Probabilistic Modeling of Long-Term Shoreline Changes in Response to Sea Level Rise and Waves

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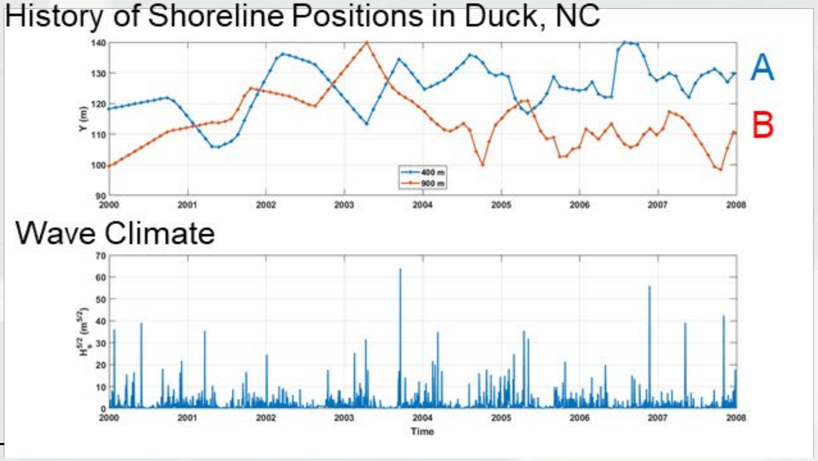
Outline

- Introduction: Sea Level Rise Impact on Shoreline Evolution
- Shoreline Evolution Model for Sea Level Change Impact
- Monte-Carlo Simulation for Risk Estimation of Shoreline Erosion
- Model Validation by Simulating Shoreline Changes in Duck, NC
- Probabilistic Shoreline Change Modeling for Duck coast
- Remarks

Long-Term Shoreline Changes

- Multiple physical processes drive shoreline changes: wave, wind, tide, storm, current, **sea level change/sunsidence**, 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.



Global Mean Sea-Level Trend (IPCC)

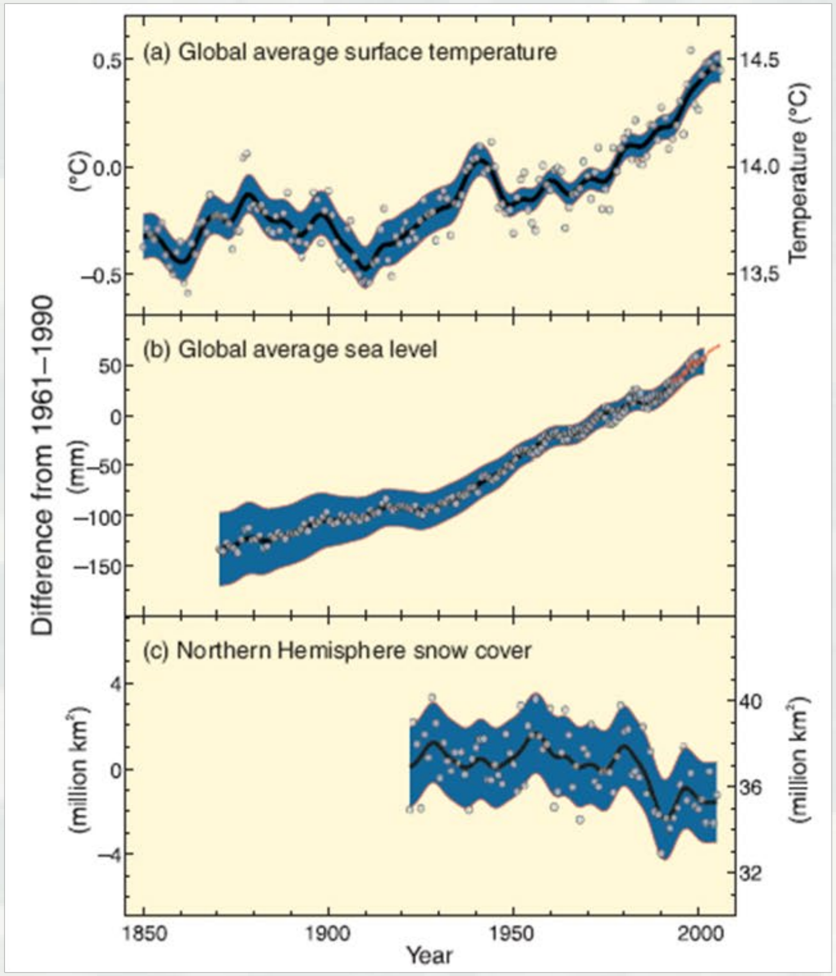
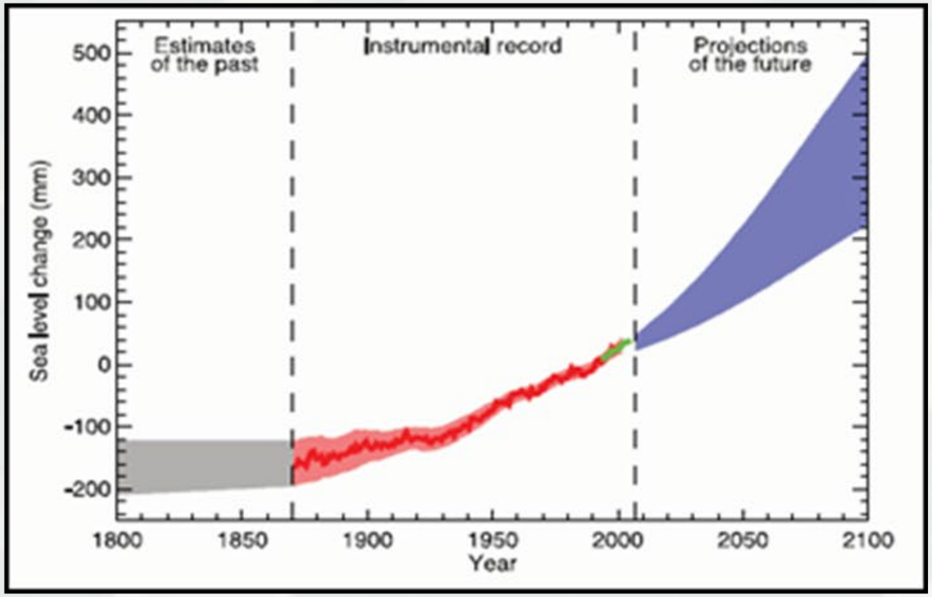


Fig. Observed changes in (a) **global average surface temperature**; (b) **global average sea level from tide gauge** (blue) **and satellite** (red) **data**; and (c) **Northern Hemisphere snow cover for Mar.-Apr.**



Global Mean Sea Level (IPCC AR4)

- 1.0-2.0 mm/year during the 20th century
- Rate=0.1 to 0.2 mm/year over 3,000 years
- 120m GMSL Rise from 20, 00 years ago

Global Mean Sea Level Trend (AR5)

- 40~ 60 cm by 2100 (IPCC, 2013)

Projected Global Mean Sea Level Change

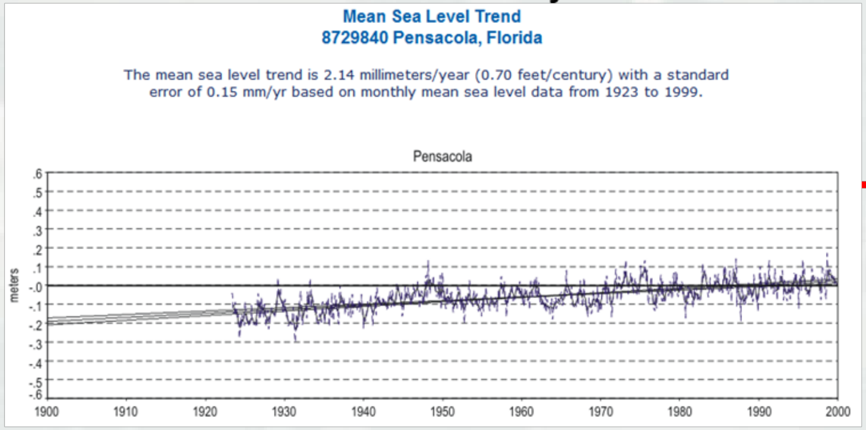
– IPCC Representative Concentration Pathways (RCP) scenarios

Scenario	Radiative forcing in year 2100 relative to 1750 (W/m^2)	Approximate carbon dioxide (CO_2)-equivalent concentration (ppm)	Median value and likely range of temperature change (°C)	Median value and likely range of sea-level rise (m)
RCP2.6	2.6	475	1.0 [0.3–1.7]	0.40 [0.26–0.55]
RCP4.5	4.5	630	1.8 [1.1–2.6]	0.47 [0.32–0.63]
RCP6.0	6.0	800	2.2 [1.4–3.1]	0.48 [0.33–0.63]
RCP8.5	8.5	1,313	3.7 [2.6–4.8]	0.63 [0.45–0.82]

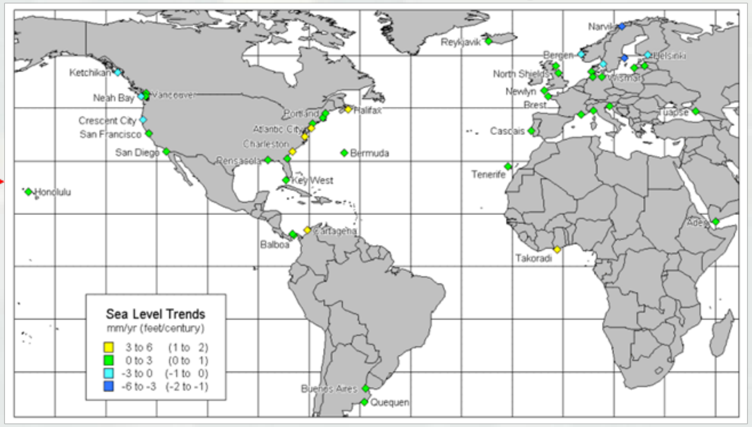
Projected global surface warming and sea-level rise for the late twenty-first century (2081–2100) relative to the reference period of 1986–2005 by the IPCC AR5 (IPCC 2013)

Long-term Variations in Local Sea Level

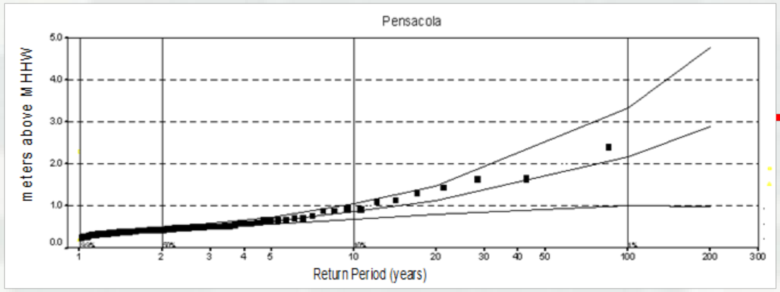
NWLON Station Analyses



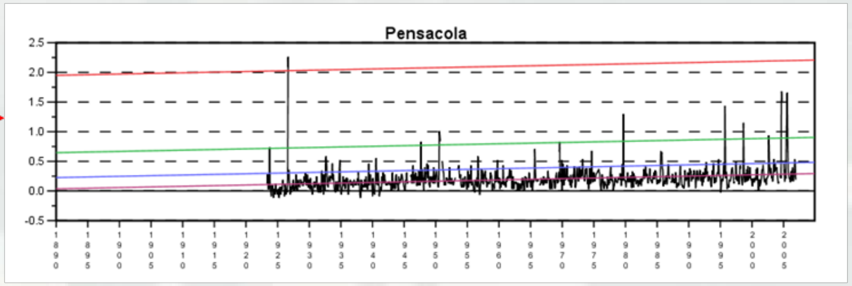
New Global Station Analyses



Exceedance Probability Analyses and the 100-year Event :*



Annual Exceedance Probability Curves



1%, 10%, 50%, 99% Exceedance Probability Levels

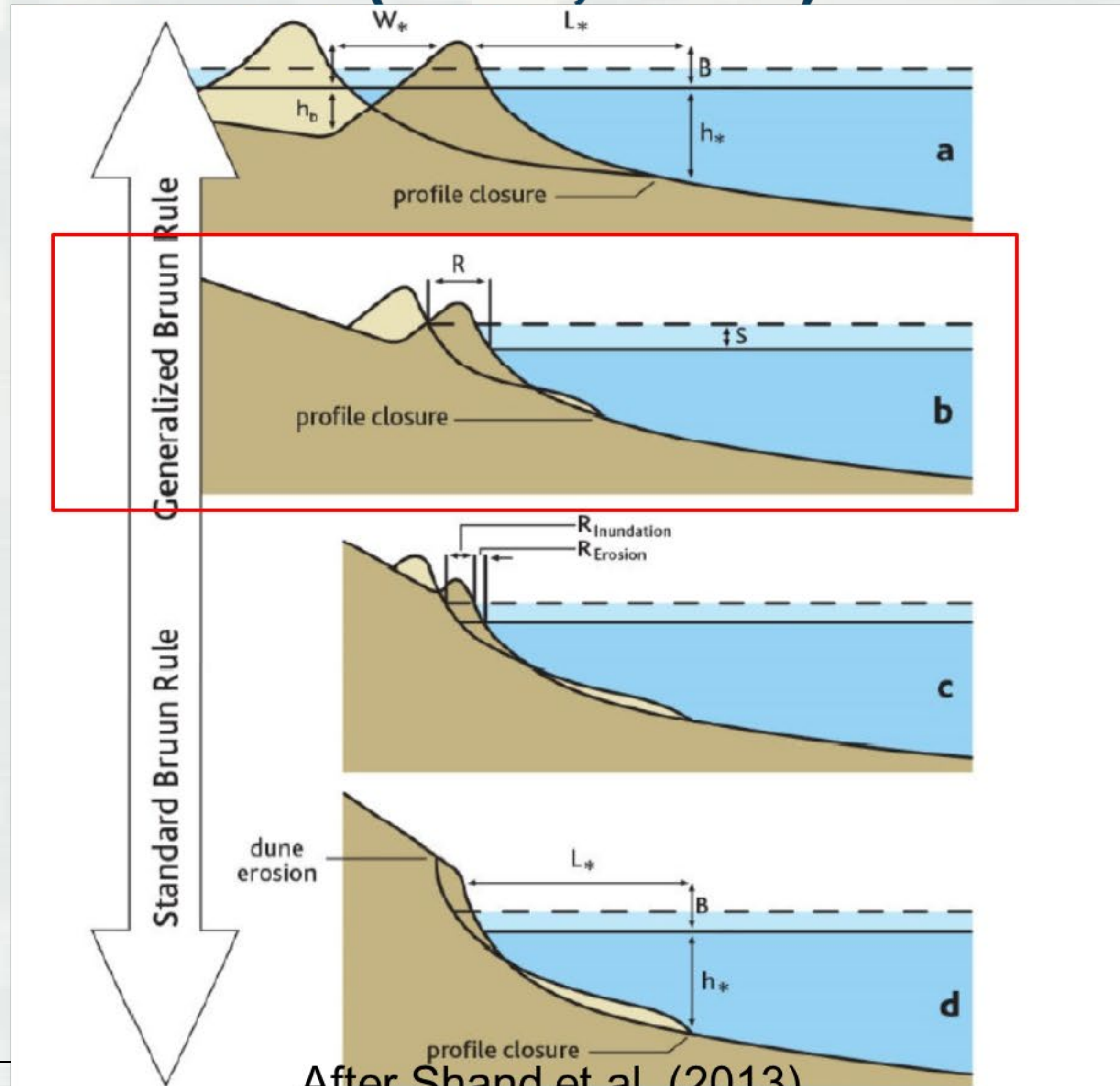
http://www.tidesandcurrents.noaa.gov/sltrends.html

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

Shoreline Retreat rate

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

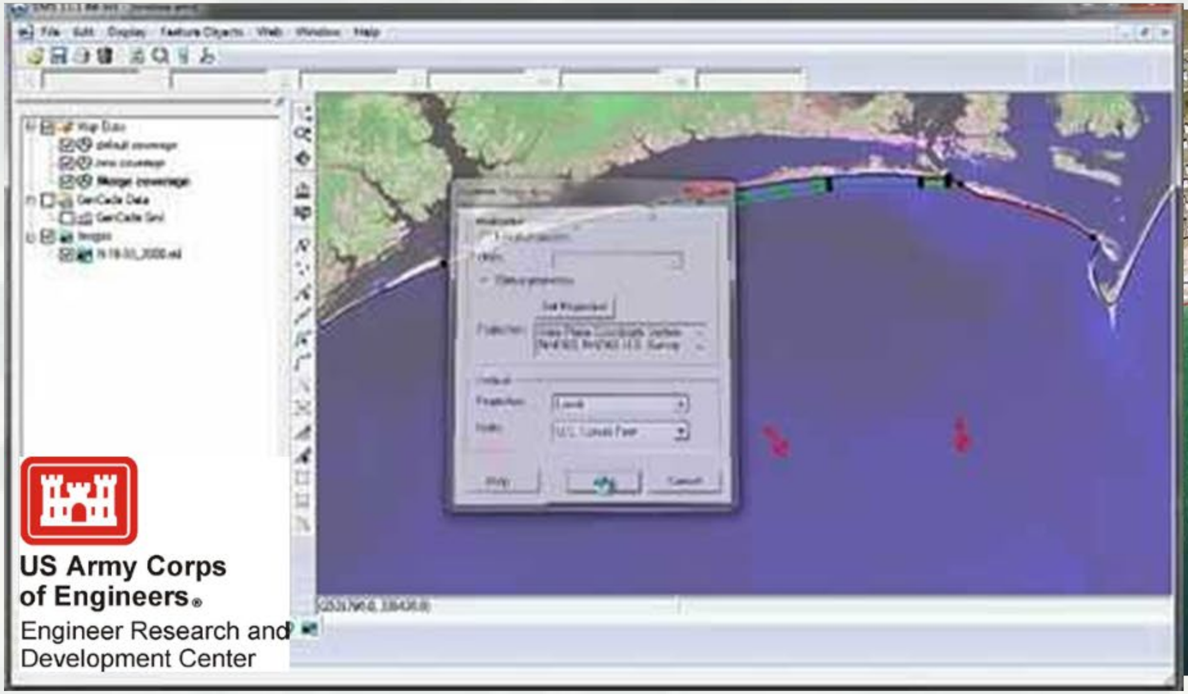
S: Sea level rise rate
h* = sediment closure depth
B = Berm Height

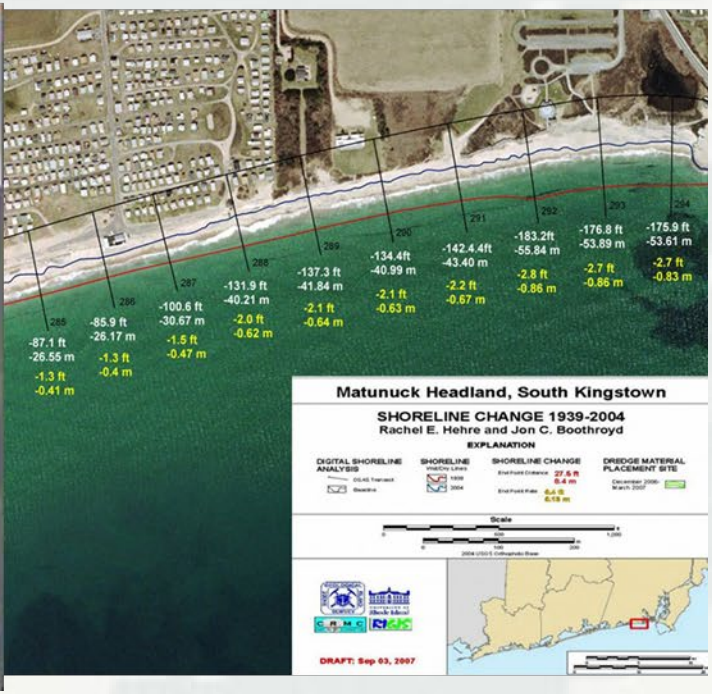


After Shand et al. (2013)

GenCade

The GenCade (Frey et al. 2012) is a shoreline evolution model (a one-line model), using a alongshore sediment transport model to simulate shoreline changes driven by offshore wave climate. The SMS (Surfacewater Modeling System) provides a user-interface for GenCade, including data input and visualization





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GenCade Shoreline Evolution Model with SLR and Cross-Shore Transport

- Shoreline Change Equation with SLR

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

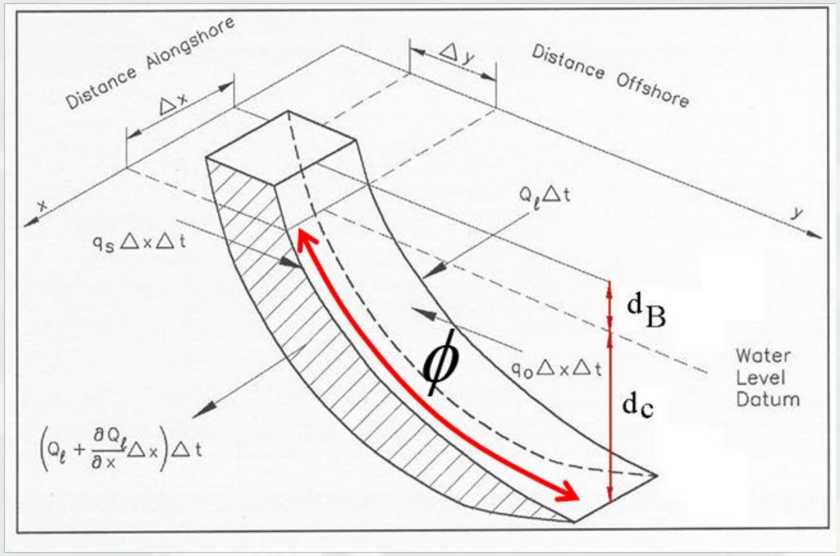
ϕ : Cross-shore sediment transport rate

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

$(\frac{\Delta Z}{\Delta t})_{subsidence}$: Sea Level Change Rate

$tan\beta$: beach slope

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



- Berm height varies with sea level change

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

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*

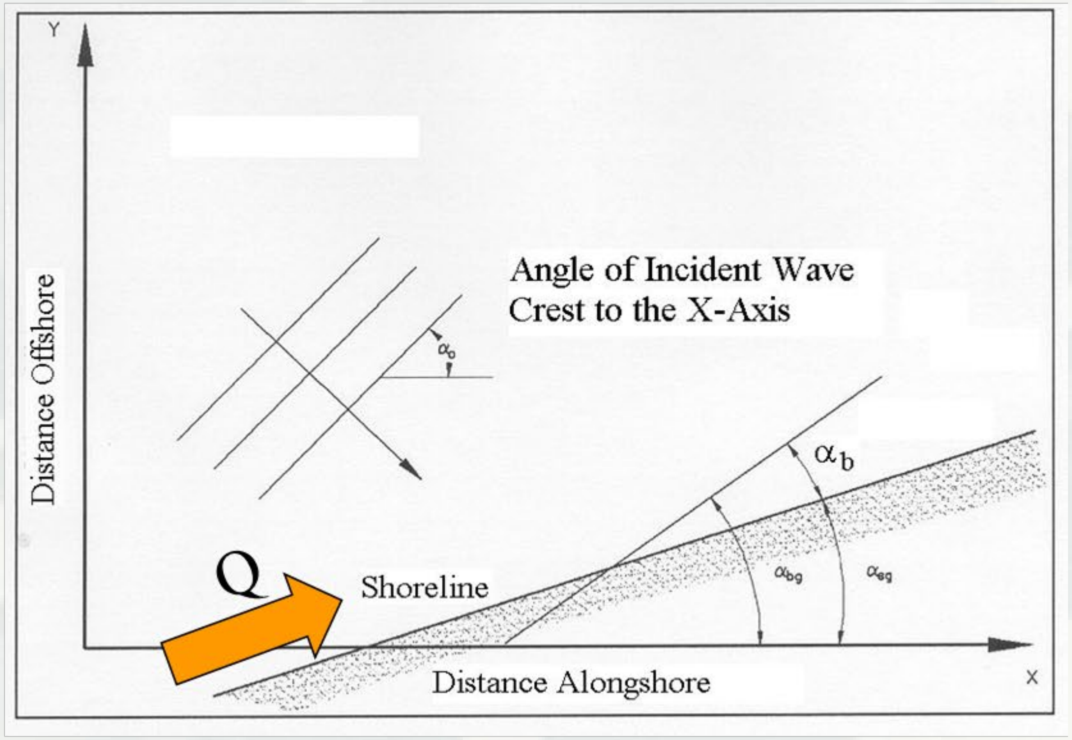
C_{gb} : *Group speed at breaker line*

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

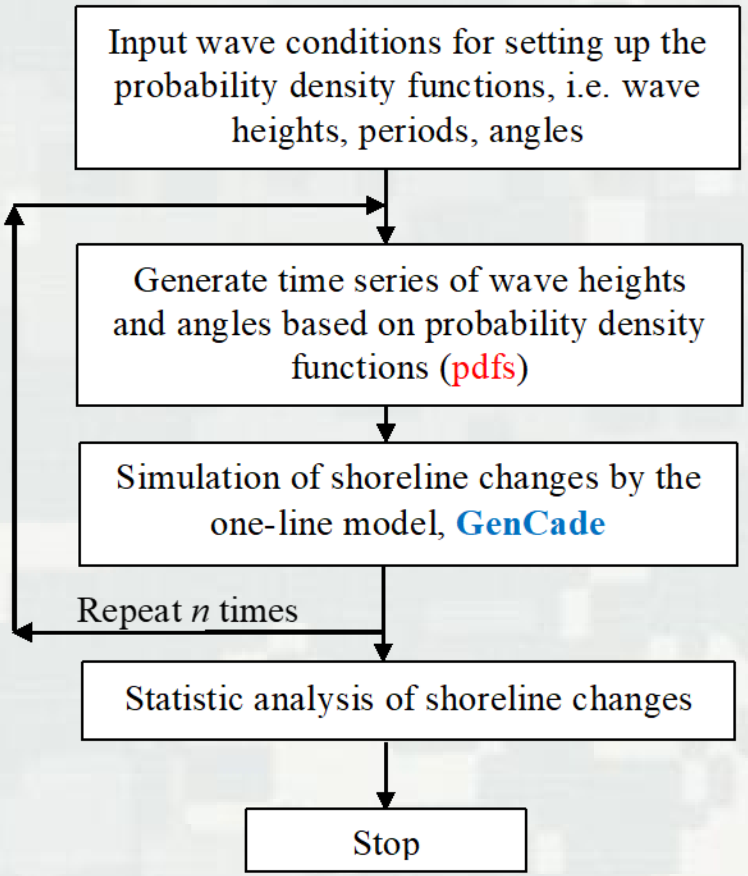
$$a_2 = \frac{K_2}{8(s-1)(1-p)\tan\beta 1.416^{2.5}}$$

K_1, K_2=*empirical coefficients*

Typically, $0.5K_1 < K_2 < 1.5K_1$



Flow chart of shoreline change simulation by Monte Carlo Method

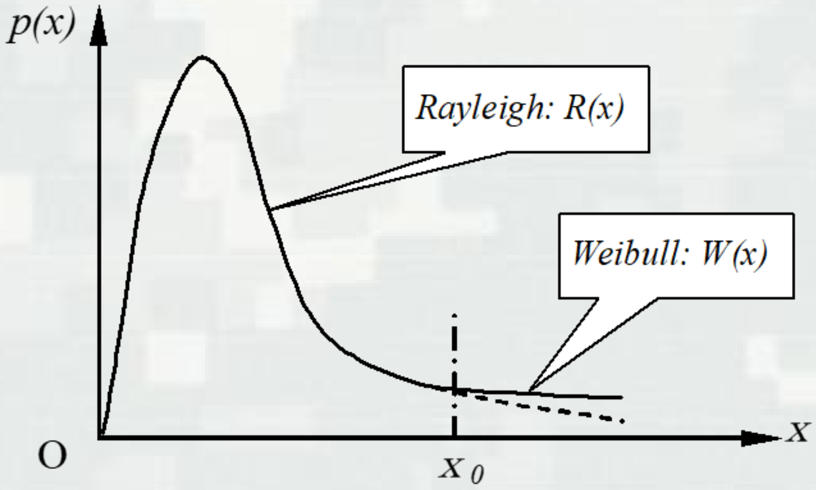


Probabilistic Distribution of Wave Height

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

ε: parameter

x_0: a truncated extreme value of wave height



Rayleigh Distribution (for normal waves) :

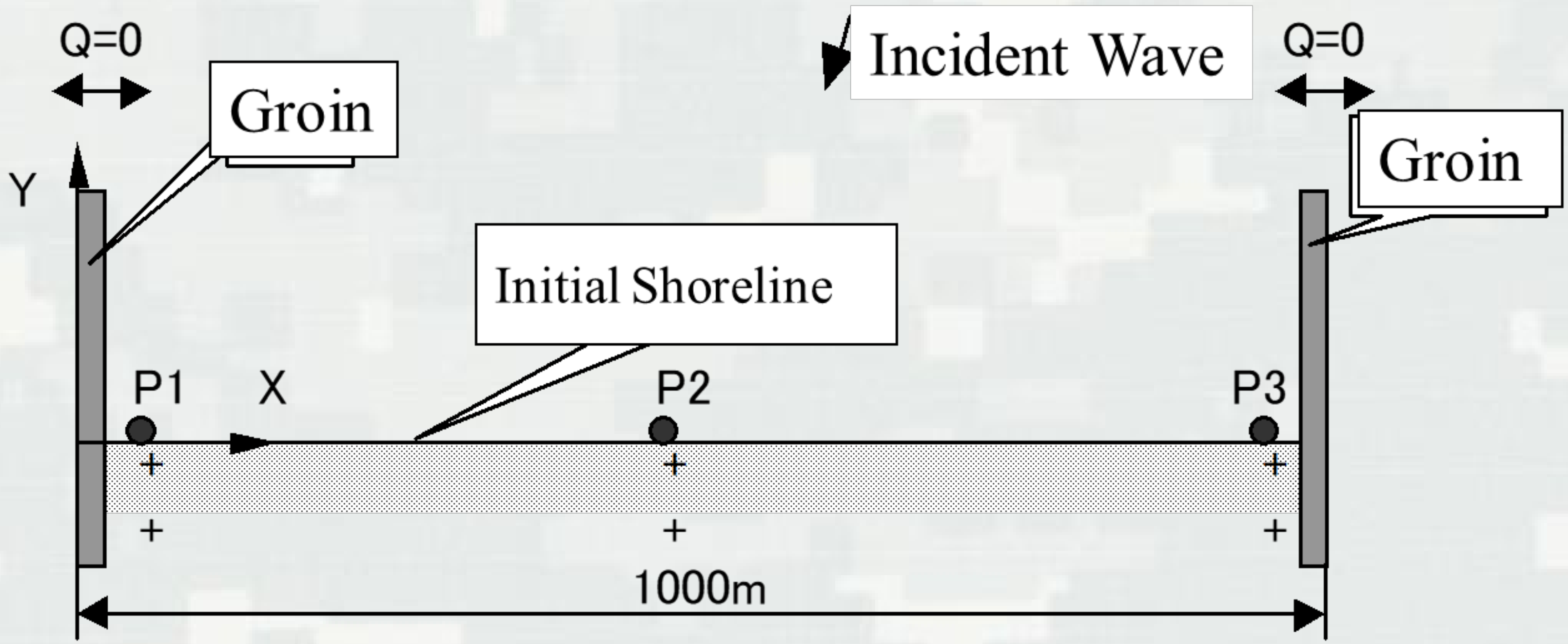
$$R(x) = -\frac{\pi}{2} x \exp\left(-\frac{\pi}{4} x^2\right)$$

Weibull Distribution (for extreme waves):

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

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

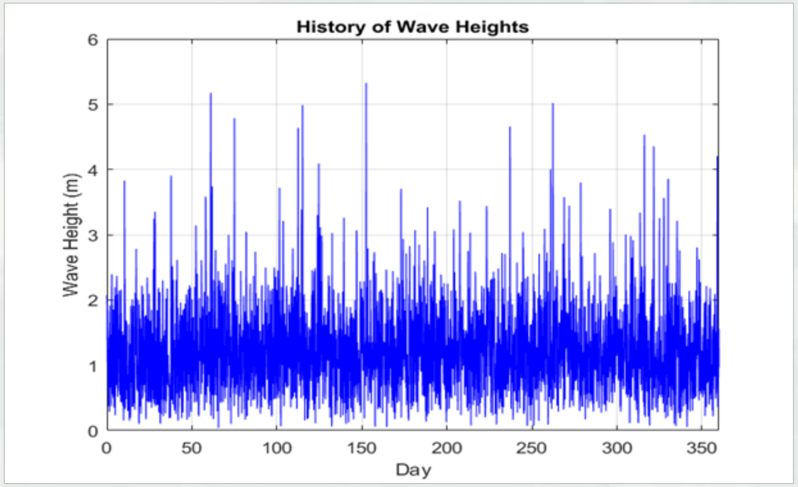
Test Cases for Model Sensitivity

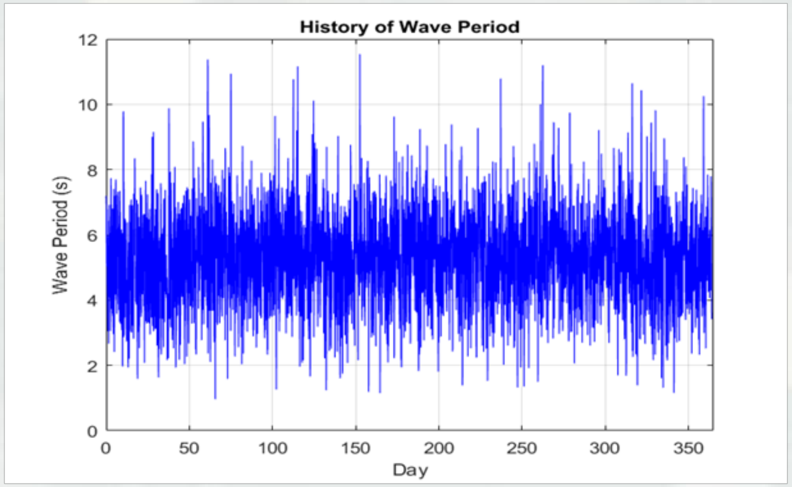


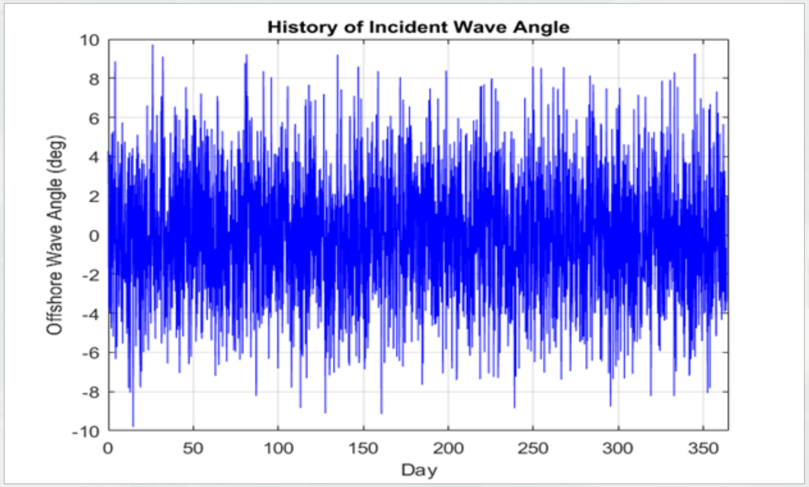
Inputs:

- Wave height, period, and direction
- SLR scenarios: IPCC AR5 (IPCC 2013)
- Subsidence: Florida Coast
- Onshore Sediment Transport: Florida Coast
- Beach Slope: 1:100

Wave Parameters
- Mean Wave Direction is at shore normal direction







- 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

Computational Conditions for sea level rise, subsidence, and onshore transport

Case No.	Climate Change Scenarios*	IPCC Global SLR (m) (2015-2065)	SLR Rate (mm/year)	Subsidence** (mm/year)	Onshore Sedtran*** (m^3/(m-year)
SLR0		0.0	0.0	0.0	0.0
SLR1	RCP 2.6	0.23 ± 0.05	4.6	0.5	3.1
SLR2	RCP 4.5	0.26 ± 0.05	5.2	0.5	3.1
SLR3	RCP 6.0	0.24 ± 0.05	4.8	0.5	3.1
SLR4	RCP 8.5	0.32±0.05	6.4	0.5	3.1

*IPCC Representative Concentration Pathways (RCP) scenarios: IPCC AR5 report (IPCC 2013)
** a typical subsidence in the Florida southwest coast (Houston 2015)
*** An average onshore transport rate, 3.1 m^3/(m-year), was given based on Dean and Houston (2016)

Annual shoreline changes if no wave action

Case No	By Sea Level Rise * (m)	By Subsidence (m)	By Onshore Transport (m)	Total Change (m)
SLR1	-0.460	-0.050	0.282	-0.228
SLR2	-0.520	-0.050	0.282	-0.288
SLR3	-0.480	-0.050	0.282	-0.248
SLR4	-0.640	-0.050	0.282	-0.408

Shoreline Change due to SLR : $\left((\frac{\Delta Z}{\Delta t})_{SLR} \right) \frac{1}{\tan \beta}$

Shoreline Change due to subsidence : $\left((\frac{\Delta Z}{\Delta t})_{Subsidence} \right) \frac{1}{\tan \beta}$

Shoreline Change due to Onshore transport : $\frac{\phi}{(d_c + d_b)}$

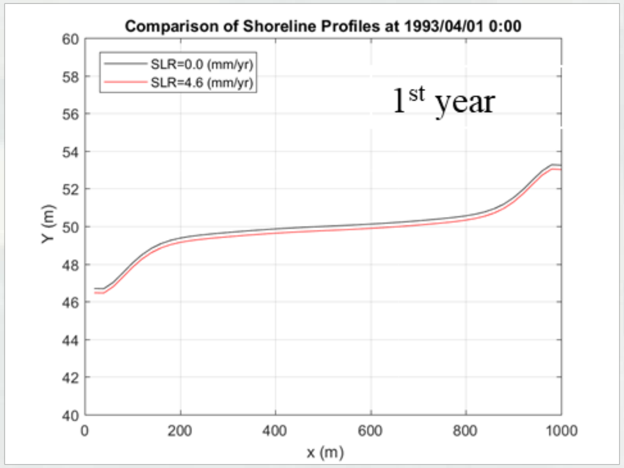
Slope = 1:100

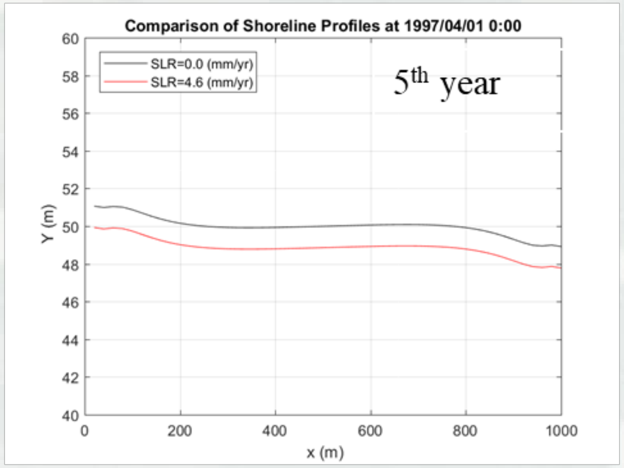
d_c=10m

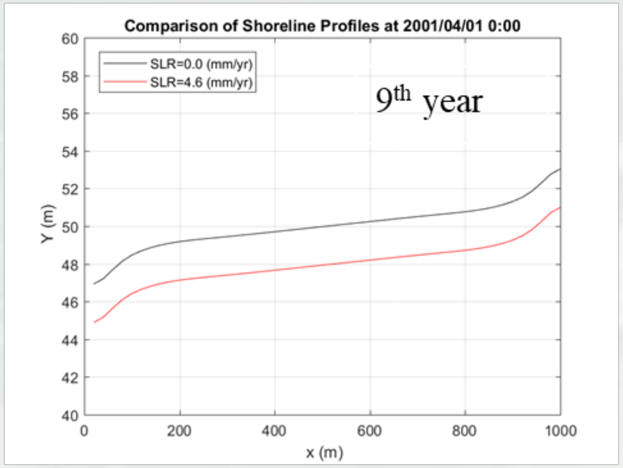
d_b=1.0 m

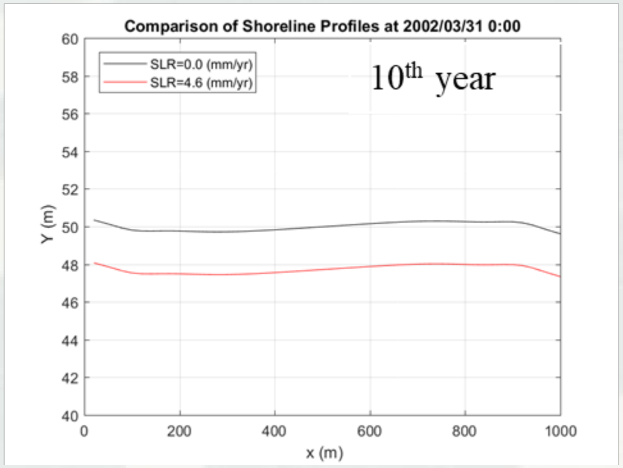
History of Shoreline Profiles without SLR (=0)

Shoreline Profiles (SLR0 vs SLR1)

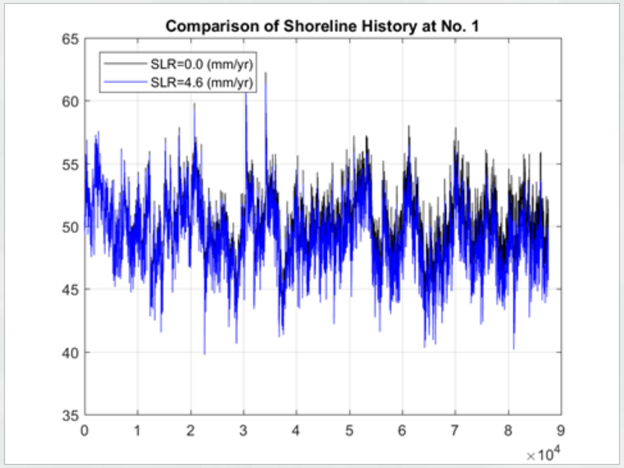


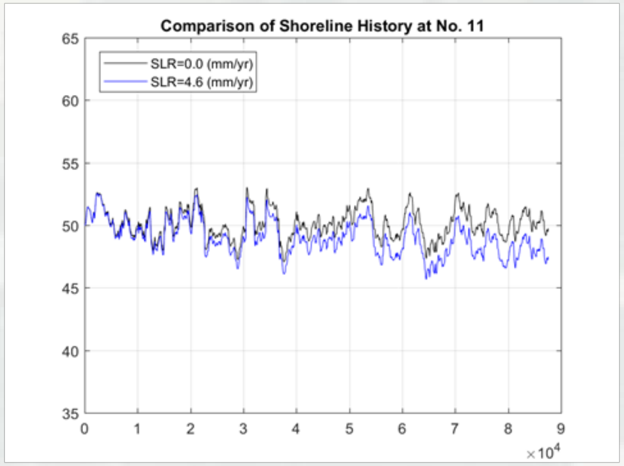


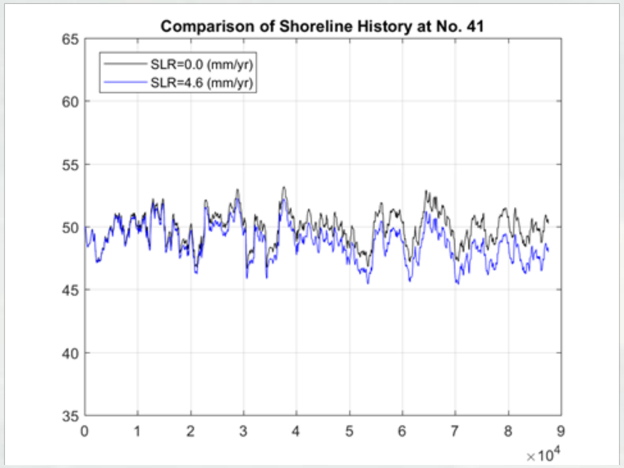


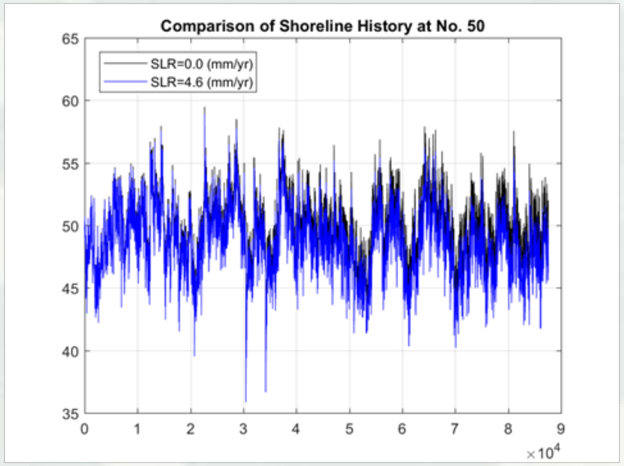


History of Shoreline Position (SLR0 vs SL1)

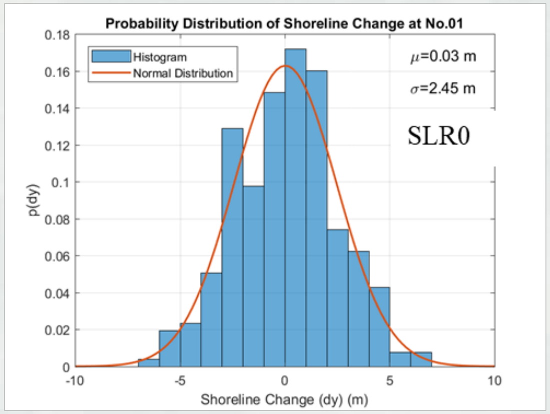


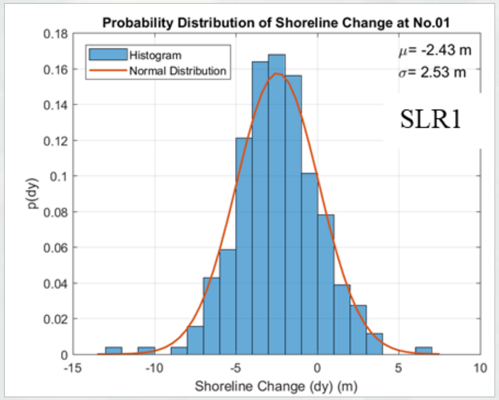


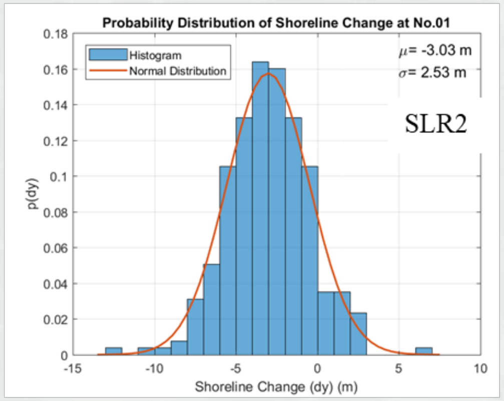


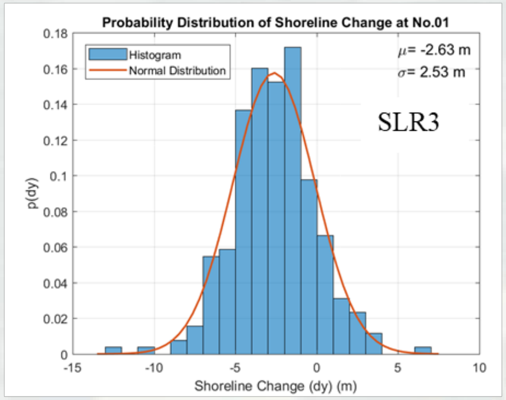


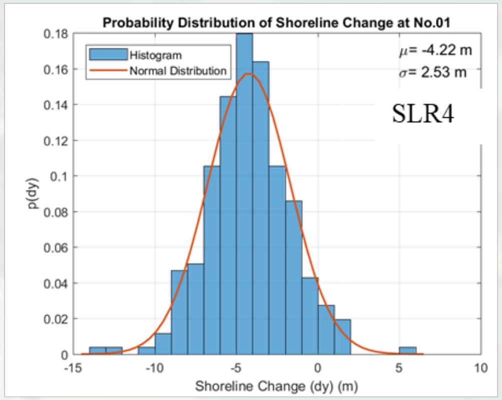
Probabilities of Shoreline Changes at the left groin
(256 Monte Carlo Simulations)



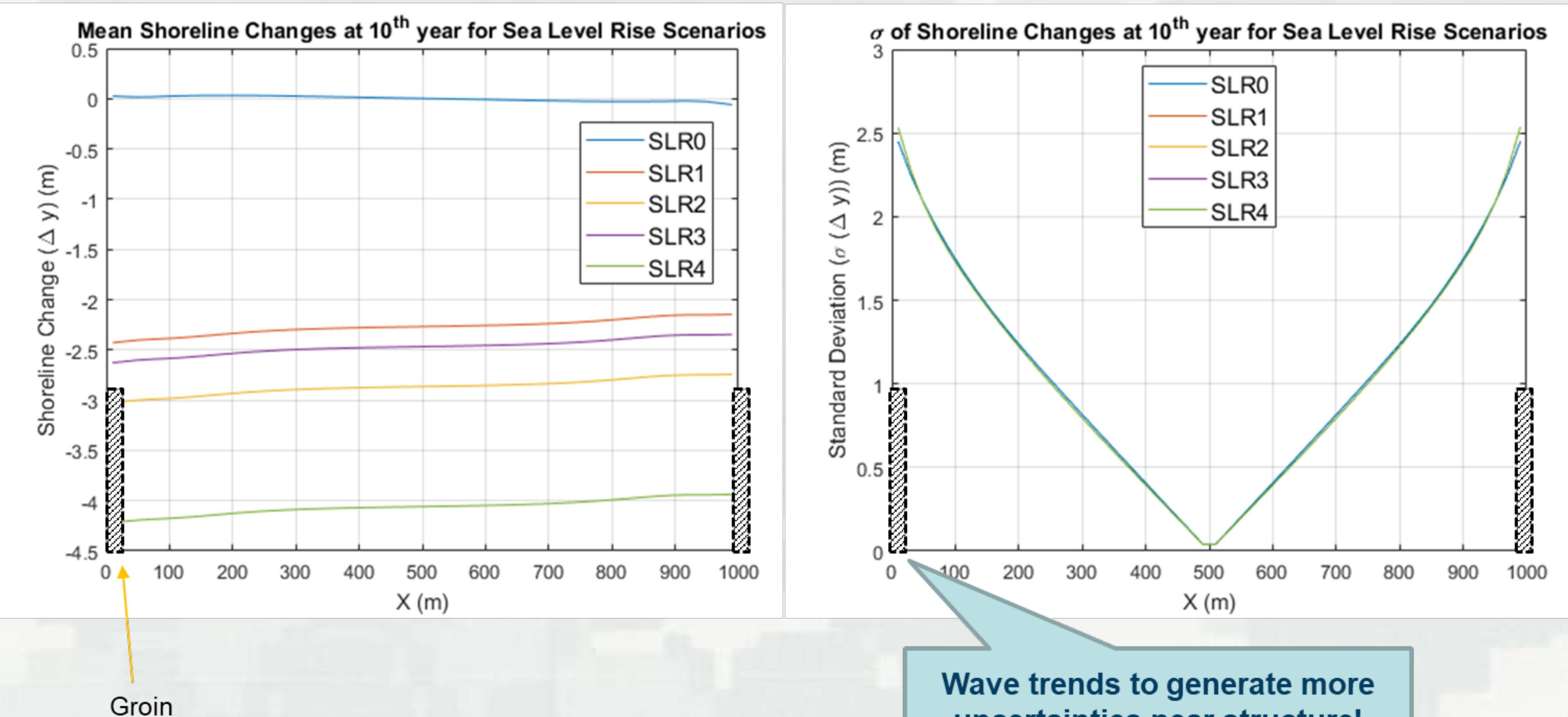






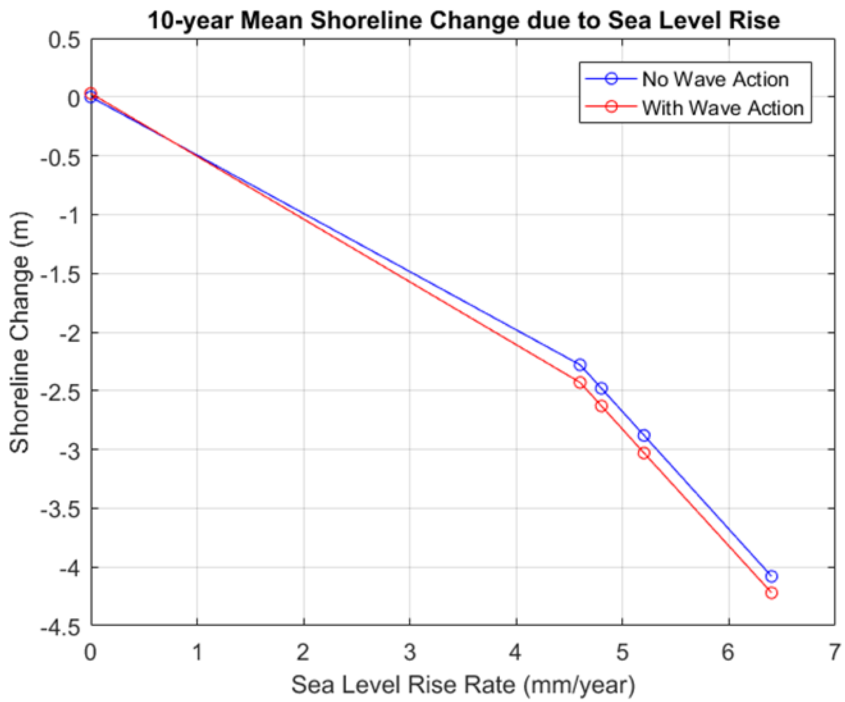


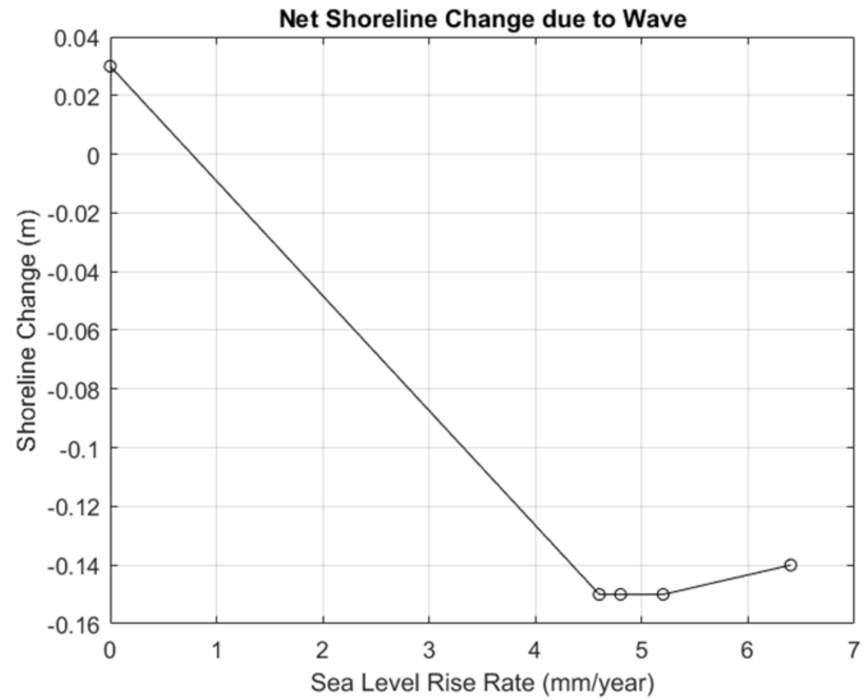
Mean and Standard Deviation of Shoreline Changes vs SLRx



Wave trends to generate more uncertainties near structure!

Mean Shoreline Change after 10 years vs. Sea Level Rise

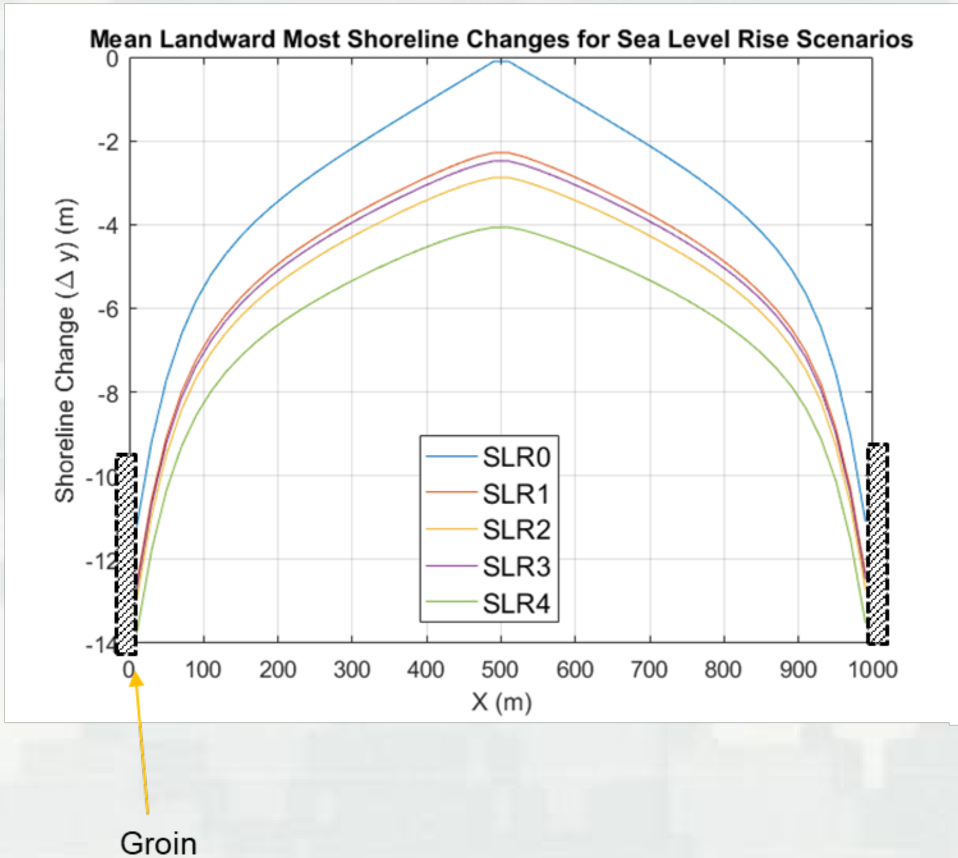


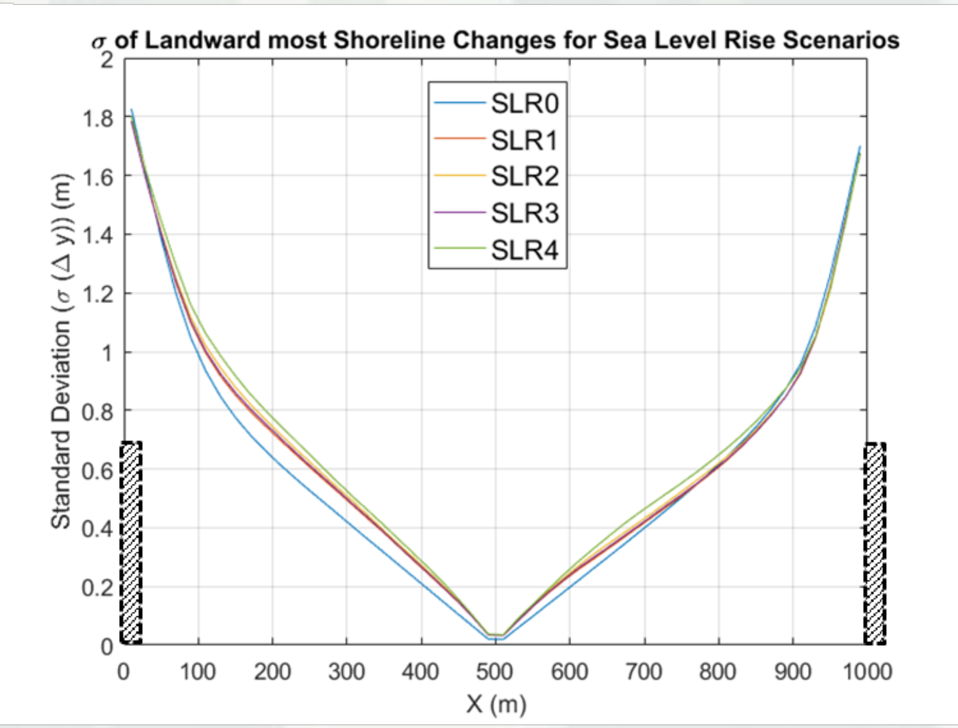


(a) Mean Shoreline Change vs SLR

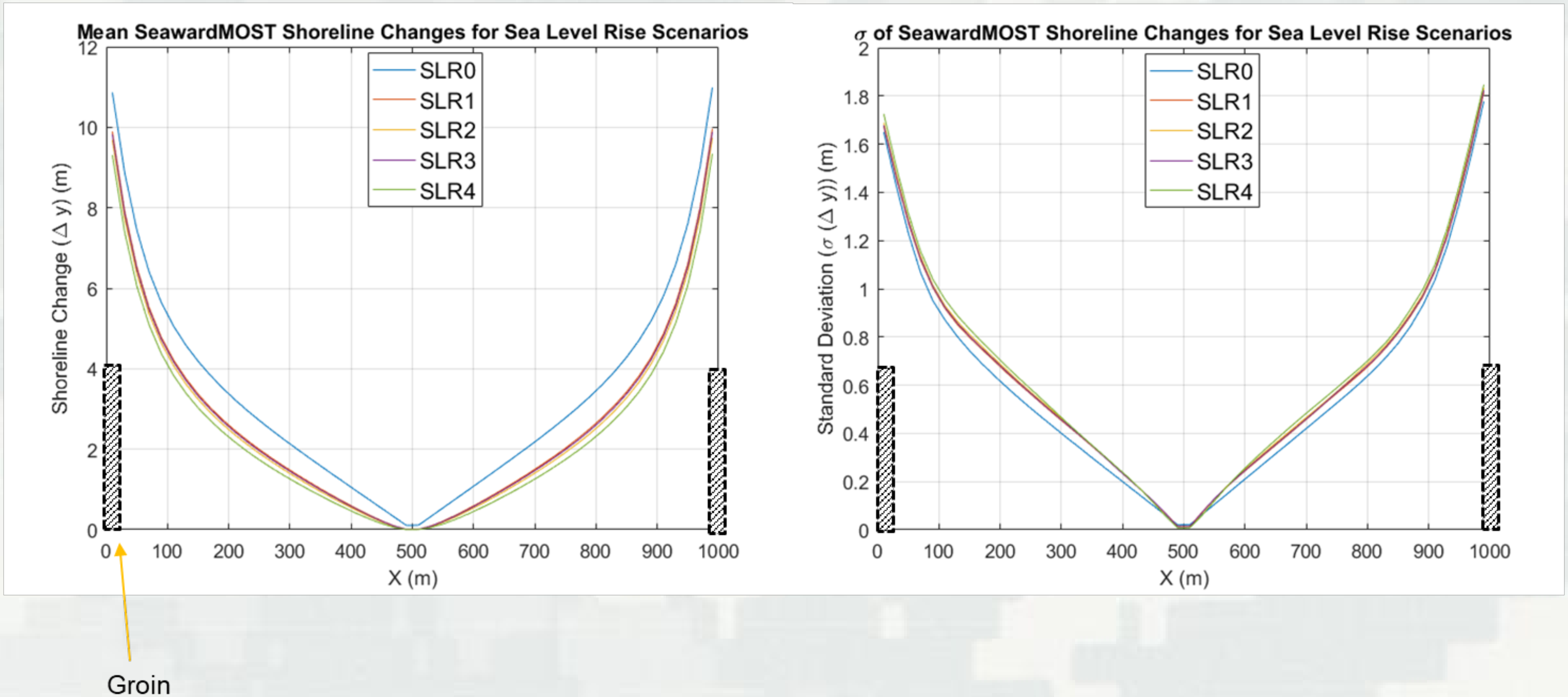
(b) Mean Shoreline Change due to Wave

Landward-most Shoreline Changes vs SLR
(Maximum Shoreline Erosion and Uncertainty)

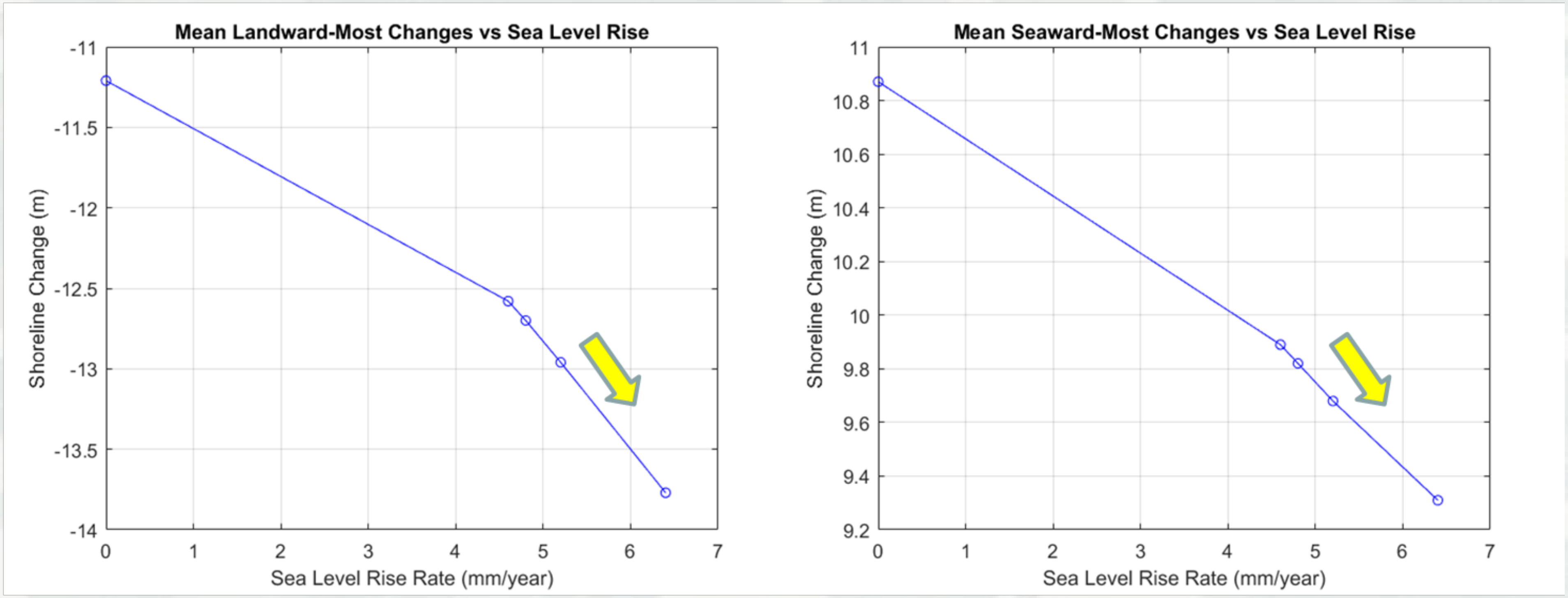




Seaward-Most Shoreline Changes vs SLR
(Maximum Accretion and Uncertainty)



Mean Landward-Most and Seaward-Most Shoreline Change vs SLR



Max. shoreline retreat may speed up!

(a) Mean Landward-Most Change near Groin

(b) Mean Seaward-Most Change near groin

New Feature of GenCade (1) - Cross-shore Sediment Transport due to Wave Asymmetry and Nonlinearity

Transport Rate due to Velocity Skewness (Hsu et al. 2006)

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

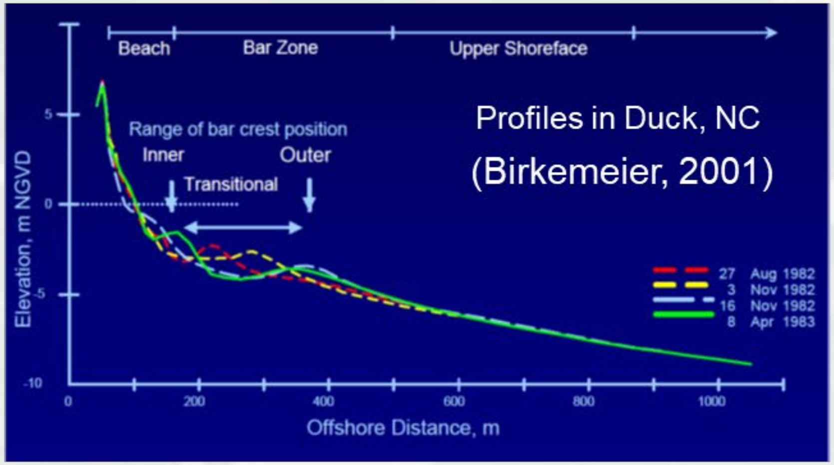
α_D=empirical parameters, p=porosity of sediment

Q_v and Q_C are the net sediment transport due to waves and currents

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

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

U_0 = the wave orbital velocity vector,
U_t = the total velocity vector (waves plus currents), and
U = the current velocity vector, related to longshore current and undertow current.
φ = the friction angle
W_0 = the sediment fall velocity
C_w, C_C, ε_B, ε_S = empirical parameters



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

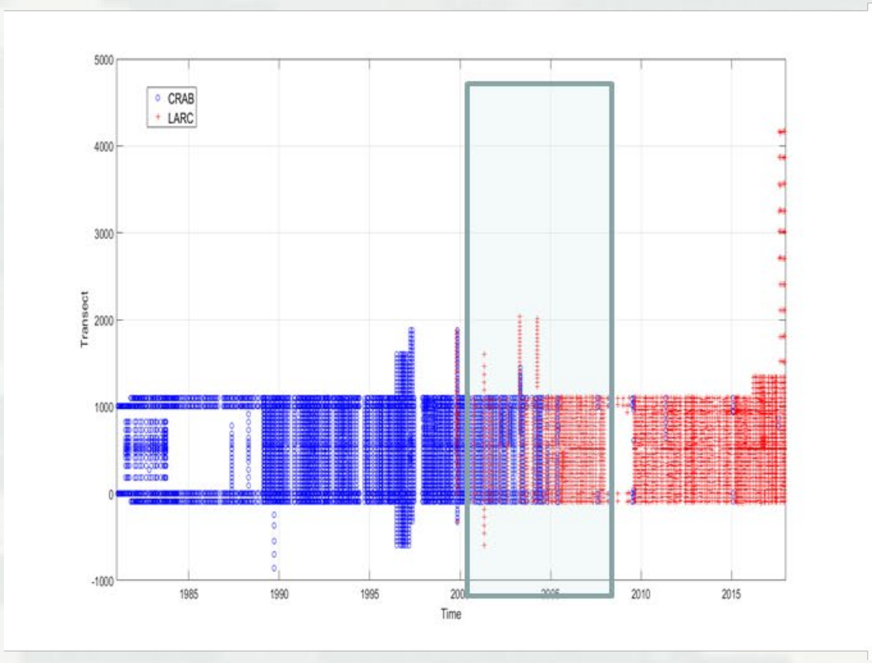
Model Validation: Modeling of Shoreline Change in Duck, NC

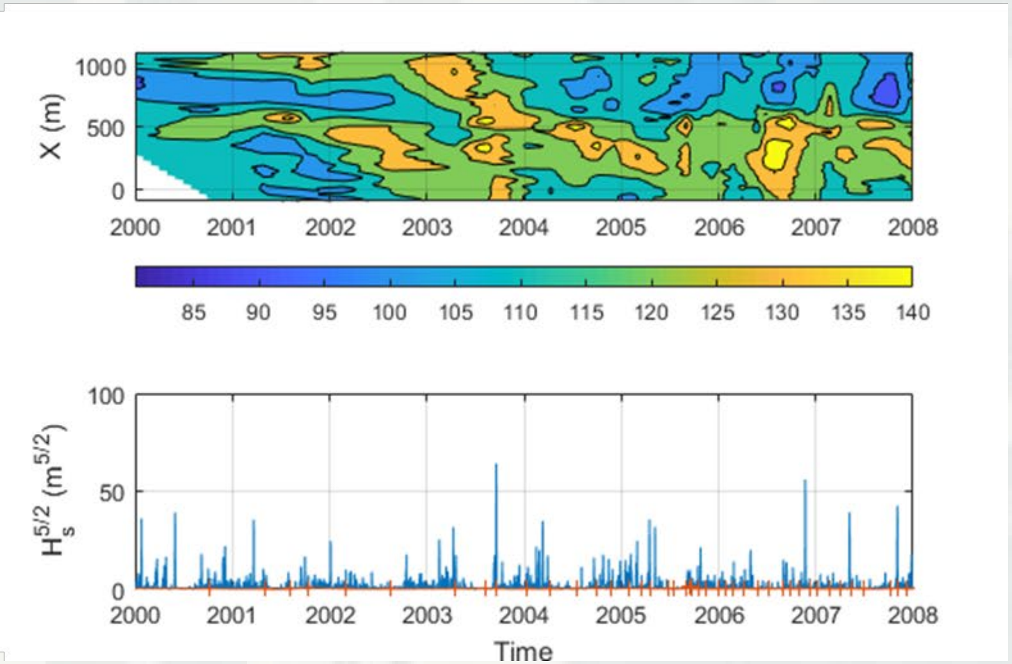
FRF in Duck, NC

Computational Period: 6 years
1999/10/23 0:00 - 2005/10/23 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: Pined
Grid Size = 20 m
Sea Level Rise and Subsidence rate: 4.55mm/year

Calibrated Model Parameters:
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)

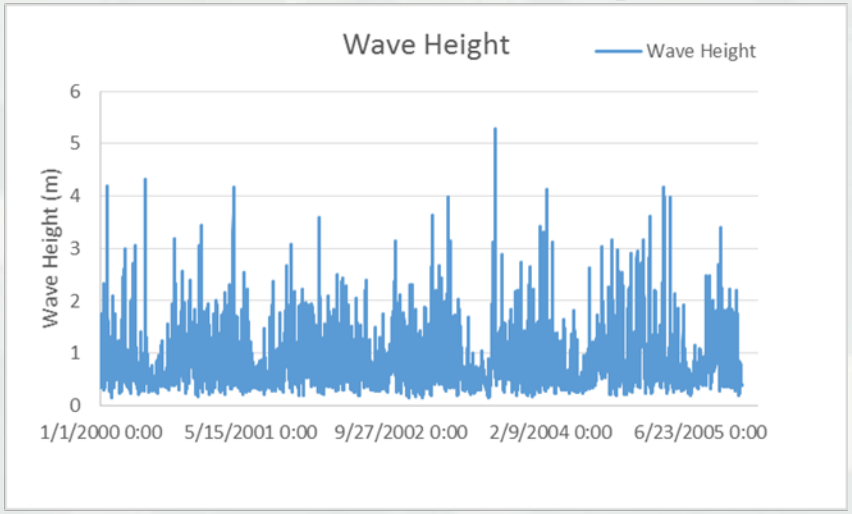
V&V of GenCade for FRF Shoreline: Data Analyses

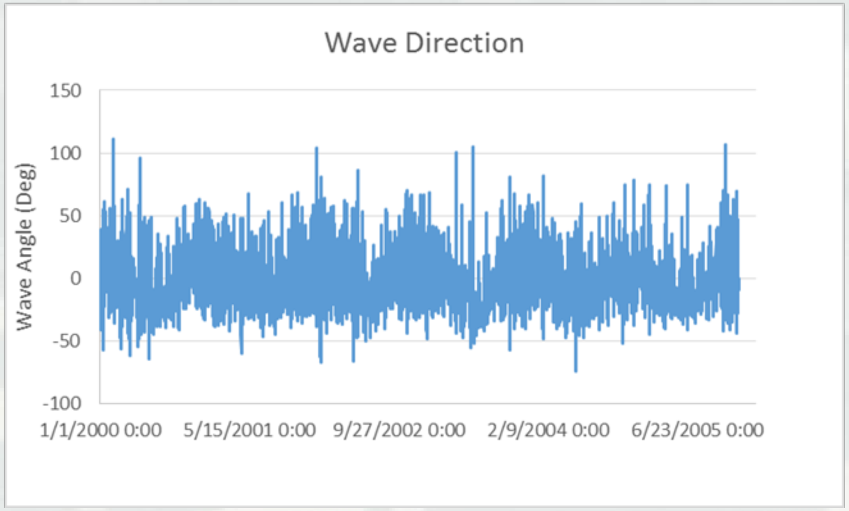




Wave Data (2000/1/1 – 2006/1/1)

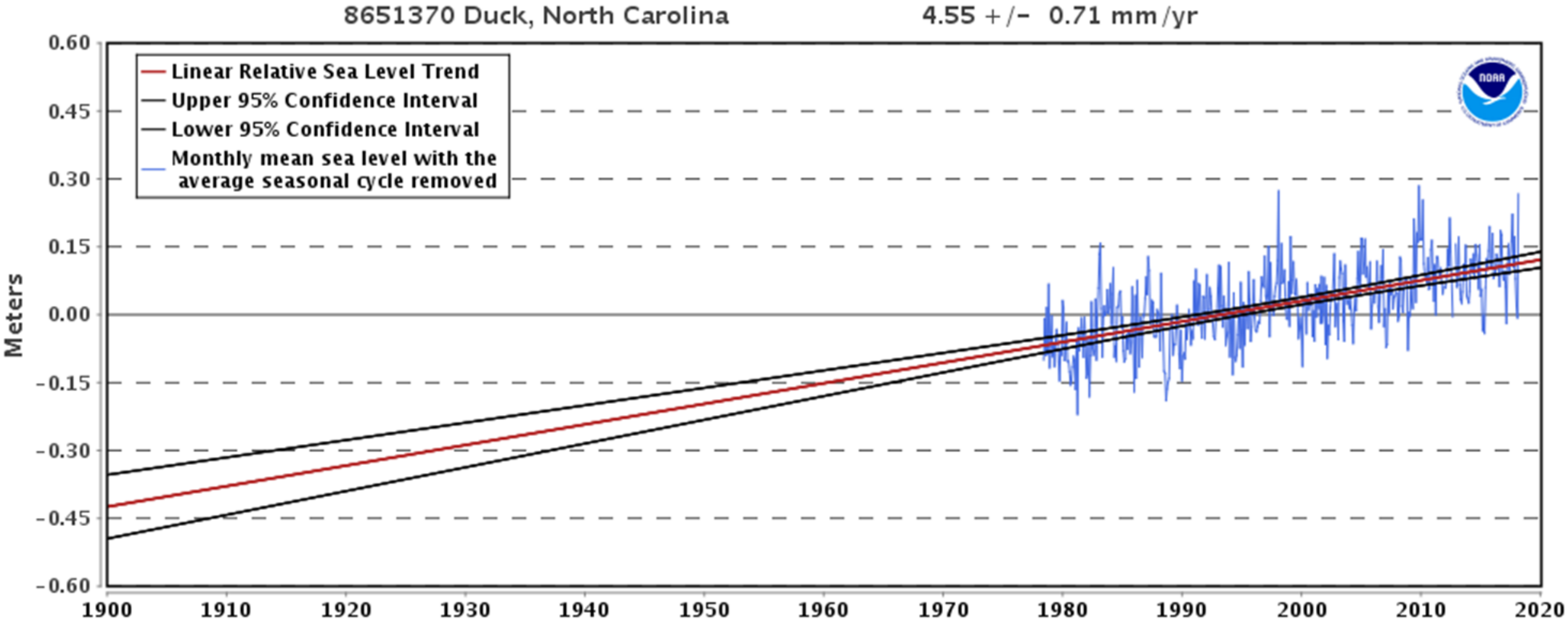
	H (m)	T (s)	alfa (deg)
Average	0.82	9.18	-5.06
Min	0.14	3.09	-74.62
Max	5.28	18.96	111.32
σ	0.53	2.68	18.52





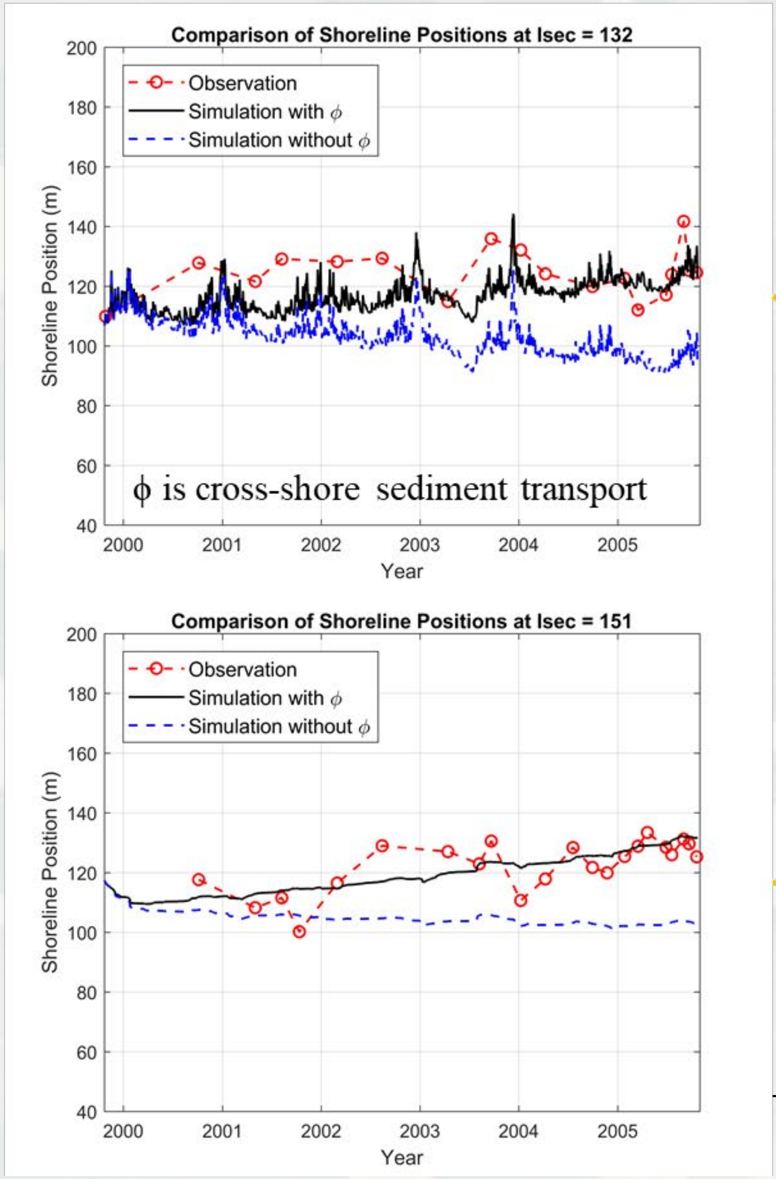
Sea Level Rise Trend

NOAA-NOS #8651370 Duck, North Carolina



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

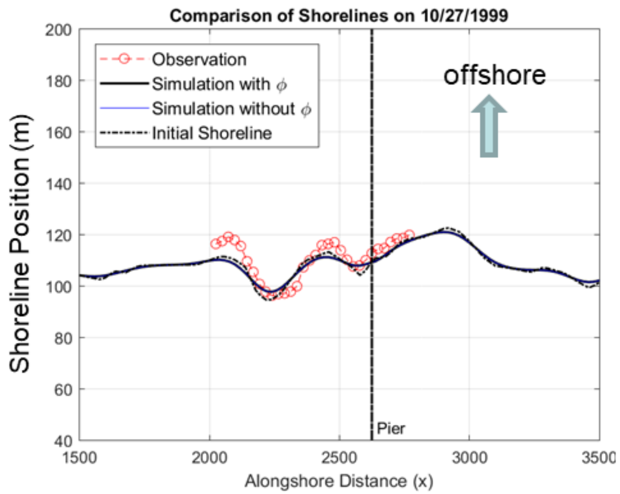
Model Validation: Comparison of Shoreline Evolution (1999-2005) at FRF, Duck, NC

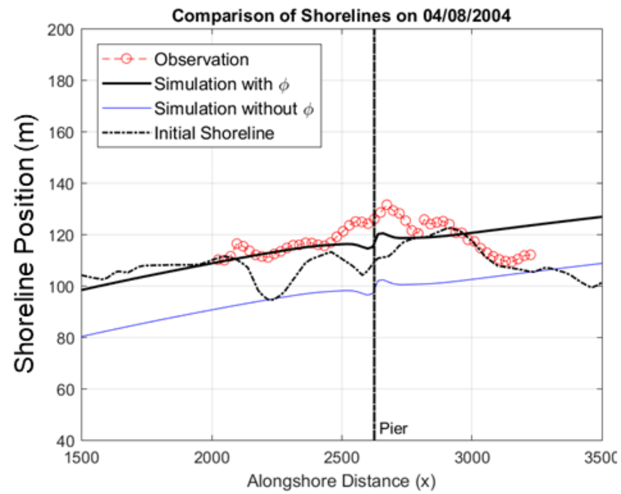


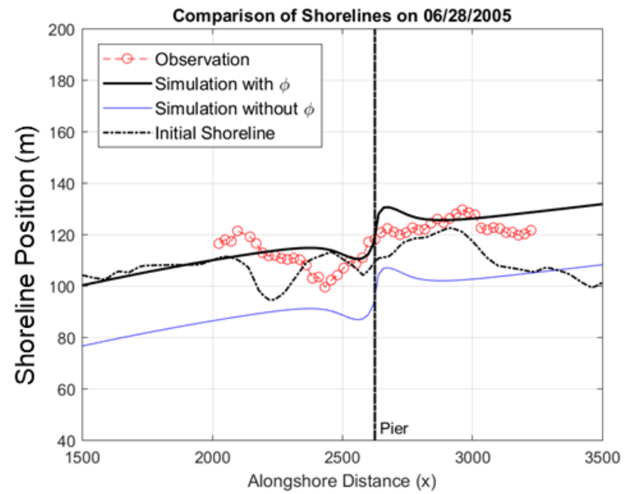
FRF in Duck, NC

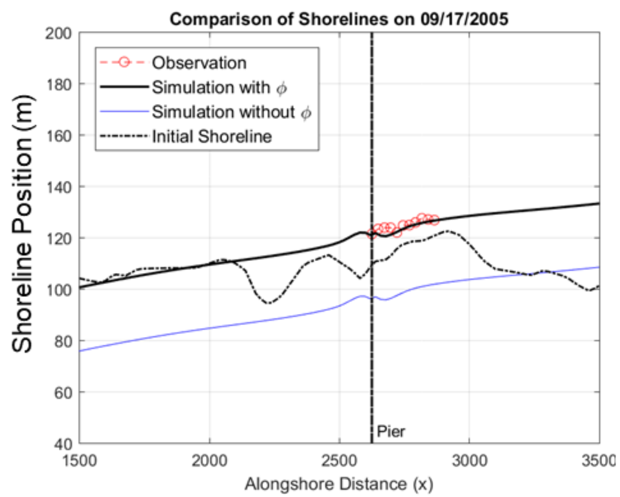
Model Validation:

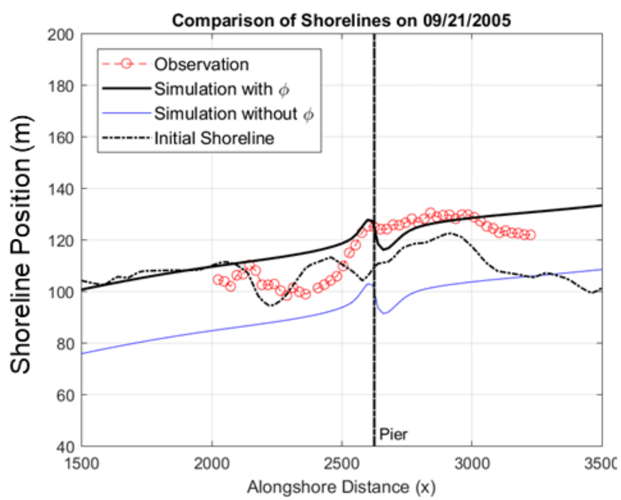
Comparisons of Shoreline Positions (1999-2005)

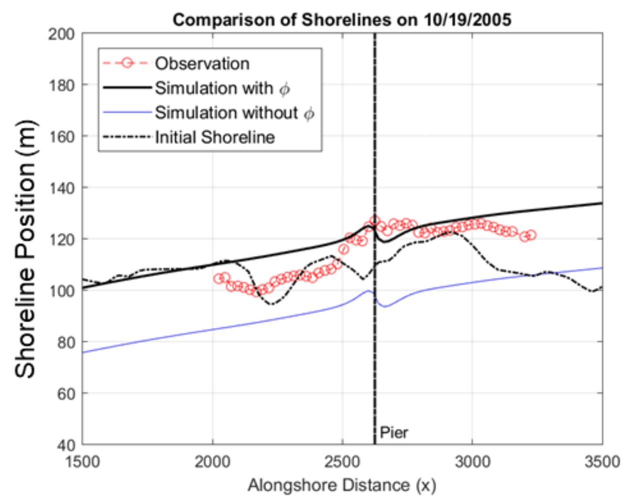




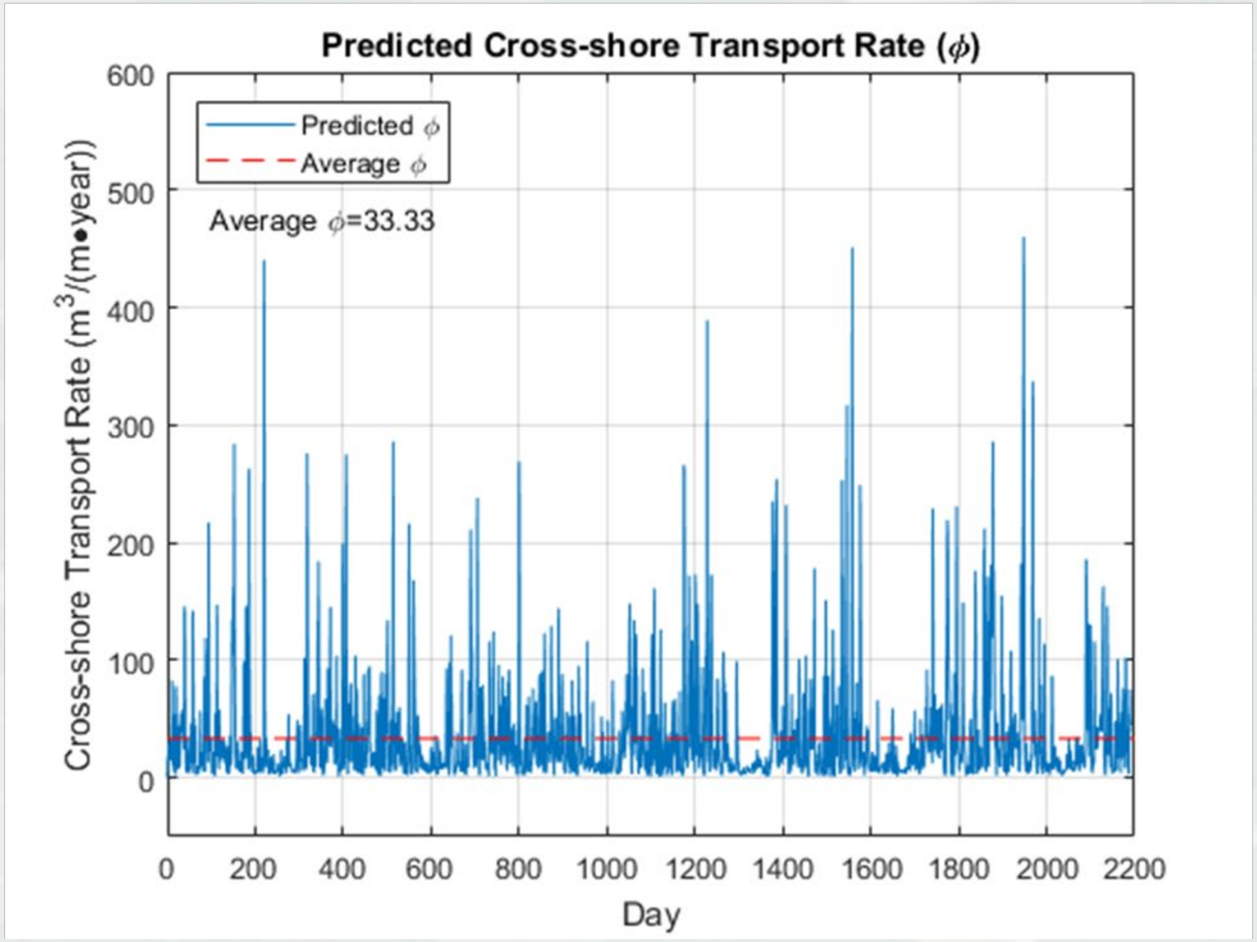




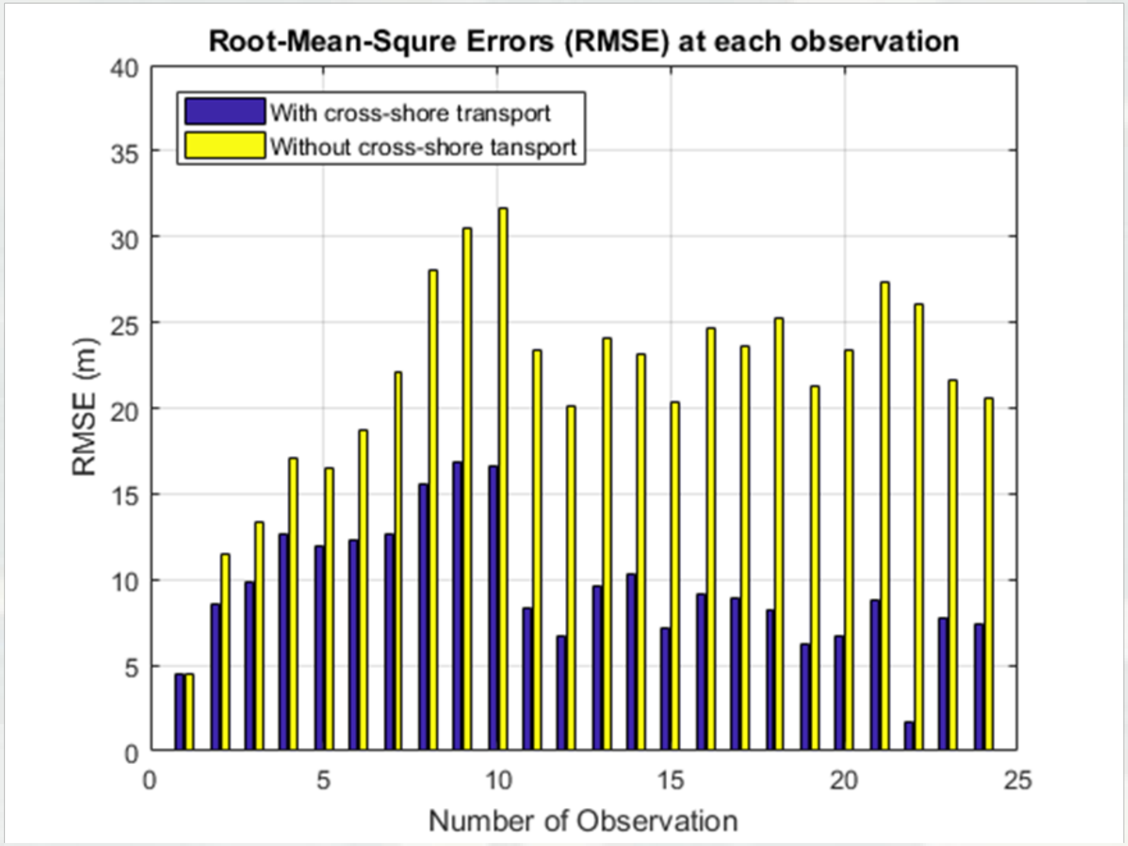




Predicted Cross-Shore Transport Rate (1999-2005)

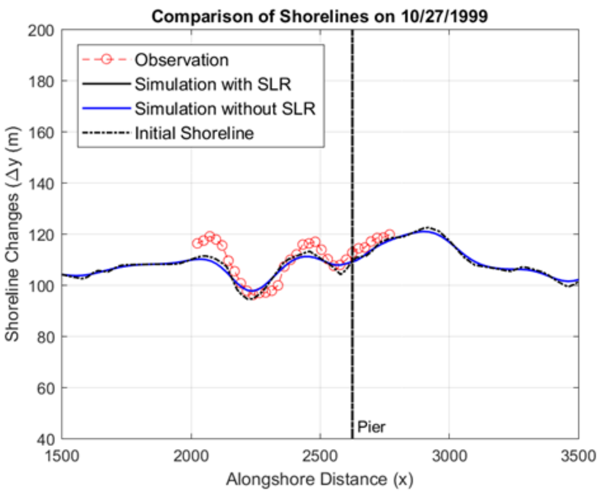


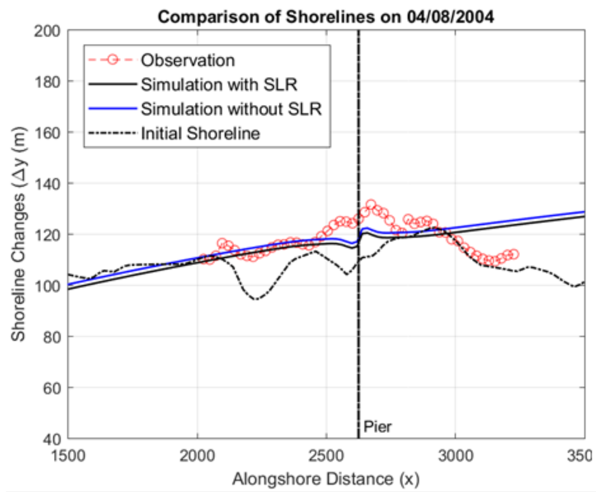
Model Skill Assessment:
Root-Mean-Square Errors at Observation Times (1999-2005)

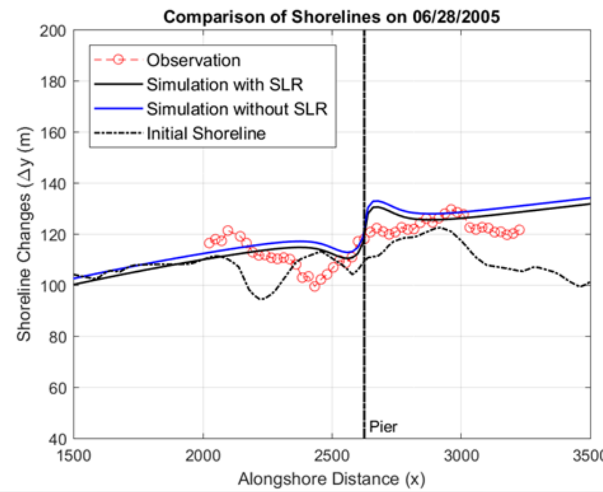


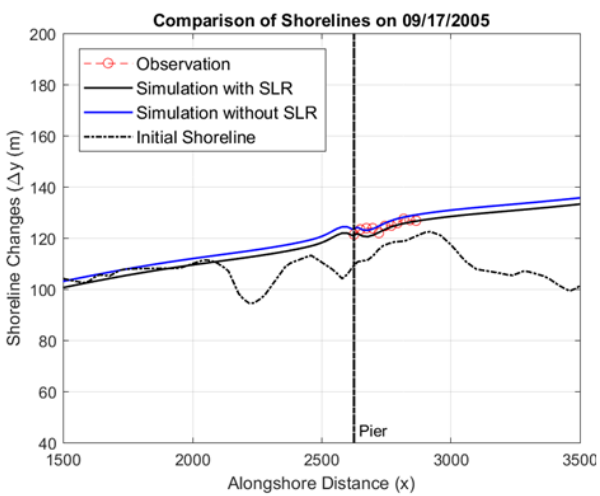
Model Validation (Impact of SLR)

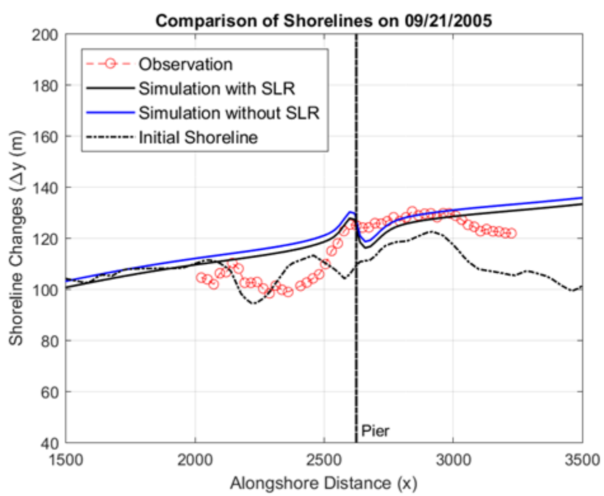
Comparisons of Shoreline Positions (1999-2005)

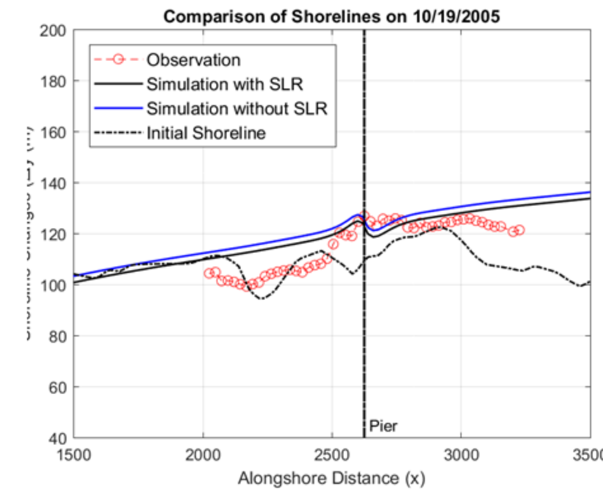






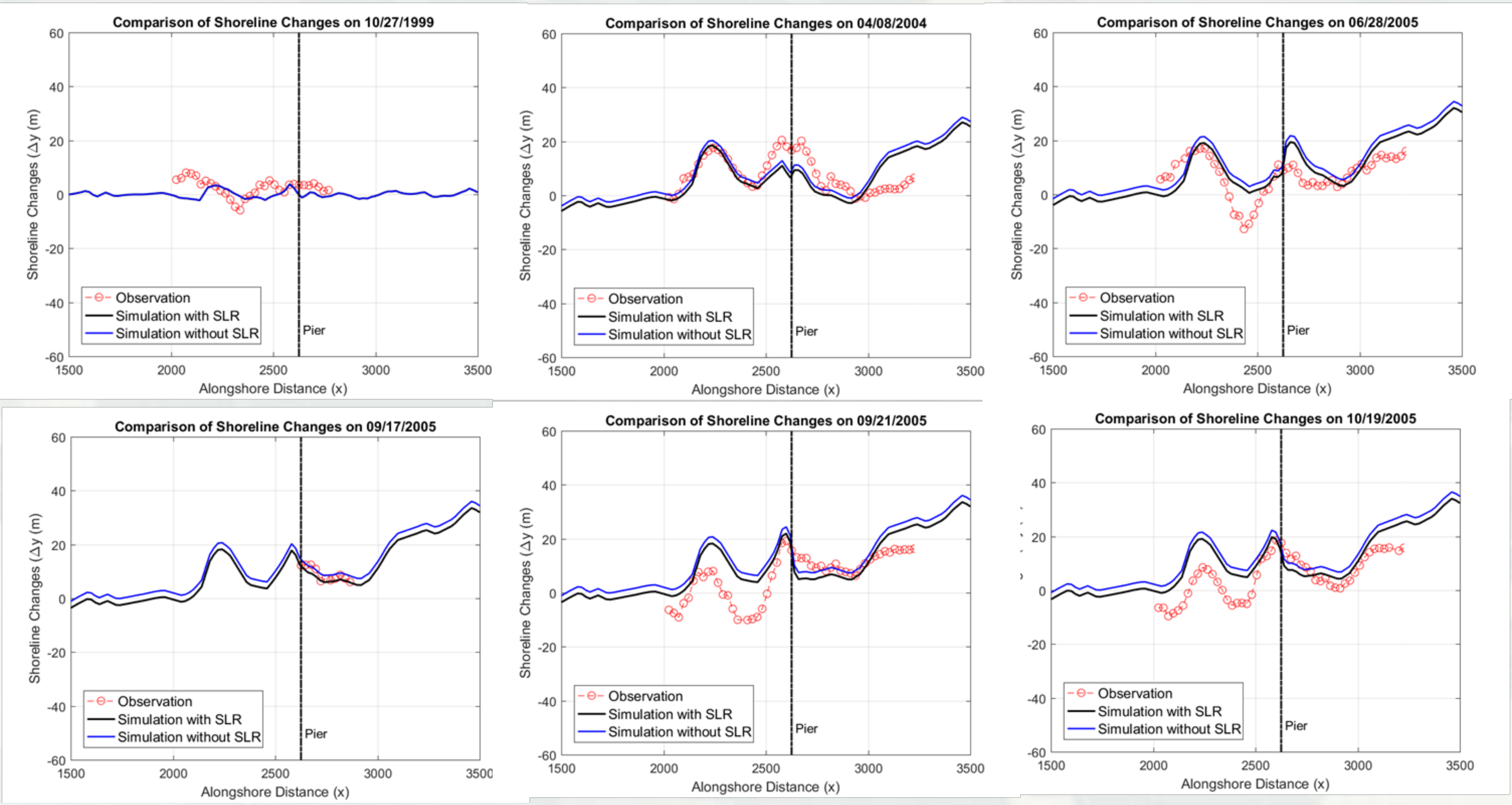




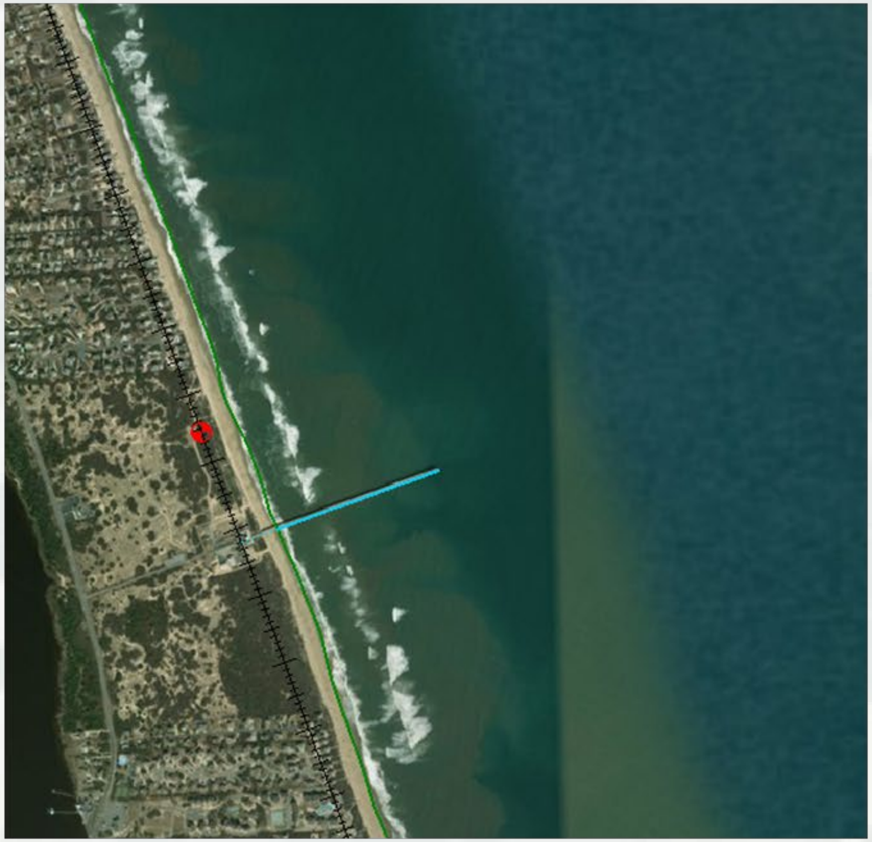


Model Validation (Impact of SLR)

Comparisons of Shoreline Changes (1999-2005)



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)

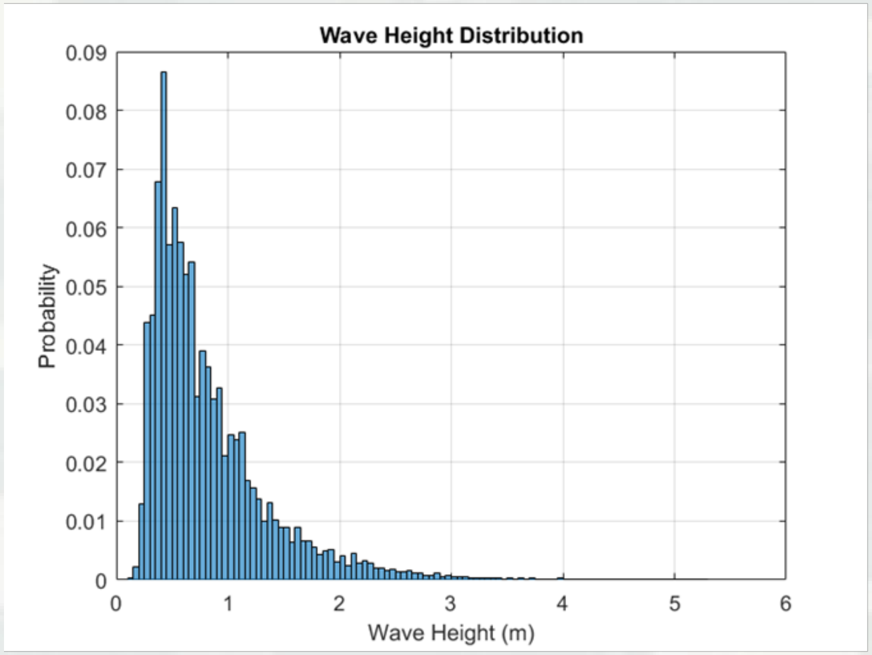
Boundary Conditions: Pined

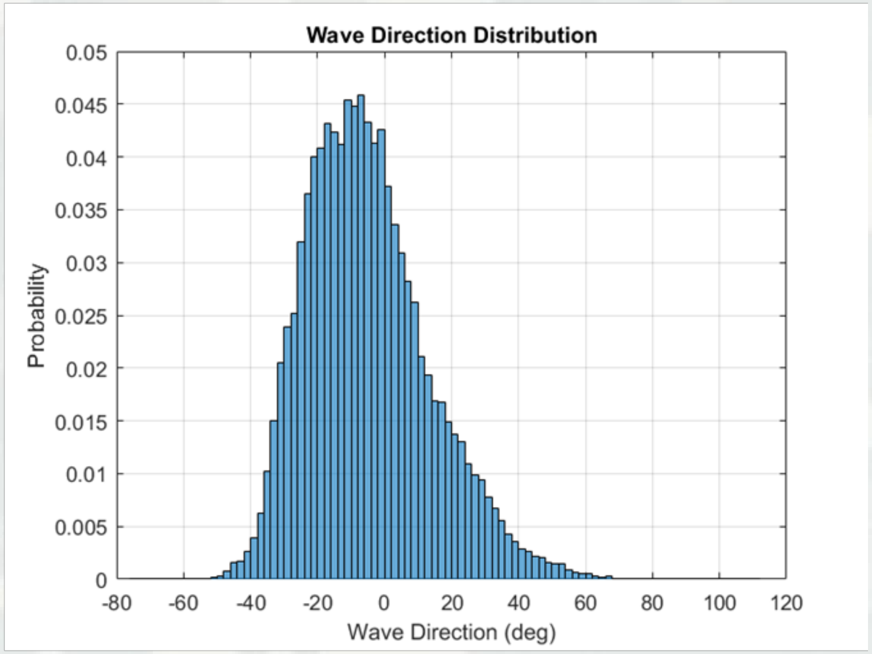
Grid Size = 20 m

Permeability of Pier = 0.6 (no diffracting)

Scaling parameter of cross-shore transport: 0.182

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



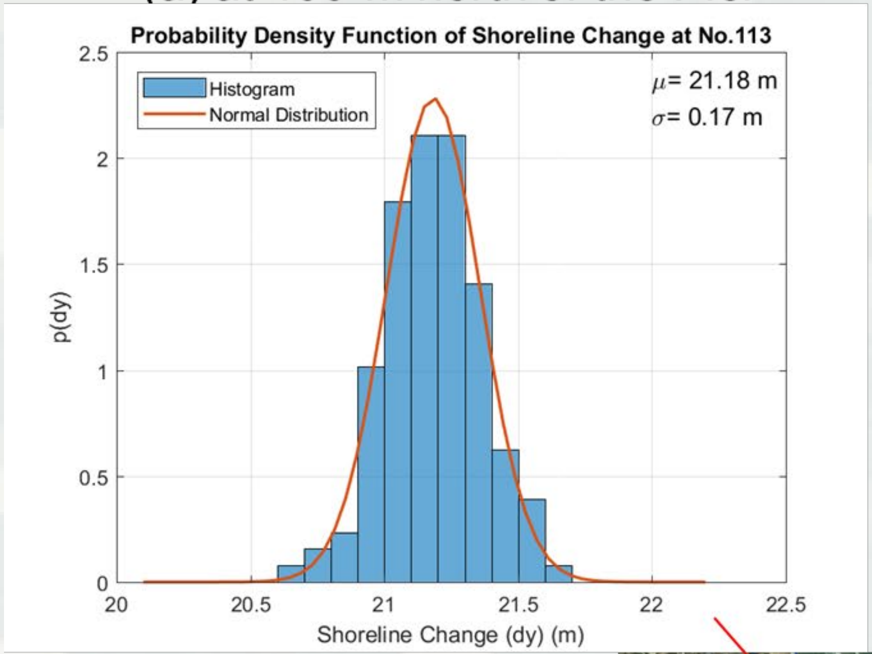


Mean H_s = 0.82 m

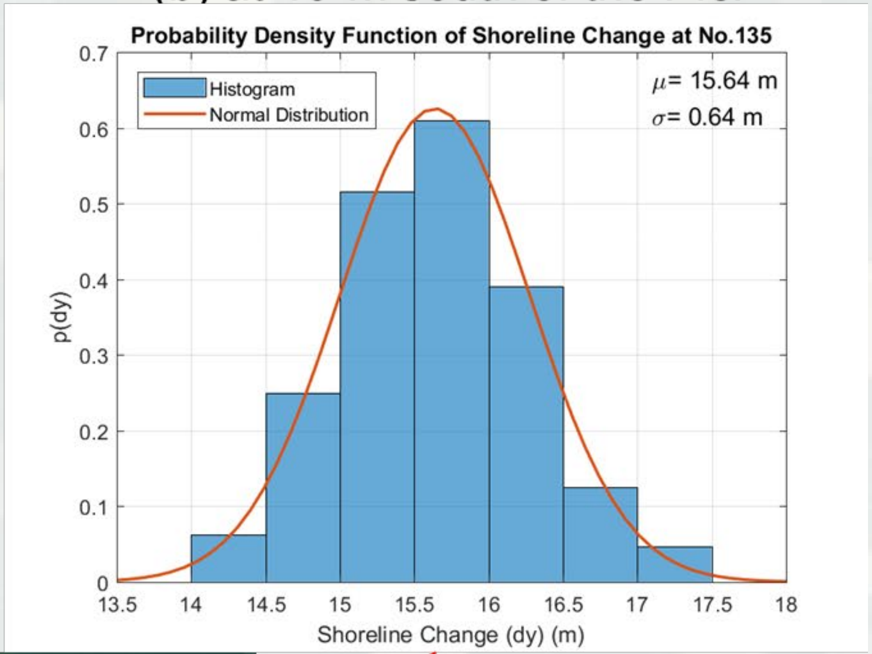
Mean wave angle = -5.06°

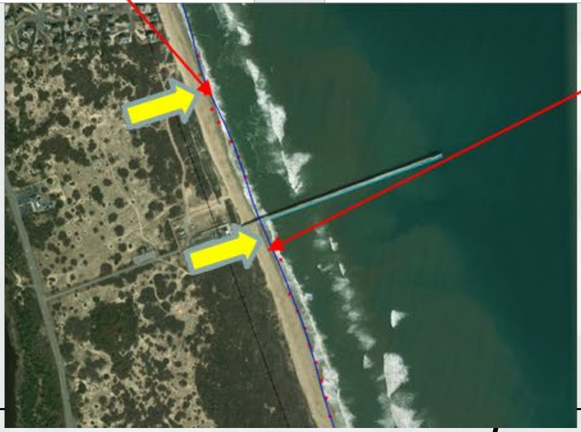
Probability Density Functions: 6-Years Shoreline Change

(a) at 400-m north of the Pier

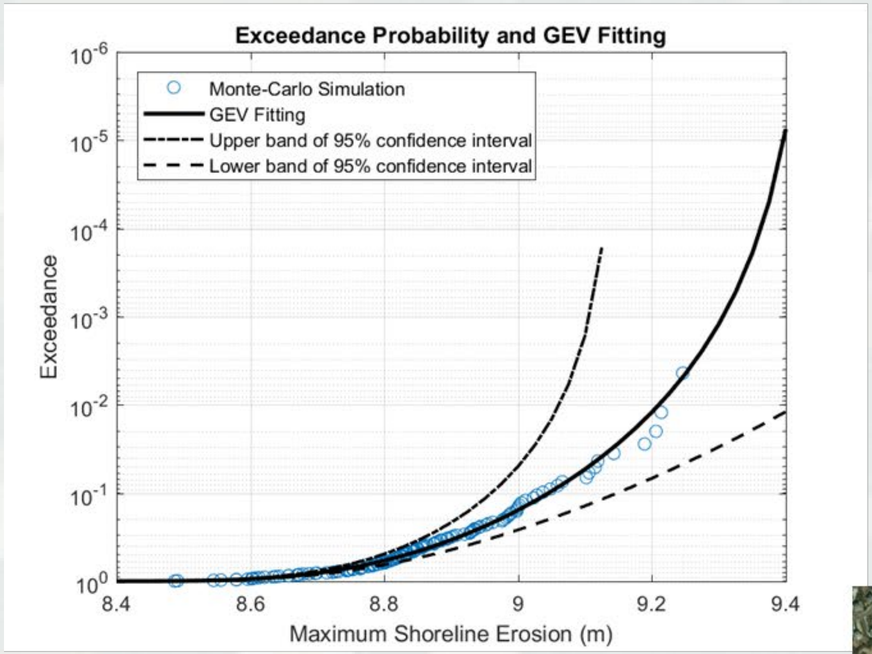


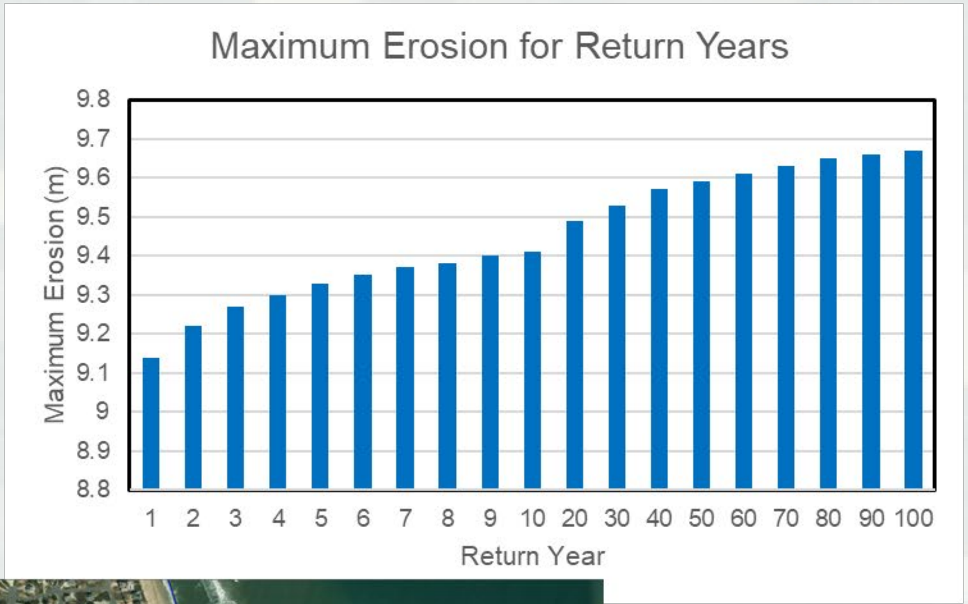
(b) at 40-m south of the Pier

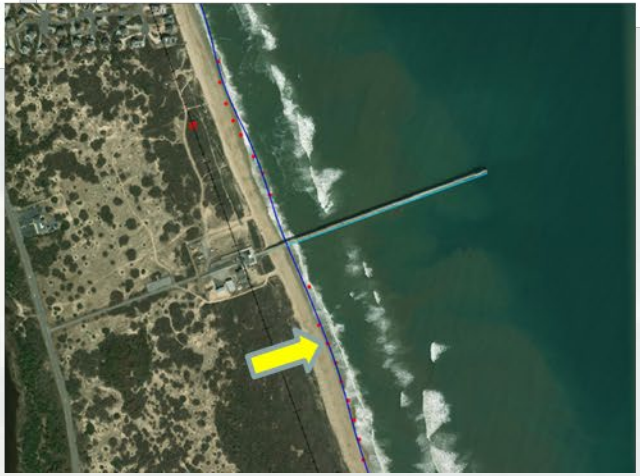




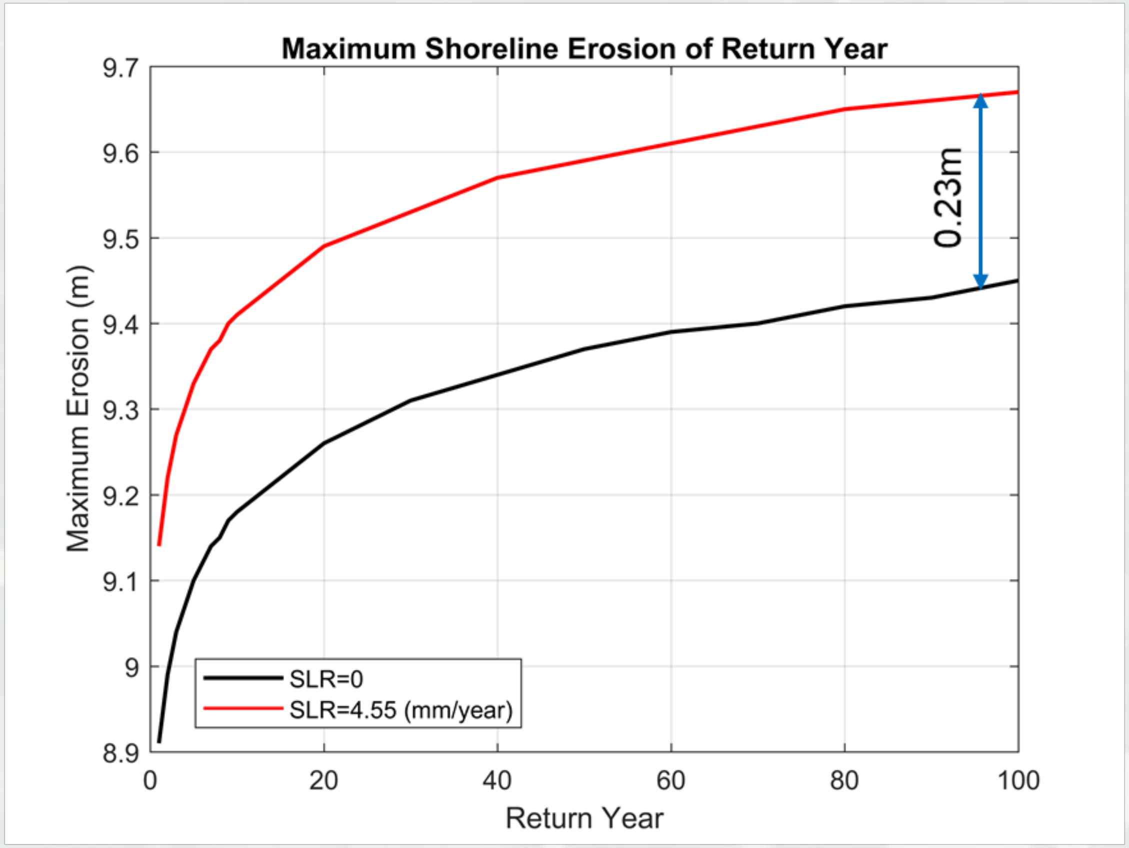
Estimation of Maximum Erosion at 300-m south of Pier (SLR=4.55mm/yr)







Shoreline Retreat Risk at 300-m south of Pier due to Sea Level Rise



Maximum shoreline erosion at return year

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.
- A one-line model, GenCade is adopted to simulate the shoreline evolution in a coast.
- The probabilities of the maximum shoreline erosions in a hypothetical coast were analyzed by using the extreme probability distribution model (Weibull function). The risks of maximum shoreline erosions 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 changes in Duck, NC are reasonable. Estimation of extreme shoreline changes provides maximum erosion risk in a return-interval manner.

Acknowledgements

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