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WHAT FEATURES MAKE POCKET BEACHES UNIQUE IN TERMS OF COASTAL PROCESSES?

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ABSTRACT

Due to the stability of the shoreline in pocket beach environments, confined coasts are under huge development pressures worldwide, and global understanding of their physical functioning is poor in comparison to open coast beaches. This study aims to fill gaps in understanding of nearshore currents and also to determine the importance of local wind and tide factors in generating nearshore currents in micro tidal pocket beaches. This study is based on fieldwork and numerical modeling, using the two dimensional XBeach model. The observations showed that currents were generated by incident waves in areas behind the surf zone and only local winds could influence the strength of the currents. However, surf zone currents were significantly influenced by tides and the effect of local winds on the currents were inconsiderable. The results of the model indicated that geometry of pocket beaches can influence the strength of currents and the length of longshore currents inside the bay, although the current system remains constant.

1. INTRODUCTION

Pocket beaches are a subcategory of headland-enclosed bay beaches. They are constrained between two longshore extremes such as rocky headlands, groynes, breakwaters and peninsulas, either artificial or natural. In the past few decades artificial pocket beaches, created using parallel pairs of shore-normal hard structures, have been recommended for many eroding coastlines around the world as a tool to stabilize the shoreline (Ojeda and Guillen, 2008). Examples of artificial pocket beaches can be seen along the shorelines of Barcelona, Spain; Chesapeake Bay, USA; and Rayong, Thailand (Hardaway and Gunn, 2010; Hsu *et al.*, 2010). Therefore, the operation of these processes under the influence of the combination of waves, winds and tidal ranges in headland-enclosed bay beaches, especially for beaches with two natural long headlands (pocket beaches), is poorly documented.

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The aim of this study is to examine hydrodynamic processes in two micro-tidal pocket beach environments with different geometric characteristics. In order to address this aim, fieldwork and numerical modeling using the two dimensional XBeach model (Roelvink *et al.,* 2009) are used to study a moderate wave-energy condition. This study also evaluates the importance of local winds and tides in controlling nearshore currents in pocket beaches. A review evidence from previous literature about current circulations and importance of winds and tides on near shore currents in pocket beaches are discussed in the following paragraphs.

Most research on the hydrodynamics and morphodynamics of headland enclosed bay beaches has been conducted on embayed beaches confined by a single headland (Hsu and Evans, 1989; Silvester and Hsu, 1999; Hsu *et al.,* 2008; Klein *et al.,* 2002, 2010). In such environments, a longshore current moving towards the headland converges with a reverse longshore current moving from the headland and, thus, a rip current is formed in proximity to the headland (Silvester and Hsu, 1999). Depending on the approaching wave directions, the location of the rip current may move away from the headland.

Studies of wave-generated nearshore current circulations in embayments, including pocket beaches, have been completed by Short (1999, 2010). According to Short's research, single-headland embayed beaches have circulation systems that are transitional between longshore and rip-dominated, with their currents being influenced by the shape and size of the embayment. Pocket beaches, however, have cellular circulation systems, with headland geometry, including the indentation ratio, the ratio between the depth of an embayedment to the distance between two headlands (Klein *et al.,* 2002). Short (1999, 2010) also describes the existence of one or two rip currents (or megarips), formed in proximity to the headlands in these environments. However, none of the above studies considered the effect of local winds and tidal ranges on nearshore currents and their results were limited to the wave-driven currents.

Local winds could play a crucial role in the hydrodynamics of pocket beaches. Since swell waves can only approach the shoreline from a limited directional sector, the strength of wave-driven nearshore currents may differ from that of open coast beaches. As a result, local winds could considerably influence nearshore currents inside pocket beaches (Dehouck *et al.,* 2009). In some cases wind may even generate stronger mean current velocities than swell waves in embayed or pocket beaches (e.g. Dehouck *et al.,* 2009; Sedrati and Anthony, 2007; Storlazzi and Field, 2000; Hegge, 1996). For instance, Dehouck *et al.* (2009) found that winds generated mean cross-shore and longshore current velocities twice that of high energetic swell waves in pocket beaches.

In additional to waves and winds, tidal currents may significantly influence nearshore currents in pocket beaches and, in turn, sediment transport. Small variations in water level, such as micro tides, could potentially move the position of the surf zone a few hundred meters seaward in gently-sloping environments. Depending on the indentation ratio, these changes in the surf zone could affect sediment transport exchanges between pocket beaches and adjacent shorelines.

Few studies have been conducted into the effect of tidal currents on nearshore wave-induced currents in pocket beaches, especially in micro-tidal pocket beaches (Klein *et al.,* 2001; Vousdoukas *et al*., 2009). As for open beaches, coastal researchers investigating tidal currents have mostly focused on macro-tidal embayments (Dehouck *et al.,* 2009). The general findings, including the effect of tides on longshore and cross-shore currents, are similar to the findings in meso- and macro-tidal open coast beaches (Dehouck *et al.,* 2009; Anthony *et al.,* 2004; Wright *et al.,* 1982). Although most studies conducted on the morphodynamics and hydrodynamics of embayed and pocket beaches, the importance of tidal currents on nearshore currents (Dehouck *et al.,* 2009; Masselink and Pattiaratchi 2000; Storlazzi and Jaffe, 2002; Hegge *et al*., 1996), and sediment transport processes are still poorly documented, especially in micro-tidal pocket beaches. Therefore, studies on both reflective and dissipative micro-tidal pocket beaches are needed to compare and evaluate the importance of tides on nearshore currents in micro-tidal pocket beach environments.

2. METHODOLOGY

Measurements of wave patterns and current velocity and direction were collected in the surf zone and in the middle and outside of a micro-tidal pocket beach environment, Okains Bay, during different wave conditions (Figure 1). According to the nearest tidal gauge to Okains Bay located in Lyttelton Harbour, about 22 km to the west, the spring and neap tidal ranges are 2.3 m and 1.33 respectively (Land Information New Zealand, 2012). The data were collected using an array of instruments: a *Nortek* Acoustic Doppler Velocimeter (ADV), an *Interocean S4* current meter, two units of Teledyne RD Acoustic Doppler Current Profiler (ADCP), a *RBR XR 620 data logger,* using a pressure sensor, and a wind station at the beach-dune interface (Table 1).

In order to increase the accuracy of confidence interval estimates in tidal analysis, it is important to remove sub-tidal (i.e. non-tidal, low frequency) signals from the raw data. Therefore, a low-pass filter was applied to all data using WaveLet, a toolbox in Matlab and then the Utide Matlab Functions (Codiga, 2011) were applied to separate out the tidal components of the measured currents for all sites.

In order to determine current circulations, the two dimensional XBeach model was run for two adjacent pocket beaches, Okains Bay and Lavericks Bay (Figure 1), with different headland lengths and beach orientations. Note that Okains Bay and Lavericks Bay are classified as a dissipative and reflective pocket beaches respectively. The model was run for moderate energy waves in Okains Bay and Lavericks Bay. The simulations lasted 24 hours using the tide, wind and wave data measured between 7th and 8th of April 2012, as the input data for the simulations. The purpose of these simulations was to compare the results of the model with measured data at sites O2 and O3 and better understand the current circulations inside the pocket beaches. Also these simulations serve to examine whether geometry of pocket beaches can influence nearshore current circulations.

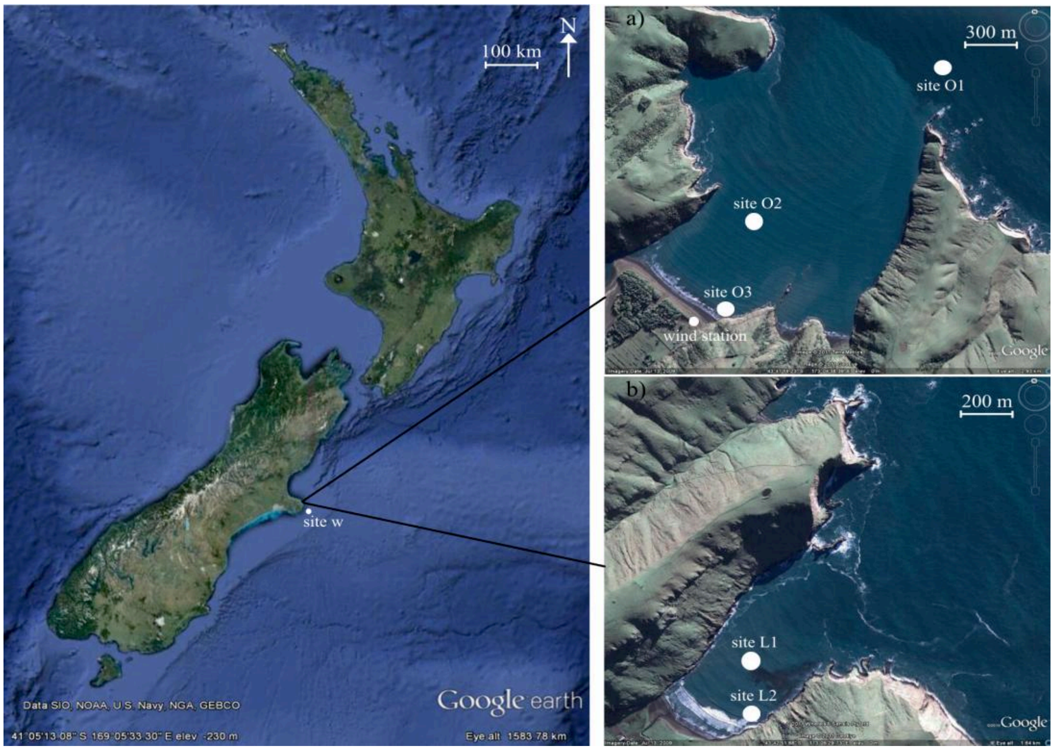

Figure 1 The location of Okains Bay (a) and Lavericks Bay (b) on Banks Peninsula, New Zealand, including instrument field sites in Okains Bay (modified from Google Earth, 2012).

Table 1 Details of the field experiment deployments.

Site	**Instrument name**	**Deployment period**	**Water depth- BSL (m)**	**Burst duration (min)**	**Time between bursts (min)**	**Sampling frequency (Hz)**
O1	ADCP	20/Apr/2011 to 10/May/201	12	20	60	2
O2	ADCP	20/Apr/2011 to 10/May/201	5	20	60	2
O2	ADCP	04/Apr/2012 to 13/Apr/2012	5	20	60	2
O3	RBR data loggers	06/Apr/2012 to 08/Apr/2012	2	continuously	-	6
O3	ADV current meter	06/Apr/2012 to 08/Apr/2012	2	10	10	4
W	Canterbury wave gauge	04/Apr/2012 to 13/Apr/2012	76	20	60	1.28
On the beach	Weather station	04/Apr/2012 to 08/Apr/2012	-	10	10	-

3. RESULTS AND DISCUSSION

3.1 Observations in Okains Bay

When incident waves approach pocket beaches their directions notably change. The results of measurements showed that wave directions inside Okains Bay, as an example of pocket beaches, are mostly in normal for different wave conditions (Figure 2 and 3). The difference between predominant incident wave directions inside and outside of Okains Bay is about 60°. However, the depth changes from about 12 m to 6 m and according to Linear Wave Theory, this much variation in the depth cannot change the wave directions about 60°. This significant change in the wave directions is because the headlands filter approach waves and only those waves with directions within wave directional sector can directly enter the bay. However, other waves are significantly influenced by diffraction and reflection and propagate into the bay.

As depicted in figures (2) and (3), wave heights also decreased significantly when they travelled from site O1 to O2. If waves approach at an angle greater than approaching directional sector of Okains Bay, they cannot directly enter the bay and their heights decrease as a result of diffraction and reflection from the headlands. However, waves approaching at an angle within the directional sector can directly enter the bay and their heights are affected by refraction and shoaling similar to wave transformation processes in open coast beaches.

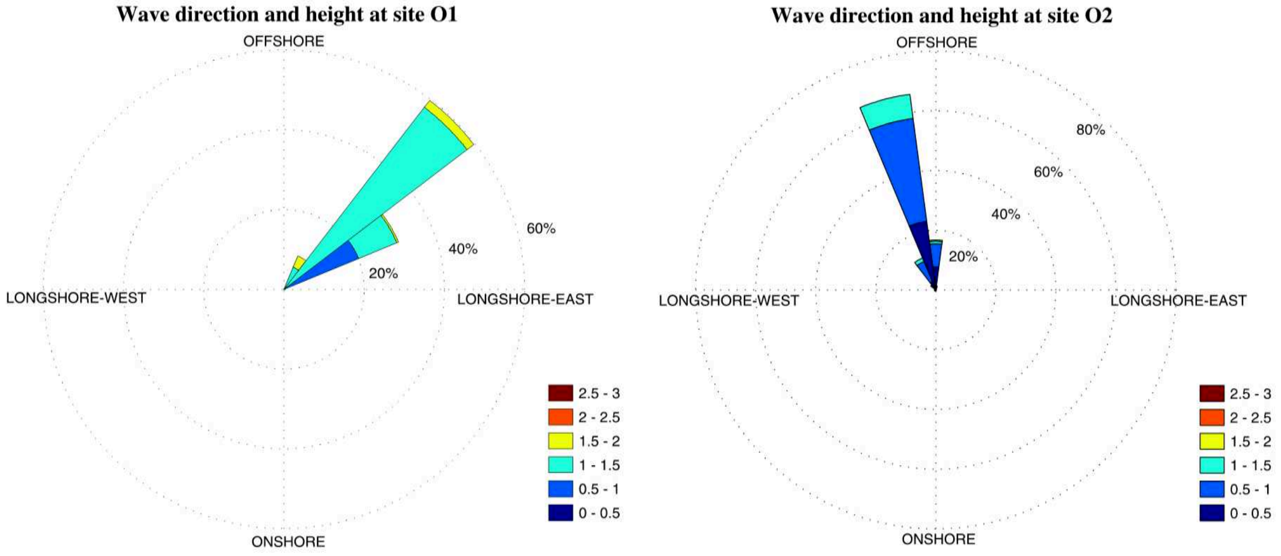

Figure 2 Rose plot showing wave height and direction measured at site O1, in the depth of 12 m, and site O2, in a depth of 6, at Okains Bay during April 2012.

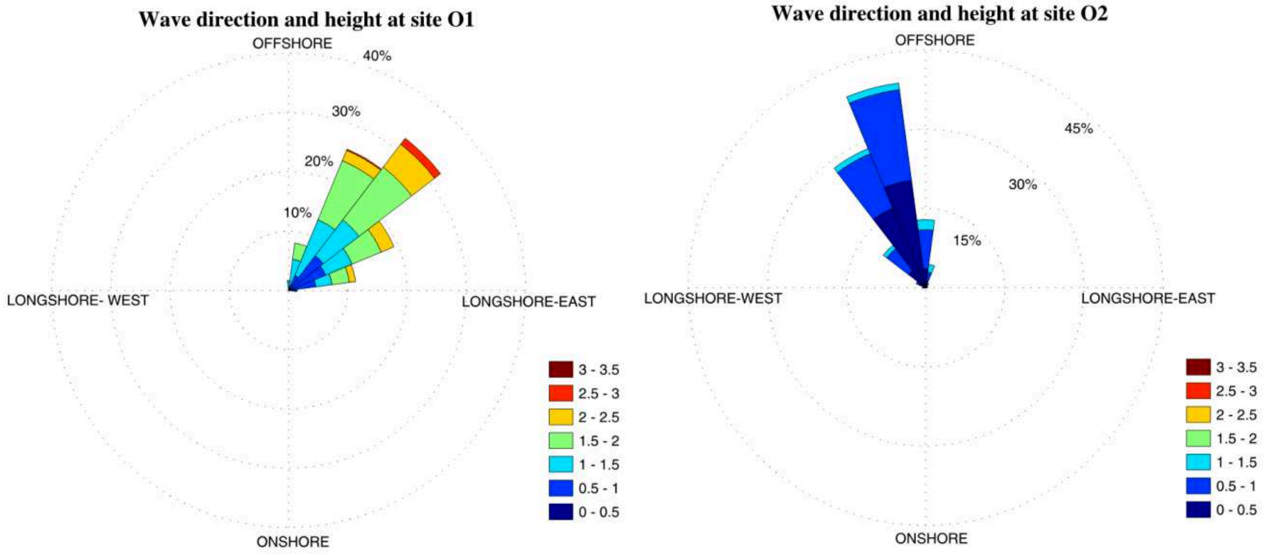

Figure 3 Rose plot showing wave height and direction measured at site O1, in the depth of 12 m, and site O2, in a depth of 6, at Okains Bay during April and May 2011.

Since wave directions were mostly normal to the shoreline and wave heights significantly decreased inside Okains Bay, wave-generated currents are expected to be lower than those in adjacent open coast beaches. The measurements during April 2012 showed that the current velocities at 1 m above the bed at site O2 varied from 0.012 ms^{-1} to about 0.21 ms^{-1} with an average of 0.057

ms^{-1} s, when the predominant wave height and direction at site O1 were 1.5 m and 45° to the shoreline respectively (Figure 4). This indicates that waves generate weak currents behind the surf zone of the pocket beach, when waves approach at an angle greater than approaching wave directional sector. However, current velocities increased at site O3 inside the surf zone where waves break. The current velocities at 20 cm above the bed at site O3 varied from 0.065 ms^{-1} to about 0.27 ms^{-1} with an average of 0.11 ms^{-1} s (Figure 5). The current velocities and directions inside the surf zone could possibly be affected by other factors, such as local winds and tides.

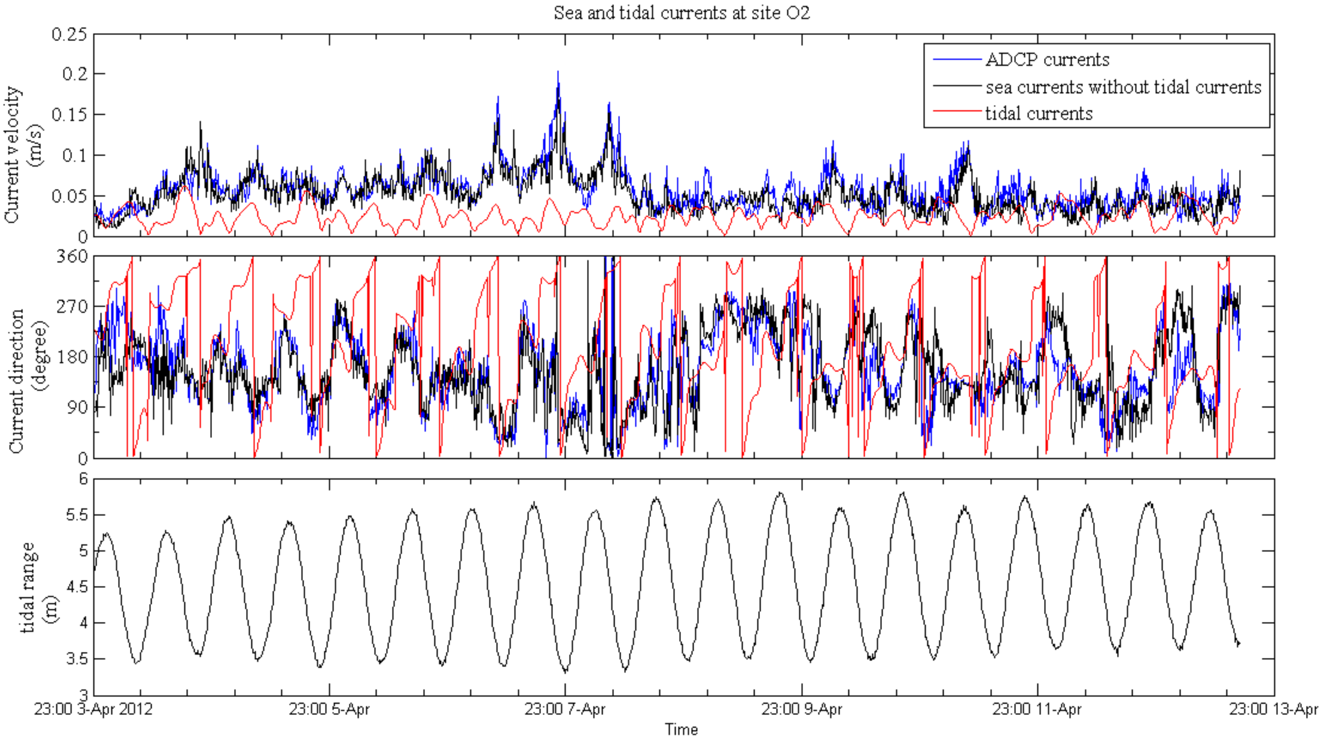

Figure 4 Plot showing measured and tidal current velocities at site O2, in the depth of 5 m, at Okains Bay during April 2012

Tidal currents play an important role in controlling nearshore currents in the surf zone of Okains Bay (Figure 5). Tidal current analysis using Utide Matlab Functions (Codiga, 2011) showed that tidal currents dominated the sea currents at site O3 (Figure 5); that is, the surf zone current velocities changed significantly during low and high tides. This indicates a significant influence of tidal ranges on nearshore currents in the surf zone, although, wave heights varied from 0.6 m to 1.25 m with an average of 0.8 m at site O3. On the contrary, the tidal analysis at site O2 showed that the tidal range had insignificant effect on sea currents behind the surf zone (Figure 4). It can be concluded that currents inside the surf zone of Okains Bay are significantly influenced by tidal currents, while wave-generated currents dominated the area behind the surf zone.

Another important factor influencing nearshore currents is local winds. Local winds tend to blow in offshore or onshore directions as Okains Bay is surrounded by two high headlands. However, larger scale synoptic patterns occur in different directions, commonly in longshore directions (Figure 6). This indicates that the geometry of pocket beaches similar to Okains Bay can influence the direction of local winds and, subsequently, their effects on nearshore currents could differ from those in adjacent open coast beaches.

The results of measurements showed that winds can affect the nearshore currents at 1 m above the bed at site O2 (Figure 7). In contrast to tidal effects, local winds could notably influence the currents at site O2, while this effect was insignificant at site O3 inside the surf zone (Figure 8). The correlation coefficient between wind speed and current velocity at site O2 was about 0.6, showing a considerable influence of wind on currents, whereas the coefficient dropped to 0.2 at site O3, indicating an insignificant effect of local winds on currents in the surf zone of Okains Bay.

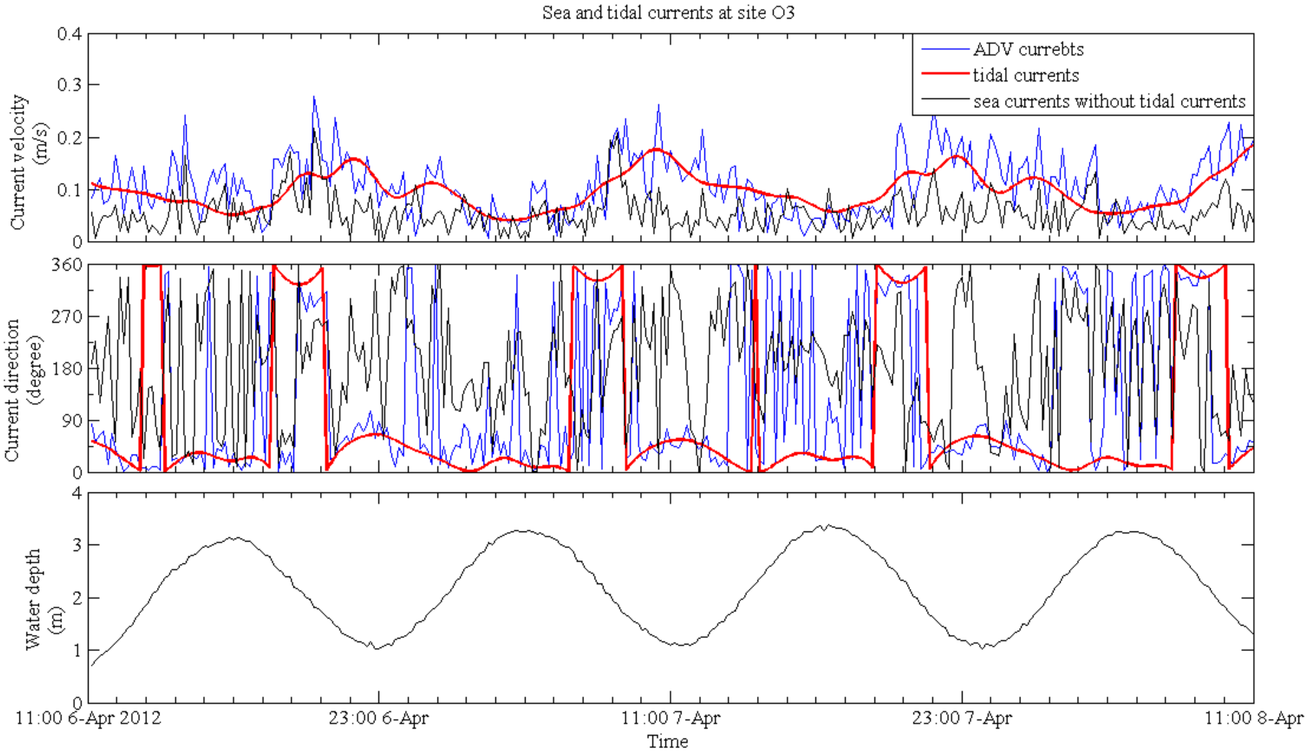

Figure 5 Plot showing measured and tidal current velocities at site O3, in the depth of 2 m, at Okains Bay during April 2012.

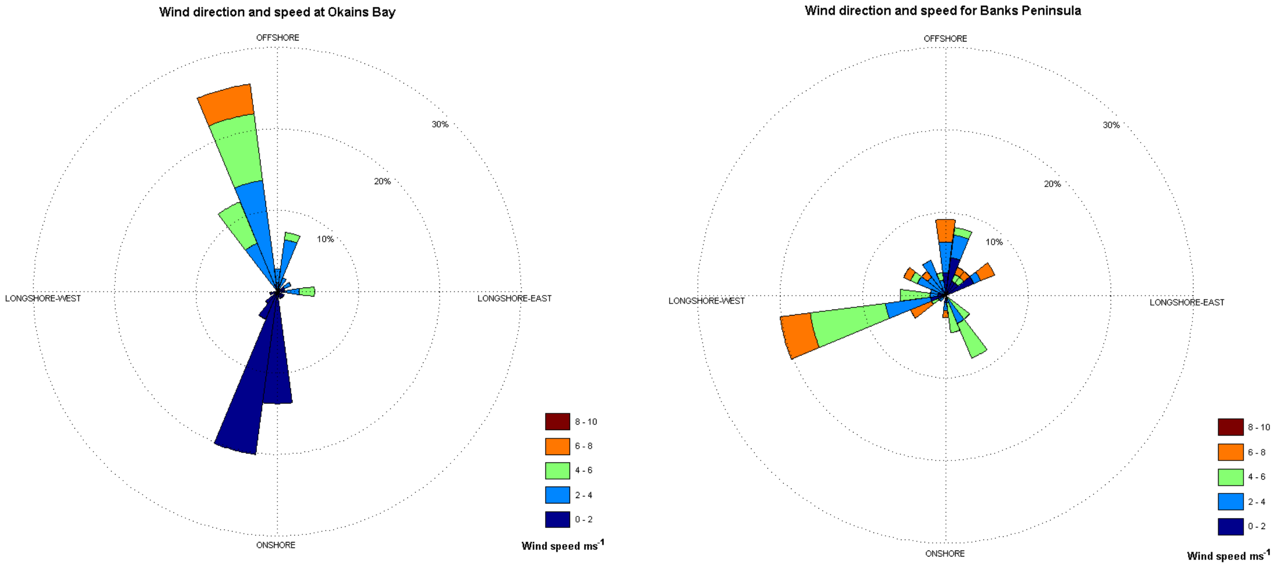

Figure 6 Plot showing wind directions and speed in Okains Bay and for larger scale synoptic patterns (Banks Peninsula) during April 2012.

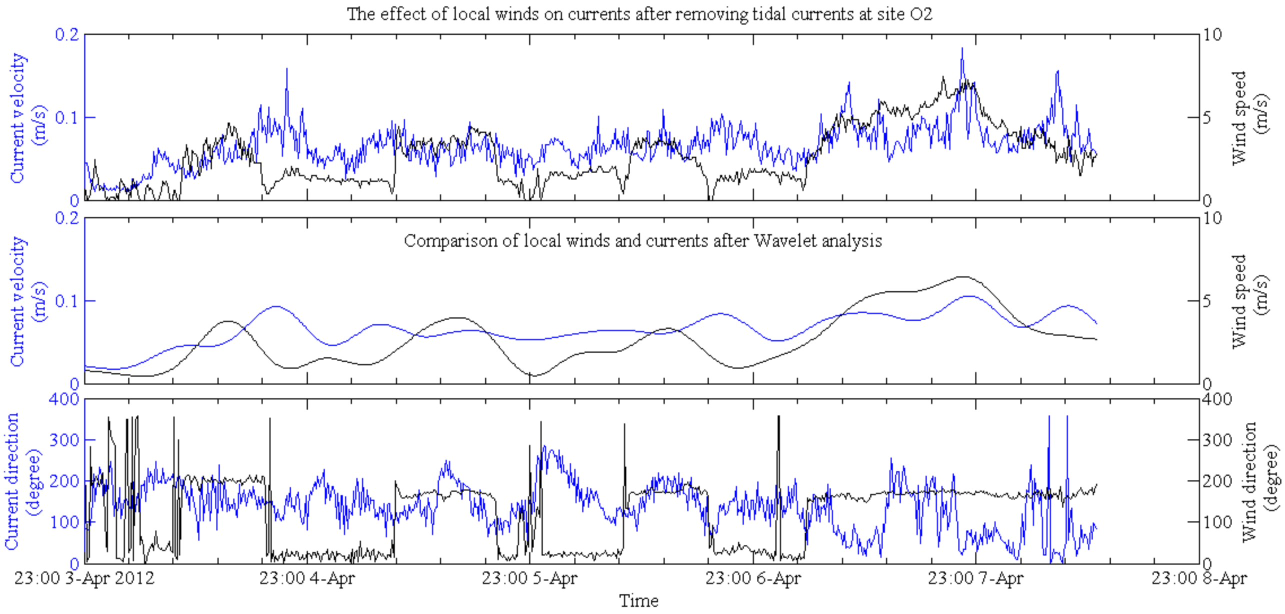

Figure 7 Plot showing the influence of local winds on nearshore currents close to the bed at site O2 in Okains Bay, during April 2012.

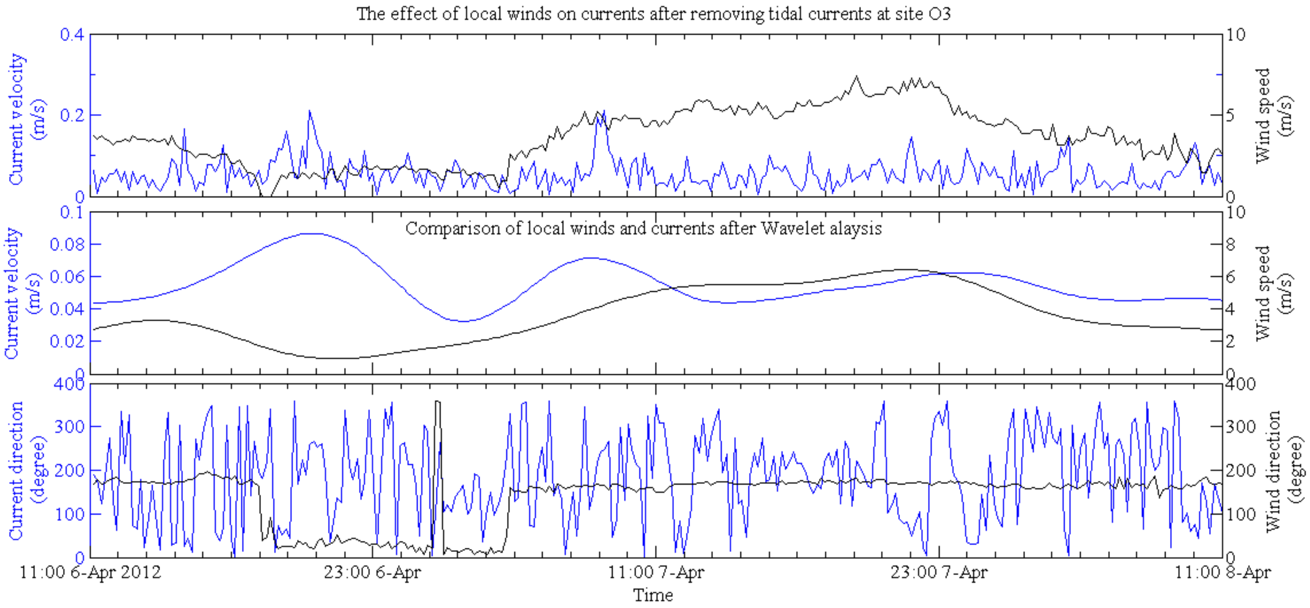

Figure 8 Plot showing the influence of local winds on nearshore currents close to the bed at site O3 in Okains Bay, during April 2012.

The effect of local winds can be accentuated in the surf zone at site O3 when local winds are fairly strong. The results showed that a moderate wind speed with an average of 3 ms^{-1} can influence the current velocities behind the surf zone at site O2, while currents inside the surf zone at site O3 increase when wind speeds exceeded 5 ms^{-1}. It can be concluded that since the surf zone currents are dominated by tidal currents, only strong winds can influence the nearshore currents, whereas in deeper areas as the effect of tidal currents are reduced, the effect of local winds is more accentuated.

3.2 Numerical modeling analysis in Okains Bay and Lavericks Bay

The model was run for two adjacent pocket beaches, Okains Bay and Lavericks Bay (Figure 1), for duration of 24 hours. Observations were only available at Okains Bay, so the results of the model were first compared with the measured data at this bay. Then the results in Lavericks Bay were used to examine whether the geometry of pocket beaches can influence the nearshore current circulations.

Validation of modeled currents against observations at both sites O2 and O3 was completed using Index Of Agreement (IOA), a statistical performance. As illustrated in Figure 9, there is a good agreement between modeled current velocities and measurements at both sites O2 and O3 with an IOA of 0.7. The comparison also shows that the model can reasonably predicts the current directions with an IOA of 0.65. However, the results indicate that the model tends to underestimate the values of nearshore currents. The discrepancy between the predictions and observations is because the model was designed to average currents from the bed to surface, while the observations were measured at either one specific point or cell in water column. Despite the fact, it can be concluded that XBeach model is capable of considering the effect of headlands on filtering incident waves and on nearshore currents. Therefore, we presumed the model can be applied to different types of pocket beaches and this led us to examine if geometry of pocket beaches can influence the nearshore current circulations.

The results of the model in Okains Bay showed that the current system in the surf zone was a combination of onshore, longshore and offshore currents (Figure 10). In an area close to the downcoast headland, currents moved towards the shoreline from outer breaking zone to the surf zone. Inside the surf zone, the currents turned to a longshore direction towards the upcoast headland. Finally, in an area close to the upcoast headland, currents gradually turned to the offshore and formed rip currents, controlled by the upcoast headland. This current system in Okains Bay is similar to the findings of Short (1999) in embayedments, indicating headlands influence longshore currents and one or two rip currents form in proximity to the headlands.

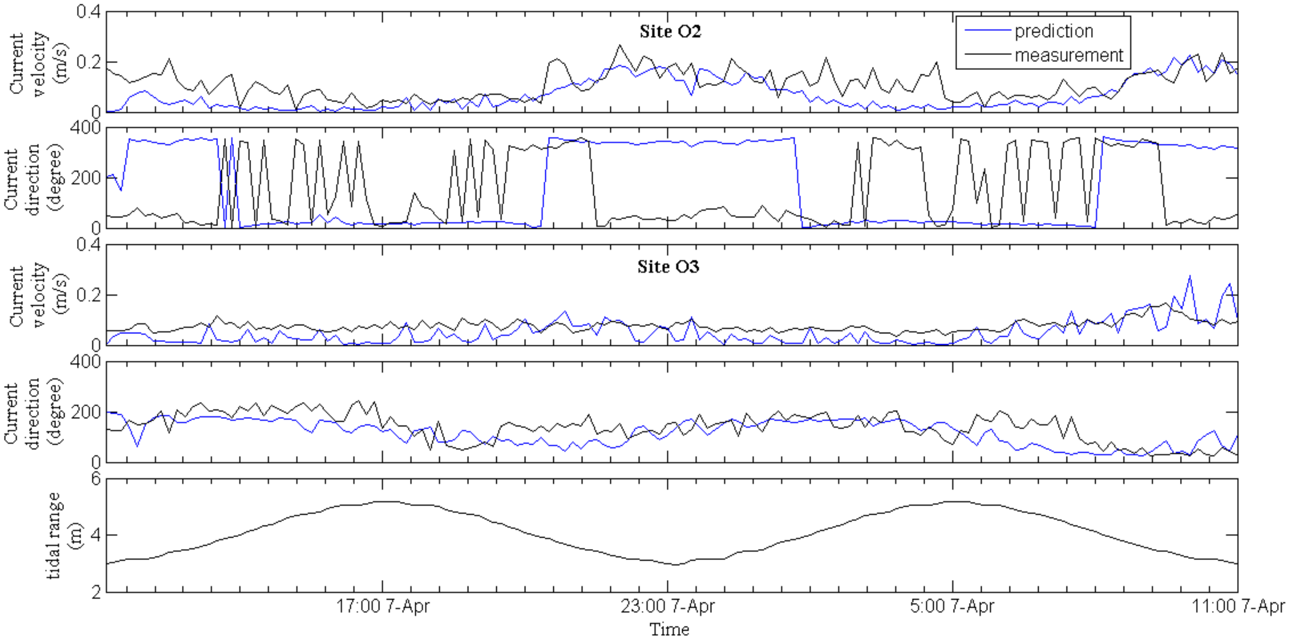

Figure 9 A comparison between the results of XBeach model and measurements behind the surf zone at site O2, and inside the surf zone at site O3 in Okains Bay.

The longshore currents inside the surf zone were in an opposite direction to the expected oblique wave-induced longshore current. Since upcoast headland blocks a part of the shoreline of Okains Bay from oblique incident waves, the wave height in an area exposed to the downcoast headland was greater than that of the blocked area (or shadow zone). Therefore, water flowed from the high level to the low level and generated a longshore current. This current differs from that in open coast beaches as the longshore currents are generated by oblique incident waves.

The results of the model in Lavericks Bay showed a similar current system to Okains Bay (Figure 10). Since the width of Lavericks Bay is smaller relative to Okains Bay, longshore currents moved in a shorter distance from the downcoast to upcoast headlands and they were significantly affected by the onshore and offshore currents, dominated the area close to the downcoast and upcoast headlands respectively.

The current velocities inside Lavericks Bay were fairly stronger than Okains Bay. Since Lavericks Bay is a reflective beach and its shoreline is blocked by shorter headlands relative to Okains Bay, waves were less affected by the upcoast headland. Therefore, waves less lost their energy inside the surf zone and generated stronger nearshore currents compared to those in Okains Bay. It can be inferred that the geometry of pocket beaches, including the size of the headlands and width of bays, can notably influence nearshore currents, especially longshore currents processes inside the surf zone. Longshore currents are significantly influenced by offshore and onshore currents in pocket beaches with narrower width.

4. CONCLUSION

Pocket beaches are areas sheltered between two natural or artificial headlands, so their unique geometries can significantly affect wave processes and nearshore currents relative to open coast beaches. In contrast to open coast beaches, wave directions in Okains Bay, as an example of pocket beach environments, were mostly in normal regardless the direction of incident waves. That is because headlands filter approach waves and only those waves with directions within wave directional sector can directly enter the bay.

Since waves can only approach to the shoreline from a limited directional sector, other factors, such as local winds and tides, can importantly influence the nearshore currents in pocket beaches. The results of this study showed tidal currents can significantly influence the surf zone currents, while this effect decreases in the seaward direction, especially behind the surf zone. On the contrary, a moderate local wind could affect nearshore currents in an area behind the surf zone, whereas only a strong local wind could possibly influence the surf zone currents, mostly dominated by tidal currents.

In order to examine the importance of the geometry of pocket beaches in controlling nearshore currents, XBeach model was applied to two adjacent pocket beaches, Okains Bay and Lavericks Bay. The results showed that if the width of the pocket beaches decreases, it influences the strength of nearshore currents and also the length of longshore currents. However the current system remains constant; that is, onshore and offshore currents form close to the downcoast and upcoast headlands respectively, and the longshore currents are generated by water level gradient.

Further studies need to be done during wave conditions, including storm, to quantify nearshore currents and thus sediment transport in pocket beaches.

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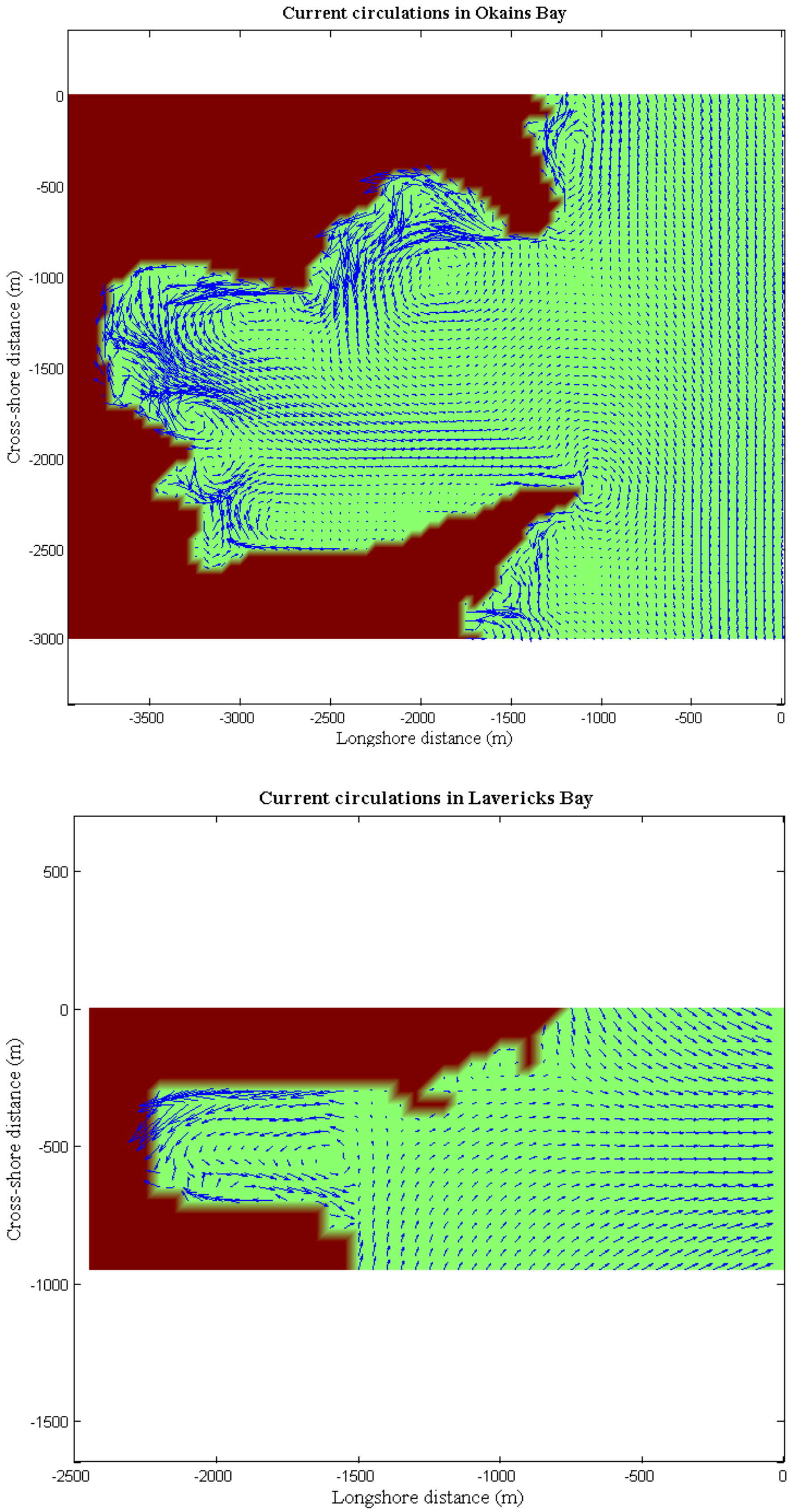

Figure 10 Current systems in Okains Bay (a), and Lavericks Bay (b).

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