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Storm impacts and shoreline recovery: Mechanisms and controls in the southern North Sea

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ABSTRACT

Storm impacts play a significant role in shoreline dynamics on barrier coastlines. Furthermore, inter-storm recovery is a key parameter determining long-term coastal resilience to climate change, storminess variability and sea level rise. Over the last decade, four extreme storms, with strong energetic waves and high still water levels resulting from high spring tides and large skew surge residuals, have impacted the shoreline of the southern North Sea. The 5th December 2013 storm, with the highest run-up levels recorded in the last 60 years, resulted in large sections of the frontline of the North Norfolk coast being translated inland by over 10 m. Storms in March and November 2007 also generated barrier scarping and shoreline retreat, although not on the scale of 2013. Between 2008 and 2013, a calm period, recovery dominated barrier position and elevation but was spatially differentiated alongshore. For one study area, Scolt Head Island, no recovery was seen; this section of the coast is being reset episodically landwards during storms. By contrast, the study area at Holkham Bay showed considerable recovery between 2008 and 2013, with barrier sections developing seaward through foredune recovery. The third study area, Brancaster Bay, showed partial recovery in barrier location and elevation. Results suggest that recovery is promoted by high sediment supply and onshore intertidal bar migration, at rates of 40 m a^{-1}. These processes bring sand to elevations where substrate drying enables aeolian processes to entrain and transport sand from upper foreshores to foredunes. We identify three potential sediment transport pathways that create a region of positive diffusivity at Holkham Bay. During calm periods, a general westward movement of sediment from the drift divide at Sheringham sources the intertidal bar and foredune development at Holkham Bay. However, during and following storms the drift switches to eastward, not only on the beach itself but also below the −7 m isobath. Sediment from the eroding barrier at Brancaster Bay, and especially Scolt Head Island, also sources the sediment sink of Holkham Bay. Knowledge of foredune growth and barrier recovery in natural systems are vital aspects of future coastal management planning with accelerated sea-level rise and storminess variability.

1. Introduction

Shoreline response to variation in environmental forcing, both chronic (sea-level rise) and acute (storms), is a vitally important yet highly complex issue, dependent on numerous inter-related factors. Over the latter half of the twentieth century the rate of global mean sea level rise was 1.7 ± 0.3 mm a^{-1} (Church and White, 2006) and a comparable 1.4 ± 0.2 mm a^{-1} around UK coasts (Woodworth et al., 2009). More recently, this rate appears to have accelerated globally (Ablain et al., 2009) as well as regionally around the UK (Wahl et al., 2013). At the same time, ongoing uncertainty characterises future variability in tropical and extra-tropical storminess (IPCC, 2013). For coastal communities, infrastructure and biodiversity, elucidating the resulting morphodynamic linkages between storm forcing and shoreline recovery presents a further challenge. These issues are particularly pressing on low-lying coasts because in such low gradient settings both long-term and short-term water level increases can translate a long distance inland (Michener et al., 1997). Not surprisingly, therefore, there has been considerable recent research on storm impacts on barrier shorelines (e.g. Stone et al., 2004; Sallenger et al., 2006; Houser et al., 2008). Most recently, research has focussed on the coastlines of Northwest Europe where the most extreme storm sequence for 60 years occurred during winter 2013–14 (Dissanayake et al., 2014; Castelle et al., 2015; Masselink et al., 2015; Wadey et al., 2015), affecting wide areas of Atlantic France, western England (especially on SW coasts) and the southern North Sea. These studies have served to further reinforce the need for a better understanding of the spatio-temporal dynamics of storms and their interaction with surges and extreme waves and how these impact upon the considerable morphological variability that characterises the coastal receptor (e.g. Ciavola et al., 2007; Sabatier et al., 2009; Vousdoukas et al., 2012; Anthony, 2013; Spencer et al.,

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2014). Combinations of maximum still water levels, peak significant wave heights and direction of wave approach result in a complex and varied relationship with the shoreface that they encounter (Betts et al., 2004; Haerens et al., 2012).

Progressive technical advances over the past two decades in particular can be utilised to elucidate more clearly some of these complexities. Vertical aerial photography of shoreline position can now be better ground-referenced by the use of high resolution (three dimensional data quality of <50 mm and often <20 mm) instrumentation. More recently, these methods have been supplemented with airborne and terrestrial LiDAR datasets to ensure wider spatial coverage and more accurate determination of volumetric change. Thus, for example, Anthony et al. (2006) provide a comprehensive assessment of 3-D sediment exchanges between the beaches, foredunes and established dunes of the North Sea coast of France using laser scanning techniques. To link storm-induced shoreline changes to particular storm events or sequences of storms where still water levels, peak significant wave height and direction of approach are so important, there now exist archival data sets from wave buoys and tide gauge networks that can be time-matched to capture the extreme storm-driven sea states that can lead to large scale shoreline re-positioning (e.g. for UK coasts: Hackney et al., 2013; Earlie et al., 2015; Brooks et al., 2016). Adopting a methodology that combines GIS-based assessment of shorelines digitised from aerial photographs (e.g. use of the USGS Digital Shoreline Analysis System (Thieler et al., 2009)); cross-shore profile analysis; field measurements for ground-referencing; and archival records of storm occurrences strengthens our understanding of the way shorelines behave during both storm impact and storm recovery phases. This approach allows consideration as to whether or not such shorelines exhibit some sort of longer term equilibrium, allows identification of the primary controls on shoreline recovery, and informs debate on future shoreline response to rising sea levels and storm variability.

An earlier study (Brooks et al., 2016) focussed on storm impacts along a 6 km-long shoreline barrier, Scolt Head Island on the North Norfolk coast. In this paper we triple the lateral extent of frontage considered, from Holkham Bay (to the east) to Brancaster Bay (in the west), and extend our analysis to consider morphodynamic processes in the intertidal and subtidal zones. Specifically, we:

1. Investigate both cross-shore changes in shoreline profiles and alongshore changes in shoreline position to examine variations in decadal (1992–2014) behaviour;
2. Examine in detail the shoreline positional change at these locations in response to four high magnitude storms that have been identified from the archival record contained within tide gauge and wave buoy records; and
3. Use intertidal zone cross-shore profile analysis for years of no known storm occurrence (calm periods) to identify contrasting recovery behaviour at these locations for recent (2008–2013 and 2014–2015) post-storm periods and explore their alongshore interactions.

2. Location and setting

The North Norfolk Coast stretches over 45 km from Hunstanton in the west to Kelling Hard in the east (Fig. 1A). The regional geology is characterised by a shallow, gently-inclined offshore slope which, under the influence of a macro-tidal range and moderate wave energy climate, has given rise to a wide Holocene sedimentary prism. This is characterised by a wide beach or sandflat in front of sand and gravel barriers with inter-barrier tidal channels and back-barrier salt marshes (both natural and reclaimed) (Andrews et al., 2000).The higher barriers support sand dunes (locally with pine woodlands). Brackish water reedbeds are found where freshwater streams and seepages reach the coast. Small coastal settlements are restricted to the higher (ca. > 10 m) landward hinterland.

In this study we focus on three sub-sections of the North Norfolk (Fig. 1A) coast that together comprise the UK Environment Agency's 'Superfrontage 2' of Cell 5 of the 'Second Generation' Shoreline Management Plan (SMP5; East Anglian Coastal Group, 2010; Figs. 1B, 2). The most westerly study area is Brancaster Bay (Fig. 2A), comprising a dune barrier varying in elevation, reaching a maximum height of 15 m east of the Royal West Norfolk Golf Course. Part of this frontage has been protected with groynes and revetments, a response to rapid shoreline erosion and retreat over the past two decades. The westward end of Brancaster Bay is terminated by a tidal delta at Titchwell; here the beach seaward of the dunes is wide and gently sloping. Eastward from Brancaster Bay, Scolt Head Island (Fig. 2B and D) projects into the sea and forms a barrier island that stretches 6 km alongshore. Scolt is a relatively young feature, forming over the past 3000 years (Andrews et al., 2000). The main gravel and sand spine of the island supports an irregularly-spaced series of landward-trending gravel ridges, or ' laterals', which enclose well developed back barrier marshes (Steers, 1934). There has been progressive setting back of the barrier over time (with the effect of recent storms (since 2006) being documented in Brooks et al., 2016) but it also extended westwards at an average rate of 2.53 m a^{-1} over the period 1891–2013. The third setting is Holkham Bay (Fig. 2C) between the eastern end of Scolt Head Island and Wells-next-the-Sea. Holkham Bay has extensive sand dunes comprising the barrier, with very little gravel present. Behind are young back barrier marshes that have been accreting rapidly over the past decade, to form 20 ha of embryonic saltmarsh, characterised by the common saltmarsh-grass *Puccinellia maritima*. The dunes, up to 12 m in elevation, are colonised by marram grass (*Ammophila* sp.) and there are signs of foredune and embryo dune development (Fig. 2E, F). The dunes were cut back by up to 15 m in the storm of 5 December 2013 (Spencer et al., 2015). Landward of Holkham Bay is the largest area of reclaimed freshwater grazing marsh along the North Norfolk coast, at 295 ha (East Anglian Coastal Group, 2010).

The mean significant wave height along the North Norfolk coast is 0.49–0.73 m as recorded in nearshore wave buoys at Scolt and Cley (5 and 7 m water depth respectively) between September 2006 and September 2009. Further offshore at the Blakeney Overfalls wave rider buoy (10 km offshore, 18 m water depth), monthly mean significant wave height ranged from 0.8 to 1.0 m over the same period (Environment Agency, 2014). There is a macrotidal semi-diurnal tidal regime, with mean spring tidal range falling from 6.4 m at Hunstanton to 4.7 m at Cromer. Mean High Water Springs and Highest Astronomical tide are 2.35 m and 2.99 m ODN respectively (ODN = Ordnance Datum Newlyn where 0.0 m approximates to mean sea level) at Cromer (http://www.ntslf.org/tides/hilo?port=Cromer), 15 km to the east of the study area's eastern boundary. However, under storm surge conditions maximum water levels can considerably exceed predicted tidal heights. Thus in both the 1953 and 2013 storm surges, maximum water levels of >6 m ODN were recorded at Blakeney Harbour Quay (Spencer et al., 2015). The typical wind regime of the North Norfolk coast reflects the passage of low pressure systems from the west, with a dominant south-south westerly component. From this direction winds rarely reach speeds in excess of 16 m s^{-1}, but the occurrence of windspeeds over 8 m s^{-1} is common (Weybourne weather station, 2008–2013). Around 5% of winds from a south-south westerly direction exceed 8 m s^{-1}. During storms when winds approach from the north west, north and north east, wind speeds are almost always in excess of 8 m s^{-1}, commonly exceed 12 m s^{-1} and can exceed 16 m s^{-1}; in addition, fetch lengths are at their maximum from the north and north east.

Thus the coast of North Norfolk is vulnerable to, and shaped by, high-magnitude storms which approach from a northerly direction. Such events can generate large surge residuals and strong onshore waves, particularly when they coincide with high spring tides. Twenty such storm events have been identified since 1881 that have been sufficiently damaging to have been reported in the media (Brooks et al., 2016). The

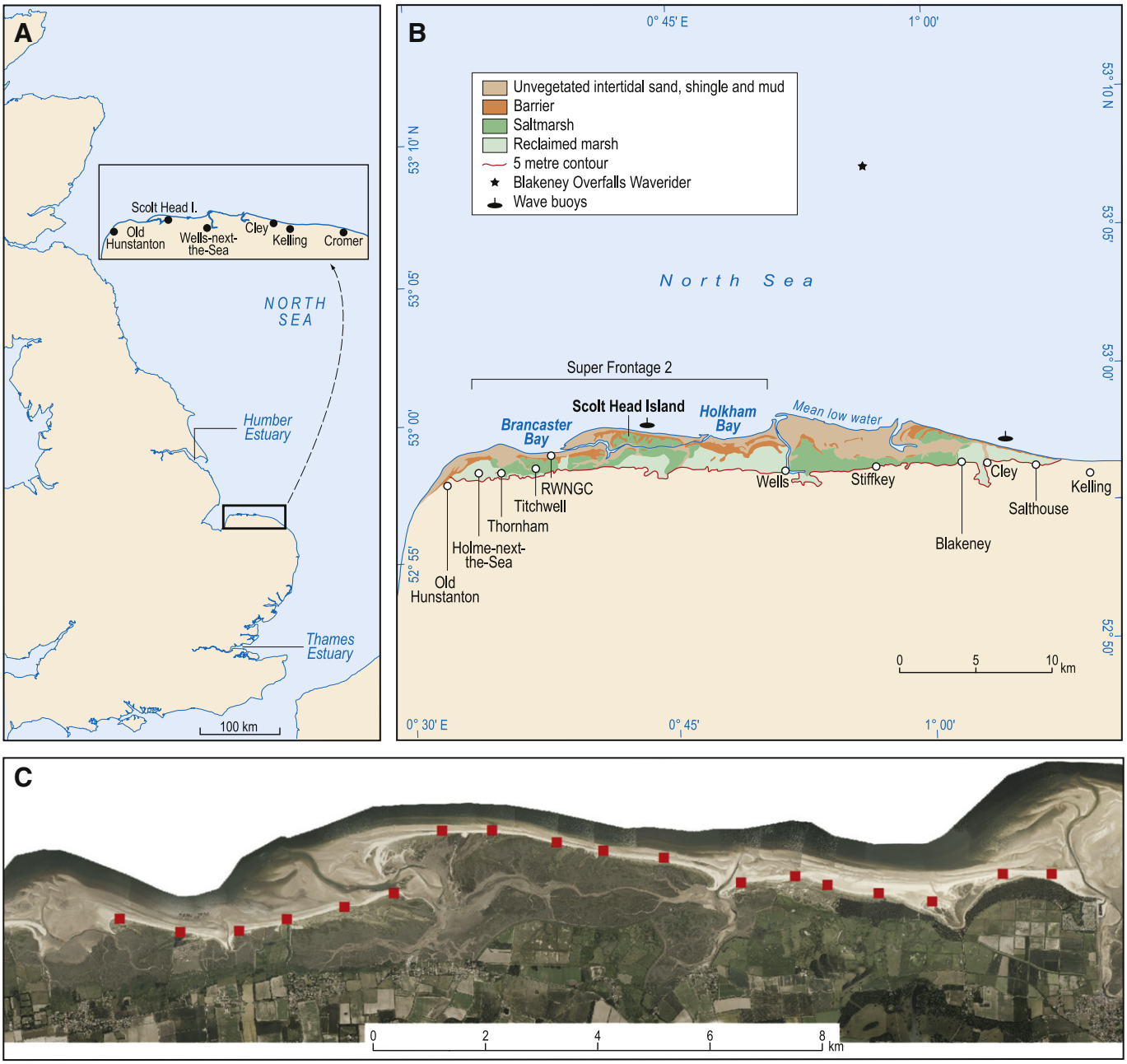

Fig. 1. General location and environmental setting of Brancaster Bay, Scolt Head Island and Holkham Bay, North Norfolk Coast. A) Location within the general setting of the UK east coast and (inset) North Norfolk coast. B) Superfrontage 2 with the three study site locations, and their main landforms and habitats. Wave recording locations are also shown at Cley, Scolt Head and Blakeney Overfalls. C) North Norfolk Coast aerial photograph from 15th July 2013 with symbols showing Environment Agency cross-shore profile locations. © Environment Agency copyright and/or database right 2015. All rights reserved.

most devastating storm in terms of coastal inundation, damage to infrastructure and agriculture, and loss of life was the 31st January–1st February 1953 storm which claimed >2000 lives in The Netherlands (Gerritsen, 2005). The 5th December 2013 storm surge in places along the North Norfolk coast generated higher water levels than in 1953 (Spencer et al., 2015). With strengthened post-1953 defences and better early warning systems, no lives were lost from this event. Nevertheless shoreline impacts were considerable in terms of retreat in the barriers, overtopping and breaching as well as flooding.

3. Methods

We used a variety of methods to develop a picture of positive (advance) or negative (retreat) shoreline change. The details are described further below, but in summary they include: 1) digitising shorelines from annual (typically August–September) UK Environment Agency (EA) aerial photography; 2) using EA bi-annual cross-shore profiles (6-monthly intervals from 1992 to present, with a 'summer' (typically August–September) and a 'winter' (typically January–February) survey each year) to provide a 2-dimensional assessment of change at point locations; 3) obtaining field Real Time Kinematic (RTK) data to identify the shoreline position following the 5th December 2013 storm; and 4) using available records of waves (https://www.cefas.co.uk/cefas-data-hub/wavenet/) and still water levels (https://www.bodc.ac.uk/data/online_delivery/historical_uk_tide_gauge_data/) to assess the sea states experienced during periods of greatest shoreline change. We also consulted the Weybourne weather station for wind speed and duration (recorded every minute) on specific days in the recovery phases. These

Fig. 2. Superfrontage 2 (East Anglian Coastal Group, 2010) on the North Norfolk coast. A) Brancaster Bay looking east towards Scolt Head Island in the far distance, showing barrier cliffing following the 5th December 2013 storm (photo: SM Brooks 12.01.2016); B) Scolt Head Island following the 7th–8th November 2007 storm showing breaching and overwash of the barrier (photo: D. Friess 11.12.07); C) the barrier at Holkham Bay looking east towards Wells-next-the-Sea shortly after the 5th–6th December 2013 storm (photo T. Spencer 16.1.2014); D) general setting of Scolt Head Island showing the barrier and the back barrier marshes following the 5th December storm with Brancaster Bay in the far distance (photo: M. Page 9.12.13) E) Holkham Bay looking east showing steep seaward facing dunes of 12 m fronted by foredunes of 5 m (photo: S.M. Brooks 30.12.15); F) sand saltation on Holkham Beach in winds of 12.07 m s^{-1} from 241.3° at Weybourne, with a wet beach section in the breaking zone associated with the landward face of the intertidal bar preventing saltation (photo S.M. Brooks 30.12.16).

datasets were used to: 1) establish the shoreline position for the entire decadal-scale period of available records (1992 to 2014) and for shorter periods between 2006 and 2007, 2007–2008, 2008–2013 and 2013–2014; 2) provide the 6-monthly change in the crest of the shoreline barrier between summer 2006 and summer 2014; 3) assess cross-shore profile change for the same periods, but also including the period 2014–2015 (following the major storm of 2013). Wave and still water level data sets were used to define thresholds for three large storms, identified from the EA Sea State Reports for 2006–2007 and 2006–2009 (Environment Agency, 2014; Brooks et al., 2016) and from archival records (Brooks et al., 2016). The threshold used to define these storms was taken as the combination of significant wave heights exceeding 3.5 m at Blakeney Overfalls (offshore) or 2.2 m at Scolt Head Island (inshore); a northerly (337.5–22.5°) direction of wave approach; and still water levels exceeding 3 m ODN in the Immingham tide gauge record. The dates of the storms thus identified occurred between 31st October–3rd November 2006, 17th–20th March 2007, 7th–11th November 2008 and 5th–6th December 2013. The nature and impacts of the last storm in this sequence has been well documented (Spencer et al., 2015; Wadey et al., 2015). We were unable to consider storms before summer 2006 as there were no datasets to provide nearshore wave information in the locality before summer 2006. Thus the key time periods for the following analysis were: (a) 1992–2014 to assess decadal shoreline change; (b) 2006–2007, 2007–2008 and 2013–2104 to assess storm impacts; (c) 2008–2013, a long period of no major storms; and (d) 2014–2015 to assess recovery following the large surge event of 5th December 2013.

3.1. Alongshore shoreline change for the entire North Norfolk barrier coastline

A major issue for studies such as this one is that of defining the shoreline (Moore, 2000; Stockdon et al., 2002). This is especially a problem when there is no clearly defined point where topography and

vegetation change abruptly over small distances. When a barrier has recently been scarped by storms this line is sharp and clearly identifiable from aerial photography. However, as the barrier recovers, local patterns of erosion and deposition, and the accompanying re-vegetation of the shoreline profile, makes it more difficult to define the shoreline position. To deal with this problem, EA ground survey cross-shore profile data were used to define the maximum break-of-slope. These points were then plotted in their exact x-y locations on the closest aerial photograph to the survey date. The image was inspected for degree of vegetation cover and pixel colour change, with the point of maximum change taken to be the shoreline position. Errors with this method arise from difficulties in identifying correctly the colour change but are estimated to be no >0.75 m horizontal distance for aerial photographs with a pixel size of 0.25 m (e.g. 2006 vertical aerial photography) and 0.60 m for a pixel size 0.20 m (e.g. 2014 imagery). Geo-rectified UK EA vertical aerial photographs for 1992 and 2014 were used to digitise the shoreline position within ArcMap 10.1, using the above methodology. The Digital Shoreline Analysis System (DSAS; Thieler et al., 2009) was then applied, with shore-normal transects spaced at 10 m alongshore intervals, to find the Net Shoreline Movement (NSM; m) over this 22-year time period.

In order to investigate the impact of major storms on shoreline position in the latter part of the decadal record, shorelines were then digitised from the summer 2006, 2007, 2008, 2013 and 2014 imagery. Defining the shoreline as the crest of the barrier was straightforward and clear for the summer 2014 photograph because there was a sharp break of slope resulting from barrier cutting during the December 2013 storm, and Real Time Kinematic (RTK) surveys were undertaken along the barrier immediately after the storm. The aerial photographs from summer 2006, summer 2007 and summer 2008 had many sections (covering around 60% of the total shoreline length) where the barrier crest could be defined clearly with sharp changes in adjacent pixel colour from well vegetated to non-vegetated surfaces. Using the Digital Shoreline Analysis System (Thieler et al., 2009), shore-normal transects were cast from a baseline at 10 m alongshore spacing, allowing assessment of shoreline change at a very high level of spatial densification. Brancaster Bay, Scolt Head Island and Holkham Bay included a total of 518, 591 and 613 transects, respectively. Some transects were removed from the analysis, where stream outlets prevented clear digitising of the shoreline, where overwash deposits masked the shoreline position, where there were artificial structures defending the shoreline, or where the shoreline was so sinuous that transects crossed the shoreline at a highly oblique angle. For the remaining 299, 511 and 328 transects at Brancaster Bay, Scolt Head Island and Holkham respectively, the alongshore End Point Rate (EPR, m a^{-1}) for the years 2006–2007, 2007–2008 and 2013–2014 was then calculated for each of the three study areas. This statistical measure is generated from the distance between the two shorelines at each transect, divided by the time interval, to return the average annual retreat over the period. It is therefore independent of the time period used for the assessment.

To assess shoreline recovery in the period without major storms, the digitised shorelines from summer 2008 and summer 2013 were used to quantify shoreline change, again using the End Point Rate statistic from DSAS with an alongshore transect spacing of 10 m.

3.2. Decadal cross-shore (at-a-point) shoreline change, 1992–2014

The alongshore analysis was validated by the use of the EA cross-shore profile data (Fig. 1C). Positional accuracy with this method is to within ±20 mm horizontally and ±30 mm vertically (Lee, 2008). The most seaward located sharp break-in-slope occurring at an elevation above 4 m ODN was defined as the crest of the barrier. The difference in location of this crest position between 1992 and 2014 was used as the metric for barrier migration. EA cross-shore profile spacing is 1 km alongshore; thus a total of 6, 5 and 7 cross-shore profiles were available for the Brancaster Bay, Scolt Head Island and Holkham Bay study areas respectively. 15 of the 18 profiles were amenable to further analysis. One profile from Brancaster Bay crossed the heavily defended section of shoreline at the clubhouse of the Royal West Norfolk Golf Club and a further profile from the eastern end of Brancaster Bay was not included because it crosses a beach with no landward dune or barrier. Similarly one of the profiles from Holkham Bay (the furthest eastward) did not cross the dunefield and was discounted.

In order to assess the impact of the four identified major storms, the summer cross-shore profiles were plotted for each year between 2006 and 2014. The summer-to-summer plots were used to calculate change in the crest location for each year. This was not possible for all profiles, as defining crest location for washover deposits (e.g. EA profile reference number N017) and for gently-sloping sand dunes (e.g. N021) where the surface is gently undulating, is problematic. Hence the number of cross-shore profiles included in this analysis was a total of 11 from the 15 available profiles.

3.3. Annual cross-shore profile analysis 2008–2015

The assessment of shoreline recovery was carried out for two distinct phases of no storm activity. Between summer 2008 and summer 2013 there was recovery which we assessed using the EA cross-shore profiles and by carrying out a DSAS assessment of change. A second phase of recovery was also assessed following the 5th December 2013 storm, again using the EA cross-shore profiles. In these recovery assessments we not only looked at the shoreline position (as defined by the barrier crest) but also assessed in detail morphological changes taking place upon the beach in the intertidal region of the profile. The tidal range is slightly different for each of the study locations, involving an east-west gradient in tidal range along the North Norfolk Coast (Admiralty Tide Tables, 2010). This gradient generates higher extreme water levels in the west of around +1.5 m at Hunstanton compared with Cromer (East Anglian Coastal Group, 2010). Data reported in the Shoreline Management Plan for Mean High Water Springs (MHWS) along the coast at Hunstanton, Burnham, Wells, Blakeney and Cromer were also used to fit an Ordinary Least Squares Regression ($r^2 = 0.95$) which was then used to find the level of MHWS at each EA cross-shore profile location. EA cross-shore profiles were used to plot the profile section from the elevation between MHWS and 0.0 m ODN, and then from 0.0 m ODN extending seaward as far as the data were available.

Finally, we assessed morphological changes in the EA cross-shore profiles below 0.0 m ODN by plotting summer survey data from summer 2008 through to summer 2013 (just before the 5th December 2013 storm) and then looked in greater detail at the region below 0.0 m ODN for the 6 monthly surveys (winter and summer) for the period summer 2011 to summer 2015.

4. Results

4.1. Decadal shoreline change, 1992–2014

Over the longest timescale (1992–2014) changes in shoreline position are shown using the Net Shoreline Movement (m) statistic from DSAS (Fig. 3). Also shown are the calculations of change using the 15 EA cross-shore profiles; it is clear that the at-a-point results from the cross-shore profiles verify the results from the alongshore DSAS analysis. For Brancaster Bay, the maximum shoreline retreat was 44.97 (±2.30) m. In places there was some moderate shoreline advance but the average Net Shoreline Movement along this frontage was 17.42 (±0.87) m of retreat. At Scolt Head Island, there was less alongshore variability (Fig. 3), apart from transects from the advancing western end of the barrier (0–80 m chainage; note the large advance between these transects which defines the considerable westward extension in the barrier over this period). As the system is behaving differently at this location, these transects were removed from the calculation of

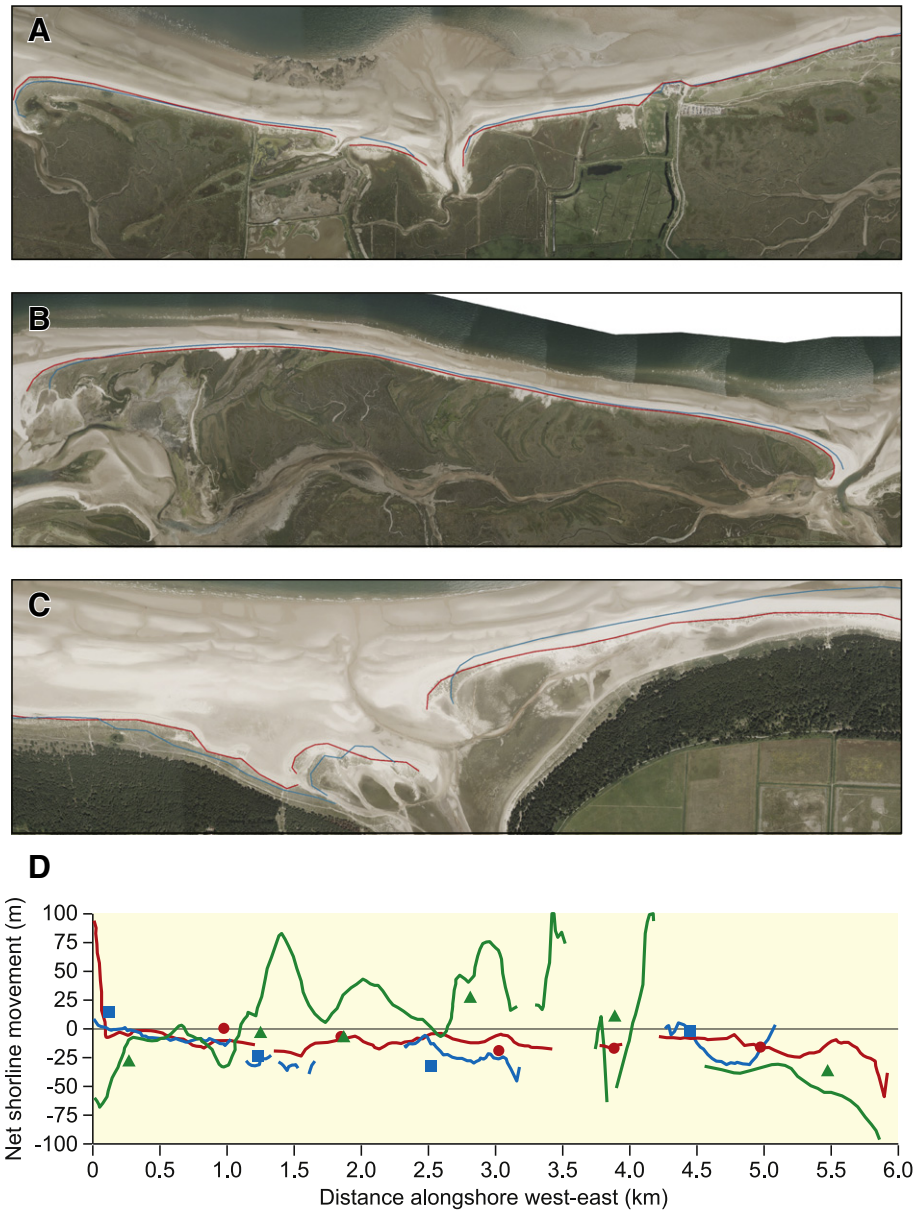

Fig. 3. A) Shoreline positions in 1992 (blue in online version/dark grey in printed version) and 2014 (red/light grey) for A) Brancaster Bay; B) Scolt Head Island and C) Holkham Bay. The recurved laterals first identified by Steers (1934) and providing evidence of the episodic nature of barrier development can clearly be seen in B). D) Net Shoreline Movement (m) for Brancaster Bay (blue in online version/black in printed version), Scolt Head Island (red/light grey) and Holkham Bay (green/dashed) for the period 1992–2014 (negative values = shoreline retreat, positive values = shoreline advance). Gaps in the alongshore plots are due to the occurrence of tidal inlets (Brancaster Bay); shoreline washover deposits (Scolt Head Island); or to the ends of the dunes where high shoreline curvature leads to transects being cast at highly oblique angles to the main shoreline trend (Holkham Bay). Symbols indicate changes in barrier crest position between 1992 and 2014 found using the EA cross-shore profile analysis.

average rates of shoreline change so we could gain a clearer picture of the retreat of the barrier. Maximum Net Shoreline Movement was 59.52 (±2.98) m landward at the eastern end of the barrier. Average Net Shoreline Movement was 18.48 (±0.92) m landward, slightly higher than the rate recorded for Brancaster Bay. For Holkham Bay, the average Net Shoreline Movement between 1992 and 2014 was 0.69 (±0.03) m of retreat, far less than at either Scolt Head Island or Brancaster Bay. This figure, however, disguises a high level of variability in shoreline behaviour at this location. Both the western and the eastern ends of the embayment show a movement landward, with the maximum retreat at the western end of 70.17 (±3.51) m and at eastern end of 96.23 (±4.81) m. A 4.5 km stretch in the central sector of this frontage showed a highly variable state of shoreline advance, reaching 95.51 (±4.78) m at the point of maximum seaward advance (Fig. 3).

4.2. Event scale shoreline change, 2008–2014

Typical cross-shore profiles for Brancaster Bay (EA profile reference number N008), Scolt Head Island (N015) and Holkham Bay (N024) are shown in Fig. 4 for each summer from 2008 to 2014. Variations in response are evident. The crest of the barrier at Brancaster Bay showed a progressive inland movement between 5th September 2006 and 30th August 2007, between 30th August 2007 and 11th September 2008, as well as between 4th September 2013 and 9th September 2014. Between 11th September 2008 and 4th September 2013, the position of the barrier crest changed very little with respect to the shoreline. However, some foredune recovery to seaward of the crest was recorded in this time period and the crest elevation increased from 5.67 to 6.89 m ODN. At Scolt Head Island, the barrier was progressively reset landward

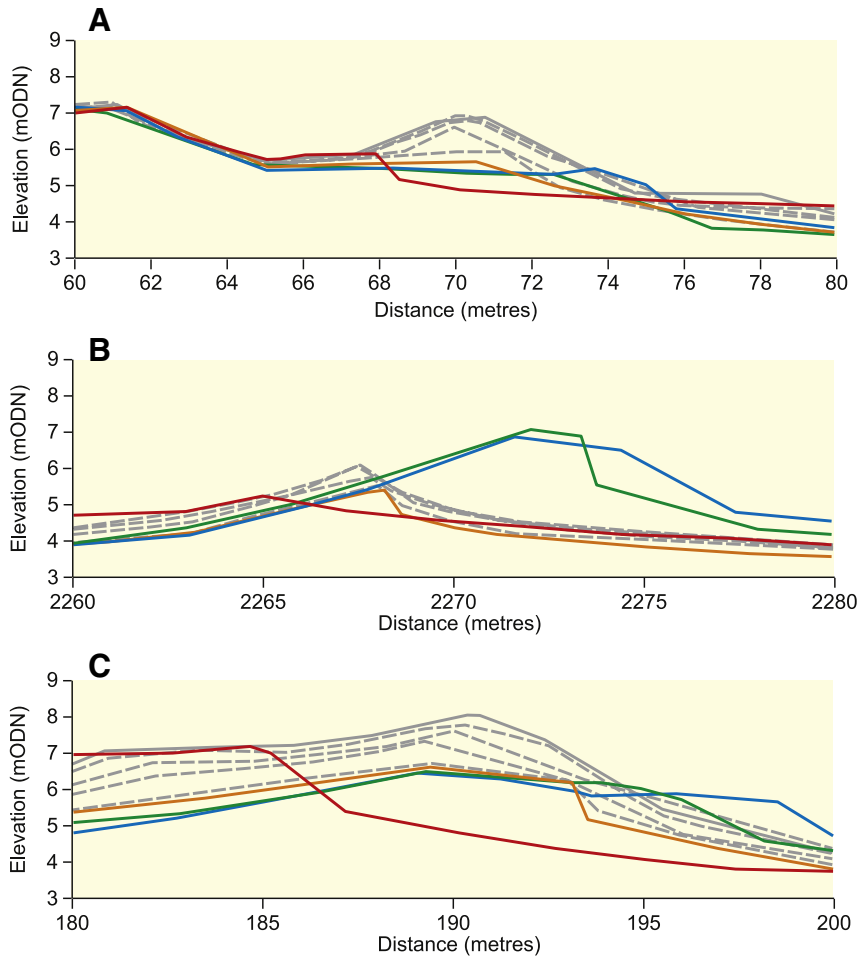

Fig. 4. Typical summer cross-shore profiles in 2006 (blue in online version/black in printed version), 2007 (green/black), 2008 (orange/black), 2013 (grey/black) and 2014 (red/black) at A) Brancaster Bay; B) Scolt Head Island; and C) Holkham Bay. Note changes to barrier crest location and elevation changes. The years between 2008 and 2013 are shown as grey stippled lines.

during the periods of major storm activity and, as at Brancaster Bay, the position of the barrier crest changed very little in the intervening years (September 2008 to September 2013). Finally for Holkham Bay, while shoreline position was also relocated inland during the stormy periods this dynamic was accompanied by clear shoreline advance between September 2008 and September 2013. There was also evidence of recovery in the foredunes between 2008 and 2013 taking place at Brancaster Bay and, more evidently, at Holkham Bay but not at Scolt Head Island.

The changing position of the barrier crest for each analysed cross-shore profile along the Superfrontage between summer 2006 and summer 2014 (Fig. 5) shows that periods of retreat coincide with winters with high magnitude storms. Previous research has constrained the retreat to within 6-monthly intervals and shown for Scolt Head Island that the 2006–2007 retreat happened under the 17th–19th March 2007 event (no storm surge but the coincidence of high tides and large waves) and that the 2007–2008 retreat accompanied a significant storm surge on 7th–8th November 2007 (Brooks et al., 2016). This is

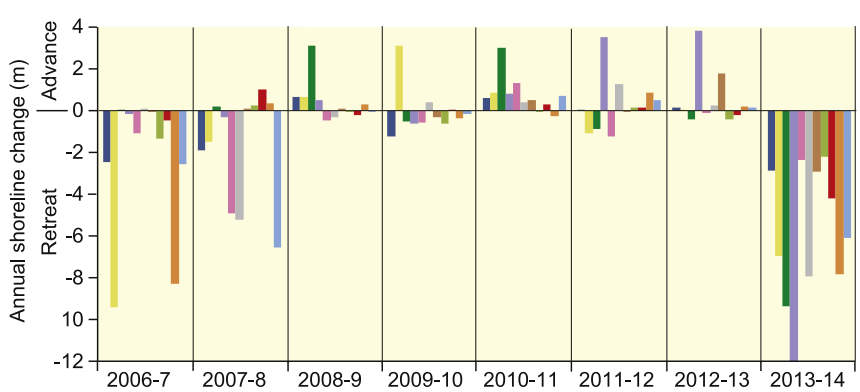

Fig. 5. Change in barrier crest position between summer 2006 and summer 2014 from analysis of 11 EA cross-shore profiles. Note high retreat rates at individual profiles during 2006–2007, 2007–2008 and particularly 2013–2014 compared with limited retreat and advance in the period 2008–2013.

further supported here by cross-shore profiles from Brancaster Bay and Holkham Bay where the 6-monthly retreat in the barrier crest at each alongshore location took place either in the period 24th January–30th August 2007 (22nd January–11th September 2007 for Holkham) or in the period 30th August 2007–8th February 2008 (11th September 2007–5th January 2008 for Holkham). Further, for 2013–2014, shoreline displacement took place in the period 4th September 2013–12th March 2014 (22nd August 2013–28th February 2014 for Holkham) and not in the other half of the year. As previously, field RTK surveys showed that the cliffed edge of the barrier was more or less coincident with the 2014 shoreline from aerial photography and set back from the 2013 shoreline. This fixes the shoreline movement in the same 6-monthly period as the storm of 5th December 2013.

Using the digitised shorelines from 2006, 2007, 2008, 2013 and 2014 enabled the End Point Rate (EPR; m a^{-1}) to be calculated for each time period (Fig. 6). Alongshore variability is evident for all storms. A considerable impact is associated with the 5th December 2013 storm, embedded within the 2013–2014 retreat rates, since our RTK field surveys testify to the fact that the annually averaged shoreline change was achieved by just this one large event. Brancaster Bay, Scolt Head Island and Holkham Bay all had very large inland translations of the shoreline during this storm, with averages of 4.29 (±0.22), 4.81 (±0.24) and 7.36 (±0.97) m, respectively. By contrast, the EPR for the period between summer 2008 and summer 2013 shows a very limited change in shoreline position. At Brancaster Bay there was an average net movement seaward of just 0.29 (±0.02) m per year (1.45 (±0.07) m total), for Scolt Head Island this was even less at 0.12 (±0.01) m (0.60 (±0.03) m total) whereas at Holkham the shoreline position advanced at an average EPR of 1.54 (±0.08) m. This implies a Net Shoreline Movement seaward by 7.79 (±0.44) m at Holkham Bay, slightly more than the subsequent average retreat during the storm of 5th December 2013. While the barriers at Brancaster Bay and Scolt Head Island appear to be being progressively set further inland (consistent with the long-term behaviour shown in Fig. 3), the behaviour at Holkham Bay is rather different, demonstrating resilience and recovery between storms and even showing recovery towards an ever further seaward location in this period.

4.3. Cross-shore profile analysis, 2008–2013

Annual cross-shore profiles (2008–2013) between 0.0 m ODN and MHWS for a representative cross-shore profile location in each of the study areas are shown in Fig. 7. The frontage at Scolt Head Island, where the barrier is retreating in its central/eastern section, shows no inter-storm recovery. The shoreface gradient is steep (gradient = 2.44°) and narrow (60–100 m) between MHW and MSL (=0.0 m ODN). By contrast, the shoreface is of lower slope at Brancaster Bay and Holkham Bay (0.91°–0.82°), with narrow beaches (190 m) at Brancaster Bay compared to Holkham Bay (320 m) (Fig. 8A). Within the intertidal zone, the cross-shore profiles reveal the existence of intertidal bars at Holkham Bay, not so clearly evident in cross-shore profiles from Brancaster Bay or Scolt Head Island (Fig. 8B).

The North Norfolk bars closely resemble those described from Faro, southern Portugal (Vousdoukas et al., 2012) and particularly the bars seaward of the Skallingen barrier, Danish North Sea coast (Aagaard et al., 2004). Here we follow the Danish terminology of an offshore inner bar and an inshore intertidal bar (Fig. 9A). The onshore movement of the inner bar to become the intertidal bar between September 2006 and September 2013 involved 500 m of inland translation, at a migration rate of ca. 70 m a^{-1}. The intertidal bar migrated 200 m onshore between 2008 and 2013, occupying progressively higher elevations within the tidal frame over this period (Fig. 9B). This intertidal bar migration took place at a rate of 40 m a^{-1}, a similar value to that found for intertidal bars at Skallingen (Aagaard et al., 2004). Thus, it appear to take around 5 years for the inner bar to migrate from below MLWS to an intertidal position and then a further 5 years for this new intertidal bar to move to an elevation of +1 m ODN.

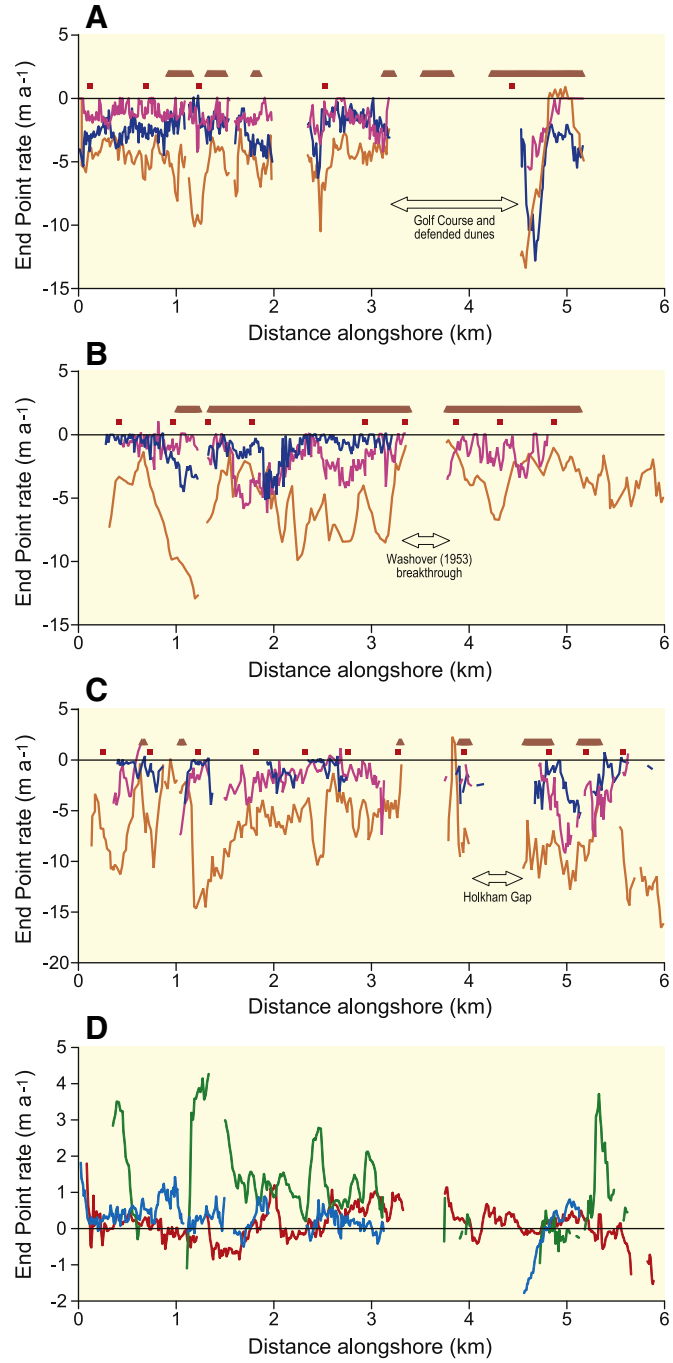

Fig. 6. End Point Rate (m a^{-1}) for the barrier coast for the storm periods 2006–2007 (blue in online version/black in printed version), 2007–2008 (pink/light grey), and 2013–2014 (orange/dashed) for A) Brancaster Bay; B) Scolt Head Island; and C) Holkham Bay. Also shown are the cross shore profile locations (used to constrain the digitising of the shoreline for earlier periods) and alongshore extents of reliable RTK field survey data (used to constrain the digitising for the 2014 shoreline). D) End Point Rate (m a^{-1}) for the period summer 2008 to summer 2013, a period of no storm activity, along the barrier for Brancaster Bay (blue/black), Scolt Head Island (red/light grey) and Holkham Bay (green/dashed).

The most recent movement of the intertidal bar at 6-monthly intervals is shown in Fig. 10 for Holkham Bay. Between 2012 and 2015, the onshore migration was of the order of 150 m (i.e. 50 m a^{-1}) and elevation gain was of the order of 1 m. These bars migrate, gain elevation and become progressively exposed to a wider range of complex sediment exchange processes (see Jackson et al., 2016 for intertidal bar behaviour on a shorter timescale). Interestingly, the severe 5th December 2013

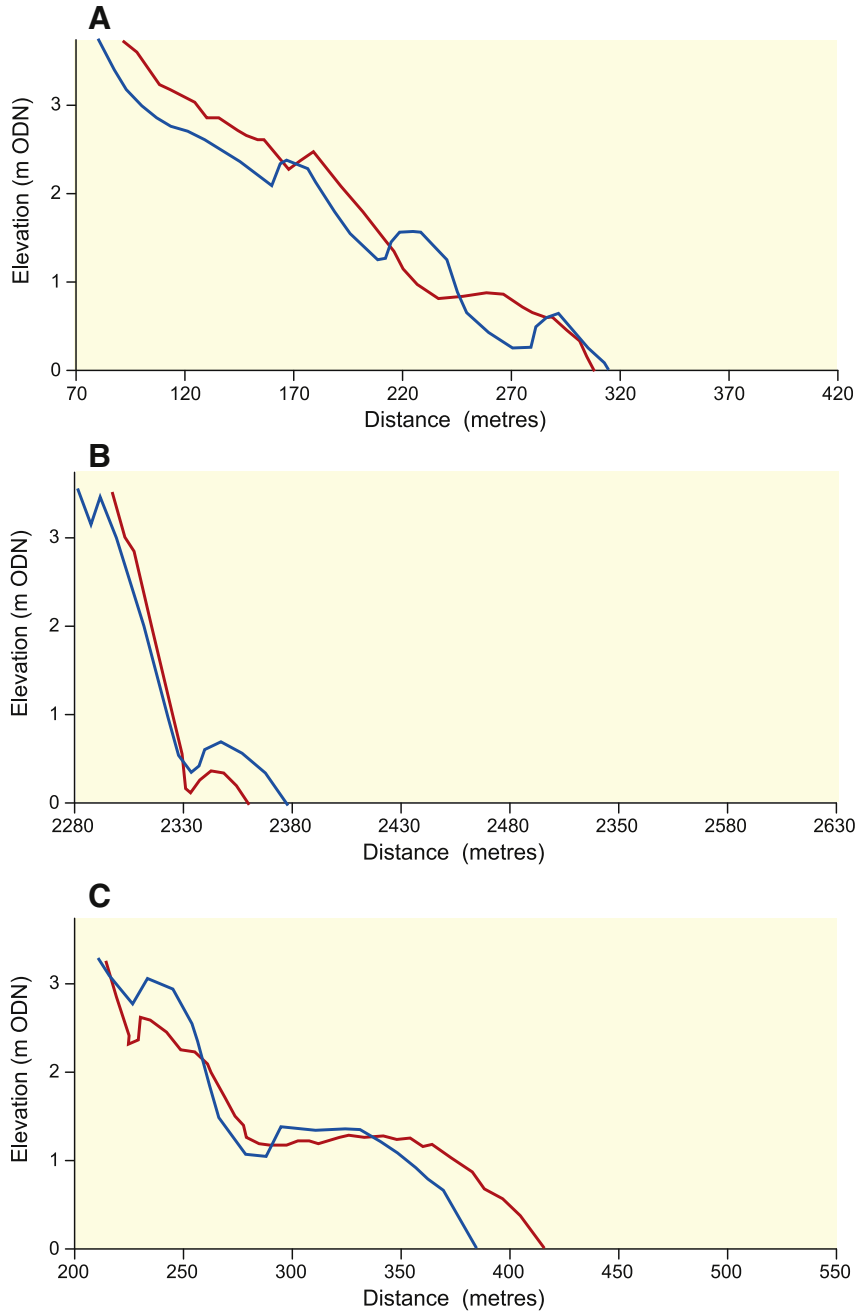

Fig. 7. Cross-shore profiles between 0 m ODN and MHWS for 2008 and 2013 for A) Brancaster Bay (at EA cross-shore profile N008); B) Scolt Head Island (N015); and C) Holkham Bay (N024).

storm surge event (the highest magnitude event of its type in the last 60 years) appears to have played only a limited role in onshore intertidal bar migration. The year to year onshore movement seems very consistent with no discernible difference in the intertidal bar migration rate between summer 2013 and winter 2014 than that indicated for any other 6-month interval. The 2015 summer bar also appears to have developed a trough offshore from the main bar crest, while the continued upward direction of travel has taken this bar to above 0 m ODN.

5. Discussion

Shoreline change along the entire 15 km Superfrontage 2 of the North Norfolk coast involves periods of clear landward shoreline translation under individual high magnitude storms characterised by high still water levels (whether through surge mechanisms or because they coincide with high spring tides or both) combined with large onshore waves. These storm impacts are, however, separated by spatially-variable barrier responses during non-storm phases. These responses can be classed as either stasis (Scolt Head Island), partial recovery (Brancaster Bay) or full recovery with shoreline advance (Holkham Bay). Alongshore variability in response is the result of the interaction between shoreface bathymetry, sediment availability and inshore hydrodynamics (including wave energy dissipation, radiation stress gradients, longshore currents and set-up). These controls operate at a series of spatial and temporal scales.

At the macro-scale, List et al. (2006) found strong 'mirroring' behaviour in post-storm retreat and recovery along the uninterrupted, sandy outer barriers of the United States east coast, with storm erosion pockets being rapidly countered by accretion in the same locations to restore the

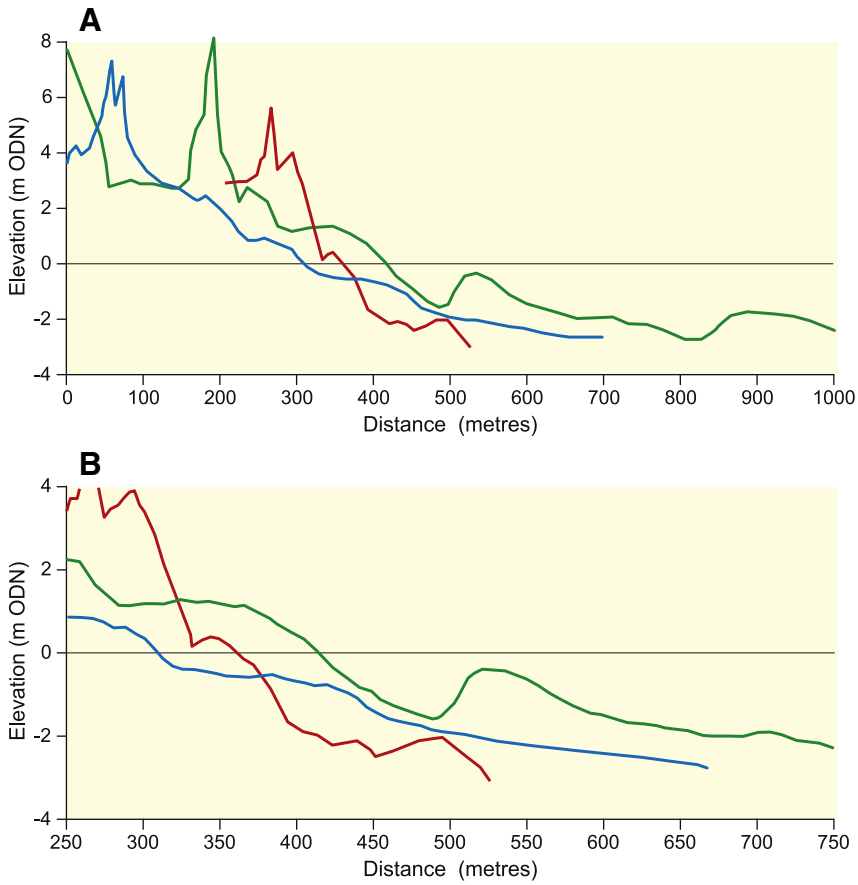

Fig. 8. Typical cross-shore profiles for the three study areas between A) Supra-tidal environments to ca. MLWS; and B) MHWS to MLWS in detail. Note: these cross-shore profiles are the same as those reported earlier for the three study sites. Dashed line is Brancaster Bay, solid line is Scolt Head Island and irregular dashed line is Holkham Bay.

pre-storm shoreline. Comparison with this study is not straightforward in that our study documents changes in barrier margins (i.e. upper foreshore) whereas List et al. (2006) took Mean High Water as their measure of shoreline position. Even so, there is no clear evidence that this section of the North Norfolk coast exhibits similar erosion/deposition, 'reversing hotspot' behaviour. This is due to three factors. First, the long NE USA shorelines (45 km at Cape Cod and 113 km on the Outer Banks, North Carolina) allow the capture of multiple hotspots alongshore which is not possible along the restricted 17 km North Norfolk frontage. Secondly, it is clear from List et al. (2006) that the erosion/accretion cycle is completed within 5–12 days of storm impact, a much finer temporal resolution than the longer-term shoreline change discussed here. And thirdly, it is likely that the greater spatial complexity and sedimentary variability of the North Norfolk coastline - from the presence of mixed sand and gravel barriers, inter-barrier tidal inlets (with associated flood and ebb tide deltas) and fine sediment exchanges between mudflats and vegetated marsh platforms - forces a more complex retreat-recovery signal.

These observations feed into a wider discussion of nearshore sediment exchange along this barrier coastline and engage with wider debates on how shoreline orientation relative to the incident wave climate is a major factor in storm retreat-recovery interactions (Ashton and Murray, 2006a, 2006b). Since the earliest mapping and interpretations of Steers (1934, 1960), there have been many conceptual, sedimentological and numerical modelling studies of sediment transport that suggest a dominant westward transport between Sheringham (30 km east of Holkham Bay) towards Hunstanton in the west (e.g. Steers, 1927; McCave, 1978; Vincent, 1979; Oynett and Simmonds, 1983). The Shoreline Management Plan (East Anglian Coastal Group, 2010) shows a consistent net sediment transport direction (270°; W) along the entire beach front between Blakeney Point and Brancaster. At Scolt Head Island drift rates are of the order of 190,000 $m^3 a^{-1}$. However, results from offshore sediment type mapping (Evans et al., 1998) have suggested a contrasting west-east direction for sediment transport below the −7 m isobath, offshore from the steep beach face onto the Burnham Flats (reported in HR Wallingford, 2002 appendix 11; East Anglian Coastal Group, 2010). There is no reason to discount an alternative model for the beach face that suggests that, at Scolt Head Island, sediment movement is also west to east, involving easterly-migrating sand waves moving over an ebb tide delta in the Brancaster Harbour Channel to then weld onto the western end of the barrier. It has also been suggested that late nineteenth century land reclamation might be responsible for an easier passage of the sand waves across the harbour channel due to a reduction in the tidal prism after this time (Royal Haskoning and Pethick, 2003; Brooks et al., 2016). Thus in both the beach face and below the −7 m isobath there are likely to be alongshore sediment exchanges which potentially result in sediment being supplied to the more easterly locations along this frontage.

On way of reconciling these different models is through the possibility of differing barrier dynamics between 'calm' and 'storm' periods. This is particularly apparent at Scolt Head Island where the framework of the island consists of both a main E-W spine and a series of irregularly spaced, broadly N-S trending 'laterals'. It was J.A. Steers (1960) who first argued that the dominant behaviour during calm, inter-storm periods is a westward extension of the island, while during storm events this westward growth is halted and the barrier driven landward. In the periods of island extension, the laterals, generated by sediment transport under strong wave refraction, show a characteristic smooth 'recurve' geometry. However, the high angle of intersection between the older, more easterly laterals and the main island spine provides

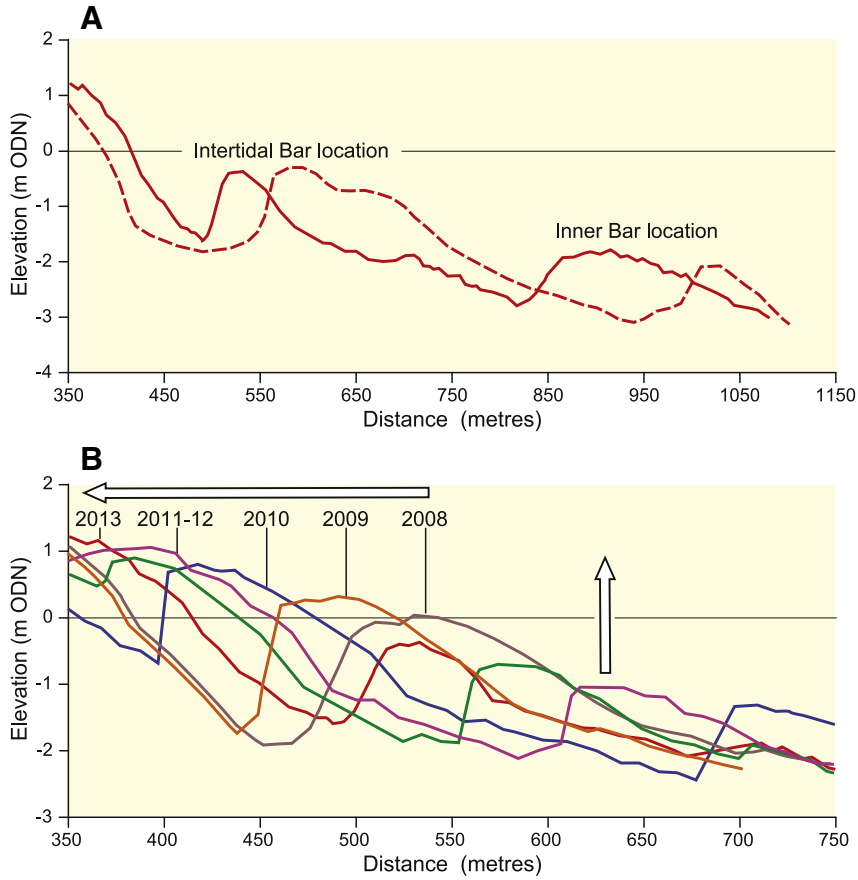

Fig. 9. Representative cross shore profile (EA reference N024) for Holkham Bay showing the locations of A) the Inner and Intertidal Bars in September 2006 (dashed line) and September 2013 (solid line) and B) the Intertidal Bar position each summer 2008–2013 (Note appearance of Inner Bar in profiles for 2010/11, 2012 and 2013).

evidence for the truncation of these fixed laterals from the long-term landward retreat of the barrier. These arguments are confirmed by Fig. 6D which shows that in calm periods, the barrier is characterised by erosion at its eastern end but deposition at its western terminus. While storm impacts at Scolt generate Steers' (1960) record of landward translation (Fig. 6B), the long-term behaviour of the barrier reflects the fact that these episodes are short-lived perturbations in a general history of eastern erosion, along-barrier sediment transport (which smooths out the fine detail of storm retreat (Fig. 6B) and westward extension (Fig. 3B).

Finally at this scale, these observations and models suggest that the recovery taking place at Holkham Bay is sourced by the three-fold sediment transport regime that makes Holkham Bay a dynamic sediment sink (or zone of 'positive diffusivity' (Ashton and Murray, 2006b)).

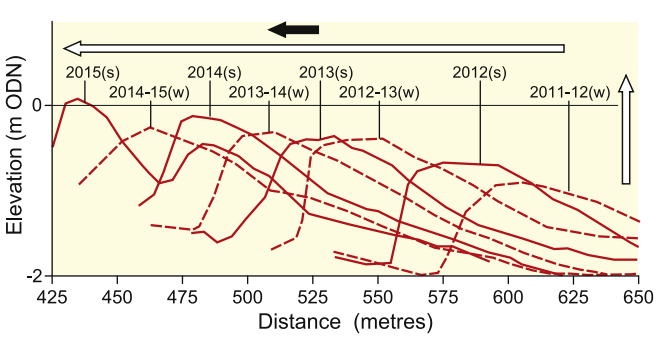

Fig. 10. Vertical and lateral intertidal bar migration at Holkham Bay between six-monthly winter (w) and summer (s) surveys, 2012–2015 for a representative cross-shore profile (EA reference number N024). The time period affected by the 5th December 2013 storm surge is shown by the uppermost horizontal arrow.

This regime has the following components: under calm conditions, westward sediment transport from the drift divide located to the east at Sheringham; eastward transport in the beach zone by migrating sand bars when the dominant wave direction is from the west; and eastward movement of sediment below the −7 m isobath across the Burnham Flats and emplaced during, and immediately after, storms from barrier retreat at Brancaster Bay and Scolt Head Island, the latter being especially important as a sediment source to maintain such transports.

At the meso-scale, Masselink and Short (1993) categorise the foreshore into four zones: 1) the subtidal zone influenced by shoaling wave processes; 2) the lower intertidal zone characterised by surf and shoaling wave processes; 3) the mid-intertidal zone with swash and surf; and 4) the upper intertidal zone with swash and aeolian processes. The width of each zone varies with tidal range and gradient of the shoreface. Sediment exchanges take place between these zones, ultimately leading to sediment being made available for aeolian transport to foredunes and established dunes. Intertidal bars driven onshore (Aagaard et al., 2006; Masselink et al., 2006) ultimately reach elevations that permit drying times conducive to consequential aeolian transport. Moisture content (precipitation and tidally influenced) has been shown to be the primary control on aeolian transport as, through variations in shear strength, it directly affects the fetch length over which the wind can entrain sediment (Sherman et al., 1998; Yang and Davidson-Arnott, 2005; Delgado-Fernandez, 2010, 2011). Drying opportunity is strongly related to beach gradient through the extent and persistence of the seepage face associated with fluctuations in beach water-table (Jackson and Nordstrom, 1998). Hence, even allowing for sediment size differences, there is far less drying potential on steep, narrow reflective beaches than on wide, dissipative beaches. At Scolt Head Island, the offshore gradients are steep and there is no evidence in the

cross-shore profiles to suggest the existence of onshore migrating inner bars. As a result there is limited sand supply and limited potential for development of an upper beach flat that can generate a drying sand source for aeolian entrainment and transport. Here sand dune recovery in calm periods is largely non-existent. At Brancaster Bay, there is little evidence for the presence of significant inner or intertidal bars. In addition, due to higher tidal levels (0.54 m higher at MHWS than further east), the upper beach at Brancaster Bay inundates more frequently than at Holkham; the rising tide here covers an additional 28.65 m in the cross-shore orientation. Between 2008 and 2013, foredune development seaward of the main dune barrier at Brancaster Bay resulted in vertical elevation gains of ca. 1 m on shore-normal profiles and lateral seaward extension of the upper foreshore by ca. 5 m. It can be concluded, therefore, that foredune recovery in calm periods does take place at Brancaster Bay but not at a rate that keeps pace with the long-term (1992–2014) landward shoreline displacement that results from storm impacts. Finally, at Holkham Bay, the combination of progressive onshore migration of inner and intertidal bars, leading to extensive areas of drying sand in the upper intertidal zone, and exposure of these areas to onshore and alongshore winds provides an ample sand supply to re-build foredunes and allow their seaward expansion in calm inter-storm periods. Here between 2008 and 2013, foredunes showed vertical growth of 1.5 m with seaward advance of ca. 10 m. Furthermore, since the December 2013 storm, and unlike at the other two study areas, the shoreline at Holkham Bay has undergone significant foredune development linked to onshore intertidal bar migration.

The primary controls on shoreline recovery operating along this 17 km frontage are, therefore, the presence of migratory nearshore inner and intertidal bars, low shoreface gradients, sufficient drying times for sand entrainment on the upper beach flat and aeolian transport in winds above thresholds of around 8 m s^{-1}. Similar controls have been observed elsewhere around the southern North Sea (Aagaard et al., 2004; Anthony et al., 2006; Anthony, 2013). Finally, following Houser (2009), it is vital to understand how transport and supply of sediment are synchronised, involving the spatial and temporal coupling of nearshore and aeolian processes. Strong recovery is only possible with synchroneity between transport and supply. Between storms when drying is at a maximum (large supply), winds tend to be weak (transport-limited), while during storms, winds are strong (large transport potential) but the backshore readily becomes wet, limiting the sediment supply (supply-limited). In the presence of a strong sand supply, the building of dunes supplied by sand from the upper beach flat is highly dependent on this synchronisation. When strong winds above sand entrainment thresholds coincide with falling tides, and low still water levels produce prolonged beach exposure and efficient drying, there is potential for dune building. More data are required on the interactions between wind strength and direction and fluctuating moisture content in the beach on diurnal, monthly and annual timescales and the implications for beach-dune sediment exchanges. There is also a need to explore these relationships on inter-annual timescales and, ultimately, how they relate to decadal-scale fluctuations in storm impacts and variable inter-storm periods.

6. Conclusions

For the barrier coast of North Norfolk, storms have a differential impact, even over relatively short alongshore distances, depending on shoreline setting. Landward retreat during storms can be up to 15 m in a single event, depending on the morphological and sedimentological mobility of the barrier. Between large storms, this barrier coastline is characterised predominantly by stasis at Scolt Head Island, partial recovery at Brancaster Bay and full recovery at Holkham Bay. At the latter site there was considerable shoreline advance in the period 2008–2013. This combination of response and recovery has resulted in long-term shoreline retreat (1992–2013) of 17.42 ($\pm$0.87) m at Brancaster Bay and 18.48 ($\pm$0.92) m at Scolt Head Island but only 0.69 ($\pm$0.04) m at Holkham Bay where large coastal tracts show clear long-term net shoreline advance. As well as changes to the actual shoreline position, the area seaward of the barrier crest also shows the way in which the shoreline is evolving. While at Brancaster Bay foredunes developed between 2008 and 2013, no such change was observed at Scolt Head Island. Even larger foredunes than those at Brancaster Bay developed in this period at Holkham Bay. Within a context of regional sediment transport, variously westwards and eastwards, explanations for these differences can be found in the beach and shoreface gradient in the different study areas (steeper at Scolt Head Island) and differences in the tidal range (smallest at Holkham), resulting in differing inundation regimes along this coastline. In addition, migratory subtidal and intertidal bars play a key role in shoreline recovery as these dynamics provide a mechanism for the onshore movement of sediments that ultimately provide source materials for foredune construction.

Temporally, barrier recovery potential from storm impacts underpins the future survival of coastal landscapes, ecosystems, human communities and infrastructure on high-energy coasts. The concern over future sea-level rise and changes to the tracks and magnitudes of extra-tropical storms and storm sequences (Vousdoukas et al., 2012; Castelle et al., 2015; Masselink et al., 2015), makes the understanding of shoreline recovery potential and resilience between storms an important part of both research and coastal management agendas (Woodworth et al., 2009; Horsburgh and Lowe, 2013; Wahl et al., 2013). Spatially, the differential recovery capacity recorded here at three locations found over a total distance of 15 km shows the importance of topographic and bathymetric setting – and their impact on coastal hydrodynamics and sediment transport - in determining system response and differential shoreline recovery. Taken together, a better appreciation of the time-space dynamics of barred shorelines, their beach faces and dunefields, provides important input into the shoreline management planning process, particularly where the use of scarce resources for management needs to be effectively prioritized.

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