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Key Points:

- Reef shoreline variability can be primarily controlled by seasonal changes in subtidal water level rather than changes in wave energy
- Interannual shoreline variability is modulated by ENSO events due to their effect on the Leeuwin Current and associated water levels
- Alongshore sediment transport generates an out-of-phase response between beach sections fronted by reefs and sections without reefs

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Seasonal Shoreline Variability Induced by Subtidal Water Level Fluctuations at Reef-Fringed Beaches

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Abstract The comparative role of subtidal water level and wave height variations on seasonal shoreline changes was investigated at a reef-fringed beach in southwestern Australia. The data set consisted of continuous sea level and wave records, monthly topographic beach surveys over a 2 year period, and bimonthly high-resolution aerial images over a 7 year period. Shorelines were extracted from images and topographic surveys, and then an empirical orthogonal function (EOF) analysis was applied to both data sets. The temporal amplitudes of the first EOF mode of the image-derived shoreline data set (~60% of the variance) were most correlated with 30 day averages of the subtidal water level (variations up to ± 0.2 m) driven by geostrophic adjustment of the Leeuwin Current. The geostrophic response of the Leeuwin Current was found to be further correlated with the phasing of the El Niño–Southern Oscillation, leading to higher water levels during La Niña and lower levels during El Niño, which as a consequence resulted in interannual variations in the shoreline behavior reflected in the first EOF mode. The temporal amplitudes of the second EOF mode (~20% of the variance) were most correlated with 50 day averages in offshore wave height. Our results indicate that the seasonal beach response was primarily influenced by seasonal variations in offshore water level rather than by wave heights as has been generally observed in exposed beaches. A simple EOF-based model is presented, which reproduces the alongshore-variable shoreline response and its seasonal and interannual modulation due to El Niño–Southern Oscillation events over the study period.

1. Introduction

Fringing reefs are prevalent features along tropical and subtropical coastlines worldwide and typically consist of submerged rocky or coral reefs that extend seaward from the shore, often with depths of only a few meters below the low tide level (Sheppard et al., 2013). These reef structures are generally close to shore (compared to barrier reefs), may be shore attached or separated from the shoreline by a shallow lagoon, and are often backed by sandy beaches (Kennedy & Woodroffe, 2002; Smithers, 2011). Reefs can produce strong dissipation of incident waves by both depth-limited breaking and bottom friction due to their large roughness, which can often lead to wave height reductions of 80% or greater (Alegria-Arzaburú et al., 2013; Ferrario et al., 2014; Lowe et al., 2005). During dissipation of incident waves, energy is transferred in the cross-shore direction into an increase in mean sea level (i.e., wave setup), with gradients in wave setup often driving cross-reef flows over the reefs (Gourlay, 1996; Symonds et al., 1995; Tait, 1972). Wave heights, wave setup, and wave-driven flows can be modulated by water depth changes over the reefs (Becker et al., 2014; Brander et al., 2004; Lugo-Fernández et al., 1998; Storlazzi et al., 2004; Taebi et al., 2011) due to saturation of the surf zone and the corresponding variability in depth-limited wave breaking (Thornton & Guza, 1982). In most cases, this dependence on water level has been observed during different tidal stages, with high-tide conditions resulting in larger waves transmitted across reefs (Brander et al., 2004; Storlazzi et al., 2004), and in turn less wave dissipation and smaller wave setup generated over the reefs (Becker et al., 2014; Lugo-Fernández et al., 1998; Taebi et al., 2011). Alongshore sediment transport at shorelines fringed by reefs also appears to increase with higher water levels according to numerical simulations (Alegria-Arzaburú et al., 2013; Grady et al., 2013). Despite these prior studies, it is unclear how variability in the nearshore hydrodynamics induced by longer-term variability (i.e., much greater than tidal time scales) influences the morphological response of beaches in the lee of reefs, especially if there are significant sea level changes that persist over extended periods of time that allow a beach to develop a distinct response and potentially toward a new equilibrium morphology. As significant changes in the water level over fringing reefs are projected to occur with sea level rise as a result of climate change (Church et al., 2004), it is important to understand the effect of water-level

Figure 1. Study Site. (a) Location of the study area at Garden Island, Western Australia (WA). The locations of the Rottne wave buoy, acoustic wave gauge, and tide gauge from which the wave and water level data were obtained are also shown (black points). (b) Image of the study site obtained in June 2014. The shallow reefs are highlighted by areas with breaking waves.

variations on the morphological response of reef-fringed beaches in order to better understand how they will likely change in the future.

Along the coast of Western Australia (WA), there are strong seasonal variations in subtidal water levels that can annually vary with a range of 0.4 m (or ± 0.2 m relative to mean sea level) (Feng et al., 2003; Pattiaratchi & Eliot, 2008). This is comparable to the mean tidal range in this microtidal region of only ~ 0.4 m (Lemm et al., 1999). The seasonal variations in water levels have been linked primarily to seasonal changes in the strength of the Leeuwin Current, a warm water coastally trapped boundary current that flows south along the coast of WA (Godfrey & Ridgway, 1985). The geostrophic transport of the Leeuwin Current increases from February to June, generating higher sea levels along the coastal region of WA, while from July to November the coastal sea level decreases as the current transport diminishes (Feng et al., 2003; Smith et al., 1991). Interannual changes in the strength of the Leeuwin Current, and thus coastal sea level, also have been shown to exhibit strong links with the El Niño–Southern Oscillation (ENSO) cycle (Feng et al., 2003; Pariwono et al., 1986; Pearce & Phillips, 1988). In general, during La Niña years the Leeuwin Current tends to be stronger thereby generating higher coastal sea levels throughout southwestern Australia; whereas during El Niño years the current is weaker and the sea levels are lower (Feng et al., 2003; Pariwono et al., 1986; Pattiaratchi & Eliot, 2008). The difference between the sea levels occurring during La Niña and El Niño periods is often ~ 0.2 m (Feng et al., 2003; Pariwono et al., 1986; Pattiaratchi & Eliot, 2008).

In this study we investigate how seasonal variability in regional subtidal water levels and incident wave energy influence the shoreline behavior at a microtidal reef-fringed beach in southwestern WA using a data set consisting of 19 ($\sim$ monthly) beach topographic surveys and 44 high-resolution aerial images taken over 7 years. To analyze the beach response, the shoreline contour was extracted from both images and

Figure 2. Study domain and image-derived shoreline detection. (a) Aerial Lidar bathymetry of Garden Island (collected by Fugro LADS Corporation Pty. Ltd., 2009) with 0 m and -1 m elevation contours to emphasize areas with shallow reefs. UTM coordinates of the site were rotated 11° clockwise and referenced to a location in the SE corner of the study site, resulting in a new reference frame (x , y). (b) High-resolution aerial image obtained on 15 March 2015 at the study site. The shorelines derived from the image and the topographic survey collected on the same day are also displayed. Additionally, salients (S1 and S2) and embayments (E1 and E2) are shown (the exact boundaries between these sections are defined in Figure 4b). (c) Zoomed area to emphasize the beach step over which the shoreline from the image was defined. (d) Temporal correlations between the mean shoreline position (temporal mean removed) averaged over salients (S1 and S2) and embayments (E1 and E2), from images and surveys (separated by ≤ 2 weeks). For each section, the value of R^2 is shown at the right interior corner.

topographic surveys, and an empirical orthogonal function (EOF) analysis was applied in order to decompose the spatial and temporal patterns in the shoreline variability. We quantified the relationship between the EOF temporal patterns and average values of waves and water levels in order to assess the links between beach response and physical forcing. Finally, a shoreline position model was developed based on the EOF spatial patterns and relationship to physical forcing conditions, which accurately reproduces the shoreline position over the entire 7 year period.

2. Observations and Methods

2.1. Study Site

The study site consists of an approximately 1 km stretch of beach located on the western side of Garden Island in southwestern WA (Figures 1a and 1b). Beaches along this section of coast feature a number of submerged limestone reefs (either shore attached or just offshore), each with mean depths of 0.5 m to 1 m below still water level (Figure 2a). At the specific study site, two seasonally varying salients are present in the lee of two shore-attached reefs (Figures 2a and 2b) and exhibit a berm at the shoreline with a flat profile landward that extends to the dune toe. In contrast, sections of adjacent beaches not fronted by reefs (i.e., the “embayments,” Figures 2a and 2b) show a relatively steeper profile (slope $\sim 1:6$ – $1:5$). The incident wave heights are seasonally variable, with larger wave heights and longer periods from May to September (Figures 3a–3c) (Lemm et al., 1999). The subtidal water levels also show strong seasonal oscillations (Figures 3d and 3e), with the maximum water levels occurring in June leading the maximum wave heights by approximately 3 months

Figure 3. Wave conditions, water level, and shoreline positions. (a) Time series of daily, 30 day and 60 day running means of significant wave height (H_s) (the survey and image dates are indicated by the open circles and triangles, respectively). (b) Wave peak period (T_p), (c) wave peak direction (θ_p) measured offshore of Rottnest Island, and (d) mean water level (WL) measured at Fremantle tide gauge (relative to the mean of the period 2010–2016: 0.09 m Australian Height Datum). (e) Offshore water level derived from Fremantle tide gauge and wave height from Rottnest wave buoy. Both signals were smoothed with a running mean of 6 months (± 3 months). El Niño and La Niña events are indicated by the blue and red bands, respectively, with the mean water level during El Niño and La Niña periods denoted by the blue and red triangles, respectively. (f) Image-derived shoreline position averaged over embayment 2 ($y = 80$ m–190 m) and over salient 2 ($y = 190$ m–325 m, the exact boundaries between the salients and embayments are defined in Figure 4b). In all panels the gray areas denote the austral autumn–winter months.

(Figure 3e). This oscillation in the water level is related to the seasonal fluctuations in the strength of the Leeuwin Current that produces higher elevations during the austral autumn and early winter along the southwestern WA coast when the current transport is the largest (Feng et al., 2003; Pattiaratchi & Eliot, 2008).

In addition, the subtidal water levels display interannual variability linked to El Niño and La Niña events that modulate the strength of the Leeuwin Current (Feng et al., 2003; Pariwono et al., 1986; Pearce & Phillips, 1988). According to the Southern Oscillation Index over the period 2010–2016, La Niña events (with higher water levels) occurred during the periods May 2010 to April 2011 and September 2011 to March 2012; whereas El Niño events (with lower water levels) occurred during the periods January 2010 to May 2011 and April 2014 to April 2016 (Figure 3e) (Australian Bureau of Meteorology, 2017).

2.2. Wave and Water Level Observations

Hourly observations of the incident wave conditions for the study period between 2010 and 2016 (Figures 3a–3c) were obtained from a directional wave buoy located offshore of Rottnest Island, approximately 30 km NNW of Garden Island in 48 m water depth (Figure 1b). Additionally, water levels were recorded every 5 min by a tide gauge located in Fremantle Port, approximately 20 km north of the study area (Figure 1b). These water levels are referenced to the Australian Height Datum (AHD), which is defined as the mean water level for the period 1966–1968. In this study we refer to the water levels (Figures 3d and 3e) relative to the mean water level for the study period 2010–2016 which was 0.09 m AHD. The wave heights from the Rottnest wave buoy and water levels from Fremantle have both been found to be strongly correlated ($R^2 = 0.8$ and $R^2 = 0.9$, respectively) with their corresponding values recorded ~3 km offshore of Garden Island (Figure 1a) during a 4 month (December 2014–March 2015) in situ acoustic wave gauge (Nortek AWAC) deployment, indicating that variability in wave heights from the Rottnest wave buoy and water levels from the Fremantle tide gauge were representative of those occurring nearby at Garden Island.

2.3. Shoreline Observations

The shoreline position was extracted from 44 georectified high-resolution aerial photographs (0.075 m per pixel) taken on average every 2 months between March 2010 and November 2016 by Nearmap Pty. Ltd (2009) as well as from 19 approximately monthly topographic surveys conducted between January 2014 and July 2015 (see dates in Figure 3a). The surveys and the images for the period 2013–2016 covered an area from $y = 80$ to $y = 1,300$ m (Figure 2b), whereas the first 18 images (2010–2012) did not cover the northern portion of the beach ($y > 780$ m). For this reason, the analysis of the image-derived shorelines is limited to the beach section bounded between $y = 80$ m and $y = 780$ m (Figure 4a) providing a 7 year time series of shorelines. The shorelines derived from the topographic surveys covering a larger area will be shown in some of the results (Figures 4b and 4c) in order to understand the behavior of the beach beyond the image limits; however, our analysis is primarily focused on the image-derived shorelines given their greater temporal extent (i.e., 7 years versus 1.5 years for the beach surveys).

The image-derived shorelines were digitized manually based on identifying the location of the seaward edge of the beach which often consisted of a beach step (Figure 2b). In each image, the beach step was identified either by the distinct contrast in water color between the step crest and deeper water or by white water generated by waves breaking over the step (Figure 2c). The constant presence of this visually discernible feature at Garden Island makes it a robust shoreline indicator, and it is similar to indicators used at other locations (Boak & Turner, 2005). The shorelines were rotated 11° clockwise into a local coordinate system (x and y , respectively, see Figure 2b) and interpolated onto a fixed interval of 1 m. The shoreline positions at the salients fronted by reefs and sections without reefs (embayments) showed a seasonal variability in their temporal behavior (Figure 3f).

Shorelines were also extracted from 19 topographic surveys that were carried out using a Differential Global Navigation Satellite System receiver mounted atop a survey backpack that was traversed by foot along the beach (from $y = 80$ m to $y = 1,300$ m). The surveys spanned in the cross shore between the dune vegetation line and the water line. A typical path during surveys consisted of four alongshore transects (separated by ~7 m) plus zigzag transects (~5 m spacing) at the two salients that enhanced resolution. Differential corrections were recorded at an adjacent reference station producing an horizontal and vertical uncertainty of the survey points of 0.05 m. Points from each survey then were translated and rotated to the reference system x , y and interpolated using a Triangulated Irregular Network to produce a 1 m cell-size grid surface of the subaerial beach. Grids produced using different interpolation methods (Kriging, Nearest Neighbor) were similar, and our results are not sensitive to the interpolation method. For each grid, the shoreline was defined as the 0.2 m AHD elevation contour since it was the lowest contour captured along the entire beach for all surveys (Figure 2b). Wave breaking and swash occurring at the steep embayments during autumn-winter months prevented safe collection of survey points at lower elevations. Each of the shorelines extracted from topographic surveys exhibited a strong spatial correlation with the shoreline positions corresponding to the image taken within a 2 week period from each survey ($R^2 = 0.96$, slope 0.93). However, the exact shoreline positions did not strictly coincide given that the shorelines from images were located on average ~6 m offshore from the locations extracted from the topographic surveys, as can be observed in Figures 2b and 2c. This distance was kept nearly constant at some locations of the beach (such as at the salient) resulting in a

Figure 4. Empirical orthogonal functions (EOF) analysis. (a) Map of study area showing the -1 m elevation contour (white line) and the limits of the region analyzed with images (yellow lines). (b) First spatial EOF modes (M1) and (c) second spatial modes (M2) calculated from topographic surveys and from images. The gray dashed lines are the respective EOF modes calculated from an image data set but with the same area of surveys. The limits between salients and embayments were taken as the zero-crossings of the EOF mode 1. (d) Temporal projections for EOF modes from surveys and images. La Niña and El Niño events are also highlighted by the blue and red horizontal bars. The gray areas indicate the austral autumn-winter months.

high correlation between the temporal variations of the shorelines from images and surveys ($R^2 = 0.9$ for salients 1 and 2, Figure 2d). In contrast, at the embayments, the correlation between the temporal variations was smaller because of the distance separating the shorelines from images and surveys was more variable ($R^2 \sim 0.5$ for embayments 1 and 2, Figure 2d).

2.4. Empirical Orthogonal Function Analysis

Seasonal beach variability was analyzed by calculating EOFs from the shoreline data following Miller and Dean (2007a). The advantage of the EOF analysis is that it decomposes the shoreline fluctuations into a series of orthogonal modes, with each representing a distinct spatiotemporal pattern. Since the original data used in this study consist of a time series of shoreline positions, the dominant directions represent modes of along-shore spatial variation (spatial modes) that are accompanied by a set of temporal projections. The alongshore structure of the spatial modes thus provides information on the alongshore variance of the beach response

with maximum values identifying areas of maximum variability and nodal points (zero-crossings) indicating stability. Nodal points typically separate adjacent areas of erosion and accretion and thus their presence often reveal processes of alongshore sediment exchange such as beach rotation (Clarke & Eliot, 1982; Muñoz-Pérez et al., 2001; Short & Trembanis, 2004). Alongshore uniformity in the spatial modes is more characteristic of the typical beach response to cross-shore sediment exchange that produces a uniform advance or retreat of the shoreline in the cross-shore direction (Hansen & Barnard, 2010; Miller & Dean, 2007a). In addition, the temporal projections corresponding to each spatial mode identified by the EOF analysis can be related to time series of physical forcing via linear correlations where strong correlations can be taken as a physical link between the relevant temporal mode and the physical forcing (Hansen & Barnard, 2010; Harley et al., 2015; Loureiro et al., 2012; Miller & Dean, 2007b; Quartel et al., 2008).

The EOF analysis was applied to the image-derived shorelines (temporal mean removed) in order to assess the spatial and temporal patterns in the shoreline variability. The temporal projections of the EOF modes that were obtained from the image data set were correlated with time series of offshore significant wave height (H_s) and subtidal water level to assess how each contributed to the observed shoreline response. As the shoreline response is not expected to be instantaneous, but instead reflect sustained changes in conditions over prior periods, we investigated applying different averaging intervals to the time series of physical parameters before calculating correlations (Hansen & Barnard, 2010; Loureiro et al., 2012; Miller & Dean, 2007b). Means of the wave heights and water levels were calculated from 1 to 200 days prior each shoreline observation. Similar to Miller and Dean (2007b) and Hansen and Barnard (2010), the averaging interval that produced the highest correlation coefficient (R^2) was assumed to be the period in which changes in the physical parameters (in our case, wave height, and water level) were reflected in the beach shoreline position. These time scales were also compared with those that have typically been observed on open-coast sandy beaches. To examine the consistency of our results, the EOF analysis was also carried out using the shorelines derived from the topographic beach surveys.

3. Results

3.1. EOF Analysis and Linear Correlations

The EOF spatial modes derived from the shorelines extracted from both the aerial images and topographic surveys indicate that the first two modes (M_1 and M_2) together account for ~80% of the shoreline variance (Figures 4b and 4c). For the image-derived shorelines, the first mode accounted for 59% of the variance, while the second mode accounted for 17% (Figures 4b and 4c). This was similar for the survey-derived shorelines, with the first and second modes accounting for 63% and 22% of the variance, respectively (Figures 4b and 4c). The remaining modes from both data sets each explained less than ~5% of the variance and were not considered as they cannot be separated from noise. The noise floor was determined by conducting the EOF analysis on 100 random-number data sets of the same size of the image- and topographic-derived shoreline data sets. This analysis indicates that up to 5% of the variance can be accounted for randomly by the dimensions of the data sets.

The patterns of the first spatial mode from both shoreline data sets are very similar (Figure 4b), with both showing maximum positive values at the salients where reefs front the beaches and smaller but negative values at the adjacent embayments without shore-attached reefs. This suggests that the largest shoreline variations occur at the salients and that there is an out-of-phase response between the salients and adjacent embayments. In contrast, the second spatial modes from the two data sets show somewhat differing patterns (Figure 4c), with the EOF mode 2 from the images indicating larger variations at the embayments and at salient 2 and also opposite signs between the two salients, in comparison to the EOF mode 2 obtained from the topographic surveys. The mismatch between EOF modes 2, especially at the salients, appears partially related to the spatial dimensions of the data set (700 m for images versus 1,200 m for topographic surveys). An EOF analysis applied to an image data set with the same spatial dimensions as the topographic survey data set (i.e., using only the 5 years of images which cover the same 1,200 m shoreline extent as the 1.5 years of topographic surveys) results in an EOF mode 2 with a more similar structure to the one obtained from topographic surveys showing an in-phase behavior of both salients (dashed gray lines in Figure 4c). Similarly, if an EOF analysis is applied to the survey data set but only over the same spatial dimensions as the images (700 m), the resulting EOF mode 2 has a more similar structure to the one

Figure 5. Correlation analysis. Correlation coefficients generated by linear regression between the first and second temporal modes generated from the image-derived shorelines and (a) the water level (as recorded at the Fremantle tide gauge) averaged over different number of days and (b) offshore significant wave height averaged over different number of days. EOF = empirical orthogonal function.

obtained from the original image data set (red line, Figures 4b and 4c) showing the out-of-phase behavior of the salients (not shown).

For both EOF modes from both data sets, the temporal projections exhibit a seasonal behavior, with mode 1 leading mode 2 by approximately 3 months (Figure 4d). The negative values in the temporal projections of EOF mode 1 indicate erosion of the salients and the opposite behavior (accretion) at the embayments, while the positive projections denote accretion at salients and erosion at embayments. This seasonal out-of-phase behavior between reef-fronted salients and embayments lacking reefs is also apparent in the raw shoreline positions shown in Figure 3f.

The EOF temporal amplitudes of modes 1 and 2 derived from image-derived shorelines (Figure 4d) were each compared against the observed wave heights and water levels averaged over different intervals prior to each of the 44 image collection dates. For EOF mode 1, the strongest (negative) correlations were found with the water level averaged over 20–60 days preceding each image, with a maximum correlation at 30 days ($R^2 = 0.78$, p value < 0.05) (Figure 5a). Conversely, mode 2 was strongly positively correlated with the wave height averaged over 30–60 days preceding each image with the maximum at 50 days ($R^2 = 0.82$, p value < 0.05) (Figure 5b). We note that we found no significant correlation ($R^2 < 0.1$) between the shoreline EOF modes and subtidal variations in the tidal range (i.e., due to spring-neap variations) (not shown).

The time periods of 30 and 50 days indicate that the primary modes of shoreline variability are related to the 1–2 month variations in the offshore water levels and wave heights, with both showing strong seasonal variations each year (Figures 3a and 3d). The correlation between the shoreline behavior and water levels and wave heights is further reinforced by inspecting the seasonal variability of these parameters (Figures 3a and 3d–3f): the minimum (maximum) monthly and bimonthly means of water level (Figure 3d) coincide with maximum (minimum) shoreline position at the reef-fronted salients, whereas the maximum (minimum) of monthly and bimonthly means of wave height (Figure 3a) coincide with the maximum (minimum) shoreline position at embayments. We note that high positive correlations between the first EOF mode and wave height averaged over very similar preceding intervals (~60 days) have been commonly observed on open-coast beaches and linked to the seasonal variability in integrated wave conditions that drive seasonal differences in erosion and accretion (Hansen & Barnard, 2010; Miller & Dean, 2007b).

The temporal projections (Figure 4d) also indicate considerable interannual variability, particularly for mode 1 (e.g., larger negative values, i.e., implying more erosion, during the autumn–winter of the years 2011 to 2014 than the years 2010, 2015, and 2016). The interannual variability in the shoreline position averaged over different sections and its relationship with variations in water level and offshore wave height was analyzed by removing the seasonal variability from the data sets and calculating correlations between the new seasonally adjusted time series of the shoreline position (alongshore averaged over the embayments and salients,

Figure 6. Seasonal adjustment. (a) Seasonally adjusted (i.e., seasonal anomaly removed) of mean shoreline position averaged over embayments and water level and (b) wave height. (c) Seasonally adjusted of mean shoreline position averaged over salients and water level and (d) wave height. The correlation coefficients between the mean shoreline position and water level (a, c) and wave height (b, d) are also shown.

Figure 4b) and the seasonally adjusted water levels and offshore wave heights (Figure 6). These seasonal adjustments consisted of subtracting the seasonal anomaly, defined as the monthly mean values of a variable (shoreline position, wave height, or water level) from the corresponding month across the complete 7 year time series. As some months were not captured in the 7 year image data set, the shoreline position was linearly interpolated to ensure at least one data point per month. The influence of the interannual water level variability is clear at the salients where the alongshore averaged shoreline position is strongly correlated with seasonally adjusted water level ($R^2 = 0.70$ and 0.50 , p value < 0.05 , Figure 6c). Weaker correlations are seen at embayment 2 with the seasonally adjusted water levels and at salients with the seasonally adjusted wave height (Figure 6). When the same analysis is conducted with the shoreline position averaged over its entire length (i.e., not treating the salients and embayments independently), the correlation with the seasonally adjusted water levels is high ($R^2 = 0.60$, p value < 0.05) but is low with the seasonally adjusted wave heights ($R^2 = 0.01$, p value > 0.05) (not shown). These results indicate that the interannual shoreline variability, which is dominated by the shoreline movements at the salients, is much more influenced by interannual variations in water level (which are primarily driven by La Niña and El Niño events) rather than interannual differences in wave heights. We note that we obtained similar results if the seasonally adjusted time series were produced using an alternative method based on loess smoothing following Cleveland et al. (1990) (not shown).

3.2. Shoreline Position Model

Given that a majority (~80%) of the shoreline variability can be accounted for using the first two EOF modes, the detrended shoreline position x' at a given time t can be represented as follows:

$$x'(t) = C_1(t)\mathbf{M}_1 + C_2(t)\mathbf{M}_2 \quad (1)$$

where C_1 , $\mathbf{M}_1$ and C_2 , $\mathbf{M}_2$ are the temporal projections and spatial loadings of modes 1 and 2, respectively, from the image-derived shorelines. Following the approach of Hansen and Barnard (2010), we generated a shoreline position model using equation (1) but with C_1 and C_2 predicted using the linear regression equations that relate C_1 and the water level (averaged over the previous 30 days) and C_2 and the wave height (averaged over the previous 50 days) (dashed lines in Figures 7a and 7b). These equations produce new

Figure 7. Linear shoreline model. Model of (a) EOF mode 1 and (b) empirical orthogonal function mode 2. (c and d) Time series of the observed and predicted temporal projections for empirical orthogonal function mode 1 and mode 2.

temporal coefficients (C_1 and C_2) that are in good agreement with the observations (Figures 7c and 7d). The performance of the model in reproducing the shoreline position for the 44 shorelines was assessed by calculating the alongshore mean difference between the observed and modeled positions, the standard deviation in the observed shoreline position and the ratio alongshore mean difference/ σ (Figure 8). Although there are occasionally localized errors of up to 3 m, the model is generally accurate in predicting the shoreline position. The model was also used to predict the shoreline position for five additional image-derived shorelines that were not used to derive the model (blue markers, Figure 8). The model performance statistics are similar if the salient and embayment sections of the beach are treated independently (not shown).

Figure 8. Summary of statistics for the shoreline position model. The alongshore mean difference (AMD) is defined as the observed minus predicted shorelines. The gray areas denote austral autumn-winter months. The observations from January to July 2017 (blue points and triangles, not included in the data set used to create the model) are shown to illustrate predictive capability if the water level and wave height are known.

Figure 9. Effect of wave heights and water levels on shoreline position. (a) Observed and modeled shorelines representing typical summer and winter wave conditions with the same water level (at mean sea level, 0 m): August 2014 (black) and April 2015 (orange). (b) Observed and modeled shorelines representing typical seasonal water level changes with the same wave height (1.6 m): October 2010 (orange) and April 2011 (black). The gray areas denote the locations of shore-attached reefs.

The empirical shoreline model is useful to assess the relative influence of the seasonal variation in water level and wave height. We use the model to predict the shoreline position for four scenarios. First, shorelines were predicted with water levels close to the mean value 0 m (i.e., 0.1 m AHD) but with different wave heights typical of summer and winter conditions (1.1 and 2.6 m, respectively, indicating summer and winter) (Figure 9a). The larger 2.6 m offshore waves result in erosion at the salients fronted by reefs and accretion at the embayments with no reefs, with the opposite occurring during the low 1.1 m offshore waves (Figure 9a). At salient 1, the model shows accretion with increasing wave height which is opposite to the response observed at salient 2. The observed and modeled alongshore mean shoreline variations in response to summer and winter wave conditions are approximately -1 m and -3 m (25% and 65% of the average summer to winter change: -4.5 m). Second, the relative influence of the seasonal variation in offshore water level was analyzed using scenarios with the same wave height (close to the annual mean 1.65 m) but with varying water levels representing typical seasonal changes ranging from -0.05 m to $+0.16$ m (Figure 9b). As can be observed, these changes in water level lead to large erosion of the two salients but smaller accretion at the embayments. The observed and modeled alongshore mean shoreline changes between low and high water levels are approximately -3 m and -5 m (65% and 110% of average summer to winter change). Consistent with the observations, the model indicates that changes in the mean shoreline position caused by seasonal differences in water level are larger than the magnitude of changes generated by seasonal variation in wave height.

4. Discussion

Our results demonstrate that the observed seasonal beach response was primarily dictated by seasonal variability in subtidal water levels. This clearly differs from the focus of other studies of open coast (Hansen & Barnard, 2010; Yates et al., 2009) and reef-fringed (Alegria-Arzaburú et al., 2013; Eversole & Fletcher, 2003; Norcross et al., 2002) beaches, where the seasonal variation in incident wave energy has been considered the primary mechanism in driving the seasonal shoreline variability. However, the majority of these prior observations have been performed in coastal sites with small seasonal oscillations in subtidal sea level (order centimeters) (Tsimplis & Woodworth, 1994; Wyrski, 1974) that might not generate a visible impact in the

Figure 10. Effect of El Niño–Southern Oscillation events on the water level and shoreline position. (a) Water level (running mean ± 3 months) at Fremantle with respect to the mean of the period 2010–2016 (i.e., 0.1 m Australian Height Datum). The periods classified as El Niño or La Niña by the Australian Bureau of Meteorology (2017) are indicated in blue and red, respectively. (b) Modeled change in shoreline position for typical mean winter wave conditions (~ 2.5 m offshore H_s) but with water levels representing the maximum values occurring during El Niño (0.09 m, June 2014) and during La Niña years (0.21 m, June 1999) within the period 1950–2016. The mean shoreline change (averaged along the entire beach) between these El Niño and La Niña shorelines is -1.9 m which represents 40% of the mean shoreline change from summer to winter. The gray areas denote the locations of shore-attached reefs.

seasonal response of the beach. In contrast, in southwestern WA the seasonal amplitude in subtidal water level can be up to ± 0.2 m which provides an excellent opportunity to investigate how sustained periods of sea level change modify beach behavior along reef coasts. In addition, the several month phase lag between the seasonal variations in subtidal water level and wave energy (Figure 3e) allows their individual contributions to the beach response to be discerned.

At Garden Island the monthly shoreline variation is the result of changes in subtidal water level and wave height integrated over the preceding 30–60 days caused in turn by the seasonal changes in the Leeuwin Current (Feng et al., 2003) and in wave energy (Young, 1999), respectively. The intervals of 30–60 days also reflect the time required by the beach to respond to changes in wave and water level conditions in order to approach an equilibrium morphology. Water levels ultimately regulate the wave energy that reaches the shoreline onshore of the reefs by regulating depth-limited wave breaking (Thornton & Guza, 1982). During lower water levels, less wave energy reaches the shoreline (and vice versa). This modulation has been described in detail at fringing reefs (Becker et al., 2014; Brander et al., 2004; Storlazzi et al., 2011) over individual tidal cycles; however, at Garden Island the water levels persist for ~ 30 days and drive the beach toward new morphologies over seasonal time scales. Thus, despite the magnitude of the subtidal and tidal water level fluctuations being of a similar magnitude, the response to the tidal fluctuations is minimal as a result of their short duration.

Due to the influence of regional sea level on the shoreline, the seasonal cycle of erosion/accretion is also modulated interannually (Figures 4d and 6c) by variations in the Leeuwin Current strength and thus ENSO events (Figure 10a) (Feng et al., 2003; Pariwono et al., 1986; Pearce & Phillips, 1988). According to our model (section 3.2), more erosion occurs along the reef-fronted sections during La Niña winters than during El Niño winters (Figure 10b). While there is some evidence that offshore wave heights at southwestern WA can also exhibit interannual variations, these appear to occur over decadal time scales (~ 40 years) that are not strongly correlated to ENSO events (Bossler et al., 2012; Wandres et al., 2017).

The shoreline observations also highlight the considerable alongshore variability in beach response along reef-fringed coastlines. The salients fronted by reefs exhibited the largest response and reacted primarily

out of phase to the adjacent embayments, which lacked reefs and exhibited smaller shoreline changes. The alongshore-variable behavior suggests that alongshore sediment transport controls the seasonal beach behavior, as has been observed at other sites with spatially variable EOF functions (Clarke & Eliot, 1982; Muñoz-Pérez et al., 2001; Short & Trembanis, 2004). However, unlike the sites described in these prior studies, at Garden Island the alongshore sediment transport is more controlled by seasonal variations in water level rather than in incident wave energy.

The alongshore exchange of sediment between salients and embayments can be understood by examining results from laboratory and numerical models simulating the response of beaches in the lee of submerged structures (Hanson & Kraus, 1991; Ranasinghe et al., 2010; Ranasinghe & Turner, 2006). Following Hanson and Kraus (1991), as water level increases, wave transmission over a submerged structure increases while wave diffraction decreases resulting in more wave energy reaching the shoreline and thus in more erosion in the lee of the structure, which is similar to the beach response observed at the salients of Garden Island during high water levels. Similarly, Ranasinghe and Turner (2006) and Ranasinghe et al. (2010) describe the beach response in front of a structure in terms of diverging and converging nearshore currents at the shoreline. According to their model results, over a submerged structure the wave setup is larger than at adjacent (exposed) locations due to the enhanced wave breaking at the shoreline. This alongshore gradient in wave setup drives alongshore flows diverging from the structure in both alongshore directions which contribute to eroding a beach. On the other hand, converging currents can be generated due to setup gradients along a shoreline due to smaller waves breaking in the lee of the structure (with larger waves breaking in adjacent areas exposed to offshore incident waves). Depending on the geometry of the submerged structure and its distance from the shoreline, the diverging circulation over the structure can change to a converging pattern when water levels decrease over the structure (Ranasinghe et al., 2010). By analogy, converging circulation due to refraction around the rocky reefs at Garden Island appears to be the likely mechanism driving the recovery of salients during low water levels. However, in situ measurements or numerical simulations of nearshore currents and sediment transport in future work would be necessary to develop a detailed process-based understanding of the sediment dynamics at Garden Island and their dependency on water levels.

Finally, the seasonal and interannual variations in the water level reveal the likely importance of the Leeuwin Current (and dynamics occurring on the shelf, in general) in driving the shoreline changes at beaches along the southwestern WA coast. This had been hypothesized by Clarke and Eliot (1983) from observations at southwestern WA sites lacking reefs, but until the present work, this had not been quantified. Our results, linking the response of reef-fringed beaches to mean sea level changes, is also valuable for understanding and predicting coastal behavior as sea levels rise in the future. In addition to the sea level rise forecast due to global warming (e.g., Church et al., 2006), the strength and frequency of ENSO events have also been suggested to increase in the future (Cai et al., 2014, 2015). How shorelines will respond in the future may thus not solely depend on how climate change will modify long-term trends in mean sea level but also how climate variability will modify interannual water level variability.

5. Conclusions

The results of this study indicate that subtidal water level variations can be more important than changes in wave energy in driving the shoreline response at reef-fringed beaches. At Garden Island the seasonal range in the subtidal water level is up to 0.4 m and is correlated with the seasonal variation in the strength of the Leeuwin Current. Our results show that during periods of low sea levels (weaker Leeuwin Current) and low wave heights, sections of beaches fringed by reefs accrete while the adjacent regions without reefs erode, with this pattern reversing during high sea levels (stronger Leeuwin Current) and larger waves. This accretive/erosive seasonal cycle is modulated interannually due to variations in the strength of the Leeuwin Current and associated water levels caused by ENSO events. Our results suggest that during La Niña years, during which the Leeuwin Current is stronger and sea levels are higher, more seasonal erosion occurs at the beach sections fronted by reefs than during El Niño years which feature lower sea levels. Thus, the future response at reef-fronted shorelines along southwestern Australia will be determined by changes in the global mean sea level but also changes in the Leeuwin Current, revealing an interesting coupling between large-scale dynamics of an ocean boundary current system driving coastal water level variability

and nearshore processes driving beach erosion; processes that for the most part have been assumed to be largely uncoupled in studies of seasonal and interannual beach variability.

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