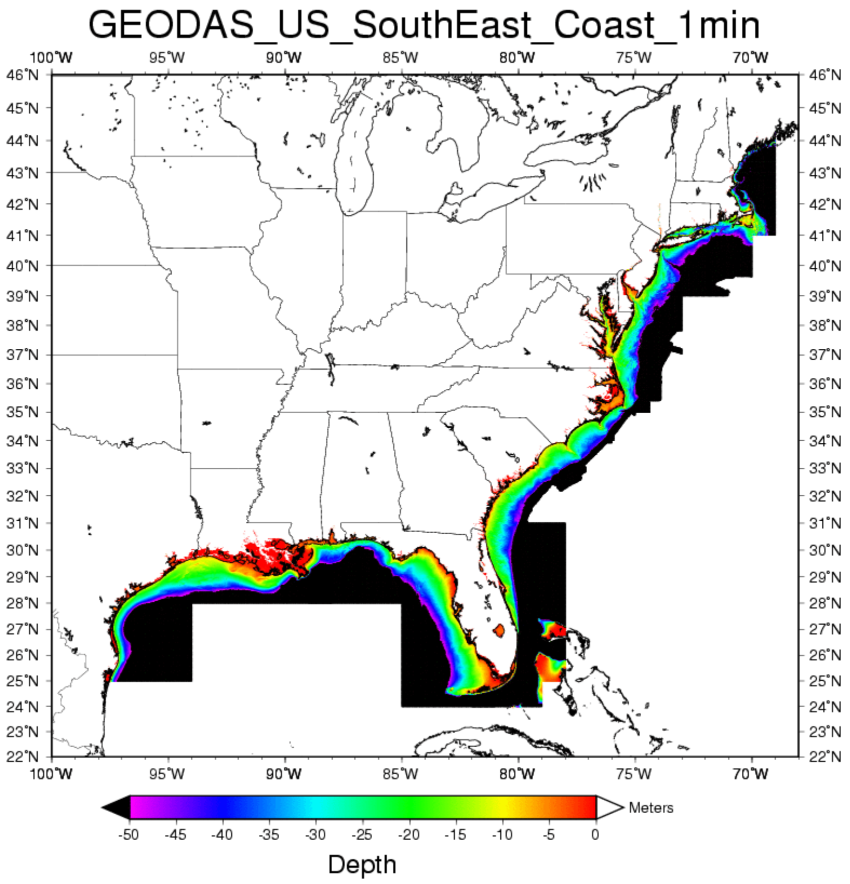
Surge on coastline

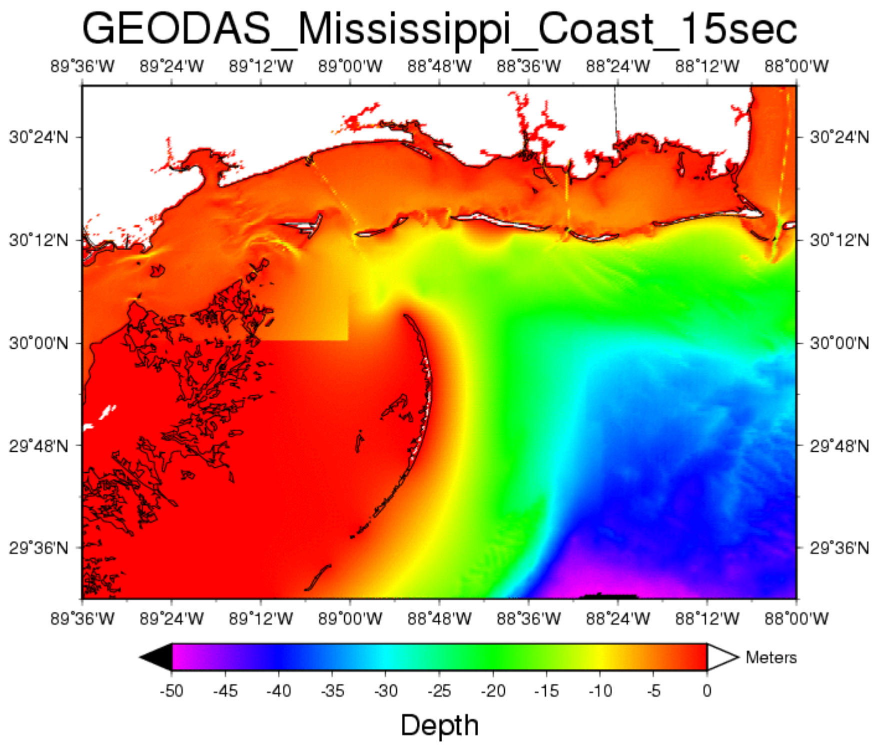
Other components for consideration

- Tide
- Steric setup – (water expansion or contraction from water temperature, small)
- Nonlinear advection (small, neglected in some models)
- Dissipation terms

Note that, in two dimensions, all eight interactions become more complicated

Surge varies due to different bathymetries and boundaries

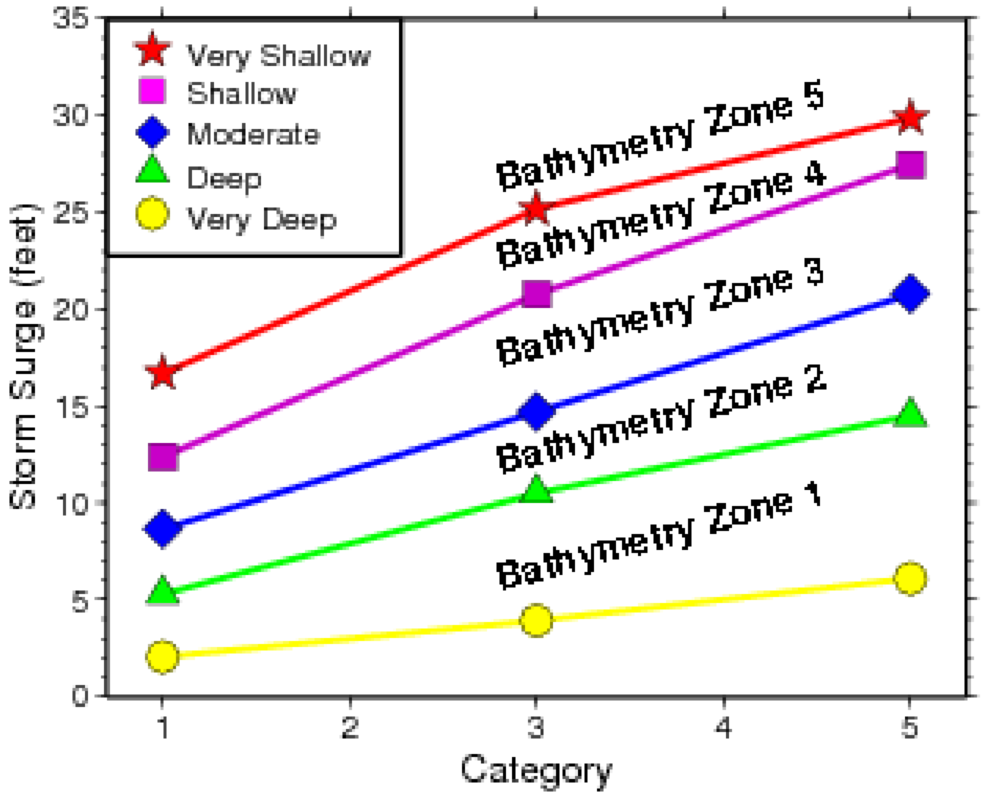




Thought question --- where would surge be worse for a major hurricane?

Effect of hurricane intensity, size, and speed on storm surge

Cat 1, 3, 5 hurricanes, average size, average speed



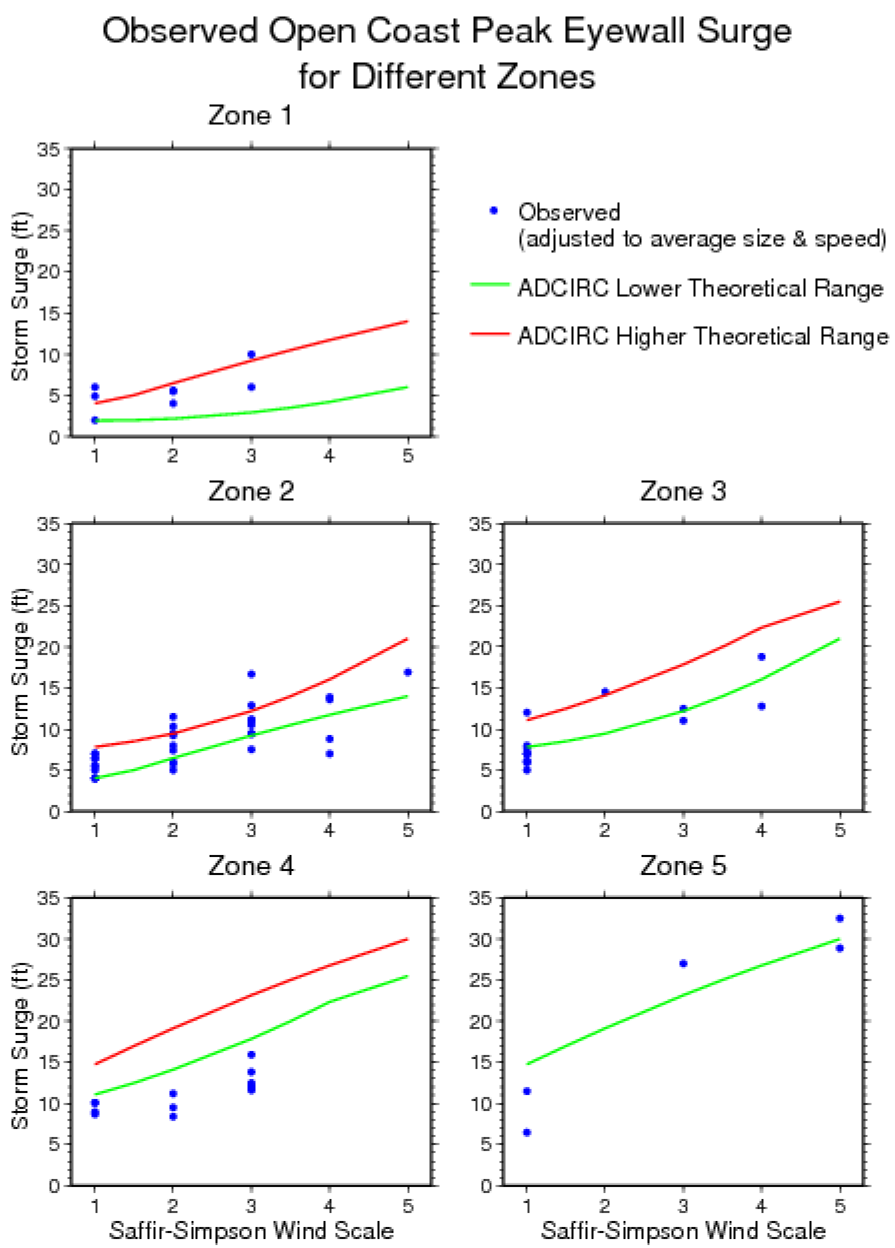
Correction factors for speed and size

Size

- **Zone 2:** ± 1.5 (Cat 3–5)
- **Zone 3:** ± 1.0 (Cat 1–2), ± 1.8 (Cat 3), ± 2.5 (Cat 4–5)
- **Zone 4:** ± 1.6 (Cat 1–2), ± 2.5 (Cat 3), ± 3.6 (Cat 4–5)
- **Zone 5:** ± 2.3 (Cat 1–2), ± 3.3 (Cat 3), ± 4.3 (Cat 4–5)

Speed

- **Zone 4:** ± 1.5 (Cat 1–2), ± 2.0 (Cat 3), ± 2.6 (Cat 4–5)
- **Zone 5:** ± 3.0 (Cat 1–2), ± 3.9 (Cat 3), ± 5.2 (Cat 4–5)


Observed Open Coast Peak Eyewall Surge
for Different Zones
Zone 1
Zone 2
Zone 3
Zone 4
Zone 5
Storm Surge (ft)
Saffir-Simpson Wind Scale
Observed
(adjusted to average size & speed)
ADCIRC Lower Theoretical Range
ADCIRC Higher Theoretical Range

Surge modeling – SLOSH or ADCIRC

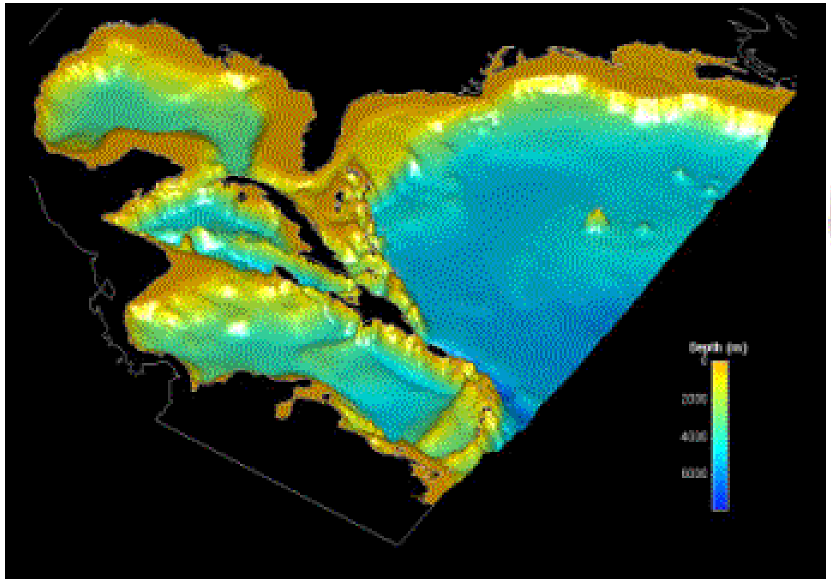
- *Forecasting*
- *Scientific studies*
- *Mitigation*
- *Legal cases*

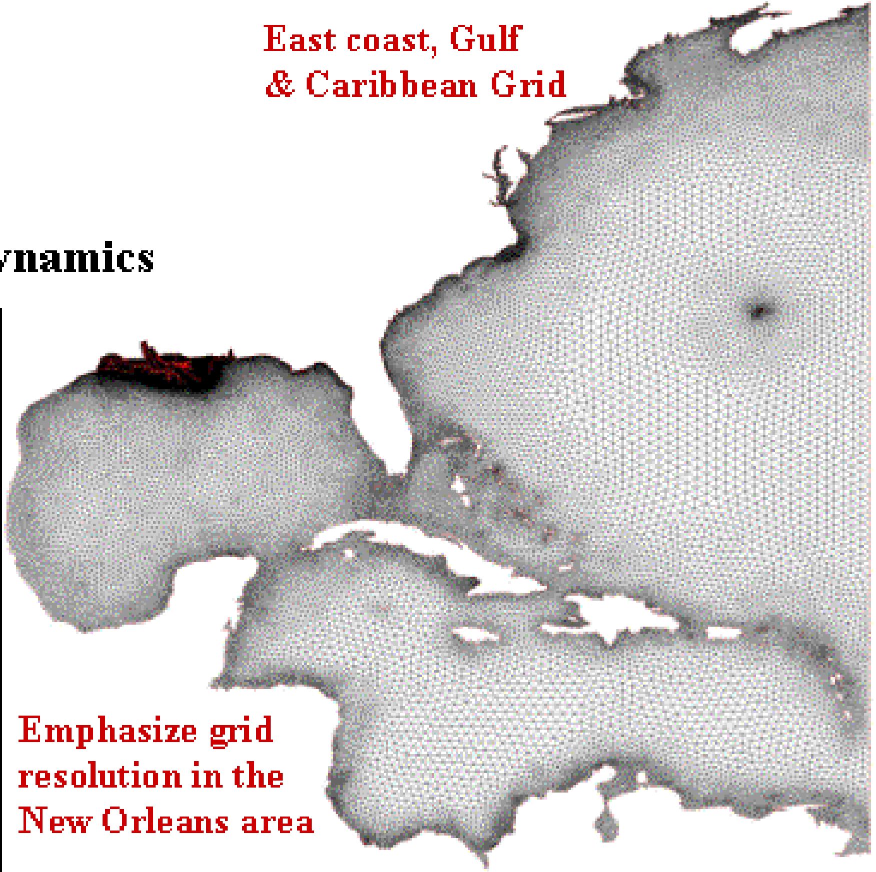
ADCIRC Storm Surge Implementation

Simulation of coastal regions – **Large Domain Strategy**

Correctly capture

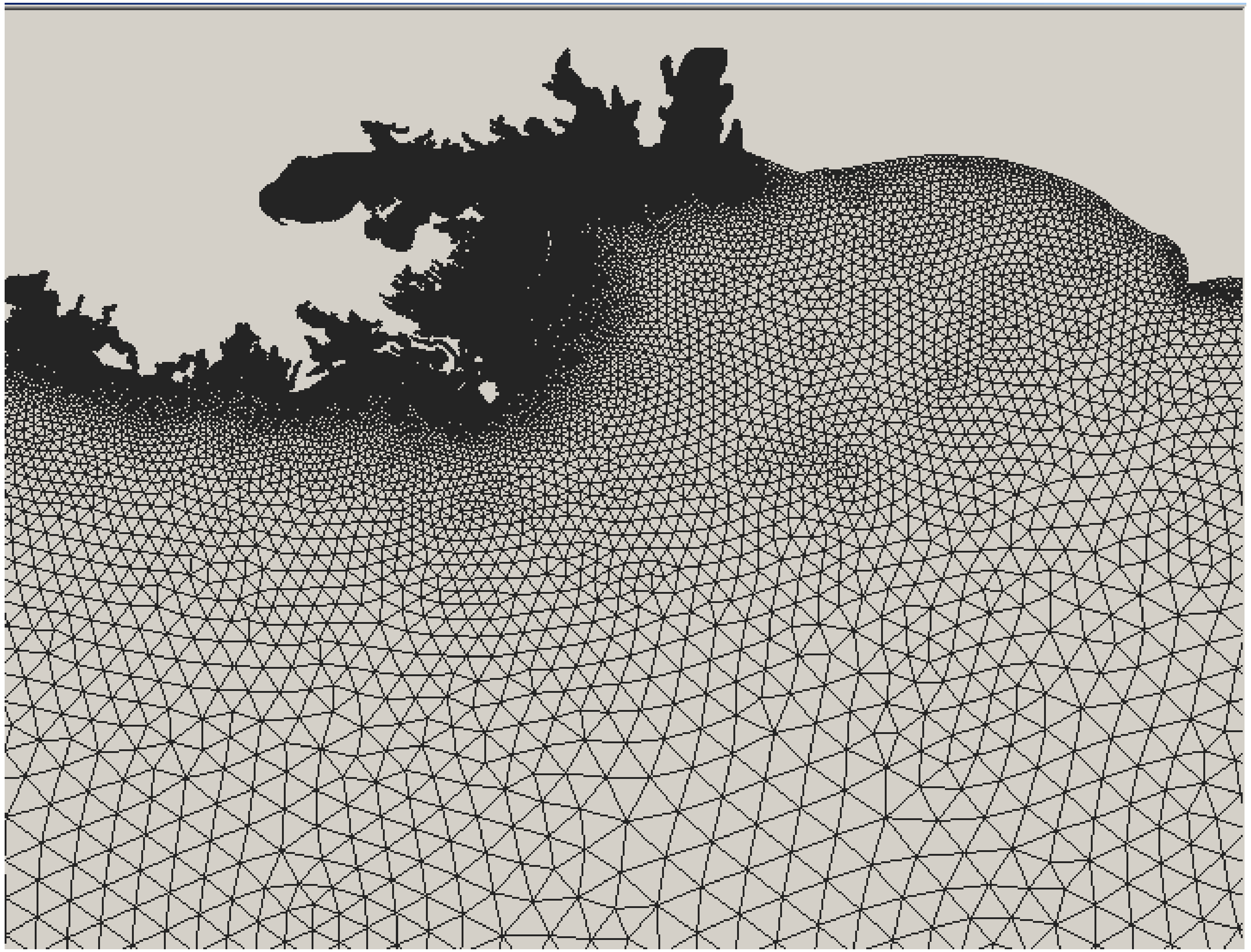
- Basin to basin interactions
- Basin to shelf dynamics
- Shelf to adjacent coast/land dynamics





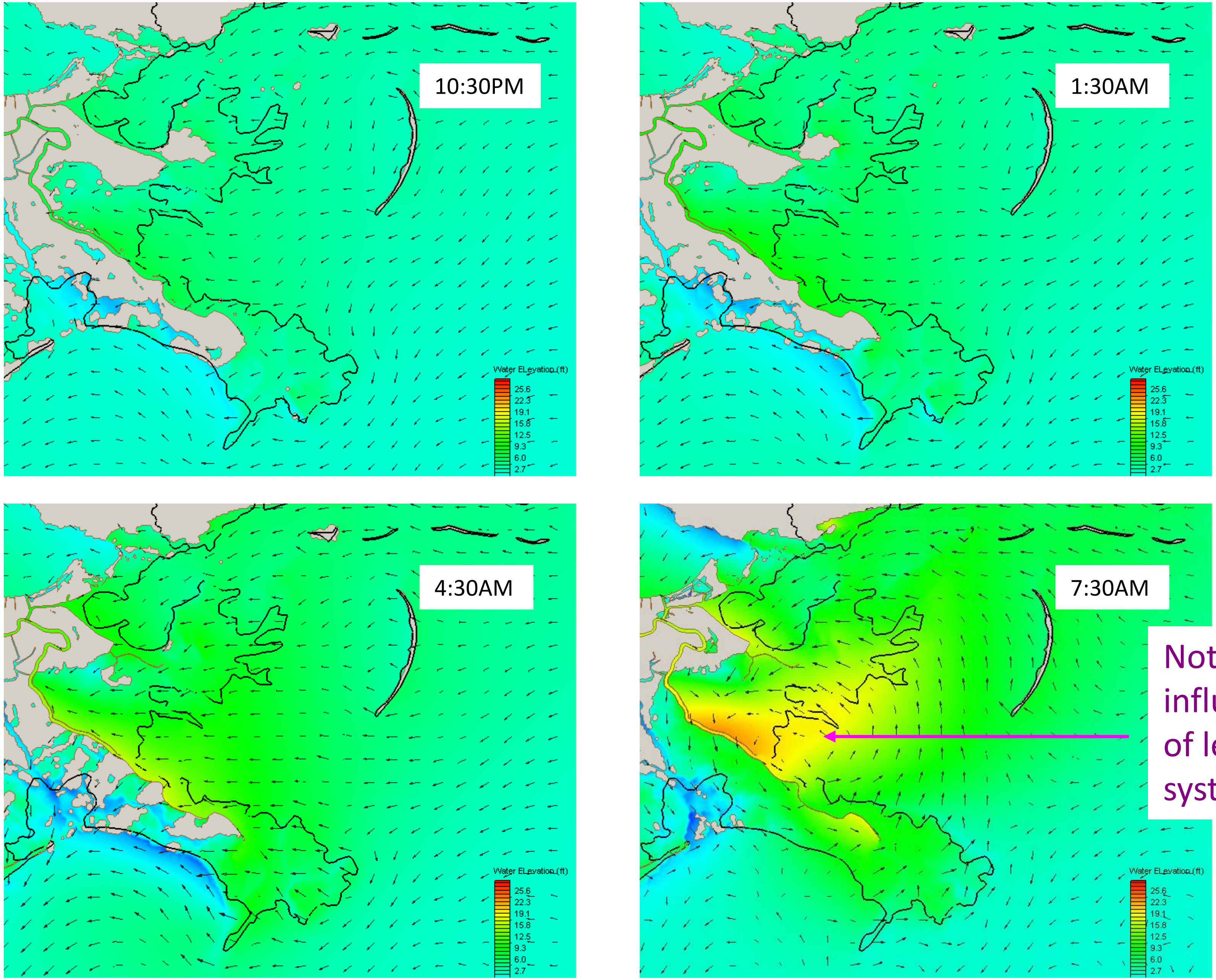
WORLDWINDS

ADCIRC grid – zoom in of North Gulf Coast

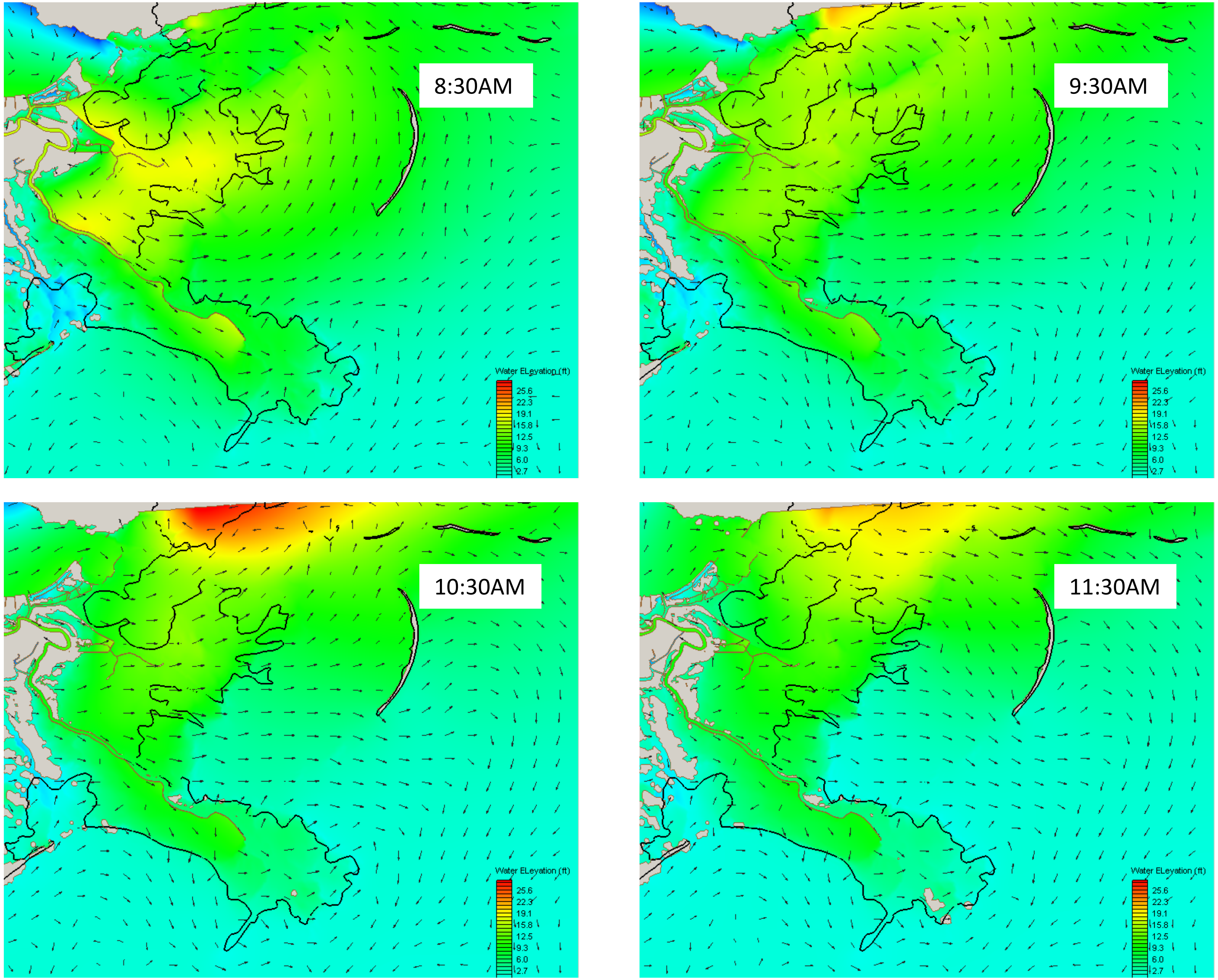


Calculations done at each point. Higher resolution done along shoreline, bays, and bayous to accurately simulation storm surge.

Computer simulation of Katrina storm surge in Louisiana marsh

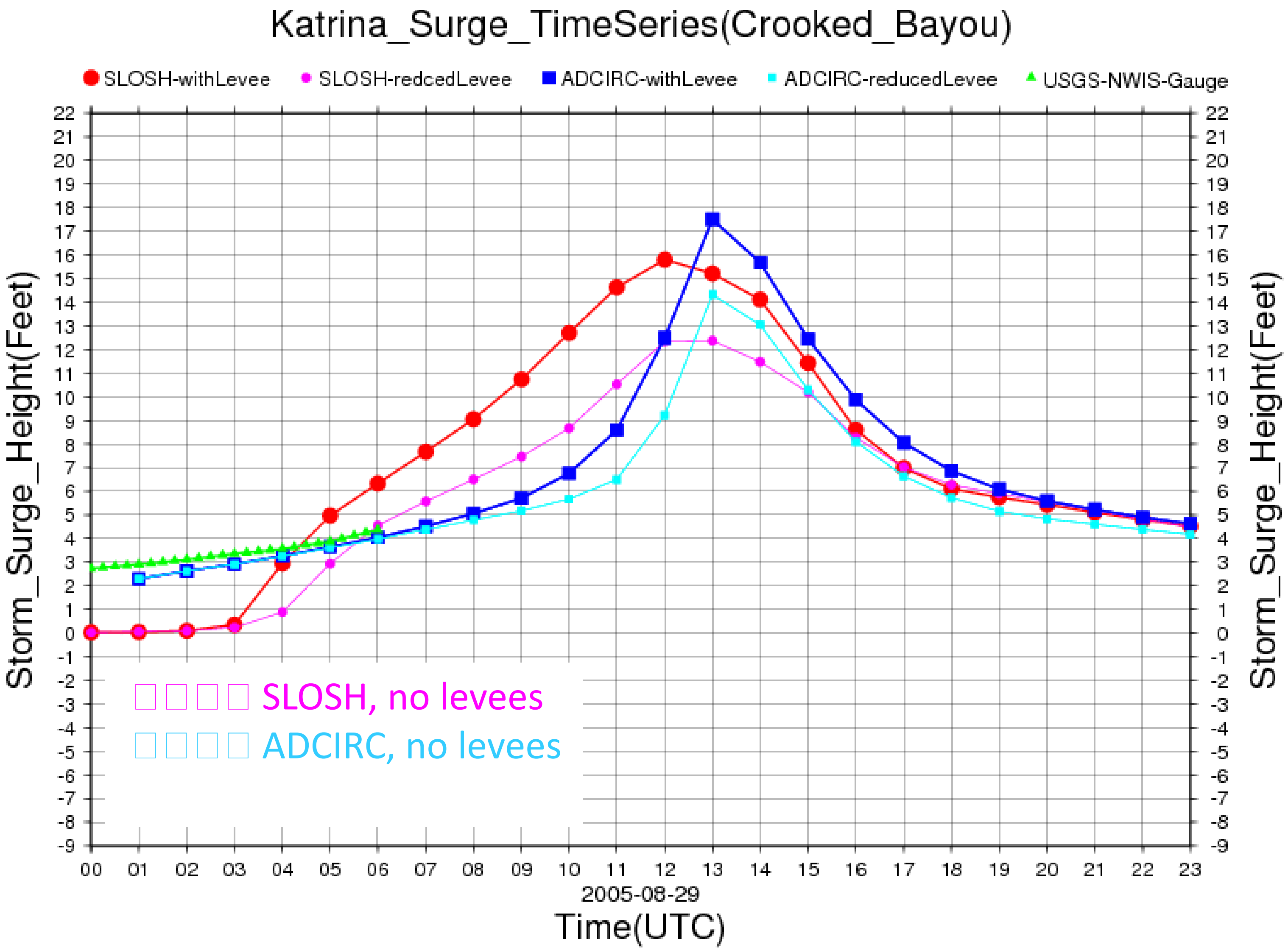


Computer simulation of Katrina storm surge in Louisiana marsh

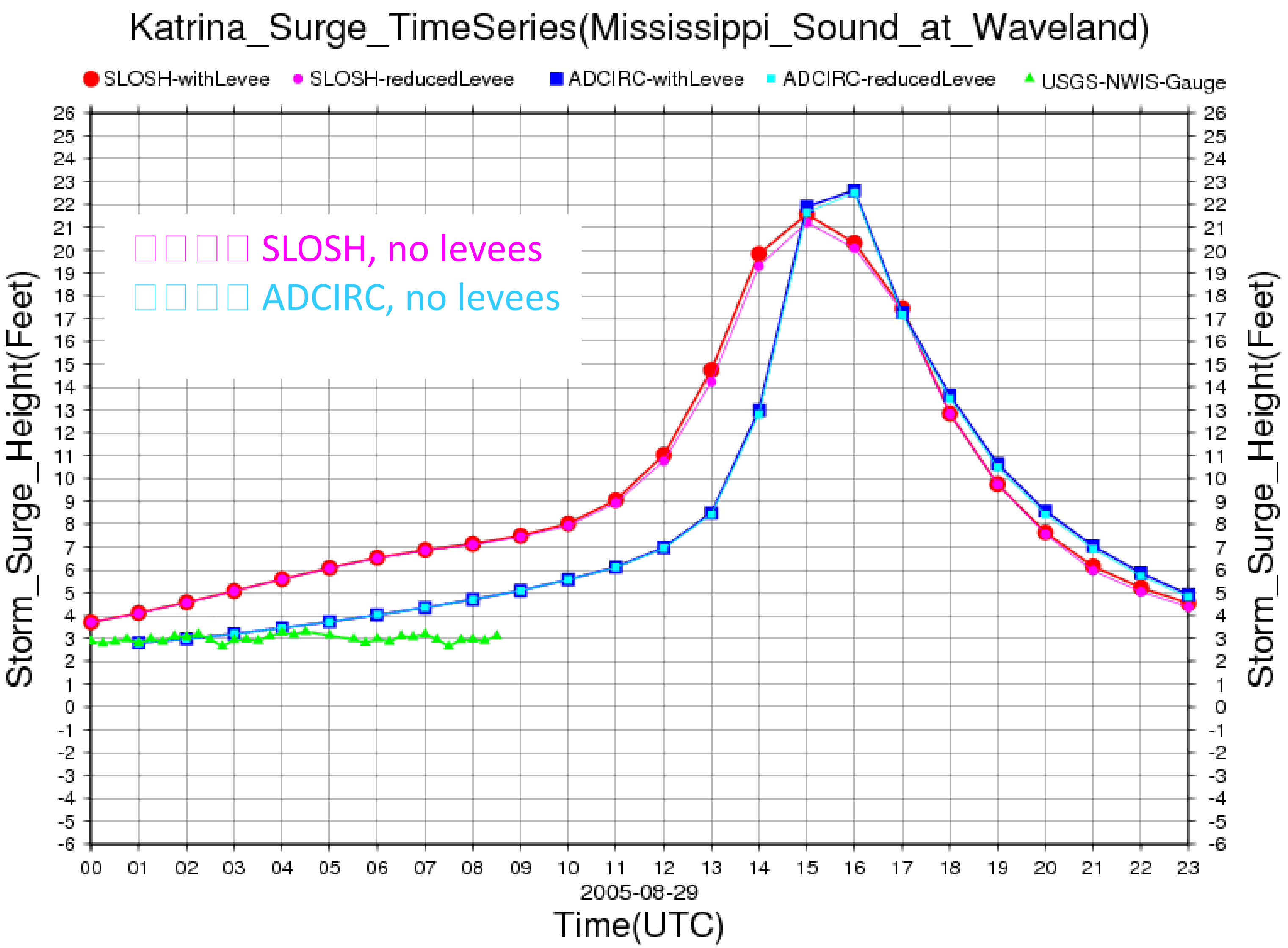


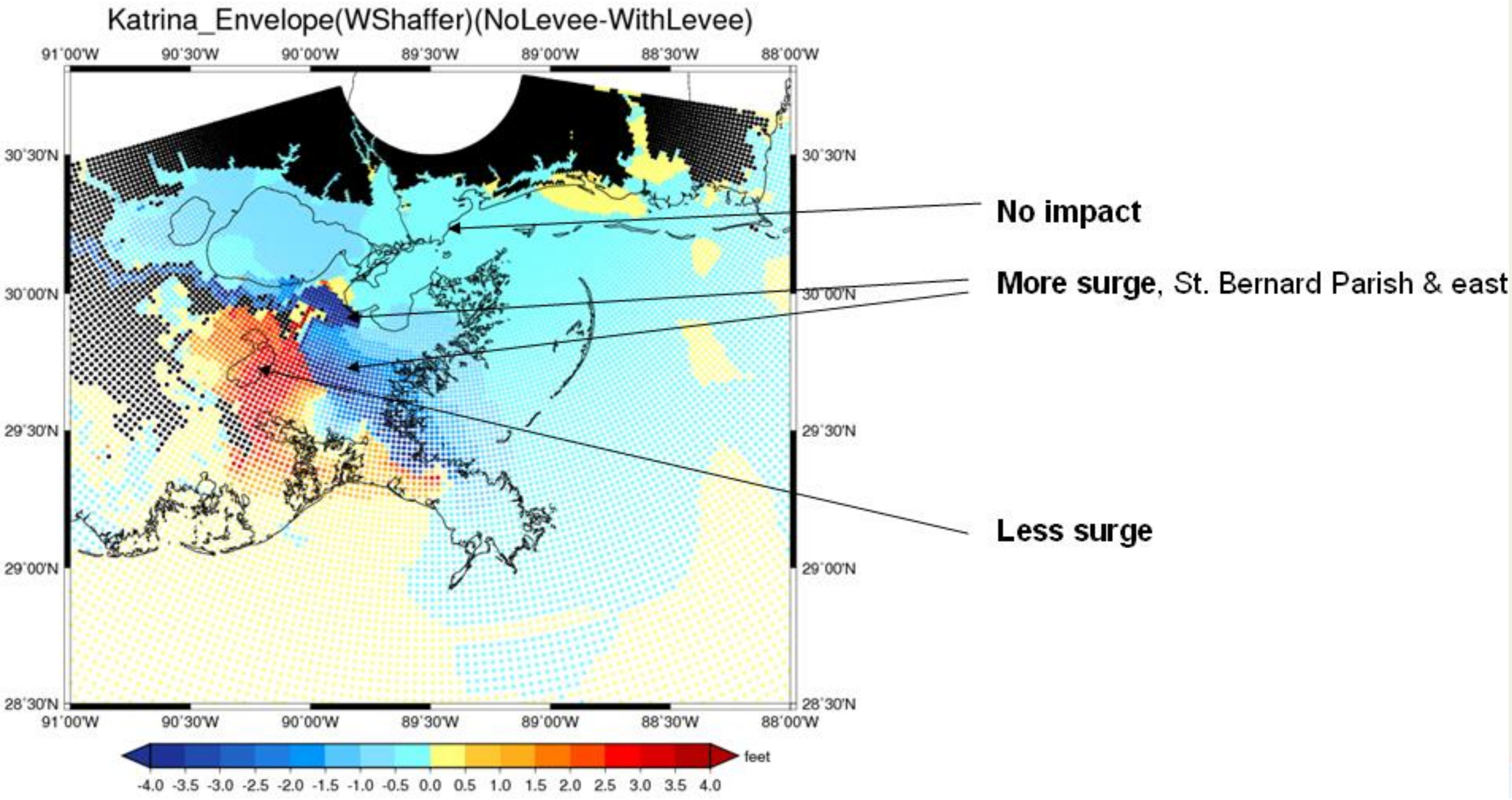
Scientific studies

Impact of levees



Katrina_Surge_TimeSeries(Crooked_Bayou)
SLOSH-withLevee
SLOSH-redcedLevee
ADCIRC-withLevee
ADCIRC-reducedLevee
USGS-NWIS-Gauge
Storm_Surge_Height(Feet)
Time(UTC)
2005-08-29
SLOSH, no levees
ADCIRC, no levees


Katrina_Surge_TimeSeries(Mississippi_Sound_at_Waveland)
SLOSH-withLevee
SLOSH-reducedLevee
ADCIRC-withLevee
ADCIRC-reducedLevee
USGS-NWIS-Gauge
SLOSH, no levees
ADCIRC, no levees
Storm_Surge_Height(Feet)
2005-08-29
Time(UTC)

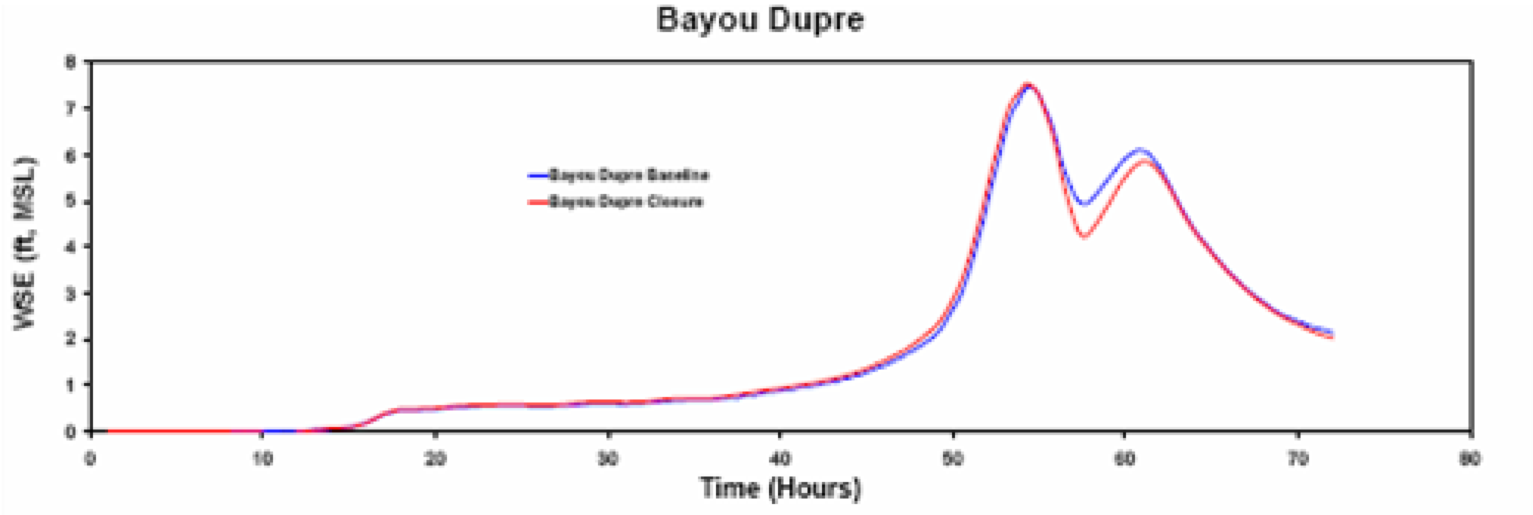


Katrina_Envelope(WShaffer)(NoLevee-WithLevee)
91°00'W
90°30'W
90°00'W
89°30'W
89°00'W
88°30'W
88°00'W
30°30'N
30°00'N
29°30'N
29°00'N
28°30'N
No impact
More surge, St. Bernard Parish & east
Less surge
feet
-4.0 -3.5 -3.0 -2.5 -2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0

Contribution from large canals

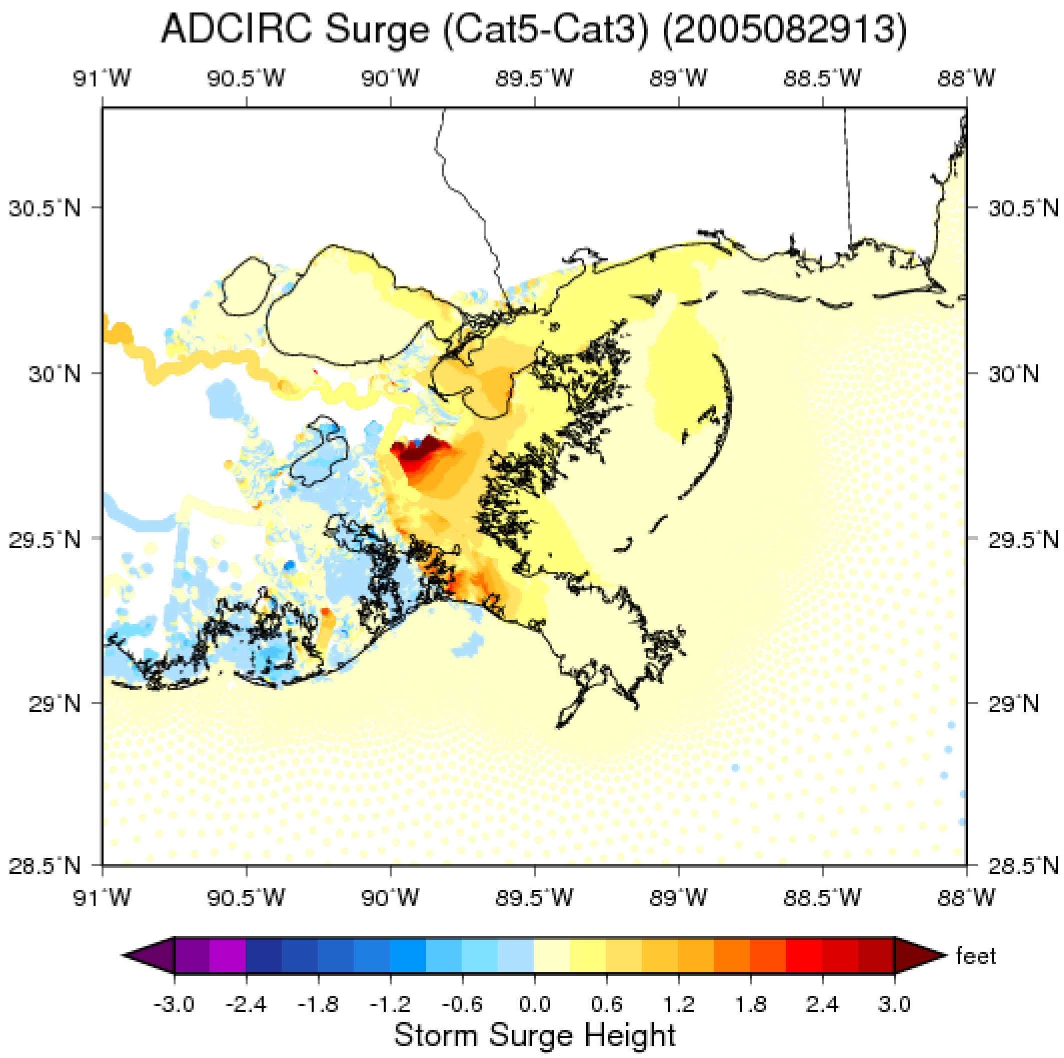
New Orleans and eastern marsh system

ADCIRC simulations with MRGO open (blue) and closed (red)



Little impact of the MRGO on the storm surge at Bayou Dupre south of Lake Borgne. This result is typical throughout the region.

Impact of Katrina Cat 5 offshore versus Cat 3 offshore



Katrina's offshore Cat 5 contribution less than 1 ft in most places

Mitigation

- Insurance rates
- Base flood levels for mitigation
    i. New Orleans levees
    ii. Nuclear power plants

Example - “100-year” surge events

One hundred year level of protection means reducing risk from a storm surge that has a 1% chance of being equaled or exceeded in any given year.

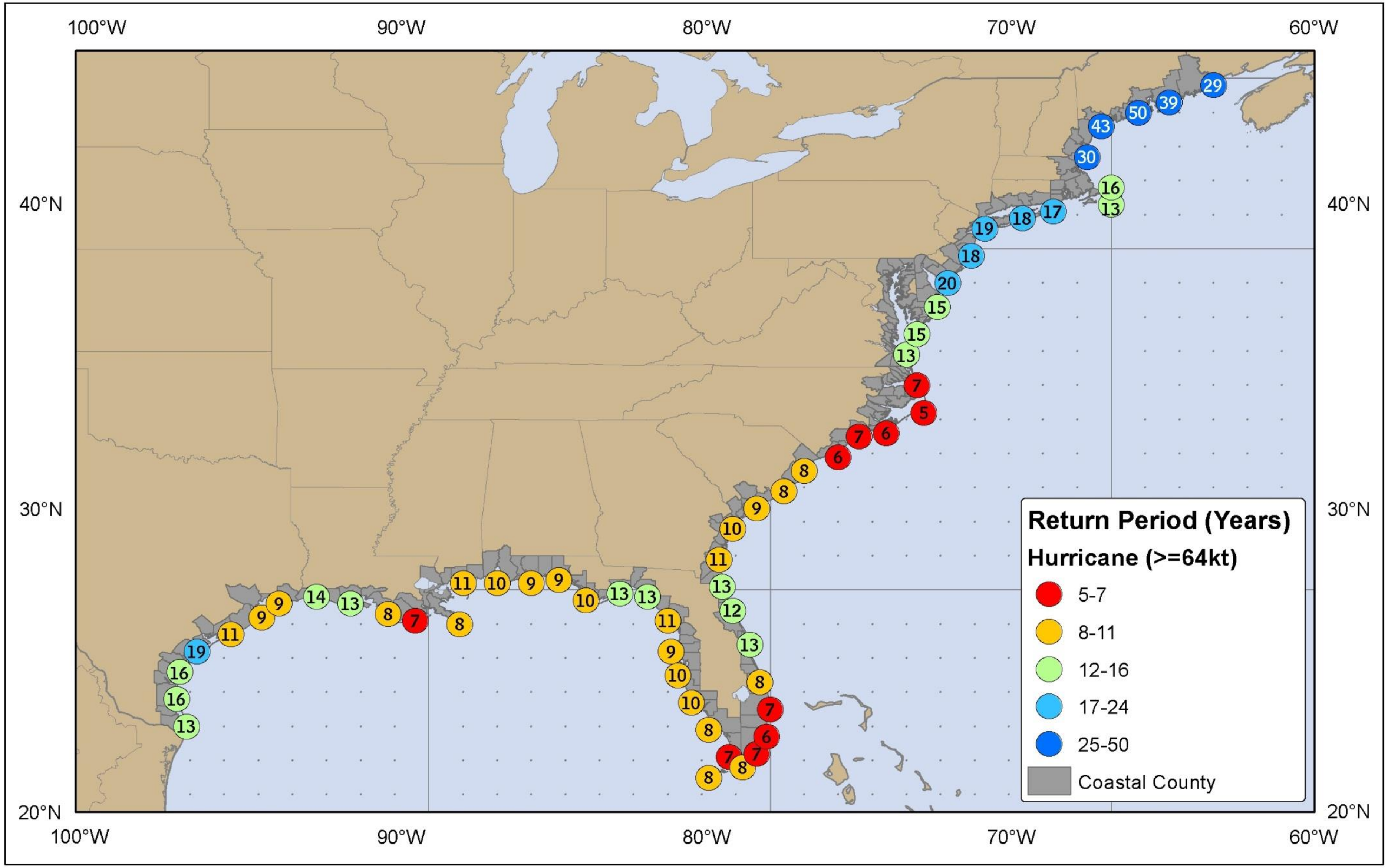
Based on the combined chances of a storm of a certain size and intensity following a certain track. Different combinations of size, intensity and track can result in a 100-year surge event.

Also called a 100-year return period.

Bad term, since the probability of a 100-year surge event occurring in 30 years (the lifetime of avg mortgage) is 26%

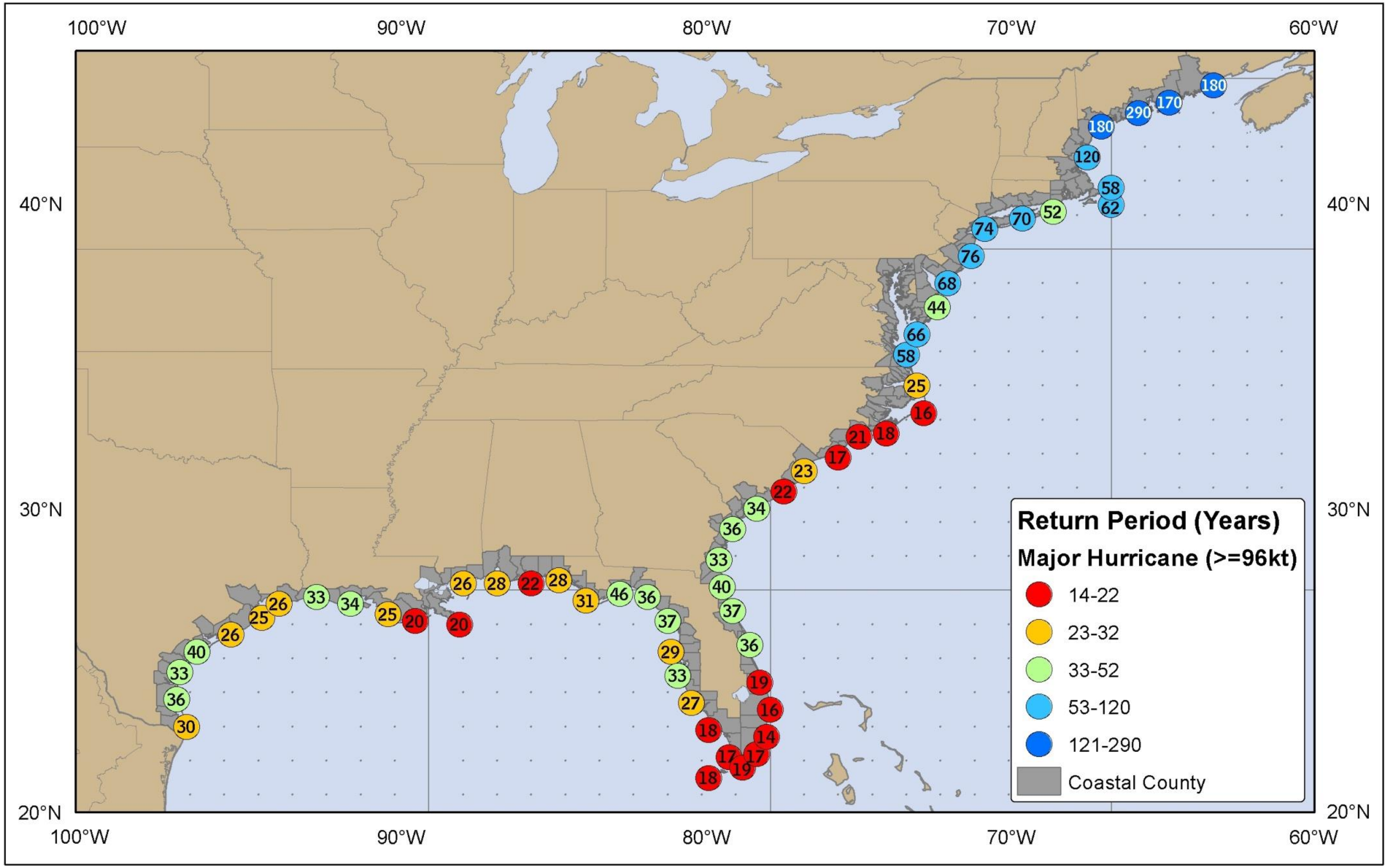
(Can also develop metrics for 500-year events, 10,000 year events, etc.)

Return periods, U.S. hurricanes



From http://www.nhc.noaa.gov/climo/, data based on 1900-2010

Return periods, U.S. major hurricanes



From http://www.nhc.noaa.gov/climo/, data based on 1900-2010

Surge very sensitive to track and intensity in SE Louisiana

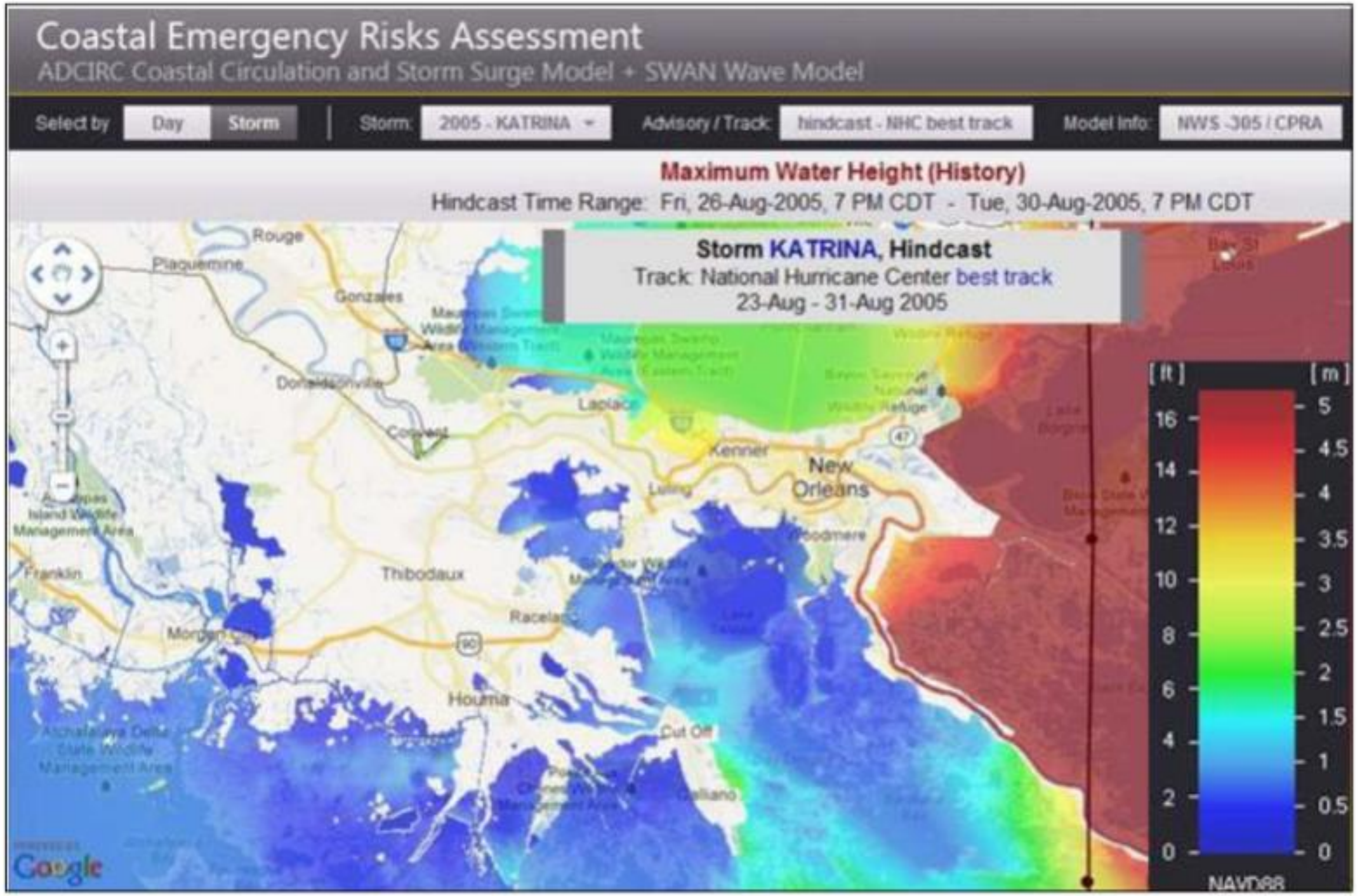


Figure 3.29 Map of the estimated maximum storm surge during Hurricane Katrina.

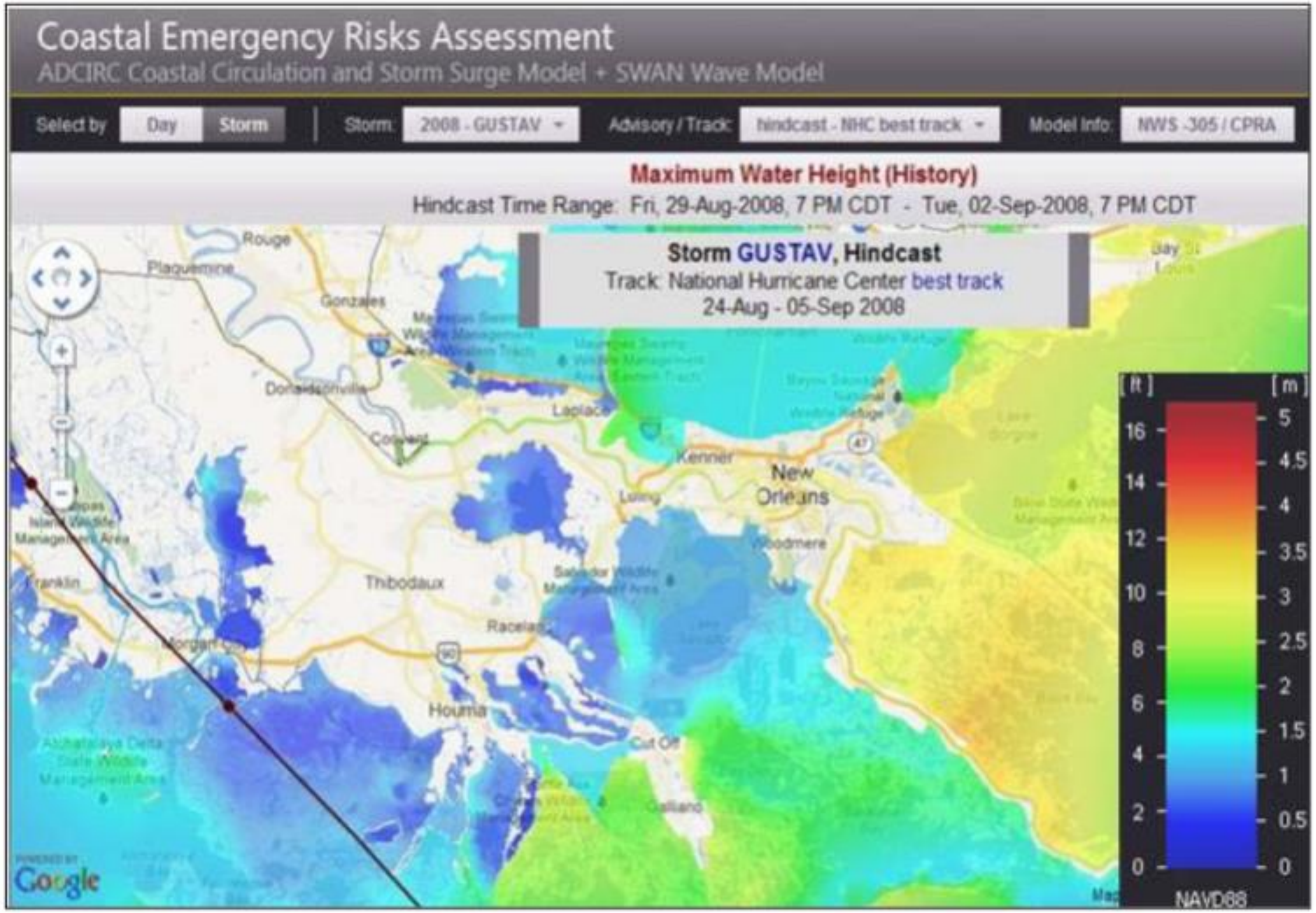


Figure 3.28 Map of the estimated maximum storm surge during Hurricane Gustav.

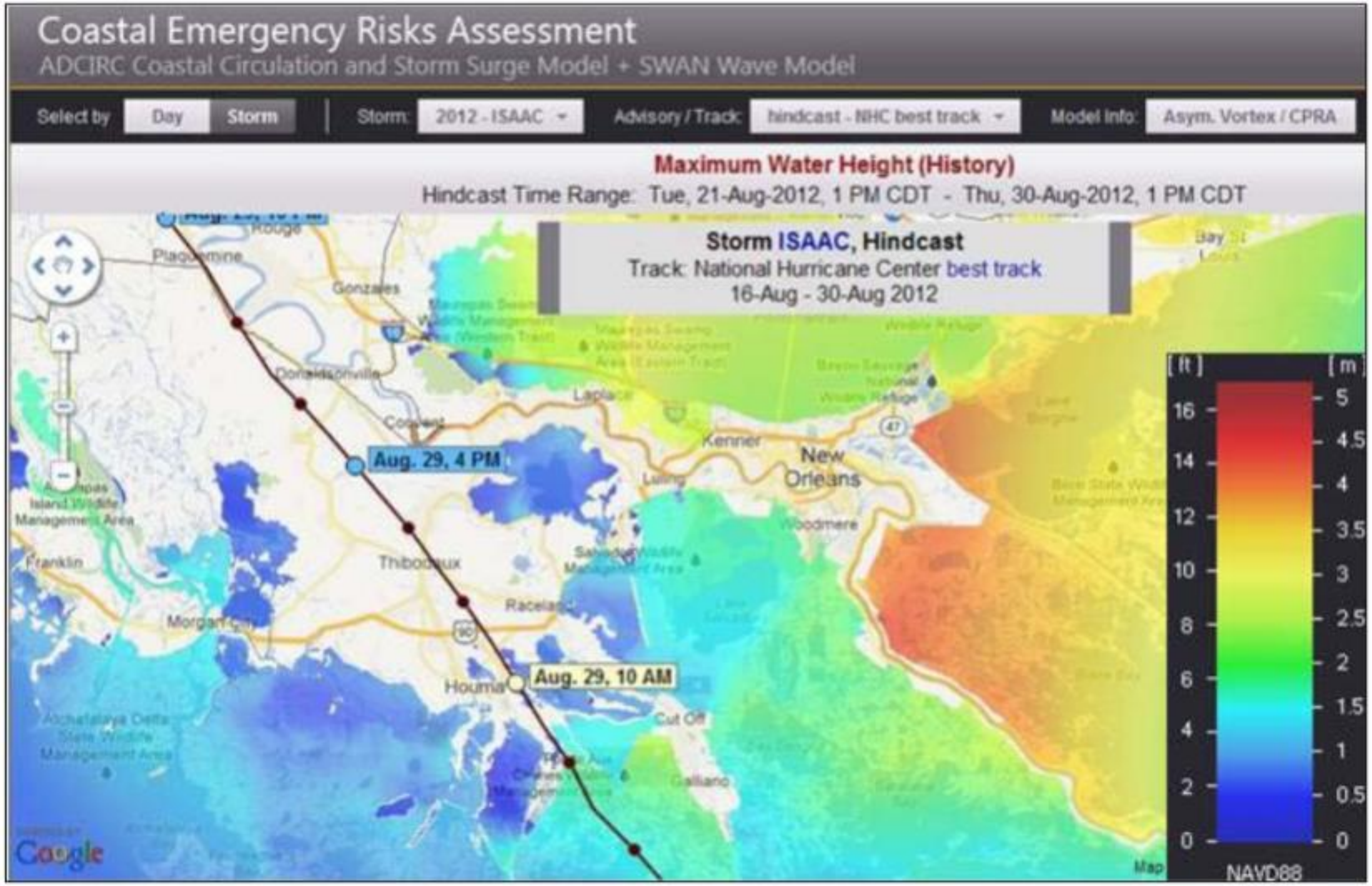


Figure 3.27 Map of the estimated maximum storm surge during Hurricane Isaac.

How “100-year” surge event is determined

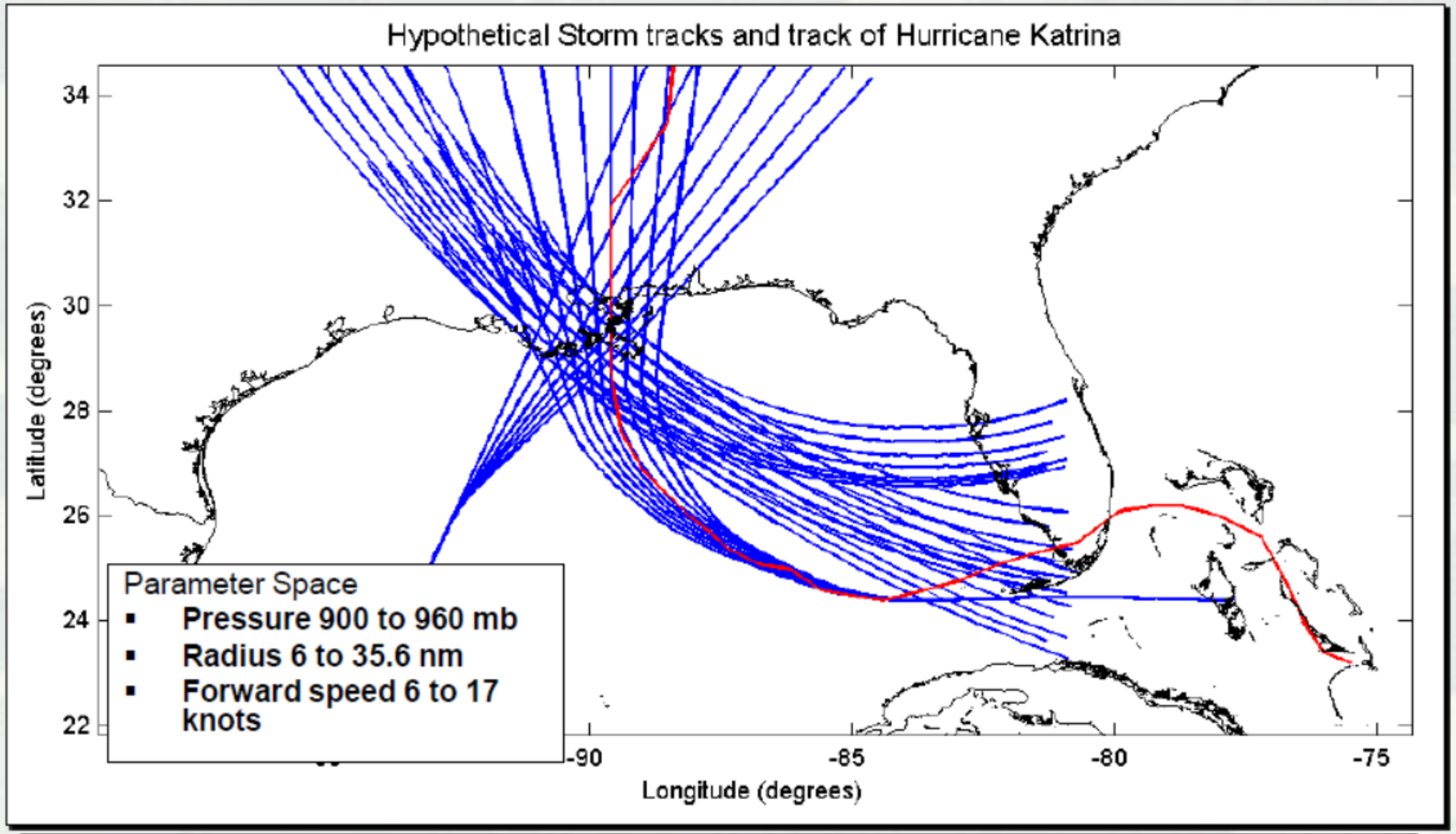
- Develop probability distributions for each storm parameter (size, intensity, etc.) from observations
- Establish rate of storm occurrence in space and time
- Construct hypothetical storm tracks
- Conduct storm surge simulations
- Determine rate of occurrence for each storm
- Compute highest surge for locations of interest, tag it with rate of occurrence
- Construct a histogram of rate versus surge height
- Find the 1% surge elevation for each location

Summary: All possible storms are considered, weighted to appropriate rate of occurrence, and a probability distribution is derived from the sample

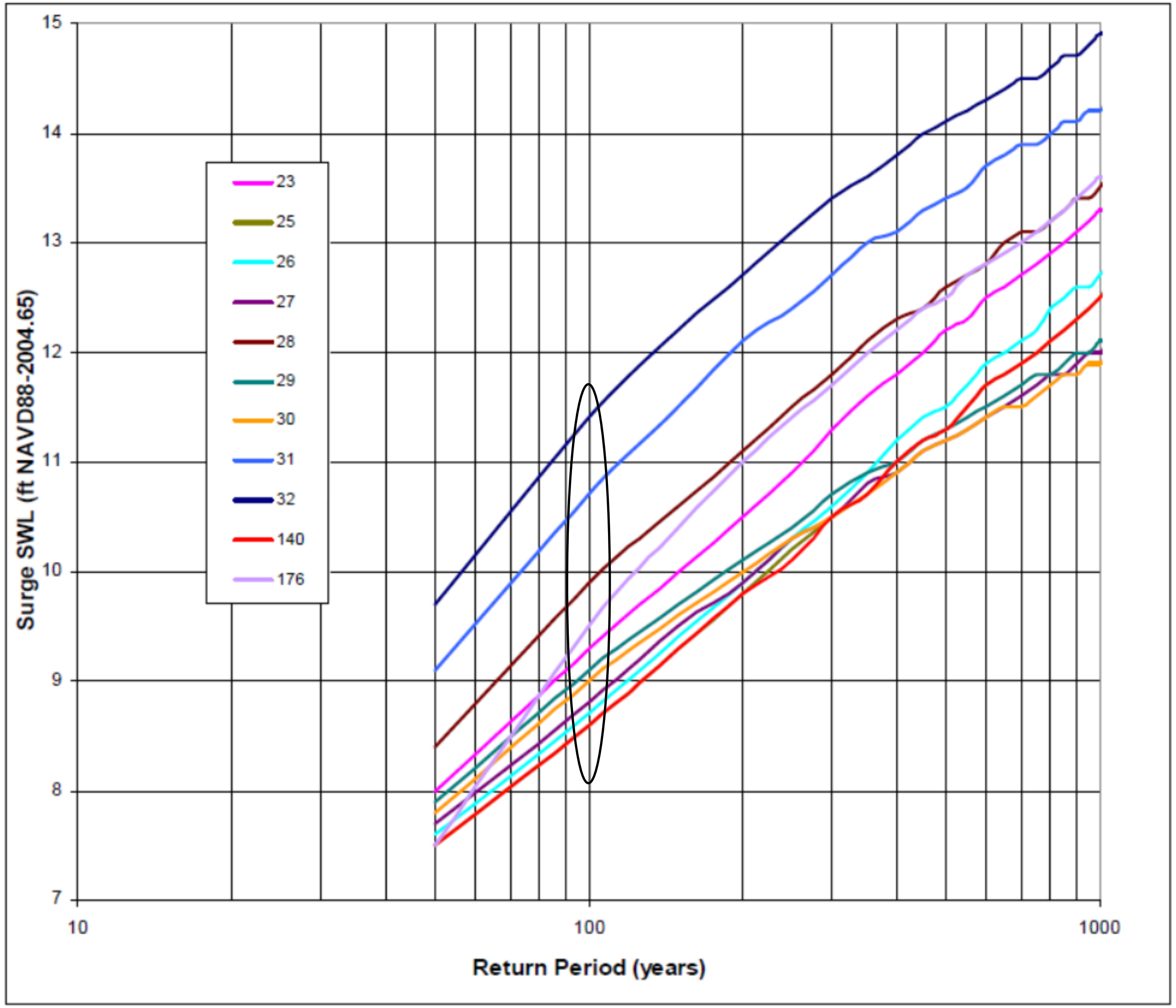
Table 1. Summary of the 152 HSDRRS JPM-OS hurricane tracks, stratified by central pressure, radius of maximum winds, translation speed, track direction, primary and secondary plus intensity (Saffir-Simpson scale), and number of storms in each group. From Jacobsen (2013).

GoM CP mb	GoM R_{max} miles	Landfall V_f mph	θ direction from	Track Set (Number)
960	40.9	12.7	Central	P (5)
	28.3	12.7	SE	P (4)
			SW	P (4)
	24.2	12.7	Central	P (5)
	20.9	12.7	SE	P (4)
			SW	P (4)
	20.4	12.7	Central	S (4)
			SE	S (3)
			SW	S (3)
		6.9	Central	P (5)
				S (4)
	12.7	12.7	Central	P (5)
930	29.7	12.7	Central	P (5)
	20.4	19.6	Central	P (5)
				S (4)
			SE	P (4)
				S (3)
			SW	P (4)
				S (3)
		12.7	Central	P (5)
		6.9	SE	P (4)
				S (3)
			SW	P (4)
				S (3)
	9.2	12.7	Central	P (5)
900	25.1	12.7	Central	P (5)
	21.2	12.7	SE	P (4)
			SW	P (4)
	20.4	12.7	Central	S (4)
			SE	S (3)
			SW	S (3)
		6.9	Central	P (5)
				S (4)
	17.1	12.7	Central	P (5)
	14.4	12.7	SE	P (4)
			SW	P (4)
	6.9	12.7	Central	P (5)
3 CP	**15 CP-R_{max}**	**19 CP-R_{max}-V_f**	**30 CPD-R_{max}-V_f-θ**	**152 Storms**

Selection of Synthetic Storms



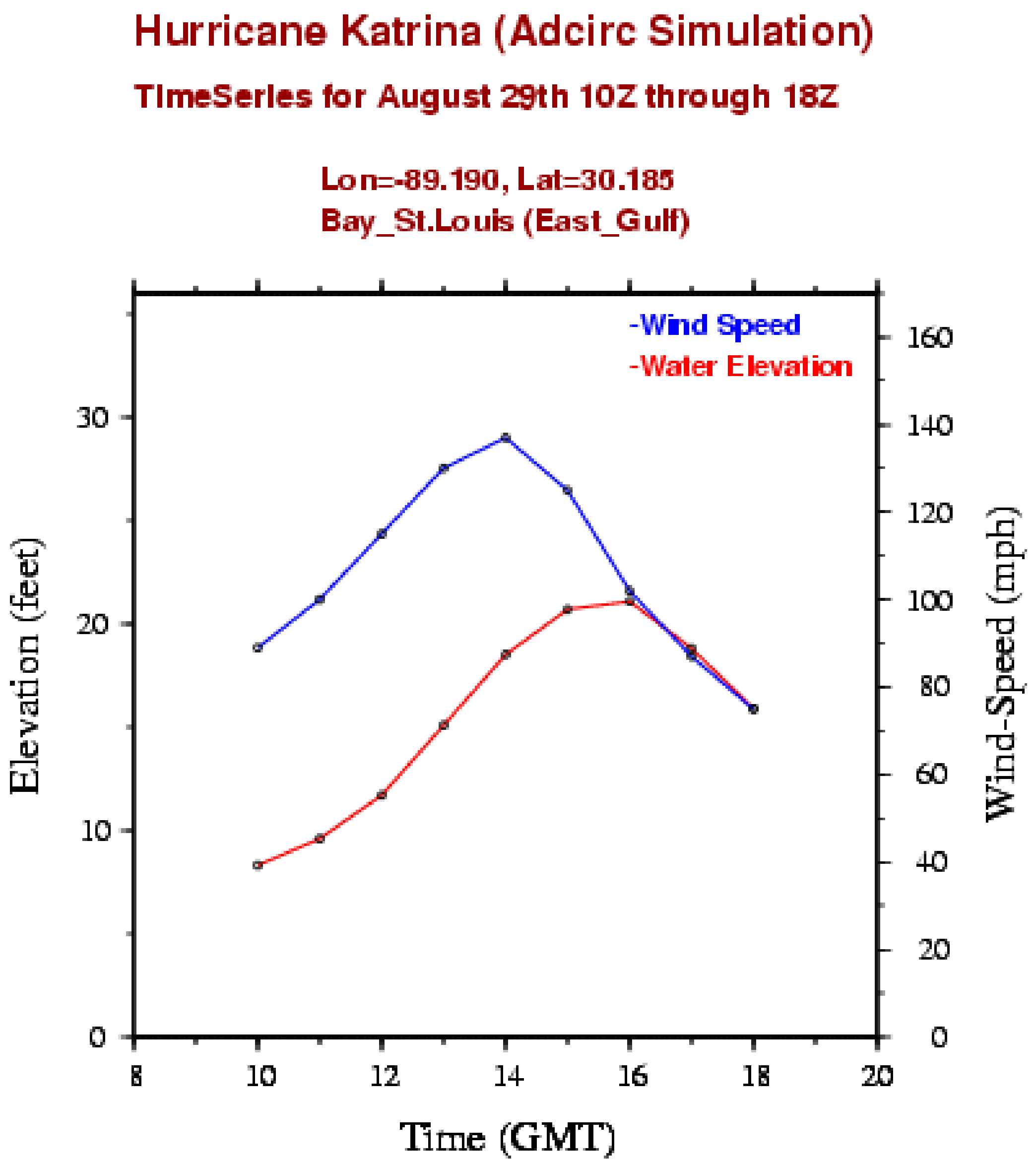
Example 100-year surge curves for southshore



Legal cases

Wind and surge time series for litigation purposes

“wind versus water” cases



Product of Mississippi State University, GeoResources Institute, Stennis Space Center.

Time series of sustained wind, wind gust, and surge in Bay St. Louis

Time (Aug. 29)	*Sustained wind (mph)*	*Wind gusts (mph)*	*Storm surge relative to sea level (feet)*	*Storm surge relative to land (feet)*	*Inundation in house (feet)*
1:00AM	40 (northeast)	50	3.5	land dry	house dry
4:00AM	54 (northeast)	68	4.0	land dry	house dry
5:30AM	58 (east-northeast)	80	6.0	2.0 (land partly inundated)	house dry
6:30AM	71 (east-northeast)	110	6.3	2.3	house dry
7:00AM	83 (east-northeast)	120	6.6	2.6	house dry
8:30AM	99 (east-northeast)	130	8.0	4.0	house dry
9:30AM	110 (east-southeast)	140	8.5	4.5	house dry
10:00AM	102 (east-southeast)	135	10.0	6.0	house dry
10:30AM	93 (southeast)	110	13.0	9.0	occasional inundation from 1-foot waves
11:30AM	79 (southeast)	95	20.5	16.5	6.0
12:00PM	72 (south)	85	22.2	18.2	8.2
1:00PM	60 (south-southwest)	75	18.5	14.5	4.5
4:00PM	48 (southwest)	55	8.5	4.5	house dry

Time series of sustained wind, wind gust, and surge in Bay St. Louis

Time (Aug. 29)	*Wind (mph)*	*Wind gust (mph)*	*Storm surge (feet)*
3:00AM	40 (east-northeast)	46	4
5:30AM	75 (east-northeast)	97	6
6:30AM	86 (northeast)	112	6
8:30AM	103 (east)	140	9
9:30AM	120 (southeast)	145	13
10:30AM	100 (south)	115	22
11:30AM	90 (west)	104	19
12:30PM	80 (west)	92	16

Numerous squall lines passed through the area after 3AM.

Tropical storm-force winds begin after midnight.
Hurricane-force winds begin around 5AM.

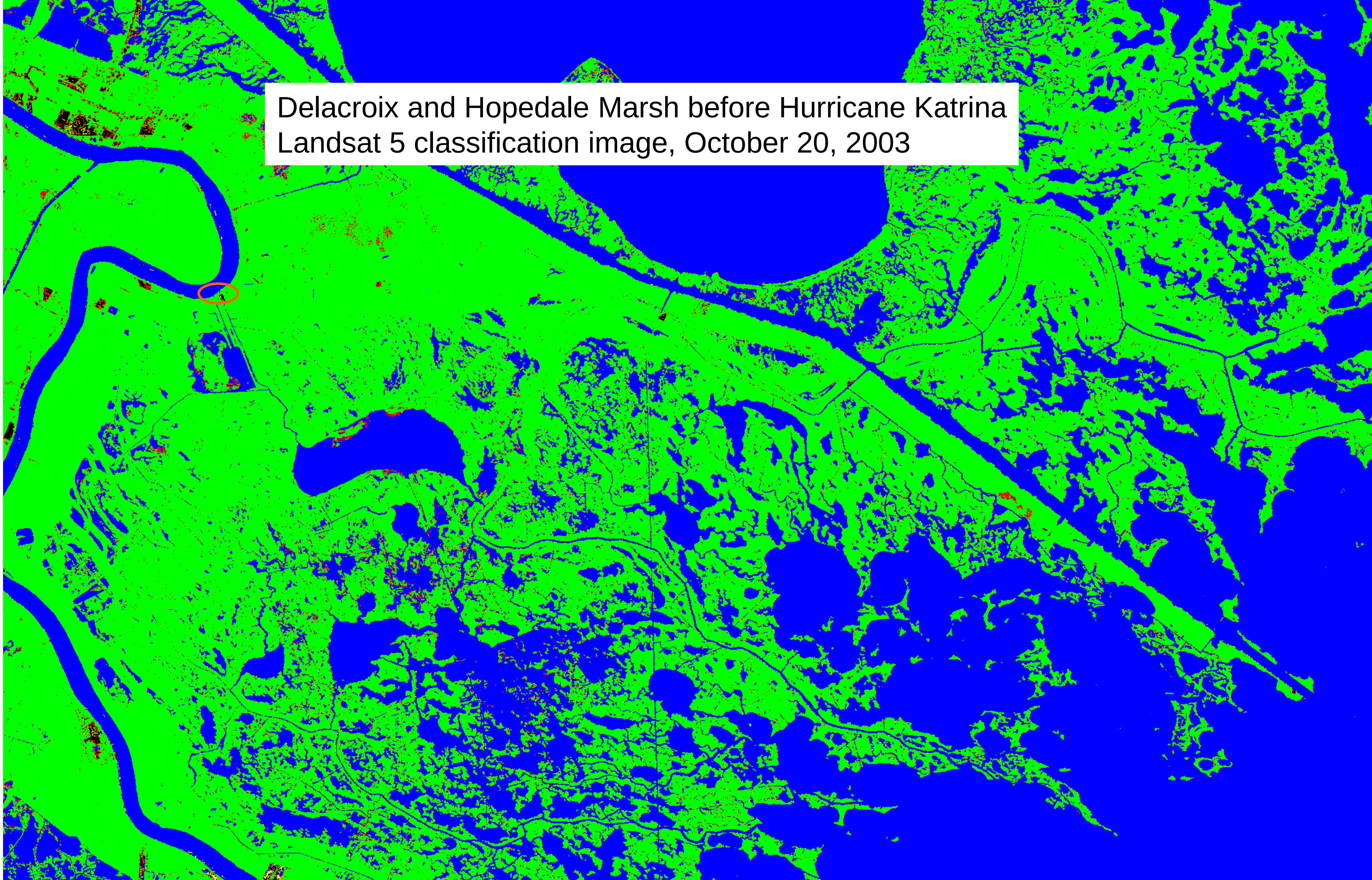
Environmental issues

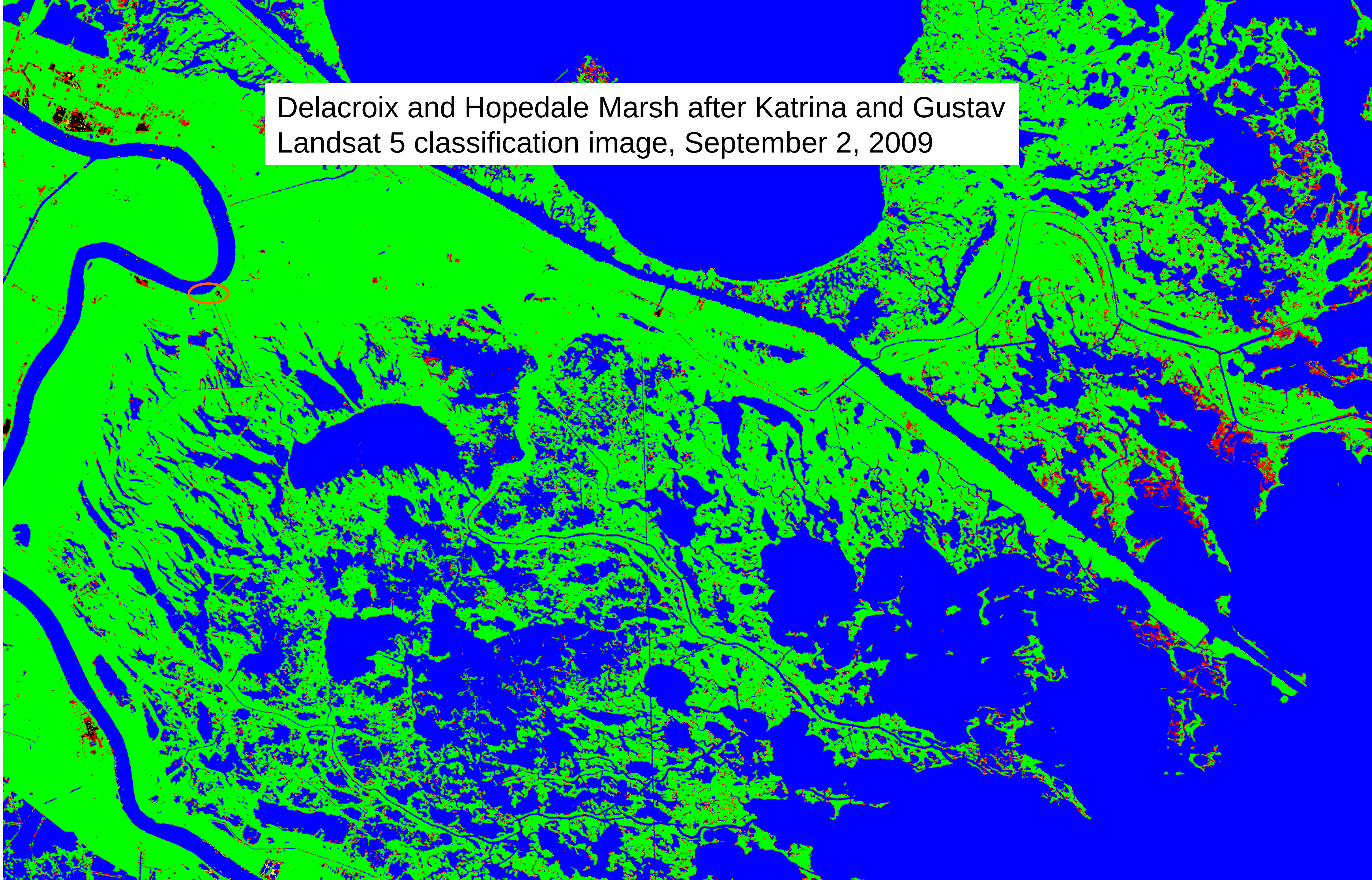
- Exposes fragile marsh due to nutrient overload
- Deepwater Horizon oil incursions due to cyclones

Wetland loss associated with hurricane storm surge near the Caernarvon freshwater diversion

Pat Fitzpatrick*, Yee Lau*, Jim Chen^, Kelin Hu^, Valentine Anantharaj#, and Suzanne Shean*

* Miss State Univ --- Stennis ^ Louisiana State Univ # Oak Ridge National Laboratory


Delacroix and Hopedale Marsh before Hurricane Katrina
Landsat 5 classification image, October 20, 2003


Delacroix and Hopedale Marsh after Katrina and Gustav
Landsat 5 classification image, September 2, 2009

Where did land go? West towards MS River

USGS
science for a changing world
Delacroix, Louisiana: Photo F
Examples of Shearing After Hurricanes Katrina and Rita
Shear Zone
Lake Lery
Bayou Mandeville
Shear Zone
D P Canal
Le Blanc Bayou
Shear Zone
Wrack
NNE
Photo Date: Nov. 18, 2005
From Barras
References Map ID: USGS-NWRC 2006-11-0185
U.S. Geological Survey

Outfall Marsh

East Control
in direct path of
Katrina

USGS
science for a changing world

Soil Quality: with long-term (30+ years) river water influx decomposition appears enhanced (same plant community, *Panicum hemitomon*)

River water

Rain water

- No difference in year-end standing biomass

- No difference in accretion rates

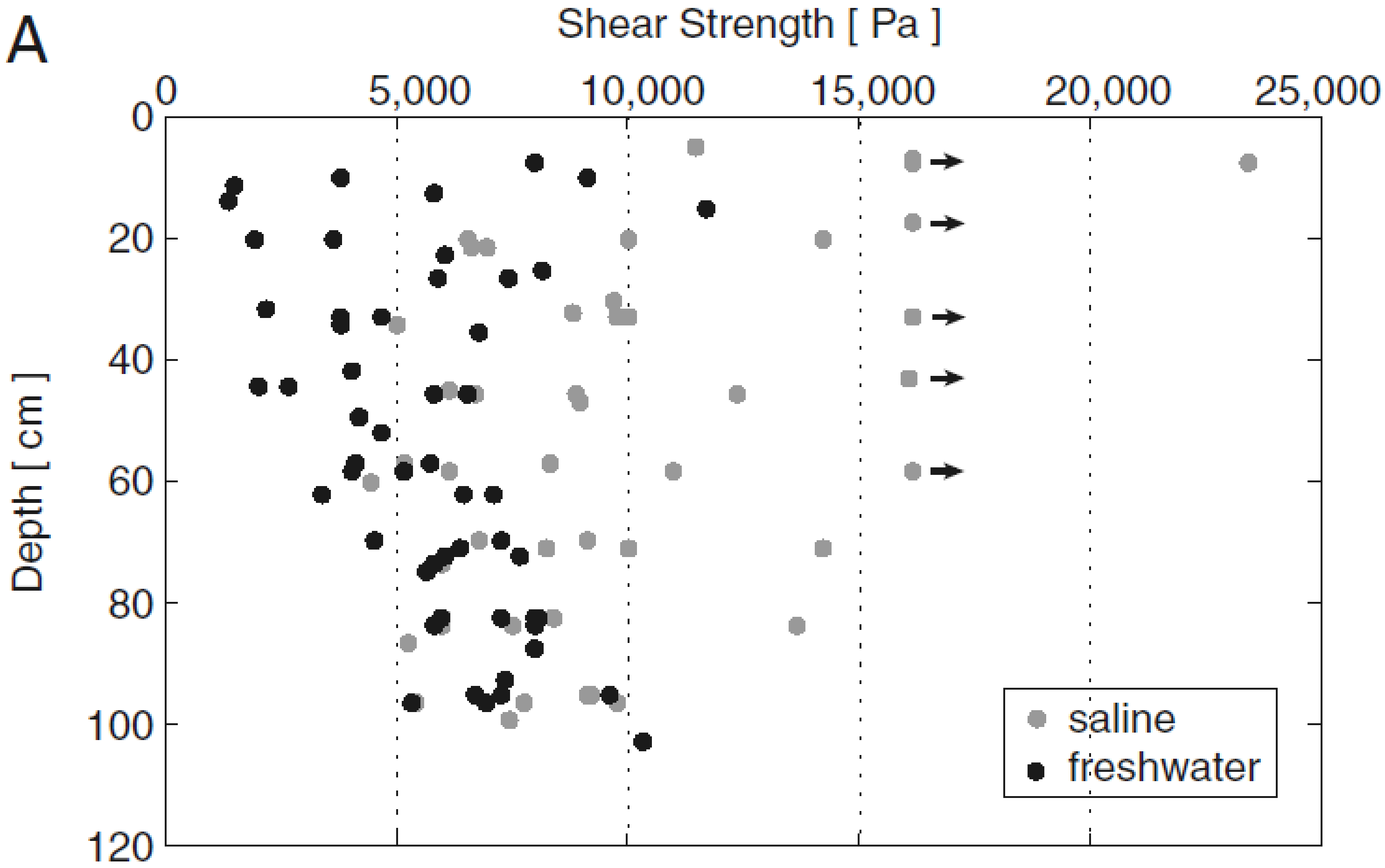
BUT:

- Soil is much more decomposed

- links to river water include sulfate, nitrate, alkalinity

USGS

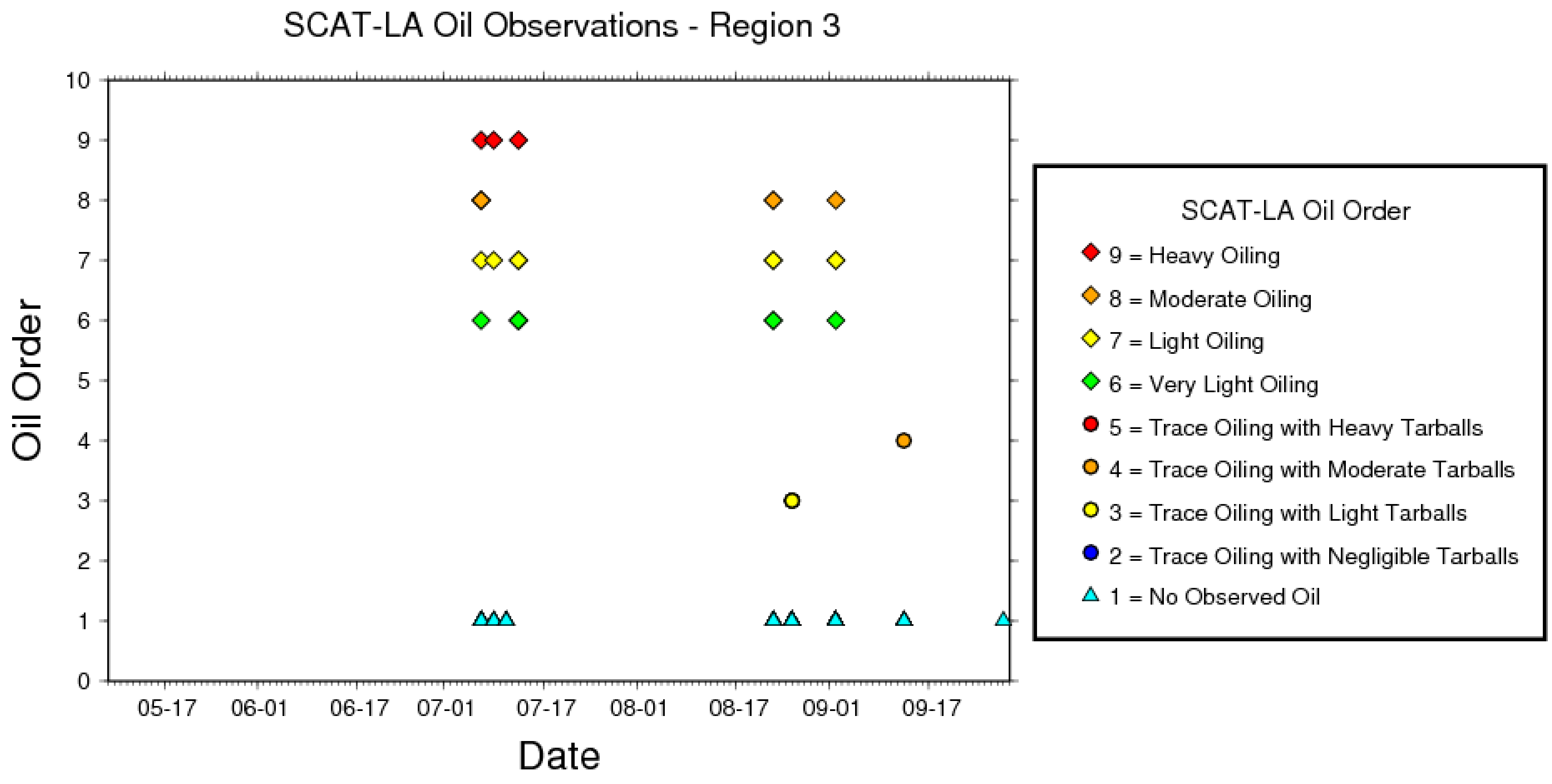
From Howes et al. 2010



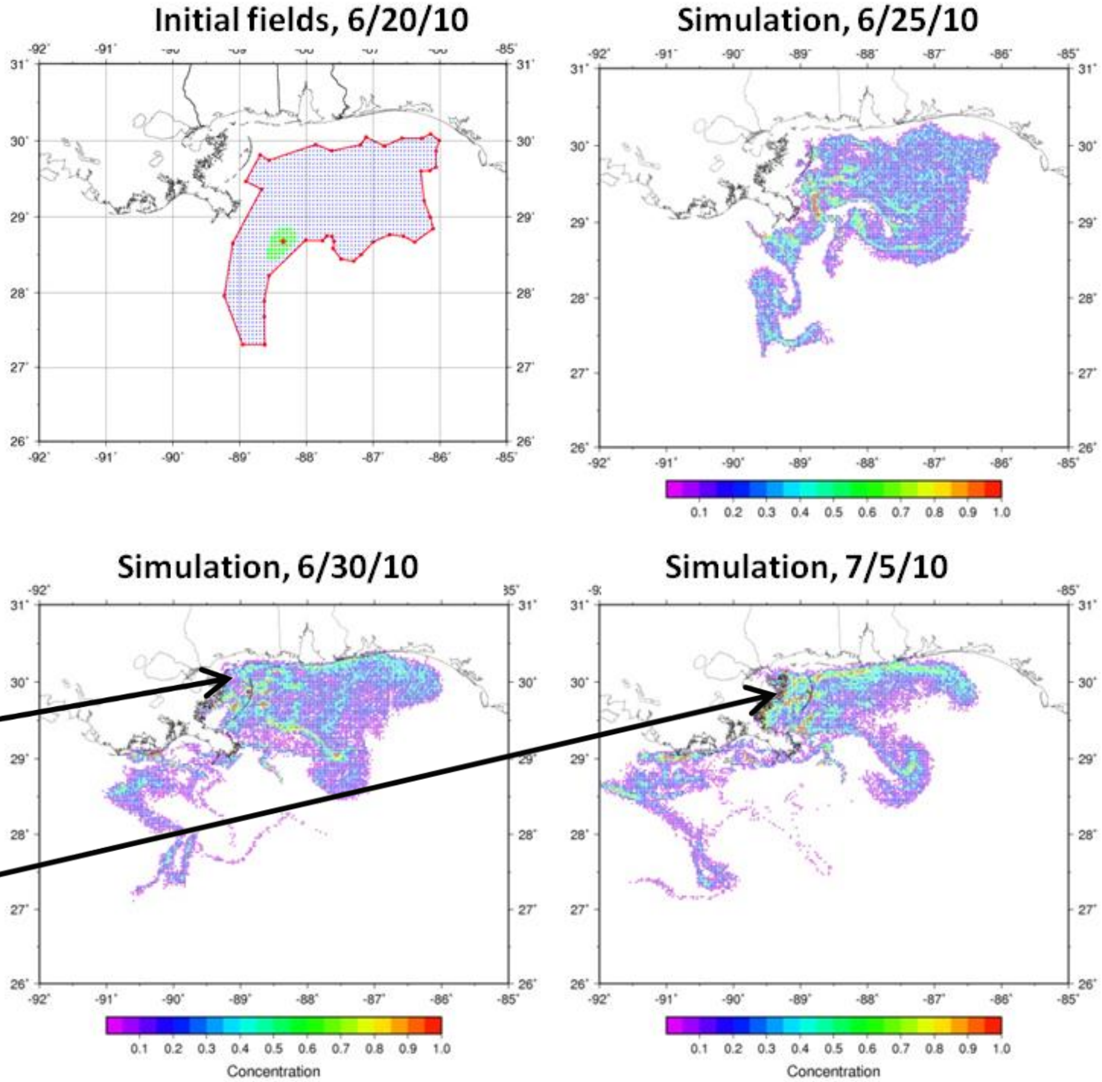
Reference: Howes et al., 2010, Hurricane-induced failure of low salinity wetlands, *Proceedings of the National Academy of the United States of America*, **107(32)**, pp. 14014–14019.

Deepwater Horizon oil movement due to surge effects from cyclones

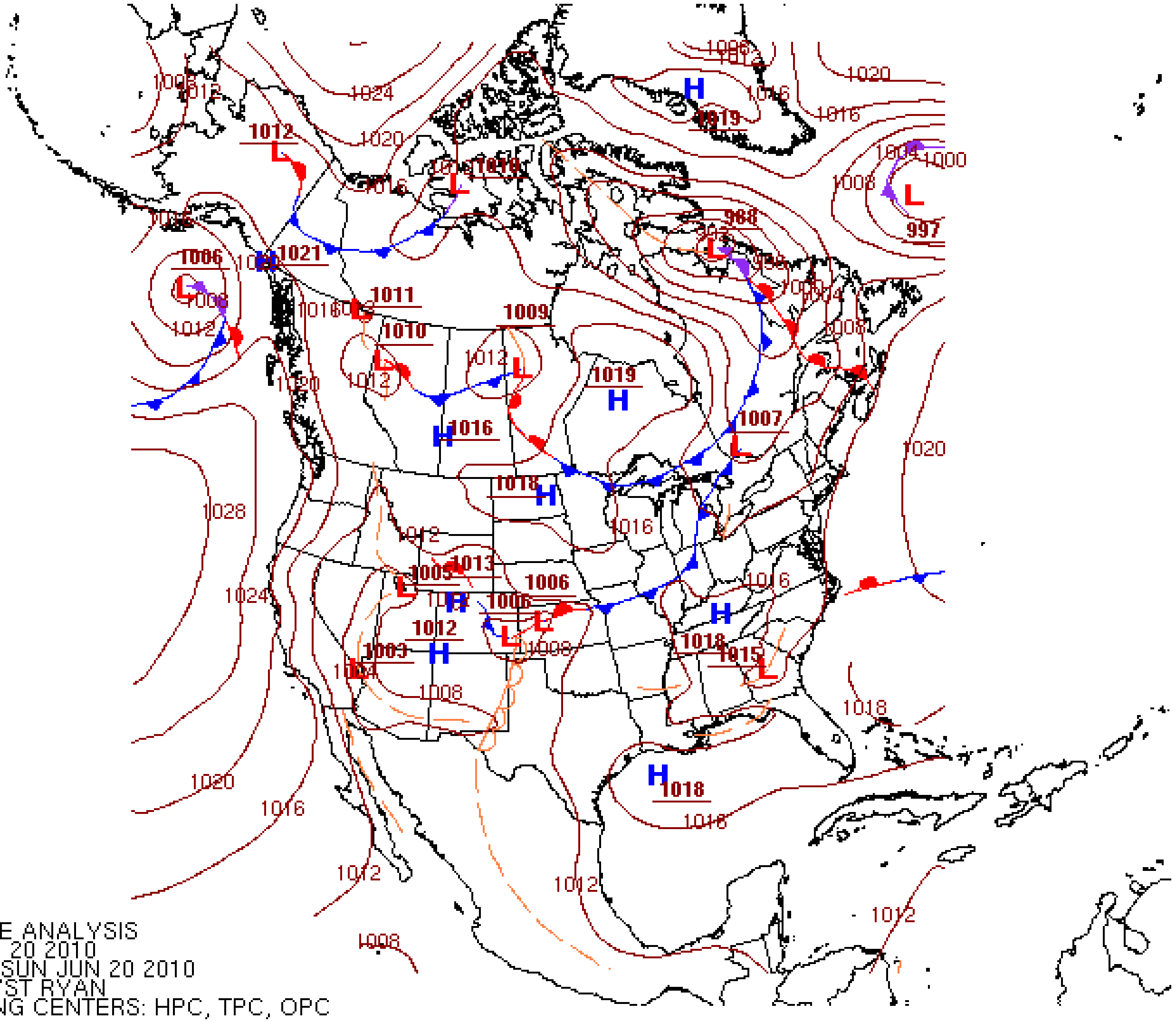
Lake Borgne and Lake Pontchartrain oil spill observations



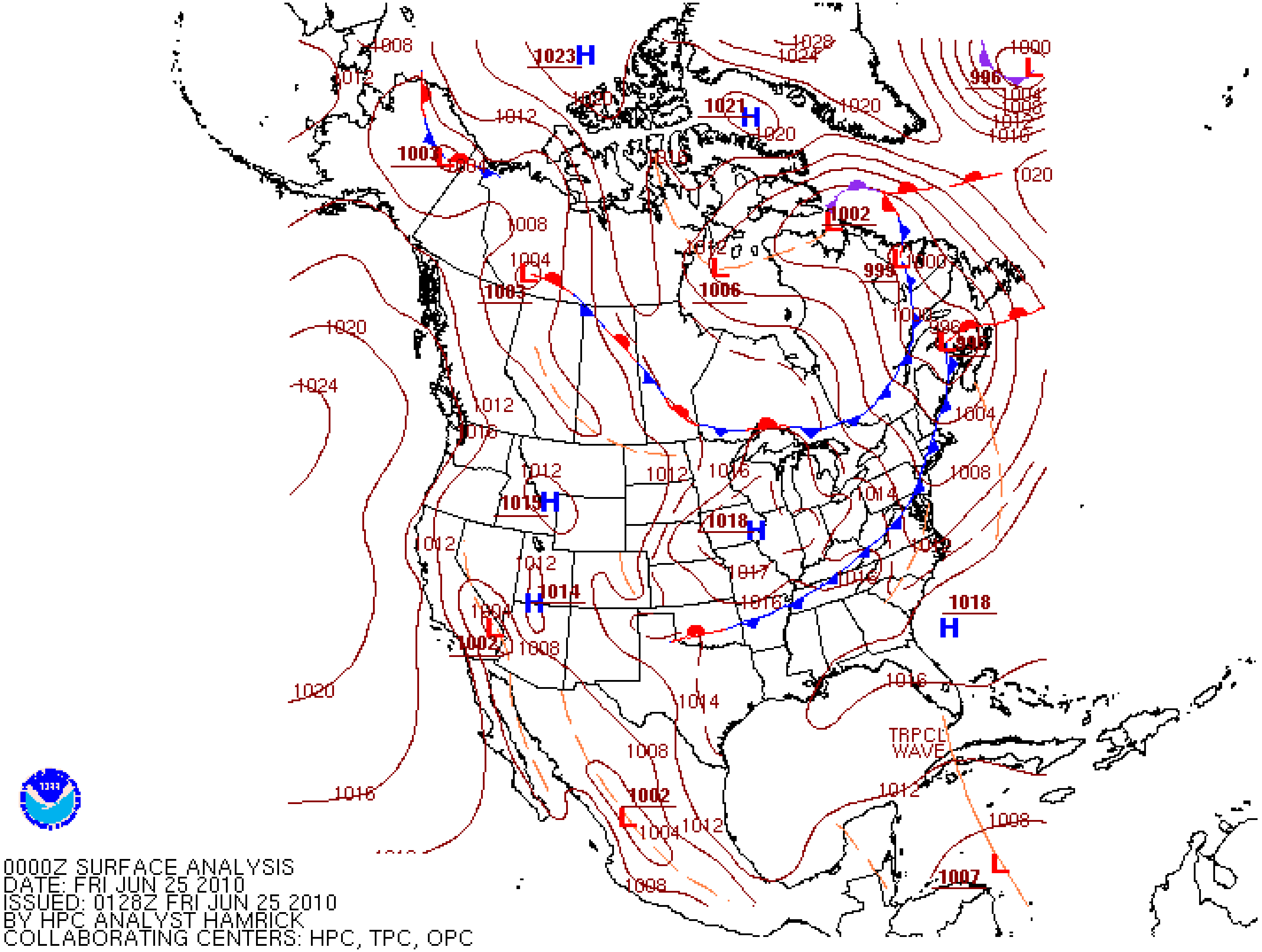
Oil spill simulation from
6/20/10-7/10/10
using AMSEAS NCOM data

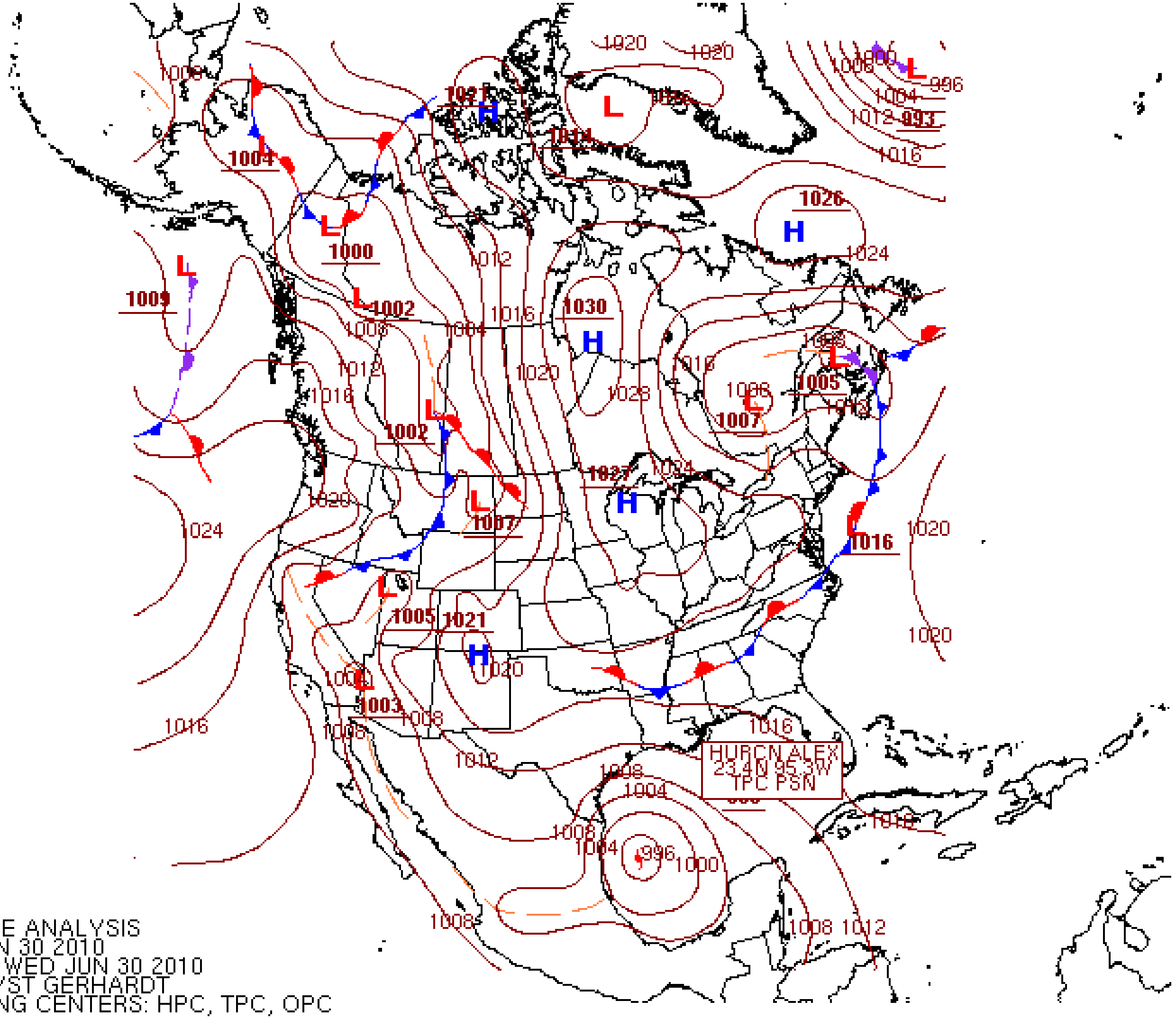


Note inshore movement of oil starting late June

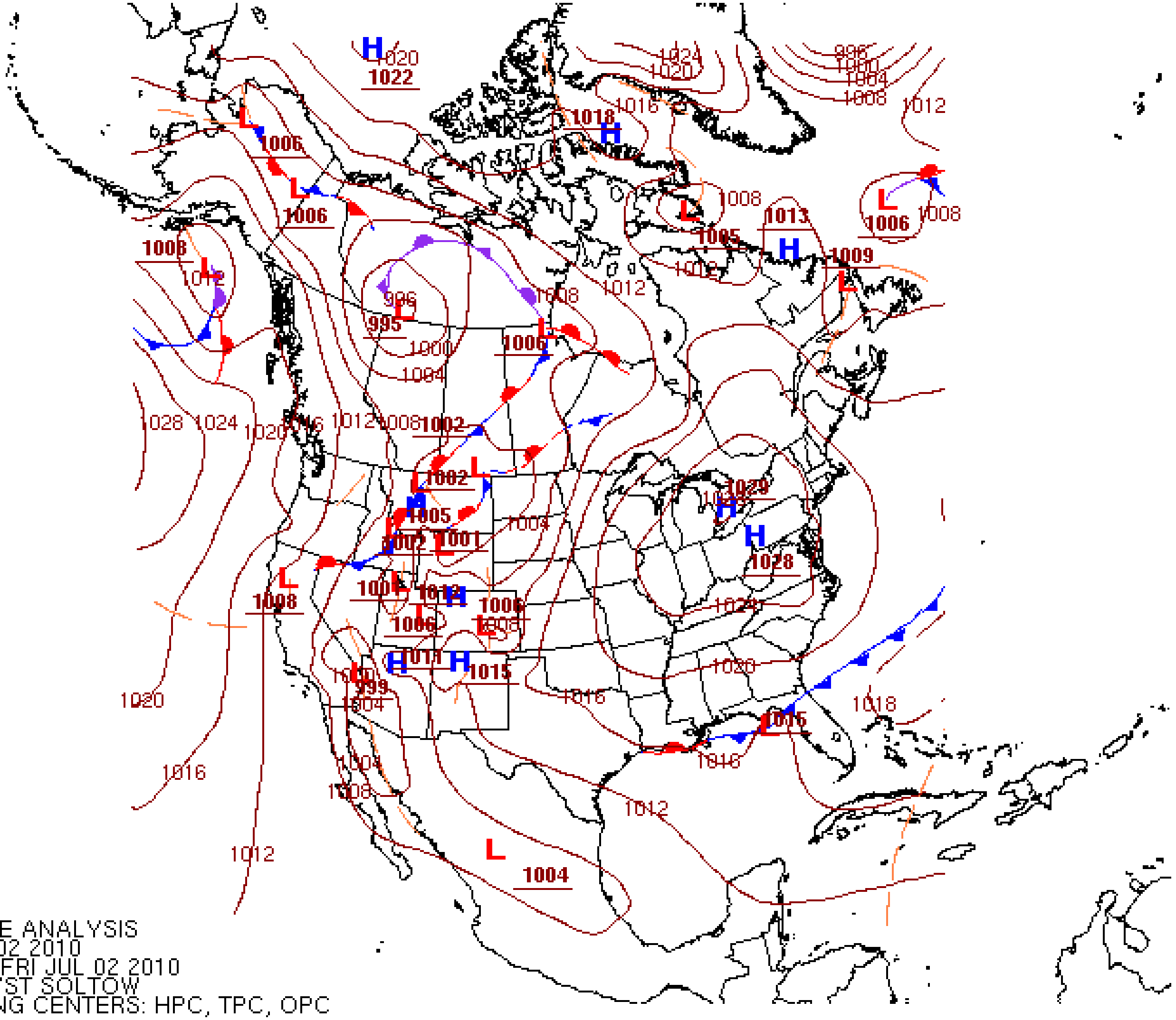


0000Z SURFACE ANALYSIS
DATE: SUN JUN 20 2010
ISSUED: 0128Z SUN JUN 20 2010
BY HPC ANALYST RYAN
COLLABORATING CENTERS: HPC, TPC, OPC

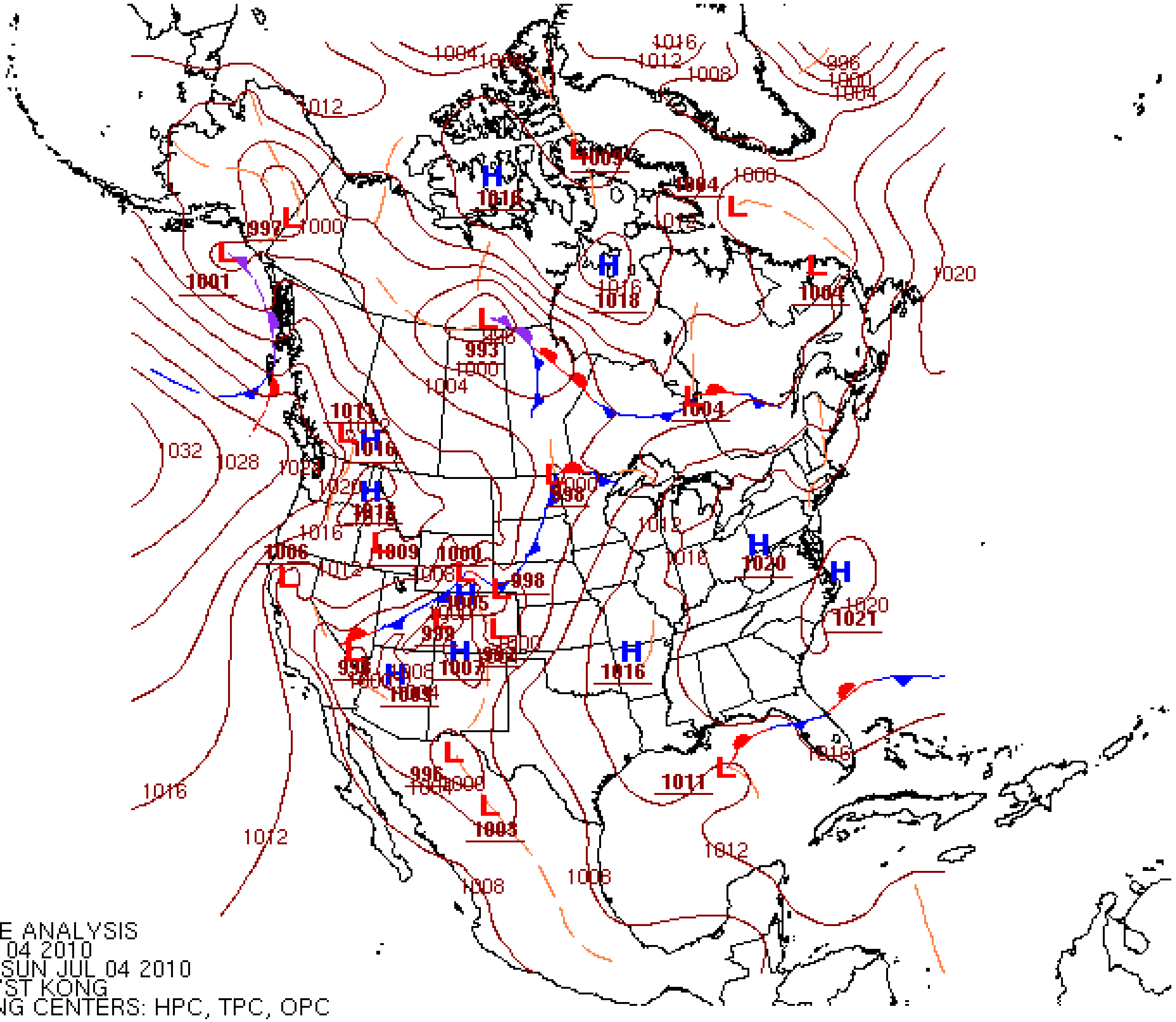

0000Z SURFACE ANALYSIS
DATE: FRI JUN 25 2010
ISSUED: 0128Z FRI JUN 25 2010
BY HPC ANALYST HAMRICK
COLLABORATING CENTERS: HPC, TPC, OPC
TRPCL
WAVE



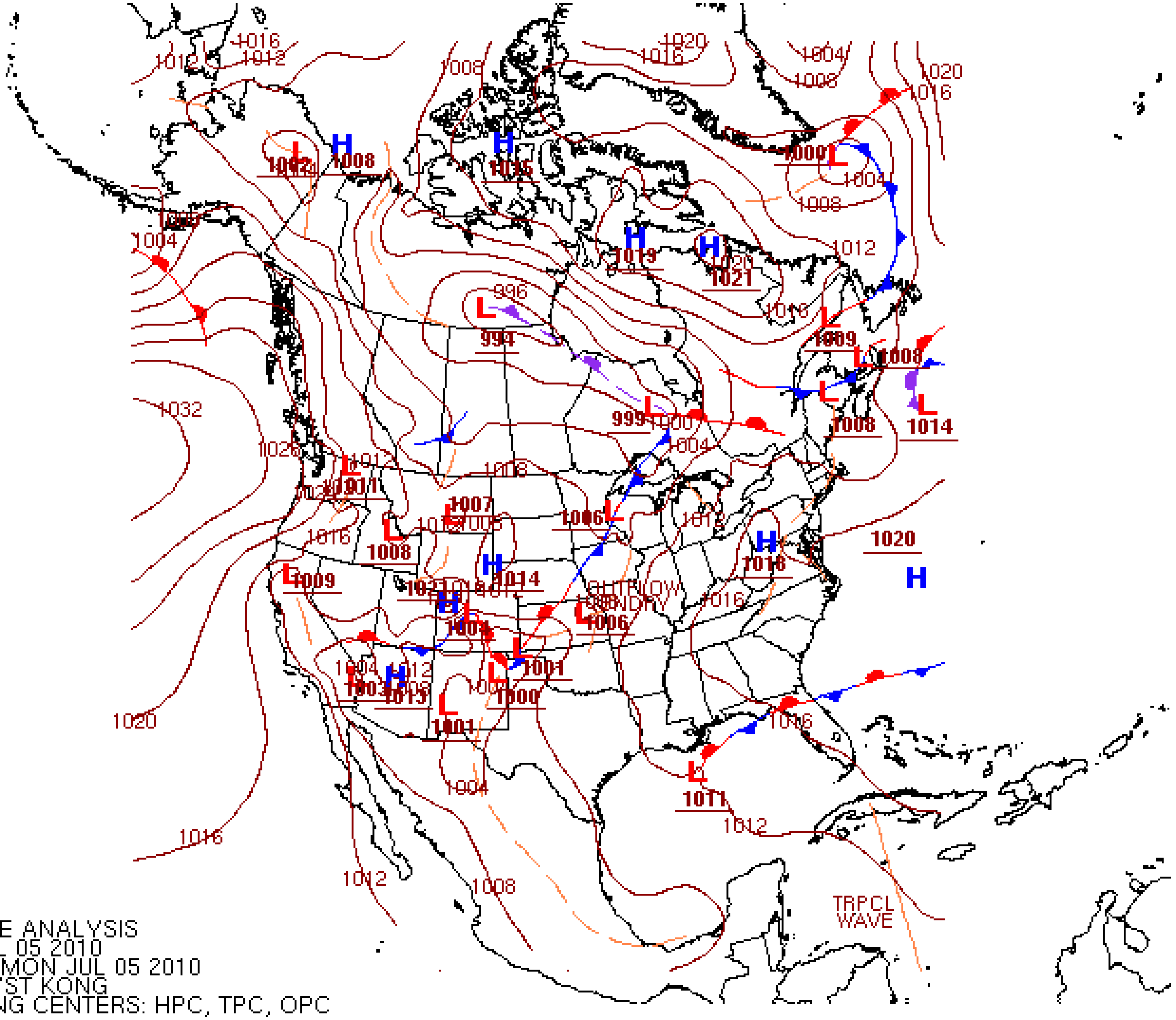
1200Z SURFACE ANALYSIS
DATE: WED JUN 30 2010
ISSUED: 1335Z WED JUN 30 2010
BY HPC ANALYST GERHARDT
COLLABORATING CENTERS: HPC, TPC, OPC



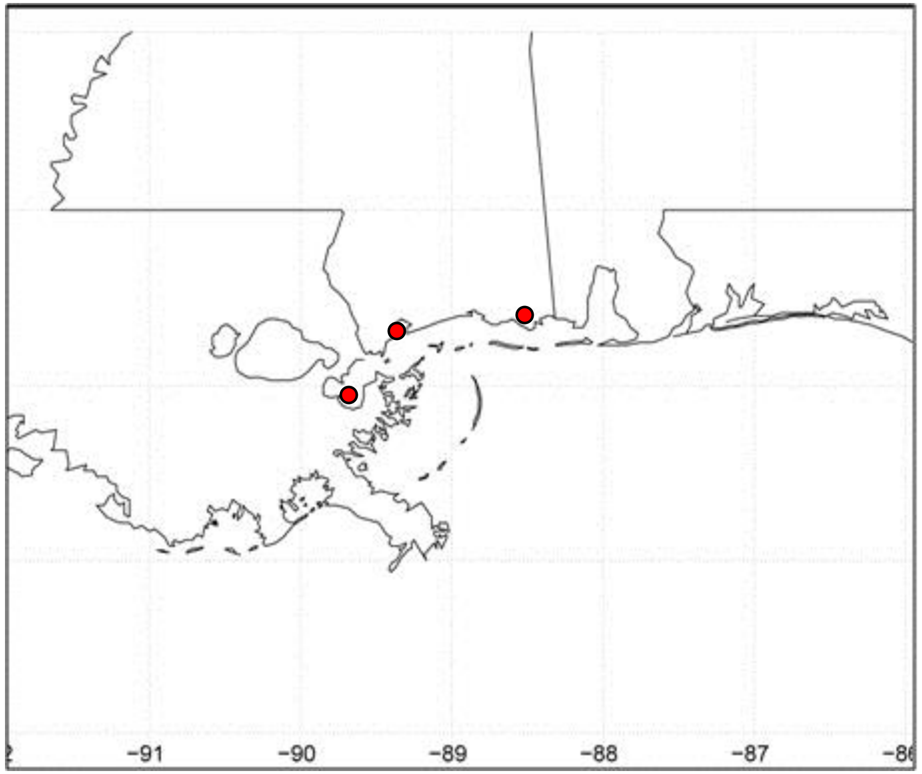
1200Z SURFACE ANALYSIS
DATE: FRI JUL 02 2010
ISSUED: 1333Z FRI JUL 02 2010
BY HPC ANALYST SOLTOW
COLLABORATING CENTERS: HPC, TPC, OPC

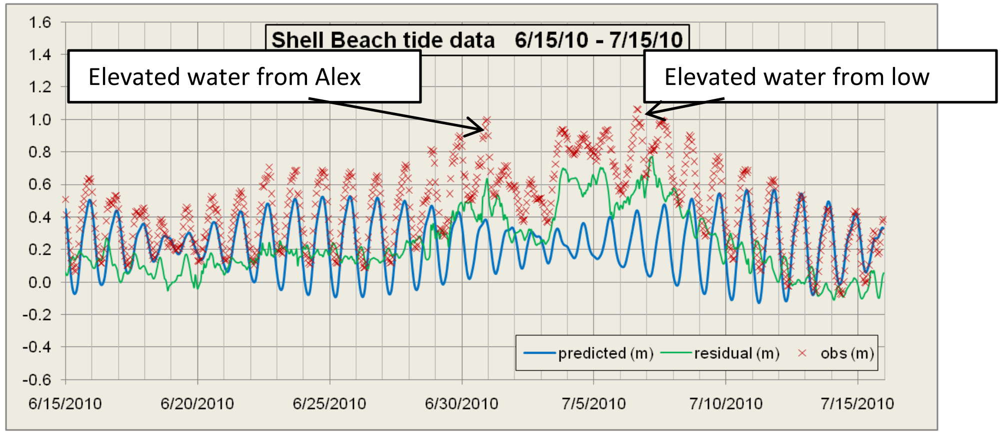


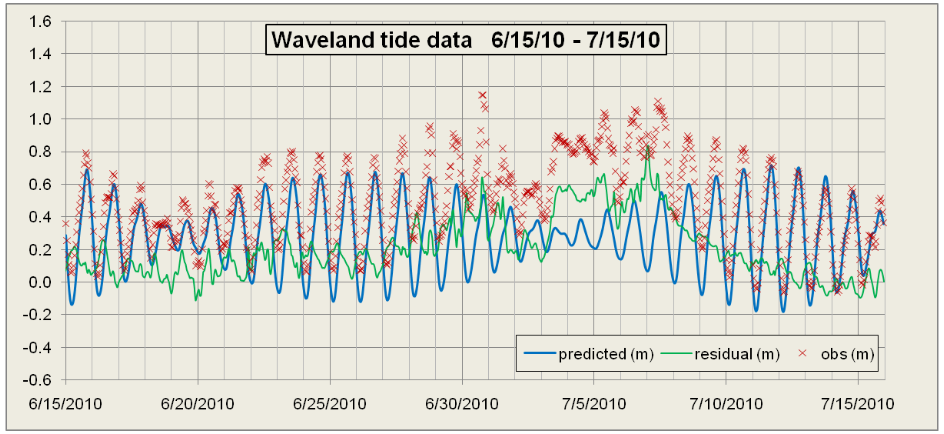
0000Z SURFACE ANALYSIS
DATE: SUN JUL 04 2010
ISSUED: 0130Z SUN JUL 04 2010
BY HPC ANALYST KONG
COLLABORATING CENTERS: HPC, TPC, OPC

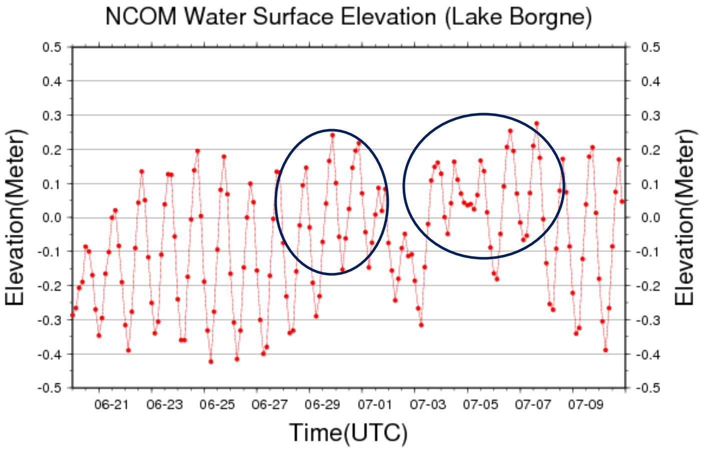


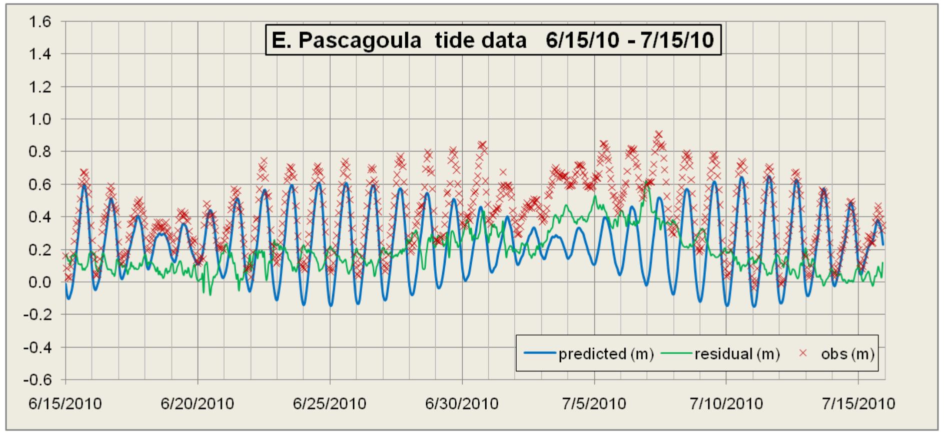
0000Z SURFACE ANALYSIS
DATE: MON JUL 05 2010
ISSUED: 0139Z MON JUL 05 2010
BY HPC ANALYST KONG
COLLABORATING CENTERS: HPC, TPC, OPC


-91
-90
-89
-88
-87


Shell Beach tide data 6/15/10 - 7/15/10
Elevated water from Alex
Elevated water from low
predicted (m)
residual (m)
obs (m)
6/15/2010
6/20/2010
6/25/2010
6/30/2010
7/5/2010
7/10/2010
7/15/2010


Waveland tide data 6/15/10 - 7/15/10
predicted (m)
residual (m)
obs (m)
6/15/2010
6/20/2010
6/25/2010
6/30/2010
7/5/2010
7/10/2010
7/15/2010

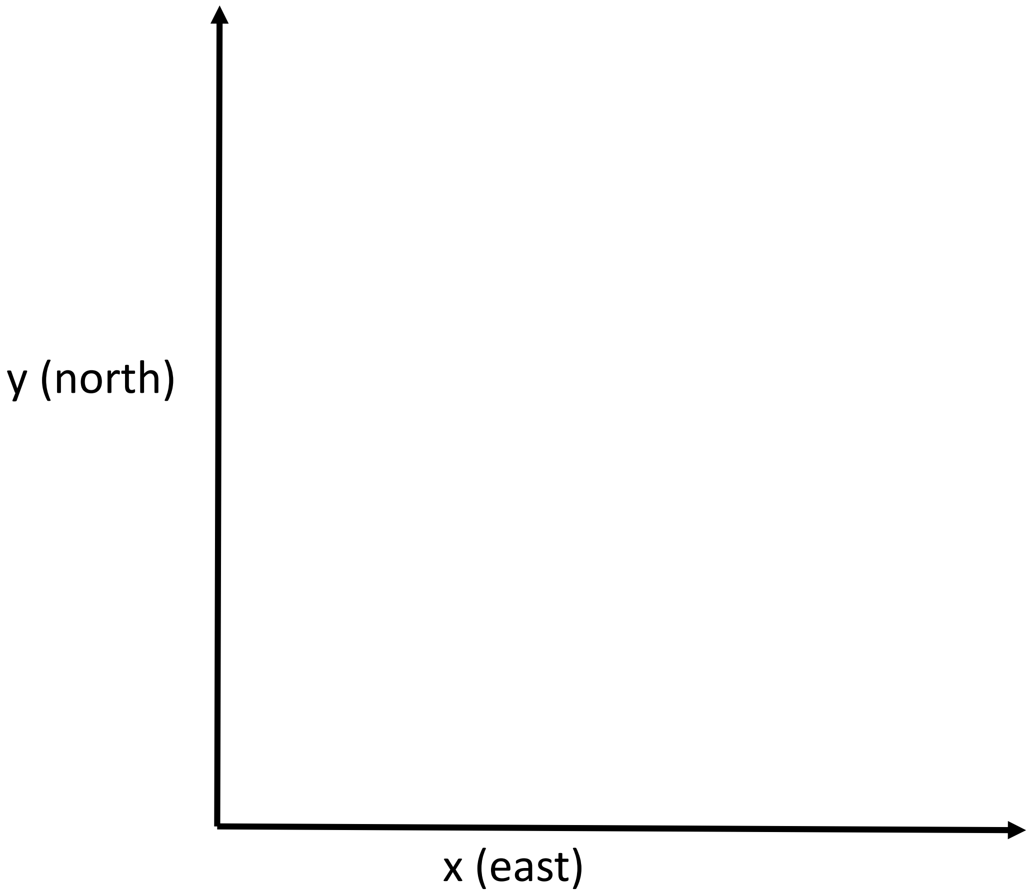

NCOM Water Surface Elevation (Lake Borgne)
Elevation(Meter)
Time(UTC)
06-21
06-23
06-25
06-27
06-29
07-01
07-03
07-05
07-07
07-09


E. Pascagoula tide data 6/15/10 - 7/15/10
predicted (m)
residual (m)
obs (m)
6/15/2010
6/20/2010
6/25/2010
6/30/2010
7/5/2010
7/10/2010
7/15/2010

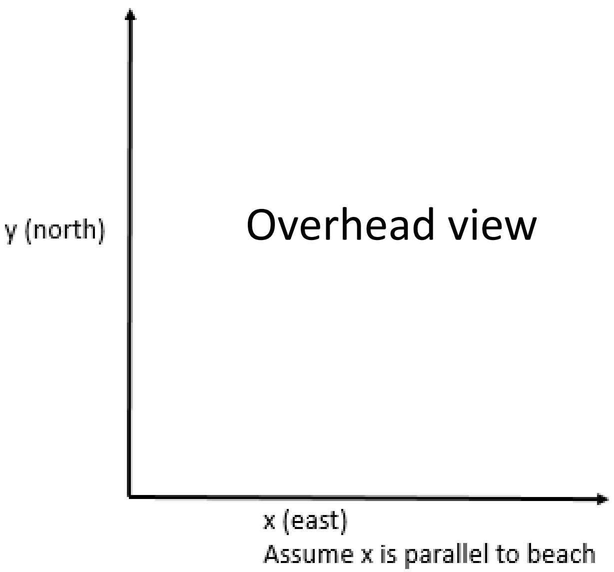
Closing thought before exercise

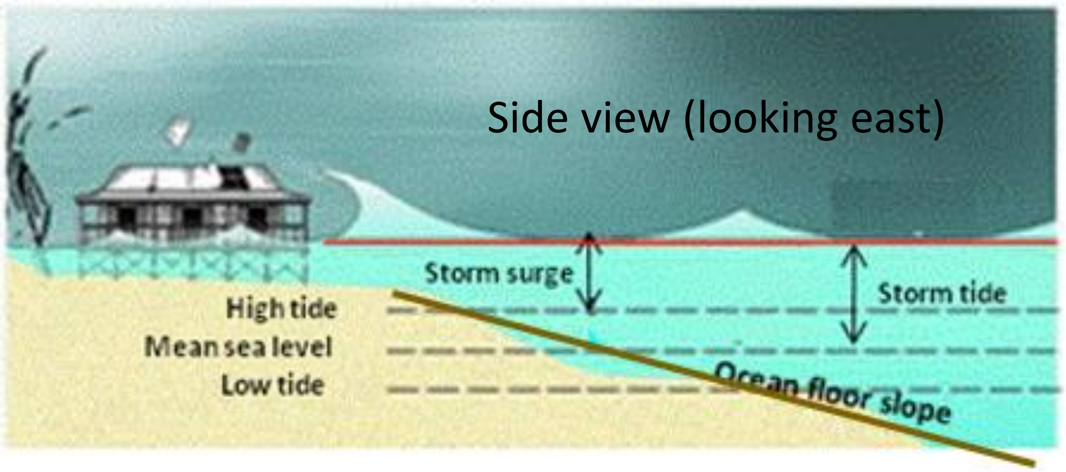
- Find a technical specialty, and learn everything about it
- Learn to use technology, software, and programming languages
- Learn statistics and mathematics
- Learn to write technical reports
- The applications can be diverse and the opportunities surprising. Keep your eyes open and meet as many people as possible
- Career opportunities for scientists have shifted. More possibilities in the private sector, less in government. And more government jobs now require writing proposals to sustain funding in a budget cut environment, a sometimes unpleasant situation (but still rewarding in the right job)

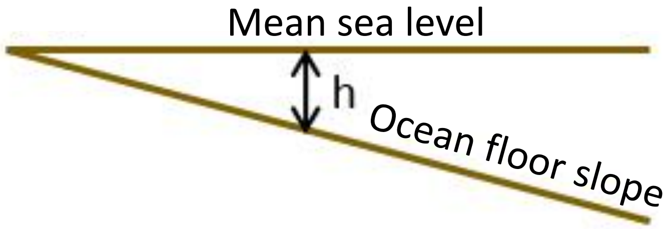
(switch to surge exercise)



Assume x is parallel to beach


y (north)
Overhead view
x (east)
Assume x is parallel to beach


Side view (looking east)
Storm surge
Storm tide
High tide
Mean sea level
Low tide
Ocean floor slope


Mean sea level
h
Ocean floor slope