Probabilistic Shoreline Change Modeling and Risk Estimation of Erosion

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Outline

- Introduction to GenCade
    - Discussion of new features
- Simple study case
- Monte Carlo simulation of shoreline change at Duck, NC
- Conclusions

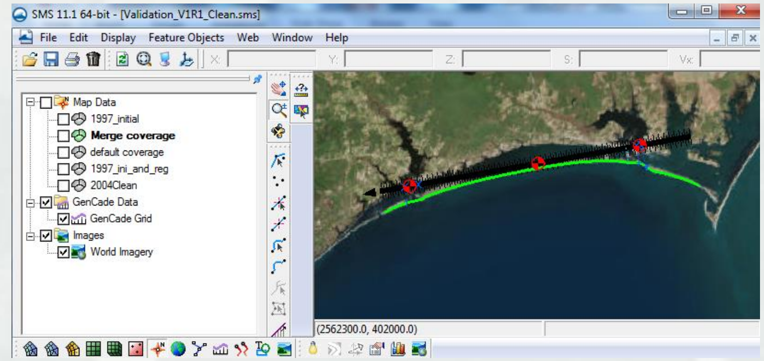
Objectives

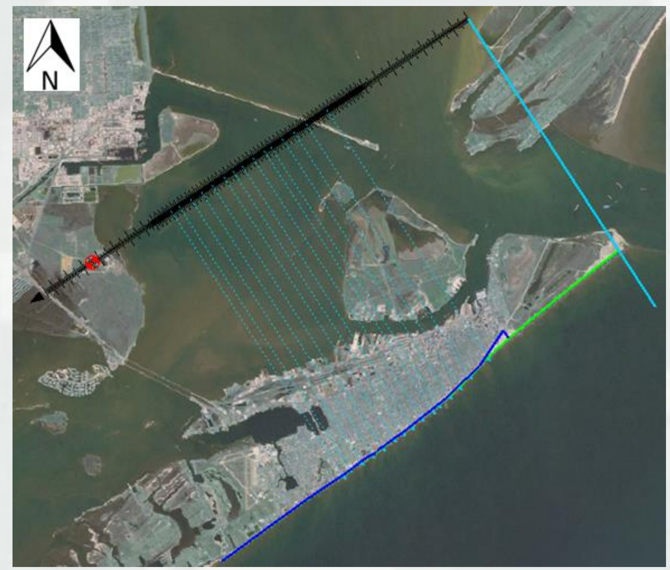
- **Estimation of probability of shoreline change for risk analysis**

  Use a stochastic method (Monte Carlo Simulation) to consider uncertainty in shoreline changes under natural wave and current conditions
- Develop probability density functions to model offshore waves under fair weather and extreme conditions
- Develop a Monte Carlo Model for USACE's shoreline evolution simulation model, GenCade
- Verify and validate this newly-developed Monte Carlo model to estimate shoreline change probabilities.

GenCade Background

- A one-dimensional shoreline change, sand transport, and inlet-sand sharing model developed by the CIRP
- Combines the engineering power of GENESIS with the regional processes capability of the Cascade model
- Development began in 2009, GenCade Version 1 was released in 2012
- Operated within the Surface-Water Modeling System (SMS) 11.1 or higher





Top: Onslow Bay, NC application (for SAW)
Bottom: Galveston, TX (Galv. Park Board)

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Model Formulation

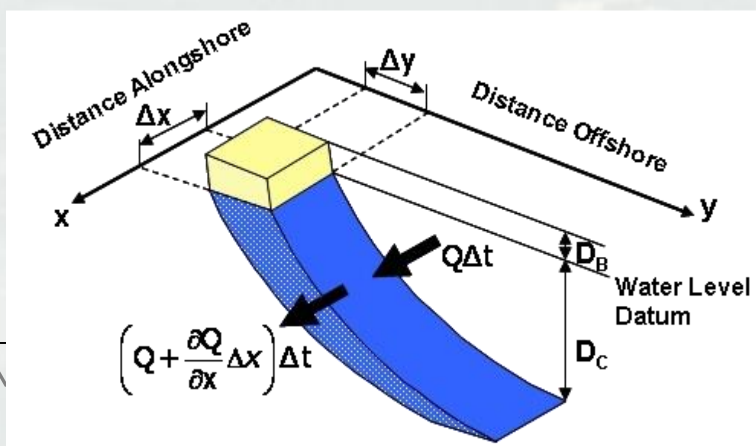
Longshore Net Volume Change: $$\frac{dQ}{dt} = \left(\frac{\partial Q}{\partial x}\right) dxdt$$

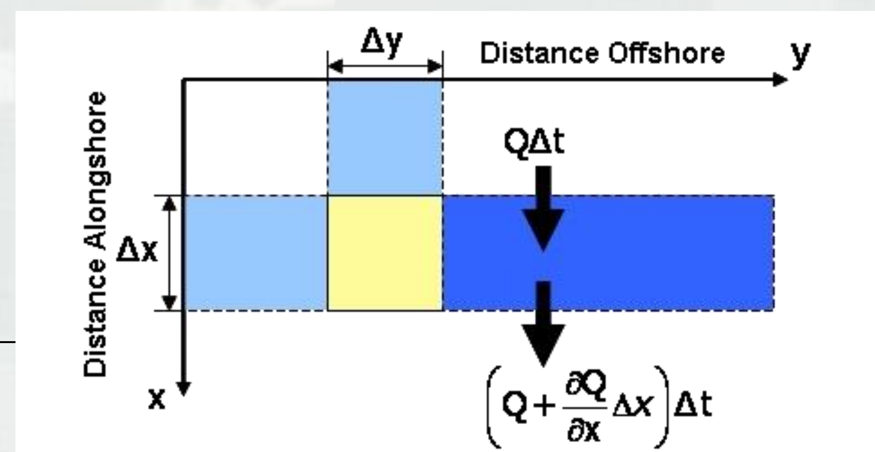
Cross-shore Net Volume Change: $$dqdt$$

Total Volume Change: $$dV = dxdy\left(D_B + D_C\right) = \left(\frac{\partial Q}{\partial x}\right) dxdt + qdxdt$$

$$\therefore \text{ as } dt \rightarrow 0: \quad \frac{\partial y}{\partial t} + \frac{1}{D_B + D_C} \bullet \left[\frac{\partial Q}{\partial x} - q\right] = 0$$

x = direction alongshore; y = location of shoreline; Q = longshore sediment transport rate
q = source or sink of sediments; d_c = offshore closure depth; d_b = berm height;
$D_s = d_c + d_b$ = height of sediment movement





Model Formulation

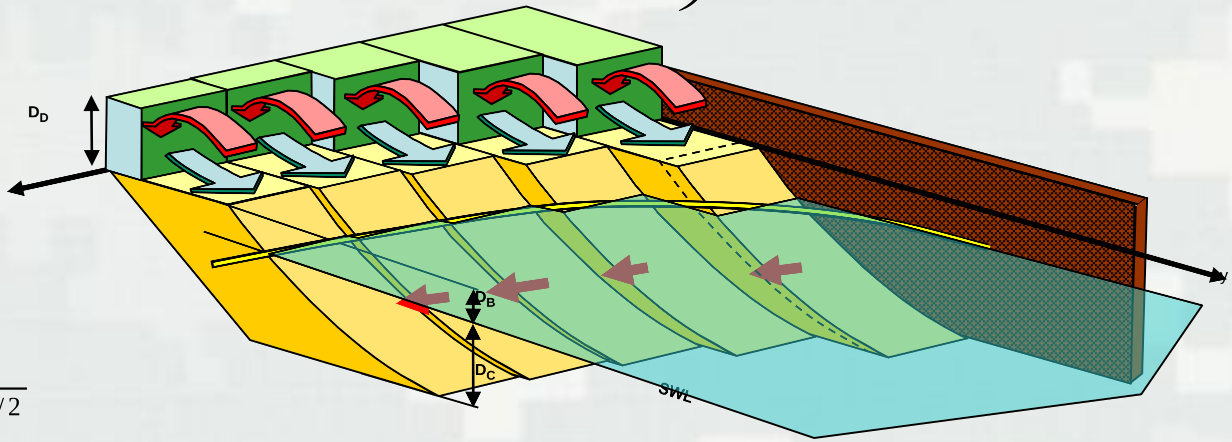
Sediment transport rate Q (m^3/s):

$$Q = \left(H^2 C_g\right)_b \left(a_1 \sin 2\alpha_{bs} - a_2 \cos \alpha_{bs} \frac{\partial H_b}{\partial x} \right)$$

Where,
H = wave height (m)
C_g =wave group speed (m/s)
α_{bs} = angle of the breaking

$$a_1 = \frac{K_1}{16(\rho_s/\rho - 1)(1-p)1.416^{5/2}}$$

$$a_2 = \frac{K_2}{8(\rho_s/\rho - 1)(1-p)\tan\beta\ 1.416^{5/2}}$$

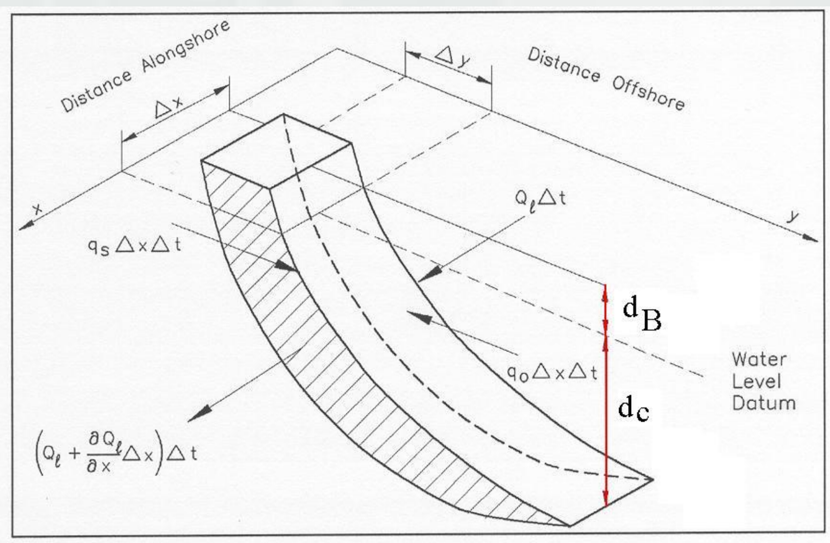


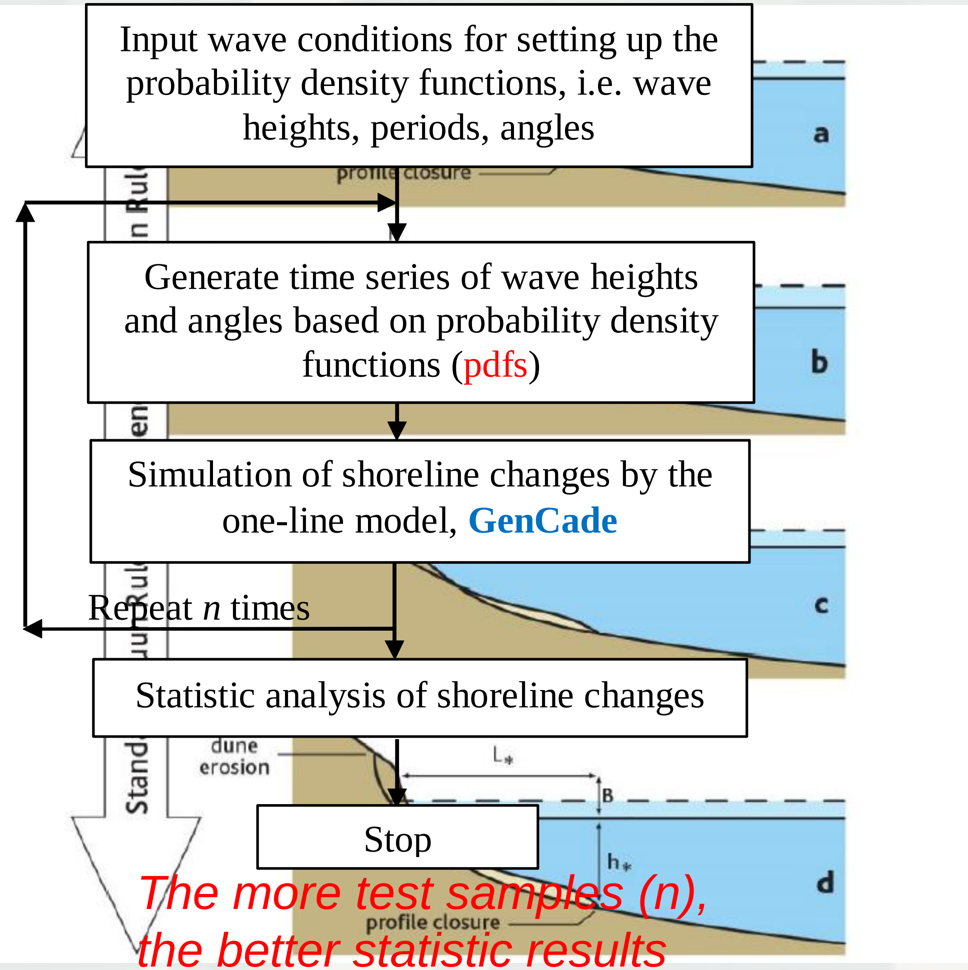
Where,
K_1 = Primary empirical transport coefficient (controls magnitude of longshore transport rate)
K_2 = Secondary empirical transport coefficient (controls distribution of sand within an area; esp. where large wave height gradients, e.g. salients)
tanβ = average bottom slope

Typically, value of K_2 is:
$0.5K_1 < K_2 < 1.5K_1$

New GenCade Features

- Cross-shore transport
- Shoreline recession due to Sea Level Rise
- Monte Carlo simulation of shoreline change





The more test samples (n), the better statistic results

From Shand et al. (2013)

GenCade Shoreline Evolution Model with Cross-Shore Transport and SLR

$$\frac{\partial y}{\partial t} + \frac{1}{D_s}\left(\frac{\partial Q}{\partial x} - q - \phi\right) + \left((\frac{\Delta Z}{\Delta t})_{SLR} - (\frac{\Delta Z}{\Delta t})_{subsidence} \right) \frac{1}{\tan\beta} = 0$$

ϕ : Cross-shore sediment transport rate

$(\frac{\Delta Z}{\Delta t})_{SLR}$: Sea Level Change rate

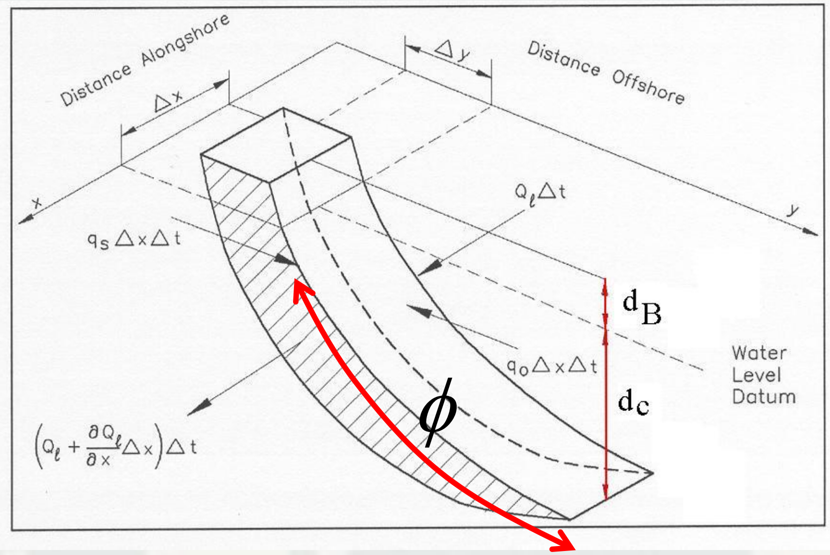
$(\frac{\Delta Z}{\Delta t})_{subsidence}$: Land subsidence rate

$tan\beta$: beach slope

$$D_S = d_c + d_b(t)$$

- Berm height varies with sea level change

$$d_b(t) = d_{b0} - ((\frac{\Delta Z}{\Delta t})_{SLR} - (\frac{\Delta Z}{\Delta t})_{subsidence})t$$



Probabilistic Distributions of Wave Heights

According to observations of random wave heights in deepwater, the stochastic features of wave heights can be approximately described by Rayleigh function

$$R(x) = -\frac{\pi}{2} x \exp\left(-\frac{\pi}{4} x^2\right)$$

$x = H/H_{mean}$, *Hmean* is the mean value of wave height

- *May miss extreme waves in a limited discrete series of the wave samples*

Weibull density function can describe the extreme random wave heights in a long observation period

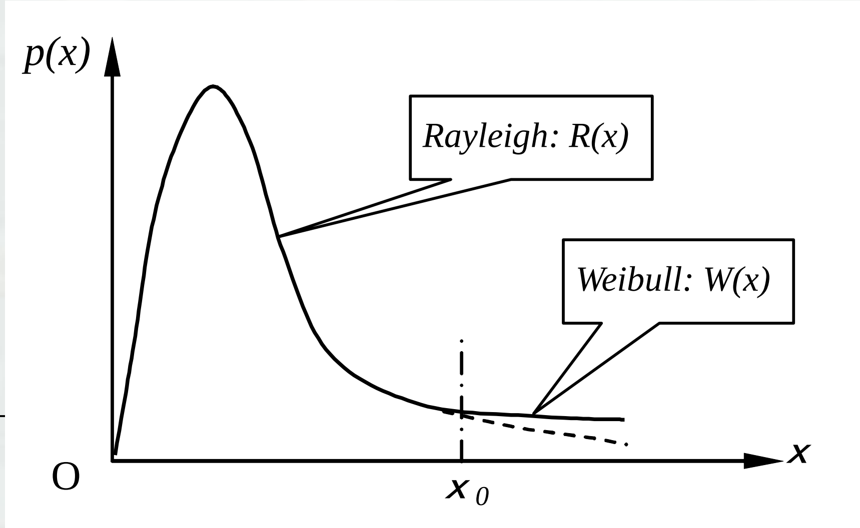
$$W(x) = \frac{1}{k}\left(\frac{x-B}{A}\right)^{k-1} \exp\left(-\left(\frac{x-B}{A}\right)^{K}\right)$$

A, *B*, and *k* : Weibull's parameters

$$p(x) = \begin{cases} R(x) & x \in [0, x_0) \\ \varepsilon W(x) & x \in (x_0, +\infty) \end{cases}$$

ε: parameter

x_0: an extreme value of wave height



Wave Direction and Period

Incident Wave Angles: Gaussian Distribution

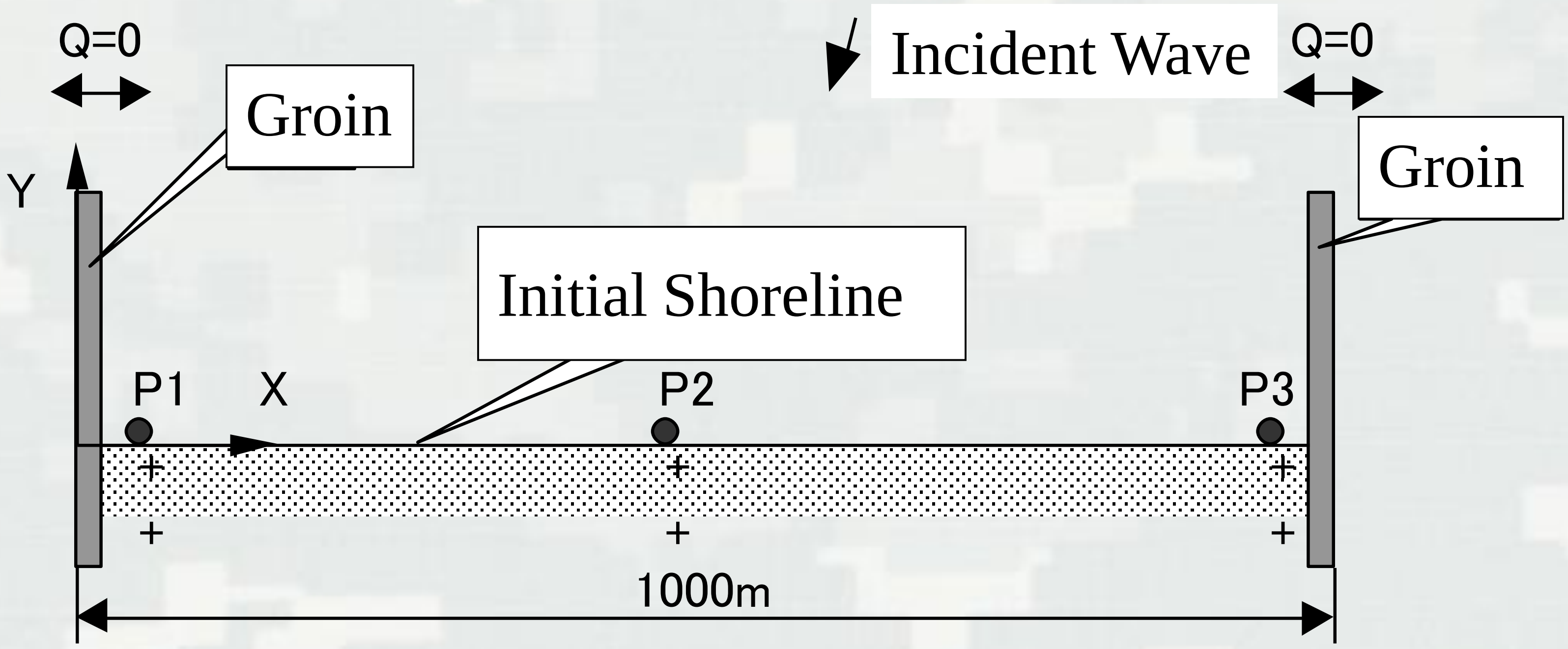
$$p(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2} \right)$$

σ: Standard deviation of wave direction
μ: Mean value of direction

Significant Wave Period: based on Pierson-Moskowitz Spectrum

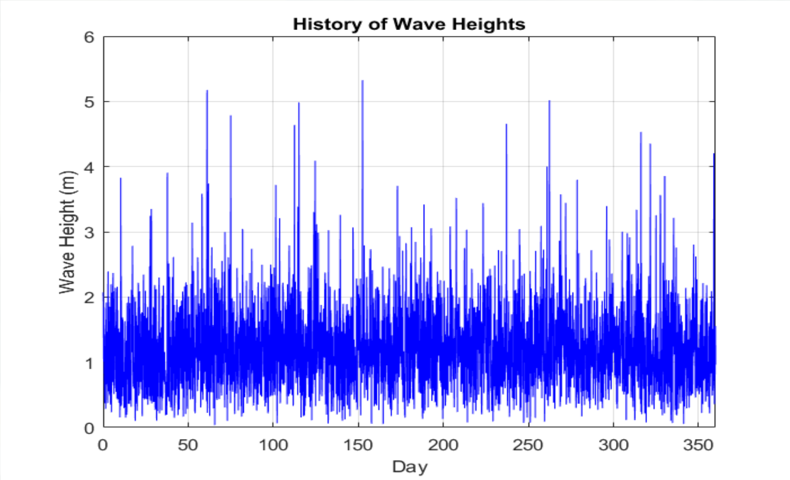
$$T_s = 5\sqrt{H_s}$$

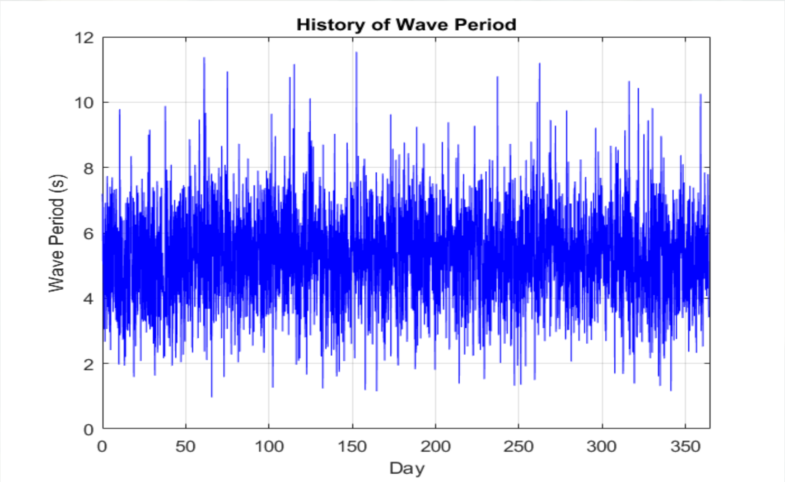
Study Case

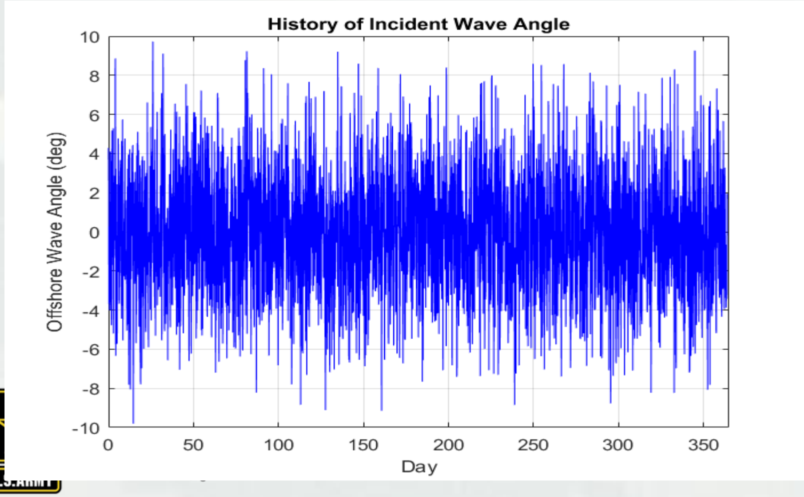


Stochastic variables: wave height and direction
Computational period: 10 years
Numerical experiments: 256

Wave Parameters Generated by Wide Band Spectrum





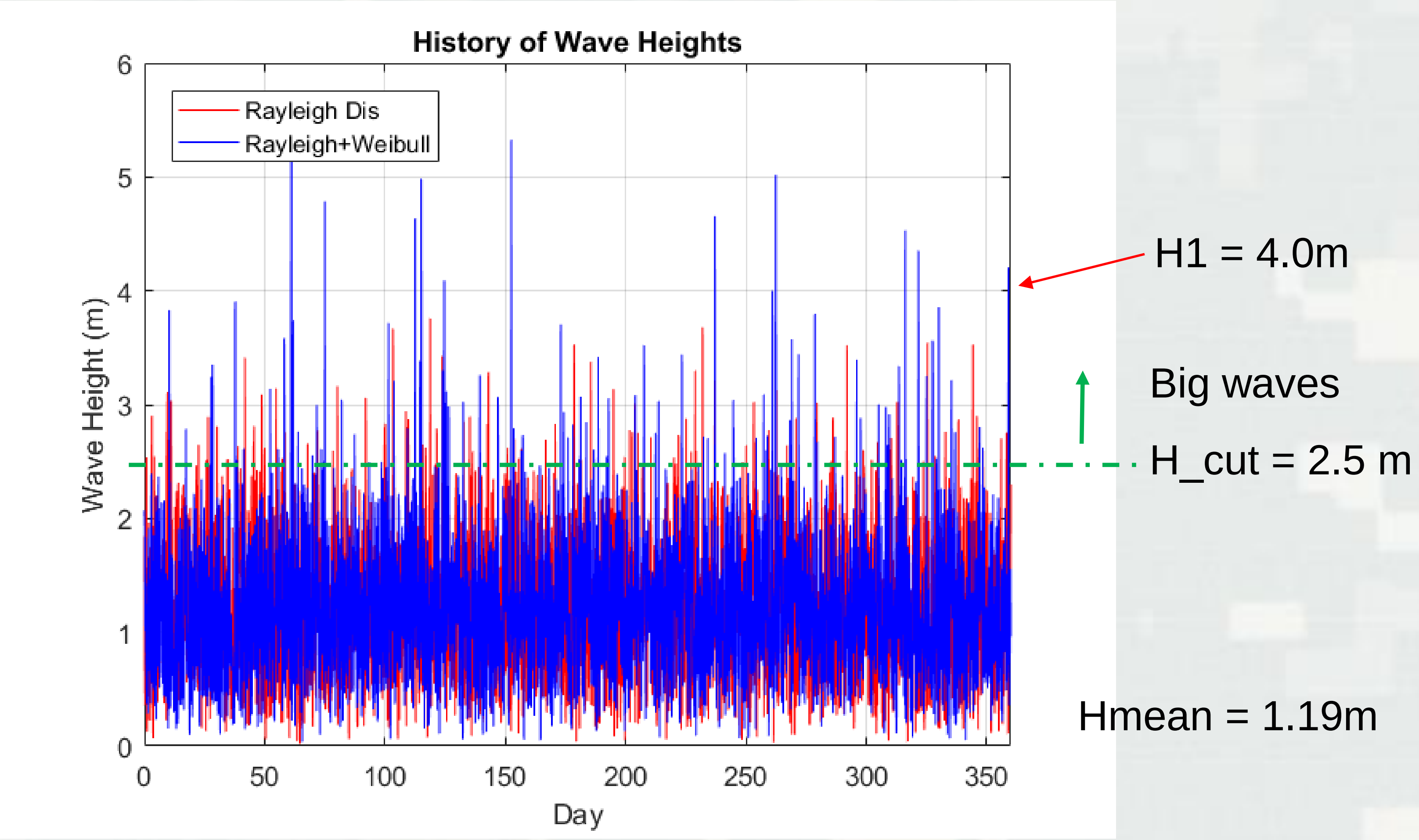


- Hmean = 1.19m
- Mean Angle = 0.0 with σ^2=10
- Data Interval = 3.0 hours

$$p(x) = \begin{cases} R(x) & x \in [0, x_0) \\ \varepsilon W(x) & x \in (x_0, +\infty) \end{cases}$$

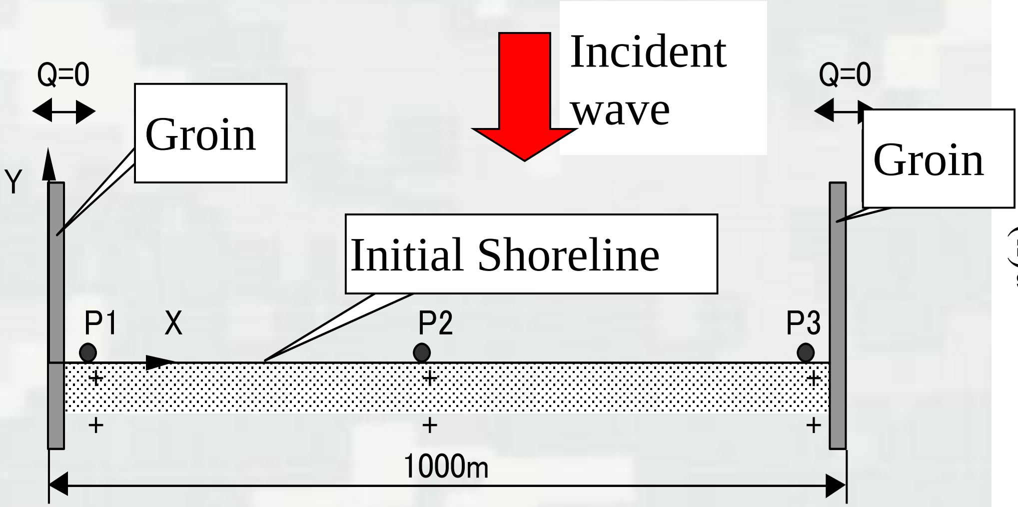
H_cut = 2.5 m

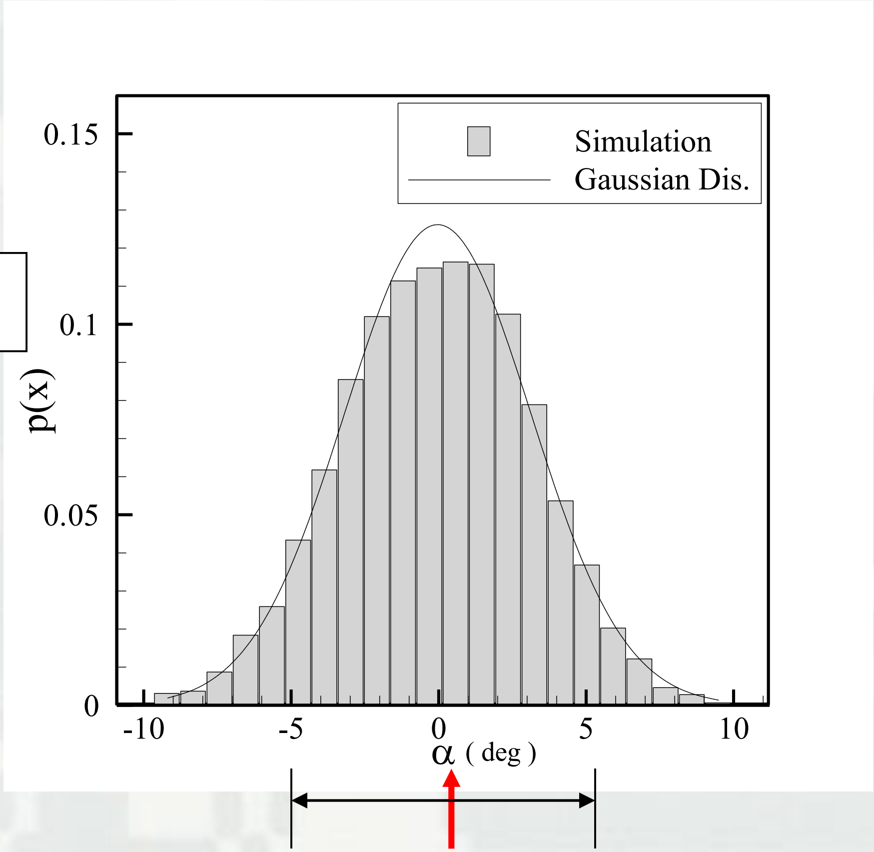
Comparison of Wave Heights by Two Wave Spectra



Observation data: 4.0 m wave height
for one-year return period

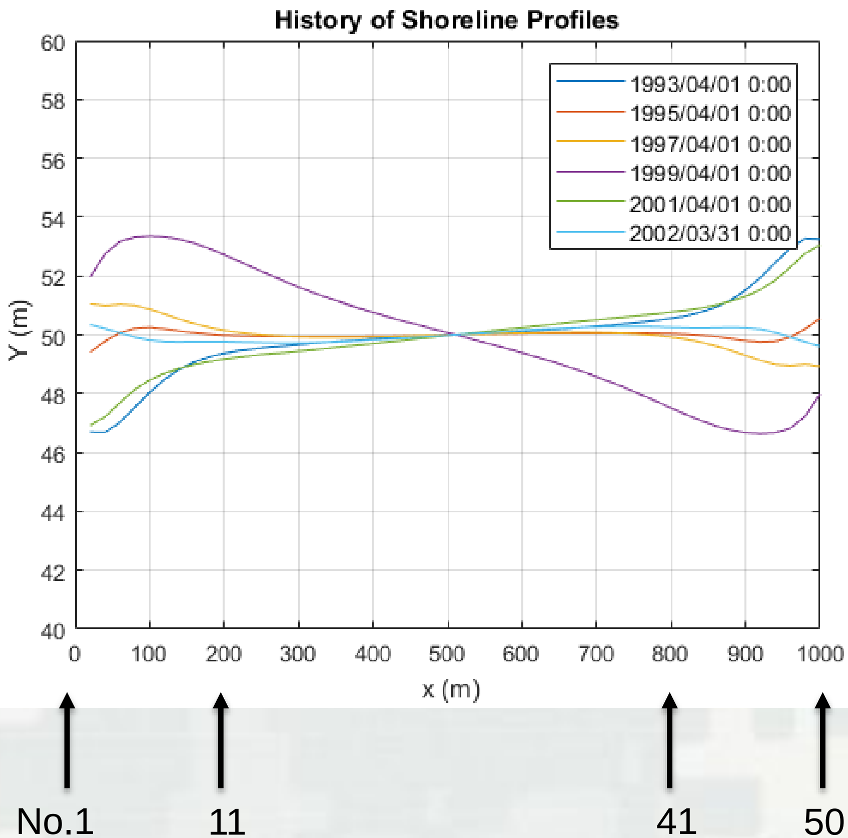
Probability Distribution of Wave Direction in Case 1 (Normal Wave Direction)

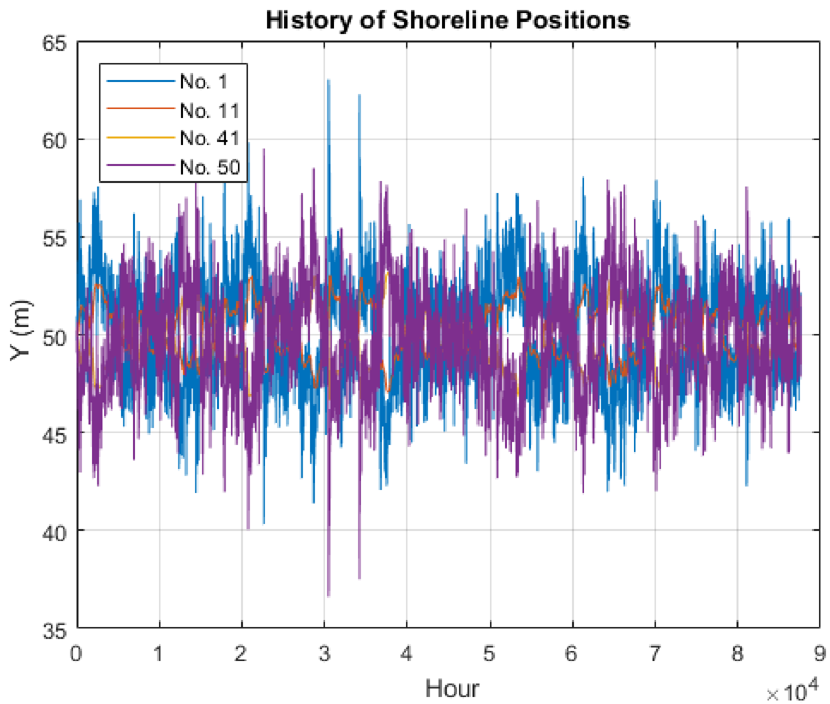




Case 1: Mean Angle $\mu = 0$ deg, $\sigma^2 = 10$ deg

Shoreline Profiles and Changes (A 10-Year-long Simulation)





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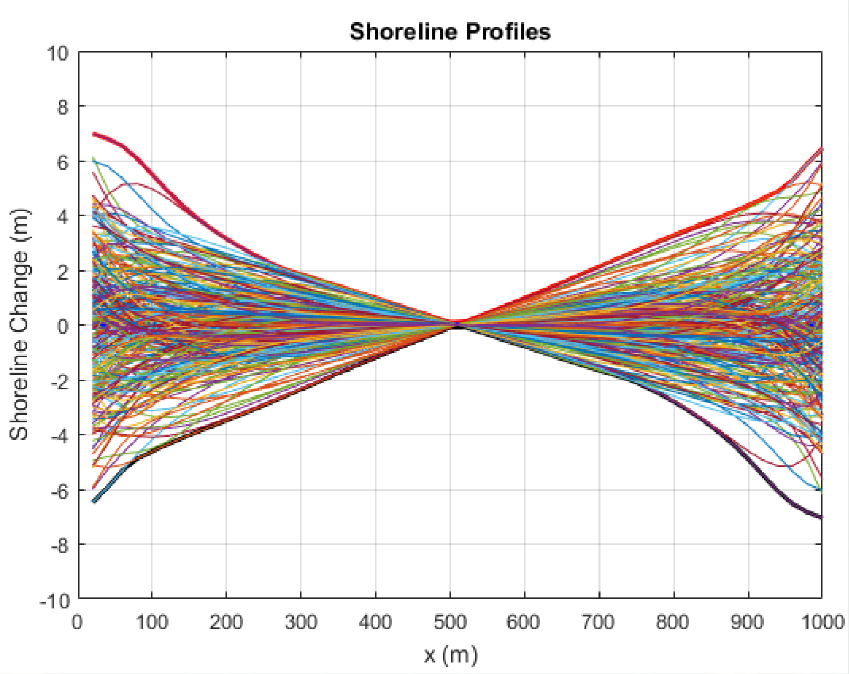
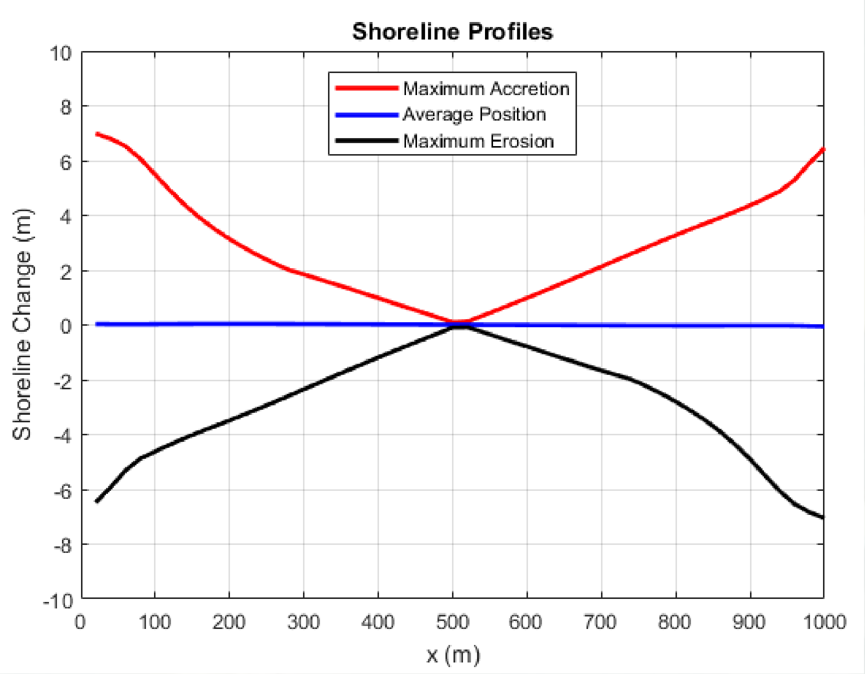
Shoreline Profiles After 10 Years



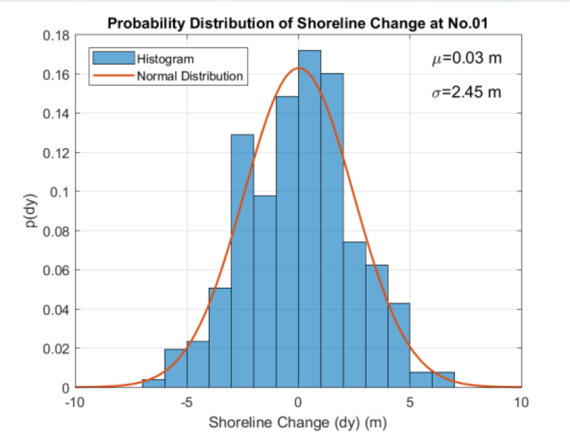
All 256 shorelines

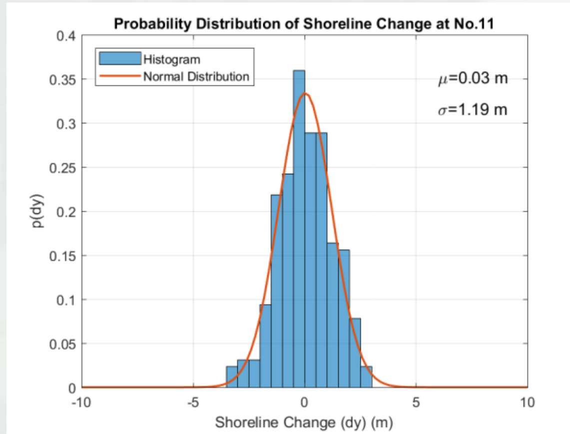


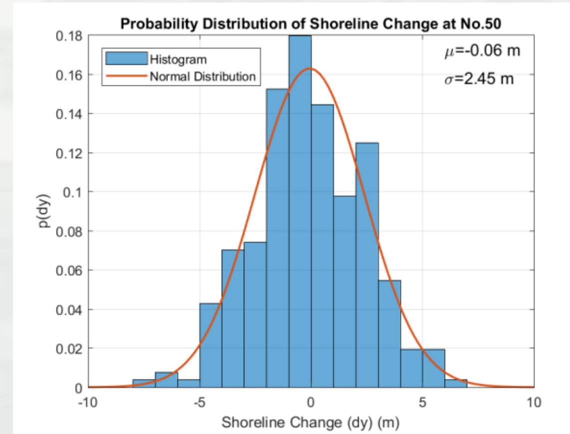
Max., average, and min positions

Probability Distribution of Shoreline Changes

(a) By Broad Wave Spectrum (Rayleigh + Weibull)

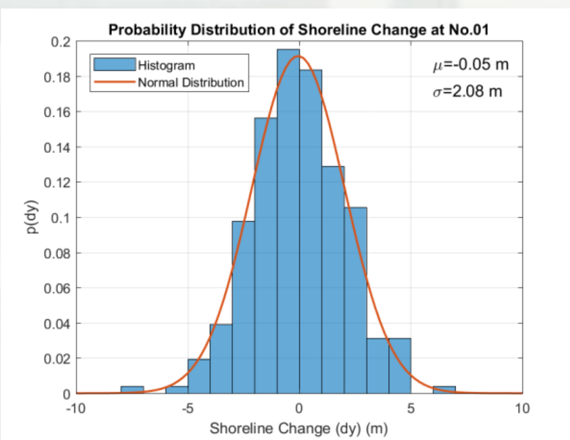


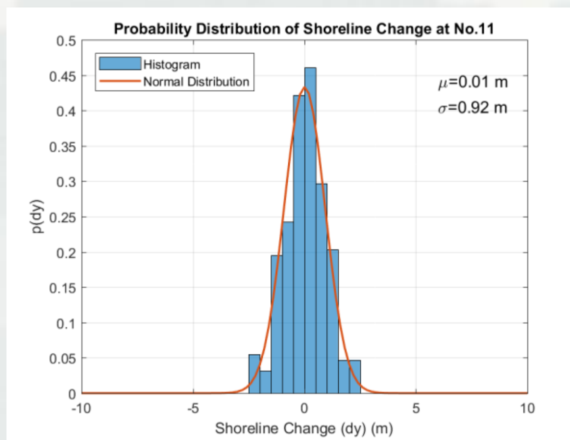


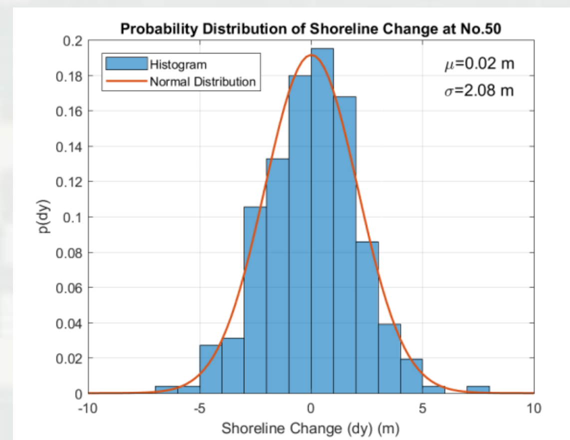


$\mu_{Broad} \approx \mu_{Narrow}; \sigma_{Broad} > \sigma_{Narrow}$

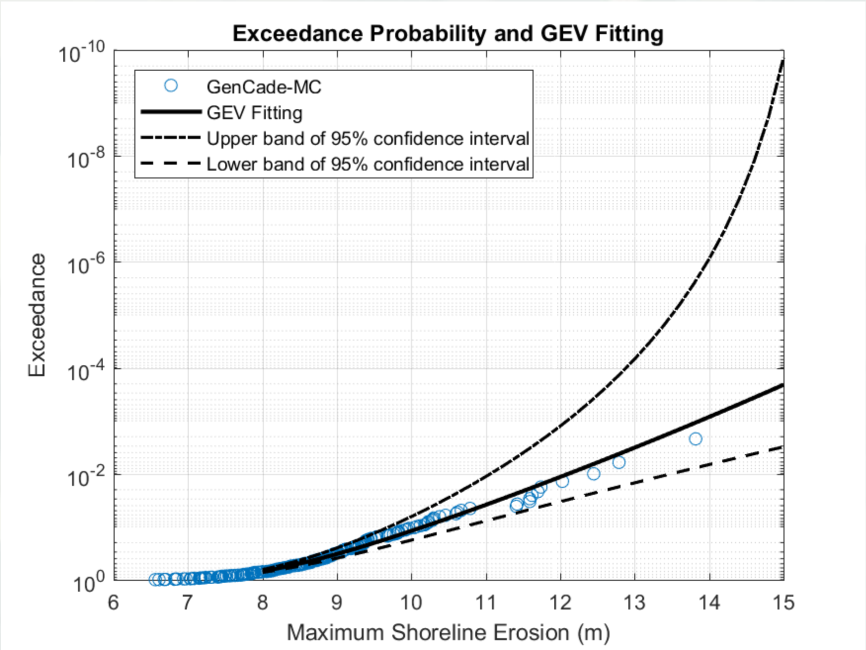
(b) By Narrow Wave Spectrum (Rayleigh only)



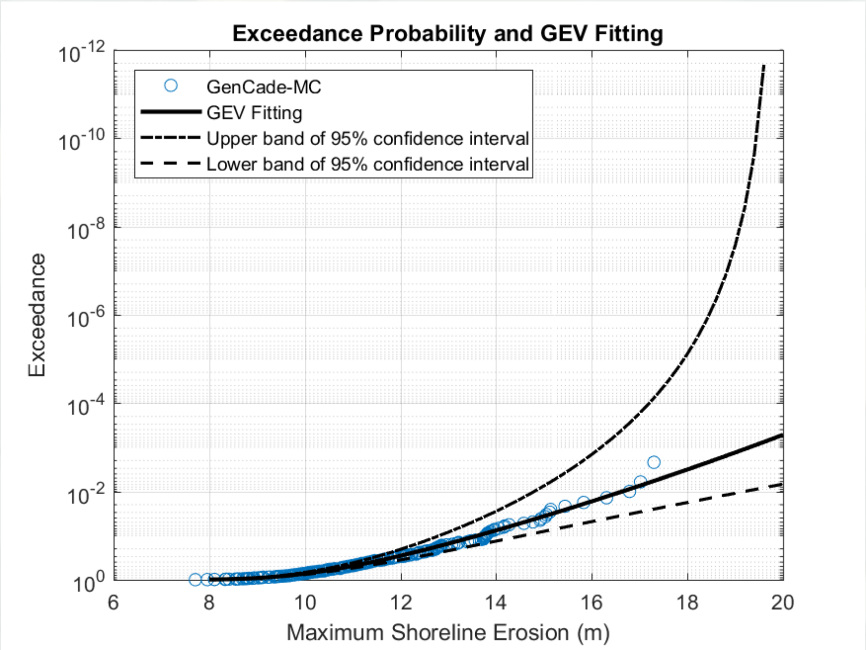




Prediction of Maximum Shoreline Erosion (Landward-most) (α_{mean}=0.0º)



Narrow Wave Spectrum

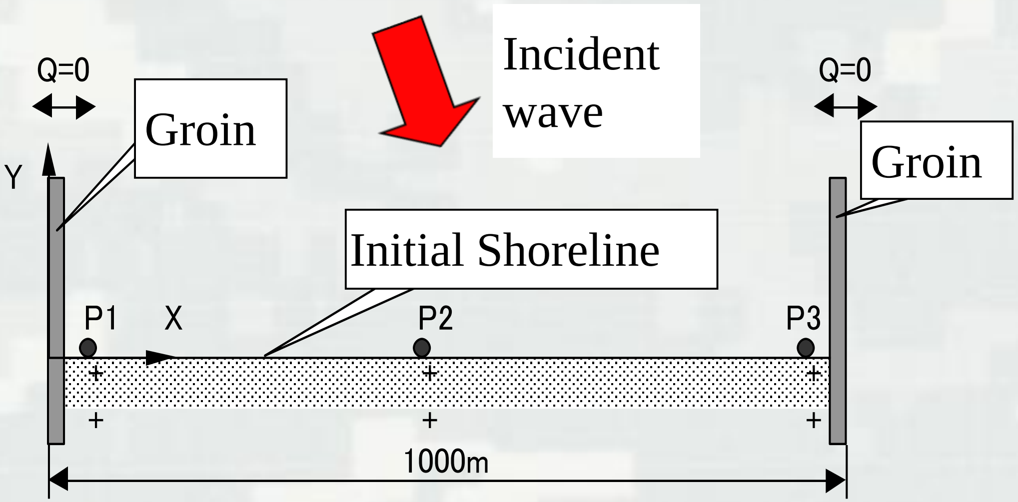


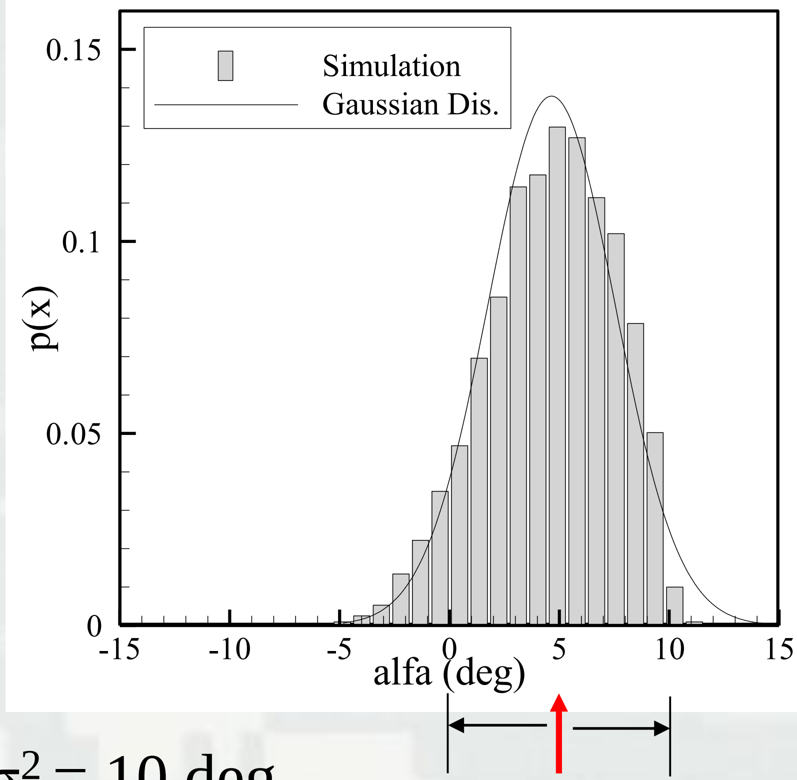
Broad Wave Spectrum

Table Estimated maximum shoreline erosion at *Point No. 1* in three return years (α_{mean}=0.0º)

	Return Period (Year)		
	10	20	30
Broad Spectrum	18.31 m	19.30 m	19.88 m
Narrow Spectrum	13.12 m	13.74 m	14.11 m

Probability Distribution of Wave Direction in Case 2 (Oblique Wave Direction)

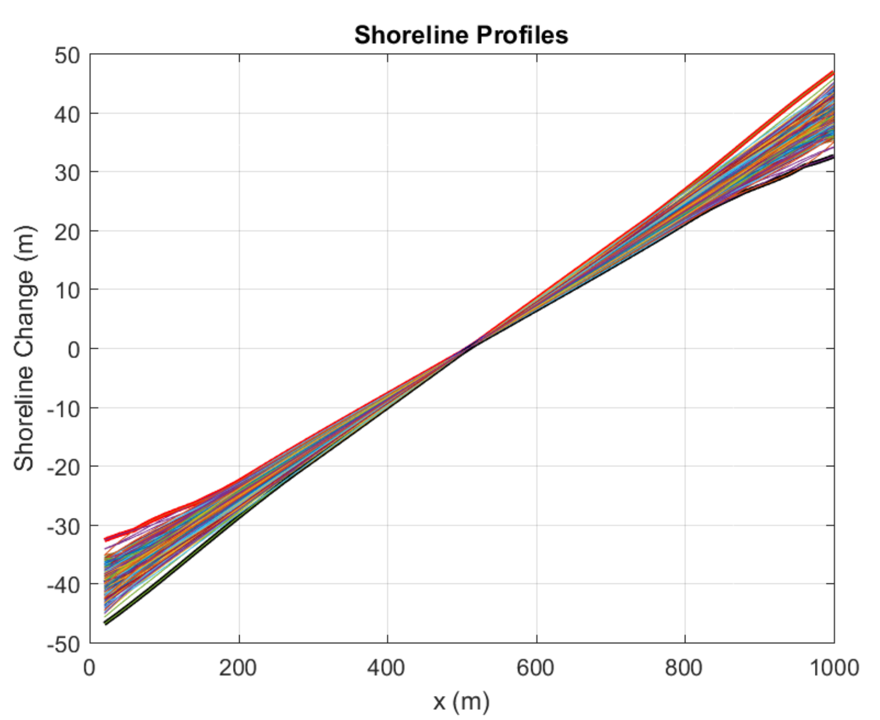




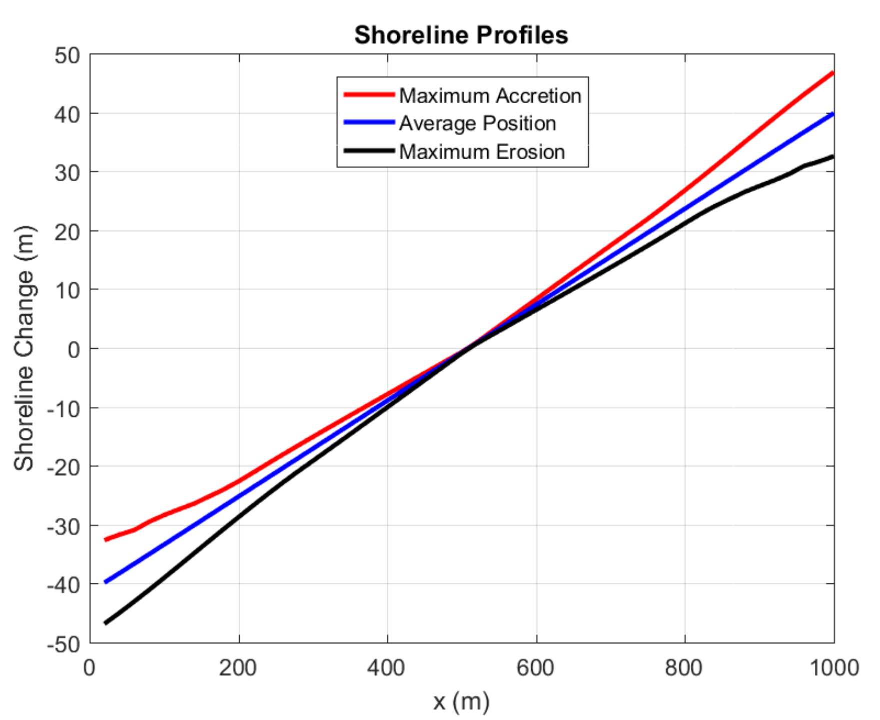
Case 2: Mean Angle μ = 5 deg, σ^2 = 10 deg

Dominant waves in summer in the study coast

Shoreline Change Profiles After 10 Years



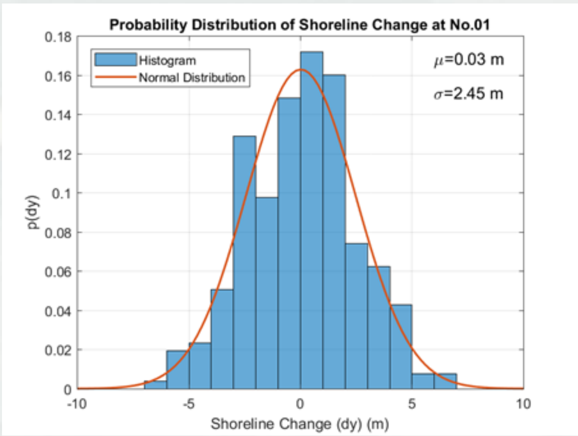
For all 256 shoreline changes



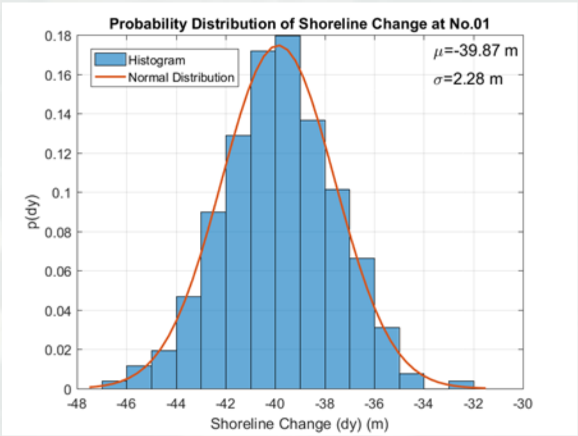
Max., average, and min positions

Statistical Results of 10-year Shoreline Changes at P_1

CASE	H_{mean}	α_{mean}	Statistical Properties at Point No.1 (P_1)		
			μ_p	σ_p	y_{max}(t=10year)
1	1.19m	0.0	0.03m	2.45m	6.48m
2	1.19m	5.0	-39.87m	2.28m	46.86m

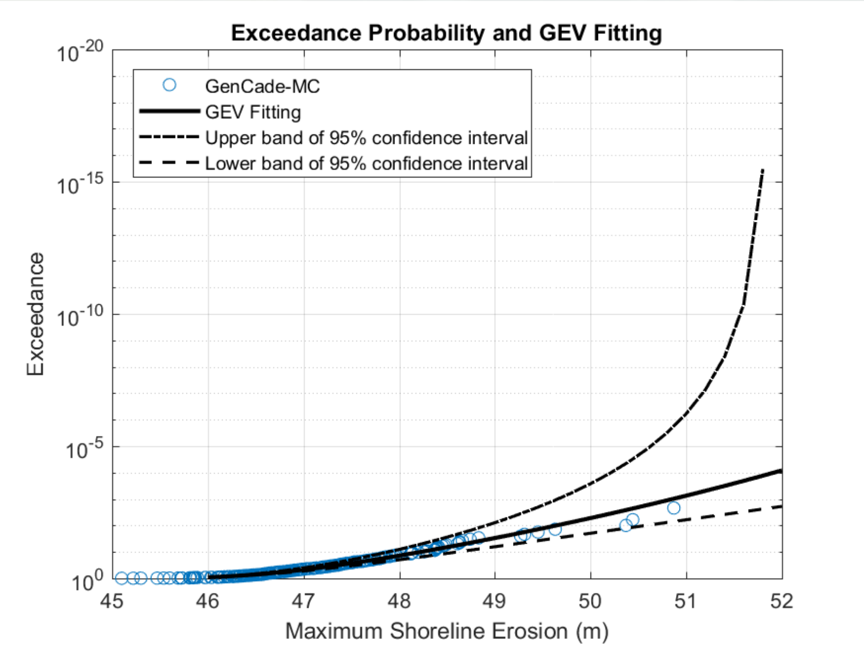


Case 1

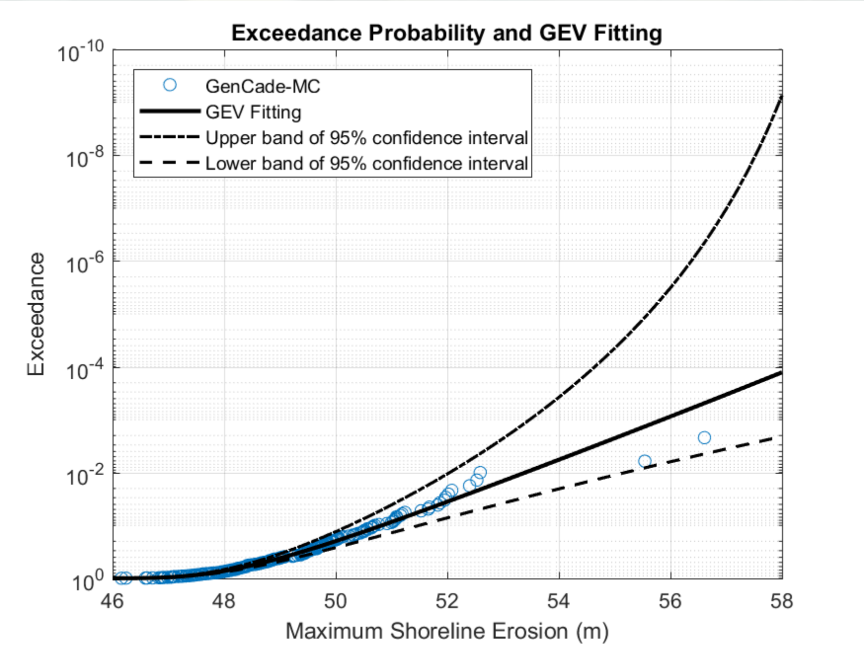


Case 2

Prediction of Maximum Shoreline Erosion (Landward-most) (α_{mean}=5.0º)



Narrow Wave Spectrum

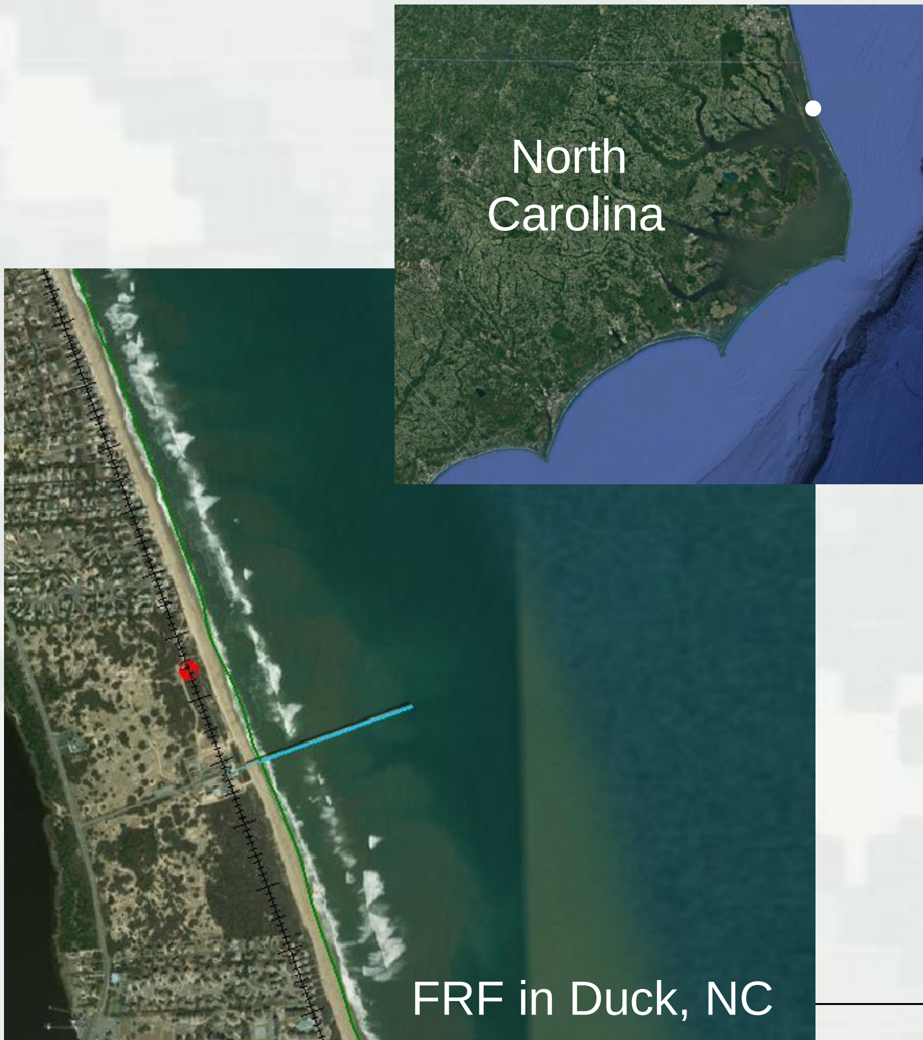


Broad Wave Spectrum

Estimated maximum shoreline erosion at *Point No. 1* in three return years (α_{mean}=5.0º)

	Return Period (Year)		
	10	20	30
Broad Spectrum	54.54 m	55.32 m	55.78 m
Narrow Spectrum	50.49 m	50.97 m	51.25 m

Model Validation: Modeling of Shoreline Change in Duck, NC



Computational Period: 6 years
10/23/1999 0:00 - 10/23/2005 0:00
Time step = 3 minutes
Grain size = 0.20 mm
Berm height = 1.0 m
Closure depth = 7.0
Smooth parameter = 1 (no smoothing)
Boundary conditions: Pinned
Grid size = 20 m
Sea Level Rise rate: 4.55mm/year
Subsidence : 0.0 (N/A)

K1 = 0.40; K2 = 0.25
Permeability of Pier = 0.6 (no diffracting):
Scaling parameter α_D= 0.182
C_w, C_C, ε_B, ε_S by Fernández-Mora et al. (2015)

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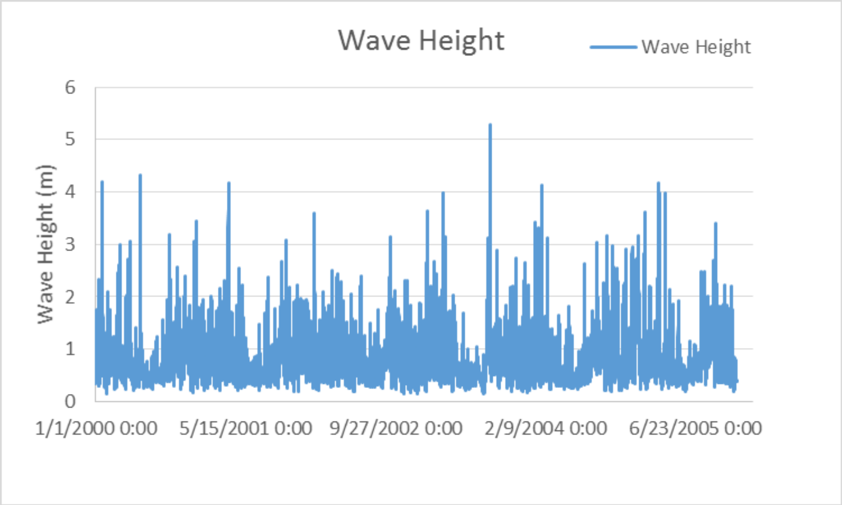
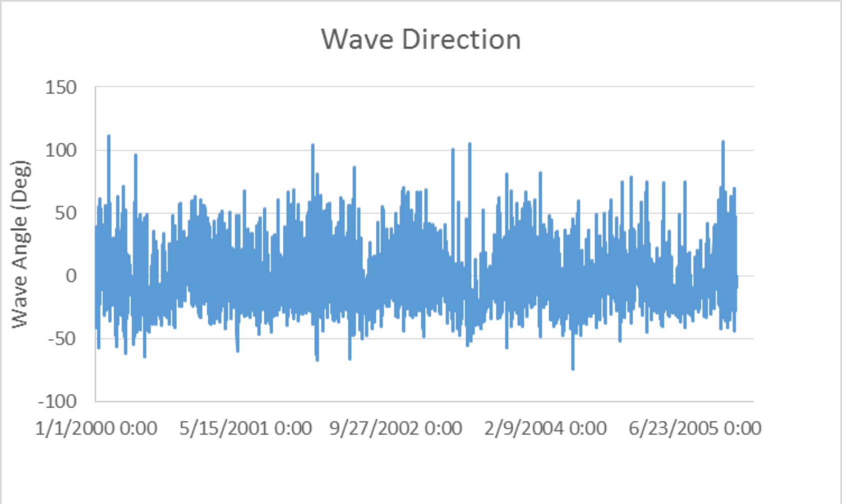
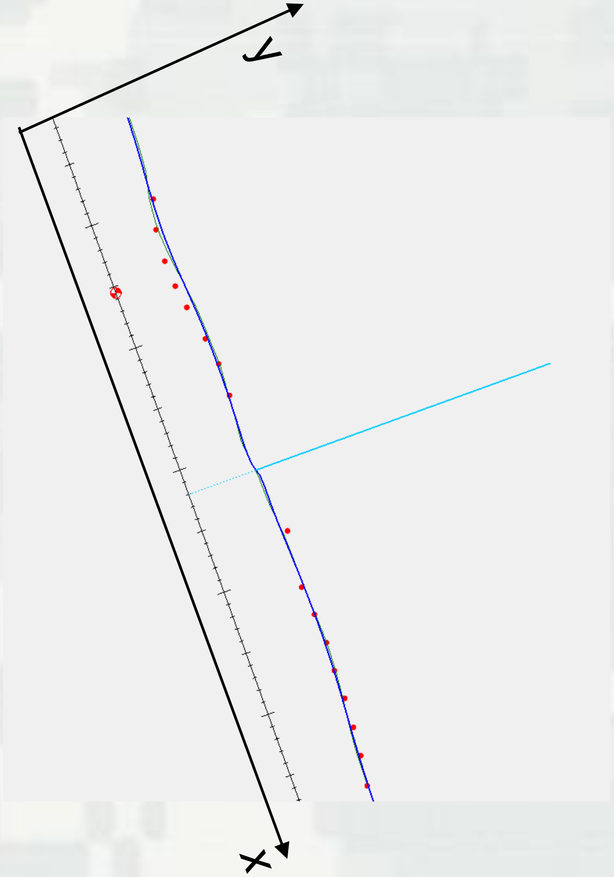
Wave Data (1/1/2000 – 1/1/2006)

	H (m)	T (s)	alpha (deg)
Average	0.82	9.18	-5.06
Min	0.14	3.09	-74.62
Max	5.28	18.96	111.32
σ	0.53	2.68	18.52

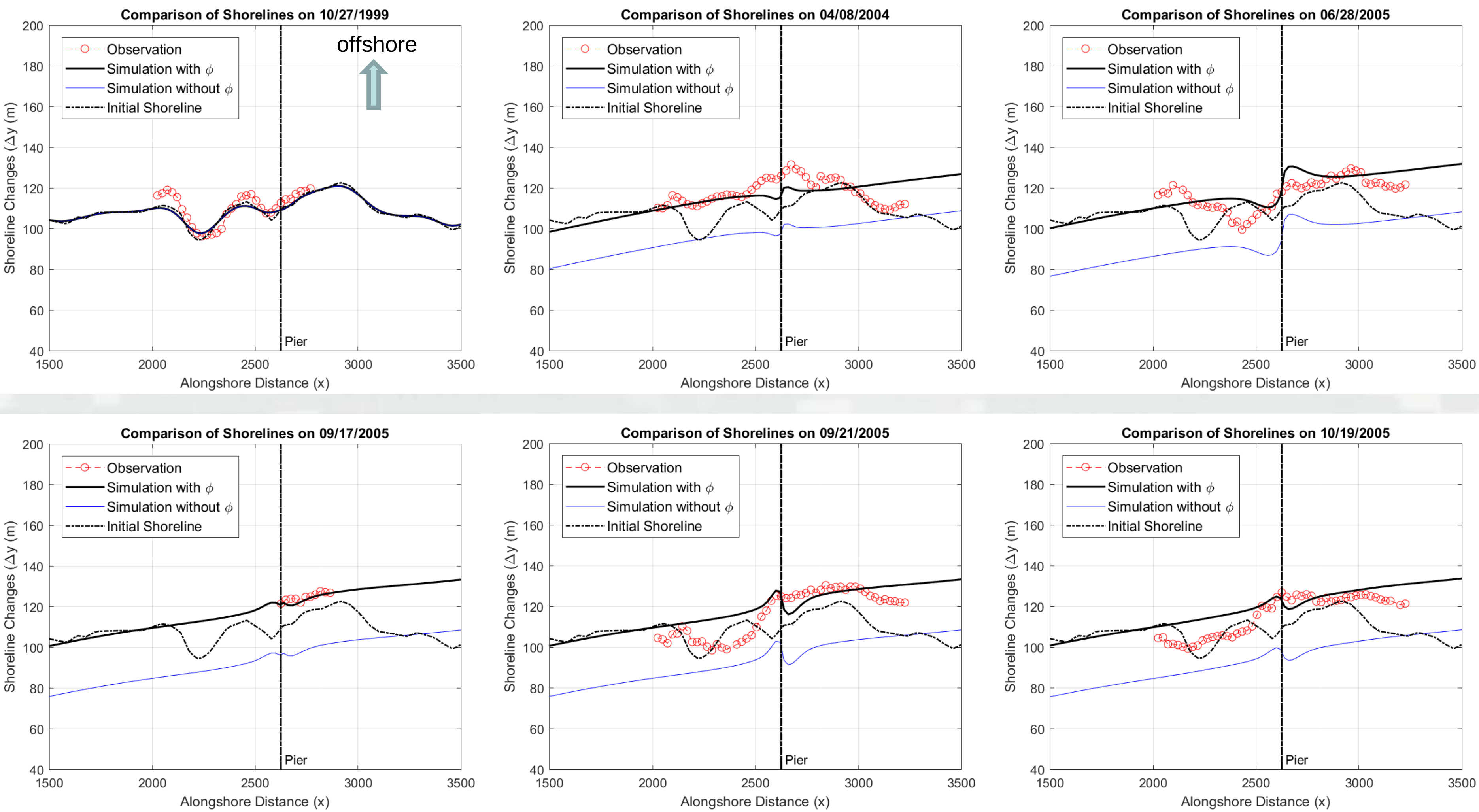




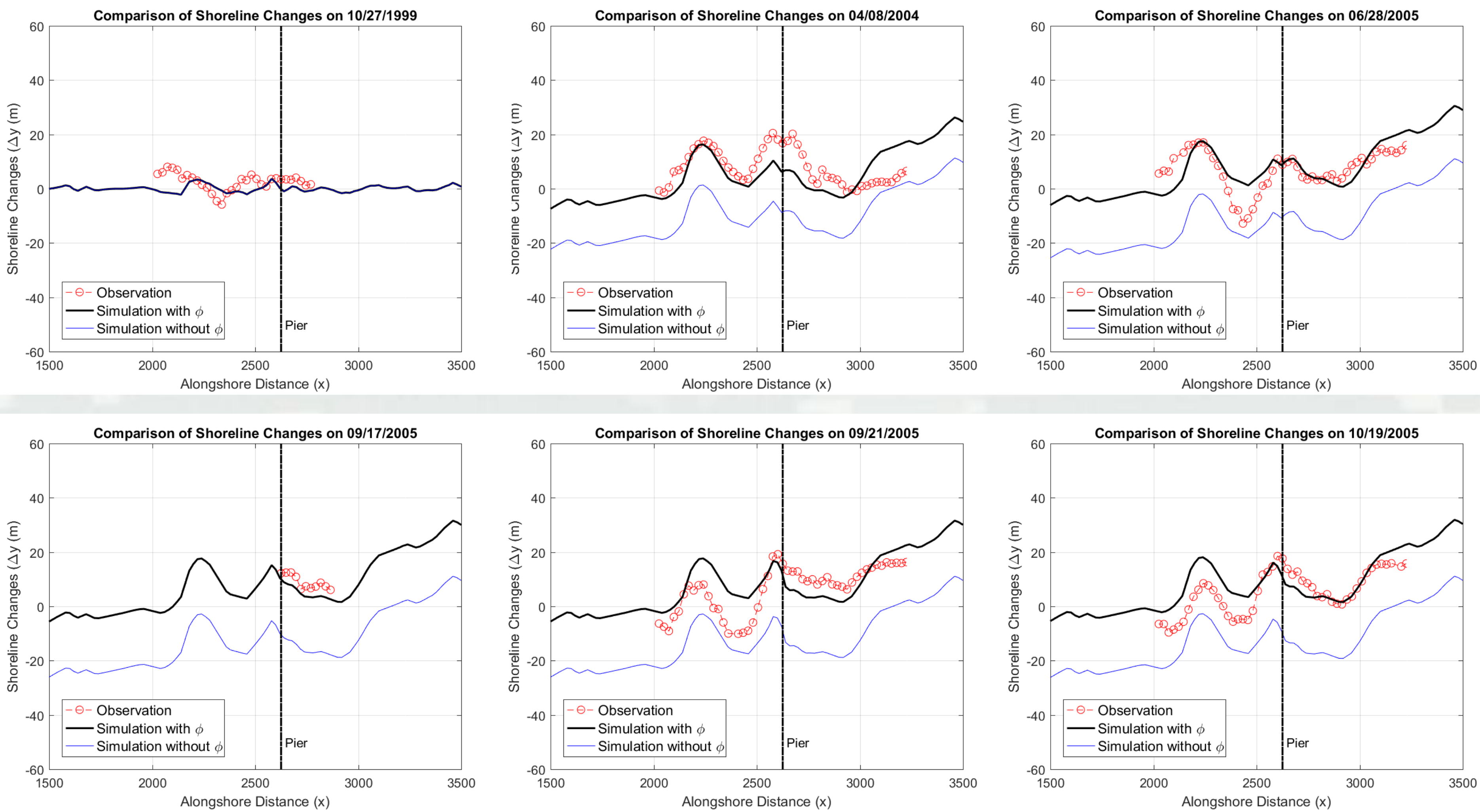
Model Validation: Shoreline on 11/1/1999 (after 1 week)



Model Validation: (With and Without Cross-Shore Transport)

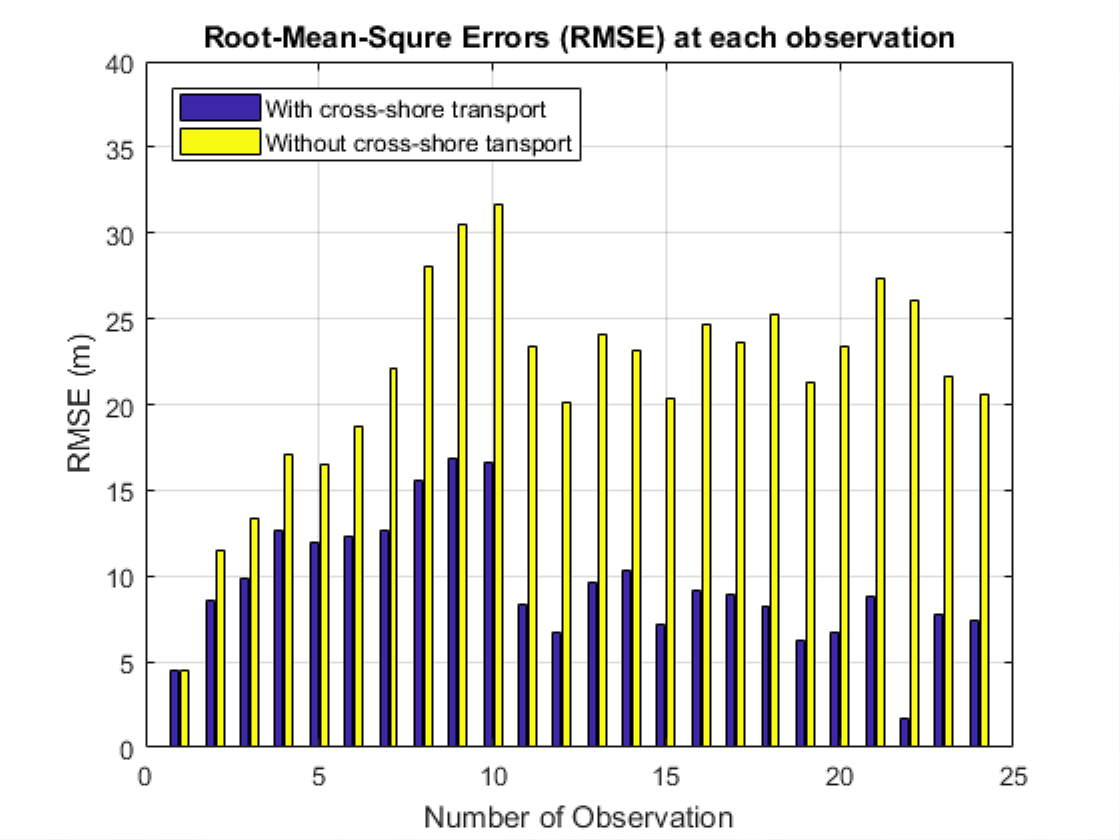


Model Validation: (With and Without Cross-Shore Transport)

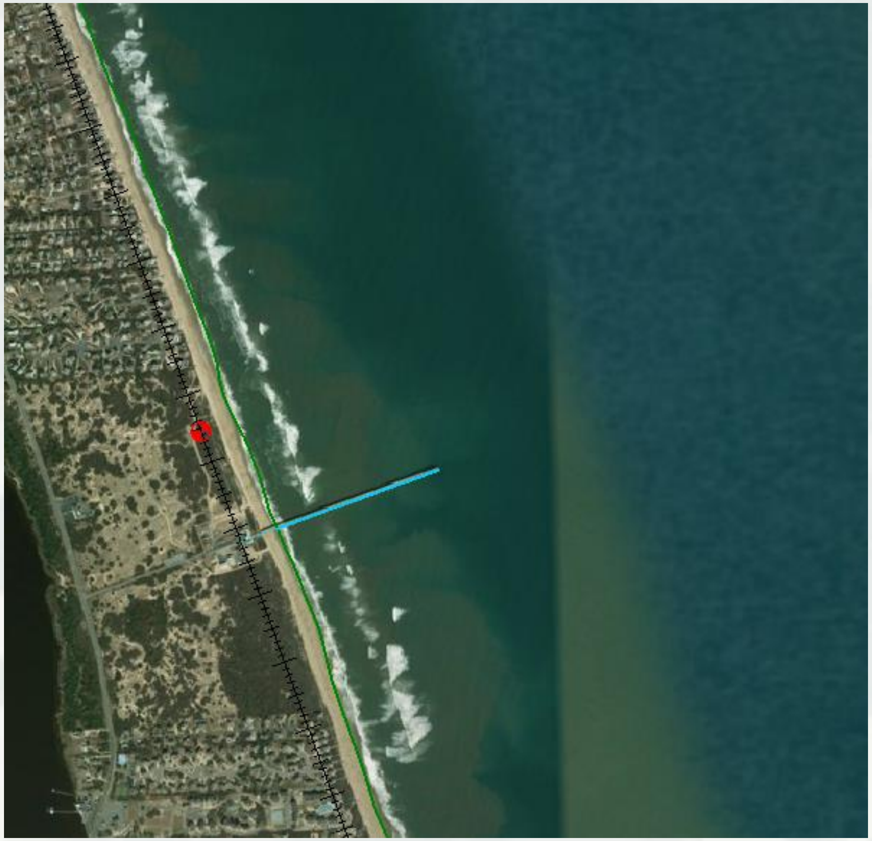


Model Skill Assessment:

Root-Mean-Square Errors at Observation Times (1999-2005)



Monte Carlo Simulation of Shoreline Change in Duck, NC



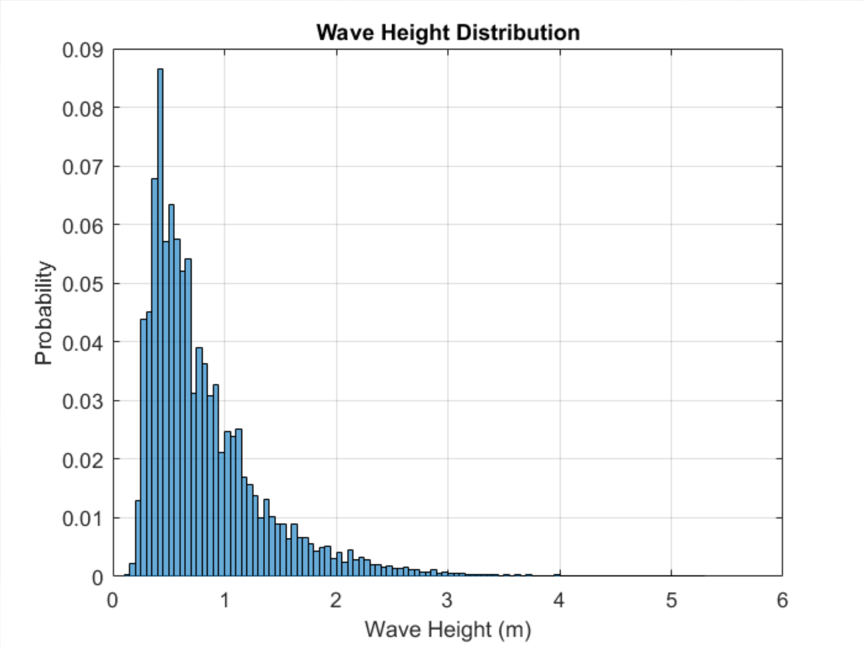
Number of Monte Carlo = **128**

Wave Conditions:

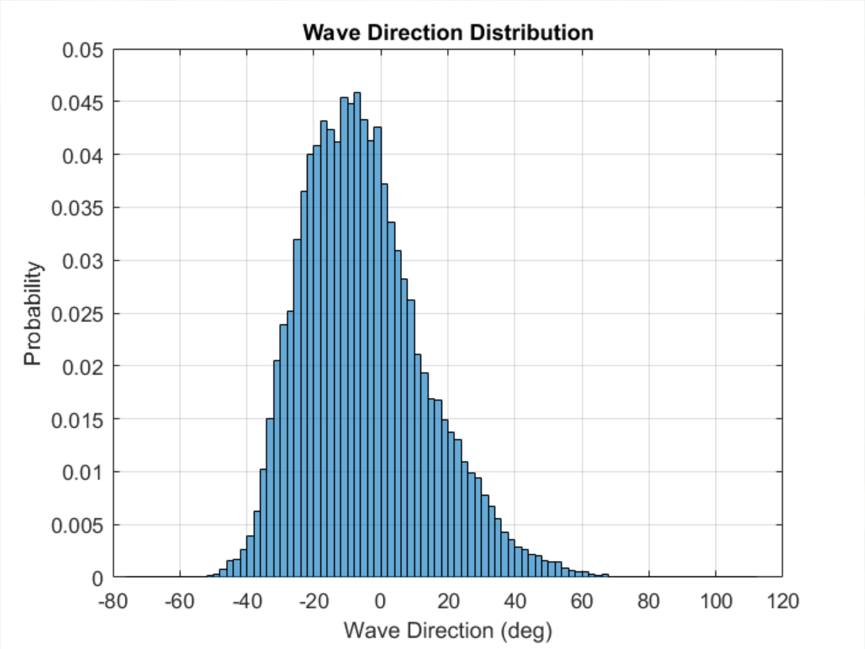
- **Wave Height: Rayleigh+Weibull**
- **Direction: Gaussian**
- **Period: PM Spectrum**
- **Truncated Wave Height: 2.0 m**

Computational Period: 6 years
10/23/1999 0:00 - 10/23/2005 0:00
Time step = 3 minutes
K1 = 0.40; K2 = 0.25
Grain size = 0.20 mm
Berm height = 1.0 m
Closure depth = 7.0
Sea Level Rise Rate = 4.55 mm/year
Smooth parameter = 1 (no smoothing)
Boundary conditions: Pibned
Grid size = 20 m
Permeability of Pier = 0.6 (no diffracting)
Scaling parameter of cross-shore transport: 0.182

Monte Carlo Simulation for Shoreline Change in Duck, NC (1999-2005)



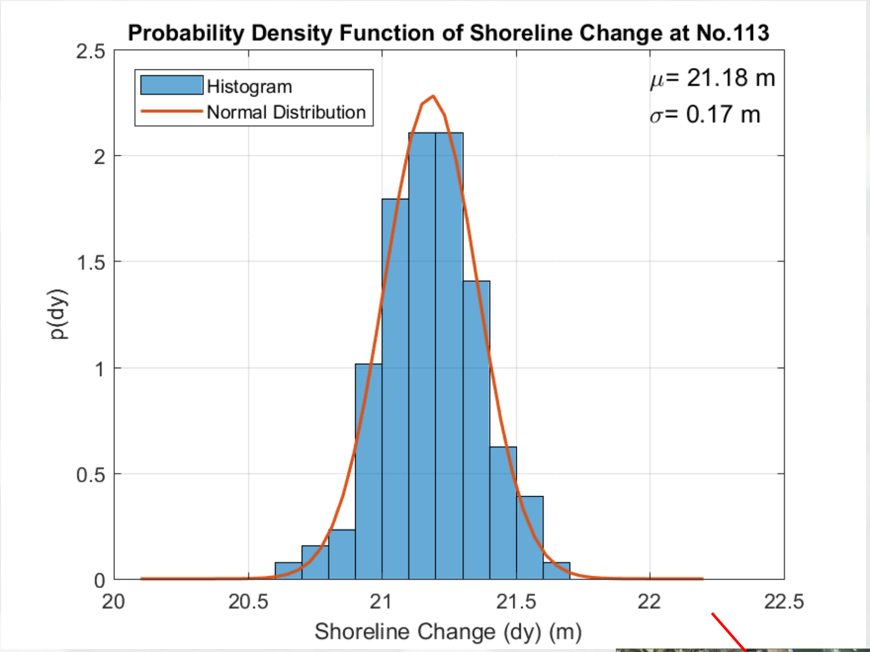
Mean H_s = 0.82 m



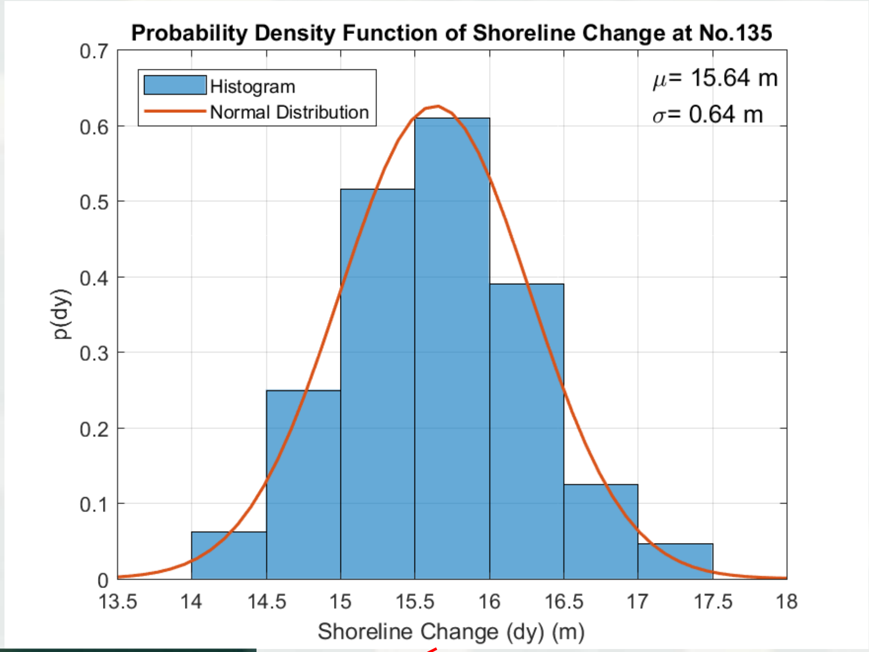
Mean wave angle = -5.06^{O}

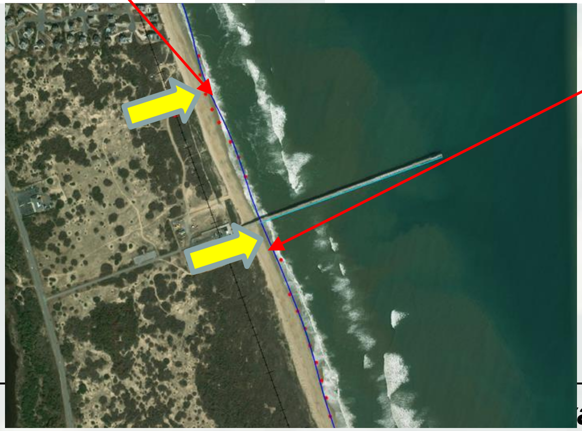
Probability Density Functions: 6-Years Shoreline Change

At 400-m north of the Pier



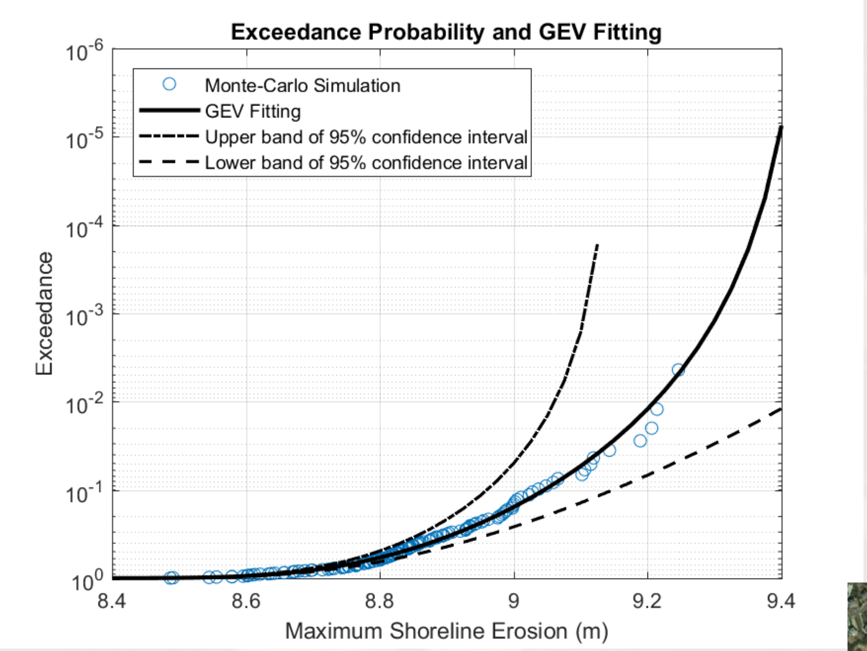
At 40-m south of the Pier

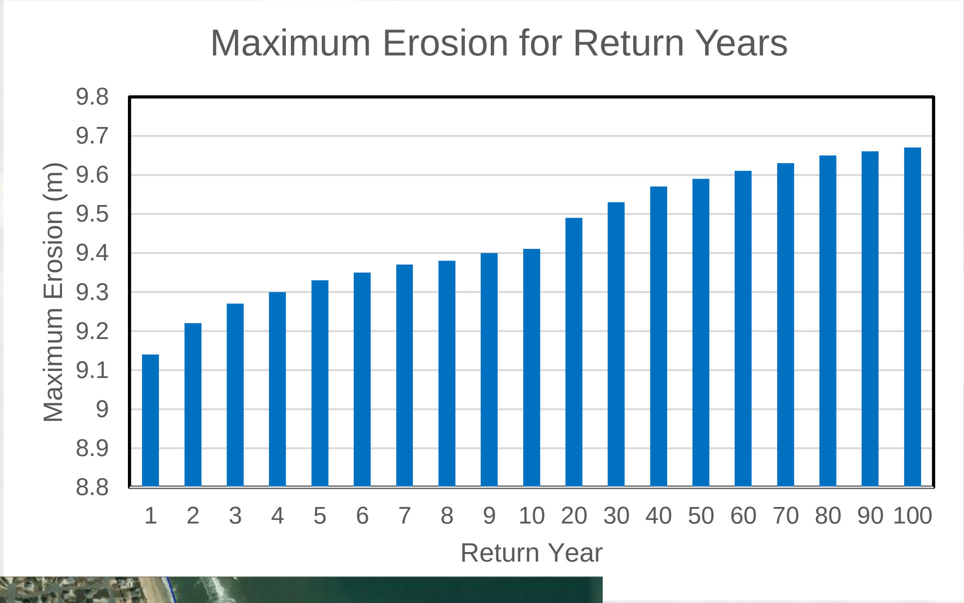


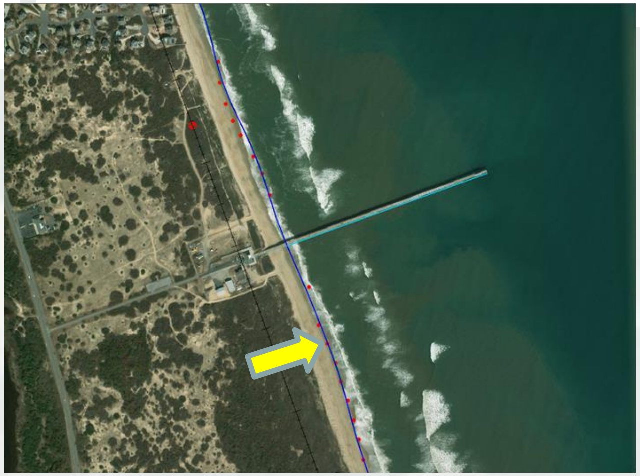


...ative solutions for a safer, better world

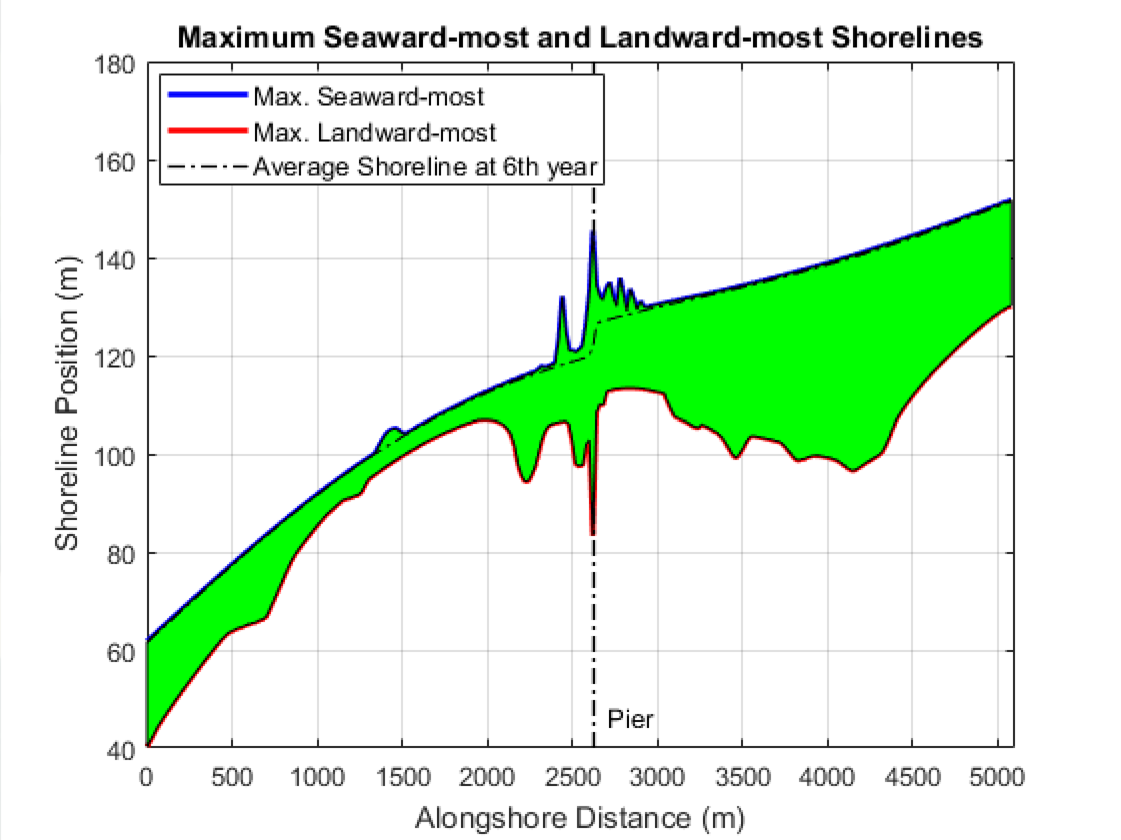
Estimation of Maximum Erosion at 300-m South of Pier







Maximum Seaward-most and Landward-most Shoreline Positions



The filled area is a spatial range of shoreline variations (from maximum landward-most position to maximum seaward-most position) during the simulation period of 6 years.

Conclusions

- This presentation presents a stochastic approach to simulate probabilistic shoreline change by using Monte Carlo numerical experiments.
- A combined probability density function is proposed to combine large wave and small wave heights in limited simulation duration.
- The probabilities of the maximum shoreline erosion on a hypothetical coast were analyzed by using the extreme probability distribution model (Weibull function). The risks of maximum shoreline erosion at different return periods (years) are quantified.
- Cross-shore sediment transport is important in simulating shoreline evolution in Duck, NC. With cross-shore transport, validation of GenCade is successful.
- Preliminary results of probabilistic shoreline change at Duck, NC, are reasonable. Estimation of extreme shoreline change provides maximum erosion risk in a return-interval manner.

Thank you for your attention!

Questions?

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