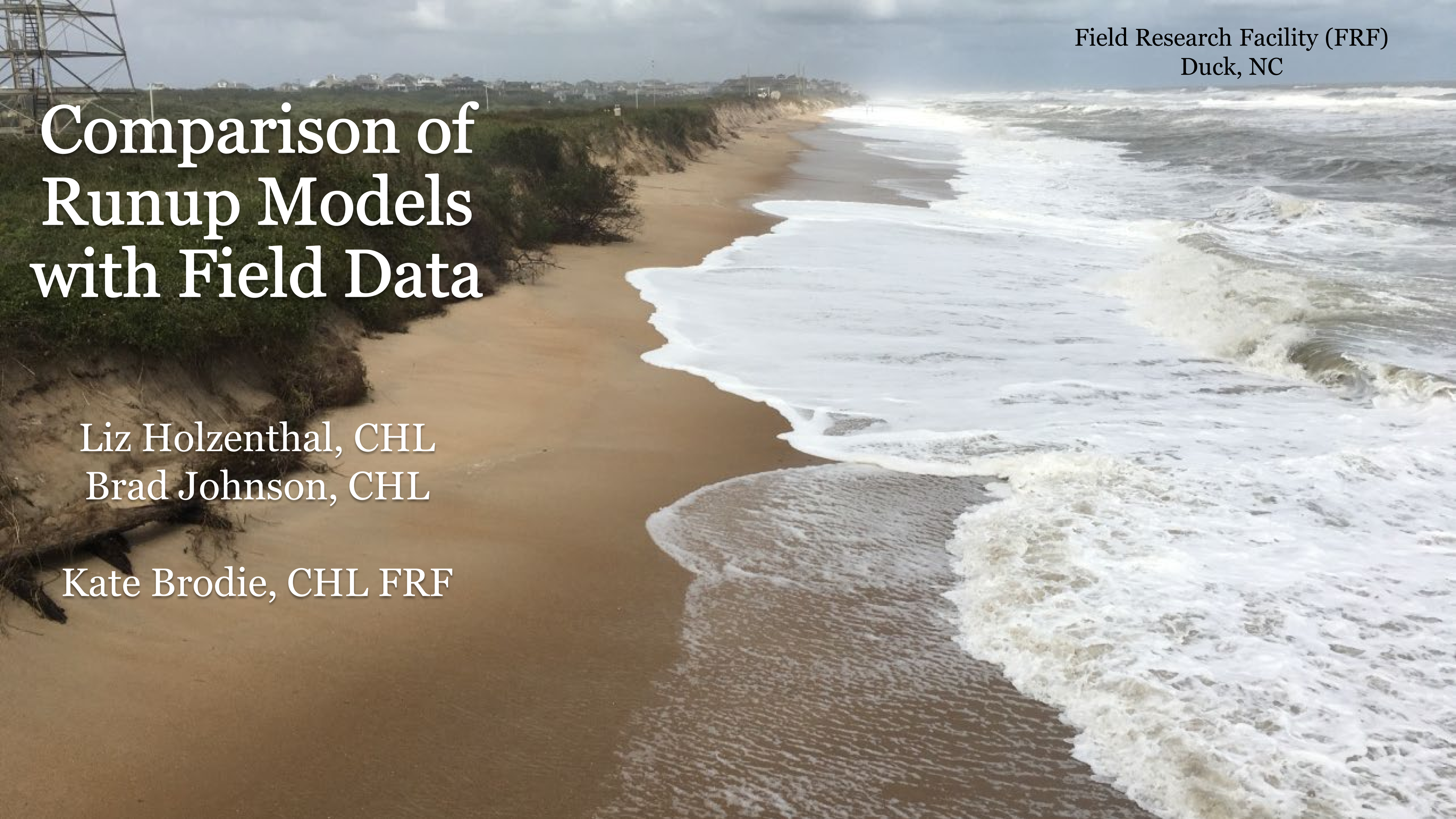
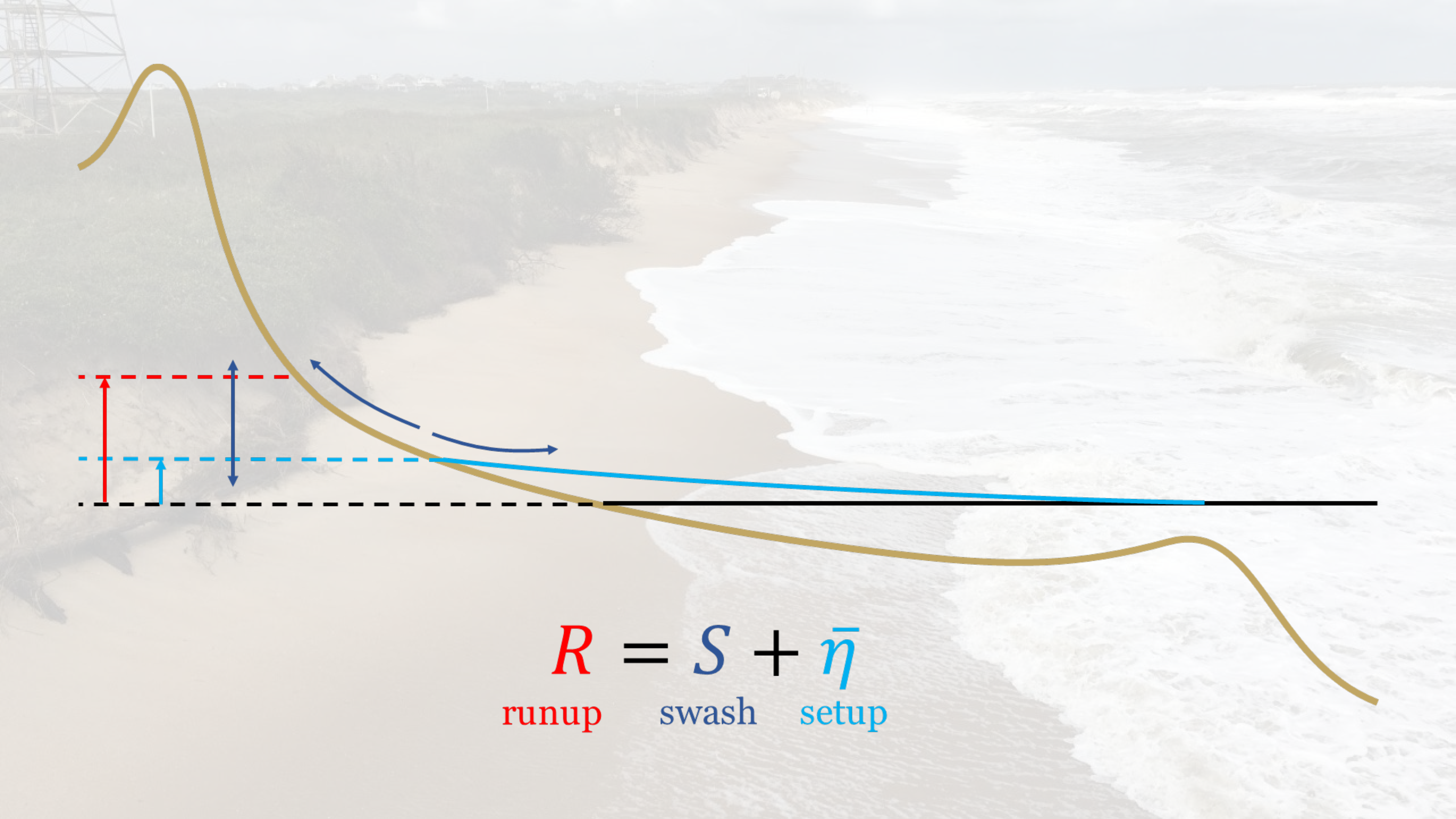


Field Research Facility (FRF)
Duck, NC

Comparison of Runup Models with Field Data

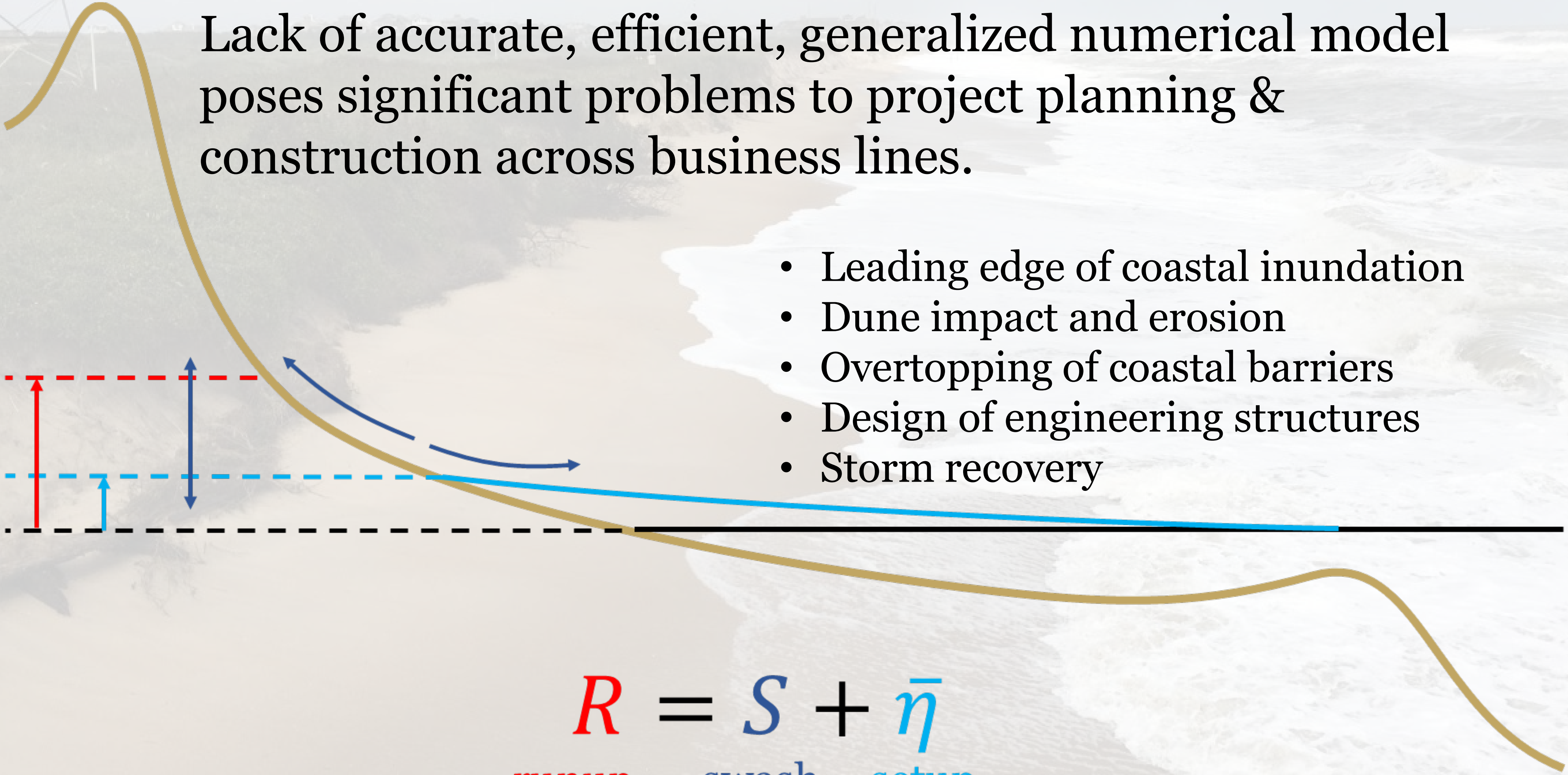
Liz Holzenthal, CHL
Brad Johnson, CHL

Kate Brodie, CHL FRF


$R = S + \bar{\eta}$
runup
swash
setup

Lack of accurate, efficient, generalized numerical model poses significant problems to project planning & construction across business lines.

- Leading edge of coastal inundation
- Dune impact and erosion
- Overtopping of coastal barriers
- Design of engineering structures
- Storm recovery



$$R = S + \bar{\eta}$$

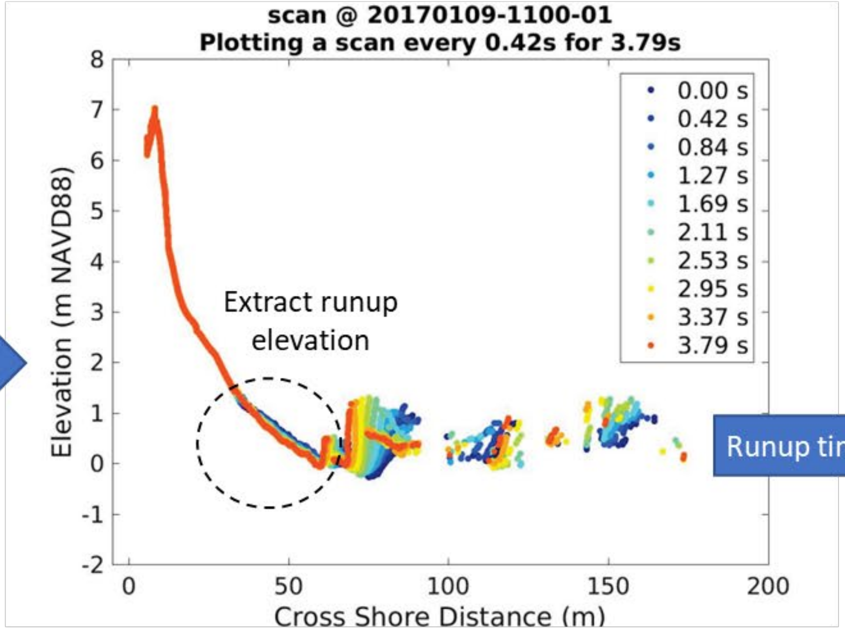
runup swash setup

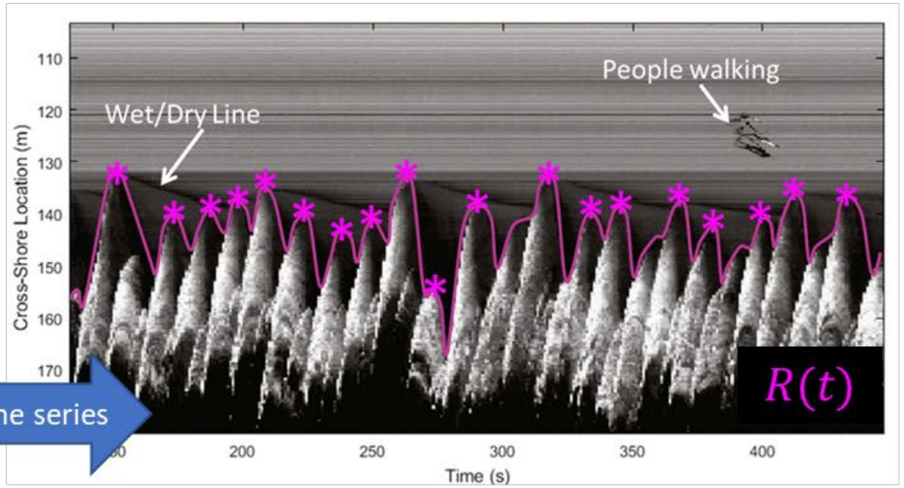
Modeling approaches

1. **Empirical** – algebraic relationship between beach slope and wave conditions, but *requires calibration, lacks physical processes, and only dependent on offshore conditions and general beach characteristics*
2. **Time averaged swash** – wind wave (swell) evolution model is coupled with swash momentum closure expressions, *which are derived empirically*
3. **Surfbeat** – broken wave modeled as bore, but assumes infragravity (IG) wave frequency band dominates swash component, *neglecting wave-wave (and swash-swash) interactions*
4. **Nonhydrostratic** – fully resolved wave-by-wave modeling including dispersive effects, but *computationally inefficient for practical purposes*

Modeling approaches

Given a high-quality dataset of runup observations for known wave conditions, how do existing models quantitatively compare in terms of accuracy and speed?





Left, middle, right photos taken from Brodie et al., 2018 (ERDC/CHL SR-18-3)

Modeling approaches

Modeling approaches, cont

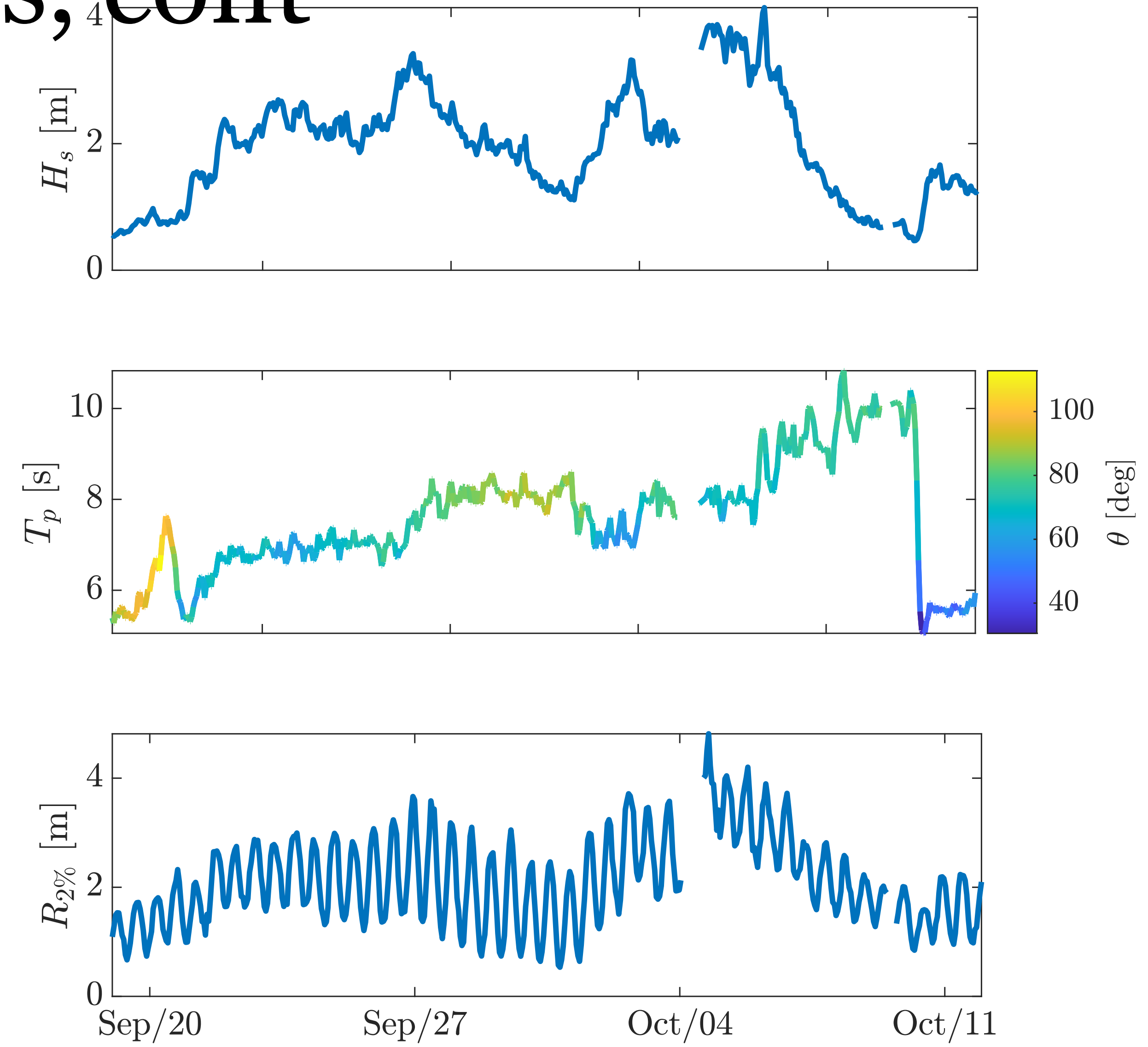
Empirical – *Stockdon equation*

Time averaged swash
- *Coastal Modeling System (CMS)*
- *CSHORE*

Surfbeat – *XBeach-SB*

Nonhydrostatic – *XBeach-NH*

$R_{2\%}$ *= 2% exceedance probability, used to inform FRM design*

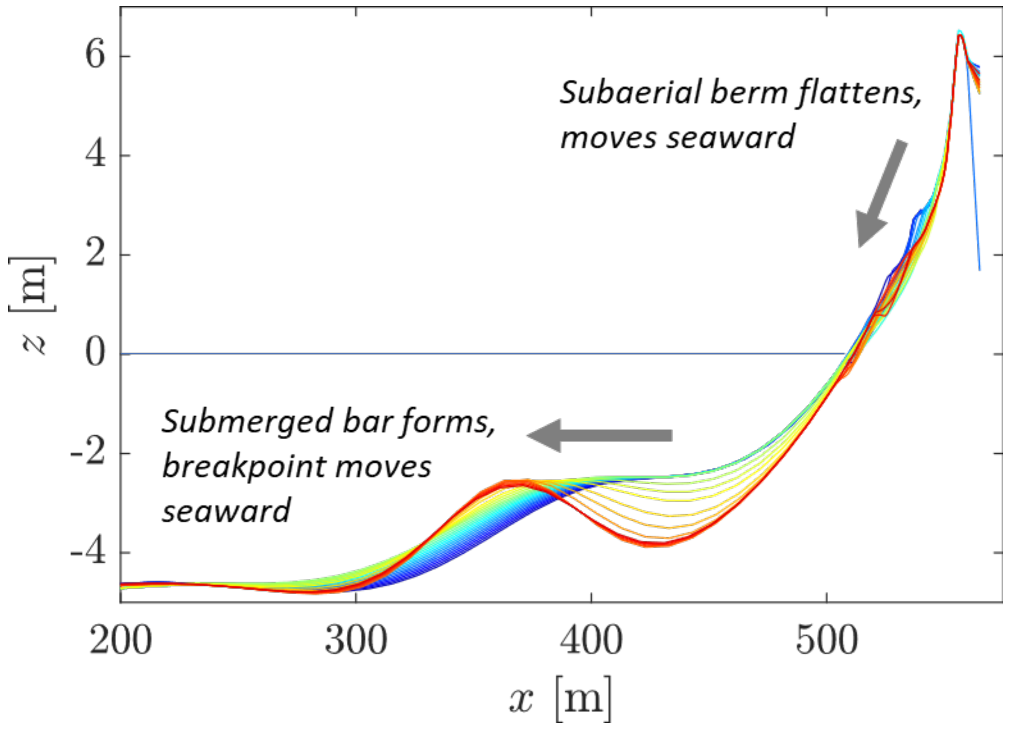


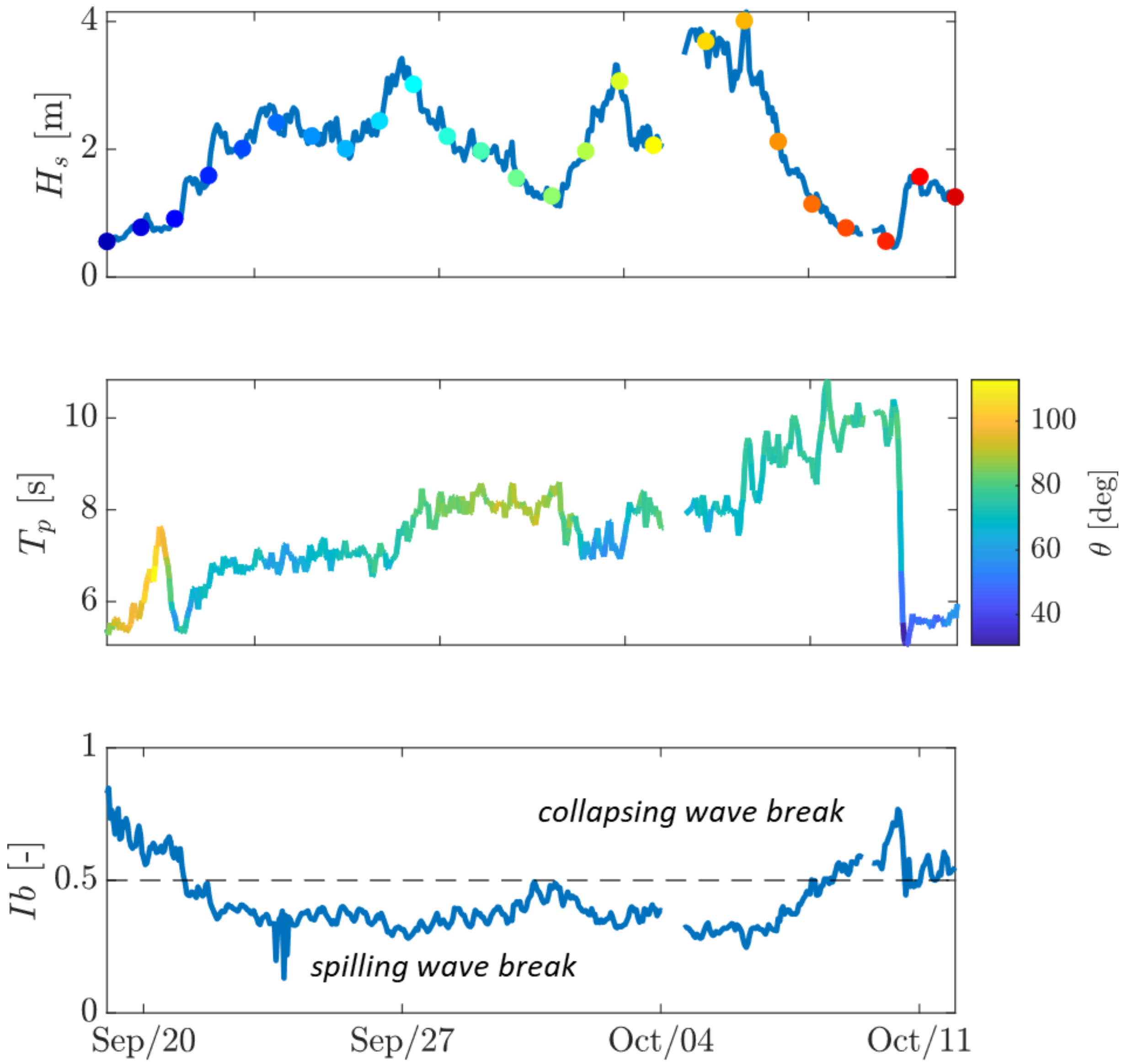
H_s = significant wave height, T_p = peak wave period

Modeling approaches

533 unique simulations per model

- *Lidar-derived bathymetry*
- *Offshore hydro from wave gauges*
- *Run until equilibrium reached (steady state)*



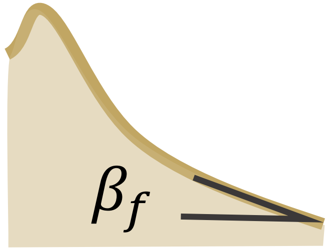


Model 1 – Stockdon, et al. (2006)

- Empirical formulation
- Based on a large dataset (collected from FRF, California, Oregon, Netherlands)
- Somewhat different with respect to Iribarren (*Ib*) models (Mase, Hunt, Holman, etc.), but more general

$$R_{2\%} = 1.1\left\{0.35\beta_f(H_{mo}L_o)^{1/2} + \frac{1}{2}(H_{mo}L_o\left[0.563\beta_f^2 + .004\right]^{1/2}\right\}$$

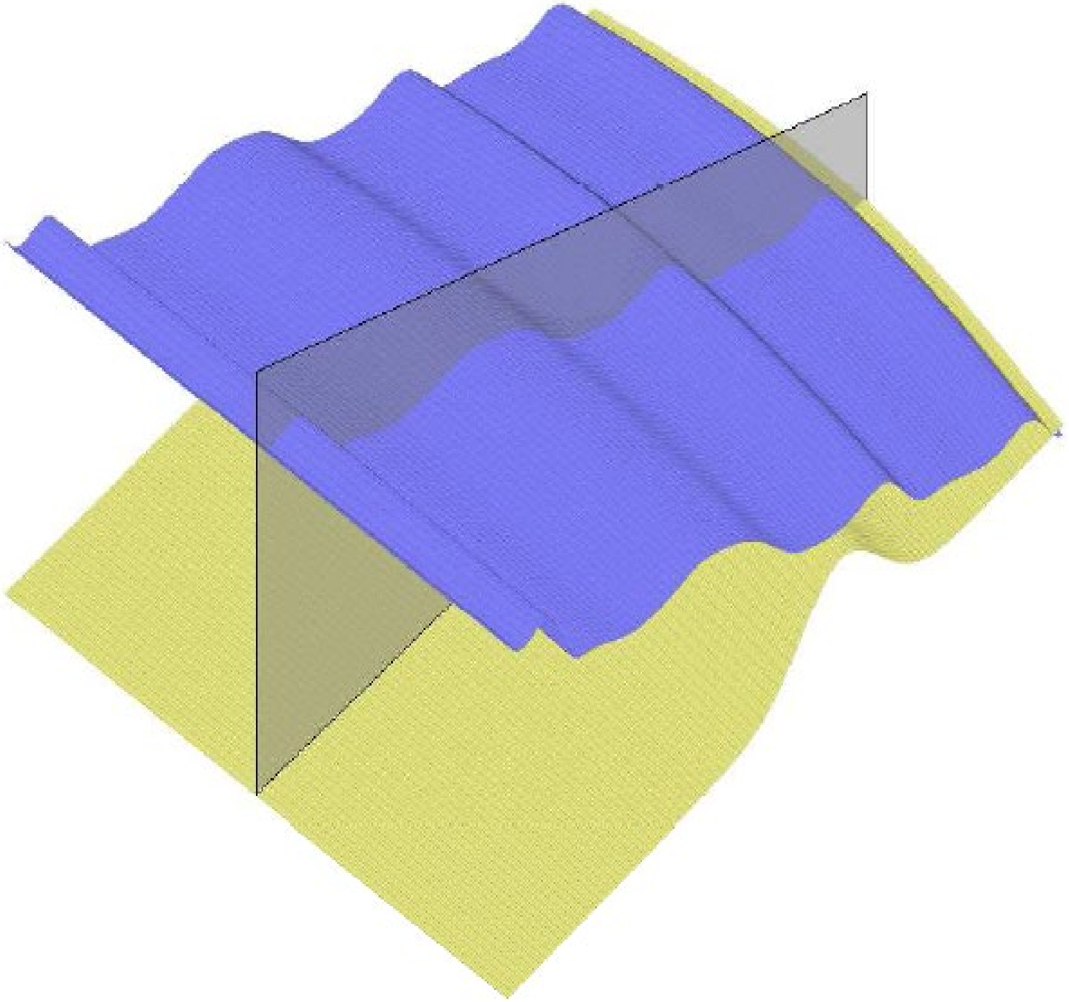
$$Ib = \frac{\tan(\beta)}{\sqrt{H/L_0}}$$



H_{mo} = deep water wave height, L_o = deep water wavelength

Model 2 – CSHORE

- Assumes longshore uniformity
- Solve equations for <u>time-steady</u> wave energy, momentum for time-averaged hydrodynamics
- Same number of equations & unknowns in fully wet (with linear radiation stress)
- *No explicit prediction of IG component*
- e.g CSHORE, SBEACH, Unibest



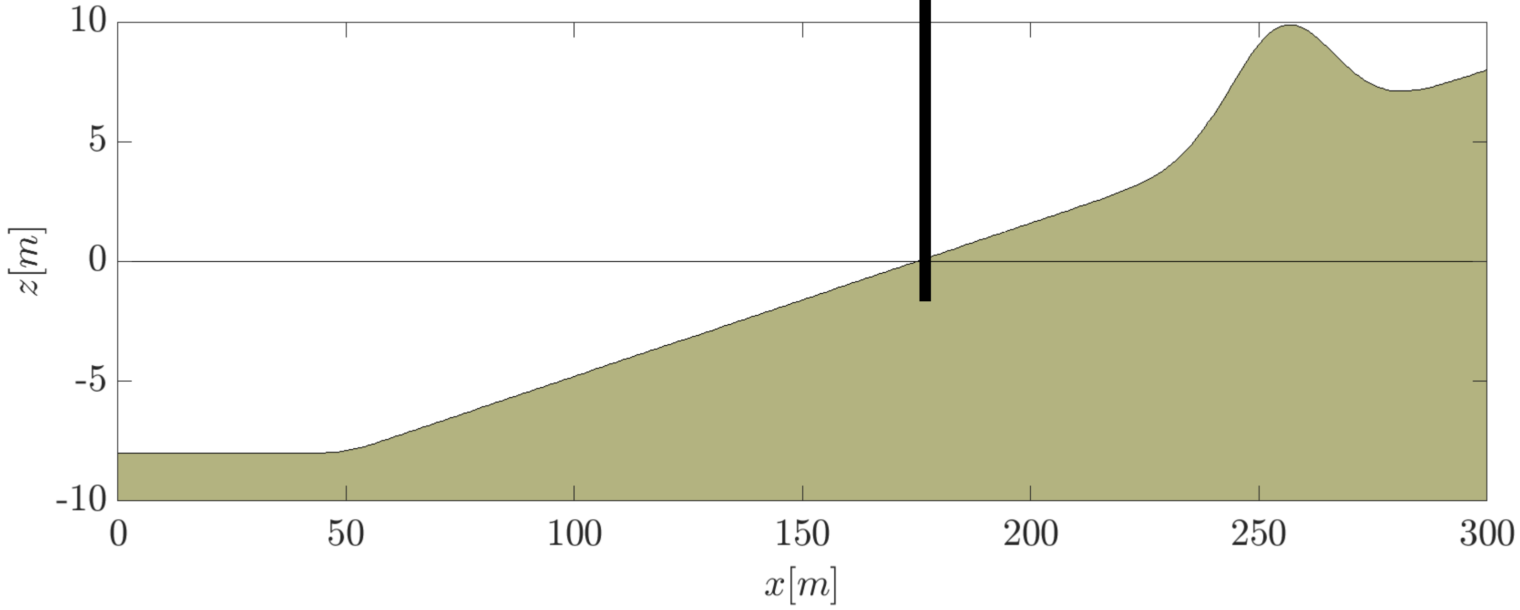
Model 2 – CSHORE

Fully wet portion

- Energy, Momentum, Mass conservation
- Gaussian random variable for wave processes

Partially wet/dry portion

- Momentum, Mass conservation
- Exponential random variable for wave processes
- Necessarily empirical



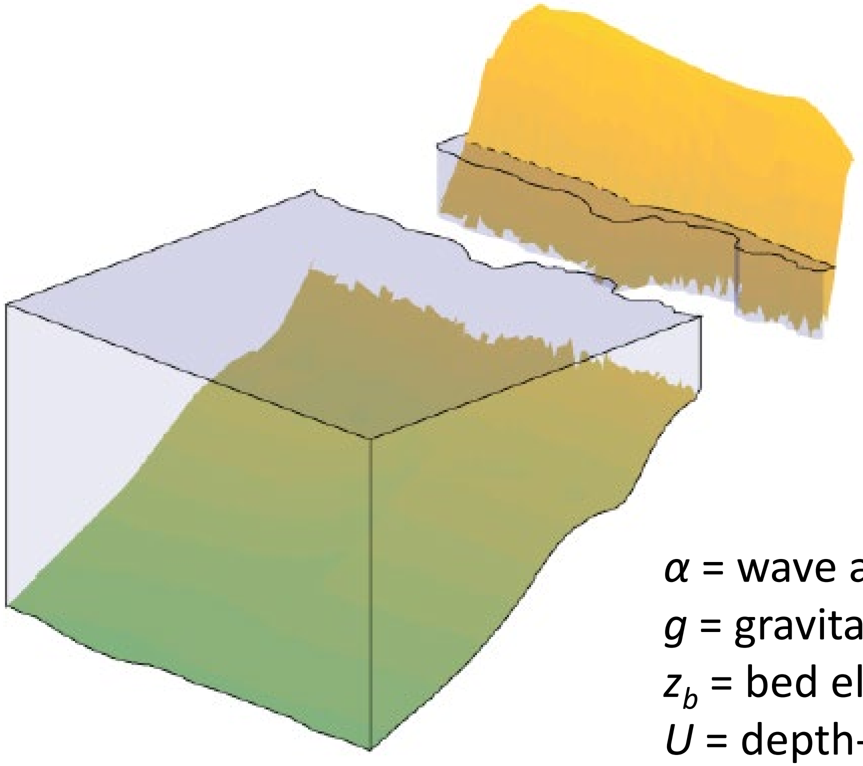
Model 3 – CMS

- Mass, momentum, and energy conservation equations in fully-wetted domain
- Solution of drastically simplified momentum equation for water depth in swash
- Assumes Rayleigh distributed peaks
- Uses same geometric argument to predict runup statistics from time-averaged hydrodynamics
- Initially used constant swash parameter, now: $A_o = 2.6 + 4.5\zeta$

$^{**}A_o$ was tailored to these data, other models are run without calibration.

$$\frac{\partial}{\partial x}(M\cos\alpha) = -g\bar{h}\frac{\partial z_b}{\partial x} - c_f\overline{|U|U}\cos\alpha$$

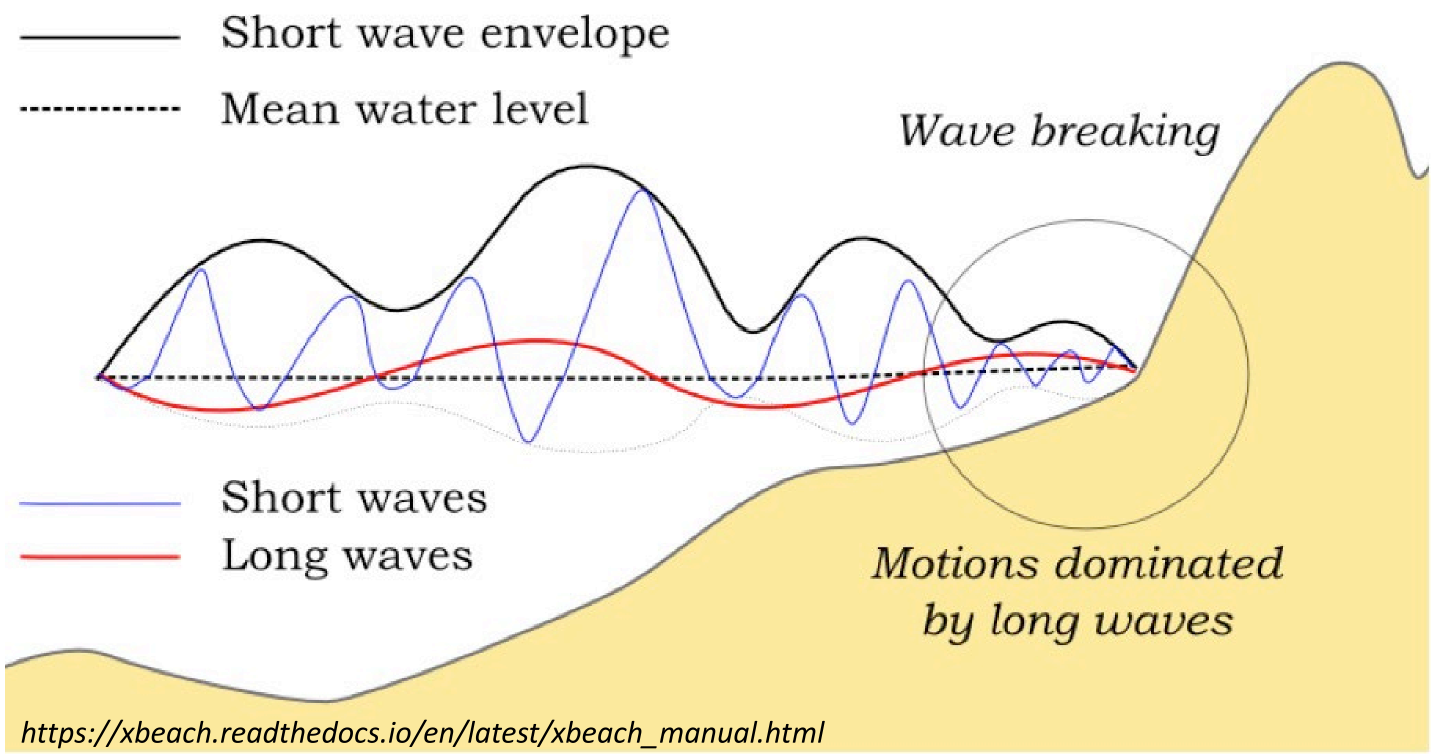
$$M \simeq A_0 g\bar{h}^2$$



α = wave angle
g = gravitational acceleration
z_b = bed elevation
U = depth-averaged velocity
c_f = drag friction coefficient

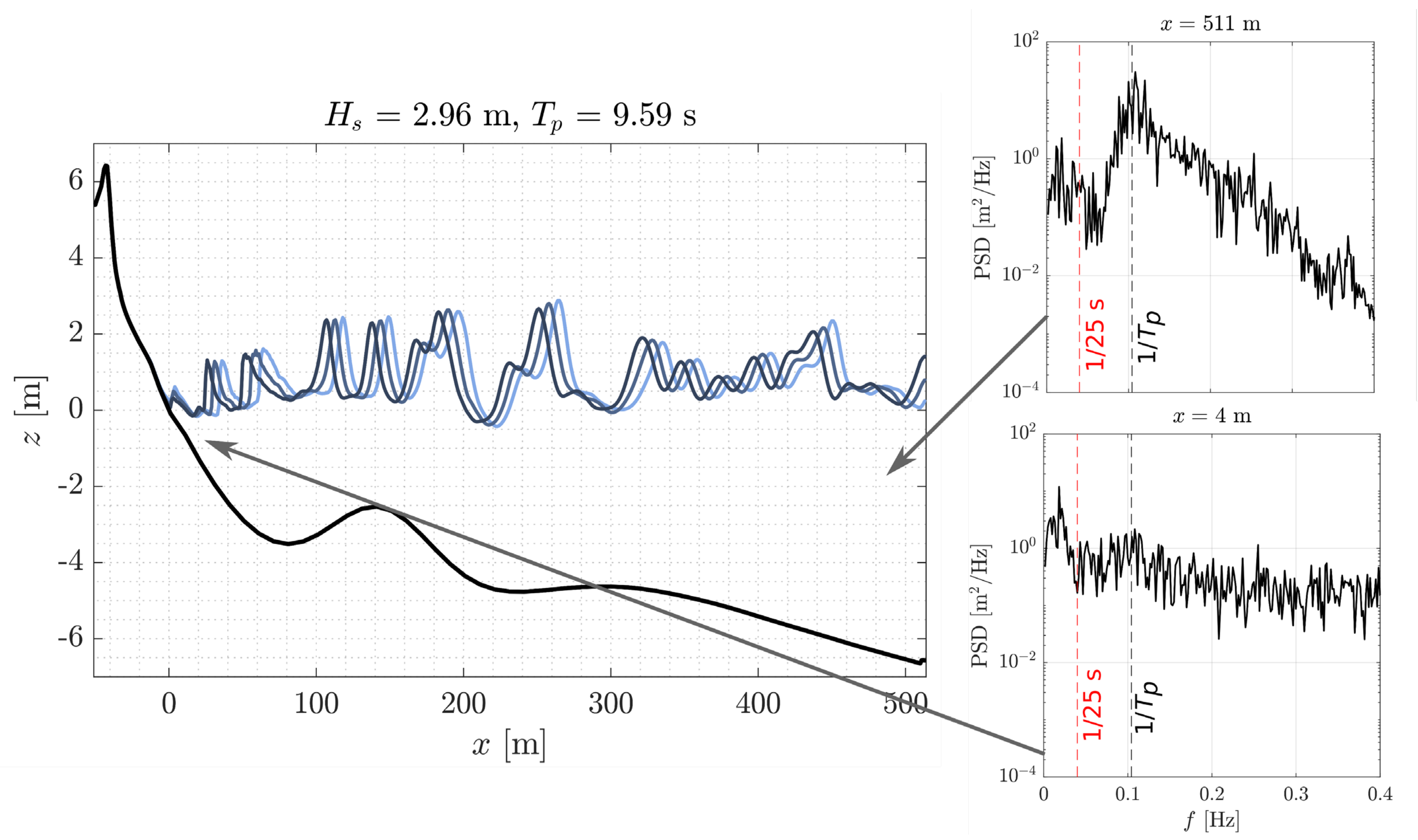
Model 4 – XBEACH-SB

- Phase-averaged, but IG resolving
- Swash routine forced by both IG and wave envelope energy
- Boundary conditions derive from power spectral density (PSD) spectra, so phasing is random



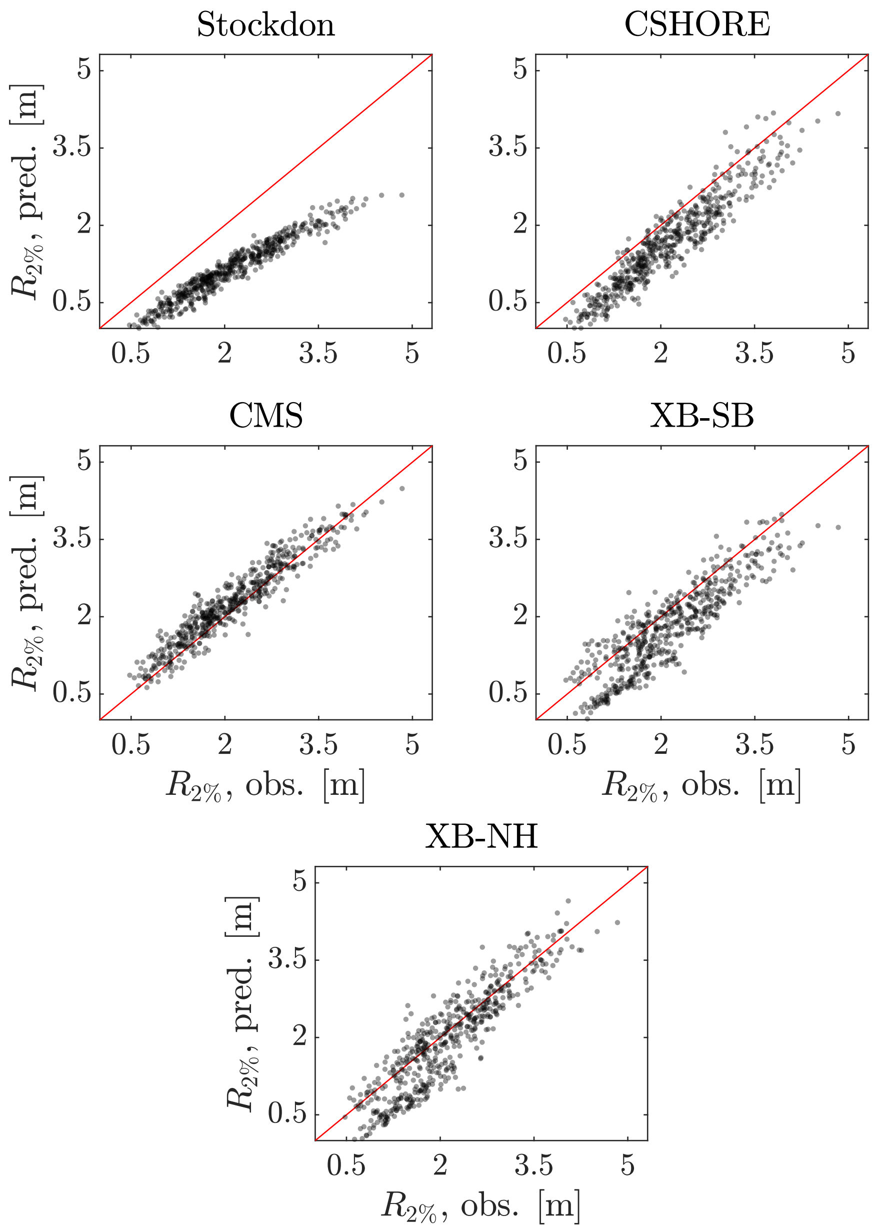
Model 5 – XBEACH-NH

- Phase-resolving, similar to Boussinesq models
- Boundary conditions as in XBeach
- Spectrum naturally evolves according to nonlinear transfer and breaking
- Steady state in 15 minutes, total simulation time 1 hr (model time)



Results – Model error vs. speed

	Runtime	RMSE (m)	NRMSE (-)
Stockdon	0.18 s	1.01	0.89
CSHORE	25.0 s	0.55	0.34
CMS	4.1 min	0.29	0.13
XB-SB	35.5 hr	0.53	0.30
XB-NH	124.4 hr	0.45	0.23



CMS *– positive bias, but lowest (N)RMSE*

XB-NH *– error more normally distributed, but higher variability*

(N)RMSE = (normalized) root mean square error

Results – Model error vs. speed

	Runtime	RMSE (m)	NRMSE (-)
Stockdon	0.18 s	1.01	0.89
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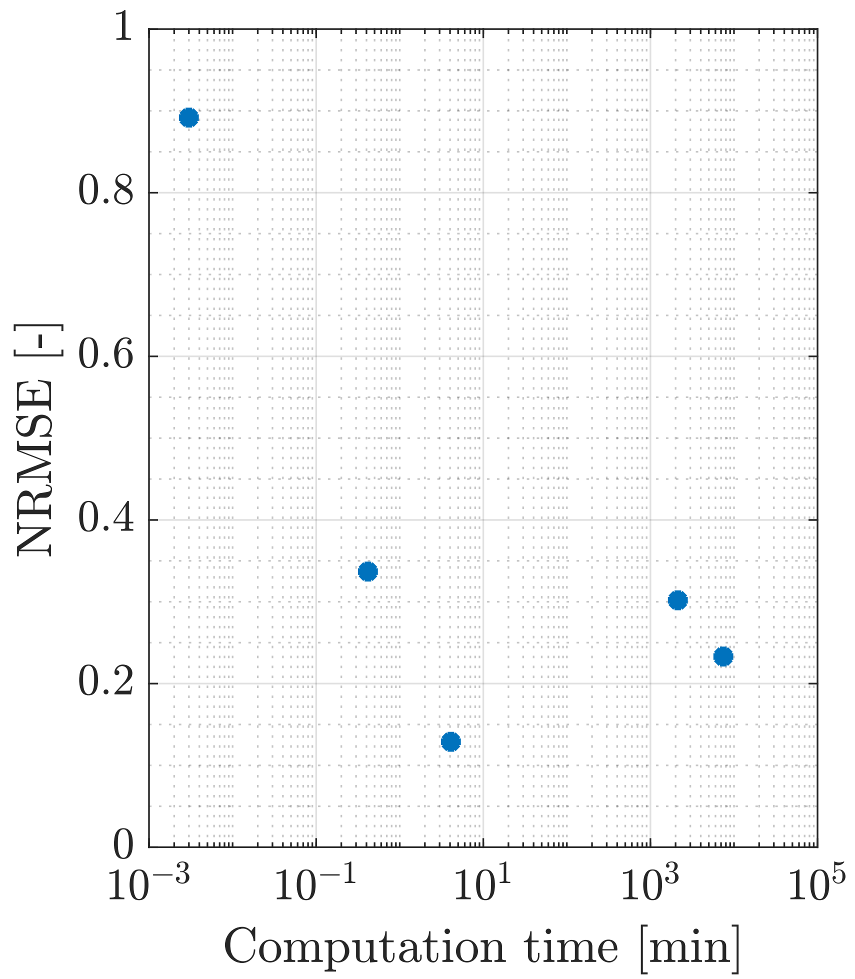
XB-SB	35.5 hr	0.53	0.30
XB-NH	124.4 hr	0.45	0.23

***CMS** – positive bias, lowest (N)RMSE*

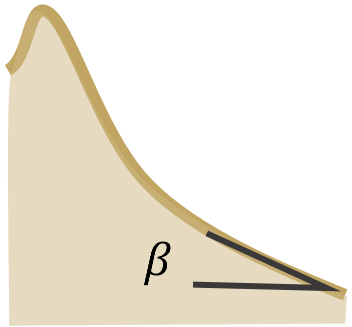
and more than 2 orders of magnitude faster!

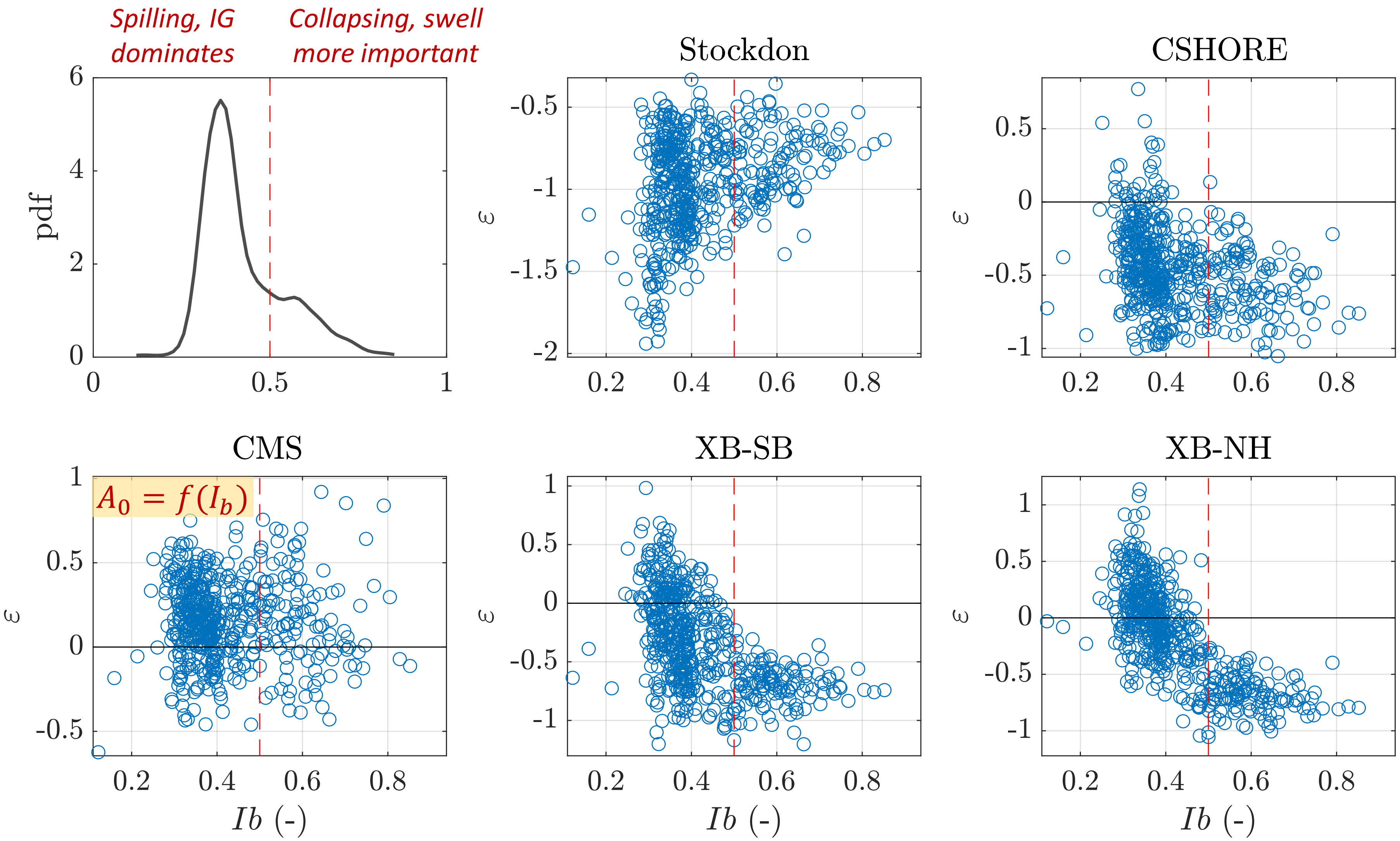


Results – Model error vs. hydrodynamics

Iribarren number or surf similarity parameter

$$Ib = \frac{\tan(\beta)}{\sqrt{H/L_0}}$$

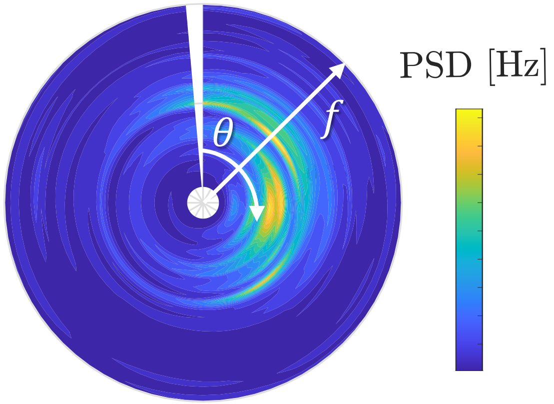




ε = model prediction – observation (error)

Results – Model error vs. hydrodynamics

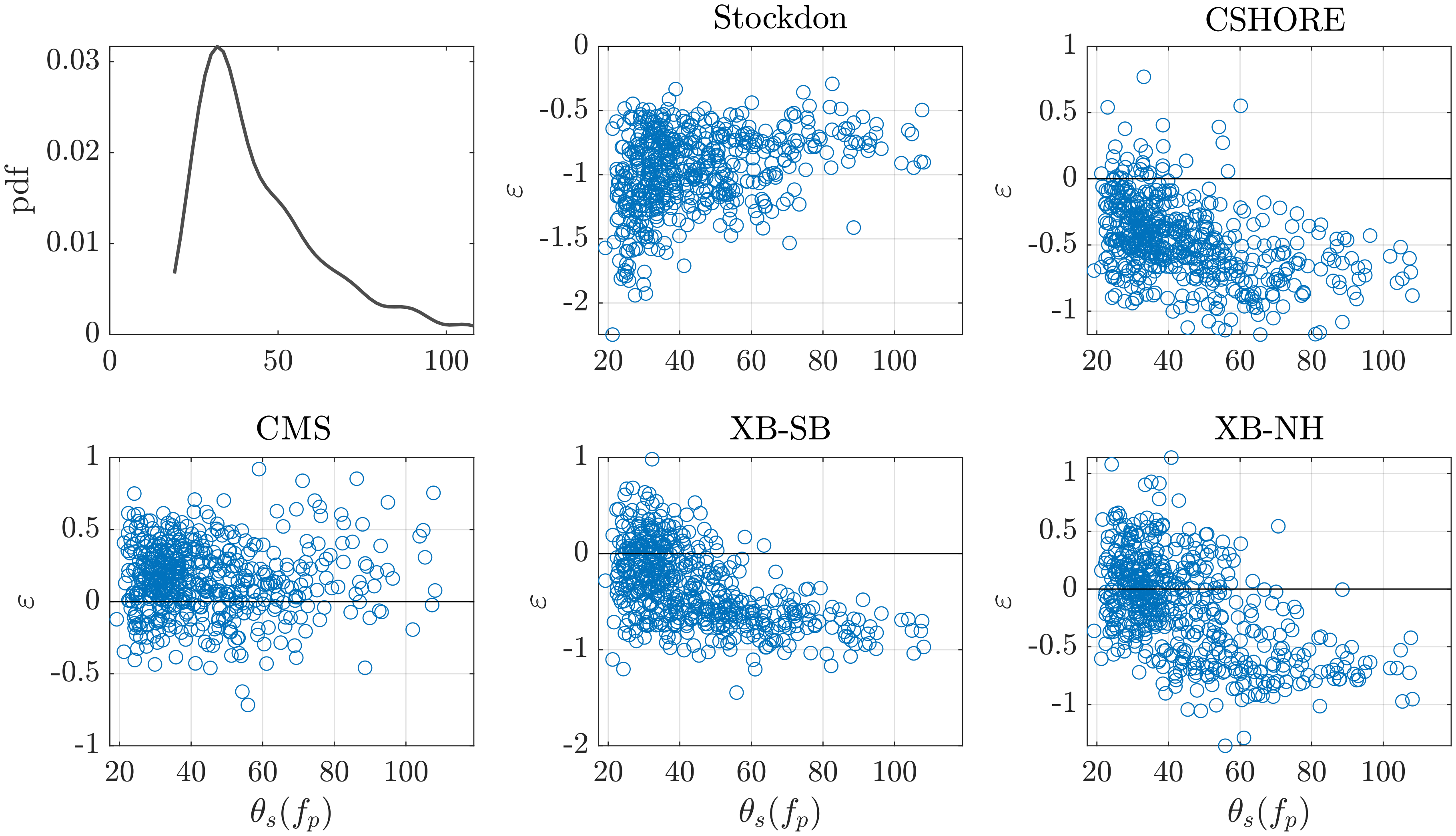
Directional spread (θ_s) calculated from directional wave spectra



$$\theta_s(f) = \frac{\int_0^{2\pi} E(f,\theta)\theta d\theta}{\int_0^{2\pi} E(f,\theta) d\theta}$$

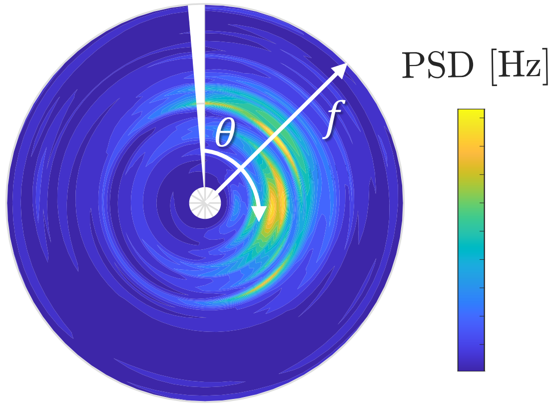
Young (1994)

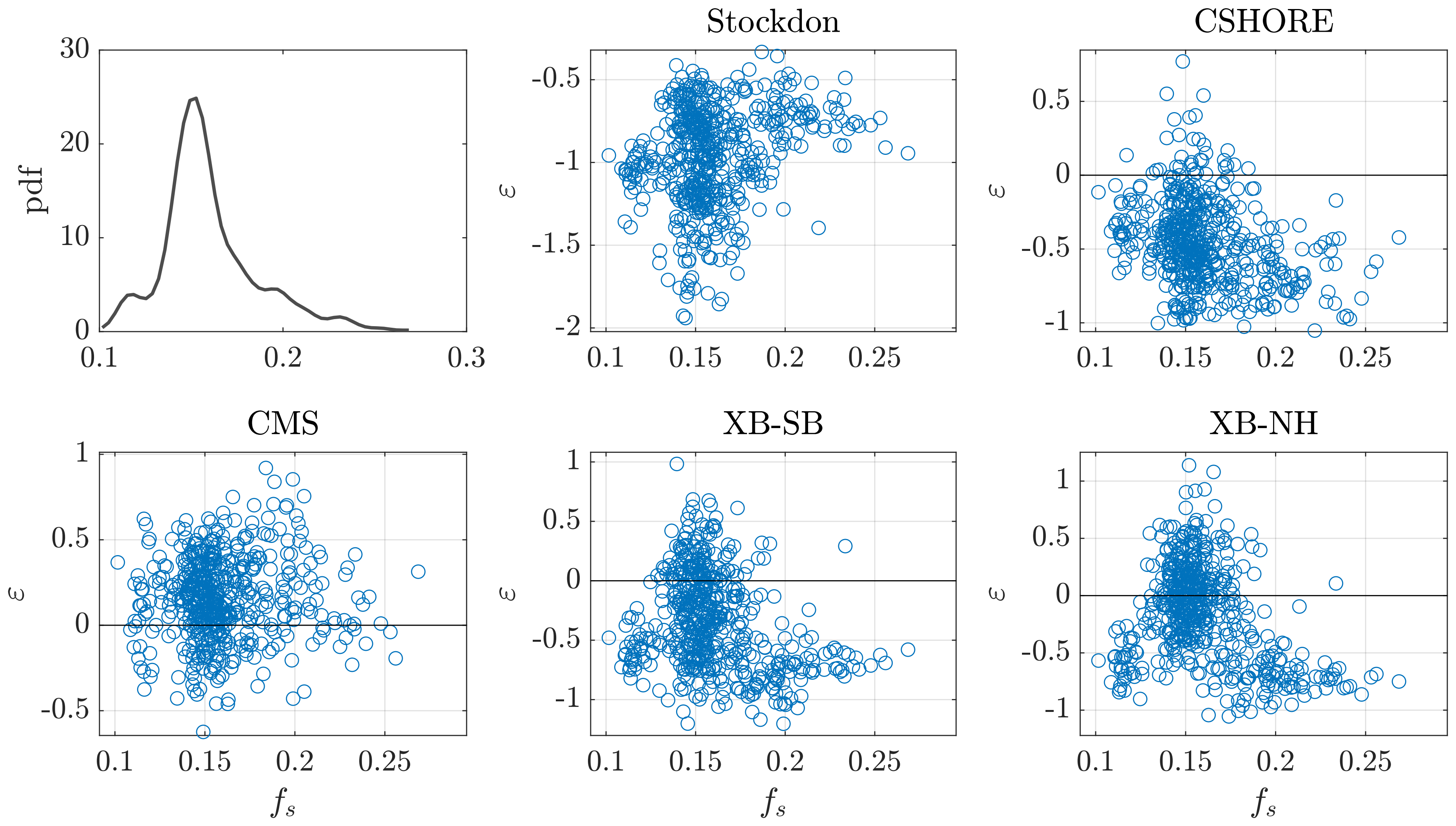
$f_p = 2\pi/T_p$



Results – Model error vs. hydrodynamics

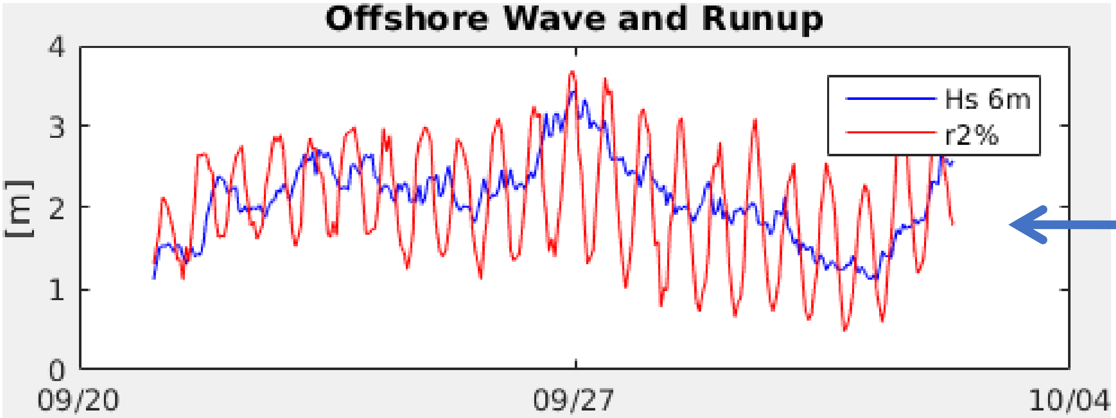
Frequency spread (f_s) calculated from directional wave spectra



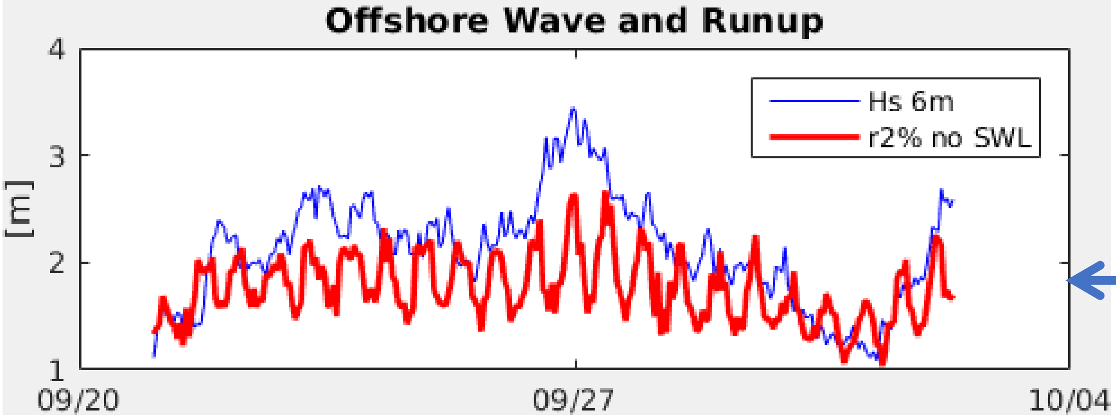


Results – Model error driven by bathymetry

Models based on offshore conditions alone suffer error when nearshore bathy details are not included. Consider:



Observed runup has pronounced tidal modulation



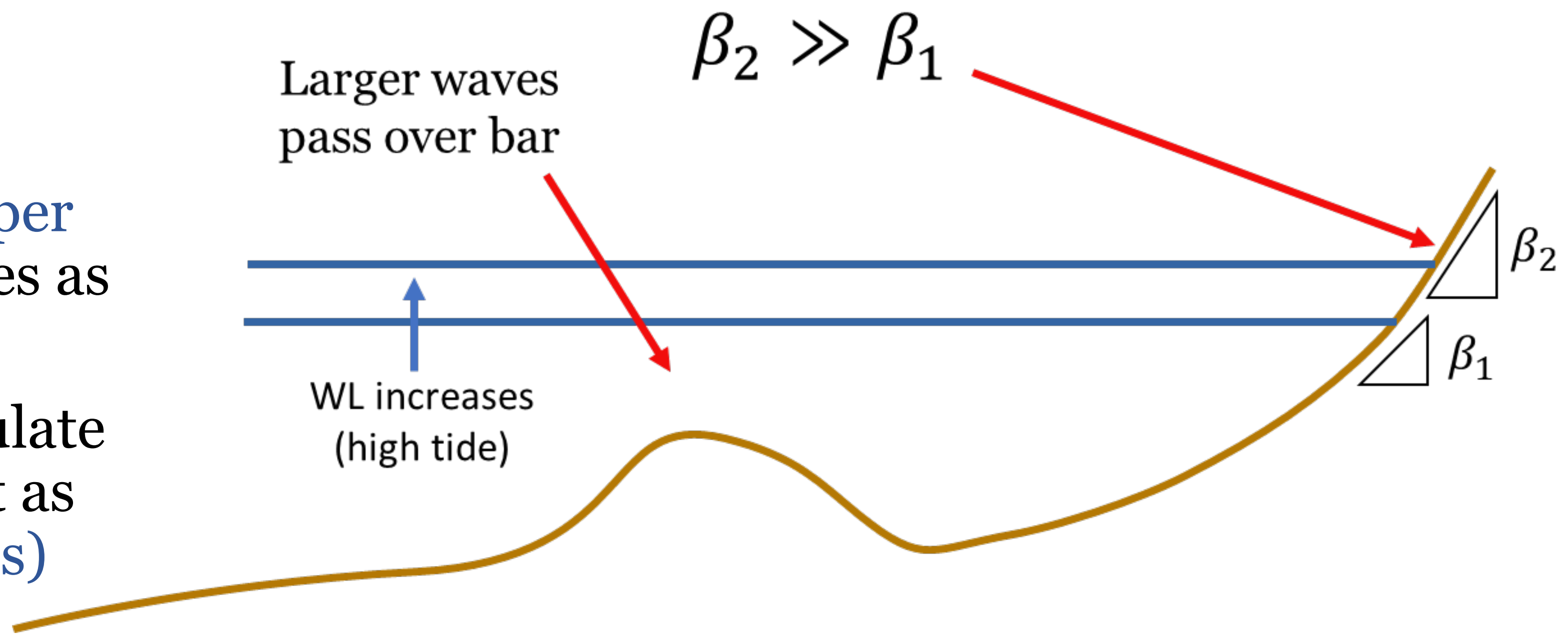
When mean water level (MWL) removed, tidal signal persists

Results – Model error driven by bathymetry

How can we explain this *tidal modulation of runup that is uncorrelated with offshore wave height,* even after we remove the MSL contribution?

Two possibilities:

- Algebraic models (and observations) indicate increased runup with steeper beach slope, slope increases as WL increases
- A sandbar can act to modulate the wind-wave component as WL increases (H_b increases)

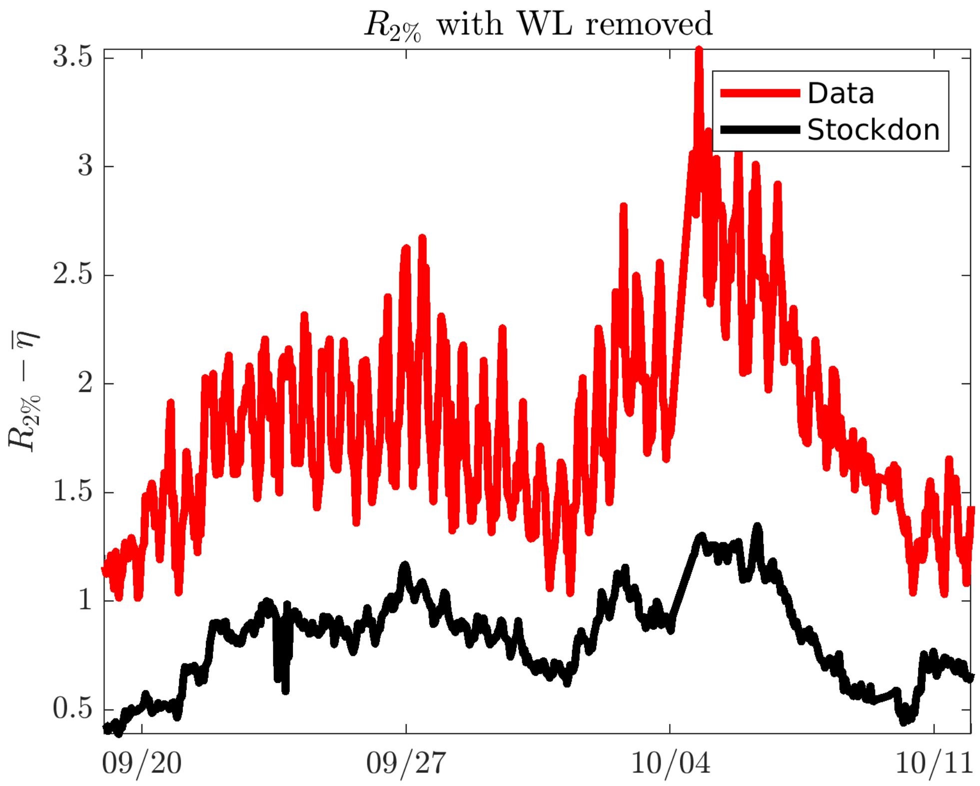


H_b = breaking wave height

Results – Model error driven by bathymetry

How can we explain this *tidal modulation of runup that is uncorrelated with offshore wave height,* even after we remove the MSL contribution?

- The impact of steeper foreshore found to be insignificant
  - When MSL removed, tidal signal of Stockdon prediction much lower than observed
- Therefore, observations are ascribed to the increased wave heights within the inner surf, indicating the importance of bar geometry in runup predictions



Summary

- As compared with more physically/numerically complex models (XB-SB and XB-NH), CMS model:
  - Predicts large data set (533) $R_{2\%}$ with **lower mean square error**
  - Produces predictions in a **fraction of the time**

- Although only calibrated based on Iribarren number,
  - CMS error is **not sensitive** to increased frequency and directional spread, as other models (higher and lower fidelity) are

- Tidal modulation of $(\boldsymbol{R_{2\%}} - \overline{\boldsymbol{\eta}})$ shown to be unexplained by increased beach slope only
  - **Nearshore bar** acts to limit wave heights incident to beach face
  - Implies need for **full resolution of beach profile** and corresponding wave transformation