Longshore wave variability along non-straight coastlines

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Abstract

The present paper demonstrates the role of wave direction and shoreline alignment on wave attenuation along a non-straight coastline. A numerical model was calibrated against measured data at six locations along a non-straight coastline and a hybrid method composed by wave case selection/simulation and nearshore time series reconstruction was applied to transfer 20 years of wave time series from offshore to nearshore. The results highlight the importance of the orientation of the coastline to different degrees of wave exposure to the wave attenuation process. The varying orientation of the coastline, at each of the six sites, resulted in non-uniform wave attenuation alongshore under different wave directions. The extreme wave conditions at each of the sites were also shown to vary significantly along the coast, e.g. ~18% alongshore (at -17 m Australian Height Datum - AHD) and as much as 34% from offshore (-70 m AHD) to nearshore (-17 m AHD). The results presented here reinforce the importance of assessing variations in wave attenuation along the coast as opposed to simply using the closest offshore wave dataset available. Improved understanding of nearshore wave attenuation along non-straight coastlines aids in better informing future coastal protection and management strategies.

Key Words: *wave attenuation; wave direction; average recurrence interval; Delft3D.*

1. Introduction

The assessment of wave conditions in coastal zones is of essential importance for coastal protection and management. It has been shown that offshore wave conditions vary significantly from offshore to nearshore largely due to wave attenuation. A range of factors influence wave attenuation such as: bottom friction, wave refraction, diffraction and deep-water wave characteristics including height, period, wave direction and directional spreading.

Studies that examined wave attenuation across the continental shelf in the absence of local winds (Herbers et al., 2000; Ardhuin et al., 2003) found that wave attenuation was primarily driven by bottom friction. In the cross-shore direction the steepness of the shelf will directly impact the loss of wave energy due to bottom friction with steeper and narrower shelves having a smaller effect on wave attenuation than wider and flatter shelves (Kurian and Baba, 1987). The effect of bed friction on wave attenuation has particular importance in presence of vegetation (Hardy et al., 1990; Möller, 2006; Stratigaki et al., 2014), porous seabeds (Torres-Freyermuth et al., 2017), reefs (Masselink and Pattiaratchi, 2001; Lowe et al., 2005) and presence of mud banks (Pereira et al., 2011; Samiksha et al., 2017).

Wave refraction and diffraction generated by underlying bathymetry and obstacles, respectively, will produce shadow zones in coastal areas. Refraction of the incoming wave field will occur as the incident waves begin to feel the bottom and change direction.

Diffraction will occur when a wave reaches an obstacle such as an island or a headland and the energy is distributed along the wave crest direction towards the shadow zone. Wave diffraction and refraction can occur together and play an important role on wave attenuation along non-straight coastlines.

For shore-normal incident waves on an open coast, higher amplitude and longer period waves tend to attenuate more than those with smaller amplitudes and shorter periods (Kurian and Baba, 1987, Herbers et al., 2000, Masselink and Pattiaratchi, 2001, Ardhuin et al., 2003, Londhe, 2009). Masselink and Pattiaratchi (2001) demonstrate that the nearshore (non-directional) wave heights at a depth of 17m on the sheltered coastline of Perth, Western Australia, are usually 40 to 45 % of the offshore (48 m depth) wave height. For the

Gold Coast, Queensland, Australia, the wave power is reduced by 50 % from offshore exposed waters to sheltered Kirra Beach (Chapman, 1978; Browne et al, 2007).

Wave attenuation in the nearshore region has been shown to have a significant effect on sediment transport, wave run-up and beach erosion. Taking the wave direction into consideration for Búzios Cape (Brazil), Bulhøes and Fernandez (2011) showed that the waves distribute their energy differently depending on the wave direction leading to distinct trends of sediment transport. Vieira da Silva et al. (2016) showed that for a protected stretch of coast where only diffracted waves are present, despite their reduced heights, the uni-directional oblique waves are the main forcing responsible for sediment transport. Bonetti et al. (2012) and Vieira da Silva et al. (2017) demonstrated the importance of using wave parameters after they have undergone nearshore refraction and attenuation for estimating wave run-up on embayed beaches. Harley et al. (2017) and Mortlock et al. (2017) demonstrated the importance of wave direction on beach erosion by analysing an Australian East Coast Low (ECL) storm event that impacted Sydney, Australia in 2016. The ECL presented an offshore significant wave height average recurrence interval (ARI) of only 2 years, however, some beaches experienced the worst erosion in 40 years due to the rare angle of incidence that the resulting nearshore waves had upon arriving at the coast (Mortlock et al., 2017).

Obtaining realistic nearshore wave conditions is therefore essential for coastal engineering, wave energy conversion and coastal management strategies. Local, state and federal government authorities rely on wave climate data to implement coastal protection strategies including the design and implementation of beach nourishment campaigns and installation of coastal protection structures. Coastal protection strategies or wave energy converter design and optimisation strategies that utilise data which under/over-estimates the effects of wave conditions may lead to inefficient and more expensive interventions than required. A balance between cost and efficiency is always the target of industry, coastal communities (tax payers) and decision makers.

To assess the nearshore wave climate two options are available: measured and modelled data. Long term nearshore in-situ measured data is rare and is usually restricted to a given location rather than an alongshore array of instruments. Wave attenuation due to refraction and/or the presence of headlands or islands can significantly change the wave conditions within a few kilometres of coastline. While global or regional hindcast (model) data covers a wider area and is usually very good for representing deep water wave conditions, these models become less accurate in the shallow nearshore zone. Therefore, numerical models that take into account the shallow water processes to assess long term wave conditions in nearshore areas are often applied.

Propagating a long-term, full time series of offshore wave conditions to the nearshore at high spatial resolution demands significant computational effort and even using High Performance Computers (HPCs) this task is time consuming and uneconomical to accomplish in a reasonable timeframe. Consequently, during the last few decades different methods have been developed to obtain a subset of representative wave parameters that adequately describe the nearshore wave climate at selected points of interest. These are divided into two basic types: i) statistical approach (e.g. Makarynsky et al., 2005; Browne et al., 2007) and; ii) hybrid approach, combining simulations and statistics to reduce the computational effort (e.g. Camus et al., 2006; Gaslikova and Weisse, 2006; Breivik et al., 2009; Camus et al., 2013).

The aim of this paper is to apply a hybrid technique to evaluate the role of wave direction and period on wave attenuation along a non-straight coastline and its implications for extreme wave analysis.

1.1 Study area

The Gold Coast is located on the southeast coast of Queensland, Australia (Figure 1). It is arguably Australia's premier coastal tourist destination that stretches along 37 km of open ocean coastline, consisting of eight sandy beaches (Short, 2000). The sand is classified as

fine ($d_{50} = 0.22$ mm) and composed mainly of quartz (Strauss and Tomlinson, 2009). Based on 45 years of beach profile survey, Strauss et al. (2013) found that the depth of closure is located approximately at -14 m (Australian Height Datum, AHD, which is approximately equivalent to the local mean sea level, MSL). Tides are semi-diurnal and micro-tidal, with tidal amplitude ranging from 0.2 to 2.1 m with a mean range of 1 m (Kobashi et al, 2014). The region is subject to moderate to high wave energy with significant seasonal and inter-annual variation. Seas and swells are strongly related to the broad scale weather patterns on the east coast of Australia and are characterized by Allen and Andrews (1997) into:

- Well defined summer season (December to April), including tropical storms (and cyclones) capable of generating extreme sea states (significant wave height, $H_s > 7$ m);
- Sequences of high pressure systems over southern Australia in summer causing persistent trade winds and moderate swell in offshore areas – these winds are moderated by early morning land breezes and afternoon sea breezes that have an important effect on the often locally generated sea waves;
- Northward migration of high pressure systems in winter, forming typically southwest to southeast winds and predominantly south to southeast swells;
- Intense low pressure systems off the New South Wales (NSW) coast (East Coast Lows) more common in winter, but may occur year round and often in clusters, generating moderate to high southerly swells.

According to Chapman (1978), the wave power reduces more than two times from offshore of the Gold Coast to Kirra Beach (at the southernmost end of the study area) attributed to wave attenuation related mainly to refraction of the predominant SE swell.

Figure 1: Study area: location of wave buoys and detail of bathymetry along the coast (right).

2. Material and Methods

The methods outlined in this section describe the application and verification of a hybrid method to obtain long term time series of waves in specific locations along the Gold Coast and to use this data to calculate wave attenuation, estimate extreme values and demonstrate the longshore variability of wave parameters.

2.1 Offshore wave data

The offshore wave data was measured with a waverider buoy maintained by the Queensland Government (<https://data.qld.gov.au/>). Brisbane buoy is located 11 km offshore (see Figure 1) and approximately 50 km to the north of the study area at -70 m (AHD). The buoy was first deployed in 1976 and was upgraded to collect directional wave data in late 1996. For the present paper only the directional part of the dataset (1996-2016) was used. The highest

value of H_s recorded during the period was 7.21 m with an associated peak period (T_p) of 12.17 s. The highest recorded T_p was 21.1 s, with associated H_s of 0.67 m. H_s was lower than 1.5 m for 50% of the time and T_p did not exceed 9.34 s for 50% of the record. The highest H_s was recorded during the summer months, followed by autumn, winter and spring. The dominant wave direction measured at the Brisbane buoy is from the SSE and includes a significant portion of the waves with $H_s > 2$ m. In contrast, E and ESE waves dominate the Gold Coast nearshore waverider buoy site (at -17 m AHD). Around 85% of the nearshore waves have $H_s < 2$ m.

2.2 Numerical Modelling

A Delft3D-Wave model was set up covering the entire Gold Coast. Delft3D-Wave has the third generation SWAN wave model (Booij et al., 1999) implemented and was used to simulate the wave propagation from offshore (Brisbane buoy) to nearshore. The SWAN wave model is fully spectral in frequencies and directions and can provide realistic estimates of wave propagation in the coastal zone. A detailed model description is found in Booij et al. (1999) and Ris et al. (1999). The Brisbane buoy presents a total of 293,232 directional records of wave parameters. The propagation of every single case from the Brisbane Buoy to the Gold Coast nearshore would be very time consuming. Therefore, a lookup table has been developed to transfer the 20 year wave data time series from offshore (Brisbane buoy) to nearshore locations. To do so, a hybrid approach combining a numerical simulation of selected cases and the reconstruction of the complete series at selected points of interest was carried out. The wave lookup table and interpolation method part of our approach summarised in Figure 2 was described in detail by Camus (2006) and Bonanata et al. (2010). The method consists of wave case reduction (significant wave height – H_s , peak wave period - T_p and peak wave direction - $Dirp$), numerical propagation and reconstruction of the complete wave parameters (H_s , T_p , $Dirp$) time series at a nearshore location. The applied method is detailed in Figure 2 and the wave lookup table and interpolation steps are described in detail below.

Figure 2: Applied methodology to transform offshore wave climate from the Brisbane waverider buoy data to the nearshore region. Two dashed rectangles highlight the methods for the wave lookup table (left) and the model validation (right).

1) Offshore wave case selection

The selected wave cases for propagation encompass the entire dataset to allow the reconstruction of the nearshore time series. The selected cases consist of a uniform spacing of H_s (0.5 m), T_p (4 s) and $Dirp$ (22.5°). As the offshore wave dataset presented waves with $H_s < 0.5$ m, a 0.25 m wave height was also selected so that all the Brisbane waverider buoy conditions were covered by the selected wave cases (Figure 3).

Figure 3: Brisbane buoy data (black dots) and selected wave cases (grey diamonds). Peak wave direction (°) vs peak wave period (s) vs significant wave height (m).

2) Wave propagation (Delft3D-Wave)

The resulting 1,148 wave cases were propagated shoreward from the model boundary using two different nested grids (Figure 4). The wave model domain spans the east coast from Point Lookout on North Stradbroke Island, QLD to Byron Bay, NSW increasing its resolution shoreward. The largest grid provides a relatively coarse bathymetry for propagation of waves from deep water and the smallest grids resolve shallow water features in progressively more detail. Samples used to establish the nearshore bathymetry were obtained from the City of Gold Coast Hydrographic surveys.

- The large grid has 221 x 25 elements and resolution of 700 x 500 m;
- The smallest grid has 301 x 32 elements and resolution varying from 150 x 250 m to 50 x 100 m.

The selected wave cases were imposed as a uniform boundary on the largest grid at the eastern boundary and the waves were propagated towards the shore over the nested grid.

The study area presents a fairly uniform bottom type composed mainly of sand. Therefore, to evaluate the role of wave direction and period on wave attenuation, a uniform bottom friction coefficient (JONSWAP – Hasselmann et al., 1973) of $0.067 \text{ m}^2\text{s}^{-3}$ was adopted. The analysis of bottom friction effects on wave attenuation has previously been investigated by several authors (Hardy et al., 1990; Masselink and Pattiaratchi, 2001; Lowe et al., 2005; Möller, 2006; Pereira et al., 2011; Stratigaki et al., 2014; Samiksha et al., 2017; Torres-Freyermuth et al., 2017). In this paper, bottom friction effects could not be considered, based on the hypothesis of a locally uniform bottom.

The propagated wave conditions were obtained at points of interest along the coast and were used to reconstruct the complete (same length as Brisbane buoy) nearshore time series.

3) Defining a propagation coefficient

Every propagated wave case presents a respective result for the point of interest. The ratio between the nearshore and offshore wave parameter is the coefficient of propagation – each propagated case will produce a coefficient for H_s , T_p and $Dirp$. The coefficient of propagation of each propagated case (cube corners) will be used to transform any offshore case that falls inside the cube (see Figure 3) to their nearshore correspondent.

4) Interpolating the entire offshore wave condition to any point within the numerical grid

The coefficient of propagation of each offshore wave case is defined by a three dimensional (H_s , T_p and $Dirp$) linear interpolation of the propagation coefficient of the surrounding simulated wave conditions (cube corners - see Figure 3). The nearshore result is a wave time series with the complete offshore “propagated” series – one nearshore output for each offshore wave condition.

Figure 4: Left: two model grids (Large and Local) used for simulation; Right: Detail of Local grid, wave and ADCPs locations (see section 2.3) and locations where the extreme analysis was carried out (see section 2.4.2).

2.3 Model validation

A validation model was setup and run using the same configuration as the wave lookup table model. The only difference between this model and the wave lookup table model are the wave conditions. Whilst the wave lookup table model ran selected representative cases, the

validation model ran the complete Brisbane buoy time series between April and May 2011. This time period was chosen as it coincided with an experiment whereby the City of Gold Coast engaged the Danish Hydraulic Institute (DHI) to deploy Acoustic Doppler Current Profilers (ADCPs) in order to measure waves at five nearshore locations (see Figure 4) along the Gold Coast in water depths of approximately -7 m (AHD) (DHI, 2011). Two analyses were carried out: (1) checking how well the model reproduces the real wave condition by comparing the reconstructed time series with the ADCP data and (2) checking the lookup table method itself by comparing the simulated time series with the reconstructed time series (wave lookup table method).

2.4 Nearshore analysis

2.4.1 Wave attenuation calculation

The wave attenuation was calculated for the entire time series. To do so the first step is to use a lookup table to reconstruct the parametric wave time series (H_s , T_p and Dir_p) at 6 locations nearshore (the 5 ADCP locations as well as the Gold Coast Buoy – see Figure 4). Secondly, the reconstructed time series were compared with the offshore wave conditions (Brisbane Buoy). Then, the wave attenuation was simply calculated as $1 - (H_{s_{nearshore}} / H_{s_{offshore}})$ so that values equal to 1 represent completely attenuated waves while 0 represents no attenuation (identical offshore and nearshore wave heights). For each location and direction bin the mean wave attenuation and the related standard deviation were calculated. To do so, the directions were split into 16 bins each one spanning 22.5° . Note that because the Gold Coast buoy is located in -17 m (AHD) whereas the ADCPs were located in -7 m (AHD), the wave attenuation values are not directly comparable.

2.4.2 Average Recurrence Interval (ARI)

The extreme wave average recurrence intervals were calculated for three locations along the coast: Gold Coast Buoy, Centre and South, all at the same depth (-17 m AHD) – see Figure 4.

The extreme wave analysis requires a sample to be selected from the full data set. The sample should be representative of extreme wave events in the dataset and it is usually much smaller than the full dataset (Mathiesen et al., 1994), therefore, a long time series is important. The extreme events were selected using the peaks over threshold (POT) method. This method consists of defining a threshold for wave height and sampling the peak of each event higher than the threshold. Selecting only the peak rather than each record above the threshold guarantees the independence of the samples as required for further analysis. This method is widely used and recommended by many authors (e.g. Mathiesen et al., 1994; Kamphuis, 2010; Shand et al., 2010). For consistency, the threshold chosen for all locations corresponds to a value non-exceeded for 99% of the time.

After the sample selection the most commonly used practice is to fit a statistical distribution to the data. The fitted distribution is used to estimate the probability of non-exceedance of a given value. The Generalized Extreme Value (GEV) was applied as recommended by Rueda et al. (2016). The GEV distribution is given by:

$$F(y) = \exp \left\{ 1 - \left[\xi \left(\frac{y - \mu}{\psi} \right) \right]^{\frac{-1}{\xi}} \right\}$$

The model has three parameters: the location parameter (μ), the scale parameter (ψ), and the shape parameter (ξ).

The GEV is a distribution family which includes the Frechet (when $\xi > 0$) distribution where the distribution tail decays in a polynomial way, Weibul (when $\xi < 0$) distribution characterized by a bounded tail and the Gumbel distribution (when $\xi = 0$) with an exponentially decaying tail.

3. Results

3.1 Model validation results

The simulated time series were compared against the measured data for two deployments; (1) between 12/04/2011 and 04/05/2011 and; (2) between 09/05/2011 and 30/05/2011. The

results presented in Figure 5 show a good agreement between the reconstructed time series and the measured data along the coast. The wave height is well represented with root mean square errors (RMSE – see Table 1) varying between 15 and 20 cm. The peak wave period is well represented during the analysed period with RMSE between 1.38 and 1.59 s. The modelled peak wave direction is fairly well represented for the Gold Coast buoy as well as for each ADCP location, with RMSE varying between 6.41 and 14.34 °.

To analyse the errors related to the use of a lookup table the simulated time series (for the period of ADCP deployment) was compared to the reconstructed series. The results indicate that virtually no error is added to the analysis by using the lookup table when compared to a time series simulation (Table 1). The RMSE for H_s was 0.1 m for all locations, for T_p RMSE varied between 0.12 and 0.13 s and for direction RMSE varied between 0.98 and 2.74 °.

Figure 5: Model validation at six locations on the Gold Coast. Left column: significant wave height; central column: peak wave period; Right column: peak wave direction. Each row represents one location from north (top) to south (bottom).

Table 1: Root mean square errors of simulations for: (1) model validation – measured vs simulated time series and (2) lookup table validation – simulated time series vs reconstructed time series.

Location / RMSE	Model Validation			Lookup table validation		
	Hs (m)	Tp (s)	Dirp (°)	Hs (m)	Tp (s)	Dirp (°)
Gold Coast Buoy	0.15	1.53	14.34	0.01	0.13	2.74
Narrowneck	0.16	1.38	12.8	0.01	0.13	2.55
Burleigh	0.17	1.44	6.41	0.01	0.13	1.20
Palm Beach	0.20	1.45	11.44	0.01	0.13	0.98
Tugun	0.17	1.59	8.61	0.01	0.12	1.49
Kirra	0.19	1.59	8.99	0.01	0.13	1.73

3.2 Nearshore analysis results

3.2.1 Wave attenuation results

Figure 6 presents the wave field along the Gold Coast for the same offshore wave height ($H_s = 1.5$ m) and period ($T_p = 8$ s) and for four incident wave directions (NE, E, SE and S). The simulations demonstrate the importance of offshore wave direction with respect to the resultant nearshore wave field along the coast.

Figure 6: Wave fields along the Gold Coast (local grid- see Figure 4) under different wave directions. Colours represent the wave height in meters and arrows the peak wave direction. For comparison, all four cases present an offshore wave height of 1.5 m and peak period of 8 s.

Figure 7 presents the results of 20 years of offshore wave data and the respective nearshore conditions coloured by peak wave period. Waves from the north present similar attenuation in northern (Narrowneck: 0.41 ± 0.05) and southern (Kirra: 0.42 ± 0.06) ends of the coast. Waves from the east show the smallest amount of attenuation at the north portion of the coast (0.17 ± 0.02) at Narrowneck whereas east-northeast waves are less attenuated on the southern portion at Kirra (0.33 ± 0.04). Southeast waves, as opposed to waves from the north, attenuate more at the southern portion of the coast (0.58 ± 0.06) at Kirra and less to the north (0.31 ± 0.03) at Narrowneck. Waves from the south are highly attenuated along the whole coast, with a decreasing trend in attenuation from the south of the region, (0.81 ± 0.04) at Kirra, to the north (0.51 ± 0.03) at Narrowneck. All other directions from southwest (clockwise) to northwest waves present an attenuation coefficient of 0.84 ± 0.04 for the Gold Coast buoy (-17 m AHD) and 0.88 ± 0.03 for Narrowneck and even higher elsewhere. The orientation of the coast to the incoming wave direction is the controlling factor of wave refraction and, in turn, the attenuation on non-straight coastlines. Figures 6 and 7 demonstrate the importance of the wave direction and orientation of the coast to incoming wave direction when assessing certain wave conditions such as nearshore extreme waves.

Figure 7: Wave attenuation per direction. Solid dots represent the data ($1-H_{s_{nearshore}}/H_{s_{offshore}}$) and are coloured based on offshore wave period, lines represent the mean attenuation with respective standard deviation per direction (22.5° window) for a) Gold Coast buoy; b) Narrownneck; c) Burleigh; d) Palm Beach; e) Tugun; f) Kirra; g) is average wave dissipation for all stations (ADCPs and Gold Coast Buoy) per direction.

3.2.2 Average Recurrence Interval (ARI) results

To demonstrate the implications of variable wave attenuation along the coast, Figure 8 and Table 2 present the ARI for significant wave height (H_s) in three nearshore locations as well as for Brisbane buoy. The Brisbane directional waverider buoy is located at -70 m (AHD) and is the most (offshore) exposed measurement location to waves from all directions. For consistency the nearshore extreme wave analysis was carried out at Gold Coast buoy (-17 m AHD) and two other locations along the coast at the same water depth (named Centre and South). There is an apparent reduction in extreme wave values along the coast from north to south. Figure 8 shows a clear reduction in H_s ARI along the Gold Coast from north to south. While waves are less attenuated at the Gold Coast Buoy location, increased attenuation is observed at the Centre and South locations. The southern part of the Gold Coast is the most protected section of the coast for extreme wave height events from the east to south east, typical of East Coast Lows (ECLs) which form in the Tasman Sea to the south of the Gold Coast. However, the southern Gold Coast remains highly vulnerable to impacts of extreme waves from the N to NE which are more frequently associated with Tropical Cyclones forming in the Coral Sea, to the north of the Gold Coast.

Figure 8: Average recurrence intervals along the Gold Coast. The 95% confidence intervals were suppressed from the figure for clarity. Please refer to Table 2 for values.

Table 2: Average recurrence intervals (ARI) and respective 95% confidence intervals (CI95%) for offshore Brisbane buoy (-70m AHD), Gold Coast buoy (-17 m AHD), Centre and South locations (-17 m AHD).

ARI (years)	Brisbane (m $\pm$ CI _{95%})	Gold Coast (m $\pm$ CI _{95%})	Centre (m $\pm$ CI _{95%})	South (m $\pm$ CI _{95%})
10	6.73 $\pm$ 0.57	5.43 $\pm$ 0.70	5.01 $\pm$ 0.68	4.47 $\pm$ 0.64
20	7.07 $\pm$ 0.74	5.84 $\pm$ 0.98	5.40 $\pm$ 0.97	4.82 $\pm$ 0.90
50	7.49 $\pm$ 1.01	6.33 $\pm$ 1.41	5.87 $\pm$ 1.44	5.24 $\pm$ 1.34
100	7.77 $\pm$ 1.24	6.69 $\pm$ 1.80	6.20 $\pm$ 1.86	5.54 $\pm$ 1.72

4. Discussion

The lookup table method utilised to reduce the original dataset to a significantly smaller dataset for improving model run time has been shown to work well for the Gold Coast. The 293,232 Brisbane buoy records were reduced to 1,148. This represents a reduction of 255.4 times the computational effort and simulation time. Considering that the computational time to simulate the 1,148 cases (with a typical desktop computer) was around 1 day, to simulate the entire series would take 8.5 months. The method validation showed a very good agreement between the time series propagation and the reconstructed time series.

Therefore, once the wave model is calibrated for the study area, the wave lookup table method can be used to assess the wave conditions (H_s , T_p and Dir_p) at any location within the model grid with errors virtually identical to the calibration model.

The validation of the simulated series against the nearshore measurements (Gold Coast buoy and ADCPs) showed an overall good agreement, reinforcing the assumption of uniform bottom friction adopted for this study. Some discrepancies between measured and reconstructed peak wave period were observed in some cases (Figure 5). This can be explained by the presence of bimodal wave conditions (i.e. mixed swell and sea) observed on the Gold Coast, where the swell component progressively loses energy and the sea begins to be responsible for a higher proportion of wave energy on the coast (or vice-versa). However, as shown in Figure 5, these discrepancies are not frequent at this study area. A similar pattern was observed by Vieira da Silva et al. (2016) on the Santa Catarina Island North Shore, southern Brazil. In general, the model represented well the wave conditions along the coast and the results could be used with confidence to obtain a long time series (~20 years) of wave conditions nearshore. The model presented here has been applied to the Gold Coast, however, the method presented can easily be applied to other target areas.

Comparison between the Brisbane wave buoy and the reconstructed wave time series along the coast showed that the peak wave period plays an important role in wave attenuation for all locations - the higher the wave period, the less attenuated the nearshore waves tend to be. The scattering around the average line in Figure 7 is attributed to: 1) wave shoaling, as

longer period waves will start the shoaling process before short period waves; 2) wave refraction, as similarly to wave shoaling, the process will start earlier for longer period waves and, despite of the increased wave attenuation due bottom friction, these waves will refract more effectively towards sheltered areas than shorter period waves. Also important is the wave attenuation variability along the coast due to wave direction and coastline exposure.

Waves from the south and southeast present decreasing wave attenuation coefficients towards the north of the region. Point Danger is a prominent feature that causes sheltering of southerly waves as demonstrated by GCCM (2016). The Gold Coast is a zeta-shaped coastline with a northerly facing orientation in the south, curving around to an easterly facing beach in the north. As wave direction rotates anticlockwise from southeast, the attenuation coefficient tends to be greater for the south beaches (Kirra) and smaller for the north beaches (Narrowneck). Easterly waves are the least attenuated (see Figure 6 for wave fields) while the northeast waves present the most homogeneous wave attenuation along the coast. Both east and northeast wave directions experience much less refraction than the more obliquely angled incident waves from the southeast and south. Northerly waves, as opposed to southerly waves, are more attenuated from the centre to the north of the Gold Coast and less to the south. These results corroborate Chapman's (1978) findings who suggested that the offshore wave energy can attenuate more than 2 times by the time the waves arrive at Kirra. This attenuation increase to the north of Narrowneck is due to the presence of a residual ebb delta lobe at the historical site of the Nerang river mouth as described by Patterson (2007). Furthermore, the propagation of waves from the north is also influenced by the present-day large ebb-tide delta and trained (jettied) entrance of the Gold Coast Seaway (see Figure 4), around 5km north of Narrowneck beach. The delta and jetty extend 1.5km and 0.45km offshore of the coastal alignment, respectively.

As presented by several authors (e.g. Chapman, 1978; Bonetti et al., 2012; Vieira da Silva et al., 2016, 2017; Harley et al., 2017; Mortlock et al., 2017; Browne et al, 2007) the wave propagation and transformation from offshore to nearshore plays an important role on how

attenuated the waves will be at the nearshore point of interest. This has significant implications for beach management, beach erosion, sediment transport, longshore and rip current generation as well as surf quality. Being able to understand and predict wave attenuation along a non-straight coastline will aid industry, government and local stakeholders in addressing spatial variability in beach management planning and implementation, defining locations suitable for wave energy conversion as well as improving models for forecasting surf conditions.

As demonstrated by Harley et al. (2017) and Mortlock et al (2017), even a 2 year ARI offshore wave height can cause severe erosion depending on the direction the waves have as they reach the coast. Therefore, to assess the extreme wave conditions nearshore it is recommended to obtain a long time series of wave conditions at a range of points of interest alongshore so that statistics can be applied directly at the point of interest rather than derived from a single offshore source alone. Extreme H_s estimated for the Brisbane buoy (see Figure 8 and Table 2) was very similar to the values found by Shand et al. (2010, 2011). However, because of the different degrees of protection to various wave angles along the coast, the results presented here show a decrease of extreme ARI values from north to south. As waves propagate from the Brisbane buoy towards the Gold Coast the extreme wave values are expected to be on average 17% lower at the location of the Gold Coast buoy (located at -17 m AHD); 23% lower at the central Gold Coast and 31% lower at the southern Gold Coast. This can be explained by the relatively high frequency of waves from the southeast and south-southeast recorded by the Brisbane buoy (representing together 25.4% of the records) and, as demonstrated, these directions are well attenuated at the southern end of the coast. During storms created by tropical cyclones, generally associated with N to NE direction, the lower values should be found on the north as the waves tend to be less attenuated towards the south (Figure 7 g). This paper demonstrates that not only the wave height must be considered for the extreme events assessment but the wave direction and period are also very important parameters, particularly for coasts exposed to a highly

variable range of extreme wave directions. This inherently creates spatial variability in both coastal management issues during extreme wave events, as well as surf conditions, with surfing and surf-related tourism being recognised as a \$3.3 billion dollar a year industry on the Gold Coast (AEC, 2009).

As pointed out by Hemer et al. (2013) climate change has been shown to impact the mean wave direction around the world. According to the authors, the east coast of Australia will experience an anticlockwise rotation of wave direction. This suggests that the southern portion of the Gold Coast will become more exposed to high wave energy events (see Figure 6). Furthermore, a change in the mean wave direction leads to a change in wave-driven sediment transport and potentially changes in erosion/accretion patterns along the coast. The understanding of the impacts of wave direction on wave height attenuation and subsequent coastal processes due to changes in deep water wave climate is, therefore, a major concern for coastal managers in the near future.

In summary, the results presented here demonstrate the longshore variability of wave attenuation due to various wave directions (and the orientation of the coasts to the incoming waves) and propose a comprehensive method to assess the effects of extreme events for specific locations along non-straight coastlines. The results clearly show that the wave attenuation must be taken into account to study different sectors of the coast.

5. Conclusions

On non-straight coastlines with an assumed uniform bottom roughness obstacles and the underlying bathymetry will lead to variations in wave attenuation along the coast depending on the offshore wave direction and period. In-situ measurements of waves in the nearshore zone, particularly at shallow water depths are cumbersome and non-trivial. Therefore by applying nearshore wave models to improve the understanding of spatial variability in wave attenuation along a non-straight coastline better management practices may be employed. This paper assessed the wave attenuation along the non-straight coastline of the Gold

Coast, Australia. A hybrid method comprising wave case selection for propagation and transformation with a numerical model and time series interpolation to obtain long term time series at specific points of interest was applied and the results are in very good agreement with the simulated time series data. Furthermore, the nearshore time series presented a good agreement with measurements at six locations along the coast: Gold Coast Waverider Buoy (Main Beach), ADCP's (Narrowneck, Burleigh, Palm Beach, Tugun and Kirra).

The results clearly demonstrate the uneven wave attenuation along the coast, for different wave directions. The alongshore difference in wave height is mainly related to the different degrees of exposure of the coast to various wave directions. The southern portion of the Gold Coast is more exposed to waves from the east to northeast, whilst it is protected from seas and swell from the southeast to south. The northern end of the coast displayed reduced rates of wave attenuation when exposed to waves from the southeast. Offshore waves from the east display the smallest amount of attenuation along the entire (non-straight) coastline, as they approach perpendicular to the continental shelf and, therefore, do not experience as much refraction as waves from north and south. Furthermore, waves from the southeast (i.e. the most common wave direction offshore of the Gold Coast) are diffracted and attenuated by the headlands. This is most evident at Point Danger resulting in a wave (or swell) shadow at the southern end of the coast.

This paper also demonstrates that the extreme wave conditions along a non-straight coastline can vary significantly. For example, between the northern and the southern part of the coast the extreme wave height can differ by $\sim 18\%$ and between the offshore Brisbane buoy (-70 m AHD) and Kirra Beach (-7 m AHD) the wave attenuation is as high as 34%. Therefore, the paper suggests that the assessment of extreme wave events on non-straight coastlines must take into consideration the non-uniform wave attenuation alongshore. This is particularly important for implementing coastal management strategies and assessing their potential impacts on adjacent beaches.

Improving the overall understanding of longshore variability in wave attenuation through the use of nearshore numerical models along a non-straight coastline will have flow on effects for understanding spatial and temporal variability in hydrodynamic and morphodynamic processes. This is important for predicting the effects of storms on a coastline, forecasting surf, forecasting spatial and temporal changes in beach morphology, erosion and accretion processes, sediment transport as well as their associated engineering and management issues.

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