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The Influence of Sand Bar Morphology on Surfing Amenity at New Zealand Beach Breaks

Karin R. Bryan[†*], **Jai Davies-Campbell**[†], **Terry M. Hume**[††], **and Shari L. Gallop**[†]

[†]University of Waikato
Hamilton, New Zealand

[††]Hume Consulting Ltd
Waiheke Island, New Zealand

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ABSTRACT

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Wave breaking patterns on many of New Zealand's prominent surfing beaches are controlled by surf zone sand bar morphology. In turn, sand bars change in response to wave breaking and surf zone current patterns, with well-known theories predicting more linear bars during winter, and more three dimensional patterns during lower energy conditions. Here four databases of sand bar morphology from New Zealand, collected at Aramoana, Piha, Lyall Bay, and Tairua, are analysed to detect changes in key parameters that control wave surfability: the length and orientation of the bar. Longer bars provide the potential for longer surfing rides, whereas the orientation determines the peel angle or the difficulty of the ride. Computer algorithms were used to detect sandbars from light intensity maxima patterns obtained from averaged, geo-rectified video imagery collected at each beach. The length of bar was inversely correlated with orientation, with longer beaches also having longer bars. Sand bar length and orientation was highly variable, both spatially (with location along the beach) and temporally (seasonal and interannual variability), making it difficult to detect any significant changes between location or with time. However, sand bars were generally shorter and more obliquely-oriented near the ends of these headland-enclosed beaches. Although no significant seasonal variations were detected, there were detectable interannual variations on the two beaches with the longest datasets, which were correlated with the Southern Oscillation Index. Implications of the study are that, unless changes are substantial such as caused by groins and seawalls, long monitoring datasets are needed to detect anthropogenic impacts on surf breaks.

ADDITIONAL INDEX WORDS: *Sand banks, rip current channels, beach geomorphology, climate patterns.*

INTRODUCTION

Many of New Zealand's most valued surf breaks are on sandy beaches, where the surfing conditions change considerably over time with season and between years, and also spatially along the beach. There are multiple physical features that can influence surfing wave quality, including bathymetric irregularities such as headlands and islands that can condition waves before they arrive on the beach (Mead and Black, 2001a,b). More locally, sand bar morphology influences the suitability of waves for surfing (*e.g.*, depending on bar proximity to shore, depth, orientation and length of bar). One key determinant of sand bar morphology is channel rip current patterns. Channel rip currents are narrow, seaward flows that occur in the relatively deeper areas adjacent to the wave breaking areas on sand bars (Castelle *et al*., 2016; Short, 2007). Therefore, sand bar morphology is also a driver of beach hazards and should influence decisions on wave safety.

A range of processes can cause temporal and spatial changes to sand bars, some of which act on the beach as a whole, while others cause more localised changes. Sand bars can move relatively uniformly along the entire beach by onshore-offshore sediment exchange caused by accretion and erosion events, and bars can change their overall orientation and curvature with changes to the wave angle of approach (Blossier *et al*., 2016, 2017). More localized temporal and spatial patterns in sand bar morphology are usually associated with the aforementioned channel rip currents, and also headland rip currents. The dynamics of rip currents can also accompany large scale changes in the wider beach morphology; for example, larger rip currents are more likely when the beach is in a rotated state (van de Lageweg *et al*., 2013). In general, the development of rip currents, whether channel or headland rips, and the evolution of small-scale changes to the orientation and length of bars are inherently coupled (Castelle and Coco, 2012).

Alongshore variation in sand bar morphology is an important control on wave peel angle, which is one of the key characteristics of a good surfing wave. Peel angle is the angle of the line tracking the interface between the broken and unbroken wave crest (Hutt, Black, and Mead, 2001; Walker, 1974). If an incident wave begins to break at approximately the same cross-shore location along the entire length of the crest, the peel angle is small or even zero if this breaking is simultaneous along the crest. In this case, the breaking edge travels too quickly along the crest for the wave to be surfed before it "closes out" (Figure 1). On the other extreme, if the breaking edge travels shoreward, as well as alongshore, at a much slower speed, the peel

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*Corresponding author: karin.bryan@waikato.ac.nz

angle is large so the wave is more easily surfed and the potential ride length is long (although if the peel angle becomes too great it cannot be surfed either). Walker (1974), followed by Hutt, Black, and Mead (2001) and many subsequent studies (see Scarfe *et al.* (2003) for a review) used the peel angle in a classification of surfability. At beach breaks, wave peel angle should relate to the geometry of the alongshore bar (Mead, 2000). This is because waves begin to break when the water depth becomes shallower than H_s/γ, where H_s is significant wave height, and γ is an empirically-defined constant dependent on the slope of the wave face relative to the slope of the seabed (≈ 0.7 according to Ruessink *et al*. (2003)). If the bar has little alongshore variation, then the breaking criterion will be reached at the same cross-shore location at every alongshore location, so the breaking edge will travel quickly and the peel angle is small (Figure 1b). However, if the bar is oriented at an oblique angle to the shoreline, the wave will break at the seaward point first, and the breaking face will migrate shoreward (translates laterally) along the bar crest. Therefore, oblique bar orientation can create oblique breaking wave crests, which create a longer, more easily surfed, ride for the surfer (Figure 1a).

A: Crescentic bar and trough beach state with high peel angle

B: Longshore bar and trough beach state with low peel angle

Figure 1. Schematic showing the location of the alongshore bar (black line), and the location of the breaking face of the wave (magenta line). Panel A: A case in which the bars are oriented at a oblique angle to the beach such as occurs when the beach state is ‘crescentic bar and trough’, which will increase peel angle making the waves more amenable for surfing. Panel B: A case where the bars are more parallel to the shoreline such as occurs when the beach state is ‘longshore bar and trough’, and waves break parallel to the beach so peel angle is small, the waves “close out” and not as suitable for surfing.

Sand bar morphology is also an integral characteristic of the morphodynamic beach state (*e.g.*, Wright and Short (1984)), where the bars become progressively more oblique relative to the shoreline the beach becomes more reflective. In addition to differences in beach state between beaches, many intermediate beaches change state seasonally, becoming more dissipative in winter and more reflective in summer (*e.g.*, Bogle *et al*., 2001). Given that beach state is diagnosed largely from sand bar morphology, it has an important relationship to beach surfability. For example, images of wave breaking patterns from the single-barred Tairua Beach in New Zealand (Figure 1) show the beach in a ‘Crescentic Bar and Trough’ state, which is closer to the reflective extreme (Panel A). Panel B shows the beach in a ‘Longshore Bar and Trough’ state which is more dissipative. These images indicate lateral translation of the break point (Panel A) and coincident breaking of the wave crest (Panel B).

Having appropriate methods to detect and quantify natural variability in surfing conditions is critical to being able to measure and predict any effects caused by anthropogenic changes to surfing wave quality. For example, offshore dredge spoil disposal builds mounds on the seabed that may be in the swell corridor (Atkin and Greer, 2019), which can modify incident waves and change the way they are pre-conditioned before they reach the surf zone (Mead and Black, 2001a,b). Moreover, changes to sediment supply caused by dredging nearby inlets, or locking sand into dune environments through dune planting have been blamed for changing the surfing conditions in New Zealand (Atkin *et al*., 2013, 2017; Dahm, 2013; Scarfe *et al*., 2009). Coastal engineering structures such as breakwaters and jetties can also reduce the quality of surfing waves through their influence on coastal morphology (Corne, 2009; Scarfe *et al*., 2009). While most coastal development results in negative impacts on surfing, in some cases there can be positive changes, such as where groynes trap sand to produce longer, more consistent peeling breaks. In addition to anthropogenic changes, natural variations in sediment supply is also often associated with changing surfing conditions (Atkin *et al*., 2017).

In this study we use video camera observations from four New Zealand beaches to determine the processes controlling sand bar morphology, and to infer how these changes might influence surfing characteristics. Sand bar morphology is quantified by measuring the orientation and length of bar, which reflect changes to the peel angle and length of surfing ride and are easily measured using automated techniques. To achieve this aim, the objectives are: (1) to determine alongshore variation in sand bar morphology (length and orientation), and relate to beach characteristics such as beach length and nature of headlands; and (2) to quantify any seasonal and interannual variations in bar morphology and relationship to climate indices. This study focuses on four beaches in New Zealand with a range of environmental settings: Aramoana Beach in Otago, Lyall Bay in Wellington, Piha Beach north of Auckland, and Tairua Beach in the Coromandel Peninsula (Figure 2). In addition to providing a new approach to estimating beach surfing characteristics, the data will provide a baseline against which to assess the minimum detectable impact of anthropogenic effects.

FIELD SITE DESCRIPTION

Video camera installations were used to quantify variations in sand bar length and orientation. The video monitoring technique for surf zone morphology was originally developed for use with “ARGUS” imagery collected by the Coastal Imaging Lab at Oregon State University (Lippmann and Holman, 1989). A similar approach was adopted in New Zealand in 1998 as part of the Cam-Era video imaging network operated by the National Institute of Water and Atmospheric Research Ltd (NIWA), then as part of the project on characterising surf breaks of national and regional significance (Atkin *et al*., 2017; Mead and Atkin, 2019). Cam-Era images have been used in multiple studies in New Zealand to investigate sand bars (Harrison *et al*., 2017; van de Lageweg *et al*., 2013), shoreline change (Blossier *et al*., 2017, 2018), rip channels (Gallop *et al*., 2009, 2011), cusps (Almar *et al*., 2008), infragravity waves (Guedes *et al*., 2013) and run-up (Guedes *et al*., 2013; Salmon *et al*., 2007), although have not been specificall applied to surf breaks. Here we analyse observations from two Cam-Era stations (Aramoana and Tairua) and two new stations (Piha and Lyall Bay) (Figure 2). These four stations represent a variety of geological, wave, and tidal conditions of embayed beaches. In each case, a sequence of 20 minutes of video imagery (1200 images) is collected every daylight hour, and averaged to remove short-term variations.

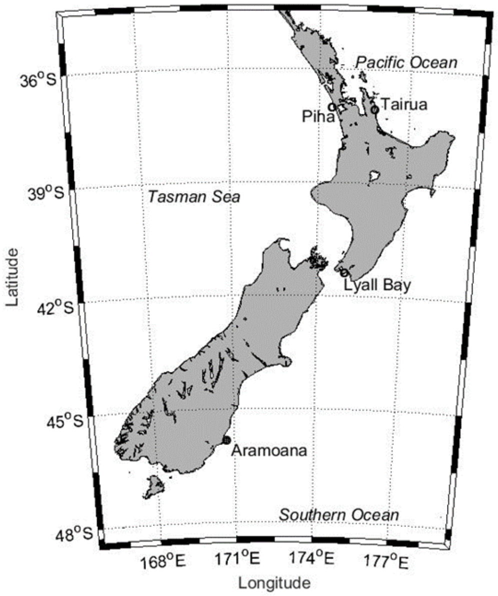

Figure 2. Map showing the location of the video stations. Sites at Piha and Lyall Bay were installed as part of this study, and the site Tairua and Aramoana are run by the Cam-Era network (National Institute of Water and Atmospheric Research Ltd), with Tairua owned by Waikato Regional Council and Aramoana owned by the Port of Otago.

Tairua

Tairua Beach (also locally called Ocean Beach) is situated on the north-east coast of the Coromandel Peninsula. It is one of a series of embayed beaches that are enclosed by volcanic outcrops and plugs that characterise the Coromandel ranges (Edbrooke, 2001). The beaches are generally considered part of closed systems, in which little sand is transferred up and down coast (Hume *et al*., 1992; Pilkey and Hume, 2001). Hart and Bryan (2008) showed the probability of sand by-passing headlands and moving between these beaches is on the order of 2%. Tairua Beach is approximately 1 km long and is enclosed by Paku Hill to the south where the camera is situated with a north-westward view (Figure 3a), and Pumpkin Hill to the north (Figure 3a and b). The beach is partially sheltered from waves by Shoe Island which lies some 3.5 km offshore from the southern end of the beach.

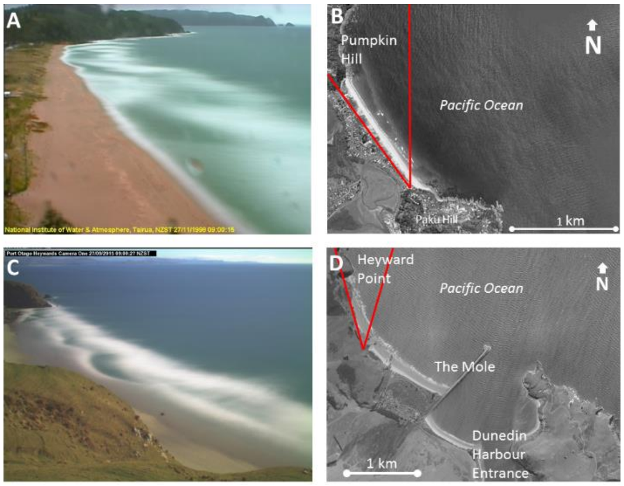

Figure 3. An example time-averaged image from two of the video installations. A: Tairua Beach; C: Aramoana. An aerial photograph of each site with the approximate field of view of the camera shown in the images on the left marked in red. B: Tairua Beach; D: Aramoana. Aerial photos extracted from the Land Information NZ database.

The camera at Tairua Beach was the first camera installed for the Cam-Era programme. Its purpose was to supplement the WRC beach monitoring programme, with the ultimate goal of selecting an indicator beach for intensive monitoring that would generally represent variations at all key Coromandel beaches. The video imagery dataset has been used in multiple projects to study rip currents (*e.g.*, Gallop *et al*. 2009; 2011), sand bar patterns (*e.g.*, van der Lageweg *et al*., 2013) and shoreline variations (Blossier *et al*., 2017). For this project, bars were extracted from imagery collected between 6th November 1998 and 2008. There are no significant anthropogenic modifications to this beach, except in recent years when beach scraping occurs after storm events, but not within the time frame of these observations.

Wave conditions along the north-east coast of the Coromandel are much more quiescent than at Aramoana Beach, because the orientation of the North Island means that this region is protected from Southern Ocean swell. The mean wave height is 0.86 m (Gorman *et al*., 2003a), with extremes occurring during the passage of tropical cyclones. The Southern Oscillation Index (SOI) and Pacific Decadel Oscillation (PDO) are associated with changes in wave height which have the opposite trend to at Aramoana (the wave height increases on the Coromandel as conditions shift toward La Niñas). The SAM has no significant effect on conditions along this coast (Godoi *et al*., 2016).

Aramoana

Aramoana Beach (also known locally as Spit Beach or the Spit) is situated some 20 km northeast from Dunedin City at the north side of the entrance to Otago Harbour (Figure 3c), where the Port of Otago is located. The 1.8 km-long sandy beach faces north-east and is bounded to the north-west by a small rocky headland

(Heyward Point) which extends seawards approximately 250 m from the shoreline, and by a 1200 m-long breakwater ("The Mole") in the south-east (Figure 3d). The Port dredges the Harbour and entrance to maintain the shipping channel, and the dredge spoil is disposed offshore (although no significant dredging events occurred during the observation period reported here). The Aramoana station (Figure 2 and 3c and d) was installed to monitor beach variations during dredging as part of Port Otago's application for renewed dredging consent in 2017. The camera is situated halfway along the beach, with the field of view covering approximately 850 m alongshore, and the camera points northward along the beach (Figure 3d). Bars were extracted from imagery collected between 20th September 2013 and 24th August 2017.

The Otago Peninsular is on an exposed south-east facing coast and so is subjected to frequent and energetic swells from the Southern Ocean. Less common north-easterly swells are generated by cyclones in summer and intermittent lower latitude depressions in winter that, generally, track over the north island. The Otago Peninsular shelters the northern beaches of Otago from the southerly swells, but not from north and north-easterly swells. As a result, typical wave heights are around two metres along this coast (Gorman *et al*., 2003a,b). Wave heights are increasing by a few centimetres per decade, and are influenced by changes in climate such as quantified by the Southern Annular Mode (SAM), Southern Oscillation Index (SOI) and Pacific Decadal Oscillation Index (PDO) (Godoi *et al*., 2016).

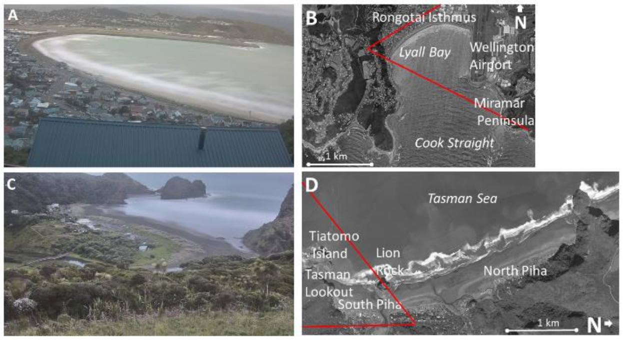

Figure 4. An example time-averaged image from each of the video installations. A: Lyall Bay; C: South Piha. An aerial photograph of each site with the approximate field of view of the camera for images on the left marked in red. B: Lyall Bay; D: South Piha. Aerial photos extracted from the Land Information NZ database.

Lyall Bay

Lyall Bay is located along the southern coast of Wellington City (Figure 2) and lies along Rongotai Isthmus, the old entrance to Wellington Harbour, which connected Evans Bay within the Harbour to Lyall Bay on the seaward side. The entrance lies along a secondary fault which probably separated Miramar Peninsula to the east from the mainland approximately 6,000 years ago (Pillans and Huber, 1992). The two headlands that enclose Lyall Bay extend approximately 2 km seaward, which means that waves arriving from Cook Strait can only approach the beach from a narrow sector (Figure 4b). Furthermore, the waves are strongly refracted by the time they reach the beach, so the beach has the classic curvilinear planform shape of an embayed beach, unlike Tairua Beach and Aramoana Beach where waves approach from a much wider range of directions. The camera was installed on the western end of Lyall Bay, looking eastward toward Miramar Peninsula (Figure 4a and b). The site was selected to represent a highly-modified beach environment. Where there was previously an established dune field, there is now residential and commercial buildings and infrastructure, although the council is currently undertaking a restoration project of the dunes (Mead and Phillips, 2016). The bay is semi-enclosed by walls, roads and parking areas, and storm water discharges in to the bay from over 20 different outfalls. The eastern third of the bay was reclaimed for the airport where the runway extends 850 m seaward of the natural shoreline Bars at Lyall Bay were extracted from imagery collected between 4th July, 2017 and 7th April 2018.

The wave climate offshore of Lyall Bay is low energy, with a mean annual Hs of 1.23 m (Gorman *et al*., 2003a). Waves tend to come from the south, propagating up the southeast coast of the South Island. The wave climate is variable, with extreme events and clusters of wave events commonplace (Godoi *et al*., 2017, 2018). The climate drivers are complex, but most likely similar to the south east coast of the South Island.

Piha

Piha is located on the north-west coast of the North Island, some 30 km west of central Auckland. The c. 2.75 km long embayed beach is composed of fine black sand and is split into North Piha and South Piha by the iconic Lion Rock (Figure 4d). Piha is a site of regionally significant breaks, with South Piha host to a beach break called the Piha Bar, a left hander that breaks best at low tide from Taitomo Island (also called Camel Rock or the Beehive) to across the bay toward Lion Rock (Figure 4d). Anecdotal evidence suggests that surfing conditions at Piha have declined in recent years, with locals attributing this to anthropogenic activities such as dune planting and expansion of the carpark, although with some recognition that changes to the sediment supply might also be due to natural fluctuations (Atkin *et al*., 2017).

The camera was installed as part of the project on surf breaks of national and regional significance (Atkin *et al*., 2017). It views South Piha from a vantage point on the hills backing the beach. It has a field of view of 400 m approximately covering the beach enclosed by Lion Rock in the north to Tasman Lookout to the south (Figure 4c and d). Seaward of Tasman Lookout is Taitomo Island (visible in the images), which is attached to the mainland at low tide. Piha sand bars were extracted from imagery collected between when the camera was installed in 16th October 2017 and 19th April 2018.

As with most of the west coast of New Zealand, waves at Piha Beach are notoriously large (with heights commonly between 1.5 and 2.5 m (King *et al*., 2006), as the beach receives swell directly from the Southern Ocean. The waves have low interannual and seasonal variability, but are still significantly correlated to the SOI and PDO. The correlation is opposite to at Tairua, so on the west coast increases in wave wave height are associated with El Niño conditions. Conditions here are also influenced by the quasi-stationary planetary wave-number pattern 3, which is associated with wind fields in the Southern Ocean and the extent of sea ice

(Turner *et al*., 2016). This pattern only has significant influence on west coast wave climates (Godoi *et al*., 2016).

METHODS

Images from the cameras were rectified in a three-stage process. First, images were corrected for lens distortions using the Matlab image analysis toolbox, and images of a black and white checkerboard grid collected prior to installation of the camera. Second, images were transformed from image coordinates (pixels) to ground coordinates, assuming a vertical plane equal to the mean sea level, and using an estimate of the orientation and position of the camera and the collinearity equations. A series of ground control points that were collected using land or boat based RTK-GPS, and that were visible in the camera field of view, were used to find the optimum value of the orientation and position of the camera. Third, images were rotated to a local coordinate system, where the beach was approximately parallel to one axis. Once the camera position was calculated, this information was used to rectify the whole image. Images can only be rectified by assuming a known vertical level. If this level is too high, the parallax effect will mean that features are smaller than they should be and vice versa. The sand bar patterns were assumed to be at the water level. The water level at the time of each image was estimated using the level of the tide, which was extracted from the NIWA online tidal predictor.

A computer algorithm was developed to search the across-shore distribution of light intensity (Figure 5, blue line) to find local maxima and minima within the surf zone (following Gallop *et al*., 2011). Prior to searching, the image was filtered with a low-pass filter (magenta line in Figure 5). This provided a spatial map of all the local maxima and minima within the surf zone (Figure 6 shows an example from Tairua Beach).

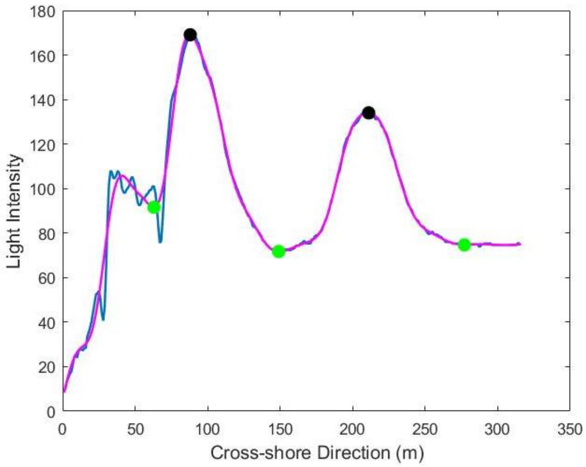

Figure 5. Example showing the barline detection algorithm. The light intensity (blue line) is extracted from a row in the rectified, rotated image, which is perpendicular to the beach, where 0 is on the beach face and 350 is in the blue water offshore. The magenta line is the filtered version of the blue line, and the black and green circles represent local maxima and minima extracted along the magenta line.

Despite filtering, there were a number of isolated points that were not related to sand bars that were removed using a purpose-built tool that removes the sand bar in the database that is closest to a point selected with a mouse. In order to calculate the length and orientation of bars, the local maxima were grouped according to whether they form the same bar. This was achieved using a connectivity algorithm; at each alongshore location, the maxima at the next alongshore location were mapped to the first alongshore location by calculating the Euclidean distance between the maxima. Bars of less than 20 maxima points were removed, then remaining bars were broken apart at locations where their orientation changed, leaving continuous linear sections of bars. The orientation was measured by fitting a regression line to these sections, and the length was measured by calculating the distance between the two ends. (All fitted lines were significant to $p < 0.05$). The r-square was used as a measure of whether the bar should be retained as a single bar ($r^2 > 0.8$), or broken into two bars ($r^2 < 0.8$). (The criterion was arbitrarily chosen). Figure 6b shows an example of final configuration of the bars extracted from a case at Tairua Beach.

RESULTS

Bars varied substantially in orientation and length within and between beaches, and over time. Nevertheless, some clear relationships between bar morphology and beach setting were identified. For example, the length of bar sections was positively correlated to beach length. The shortest beach (South Piha) also had the shortest bars (Figure 7c). The intermediate-length beaches Aramoana and Tairua had similar length bars to each other. Aramoana Beach is about twice as long as Tairua Beach, but there are three large rock outcrops in the middle of Aramoana Beach which may interrupt the alongshore movement of sand, and the camera views only the northern end of Aramoana. The longest beach uninterrupted by outcrops (Lyall Bay) had the longest bars (Figure 7e).

In terms of alongshore variation of bar orientation within individual beaches, the bars at Aramoana varied least, with the bars on the remaining beaches having similar variations to each other (Figure 7 b,d,f,h). However, some of the variation in orientation at Lyall Bay is because it is a strongly curvilinear beach (Figure 4b), and bars will naturally change consistently in orientation from one end of the beach to the other, even when they are parallel to the beach. When the orientation of the shoreline at each alongshore location was removed from the barline orientation data collected at that location, the orientation varied much less at Lyall Bay, but still were of a similar order to Piha and Tairua. Note that at all beaches, few orientations of exactly parallel to the beach were measured, because the point where a continuous (*e.g.*, crescentic) bar was parallel, was the point which was chosen to break the bar into segments (this is why the distribution of orientation appears bimodal in Figure 7). Bar length was generally weakly, but significantly negatively correlated with orientation, so that shorter bars tended to be more oblique ($r^2 = 0.5$, 0.16, 0.20 and 0.18 for Aramoana, Lyall, Piha and Tairua respectively).

Little seasonal variation was detected in bar morphology (Figure 8 and 9). There was a slight increase in the alongshore variability of bar length at Aramoana during the winter months, but orientation exhibit no trend (Figure 8). Tairua bars increased in length during the winter, remaining longer throughout the autumn. Orientation increased in spring and autumn and decreased in winter and summer. Lyall Bay exhibited no seasonal trend (probably because the dataset was simply too short relative to interannual and storm-driven variability needed to characterize differences).

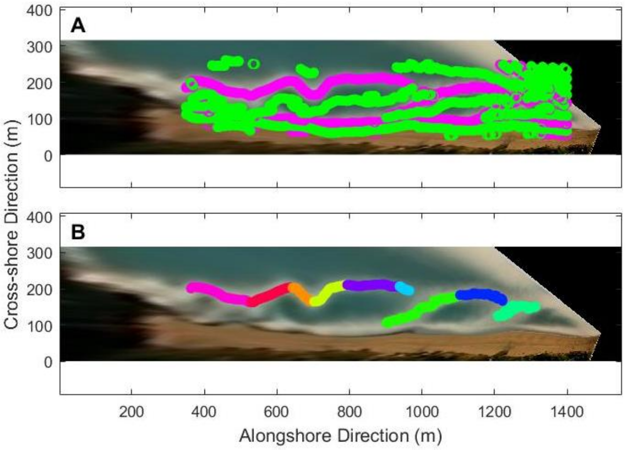

Figure 6. Panel A: The map of maxima (magenta circles) and minima (green circles) extracted from the rectified time-averaged image from Tairua Beach. Panel B: The location of sandbars after the algorithms to remove noise and to identify unique bar sections have been run. The colors represent different segments of bar. See text for more detail.

One of the most interesting results was the strong increase in the length of the bar following a year of more La Niña conditions. Only the datasets from Aramoana and Tairua were long enough to study interannual changes. The median bar length at Tairua was significantly inversely correlated with the median SOI of the previous year (r^2=0.61, p<0.01). Figure 10 shows the mean annual changes in bar length, along with the mean annual value of the SOI of the year before. If the mean is removed from the bar length data from Tairua and Aramoana and the data pooled, the bar length is again significantly inversely correlated (r^2=0.55, p<0.01, Figure 11). Orientation is not correlated with the SOI.

There was strong and consistent alongshore variation in bar length and orientation of bars along each beach. Bars located at each end of the beach were considerably shorter and varied much less alongshore compared to bars in the middle of the beaches (Figure 11). Orientation also shows some differences, with bars near the ends of beaches oriented differently to those in the middle, at all beaches except Aramoana. At Piha, orientations were the same at both ends of the beach whereas at Lyall Bay and Tairua, the bars had different orientations at each end (positive on one end and negative on the other end). This is likely due to the shape and size of the headland at each beach. Lyall Bay had strong variations in bar orientation, with the whole east end of the beach (at the airport runway end) varying very little and the more exposed end of the beach varying several orders of magnitude more.

DISCUSSION AND CONCLUSIONS

In general, the variability in sand bar morphology (length and orientation) was large, much more at a single location than the difference between seasons, along the beach and between years. This means that standard statistical techniques (for example, a difference of means test) cannot detect changes due to natural variation, unless very long time series are collected. As a consequence, bar morphology changes resulting from anthropogenic activity would have to be substantial to be detectable. The longest dataset (Tairua, 10 years) suggests that the interannual changes in bar morphology at Tairua may be driven by long-timescale climatic variations, due to the El Niño-Southern Oscillation (ENSO) cycle switching between El Niño and La Niña conditions (ENSO has oscillations with timescales of over 10 years and is associated with the PDO).

The strong alongshore variability on individual beaches is likely driven by offshore islands causing changes offshore to the bathymetric contours in the swell corridor (which are essential to wave preconditioning) and headland configuration. Such alterations in the swell corridor by islands and headlands changes the incident wave angle and causes wave shadowing, which drive gradients in wave energy alongshore. For example, shadowing from Shoe Island (just offshore of Paku Hill at the southern end of Tairua Beach on Figure 3c) changes the alongshore distribution of wave energy as the incoming wave angle of approach changes (Gallop *et al*., 2011; Bryan *et al*., 2013), and causes alongshore variation in surf zone morphology. Through a similar process, although not detected here, dredge spoil disposal offshore of Aramoana Beach is known to change the wave approach angle, and influences the surf zone morphology (Atkin *et al*., 2017). Kilpatrick (2005) measured the bathymetry of Aramoana before and after dredging, which enabled him to make a direct assessment of wave transformations that occurred before and after the spoil mound was present. He concluded that it was the combined effect of focusing on the Otago Harbour ebb tidal delta and the spoil mound that caused the caused an alongshore gradient in wave height, promoting wave peeling and favourable surfing conditions at Aramoana (Kilpatrick, 2005; Scarfe *et al*., 2009a,b).

The overall length of each beach played a role in determining sand bar length. Shorter beaches have shorter segments of sand bars, which probably relate to the average geometry of rip current circulation cells. On shorter beaches, the headlands influence a larger proportion of the beach and have a strong control on the geometry of circulation cells (Short and Masselink, 2009), and headland controlled rip currents are often present (Castelle *et al*., 2016). Modelling studies show that as morphology evolves with time, the headlands first influence the bars near the headlands by the formation of headland rips, which in turn influence the shape of the bar toward the middle of the beach (Castelle and Coco, 2012). So a 2D uniform alongshore bar gradually evolves to 3D, with the 3D pattern initiating near each headland. The timeframe over which 3D-patterning evolves to reach the middle of the beach is smaller for shorter beaches. Therefore, shorter beaches are likely to have more rip currents, and more dissected bars which are shorter and more oblique. Also, the bars in video images (as used in this study) are only observable from the cameras when waves are breaking on them, and so by definition can only exist in the surf zone. Therefore the seaward extent of the bar must be constrained by the breakpoint, which means also that bars that are more parallel to the beach are able to be longer.

The lack of seasonality in our observations is contrary to what would be expected with associated changes to beach state that should occur in more energetic winter months. The Wright and Short (1984) model shows that bars should become more alongshore-uniform as wave energy increases and the beach shifts toward a more dissipative state. In addition, Short (1985) showed that rips during erosional conditions tend to become more widely spaced, and vice versa, so we should expect the bar segments to become longer in winter when the system is more energetic (Short, 1985). Only Tairua, with 10 years of data, shows any statistically-detectable seasonal variations, which suggests that the other datasets are too short. According to Wright and Short (1984), our most energetic beaches (Piha and Aramoana) should have the longest, most shore-parallel bars. Observations from Aramoana show the smallest orientations (Figure 7b); conversely the very short nature of Piha South means that interference of the headland appears to dominate the bar patterns rather than the dissipative beach state. Studies on Whanganui Beach (called Wanganui Beach in their study) on New Zealand's west coast have similarly shown a lack of seasonality in beach morphodynamics which they attributed to the importance of antecedent morphology in controlling bar dynamics (Shand *et al*., 2001).

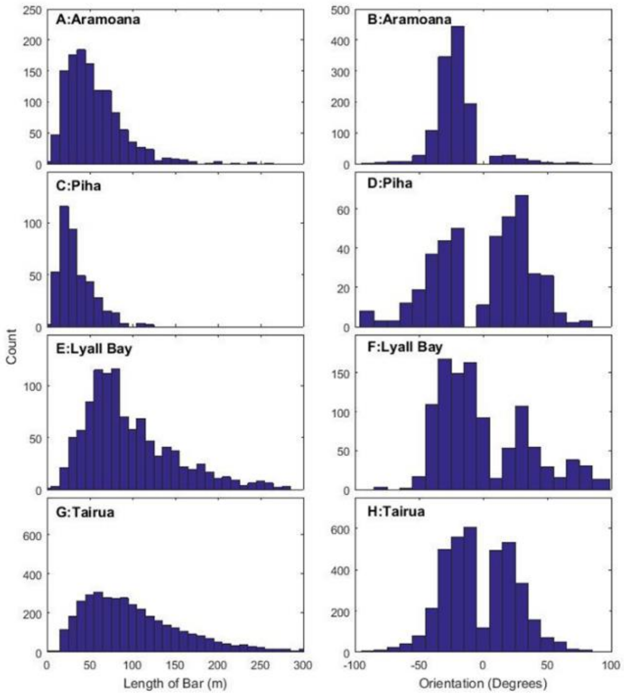

Figure 7. Panels A, C, E and G: Frequency of occurrence of the lengths of bar segments at each of the sites. Panels B, D, F and H: Frequency of occurrence of the orientation of bar segments at each of the sites.

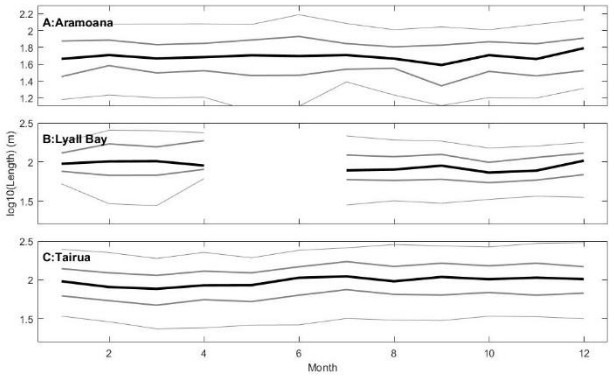

Figure 8. Seasonal variation in the length of bar from the 3 sites with sufficient length of record to cover the majority of seasons. Thick dark grey lines represent the 25th and 75th percentiles, the thick black line is the median and the thin grey lines are the 5th and 95th percentiles. Tairua shows 10 years of data, Lyall Bay shows 10 months of data and Aramoana shows 5 years of data. Note differences in scale.

Our observations clearly showed that bars near headlands are generally much shorter than those in the middle of the beach. This trend was likely associated with changes to the geometry of the rips that occur around headlands. The headland blocks the alongshore current and directs the current seaward into a rip current (*e.g.*, as reviewed in Castelle *et al*., 2016), which would also force the bars to become more perpendicular to the beach, and their lengths to shorten as the surf zone width limits their extent. In addition to headland rips, shadow rips can also form at the end of the beach on the down-wave wide of a rigid boundary such as a headland (Castelle *et al*., 2016; Pattiaratchi *et al*., 2009). When the surf zone width is about the same as the headland length, then these rips become particularly strong and hazardous (Scott *et al*., 2016).

The shape of a headlands plays a role in orienting the bars associated with headland rips and also influences rip current characteristics (Scott *et al*., 2016). Tairua beach has prominent headlands at either end, extending approximately 500 m seaward and oriented at an oblique angle to the beach (positive at north end and negative at south end relative to shore parallel) (Figure 3b). The headland rips follow the headland orientation (Gallop *et al*., 2011) so they are also orientated obliquely in opposing angles at each end of the beach, so that the associated sand bars at each end of the beach also have opposite orientations (Figure 12d). Lyall Bay also has two prominent headlands, where the eastern headland is orientated slightly outward (negative) compared to the southerly wave climate, and the western shore consists of the airport runway which almost perpendicular to the beach (Figure 4b). There is a positive sand bar orientation at the west end, and negative at the east end, which is consistent with the orientation of the headland/barrier at each end. The headlands at Piha are highly asymmetric in that the southern headland is prominent with similar orientation relative the shoreline as Tairua, which affects bar orientation, while in the north Lion Rock is more a break in morphology between South and North Piha beaches and does not appear to orient the sand bar morphology in the same way. The small headland at the north end of Aramoana (only 250 m in extent) means there is not a strong effect of headlands on the bar characteristics at this end of the beach.

The degree of variability of bar characteristics also showed spatial variation alongshore, with the most exposed sections in the middle of the beach experiencing the greatest temporal variability in bar length and orientation. This could be because of differences in the wave climate in the middle of the beach, or it could be because the ends of the beach are simply less variable due to the persistent influence of the headland on the headland rip currents and the nearby sand bar. Lyall Bay is particularly interesting because the western end is much more variable than the eastern end, which may be because of the influence of the airport runway seawall stabilising conditions along that side (which also might be why this region of the beach is known for stable surfing conditions (Atkin *et al*. 2017). Piha also has highly variable bar orientations compared to Tairua and Aramoana (which have very little variability), which may be why it is known for its dangerous and unpredictable rips and swimming conditions.

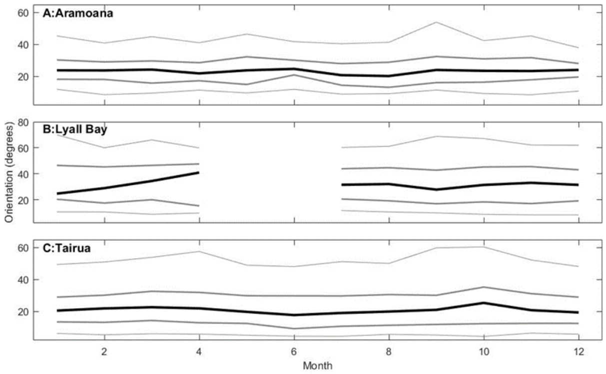

Figure 9. Seasonal variation in the orientation of the bar from the 3 sites with sufficient duration to cover the majority of seasons. Thick dark grey lines represent the 25th and 75th percentiles, the thick black line is the median and the thin grey lines are the 5th and 95th percentiles. Tairua shows 10 years of data, Lyall Bay shows 10 months of data and Aramoana shows 5 years of data. Note differences in scale.

Many of the characteristics of the sand bar morphology that we have identified are consistent with the impressions of surfers that were documented at stakeholder meetings (Atkin *et al*., 2017) at Piha, Aramoana and Lyall Bay and in surfing surveys carried out by Port Otago Ltd (McKenzie, 2015). In general, longer bars will offer longer surfing rides, however, this is a function of the sand bar orientation and the angle of the incident breaking wave. Thus, bars that are longer and that are oriented more obliquely will offer longer rides with greater peel angles, and as long as the incoming breaking waves are from a favourable direction, will make for better surfing conditions (assuming the wave shape is similar).

However, the peel angle and bar orientation are only weakly correlated at Aramoana (Davies-Campbell, 2018), which may be due to the length of datasets needed to characterise the relationship. This could also be because the waves may be affected more by the offshore features such as the ebb tidal delta and the dredge spoil mount, than they are by local features. The orientation of the wave approach angle relative to the orientation of the bar play a critical role in surfing, where the left side of the breaking wave face can peel at a different angle than the right side of the breaking face.

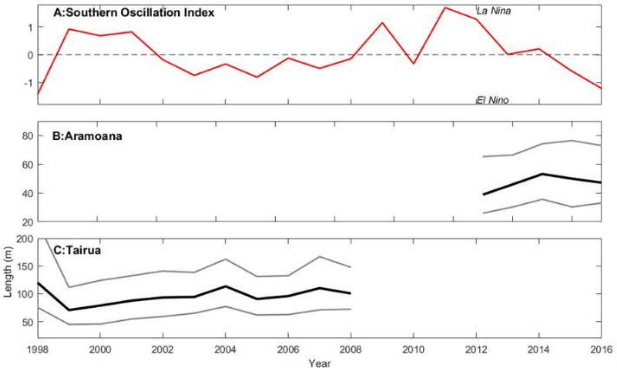

Figure 10. Panel A: The median value of the SOI (Southern Oscillation Index) averaged over the previous year, sourced from the National Oceanographic and Atmospheric Administration (USA) website. Panel B: The median length of sand bars at Aramoana over each year (thick black line). Panel C: The median length of sand bars at Tairua over each year (thick black line). Thin grey lines represent the 25th and 75th percentiles.

This difference in peel angle is critical to surfing because, in general, small peel angles suit more highly-skilled surfers and higher peel angles suit surfers with poorer skills. Thus, in theory, one bar can accommodate many surfing abilities. At Aramoana, bars increased in orientation but decreased in length over autumn and winter compared to spring and summer. Therefore, despite the shorter rides, surfing conditions were better during autumn and winter, because the bars became less parallel to the beach and peel angles should consequently increase. In contrast, despite the potential for longer rides, the decreased bar orientation in spring and summer resulted in more ‘close outs’ of incoming breaking waves because in this case the peel angle would be nearly parallel to the beach. At Aramoana, wave height from southerly swells was greater in autumn and winter, compared to smaller waves from northerlies in summer and spring. With the addition of the preconditioning of the southerly swell waves, which refract around Taiaroa Head, over the Otago Harbour ebb tidal delta, the wave height can be larger at localised points along the wave crests, which initiates the “peaky” breaking waves, for which Aramoana is famous for. These peaks work best at low tide and during offshore winds.

At Tairua Beach, where we have a longer dataset, we were able to show that bars became longer during the winter storm season. Orientation also decreased during the winter months, suggesting a reduction in peel angle in winter which make the conditions too fast to ride (except for the best surfers). Interestingly, the orientations increased in spring and autumn at Tairua beach, which may be an indication that the bar configurations are reorganising as they transition from the summer beach state to the winter beach state. Presumably, this increase in orientation is an indication that surfing conditions at Tairua are best in spring and autumn.

Our results show that surfing conditions are likely to be most stable near prominent headlands, and so more favourable to surfers. Although the bars are shorter, and the length of ride likely also shorter, the orientations are higher, indicating that the waves are more easily surfed. This observation is consistent with impressions provided at stakeholder meetings with surfers held as part of our project on developing guidelines for managing surf breaks (see Atkin *et al*., 2017 for more information). The most valued surfing location at Piha as documented in Atkin *et al*. (2017) is along the headland near Taimoto Island, where the headland and island geometry influence the morphology. At Lyall Bay, the morphology at the east end of the beach, where the runway intersects with the beach, provides stable and consistent surfing conditions.

This study has highlighted that long monitoring datasets are critical to being able to detect anthropogenic change on beaches because the natural variability between years in inherently large. Only substantial modifications to the beach, such as groins, causeways or seawalls, would cause easily detectable changes to the surfing conditions. There is an urgent need to install monitoring stations to provide the necessary long-term information needed prior to consent for more diffuse impacts to surfing, such as changes to the sediment supply and offshore wave conditions.

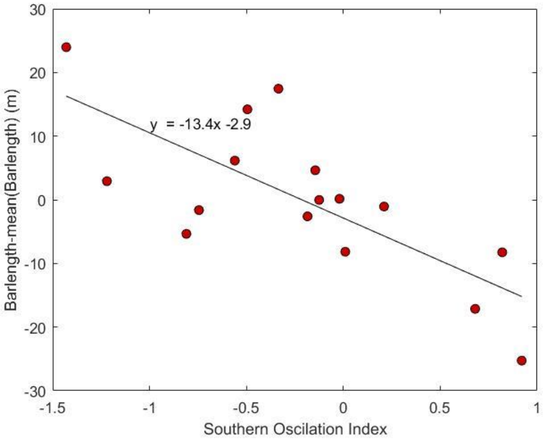

Figure 11. Correlation of the length of the bar against the SOI. Data for Tairua and Aramoana are shown, with the mean value of each beach subtracted prior to analysis.

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