Analysis of a bathymetric storm surge scale

Pat Fitzpatrick and Yee Lau
Geosystems Research Institute
Stennis Space Center (near MS-LA state line)
Mississippi State University

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 3.9 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!*

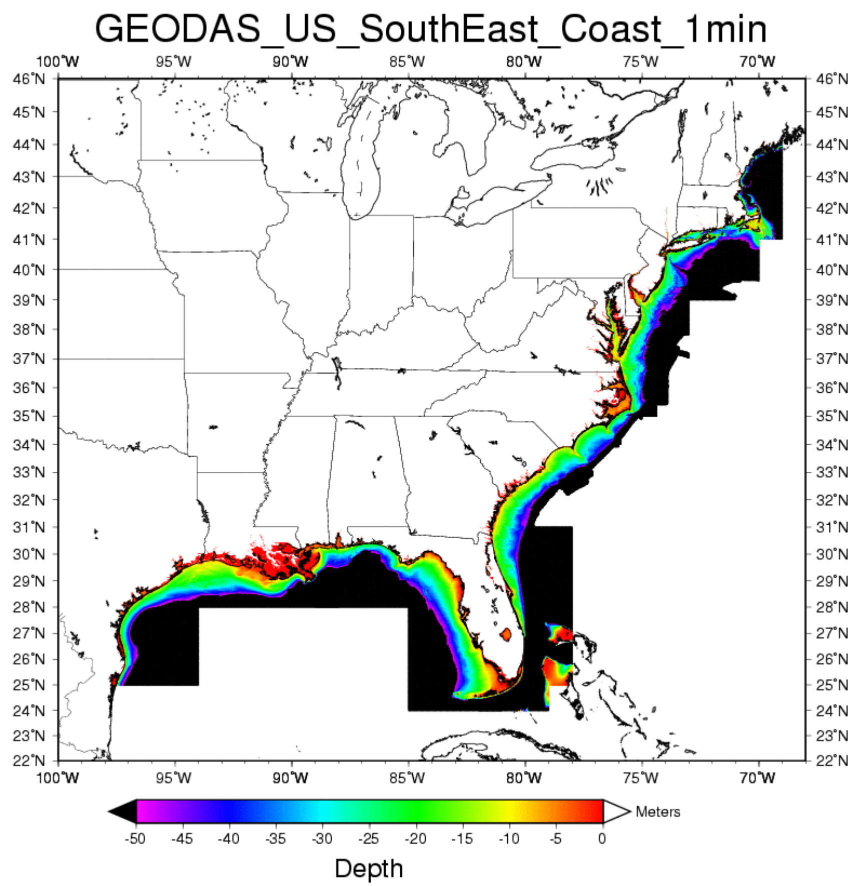
- Geostrophic adjustment – *water levels adjust to a developing longshore current.*
  - *Impact increases for slow-moving tropical cyclones*
  - *Impact increases for larger tropical cyclones*
  - *Causes a storm surge "forerunner"*

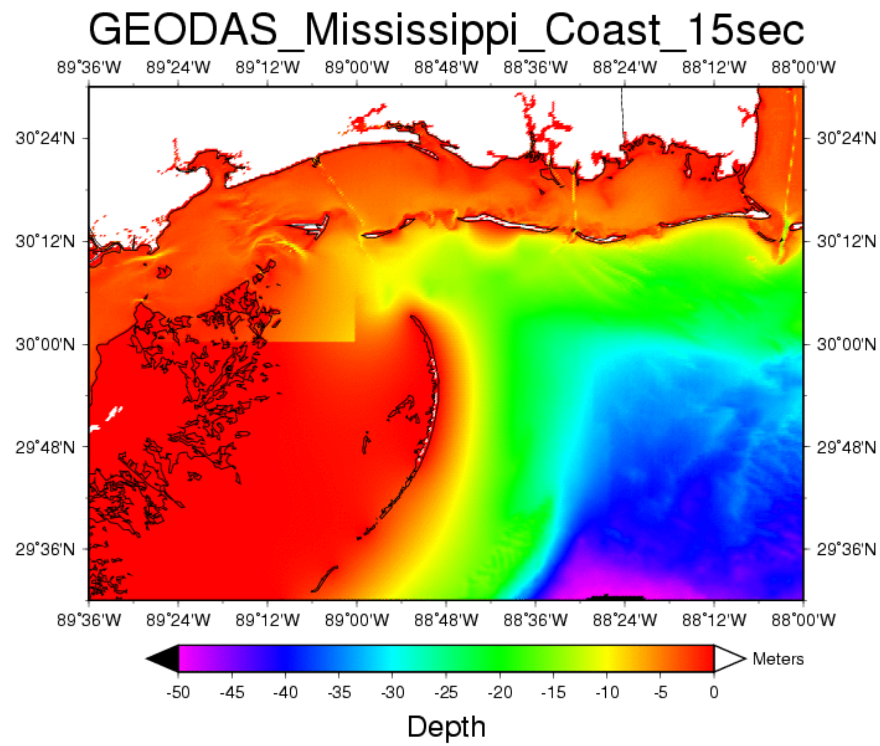
- Wave setup - *increase due to onshore waves.* Incoming water from wave breaking exceeds retreating water after wave runup.
  - *Impact minor in shallow bathymetry (0.5-1 ft); may contribute up to 3 ft surge in deep bathymetry (still the subject of debate)*

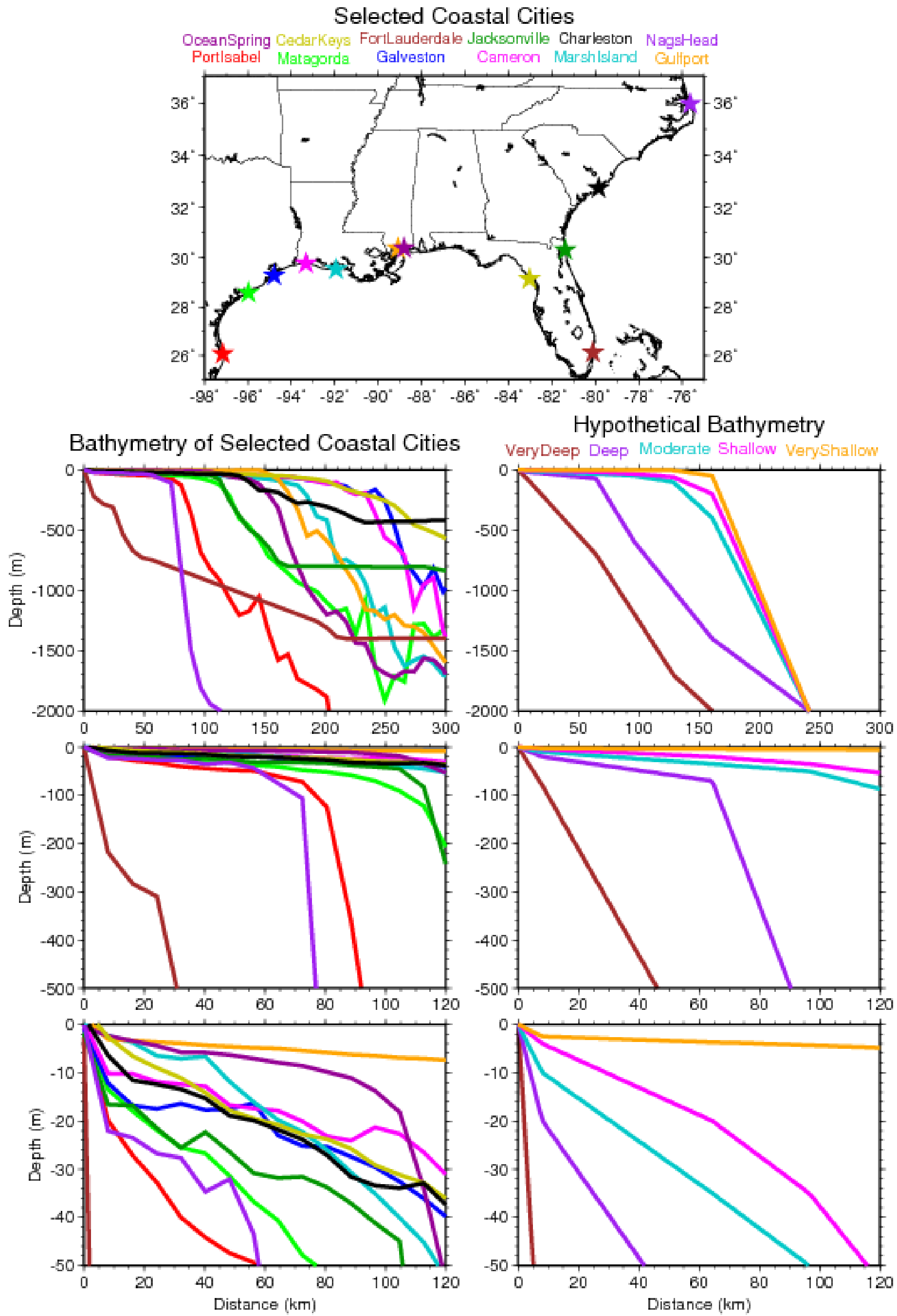
Investigated sensitivity of surge to intensity, size, speed, and bathymetry using:

- ADCIRC model
- 1D model

Except in extremely shallow water where handling numerical stability becomes an issue, both give similar peak surge values


GEODAS_US_SouthEast_Coast_1min
100°W
95°W
90°W
85°W
80°W
75°W
70°W
46°N
45°N
44°N
43°N
42°N
41°N
40°N
39°N
38°N
37°N
36°N
35°N
34°N
33°N
32°N
31°N
30°N
29°N
28°N
27°N
26°N
25°N
24°N
23°N
22°N
Meters
-50 -45 -40 -35 -30 -25 -20 -15 -10 -5 0
Depth


GEODAS_Mississippi_Coast_15sec
89°36'W
89°24'W
89°12'W
89°00'W
88°48'W
88°36'W
88°24'W
88°12'W
88°00'W
30°24'N
30°12'N
30°00'N
29°48'N
29°36'N
Meters
-50 -45 -40 -35 -30 -25 -20 -15 -10 -5 0
Depth


Selected Coastal Cities
OceanSpring CedarKeys FortLauderdale Jacksonville Charleston NagsHead
PortIsabel Matagorda Galveston Cameron MarshIsland Gulfport
Bathymetry of Selected Coastal Cities
Hypothetical Bathymetry
VeryDeep Deep Moderate Shallow VeryShallow
Depth (m)
Distance (km)

Simulations assumed a wind profile based on Holland (1980)

$$p = p_c + [p_{env} - p_c]e^{-Ar^{-B}} \; ; V = \left[\frac{AB[p_{env} - p_c]e^{-Ar^{-B}}}{\rho r^B} \right]^{1/2} ; \quad A = R_{\max}^B$$

Where:

p = pressure at radius r, ranging from central pressure p_c to environmental pressure p_{env}

V = tangential wind speed

B=scaling parameter that affects wind profile, typically varies from 0.5 to 2.0

A=function of Radius of Maximum winds (R_{max}) and B

R_{max} from Kimball and Mulekar (2004); Cat 1,3: 20-25 km, Cat 5: 12-18 km

ρ=air density (1.15 kg m-3)

Storm motion is included in V

Winds are converted to u,v components, an inflow angle of 20 deg is assumed within 100 km, and 10 degrees otherwise

Three storm sizes based on radius of tropical storm winds: 150, 250, and 350 km

Three storm movement speeds: 5, 10, 15 mph

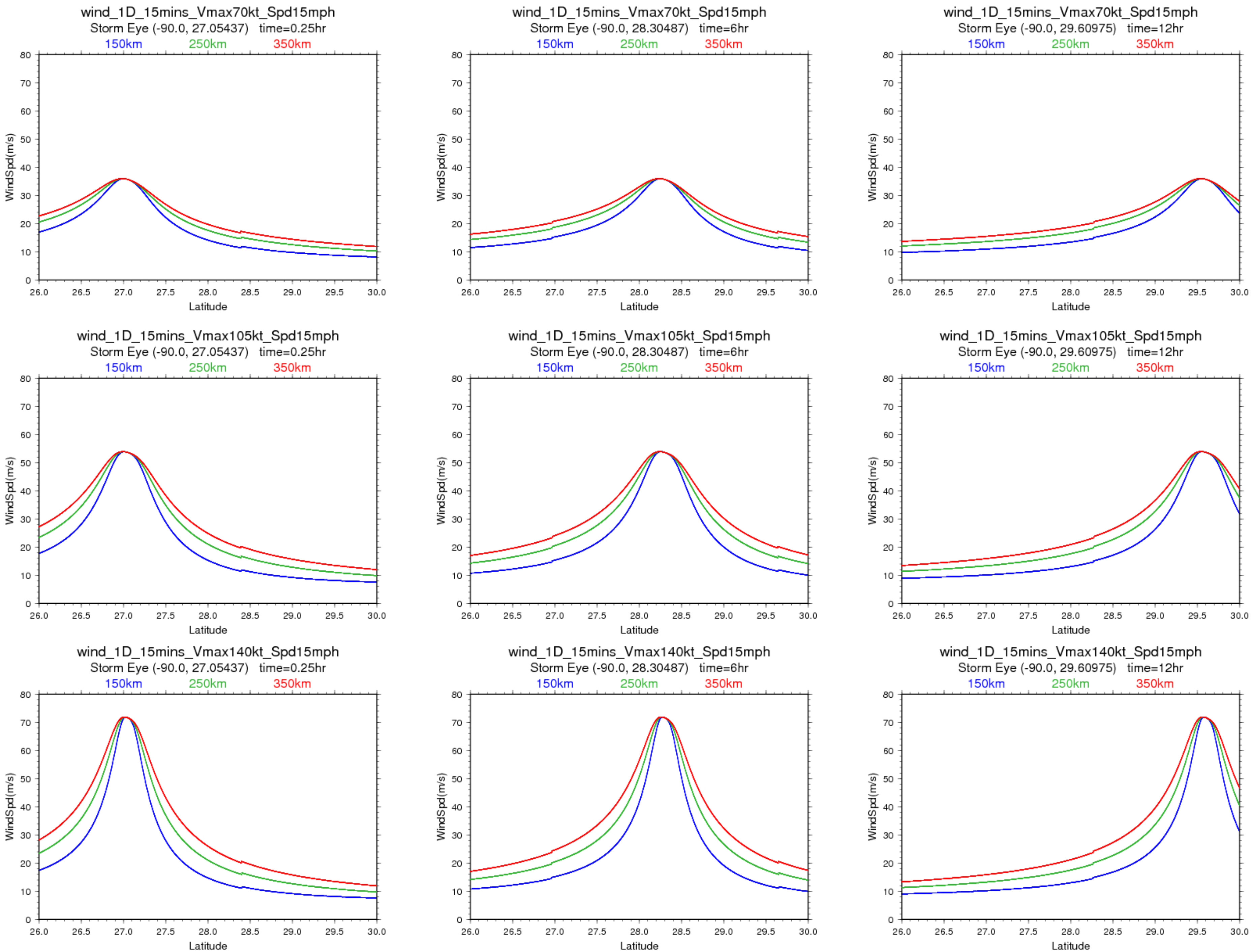
Maximum winds: 85, 120, 155 mph

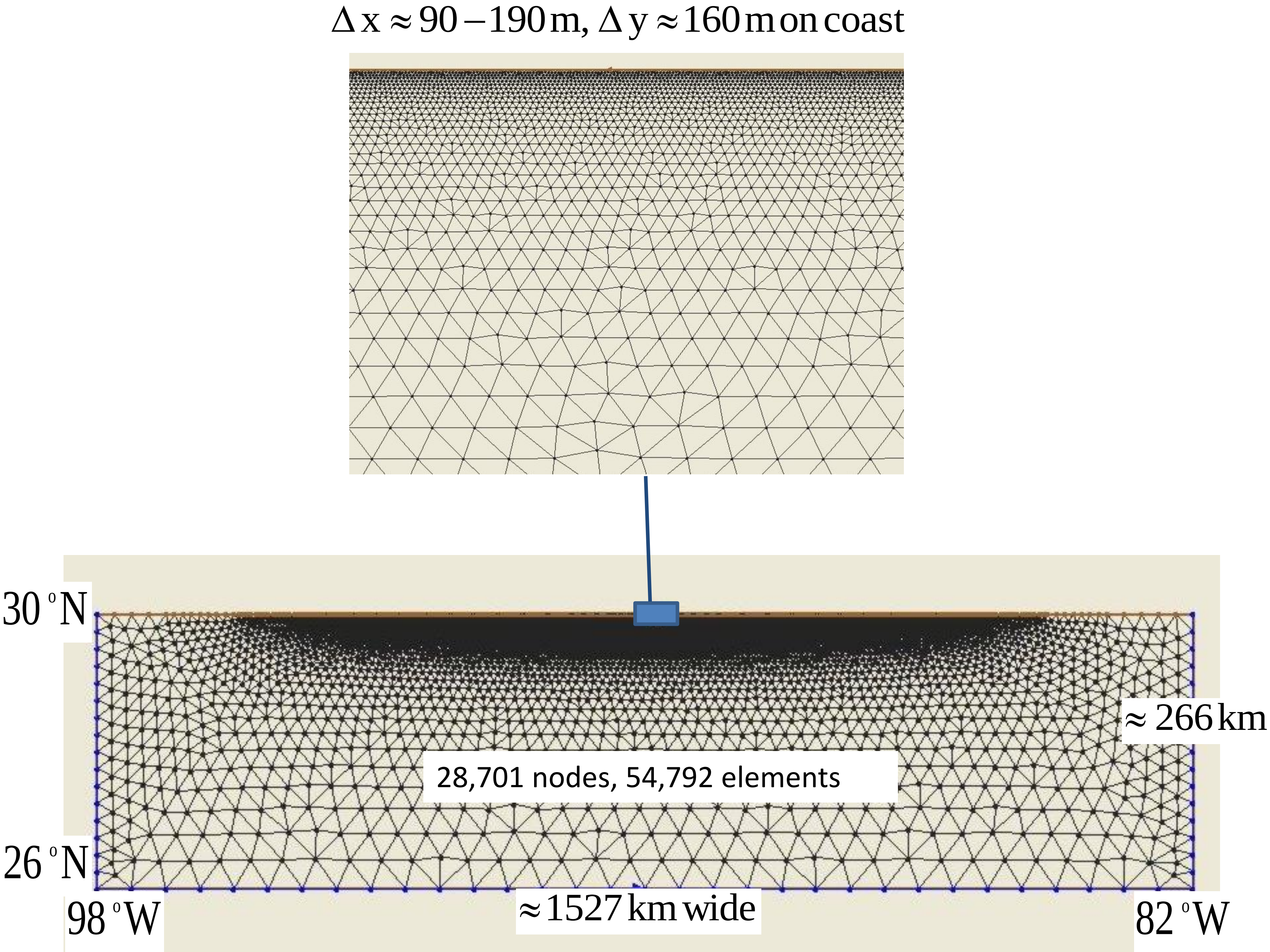
KEY POINT

Vmax + Storm motion = 85, 120, or 155 mph
In all three experiments

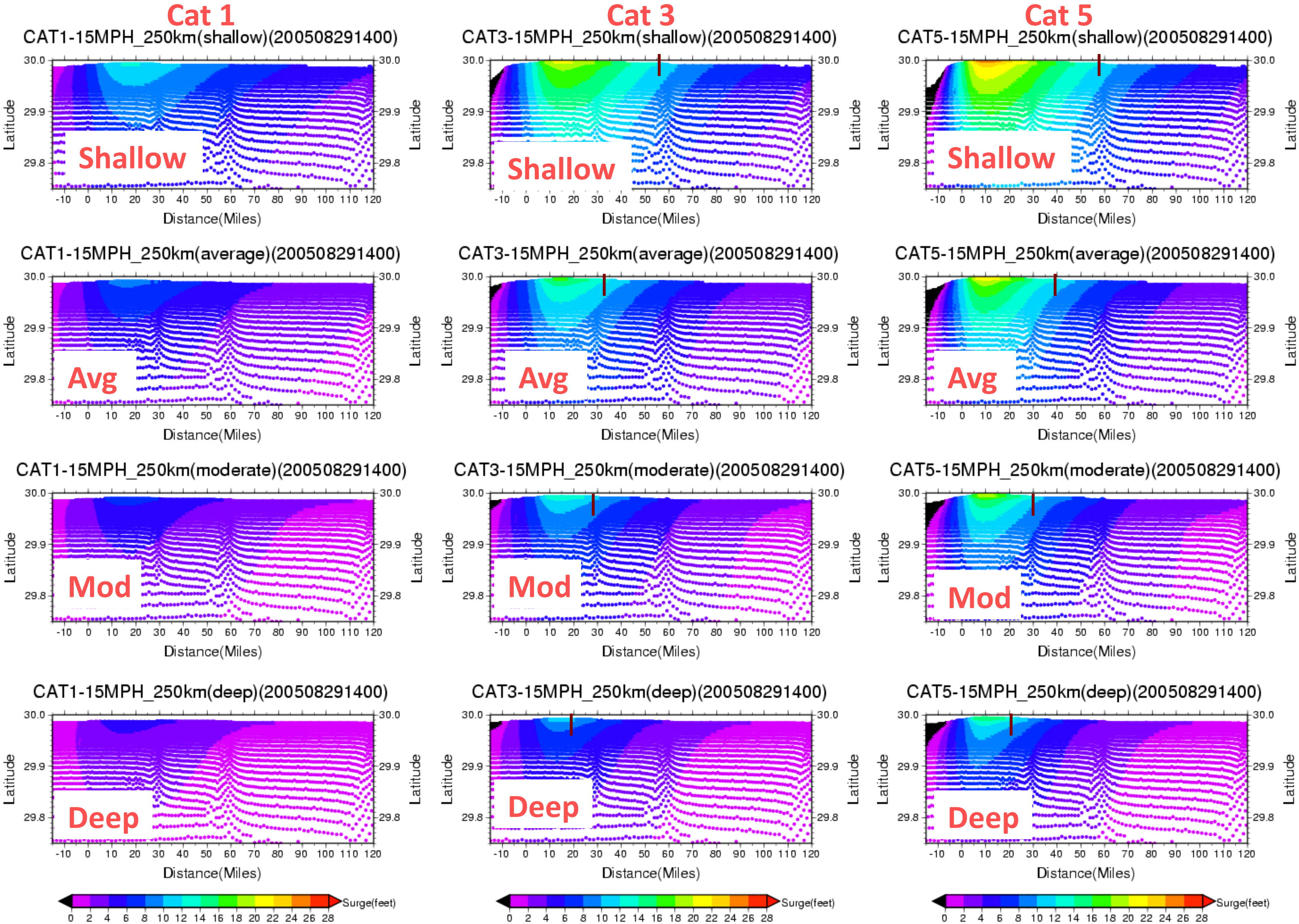
Storm size (Radius 39 mph winds) also includes storm motion and is 150, 250, or 350 km in all three experiments

One must have consistent wind forcing for comparisons!


wind_1D_15mins_Vmax70kt_Spd15mph
Storm Eye (-90.0, 27.05437) time=0.25hr
150km 250km 350km
wind_1D_15mins_Vmax70kt_Spd15mph
Storm Eye (-90.0, 28.30487) time=6hr
150km 250km 350km
wind_1D_15mins_Vmax70kt_Spd15mph
Storm Eye (-90.0, 29.60975) time=12hr
150km 250km 350km
wind_1D_15mins_Vmax105kt_Spd15mph
Storm Eye (-90.0, 27.05437) time=0.25hr
150km 250km 350km
wind_1D_15mins_Vmax105kt_Spd15mph
Storm Eye (-90.0, 28.30487) time=6hr
150km 250km 350km
wind_1D_15mins_Vmax105kt_Spd15mph
Storm Eye (-90.0, 29.60975) time=12hr
150km 250km 350km
wind_1D_15mins_Vmax140kt_Spd15mph
Storm Eye (-90.0, 27.05437) time=0.25hr
150km 250km 350km
wind_1D_15mins_Vmax140kt_Spd15mph
Storm Eye (-90.0, 28.30487) time=6hr
150km 250km 350km
wind_1D_15mins_Vmax140kt_Spd15mph
Storm Eye (-90.0, 29.60975) time=12hr
150km 250km 350km
WindSpd(m/s)
Latitude


$\Delta x \approx 90-190\,m, \Delta y \approx 160\,m$ on coast
30 °N
26 °N
≈ 266 km
28,701 nodes, 54,792 elements
98 °W
≈1527 km wide
82 °W

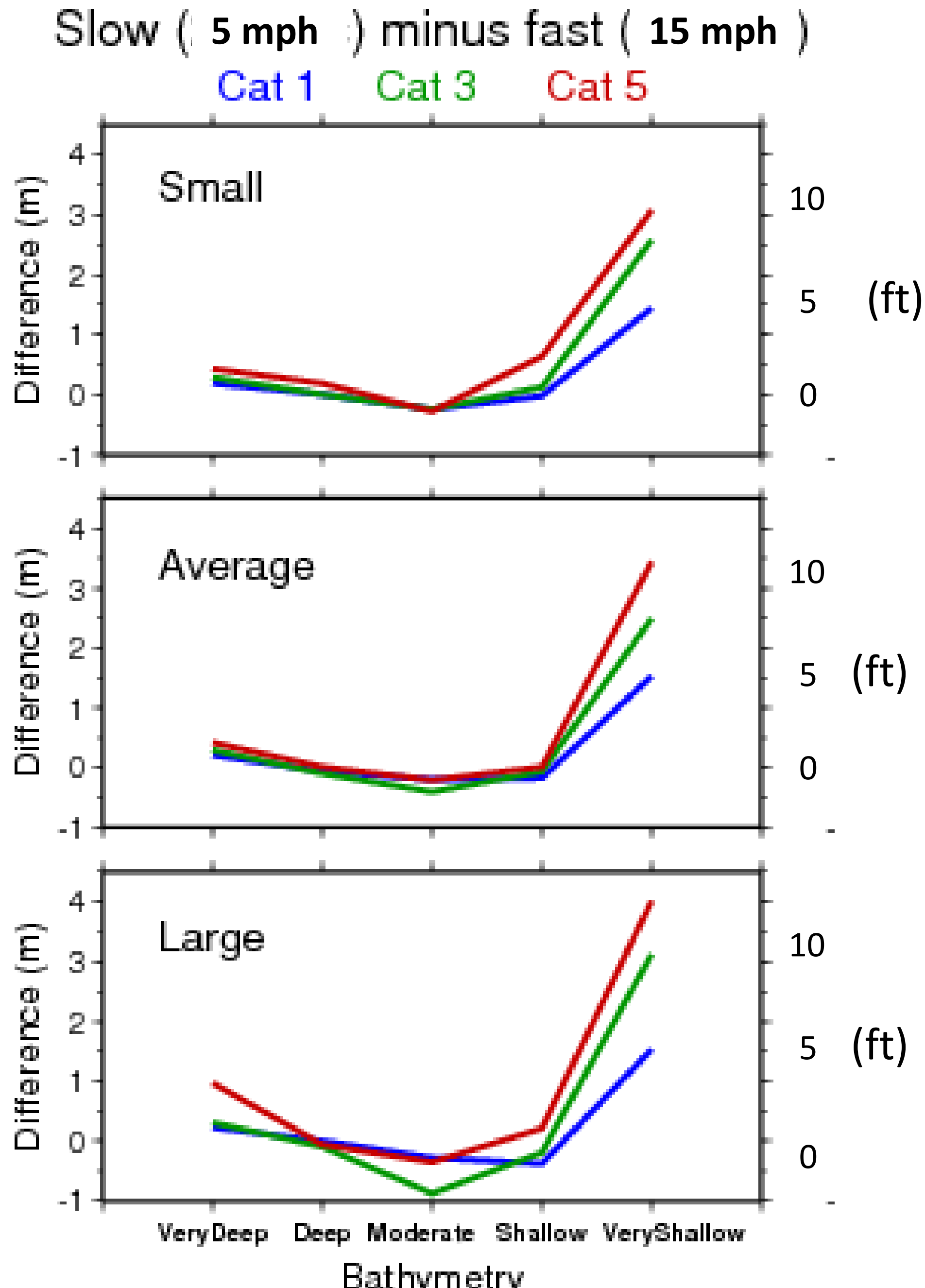
Different Bathymetry, Different Intensity, Speed=15mph, Size=250km



Speed influence

Differences occur :

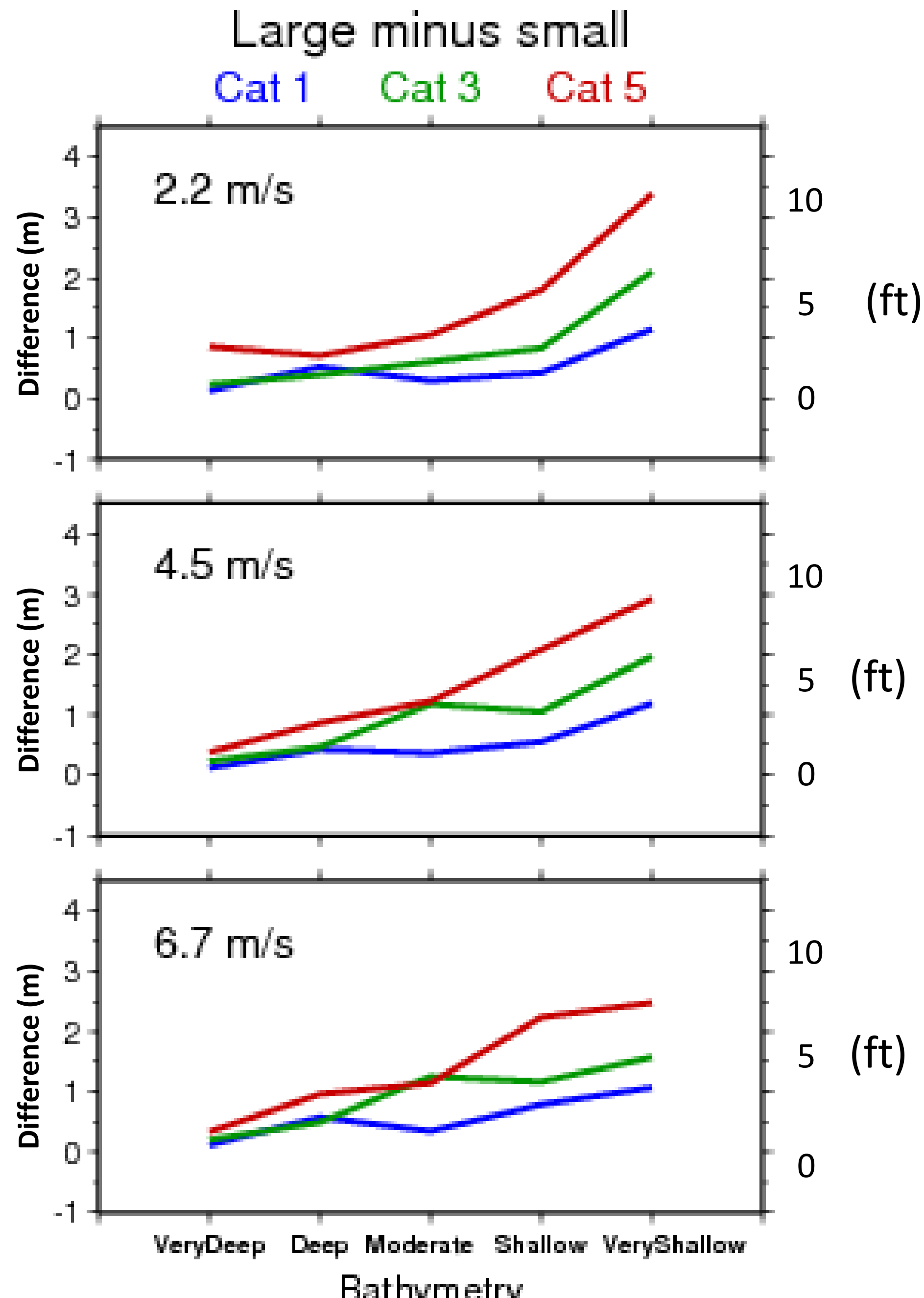
- In shallow bathymetries
- Proportional to intensity
- Proportional to size

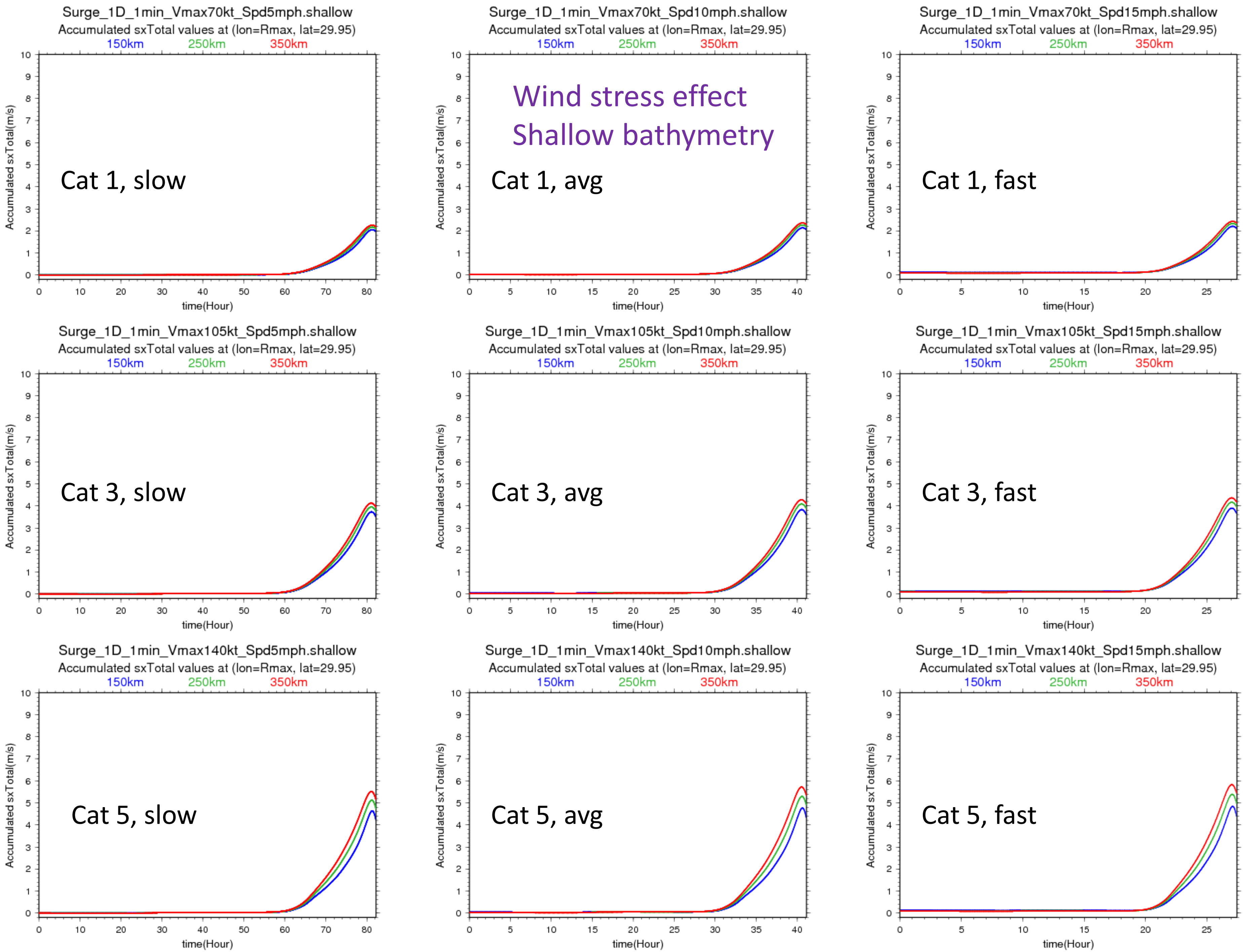


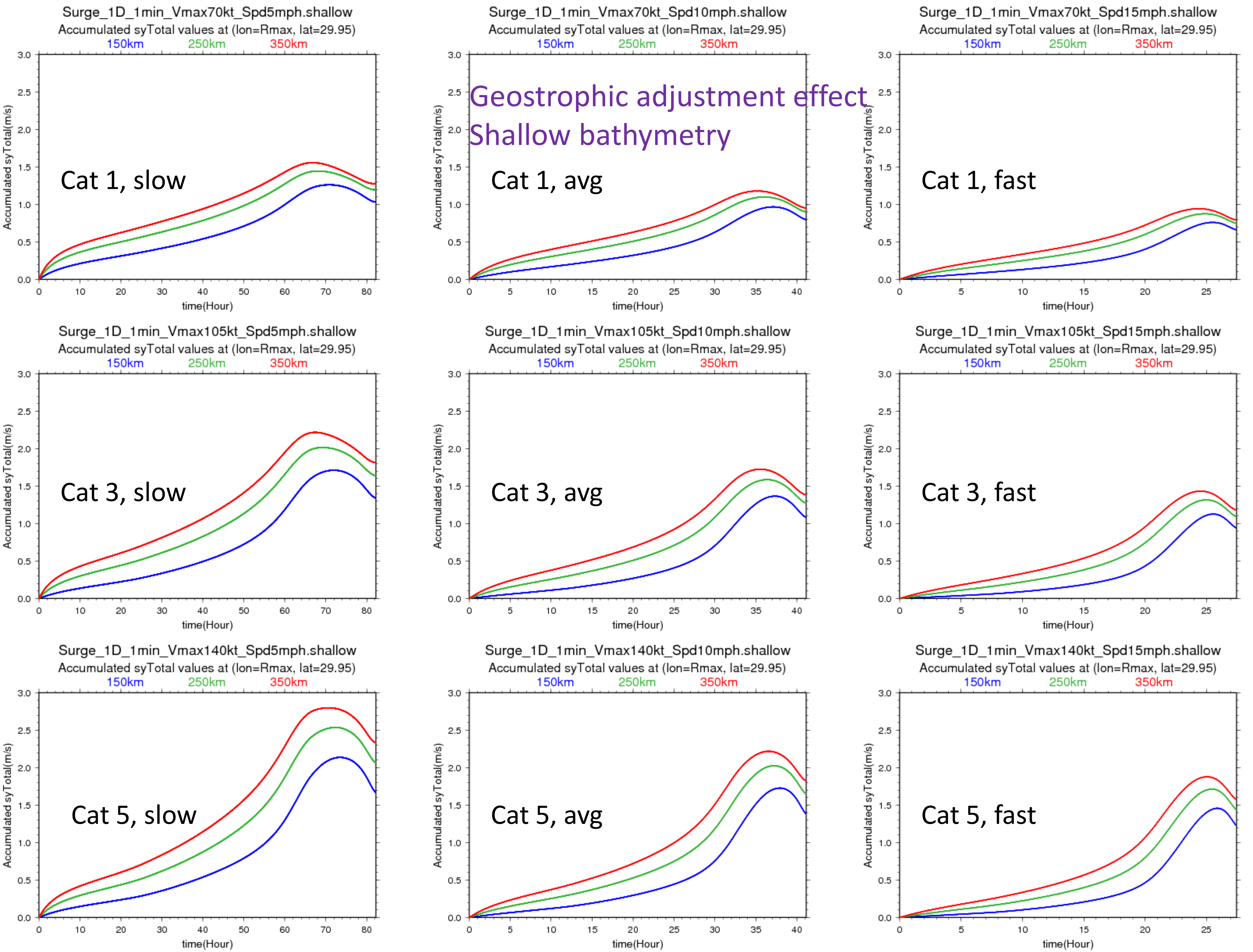
Size influence

Differences occur :

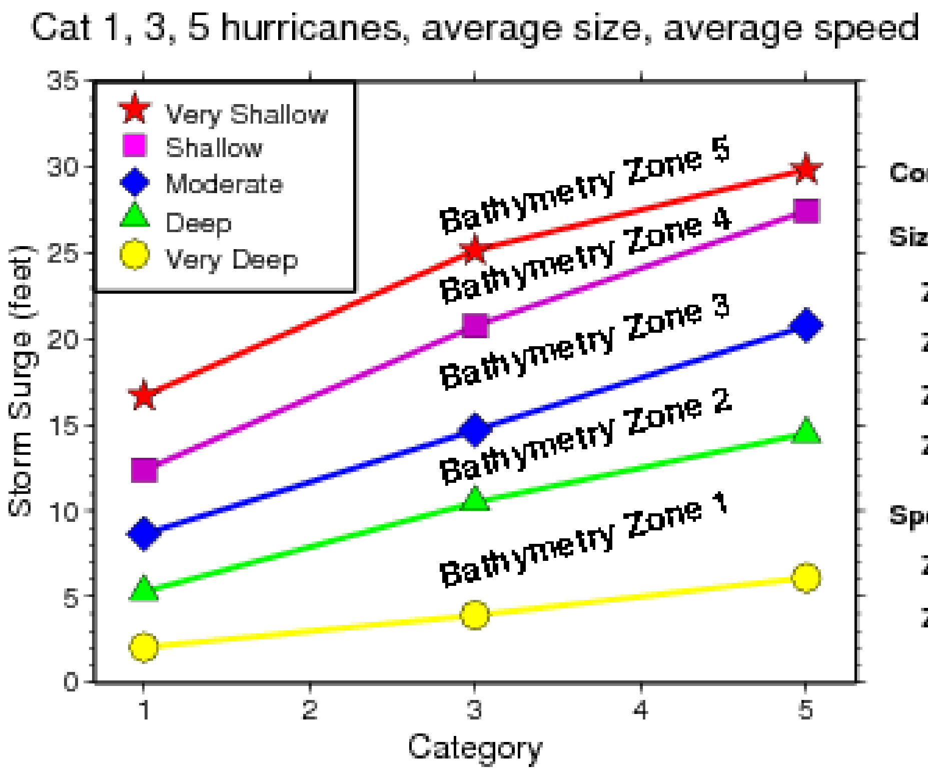
- Proportional to intensity
- Inv. proportional to speed
- Inv. proportional to depth




Wind stress effect
Shallow bathymetry
Surge_1D_1min_Vmax70kt_Spd5mph.shallow
Accumulated sxTotal values at (lon=Rmax, lat=29.95)
150km 250km 350km
Cat 1, slow
Surge_1D_1min_Vmax70kt_Spd10mph.shallow
Accumulated sxTotal values at (lon=Rmax, lat=29.95)
150km 250km 350km
Cat 1, avg
Surge_1D_1min_Vmax70kt_Spd15mph.shallow
Accumulated sxTotal values at (lon=Rmax, lat=29.95)
150km 250km 350km
Cat 1, fast
Surge_1D_1min_Vmax105kt_Spd5mph.shallow
Accumulated sxTotal values at (lon=Rmax, lat=29.95)
150km 250km 350km
Cat 3, slow
Surge_1D_1min_Vmax105kt_Spd10mph.shallow
Accumulated sxTotal values at (lon=Rmax, lat=29.95)
150km 250km 350km
Cat 3, avg
Surge_1D_1min_Vmax105kt_Spd15mph.shallow
Accumulated sxTotal values at (lon=Rmax, lat=29.95)
150km 250km 350km
Cat 3, fast
Surge_1D_1min_Vmax140kt_Spd5mph.shallow
Accumulated sxTotal values at (lon=Rmax, lat=29.95)
150km 250km 350km
Cat 5, slow
Surge_1D_1min_Vmax140kt_Spd10mph.shallow
Accumulated sxTotal values at (lon=Rmax, lat=29.95)
150km 250km 350km
Cat 5, avg
Surge_1D_1min_Vmax140kt_Spd15mph.shallow
Accumulated sxTotal values at (lon=Rmax, lat=29.95)
150km 250km 350km
Cat 5, fast
Accumulated sxTotal(m/s)
time(Hour)


Geostrophic adjustment effect
Shallow bathymetry
Surge_1D_1min_Vmax70kt_Spd5mph.shallow
Accumulated syTotal values at (lon=Rmax, lat=29.95)
150km 250km 350km
Cat 1, slow
Surge_1D_1min_Vmax70kt_Spd10mph.shallow
Accumulated syTotal values at (lon=Rmax, lat=29.95)
150km 250km 350km
Cat 1, avg
Surge_1D_1min_Vmax70kt_Spd15mph.shallow
Accumulated syTotal values at (lon=Rmax, lat=29.95)
150km 250km 350km
Cat 1, fast
Surge_1D_1min_Vmax105kt_Spd5mph.shallow
Accumulated syTotal values at (lon=Rmax, lat=29.95)
150km 250km 350km
Cat 3, slow
Surge_1D_1min_Vmax105kt_Spd10mph.shallow
Accumulated syTotal values at (lon=Rmax, lat=29.95)
150km 250km 350km
Cat 3, avg
Surge_1D_1min_Vmax105kt_Spd15mph.shallow
Accumulated syTotal values at (lon=Rmax, lat=29.95)
150km 250km 350km
Cat 3, fast
Surge_1D_1min_Vmax140kt_Spd5mph.shallow
Accumulated syTotal values at (lon=Rmax, lat=29.95)
150km 250km 350km
Cat 5, slow
Surge_1D_1min_Vmax140kt_Spd10mph.shallow
Accumulated syTotal values at (lon=Rmax, lat=29.95)
150km 250km 350km
Cat 5, avg
Surge_1D_1min_Vmax140kt_Spd15mph.shallow
Accumulated syTotal values at (lon=Rmax, lat=29.95)
150km 250km 350km
Cat 5, fast
Accumulated syTotal(m/s)
time(Hour)

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



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)

Validation of bathymetric scale for open coast

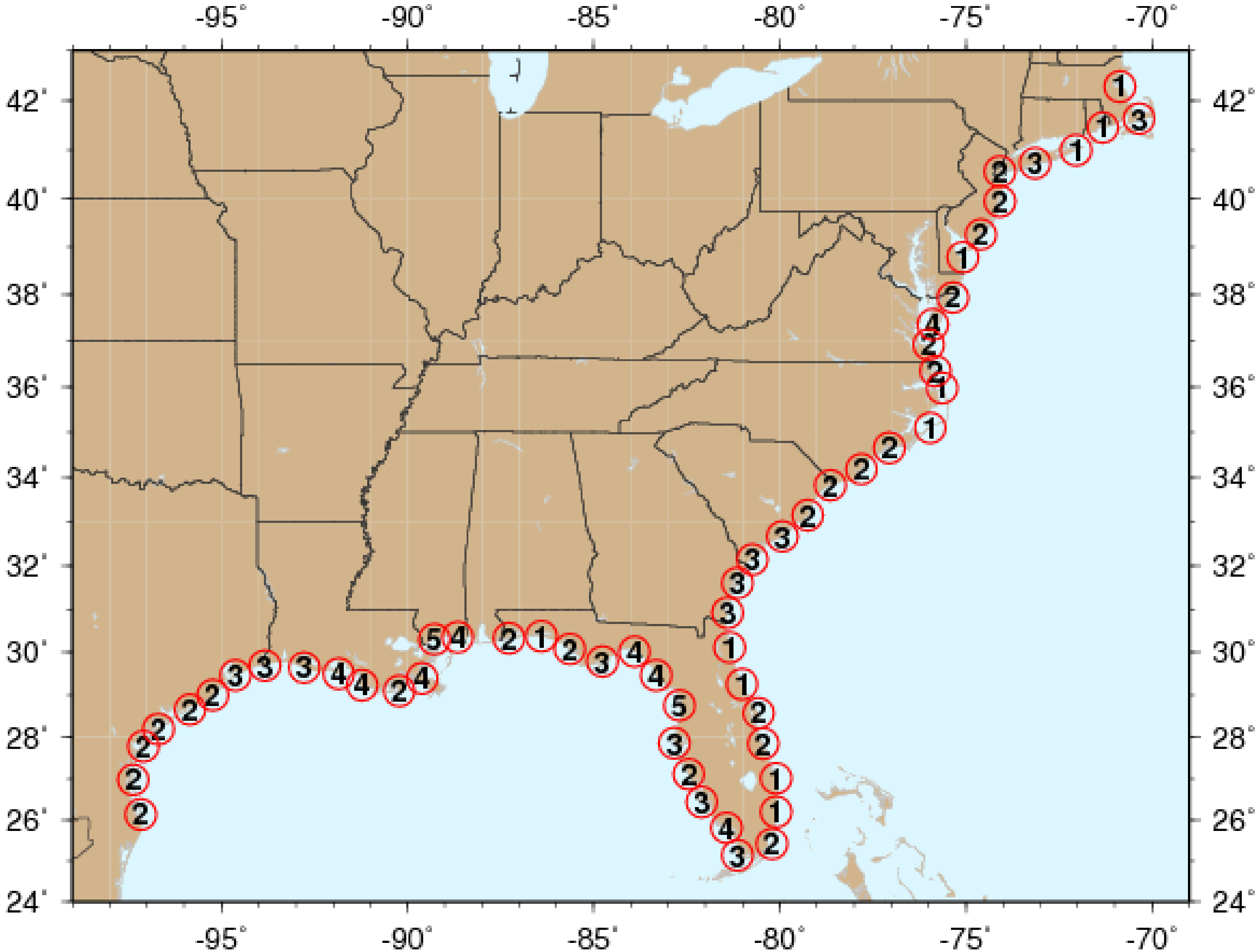
Developed a storm surge dataset from 1960-2009 using:

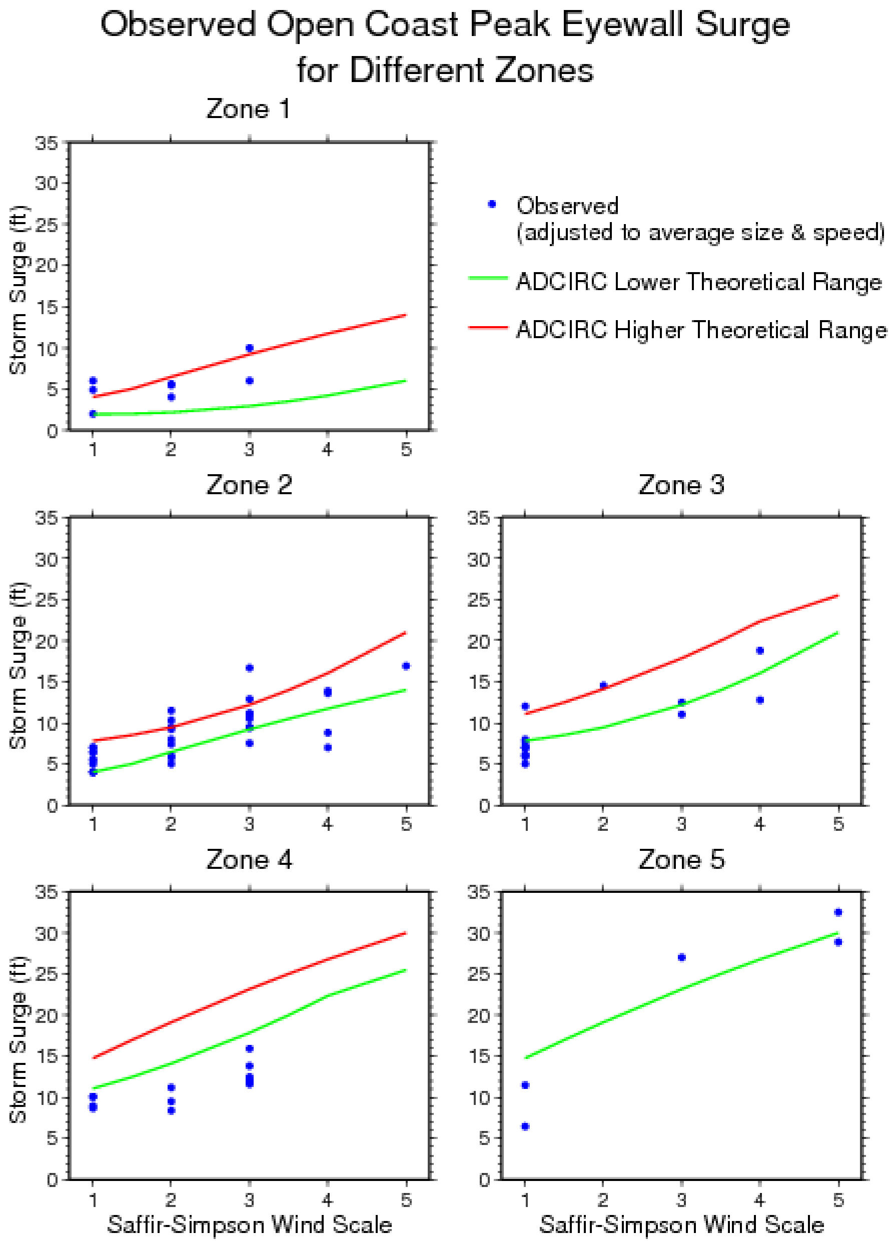
- NHC annual reports
- High water mark datasets
- Miscellaneous case study journals
- Army Corps Tech reports
- Tide gauge data

Storm size and speed also included from extended best track, old NHC text reports, case study journal articles

Lots of quality control imposed. All references tabulated.

Selected Coastal Points with Bathymetry Zone





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

How about Integrated Kinetic Energy (IKE)?

Powell and Reinhold (2007) have suggested using Integrated Kinetic Energy as a replacement to maximum sustained wind in the Saffir-Simpson scale

Table 2. A wind and storm surge/wave destructive potential rating for hurricanes based on integrated kinetic energy (TJ).

Wind destructive potential rating	Wind damage-weighted IKE	Surge/waves destructive potential rating	Storm surge and waves IKE_{TS}
0.1	0.5	0.1	0.7
1.0	34.5	1.0	2.7
2.0	78.0	2.0	11.7
3.0	135.0	3.0	29.5
4.0	30 IKE_{SS} 1.1	4.0	61.0
5.0	30 IKE_{SS} 50	5.0	119.5
5.9	30 IKE_{SS} 298	5.9	260.0

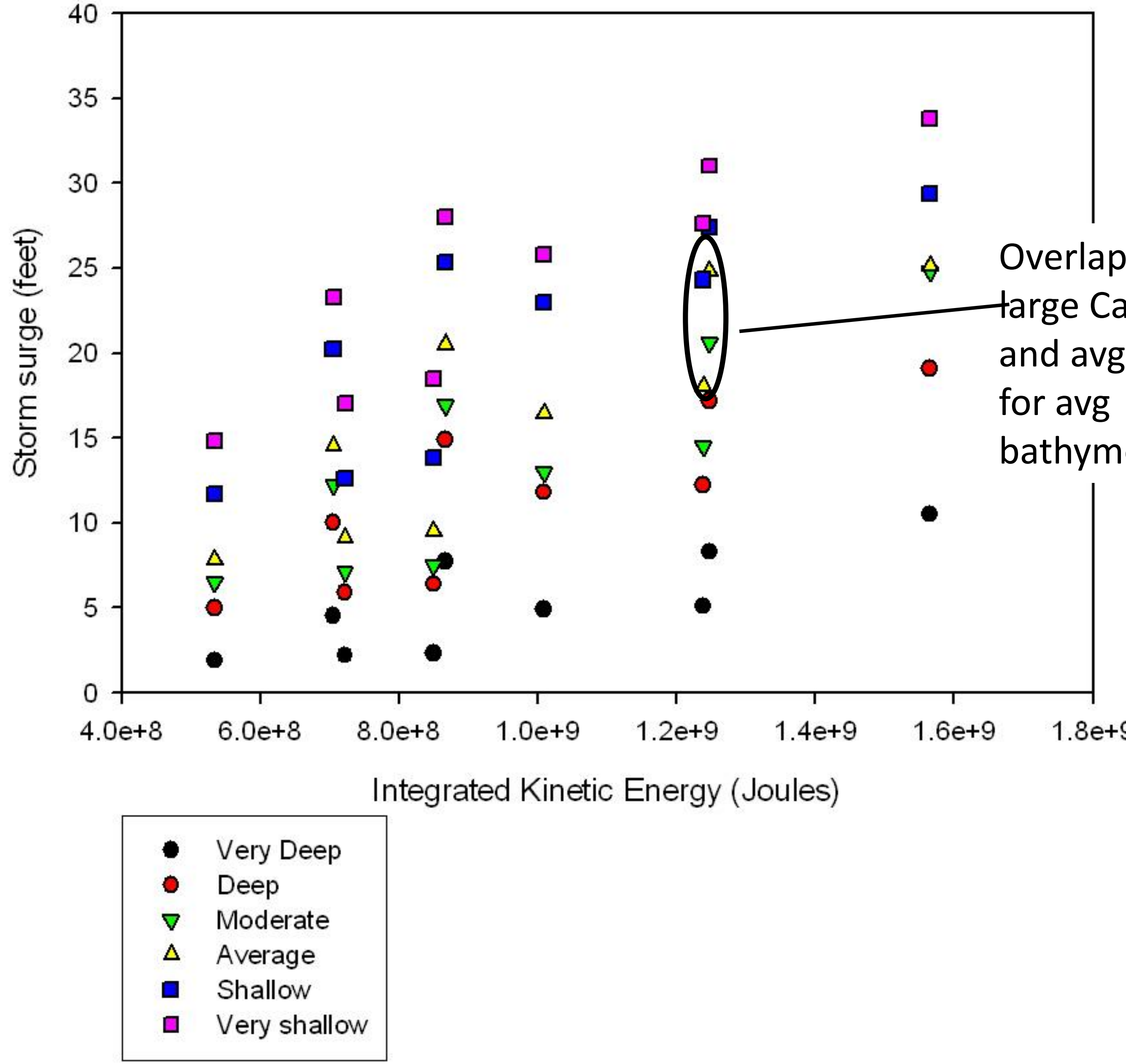
$$IKE = \int_0^z \int_0^r \int_0^{2\pi} \frac{1}{2} \rho V^2(r)\, d\theta\, dr\, dz$$

The analytic solution for IKE based on Holland profile is:

$$IKE = \frac{\pi[p_{env} - p_c] r_{env}}{B} \left\{ B e^{-A r_{env}^{-B}} - \left[A r_{env}^{-B}\right]^{1/B} \Gamma\left(-\frac{1}{B}, A r_{env}^{-B}\right) \right\}$$

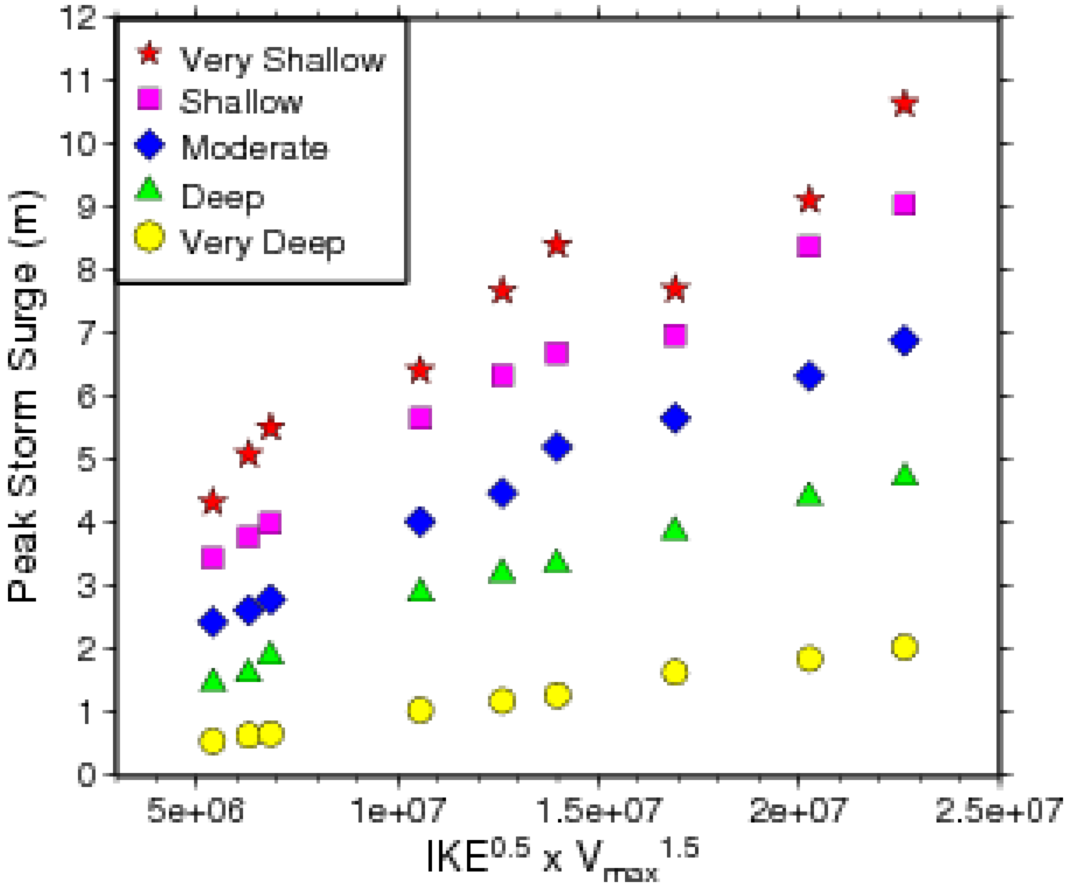
Γ =Lower incomplete gamma function ;   z =1 meter

Cat 1, 3, 5 hurricanes, all sizes, moving 10 mph



Overlap of large Cat 3 and avg Cat 5 for avg bathymetry

IKE variant shows some potential



Conclusions

- A bathymetric scale, corrected for speed and size, shows potential for estimating peak surge on the *open coastline*

- Has educational uses. Can help explain why the Saffir Simpson scale failed. Perhaps can be utilized if a storm surge model is not available.

- Needs further validation effort and development, and also indicates accurate storm surge and wind datasets are very important.

- Shows the importance of adjusting analysis fields to EQUAL PEAK WIND STRESS when varying storm speed. Many previous studies (and MEOW maps) incorrectly show surge increasing with storm speed. Because of geostrophic adjustment processes, the opposite is true.

- Integrated Kinetic Energy probably does not correlate well enough to surge for practical use, but IKE variants cannot be ruled out yet and deserve further study.