GenCade Modernization/Update: New Capabilities and Probabilistic Shoreline Change Modeling

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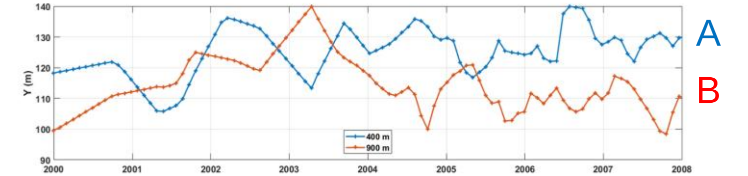
Outline

- New Capabilities in GenCade:
  - New Processes: Estimation of Cross-shore Sediment Transport, Shoreline Retreat due to Sea Level Rise and Subsidence
  - New Simulation Approach: Probabilistic Shoreline Change Modeling using Monte-Carlo Simulation
- Validation of GenCade new Processes:
  - CHL Field Research Facility in Duck, NC
  - Fenwick Island, DE with inclusion of Beachfills
  - Indian River Inlet, DE
- GenCade-based Monte-Carlo Simulation for Risk Estimation of Shoreline Change
- Probabilistic Shoreline Change Modeling for Duck coast
- Remarks

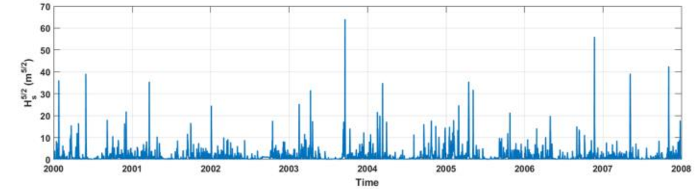
Long-Term Shoreline Changes

- Prediction of long-term shoreline changes is a key task in coastal management practice.
- Multiple physical processes drive shoreline changes: wave, wind, tide, storm, current, **sea level change/subsidence**, sediment properties, **longshore/cross-shore sediment transport**, **human activities** (structure installation, beach refill, beach recreation),etc.
- Shoreline changes induced by natural physical processes in general are highly irregular.
- **Probabilistic shoreline change prediction** is needed for best shoreline management practice for long-term protection purpose.
- **Uncertainty estimation** of shoreline changes is required for best shoreline erosion control management.

History of Shoreline Positions in Duck, NC



Wave Climate



Shoreline Change due to Coastal Management Practices

- Construction or modification of inlets for navigational purpose
- Construction of harbors with breakwaters built in nearshore regions
- Beachfills (sand nourishment)
- Sand Bypass
- Sand Mining
- Dredging Material Disposals

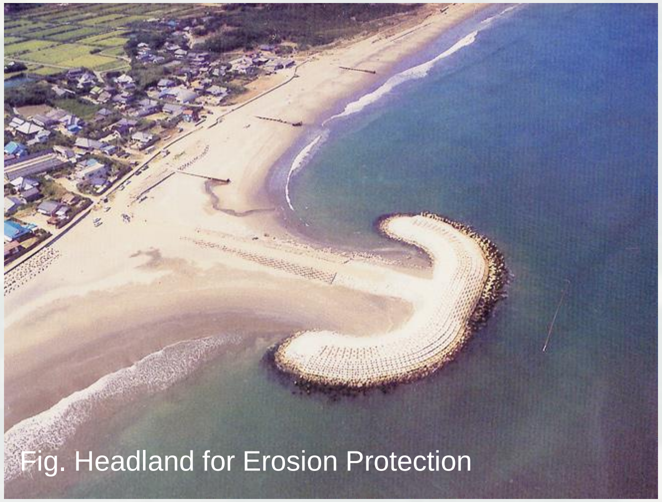
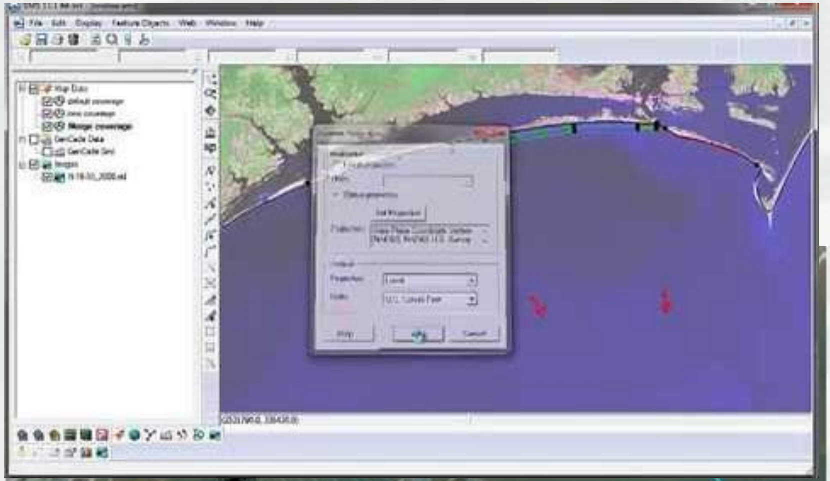


Fig. Headland for Erosion Protection


Fig. Sand Bypass in Indian River Inlet, DE

GenCade:
USACE Shoreline Evolution Simulation Model

- GenCade: A one-dimensional shoreline change model driven by longshore sediment transport, including modules for inlet-sand sharing, beach nourishment, structure effect, etc.
- Combines the engineering power of GENESIS with the regional processes capability of the Cascade model.
- Development began in 2009, GenCade Version 1 in SMS Ver. 11.1 was released in 2012 (Frey et al. 2012)
- Applications in US and other international coasts.



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

Longshore Sediment Transport
- Energy Flux Method (CERC formula)

$$Q = H_b^2 C_{gb}\left(a_1 \sin 2\alpha_b - a_2 \cos\alpha_b \frac{\partial H_b}{\partial x} \right)$$

H_b : *Wave Height at breaker line*

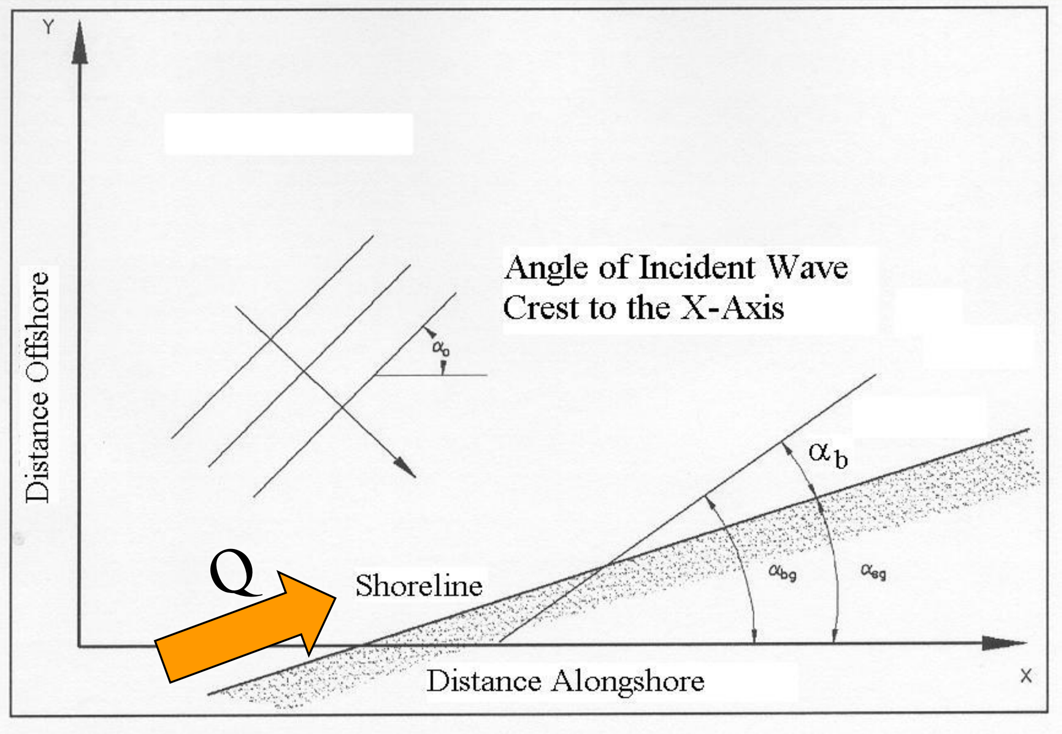
C_{gb} : *Group speed at breaker line*

$$a_1 = \frac{K_1}{16(s-1)(1-p)1.416^{2.5}}$$

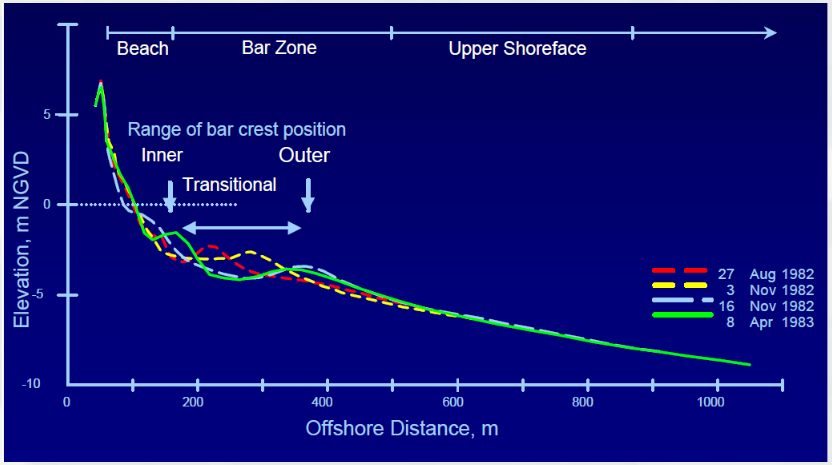
$$a_2 = \frac{K_2}{8(s-1)(1-p)\tan\beta 1.416^{2.5}}$$

K_1,K_2=*empirical coefficients*

Typically, $0.5K_1 < K_2 < 1.5K_1$



Cross-Shore Sediment Transport vs Nearshore Wave Asymmetry and Nonlinearity



Beach Profile Changes in Duck, NC (Birkemeier, 2001)

Contributors to Cross-Shore Transport:

- Sandy bar migration (on-offshore directions)
- Undertow due to storm waves (offshore)
- Orbital motion of small waves (onshore)
- Overwash and overtopping
- …

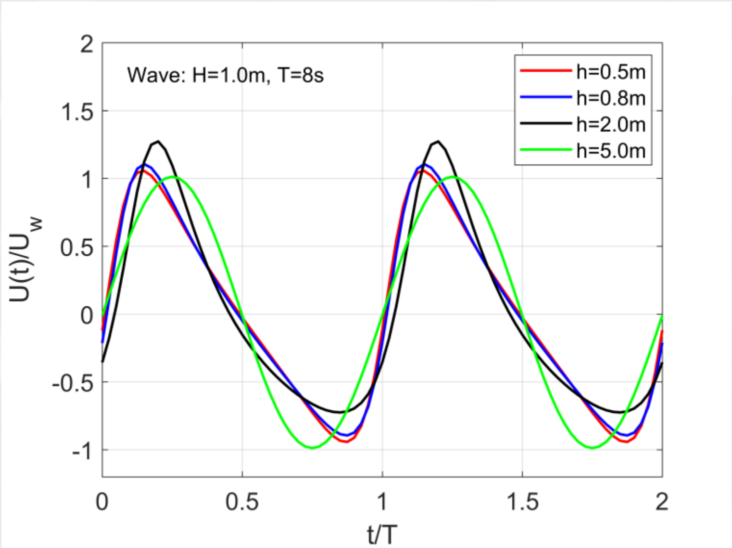


Figure. Near-bed orbital velocities for a wave (height H=1.0 m and period T=8 s) at four water depths. The positive sign denotes onshore direction

Cross-shore Sediment Transport due to Wave Asymmetry and Nonlinearity

Cross-Shore Transport Rate due to Velocity Skewness

$$\phi = \frac{\alpha_D}{1-p}(Q_V + Q_C + Q_D)$$

α_D=empirical parameters (=1~2), p=porosity of sediment

Q_v and Q_C are the net sediment transport due to waves and currents (Bailaid & Inman 1981, Hsu et al. 2006)

$$Q_V = \frac{C_W}{(s-1)g}\left(\frac{\varepsilon_B}{\tan\varphi} < \left|\vec{U}_0\right|^2 U_{0,x} > + \frac{\varepsilon_S}{W_0} < \left|\vec{U}_0\right|^3 U_{0,x} >\right)$$

$$Q_C = \frac{C_C}{(s-1)g}\left(\frac{\varepsilon_B}{\tan\varphi} < \left|\vec{U}_t\right|^2 U_x > + \frac{\varepsilon_S}{W_0} < \left|\vec{U}_t\right|^3 U_x >\right)$$

Energy Dissipation

Wave Skewness

U_0 = wave orbital velocity vector,
U_t = the total velocity vector (waves plus currents), and
U = current velocity vector, related to longshore current and undertow current.

φ = friction angle
W_0 = sediment fall velocity
C_w, C_C, ε_B, ε_S = empirical parameters obtained by Fernández-Mora et al. (2015)

Q_D represents a diffusive transport due to downslope move of sand:

$$Q_D = \frac{\lambda_d \nu \tan\beta}{\tan\varphi(\tan\varphi - \tan\beta)}$$

λ_D, v=empirical parameters

Calculation of Near-Bed Horizontal Orbital Velocity: An Asymmetrical Wave Shape Model

- Abreu et al. (2010) introduced a simple analytical expression for the free-stream near-bed horizontal orbital motion

$$\tilde{U}_0(t) = U_w f \frac{\sin(\omega t) + \dfrac{r \sin\varphi_w}{1+\sqrt{1-r^2}}}{1 - r\cos(\omega t + \varphi_w)}$$

r = nonlinearity measure calculated by Skewness and Asymmetry parameters (Ruessink et al. 2012)

$$f = \sqrt{1-r^2}$$

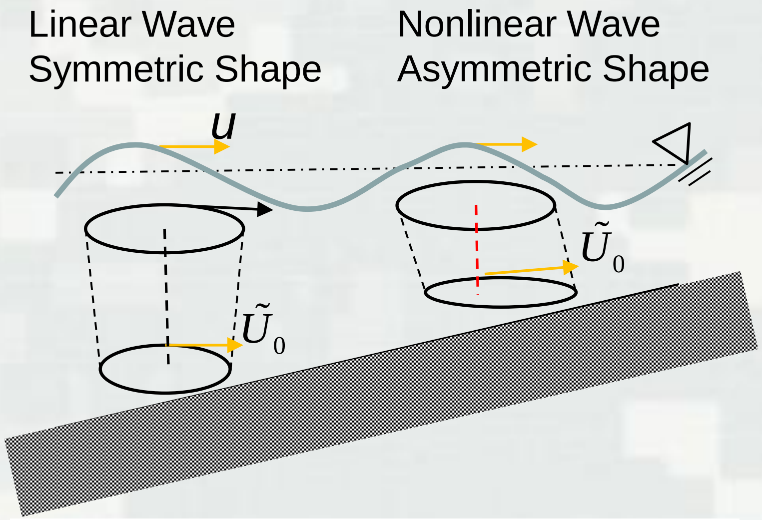
Combination of mean current and orbital velocity

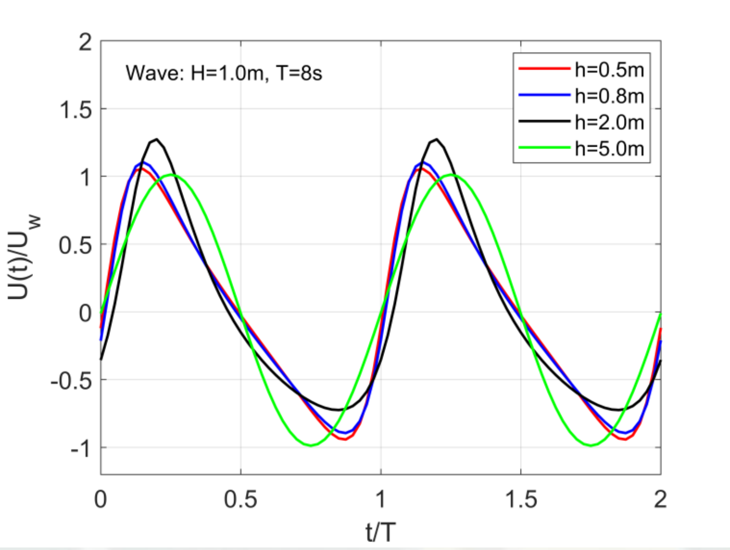
$$\vec{U}_0(t) = (U_{undertow} + \tilde{U}_0(t)\cos\theta)\vec{i} + (U_{alongshore} + \tilde{U}_0(t)\cos\theta)\vec{j}$$

i: cross-shore direction, *j*=alongshore direction

$U_{undertow}$ = undertow current in cross-shore direction

$U_{alongshore}$ =mean current alongshore



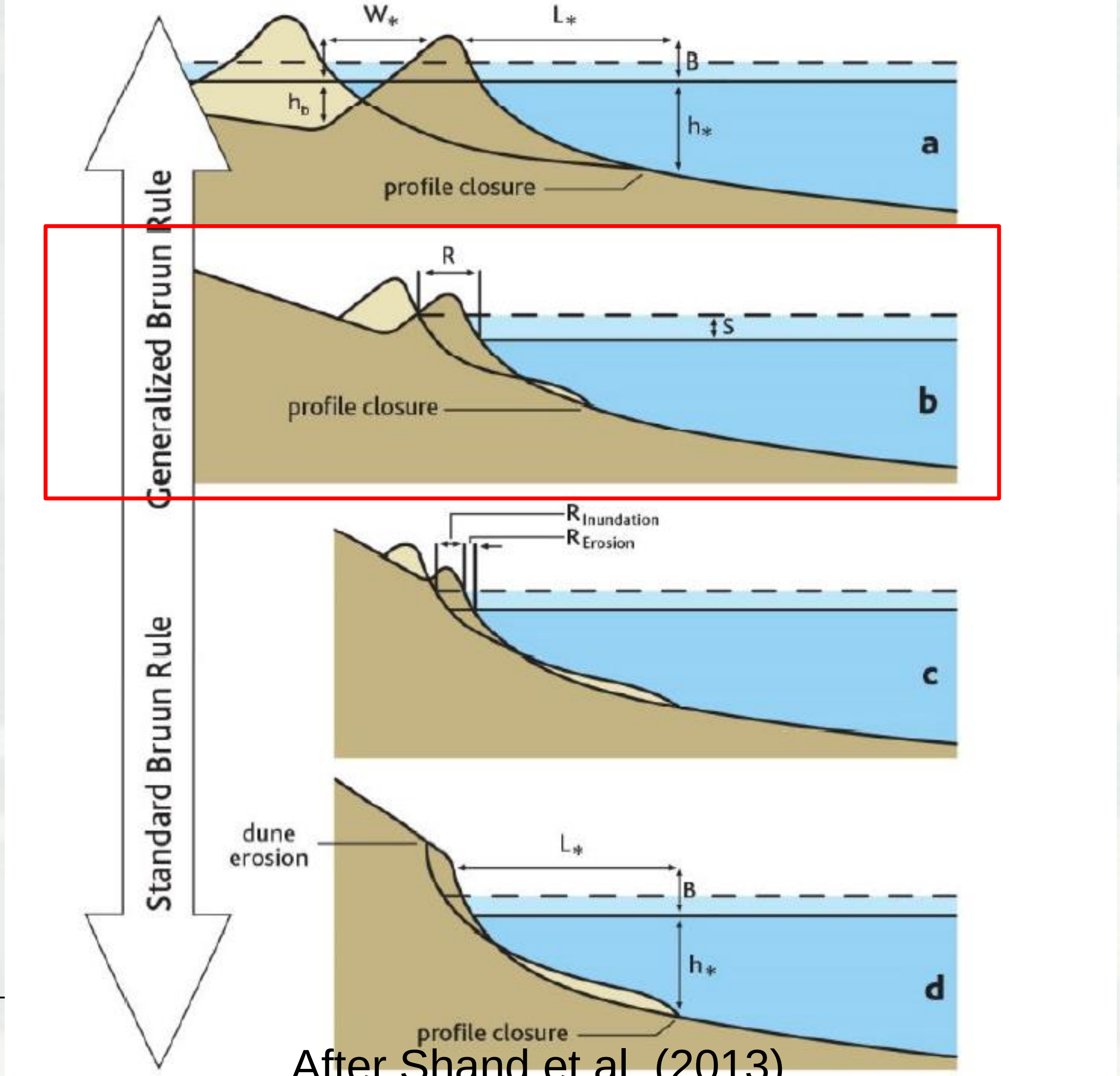


Shoreline Recession due to Sea Level Rise: Bruun Model (1962, 1988)

Shoreline Retreat rate

$$R = \frac{SW_*}{h_* + B}$$

S: Sea level rise rate
h* = sediment closure depth
B = Berm Height



After Shand et al. (2013)

New Features of GenCade for Shoreline Evolution Model with Cross-Shore Transport and SLR

- Shoreline Change Equation with Sea Level Rise (SLR)

$$\frac{\partial y}{\partial t}+\frac{1}{D_s}\left(\frac{\partial Q}{\partial x}-q-\phi\right)+\frac{R+S}{\tan\beta}=0$$

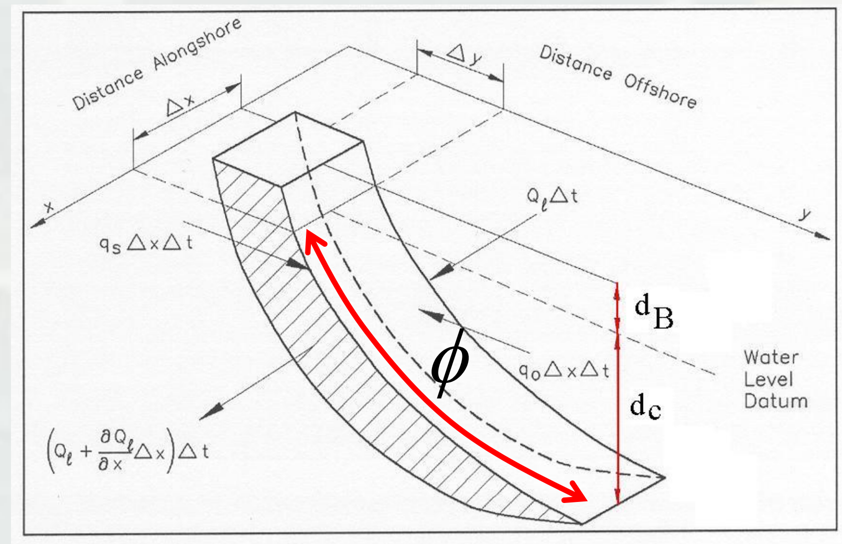
ϕ : Cross-shore sediment transport rate

R : Sea Level Change Rate

S : Subsidence Rate

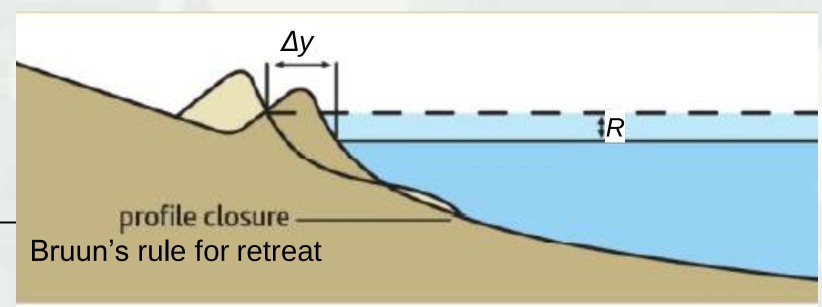
$tan\beta$: beach slope

$D_S = d_c + d_b(t)$: Total closure depth



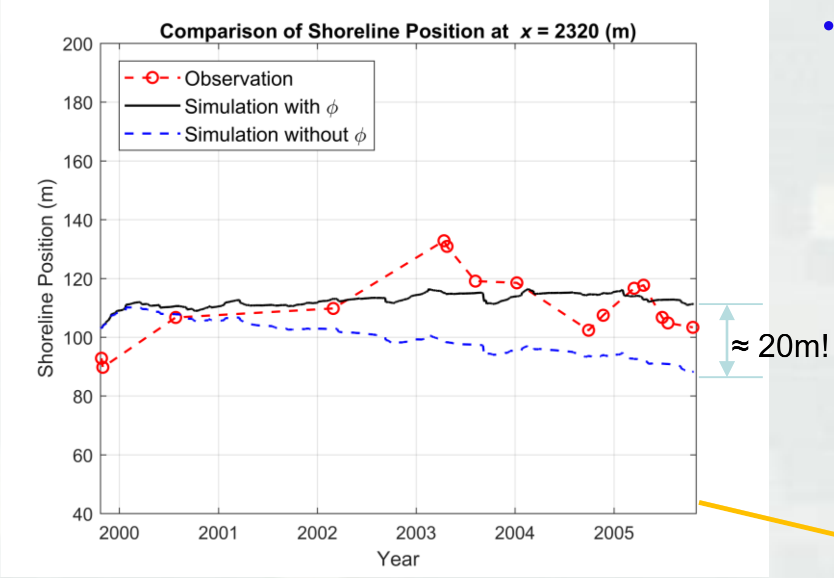
- Berm height varies with sea level change

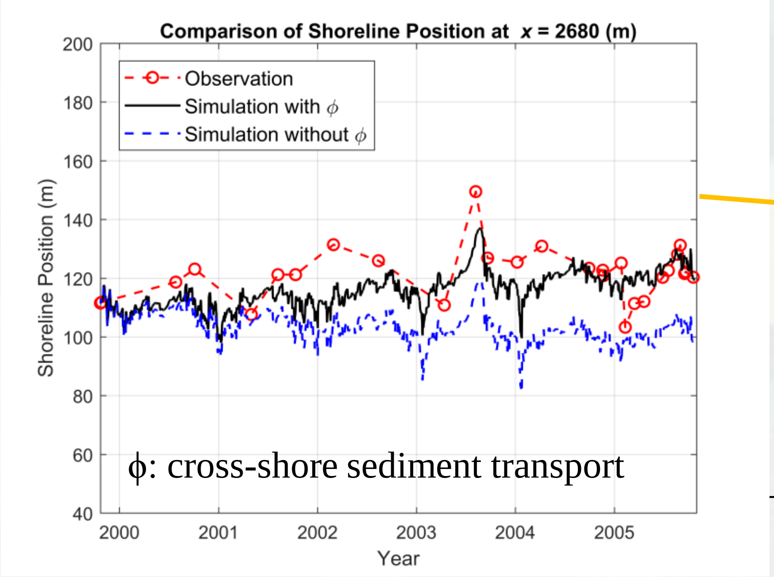
$$d_b(t) = d_{b0} - (R+S)t$$



Bruun's rule for retreat

Model Validation:
Shoreline Changes (1999-2005) at FRF, Duck, NC

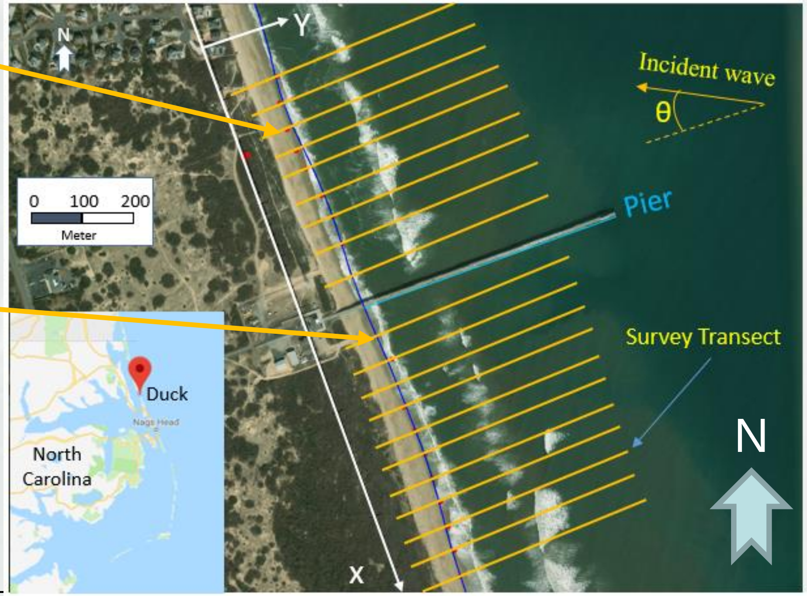




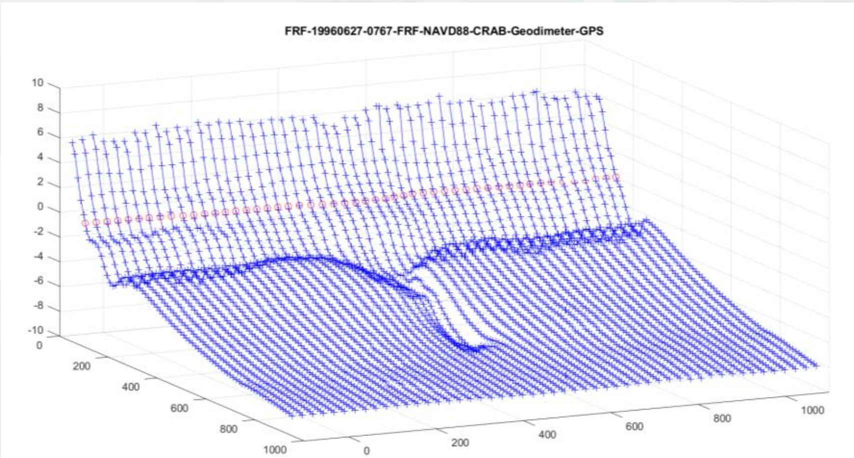
- Model Parameters

d_c (m)	d_b (m)	d_{50} (mm)	R+S (mm/yr)	K_1	K_2	Δt (min)	Δx (m)
7.0	1.0	0.2	4.55	0.40	0.25	3.0	20.0

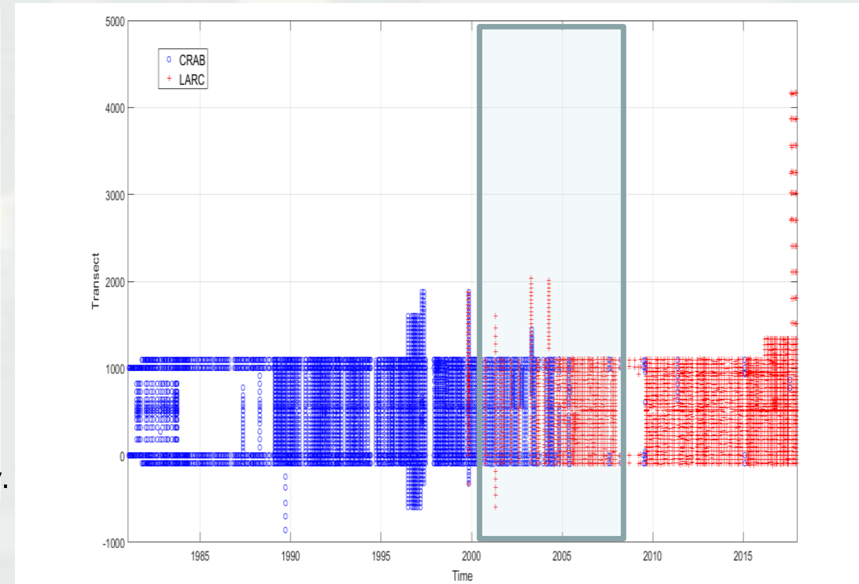
Wave: Senso-Metric 8m Array
Boundary Conditions: Pined
Permeability of Pier = 0.6 (no diffracting):
Parameters for Cross-Shore Transport
Scaling parameter α_D= 1.50
C_w, C_C, ε_B, ε_S by Fernández-Mora et al. (2015)



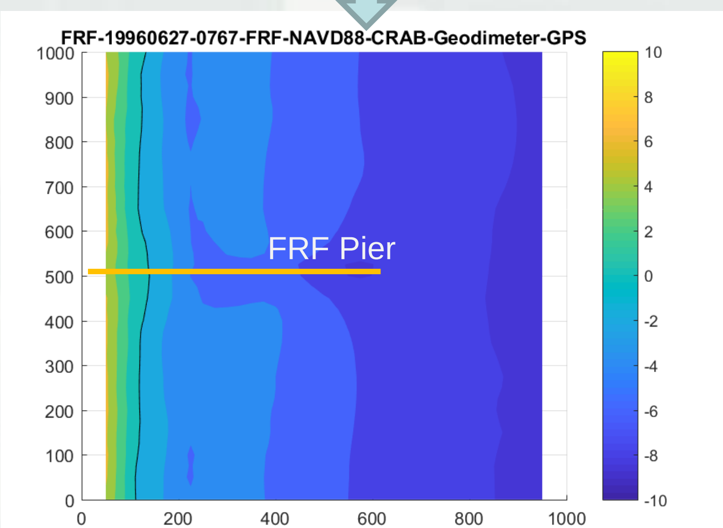
Determining Shoreline Positions from FRF Survey Data of Beach Profiles



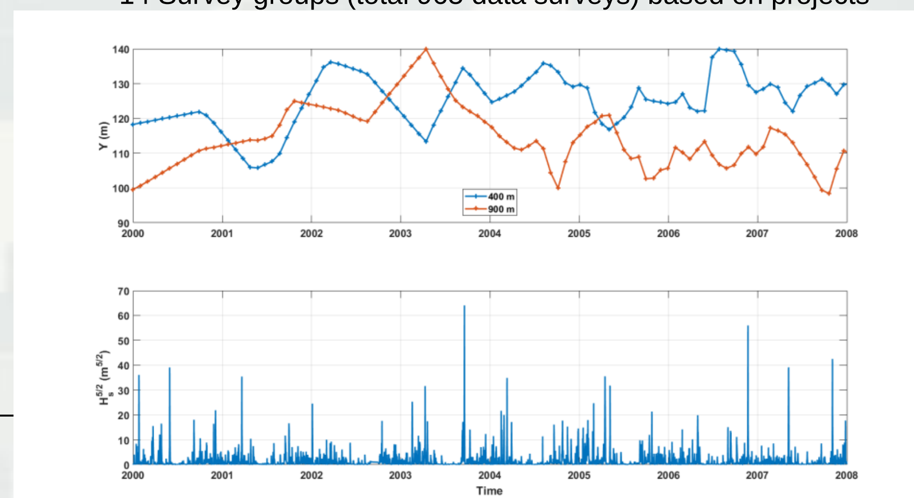
Representative beach profile coverage area along the FRF property.
CRAB =Coastal Research Amphibious Buggy
LARC=Lighter Amphibious Resupply Cargo



- Beach profile locations dating back to 1985 illustrating the cross-shore and temporal coverage
- 14 Survey groups (total 965 data surveys) based on projects



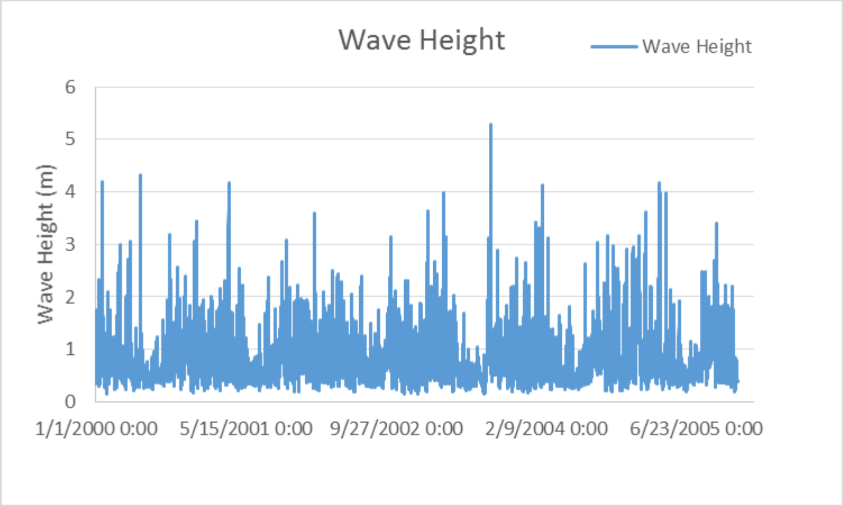
Bathymetric contour plot showing the relatively straight and parallel contours except in the vicinity of the pier

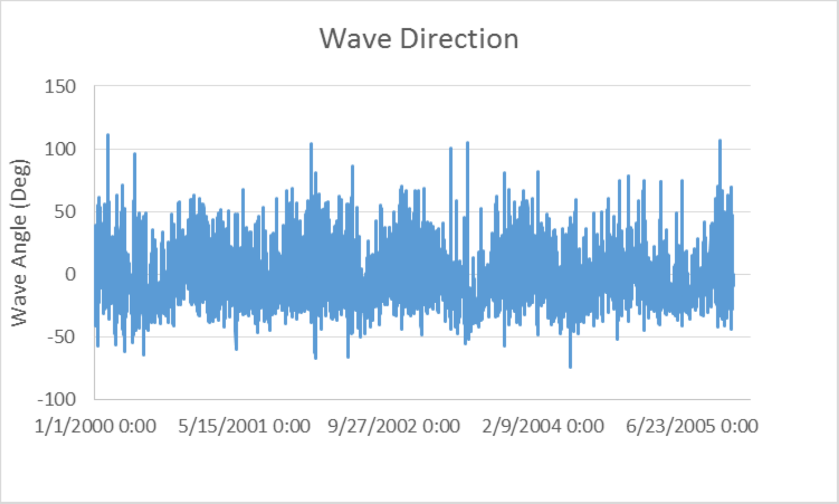


Wave Data (2000/1/1 – 2006/1/1)

The wave measurements at the 8-m array during the six year study period (1999-2005) include a blend of low-energy periods and energetic storm conditions

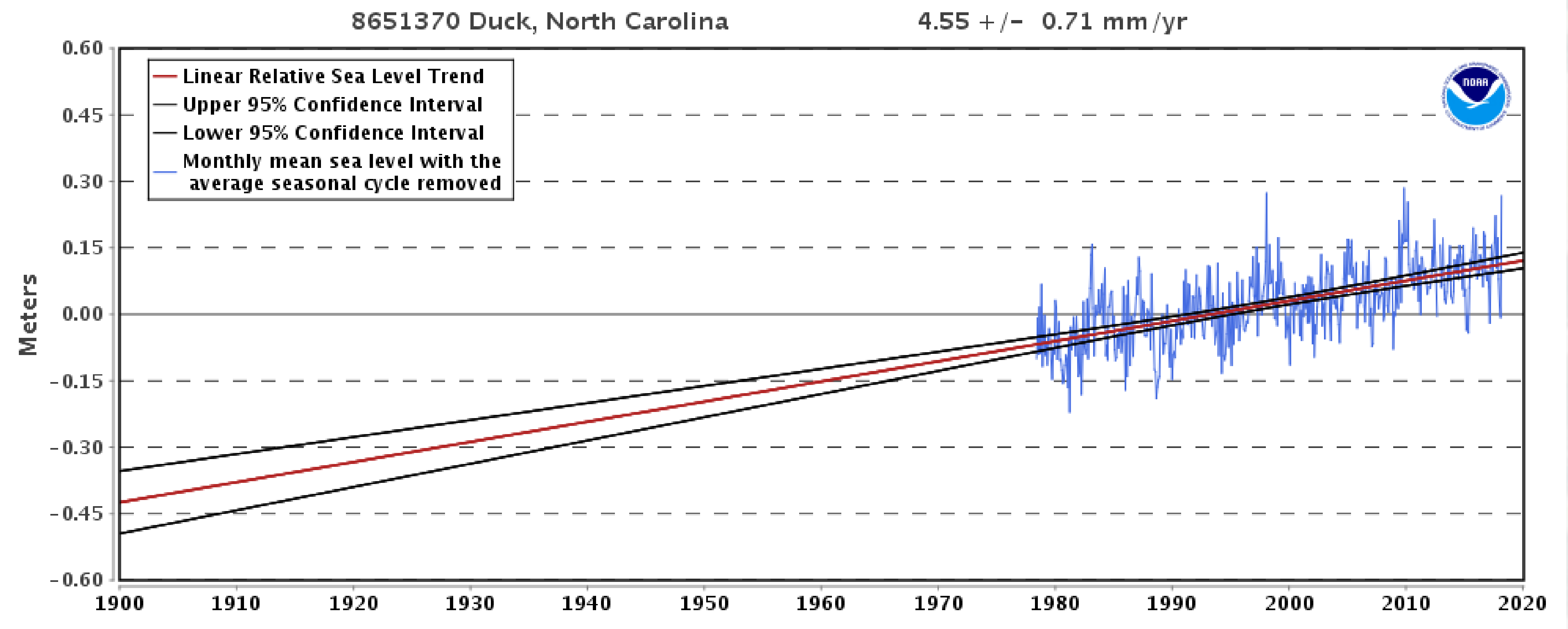
	H (m)	T (s)	alfa (deg)
Average	0.82	9.18	-5.06
Min	0.14	3.09	-74.62
Max	5.28	18.96	111.32
σ	0.53	2.68	18.52





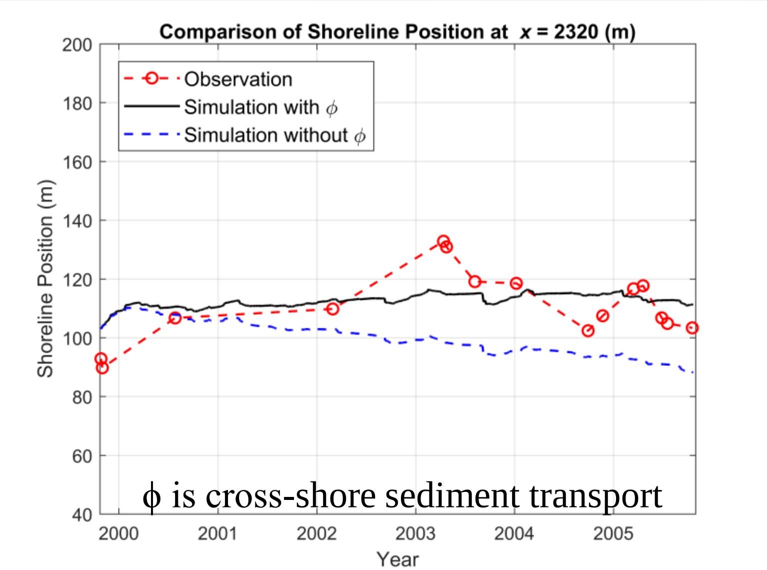
Sea Level Rise Trend

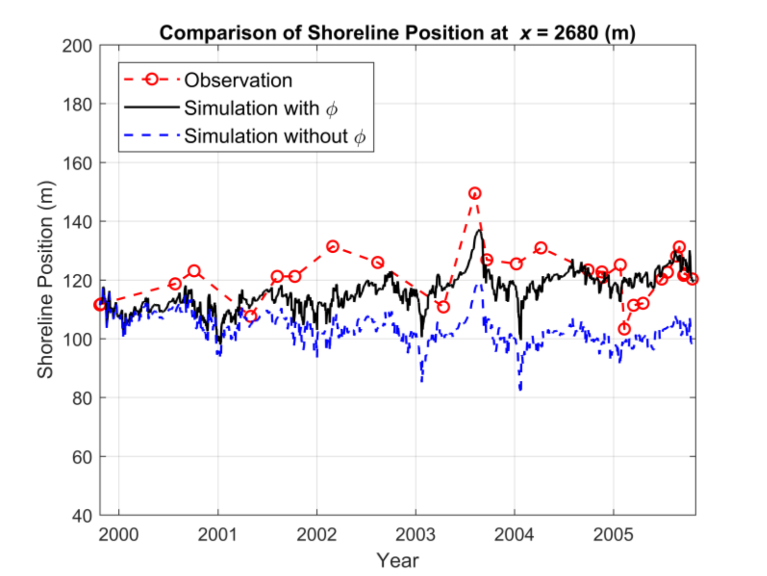
NOAA-NOS #8651370 Duck, North Carolina

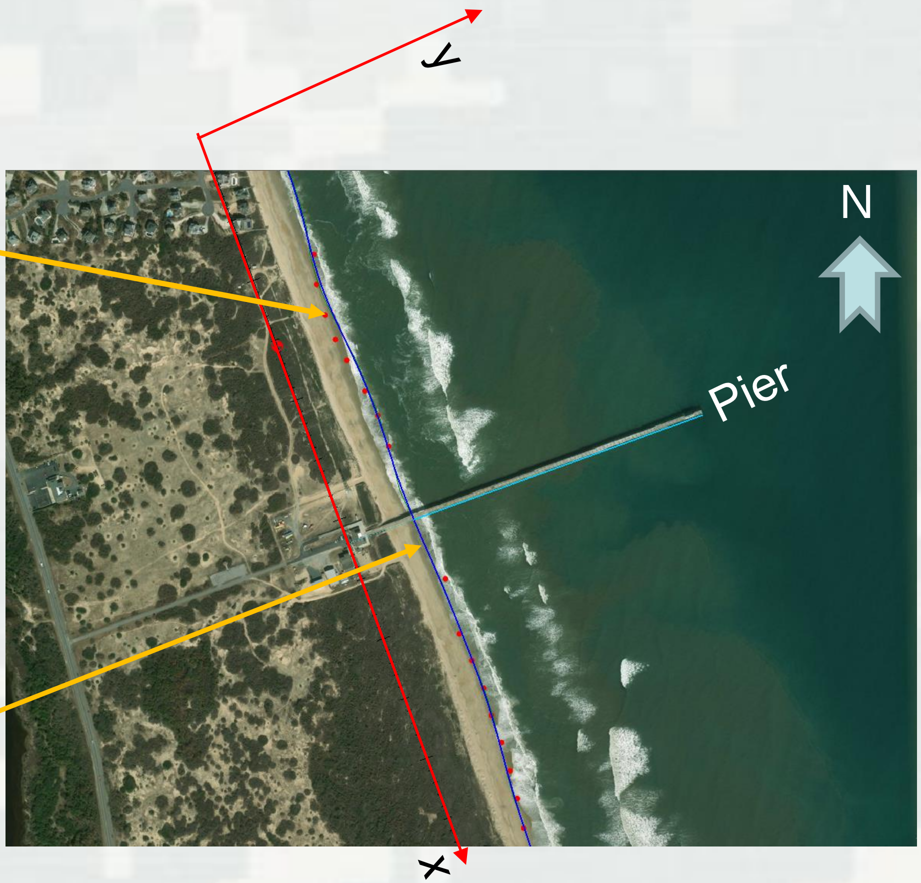


https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8651370

Model Validation: Comparison of Shoreline Evolution (1999-2005) at FRF, Duck, NC



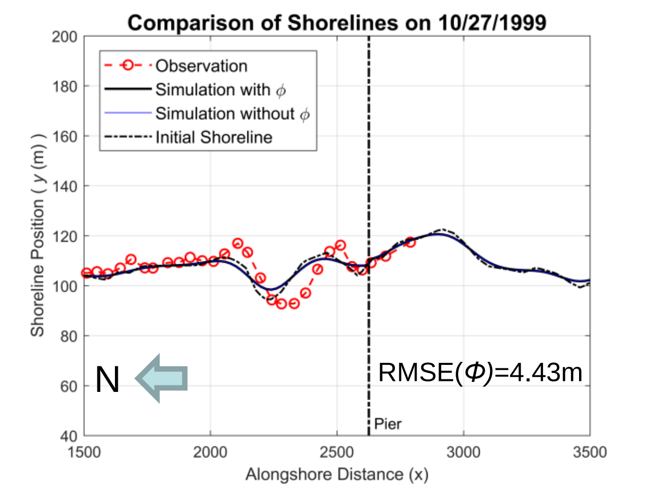


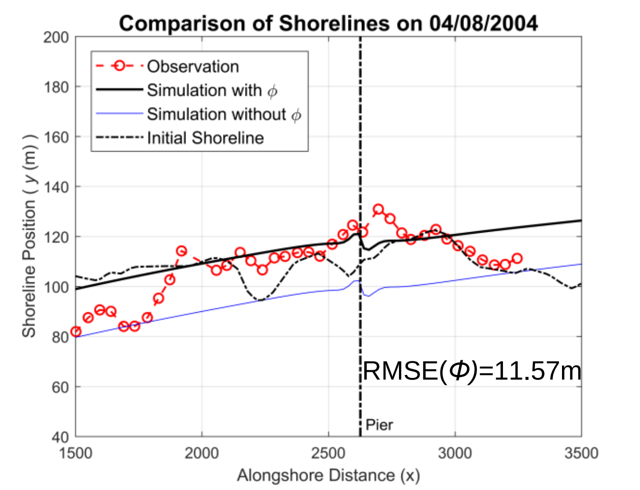


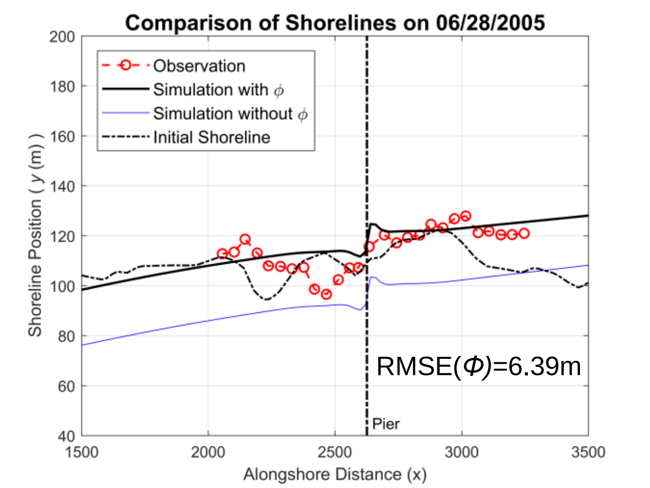
FRF in Duck, NC

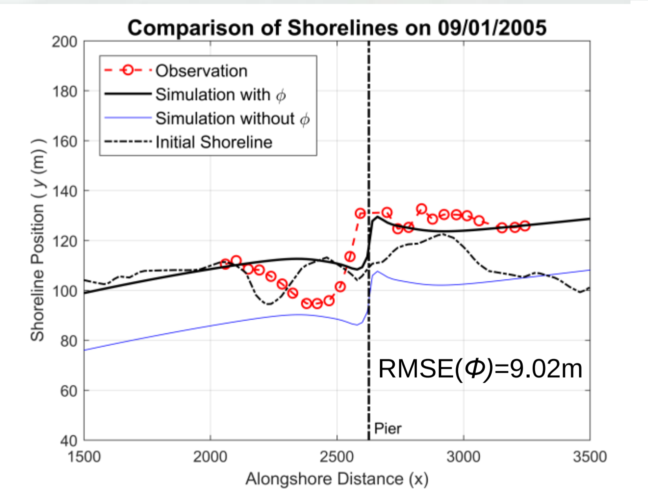
Model Validation:

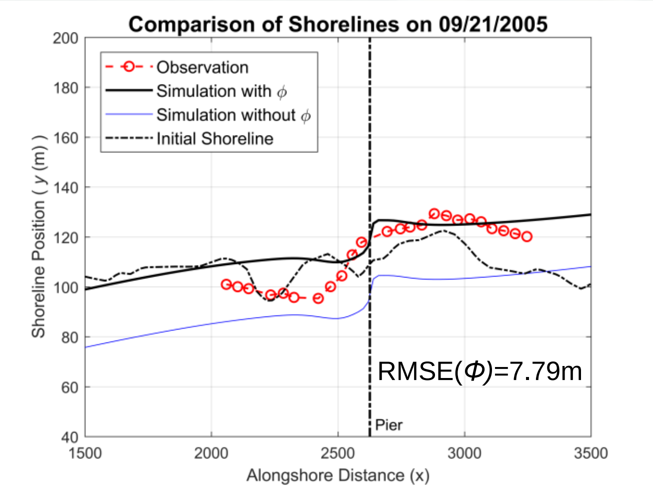
Comparisons of Shoreline Positions (1999-2005)

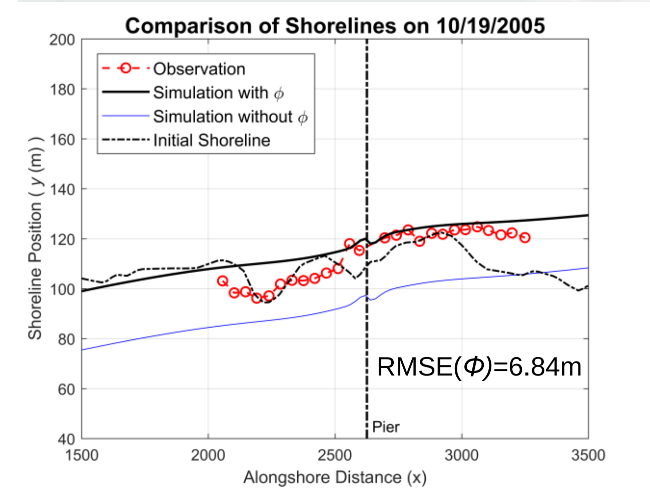








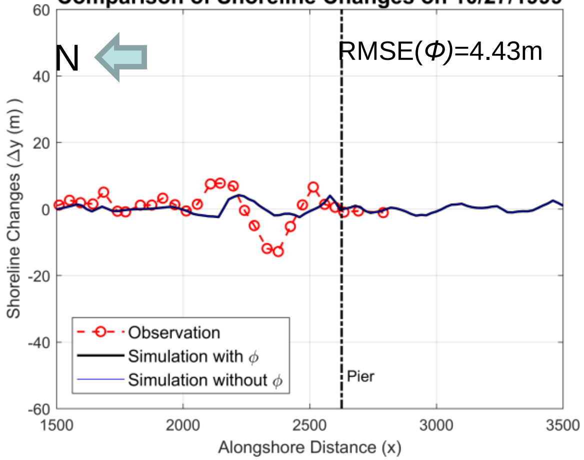




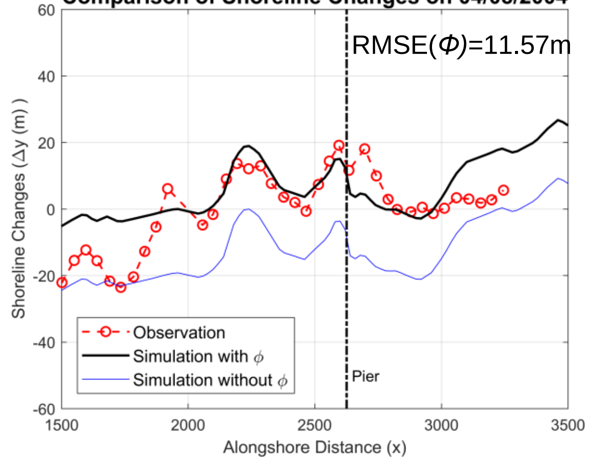
Model Validation: (w or w/o xshore)

Comparisons of Shoreline Changes (1999-2005)

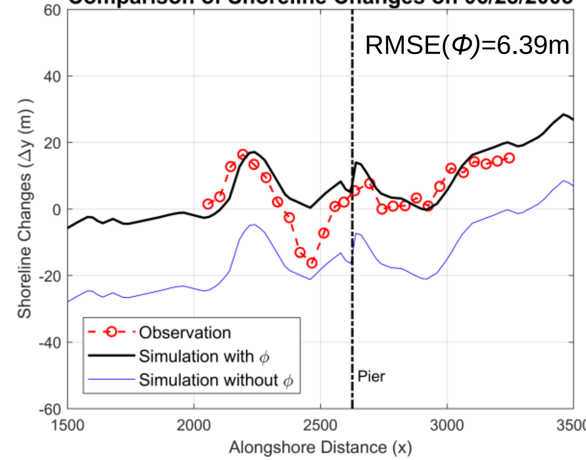
Comparison of Shoreline Changes on 10/27/1999



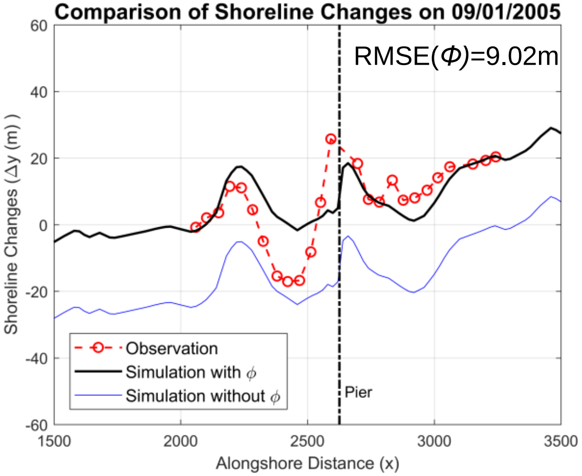
Comparison of Shoreline Changes on 04/08/2004



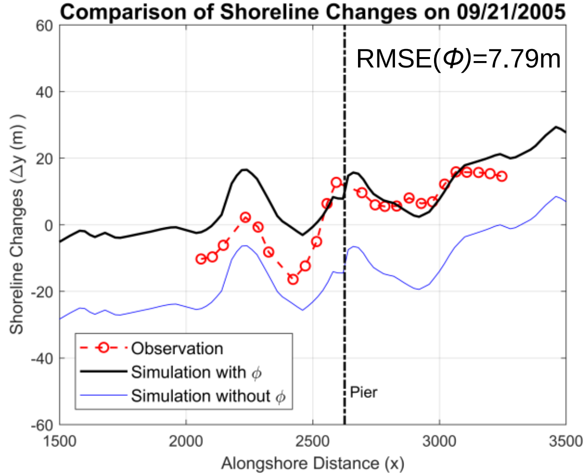
Comparison of Shoreline Changes on 06/28/2005



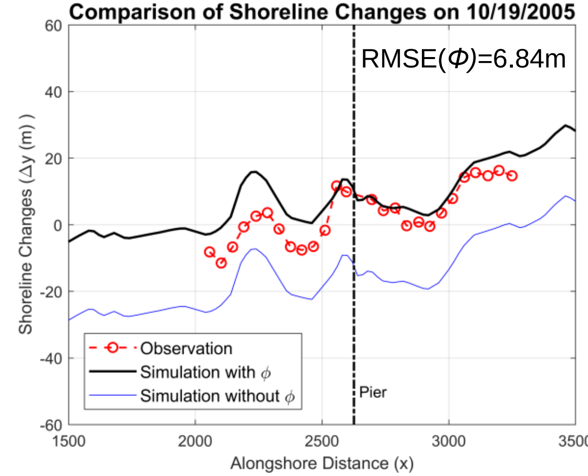
Comparison of Shoreline Changes on 09/01/2005



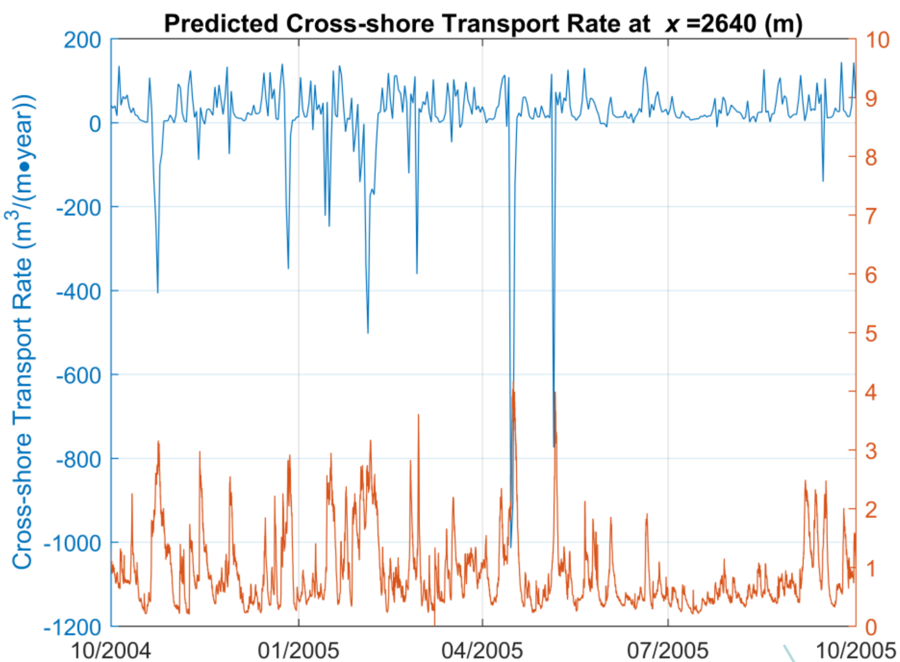
Comparison of Shoreline Changes on 09/21/2005

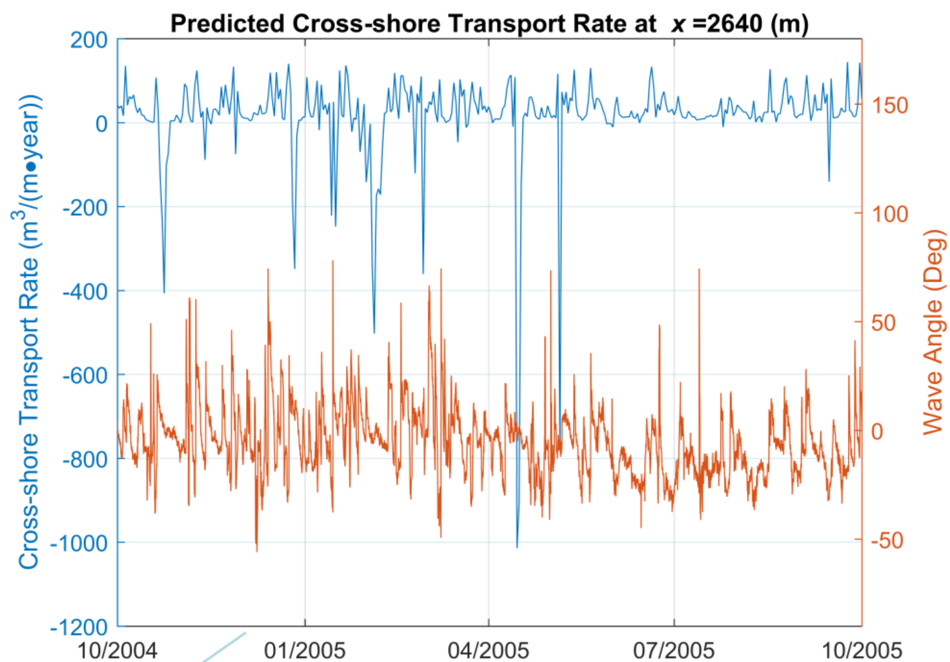


Comparison of Shoreline Changes on 10/19/2005

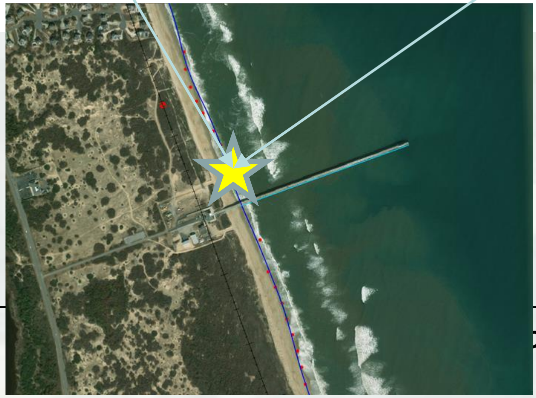


Predicted Cross-Shore Transport Rate (Φ) (1999-2005)



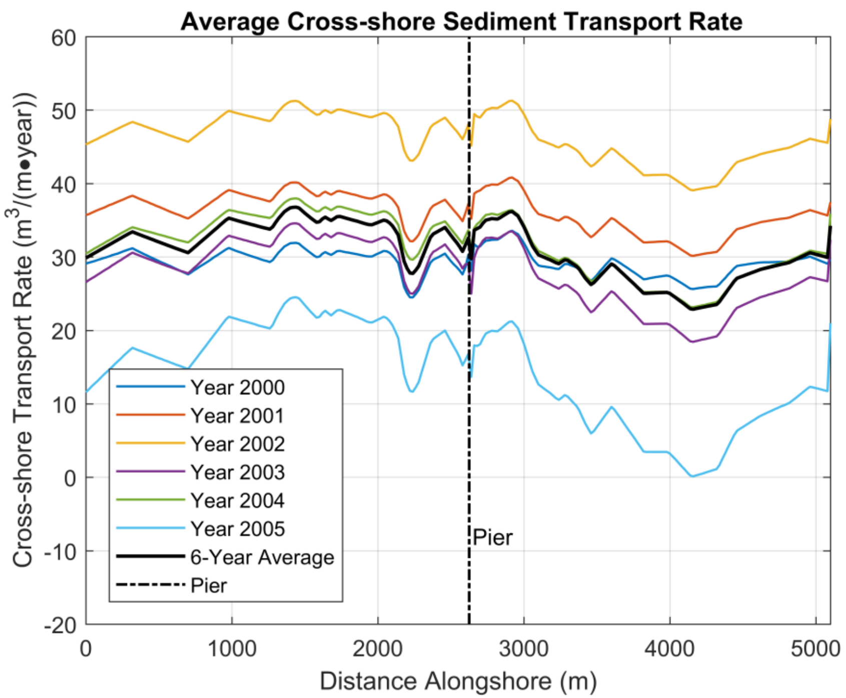


(a) Φ vs Hs



(a) Φ vs α (angle)

Annual Cross-Shore Transport Rate

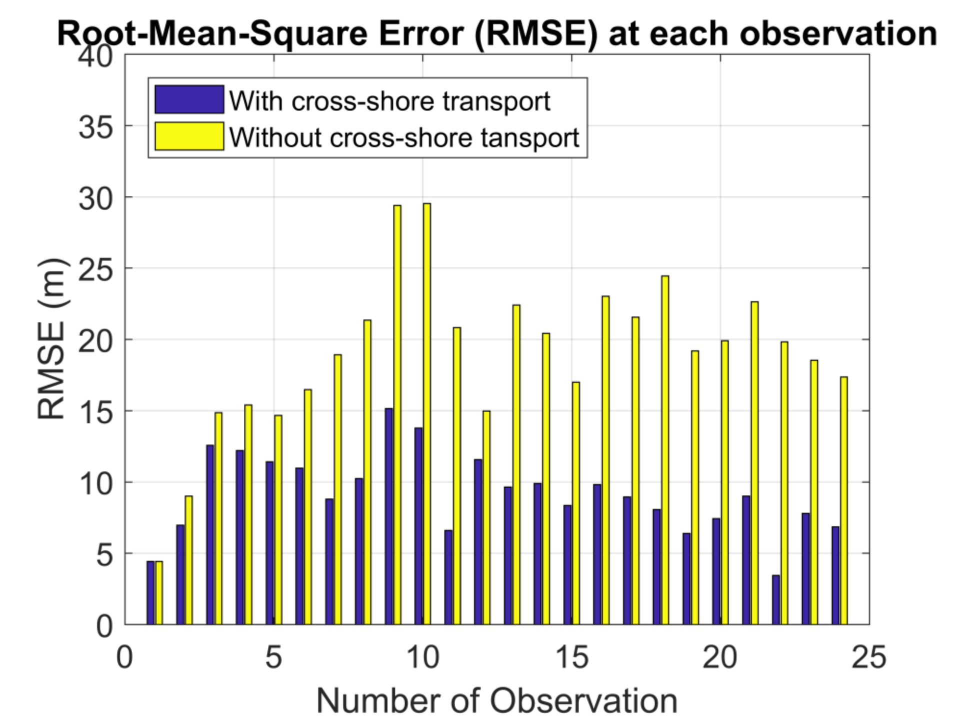


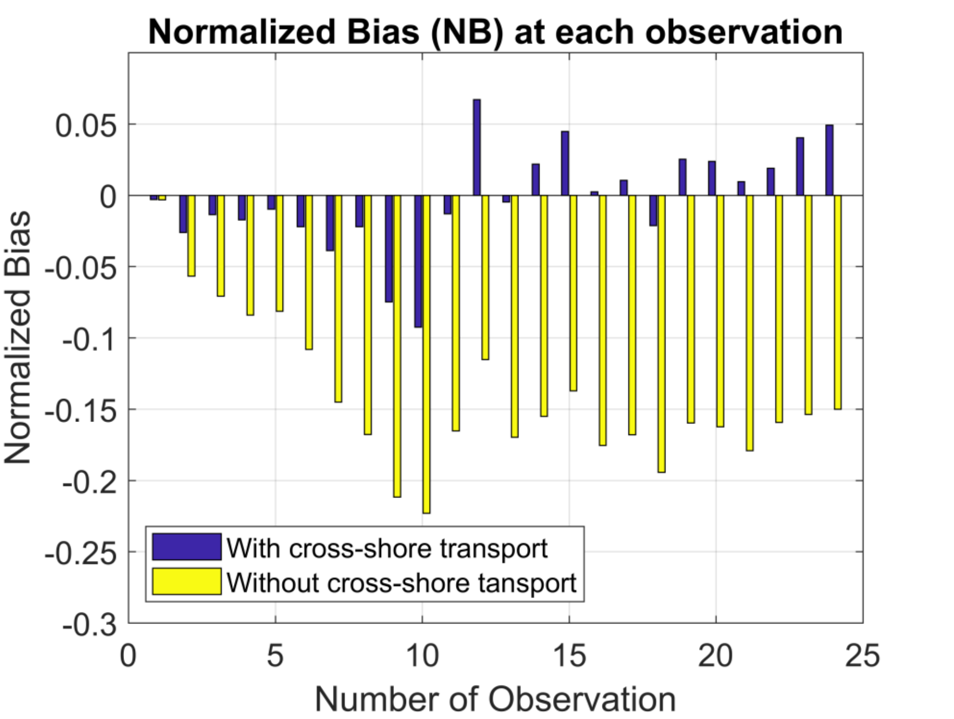
(1) Annual Average Φ

(2) 6-year Average Φ

Model Skill Assessment:

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





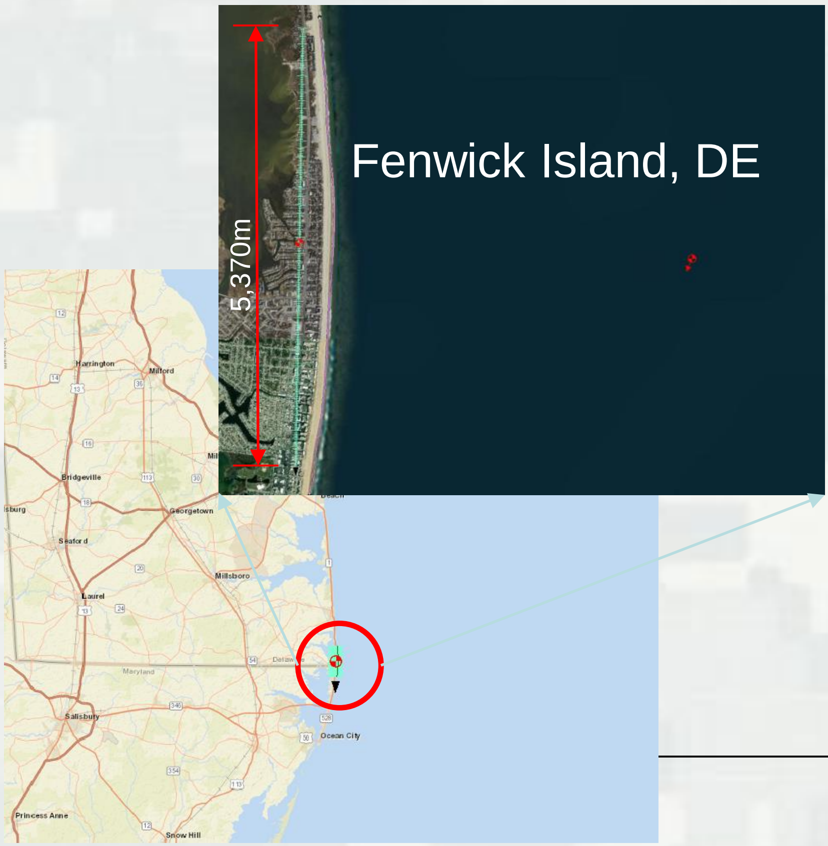
$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(m_i - O_i\right)^2}$$

$$\text{NB}=\frac{\frac{1}{\text{N}}\sum_{i=1}^{N}(m_i - O_i)}{\frac{1}{\text{N}}\sum_{i=1}^{N}\left|O_i\right|}$$

m_i: model values
O_i: Observation data

Modeling of Shoreline Change in Fenwick Island, DE

Objectives: (1) to validate the GenCade model by using shoreline survey data provided by NAP and DNREC, and (2) to evaluate shoreline erosion after beach fill completed in Sept. 2013.



Computational Parameters

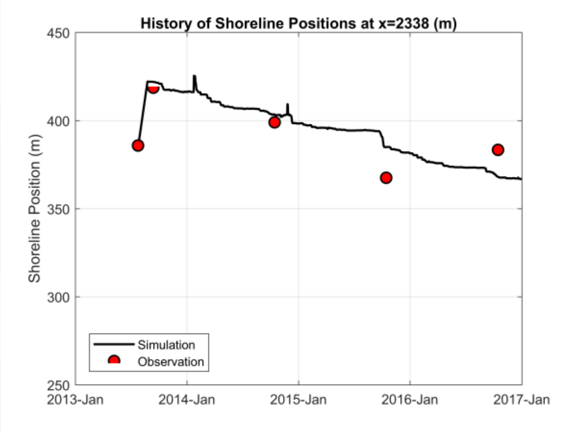
Computational Period: 3.5 years
2013/09/13 0:00 - 2017/01/01 0:00
after the beach fill in Sept. 2013

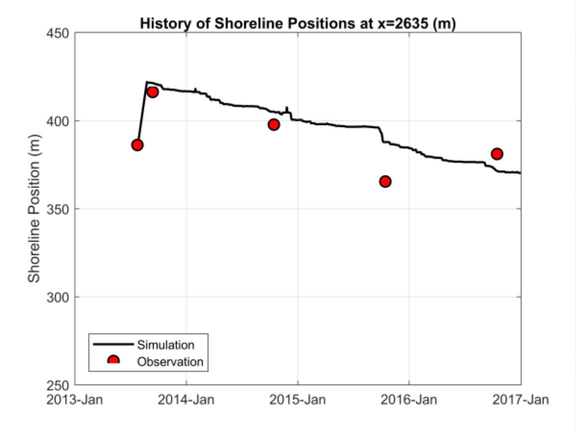
Time step = 3 minutes
Grain size = 0.30 mm
Berm Height = 1.0 m
Closure depth = 10.0m
Smooth parameter = 1 (no smoothing)
No regional contour
Boundary Conditions: Moving (retreat 2.5 ft/year)
Grid Size = 20 m
Sea Level Rise rate: 4.50mm/year (based on tide gauges)
Subsidence : included

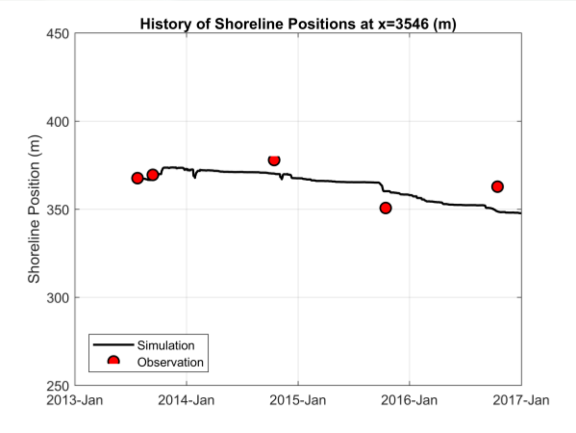
Calibrated Model Parameters:
K1 = 0.90
K2 = 0.35

Cross-shore transport included
Scaling parameter α_D= 0.16
C_w, C_C, ε_B, ε_S by Fernández-Mora et al. (2015)

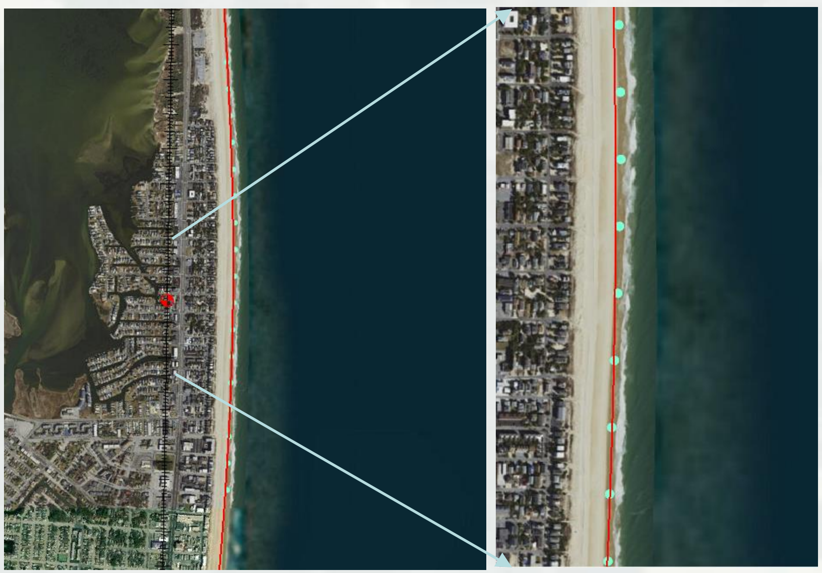
History of Shoreline Positions in Fenwick Island, DE

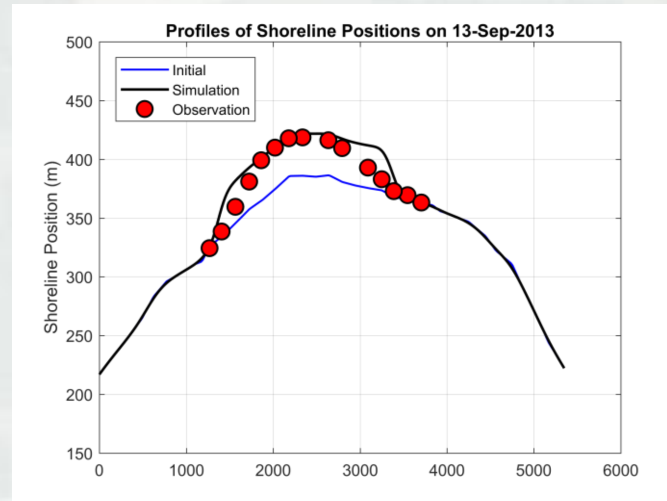


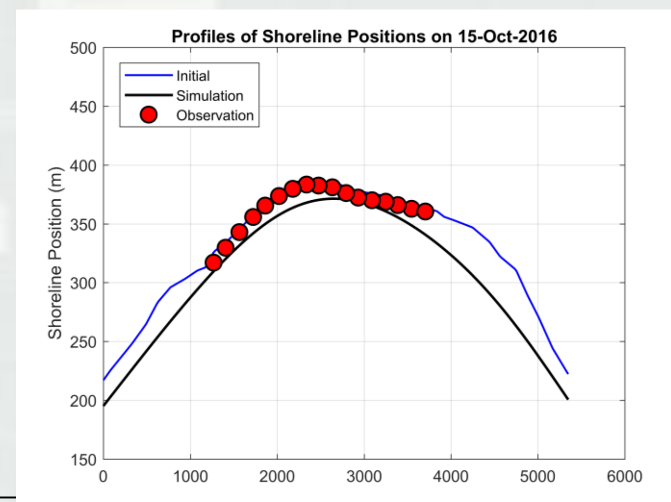




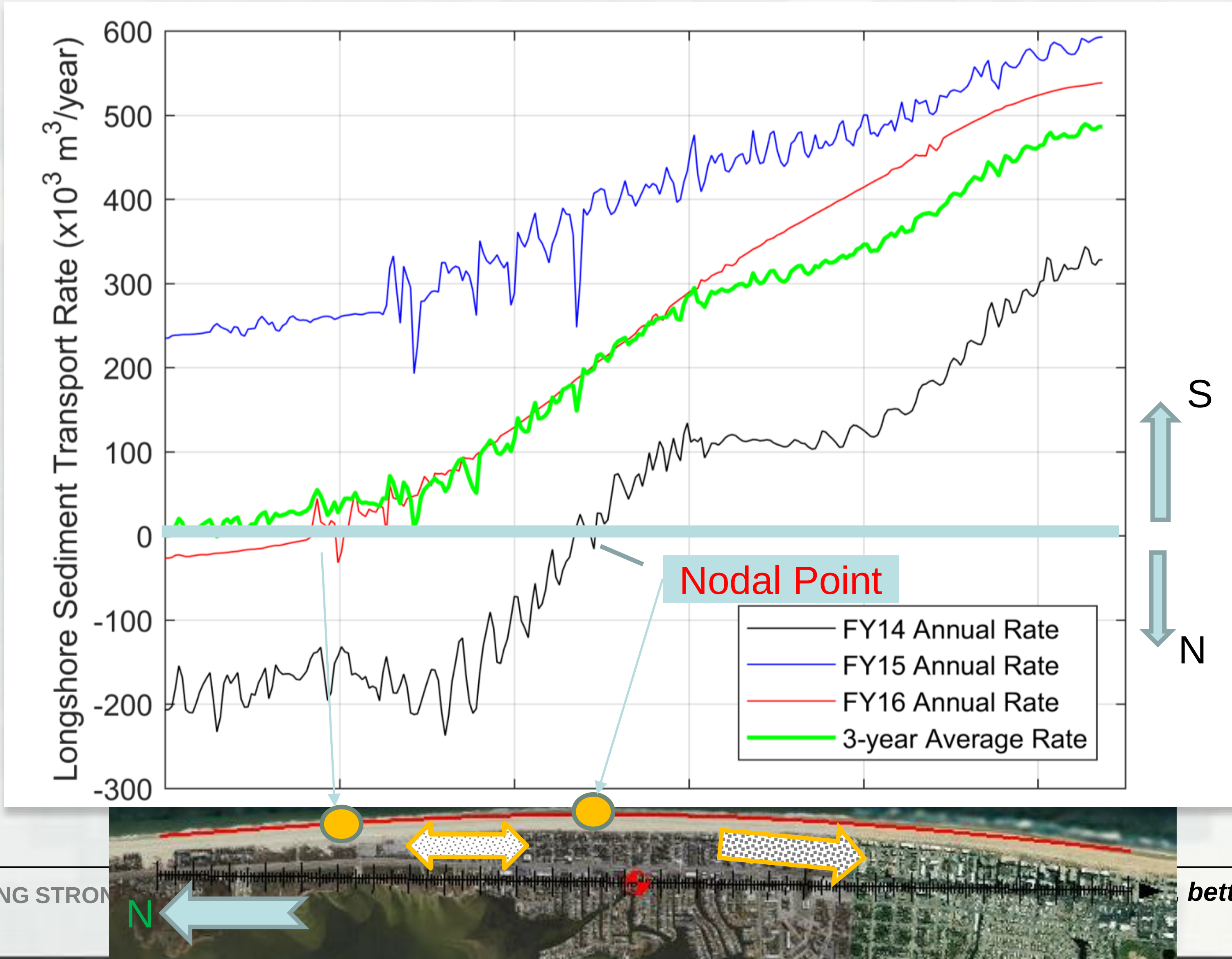
Comparisons of Shoreline Positions on 09/13/2013 and 10/15/2016



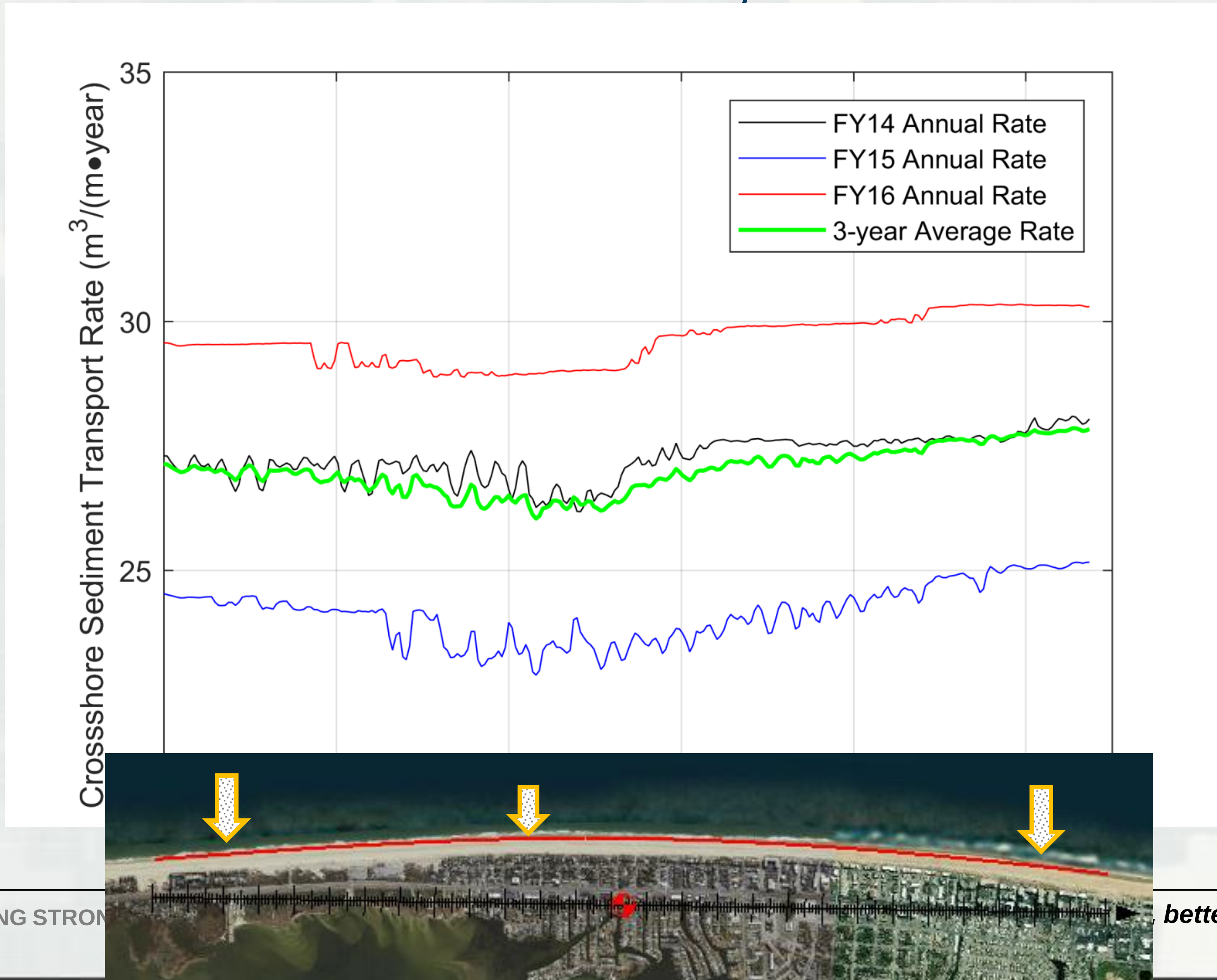




Annual Longshore Sediment Transport Rate in Fenwick Island, DE



Annual Crossshore Sediment Transport Rate in Fenwick Island, DE



GenCade-Based Monte Carlo Simulation

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

Wave Generator

GenCade

Statistic Analysis

- Maximum Likelihood Estimation

Input wave conditions for setting up the probability density functions, i.e. wave heights, periods, angles

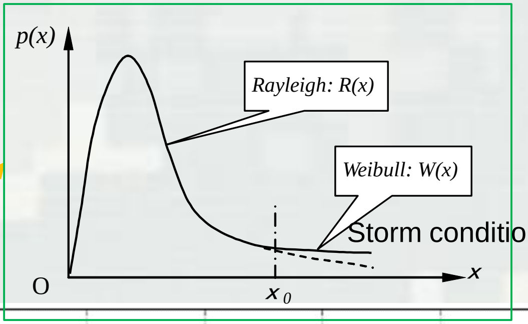
Generate time series of wave heights and angles based on probability density functions (pdfs)

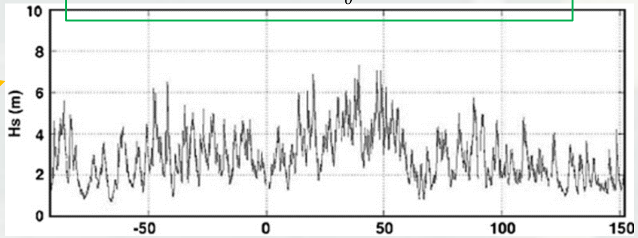
Simulation of shoreline changes by the one-line model, **GenCade**

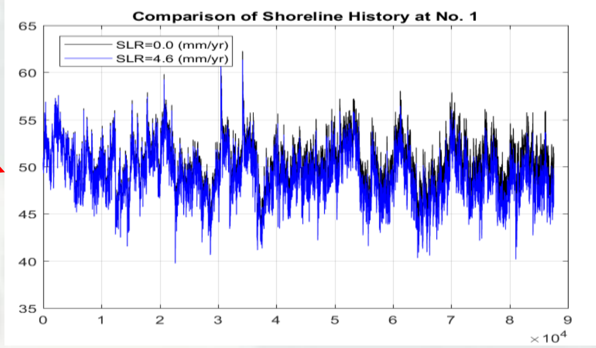
Repeat N times

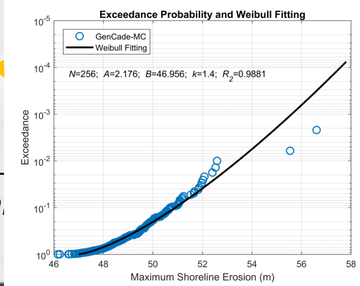
Statistic analysis of shoreline changes

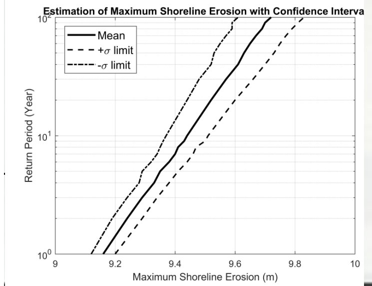
Stop







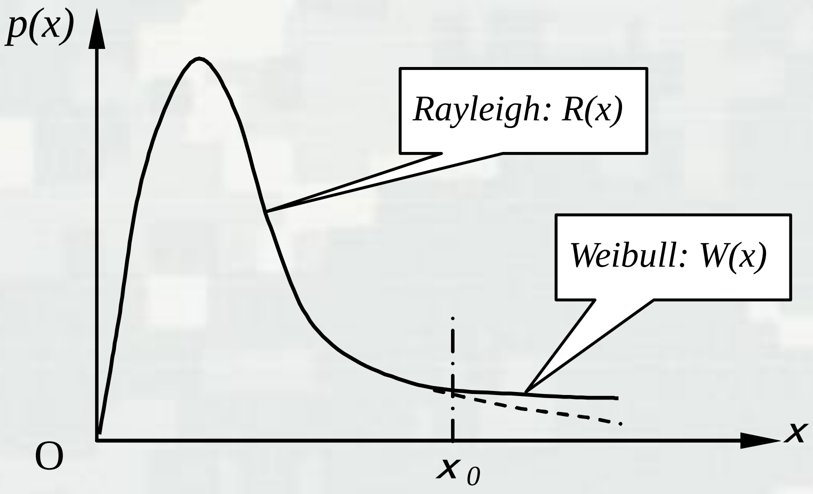




The more test samples (N), the better statistic results

Probabilistic Distribution of Wave Height

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



ε: parameter

x_0: a truncated extreme value of wave height

Rayleigh Distribution (for normal waves) :

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

Weibull Distribution (for extreme waves):

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

Parameters k, A, B, and x_0 are determined from wave observation data

$$\int_{-\infty}^{+\infty}p(x)=1 \quad \Rightarrow \quad \varepsilon=\frac{e^{-\frac{\pi}{4}x_0^2}}{e^{-\left(\frac{x_0-B}{A}\right)^{K}}}$$

Determining Distribution Parameter from Wave Observation Data

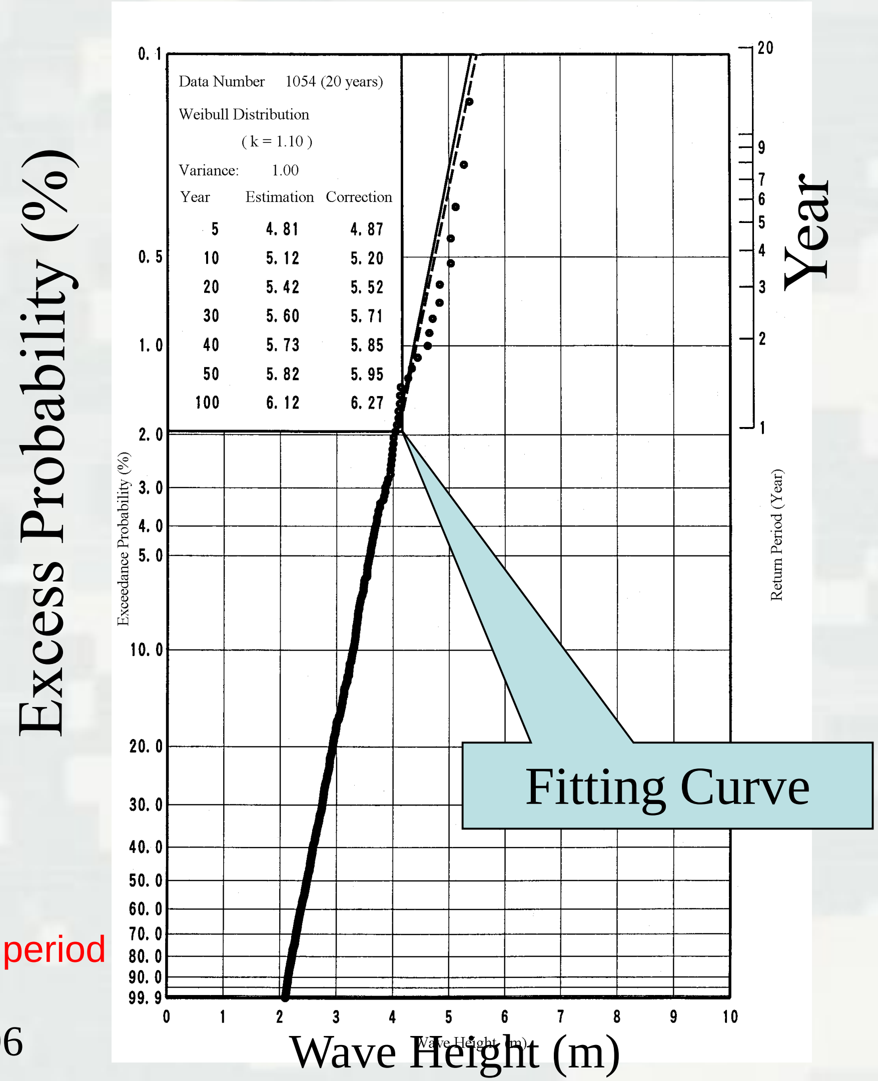
Density distribution of wave height is fitted as mixing distribution of Rayleigh and Weibull distributions

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

where $x = H / H_{mean}$,
in $W(x)$, $k = 1.1$, $A = 0.5792$, $B = 2.0554$, $x_0 = 2.1$

$Hmean = 1.19$ m

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



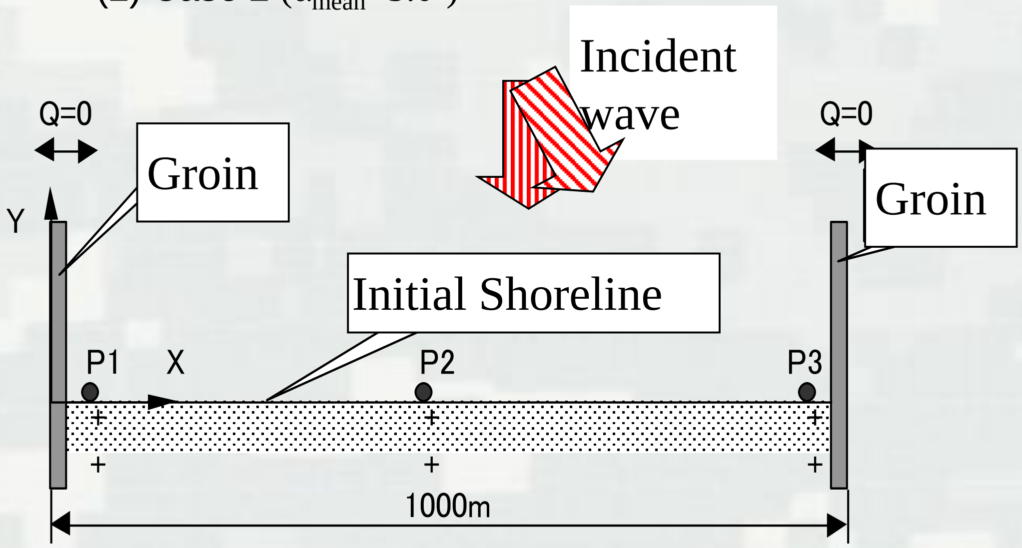
Observation data at Naka Port, Japan, from 1980 to 1996

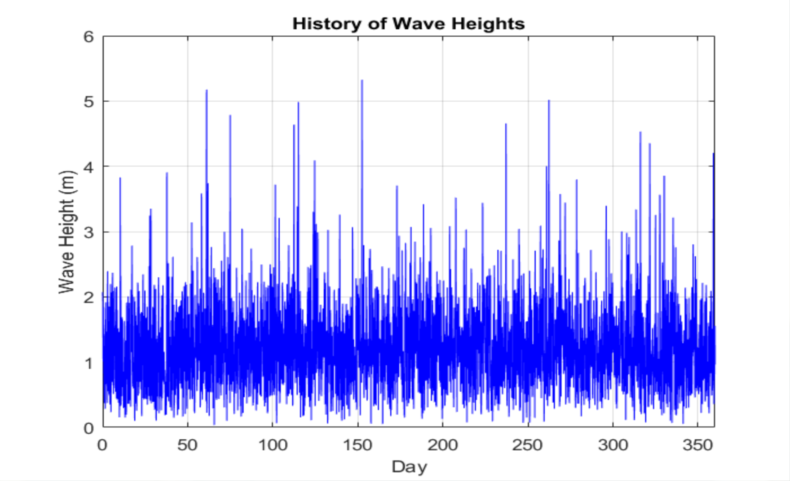
Probabilistic Shoreline Change Modeling in an Idealized Coast: Sensitivity Study

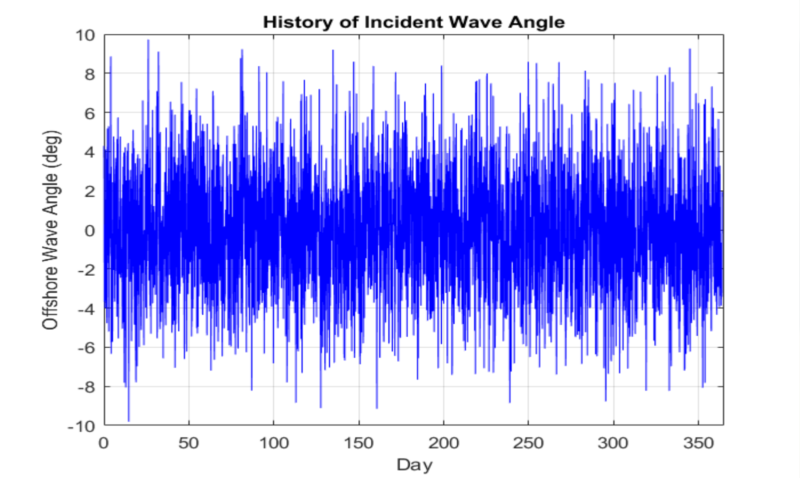
Two Test Cases:

(1) Case 1 (α_{mean}=0.0°)

(2) Case 2 (α_{mean}=5.0°)







- Hmean = 1.19m
- Beach Slope: 1:100
- H_cut = 2.5 m
- Data interval: 3 hours
- Monte-Carlo Simulations: 256

H_cut = 2.5 m

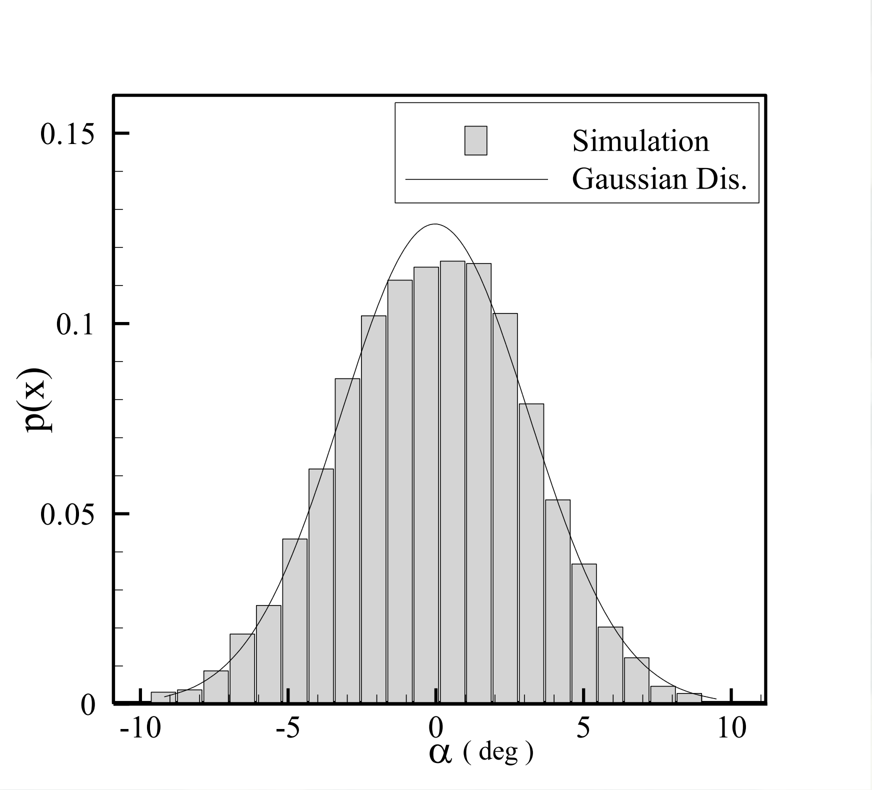
Wave Direction and Period

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

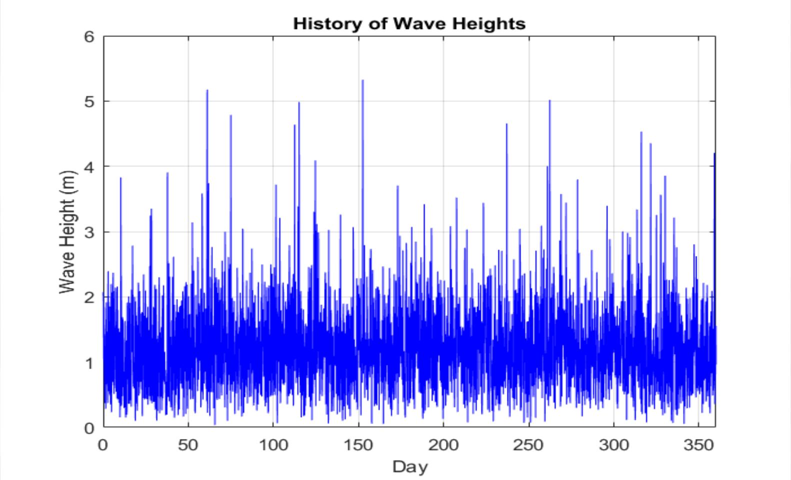
μ : Mean value of direction

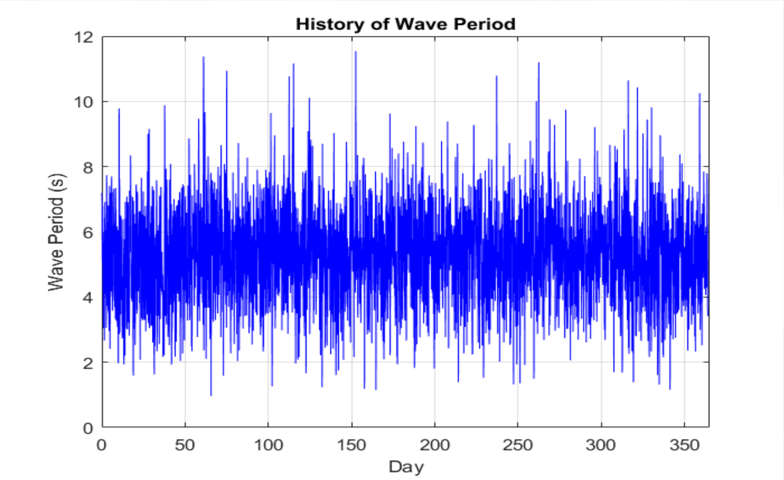


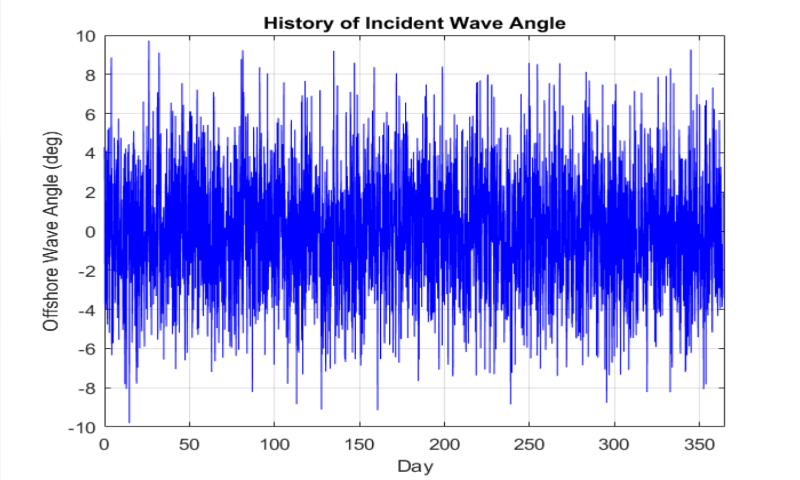
Significant Wave Period: based on Pierson-Moskowitz Spectrum

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

Wave Parameters Generated by Wide Band Spectrum
(Case 1: One Year, 256 Monte Carlo Experiments)





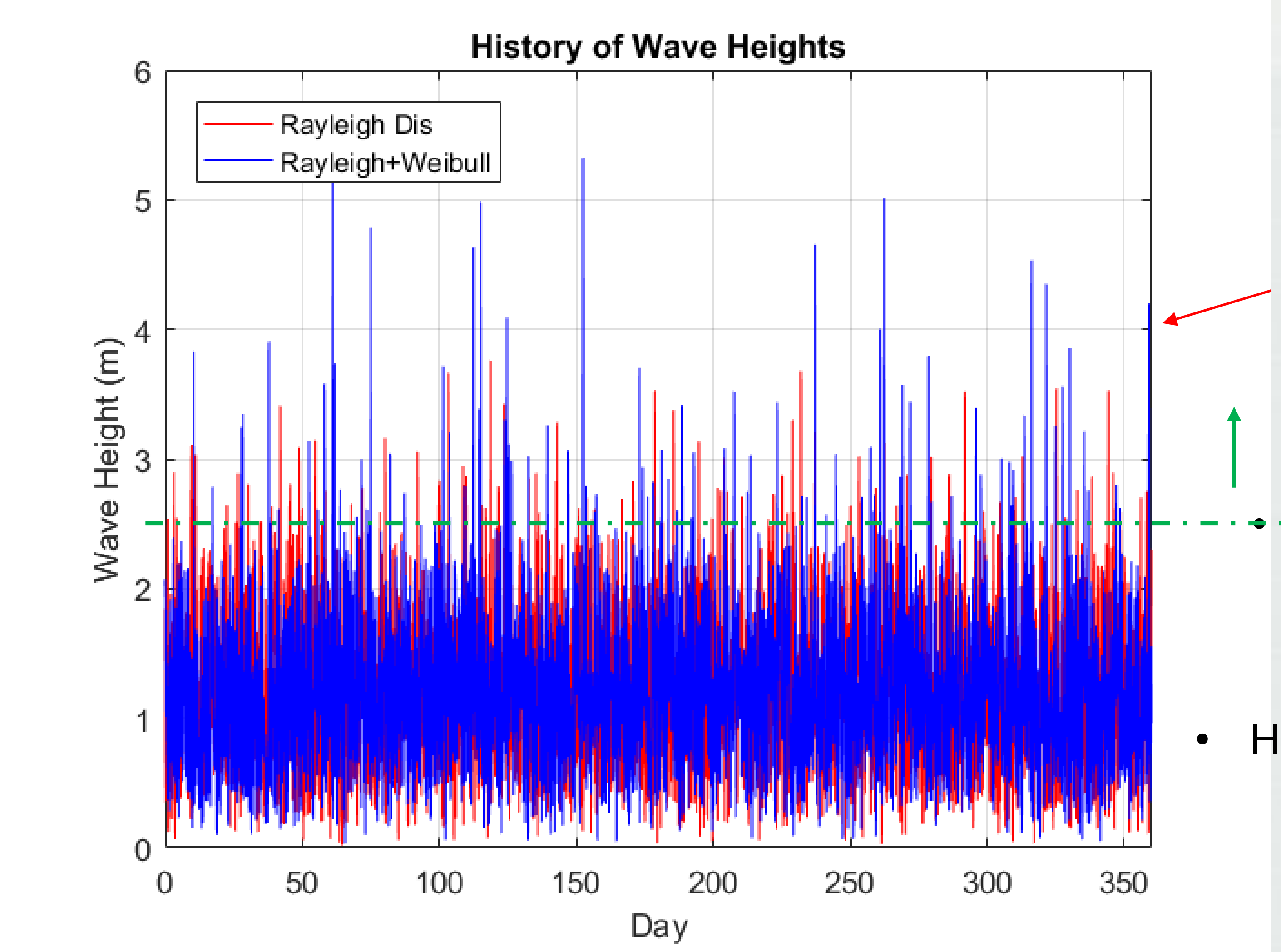


- Hmean = 1.19m
- Mean Angle = 0.0 with σ^2=10
- Data Interval = 3.0 hours

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

H_cut = 2.5 m

Comparison of Wave Heights by Two Wave Spectra



H1 = 4.0m

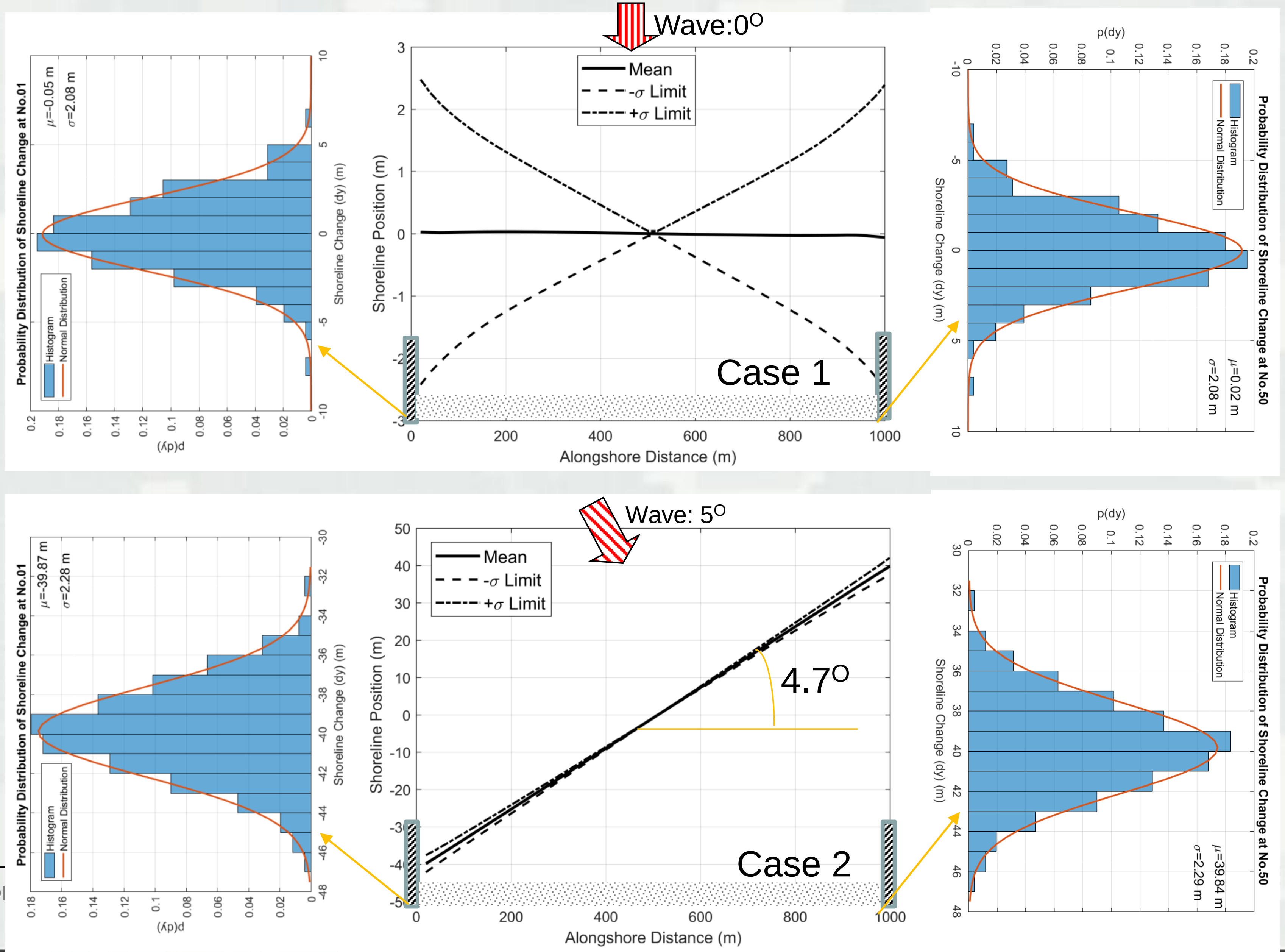
Big waves

- H_cut = 2.5 m

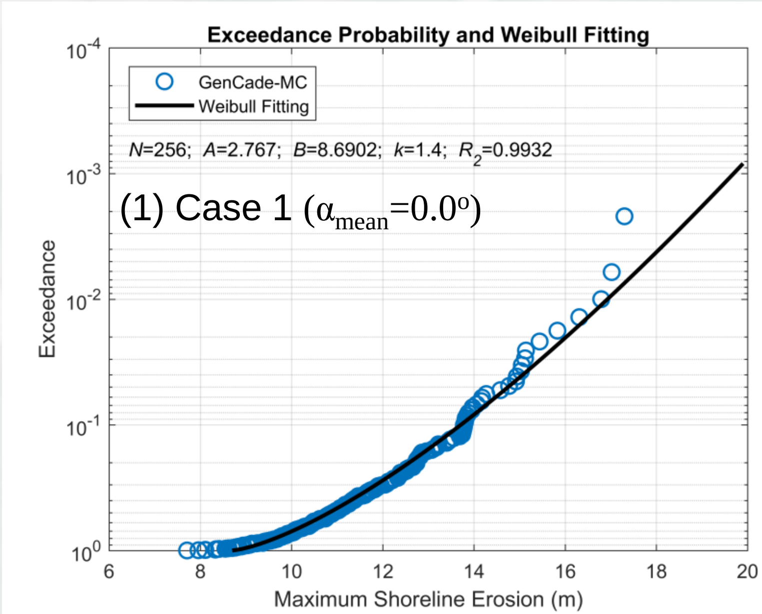
- Hmean = 1.19m

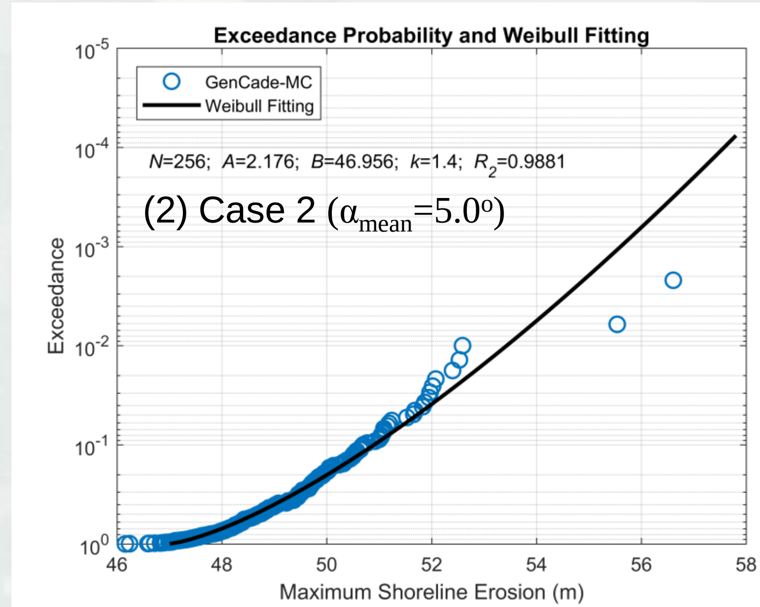
Observation data: 4.0 m wave height for one-year return period

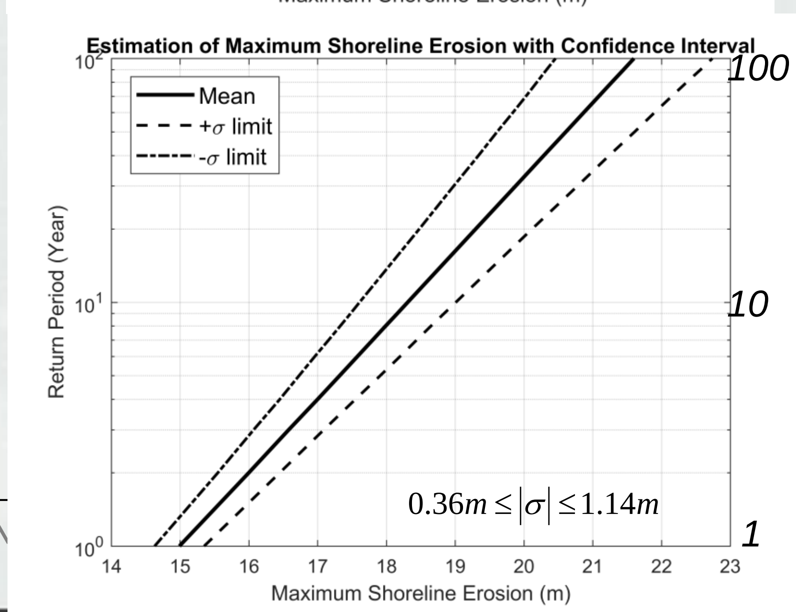
Predictions of Mean Shoreline Changes after 10 Years with Confidence Interval

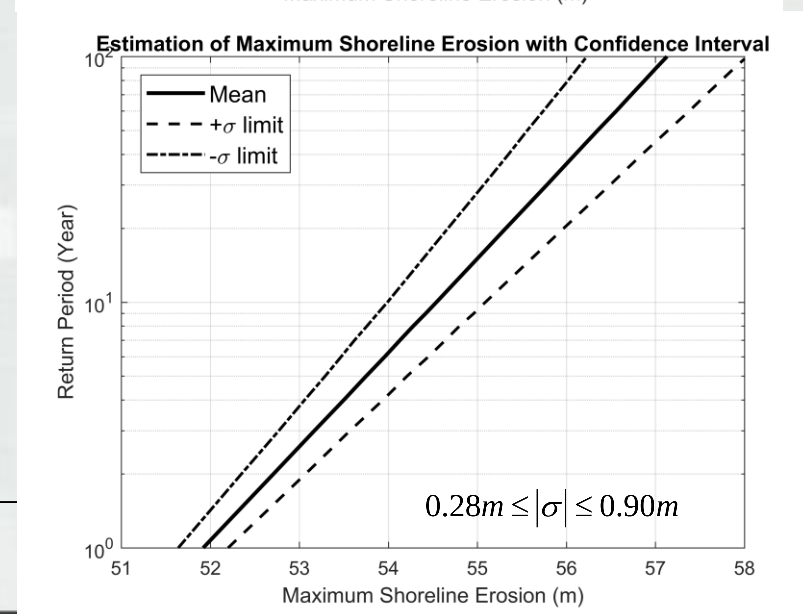


Estimation of Maximum Shoreline Erosion in the Future: Maximum Likelihood Estimation

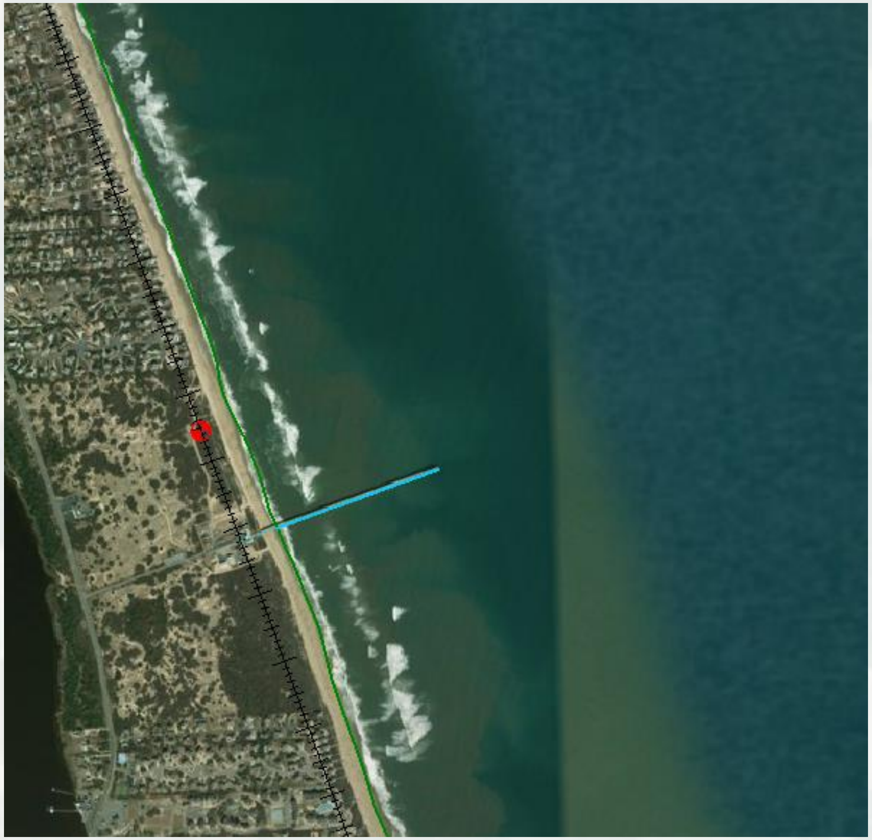








Monte Carlo Simulation of Shoreline Change in Duck, NC



FRF 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

1999/10/23 0:00 - 2005/10/23 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)

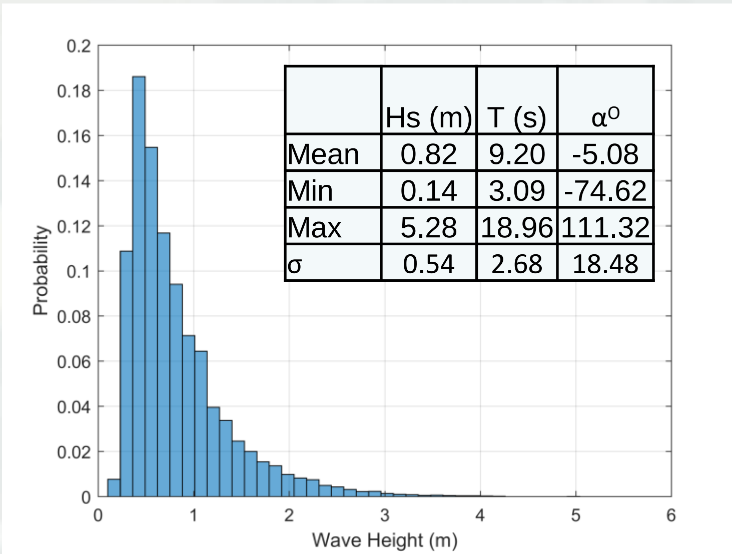
Boundary Conditions: Pined

Grid Size = 20 m

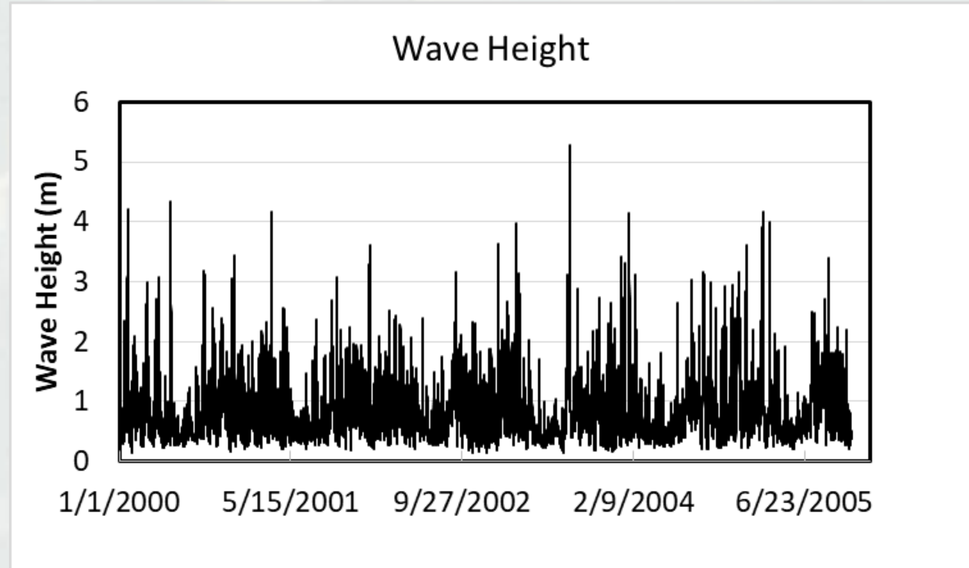
Permeability of Pier = 0.6 (no diffracting)

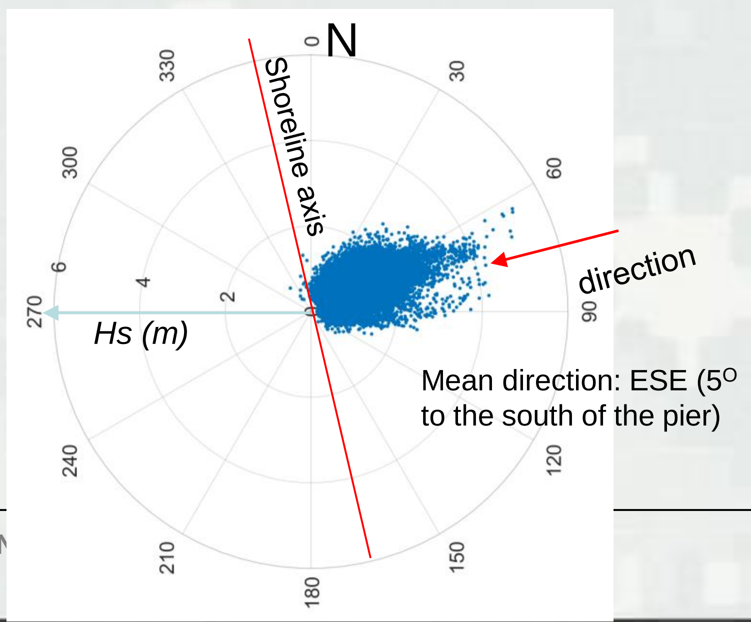
Scaling parameter of cross-shore transport: 0.182

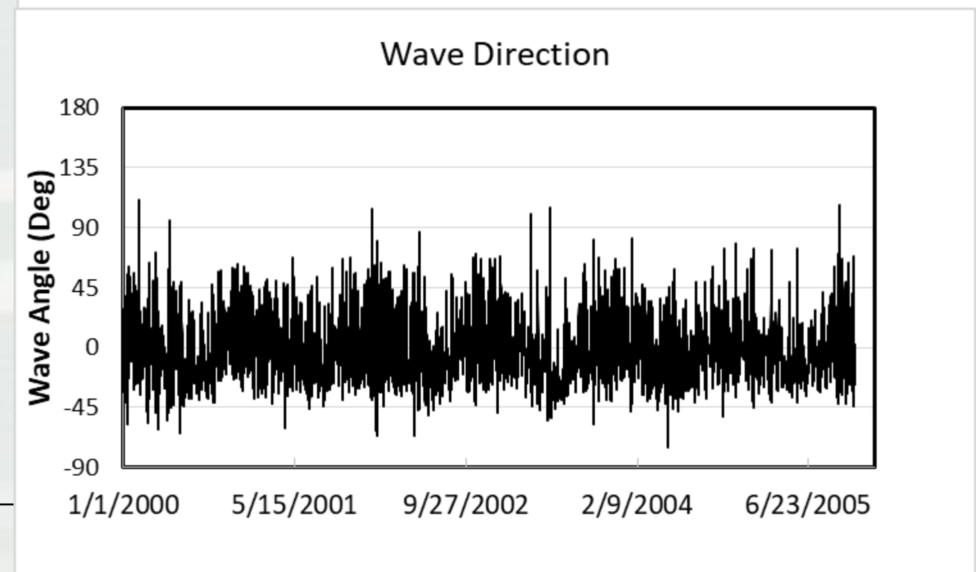
Wave Data (2000/1/1 – 2006/1/1)



	Hs (m)	T (s)	α^{O}
Mean	0.82	9.20	-5.08
Min	0.14	3.09	-74.62
Max	5.28	18.96	111.32
σ	0.54	2.68	18.48

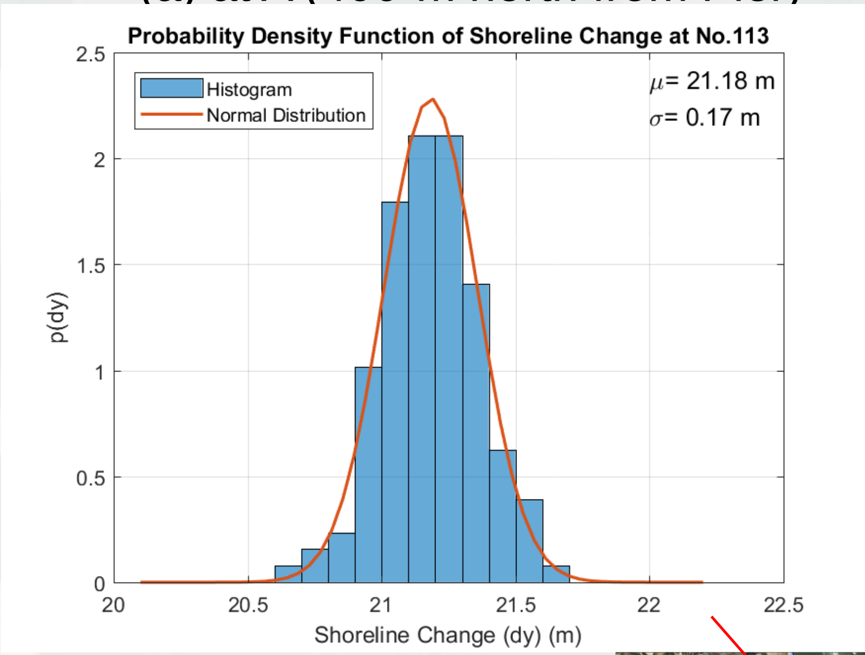




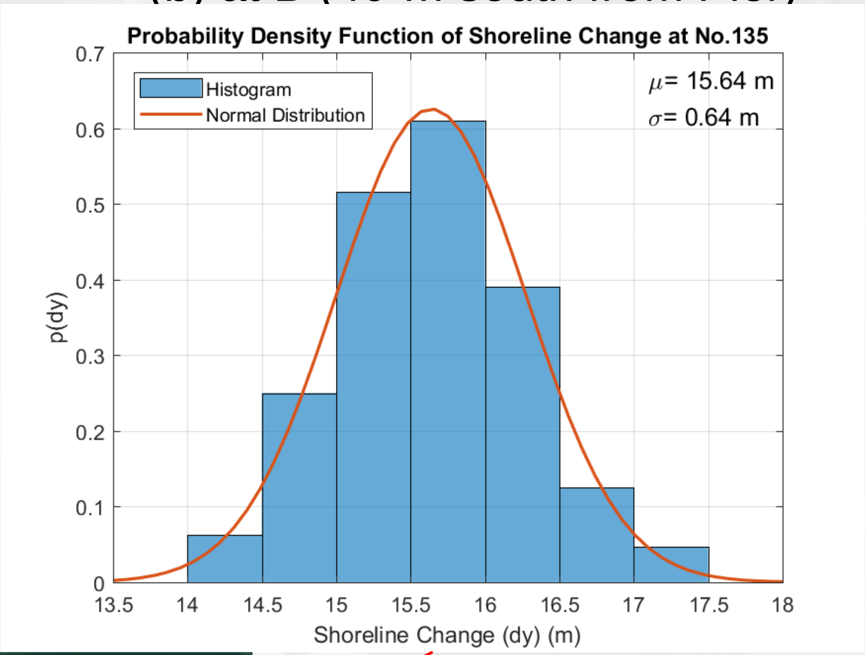


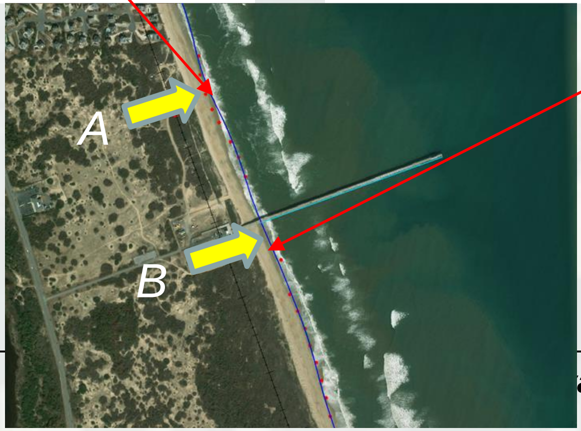
Probability Density Functions: 6-Years Shoreline Change

(a) at A (400-m north from Pier)

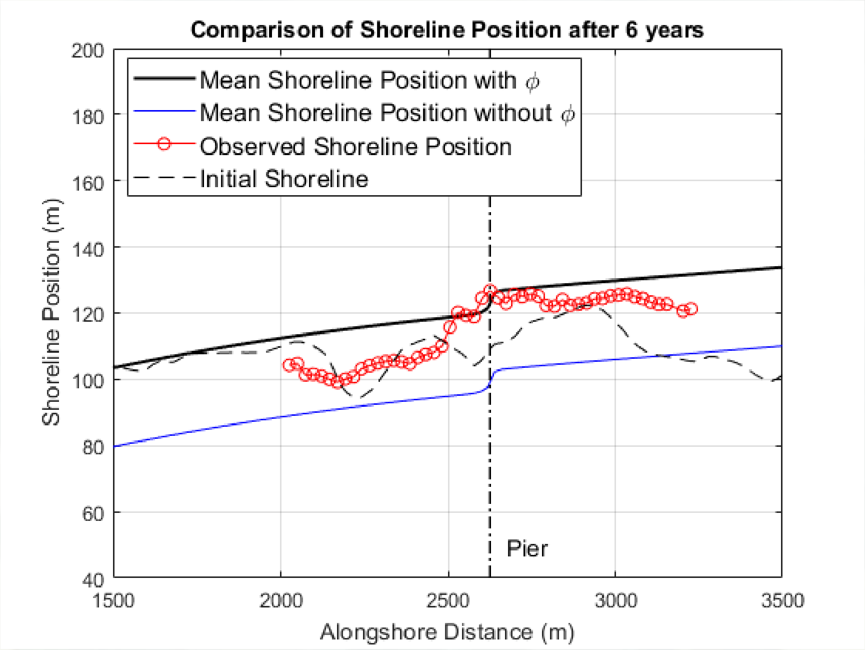


(b) at B (40-m south from Pier)

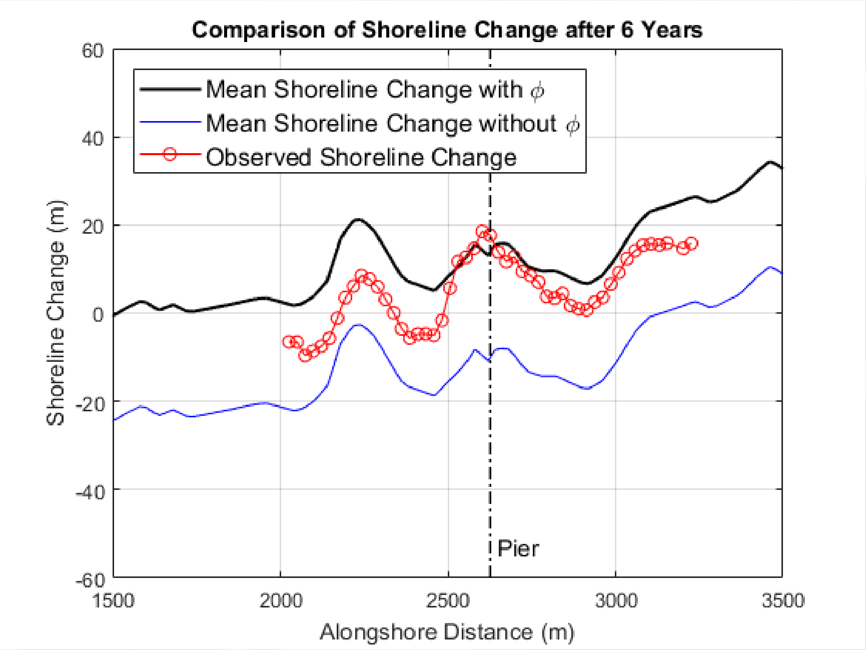




Comparison of Mean Shoreline Position and Changes

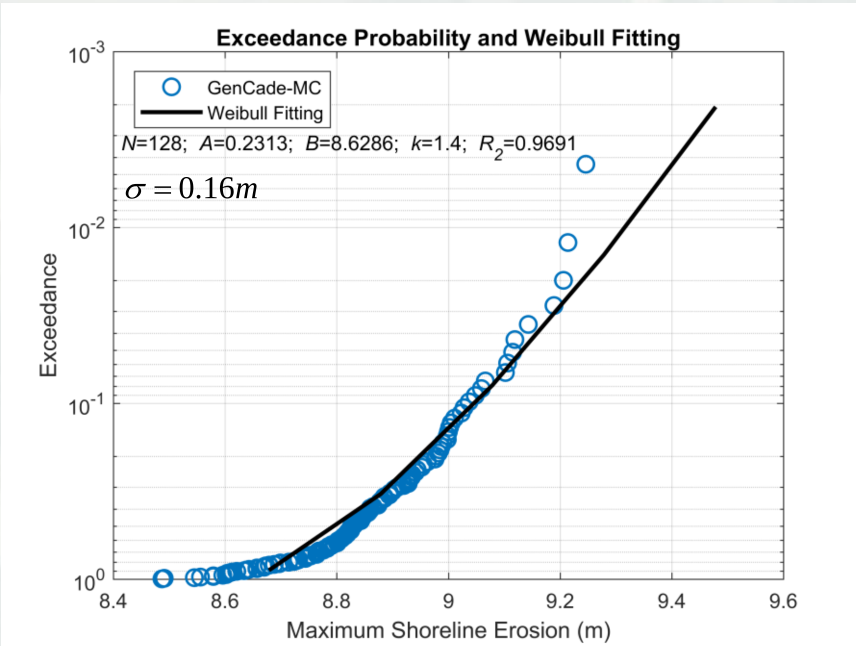


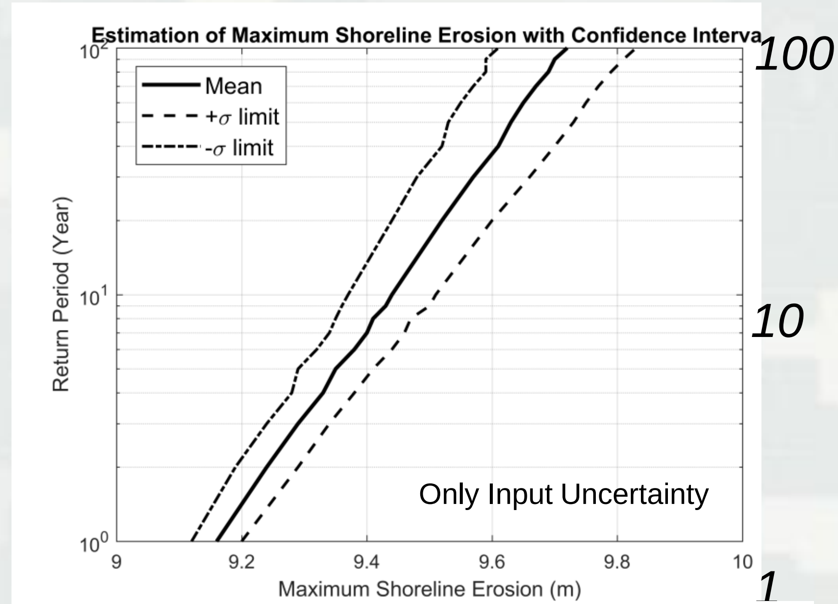
(a) Shoreline Positions on 10/19/2005

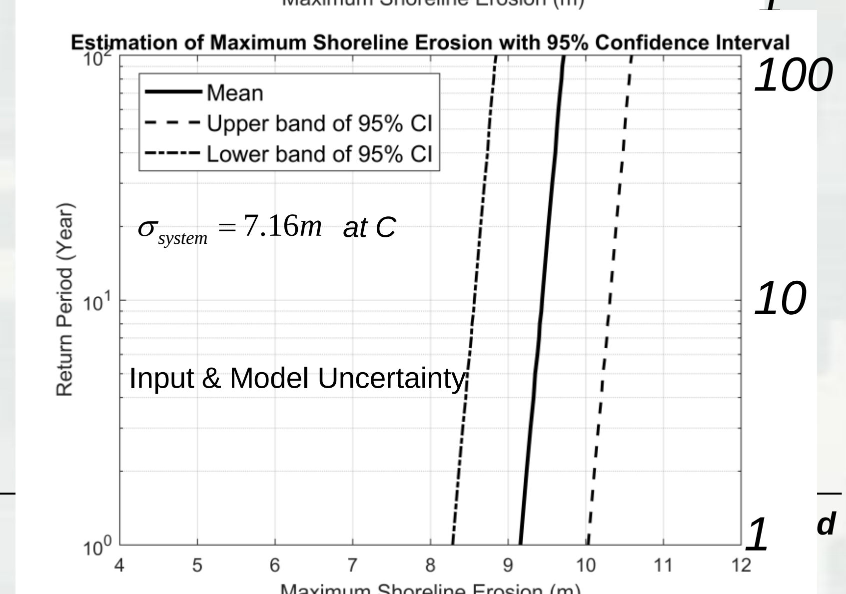


(b) Shoreline Change on 10/19/2005

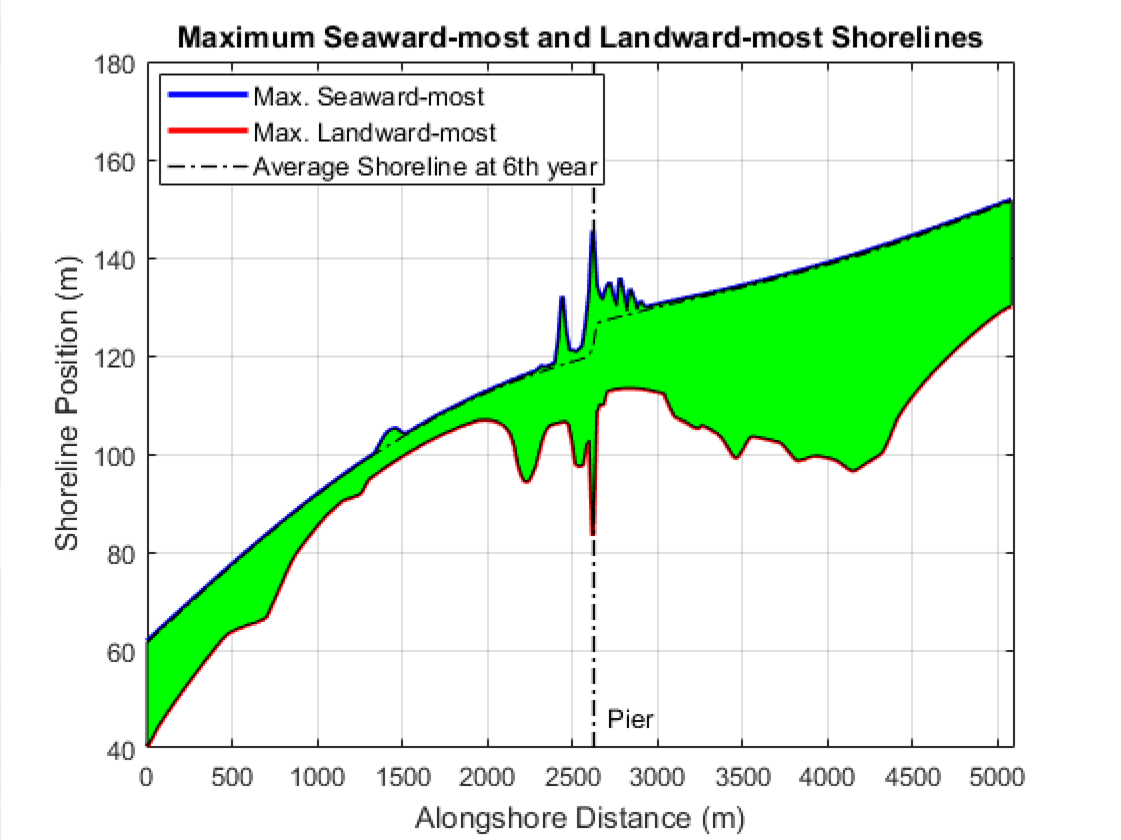
Uncertainty Estimation of Maximum Erosion at Point C







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.

Remarks

- GenCade's new capabilities (Cross-shore sediment transport, SLR effect) are important in simulating shoreline evolution. Nonlinearity of waves plays an important role in driving net cross-shore transport in nearshore zone.
- Inclusion of cross-shore sediment significantly reduced model error (uncertainty)
- GenCade-based Monte-Carlo simulation provides a useful approach to assess uncertainty of shoreline change driven by waves.
- Estimation of extreme shoreline changes provides risk of erosion in a return-interval manner, which is useful for risk/uncertainty-based coast design
- Further investigation of uncertainties by other factors (model parameters, boundary conditions, etc) is needed.

References

- Abreu, T., Silva, P.A., Sancho, F. and Temperville, A., (2010). Analytical approximate wave form for asymmetric waves. Coastal Engineering, 57(7), pp. 656-667
- Bruun, P., (1962). Sea-level rise as a cause of shore erosion. J. Waterway. Harbours Div. 88: 117–130.
- Birkemeier, W. A. and Thornton, E. B., (1994), The DUCK94 Nearshore Field Experiment, Proceedings of the Conference on Coastal Dynamics '94, 815-821.
- Fernández-Mora, A., Calvete, D., Falqués, A., and de Swart, H. E., (2015). Onshore sandbar migration in the surf zone: New insights into the wave-induced sediment transport mechanisms. Geo. Phys. Res. Ltrs., 10.1002/2014GL063004, 2869-2877.
- FRF (2019). FRF 8m Linear Array Directional Waves, http://www.frf.usace.army.mil/dksrv/dk94/frf/FRF8m.html, accessed on Jan. 22, 2019.
- Rosati, J.D., Dean, R.G., and Walton, T.L. (2013). The modified Bruun rule extended for landward transport, Mar. Geol. 340, 71-81.
- Ruessink, B. G., Ramaekers, G., and van Rijn, L. C., (2012). On the parameterization of the free-stream non-linear wave orbital motion in nearshore morphodynamic models. Coastal Engineering, 65(7), pp. 56-63.
- Thornton, E., Humiston, R., Birkemeier, W., (1996). Bar-trough generation on a natural beach. J. Geophys. Res 101, 12097–12110.

Recent Publications on GenCade

- Frey, A. E., Connell, K. J., Hanson, H., Larson, M., Thomas, R. C., Munger, S., Zundel, A., (2012) *GenCade version 1 Model theory and user's guide*. US Army, Engineer Research and Development Center, ERDC/CHL TR-12-25, 169 pp.
- Ding, Yan, Kim, Sung-Chan, and Frey, Ashley, (2018). Probabilistic Shoreline Evolution Modeling in Response to Sea Level Changes, In Proceedings of the ASCE-EWRI 2018 Congress, June 3-7, 2018, Minneapolis, NM, 13p. (https://doi.org/10.1061/9780784481424.021)
- Ding, Y., Kim, S.-C., Frey, A.E., Permenter, R. L., and Styles, R. (2018). Probabilistic modeling of long-term shoreline changes in response to sea level rise and waves, In: Scour and Erosion IX: Proceedings of the 9th International Conference on Scour and Erosion, K.-C. Yeh Ed., pp203-211, Taylor & Francis Group, London, ISBN 978-0-367-07467-8
- Ding, Y., R. Styles, S.C. Kim, R. Permenter and A. Frey, (2019). Cross-shore transport feature for GenCade. ERDC/CHL CHETN-IV-??. Vicksburg, MS: US Army Engineer Research and Development Center (under review).
- Ding, Y., Kim, S.-C., Permenter, R.L., Styles, R., and Beck, T.M. (2019). Cross-shore sediment transport for modeling long-term shoreline changes in response to waves and sea level changes, In: Proceedings of Coastal Sediment 2019.
- 3Kimberly Townsend, Robert Thomas, Ashley Frey, David King, Julie Rosati, Sung-Chan Kim, Richard Styles, Yan Ding, and Rusty Permenter, 2018. Comparison of GenCade, Pelnard-Considere, and LITPACK. ERDC/CHL CHETN-IV-??. Vicksburg, MS: US Army Engineer Research and Development Center. (Under Review)

Thank you for your attention!

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