Impacts of Enhanced Central Pacific ENSO on Wave Climate and Headland-Bay Beach Morphology

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ABSTRACT

Wave climate and Pacific basin coastal behaviour associated with El Niño Southern Oscillation (ENSO) is understood at a reconnaissance level, but the coastal response to different central Pacific (CP) versus eastern Pacific (EP) flavours of ENSO is unknown. We show that CP ENSO events produce different patterns of directional wave power to EP ENSO along the southeast Australian shelf and southwest Pacific region, because of significant variability in trade-wind wave generation. The modulation of the trade wind wave climate during CP ENSO has thus far been neglected in existing coastal process studies. We also show that coastal change between CP and EP ENSO cannot be inferred from shifts in the deepwater wave climate. This is because variability in trade wind wave generation is masked in deepwater by the persistence of high power extra-tropical waves that have reduced impact on nearshore processes due to high wave refraction. Morphodynamic modelling in a

headland-bay beach indicates that CP ENSO leads to higher coastal erosion potential and slower post-storm recovery than EP ENSO during an El Niño/La Niña cycle. We show that the alongshore variability in beach morphological type can be used to model the static equilibrium planform response for each ENSO phase. Results indicate that shoreline response to ENSO in most headland-bay beach coasts is not as simple as the existing paradigm that (anti-) clockwise rotation occurs during El Niño (La Niña). Our methods provide a second-order approach to project coastal response and predict the discrete shoreline rotations for ENSO flavours.

KEYWORDS

ENSO; Wave climate; Headland-bay beach; Coastal processes; Sediment transport

1. INTRODUCTION

There remains considerable uncertainty in the prediction of future shifts in ENSO behaviour from Global Climate Modelling (GCM) because of the non-linearity of ENSO and complex coupled feedbacks (Watanabe *et al.*, 2012). Downscaled projections of regional wave climate inherit this uncertainty and are highly variable, especially for Pacific regions directly impacted by ENSO and on sub-annual timescales (Mori *et al.*, 2013; Hemeret *et al.*, 2013). There remains, therefore, a significant knowledge gap in how Pacific coasts will respond to future changes in ENSO.

Multi-decadal wave buoy observations along the south east Australian shelf (SEAS), in the south west Pacific, have shown that ENSO significantly modulates wave climate directionality and intensity (Goodwin, 2005; Harley *et al.*, 2010). In broad terms, El Niño promotes bi-directional south easterly and easterly wave conditions, while La Niña and ENSO-neutral phases are correlated with a more uni-directional south easterly wave climate. A greater number of storms occur during La Niña (Browning and Goodwin, 2013), in contrast to the eastern Pacific where El Niño is most damaging (Storlazzi and Griggs, 2000).

The latitudinal displacement of the Subtropical Ridge (STR), the latitude of highest pressure over East Australia, also exerts a strong influence on the seasonal wave climate (Mortlock and Goodwin, 2015) and impact of ENSO. ENSO wave climates are also coupled to the Southern Annular Mode (SAM) (Hemer *et al.*, 2009), particularly during Austral winter. The SAM describes the see-saw of atmospheric mass between the mid-latitude westerlies and Antarctica (Marshall, 2003). Positive SAM represents a poleward displacement of the westerlies, and reinforces a La Niña wave climate through the modulation of Southern Ocean and Southern Tasman Sea wave generation. The opposite is true during negative SAM and El Niño wave climate.

Mortlock and Goodwin (2015) have showed that the directional wave climate along the SEAS can be encapsulated in three primary modes of variability (Figure 1 a). A sub-tropical easterly mode is modulated by south Pacific trade winds (Mode 1); a south-easterly mode is generated locally in the Tasman Sea (Mode 2) and an extra-tropical southerly mode is related to the strength of the mid-latitude westerlies (Mode 3).

Similar to other Southern Hemisphere coastlines, the south east Australian coast is meridionally oriented with a predominant south to north longshore sediment transport regime (Figure 1 a). Sediment transport cells are divided by prominent headlands, leading to the repetition of headland-bay beach morphology along much of the 1,200 km of coastline length. Under this configuration, the headland is located to the south, with the parabolic beach adjacent to the north. A Mode 1 wave climate produces cross-onshore wave conditions, Mode 2 onshore, and Mode 3 oblique (Figure 1 b). The planform geometry of these coastal sections is well described by the Parabolic Bay Shape Equation (PBSE) developed by Hsu and Evans (1989). Downdrift (north) of the parabola, the planform is oriented normal to the modal wave direction.

Shifts in the orientation of headland-bay beach compartments are linked to directional variability in the SEAS wave climate with ENSO (Goodwin *et al.*, 2006; 2013). Collaroy-Narrabeen Beach and Palm Beach, two embayed compartments in Sydney, rotate clockwise (anti-clockwise) during biennial El Niño (La Niña) events (Short *et al.*, 2000; Ranasinghe *et al.*, 2004), because of shifts in wave directionality (Ranasinghe *et al.*, 2004; Harley *et al.*, 2015). Recent research suggests that coastline fluctuations observed along this section of coast are part of a synchronous Pacific basin-wide response to ENSO forcing (Barnard *et al.*, 2015).

While a connection between El Niño/La Niña wave climate and coastal response is established, our current understanding of coastal impacts on Pacific coastlines has not yet accounted for different flavours of ENSO. Most observational studies relate to an eastern Pacific (EP) El Niño or La Niña climate that is characterised by a canonical pattern of surface warming or cooling in the eastern Pacific. However, ENSO anomalies also develop in the central Pacific (CP). CP ENSO events (also known as ENSO Modoki) have become more frequent in recent decades (Lee and McPhaden, 2010) and some GCMs indicate this will continue with greenhouse warming (Yeh *et al.*, 2009). It is therefore important to understand whether the wave climate and coastal response to CP ENSO is significantly different to EP ENSO.

We focus on the modal (non-storm) wave climate as a predictand of the ENSO Pacific climate state and as the principle driver of large-scale coastal behaviour. A moderate wave energy regime exists in the Tasman Sea where modal wave conditions constitute 95% of all observations (Mortlock and Goodwin, 2015). Our focus on the modal wave climate thus encapsulates the directional wave variability along the SEAS and provides a large sample size for statistical analysis. While storm events are an important driver of coastal stability, modal wave conditions are responsible for shaping the long-term planform geometry. Moreover, there is no robust relationship between storm wave directionality and phases of ENSO in Southeast Australia because of the influence of the SAM on the generation of extreme sub-tropical storms. The directionality of the modal wave climate, however, is well correlated to ENSO (Goodwin, 2005) and thus a more robust predictand of the ENSO Pacific climate state for Southeast Australia.

We use over 20 years of mid-shelf and directional buoy observations to examine shifts in wave power and wave generation with EP and CP ENSO along the south east Australian shelf. We then use a morphodynamic model to investigate whether enhanced CP ENSO

produces a distinct morphological response at Terrigal-Wamberal (33.4° S, 151.4° E), a classic parabolic shaped headland-bay beach 60 km north of Sydney. Shoreline oscillation and rotation at Terrigal-Wamberal (hereafter, 'Wamberal') is synchronous with other embayed compartments in Southeast Australia (Short *et al.*, 2014; Bracs *et al.*, 2016) and thus indicative of the region. Moreover, the shoreline planform at Wamberal is close to the limiting static planform (after Hsu and Evans, 1989), meaning results can be applied to understanding shoreline response to ENSO phases at other static-planform locations.

We also investigate the extent to which the deepwater wave climate is a valid indicator of nearshore change. The alongshore variability in surf-zone morphology is used as an indicator of coastal vulnerability and also as a measure of geometric planform change. An ensemble of coupled ENSO wave climates and beach states are presented for an idealised headland-bay beach configuration, which can be used to model scenarios of coastal impacts as GCM projections of ENSO improve.

2. METHODOLOGY

2.1 Identification of ENSO events

Austral oceanic summers (January to March, JFM) and winters (July to September, JAS) during either EP or CP El Niño/La Niña events were identified over the period of directional buoy observations, from the monthly Niño 3.4 index (NINO3.4) and El Niño Modoki Index (EMI) (Figure 2). The definition of CP ENSO in this study is therefore synonymous with ENSO Modoki after Ashok *et al.* (2007).

Where possible, a suitable coupling with the SAM and allowance for time lags between indices and wave climate response were considered. Selected EP ENSO periods were based

on those identified by the Oceanic Niño Index (ONI). Selected CP ENSO events were cross-checked with those identified in the literature (e.g. Shinoda *et al.*, 2011). The wave climates of the selected ENSO periods are given in Table 1.

2.2 Parametric Wave Data

Directional wave observations from buoys at Sydney (1992 – 2013) and North Stradbroke Island (40 km west of Brisbane, hereafter referred to as ‘Brisbane’) (1997 – 2013) were used to represent the mid-shelf (60 – 80m water depth) wave climates of ENSO periods along the SEAS (Figure 1 a). Daily-averaged significant wave height, H_s , peak spectral wave period, T_p , and mean wave direction, MWD , were used.

Since our focus is on the modal (non-storm) wave climate, all storm events were omitted from the buoy records using a Peaks-over-Threshold (PoT) method. The 10% daily exceedance H_s was used with a three-day minimum storm duration at Sydney, after Mortlock and Goodwin (2015) found this to return the best split between ambient and extreme wave distributions. At Brisbane, a second threshold using the 5% daily exceedance H_s with a 1-day minimum duration was also applied in order to filter high energy and transient tropical cyclone storm events from the record.

2.3 Directional Wave Hindcast

MWD at Brisbane was hindcast for summer 1996 using cumulative distribution function (CDF) matching (Brocca *et al.*, 2011) of summer wave directions at the Sydney buoy to capture the summer EP La Niña wave climate (Figure 3). Figure 4 d shows an improved correlation exists between CDF-matched Sydney wave directions and those observed at Brisbane, than between uncorrected Sydney wave directions and observations at Brisbane, over a blind test period (Figure 3 a).

2.4 Wave Climate Typology

The three primary modes of wave climate variability presented in Figure 1 were further decomposed into six synoptic-scale modal ‘wave climate types’ (WCT) using a combined statistical-synoptic typing method after Mortlock and Goodwin (2015). Figure 4 shows the mean sea level pressure (MSLP) anomaly patterns for each of these WCTs over the Tasman Sea. All WCTs are identifiable in both Austral summer and winter, apart from Mode 2b which at Sydney only exists as a summer pattern. Modes 3a and 3b are not seen at the Brisbane buoy due to a north-west trending shoreline north of Cape Byron. A detailed discussion of each WCT is provided in Mortlock and Goodwin (2015). Here we use the WCT discretization to relate directional wave power to zonal Pacific circulation.

2.5 Patterns of ENSO Directional Wave Power

The total wave power, P_W , delivered by each wave climate type was used to describe the pattern of directional wave power for each ENSO period. P_W is the integral of the wave power density of each daily wave event, P_0 , over the duration of each WCT, t , given in megawatt-hours per metre wave-crest-length (MWh m^{-1}):

$$P_W = \int_0^t P_0 dt \quad (1)$$

To ensure no bias of P_W away from periods with data gaps due to instrumental error, the frequency of occurrence of each WCT was up-scaled from the observed record to simulate 100% data recovery at the buoys. The frequency of occurrence of each WCT was then de-trended before calculating P_W .

A two-tailed student t-test was used to determine whether the difference between patterns of ENSO directional wave power was significant (to 90% confidence). This was based on the frequency of occurrence of each WCT during each ENSO period (Table 2).

Significant differences between wave power generated by individual WCTs, rather than the wave climate as a whole, were also determined between EP and CP ENSO climates. If differences exceeded one standard deviation of the interannual wave power variability for the respective WCT, it was considered significant to the 90% CI.

2.6 Morphodynamic Modelling of a Headland-Bay Beach

ENSO wave climates at Sydney were transformed to Wamberal, 60 km north (Figure 5), to investigate the morphodynamic response to ENSO in a typical headland-bay beach in Southeast Australia. A coupled MIKE21/3 model of the embayment was nested within a regional MIKE21 Spectral Wave (SW) model. MIKE21/3 dynamically couples a spectral wave, hydrodynamic and sand transport module to simulate bathymetric evolution by wave-driven currents based on Reynolds-averaged Navier-Stokes theory (DHI, 2014).

2.6.1 Model Configuration

The model was configured to isolate wave forcing, so no terrestrial sediment inputs, tides, local winds or ambient currents were included. Headland sand bypassing is essentially switched off for this experiment, since the embayed geometry of the regional coast and the incised nature of the Wamberal embayment prevent bypassing during modal wave conditions. A detailed description of the model configuration is provided in Supporting Information (Table S1). High spatial resolution (5 m²) LIDAR bathymetry (March 2008) was used to represent the shoreface to 30 m depth.

Bathymetric data was smoothed in the model to provide a starting bathymetry representative of a typical embayed beach configuration close to equilibrium. All subaqueous reef around Terrigal Headland was omitted, and only areas of the embayment with a sand bottom were

modelled (Figure 5). Thus while the study site was based on planform geometry and wave climate at Wamberal, the modelling case was further idealized to be regionally representative.

2.6.2 Model Validation

Nearshore model performance was verified against eight months of hourly buoy observations (August 2011 to March 2012) at 12 m depth inside the Wamberal embayment (location Figure 6). Results showed good model skill for wave power (R^2 0.76, slope 1.1) and direction (R^2 0.80, slope 0.84) during modal wave conditions (Figure 6). We attribute the over-prediction of wave period (Figure 6 b) to a lack of a local wind forcing during validation, whereby an additional wind sea would add high frequency energy to the spectrum and reduce the modelled wave period. Since ENSO near-coast wind fields are not considered in this study, we consider the model to perform adequately for wave-only conditions.

No specific morphological validation of the model was undertaken because the study site was modified to represent an idealized regional case. However, the modelled morphological behaviour conforms with observations of wave climate forcing and surf zone response observed at Wamberal from a ~40 year archive of available photogrammetry and aerial photography. Moreover, other global studies have shown MIKE21/3 to produce a good representation of morphological change on the upper shoreface when compared with observations (Zyserman and Johnson, 2002; Dronen *et al.*, 2012; Kristensen *et al.*, 2013). In addition, results presented here consider error in morphological modelling by the omission of all bed elevation change within one standard deviation of the mean ($\approx$ zero). The modelled cumulative bed elevation change was normally-distributed for each ENSO case with a mean approximate to zero after outliers were removed. Under a Gaussian distribution, all vertical difference beyond one standard deviation of the mean was considered to be significant to the 90% CI.

2.6.3 Boundary Wave Forcing

A three-month time series of daily offshore modal wave conditions for each ENSO wave climate was generated for model boundary forcing (Figure 7). The observed time series at the Sydney buoy was first indexed by WCT for each ENSO season. This was done so that each wave day could be represented by the centroid parameters H_s , T_p and MWD of the WCT to which the observation belonged, rather than the actual observation. This method obtained a clearer signal of morphological response between ENSO types in what is a complex mixed sea-swell environment. Centroid parameters were calculated separately for each ENSO period.

A continuous (gap-free) time series was required for modelling. However, missing wave days existed in the observed (buoy) record due to either instrument error at the buoy or omitted storm events. Missing days were filled by first calculating the number of extra days needed per WCT to maintain the frequency of occurrence of each WCT from the portion of the time series observed at the buoy. Each required wave day was then represented by the respective centroid parameters of the corresponding WCT. A random permutation of the required wave days was performed and then inserted into the locations of data gaps in the time series. This provides a ‘nudged random’ order of WCTs for data gap periods, as the randomness of the sequencing is already weighted by the number of wave days needed. The sequencing of the wave time series is as important as the wave climate itself, as the morphological model dynamically couples waves, flow and bed elevation change at each time step. A six-month wave climate consisting of two cycles of the respective three-month timeseries was then used to force the model to allow sufficient time for an equilibrium beach state to develop.

3. RESULTS

3.1 Impact of ENSO on Seasonal Wave Climate

At locations where the winter wave climate is strongly influenced by the SAM (south of Cape Byron), patterns of ENSO wave power are most dissimilar during Austral summer when the STR migrates $\sim 4^\circ$ poleward, displacing the SAM (and southerly Mode 3 wave power) influence on the sub-tropics. During winter, the wave climate is dominated by Mode 3 power, masking the influence of ENSO.

This is evident at Sydney, where all ENSO wave climates are dissimilar from each other during summer, but not during winter (Table 2). The exception is between summer EP La Niña and CP La Niña, which are not dissimilar (at the 90% CI) although there is a significant increase in Mode 1a wave power during La Niña Modoki (Figure 8).

While the SAM does not influence the winter wave climate at Brisbane, an open fetch for Coral Sea and Southwest Pacific tradewind wave generation means easterly Mode 1 power dominates in all ENSO phases during summer (Figure 9). As a result, no ENSO wave climates are dissimilar during summer, whereas almost all types are discrete in winter (Table 2). The exception is between winter EP La Niña and CP El Niño, which are not dissimilar.

3.2 Impact of Central Pacific ENSO on Directional Wave Power

CP ENSO produces significantly different patterns of directional wave power from EP ENSO at Sydney and Brisbane (Table 2) primarily because of the modulation of Mode 1 wave power between the different flavours of ENSO. At both locations, east to north east wave power is greater during EP El Niño than CP El Niño, and CP La Niña than EP La Niña in Austral summer, while the opposite is true in winter (Figure 8 for Sydney, Figure 9 for Brisbane).

The modulation of Mode 1 wave power represents variability in longer-period southwest Pacific trade-wind wave generation and is associated with the position and strength of the

sub-tropical Anticyclone (STAC). East to north eastwave power is maximised when the STAC is located to the north east of the North Island of New Zealand (summer EP El Niño/CP La Niña, or winter EP La Niña/CP El Niño), and weakest when in the central Tasman Sea (summer EP La Niña/CP El Niño) or over southeast Australia (winter EP El Niño/CP La Niña).

As a result, prolonged periods of CP La Niña enhance wave climate seasonality over successive summer/winters at Sydney and Brisbane, in comparison with EP La Niña. This is manifest in an anti-clockwise (clockwise) rotation of modal wave power during summer (winter). At Sydney, persistent CP La Niña results in lower total modal wave power for consecutive summer/winters (Figure 8), while at Brisbane there is an increase in total wave power in summer but a decrease the following winter (Figure 9).

3.3 Nearshore Sensitivity to Shifts in the Deepwater Wave Climate

While discrete patterns of wave power exist in deep water, changes to the nearshore wave climate are more subtle. The nearshore wave climate was output along the seaward edge of the surf zone (5m contour) in the south, centre and north of the embayment. Figure S1 (S2) in Supporting Information shows nearshore results for summer (winter) ENSO model runs with corresponding deepwater boundary wave climate. Results show the nearshore zone is relatively insensitive to shifts in offshore wave direction due to shoaling processes. On average, a one degree shift in the direction of waves entering the surf zone requires a $\sim 35^\circ$ shift offshore. At the northern (most exposed) end of the embayment, only 50 % of total offshore wave power reaches the surf zone, while in the headland shadow zone this is reduced to 11 % after refraction.

Both wave power and directional sensitivity vary considerably in the south and centre of the embayment with wave obliquity. When the deepwater mean wave direction is clockwise of

shore-normal (which is south-east at this location), a $\sim 55^\circ$ shift offshore is required for a one degree change in wave direction in the centre/south of the embayment, and only $\sim 15\%$ of the total deepwater wave power reaches the surf zone. In contrast, when the deepwater wave direction is anti-clockwise of shore-normal, only a $\sim 30^\circ$ shift is required for a one degree change in the nearshore wave direction, and twice the amount ($\sim 30\%$) of total deepwater wave power reaches the surf zone. The nearshore geometry is therefore more sensitive to small changes in east and north east waves (modal trade-wind and tropical-origin storm waves) than southerly waves (extra-tropical origin modal and storm waves), despite the latter having much greater total power in deepwater.

This indicates that ENSO-related coastal impacts cannot be directly inferred from the deepwater wave climate because the importance of east and north-easterly waves in the nearshore is masked in deepwater by the persistence of oblique southerly wave conditions which are highly dissipated upon reaching the nearshore. This can be illustrated by comparing the centroid P_W values of Mode 1a-type waves (north-easterly trade winds) and Mode 3b-type waves (southerly Southern Tasman Lows) in deepwater (Figure 4). Mode 1a waves produce a mid-shelf, mean annual P_W of 8.5 kW/m, while Mode 3b waves produce 17 kW/m, twice the magnitude of Mode 1a. However, after refraction into the nearshore both wave climate types exert comparable amounts of energy on the surf zone. Mode 1a waves retain $\sim 30\%$ of deepwater power (~ 2.6 kW/m) while Mode 3b retain $\sim 15\%$ (~ 2.6 kW/m).

3.4 Beach Morphological Response to ENSO

Figure 10 shows how the surf zone morphology in a headland-bay beach may equilibrate according to the persistence of different ENSO climate states. Morphologies can be divided into two mean states; those produced under north east to south east ENSO wave climates (typical of summer), and those with a significant southerly wave component (typical of

winter). The differences between morphologies can be viewed in terms of the alongshore variation in the Wright and Short (1984) beach state classification.

Northeast to southeast ENSO wave climates (summer EP El Niño, EP La Niña and CP La Niña and winter EP La Niña) produce a shore-normal, more energetic nearshore wave climate and rhythmic bar and beach (RBB) morphology along the majority of the planform. In the headland shadow zone sand is transferred from the beach toe to a low tide terrace (LTT) with a rip channel separating adjacent morphology to the north. To the east, negligible wave energy produces a reflective beach state with deeper water directly off the toe. The transfer of sand to the LTT is greatest during east to north east wave conditions and may contribute to an apparent anti-clockwise rotation of the shoreline, as proposed by Ranasinghe *et al.* (2004) at Collaroy-Narrabeen, 30 km south of Wamberal. If this is the mechanism for rotation at the southern end of the embayment, the sand is only moved a few metres below the water line.

In contrast, southerly ENSO wave climates (winter EP El Niño, CP El Niño and CP La Niña and summer CP El Niño) produce a steep alongshore gradient in nearshore wave power and a reduced-energy wave environment in the south and centre of the embayment, despite having the highest cumulative power offshore. This leads to a transverse bar and rip (TBR) morphology for most of the planform, grading to RBB at the (most exposed) northern end. Less sand is transferred to a LTT in the headland shadow zone during oblique wave conditions.

Only CP El Niño summer and EP La Niña winter lead to seasonal changes in the beach state, despite all summer wave climates being discrete in deep water. CP El Niño summer contains a reduced easterly component producing a more winter-like beach state than other ENSO summers. EP La Niña winter is a bi-directional north east and south east wave climate (Figure 8) producing a more summer-like beach state than other ENSO winters.

The starting bathymetry used in the model was captured two weeks after a cluster of small (one year return period) southerly storms. In all cases, an initial period of rapid (± 0.4 m/day) shoreface recovery was observed in the model lasting eight to ten weeks (from end of storm) before the rate of change significantly slowed and the morphology attained an equilibrium with ambient wave conditions. Modelled shoreface recovery was most rapid when the modal wave direction was close to the antecedent storm direction.

4. IMPLICATIONS

Results represent inter-annual ENSO wave climates coupled to variability in the SAM in the extra-tropics. A view of ENSO impact is also presented under a specific large-scale regime in terms of the STR, which is poleward of its mean position for the last 1,000 years (Goodwin *et al.*, 2014). While both these scenarios are anomalous in the long-term, they are relevant for projections for the coming century as greenhouse warming is likely to force a continued expansion of the tropics (Seidel, 2008; Allen *et al.*, 2014) and maintain a strong coupling between SAM and ENSO (Thompson and Wallace, 2000; Wang and Cai, 2013), enhanced by a continued trend towards positive SAM with ozone healing (Mayewski *et al.*, 2015).

4.1 Coastal Vulnerability with Future ENSO Behaviour

Despite recent improvements in GCM modelling, there is still no consensus on how ENSO will change with greenhouse warming (Cai *et al.*, 2015b), and regionally downscaled projections inherit this uncertainty. This affords little confidence in assessing future ENSO-related impacts. Therefore, a scenarios-based approach is required to account for this uncertainty. Results can be used with GCM-based projections of ENSO to model coastal impacts.

One scenario is an increase in ENSO amplitude, with more frequent extreme El Niño events (that influence the Austral summer wave climate) followed by extreme La Niña events (impacting the following winter and summer wave climates) (Cai *et al.*, 2015a). There is no robust projection of whether an EP or CP pattern is more likely, although extreme La Niña tends to be a central Pacific phenomenon and CP ENSO events have become more frequent in recent decades (Lee and McPhaden, 2010). The coastal impact of both EP and CP ENSO sequences can be idealised based on the coupled wave climate and beach states presented in this study (Figure 11). The alongshore variability in surf-zone morphology can be used as a measure of coastal vulnerability.

For an EP pattern, a longshore bar forms along most of the planform during the first El Niño summer, with greater bar building at the northern end because of an east and south easterly wave climate (Figure 11 a). During the subsequent La Niña winter, a rhythmic bar also forms with greater bar-building in the south/centre of the embayment than during the preceding El Niño phase because of a north easterly wave component (Figure 11 b). The second (La Niña) summer wave climate is more uni-directional south easterly, leading to a longshore bar in the centre/north of the embayment, and a transverse bar and rip cell pattern in the southerly third (Figure 11 c).

For a CP pattern, the first El Niño summer is characterised by the persistence of transverse bar and rip in the south/centre of the embayment due to (unseasonal) south south easterly wave power with a sub-dominant easterly component (Figure 11 d). The following La Niña winter is also south south easterly, but the absence of an easterly component extends the bar-and-rip morphology of the preceding summer across the whole planform (Figure 11 e). A longshore bar eventually forms during the second (La Niña) summer under a north-easterly wave climate (Figure 11 f).

The absence of a continuous bar during the first summer to winter affords less storm wave dissipation during CP ENSO. Moreover, the rip cells focus wave energy and correspond to erosion hotspots. South-easterly storms occur more often during winter and La Niña phases in south east Australia (Browning and Goodwin, 2013). Therefore, the embayment is most vulnerable to storm damage during CP La Niña winter, especially if the preceding summer is a CP El Niño pattern. By comparison, the EP ENSO wave climates provide better storm protection for the sub-aerial beach.

Shoreface recovery from storm cut is most rapid when subsequent modal wave direction is similar to the antecedent storm direction. Therefore, the CP ENSO sequence may lead to slower rates of recovery after La Niña winter storms, because the modal wave climate of the following summer is low power and from the north east while storms are south easterly. In contrast, EP La Niña summer is higher power south easterly and better placed to return sand to the surf zone.

4.2 Modelling Planform Geometry with Long-Term Shifts in ENSO

Shoreline planform geometry is a direct expression of the alongshore variation in surf zone morphology, and is a dominant feature of the classification of Wright and Short (1984). Numerous observational studies (Thornton *et al.*, 2007; Quartel, 2009; Price and Ruessink, 2013) have confirmed that surf zone variability is synchronous with shoreline change. Despite this, models have traditionally treated surf zone morphology and the shoreline separately (van de Lageweg *et al.*, 2013). Recent improvements in shoreline modelling have begun to couple the two-dimensional surf-zone morphology to a one-line expression of the shoreline (e.g. Kaergaard and Fredsoe, 2013), although their application to areas with very high planform curvature such as in the lee of headlands is uncertain. Instead, the Parabolic

Bay Shape Equation (PBSE) (after Hsu and Evans, 1989) has been shown to provide a good representation of the Static Equilibrium Planform (SEP) of headland-attached bay beaches.

However, a major source of uncertainty in applying the PBSE has always been locating the downcoast end of the parabola, or downcoast ‘control point’ (Lausman *et al.*, 2010). We suggest that the alongshore variability in the surf zone morphological type of Wright and Short (1984) can be used to locate the downcoast control point needed to model a headland bay-beach shoreline in static equilibrium. We propose that the change from either Low Tide Terrace (LTT) or Transverse Bar and Rip (TBR) to Rhythmic Bar and Beach (RBB) morphology represents the point at which the planform ceases to follow a parabola to where it aligns normal to the wave orthogonal as an equilibrium shoreline response to the persistence of each ENSO wave climate (Figure 12). By locating this point the angle of wave obliquity, β , and the control line length, R_β , can be found, from which the PBSE can be solved. Here we express R_β in terms of the compartment length, L for the method to be expanded to other compartments in south east Australia.

Our method reduces computationally intense, two-dimensional morphodynamic modelling of the embayment to a one-line expression of the shoreline for each ENSO climate. It also allows the complexity of bi-modal wave conditions (and thus more than one diffraction point) to be incorporated into the equilibrium planform for each ENSO type, which has also been a difficulty when applying the PBSE to real-world wave conditions.

While headland sand bypassing is essentially switched off in this experiment (Section 2.6.1), the control line and downdrift control point also represents the bypass strand and re-attachment point, respectively, for the cross-embayment transport of sand where it occurs. This pathway forms the connector between sand transported in the outer surf zone and the

down-coast, littoral transport when sand bypasses the headland from an updrift compartment (Goodwin *et al.*, 2013).

Our results can be used to conceptualise Static Equilibrium Planforms that are representative of the long-term persistence of each ENSO wave climate. An EP El Niño summer wave climate confines the parabolic shoreline to the first quarter of the planform (Figure 11 a). This leads to an anti-clockwise rotation of the shoreline in the lee of the headland, while the rest of the planform is flattened under predominantly shore-normal wave conditions. EP La Niña winter-type conditions lead to a similar pattern (Figure 11 b), while the persistence of an EP La Niña summer-type wave climate produces a clockwise rotation at both ends of the embayment (Figure 11 c).

In comparison, CP El Niño summer and in particular La Niña winter wave conditions lead to a substantial clockwise rotation in the planform (Figure 11 d and e). In CP La Niña winter, the parabolic shoreline describes almost 70 % of the embayment length. The CP El Niño summer response is geometrically similar to EP La Niña winter. Conversely, CP La Niña summer wave climate produces an anti-clockwise rotation of the planform (Figure 11 f) that is geometrically similar to EP El Niño summer.

Therefore, the shoreline response to ENSO wave forcing in an embayed beach is more complex than the simple paradigm that (anti-) clockwise rotation occurs during El Niño (La Niña) for an idealised bathymetry. The existing paradigm has struggled to fully describe the process of shoreline change with ENSO phases, first attributing it exclusively to alongshore (Ranasinghe *et al.*, 2004) and then cross-shore (Harley *et al.*, 2011; 2015) processes. The complex geometric response is a result of real-world shoaling processes, bi-modal wave conditions and the emergence of different flavours of ENSO climate variability. The stratification of the discrete surf zone and shoreline behaviour to each ENSO flavour enables

a new paradigm for the observed rotation process through the longshore migration of surf zone morphological types with rotating nearshore wave direction.

5. SUMMARY

While a link between ENSO, wave climate and coastal behaviour is understood at a reconnaissance level, uncertainties remain as to the coastal responses of CP versus EP ENSO. Using over 20 years of directional and mid-shelf buoy observations, we show that CP ENSO produces significantly different patterns of directional wave power to EP ENSO along the south east Australian shelf, in the south west Pacific, and differences are primarily due to the modulation of easterly, trade-wind generated wave power. The strength of trade-wind wave power is related to the position of the sub-tropical anticyclone which varies between CP and EP ENSO events.

Changes to the nearshore wave climate and coastal morphology are more subtle. Using a wave and morphodynamic model, we show that only CP El Niño summers and EP La Niña winters lead to seasonal changes in the surf zone morphology of a headland-bay beach. The nearshore is more sensitive to changes in east and north-east (modal trade-wind and tropical-origin storm) waves than oblique (extra-tropical origin) wave conditions. In deep water, the importance of the trade wind wave climate is masked by the persistence of high power extra-tropical wave conditions that have a reduced impact on nearshore processes due to high refraction. As a result, ENSO-related coastal impacts cannot be directly inferred from shifts in offshore wave direction as previously assumed.

The alongshore variability in surf-zone morphology produced by each ENSO climate state can be used as a measure of coastal vulnerability. During an Austral summer-to-summer El

Niño/La Niña cycle, a CP ENSO pattern leads to potentially higher storm erosion and slower post-storm recovery than EP ENSO. This is because CP ENSO wave climate is unseasonably oblique before and during the shore-normal La Niña winter storm season. This leads to a bar and rip cell morphology that affords less wave energy dissipation and more energy focussing than during EP ENSO. The following La Niña summer wave climate is significantly more north easterly and low power during CP ENSO than EP ENSO, and slower to return sand to the surf zone.

In addition, we propose that the alongshore variability in the Wright and Short (1984) beach morphological type can be used to locate the cross-embayment bypass strand and thus construct static equilibrium planforms for each ENSO phase. This method can be used to resolve two major uncertainties related to the application of the Parabolic Bay Shape Equation; (i) the location of the downcoast control point and; (ii) the incorporation of real-world wave conditions. Results indicate that the shoreline response to ENSO wave forcing in an embayed beach is not as simple as (anti-) clockwise rotation during El Niño (La Niña) as previously suggested, because of shoaling processes, bi-modal wave conditions and the emergence of different flavours of ENSO.

We conclude that on open ocean coastlines in the north and south east Pacific exposed to long-fetch wave climates, the response of coastal geometry to ENSO wave climate flavours may be amplified when compared to our findings for the fetch limited Tasman Sea.

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TABLES

Table 1. Three month periods used to represent ENSO wave climates from the available buoy record (1992 – 2013).

	Austral Summer	Austral Winter
EP El Niño	JFM 1998	JAS 1997
CP El Niño	JFM 2010	JAS 2002
EP La Niña	JFM 1996	JAS 1998
CP La Niña	JFM 2009	JAS 2010

Table 2. Dissimilarity matrix of Austral summer (winter) ENSO wave climates using a two-tailed student t-test. 0 (1) = distributions are (not) dissimilar between ENSO types (90% CI).

	EP El Niño	CP El Niño	EP La Niña	CP La Niña
a) Sydney				
EP El Niño	n/a	0 (1)	0 (1)	0 (1)
CP El Niño	0 (1)	n/a	0 (1)	0 (1)
EP La Niña	0 (1)	0 (1)	n/a	1 (1)
CP La Niña	0 (1)	0 (1)	1 (1)	n/a
b) Brisbane				
EP El Niño	n/a	1 (0)	1 (0)	1 (0)
CP El Niño	1 (0)	n/a	1 (1)	1 (0)
EP La Niña	1 (0)	1 (1)	n/a	1 (0)
CP La Niña	1 (0)	1 (0)	1 (0)	n/a

FIGURE CAPTIONS

Figure 1a) Three primary modes of wave climate variability in the Tasman Sea with locations of Sydney, Brisbane and Terrigal-Wamberal wave buoys. Inset shows relation to south Pacific and Southern Ocean; b) conceptualisation of planform rotation in a headland-bay beach in south east Australia.

Figure 2 Monthly values of the EMI (red line), NINO3.4 (black line) and three-month running mean of the monthly SAM index (grey shade) over the period of directional buoy operation. The sign of the SAM has been inverted for visualization of coupling with NINO3.4. Y-axis shows Sea Surface Temperature (SST) anomaly (in the case of the EMI and NINO3.4) and zonal mean SLP difference between 40° and 60° S (in the case of the SAM). Selected Austral oceanic summer (JFM) and winter (JAS) periods for EP El Niño (E.EN, blue), EP La Niña (E.LN, orange), CP El Niño (C.EN, purple) and CP La Niña (C.LN, green) are shown.

Figure 3 Cumulative Distribution Function (CDF) matching of Sydney summer *MWD* with Brisbane showing (a) scatter plot of Brisbane and Sydney daily summer *MWD* (1997 – 2012) used as model training dataset, with quantiles (blue) and linear regression (red line), (b) CDF of *MWD* observed at Brisbane (grey), observed at Sydney (blue), and CDF-matched for Brisbane (red), (c) the same for PDF of *MWD*, and (d) scatter plot with quantiles of Brisbane *MWD* observed (obs.) and modelled (mod.) for a blind test (using JFM 2013).

Figure 4 Composite anomalies (hPa) of mean sea level pressure using ERA-Interim Reanalysis 1979-2013 (Dee *et al.*, 2011) for synoptic-scale wave climate types in the Tasman Sea. Arrows are indicative of mean wave direction at the Sydney buoy.

Figure 5 Location of Terrigal-Wamberal with upper and lower shoreface (15m isobar) and lower shoreface and inner shelf breaks (30m isobar). Extent of morphodynamic model (black rectangle) and nearshore buoy are shown. Inset shows extent of regional wave model and Sydney buoy.

Figure 6 Validation of spectral wave model for (a) wave height, (b) period, (c) direction and (d) power (y-axis) against hourly buoy measurements (x-axis) for modal (non-storm) wave conditions. Quantiles are shown in blue, linear trends in red. Model parameter H_{m01} was compared to buoy parameter H_s in (a), and T_{m01} vs. T_z in (b).

Figure 7 Time series of daily modal waves for each ENSO wave climate at the Sydney buoy. X-axis shows number of days (summers = 90 days, winters = 92 days), y-axis shows wave climate type (WCT). Red dots indicate location of missing wave days.

Figure 8 Directional (mid-shelf) wave power, P_W (MWh m^{-1}), discretised by wave climate type during summer and winter EP El Niño (E.EN), EP La Niña (E.LN), CP El Niño (C.EN) and CP La Niña (C. LN) events at Sydney. Anomalous P_W between EP and CP ENSO is shown with significant anomalies in red. Total P_W for each ENSO period (ΣP_W) and the difference between EP and CP ENSO ($\Delta \Sigma P_W$) is also shown.

Figure 9 Directional (mid-shelf) wave power, P_W (MWh m^{-1}), at Brisbane discretised by wave climate type.

Figure 10 ENSO surf zone morphology at Terrigal-Wamberal. Cumulative bed level change $>$ one standard deviation, σ , around the mean, $\bar{x}$, is shown in 0.5σ increments, where σ and $\bar{x}$ are given for each case. Wave roses show offshore directional wave power density. White line shows seaward limit of upper shoreface (15 m isobar), black circles show nearshore wave output points (Figures S6 – S7), and boxes show locations of erosion hotspots.

Vectors in a) indicate time-averaged sand transport direction over the simulation period for all cases. Red boxes highlight morphology with greatest seasonal difference.

Figure 11 Idealized model of surf zone change during a summer-to-summer El Niño/La Niña cycle for EP and CP ENSO climate. Arrows represent wave direction; green (white) arrows indicate direction of (sub) dominant modal wave power (cumulative for season); red arrows indicate mean storm wave direction during La Niña winter. Areas of accretion are shown in orange with the outline of the preceding season's pattern below. Plots also show location of diffraction point, wave obliquity, β , and control line length, R_β according to change in surf zone morphology from TBR / LLT to RBB. R_β is given relative to compartment length, L .

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

ENSO Directional Wave Power at Sydney (33.8 °S)

Figure 9

ENSO Directional Wave Power at Brisbane (27.5 °S)

Figure 10

Figure 11

Eastern Pacific ENSO

Central Pacific ENSO