ESTIMATING SHORELINE RESPONSE IN A CHANGING WAVE CLIMATE

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Estimates of the impacts of sea level rise and changing wave climates on shoreline change in the future are an increasing area of interest for many coastal stakeholders, engineers, and scientists. The ability to predict such change requires accurate information on the temporal evolution of key forcing parameters, such as wave height and period. An added complexity in modelling shoreline change is that beaches evolve in time. Higher wave conditions produce more dissipative beaches, resilient to further change, while periods of low waves produce highly dynamic low to intermediate beach states. Here, a simple shoreline model based on an equilibrium principle and forced by wave height and period is used to explore potential shoreline change projections at two different beach types: a highly dynamic storm dominated beach and a more dissipative seasonally dominated coastline. In all cases, the model parameters (which are previously shown to be a function of mean beach state) are assumed to not change after the 7-year calibration period, despite changes in wave energy. At both sites, an increase in average wave energy is predicted to either slightly accrete or stabilize a beach, while increases to storm waves results in severe erosion at the dynamic storm-dominated beach and only mild erosion at the dissipative beach. The paper concludes with a discussion on the validity of constant model parameters and poses the question over what timescales does a beach evolve to changing waves and how can this information be incorporated into simple empirical-based equilibrium shoreline models.

Keywords: equilibrium shoreline model; shoreline forecasting; future wave climates

INTRODUCTION

Sandy shorelines are dynamic coastal features that are influenced by temporal variability in wave processes (i.e. wave height, period and direction) as well as sea level (e.g. Bruun 1962). Current climate change predictions state there is a high likelihood that many coastlines around the world will experience accelerated erosion and a shift from stable/accreting beaches to a receding coastline in the near future (DCCEE 2009). While the impact of sea level rise (SLR) may be a factor that changes our coastlines by 2100, the present impact of storms is quite rapid and will have a sustained impact for years to come (e.g. Frazer et al. 2009). Several findings suggest that along wave dominated coastlines, the impact of regionally-varying wave climates will have a more significant impact in the coming decades and cannot be ignored in forecasting future shoreline variability (Brunel & Sabatier 2009; Ranasinghe et al. 2012; Ruggiero 2013).

The observation that beaches exist along much of the world's coastlines; in a diverse range of wave conditions, sediment supply and tidal ranges, suggest the beaches are inherently adaptable and to a degree, in equilibrium with the prevailing forcing. One of the key challenges engineers currently face is the lack of understanding how our coastlines will potentially adapt to changing wave conditions and over what timescale this adaptation might occur. For example, on high energy coastlines, beach morphology is typically described as longshore bar and trough (Wright & Short 1984), with higher energy environments usually having multiple offshore sandbars. These sandbars act to dissipate the incoming wave energy further offshore, offering protection to inner bars and the shoreline. Conversely, low energy beaches typically lack multiple offshore sand bars and can be described as either reflective; with a steep berm at the shoreline where waves typically break, or low tide terrace, transverse bar and rip, or rhythmic bar and beach where waves break close to shore and 2D circulation is often observed in the form of rips and feeder channels (Wright & Short 1984). These lower energy dynamic beaches are far more responsive to short term changes in wave conditions as the waves typically break much closer to shore (narrow surf zones).

Along many coastlines, the change between low and high energy environments can occur on a seasonal or annual scale. Summer waves are often smaller, producing more reflective beaches, while the onset of higher winter waves draws sand off the beach and into sandbars, only to repeat this cycle year in and year out (e.g. Aubrey 1979). It is also observed that during extreme events, sand is moved sufficiently offshore that recovery can take on the timescale of a decade.

Predicting the cumulative impact of changing wave conditions along wave-dominated coastlines requires appropriate sediment transport models. For example, predicting decadal-scale trends in shoreline position along drift-dominated coastlines is most often done using 1- (or *n*-) line models, such as UNIBEST and GENESIS (e.g. Pelnard-Considere 1956; Hanson & Kraus 1989; Ruggiero et al. 2010). These models, which assume a constant cross-shore profile, do not account for the cross-shore movement of sand between the sandbar and shoreline and therefore rarely capture the seasonal to

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annual shoreline variability associated with these processes. As such, a suite of empirical shoreline models, which parameterize the cross-shore movement of sand are able to resolve both the short-term impacts of storms as well as the longer term trends related to changing wave conditions (e.g. Miller & Dean 2004; Frazer et al. 2009; Yates et al. 2009; Anderson et al. 2010; Davidson et al. 2013; Karunarathna & Reeve 2013; Splinter et al. 2014).

Here we utilize an existing equilibrium shoreline model to explore how the current trend in wave conditions (namely offshore significant wave height, $H_{s,o}$, and wave period, T_p) along 2 distinct stretches of coastline could impact shoreline evolution over the next 2 decades under the assumption that model parameters derived from a short-term calibration data set remain valid for long-term simulations. First, a short description of the model and data are presented, followed by results and the general discussion on the validity of time-invariant model parameters and present the idea of how/why these might change in time based on the time-varying modal beach state.

MODEL

Here the recently developed '*ShoreFor*' equilibrium shoreline model is used, where cross-shore sediment transport is related to temporal variability in wave height and wave period (Davidson et al. 2013; Splinter et al. 2014). The governing equation that describes the rate of shoreline change (*dx/dt*) is:

$$\frac{dx}{dt} = c(F^{+} + rF^{-}) + b \tag{1}$$

Where c ($m^{1.5}s^{-1}W^{0.5}$) is the rate parameter; F ($W^{0.5}m^{-0.5}$) is the forcing term and is split into accretionary (F^{+}) and erosive (F^{-}) components. The erosive component is multiplied by an erosion ratio (r), which accounts for differing processes impacting accretion and erosion (e.g. Miller & Dean 2004; Yates et al. 2009; Splinter et al. 2011). The model also includes a simple linear term (b; m/s) to acknowledge longer term processes not included in the present formulation.

The forcing term is defined as:

$$F = P^{0.5}\frac{\Delta\Omega}{\sigma_{\Delta\Omega}} \tag{2}$$

Where $P = EC_g$ (W) is the breaking wave energy flux; $\Delta\Omega$ is the disequilibrium in the dimensionless fall velocity between the present (instantaneous) value and a time-averaged antecedent equilibrium condition; $\sigma_{\Delta\Omega}$ is the standard deviation of $\Delta\Omega$. The erosion ratio (r) is numerically evaluated within the model to maintain the balance between accretion and erosion forcing such that no trend in the integrated values of F^{+} and F^{-} results in no trend in the modeled shoreline:

$$r = \left|\frac{\sum_{i=0}^{N}\langle F_i^{+}\rangle}{\sum_{i=0}^{N}\langle F_i^{-}\rangle}\right| \tag{3}$$

Where || indicates the absolute value, <> indicates a numerical operation that removes the linear trend but preserves the record mean and N is the total record length.

The equilibrium condition in the model (Ω_{eq}) is time-varying and based on the weighted mean of past wave conditions, represented by the non-dimensional fall velocity (Ω):

$$\Omega_{eq} = \left[\sum_{i=1}^{2\phi} 10^{-i/\phi}\right]^{-1} \sum_{i=1}^{2\phi} \Omega_i 10^{-i/\phi} \tag{4}$$

Where i is the number of days prior to the present time and ϕ is the response factor (days) and the dimensionless fall velocity is evaluated at the break point:

$$\Omega = \frac{H_{sb}}{T_p w} \tag{5}$$

and w (m/s) is the sediment fall velocity.

The present formulation includes three wave dependent model free parameters: *c*, *r* and ϕ. Provided sufficient calibration data is available, the model has been shown to reproduce storm to seasonal variability at a range of sandy beaches (Davidson et al. 2013; Splinter et al. 2013; Splinter et al. 2014) over timescales of weeks to a decade.

DATA

The two representative beaches that are used in this study were chosen based on their diverse conditions, and the availability of high-quality sub-monthly scale shoreline sampling, long record length (7+ years), and locally available time series of wave height and period. Both sites utilize shorelines derived from video-imagery based on the Argus network of cameras (e.g. Holman et al. 2003). The shoreline data set is used for the initial model calibration, while longer-term wave data at each site is used for further analysis.

Storm dominated Beaches

The example used here as a storm dominated beach is Narrabeen-Collaroy, located on the Northern Beaches of Sydney, NSW, Australia. The 3.5 km embayed beach is micro-tidal (ΔTide= 2 m), and coarse sand (d_{50} ~0.4 mm). The beach morphology at this site is dynamic, ranging from dissipative, with a longshore uniform sandbar during major storms, through all four intermediate beach states during milder wave conditions. Approximately 7 years of weekly MHW video-derived shoreline data was used to calibrate the *ShoreFor* model with corresponding hourly offshore waves from the Sydney buoy located in 74 m water depth, 11 km SE of the site.

Seasonally dominated Beaches

The example seasonally dominated beach used in this study was located at North Head, WA, USA. This beach is a 3 km long, fine sand (d_{50} ~ 0.2 mm) exposed beach located between the North Head headland and the north jetty of the Columbia River. The site is meso-tidal with a mean spring tide range (ΔTide) of 2.3 m. The nearshore is characterized by a multi-bar system (typically between 2 and 4 sandbars). Approximately 7 years of bi-weekly MHW video-derived shoreline data was used to calibrate *ShoreFor*. Wave data was obtained from wave buoy NDBC 46029 (Columbia River Bar) located in 145 m of water and gap-filled with NDBC 46041 (Cape Elizabeth) located in 114 m of water.

Wave Analysis

To determine the long-term characteristics in the wave data at these two contrasting sites, a 20 year time slice (1989-2009) of offshore wave height and period was used. At Sydney (Figure 1), offshore significant wave height ($H_{s,o}$) shows minimal seasonality while peak wave period (T_p) is larger in the southern hemisphere winter (JJA). The resulting dimensionless fall velocity (Omega) ranges from 3-4 and displays only minimal seasonality.

By contrast, at North Head (Figure 2) both wave height ($H_{s,o}$) and period (T_p) show a large degree of seasonality with smaller wave heights and periods during the northern hemisphere summer (JJA). The resulting dimensionless fall velocity ranges from 7-12 and displays a strong seasonality.

Here the focus is on the projected long-term trends of the wave data, with a specific focus on the average annual conditions as well as changes in storm wave heights. The average annual conditions (AA) were based on the annual mean value for each year where at least 70% of the data was captured at the buoy. The storm data (AS) was determined as the annual average of the top 5% of wave heights at each site, again where 70% of the data was captured. For simplicity, this current work only focuses on long term linear trends in wave height and does not examine shorter-term variability associated with ENSO cycles at either site. The results of this analysis are presented in Table 1.

Table 1. **Trend analysis of offshore wave data at Sydney, NSW and North Head, WA. Percent increase is calculated as the trend/mean.**

	AA H_s		AS H_s		$H_{s,95\%}$ (m)
	Mean (m)	Trend (m/yr)	Mean (m)	Trend (m/yr)	
Sydney	1.62	0.0035 (0.22%)	3.74	0.0152 (0.41%)	3.06
North Head	2.32	0.0180 (0.78%)	5.44	0.0178 (0.33%)	4.54

To examine the relative impact of increasing wave conditions at these two distinct beach types, the range of percent increases in wave height are used to develop theoretical future wave climates. The base data is the wave height and period from the 7 year calibration data set at each site, where wave period will remain unchanged. The relative percent increases at both sites are quite small, but may have a large impact on how shoreline changes in the future. As representative cases, here percent changes of

0.25%, 0.5% and 1% p.a. are used at each site to explore how these increases might impact shoreline position in the future when applied to either the annual average (all data) or just the storm waves ($H_s > H_{s,95\%}$) at the two contrasting beach types.

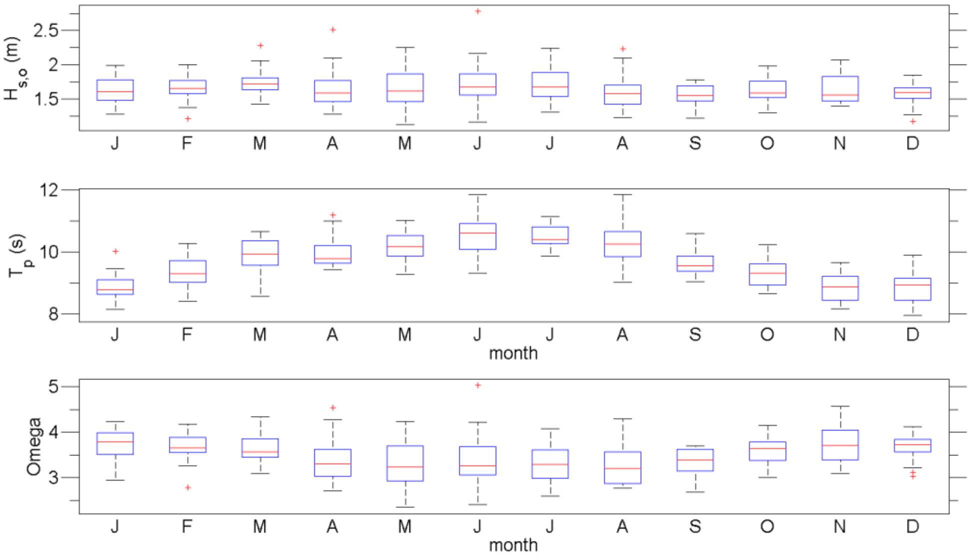

Figure 1. Monthly averaged conditions at Sydney over 1989-2009. For each box, the central mark (red line) is the median, the edges of the box (blue) are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually (red +).

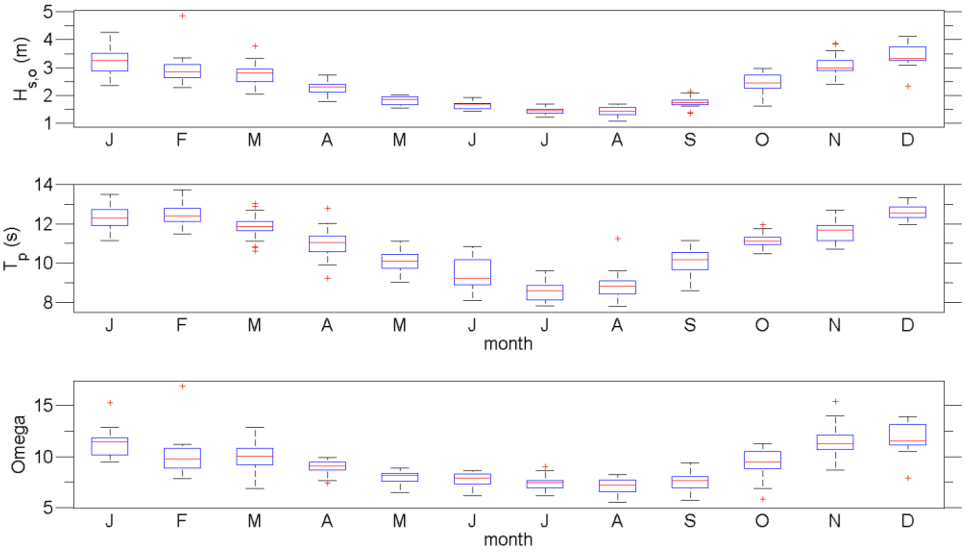

Figure 2. Monthly averaged conditions at North Head over 1989-2009. For each box, the central mark (red line) is the median, the edges of the box (blue) are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually (red +).

RESULTS

Model Calibration

Model calibration coefficients and skill are presented in Table 2. The model performed well at both sites, explaining ~70% of the observed variance over the 7-year time period. Model coefficients were significantly different between the sites reflecting the different wave climate and shoreline response. The storm-dominated site (Figure 3) had a larger response rate (c), a larger erosion ratio (r), and a smaller response factor (ϕ = 30 days), reflecting a highly variable site that responds quickly to changes in wave conditions. Conversely, the seasonally dominated dissipative site (Figure 4) had a smaller response rate, smaller erosion ratio, and a larger response factor (ϕ=1000 days), reflecting the strong seasonality in this data set and the more stable nature of the beach against small changes in wave energy. The linear trend term (b, eq. 1) at Sydney was 2.33 m/yr, while at North Head it was -2.51m/yr. This term is omitted from the future projections as it represents the impact of processes not captured in the model, such as gradients in longshore transport, which are a function of the incident wave angle as well as period and height.

Table 2. Model coefficients based on site-specific calibration and model skill based on Correlation (R) and Brier Skill Score (BSS).

	C ($m^{1.5}s^{-1}W^{0.5}$)	Φ (days)	*r*	*R*	BSS
Sydney	1.093e-007	30	0.4266	0.84	0.85
North Head	3.0238e-008	1000	0.2964	0.84	0.87

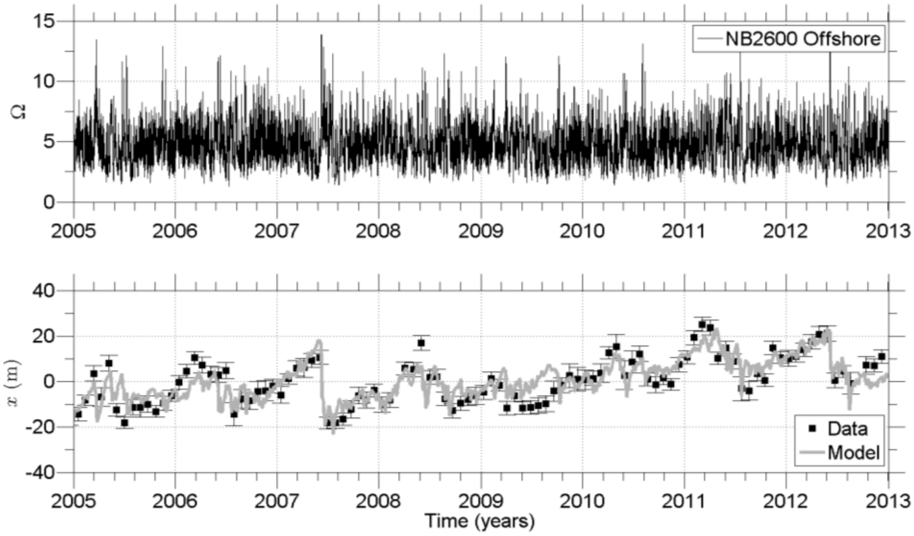

Figure 3. Calibration data set for storm-dominated beach using the Narrabeen Argus data and offshore waves.

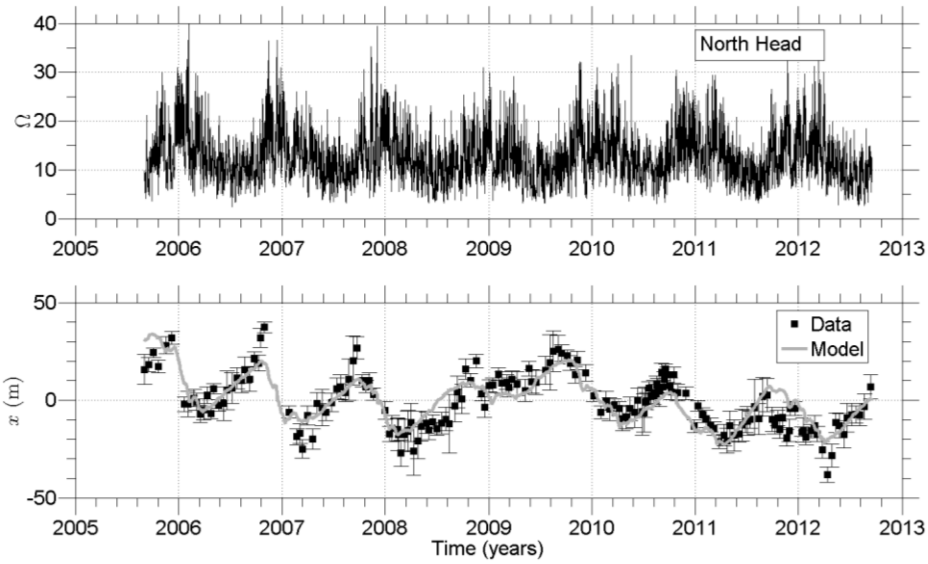

Figure 4. Calibration data set for seasonally-dominated beach using the North Head Argus data and offshore waves.

Storm-dominated Beaches

Storm-dominated beaches have a short memory (low ϕ) and respond rapidly to changes in the wave conditions. Here we present four model projections of how a storm-dominated beach might erode/accrete in the next 20 years. All the projections assume the model coefficients determined on the short-term calibration (Table 2) remain unchanged in time. The top panel shows the projected shoreline position assuming a 0.25% (Figure 5 top left) and a 1% change (Figure 5 top right) in the annual significant wave heights (AA H_s, Table 1). This percent increase is applied to all wave heights and wave period remains unchanged. The bottom panel shows the shoreline position assuming a 0.25% (Figure 5 bottom left) and a 1% change (Figure 5 bottom right) in the storm waves as defined in Table 1). Again, wave period remains unchanged in these examples for simplicity.

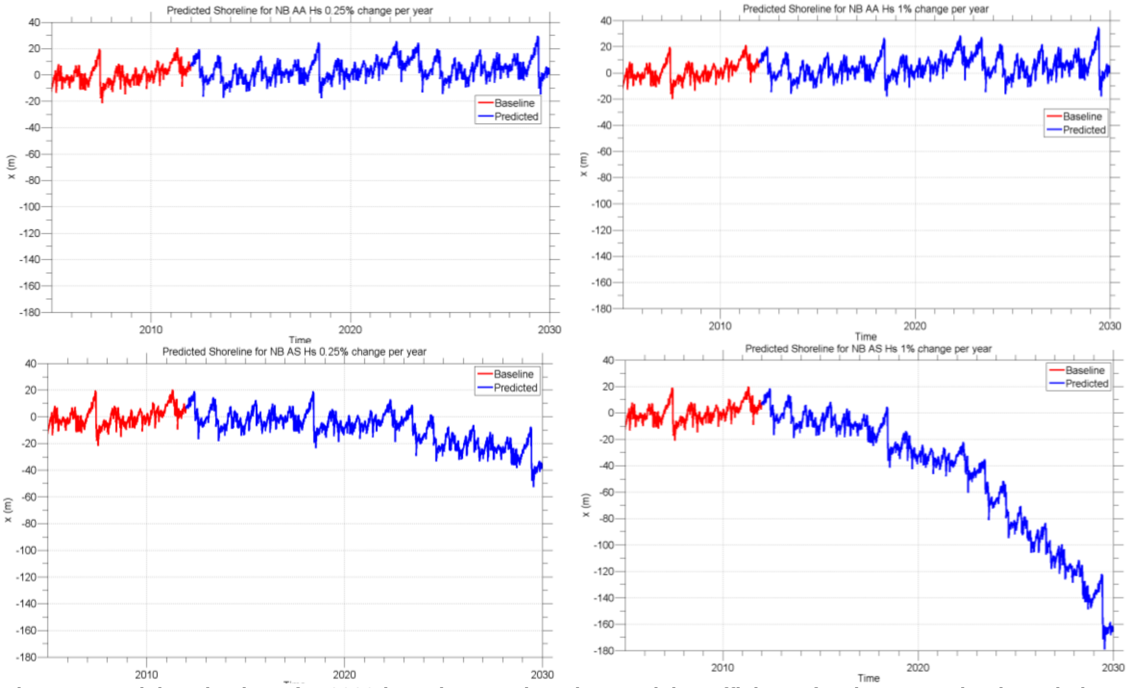

Figure 5. Model projections for 2030 based on unchanging model coefficients for the storm-dominated site. (top panel) Changes in annual average conditions of 0.25% and 1% p.a., respectively. (bottom panel) Scenario where annual average storm wave conditions (H_s>$H_{s,95\%}$) are increased by 0.25% and 1% p.a., respectively.

Several observations can be made from the storm-dominated projections shown in Figure 5. The first is that under the scenario of an increase in average wave conditions (AA) the beach continues to be stable with very little (if any) observed trend in the long-term shoreline projection for either 0.25% or 1% p.a. increase in wave height. A physical explanation for this is in the balance of onshore/offshore transport by waves. Sand is mobilized by waves and moved either onshore/offshore. The rate of transport will scale with wave height, where large waves move more sand than smaller waves. Therefore, if average conditions increase, larger average (non-storm) conditions are able to push sand back onshore after storms faster than smaller waves and a new equilibrium is reached at slightly higher wave energy. By contrast, increasing only storm waves, as shown in Figure 5 (bottom panel) has a large negative impact on this beach type causing significant erosion, particularly for the 1% p.a. increase in wave height. This can be physically explained by an imbalance in onshore and offshore transport. In the model, the direction of transport is based on the disequilibrium between an instantaneous (Ω) and a short-term background condition (Ω_{eq} with ϕ=30 days). Under the scenario of only increasing storm waves, a beach erodes more during a higher storm energy event, but the non-storm conditions remain small, inducing less onshore transport. This is enhanced by the short memory of the beach to past wave conditions, therefore, returning the beach to a low-energy equilibrium faster and onshore transport is reduced/limited.

Seasonally dominated Beaches

A very different picture emerges at the seasonally-dominated example used here. Increasing annual average wave heights based on Table 1 project a mild rate of accretion for both the 0.25% and 1% p.a.

increase in wave height (Figure 6, top panel). Similar to the case of the storm-dominated beach, the physical explanation of this is a system with larger recovery waves able to push sand back onshore more rapidly and efficiently. Contradictory perhaps to expected behavior, the model only predict minor erosion for an increase in storm waves for both the 0.25% and 1% increase (Figure 6, bottom panel). An explanation for this rather surprising outcome may lie in the long memory (ϕ=1000 days) for these types of beaches. Due to this, the equilibrium value Ω_{eq} (eq. 4) is influenced by storms up to 2000 days before, which results in a higher overall equilibrium condition and resilience to erosion.

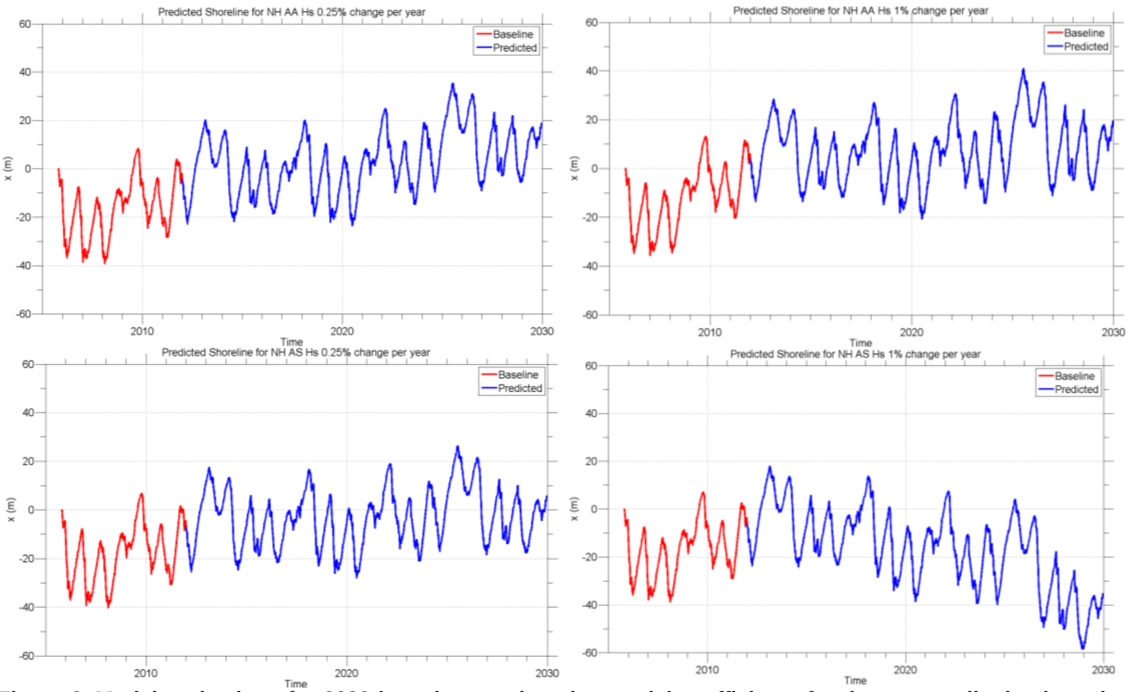

Figure 6. Model projections for 2030 based on unchanging model coefficients for the seasonally-dominated site. (top) Scenario where annual average wave conditions are increased by 0.25 and 1% p.a. (bottom) Scenario where annual average storm wave conditions (H_s>$H_{s,95\%}$) are increased by 0.25 and 1% p.a. Note that the y-axes on the these figures only ranges from -60:60 while for the storm dominated beach (Fig. 5) the y-axes were -180:40.

DISCUSSION AND CONCLUSION

The results presented in the previous section potentially spark more questions than answers. For example, does an increase in overall (average) wave conditions really promote an accretionary or stable response at all beaches? It is an interesting concept when we ask ourselves, why and how do beaches exist and know there must be a balance in the constructive and destructive forces over the long term for them to be present today. While this accretionary response potentially can be explained by an increase in sediment transport (both onshore and offshore) due to higher wave conditions, one might also expect that a beach should evolve to a new equilibrium state as well, such that accretion (or erosion) slows in time. A storm-dominated, intermediate type beach subjected to higher wave conditions should transform to a higher energy beach state in time (e.g. Wright & Short 1984; Wright et al. 1985). We see this occur on short-time scales between storm and non-storm conditions or seasonally between summer and winter at beaches all over the world.

Recently, Splinter et al. (2014) compared model parameters across 13 different data sets to examine the inter-site variability of these model parameters. They found that all three parameters (c, r, and ϕ) were dependent on the mean beach state ($\overline{\Omega}$) calculated over the ~7 year record length. While the erosion ratio (r, eq. 1 and eq. 3) linearly decreased with increasing $\overline{\Omega}$, the rate parameter (c, eq. 1) decreased rapidly as beach state transitioned from intermediate to dissipative and the response factor (ϕ, eq. 4) increased rapidly as beach state transitioned from intermediate to dissipative, capping off at 1000 days. Since model coefficients were found to be dependent on the beach state, this would suggest that for long-term simulations, model coefficients should also evolve as a beaches' mean state evolves. In the case of a highly dissipative beach, as in our example above, model coefficients are not likely to change significantly with increasing wave height based on the results of Splinter et al. (2014) because this beach is already in the stable end of the spectrum (see Figures 6-8 in Splinter et al 2014). However, the storm-dominated intermediate beach should likely evolve to a more energetic beach, resilient to higher energy conditions. As such, results such as those presented in Figure 5 can be considered a ‘worst case’ scenario.

But over what timescales should a ‘modal’ or ‘mean’ beach state be calculated? While Wright et al. (1985) suggested 30 days of past wave information was sufficient to estimate the current beach state, this may be too short a timescale to represent a modal condition. This is potentially evident in the long response factor (ϕ) of the dissipative beaches where up to 2000 days of past wave information is used to determine the equilibrium state compared to only 60 days at the intermediate beaches. Future work will examine the impact of varying model coefficients on timescales of seasonal to decadal using long-term data records to improve model applicability to long-term simulations.

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