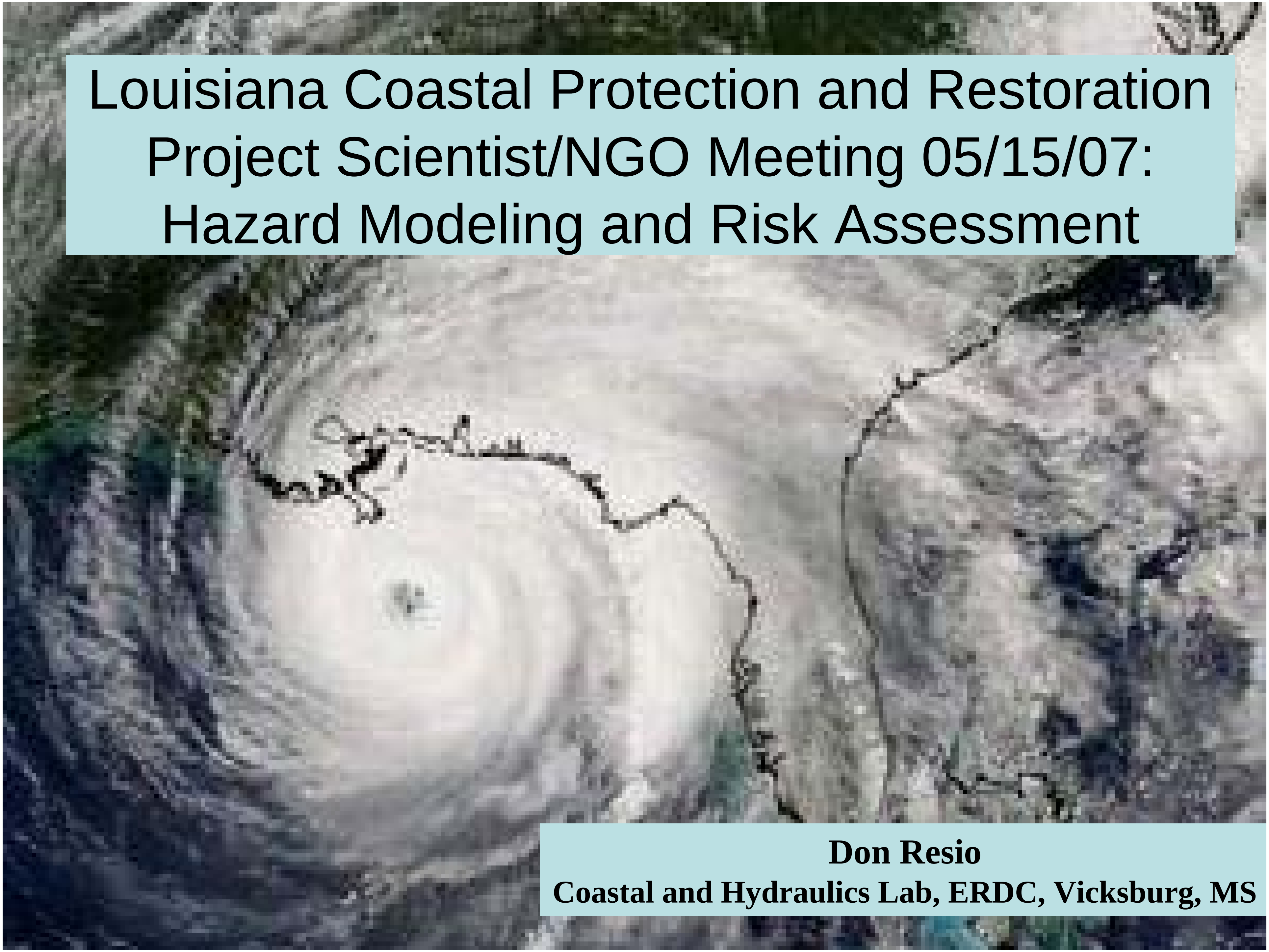
Louisiana Coastal Protection and Restoration Project Scientist/NGO Meeting 05/15/07: Hazard Modeling and Risk Assessment



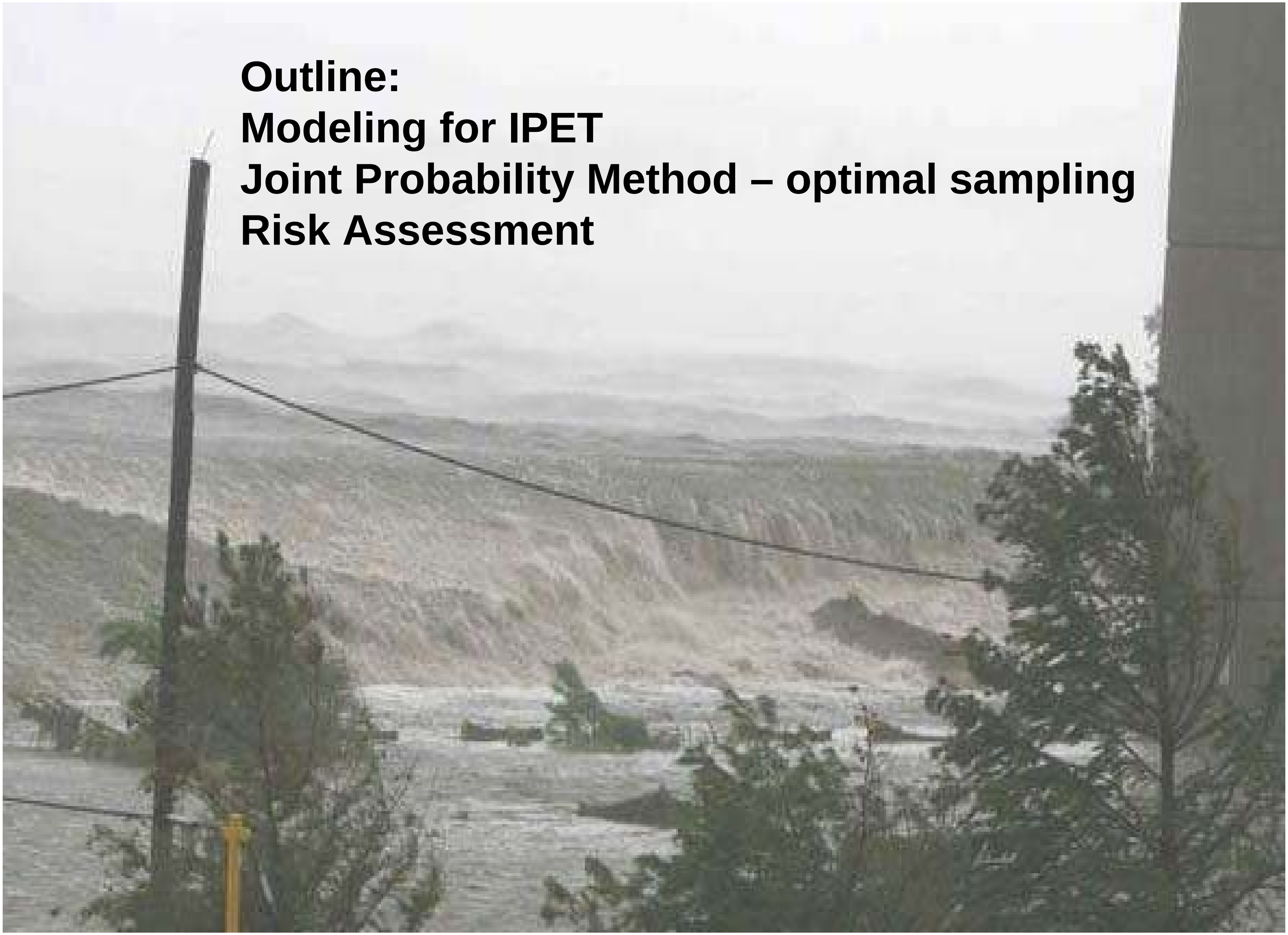
Don Resio
Coastal and Hydraulics Lab, ERDC, Vicksburg, MS

Outline:

Modeling for IPET

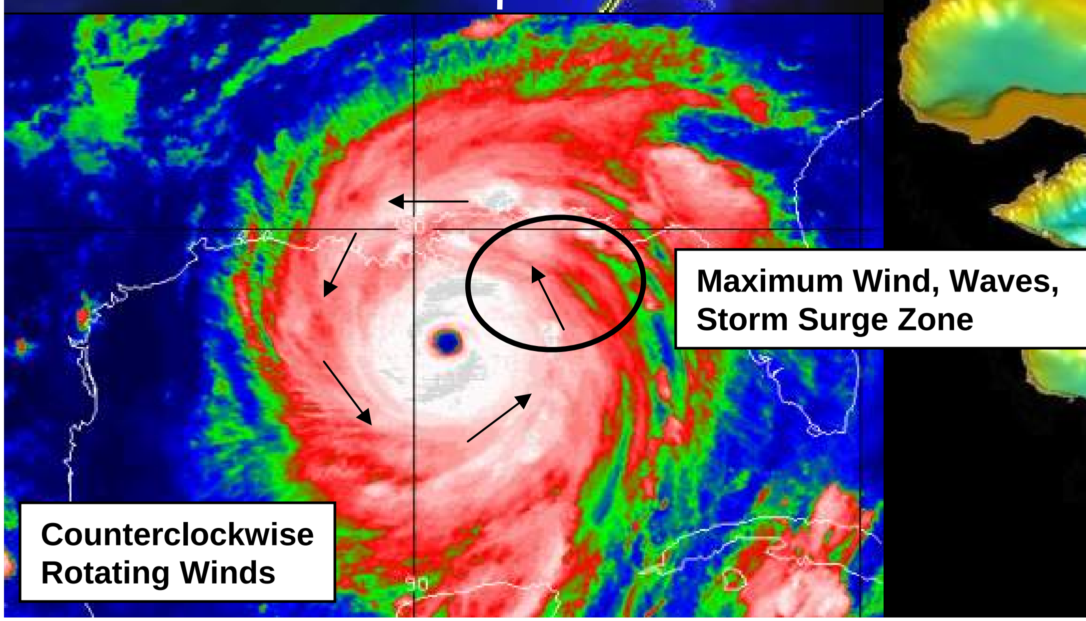
Joint Probability Method – optimal sampling

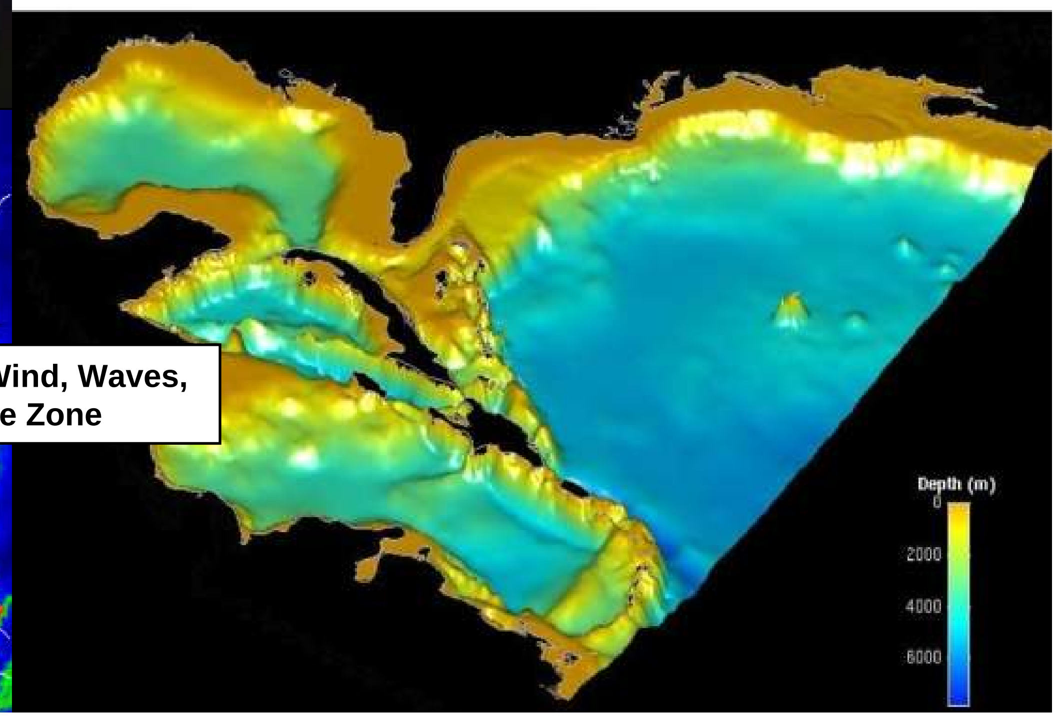
Risk Assessment



Contributors to Storm Water Levels

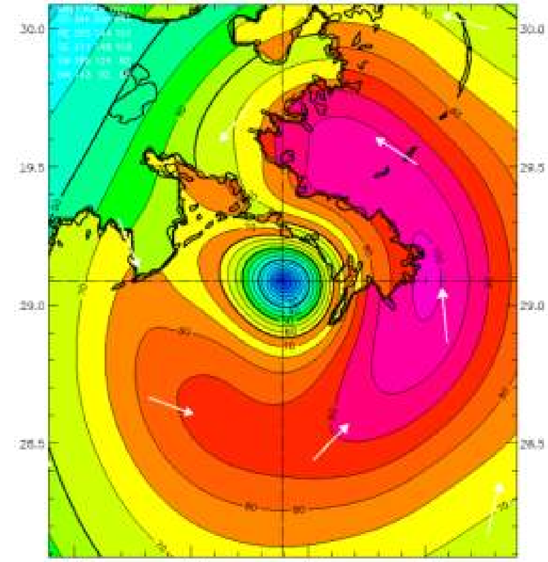
- Wind Speed/ Direction
- Topographic Controls
- Short Wave – Momentum Transfers
- Storm Center – Atmospheric Pressure
- Astronomical Tide
- River Discharge
- Precipitation

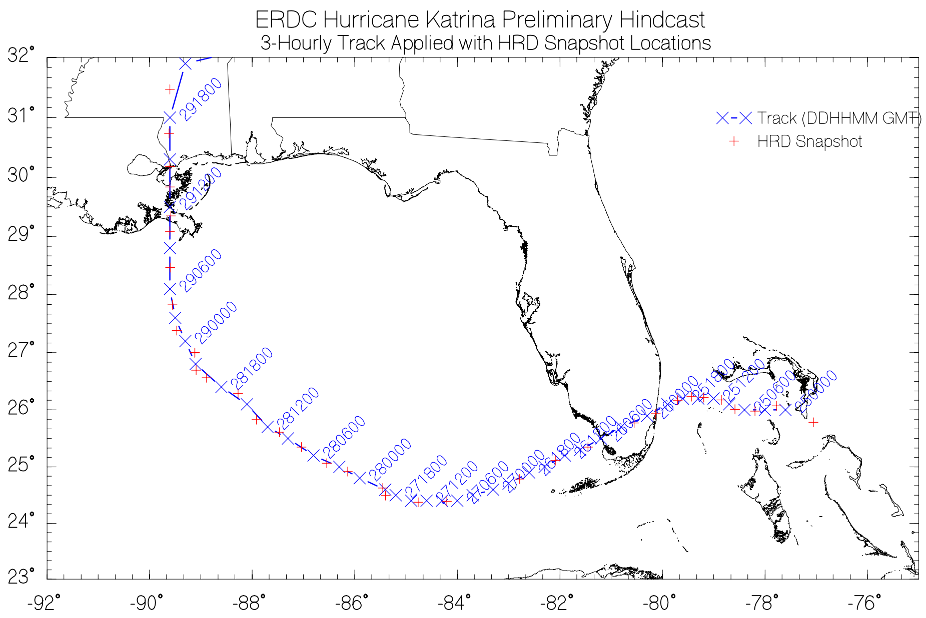


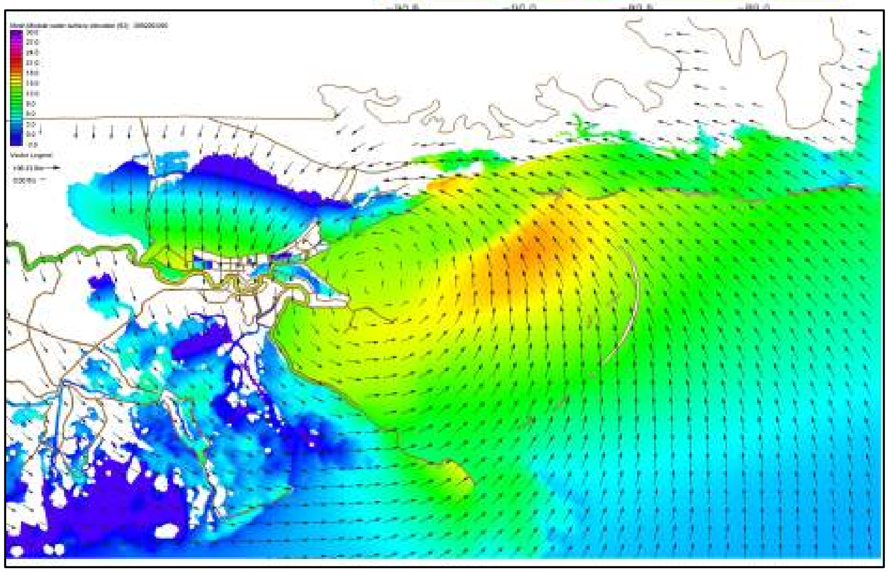


Generation of Wind and Atmospheric Pressure Fields

- Planetary Boundary Layer (PBL) Model
- H*Wind snapshots (NOAA HRD) every few hours
- Snapshots blended with background model and measured winds via IOKA procedure, by Oceanweather, Inc.)

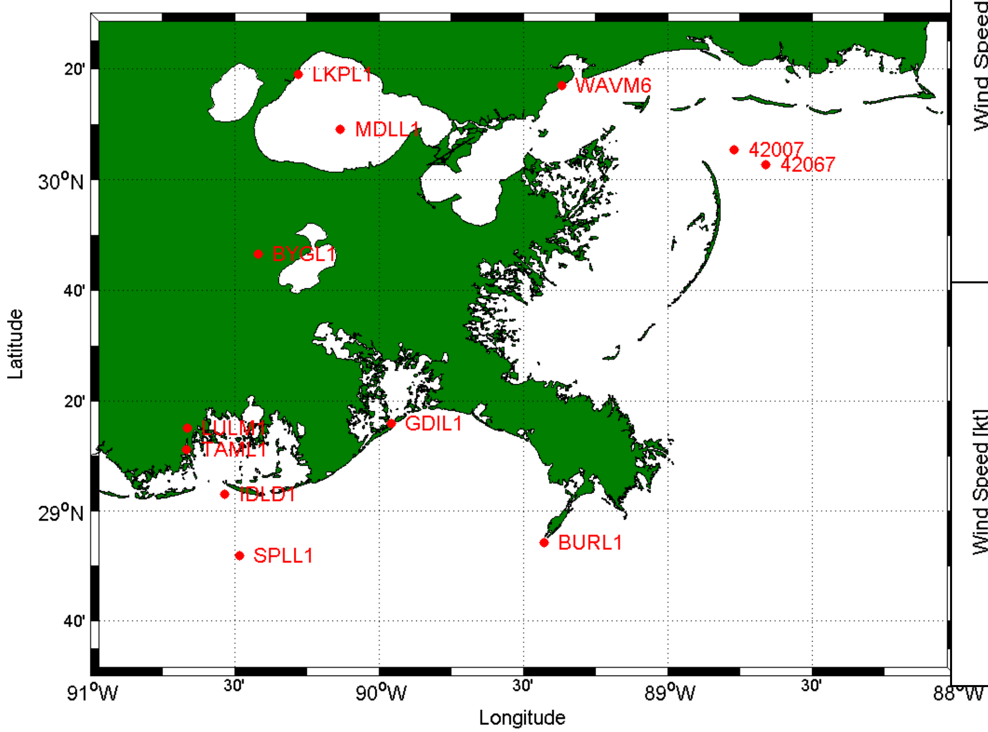


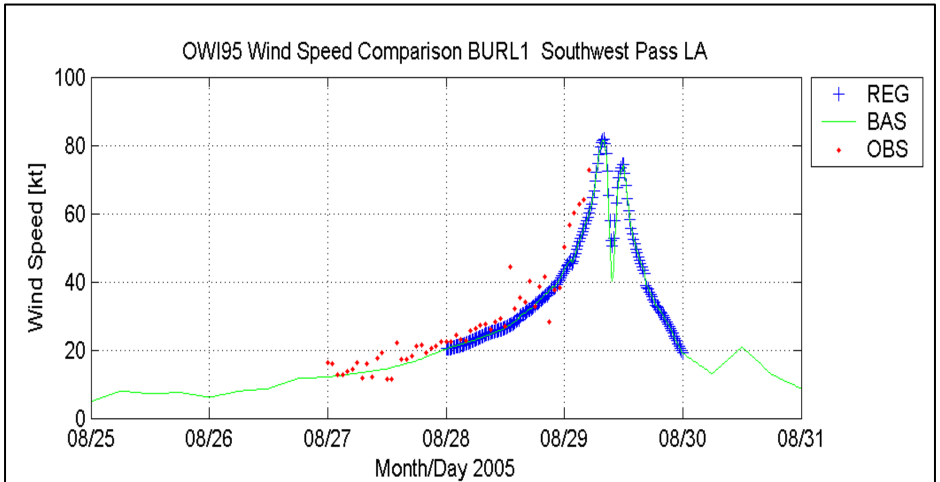


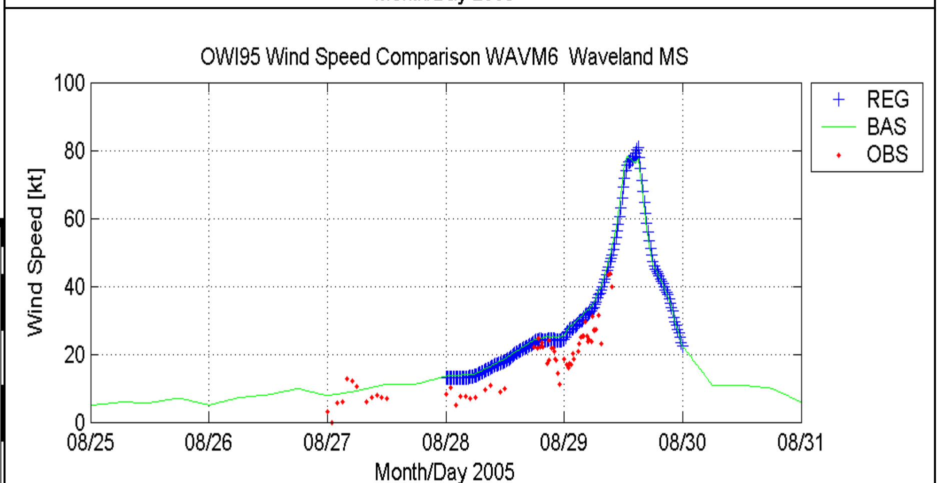


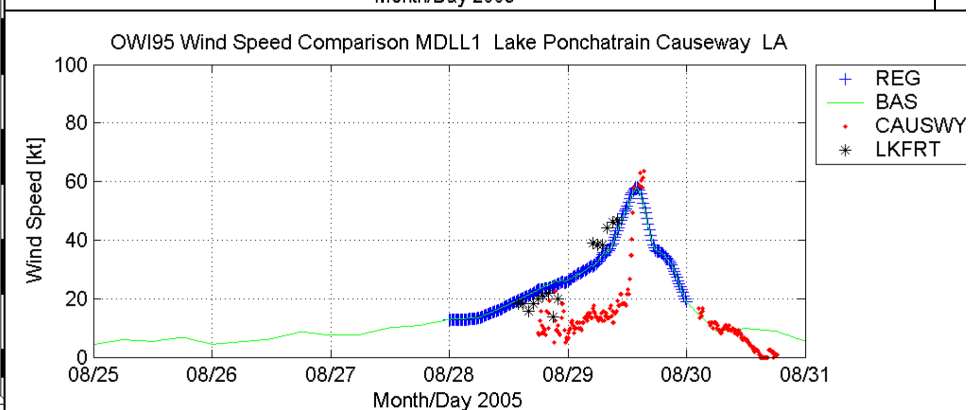
Surface Wind Measurements

- Nearly all surface anemometers in the region failed and did not capture the peak conditions
- Mid-Lake Pontchartrain gage provided most complete record, but data quality is suspect

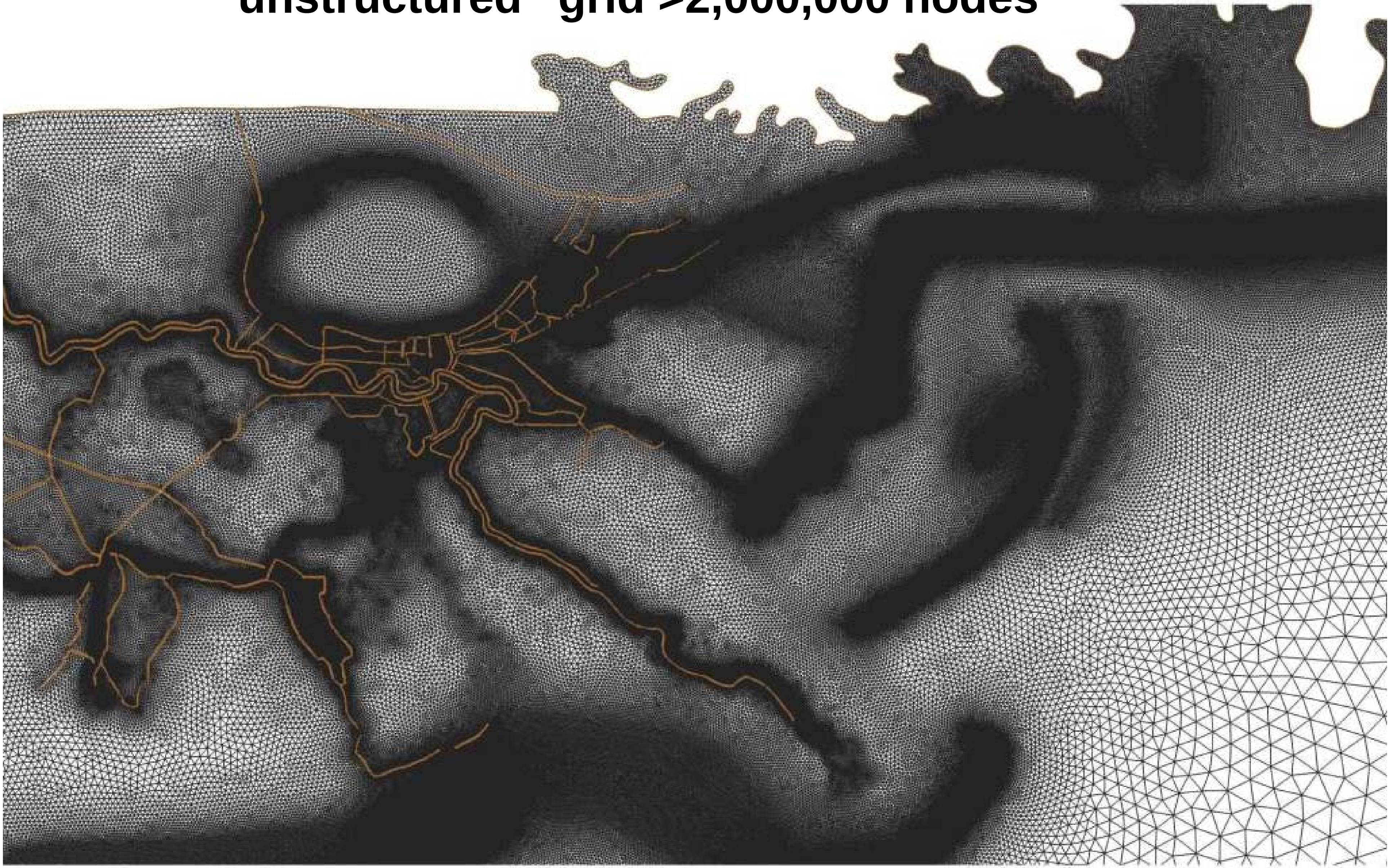




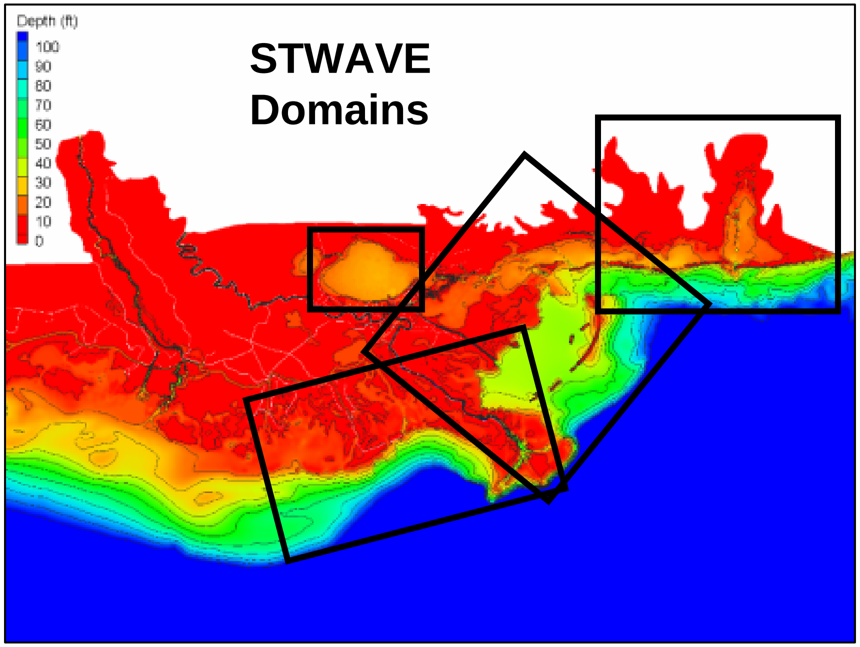




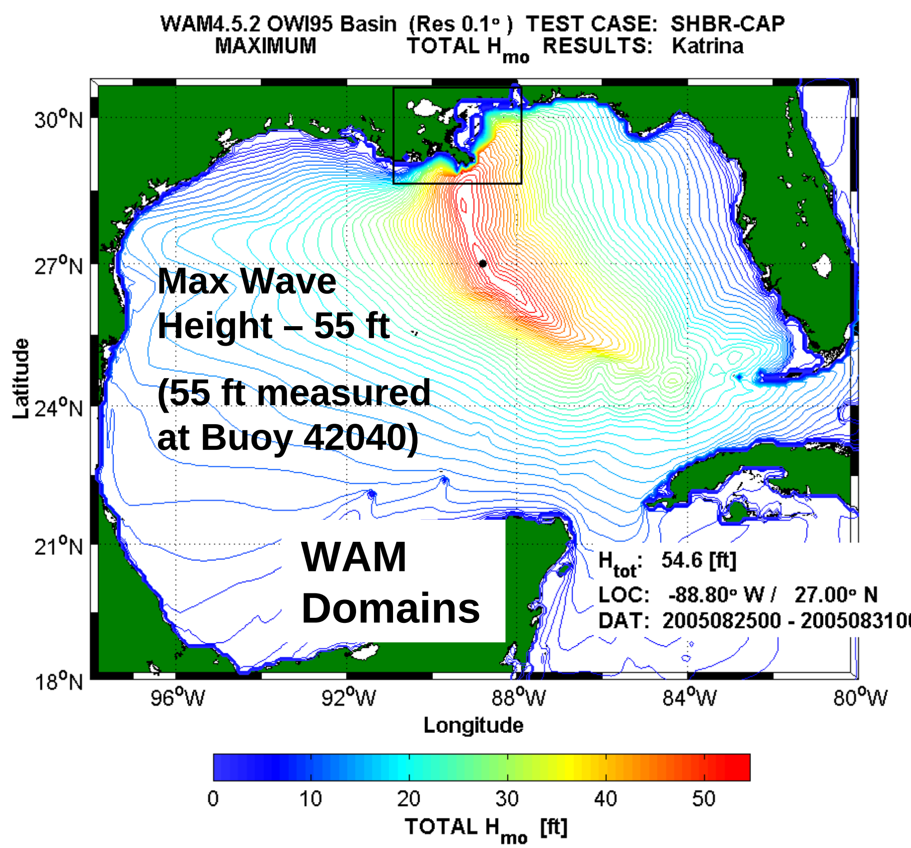
Modeling storm surges – ADCIRC
"unstructured" grid >2,000,000 nodes



Nested Wave Modeling Approach (3 Levels)

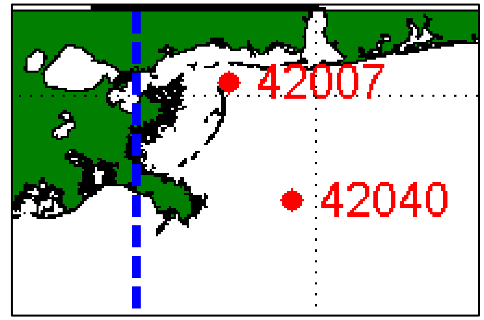


- Basin – Regional – Nearshore
- Wave-storm surge interaction handled at the nearshore level



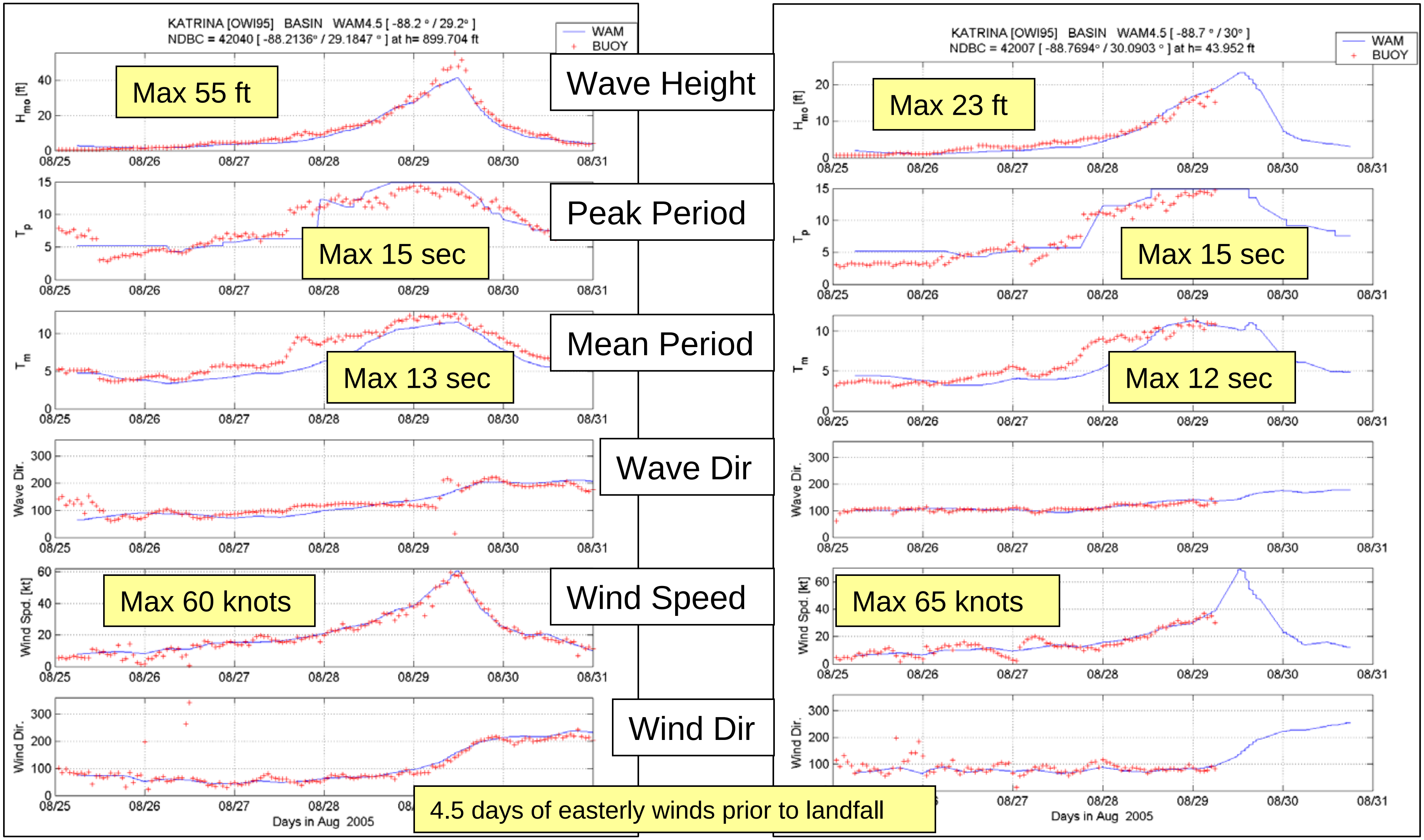
- Maximize model-to-measurement comparisons
- STWAVE compared to SWAN
- Examine steady-state assumption in STWAVE
- WAM compared to WAVEWATCH III

WAM Model Computations and Measurements – SE Louisiana

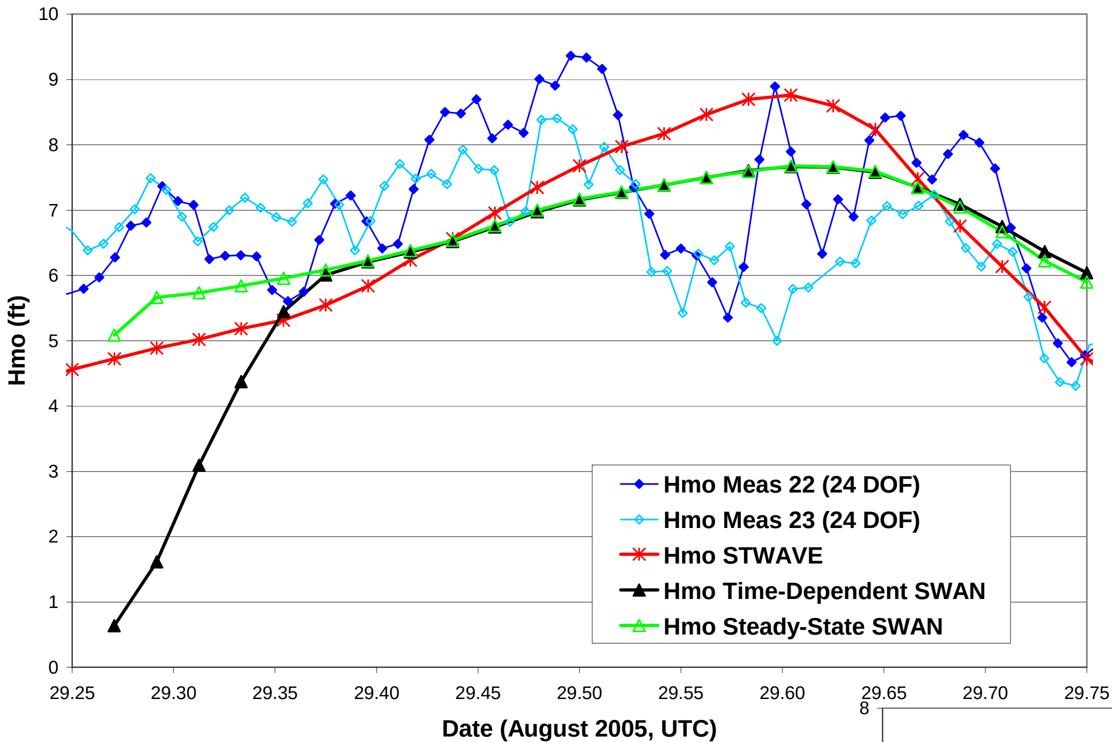


Buoy 42040

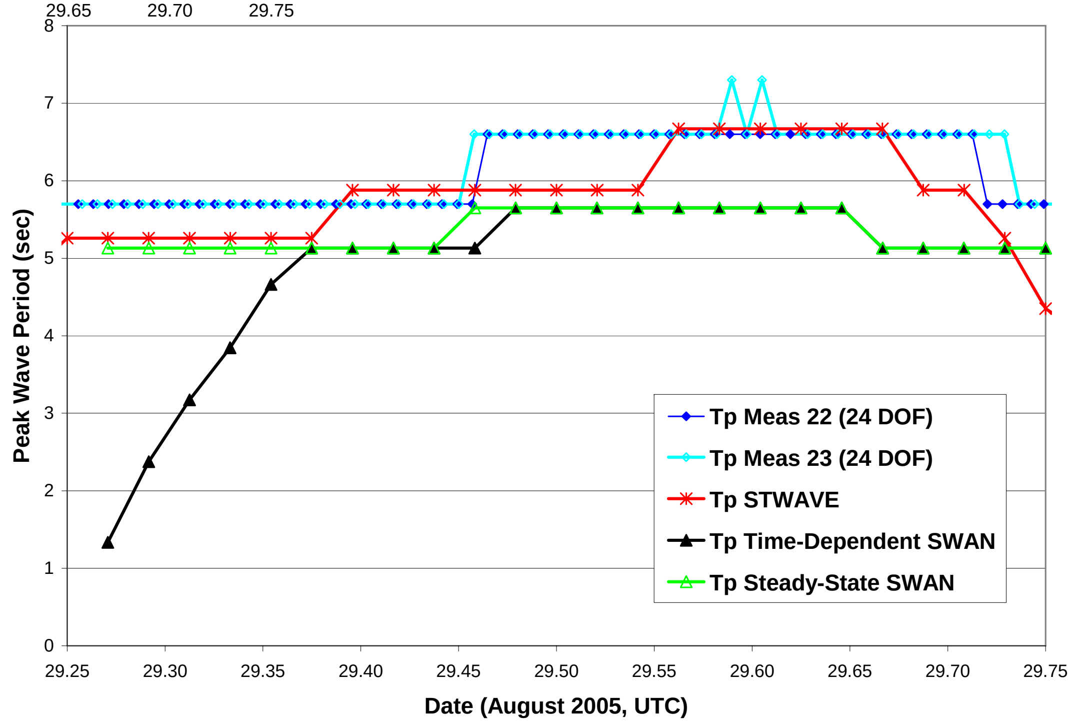
Buoy 42007



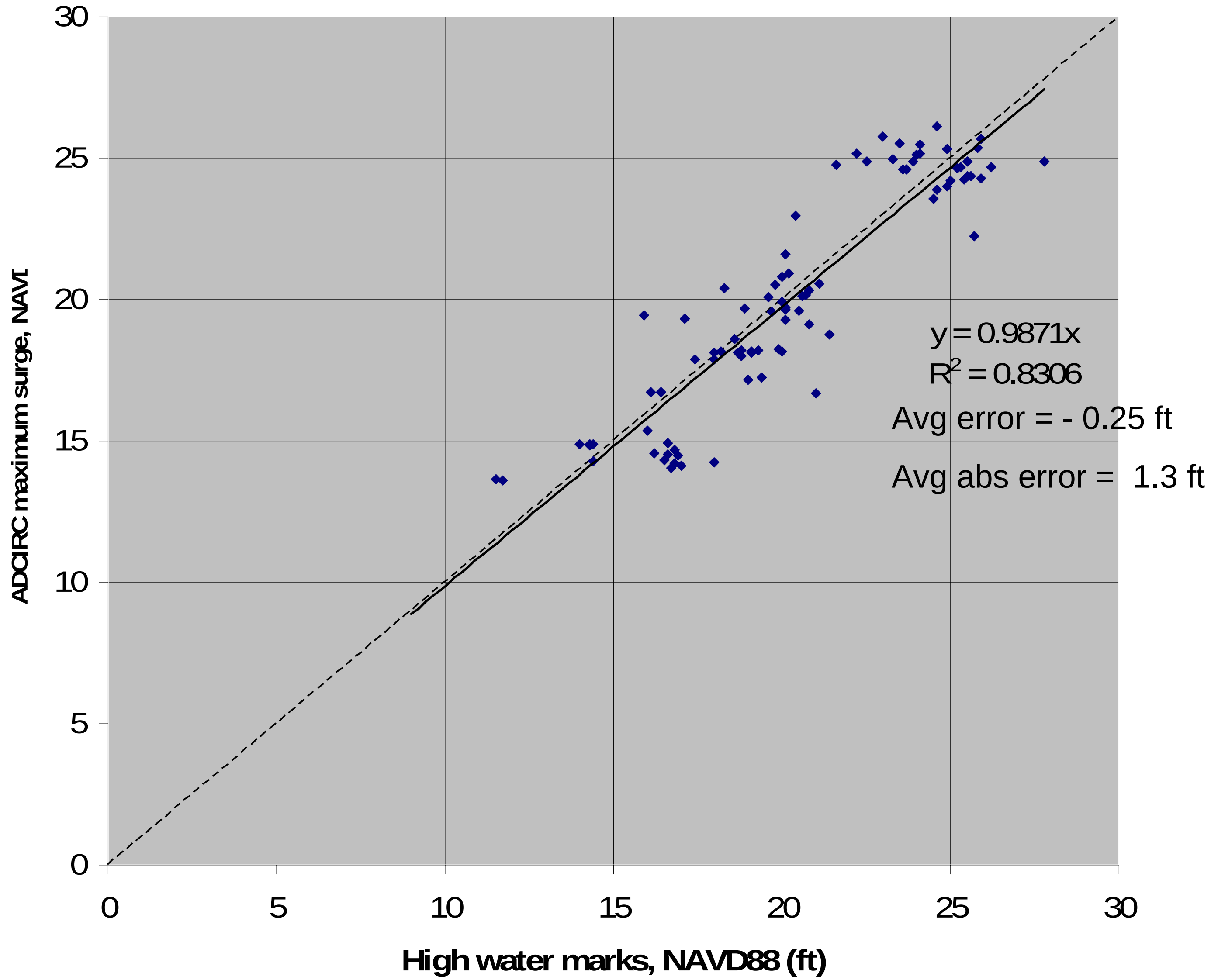
Comparisons: STWAVE SWAN Measurements



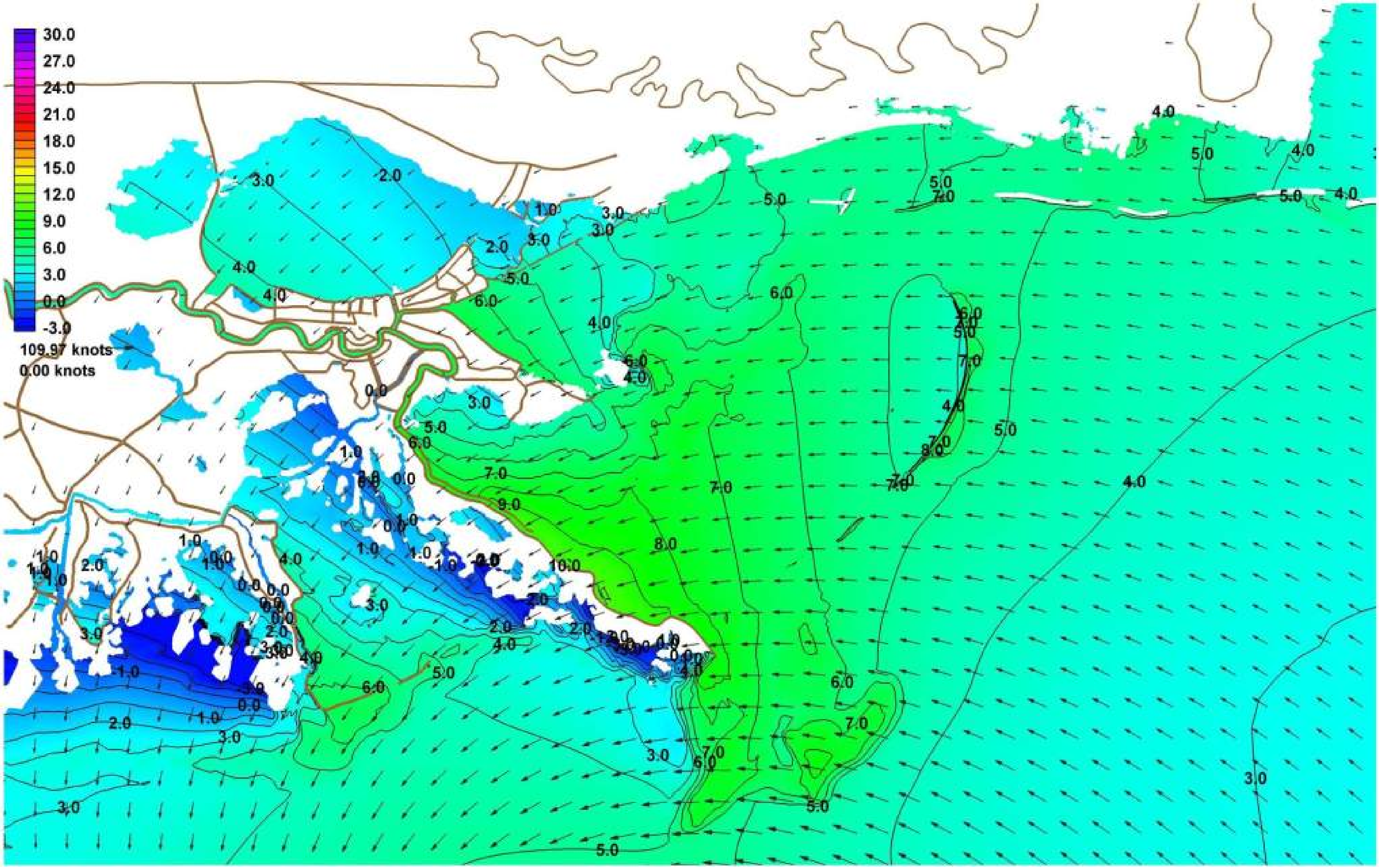
- Measurements just north of 17th Street Canal entrance (2 small buoys)
- Measured data during the peak are suspect
- Steady-state assumption of STWAVE valid



High Water Mark Comparison



8/29/07Z



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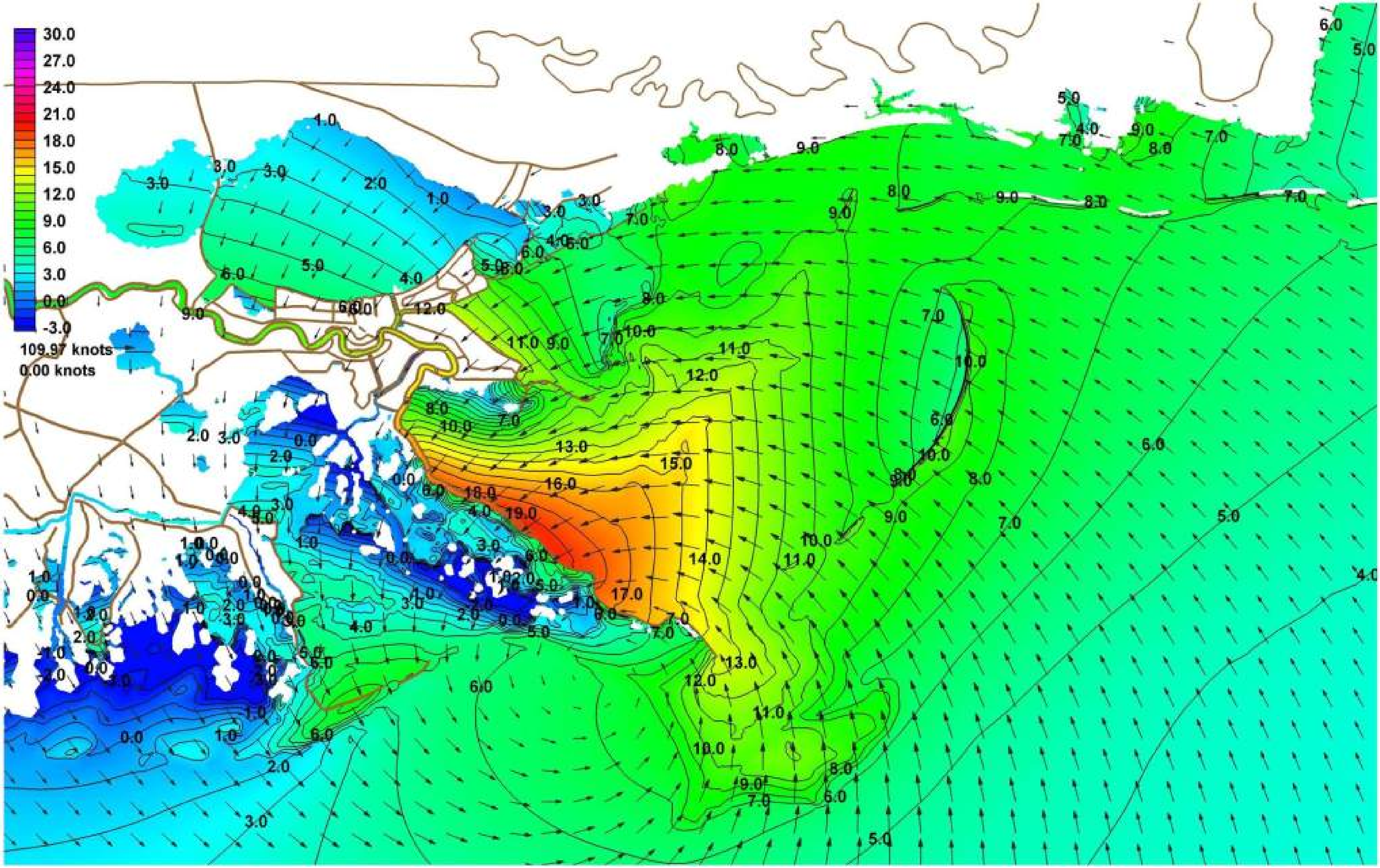
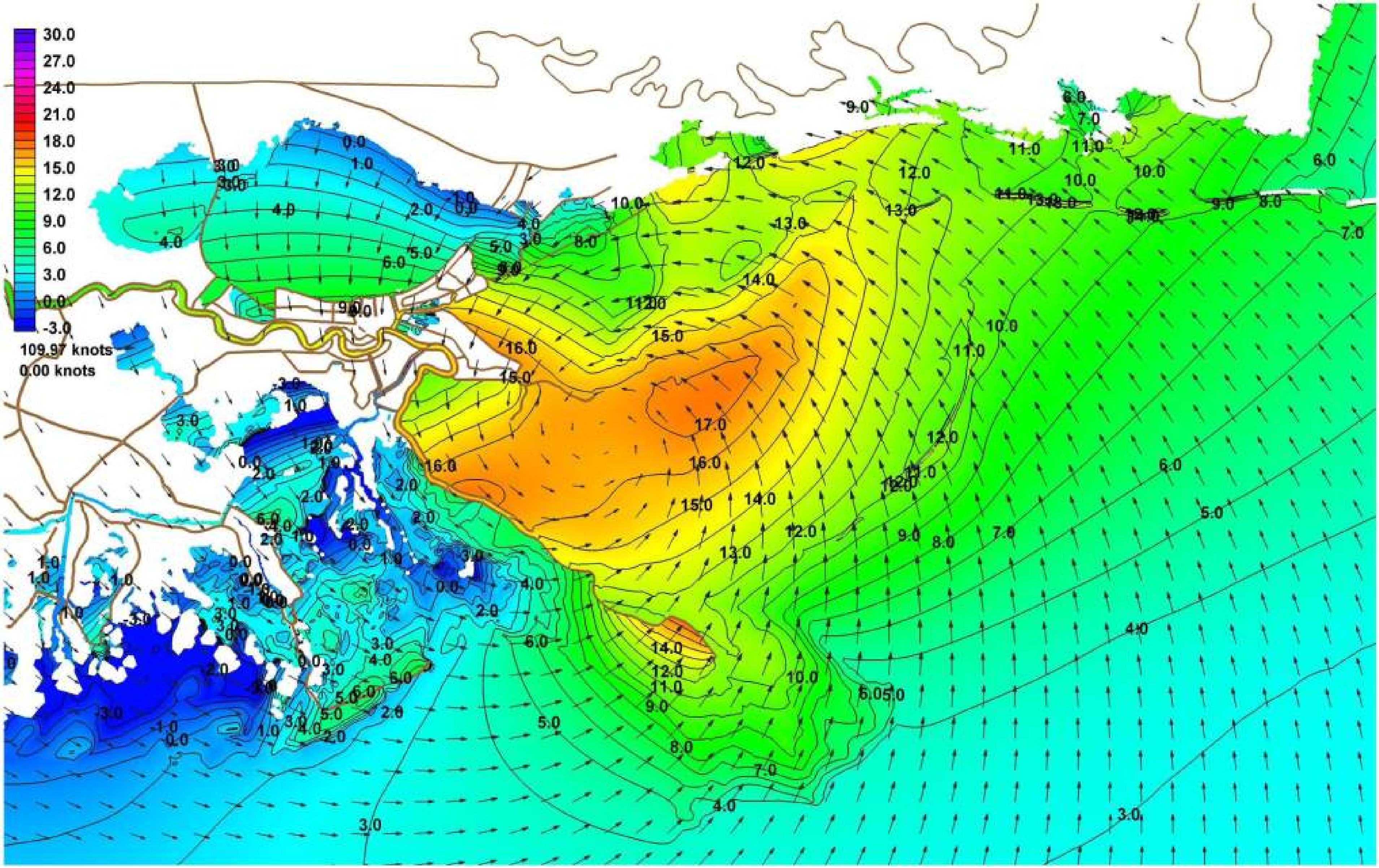
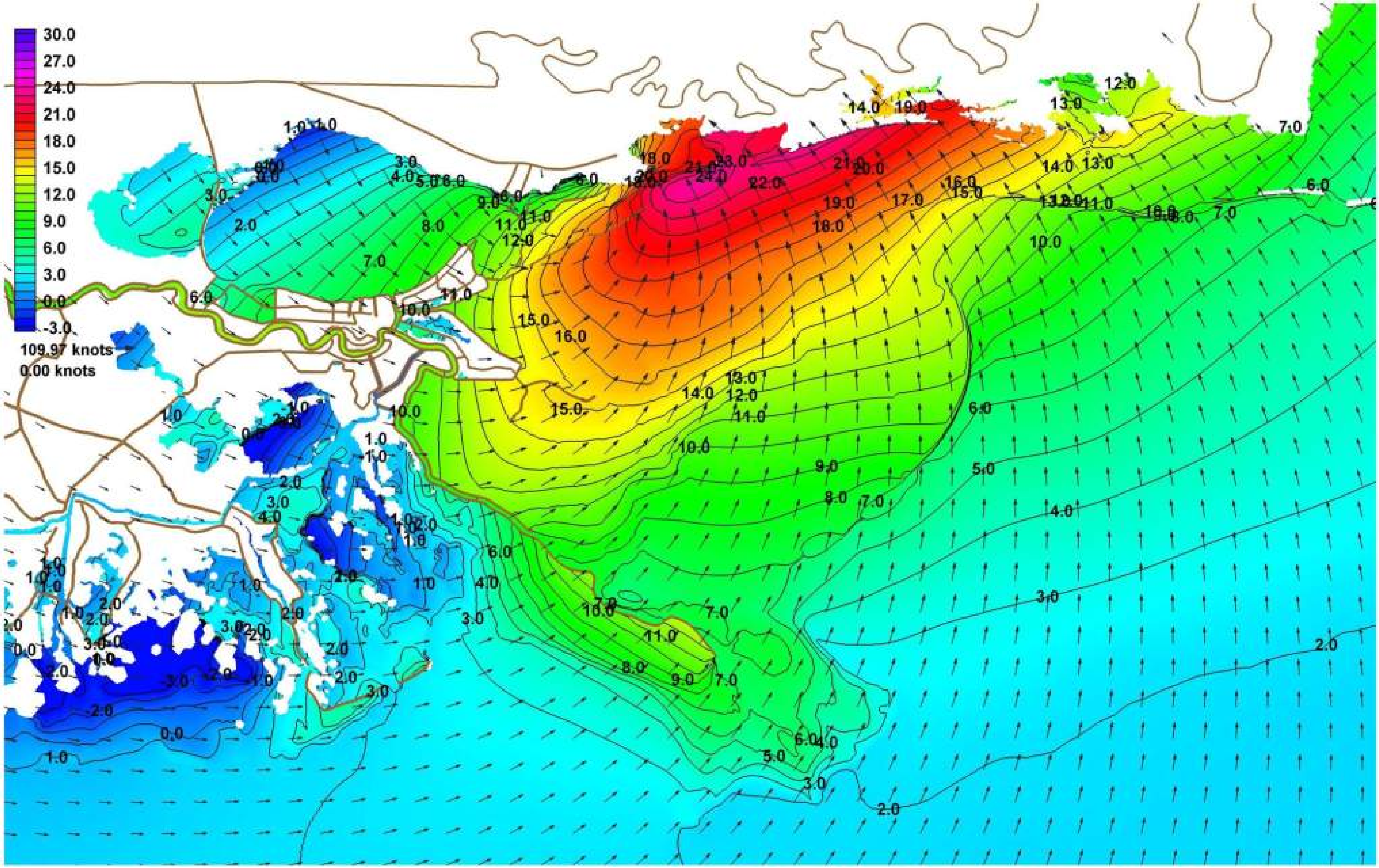


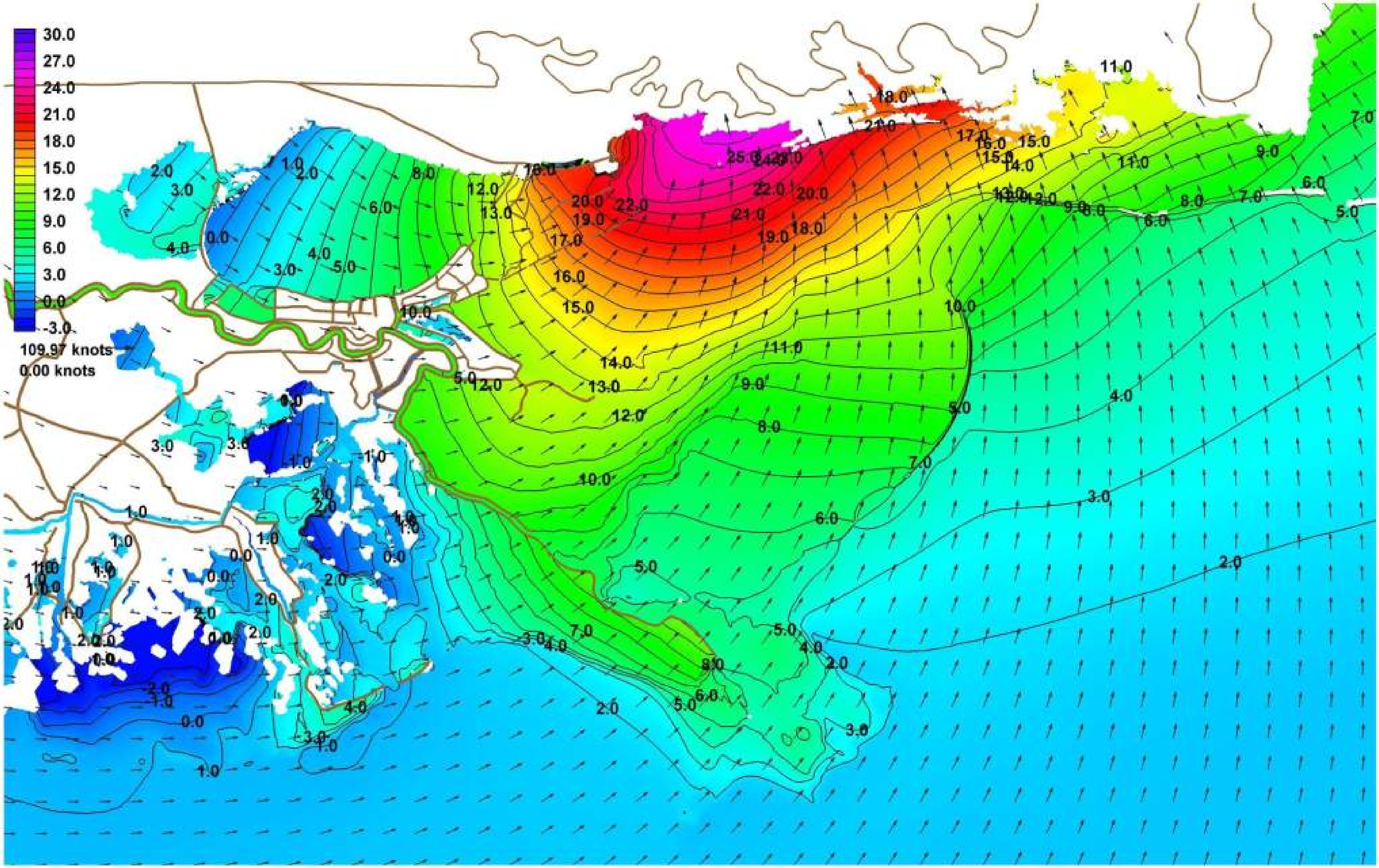
8/29/13Z



8/29/15Z



8/29/16Z



In December 2005 the Risk Assessment Group (RAG) had been formed following a meeting of national experts in Vicksburg

Team members include -

USACE:

Don Resio, Bruce Ebersole, Vann Stutts, Nancy Powell, Jay Ratcliff, Hasan Pourterhari

NOAA:

David Levinson (NCC), Mark Powell (HRD), Greg Holland* (UCAR)

FEMA:

Doug Bellamo, Emily Hirsch, David Divoky

Private Sector:

Vince Cardone (OWI), Peter Vickery (ARA), Joe Suhayda (URS),
Bill Dally (Surfbreak Engr), Sandra Werner (Exxon-Mobil),
David Driver (BP-Amoco), Cort Cooper (Chevron), Gabe Toro (Risk Engr)

Academia:

Bob Dean (U of Florida), Leon Borgman (U of Wyoming),
Pat Lynett (TAMU), Jen Irish (TAMU)

This group became the nucleus of the team to establish a joint FEMA-CORPS flood frequency methodology.

Previous Approaches to Estimating Water Level Probabilities included:

Design Storms

Historical Data Analysis

Synthetic Storm Method (Empirical Track Method)

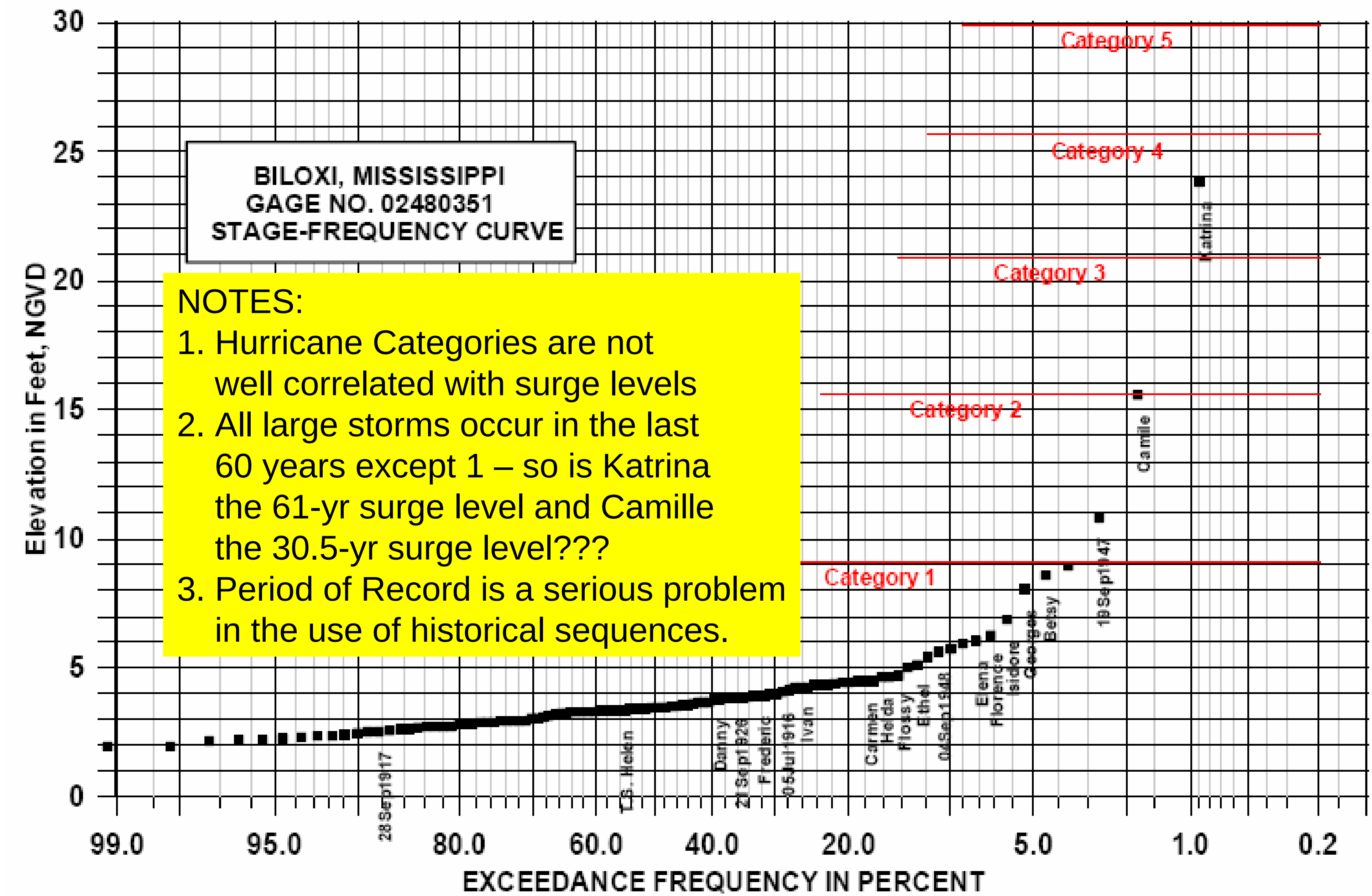
Empirical Simulation Technique (EST)

Joint Probability Method

“Forecasting can be very difficult --- particularly when it involves the future.”

Yogi Berra

NOAA Historical Data Analysis with Hypothetical Category Impact Superimposed



NOTES:

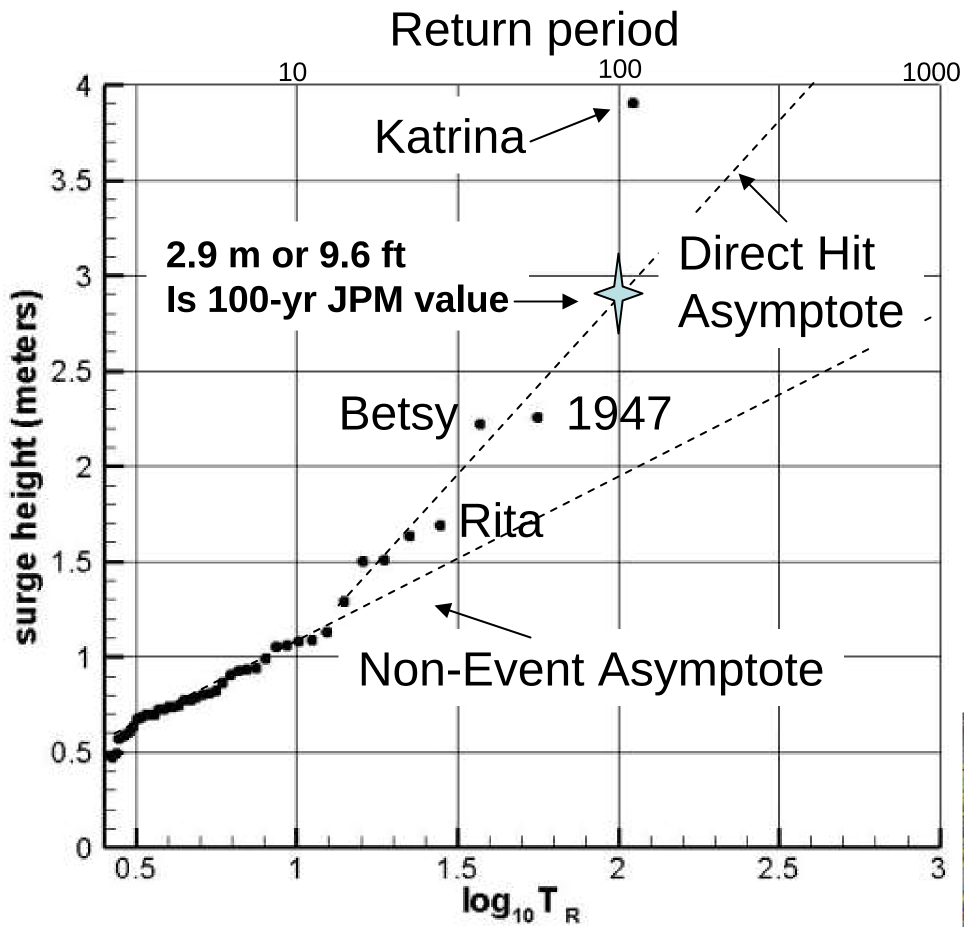
1. Hurricane Categories are not well correlated with surge levels
2. All large storms occur in the last 60 years except 1 – so is Katrina the 61-yr surge level and Camille the 30.5-yr surge level???
3. Period of Record is a serious problem in the use of historical sequences.

"Gage" is also HWM and Historical Information

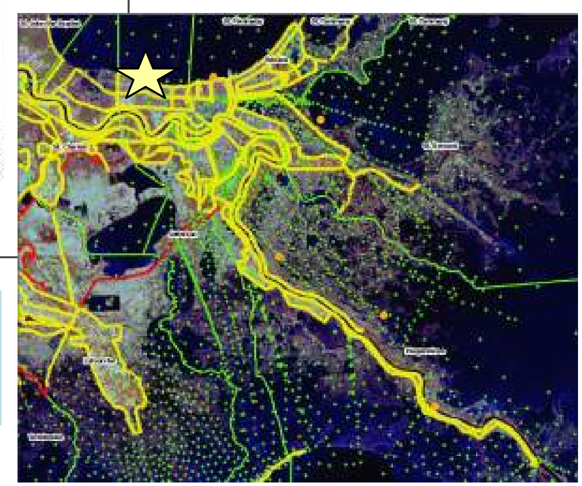
PERIOD OF RECORD, 1882-2005

Plot of ADCIRC Results from a previous study that hindcast historical storms

Lake Ponchartrain Point 1



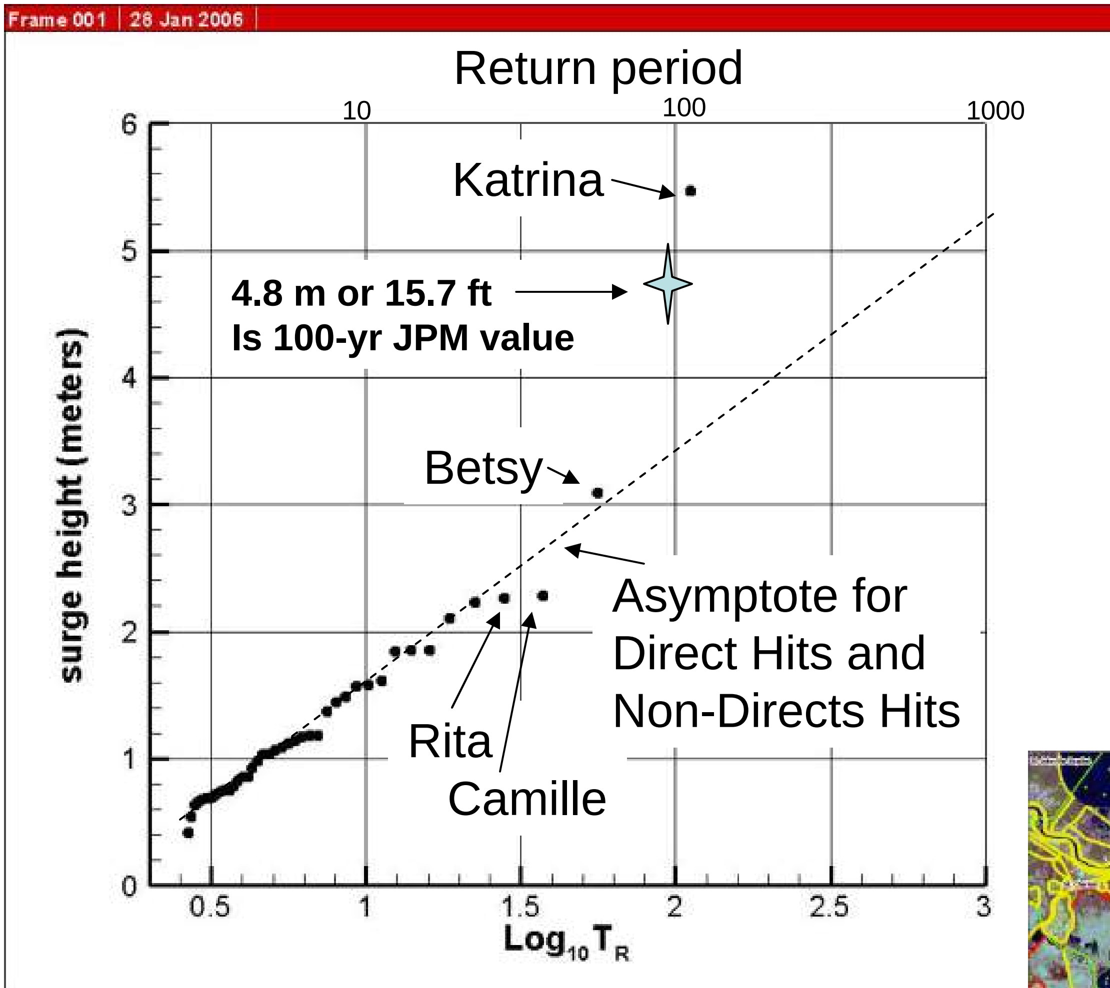
Estimate based
Poisson frequency
And CDF



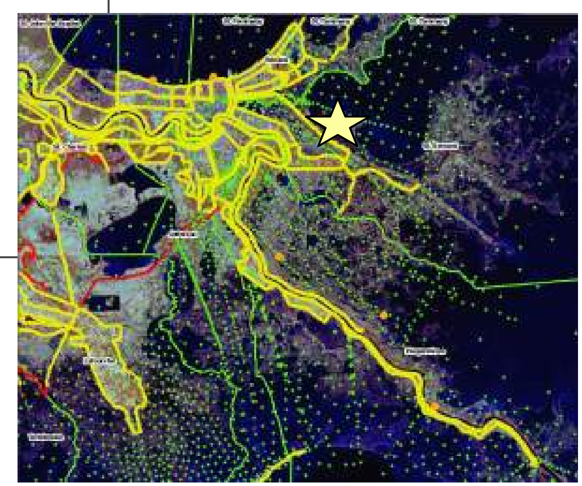
Katrina is an outlier at this site for this approach.
A primary variable is the period of record!

Simlar Plot for Point in St Bernard

Point 3 (St Bernard Parish)



Estimate based
Poisson frequency
And CDF



Again Katrina appears to be an outlier.

Older JPM:

The estimation of the surge CDF was accomplished by summing the probabilities that exceed a given surge value. The form written below explicitly shows that three terms are involved in this calculation

$$F(\eta_{\max}) = \sum \ldots \sum p(\Delta P, R_p, v_f, \theta_l, x) H[\eta_{\max} - \Phi(\Delta P, R_p, v_f, \theta_l, x)] \delta(\Delta P, R_p, v_f, \theta_l, x)$$

$p(\Delta P, R_p, v_f, \theta_l, x)$ is the continuous probability density function of 5 parameters

$\Phi(\Delta P, R_p, v_f, \theta_l, x)$ is a function (modeling suite) that estimates $\eta_{\max}$ for a set of 5 parameters

$\delta(\Delta P, R_p, v_f, \theta_l, x)$ is the 5-dimensional volume associated with a single discrete computer run's probability

H(z) is the Heaviside function = 1 if z $\geq$ 1, = 0, otherwise.

If we simply “slice and dice” the probabilities we might use something like 6 tracks, 5 angles, 3 forward speeds, 3 pressure-scaling radii, and 3 pressure differentials. This would give 810 computer runs to be made, but we are still ignoring several factors such as tide phase relative to peak surge, Holland B value, variations in decay during approach to coast, model system errors, etc.

New JPM:

The estimation of the surge CDF includes a “random” deviation term added to the modeled values. In this way we can retain important aspects of variations that would add too many dimensions to the integral to make it practical.

$$F(\eta_{\max}) = \sum \ldots \sum p(\Delta P, R_p, v_f, \theta_l, x) H[\eta_{\max} - \Phi(\Delta P, R_p, v_f, \theta_l, x) + \varepsilon] \delta(\Delta P, R_p, v_f, \theta_l, x)$$

where

ε is a random deviation due to all the neglected factors

This includes both surge-independent terms (tide and model error) and surge-dependent terms (Holland B), etc.

After some analyses of different types both Toro and Resio ended up using about 150 storms in this sum and similar magnitude epsilon terms.

In present JPM probabilities are described by

$$p(\Delta P, R_p, v_f, \theta_l, x) = \Lambda_1 \cdot \Lambda_2 \cdot \Lambda_3 \cdot \Lambda_4 \cdot \Lambda_5$$

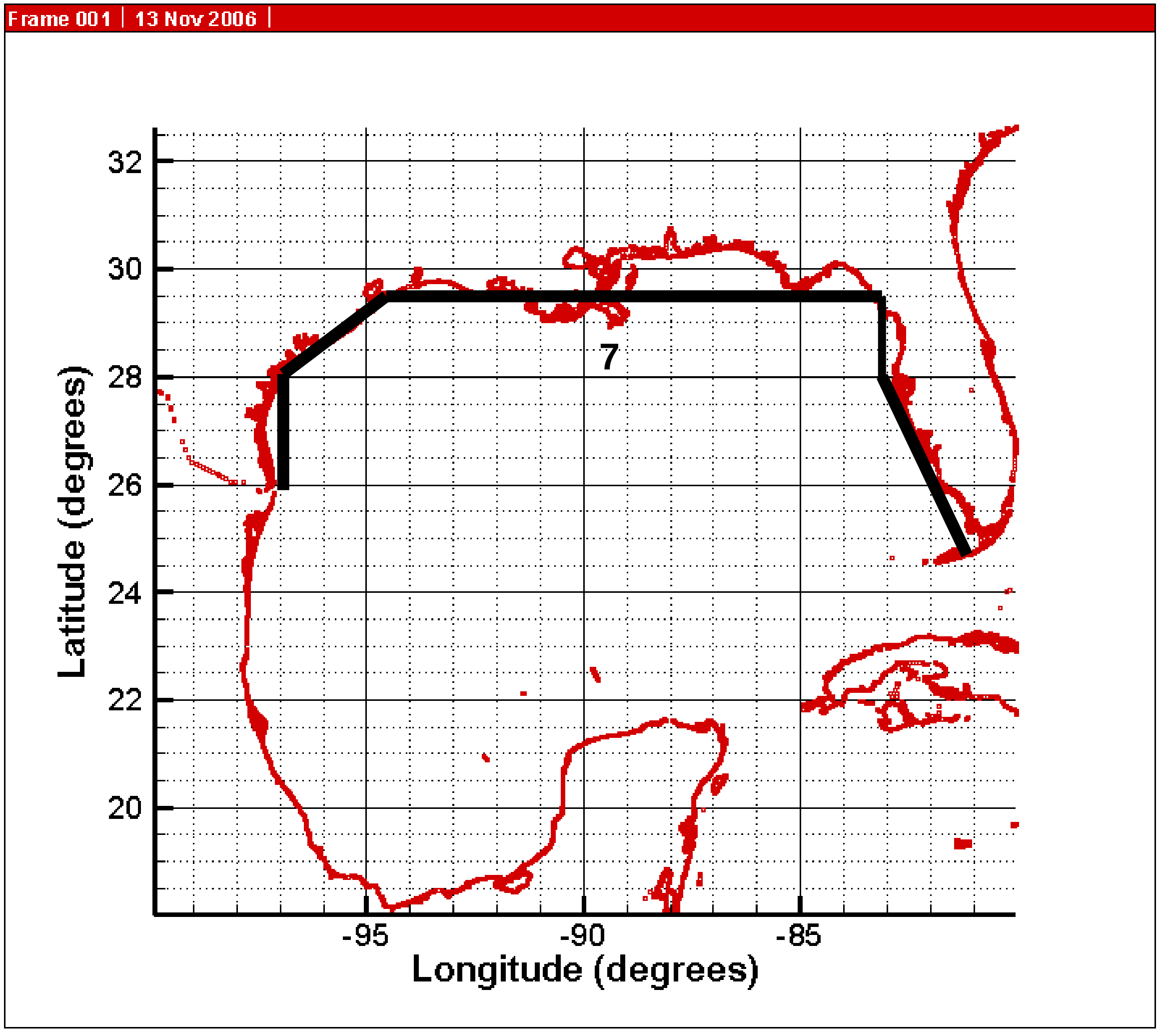
$$\Lambda_1 = p(\Delta P \mid x) = \frac{\partial F[a_0(x), a_1(x)]}{\partial c_p} = \exp\left\{ -\exp - \left[\frac{\Delta P - a_0(x)}{a_1(x)} \right] \right\} \quad \text{(Gumbel Distribution)}$$

$$\Lambda_2 = p(R_p \mid \Delta P) = \frac{1}{\sigma(\Delta P)\sqrt{2\pi}} e^{-\frac{(\bar{R}_p(\Delta P) - R_p)^2}{2\sigma^2(\Delta P)}}$$

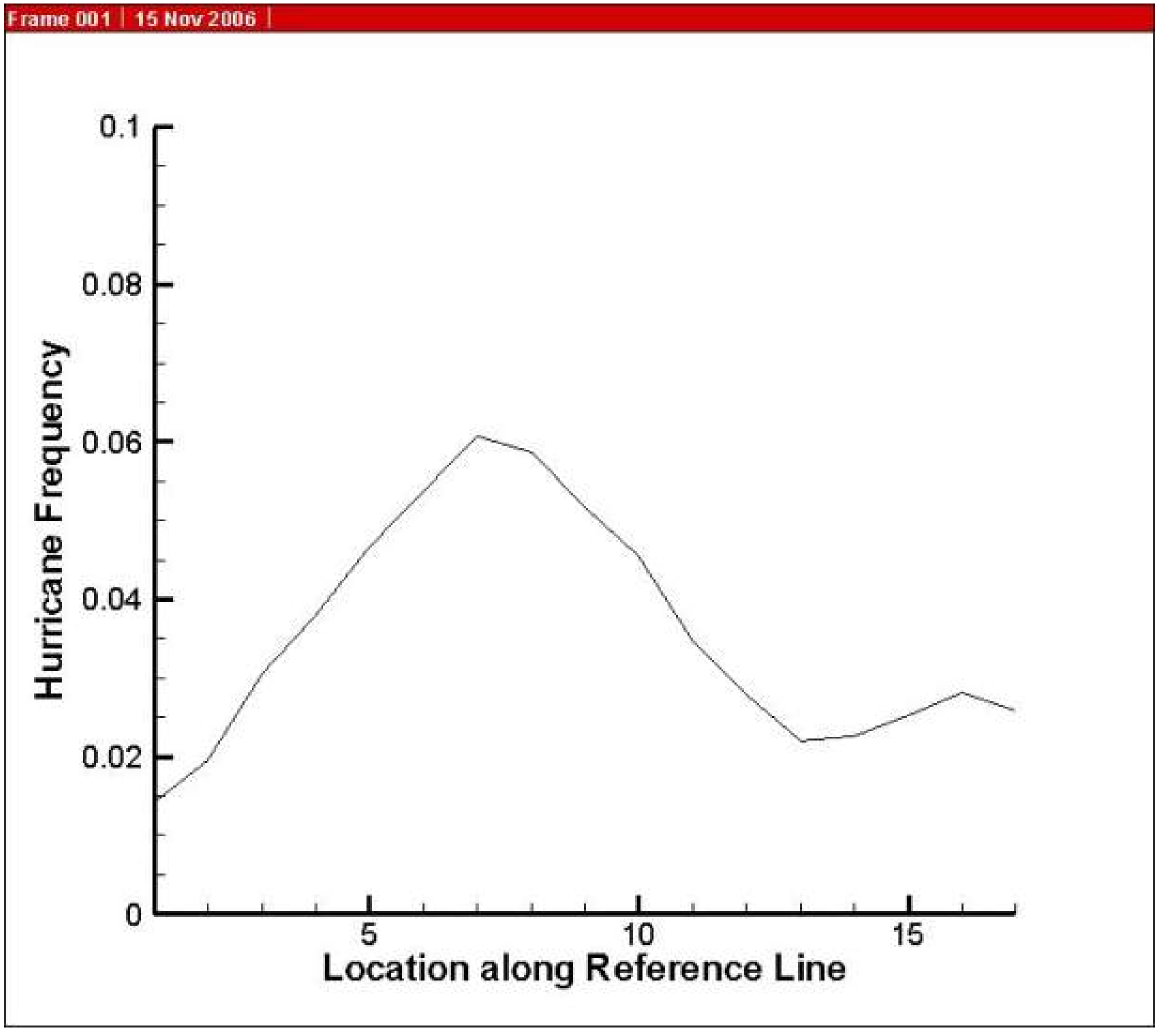
$$\Lambda_3 = p(v_f \mid \theta_l) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(\bar{v}_f(\theta_l) - v_f)^2}{2\sigma^2}}$$

$$\Lambda_4 = p(\theta_l \mid x) = \frac{1}{\sigma(x)\sqrt{2\pi}} e^{-\frac{(\bar{\theta}_l(x) - \theta_l)^2}{2\sigma^2(x)}}$$

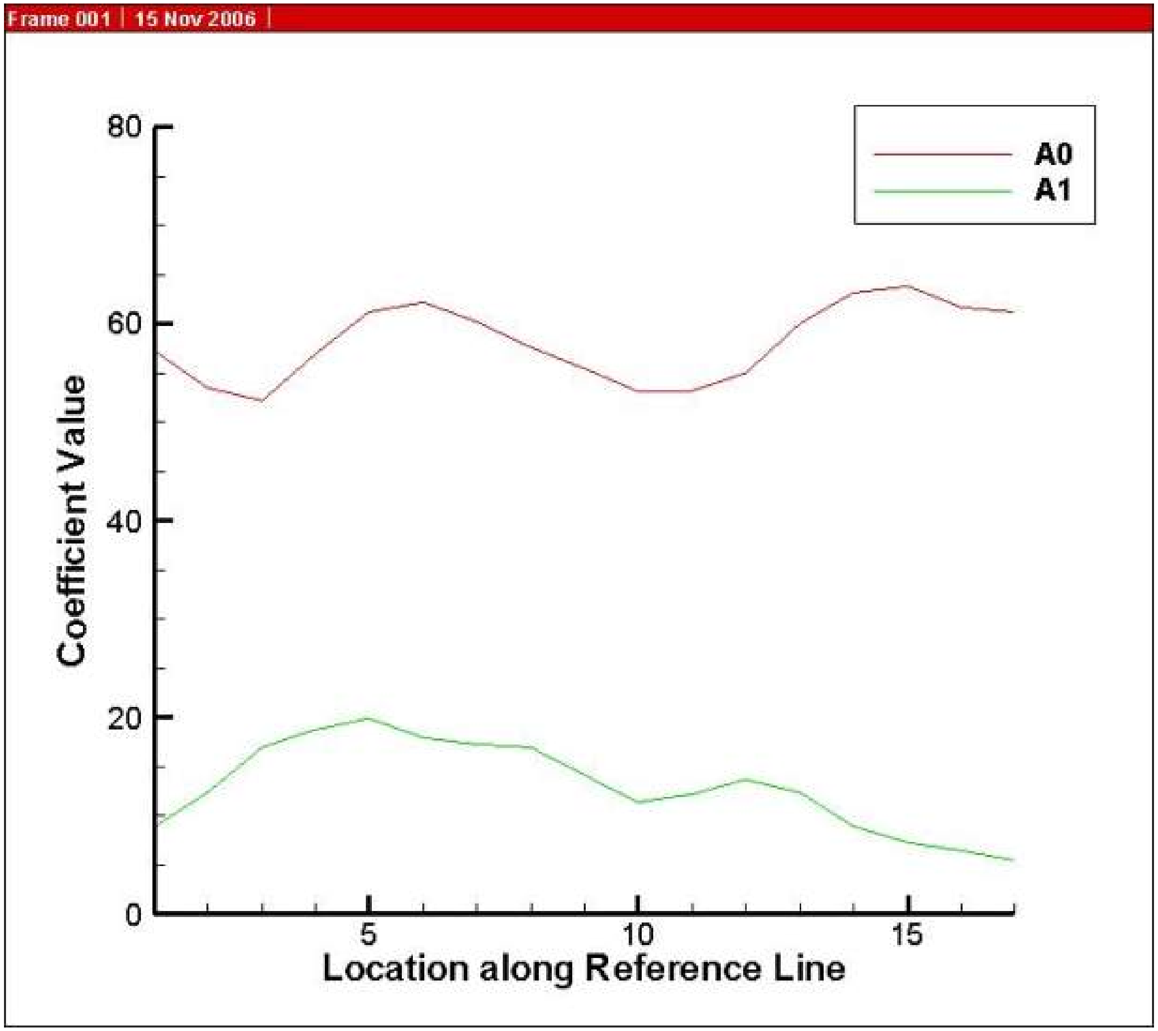
$$\Lambda_5 = \Phi(x)$$



Frequency analysis uses a “line-crossing” method; but pressures are taken from estimates at landfall. Note: Segment definition begins at easternmost point of line at 29.5 N and runs toward the west, around to the Mexican border. Segment 7 is shown for reference.

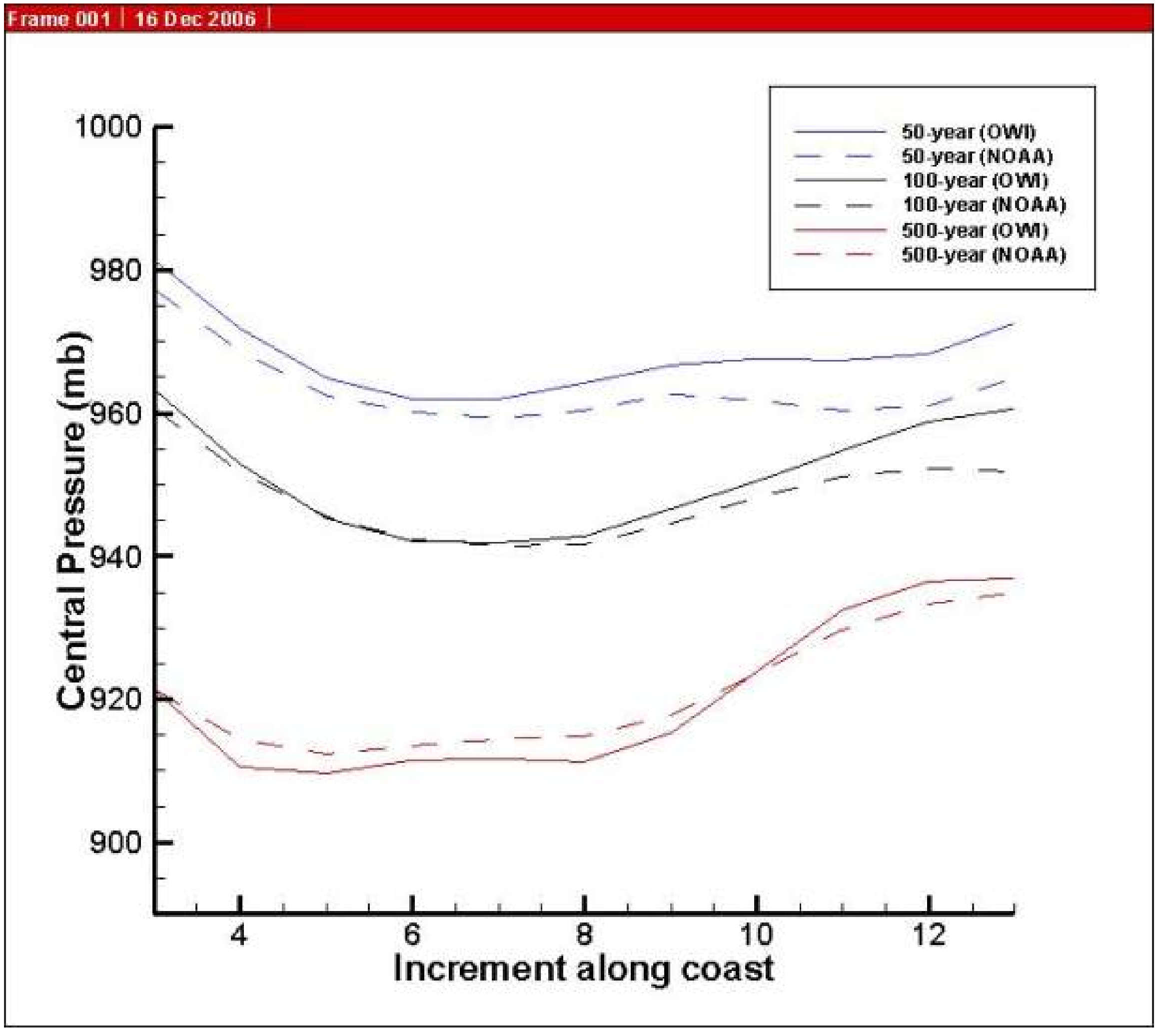


Frequency of hurricanes with central pressures less than 955 mb during passage through the Gulf of Mexico.



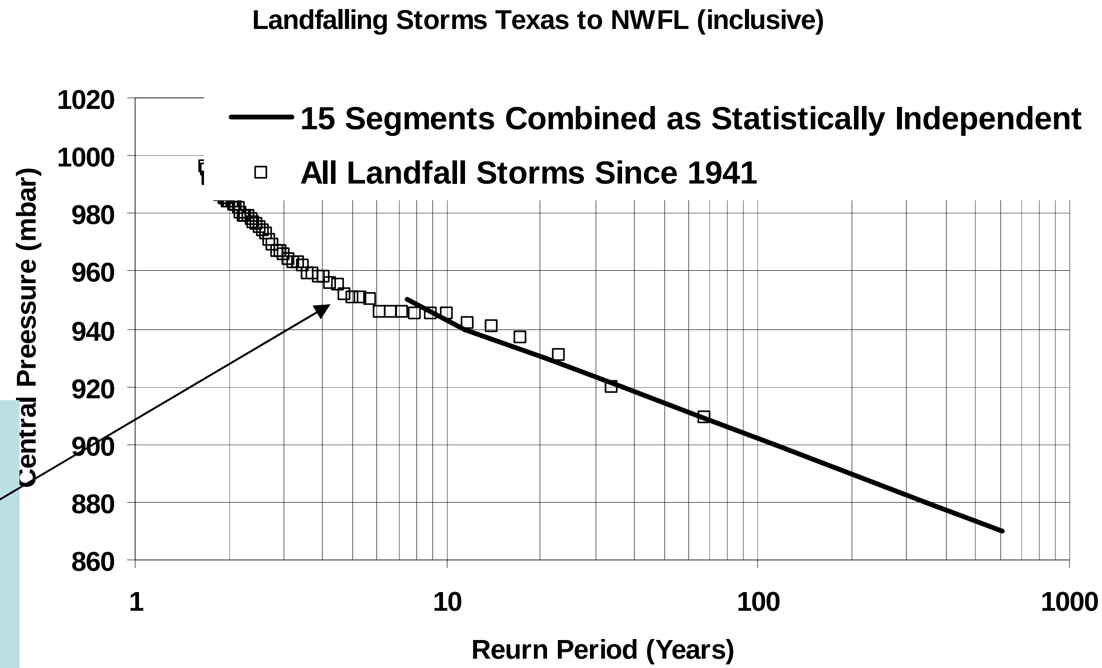
Plot of Gumbel coefficients along idealized line.

$$F(\Delta P \mid x) = \exp - \left\{ \exp - \left[\frac{\Delta P - a_0(x)}{a_1(x)} \right] \right\}$$

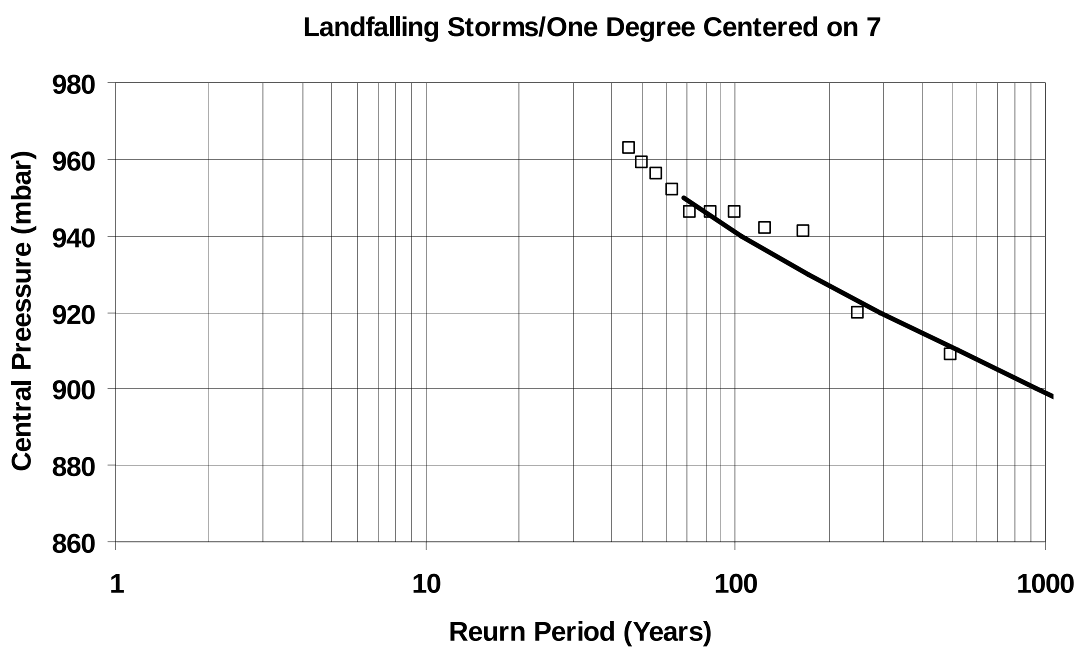


Estimates of Landfalling pressures for selected recurrence intervals.

Independent estimate of storm probabilities by Peter Vickery for Florida Panhandle through Texas

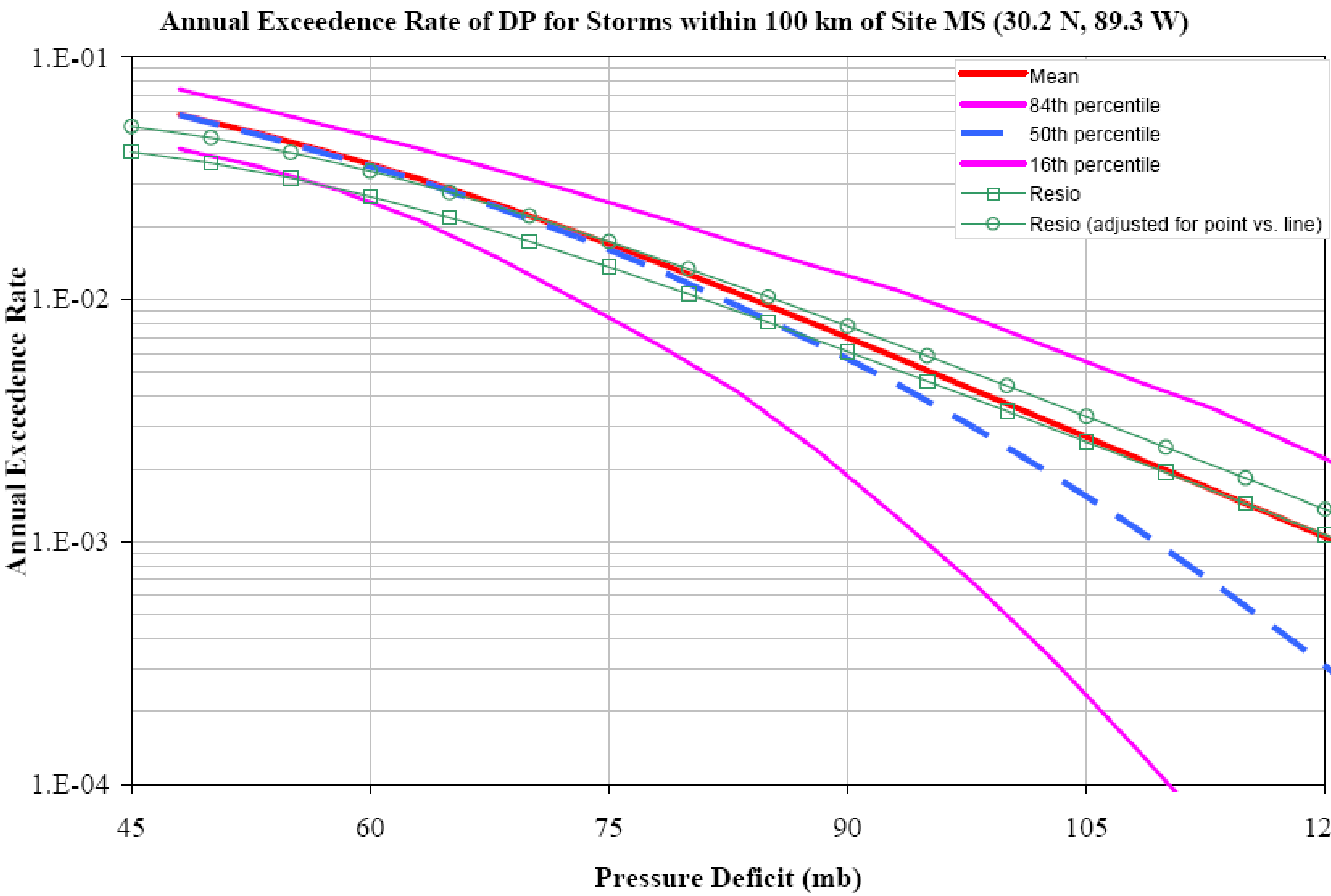


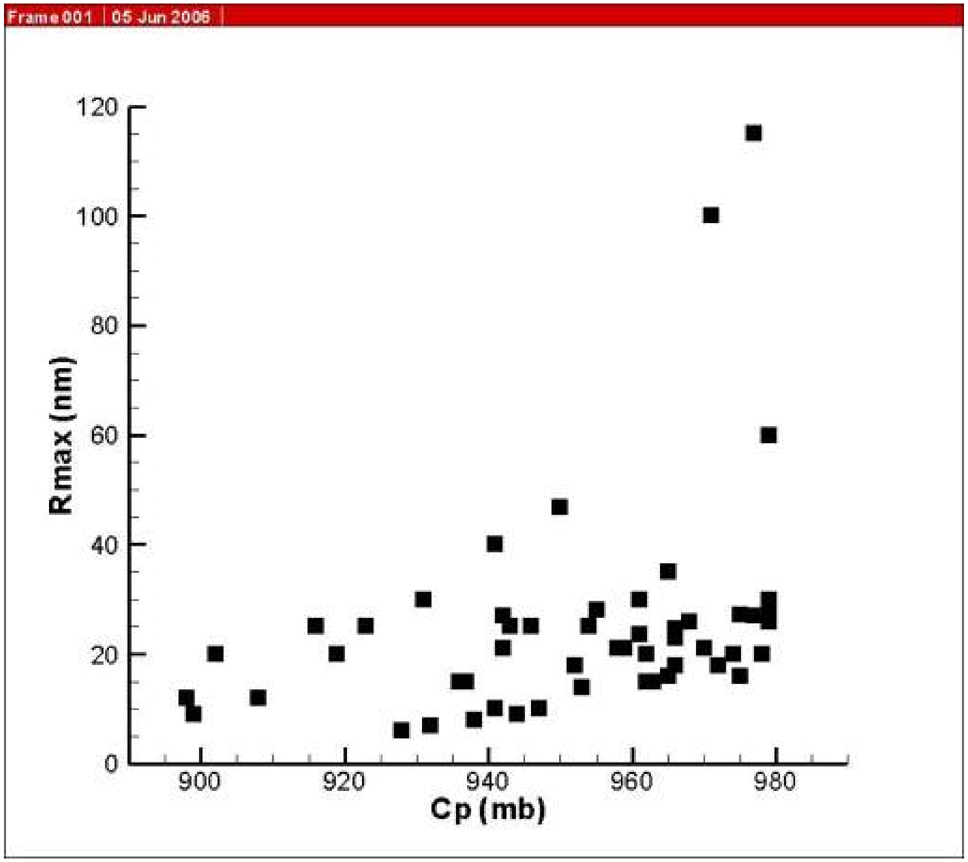
Note the reason
For stratifying the
Hurricanes based
On intensity.Gumbel
Fit to entire population
Would not fit tail well.



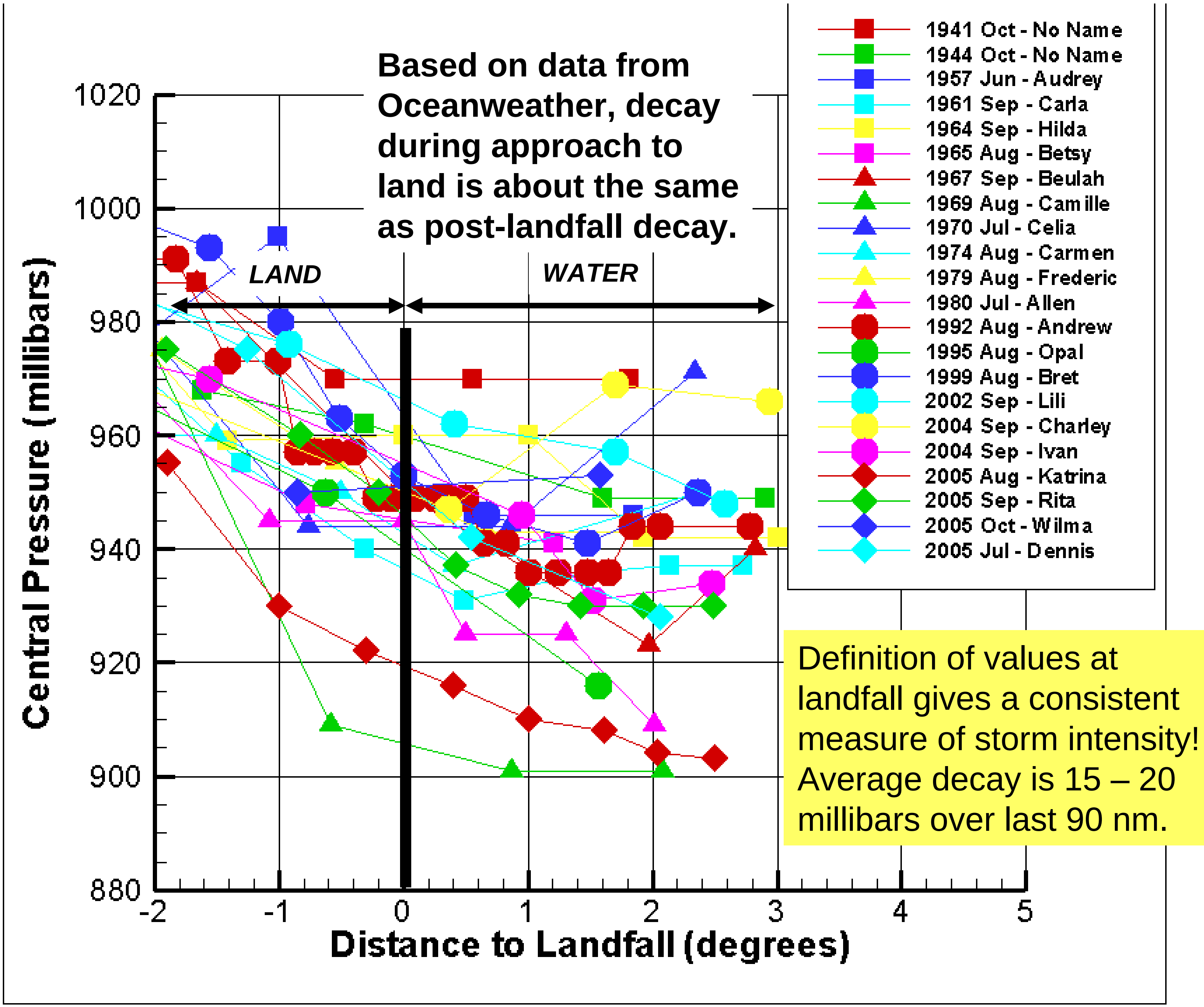
Independent estimate of storm probabilities by Peter Vickery for New Orleans Area

Independent estimate of storm probabilities by Gabriel Toro (for URS) compared to initial estimate in JPM White Paper





Plot showing relationship (offshore) between pressure-scaling radius and central pressure.



Based on data from Oceanweather, decay during approach to land is about the same as post-landfall decay.
LAND
WATER
Central Pressure (millibars)
1020
1000
980
960
940
920
900
880
-2
-1
0
1
2
3
4
5
Distance to Landfall (degrees)
1941 Oct - No Name
1944 Oct - No Name
1957 Jun - Audrey
1961 Sep - Carla
1964 Sep - Hilda
1965 Aug - Betsy
1967 Sep - Beulah
1969 Aug - Camille
1970 Jul - Celia
1974 Aug - Carmen
1979 Aug - Frederic
1980 Jul - Allen
1992 Aug - Andrew
1995 Aug - Opal
1999 Aug - Bret
2002 Sep - Lili
2004 Sep - Charley
2004 Sep - Ivan
2005 Aug - Katrina
2005 Sep - Rita
2005 Oct - Wilma
2005 Jul - Dennis
Definition of values at landfall gives a consistent measure of storm intensity! Average decay is 15 – 20 millibars over last 90 nm.

Filling rates:

Pre-landfall (Resio) – linear variation over last 90 nm

$$\Delta c_p = R_{\max} - 6$$

Post-landfall (Vickery)

$$\Delta P = \Delta P_0 \exp(-at)$$

where

$$\Delta P = P_\infty - c_p$$

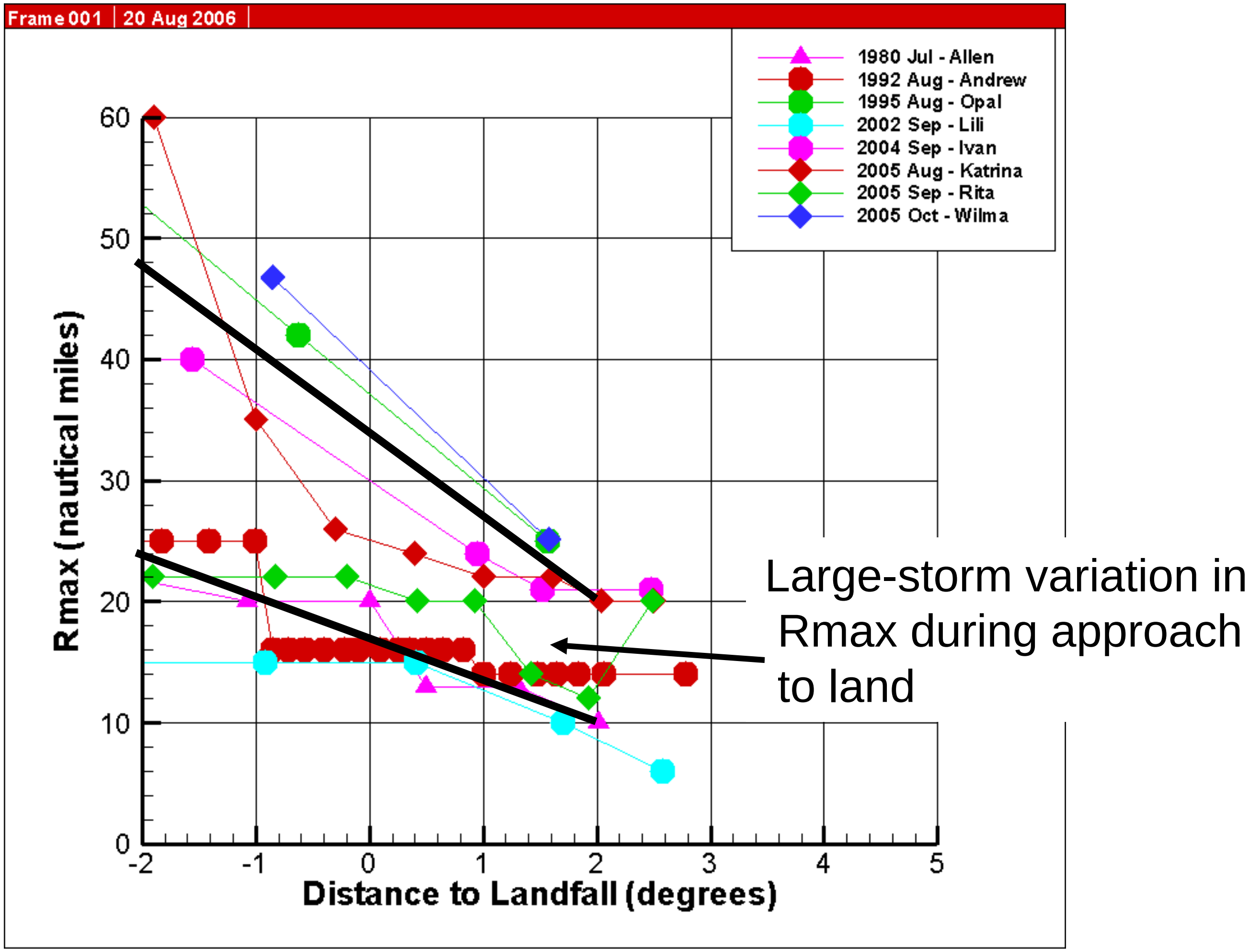
t is time in hours

subcript "0" refers to value at landfall

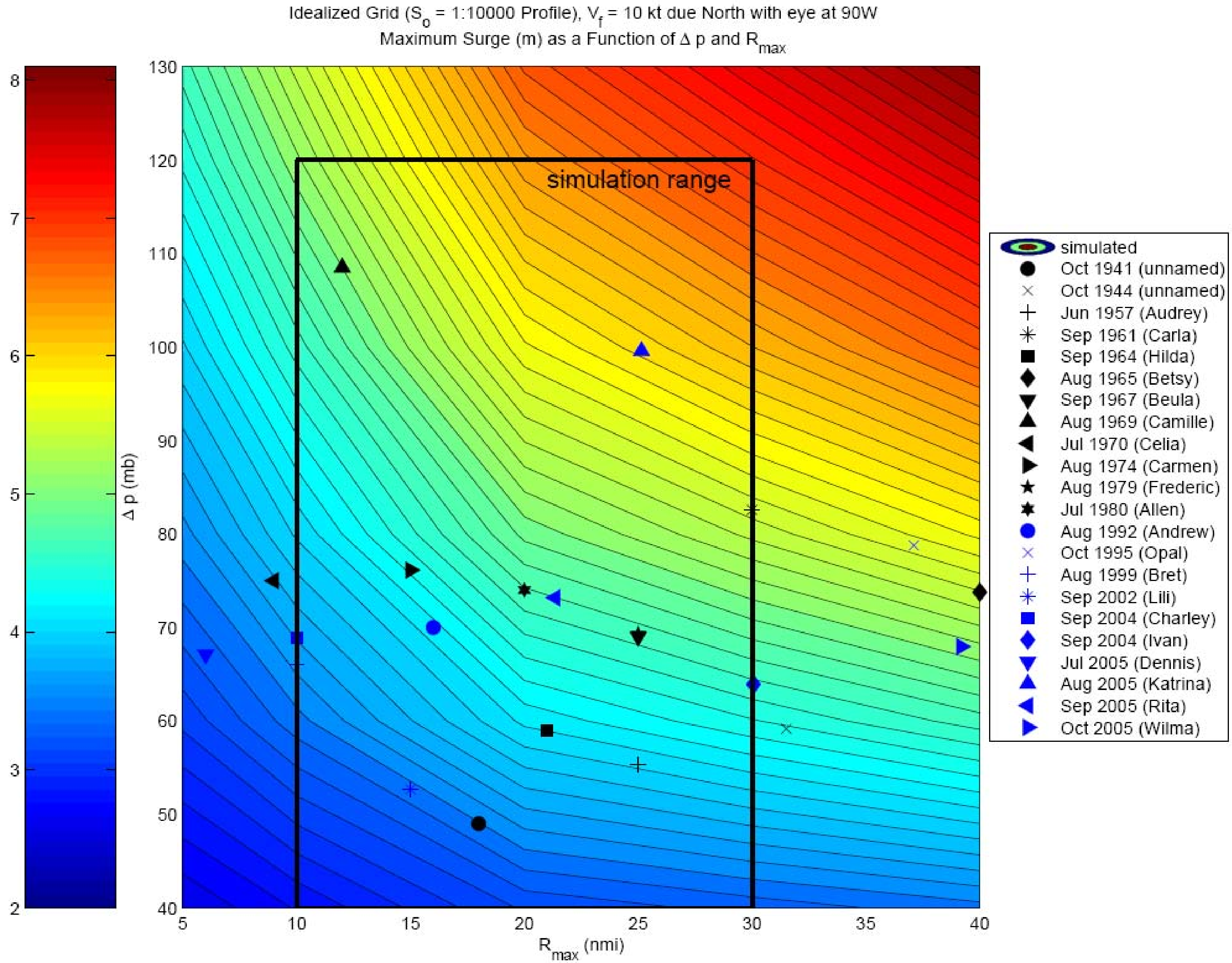
and

$$a = (0.035 + 0.0005\Delta P_0)$$

As has been typical of almost every relationship we have looked at it appears to exhibit a dependence on storm intensity.

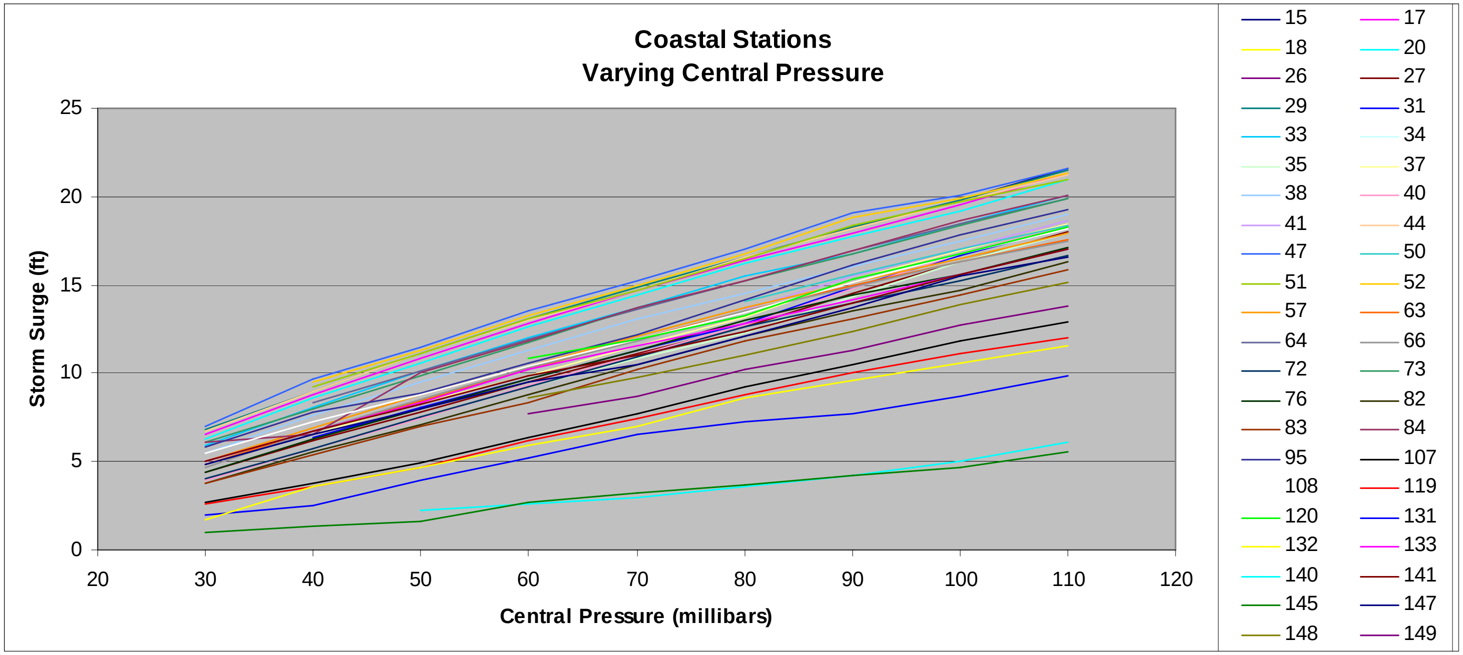


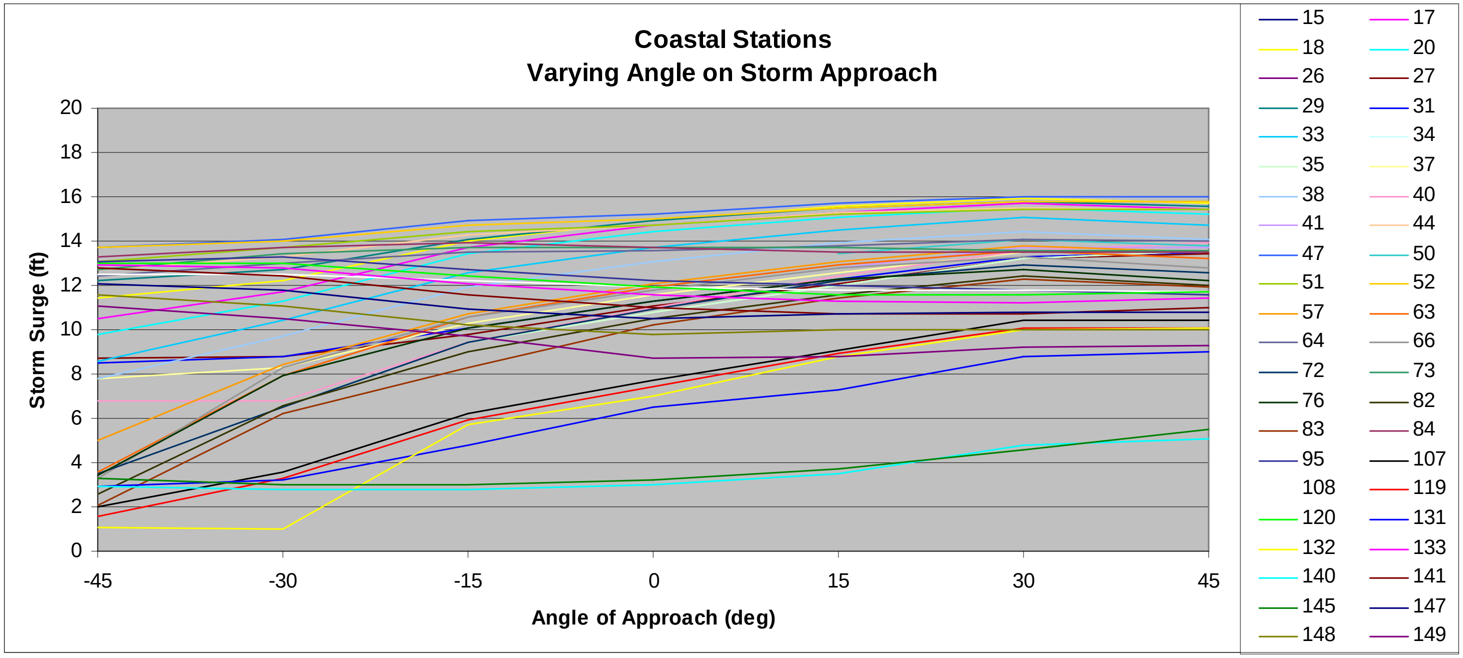
Variation in Rmax as a function of position relative to landfall. Small storms removed and only post-1980 storms included.

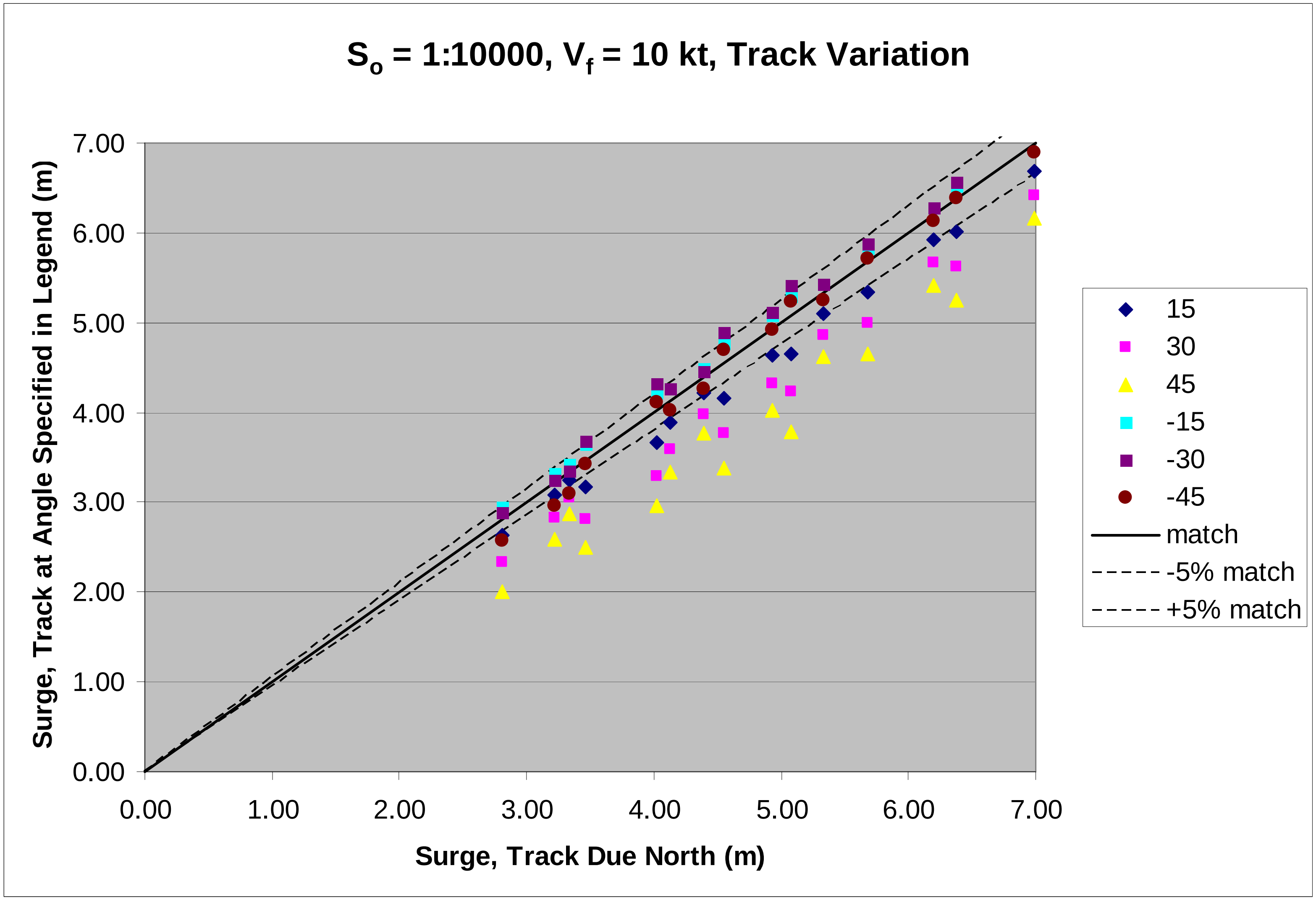


IRISH et al. (JPO – with revisions) showed that major response was Dp –Rp plane, not just storm intensity.

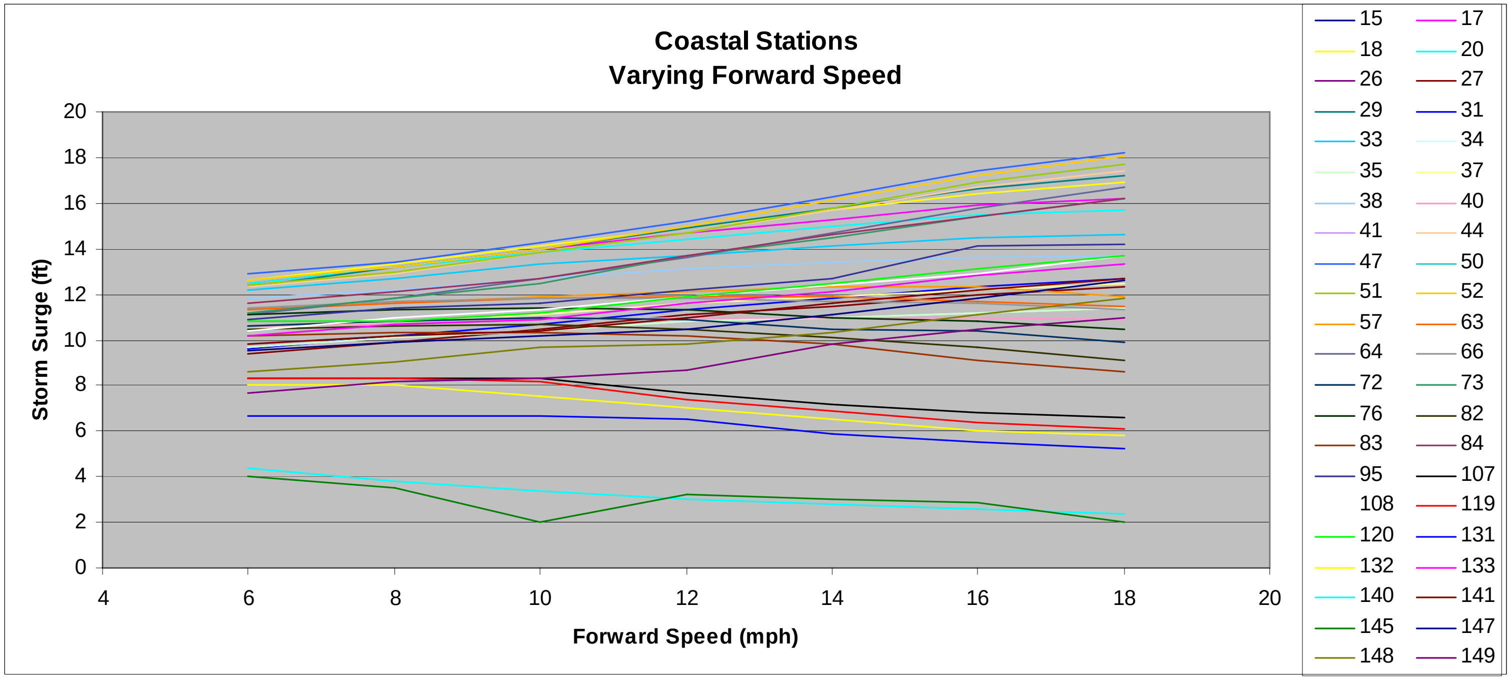
Some relevant information on surge behavior:







Irish analysis based on ADCIRC runs along idealized coast.



Forward storm speed was the least influential parameter in terms of resulting storm surge at the coast.

JPM method used by USACE – Region 6

This method is based on the analysis of response planes (from Irish study)

$$\Phi_2(\Delta P, R_p)$$

1. Define planes of surge response as a function of storm intensity and size. for each primary incoming track (RICKFAN set) at central speed.

2. Define differential response for primary +/- 45 degree tracks and apply as functional multiplier to estimate smooth response surface.

3. Define differential response for speed variations for each track, again apply as a multiplier to other response planes.

4. Add epsilon term when integrating.

```
 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 3 3 3 3 3 3 3 3 3 3 3 3 3 4 4 4 4 4 4 4 5 5
  2 2 2 2 2 2 2 2 2 2 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 4 4 4 4 4 4 4 5 5 5 5 5
  2 2 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 4 4 4 4 4 4 5 5 5 5 5 5 6 6
  3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 4 4 4 4 4 4 4 4 4 5 5 5 5 5 6 6 6 6 6
  3 3 3 3 3 3 3 3 3 3 3 3 3 3 4 4 4 4 4 4 4 4 4 4 4 4 4 4 5 5 5 5 5 6 6 6 6 6 7 7
  3 3 3 3 3 3 3 3 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 5 5 5 5 5 6 6 6 6 6 7 7 7 7
  3 3 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 5 5 5 5 5 5 6 6 6 6 6 7 7 7 7 8 8
  4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 5 5 5 5 5 5 5 5 5 5 5 6 6 6 6 7 7 7 7 8 8 8 8
  4 4 4 4 4 4 4 4 4 4 4 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 6 6 6 6 7 7 7 7 8 8 8 8 9 9
  4 4 4 4 4 4 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 6 6 6 6 6 7 7 7 7 8 8 8 9 9 9 9
  4 4 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 6 6 6 6 6 6 6 6 6 6 7 7 7 8 8 8 8 9 9 91010
  5 5 5 5 5 5 5 5 5 5 5 5 5 5 6 6 6 6 6 6 6 6 6 6 6 6 7 7 7 7 8 8 8 9 9 910101010
  5 5 5 5 5 5 5 5 5 5 6 6 6 6 6 6 6 6 6 6 6 6 6 6 7 7 7 7 8 8 8 8 9 9 91010101111
  5 5 5 5 5 5 6 6 6 6 6 6 6 6 6 6 6 6 6 6 7 7 7 7 7 7 7 8 8 8 9 9 9 9101010111111
  5 5 6 6 6 6 6 6 6 6 6 6 6 6 6 6 7 7 7 7 7 7 7 7 7 7 8 8 8 9 9 910101011111111212
  6 6 6 6 6 6 6 6 6 6 6 6 7 7 7 7 7 7 7 7 7 7 7 7 7 8 8 8 9 9 91010101111111121212
  6 6 6 6 6 6 6 6 7 7 7 7 7 7 7 7 7 7 7 7 7 8 8 8 8 8 8 9 9 9101010111111212121313
  6 6 6 6 6 7 7 7 7 7 7 7 7 7 7 7 7 8 8 8 8 8 8 8 8 8 9 9 910101011111121212131314
  6 6 7 7 7 7 7 7 7 7 7 7 7 7 8 8 8 8 8 8 8 8 8 8 8 9 9 91010101111112121213131414
  7 7 7 7 7 7 7 7 7 7 7 8 8 8 8 8 8 8 8 8 8 8 9 9 9 9 9101010111111212131313141415
  7 7 7 7 7 7 7 7 8 8 8 8 8 8 8 8 8 8 9 9 9 9 9 9 9 910101011111121213131314141515
  7 7 7 7 7 8 8 8 8 8 8 8 8 8 8 9 9 9 9 9 9 9 9 9 9101011111121213131314141515 16
  7 7 8 8 8 8 8 8 8 8 8 8 9 9 9 9 9 9 9 9 9 91010101011111212121313141415151616
  8 8 8 8 8 8 8 8 8 8 9 9 9 9 9 9 9 9 910101010101010111112121213131414151516161 7
  8 8 8 8 8 8 8 9 9 9 9 9 9 9 9 9 91010101010101010101011111212131314141515161617 17
  8 8 8 8 9 9 9 9 9 9 9 9 9 91010101010101010101010111111111121213131414151516161717 18
  8 8 9 9 9 9 9 9 9 9 910101010101010101010101111111111111212131314141515161617171818
```

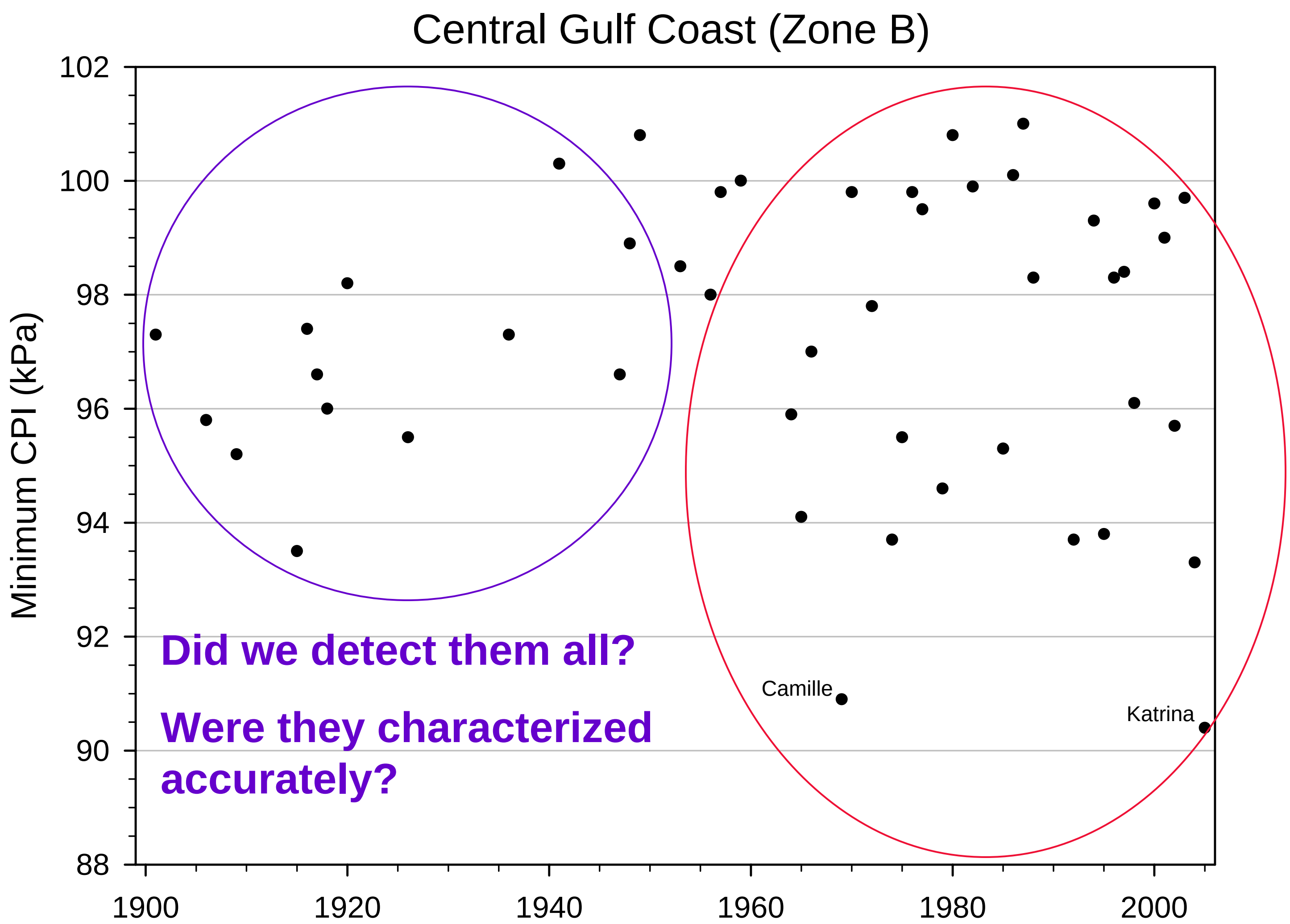
C_p (arrow pointing down)

R_p (arrow pointing right)

Example of a 2-D response plane in R,Dp.

What is the Future Hurricane Threat?

- **Are we adjusting to new information and understanding of the hurricane threat?**

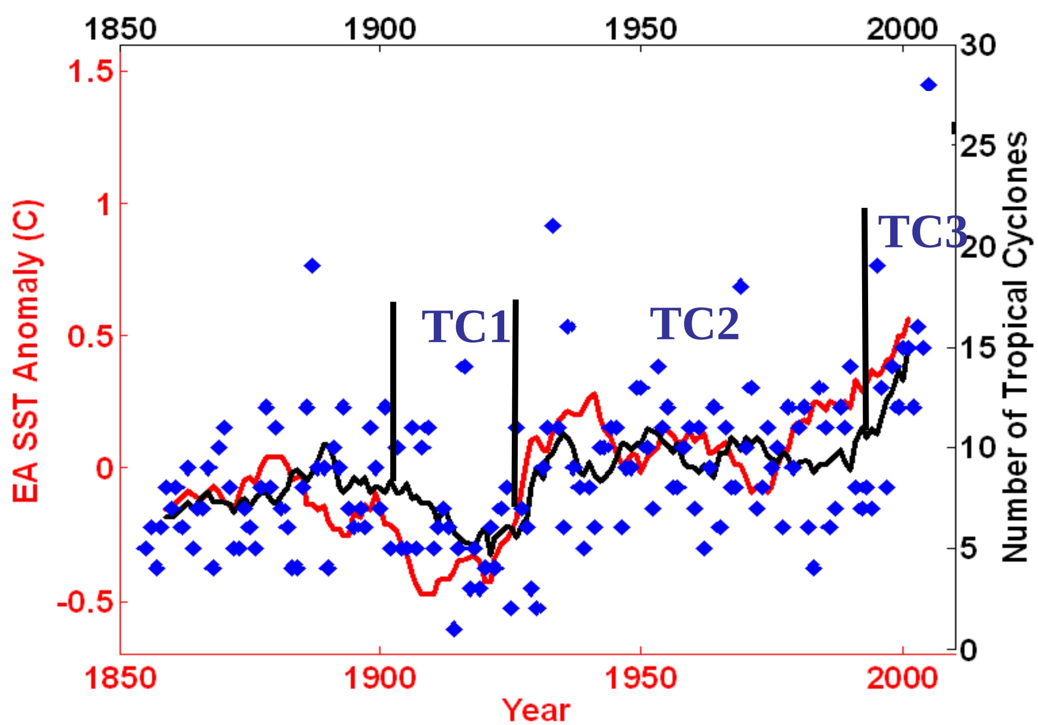


Higher storm frequency since 1960?

More intense storms?

Huge implications on level of protection provided by our projects and risk

TC Number-SST Relationship

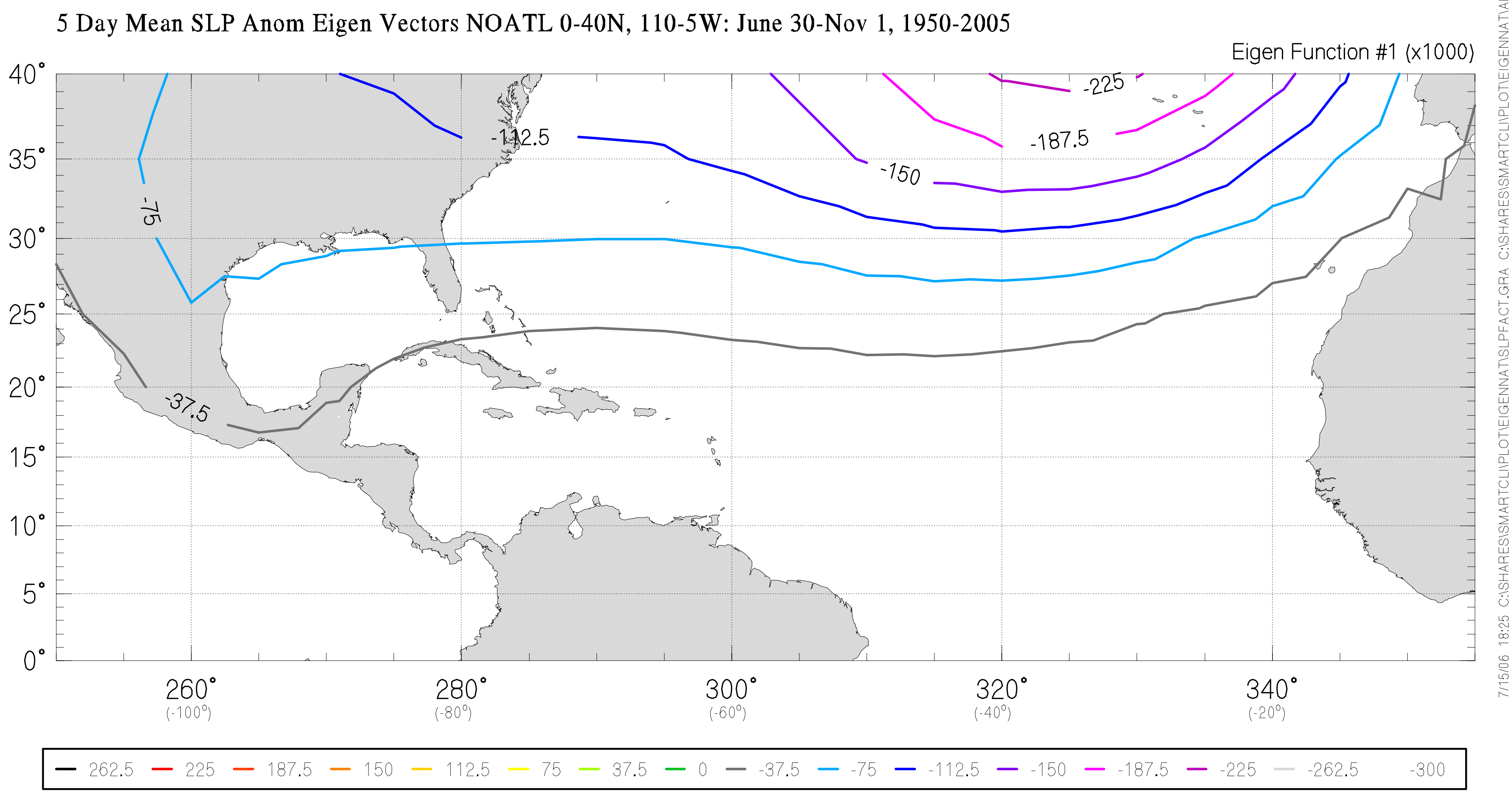


From: Holland and Webster, 2006.

Changes between TC climate regimes are accompanied by similar changes in eastern Atlantic SSTs;

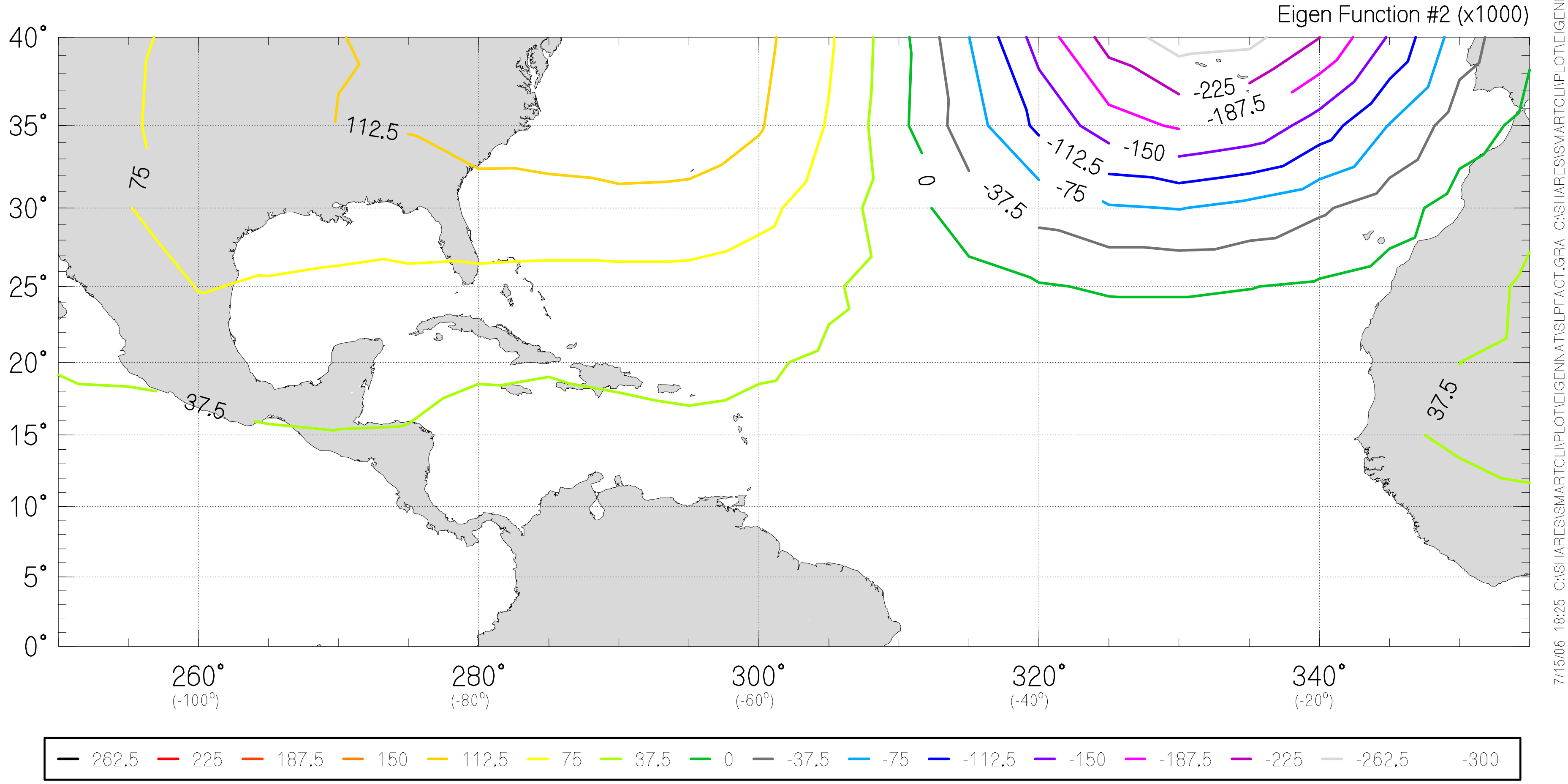
SST leads cyclone changes and explains >60% of the variance in TC numbers (due entirely to regime changes).

Have we entered a new climatic regime for hurricanes?? If so, what are the consequences on waves and surges in the Gulf of Mexico?

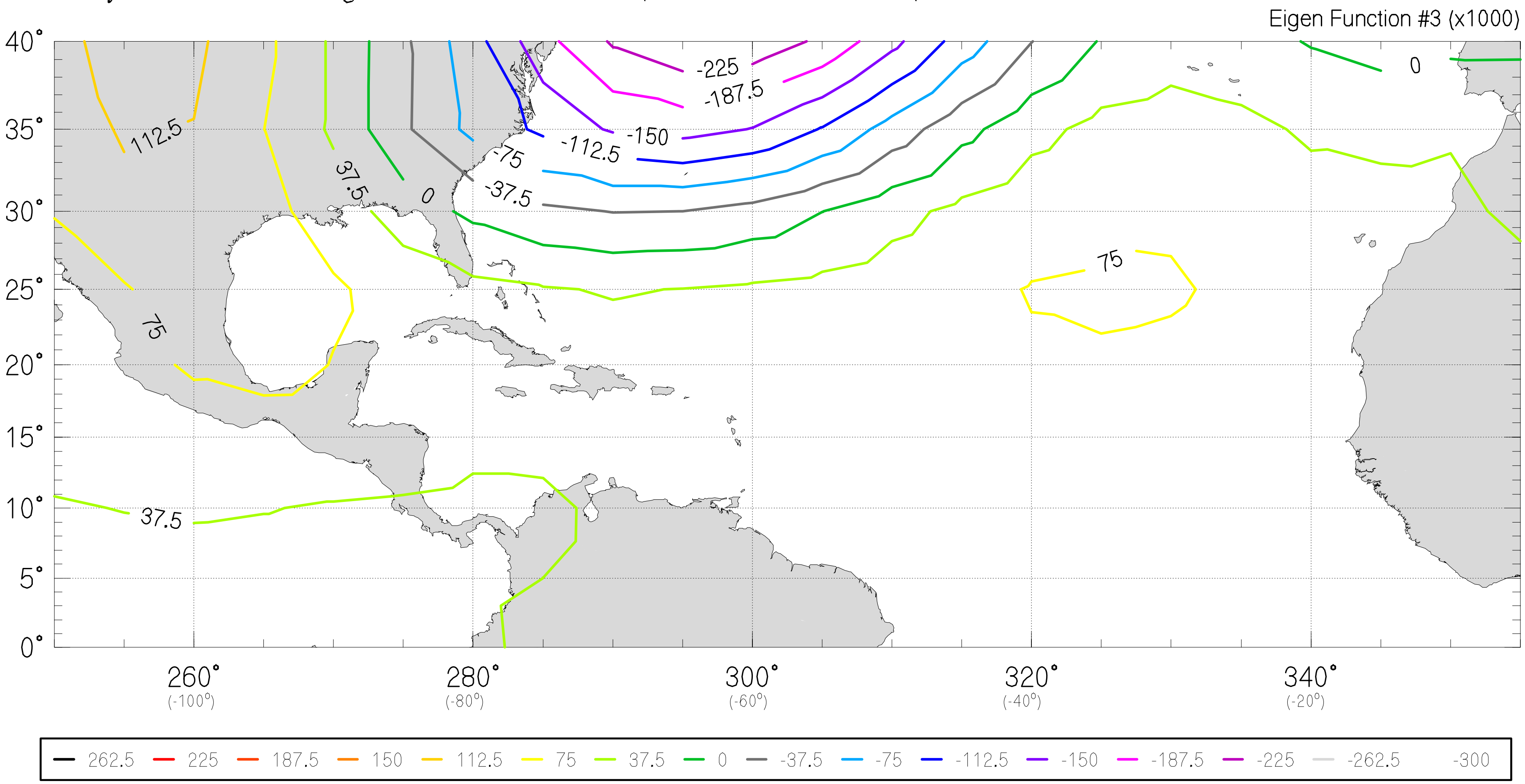


5 Day Mean SLP Anom Eigen Vectors NOATL 0-40N, 110-5W: June 30-Nov 1, 1950-2005
Eigen Function #1 (x1000)
40°
35°
30°
25°
20°
15°
10°
5°
0°
260°
(-100°)
280°
(-80°)
300°
(-60°)
320°
(-40°)
340°
(-20°)
-75
-112.5
-150
-187.5
-225
-37.5
262.5
225
187.5
150
112.5
75
37.5
0
-37.5
-75
-112.5
-150
-187.5
-225
-262.5
-300
7/15/06 18:25 C:\SHARES\SMARTCLI\PLOT\EIGENNAT\SLPFACT.GRA C:\SHARES\SMARTCLI\PLOT\EIGENNAT\ANOM5DA1.DT

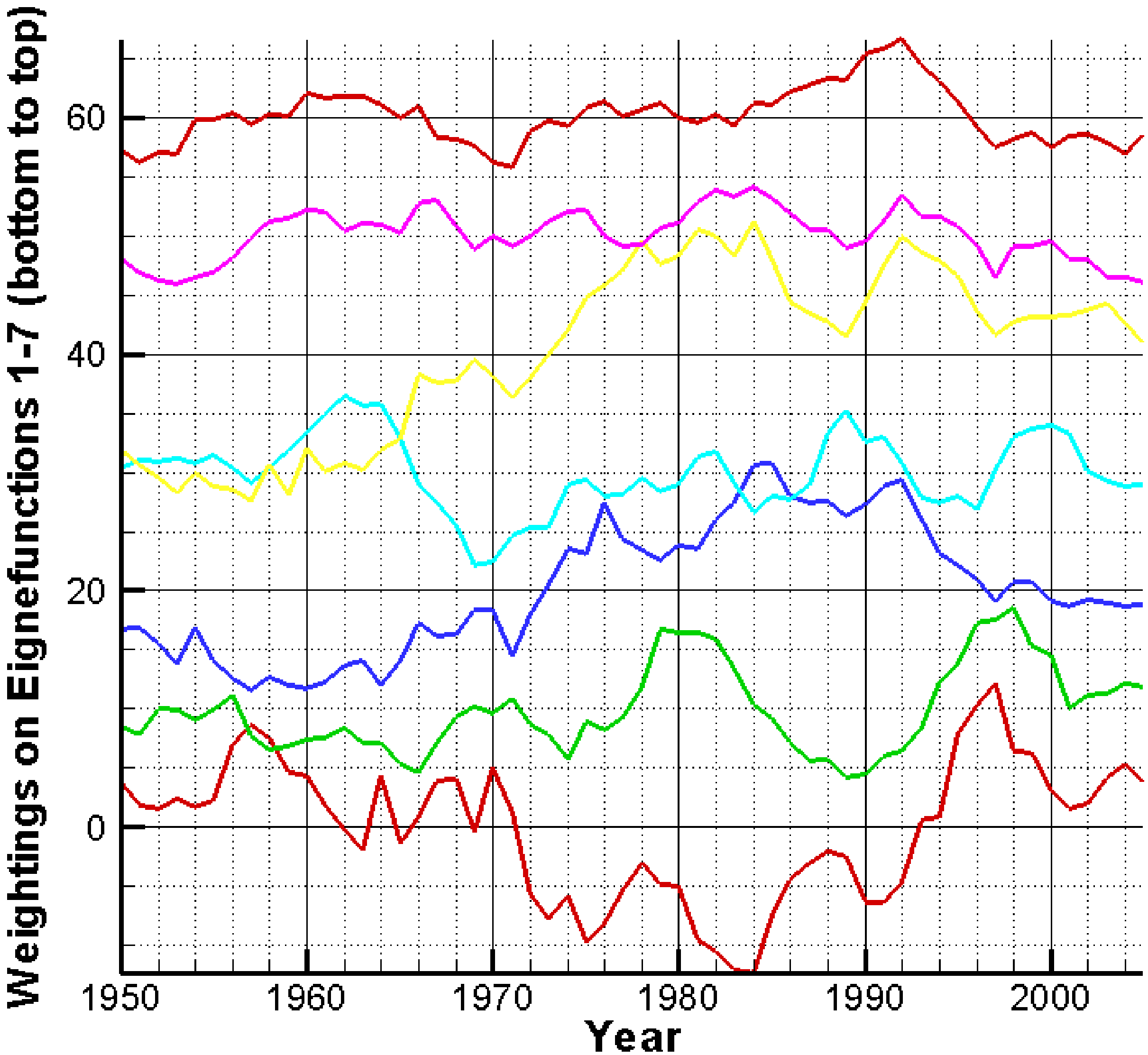
5 Day Mean SLP Anom Eigen Vectors NOATL 0-40N, 110-5W: June 30-Nov 1, 1950-2005



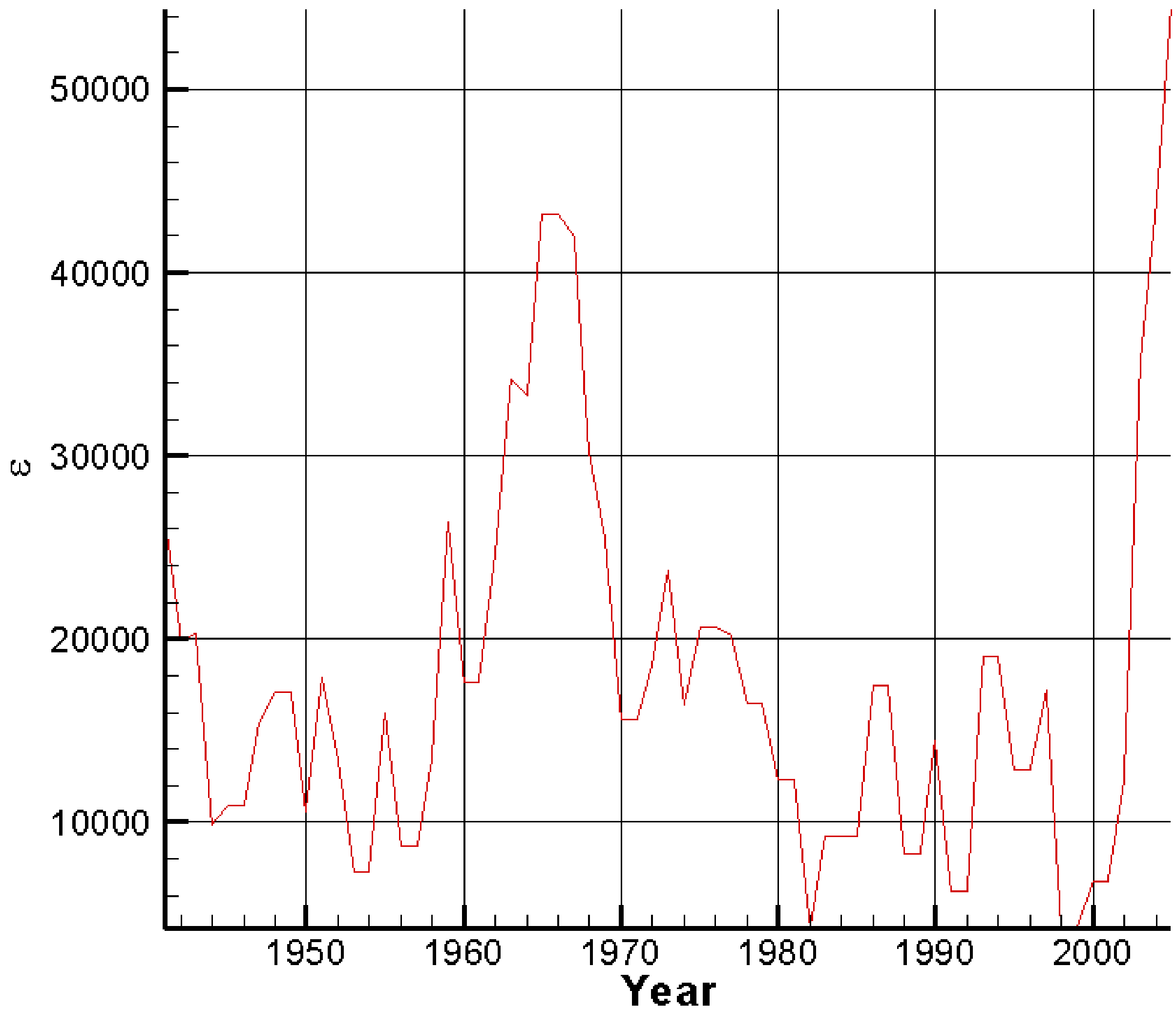
5 Day Mean SLP Anom Eigen Vectors NOATL 0-40N, 110-5W: June 30-Nov 1, 1950-2005



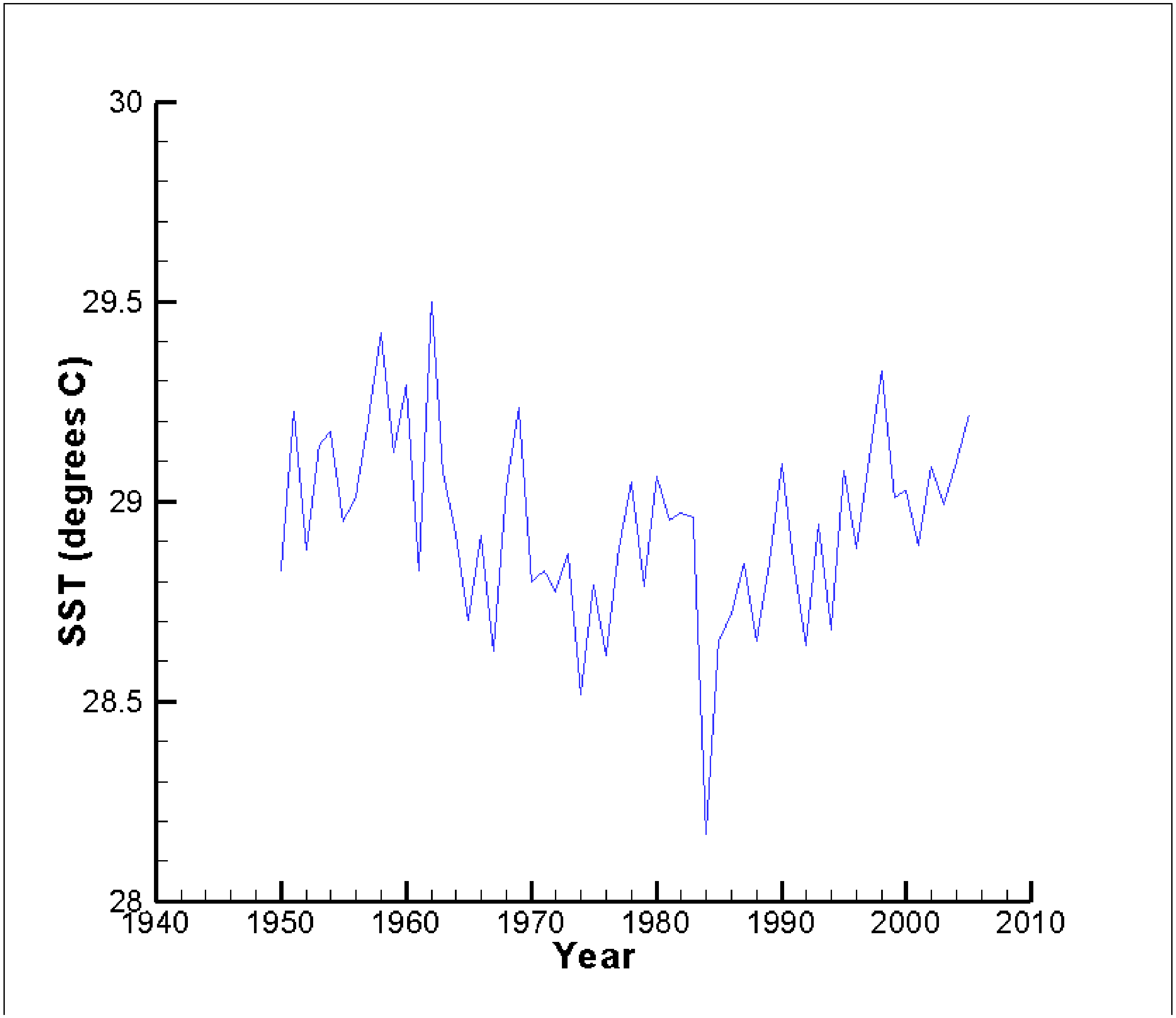
7/15/06 18:25 C:\SHARES\SMARTCLIPLOT\EIGENNAT\SLPFACT.GRA C:\SHARES\SMARTCLIPLOT\EIGENNAT\ANOM5DA3.DT



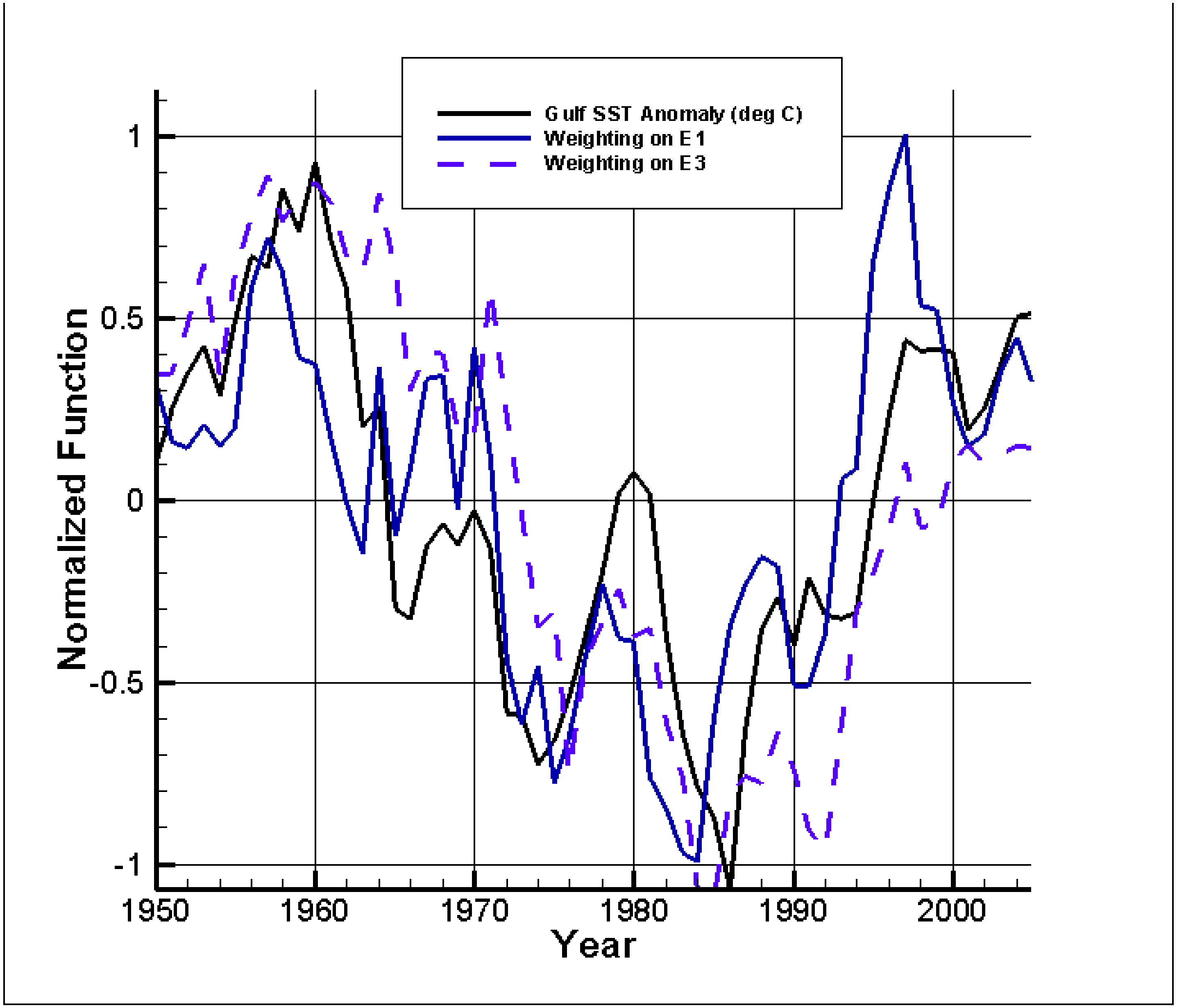
Very large decadal and longer scales of variation – not just a single cycle!!!!



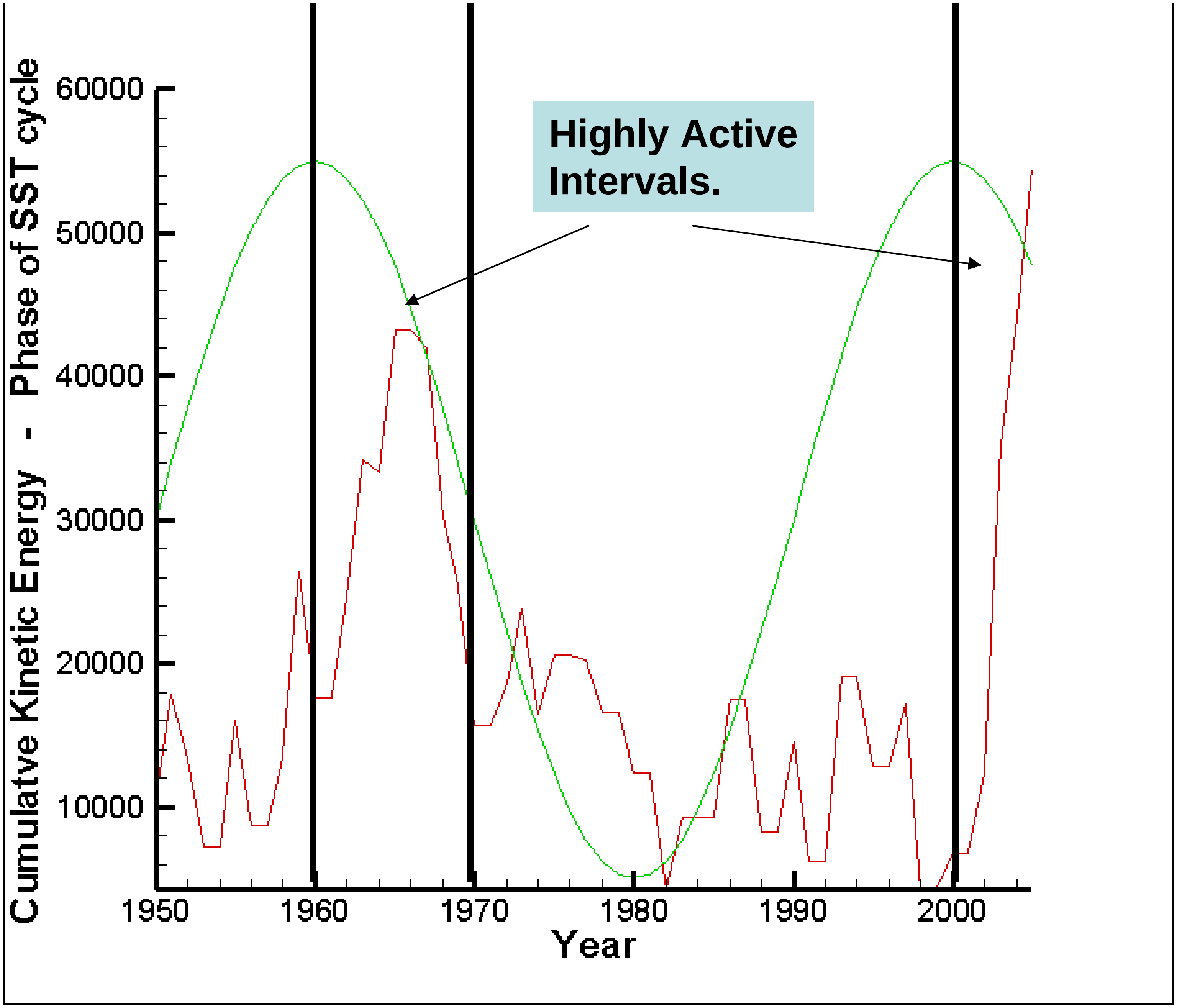
Variation in seasonal total kinetic energy in Gulf of Mexico



Variation of hurricane season Gulf of Mexico SST's 1950-2005



Weightings on Eigenfunctions 1 & 3 and SST with normalized ranges.



Total KE per season with 40-year cycle superimposed.

NOT A SIMPLE POISSON PROCESS!

Table 3. Landfalling central pressures for Group 1 and Group 2

Group 1 (39 years)			Group 2 (17 years)		
Year	Name	Central pressure (at landfall)	Year	Name	Central pressure (at landfall)
1957	Audrey	963.6	1961	Carla	936.4
1974	Carmen	942.8	1964	Hilda	960.0
1979	Frederic	949.7	1965	Betsy	945.2
1980	Allen	945.0	1967	Beulah	950.0
1992	Andrew	949.0	1969	Camille	905.8
1996	Opal	940.2	1970	Celia	944.0
1999	Earl	953.0	2002	Lili	966.3
			2004	Charley	950.2
			2004	Ivan	955.1
			2005	Dennis	951.9
			2005	Katrina	919.4
			2005	Rita	945.8
			2005	Wilma	951.1

If the distribution of x is influence by a "large-scale" variation then We can used a conditional probability integral to estimate p(x).

$$P(x) = \int P(x\,|\,\vec{S})\,p(\vec{S})\,d\vec{S} \qquad \approx \sum P(x\,|\,\vec{S}_k)\,p(\vec{S}_k)$$

For a discretized set of "populations" we can use the following form To estimate the return period T(x)

$$T(x) = \frac{1}{1 - \sum \lambda_n \beta_n F_n(x)}$$

where

λ_n is the frequency of storms in Group n

$F_n(x)$ is the cumulative distribution function (CDF) for storms in Group n

and β_n is the proportion of years in Group n

For the case where populations are identically distributed, we have

$$T(x) = \frac{1}{1 - F(x) \sum \lambda_n \beta_n}$$

where F(x) is the general CDF for all Groups.

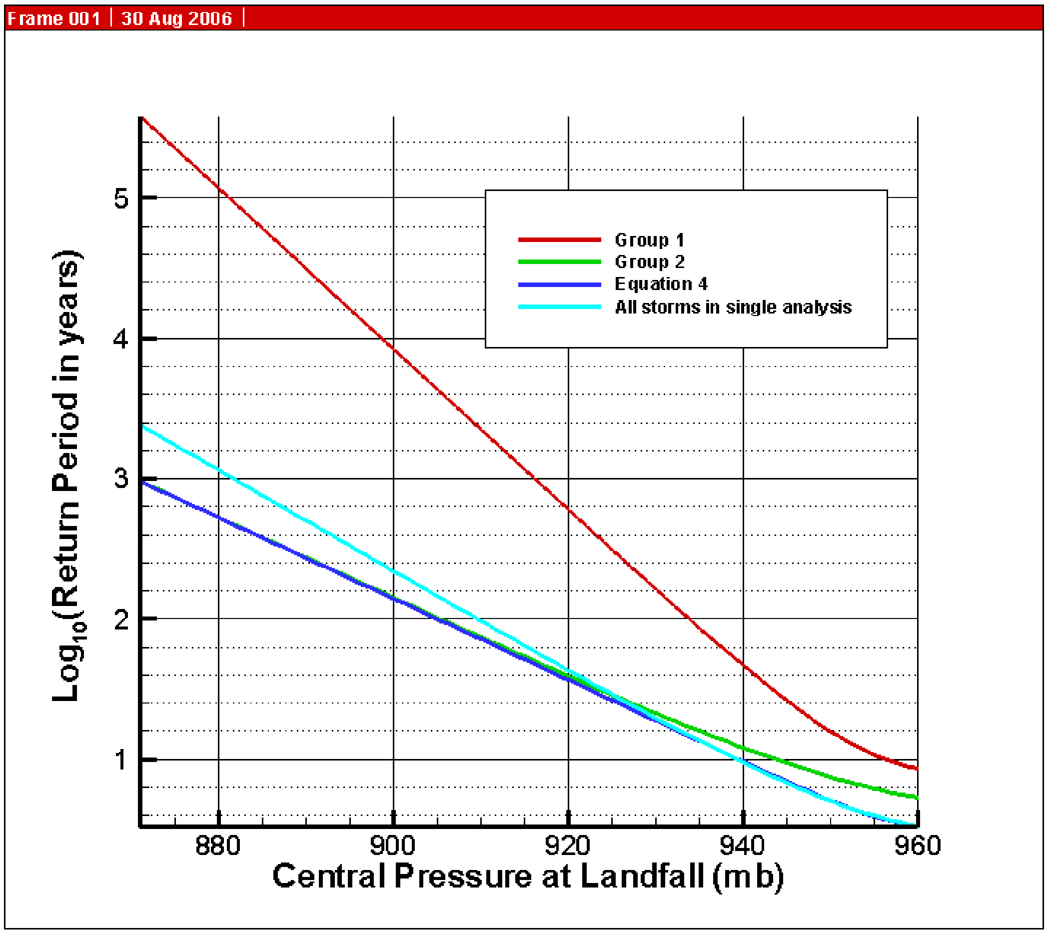
$$F(\hat{x}) = e^{-e^{-\hat{x}}}$$

GEV analysis of central pressures

where

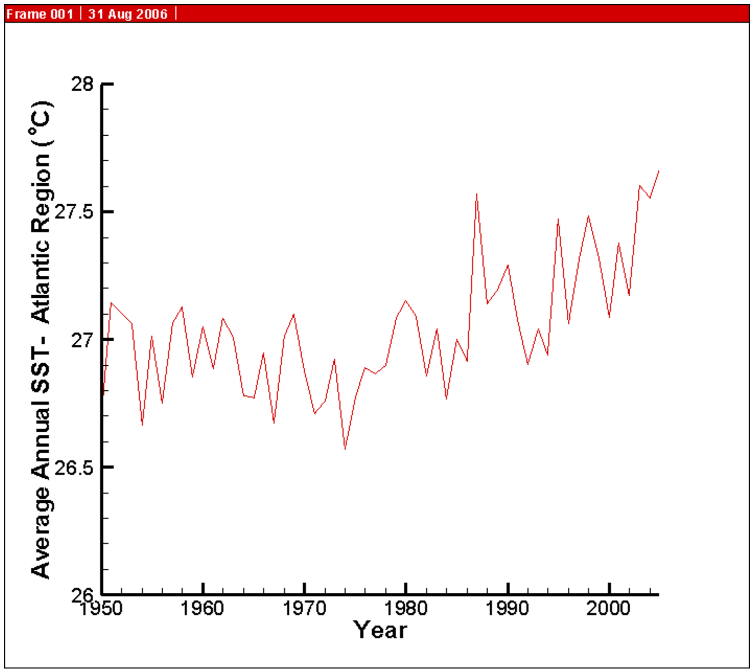
$$\hat{x} = A + B\left(\frac{1 - e^{-Cx}}{C}\right)$$

$$\hat{x} = \frac{x - a}{b}$$

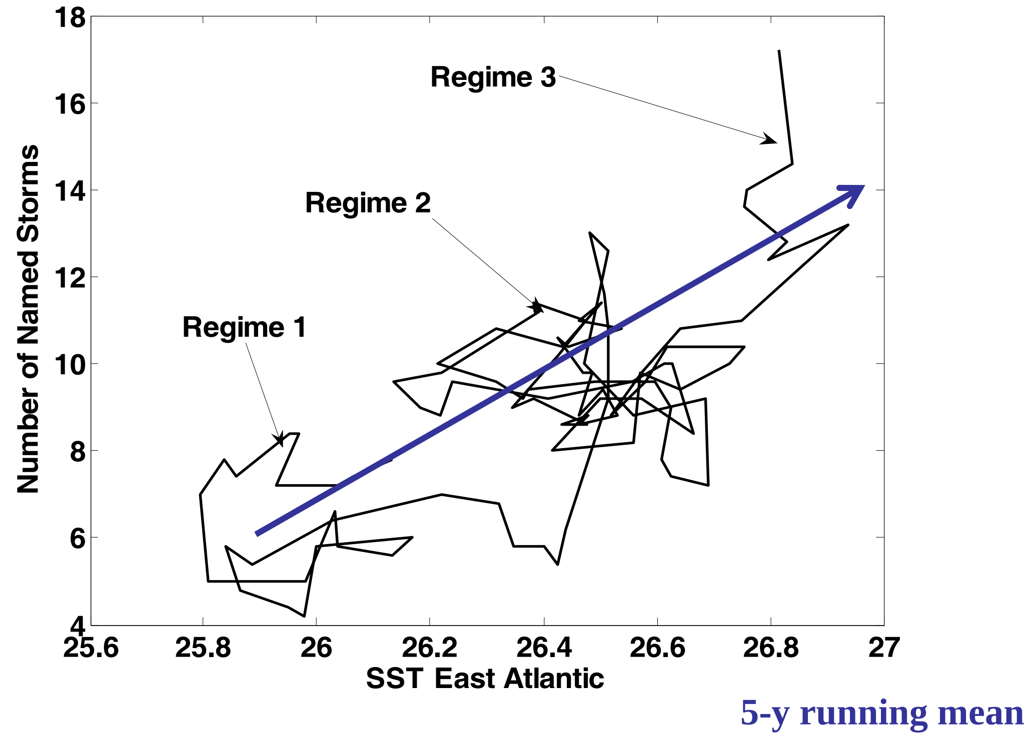


Extremes are dominated by "active-season" hurricanes.

Both the slope and the frequency of intense storms varies from one population to the other.

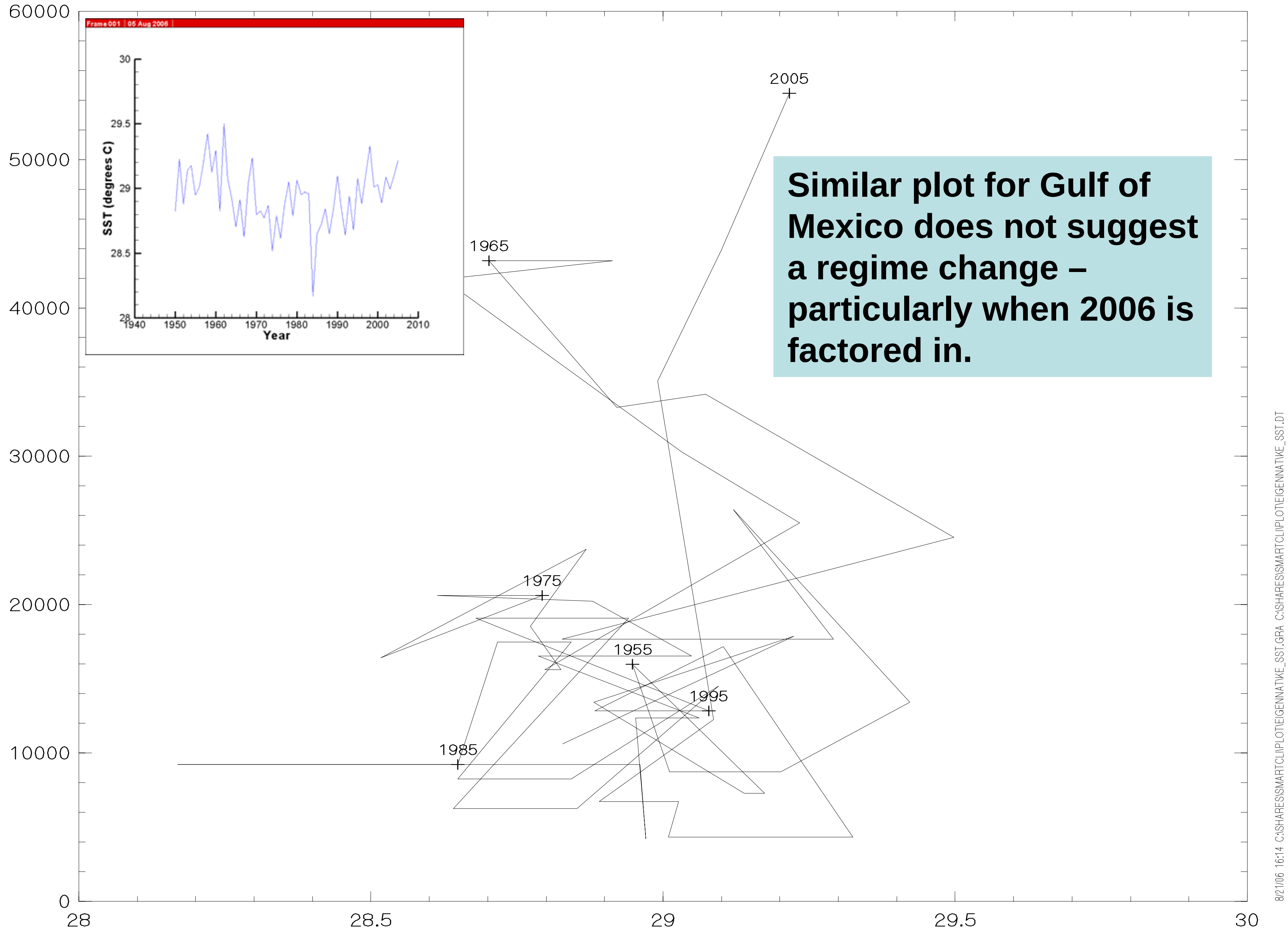


From Holland and Webster (2006)



The post-1980 SST warming provides a clear trend to the type of plot Used by Holland and Webster for showing potential transitions to alternative Regimes in tropical activity in the Atlantic Basin.

Cumulative Kinetic Energy vs. Sea Surface Temperature (deg C)



Similar plot for Gulf of Mexico does not suggest a regime change – particularly when 2006 is factored in.

Wave Scaling

$$H_{\max} \sim \frac{u_{\max}^{9/7}}{g^{2/7}} \left(< V_f - c_g > \right)^{5/7}$$

Surge Scaling

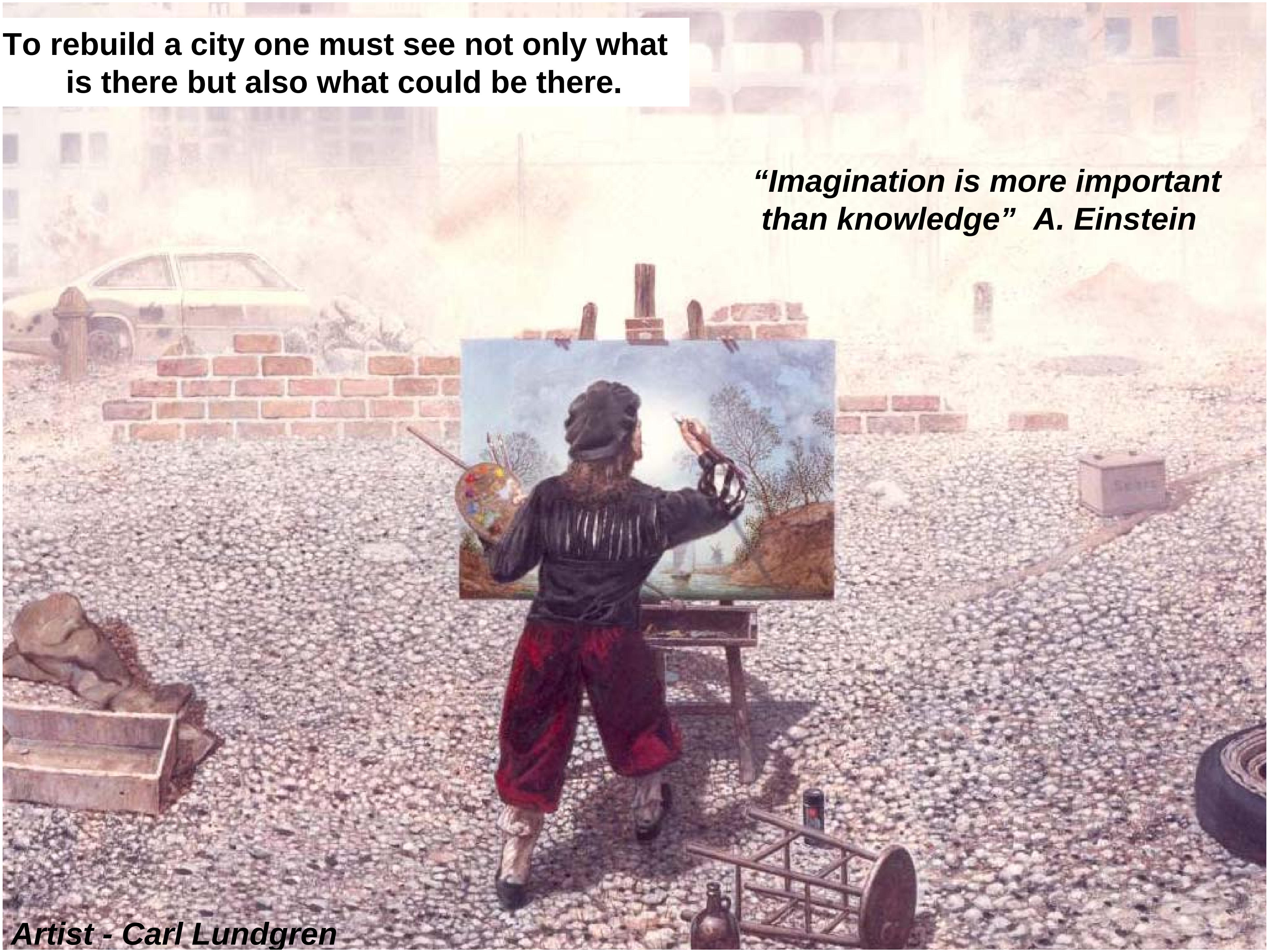
$$\eta_{\max} \sim \frac{u_{\max}^2}{g} \Psi(\hat{R}_{\max})$$

where $R_{\max}$ is a nondimensional storm size parameter, given by

$$R_{\max} = \frac{gR_{\max}}{u_{\max}^2}$$

Table 5. Estimated changes in extreme waves heights and surges for selected return periods, given a doubling of years with high hurricane activity.

Return Period (years)	Change in Wave Height (percent)	Change in surge (percent)
25	+15	+18
50	+13	+16
100	+12	+15
250	+11	+12
500	+10	+ 9


To rebuild a city one must see not only what is there but also what could be there.
"Imagination is more important than knowledge" A. Einstein
Artist - Carl Lundgren

We need to avoid more surprises from nature…..

Concept:

Teams of experts working in each field to "audit" each other's work.

To achieve our goal of risk evaluation we must carefully examine each risk element before it is put into a systems model.

For design, we must examine/validate/apply individual components rather than an entire system; otherwise, we will only find problems one at a time – provided that the elements can be analyzed in an uncoupled fashion.

$$F[\eta(x,t)_{in}] = \int \ldots \int H[\Lambda_{in}(\vec{Z},\vec{L}_e,\vec{L}_g,\vec{O}) + \varepsilon_Z + \varepsilon_{L_e} + \varepsilon_{L_g} + \varepsilon_O - \eta_{in}]$$
$$p(\vec{Z})\,p(\varepsilon_Z)\,p(\varepsilon_{L_e})\,p(\varepsilon_{L_g})\,p(\varepsilon_O)\,d\vec{Z}\,d\varepsilon_Z\,d\varepsilon_{L_e}\,d\varepsilon_{L_g}\,d\varepsilon_O$$

where

$\eta(x,y,t)_{in}$ is the level of flooding inside the protected area,

x,y, and t are the two horizontal spatial coordinates and t is time

H[arg] is the Heaviside function (=1 if arg ≥ 1; =0 otherwise)

Λ_{in} is an operator (model, set of equations, etc.) that links the set of input parameters to interior flooding levels;

$\vec{Z}$ is the vector of elements used to define the storm threat (including static levee characteristics);

$\vec{L}_e$ is the vector of elements used to define the susceptibility of interior flooding to erosional failures;

$\vec{L}_g$ is the vector of elements used to define the susceptibility of interior flooding to geotechnical failures;

$\vec{O}$ is the vector of elements used to define the susceptibility of interior flooding to operational failures;

ε_Z is the uncertainty in the storm threat;

ε_e is the uncertainty in the erosional susceptibility;

ε_g is the uncertainty in the geotechnical susceptibility; and

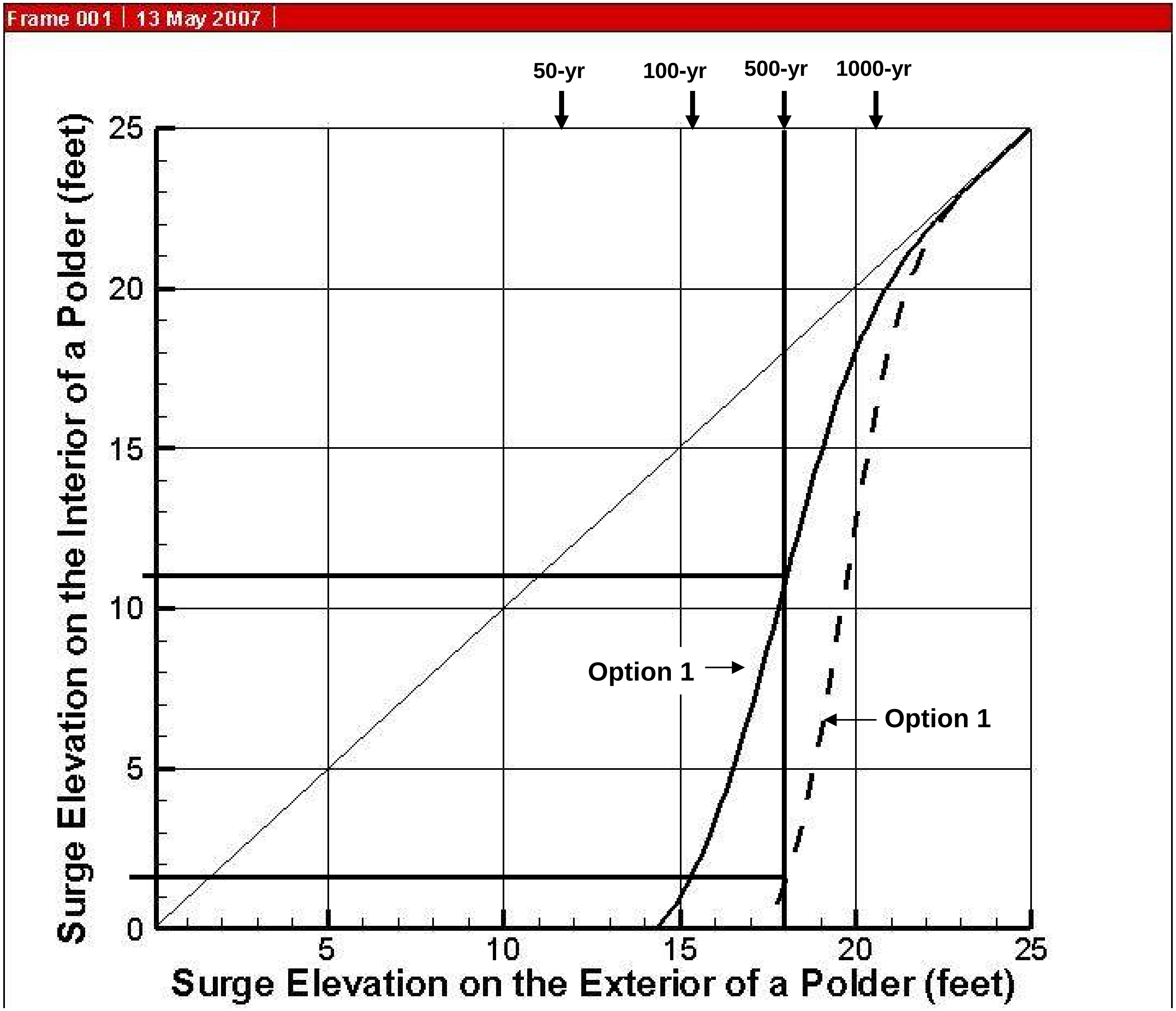
ε_O is the uncertianty in the operational susceptibility.

Estimation of interior flooding for simple case of a single polder.

[redacted]

Previous Slide Showed inside of “black box” at 1:100 scale.

Sometimes when a system becomes to complex it is critical to have some simpler (yet accurate) methods to “cross-check” the complex system. This is particularly important when there are no obvious physical constraints on model functions.



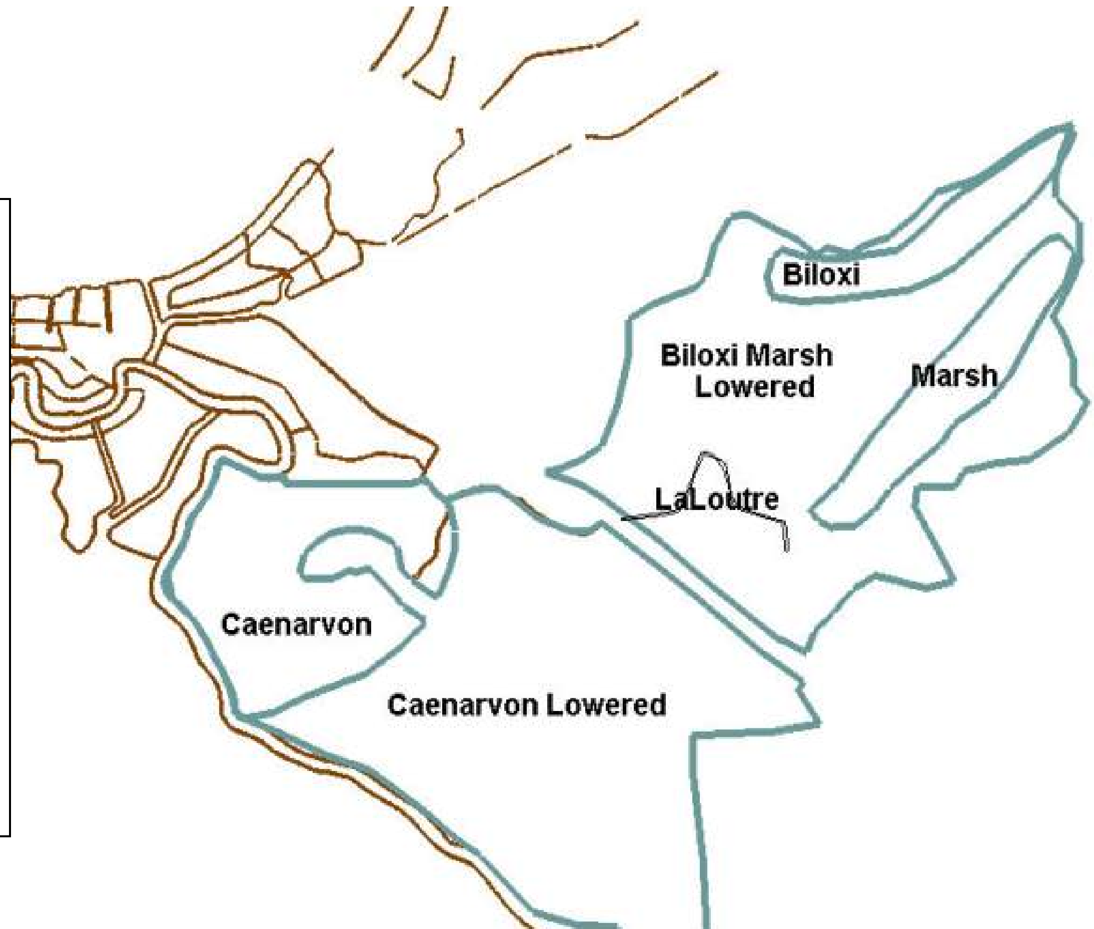
The ability to link exterior and interior water levels in an equivalent "rank ordering" system means that the time factor for interior floods is inherent in the "matching" exterior water level.

Questions???

Modifications to Storm Surge and Waves by Marsh Restoration and Degradation

Landscape Changes

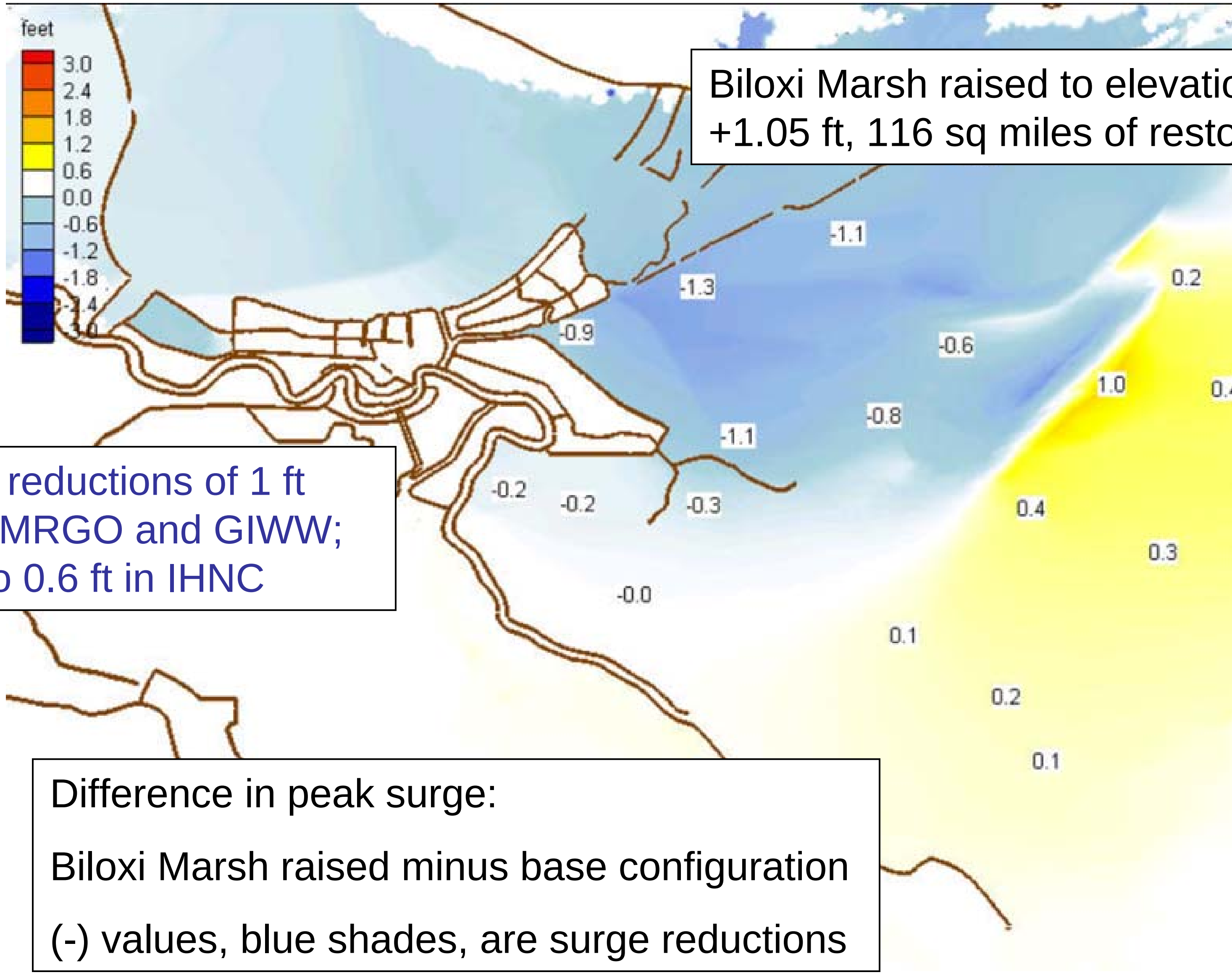
- Biloxi Marsh raised to elev +1.05 ft, 116 sq mi restored
- Biloxi Marsh lowered to elev -2.0 ft, 507 sq mi degraded
- La Loutre Ridge raised to elev +7 ft, 2 to 3 sq mi restored
- Caenarvon Marsh raised to elev +1.05 ft, 155 sq mi restored
- Caenarvon Marsh lowered to elev -2.0 ft, 620 sq mi degraded



Simulated by changing marsh elevation and surface roughness, elev in NAVD88 2004.65

Surge and wave simulations made using Katrina intensity and track and IPET models; Surge levels include regional contribution of wave set-up

Effect of Raising Biloxi Marsh on Storm Surge



Biloxi Marsh raised to elevation +1.05 ft, 116 sq miles of restoration

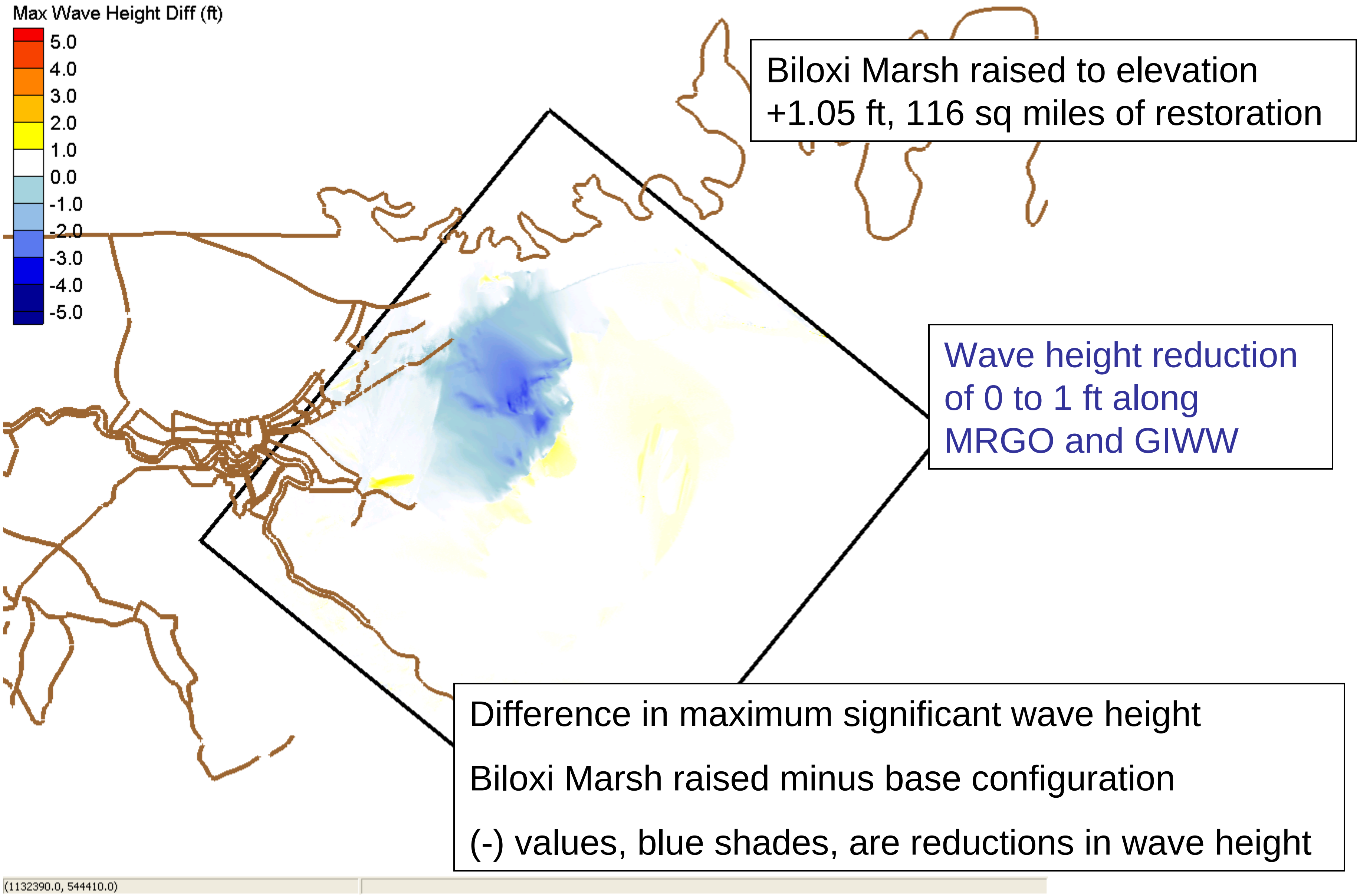
Surge reductions of 1 ft along MRGO and GIWW; zero to 0.6 ft in IHNC

Difference in peak surge:

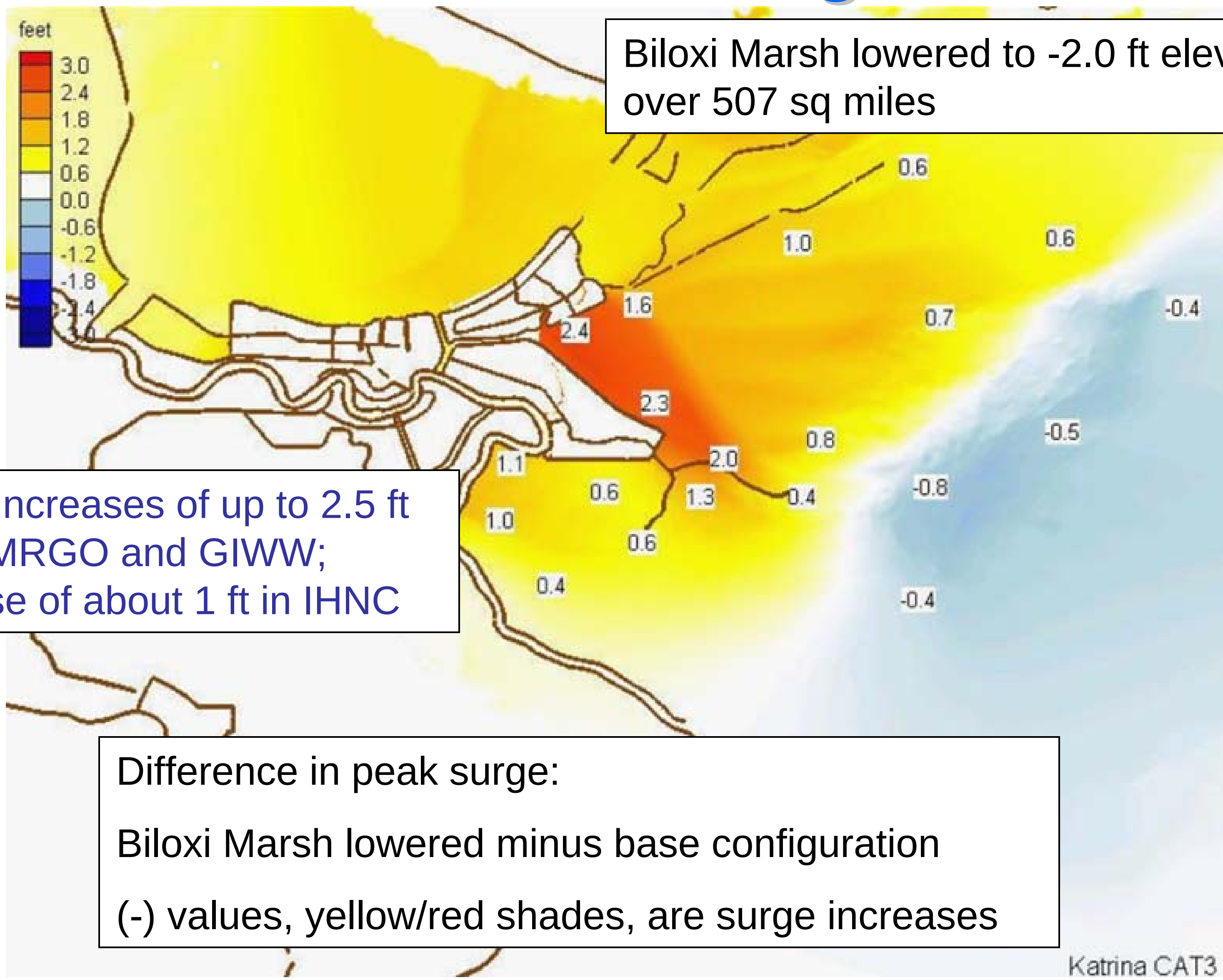
Biloxi Marsh raised minus base configuration

(-) values, blue shades, are surge reductions

Effect of Raising Biloxi Marsh on Storm Waves



Effect of Lowering Biloxi Marsh on Storm Surge



Biloxi Marsh lowered to -2.0 ft elevation, over 507 sq miles

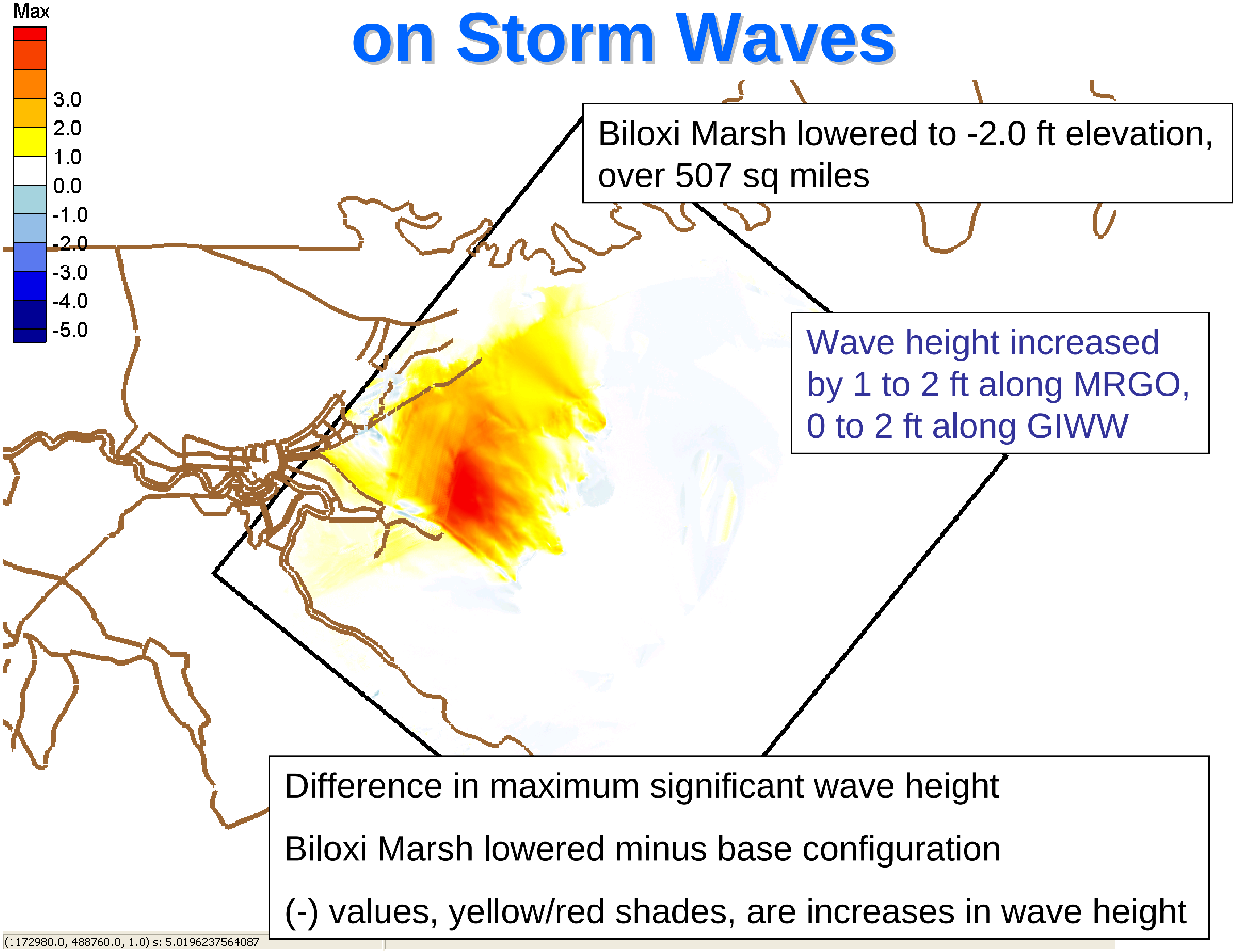
Surge increases of up to 2.5 ft along MRGO and GIWW; increase of about 1 ft in IHNC

Difference in peak surge:

Biloxi Marsh lowered minus base configuration

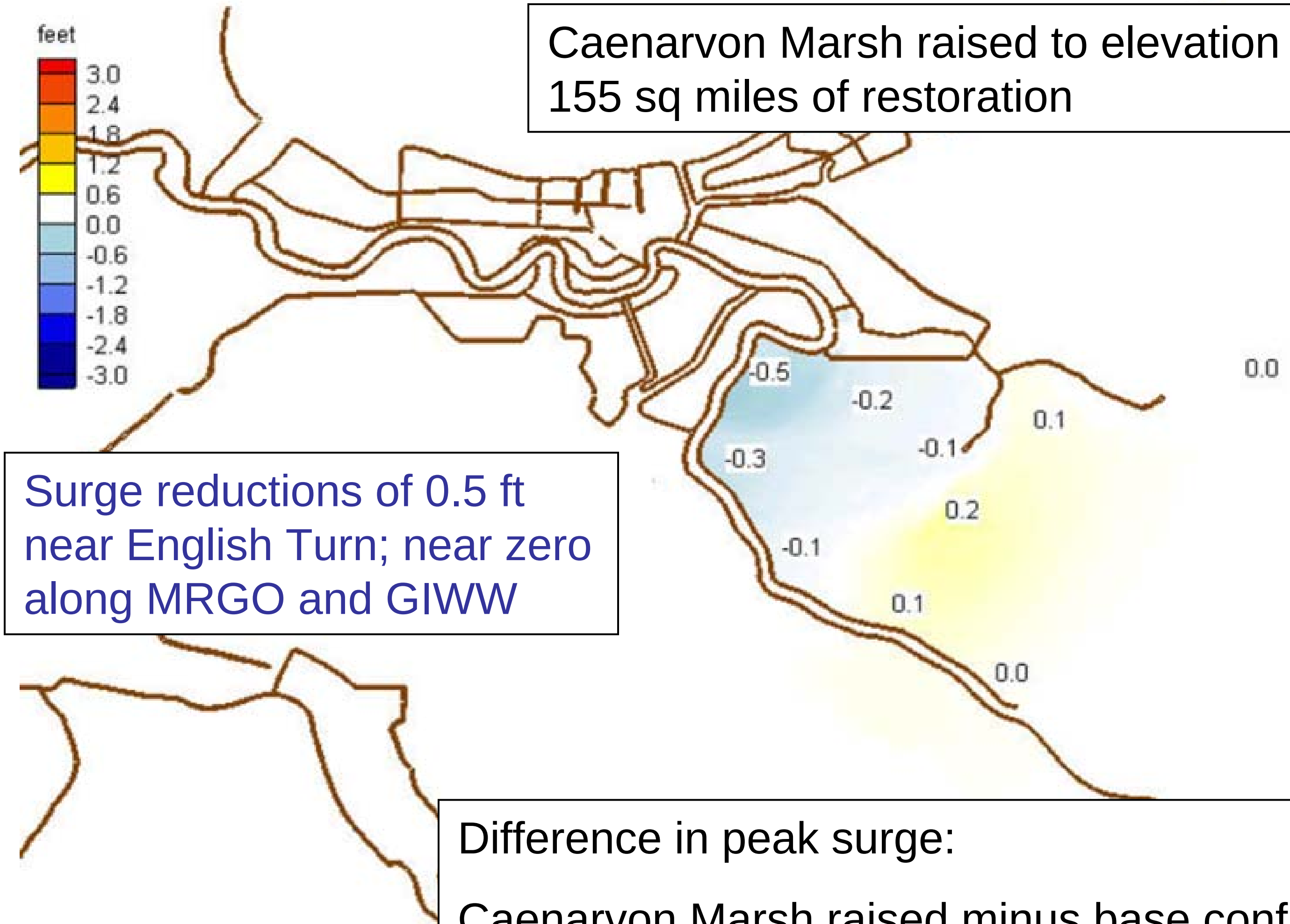
(-) values, yellow/red shades, are surge increases

Effect of Lowering Biloxi Marsh on Storm Waves



Effect of Raising Marsh at Caenarvon on Storm Surge

Caenarvon Marsh raised to elevation +1.05 ft, 155 sq miles of restoration



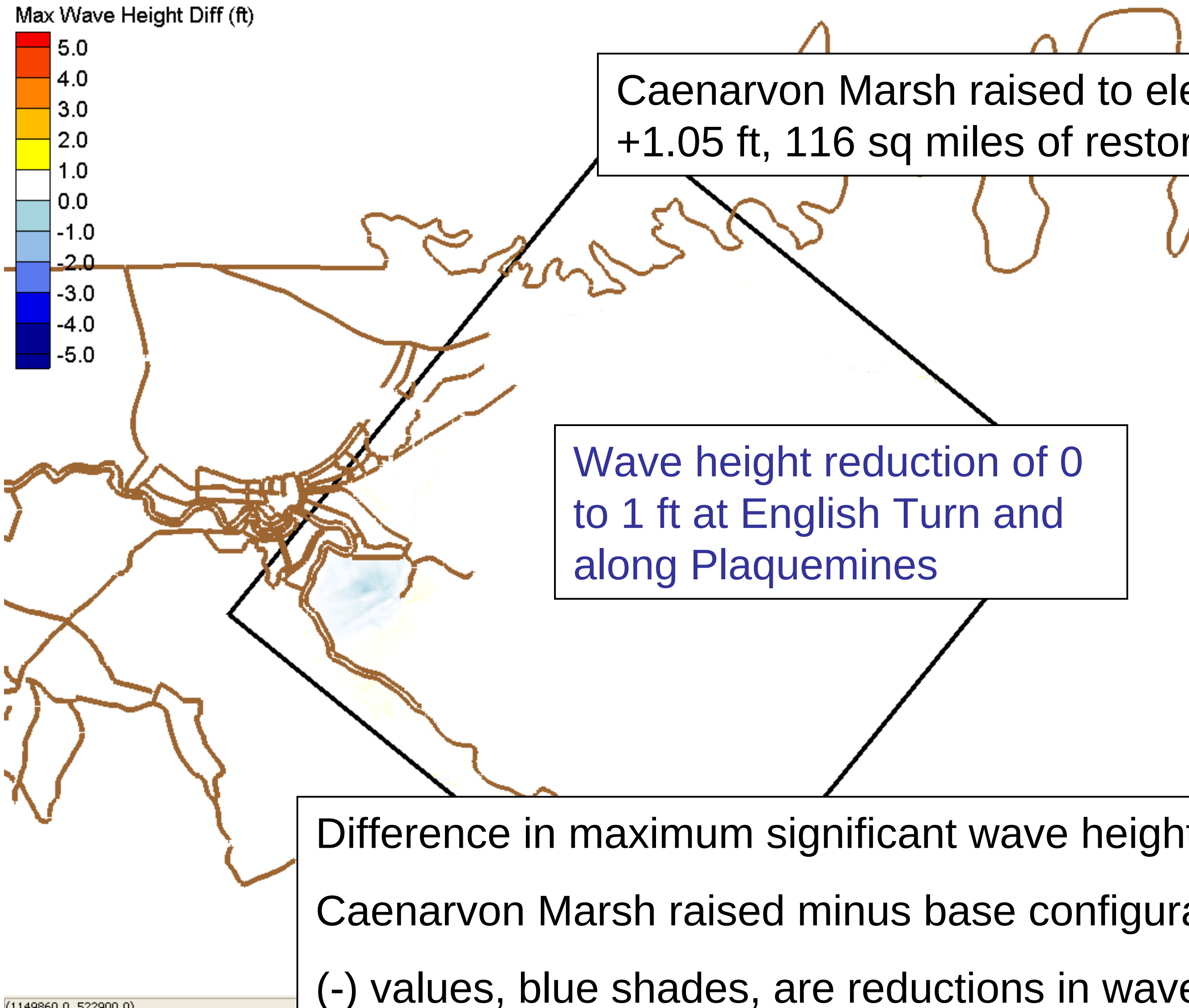
Surge reductions of 0.5 ft near English Turn; near zero along MRGO and GIWW

Difference in peak surge:

Caenarvon Marsh raised minus base configuration

(-) values, blue shades, are surge reductions

Effect of Raising Caenarvon Marsh on Storm Waves



Caenarvon Marsh raised to elevation +1.05 ft, 116 sq miles of restoration

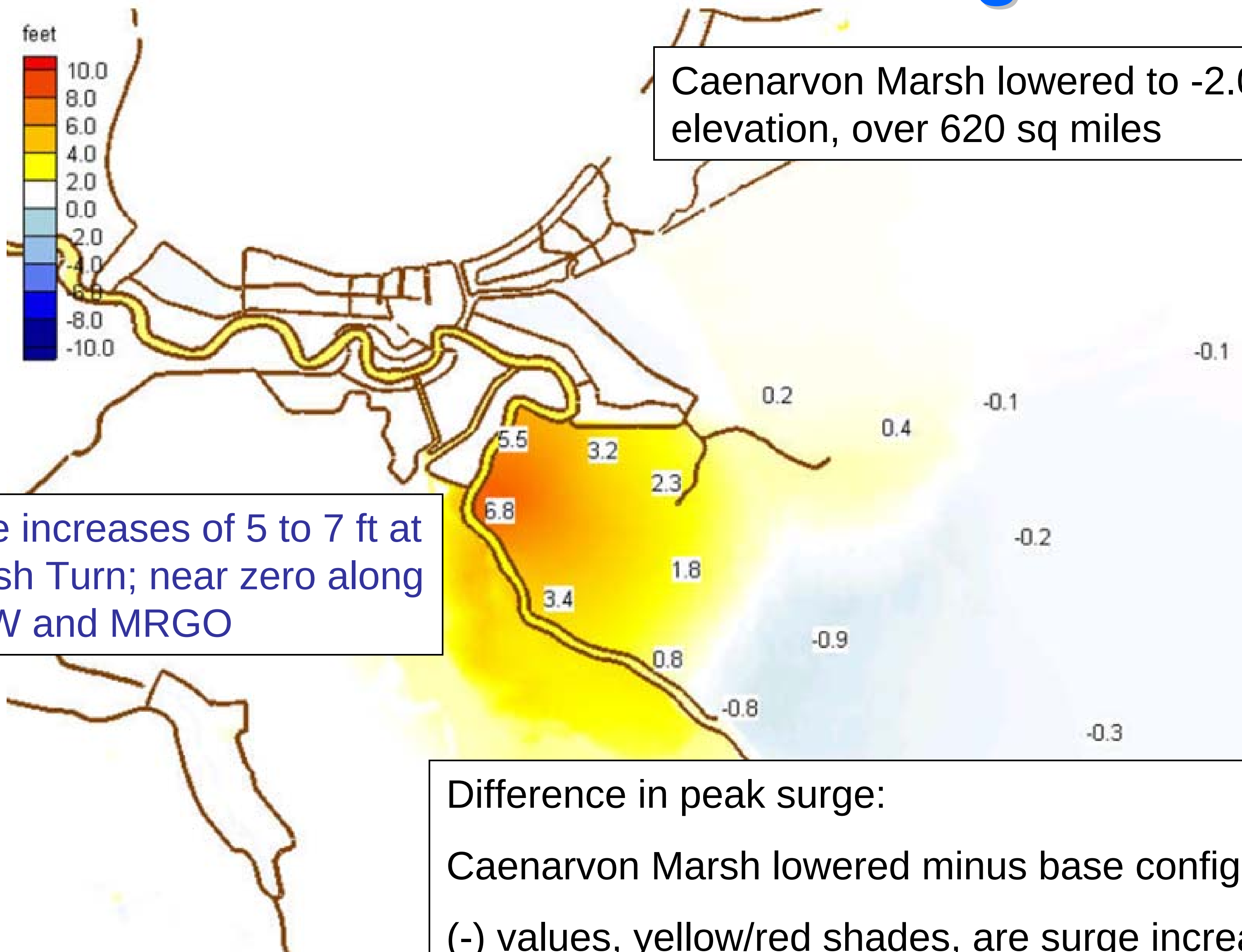
Wave height reduction of 0 to 1 ft at English Turn and along Plaquemines

Difference in maximum significant wave height

Caenarvon Marsh raised minus base configuration

(-) values, blue shades, are reductions in wave height

Effect of Lowering Caenarvon Marsh on Storm Surge



Caenarvon Marsh lowered to -2.0 ft elevation, over 620 sq miles

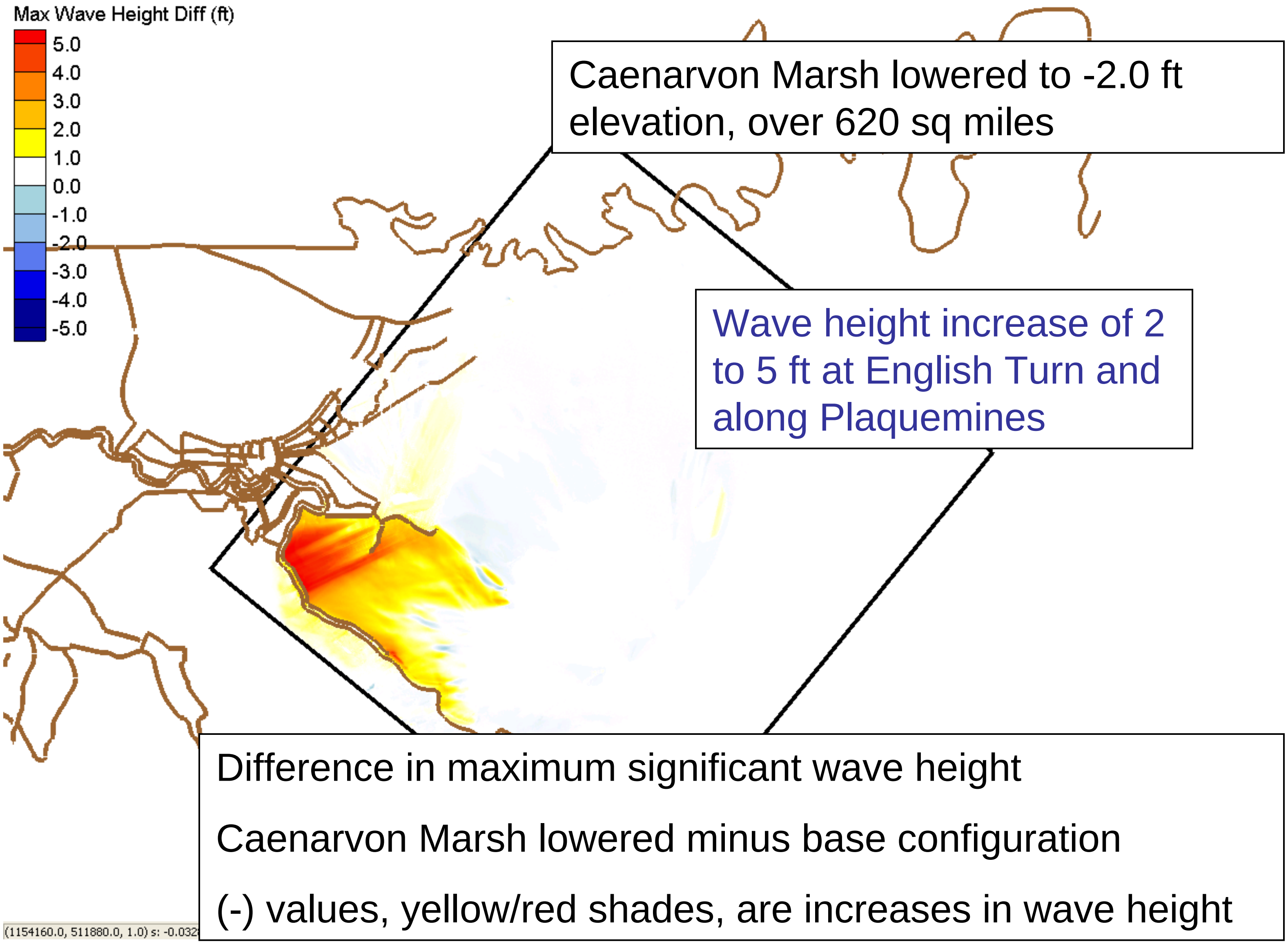
Surge increases of 5 to 7 ft at English Turn; near zero along GIWW and MRGO

Difference in peak surge:

Caenarvon Marsh lowered minus base configuration

(-) values, yellow/red shades, are surge increases

Effect of Lowering Caenarvon Marsh on Storm Waves



Caenarvon Marsh lowered to -2.0 ft elevation, over 620 sq miles

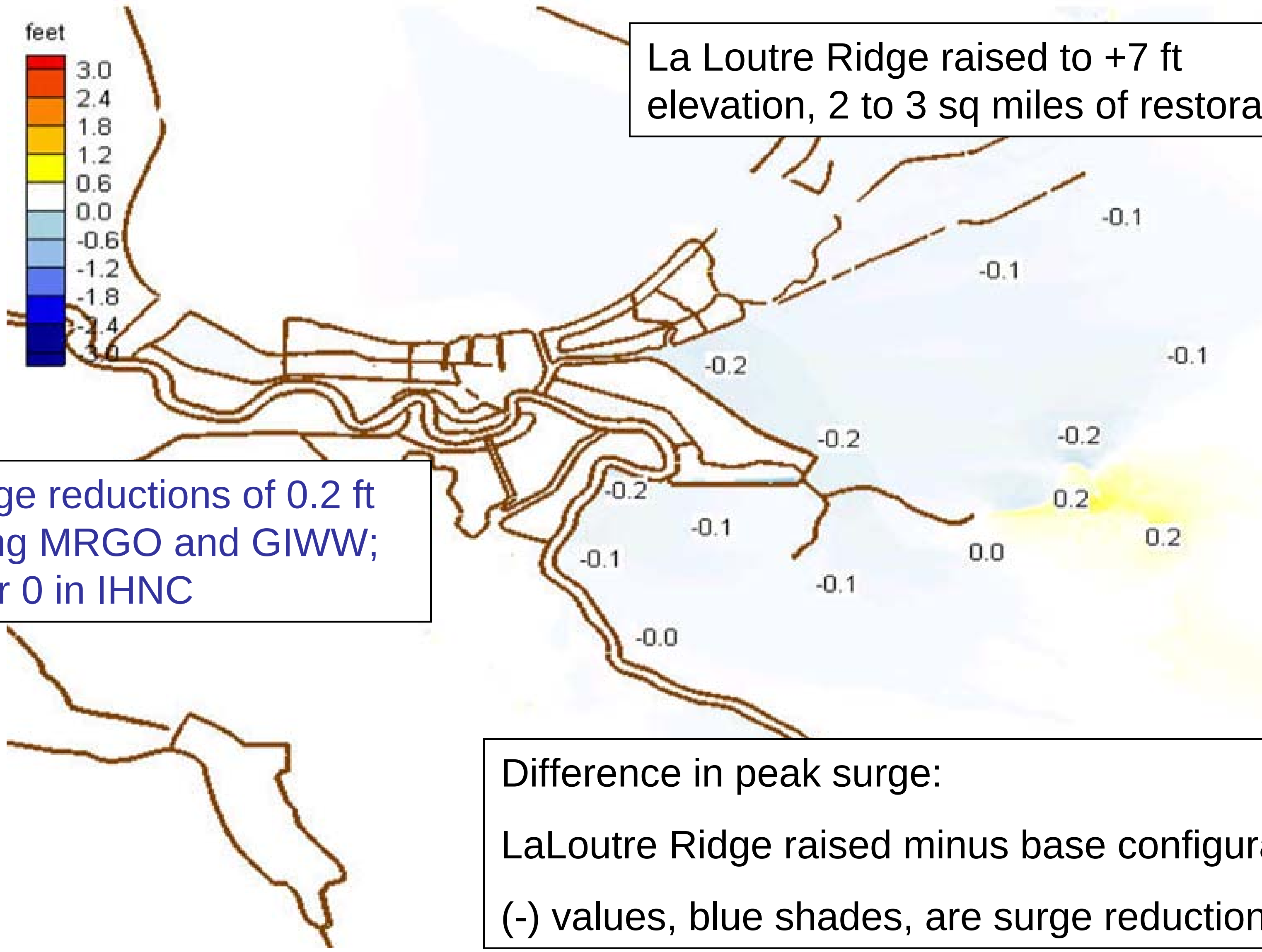
Wave height increase of 2 to 5 ft at English Turn and along Plaquemines

Difference in maximum significant wave height

Caenarvon Marsh lowered minus base configuration

(-) values, yellow/red shades, are increases in wave height

Effect of Raising la Loutre Ridge on Storm Surge



La Loutre Ridge raised to +7 ft elevation, 2 to 3 sq miles of restoration

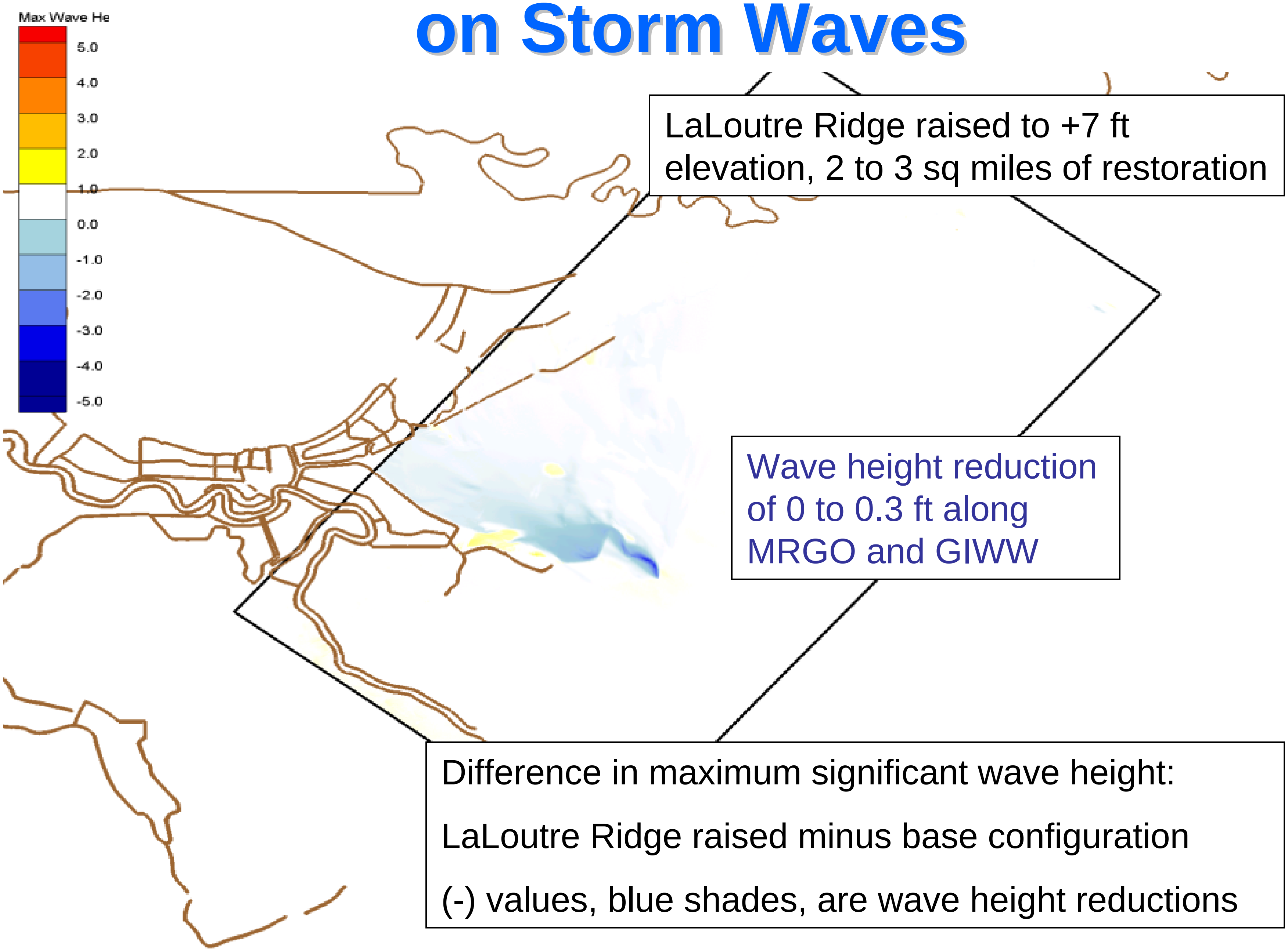
Surge reductions of 0.2 ft along MRGO and GIWW; near 0 in IHNC

Difference in peak surge:

LaLoutre Ridge raised minus base configuration

(-) values, blue shades, are surge reductions

Effect of Raising la Loutre Ridge on Storm Waves



LaLoutre Ridge raised to +7 ft elevation, 2 to 3 sq miles of restoration

Wave height reduction of 0 to 0.3 ft along MRGO and GIWW

Difference in maximum significant wave height:

LaLoutre Ridge raised minus base configuration

(-) values, blue shades, are wave height reductions

Conclusions

- Carefully consider how to best spend landscape restoration $
- Continued degradation of wetlands over long time periods (loss of elevation to subsidence or erosion, loss of vegetation, and subsequent conversion to open water) will significantly increase storm surge and waves along the HPS in places
- Earthen levees w/o front side armoring will erode under persistent wave action if there are expanses of open water in front of them
- Prevention of continued degradation is most compelling reason for wetland restoration
- Restoration is complimentary to traditional measures, with definite positive benefits, but can not replace levees/gates/walls along the HPS