EXPANDING THE REALM OF POSSIBILITY

Uncertainties in Atlantic Hurricane Characteristics with Application to Coastal Hazard Modeling

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Hurricane Simulation Modeling Usage

- Wind Hazard Mapping – Building Codes
- Insurance Risk Modeling – PML Estimates, Rate Setting (wind and coastal flood)
- Estimates of design wave conditions
- Coastal Flood Modeling – Flood Insurance Rates, Building Regulations

Background

- Premise behind hurricane simulation modeling is:
  - If we can characterize the statistics of key hurricane input parameters and use this data in a hurricane wind field model coupled with a rate model, we can artificially create long history records of wind speeds, wave heights, storm surge, etc and develop hazard curves
  - Key wind field input parameters are
    - Central pressure difference
    - Track (lat, long, heading)
    - Translation speed
    - Radius to maximum winds
    - Holland B parameter
  - Major difficulty is there is a short record of historical data and the quality and quantity of data varies over the past 100 years
  - Significant uncertainty in these input variables which propagates to large uncertainties in output hazard estimates which should be considered in decision making

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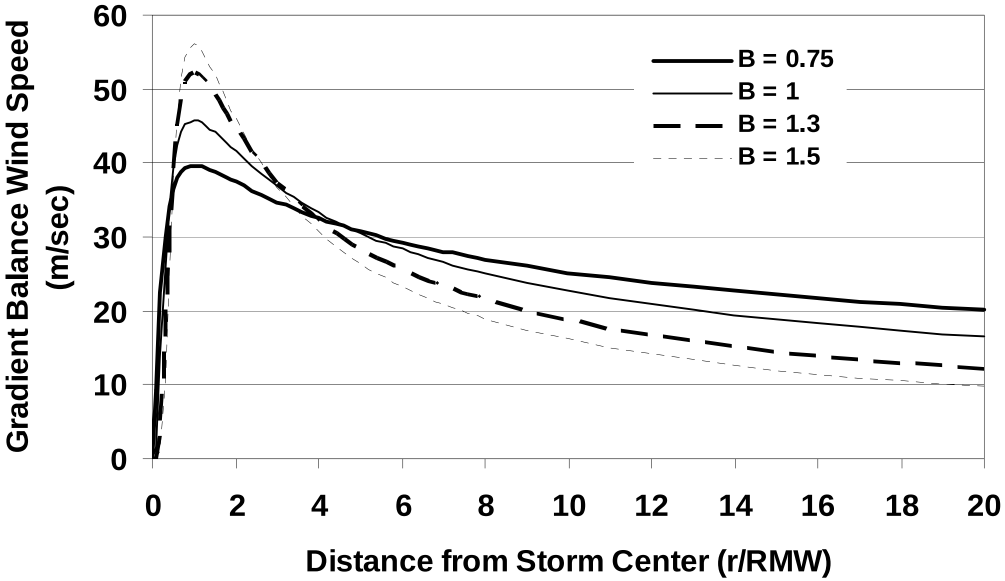
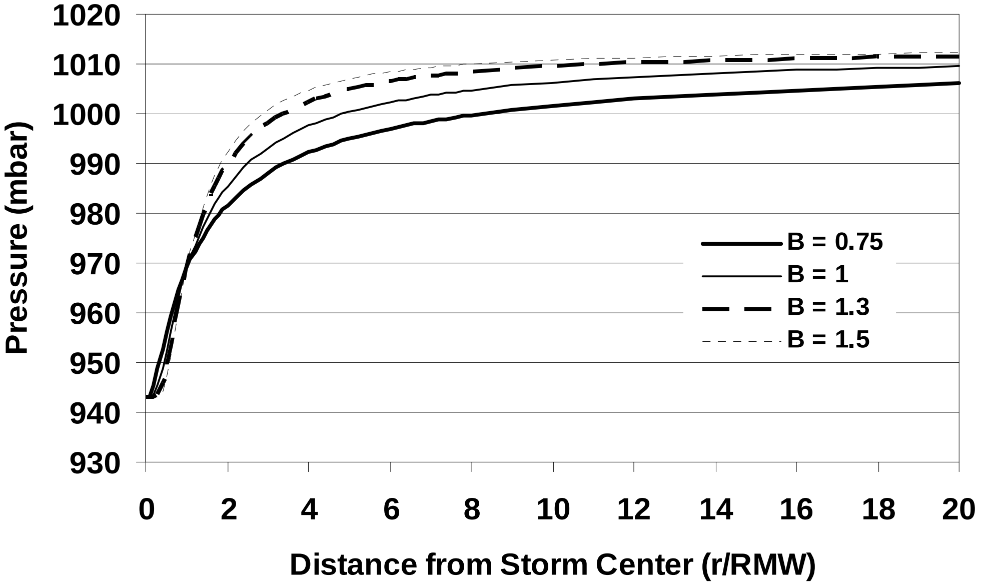
Holland *B* Parameter

Increase in B yields higher maximum wind speeds and a relatively narrow wind field

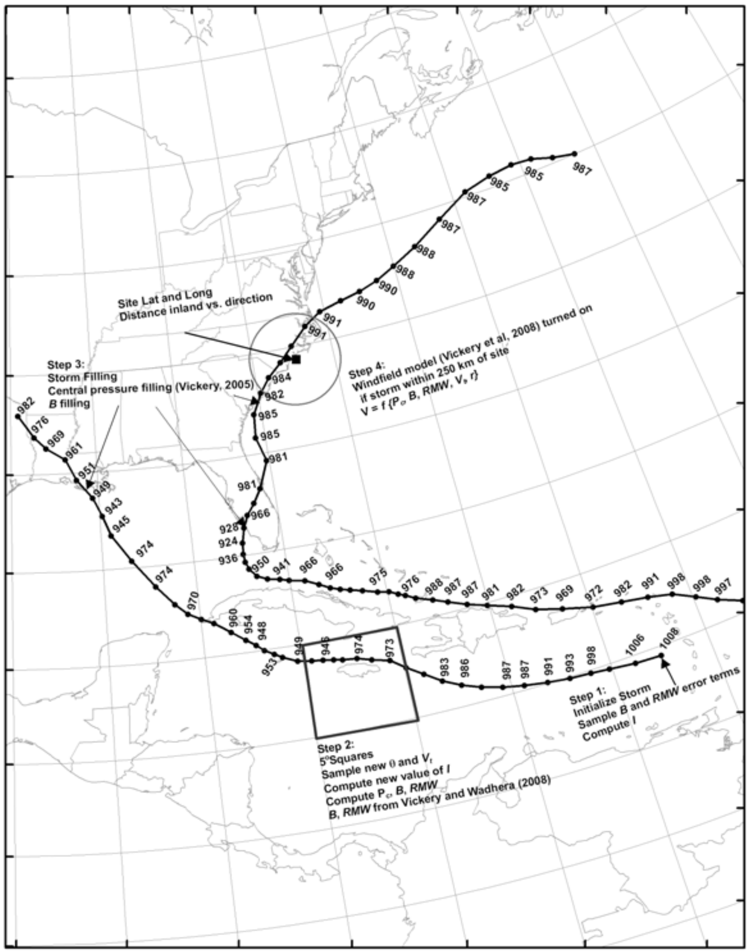
Decrease in B reduces the maximum wind speed but results in a broader storm

Sometimes referred to a tuning or calibration knob

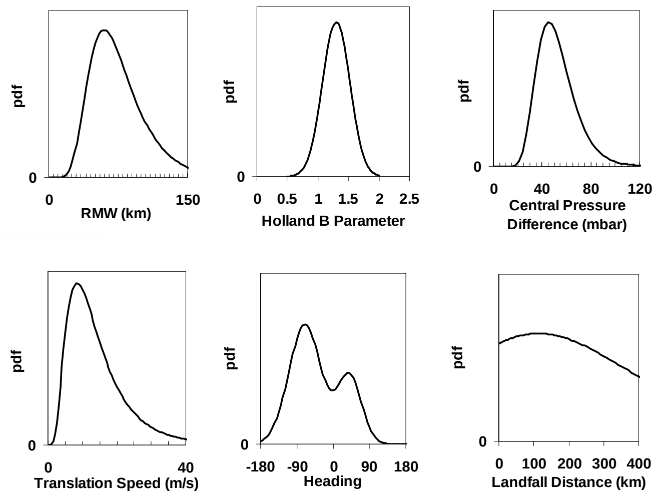




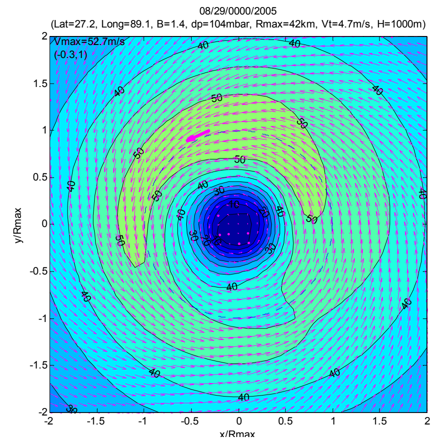
Modeling Approach



Input Probability Distributions

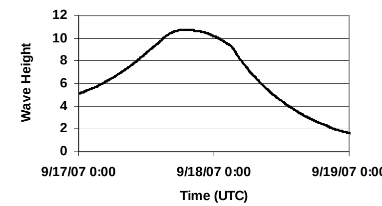


Wind Field Model



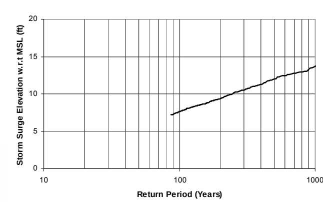
Hydrodynamic Models

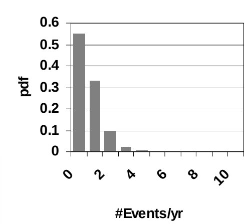
e.g. WAVEWATCH, SWAN, ADCIRC, etc

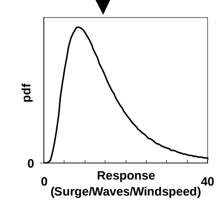


Distribution of response given hurricane

Hazard Curve







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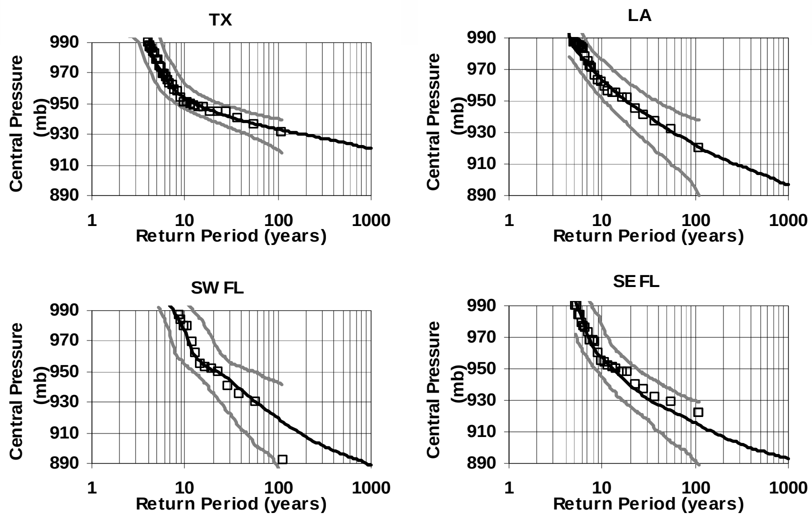
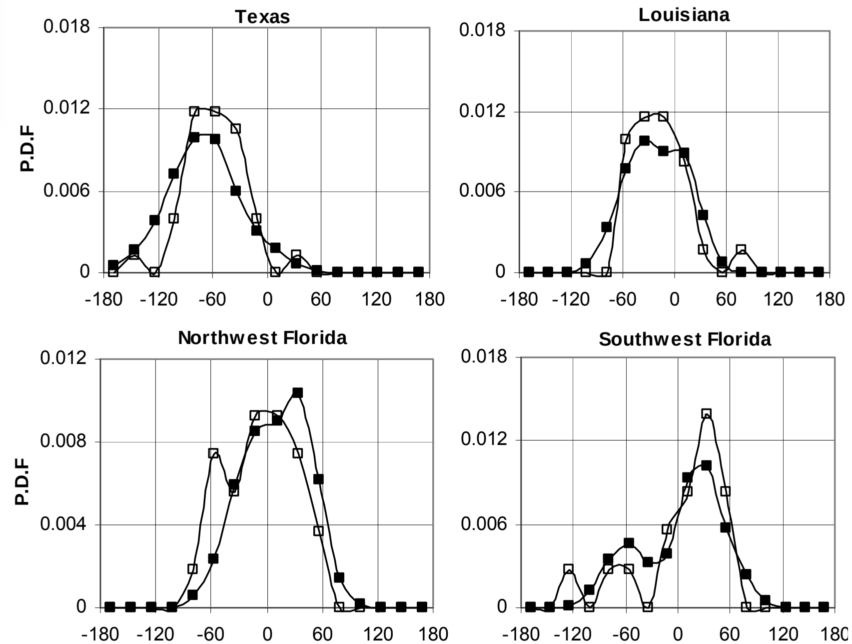
Simulation Model Validation Examples



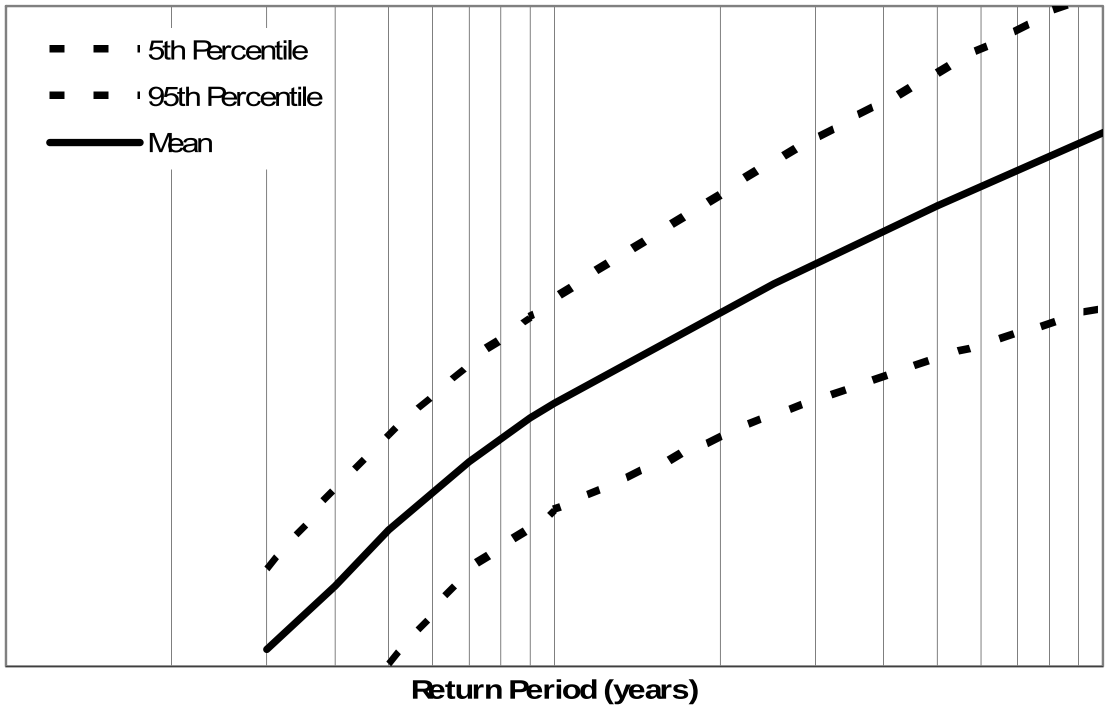


- Model validated through comparisons of statistical distributions of modeled and observed central pressures, storm heading, translation speed and occurrence rates along the Gulf and Atlantic coasts and in the Caribbean
- Separate statistical models used to model *B* and *RMW* as a function of other hurricane parameters
- Results in a model that is nominally mean centered
- Estimates of model uncertainties have to be treated separately

Objective

- Given an estimate of the uncertainties in the key model input parameters Δp, *RMW*, etc we want to know the uncertainty in the output variable such as:
  - 100 year return period wind speed
  - 100 year return period water elevation
  - 475 year return period loss
- Characterize uncertainties in the inputs and propagate through the simulation model
- Difficult time consuming process that requires significant simplifications

Example Output Hazard Curve



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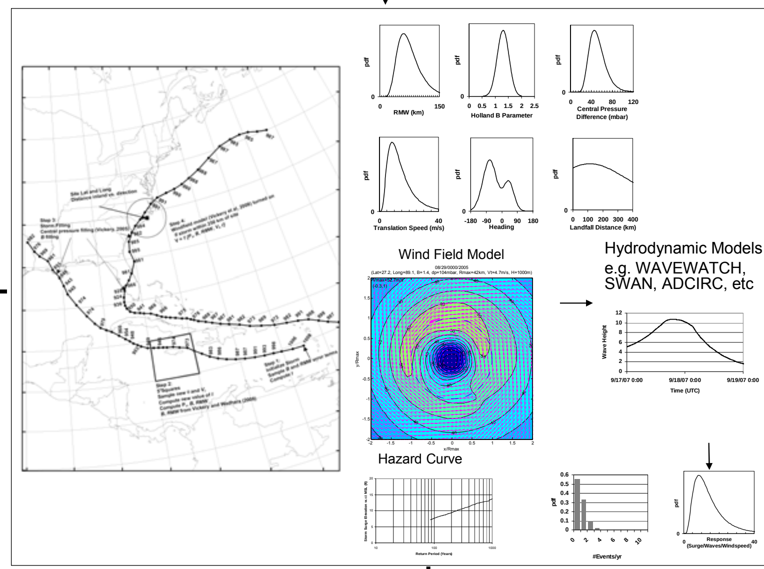
Uncertainty Estimation Approach

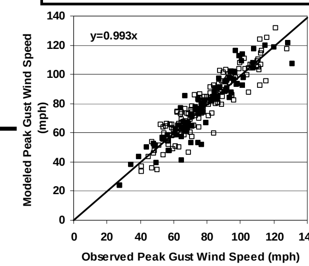
Sample errors for parameters of each input model/probability distribution (error in mean and standard deviation)

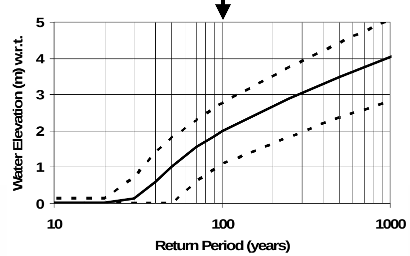
Start *N* year

Repeat *N* year simulation *M* times



Sample model errors for each storm realization

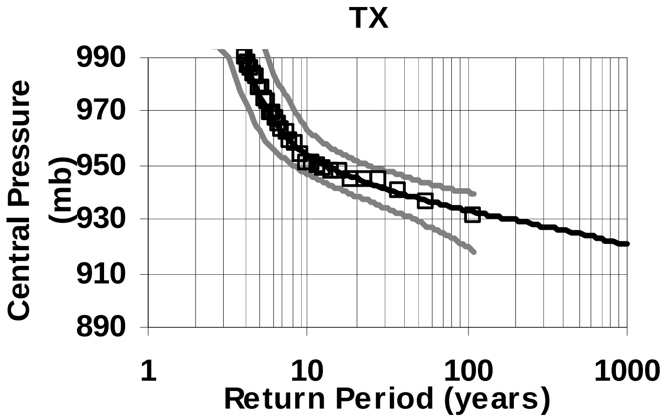


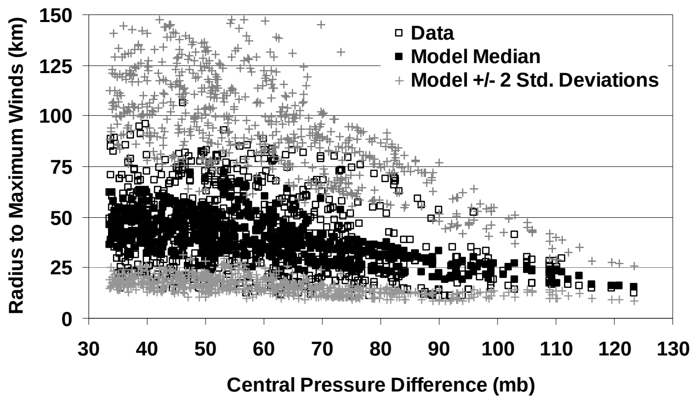


Family of Hazard Curves

Uncertainties

- Each input probability distribution (or regression model) is uncertain (i.e. errors in one or more of the mean, variance or even the chosen statistical distribution)
  - Errors will reduce as the record length increases
  - Reduce errors with improved physical models





- Physical models have errors associated with lack of understanding of the true physical processes and/or model simplifications and assumptions
  - Errors will reduce as computer power increases and model physics are improved

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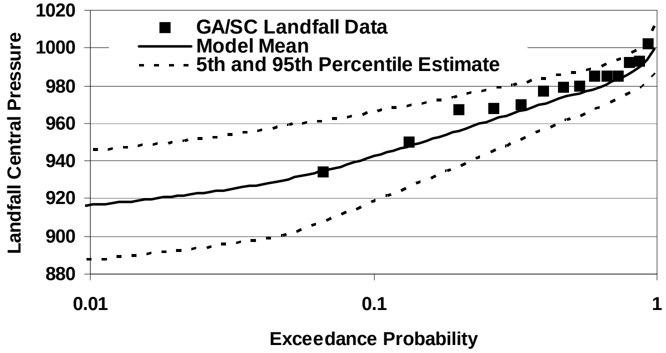
Landfall central pressure uncertainty

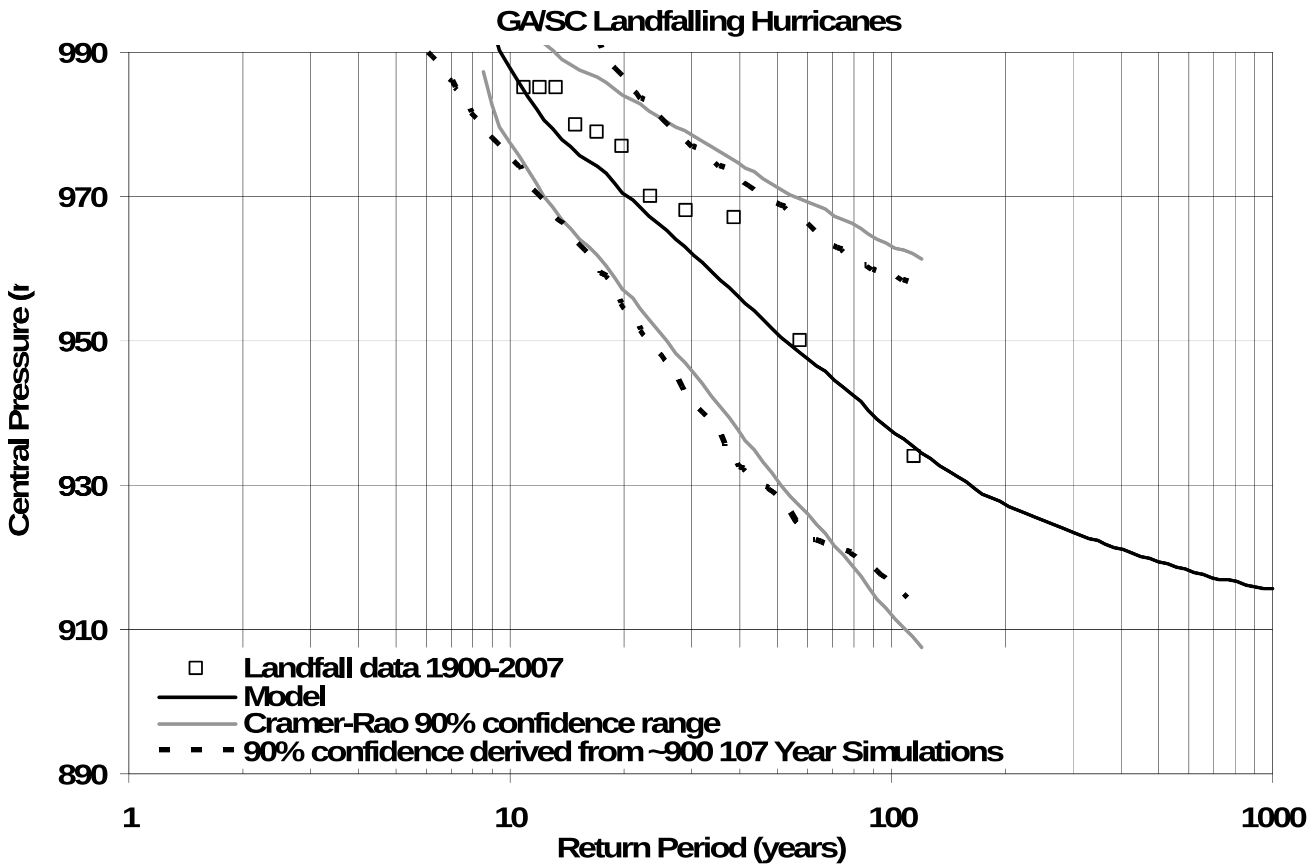
- Characterize errors assuming landfall pressure are characterized by a Type I distribution (Error estimate using Cramer-Rao)

$$\sigma_{\Delta p}(P) = (0.608[\ln(-\ln(P))]^2 - 0.514\ln(-\ln(P)) + 1.109)^{1/2} \frac{\sigma_{\Delta p}}{\sqrt{n}} \frac{\pi}{\sqrt{6}}$$

- Each 20,000 year realization effectively samples from a new distribution of landfall pressures
  - Essentially shifts the landfall pressure hazard curve up and down for an entire 20,000 year simulation
  - Error is fully correlated over the 20,000 year simulation



Pressure Uncertainty



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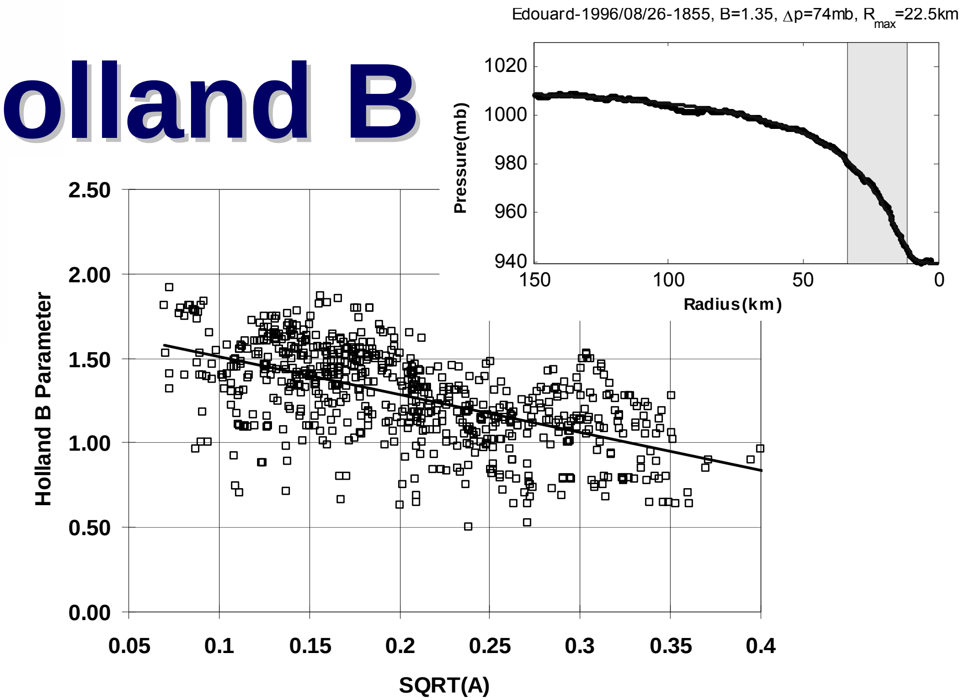
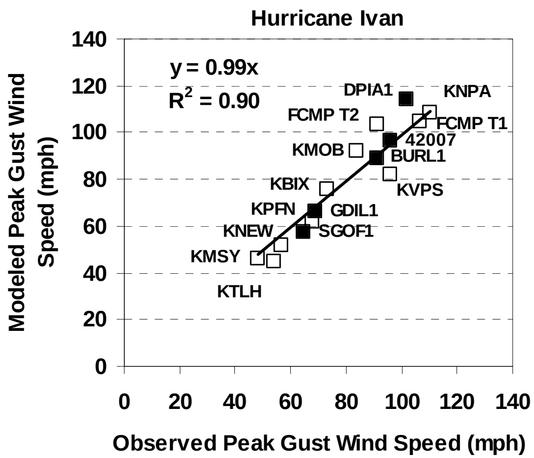
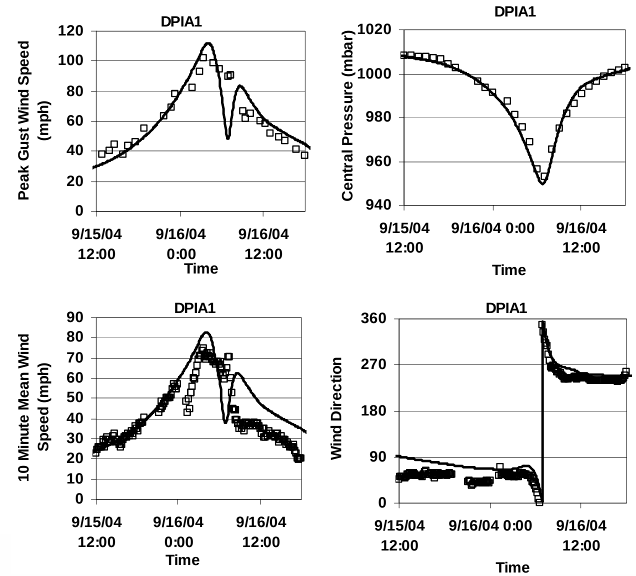
Uncertainty in Holland B Parameter

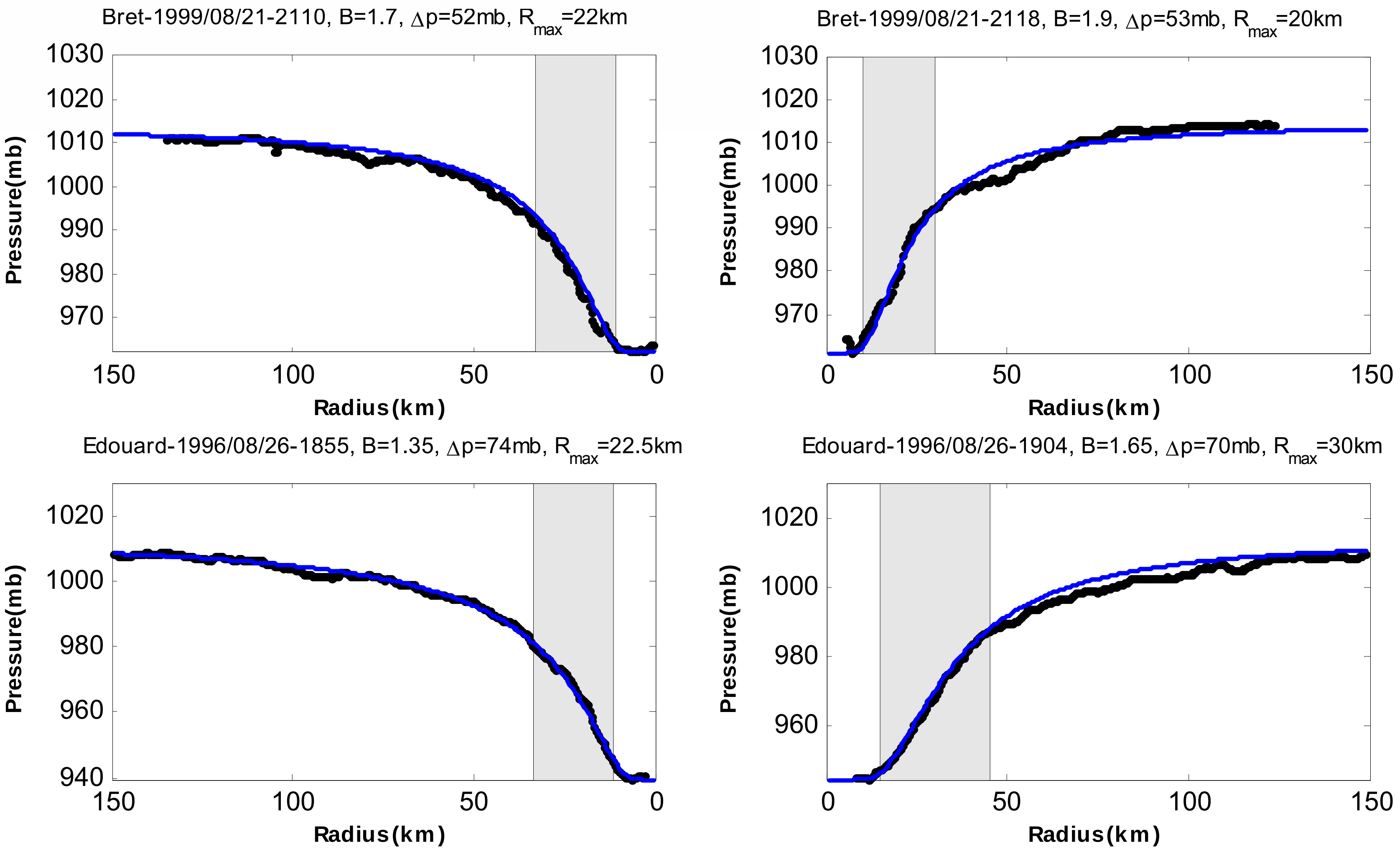
- B derived from aircraft pressure data (670 estimates of B from 35 hurricanes)
- B derived for landfalling storms by matching modeled and measured surface winds and pressures to model results obtained using wind and pressure models defined using central pressure, B, RMW, etc. Estimates for 25 landfalling hurricanes
- B models published by other researchers



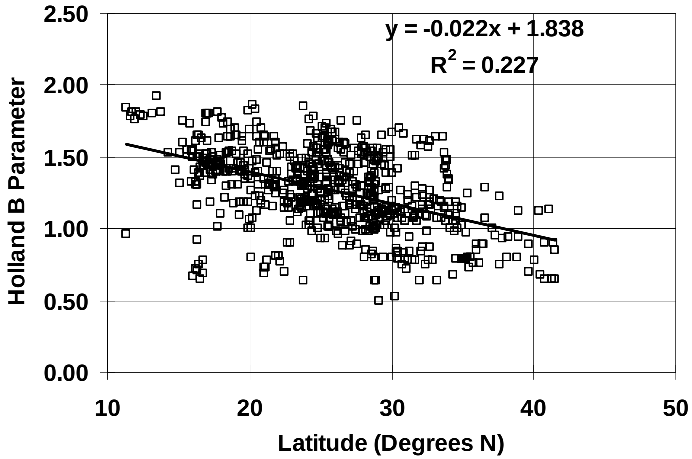


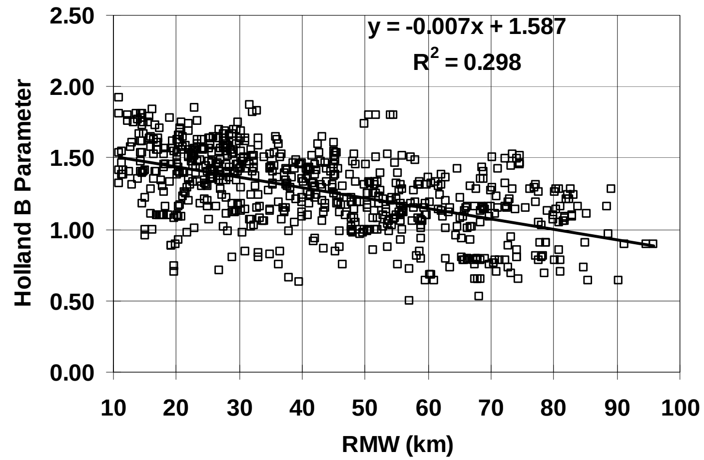


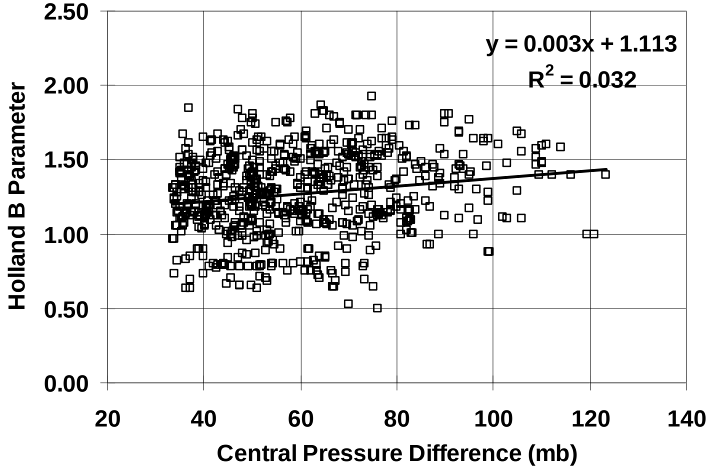
Example *B* fits

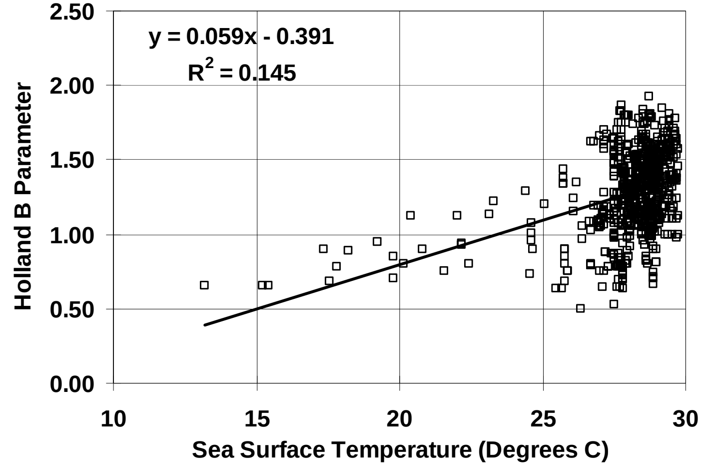


B vs. RMW, Latitude, SST and Central Pressure

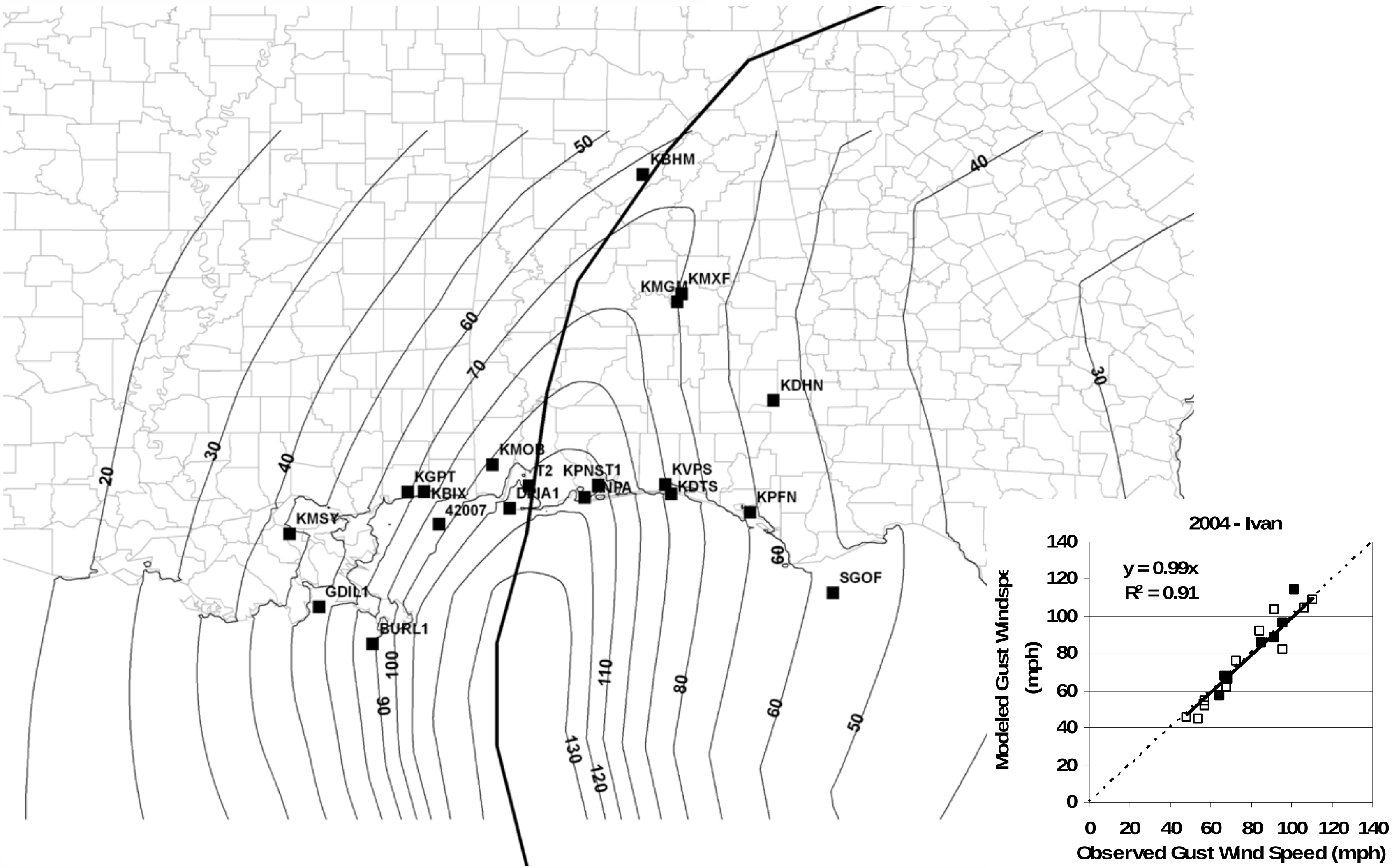




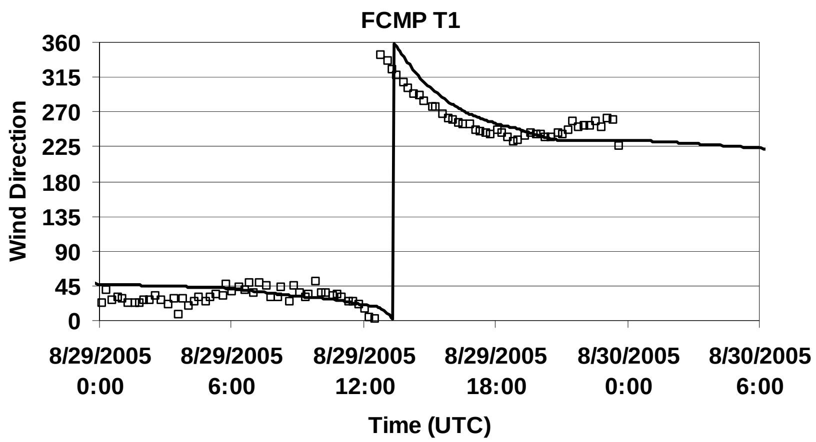


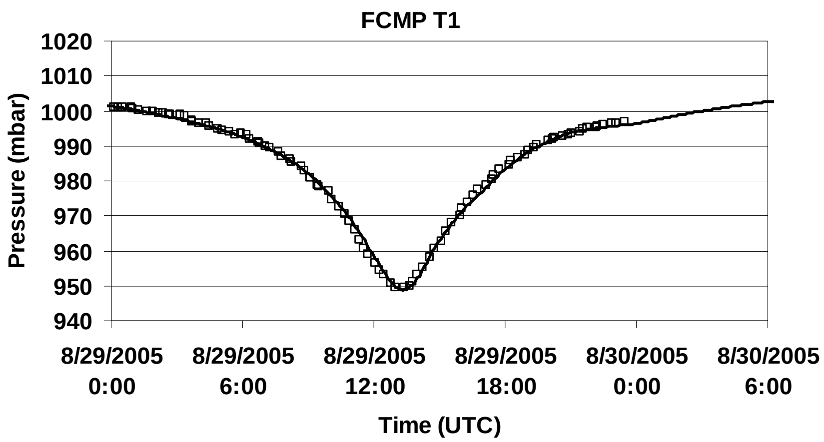


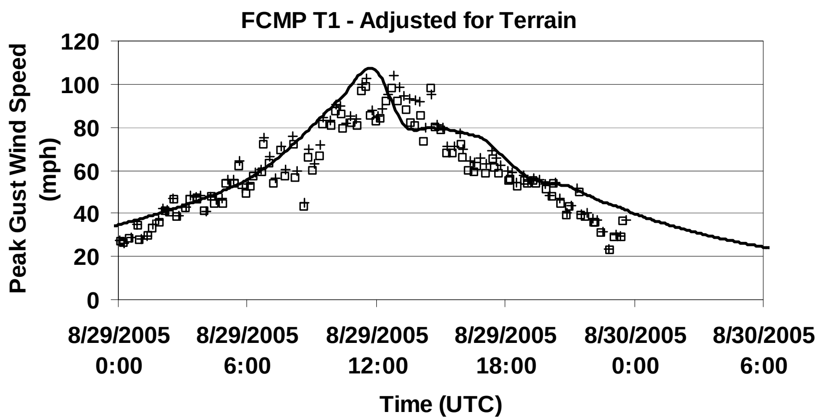
Estimation of Holland *B* Parameter

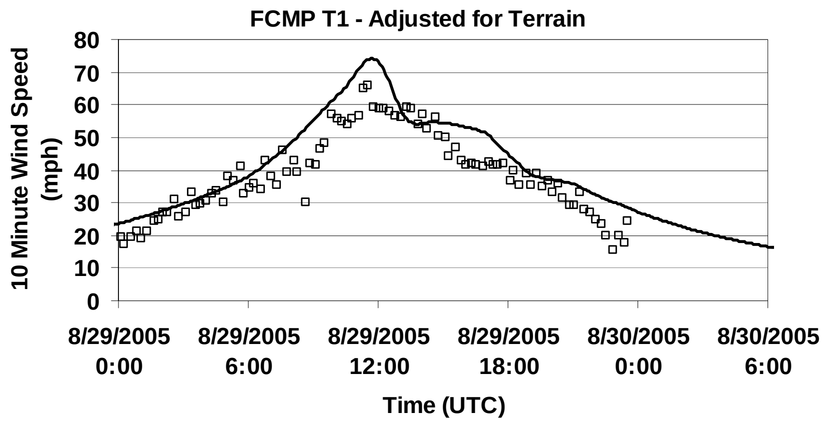


Estimation of Holland *B* Parameter

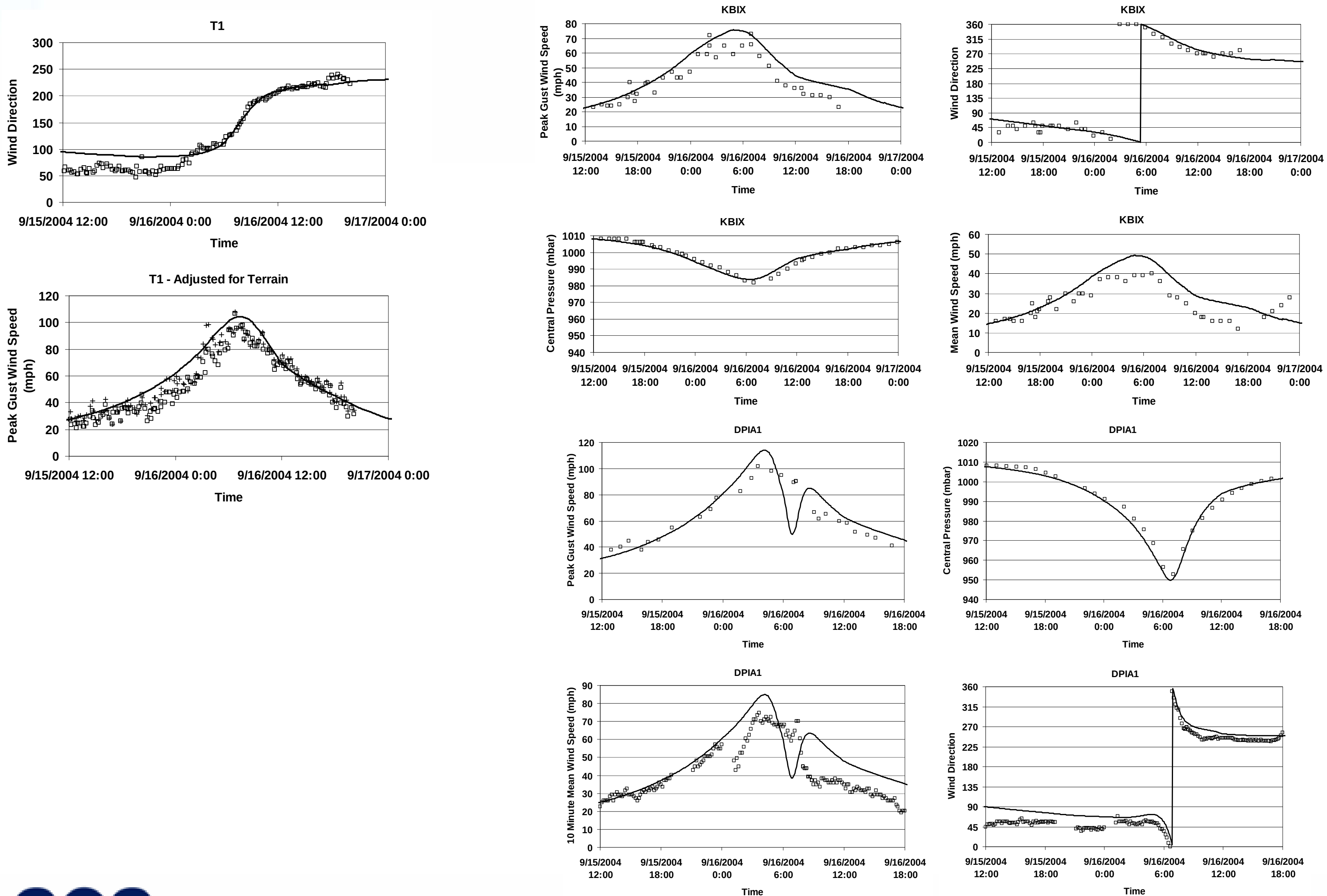




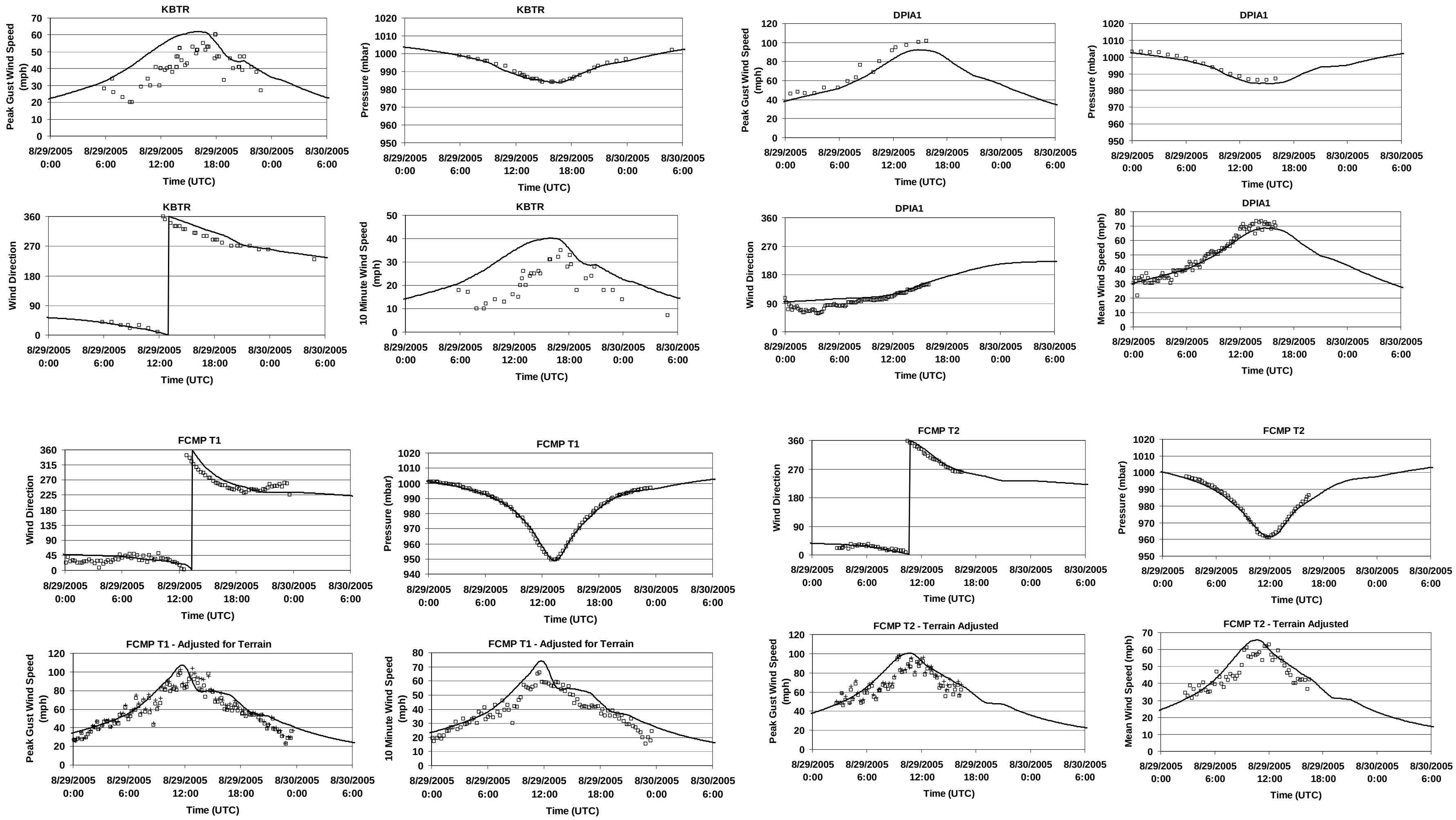




Validation Examples – Ivan



Validation Examples - Katrina



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Holland *B* Models

Powell, et al (2005)

$B = 1.881 - 0.00557RMW - 0.01097\,\psi$, r^2=0.20, $\sigma_B = 0.286$

Vickery and Wadhera (2008)

$B = 1.881 - 0.00557RMW - 0.01295\,\psi$; r^2=0.356, $\sigma_B = 0.221$

$B = 1.772 - 2.237\sqrt{A}$; r^2=0.336, $\sigma_B = 0.225$

$$A = \frac{RMW \cdot f_c}{\sqrt{2R_d T_s \cdot \ln\left(1 + \frac{\Delta p}{p_c \cdot e}\right)}}$$

Vickery, et al. (2000)

$B = 1.38 + 0.00184\Delta p - 0.0031\,RMW$; r^2=0.026, $\sigma_B = 0.38$

Analysis of Atlantic Ocean Landfalling Hurricanes

$B = 1.56 - 0.0051RMW - 0.00172\,\psi$,; r^2=0.22, $\sigma_B = 0.21$

(16 Observations, dependence on latitude not significant)

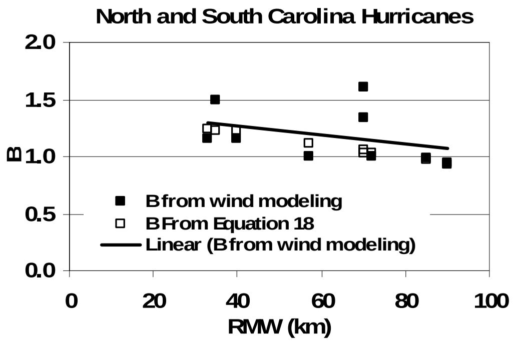
Analysis of Atlantic Ocean and Gulf of Mexico Landfalling Hurricanes

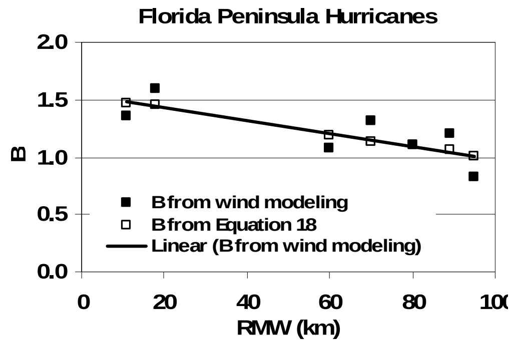
$B = 1.21 - 0.00264RMW + 0.001874\,\psi$,; r^2=-0.01, $\sigma_B = 0.26$

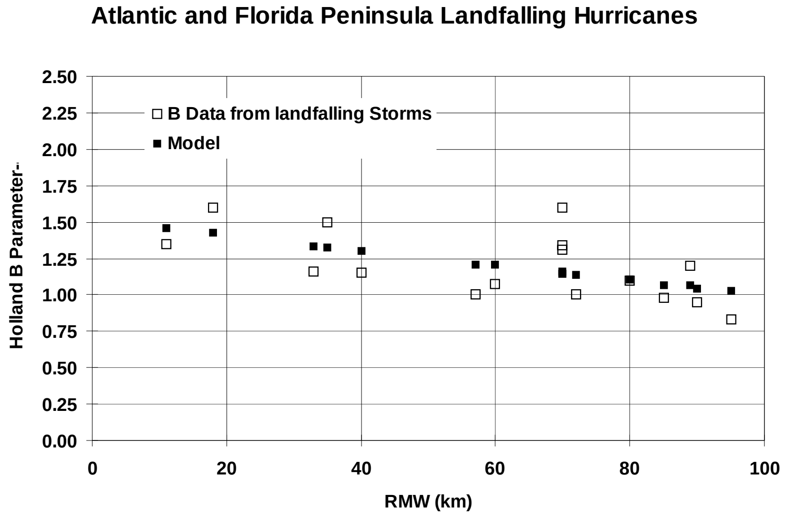
(25 Observations, latitude and RMW dependence not significant)

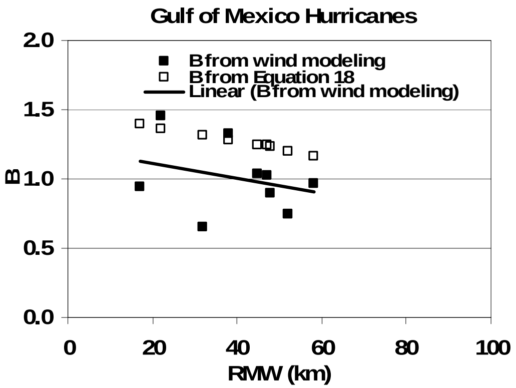
B = 1.12, $\sigma_B = 0.26$

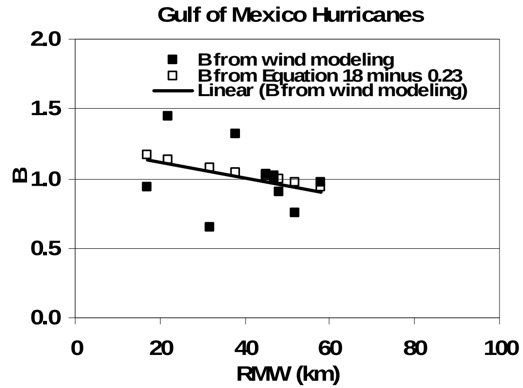
B from Landfalling Storms



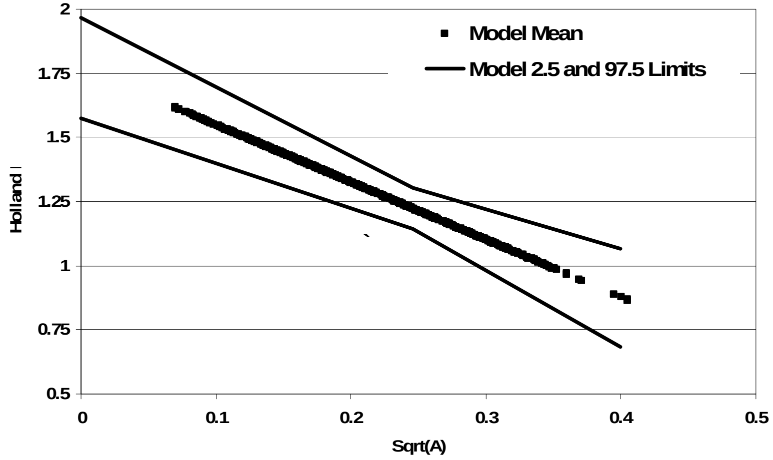


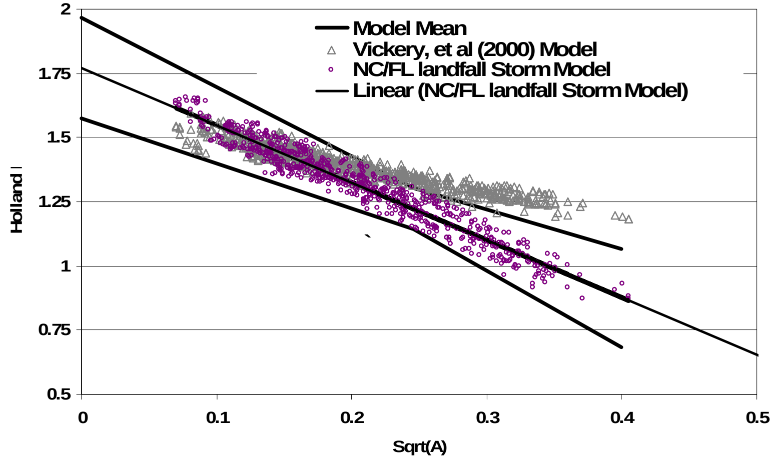


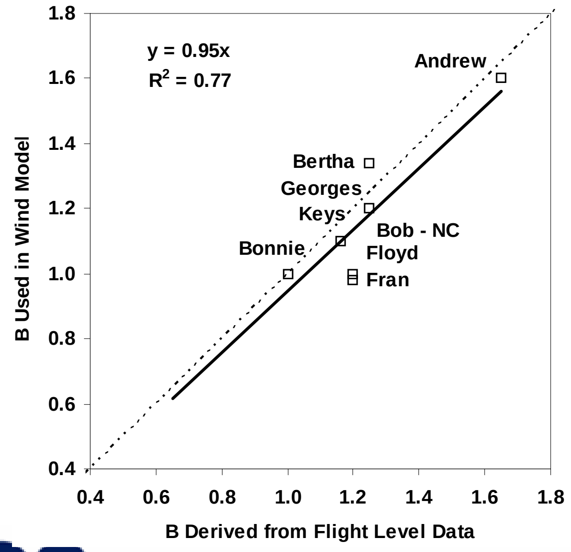


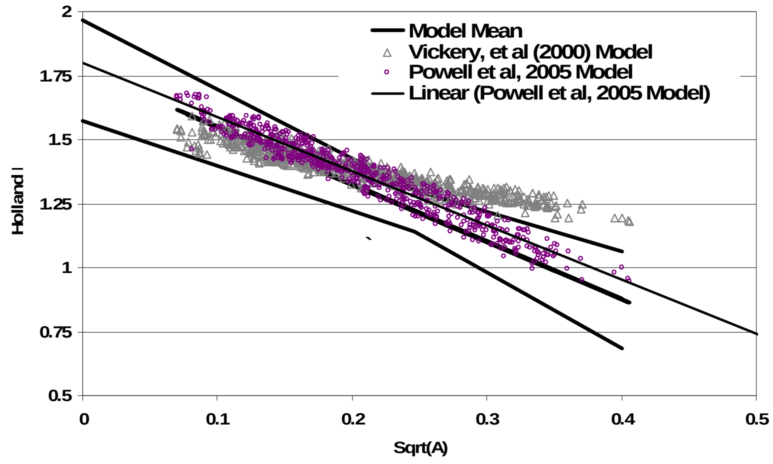


Comparison of Regression Parameter Estimates with Other Models



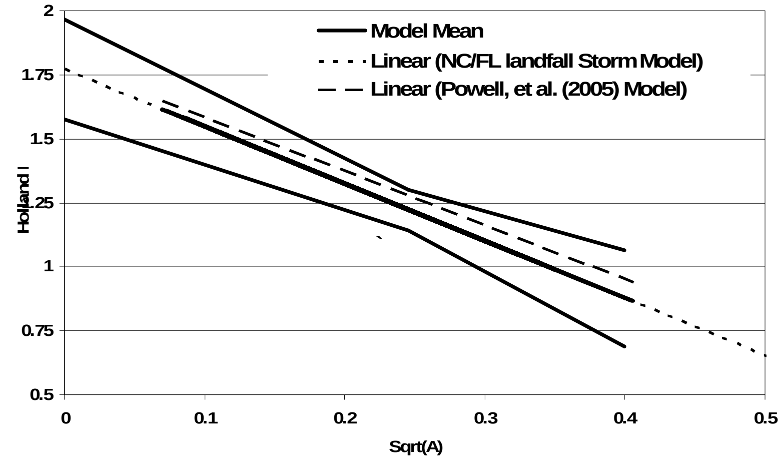


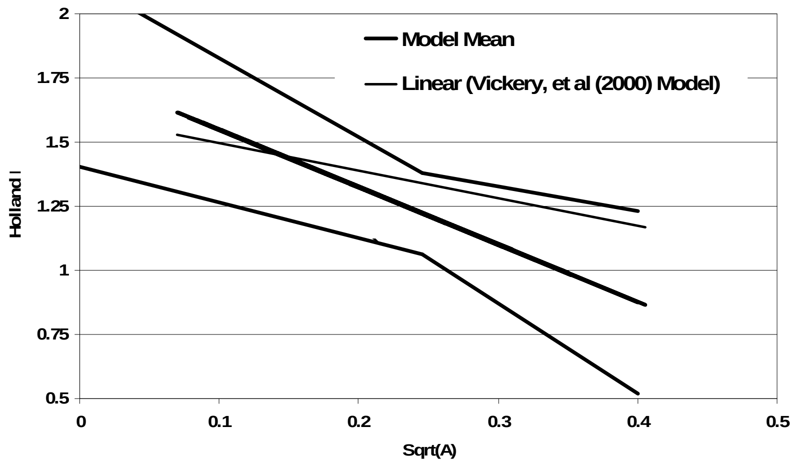




Upper and Lower Bound B Uncertainty Models

- Lower Bound Estimate
  - Standard Error in mean = 0.04
  - Standard Error in slope = 0.28
- Upper Bound Estimate
  - Standard Error in mean = 0.08
  - Standard Error in slope = 0.50





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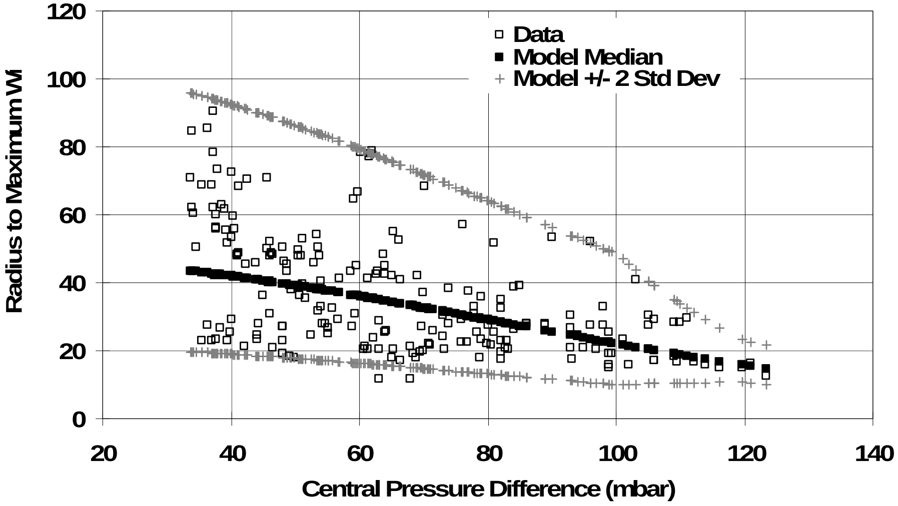
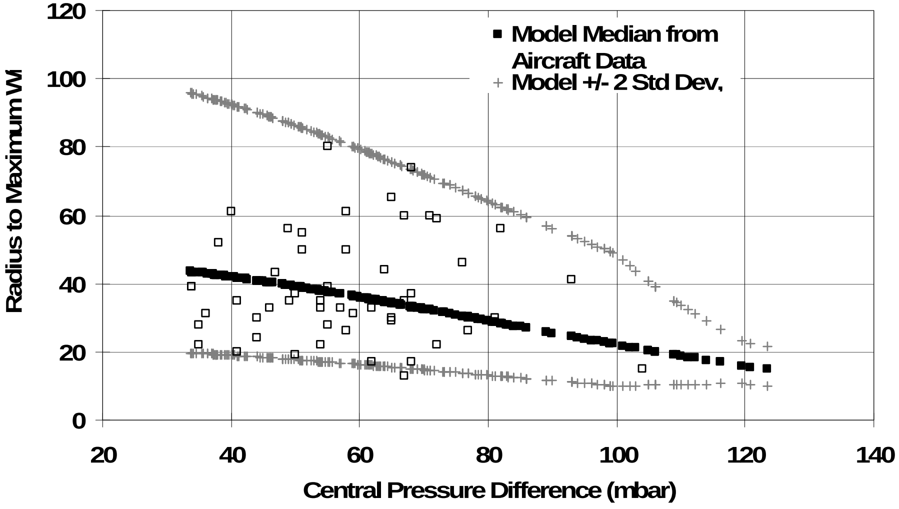
RMW Uncertainty Example

- Models derived using aircraft data (35 hurricanes) and landfall data (107 hurricanes)
- Landfall data has limited intense hurricane data (minimum pressure 909 mbar)
- In Gulf landfall data shows no RMW-Δp relationship. Rejected this model, but it should be considered in uncertainty analysis
- Used basic regression error analysis to propagate RMW errors for both Gulf and Atlantic hurricanes





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Propagation of Uncertainties Example

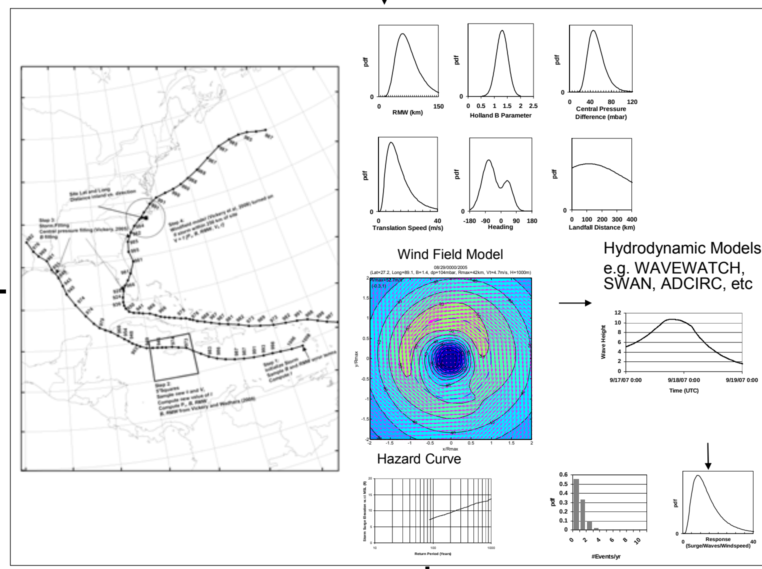
- Storm surge study for location on Kiawah Island, SC
- Straight Monte Carlo 20,000 year simulation using empirical track modeling technique coupled with a nested grid finite difference storms model.
- Finest grid resolution 200 m
- Waves not modeled
- Single point site specific example

Uncertainty Estimation Approach

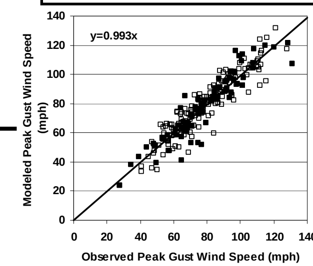
Sample errors for parameters of each input model/probability distribution (error in mean and standard deviation)

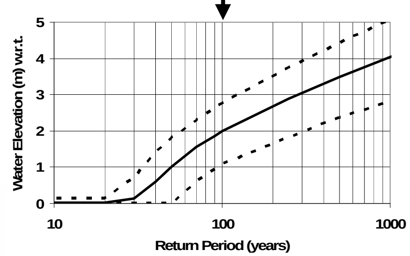
Start *N* year

Repeat *N* year simulation *M* times



Sample model errors for each storm realization





Family of Hazard Curves

Approach

- Relatively low risk location on the Southern SC coast
- Basic simulation is 20,000 years
- Estimate errors input statistical distribution parameters and models
- Compute model sensitivity coefficients (i.e. changes in water elevation caused by change in hurricane parameter)
- Repeat 20,000 simulation N times, with each 20,000 year repetition associated with a different potential realization of the statistics of the key input variables
- Generate N different hazard curves

Storm Surge Example

- Propagate uncertainty due to Holland *B*, central pressure and *RMW* at site.
- Compute sensitivity coefficients:

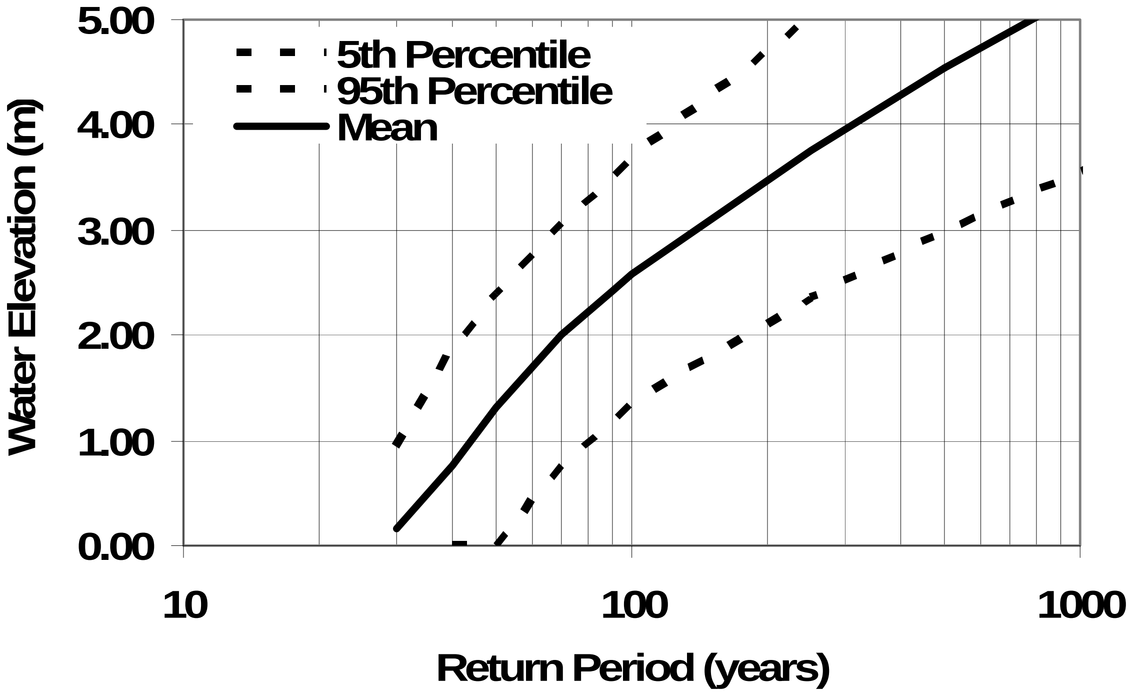
$$\frac{\partial \eta}{\partial B}, \frac{\partial \eta}{\partial \Delta p} \text{ and } \frac{d\eta}{dRMW}$$

- Sensitivity coefficient obtained by selecting ~30 simulated hurricanes at random and varying *B*, *RMW* and Δp one-at-a-time and computing the change in the water elevation at the site.
- Each storm re-modeled using mean ±0.5,1.0 and 2.0 standard deviations (6*3*30 simulations)
- Sensitivity coefficients are then used to change the computed surge values from the base case 20,000 year simulation.
- Base case storms perturbed so each simulated storm, and storm effect, is from a new underlying distribution

Example Results

Estimates of CoV

Parameter	100 Year	500 Year
Δp	14%	14%
B	13%	12%
RMW	12%	10%
Occurrence Rate	15%	6%
Total	25%	22%



Summary

- Uncertainty Estimates
  - Estimate of 100 year coastal storm surge elevation CoV ~20%-30%. Uncertainty due to Hurricane modeling only.
  - Estimates will vary with site
  - Developing uncertainties of model inputs is somewhat subjective
  - Uncertainty estimates are not usually provided, and if provided, users often not sure what do with them
  - Estimates of uncertainty *should* be considered in any economic decision making