Characterising beach intertidal bar systems using multi-annual LiDAR data

Characterising beach intertidal bar systems using multi-annual LiDAR data

Abstract

Intertidal bars are common in meso-macrotidal low-to-moderate energy coastal environments and an understanding of their morphodynamics is important from the perspective of both coastal scientists and managers. However, previous studies have typically been limited by considering bar systems two-dimensionally, or with very limited alongshore resolution. This paper presents the first multi-annual study of intertidal alongshore bars and troughs in a macro-tidal environment using airborne LiDAR data to extract three-dimensional bar morphology at high resolution.

Bar and trough positions are mapped along a 17.5 km stretch of coastline in the northwest of England on the eastern Irish Sea, using eight complete, and one partial, LiDAR surveys spanning 17 years. Typically, 3 – 4 bars are present, with significant obliquity identified in their orientation. This orientation mirrors the alignment of waves from the dominant south-westerly direction of wave approach, undergoing refraction as they approach the shoreline. Bars also become narrower and steeper as they migrate onshore, in a pattern reminiscent of wave shoaling. This suggests that the configuration of the bars is being influenced by overlying wave activity. Net onshore migration is present for the entire coastline, though rates vary alongshore, and periods of offshore migration may occur locally, with greatest variability between northern and southern regions of the coastline.

This work highlights the need to consider intertidal bar systems as three-dimensional, particularly on coastlines with complex configurations and bathymetry,

as localised studies of bar migration can overlook three-dimensional behaviour. Furthermore, the wider potential of LiDAR data in enabling high-resolution morphodynamic studies is clear, both within the coastal domain and beyond.

Key words: beach, intertidal bars, macrotidal, remote sensing, LiDAR, EOF analysis

Introduction

Intertidal bars are a defining morphological feature of many meso-macrotidal, low-to-moderate energy coastal environments (van Houwelingen et al., 2008; Anthony et al., 2007), where they fulfil an important role as sediment stores (Reichmüth & Anthony, 2007). While their formation and evolution have been studied for many years, following the pioneering work of King and Williams (1949), our understanding remains limited. Improved understanding of the development of intertidal bar systems will be beneficial to coastal managers, for whom the evolution of bars is a key factor in controlling beach levels as well as an influence on sediment transport within the intertidal zone.

A range of different intertidal bar system are found dependent upon beach characteristics and hydrodynamic conditions. Some beaches may exhibit a single bar whilst others may exhibit multiple bars; the maximum number of bars on a beach varies depending upon tidal range, wave activity and beach gradient (Masselink et al., 2006). Masselink et al. (2006) propose three main categories of intertidal bars depending primarily upon wave conditions, tidal range and nearshore gradient. One of these categories, which best represent the morphology considered in this paper, is low amplitude ridges. These are shore parallel bars, typically occurring in groups of 2-6 and intersected by shore-parallel drainage channels. They form on low gradient beaches with low to moderate wave energy and a meso- to macrotidal regime.

Generally, the number of bars present will increase as beach gradient and/or wave activity decreases. Vertical, cross-shore and longshore scales of bar dimensions are of order 0.5, 20 and 100 m respectively (Masselink et al., 2006), although considerable variation may be observed.

The most important processes acting on bars are those resulting from the dissipation of wave energy (Masselink et al., 2006), which results in bar crests being a focus for sediment transport (Cartier and Hequette, 2013). Incident waves undergo transformation processes including shoaling, breaking, reflection and refraction (Wijnberg and Kroon, 2002) all of which will determine the resultant sediment transport and thus the influence on beach morphology. While wave processes are critical to bar development, intertidal bars will experience significant modulation in the importance of different wave processes throughout the tidal cycle (Masselink et al., 2006). These can be considered in relation to the relative tidal range (RTR), which is the ratio between tidal range and significant wave height. A larger RTR, indicting a large tidal range and small waves, results in shorter residence time for swash and surf zone processes and an increased importance of wave shoaling, leading to greater variation in the direction of sediment transport. This generally leads to onshore migration of bars during low energy conditions, with flattening and offshore migration of bars during high energy conditions (Kroon & Masselink, 2002). However, other factors may influence the effect a particular wave condition will have on bar development, including wave angle and water depth at the bar crest (Walstra et al., 2012). Consequently, a wave of a particular height and period may drive either onshore or offshore bar movement and bar growth or decay, depending upon the combination of water depth and wave angle. In some locations, it has been noted that bar migration may occur consistently in one direction under a wide variety of prevailing conditions (Jackson et al., 2016). Alongshore sediment transport can also be significant in these systems, particularly within troughs due to longshore currents over the tidal cycle (Masselink et al., 2006). A number of studies have suggested that changes in bar systems are predominantly two dimensional, occurring in the form of a cross-shore redistribution of sediment (Houser and Greenwood, 2007; Masselink et al., 2008). However, few studies undertaken to date possess the spatial or temporal extent to enable identification of long-term changes in three-dimensional bar morphology (Grunnet and Hoekstra, 2004).

Longer term 3D bar evolution is challenging to study in detail due to the logistical difficulties inherent in obtaining high resolution measurements over large temporal and spatial scales (annual to decadal and 10s kilometers respectively). Beach profile surveys (e.g. Masselink & Anthony, 2001) are typically carried out several times a year and allow changes in beach volume and morphology to be calculated (Smith and Zarillo, 1990). However, profiles can only be taken at limited locations due to time and cost restrictions. Profile spacing for long term monitoring is typically of order 500 m – 1 km (Masselink and Anthony, 2001), which is sufficient to detect large scale trends in the evolution of coastal morphology but not to detect the detailed three-dimensional evolution of morphological features such as bars, and potentially misses important local changes. To the authors' knowledge, very few studies have addressed longshore bar variability, an exception being Reichmüth & Anthony (2008), who also examined low-amplitude ridges on a macrotidal beach using a number of beach profiles over a period of c. 1 year. Grunnet & Hoekstra (2004) use a rare set of beach profile surveys with a large spatial (12 km at 200 m intervals) and temporal (28 years at annual intervals) extent to examine bar variability, but the study covers nearshore rather than intertidal bars.

Airborne LiDAR offers a solution to the problem of spatial extent and resolution, by providing rapid coverage of large areas of coastline at horizontal resolutions of up to 25 cm and vertical accuracies of order 15 cm (Sallenger et al., 2003), and modern systems improve on this further with horizontal and vertical accuracies of order 10 cm (Andersen et al., 2017). As a result, LiDAR is increasingly being used as a tool for monitoring coastal change around the world. One of the main limiting factors is the cost, which is usually in the order of tens of thousands of pounds for a stretch of coastline. However, the cost of surveys continues to fall and some regions are already covered by a substantial time series of LiDAR surveys, although it is still accepted that LiDAR datasets must be supplemented with additional data in order to effectively study shorter term processes (Priestas and Fagherazzi, 2010). From 2016, the U.K.'s Open Government Initiative resulted in extensive catalogues of LiDAR data being made freely available for large parts of England and Wales, providing coverage of many coastal regions (Matthew, 2015).

A single LiDAR survey can provide valuable three-dimensional information on coastal morphology which cannot easily be determined using traditional survey methods. Saye et al. (2005) used LiDAR to calculate beach parameters including height of the most seaward frontal dune ridge, frontal dune volume, beach volume, beach width and average beach slope. They estimated that with the 15 cm vertical accuracy of the LiDAR data, the error in the calculated parameters would range from ~1% to 6% depending upon beach 'thickness' (its height relative to the survey datum). A number of more recent studies have extracted beach parameters from LiDAR data including dune toe and crest positions (Houser et al., 2008, Pye and Blott, 2016, Stockdon et al., 2009) and shorelines (Houser et al., 2008, Liu et al., 2007, Robertson et al., 2004). As with Saye et al (2005), Stockdon et al. (2009)

extracted profiles from the LiDAR digital elevation model (DEM) which in turn were used to calculate relevant beach parameters, in this case dune crest location. This technique allows for analysis usually applied to traditional beach profiles to be applied to LiDAR data, while benefitting from the greatly improved resolution that LiDAR provides. Houser & Mathew (2011) fully exploited this, extracting 2000 profiles from a single LiDAR survey, which covered 40 km of shoreline at 20 m intervals. Such results could not feasibly be achieved using traditional ground-based survey techniques.

While the application of LiDAR data has tended to focus on the analysis of dune systems or whole intertidal beach volumes, the resolutions and vertical accuracy also allows for analysis of smaller scale features such as sandbars. A few studies have exploited this to date; van Houwelingen et al. (2006) utilised a single LiDAR survey in order to analyse intertidal bars in North Lincolnshire, UK, whilst Levoy et. al (2013) utilised 2.5 years of LiDAR data in their study of transverse bars and concluded that tidal currents alone were sufficient to drive bar migration in the absence of waves. LiDAR data are well suited to the study of intertidal bars due to their high level of accuracy in x, y and z dimensions and the presence of a growing archive of coastal LiDAR data available for analysis. Long term monitoring of bar systems is necessary because long term nonlinearities in bar evolution can make bar behaviour hard to predict (Pape, 2010).

This paper provides the first study of intertidal bars using high-resolution airborne LiDAR surveys, allowing for a detailed consideration of three-dimensional bar morphology and its evolution over time. The questions that this paper aims to answer are:

- How does the bar system vary cross-shore and alongshore?
- How does the bar system evolve in time?

These will be answered through detailed analysis of LIDAR data in terms of the degree of spatial and temporal variability of the geomorphic bar parameters. Eigen function (EOF) analysis will be applied to extract common spatial bar behaviour along the large stretch of coast and determine the degree of variability. The focus of this study will be the Fylde coast, U.K., an area for which multiple LIDAR datasets are available, and in which the bars have been subject to previous study using traditional methods (King and William, 1949; Masselink and Anthony, 2001 and de Alegria Arzaburu et al. 2007).

Study Area

The Fylde coast is located in the northwest of England fronting on to the Irish Sea basin. The study area covers the entire western facing section of the coastline extending over 17.5 km (Figure 1). The southern 1.6 km of the study area is backed by a natural dune system (Figure 1, South Region). North of this, the area is fronted by sea walls (Figure 1, Central Region), with groyne fields located in the northern 6 km (Figure 1, North Region). These defences are primarily to provide flood protection to the low-lying hinterland, in particular for the adjacent resort towns of Cleveleys and Blackpool, where properties are less than 10 m above Ordnance Datum (AOD) (Figure 1). The structures also help to maintain beach levels, which are a significant asset to the tourist industry in the region. The structures vary significantly in age, construction and state of repair, with the earliest defences dating back to the 1920s through to a new scheme to the north of Cleveleys, which would have been under construction during the 2016 LiDAR survey, the most recent included in this paper. Many of the groynes are in a poor state of repair, limiting their effectiveness, although several recent rock groynes form effective barriers to longshore sediment transport.

Figure 1 TOP

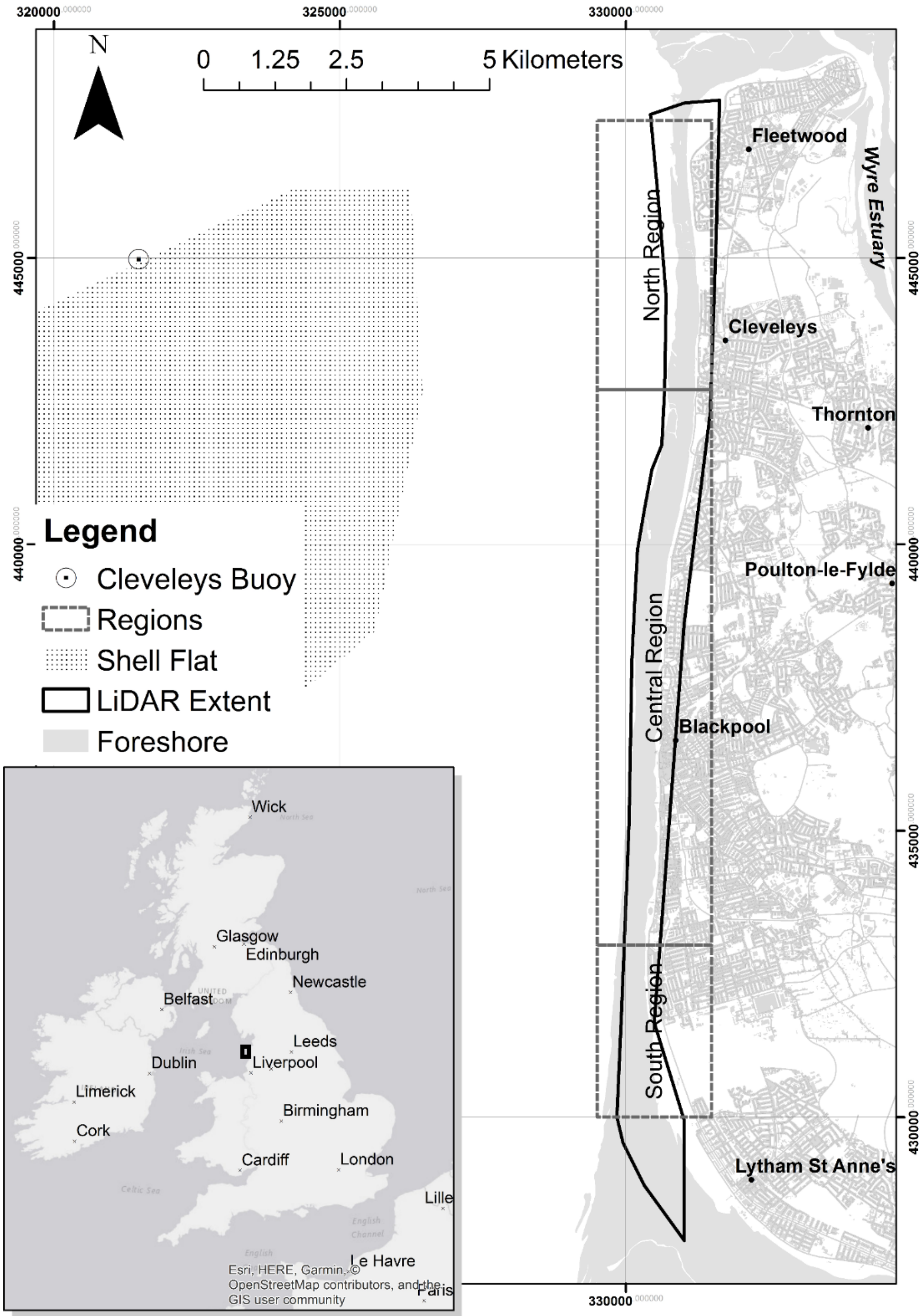

Figure 1 Study area location map showing locations of interest

The coastline experiences a macrotidal regime, with a mean spring tidal range of 8.0 m and a storm surge of over 1.0 m. It is fetch limited from all directions due to the sheltering influence of Ireland to the west, the Isle of Anglesey on the Welsh coastline to the south and the Isle of Man to the northwest, resulting in a maximum fetch of approximately 375 km from the southwest. Based on data collected by a Datawell Directional WaveRider Mk III buoy located offshore of the study site (Figure 1) and provided by the Channel Coast Observatory, the mean wave height was 0.6 – 1.5 m, wave period was 4 – 6 s and direction was 218 – 255º, during the period of June 2011 – April 2016, although the wave direction in particular demonstrates a great deal of variability. The beach is characterised by a multiple intertidal bar system, usually consisting of 2 – 3 bars, and is one of the archetypal ridge and runnel beaches as classified by King & Williams (1949). These will be referred to as bars or inter-tidal bars throughout the study. The beach is largely sandy but a shingle upper beach is also present along some sections (Pye et al., 2010).

Methods

This study is based on a time-series of 9 LiDAR datasets available for the Fylde coast, spanning 17 years from 1999 to 2016 (Table 1). It is important to note that there is substantial variability in the temporal spacing between surveys, varying from 3 months up to 9 years and 10 months. The LiDAR datasets were provided as post-processed and quality checked gridded digital elevation models (DEMs), at resolutions ranging from 0.25 m to 2.00 m by the Environment Agency’s Geomatics Group in partnership with the Cell 11 Regional Monitoring Strategy (CERMS).

Table 1 Dates and resolutions of LiDAR survey data

Name	Year	Month	Resolution (m)
1999	1999	March	2
2008	2008	December	1
2009	2009	March	0.25
2010	2010	January	1
2011	2011	March	2
2013a	2013	January	2
2013b	2013	November	1
2014	2014	February	2
2016	2016	April	1

Bar Extraction Techniques

The spatial density of LiDAR data allows for analysis of longshore variability of bar parameters and three-dimensional changes that have occurred between surveys. In order to automate the identification of bar locations, a series of profiles were extracted from the LiDAR dataset at a cross-shore and longshore resolution of 2 m. The crest positions of bars were extracted from the profiles using an algorithm written in the R programming language to determine peaks and troughs in the profile, based on the change in slope from positive to negative[1].

In order to effectively visualise the data and assess data quality, the resultant crest and trough locations were imported in to GIS software (ESRI ArcGIS 10.2) where they were overlaid on the original LiDAR elevation data (Figure 2b). Erroneous bar crest points, which occur due to the presence of manmade structures, gaps in the dataset or the presence water in the survey extent, were manually removed. A

[1] R code available at https://gist.github.com/dgromer/ea5929435b8b8c728193

numbering system was then applied to points in both crests and troughs in order to designate the bar structure to which they belonged; the first crest was considered to be offshore of the first trough; a schematic of the numbering system for bar crests is shown in Figure 2a. Bars were considered to be continuous even when bisected by drainage channels if they continued to occupy a similar cross-shore position either side of the break.

Finally, the positional attributes (location and elevation) of adjacent bar crests and troughs were used to calculate a wider range of bar parameters including bar width, bar slope and bar volume (Figure 3). These could then be used to determine longshore and cross-shore variability in the bar system, as well as temporal variability throughout the study period when compared between surveys.

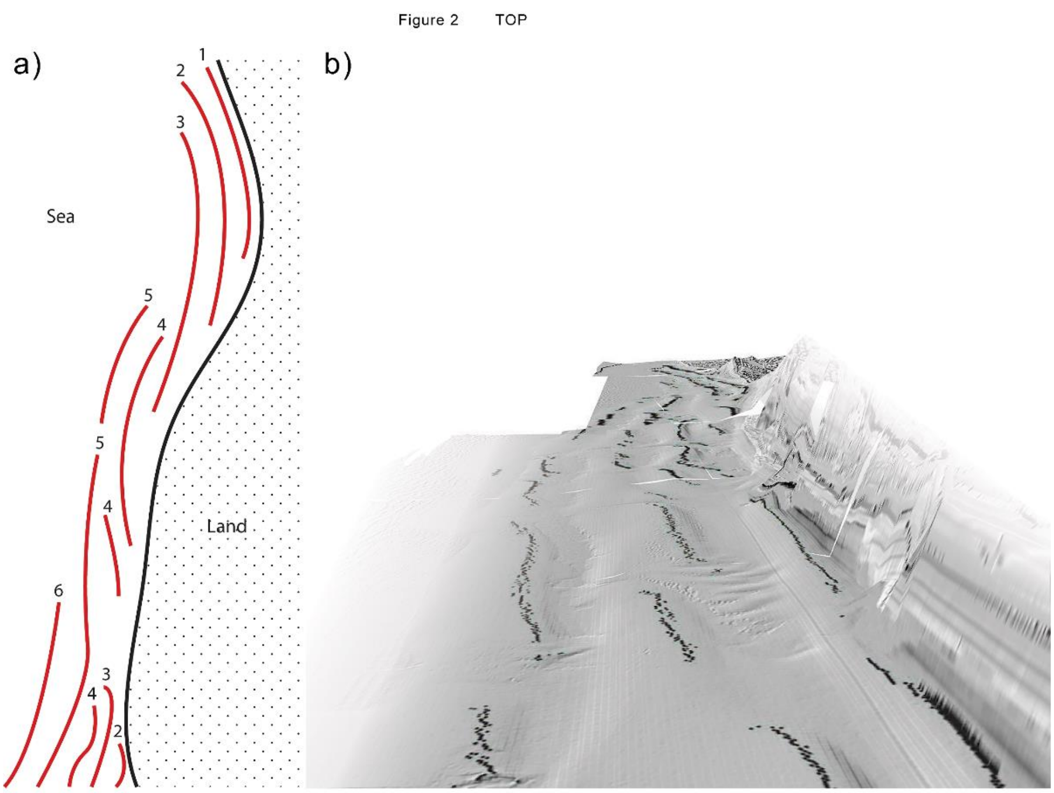

Figure 2 a) Schematic of the bar crest and trough numbering system used along the Fylde coast. This numbering system is used as reference to bar position (e.g. inner, middle, outer bar) and may result in a bar being given different designations at different points along the coast b) a 3D representation of actual bar crests extracted from the airborne LiDAR data

Figure 3 TOP

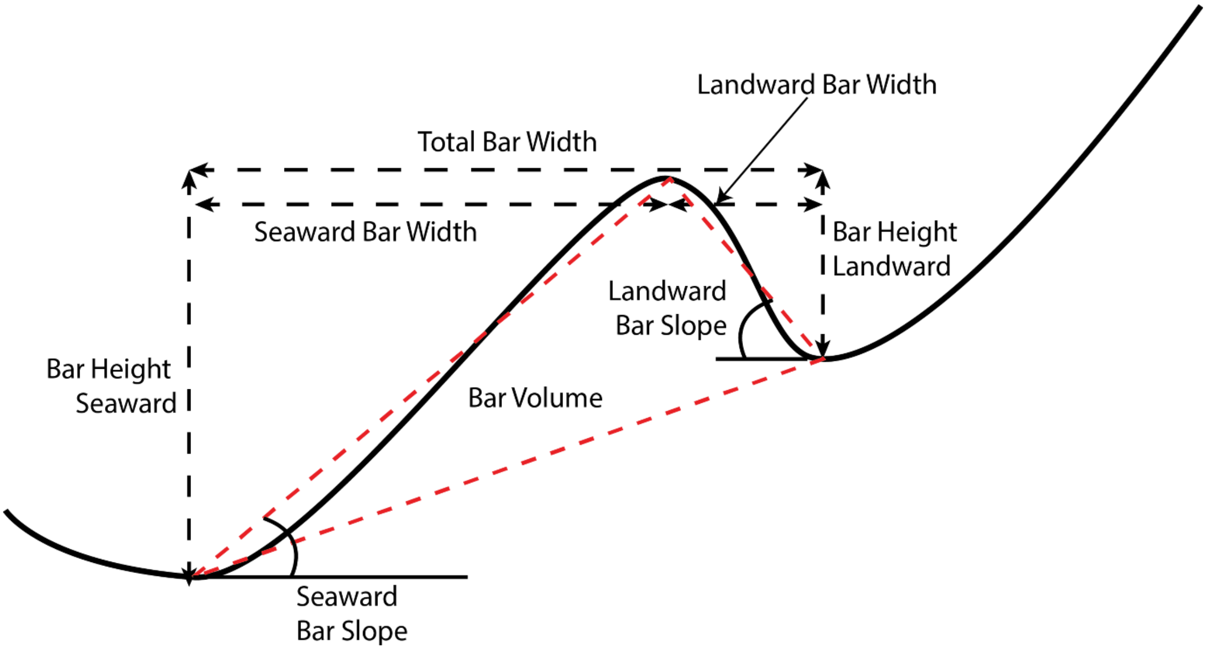

Figure 3 Bar parameters calculated using bar crest and trough positions. Heights and widths are measured in metres (m), bar volume in m3/m, slopes are calculated as a ratio.

EOF Analysis

EOF analysis has been used by a number of authors to examine the spatial and temporal evolution of beach morphology (Miller and Dean, 2007, Pruszak, 1993). The datasets used have largely been generated from widely spaced beach profiles, rather than the high-resolution dataset used in the current study, however the principles remain the same. Partially due to this low spatial resolution, many previous studies have also focused on analysis of temporal rather than spatial variability, although some have also attempted to consider the spatial component (Dick and Dalrymple, 1985, Miller and Dean, 2007). EOF analysis aims to concisely summarise complex datasets into a number of numerical functions (eigenfunctions), with each function describing a component of the variability within the dataset. Typically the first three eigenfunctions explain in the order of 90% of the total variability. As EOFs have a statistical rather than physical basis, coupling the results to physical descriptions of the coastline can be challenging (Kroon et al., 2008). However, previous studies have identified that when analysing beach topography, these first three functions typically relate well to particular physical attributes of the beach. The first function identifies the mean beach profile, the second is a ‘rotation factor’ that relates to variation in the mean profile alongshore and the third represents significant morphological features present on top of the mean profile (Larson et al., 2003; Miller & Dean, 2007). In the case of a barred beach, this will be the bars themselves and will therefore be of greatest interest within the current study.

EOF analysis requires a rectangular matrix of data on which to operate, so the coastline data were transformed by converting geographic eastings to chainage, beginning from the toe of the seawall or dune system as appropriate (Dick and Dalrymple, 1985). Analysis was limited to the upper 250 m of the beach because, due to variability in beach slope, and therefore width, any greater extent would result in areas of no data being present within some of the LiDAR datasets. This upper 250 m region typically includes the innermost two bars at any given section of coastline.

Results

Bar Crest Parameters

Examination of the bar crest positions extracted from airborne LiDAR (Figure 4) provide a number if insights regarding large scale bar configuration. The first is that, although intersected by frequent drainage channels, the bars themselves can be considered continuous over large distances, in some cases extending well over 10 km. The bars emerge in the intertidal region first around a northing of 434000, towards the south of Blackpool (Figure 4). However, their alignment with the coastline is not shore parallel, with obliquity of the bars both north and south of this location.

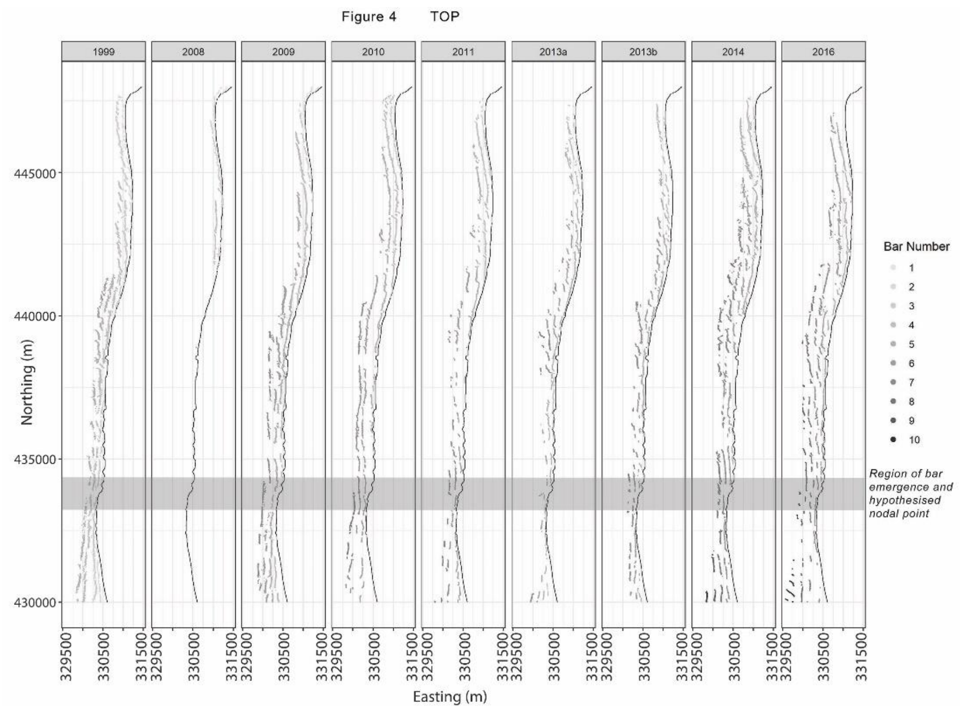

Figure 4 Bar crest positions extracted from airborne LiDAR data

Bar migration can be seen to be generally onshore over time, with bars emerging from offshore and ultimately dissipating as they merge with the upper beach. Some periods of offshore bar migration are also observed, particularly in the southern region of the coastline between 2011 – 2013a and 2014 - 2016. Due to the obliquity noted previously, a bar will occupy different cross-shore positions at different locations alongshore. As a result, a particular bar may occupy the most onshore position and be in the process of merging with the upper beach at the end located closest to the nodal point. Meanwhile, the end most distant from the nodal point could be located several hundred meters from the upper beach, and with two other bars located onshore of it. These variations in position will also correlate with the morphology of the bar, including width and steepness, which will be addressed in subsequent sections.

Analysis of the coastline was split into three regions, north, central and south (Figure 1) in order to investigate the variability of bars alongshore. Figure 5 presents bar widths across time and region for each bar. The most obvious pattern is that the bars located closer to land in each region tend to be the narrowest, suggesting they become progressively narrower as they migrate onshore. There is some indication within the central region that bars occupying central positions on the beach are widest, with narrower bars both onshore and offshore of this position – this is particularly apparent in 2010, 2011 and 2013a (Figure 5). The wider bars also demonstrate greatest variability in bar width, whether located offshore or more centrally on the beach, with mean bar width reaching in excess of 250 m and a range of almost 150 m between the upper and lower quartiles. Inner bars often approach 100 m in width, with negligible variability.

Figure 5 TOP

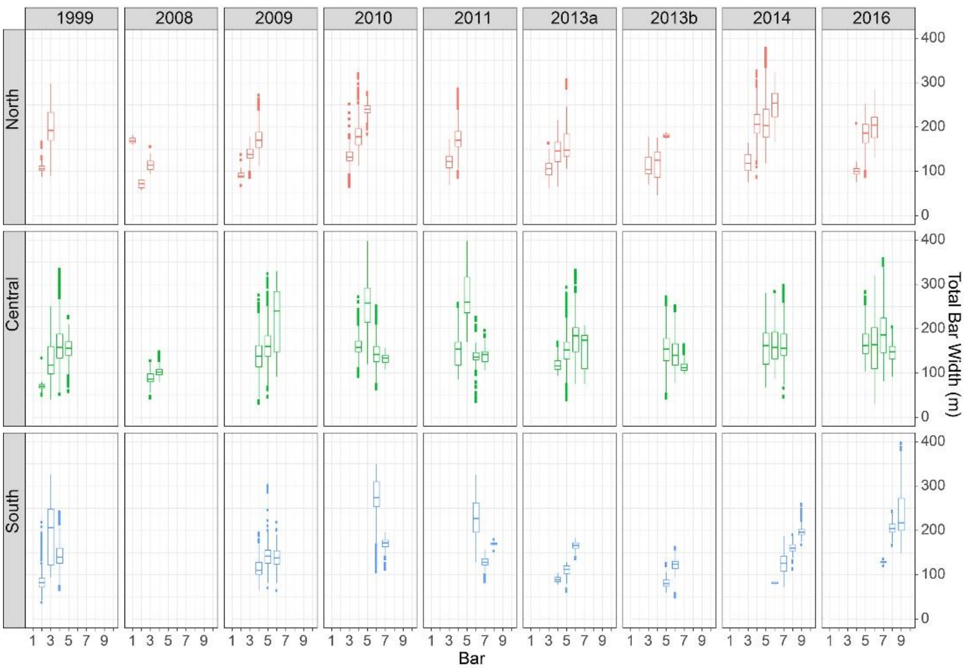

Figure 5 Bar and whisker plot of bar width

Concurrent with this narrowing of the bars is also a steepening as they migrate onshore (Figure 6). As well as being generally steeper, the more onshore located bars also show greater variability in the steepness. There are a few instances when this is not the case and the innermost bar shows extremely low variability, sometimes coupled with a drop in steepness; for example, the northern region in 2009 or the southern region in 2013a and 2014. However, this corresponds to times when only a very small section of bar remains as it merges with the upper beach, therefore reducing the opportunity for variability. Mean slope of the seaward bar face varies between ~0.03 for steep inner bars to ~0.01 for the shallower outer bars.

The most variable parameter was found to be bar volume (Figure 7), a function of both the width and height of the bar (Figure 3). It is important to note that this pertains to the volume per meter length of the bar, rather than the volume of the bar as a whole. It is therefore independent of the length of the bar, which would otherwise be the most significant factor in determining volume.

Figure 6 TOP

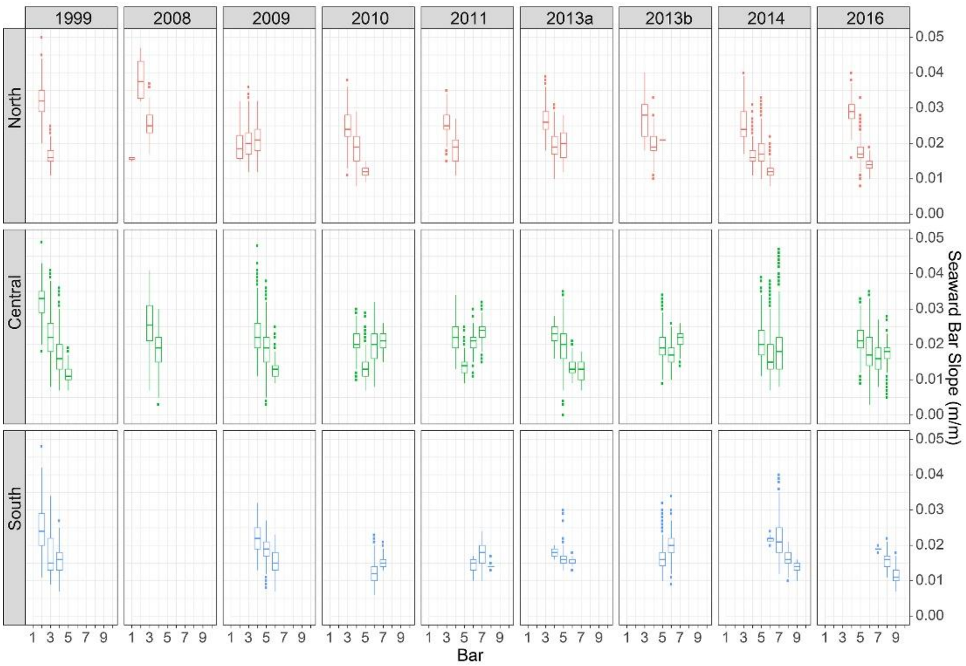

Figure 6 Bar and whisker plot of the slope of the seaward bar face

Figure 7 TOP

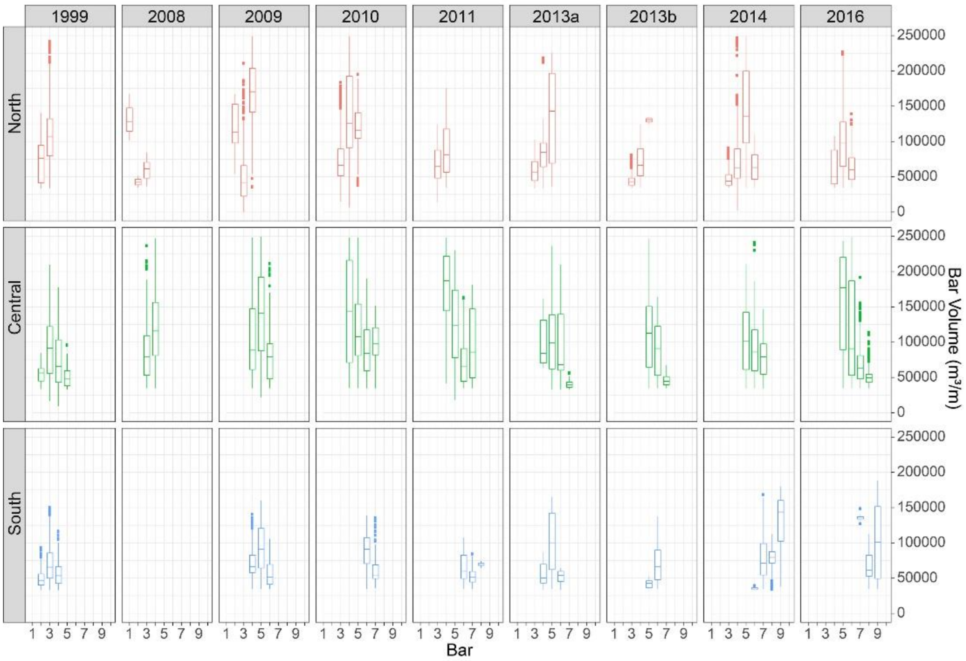

Figure 7 Bar and whisker plot showing bar volumes broken down by year and region (refer to Figure 1 for region extents).

EOF Analysis

The results of EOF analysis follow the pattern identified by previous authors, with the first three eigenfunctions representing mean profile, rotation factor and mean shape and location of bars respectively. Here, we focus on bar shape and location (the third eigenfunction, Fig 8). Typically, two bars are located within the upper 250 m of the beach; the exceptions are 1999 and 2016, which both see the innermost bar located at around 100 m chainage, and the crest of the second bar falling outside of the 250 m region analysed.

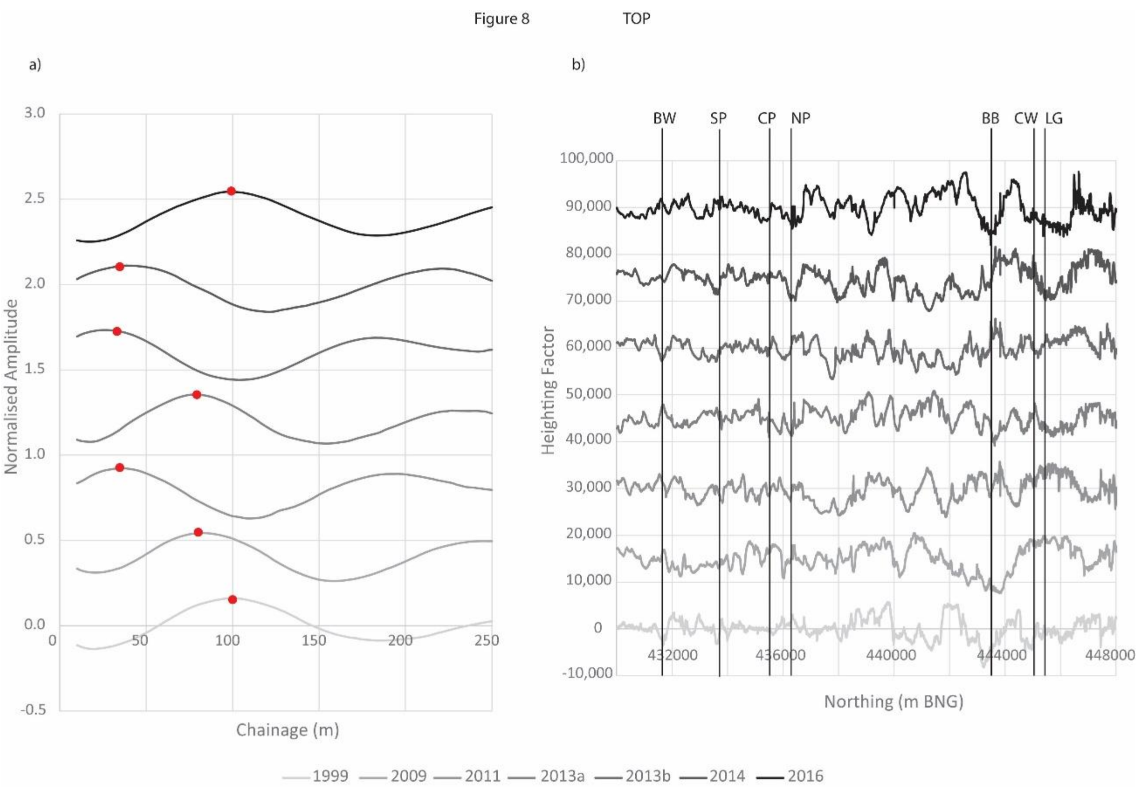

Figure 8 a) Results of the third eigenfunction, representing intertidal bars, offset vertically for 10-250 m chainage along the entire coastline. Points on lines indicate possible preferential bar locations. b) Vertically offset longshore coefficients for the third eigenfunction. BW = start of Blackpool seawall, SP = South pier location CP = Central Pier location, NP = North Pier location, BB = Blackpool and Cleveleys borough boundary CW = end of Cleveleys sea wall LG = location of extended groyne

The third eigenfunction indicates that the inner bar may position itself around one of several preferential cross-shore locations, with clusters at around 100 m (1999 and 2016), 80 m (2009, 2013a) and 35 m (2011, 2013b, 2014) (Figure 8a). Clustering is less obvious for the second bar crest, which are distributed between 175 m chainage out beyond 250 m. Narrowing and steepening of bars positioned further onshore, previously identified from analysis of the bar parameters, is clearly highlighted by the third eigenfunction, with the inner bar visibly steeper and narrower than the second bar in all cases. Analysis of beach profile data demonstrates that areas in which the coefficient of the eigenfunction is most variable also demonstrate the greatest variability in beach profile envelope, further supporting the hypothesis that the third EOF represents the bars.

The coefficient of the eigenfunction provides an indication of its variation alongshore. The coefficient for the third eigenfunction is typically quite complex and is shown in Figure 8b. This highlights the alongshore variability of the bars themselves. The largest variations at scales of 1000s of meters are observed in the northern part of the beach and are more pronounced in 2009, 2014 and 2016. Small scale variations at scales of 100s and smaller are also observed, demonstrating high variability from year to year and are related to the location of groynes and drainage channels.

Discussion

Bar configuration

Bars are generally obliquely oriented towards the shoreline, which is evident from all LIDAR surveys. The idea that bar obliquity to the shoreline influences the observed pattern of evolution has been identified as far back as King (1972), although the bars in the Fylde Coast region have typically been treated as shore-parallel. In fact, when the Fylde coast is considered in its entirety, bars appear to approach the shoreline first towards the south of the region, at a northing of around 434000 (Figure 1), and then extend obliquely from the shoreline in both directions away from this point. This behaviour is consistent with previous studies in the region which have identified the existence of a nodal point in longshore sediment transport somewhere in this vicinity (Halcrow, 2010). The obliquity in the bar system away from this point is enhanced by the embayed shape of the coastline, which would require rotation of the bar system to achieve a shore-parallel alignment. Bar obliquity is highlighted further when bar positions are visualised as a function of chainage, rather than geographical location

(Figure 9). From this perspective the more offshore bars demonstrate greater obliquity, while more onshore bars have closer alignment with the coast, although they never fully reach shore-parallel. It is hypothesized that this alignment mirrors the alignment of waves from the dominant south-westerly direction of wave approach, undergoing refraction as they approach the shoreline.

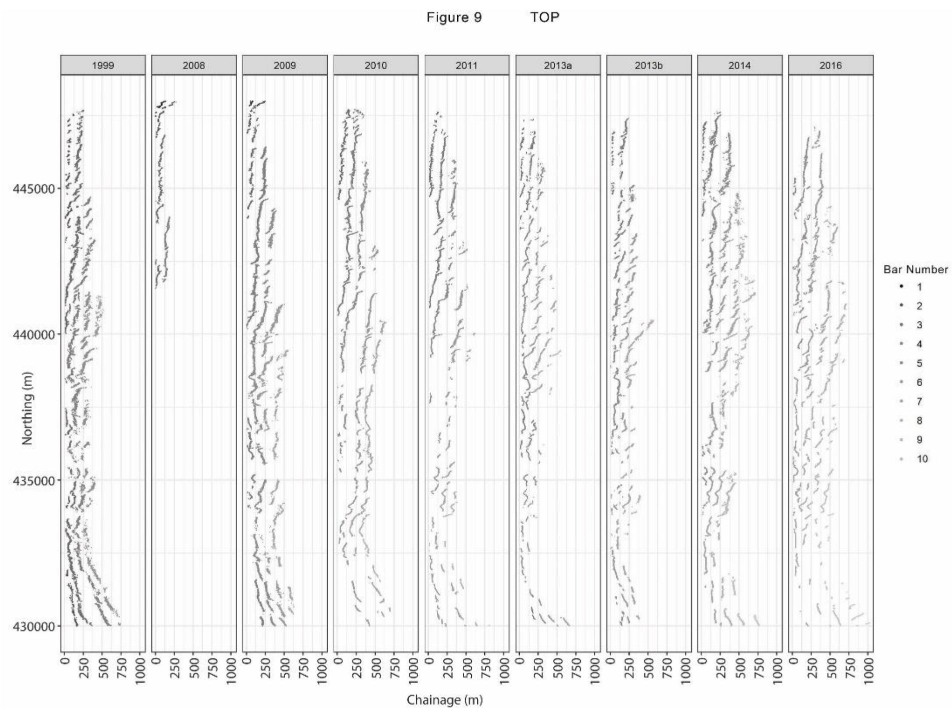

Figure 9 Plot of bar positions as a function of chainage. The obliquity of the bars becomes more apparent when the shape of coastline is removed, as does the greater alignment of innermost bars compared to those located further offshore.

While the obliquity of the bars away from the nodal point could be interpreted as longshore translation of the bars as they migrate onshore, this overlooks the influence that the bars themselves will have on longshore sediment transport both through the influence on wave breaking and through flows in and out of the runnels during flood and ebb tides, a feature of intertidal bar system previously highlighted by Sedrati and Anthony (2007).

The number of bars observed is dependent upon the tidal level during LiDAR data collection, but typically 3-4 bars are identified at any given location along the coastline. The exception is the southernmost area in which no seawall is present, resulting in a wider, shallower beach and significantly increasing the number of bars observed to as many as seven. In a natural setting, it is expected that the number of bars would similarly increase along the entirety of the coastline; in contrast, within defended regions, spring high tide reaches above the base on the seawall, indicating that the width of the beach is being artificially limited and the bar system is therefore curtailed by its presence. Beach width does not appear to be limited by defenses at the northern end of the coastline, where beach slope is steepest and fewer bars are apparent; only two intertidal bars are ever present, as compared to 3-4 further south. It is possible that sub-tidal bars are also present which cannot be observed in the LiDAR data.

Bar Location

Bar migration is seen to be typically onshore for all bars and regions of this coastline. This is in agreement with analysis of the past beach profiles collected at Cleveleys between 1991-2006 (de Alegria Arzaburu et al. 2007). The bars located furthest offshore are most dynamic, with migration rates reaching over 100 m per year in some instances (Figure 10). Bars located closest to shore have slower migration rates of the order of 10 m per year, likely to be due to the innermost bars having reduced exposure to wave activity, being submerged only during high tide conditions.

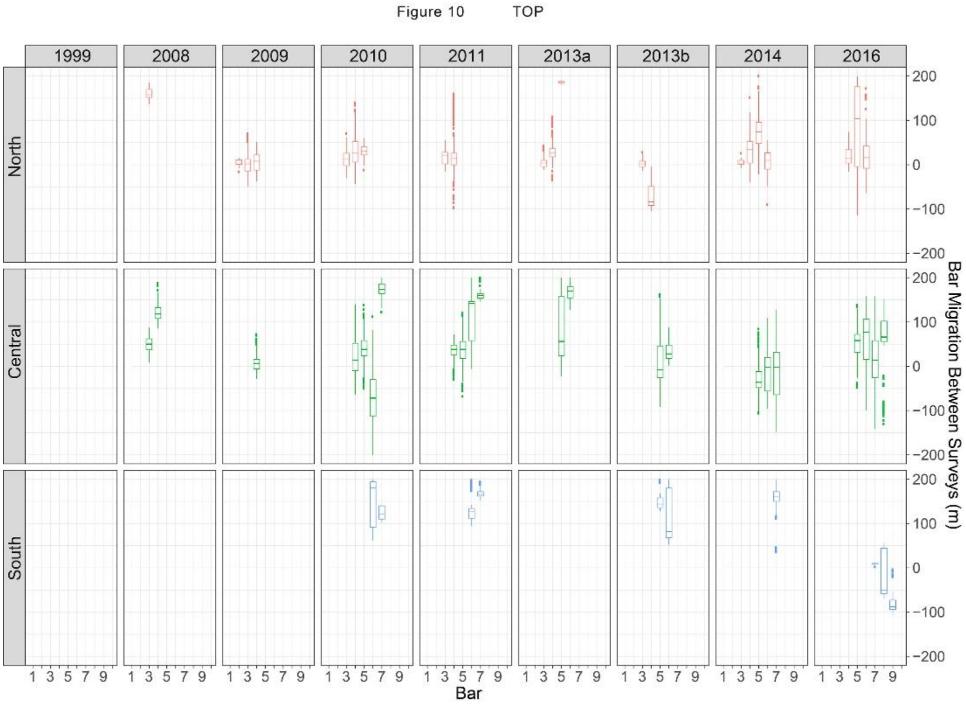

Figure 10 Bar and whisker plot of bar migration between surveys broken down by year and region (refer to Figure 1 for region extents). Positive values indicate onshore migration and negative offshore.

While onshore bar migration is dominant, periods of offshore movement are also detectable. Intertidal bars have previously been shown to migrate offshore under more energetic conditions (Mariño-Tapia et al., 2007) and, therefore, movement between consecutive surveys may depend upon antecedent conditions. However, more frequent surveys would be required to investigate this effectively.

The net onshore migration has important implications for the sediment supply in this region, because it suggests that an offshore sediment source is providing the material for bar formation. Results also suggest that the cross-shore migration rate of the bar may vary alongshore, likely in response to variation in shoreline angle relative to wave direction. This will, in effect, lead to a rotation of the bar system and could also be a function of seasonal variability in wave height and direction.

It has previously been suggested that bars on Blackpool beach occupy a number of preferential positions across the profile (Masselink & Anthony, 2001), linked to the residence times of wave driven processes at particular tidal elevations. However, analysis of bar crest elevations in the present study indicates that they are distributed evenly throughout the intertidal area. EOF analysis did suggest that the innermost bar may occupy one of a number of cross-shore positions at a given time based upon chainage. However, the obliquity of the bars and significant longshore variability means that any preferential positions are likely to be highly localised. It is possible that the same may be true for bar crest elevations, and that binning of the data into finer longshore sections would result in preferential bar positions emerging at a local scale. However, on the scale of the whole Fylde coast there is no evidence for this, and bars appear to progress steadily onshore.

Bar Parameters

One of the most significant observations from the calculation of bar parameters is the narrowing and steepening which occurs as bars move onshore, reminiscent of wave shoaling. The relative duration of the wave processes each bar is exposed to are likely to be key to this evolution, varying over the course of the spring-neap tidal cycle (Masselink et al., 2006). Analysis of several profiles from the Fylde Coast was carried out to determine the residence times of wave shoaling, breaking and swash processes during spring and neap tidal conditions. During spring tidal conditions, wave processes migrate most rapidly across the profile and, under typical low energy conditions, wave shoaling will dominate across all bars, resulting in onshore sediment transport. Under storm conditions, wave breaking will play a more significant role over the inner two bars. During neap tidal conditions the duration of wave processes over the bars will increase. Under low energy wave conditions, the inner bar will be dominated by swash processes, resulting in onshore sediment transport and providing a possible mechanism for bar steepening. Subsequent bars will experience a combination of shoaling and breaking and may undergo very little morphological change. Under energetic wave conditions all bars except the innermost will be dominated by offshore directed sediment transport. In summary, the inner bar will be dominated by onshore directed sediment transport, and as a result has the appearance of a slip-face bar attached to the upper beach. When combined with observations of bar crest orientation, which are oblique to the coastline but become increasingly shore-parallel as they move onshore, this suggests that the configuration of the bars is being influenced by overlying wave activity.

The parameter which shows the most variability between regions is bar volume (Figure 7). In the central region, it is often the innermost bar which has the greatest volume, while in the northern region the outermost or central bars typically contain the greatest volume. The southernmost region shows the greatest variation, with outer, central and inner bars all being most voluminous at different points in time.

From the analysis presented here, there are significant differences in beach parameters along the studied coastline. These variations can be attributed to two major influences. The first is the coastal configuration, e.g. gentle embayment /headland like structure in the central and northern sections. The second is due to presence of coastal structures such as piers (extending up to 350m offshore), groynes (extending up to 100m) and artificial headlands (extending up to 50m), which directly impact on the configuration of the bar system. These tend to have a persistent impact on alongshore variability across the years, although their contribution to the Eigen coefficient is still variable. This may explain the greater variability in the northern 5 km of the coastline where a groyne field is present. In addition, the presence of cross-shore drainage channels is mirrored in variations at smaller spatial scales. These channels are frequent, occurring every few hundred meters alongshore, and highly dynamic, forming and migrating on timescales which cannot be tracked using annual LiDAR surveys (Miles, 2014; Reichmüth & Anthony, 2008). It is the presence of these channels which makes the alongshore EOF coefficients so varied year on year.

While hydrodynamics have not been studied here, the shape and orientation of bars indicate a probable causal relationship between waves and bars. Nearshore wave transformation will be influenced by shoreline configuration and orientation as well as nearshore bathymetry and the bars themselves. The Shell Flat (Figure 1), is a shallower offshore area attached to the northern part of the Fylde coast. Wave energy will be transformed around the flat before reaching the adjacent nearshore zone. Hence it is expected that larger wave heights will be found on the central and southern part of the coastline. This is supported by the tracking of bar migration rates, which are typically greater in the southern region of the coastline than in north or central. While the bars are influenced by wave characteristics, the oblique angle of the bars will itself result in a variation in longshore slope which, alongside shoreline orientation with respect to incident waves, will provide gradients in longshore sediment transport.

The results presented here are in agreement with those of Grunnet and Hoekstra (2004) who analysed longshore bar variability from beach profiles at Terschelling, the Netherlands, highlighting the influence of coastal configuration and bathymetry on bar parameters and migration, albeit with a longshore resolution limited to a maximum of 200 m. Hence, we argue that our study has much wider relevance highlighting a need for 3D study of bars and in particular on coastlines with more complex configuration and bathymetry. Localised studies of bar migration can be misleading, overlooking three-dimensional behavior of the bar system. In particular the obliquity of the bars cannot easily be determined from discrete profiles.

Limitations

A number of gaps in the knowledge remain following the work in this paper, which largely revolve around understanding of the short-term (hourly to weekly) evolution of the bar system between available LiDAR surveys. This may be addressed by a combination of beach profile surveys, video monitoring and numerical modelling of the nearshore environment. Considering short-term processes will also allow for clearer links to be drawn between changes to the bar system and the hydrodynamic processes responsible for them, which currently remain largely hypothesised. This will also increase the value of the work from a coastal management perspective, enhancing understanding of the impact which the bar system has on both sediment transport and beach volumes.

Increasing the frequency of future LiDAR surveys to bi-annually would allow researchers to capture variability between summer and winter conditions. Greater consideration of tidal conditions, undertaking LiDAR surveys at or close to spring low tide, would also help to ensure the maximum possible coverage of the intertidal region. However, it is acknowledged that cost limitations make it unlikely that this will be achieved in the near future.

Conclusions

The longshore variability and dynamics of an intertidal bar system have been captured based upon nine airborne LiDAR surveys spanning the period 1999 – 2016. The findings provide new insights into the configuration and dynamics of intertidal bars on the Fylde coast and more widely. Of particular interest is the longshore variability of the bar system over 10s kilometres, both in terms of dynamics and morphology, something which is difficult to capture using traditional beach profile surveys. It also demonstrates the potential of airborne LiDAR surveys for morphological studies, not only of intertidal bar systems but also for other systems operating on similar spatial and temporal scales.

The bars are found to first approach the coast at a nodal point in sediment transport. The bars are then oriented obliquely to the coastline both to the north and south of this location, with outermost bars demonstrating greater obliquity than those closer to the shoreline. The migration rates of bars are found to vary alongshore and may advance in some locations while retreating in others, resulting in a rotation of the bar system. Typically, when such rotation occurs it is about the nodal point, with bars migrating in different directions either side of the point. However, net migration for all bars studied was onshore.

A substantial amount of the alongshore variability observed over time is due to the presence of cross-shore drainage channels, which develop and migrate much more rapidly than the bars themselves. This is demonstrated in the alongshore coefficient of the third eigenfunction, representing bars, where frequent and highly variable fluctuations are seen alongshore. Despite this, the third eigenfunction presents a sound generalisation of the bar shape and position within the upper 250 m of the coastline. The pattern of onshore migration is clear, as is the narrowing and steepening of the bar occurring as it migrates onshore, in a fashion reminiscent of wave shoaling.

This study has demonstrated the importance of considering intertidal bar systems as three dimensional and studying them at an appropriate alongshore resolution in order to fully capture and understand their morphology and evolution. Future LiDAR surveys will allow for continued expansion of this work and improved understanding of the long-term evolution of bar systems. Combining these findings with further studies into short-term bar evolution, which should also consider their three-dimensional nature, will greatly enhance our understanding of the dynamics of intertidal bars and the influence they have on sediment transport and volumes.

Acknowledgements

The authors would like the thank Wyre Borough Council and the Environment Agency for funding the research on which this study is based. They would also like to thank the anonymous reviewers and associate editor of the journal for their helpful and constructive comments.

References

Andersen MS, Gergely Á, Al-Hamdani Z, Steinbacher F, Larsen LR, Ernstsen VB. 2017. Processing and performance of topobathymetric lidar data for geomorphometric and morphological classification in a high-energy tidal environment. Hydrology and Earth System Sciences **21**: 43

Anthony, E. J., Dussouillez, P., Dolique, F., Besset, M., Brunier, G., Nguyen, V. L., & Goichot, M. 2017. Morphodynamics of an eroding beach and foredune in the Mekong River delta: Implications for deltaic shoreline change. Continental Shelf Research. **147:** 155-164

Cartier A, Hequette A. 2013. The influence of intertidal bar-trough morphology on sediment transport on macrotidal beaches, northern France. Zeitschrift Fur Geomorphologie **57**: 325-347

Castelle B, Bonneton P, Dupuis H, Sénéchal N. 2007. Double bar beach dynamics on the high-energy meso-macrotidal French Aquitanian Coast: a review. Marine Geology **245**: 141-159 de Alegria Arzaburu, A. R., Ilic, S., & Gunawardena, Y. (2007). A study of intertidal bar dynamics using the Argus video system. In Coastal Sediments' 07 (pp. 1865-1876).

Dick JE, Dalrymple RA. 1985. Coastal changes at Bethany Beach, Delaware. In *Coastal Engineering 1984*; 1650-1667.

Grunnet NM, Hoekstra P. 2004. Alongshore variability of the multiple barred coast of Terschelling, The Netherlands. Marine Geology **203**: 23-41

Halcrow. 2010. Cell Eleven Tide and Sediment Transport Study (CETaSS) Phase 2.

Houser C, Greenwood B. 2007. Onshore migration of a swash bar during a storm. Journal of Coastal Research **23**: 1-14

Houser C, Hapke C, Hamilton S. 2008. Controls on coastal dune morphology, shoreline erosion and barrier island response to extreme storms. Geomorphology **100**: 223-240

Houser, C., & Mathew, S. 2011. Alongshore variation in foredune height in response to transport potential and sediment supply: South Padre Island, Texas. Geomorphology, **125**: 62-72

Jackson DW, Cooper JAG, O'connor M, Guisado-Pintado E, Loureiro C, Anfuso G. 2016. Field measurements of intertidal bar evolution on a high-energy beach system. Earth Surface Processes and Landforms **41**: 1107-1114

King CAM, Williams WW. 1949. The Formation and Movement of Sand Bars by Wave Action. The Geographical Journal **113**: 70-85

King, C. A. M. 1972. Beaches and Coasts. New York: St. Martin Press.

Kroon, A., & Masselink, G. 2002. Morphodynamics of intertidal bar morphology on a macrotidal beach under low-energy wave conditions, North Lincolnshire, England. Marine geology **190**: 591-608

Kroon, A., Larson, M., Möller, I., Yokoki, H., Rozynski, G., Cox, J., & Larroude, P. 2008. Statistical analysis of coastal morphological data sets over seasonal to decadal time scales. Coastal Engineering, **55**: 581-600.

Larson, M., Capobianco, M., Jansen, H., Rózyński, G., Southgate, H. N., Stive, M. & Hulscher, S. 2003. Analysis and modeling of field data on coastal morphological evolution over yearly and decadal time scales. Part 1: Background and linear techniques. Journal of Coastal Research **19:** 760-775

Levoy F, Anthony EJ, Monfort O, Robin N, Bretel P. 2013. Formation and migration of transverse bars along a tidal sandy coast deduced from multi-temporal Lidar datasets. Marine Geology **342**: 39-52

Liu HX, Sherman D, Gu SG. 2007. Automated extraction of shorelines from airborne light detection and ranging data and accuracy assessment based on Monte Carlo simulation. Journal of Coastal Research **23**: 1359-1369

Mariño-Tapia I, O'Hare T, Russell P, Davidson M, Huntley D. 2007. Cross-shore sediment transport on natural beaches and its relation to sandbar migration patterns: 2. Application of the field transport parameterization. Journal of Geophysical Research: Oceans **112**:

Masselink G, Anthony EJ. 2001. Location and height of intertidal bars on macrotidal ridge and runnel beaches. Earth Surface Processes and Landforms **26**: 759-774

Masselink G, Austin M, Tinker J, O'Hare T, Russell P. 2008. Cross-shore sediment transport and morphological response on a macrotidal beach with intertidal bar morphology, Truc Vert, France. Marine Geology **251**: 141-155

Masselink G, Kroon A, Davidson-Arnott RGD. 2006. Morphodynamics of intertidal bars in wave-dominated coastal settings - A review. Geomorphology **73**: 33-49

Matthew A. 2015. Free mapping data will elevate flood risk knowledge. In *Environment Agency Blog*. Environment Agency.

Miles A. 2014. Towards an understanding of intertidal forms and processes through integrating field observations, remotely sensed data and hydrodynamic models. In *Lancaster Enviornment Centre*. Lancaster University: Lancaster.

Miller JK, Dean RG. 2007. Shoreline variability via empirical orthogonal function analysis: Part I temporal and spatial characteristics. Coastal Engineering **54**: 111-131

Pape, L., Kuriyama, Y., & Ruessink, B. G. 2010. Models and scales for cross-shore sandbar migration. Journal of Geophysical Research **115**: F03043

Priestas AM, Fagherazzi S. 2010. Morphological barrier island changes and recovery of dunes after Hurricane Dennis, St. George Island, Florida. Geomorphology **114**: 614-626

Pruszak Z. 1993. The analysis of beach profile changes using Dean's method and empirical orthogonal functions. Coastal Engineering **19**: 245-261

Pye K, Blott S, Witton S, Pye A. 2010. Cell 11 regional monitoring strategy results of sediment particle size analysis. Report (Kenneth Pye Associates Ltd.): 1

Pye K, Blott SJ. 2016. Assessment of beach and dune erosion and accretion using LiDAR: impact of the stormy 2013–14 winter and longer term trends on the Sefton Coast, UK. Geomorphology **266**: 146-167

Reichmüth, B., & Anthony, E. J. 2007. Tidal influence on the intertidal bar morphology of two contrasting macrotidal beaches. Geomorphology, **90**: 101-114.

Reichmüth, B., & Anthony, E. J. 2008. Seasonal-scale morphological and dynamic characteristics of multiple intertidal bars. Zeitschrift für Geomorphologie, Supplementary Issues, **52:** 79-90.

Robertson WV, Whitman D, Zhang KQ, Leatherman SP. 2004. Mapping shoreline position using airborne laser altimetry. Journal of Coastal Research **20**: 884-892

Sallenger AH, Krabill WB, Swift RN, Brock J, List J, Hansen M, Holman RA, Manizade S, Sontag J, Meredith A, Morgan K, Yunkel JK, Frederick EB, Stockdon H. 2003. Evaluation of airborne topographic lidar for quantifying beach changes. Journal of Coastal Research **19**: 125-133

Saye, S. E., Van der Wal, D., Pye, K., & Blott, S. J. 2005. Beach–dune morphological relationships and erosion/accretion: an investigation at five sites in England and Wales using LIDAR data. Geomorphology **72:** 128-155

Sedrati M, Anthony EJ. 2007. Storm-generated morphological change and longshore sand transport in the intertidal zone of a multi-barred macrotidal beach. Marine Geology **244**: 209-229

Smith GL, Zarillo GA. 1990. CALCULATING LONG-TERM SHORELINE RECESSION RATES USING AERIAL PHOTOGRAPHIC AND BEACH PROFILING TECHNIQUES. Journal of Coastal Research **6**: 111-120

Stockdon HF, Doran KS, Sallenger AH. 2009. Extraction of Lidar-Based Dune-Crest Elevations for Use in Examining the Vulnerability of Beaches to Inundation During Hurricanes. Journal of Coastal Research **25**: 59-65

Van Houwelingen S, Masselink G, Bullard J. 2006. Characteristics and dynamics of multiple intertidal bars, north Lincolnshire, England. Earth Surface Processes and Landforms **31**: 428-443

van Houwelingen S, Masselink G, Bullard J. 2008. Dynamics of multiple intertidal bars over semidiurnal and lunar tidal cycles, North Lincolnshire, England. Earth Surface Processes and Landforms **33**: 1473-1490

Walstra DJR, Reniers AJHM, Ranasinghe R, Roelvink JA, Ruessink BG. 2012. On bar growth and decay during interannual net offshore migration. Coastal Engineering **60**: 190-200

Wijnberg KM, Kroon A. 2002. Barred beaches. Geomorphology **48**: 103-120