Cross-Shore Sediment Transport for Modeling Long-Term Shoreline Changes in Response to Waves and Sea Level Change

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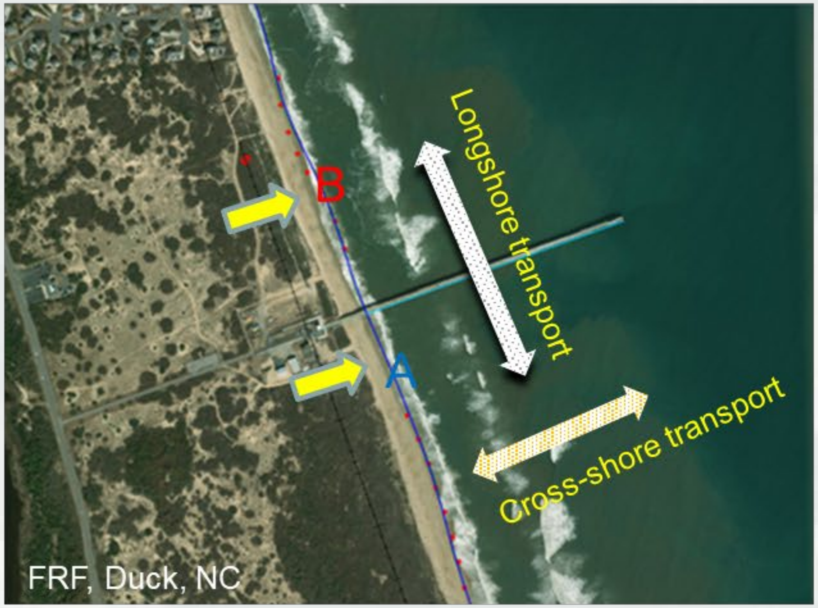
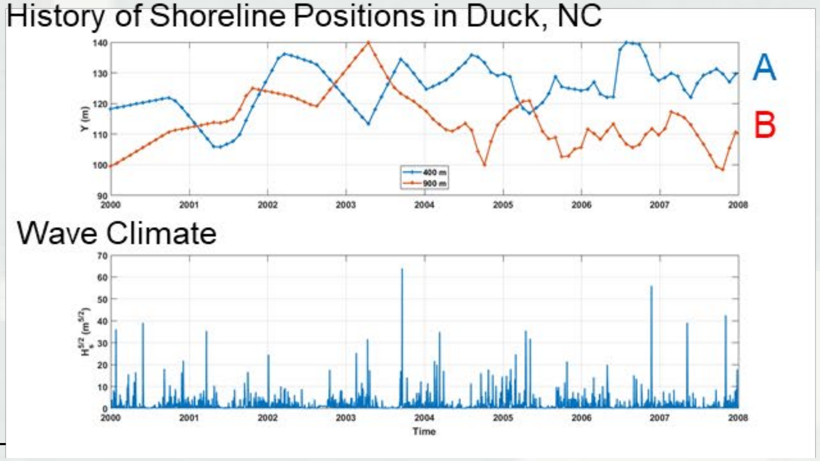
Long-Term Shoreline Changes

- 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.





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

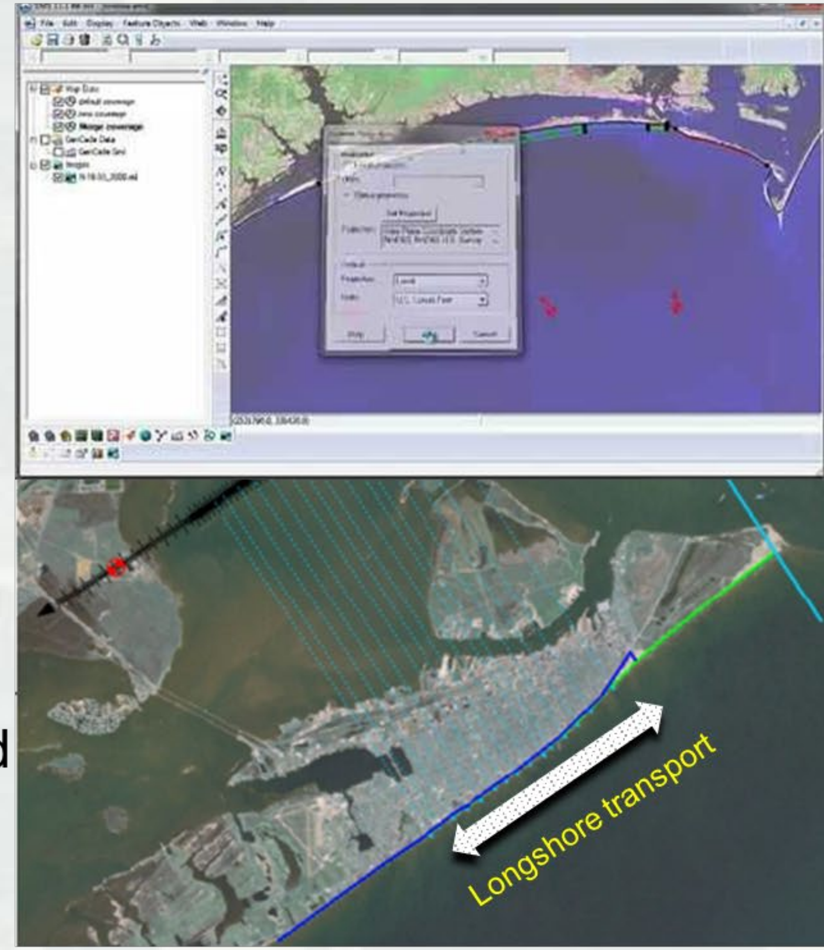

Fig. Sand Bypass in Indian River Inlet, DE

Outline

- Importance of Long-Term Shoreline Modeling for Coastal Management Practices
- GenCade: USACE Shoreline Evolution Simulation Model
- Cross-Shore Sediment Transport in Shoreline Change Simulation
- Shoreline Retreat due to Sea Level Rise
- Validation of GenCade's Cross-Shore Transport Modeling Capability:
  - CHL Field Research Facility (FRF) in Duck, NC
  - Fenwick Island, DE with inclusion of Beachfills
- Conclusions

GenCade:
USACE Shoreline Evolution Simulation Model

- GenCade: A one-dimensional shoreline <u>change</u> 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*

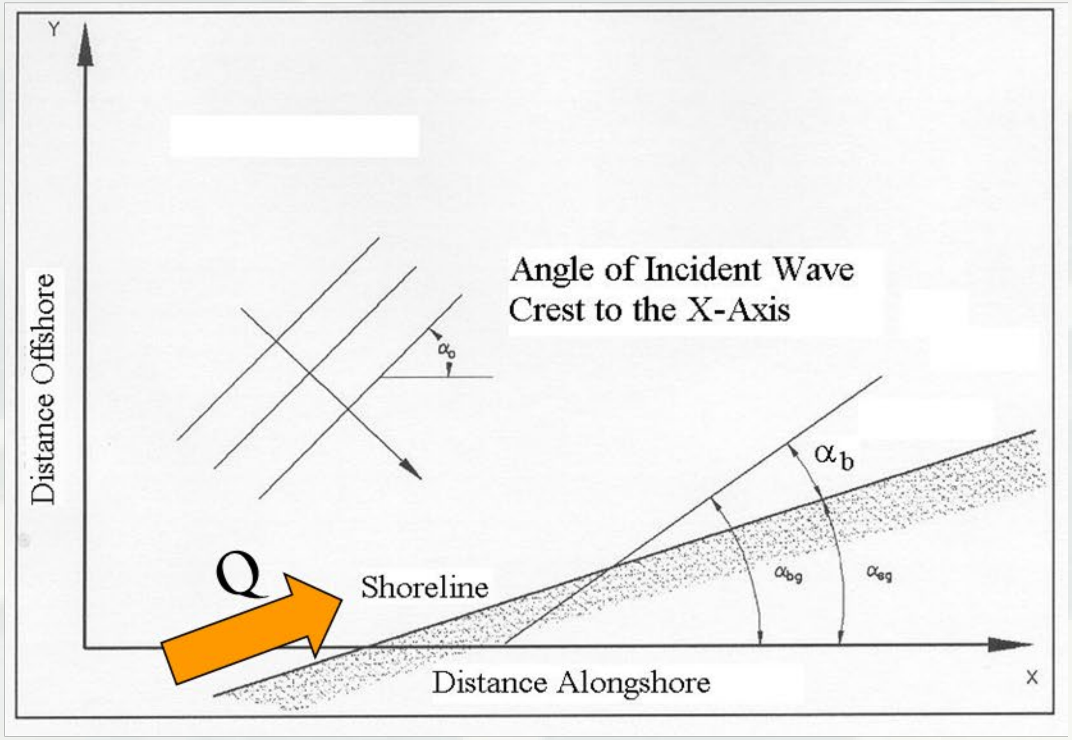
C_{gb} : *Group speed at breaker line*

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

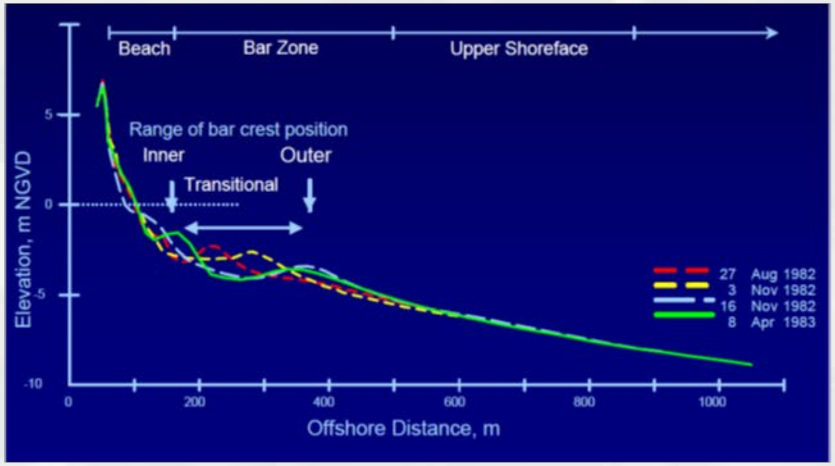
$$a_2 = \frac{K_2}{8(s-1)(1-p)\tan\beta 1.416^{2.5}}$$

K_1, K_2=*empirical coefficients*

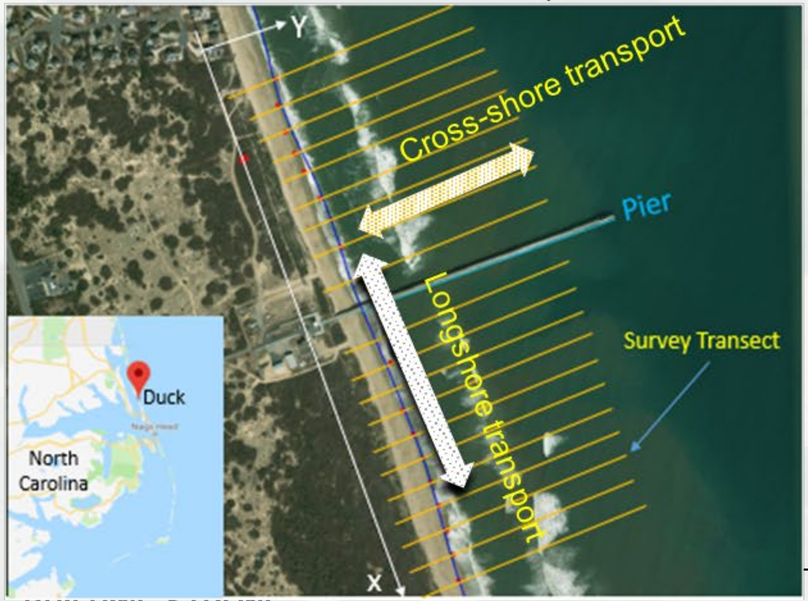
Typically, $0.5K_1 < K_2 < 1.5K_1$



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
- …

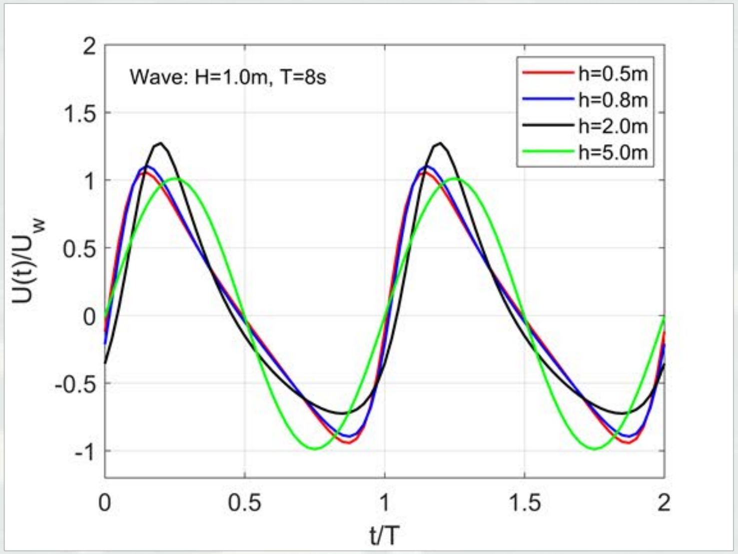


Figure. Near-bed orbital velocities for a wave (height H=1.0 m and period T=8 s) at four water depths. The positive sign denotes onshore direction

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, ν=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)

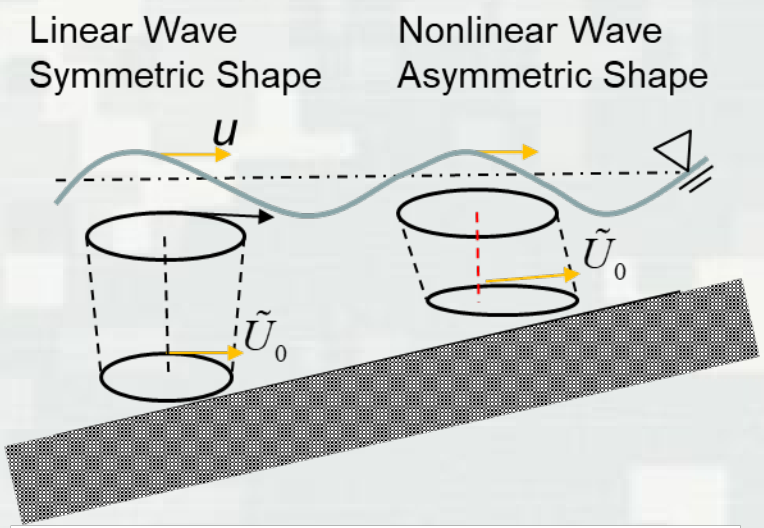
$$f = \sqrt{1-r^2}$$

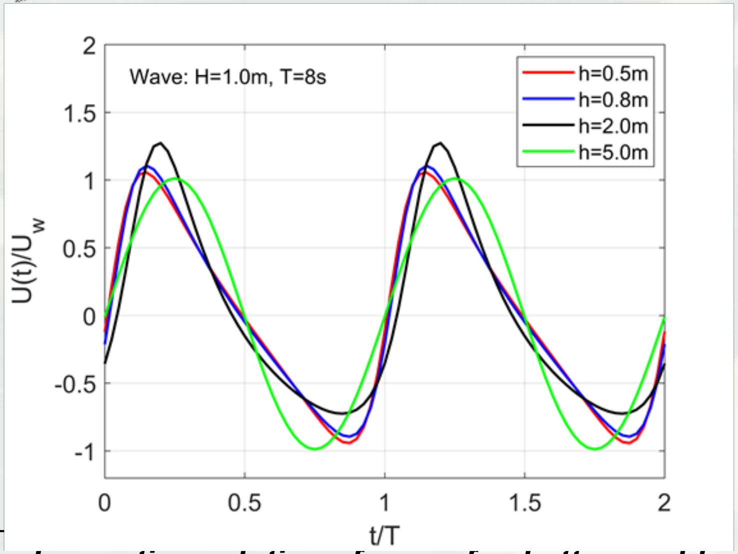
Combination of mean current and orbital velocity

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

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

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



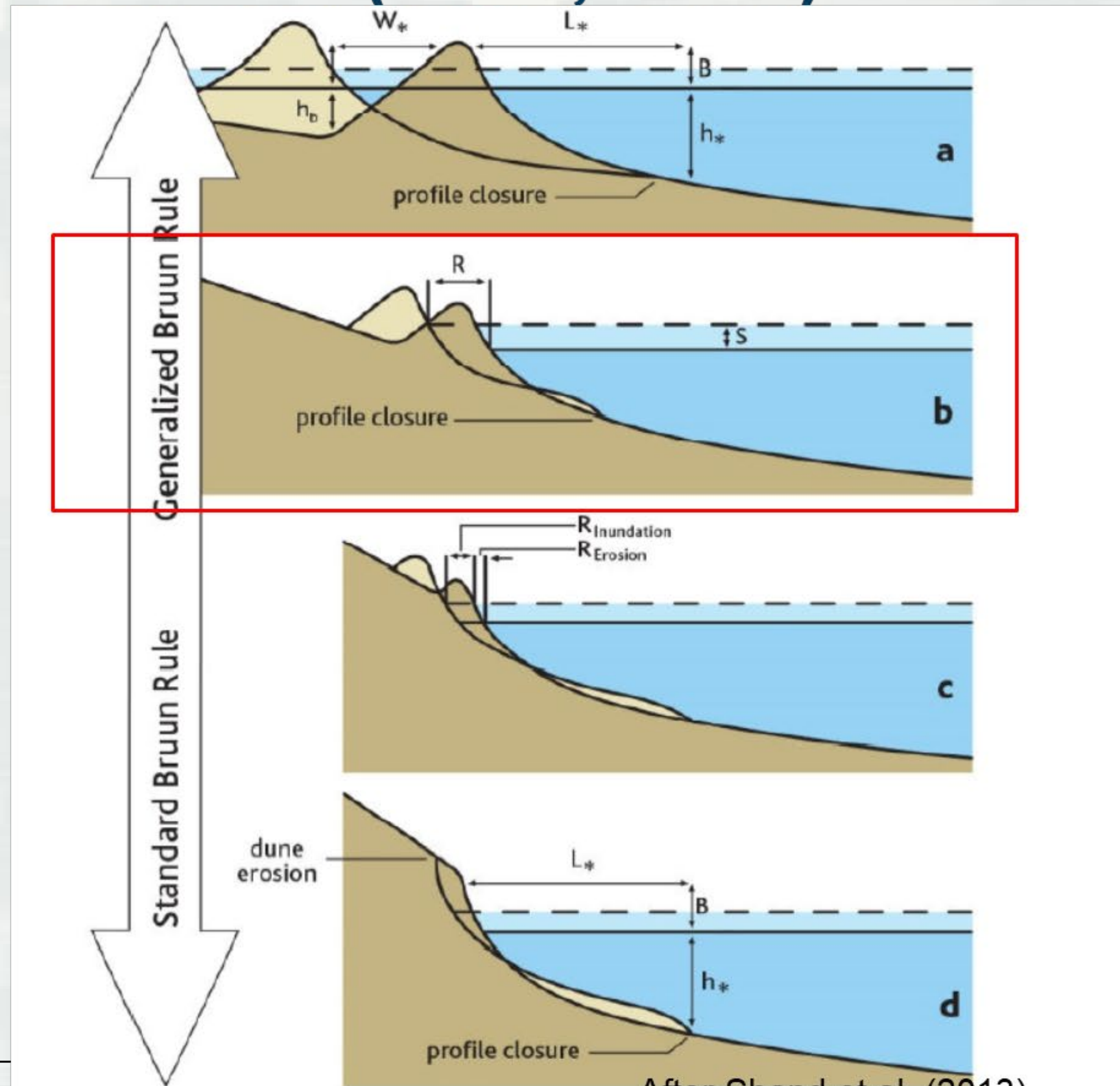


Shoreline Recession due to Sea Level Rise: Bruun Model (1962, 1988)

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)

Projected Global Mean Sea Level Change

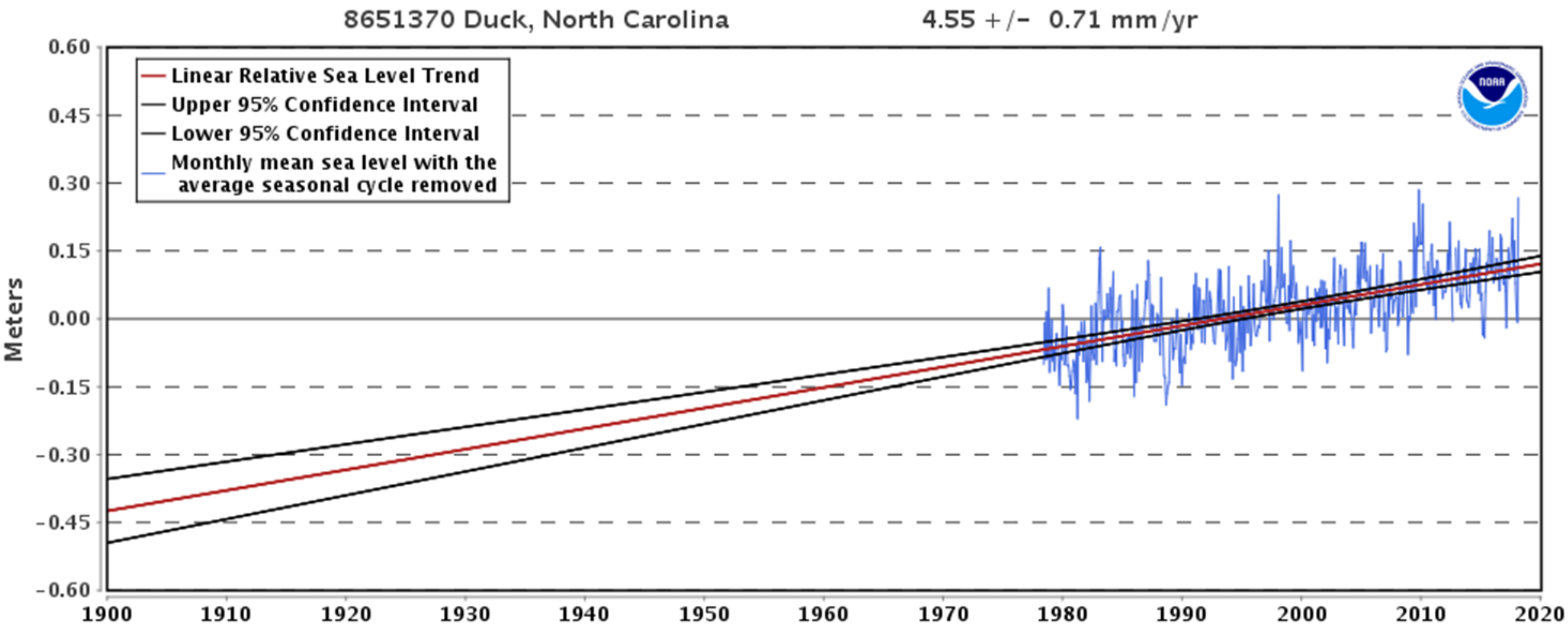
– IPCC Representative Concentration Pathways (RCP) scenarios

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)

Sea Level Rise Trend

NOAA-NOS #8651370 Duck, North Carolina



A relative current SLR in DUCK, NC, 4.55 +/- 0.71 mm/yr , includes mean water level rise and subsidence, which is close to the case of RCP4.5, 4.7+/- 0.31 mm/yr.

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

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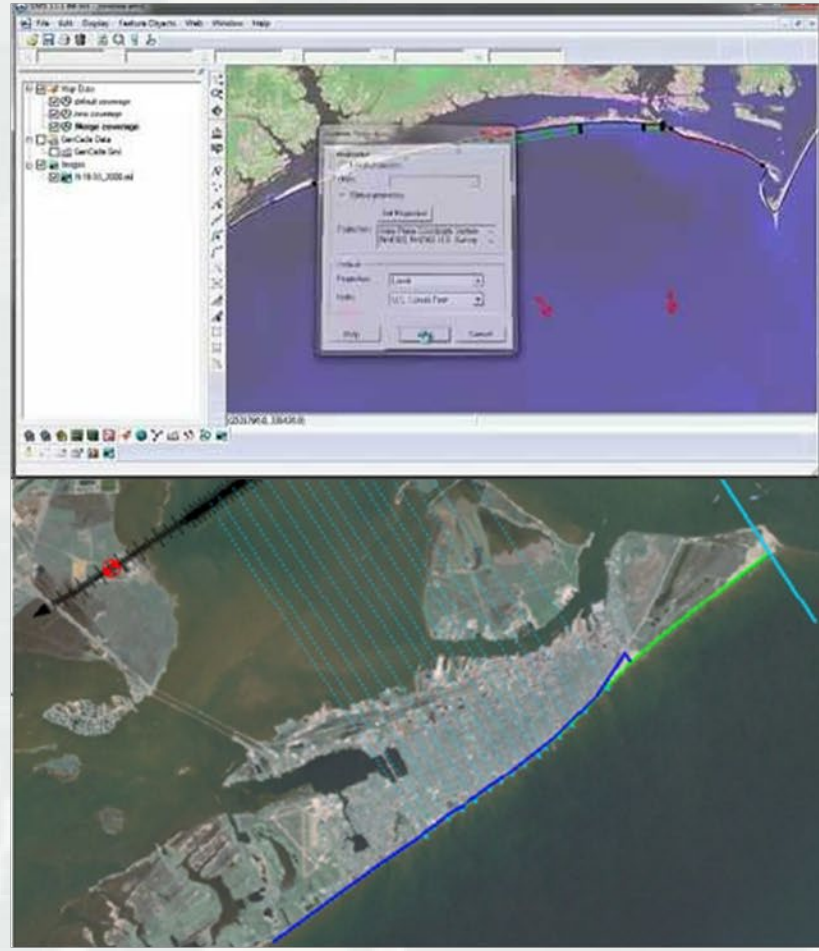


Top: Onslow Bay, NC (for SAW)
Bottom: Galveston, TX (Galv. Park Board)

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

- Shoreline Change Equation with Sea Level Rise (SLR)

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

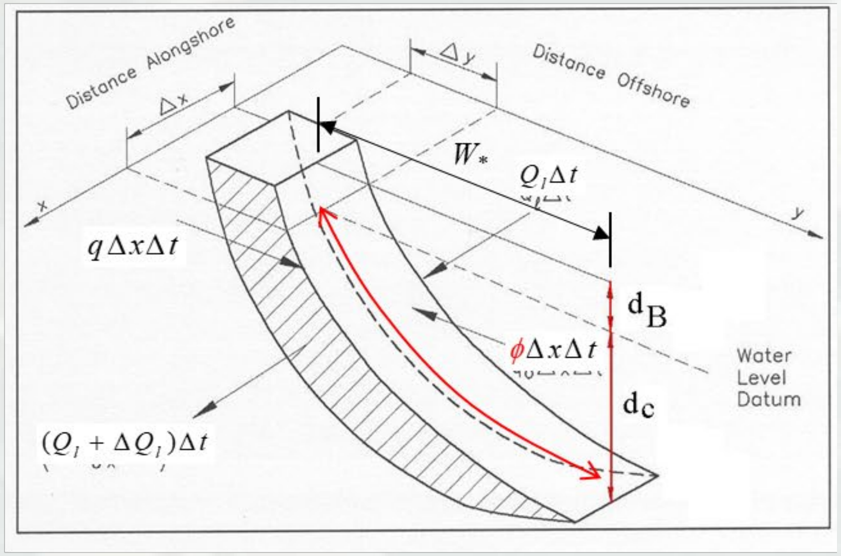
ϕ : Cross-shore sediment transport rate

R : Sea Level Change Rate

S : Subsidence Rate

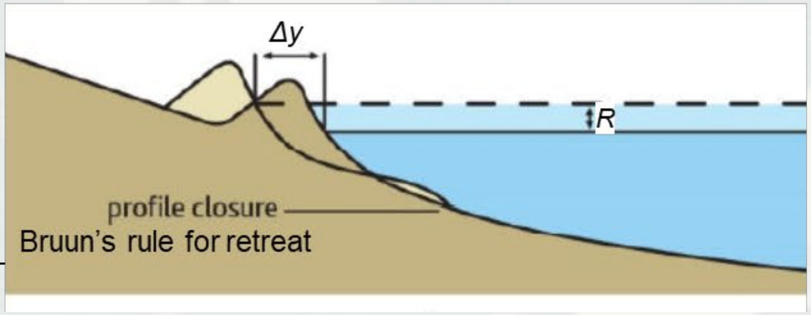
$tan\beta$: beach slope

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

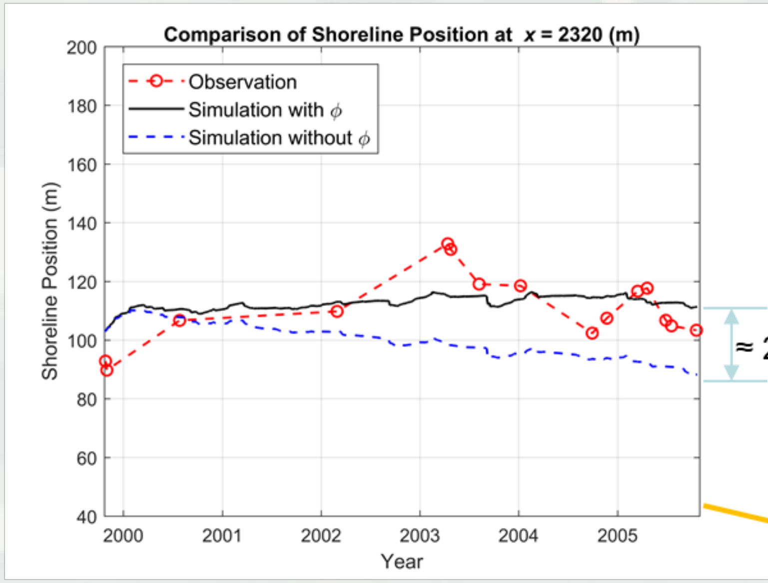


- Berm height varies with sea level change

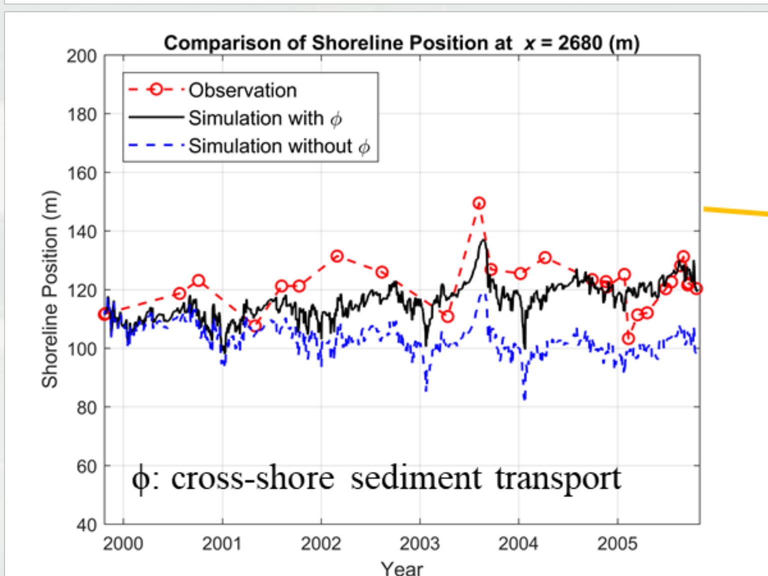
$$d_B(t)=d_{B0}-(R+S)t$$



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



≈ 20m!



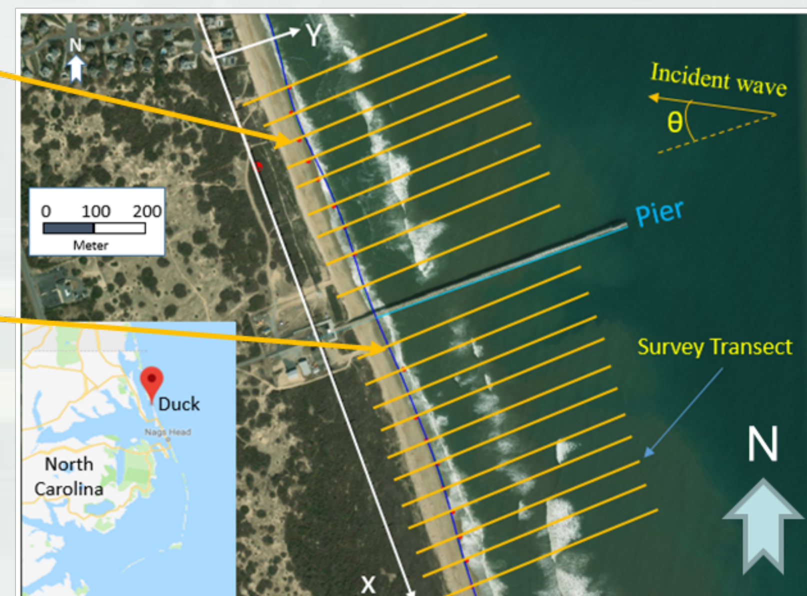
- Model Parameters

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

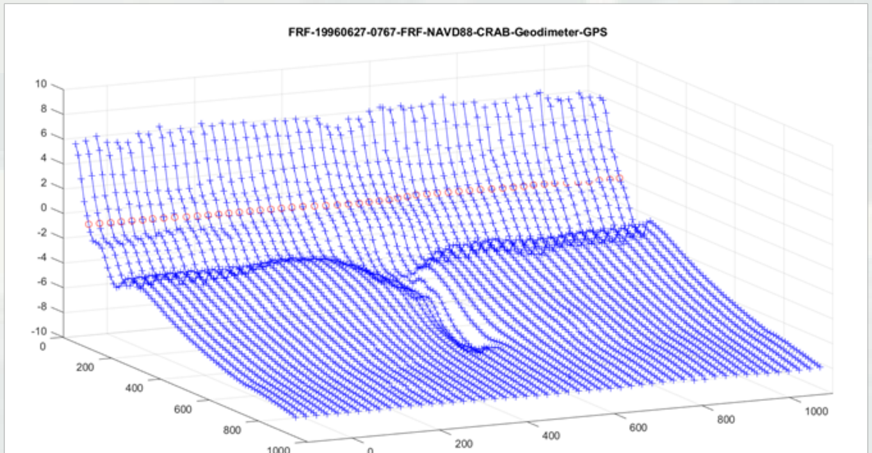
Scaling parameter α_D= 1.50

C_w, C_C, ε_B, ε_S by Fernández-Mora et al. (2015)

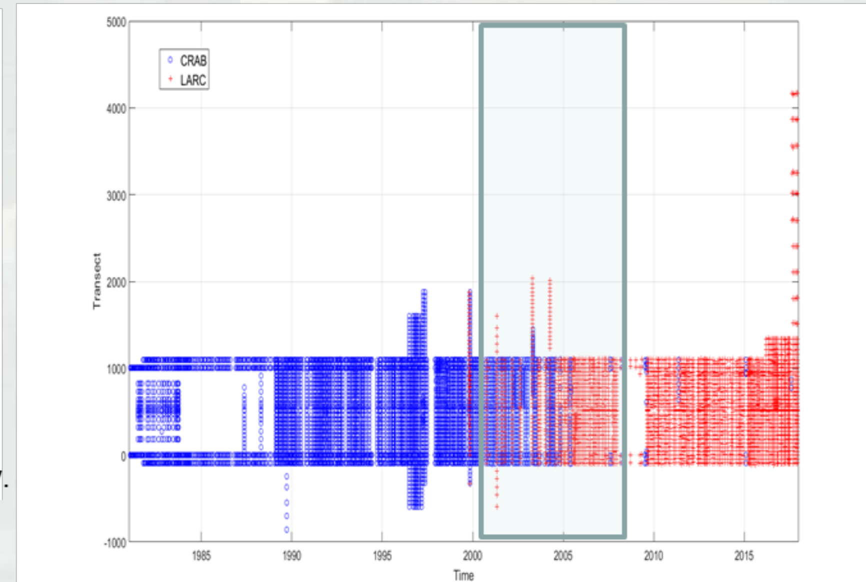


Innovative solutions for a safer, better world

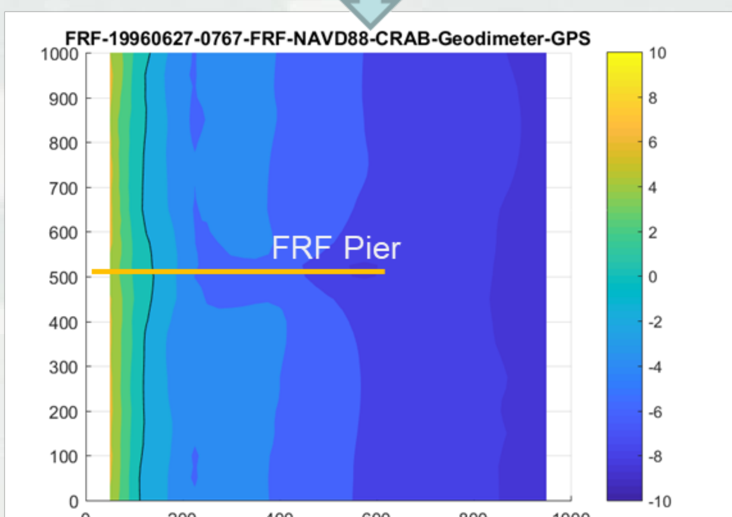
Determining Shoreline Positions from FRF Survey Data of Beach Profiles



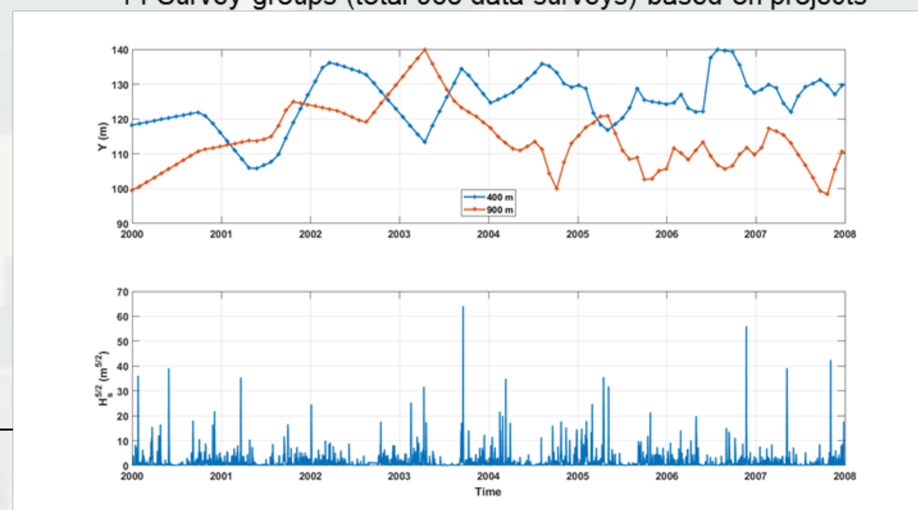
Representative beach profile coverage area along the FRF property.
CRAB =Coastal Research Amphibious Buggy
LARC=Lighter Amphibious Resupply Cargo



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



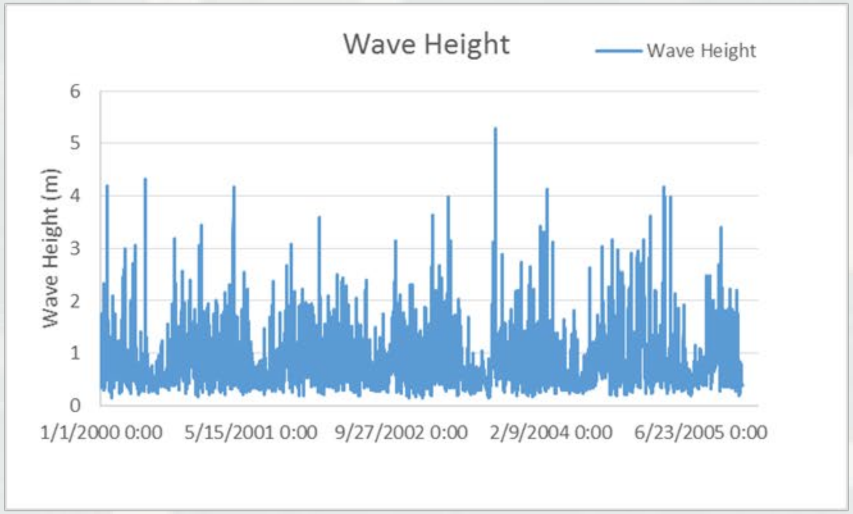
Bathymetric contour plot showing the relatively straight and parallel contours except in the vicinity of the pier

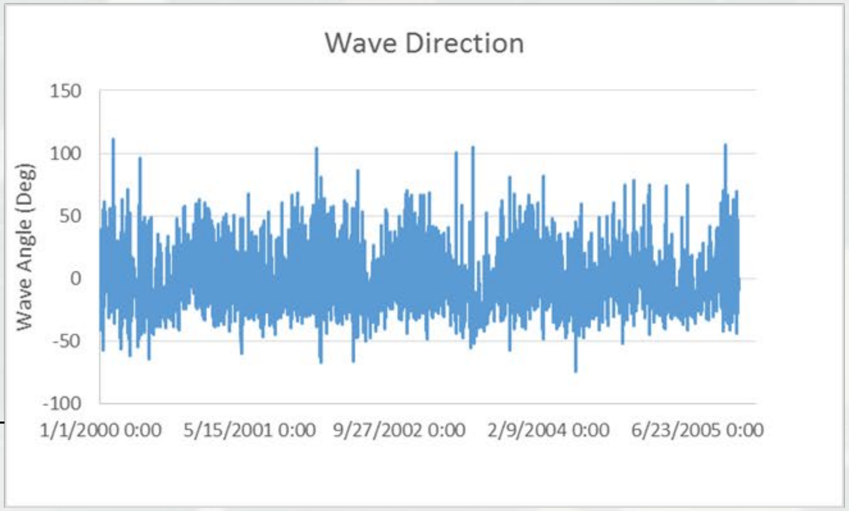


Wave Data (2000/1/1 – 2006/1/1)

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

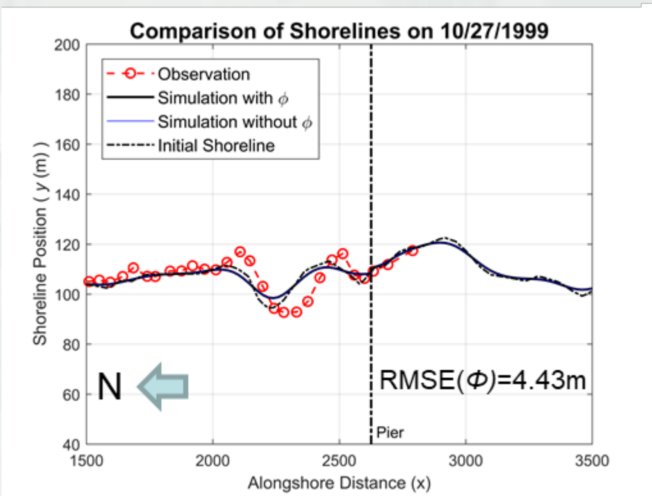
	H (m)	T (s)	alfa (deg)
Average	0.82	9.18	-5.06
Min	0.14	3.09	-74.62
Max	5.28	18.96	111.32
σ	0.53	2.68	18.52

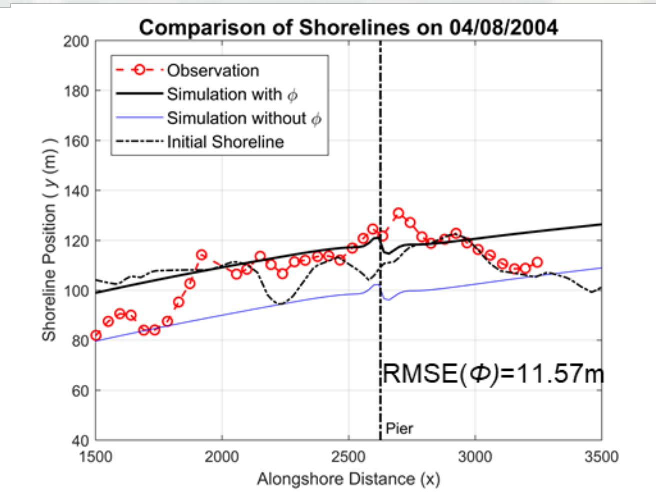


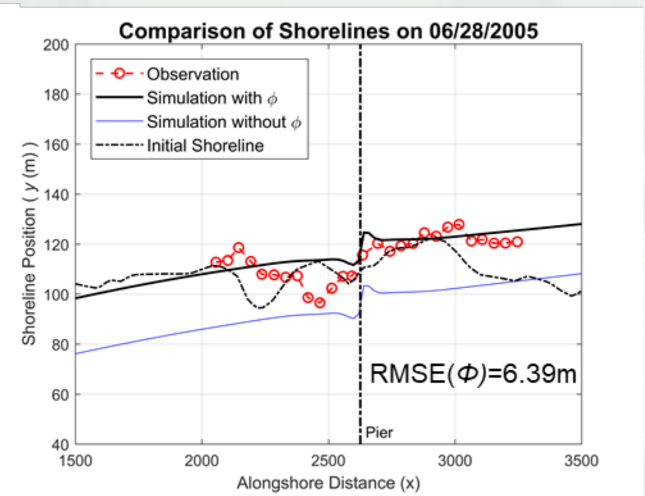


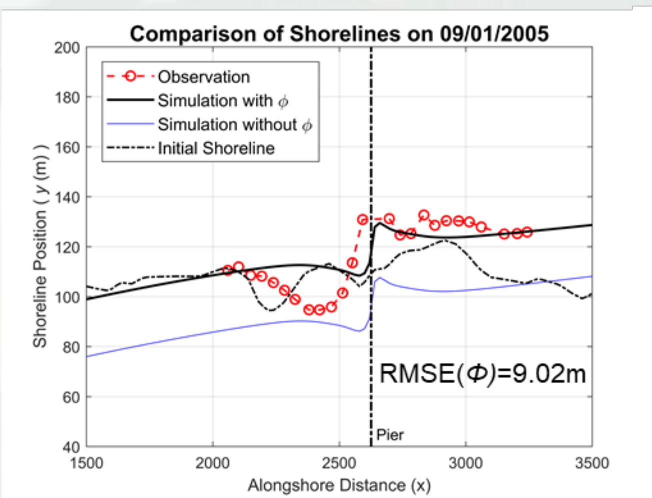
Model Validation:

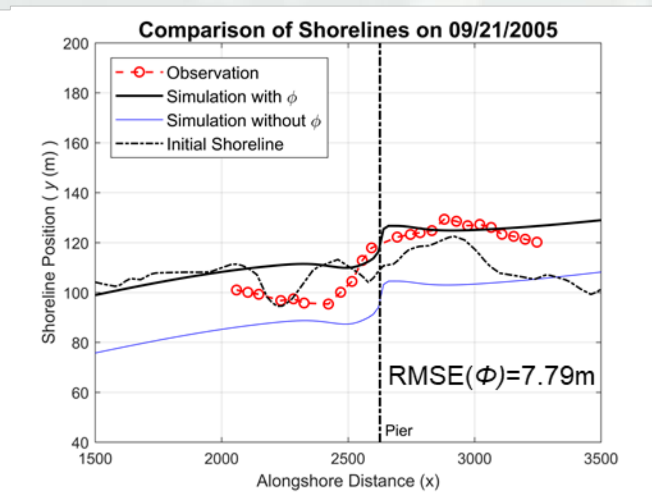
Comparisons of Shoreline Positions (1999-2005)

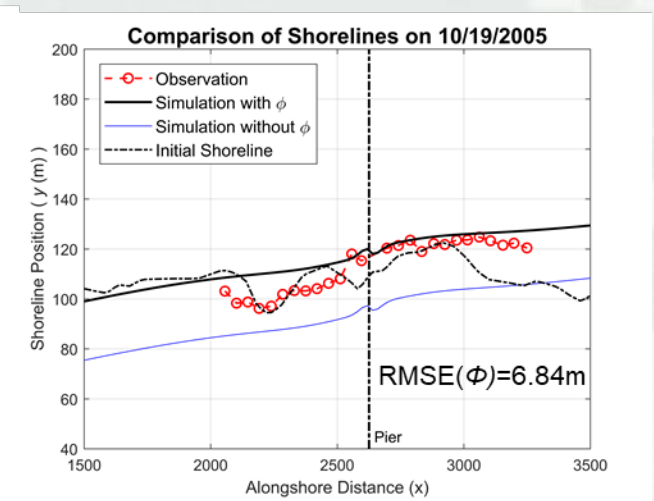






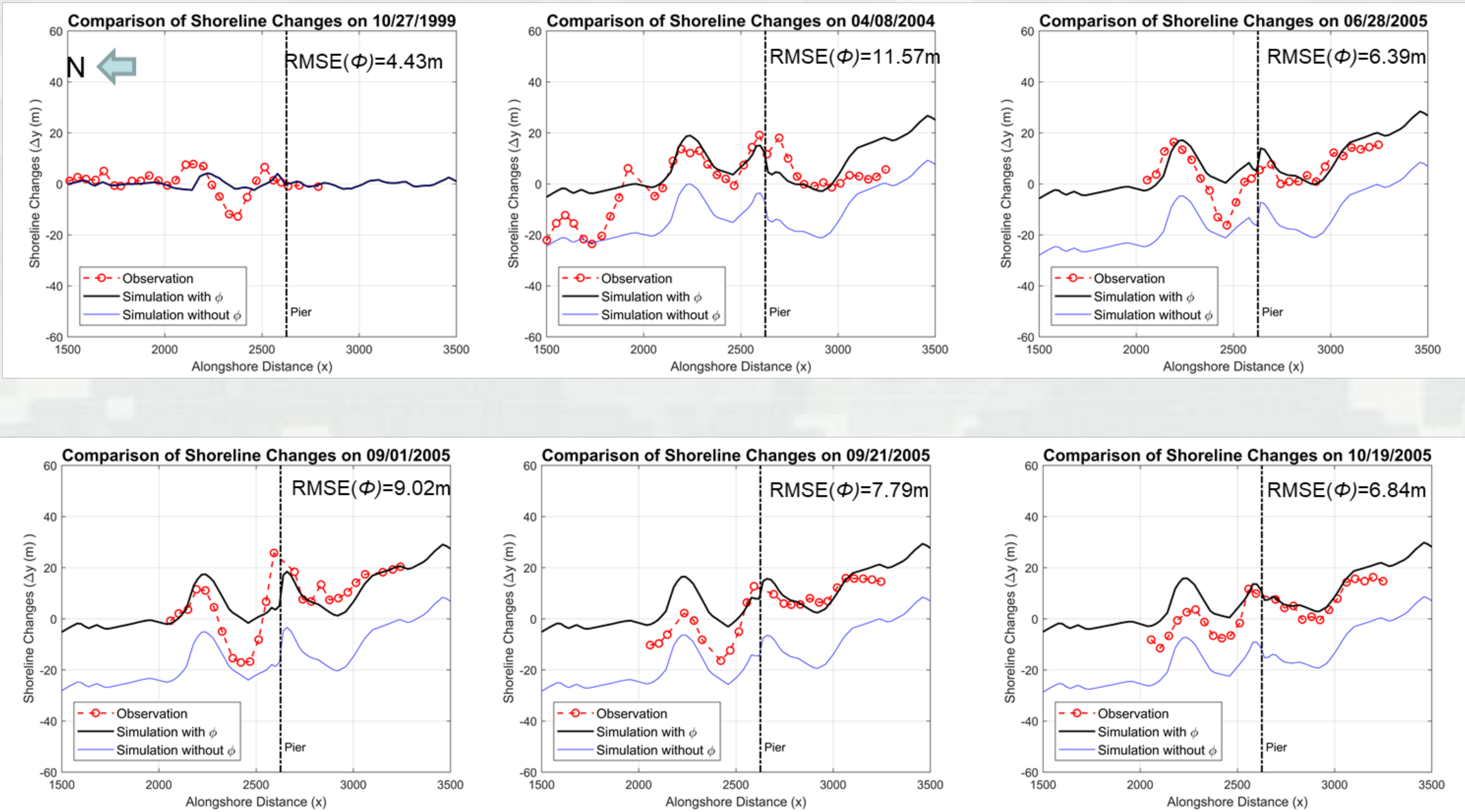




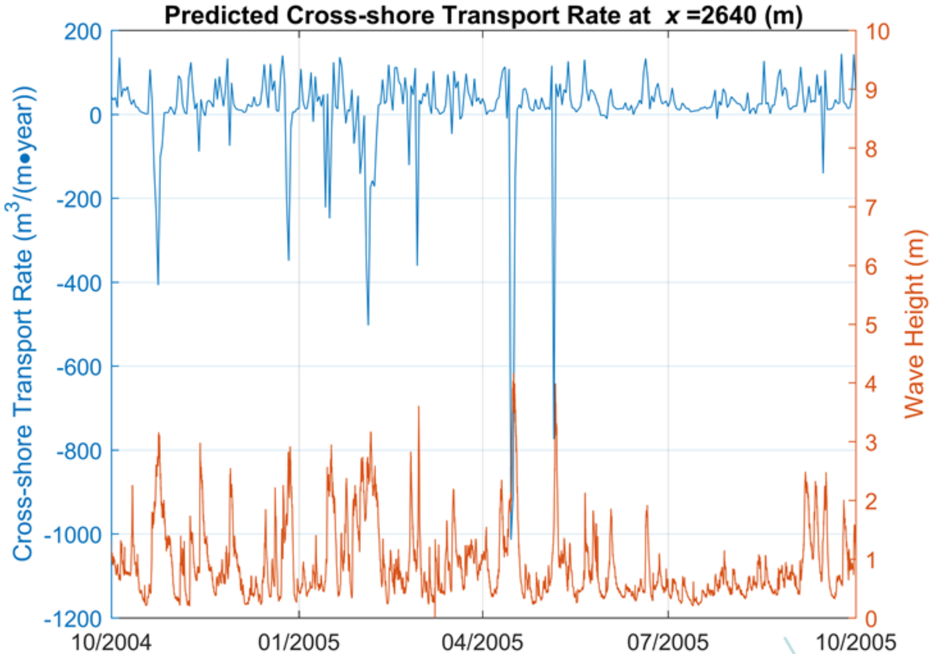


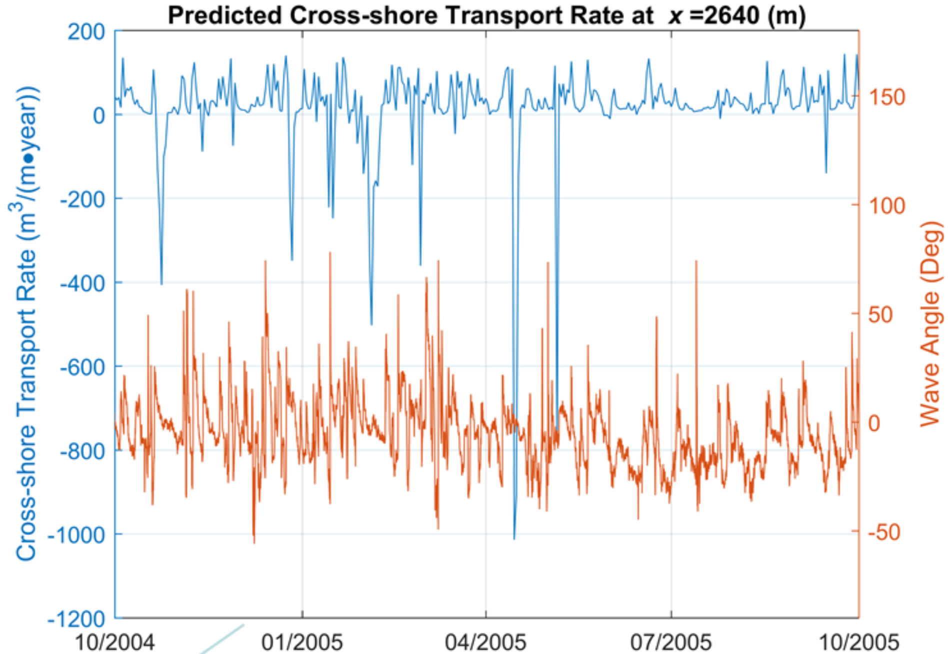
Model Validation: (w or w/o xshore)

Comparisons of Shoreline Changes (1999-2005)

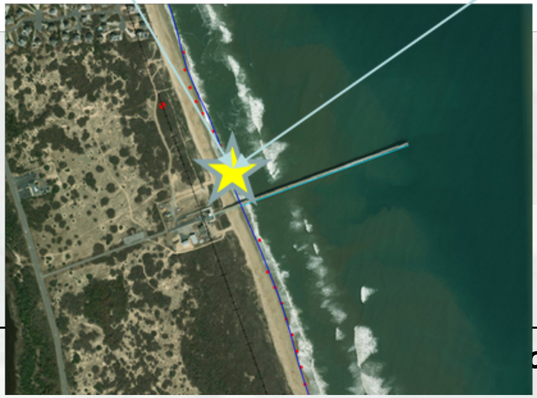


Predicted Cross-Shore Transport Rate (Φ) (1999-2005)



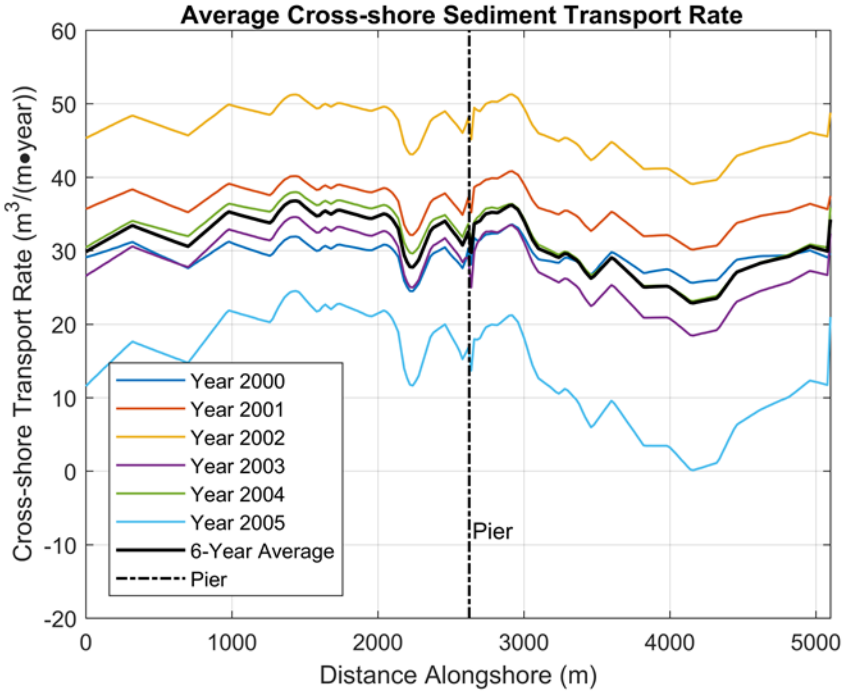


(a) Φ vs Hs

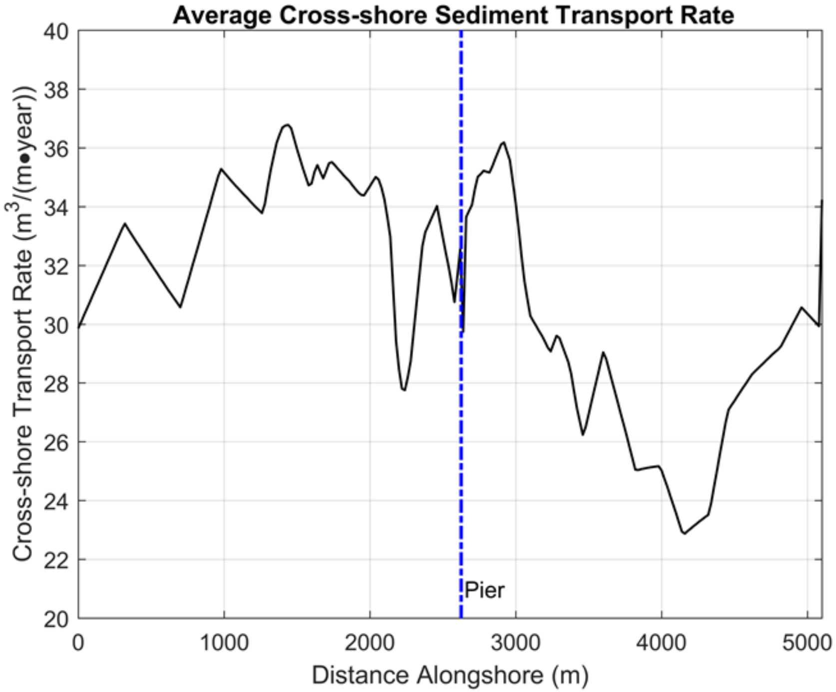


(a) Φ vs α (angle)

Annual Cross-Shore Transport Rate



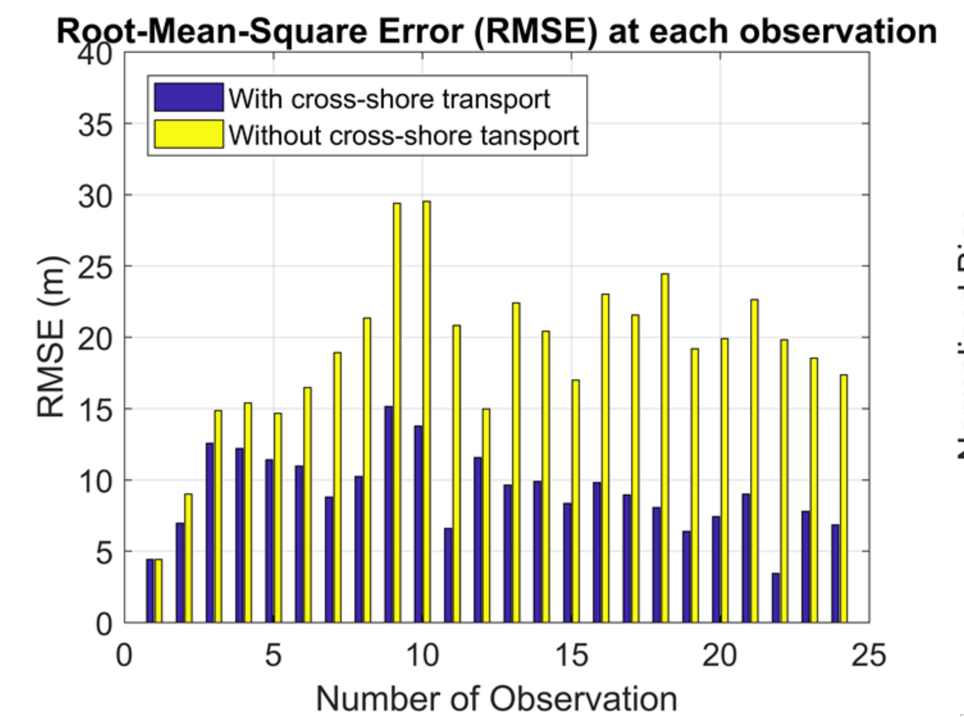
(1) Annual Average Φ

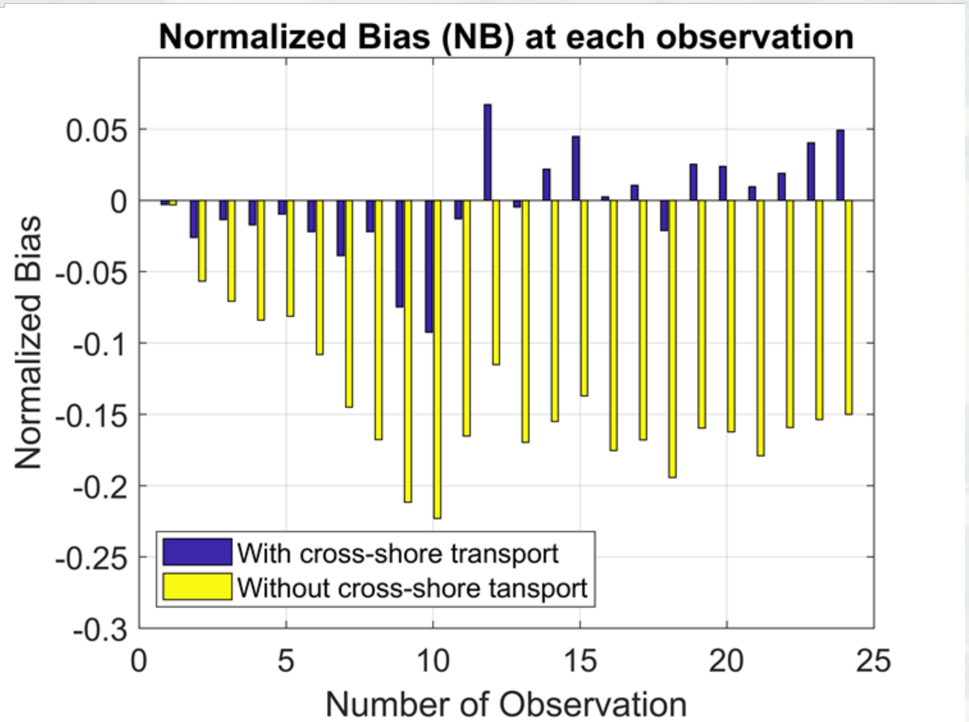


(2) 6-year Average Φ

Model Skill Assessment:

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





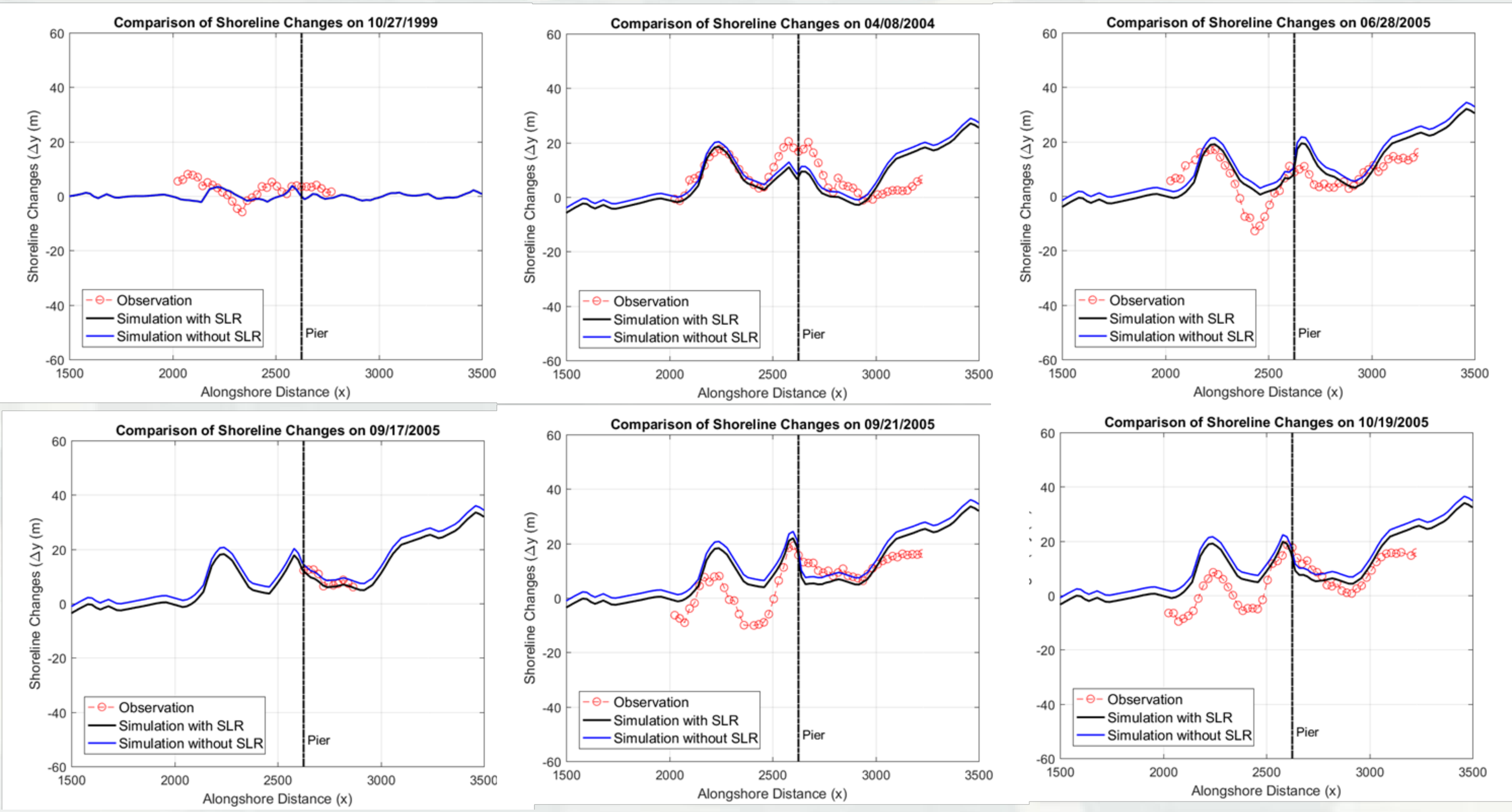
$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(m_i - O_i)^2}$$

m_i: model values
O_i: Observation data

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

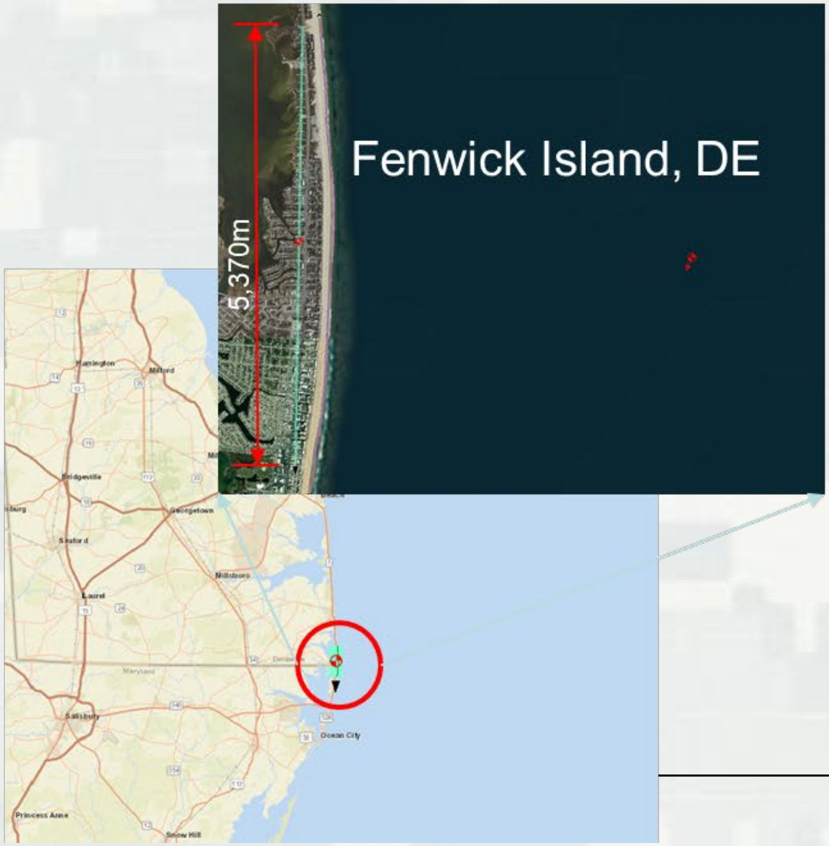
Model Validation (Impact of SLR)

Comparisons of Shoreline Changes (1999-2005)



Modeling of Shoreline Change in Fenwick Island, DE with Beachfill Event

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
2013/07/13 0:00 - 2017/01/01 0:00
starting before the beach fill in Sept. 2013

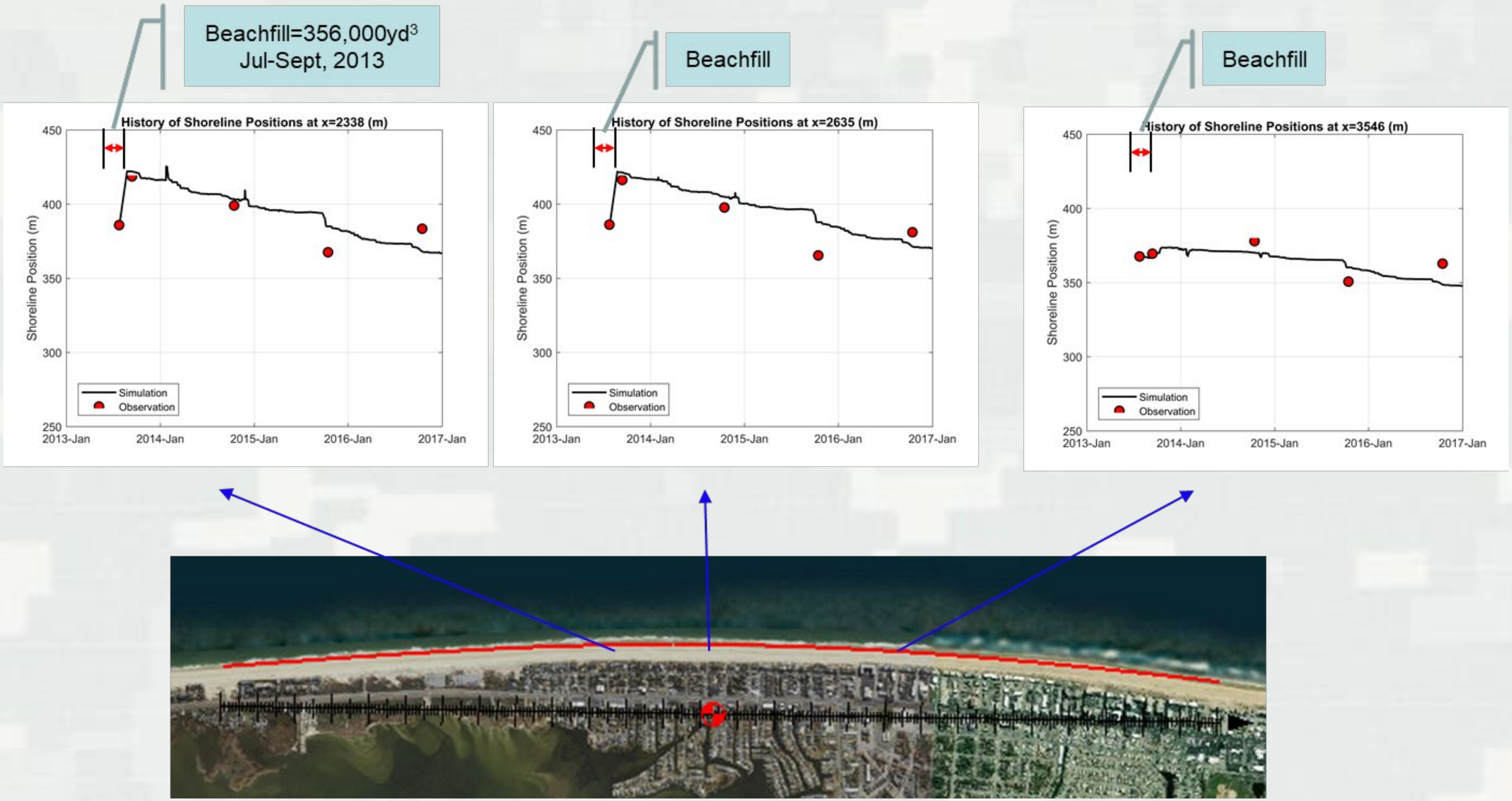
Beachfill=356,000yd^3 Jul-Sept, 2013

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

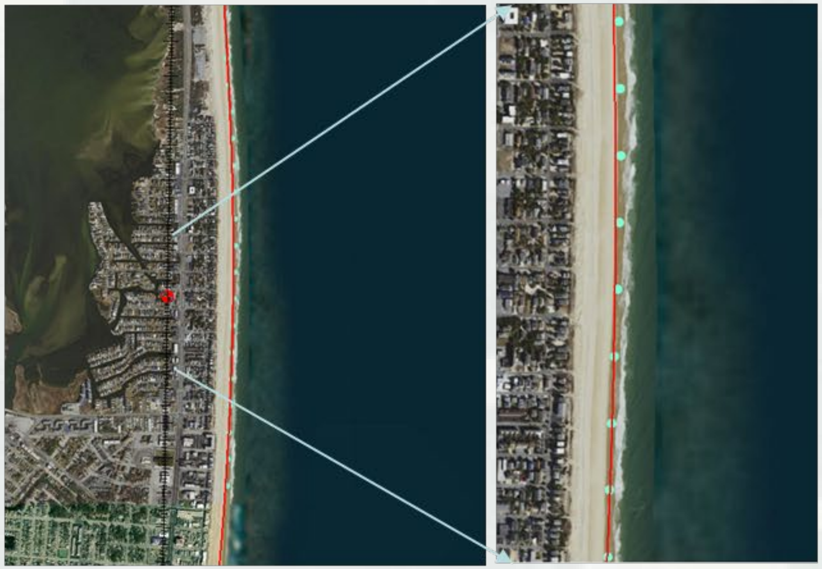
Calibrated Model Parameters:
K1 = 0.90
K2 = 0.35

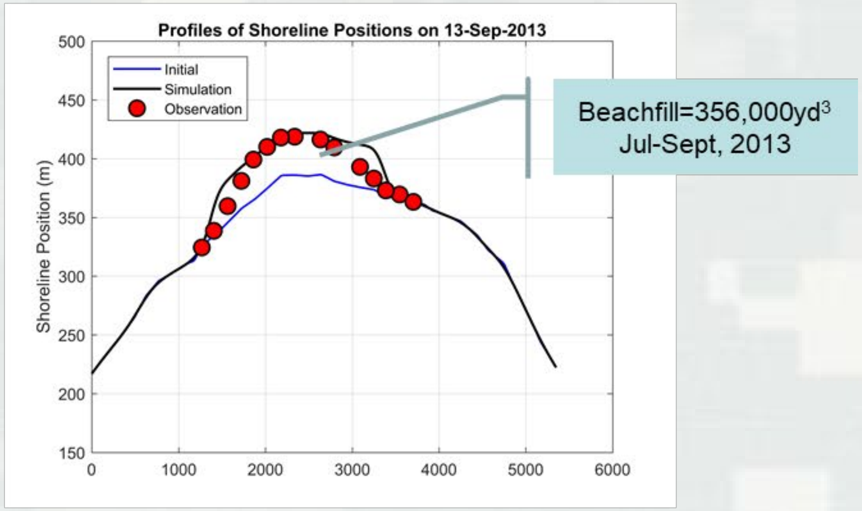
Cross-shore transport included
Scaling parameter α_D= 0.16
C_w, C_C, ε_B, ε_S by Fernández-Mora et al. (2015)

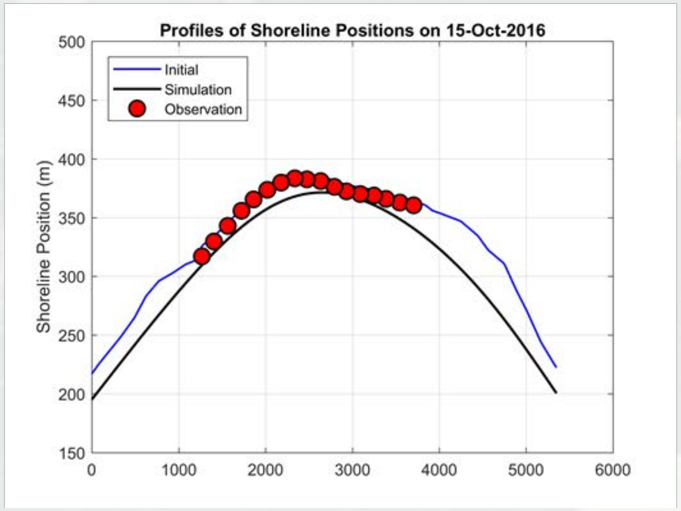
History of Shoreline Positions in Fenwick Island, DE



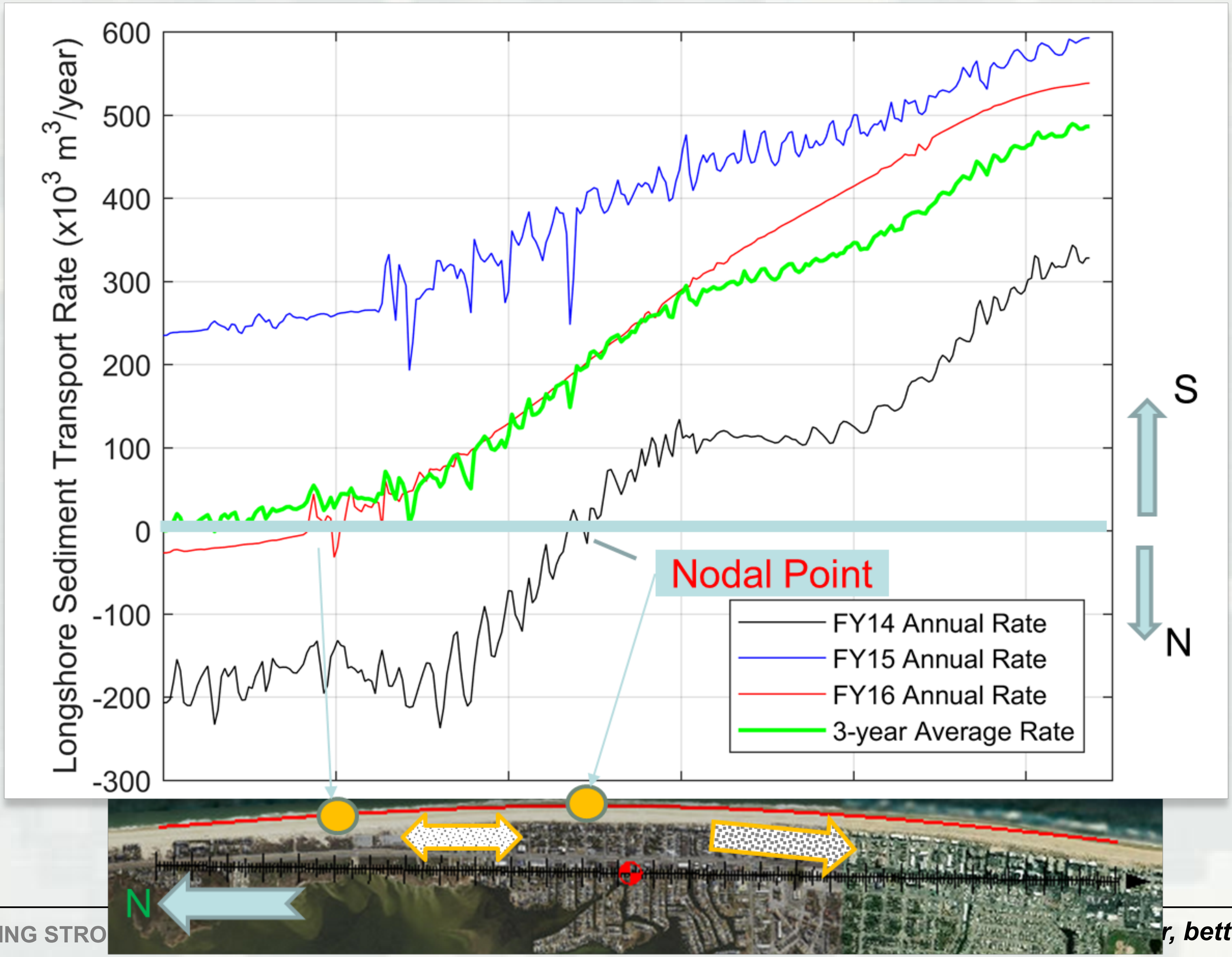
Comparisons of Shoreline Positions on 09/13/2013 and 10/15/2016



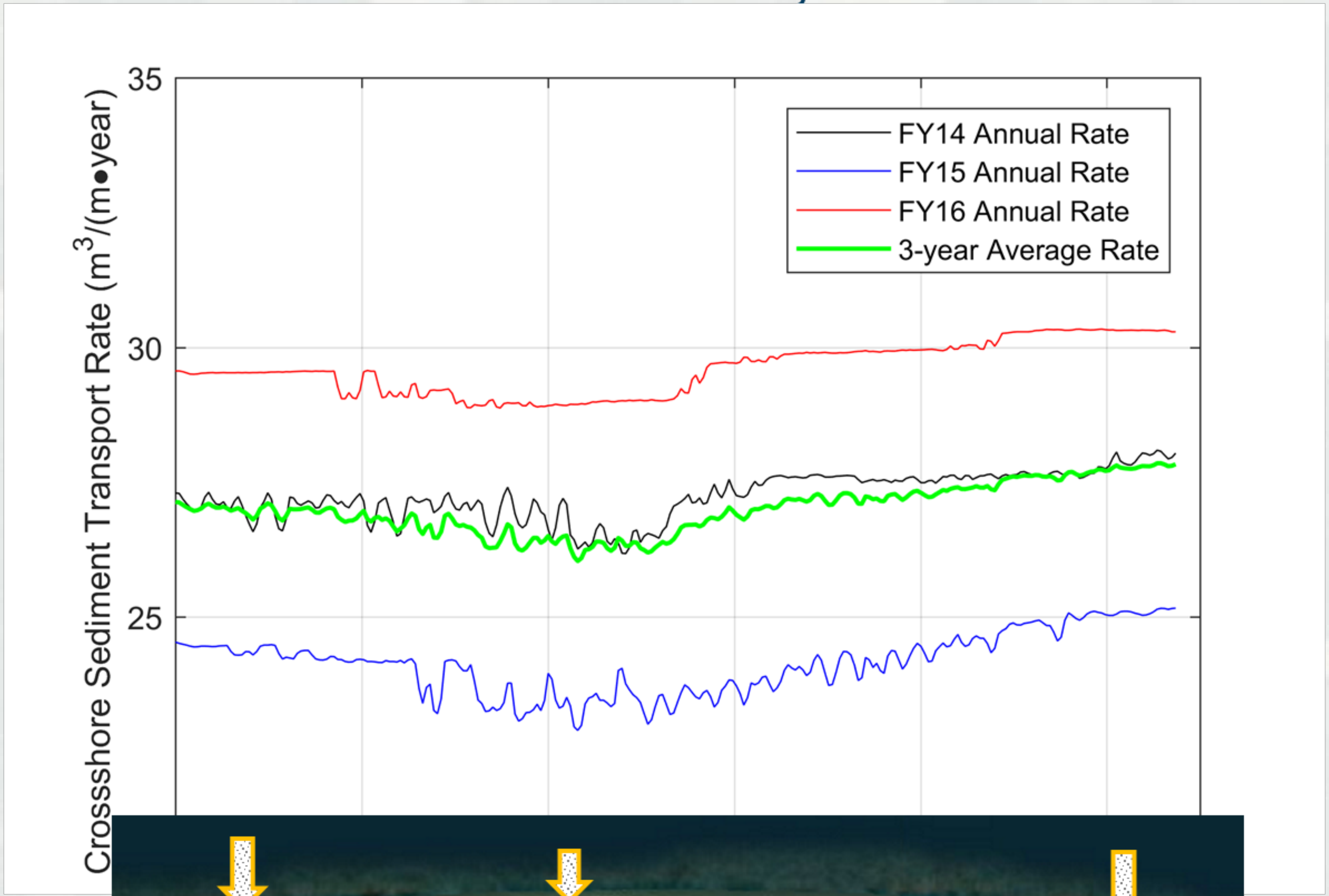




Annual Longshore Sediment Transport Rate in Fenwick Island, DE



Annual Crossshore Sediment Transport Rate in Fenwick Island, DE



Conclusion

- One-line shoreline evolution model such like GenCade is an engineering application tool with a unique capability for making long-term prediction of shoreline changes in spatio-temporally varying conditions of waves and beach morphology. Inclusion of long-term signal driving net sediment transport alongshore and cross-shore is critical to improve one-long model predictability.

- GenCade's new capabilities (Cross-shore sediment transport and SLR effect) are important in simulating shoreline evolution. Nonlinearity of wave dynamics plays an important role in estimating net cross-shore sediment transport.

- The values of empirical parameters (C_W, C_C, ε_B, and ε_S) which were calibrated in Duck coast, NC, by Fernández-Mora et al (2015) are appropriate for another Atlantic coast (e.g. the Fenwick Island coast in DE). Parametric cross-shore transport model is capable of estimating cross-shore transport rate in different coasts. So this parametric model is not site-specific.

- Further investigation of uncertainties by other factors (model parameters, boundary conditions, etc) is needed. As an ongoing research, we are developing a GenCade-Based Monte-Carlo simulation model for estimating shoreline changes probability and uncertainty.

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Thank you for your attention!

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