Wind forcing methods for storm surge modeling

Pat Fitzpatrick and Yee Lau, Mississippi State University

- Review of storm surge physics
- Hurricane parametric wind models
- MSU parametric scheme
- The potential for surrogate modeling

$$\tau_{wind} = \rho C_d U_{10}^2$$

6. Contribution of Physical Components

[73] The shallow water momentum equation can be described in terms of its components (L: local acceleration, A: advection, C: Coriolis, Z: surface gradient, P: atmospheric pressure, T: tidal potential, W: wind stress, R: wave radiation stress gradient, B: bottom stress, D: diffusion):

$$0 = -\underbrace{\frac{\partial \mathbf{u}}{\partial t}}_{L} - \underbrace{\mathbf{u}\cdot\nabla\mathbf{u}}_{A} - \underbrace{f\times\mathbf{u}}_{C} - \underbrace{g\nabla\zeta}_{Z} - \underbrace{\frac{\nabla p_s}{\rho_0}}_{P} + \underbrace{g\nabla\alpha\eta}_{T} + \underbrace{\frac{\tau_{\mathbf{s,winds}}}{\rho_0 H}}_{W} + \underbrace{\frac{\tau_{\mathbf{s,waves}}}{\rho_0 H}}_{R} - \underbrace{\frac{\tau_{\mathbf{b}}}{\rho_0 H}}_{B} + \underbrace{\frac{\mathbf{M}}{H}}_{D} \quad (13)$$

where $\mathbf{u}$ represents the depth average velocity, f is the coriolis term, ζ represents the free surface departure from the geoid, p_s represent the atmospheric pressure at the sea surface, α is the earth elasticity reduction factor, η is the Newtonian equilibrium tide potential, $\tau_{s,\text{winds}}$ and $\tau_{s,\text{waves}}$ represent the imposed surface stresses for winds and waves respectively, τ_b represents the bottom stress, and M represents lateral stress gradients.

Fundamental surge components

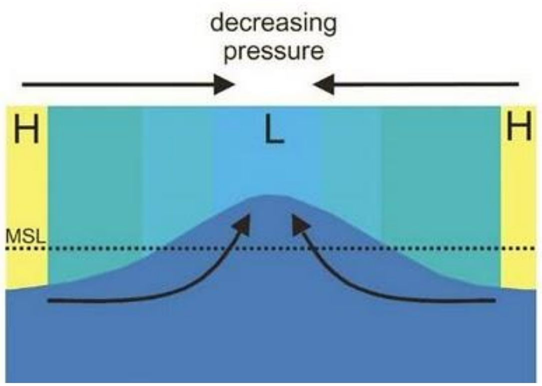
- Pressure setup - *increase in water level due to lower atmospheric pressure in storm interior.* A slight surface bulge occurs within the storm, greatest at the storm's center, decreasing at the storm's periphery. For every 10-mb pressure drop, water expands 3.9 inches.
  - *Effect is a constant*

- 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!*

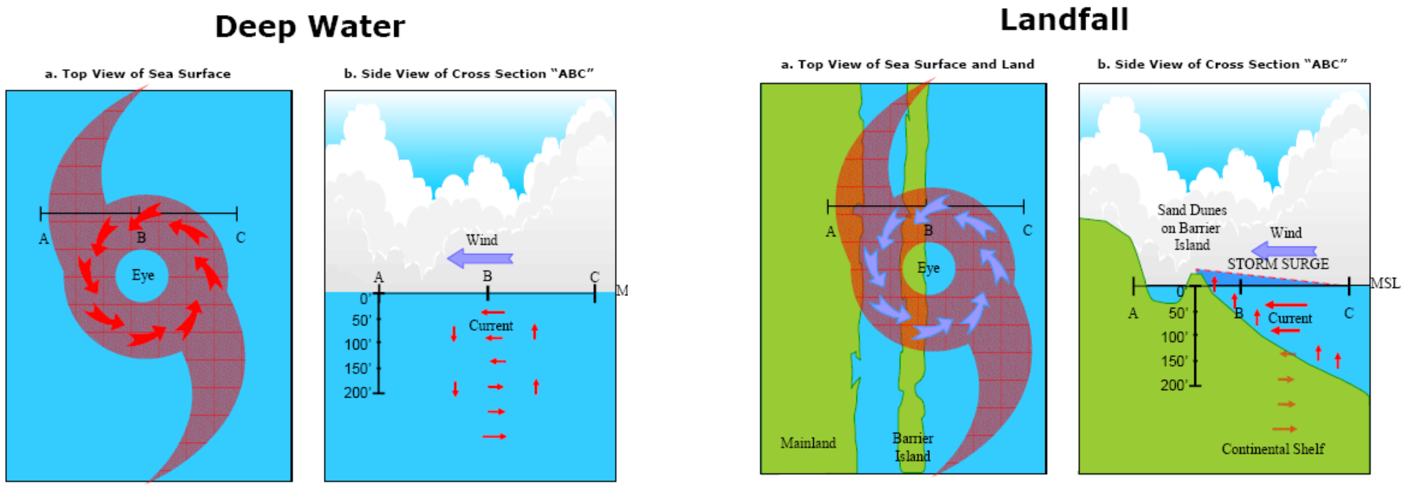
- Geostrophic adjustment – *water levels adjust to a developing longshore current.*
  - *Impact increases for slow-moving tropical cyclones*
  - *Impact increases for larger tropical cyclones*
  - *Causes a storm surge "forerunner"*

- 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)*

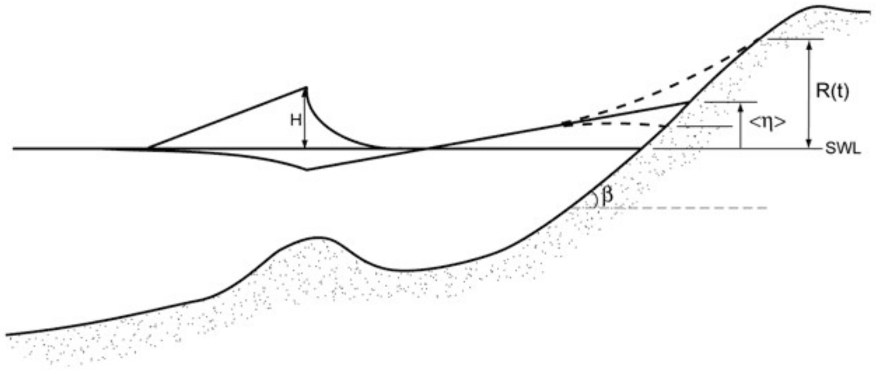
Pressure setup



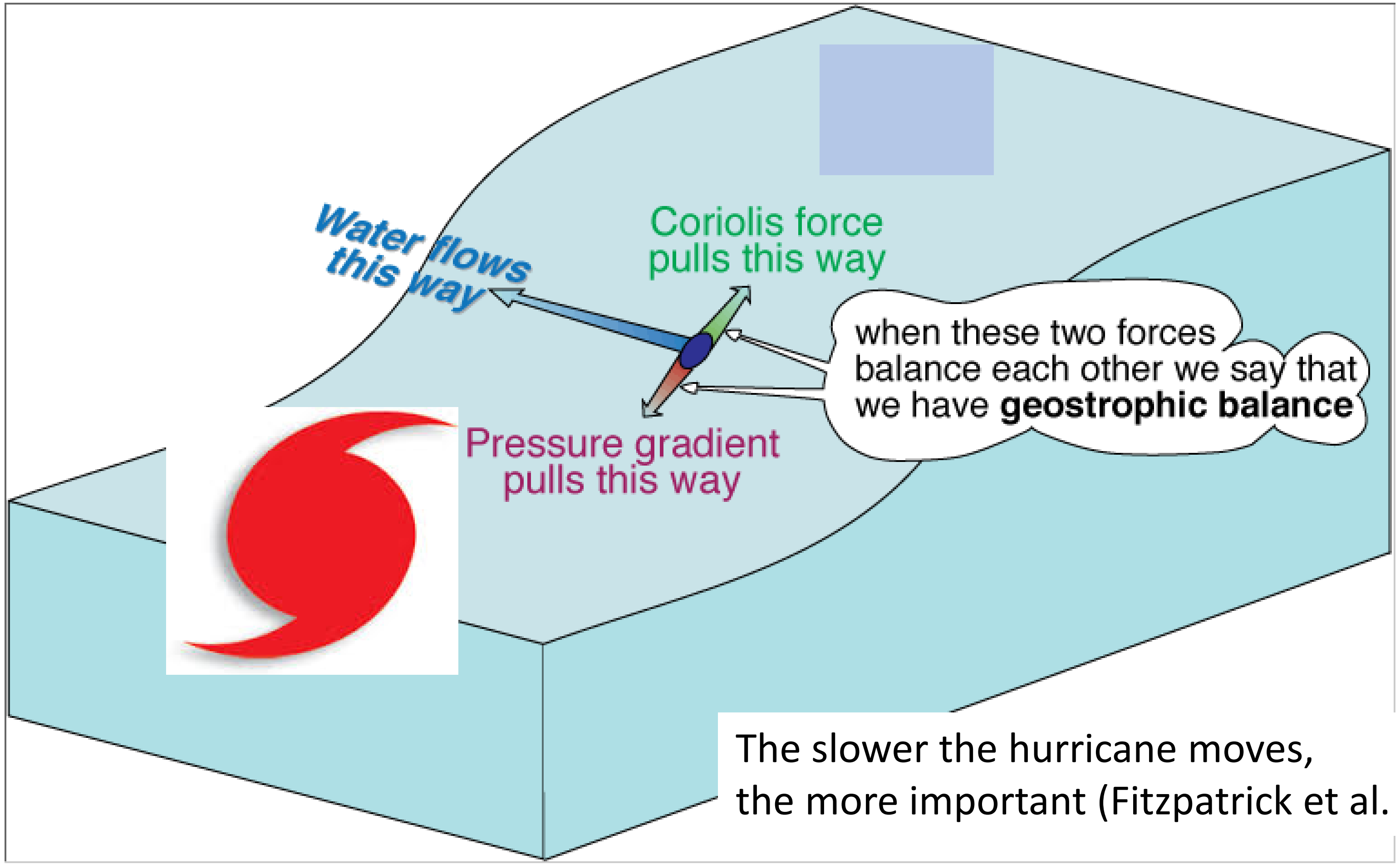
Wind setup



Wave setup



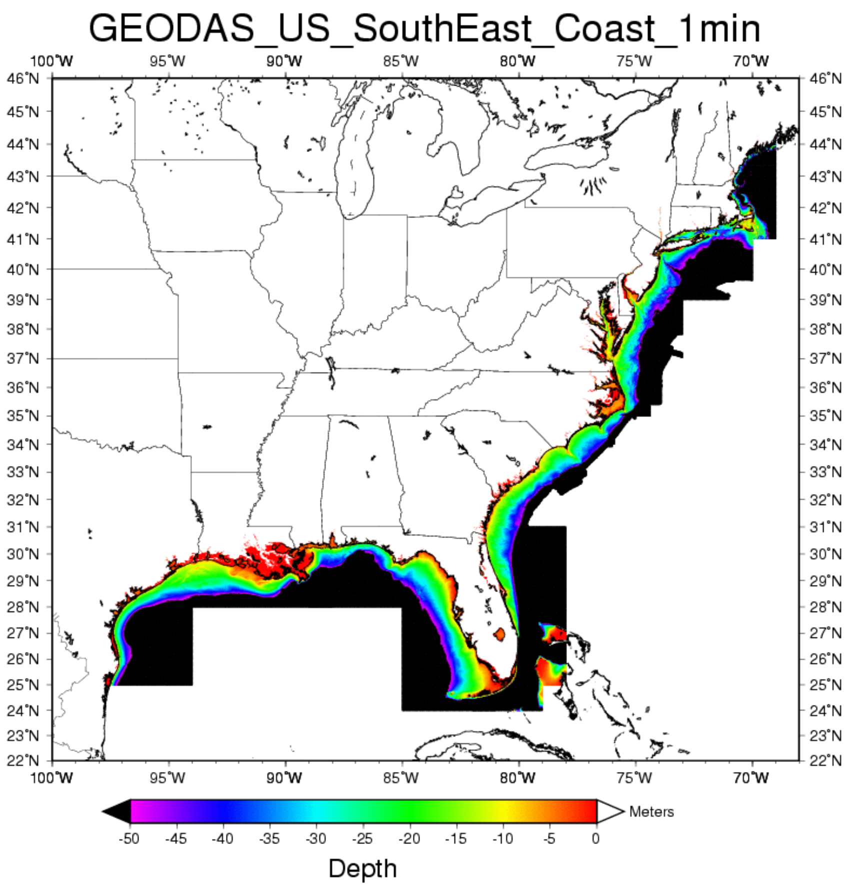
Geostrophic adjustment (creates surge "forerunner")

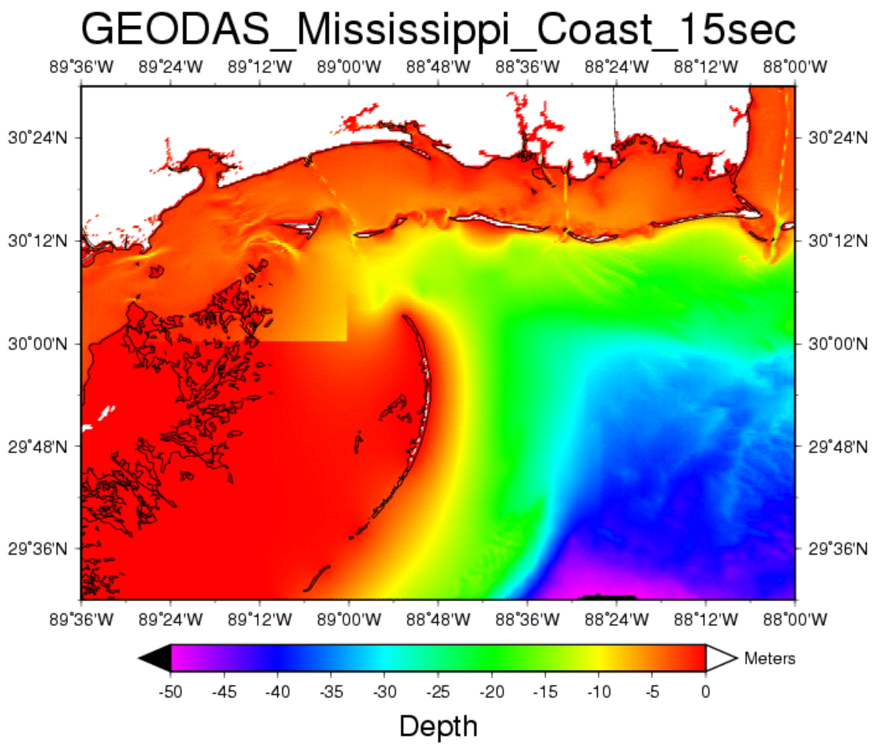


The slower the hurricane moves, the more important (Fitzpatrick et al. 2012)

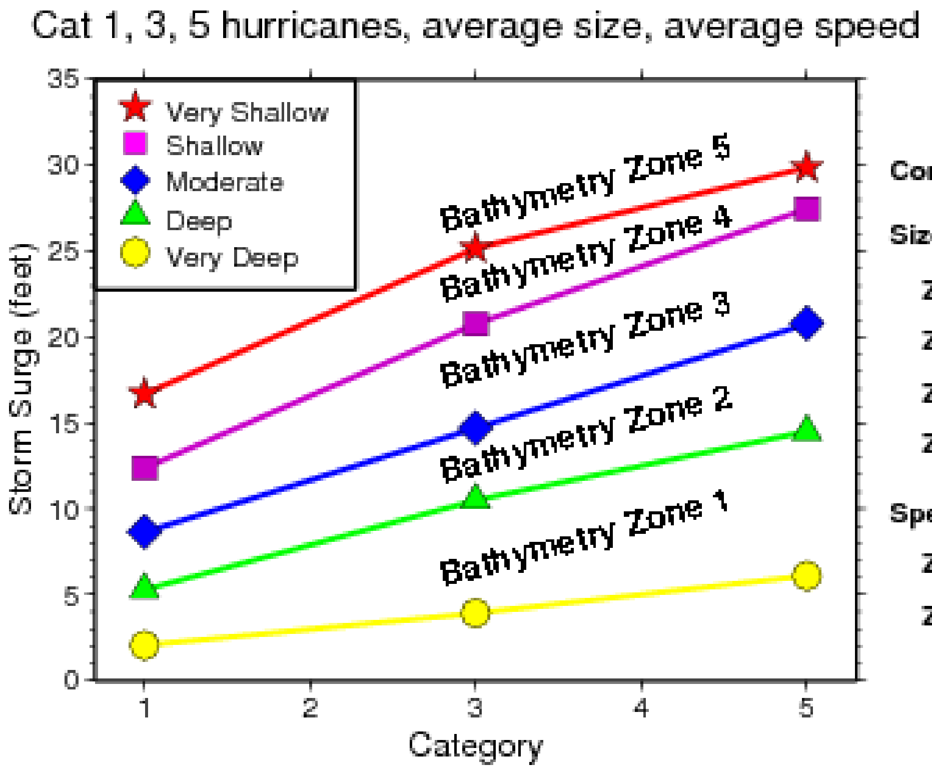
The balance between pressure gradient forces and Coriolis forces on a parcel of water is what we call geostrophic balance.

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


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

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)

Storm surge models wind forcing

Parametric equation philosophy

- $V_{sym}(\tilde{V}_{max}, r_{max}, r, x_1, x_2, x_3 \dots\dots)$ → symmetric wind field; often a shape factor is used
- $V_{total} = V_{sym} + A$ → asymmetry (A) added for total wind field from storm motion
  $\tilde{V}_{max}$ is 10-m V_{max} increased above PBL, and decreased for motion
- Compute pressure field from V_{sym} assuming gradient wind balance
  or, as in SLOSH, compute V_{sym} from pressure deficit
- Reduce total wind field to 10-meter height
- Adjust for inflow angles

Used in most storm surge model applications. Also used in hurricane risk assessments and many other purposes

SLOSH methodology – three steps

1) V_{max} computed from p_c-p_{env} using an empirical equation similar to gradient wind balance

2) $$V_{sym}(V_{max}, r_{max}, r) = V_{max} \frac{2 r r_{max}}{r^2 + r_{max}^2}$$

3) Asymmetry added using equation similar to V_{sym} format

Deficiencies with wind forcing:

- Not based on observed wind observations
- Storm size information, such as radius of 34 knots winds, not considered. In fact, storm size only a function of r_{max}, which has nothing to do with storm size
- Storm motion probably inflating intensity
- Storm motion asymmetry not based on observations. In fact, original paper even states it's a "gross correction" which provides a reasonable asymmetry

MSU parametric scheme "Fitz winds"

The hurricane winds are based on a variant of the *Holland* (1980) wind profile:

$$p(r, B, p_{env}, p_c, R_{\max}) = p_c + [p_{env} - p_c]e^{-Ar^{-B}}$$

$$V(r, B, f, p_{env}, p_c, R_{\max}) = \left[\frac{AB[p_{env} - p_c]e^{-Ar^{-B}}}{\rho r^B} + \left[\frac{rf}{2}\right]^2\right]^{0.5} - \left[\frac{rf}{2}\right]$$

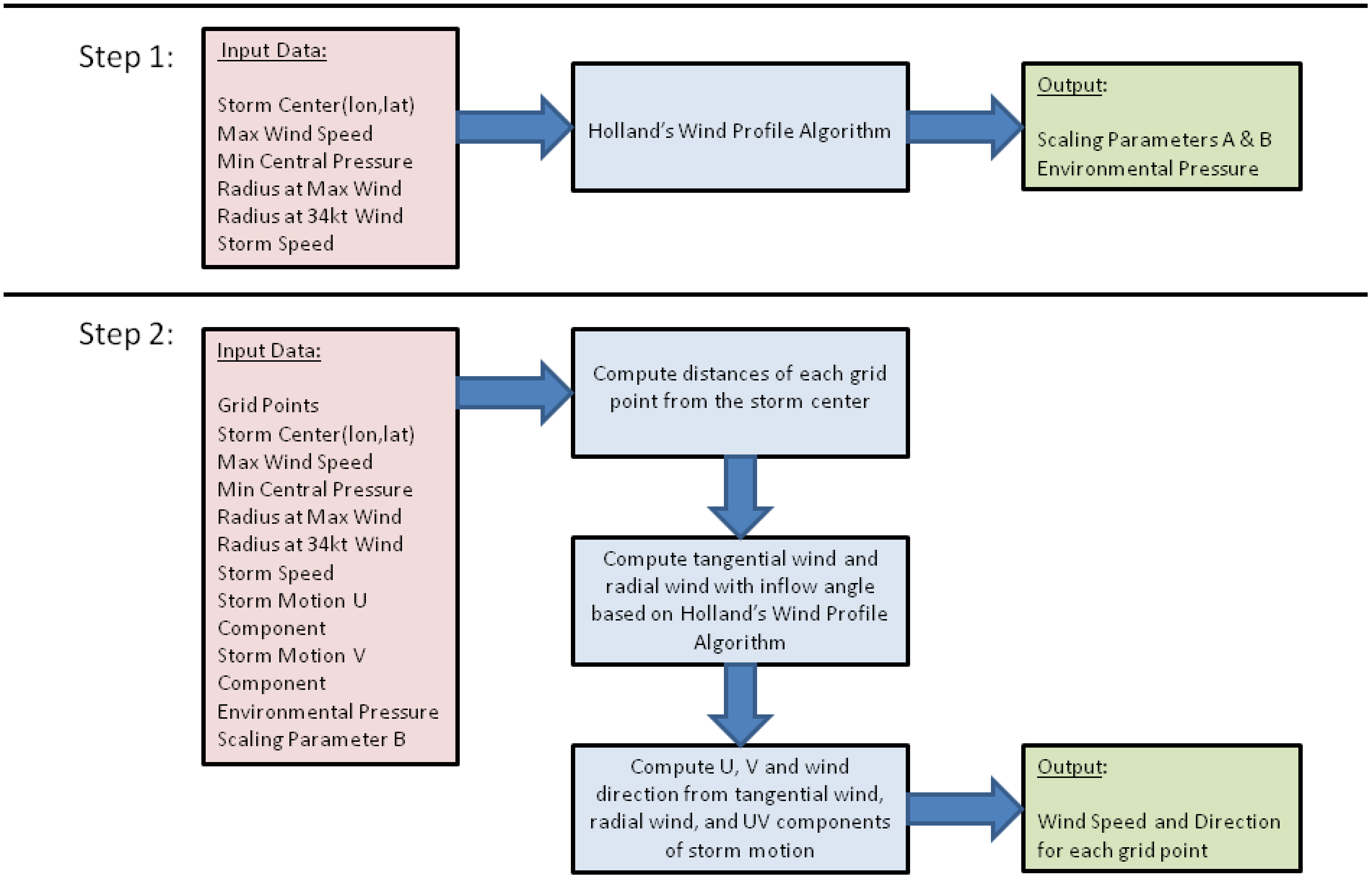
$$V_{max}(B, p_{env}, p_c) = \left[\frac{B}{\rho e}\right]^{0.5}[p_{env} - p_c]^{0.5} \;;\; A(R_{\max}, B) = R_{max}^B$$

where f is the Coriolis parameter, p_c is the storm central pressure, p_{env} is the environmental pressure (set to 1013 mb), and e is Euler's number (the base of the natural logarithm, approximately 2.71828). A and B are scaling parameters which control the radial wind profile. This formulation includes storm motion in V. Given storm motion, V_{max}, R_{max}, p_{env}, and R34, the algorithm iterates for B and then calculates p_c.

Because these equations apply above the boundary layer, but V_{max} and V34 (34-kt winds at R34) are at 10-m height within the boundary layer, V_{max} and V34 are multiplied by 1.11 before the B iteration. On average, winds are 11% faster above the boundary layer (see http://www.nhc.noaa.gov/aboutwindprofile.shtml, and Powell and Black (1990)). However, little sensitivity in the B distribution was seen with this adjustment.

```fortran
c*********************************************************************
c function statement for iteration
c
c The function is derived as follows
c
c It can be shown from Holland's paper that:
c
c penv-pc=Vmax*Vmax/(B/(rho*2.71828))
c
c substitute this into the gradient wind equation (from Holland)
c where the wind is 17.5 m/s (34 knots)
c
c now everything is known except B. Find B by iteration
c
c note that 17.5 m/s has been increased by windF then the storm speed
c is subtracted
c
c*********************************************************************

      function f(B,Vmax,storm_speed,Rmax,size,Coriolis,windF)

      implicit none

      double precision  B, Vmax, Rmax, storm_speed, size, Coriolis
      double precision  Wind34ktInMeterPerSec, rho, f, ts, windF
      parameter(Wind34ktInMeterPerSec=17.5, rho=1.15)

      ts = Wind34ktInMeterPerSec * windF - storm_speed

      f=(sqrt((((Rmax**B)*B*(Vmax*Vmax/(B/(rho*2.71828))*
     &   exp(-(Rmax**B)/(size**B))))/(rho*size**B)) +
     &   ((size**2)*(Coriolis**2)/4.0)) - (size*Coriolis/2.0))
     &   - ts

      end function f
```

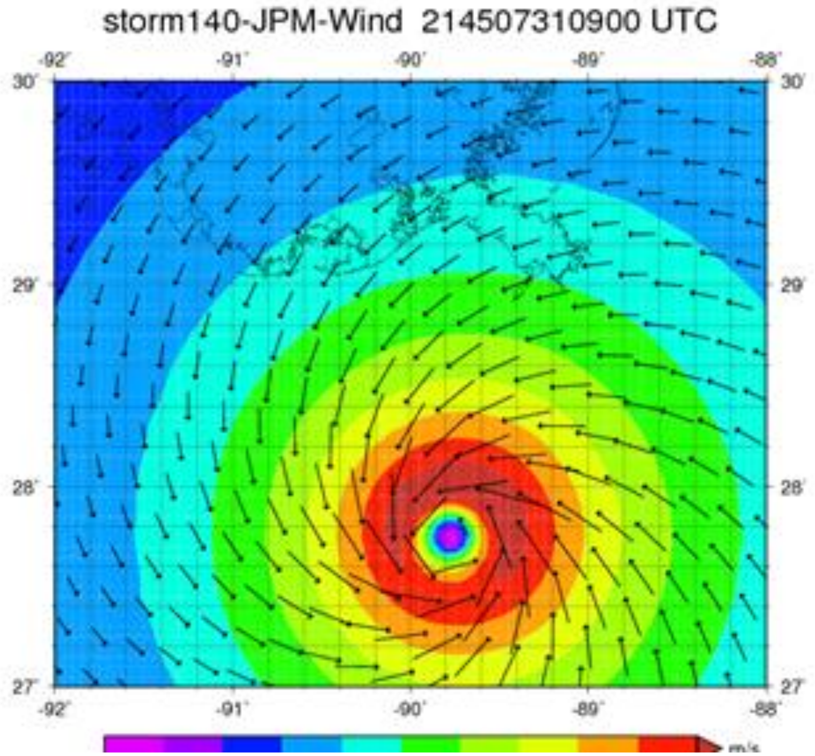
Parametric hurricane wind model flow chart

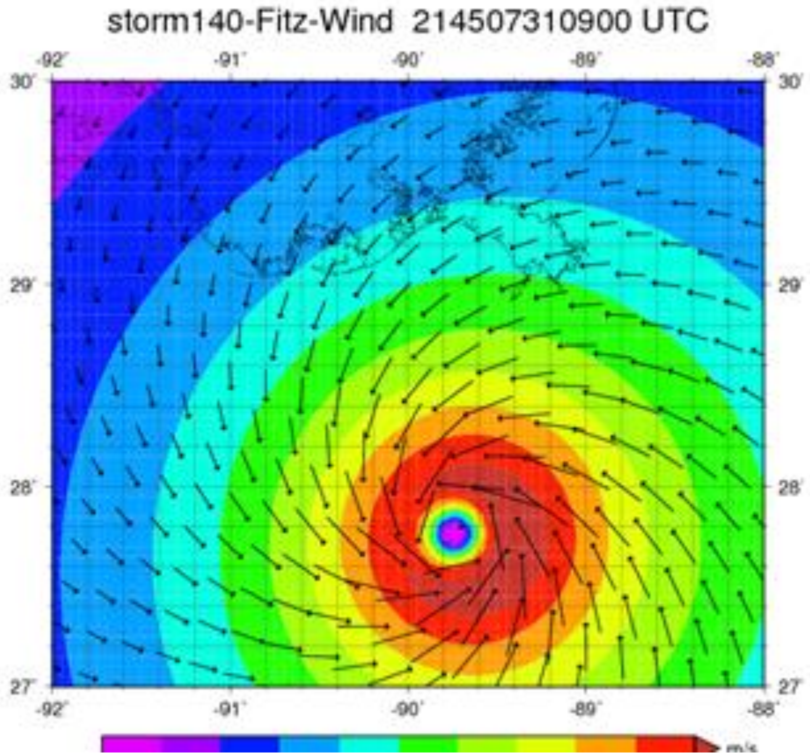


Advantage of this method

- 10-meter surface winds **match** the observed peak **eyewall wind**
- 10-meter surface winds **match** the observed **radius of 34-knots winds**
- **Holland B an iterated solution**, not predetermined
- **Specification of wind direction** that can vary radially
- **Storm motion is included in the iteration, not added afterwards**
  - ➢ Vmax=storm speed plus hurricane vortex eyewall
  - ➢ V34=storm speed plus edge of hurricane vortex
- This allows a parametric model which:
  - ➢ **Matches the National Hurricane Center forecast**
  - ➢ Can **match hindcast hurricane data** for JPM studies, theoretical studies, risk modeling, etc.
  - **Correctly uses storm motion**. Many schemes superimpose storm speed translation. This is incorrect usage. Observed winds already include storm motion.
- Version 1 released 6/11 as open source. Its also now being incorporated into SMS software. Version 2 will include a new asymmetry factor, but funding is always a problem.

Comparison of hypothetical storm (left) fitted by Fitz Wind Model (right)





The future of storm surge modeling

ADCIRC_Lite: Rapid Tropical Cyclone Surge and Wave Evaluations using Pre- computed ADCIRC Solutions

Brian Blanton, Rick Luettich, Jesse Bikman
University of North Carolina at Chapel Hill

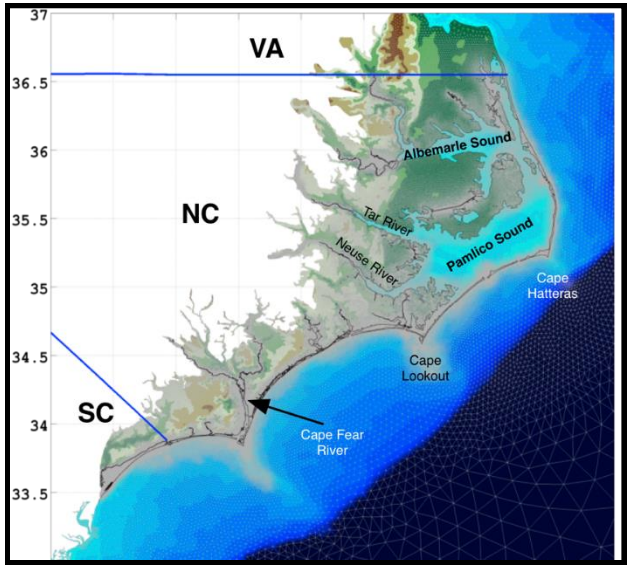
Alexander Taflanidis, Andrew Kennedy
University of Notre Dame

ADCIRC Users Group Meeting 4/3/2014

Funded by the Department of Homeland Security's Science &Technology
Coastal Hazards Center of Excellence at UNC

The Issue

- Short forecast windows
  - Forecast cycle typically 6 hours
  - Need information well within this 6-hour window
  - Want guidance information ASAP
- High-resolution, dynamic surge & wave simulations are resource intensive
  - Typical 1 - 3 hours run time on 192 processors
  - Multiple member ensemble requires more
- How to accelerate model throughput
  - Much more computer hardware (someday…)
  - Take advantage of pre-computed, high resolution solutions (e.g., Surge Atlas)



Surrogate Modeling

Implement a surrogate model that rapidly predicts a response (storm surge, waves) using familiar variables (hurricane parameters)

- Surrogate models approximate complex systems
  - Replace ADCIRC with AdcircLite
- Leverage ***existing*** database of high-resolution storm surge simulations
  - recent FEMA coastal National Flood Insurance Program Study for North Carolina
  - similar FEMA NFIP databases available for other areas
  - Supplement existing databases as desired / needed

AdcircLite Surrogate Model

Response Surface Method

- Long history in engineering, chemistry…
- More recently used for storm surge – JPM OS D. Resio; also J. Irish
- AdcircLite uses 2nd order moving least squares
- Much better accuracy compared to zeroth-order methods

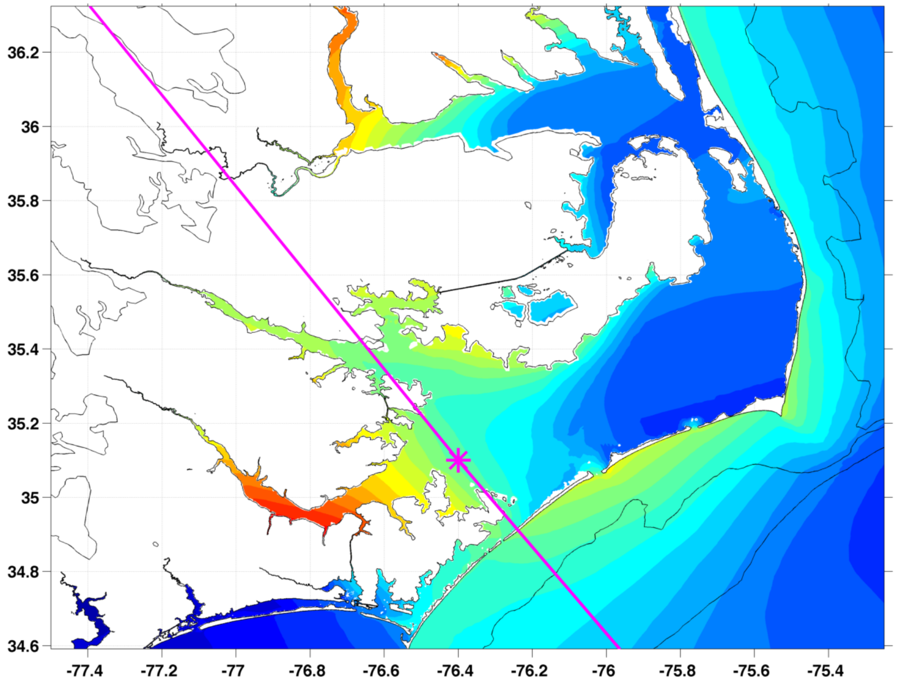
$$\underbrace{\hat{z}_i}_{\text{response estimate}}(\underbrace{\mathbf{x}}_{\text{vector of hurricane parameters}}) = \sum_{j=1}^{NB} \underbrace{b_j}_{\text{basis functions}}(\mathbf{x})\underbrace{a_{ij}}_{\text{database of dynamic model solutions x weighting coefficient found by optimization}}\{\mathbf{x}\}$$

Historical Storm Results – Isabel 2003

Maximum
Water Level

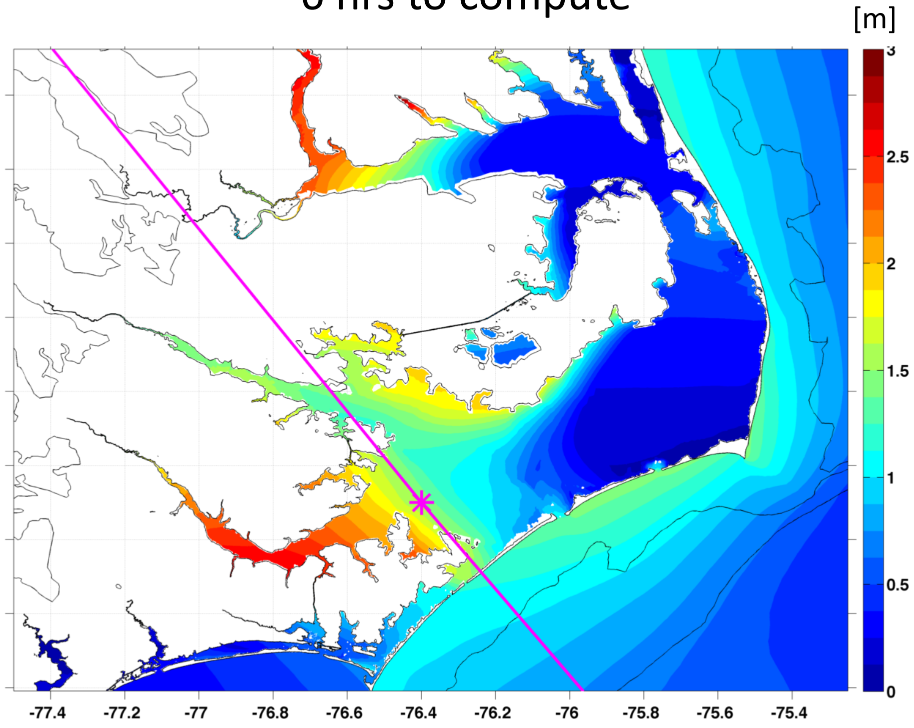
AdcircLite-NC Model Prediction

- 4 secs to compute



FEMA Validation Study

- ~6 hrs to compute



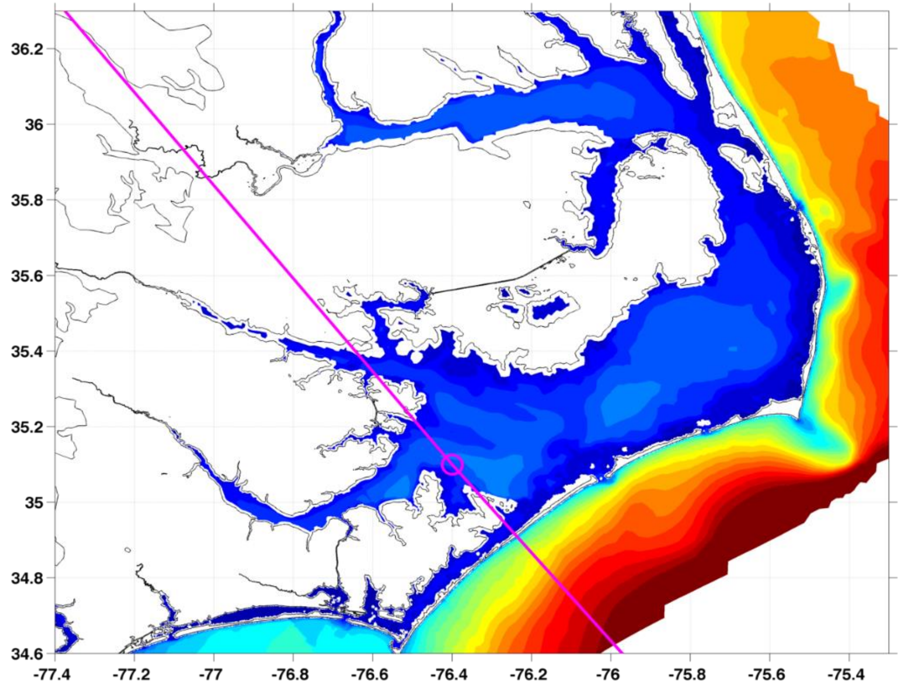
Historical Storm Results – Isabel 2003

Maximum

Significant Wave Height

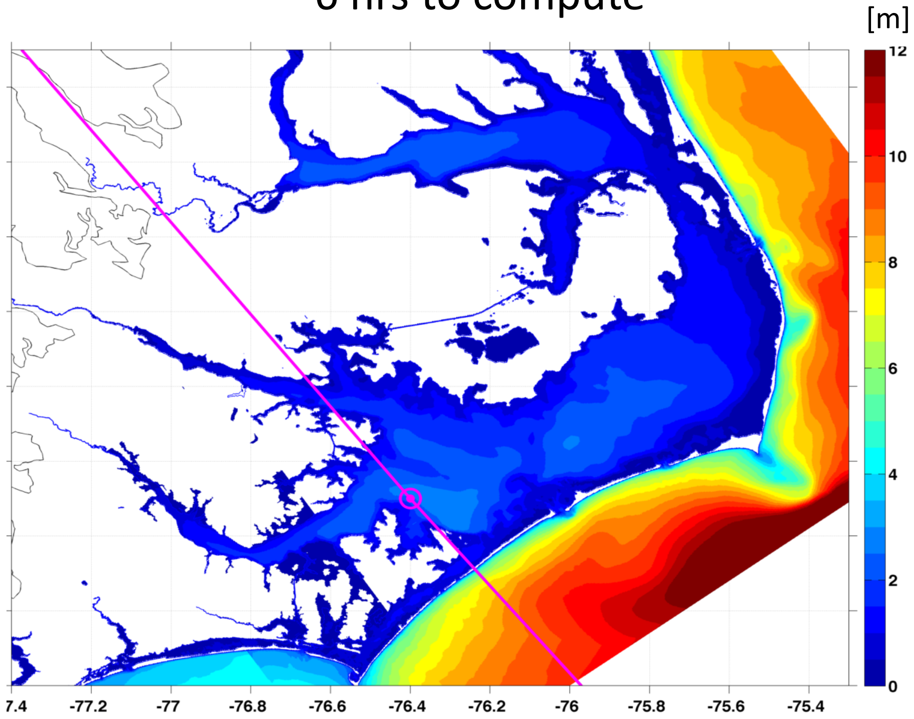
AdcircLite-NC Model Prediction

- 4 secs to compute



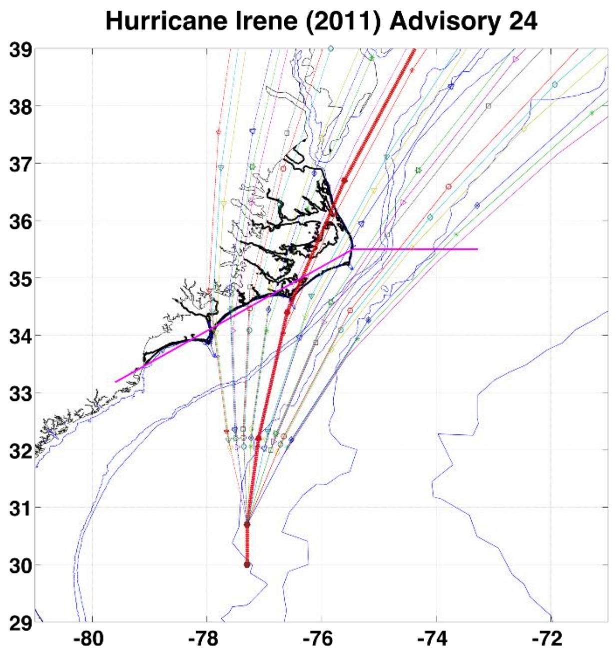
FEMA Validation Study

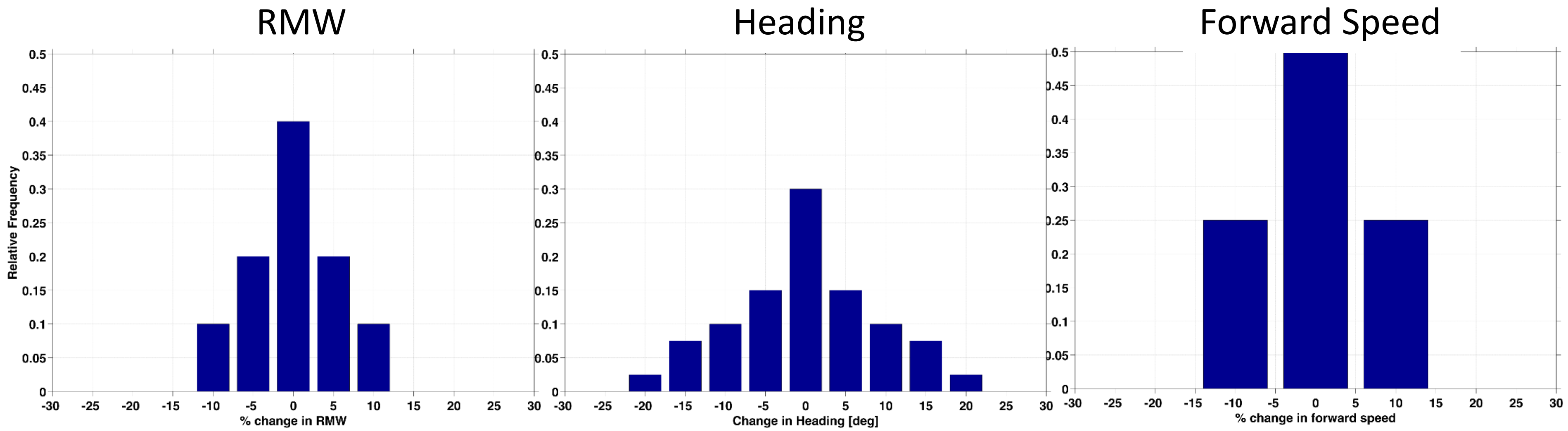
- ~6 hrs to compute



Ongoing Activities

- Ensemble Forecasting with AdcircLite
  - Method to perturb NHC forecast track
  - Outputs ADCIRC fort.22 files
  - Basic parameter variation, test distributions for RMW, Heading, Forward Speed
  - 135 ensemble members (5*7*3)

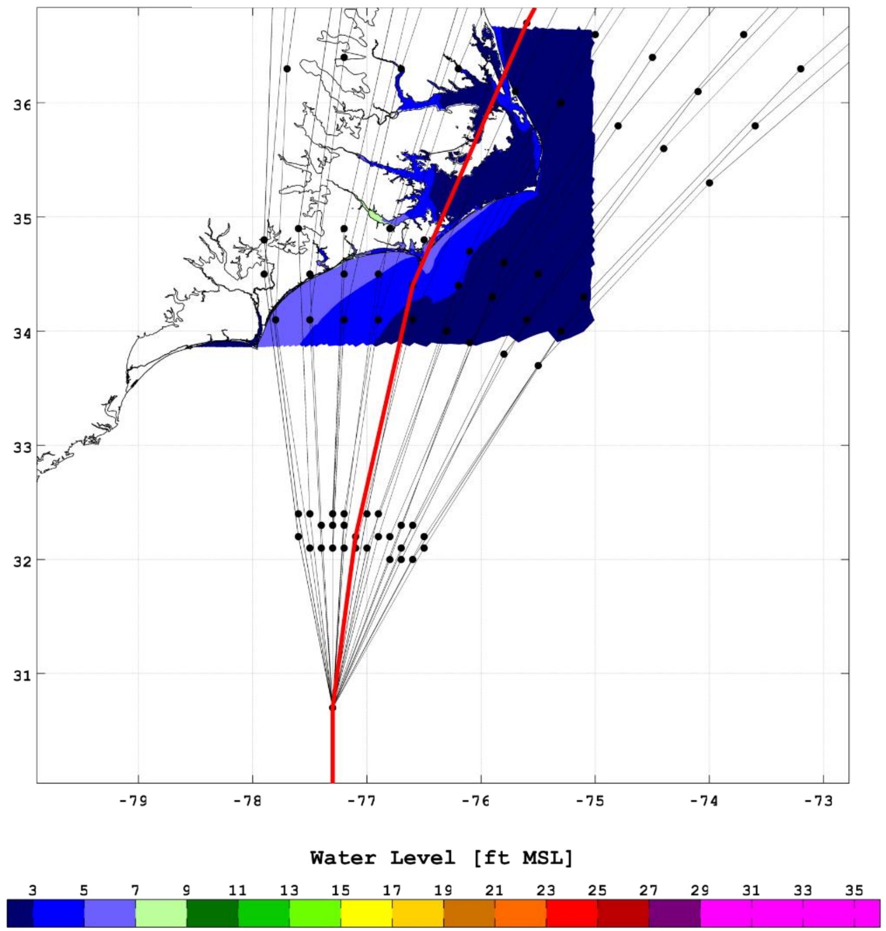




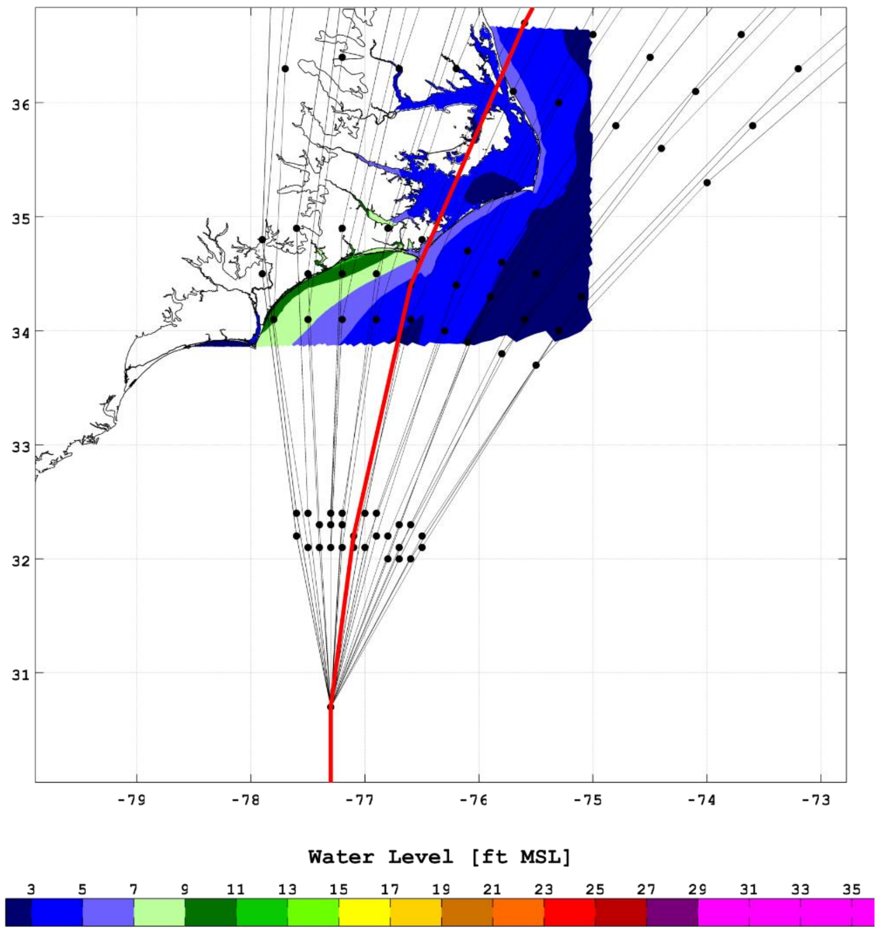
Ongoing Activities

Hurricane Irene (2011), Advisory 24

50% Exceedence Level



10% Exceedence Level



Conclusions

- Surrogate modeling approach can fill a storm surge / wave prediction gap between coarse resolution (fast) and high resolution (slow) dynamic models
- AdcircLite – Moving (Local) Least Squares Response Surface Method
  - Robust and fast once surrogate model is defined
  - Quantifiable error estimates can be obtained
- Simple to run once surrogate model defined
- Provides a mechanism to develop large, ensemble-based (probabilistic) high-resolution water level predictions