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Understanding coastal change using shoreline trend analysis supported by cluster-based segmentation

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ABSTRACT

Shoreline change analysis is a well defined and widely adopted approach for the examination of trends in coastal position over different timescales. Conventional shoreline change metrics are best suited to resolving progressive quasi-linear trends. However, coastal change is often highly non-linear and may exhibit complex behaviour including trend-reversals. This paper advocates a secondary level of investigation based on a cluster analysis to resolve a more complete range of coastal behaviours. Cluster-based segmentation of shoreline behaviour is demonstrated with reference to a regional-scale case study of the Suffolk coast, eastern UK. An exceptionally comprehensive suite of shoreline datasets covering the period 1881 to 2015 is used to examine both centennial- and intra-decadal scale change in shoreline position. Analysis of shoreline position changes at a 100 m alongshore interval along 74 km of coastline reveals a number of distinct behaviours. The suite of behaviours varies with the timescale of analysis. There is little evidence of regionally coherent shoreline change. Rather, the analyses reveal a complex interaction between met-ocean forcing, inherited geological and geomorphological controls, and evolving anthropogenic intervention that drives changing foci of erosion and deposition.

1. Introduction

Understanding the primary controls on coastal behaviour over timescales relevant to management remains extremely challenging despite the continuing extension of multi-year monitoring programmes and datasets. Shoreline management is increasingly concerned with adaptive responses to coastal change at decadal to centennial scales (Nicholls et al., 2012, 2013), invariably framed by projections of climate change and their consequences at the coast (Zhang et al., 2004; Dickson et al., 2007; Nicholls and Cazenave, 2010). However, disaggregation of the low frequency trends that typically create the most pressing management problems (Cowell et al., 2003; French et al., 2016b) from higher frequency (e.g. inter-annual) variability and event-driven change is usually very difficult (e.g. Fenster et al., 2001; Woodroffe and Murray-Wallace, 2012). Moreover, the complex interplay of natural and anthropogenic processes and influences at this mesoscale (see for example Del Río et al., 2013) makes it difficult to attribute causes to observed changes. For example, sea-level rise, elevated storm-surge water levels, high energy storm waves, depletion of sediment budgets and the construction of sea walls are all capable of promoting beach erosion. However, the time-scales over which such effects are manifest and the persistence of the associated morphological changes can be very different.

The problem of understanding shoreline change is often presented as one that can be resolved with more data, with the scarcity of multi-decadal datasets being a major obstacle to the robust quantification and attribution of trends in shoreline behaviour (e.g. Le Cozannet et al., 2014; Garcin et al., 2016). The availability of higher frequency aerial imagery and the accumulation of high resolution airborne LiDAR altimetry over the last two decades, have certainly facilitated new insights into contemporary shoreline change (e.g. Hapke et al., 2016). LiDAR altimetry data have been especially valuable as a means of relating annual to decadal changes in shoreline position to local sediment budgets (e.g. Young and Ashford, 2006; Bradbury et al., 2013; Richter et al., 2013; Pye and Blott, 2016). However, progressive trends in shoreline and coastal system behaviour tend to emerge over multi-decadal timescales and at this scale, we are still fundamentally reliant on the analysis of composite historical datasets derived from much sparser aerial photography, mapping and hydrographic surveys.

Shoreline change analysis is a well-developed field that has evolved rigorous data processing and analytical protocols (e.g. Dolan et al., 1991; Thieler et al., 2009). However, quantification of trends is only one aspect of the problem; we also need to understand the drivers of change and to be able to resolve local effects within broader regional contexts that can be important at decadal to centennial timescales (Hapke et al., 2016). Although conventional trend metrics provide a discrete measure of change over a specific time frame, they do not always capture the behaviour that underlies that change. This can be problematic where change is non-linear, cyclical and/or event-driven (Dolan et al., 1991).

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This paper presents a new approach to mesoscale shoreline behaviour analysis that combines conventional shoreline change metrics with alongshore segmentation using cluster analysis (Hennig et al., 2015). Data-driven segmentation using cluster analysis is able to reveal the spatial structure of change in terms of a set of distinct coastal behaviour units. A combined shoreline trend and cluster-based segmentation analysis is developed with reference to a regional case study of shoreline changes at high spatial resolution (100 m alongshore interval) along a 74 km stretch of the Suffolk coast, eastern England. Both centennial and intra-decadal behaviour is investigated using shoreline position datasets covering the period from 1881 to 2015.

2. Regional case study location

The approach presented here is developed around an analysis of the Suffolk coast of eastern England. The study region extends approximately 74 km between Lowestoft in the north to Felixstowe (Landguard Point) in the south (Fig. 1). The Suffolk coast is notable for the extent to which its planform and configuration has changed over the last few hundred years. Recession of soft rock cliffs has led to the loss of formerly important settlements, notably Dunwich (which rivalled London as an international port in the 14th century) between the 13th and 19th centuries (Sear et al., 2011). Stretches of actively retreating cliff are punctuated by low sand and gravel barriers (Pontee, 2005), which have blocked a series of former estuarine inlets (e.g. at Benacre, Easton and Minsmere Broads; Fig. 1) that now sustain brackish lagoon and reed bed habitats (Spencer and Brooks, 2012). Elsewhere, the alongshore continuity of the open coast sediment system is punctuated by several estuaries (Burningham and French, 2015). The smaller estuaries have complex inlet shoals, with the ebb tidal deltas being better developed than their flood equivalents. At the Blyth, Alde/Ore and Deben inlets (Fig. 1), sediment is actively exchanged between the beach and ebb tide deltas, with those of the Deben and Alde/Ore exhibiting a more cyclical growth and decay that may be interpreted as a sediment bypassing process (Burningham and French, 2006, 2007). The Felixstowe deep-water channel and Harwich approach channel provide

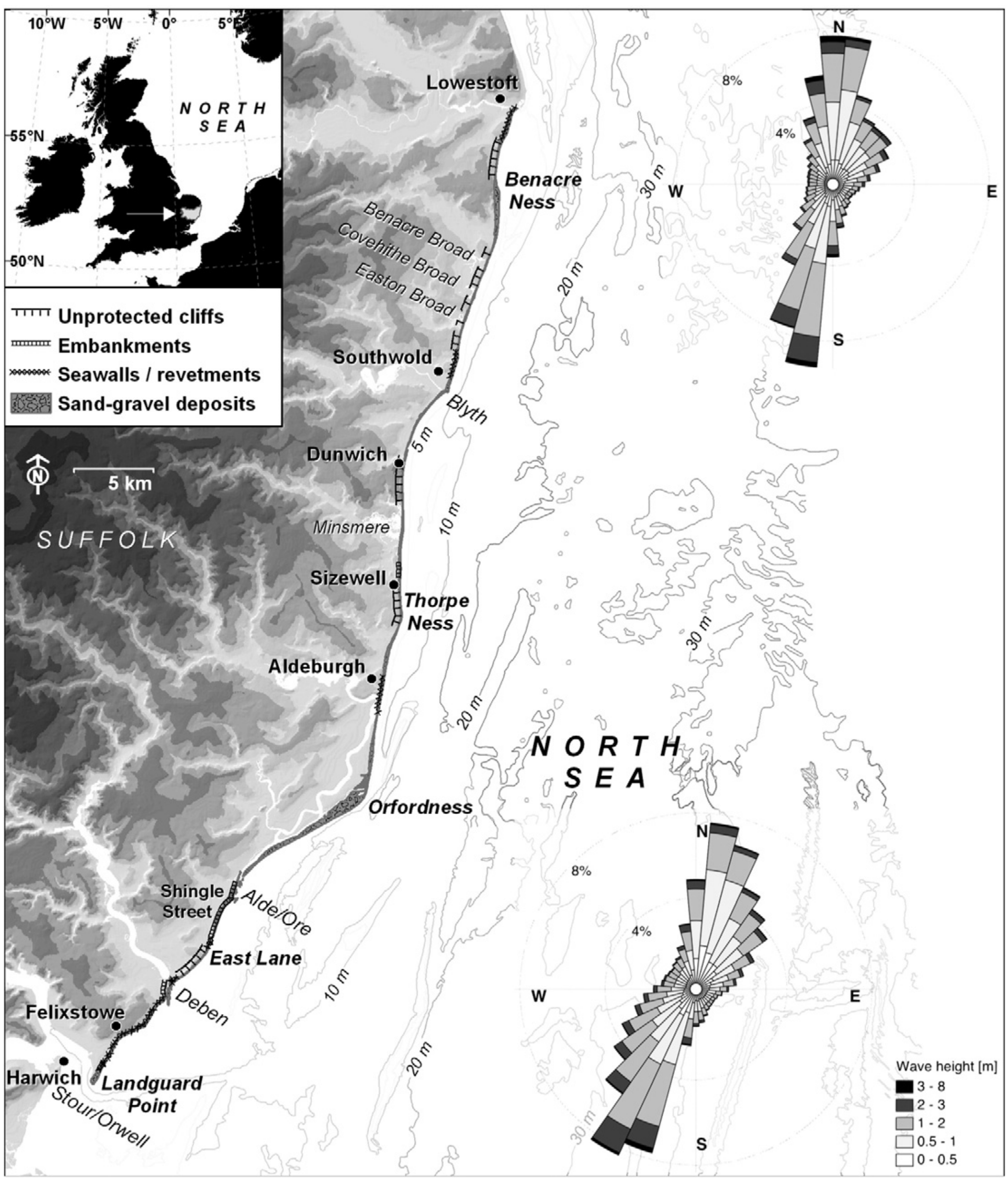

Fig. 1. Regional map of the Suffolk coast, eastern England, showing the main coastal features and locations referred to in the text, hinterland topography and shoreface bathymetry. Wave climate for the period 1980 to 2012 is summarised as directional frequency distributions for offshore locations in the north and south of the region.

an effective barrier to the littoral transport of sand and gravel further south.

The historically dynamic nature of this coast has been attributed in part to its relatively soft geology (Brooks and Spencer, 2012) and abundant local sediment supply from cliff recession, forced by a strongly bimodal wave climate under which most waves approach from either the northeast or from the south to southwest (Fig. 1). The meso-tidal regime is characterised by a large surge variance, and storm surges within the southern North Sea may trigger enhanced erosion and barrier overtopping and breaching. The coastal wave climate is locally modified by attenuation over offshore bank systems (Burningham and French, 2016), especially south of Lowestoft around Benacre and Kessingland (Coughlan et al., 2007) and between Dunwich and Sizewell (Robinson, 1980; Carr, 1981). Sea-level rise contributes an additional moving boundary condition, with the present linear trend at Lowestoft being 2.5 mm year^{-1} (Permanent Service for Mean Sea Level data for 1956 to 2015).

The contemporary coast retains erosional 'hotspots', such as the cliffs at Covehithe (Fig. 1), but the present situation is one of spatial variability that appears to reflect a complex interplay of geological controls, varied engineering interventions since the 19th century, and offshore morphology and its influence on wave climate. A recent analysis by the Environment Agency (EA, 2007) of beach profile monitoring data for 1991 to 2006 reveals that whilst 54% of the shoreline (approximately 41 km) experienced net landward retreat over this period, 28% (21 km) prograded seawards. Pye and Blott (2006) analysed historic changes in the Sizewell to Dunwich area and draw attention to its relative stability over the last 50 years compared to the 19th and early 20th centuries. Whether this reduction in the rate and prevalence of erosion is a consequence of variability or trend in extrinsic wave and tidal forcing, intrinsic factors such as realignment of the shoreline morphological changes in the nearshore bank systems, and/or management interventions remains unclear. It is also unclear whether a similar picture is evident at the regional scale. The prospect of an acceleration in the rate of sea-level rise naturally leads to concern over an attendant increase in the rate and extent of erosion and the risk of flooding along low-lying frontages, both on the open coast and within the estuaries.

3. Data and methods

3.1. Determination of historical shoreline positions

Historical shoreline behaviour was evaluated through the delineation of shoreline positions and analysis of magnitudes, rates and directions of change over the last 135 years. Mean High Water (MHW) shorelines were digitised from a range of historical map, aerial photography and airborne LiDAR resources covering the period 1881 to 2015 (Table 1). Where required, resources were georeferenced to British National Grid and vertically adjusted to Ordnance Datum (approximately mean sea level). Positional accuracy was checked at ground control points located along the hinterland, and in combination with the native resolution of the data, was used to quantity uncertainties in position for all shorelines digitised. Uncertainties were low (RMS < 5 m) across aerial photography and LiDAR datasets since the early 1990s, but larger for map and old aerial photograph resources (RMS up to 13 m).

Relative changes in shoreline position were determined using an approach similar to that employed in the Digital Shoreline Analysis System (DSAS) (Thieler et al., 2009), but implemented in computer code to enable further exploration of the transect time series. Analyses were performed at 100 m intervals along the open coast shoreline of Suffolk between Lowestoft and Felixstowe (Landguard Point). At each of 737 locations, shore-normal transects were generated against which relative changes in shoreline position were determined. In a few instances, transect locations were manually adjusted to ensure that they did not coincide with obstructions (such as engineered structures). The presence of engineered structures precluded a systematic generation of transects at a higher resolution. The 100 m interval used represents a significantly higher resolution than has been previously adopted around the UK, and provided the means to explore regional behaviour across a range of coastal geomorphology contexts through a robust statistical analysis. Shoreline change statistics were calculated for each transect, including shoreline change envelope (SCE), net shoreline movement (NSM), time-averaged (linear regression) trends (LRR) and net (end point) rates (EPR) of change. Positional uncertainties for each digitised shoreline were used to derive regression trend uncertainties, which were in the range $\pm$ 0.05–0.09 m year^{-1}. A weighted total least squares regression (WTLS) was also undertaken, but the increased accuracy of post-1990 shorelines led to a distinct bias in the calculated historical trends towards post-1990 trends, such that this was not an effective measure of centennial shoreline change.

Mean Low Water (MLW) shorelines were also digitised from the earliest (1880s) and most recent (2010s) surveys to ascertain changes in the width and gradient of the cross-shore profile. For this purpose, elevations of MHW and MLW were estimated for each transect based on linear interpolation of predicted tidal levels between Landguard Point where mean tide range (MTR) is about 2.8 m and Lowestoft where MTR is 1.5 m (UKHO, 2014). Intertidal slopes were thereby calculated from the ratio of the MTR at each transect and the intertidal width.

The irregular time interval between shoreline surveys precludes many conventional time-series analyses. Furthermore, extreme changes in shoreline position evident at a small number of sites can skew the focus towards those sites, to the exclusion of subtler, more localised, and/or cyclical behaviour that might be attributable to specific forcings. Cluster analysis (Hennig et al., 2015) provides an alternative means of identifying common patterns across large datasets. Bottom-up grouping of data with common attributes across multiple variables yields groups that describe the inherent structure within a dataset, and permit classification on the basis of a typology (Legendre and Legendre, 1998; Hennig et al., 2015). In this analysis, epochs were derived that broadly correspond to the dates of the available surveys. Where multiple surveys exist within a given epoch, the shoreline positions were time-averaged. Two sets of epochs were defined. First, 30-year epochs were used

Table 1
Summary of map, aerial photograph and LiDAR data resources used in this analysis. *Uncertainty is calculated as the sum of native resolution and RMSE in position.

Data type	Source	Dates	Scale/resolution	Uncertainty*
Ordnance Survey maps	Edina	1881–1884, 1904–1906, 1926–1927, 1951–1977	1:2500	3–11 m
Ordnance Survey maps	Edina	1938–1951, 1957–1958	1:10,560	10 m
Ordnance Survey maps	Edina	1971–1992	1:10,000	7–10 m
B&W aerial photography	Google	1945	1 m	13 m
B&W aerial photography	EA	1992, 1994, 1997	25 cm	3–4 m
Colour aerial photography	EA	2001, 2003–2009	25 cm	2–3 m
Colour aerial photography	EA	2011, 2014	20 cm	1–3 m
LiDAR	EA	2008, 2010	25 cm	1–2 m
LiDAR	EA	2015	50 cm	2 m
LiDAR	EA	2009, 2011, 2012, 2013, 2014, 2015	1 m	2–4 m
LiDAR	EA	1999, 2003, 2008	2 m	3–5 m

to explore centennial and multi-decadal change between 1881 and 2015. Secondly, 3- to 4-year epochs were used to investigate more recent intra-decadal change between 1990 and 2015. The epoch length was largely determined by the frequency of the shoreline datasets, which is much lower for historical maps compared to modern surveys. A small number of transects (mainly close to estuary mouths) were removed due to lack of data. The final dataset incorporated 733 of the original 737 transects.

3.2. Cluster analysis and shoreline segmentation

A detailed description of cluster analysis is beyond the scope of this paper (the reader is referred to Everitt et al. (2011) and Hennig et al. (2015)). In brief, it entails the calculation of distances (interpreted as the similarity) between all objects in a data matrix, on the basis that those closer together are more alike than those further apart. Hierarchical, agglomerative clustering is a bottom-up approach where objects and then clusters of objects are progressively combined on the basis of a linkage algorithm that uses the distance measures to determine the proximity of objects and then clusters to each other (Legendre and Legendre, 1998). Euclidean distance is the standard metric for distance calculation for continuous variables (Olden et al., 2012) and this was adopted here. Euclidean distance (d_{ij}) is calculated as the sum of squared differences between relative cross-shore positions at each transect (t_1, t_2, t_3 etc.) during each epoch (a) for all epochs (N) using:

$$d_{ij} = \sqrt{\sum_{a=1}^{N} (t_{ia} - t_{ja})^2}$$

Linkage options were explored, including comparison of distance- (e.g. single, average and complete) and variance- (e.g. Ward) based algorithms, and evaluated using cophenetic correlation coefficient (see Saraçli et al., 2013). Testing of alternative linkage and distance measures is advocated to promote a more rigorous analytical approach (Mouchet et al., 2008; Hennig et al., 2015). Valid solutions (monotonic cluster trees and non-singular clusters) were achieved using average (unweighted (pair group method) with arithmetic mean (UPGMA) distance) and Ward (minimum variance) distances, with the former producing tighter clusters and a higher cophenetic correlation. The final analyses were undertaken using the average linkage method (Sokal and Michener, 1958), in which the distance between clusters (L_{pq}) is calculated as the average distance (d_{ij}) between transects in one cluster (n_p) and another cluster (n_q):

$$L_{pq} = \frac{1}{n_p n_q} \sum_{i=1}^{n_p} \sum_{j=1}^{n_q} d_{ij}$$

Unlike k-means cluster analysis (see Legendre and Legendre (1998)), there is no prescribed number of clusters in hierarchical cluster analysis, and the user must evaluate distances and linkages to ascertain the most appropriate number of clusters. Although this is to some extent subjective, the purpose of cluster analysis is to organise large datasets into a smaller number of groups. Several evaluation metrics (including Calinski-Harabasz index, link inconsistency and similarity, and silhouette coefficient; Everitt et al., 2011) can be used to guide this process. Dendrograms (cluster trees) of linkage results can also be used to inform the decision, whereby larger distances between branch levels imply dissimilarity between clusters, and hence suitable points at which to cut the tree and define groups. To support this interpretive process, an iterative approach was applied whereby the number of clusters was successively increased and evaluation metrics were calculated at each step. Although this does not yield a unique final solution, it at least provides objective metrics to facilitate informed decision-making. Testing for the significance of the resulting clusters using the original data is unwise due to the fact that the clustering is implicitly derived for the source data. Instead, Kruskal-Wallis one-way analysis of variance tests (Kruskal and Wallis, 1952) on the shoreline change metrics and trends (NSM, SCE, EPR and LRR) for each cluster grouping were used to evaluate the robustness of the cluster analysis. Analysis and description of the clusters drew from this review of change metrics and trends, in addition to the relative shoreline positions through the epochs.

4. Results and analysis

4.1. Historical foreshore change

Shoreline recession or progradation rarely occurs through a simple translocation of the cross-shore profile. More often, different elevations within the intertidal zone exhibit different rates of horizontal migration, such that either flattening or steepening of the profile occurs. Steepening of coastal foreshores in response to beach nourishment has been highlighted as a particular concern in Denmark (e.g. Laustrup et al., 2001). More widely, it has been linked to the phenomenon of 'coastal squeeze' (Titus, 1991; Pontee, 2013), whereby landward migration of the high water shoreline (e.g. due to sea-level rise) is checked by either structures or steep and resistant terrain, with the result that the intertidal zone is reduced in width due to migration of the low water mark. Steepening has implications not only in terms of the extent of intertidal habitats, but also the vulnerability of structures and the risk of wave-driven overtopping during storms (e.g. Sutherland and Wolf, 2002).

A macro-scale analysis by Taylor et al. (2004) of 1084 shore profiles around the entire coast of England and Wales indicated that 61% exhibited a tendency towards steepening, based on changes in the positions of MHW and MLW prior to 1901 and after 1945. Higher resolution analysis of foreshore changes in Suffolk shows a similar narrowing and steepening trend between the 1880s and 2010s (Fig. 2). The contemporary median beach width in Suffolk is 15.3 m and 79.5% of the shoreline has an intertidal foreshore width <20 m. The median beach slope is 6.5° ($\tan\beta = 0.11$), with slopes <5° occurring along only 11.8% of the shoreline. In the 1880s, the beaches here were wider and flatter (median width and slope 23 m and 4.7° ($\tan\beta = 0.08$) respectively). Only 37.2% of the 1880s shoreline had a beach width <20 m, whilst 60.1% had a beach slope of <5°. A Kruskal-Wallis one-way analysis of variance was significant for both width and slope, indicating a significant difference in modern and historical beach profile characteristics (width $\chi^2 = 480.66$, $p < 0.001$; slope $\chi^2 = 440$, $p < 0.001$) (Fig. 3A, B). The centennial-scale picture in Suffolk is thus one of decreasing beach widths and increasing foreshore slope. For the entire east coast of England, Taylor et al. (2004) found that 64% of profiles experienced steepening over the last century, but our regional analysis shows that steepening is more widespread in Suffolk with 89% of the coast experiencing a reduction in beach width.

These results are somewhat contrary to the findings from more recent 1991 to 2006 beach profile surveys. These show that half of the Suffolk coastline has shown no significant change, with steepening along only 17% of the coast, and flattening actually being more prevalent (34% of profiles) (EA, 2011). Interestingly, narrowing and steepening at the historical timescale is far more apparent in the south compared to the north. The stretch of coast between the Deben and Alde/Ore estuaries (D-A in Fig. 3C, D) shows greater reduction in width and increase in slope than the rest of the coast. Furthermore, change between the Blyth estuary and Lowestoft (B-L in Fig. 3C, D) is close to zero, with much of the eroding cliff frontage between Southwold and Benacre exhibiting negligible change in foreshore width or steepness. Across the region as a whole, there is no systematic difference in foreshore behaviour between shorelines with or without backshore sea defences (Fig. 3E, F), but cliffed sections tend to be associated with smaller scale changes in foreshore profile (Fig. 3G, H).

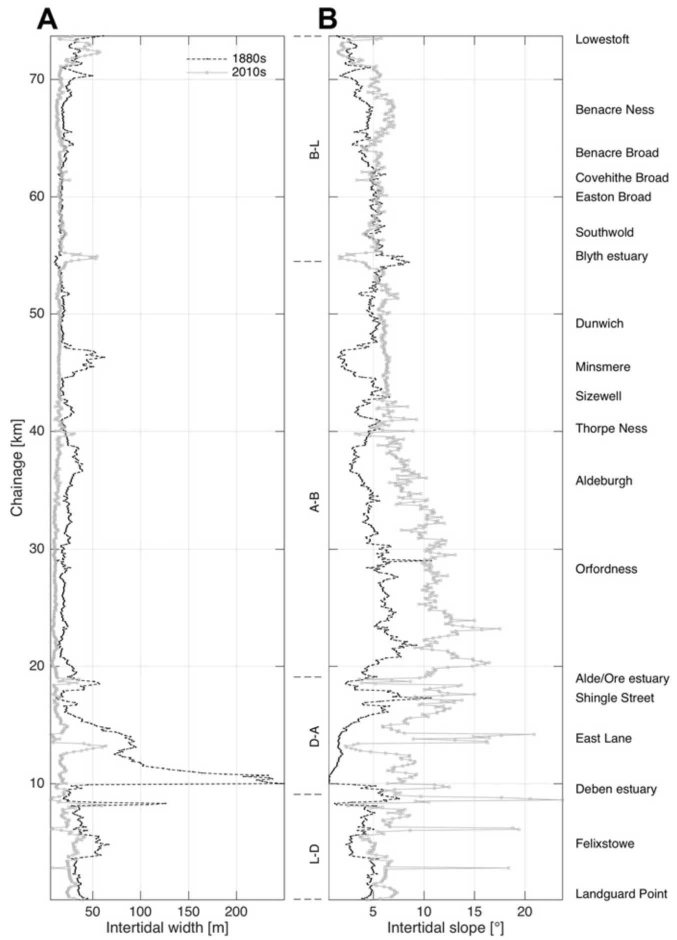

Fig. 2. Change in foreshore width (A) and slope (B) between the 1880s and 2010s. Alongshore is divided into stretches bounded by the main inlets (L-D Landguard to Deben, D-A Deben to Alde/Ore, A-B Alde/Ore to Blyth, B-L Blyth to Lowestoft), which are explored further in Fig. 3.

4.2. Historical shoreline dynamics

At a centennial timescale, the spatial pattern of shoreline variability along the Suffolk coast (the Shoreline Change Envelope, or SCE) corresponds closely with that of the Net Shoreline Movement (NSM) (Fig. 4A–C), implying that progressive and persistent change is more prevalent that cyclical or reversing behaviour. The consistently high rate of erosion of the soft rock cliffs in north Suffolk is significant here; the NSM and SCE are effectively the same for some of these erosion 'hotspots'. More generally, it is clear that magnitude of change (SCE and NSM) is greater for sites that have experienced net erosion than those that have been largely accretional (Fig. 4C, D).

Across much of the Suffolk coast, shoreline changes have been subtle, with rates of retreat or advance typically $<0.5 \pm 0.08$ m year^{-1}. This baseline, representing around 62% of the shoreline, is interrupted at a few discrete locations where rates of change are substantially greater, and where large-scale shoreline recession or advance has taken place. The most dynamic part of the Suffolk coast lies in the north (Fig. 4) where alternating stretches of cliffs and barrier beaches north of Southwold exhibit similar rates of rapid recession. The MHW shoreline here has retreated by up to 590 m since 1881, which equates to a maximum net retreat rate of 4.6 ± 0.09 m year^{-1} at the north end of the Southwold to Benacre Broad stretch. Retreat in the late 19th and early 20th century was associated with the reshaping and northward migration of the low sand and gravel foreland of Covehithe Ness into Benacre Ness (Burningham and French, 2014). The cliff-barrier hinterland exposed by this shift in the position of the foreland has subsequently eroded and retreated.

Shoreline progradation has occurred more locally and has not matched either the overall magnitude or instantaneous rates of change of erosion elsewhere. The most marked seaward progradation has been associated with the northward movement of the sand-gravel foreland of Benacre Ness (south of Lowestoft). Beach ridge deposition 2 km south of Lowestoft marks the northward migration of this foreland and the maximum shoreline advance here has been 282 m since 1881. In terms of land area, erosion and progradation are not in balance, either locally or across the region. The 8.8 km section from Southwold to the south of Benacre Ness has a mean recession rate of 2.6 ± 0.09 m year^{-1} (mean net shoreline recession of 337 m since 1881), whereas the 3.7 km section immediately to the north (Benacre Ness) has a mean progradation rate of 1.3 m $\pm$ 0.09 m year^{-1} (mean net progradation of 166 m since 1881).

Extended stretches of comparable change are also evident in the general landward recession of the low barrier shoreline between the Blyth and Dunwich (see also Pye and Blott (2009)), erosion of the apex of the Orfordness gravel foreland, and retreat south of Shingle Street. In all these cases, persistent retreat has considerably modified the shoreline planform. The embayment north of Dunwich has become more indented, the formerly acute tip of Orfordness has become more rounded, and the small promontory south of Shingle Street has been reduced.

Progradation has been very localised, with no other sites matching the scale of change seen at Benacre Ness. Of particular note are the accumulations (and associated shoreline offsets) to the north of the inlets of the Blyth, Deben and the Stour/Orwell estuaries. In the case of the Blyth, a distinct offset north and south of the two inlet jetties has developed due to accretion on the north and erosion on the south side of a fixed channel under a net north to south littoral drift. At the Deben inlet, backshore progradation updrift (to the north) and downdrift erosion (to the south) is also evident. The ebb tidal delta exhibits considerable variability over decade-century timescales (Burningham and French, 2006) and the lack of jetties means there is greater potential for sediment bypassing here. North of the inlet, the foreland is partially fixed by sheet piling installed in the early 1950s. Groynes provided further control on sediment movement in the 1960s–1980s, but are presently ineffective. To the south, an earth embankment protects a low-lying hinterland. A shift of the ebb channel to the southwest has necessitated the installation of rock armour in several phases since 2001. Sediment accumulation north of the inlet is implicated in this ebb channel migration, and the erosion of the shoreline to the south. But this behaviour is part of an ebb delta cycle that appears to have operated with a 10–30 year period for at least the last 150 years (Burningham and French, 2006).

Comparison of retreat rates at the centennial and recent decadal scale (Figs. 4D, E; 5) shows significant changes in behaviour within the region, but there are locations such as Southwold and Aldeburgh where changes are consistent across scales. Trend magnitudes at the decadal scale (1990 to 2015) exceed those at the centennial scale (1881 to 2015) at 69% of transects. This is partly explained by more rapid change in the last two decades (comparison of 1881–1990 rates with 1990–2015) (Fig. 5E), which is evident at 83% of this sub-set of transects (58% of the total coastal length; Fig. 5). In other words, changes since 1990 are far greater than those experienced throughout much of the 20th century. The envelope of change (SCE) for the 109 years prior to 1990 exceeds that experienced in the 25 years since 1990 along much of the coastline (82%), as might be expected (Fig. 5E). There are some sites where this is not the case, notably in the vicinity of the major forelands or protrusions, primarily at Benacre Ness, but also north and south of Orfordness and Thorpe Ness.

Shoreline change time-trend reversals are evident along nearly half of the coastline. Thus, 21% of the shoreline that showed net retreat between 1881 and 1990 have experienced progradation since 1990. At

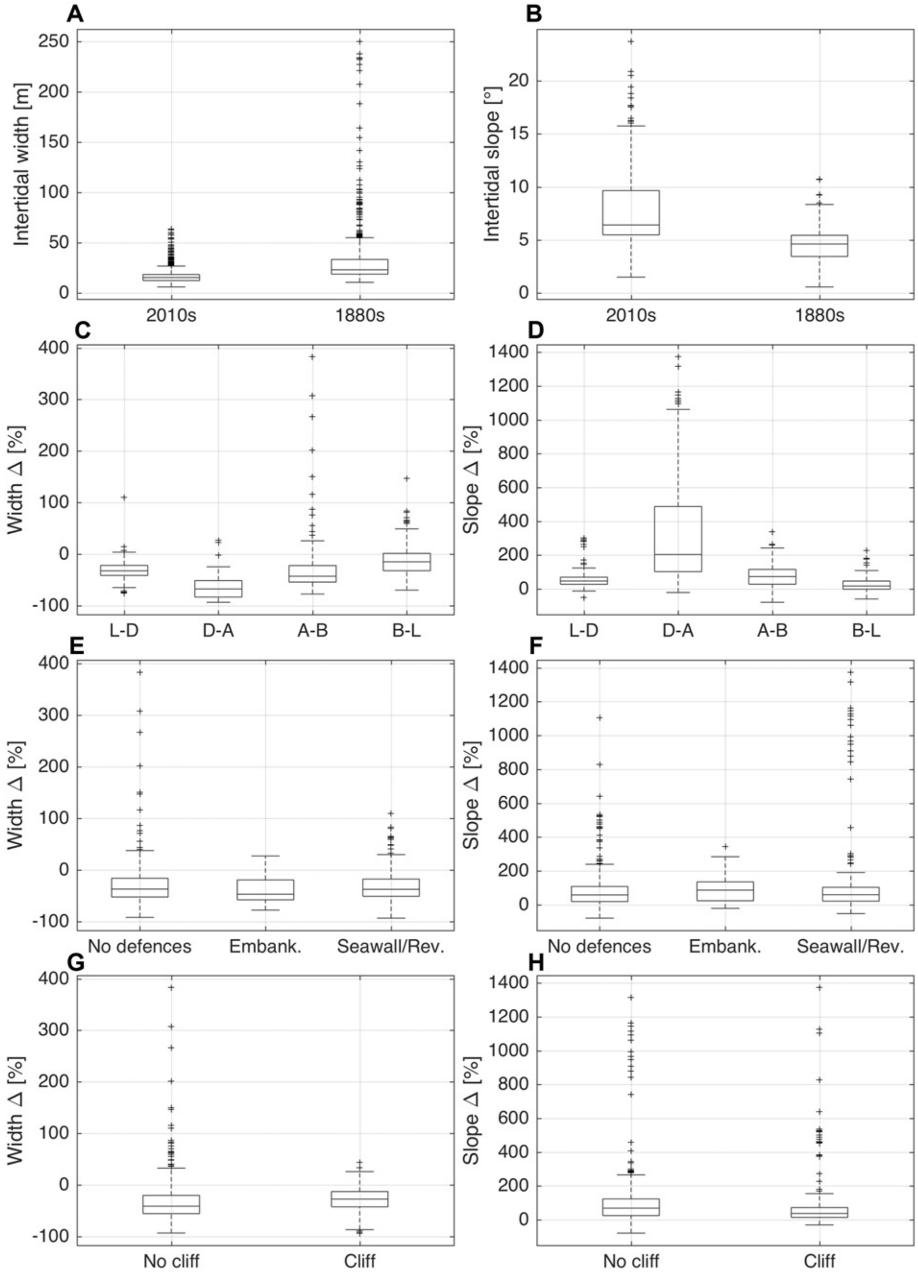

Fig. 3. Comparison of foreshore width and slope between the 1880s and 2010s (A,B) and historical change in these between different coastal stretches (as defined in Fig. 2) (C,D), and presence/absence of sea defences [flood embankments and seawalls/revetments] (E,F) and cliffed backshore (G,H).

the same time, 27% of sites showing advance prior to 1990 have since retreated. Much of the Felixstowe frontage prograded slightly through the 20th century but has more recently undergone recession prompting significant investment in new defences (EA, 2011). Similarly, the Aldeburgh to Thorpeness shoreline shows long-term progradation followed by recent erosion. The current recession at these sites is well within the envelope of advance since the 1880s. In contrast, the well-documented erosion of the Minsmere-Dunwich cliffs throughout the last millennium (Sear et al., 2011) appears to have ceased in the late 20th century, with only minimal change over the last 25 years. The barrier shoreline north of Dunwich similarly shows a slowdown in retreat over this time frame (as also noted by Pye and Blott (2009)). This is interesting since a management practice of re-profiling the barrier to reduce the risk of flooding also ceased in the early 2000s. Further south, erosion along the barrier coastline between Aldeburgh and Orfordness has decreased. Here, substantial accumulation is currently occurring just north of Orfordness, where it has reversed the erosional signature of the preceding century (Fig. 5C, D). The abundance of gravel along this beach has led to its use as sediment source for recharge works south of Aldeburgh, where narrowing of the gravel barrier has created a risk of breaching (EA, 2011).

Perhaps the most significant shifts in coastal behaviour are found around Benacre Ness. Between 1881 and 1990, the foreland migrated about 2.1 km north, shown by the peak in positive shoreline trend for 1881–1990. Sediment removal from the southern margin of the foreland, in addition to recession of the hinterland, contributed to maximum retreat rates along the coast previously occupied by the foreland. There is also evidence of erosion along the shoreline immediately north of the foreland. Continued migration of the foreland over the most recent decades is evidenced by a northward shift in the location of the peak positive shoreline trends (Fig. 5D). It seems clear that foreland

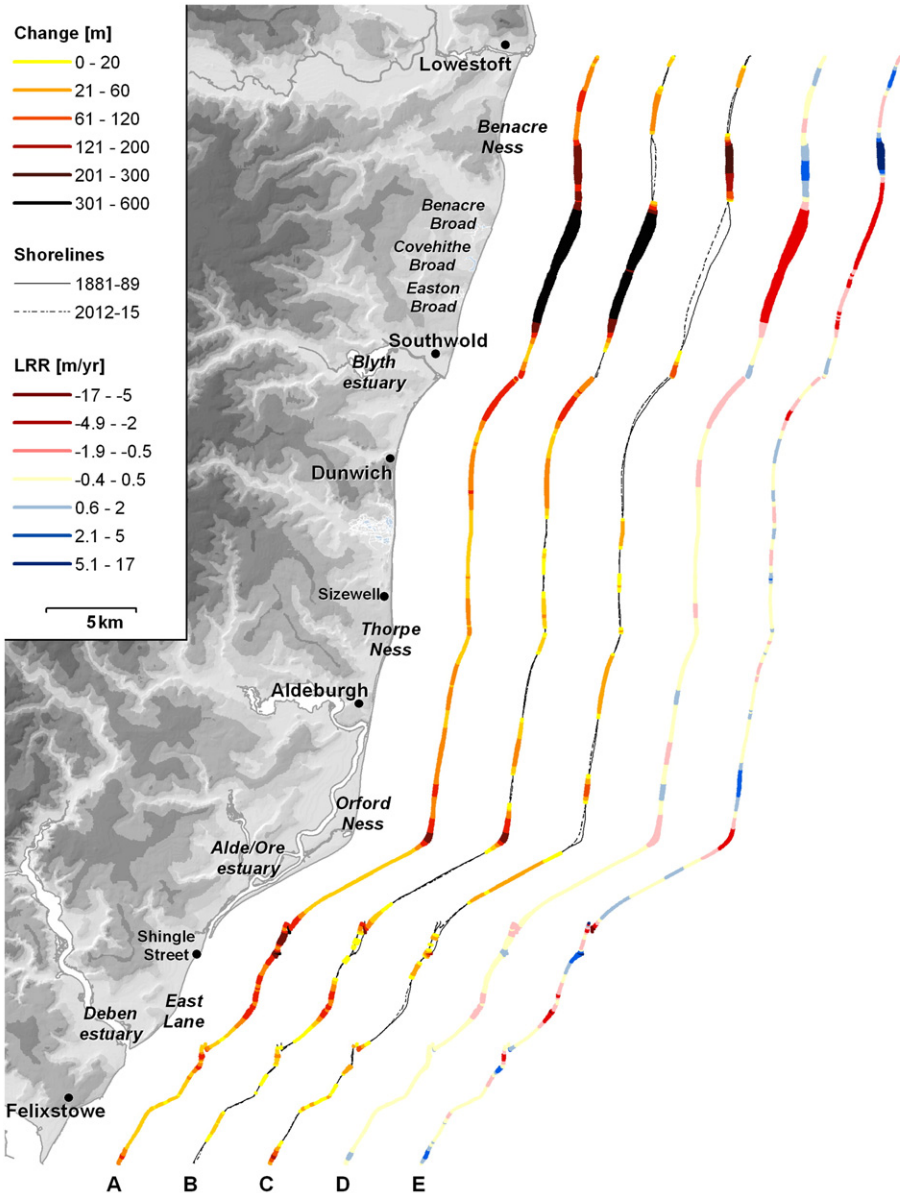

Fig. 4. Shoreline change analysis for Suffolk, showing A) shoreline change envelope (SCE), B) net shoreline recession (−ve NSM), C) net shoreline advance (+ve NSM), D) average rate of change (LRR) for 1881 to 2015 and E) average rate of change (LRR) for 1990 to 2015.

movement encourages a wave of shoreline recession in advance of the accretion associated with the foreland deposit.

4.3. Cluster-based shoreline segmentation to resolve modes of coastal behaviour

Although shoreline change analysis quantifies rates and directions of change, further analyses are needed to resolve distinct modes of coastal system behaviour. Cluster analysis of multi-decadal changes in shoreline position between 1881 and 2015 resulted in three primary clusters that capture the gross characteristics of coastal behaviour in Suffolk (Fig. 6). Unsurprisingly, widespread and rapid erosion in the north of the region exerts a strong influence on the groupings, leading to two clusters representing different magnitudes of retreat along 9% of the shoreline (cluster A – very rapid; cluster B – rapid), and the remaining cluster (C) representing varied styles of change across the remaining 90% of coastline (Table 2). Clusters A and B differentiate between the extreme rates of erosion (4 ± 0.5 m year^{-1} (A)) due to the combined movement of the low Benacre Ness foreland and cliff-barrier erosion (Fig. 7A) between Covehithe Cliffs and Boathouse Covert (Fig. 5), and the significant rates of recession (2.5 ± 1 m year^{-1} (B)) along the stretch of coastline that has not accommodated the migrating Benacre Ness over the last century (Fig. 7B). The shoreline change statistics associated with this initial classification show significant differences between clusters (Fig. 6).

A second stage of cluster analysis was applied to cluster C in order to distinguish other behaviours (the use of a larger number of clusters in the primary analysis simply divided clusters A and B further due to their much larger magnitudes of change). This generated eight further clusters that reflect more subtle differences in shoreline behaviour not evident in the primary classification. The clustering performs well in its recognition of magnitudes and directions of change (Fig. 6). Cluster D comprises a large number of sites where retreat is the clear centennial-scale signature despite the relatively small changes (Fig. 7D). This includes sites such as the Dunwich to Blyth shoreline, and north and south of East Lane, where retreat rates have changed over the last century. A large proportion of the shoreline is classified as cluster E. This resolves small-scale changes where there is less evidence for a sustained

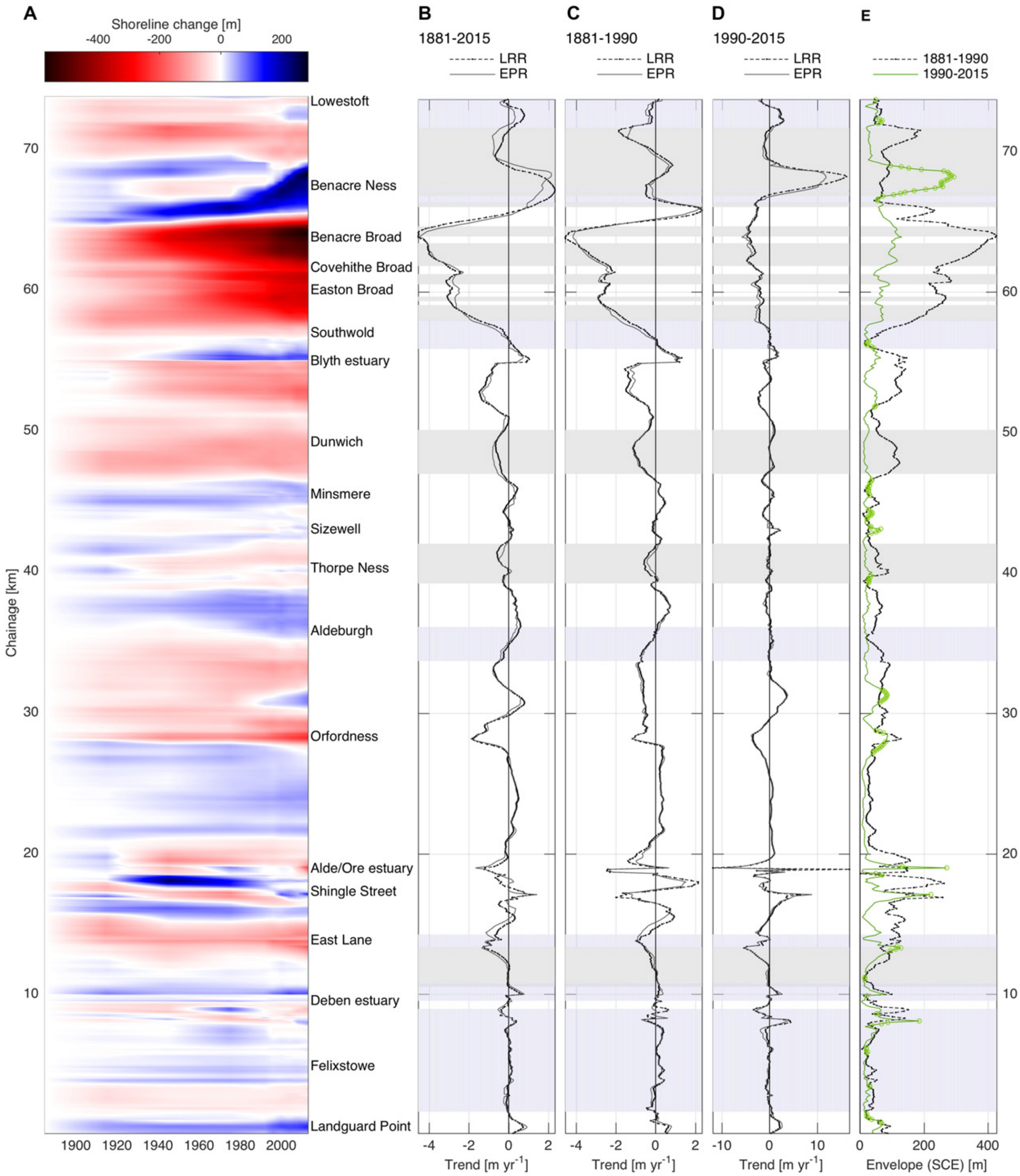

Fig. 5. Time series heat-map for Suffolk showing relative change in shoreline position since the early 1880s (A) compared with shoreline trend metrics (EPR and LRR) (right), covering the period 1881 to 2015 (B), 1881 to 1990 (C), 1990 to 2015 (D) and comparison of shoreline change envelopes (SCE) between the periods 1881–1990 and 1990–2015 (E). Note the change in scale between B/C and D. Grey shading highlights the location of unprotected cliffs and stippled shading delineates defended backshores (e.g. seawall, revetment). Highlighted data points in E show locations where the recent (25 years) change envelope exceeds that of the preceding 110 years.

significant trend (Fig. 7E) such as at Sizewell, site of a nuclear power plant. As shown in Table 2, the remaining classes recognise more localised behaviour where change is non-linear and reversals in shoreline trend are often evident (Fig. 7F–K). Much of these relate to the Benacre Ness foreland (Burningham and French, 2014) where shorelines have advanced and then retreated (clusters F, G, and J) or retreated and then advanced (cluster H and to some extent I). The alongshore sequence of these clusters, from south to north, is J, G, F and I (Fig. 6), and the time series show that the peak in shoreline advance progresses from the early 1900s (cluster J), through the mid- (cluster G) to late-20th century (cluster H), to the most recent locus of shoreline progradation (cluster I). The envelopes of change associated with the migration of this foreland feature are far wider than experienced along most of the coast (clusters D and E). The mid-century growth followed by late-century recession of cluster G also reflects changes around the Shingle Street foreland just south of the Alde/Ore estuary. Cluster analysis effectively distinguishes between sites at which similar net shoreline movement at the centennial scale arises through different behaviours. This is exemplified by a comparison between clusters J and K (secondary clusters). Both are erosional, but not at the scales

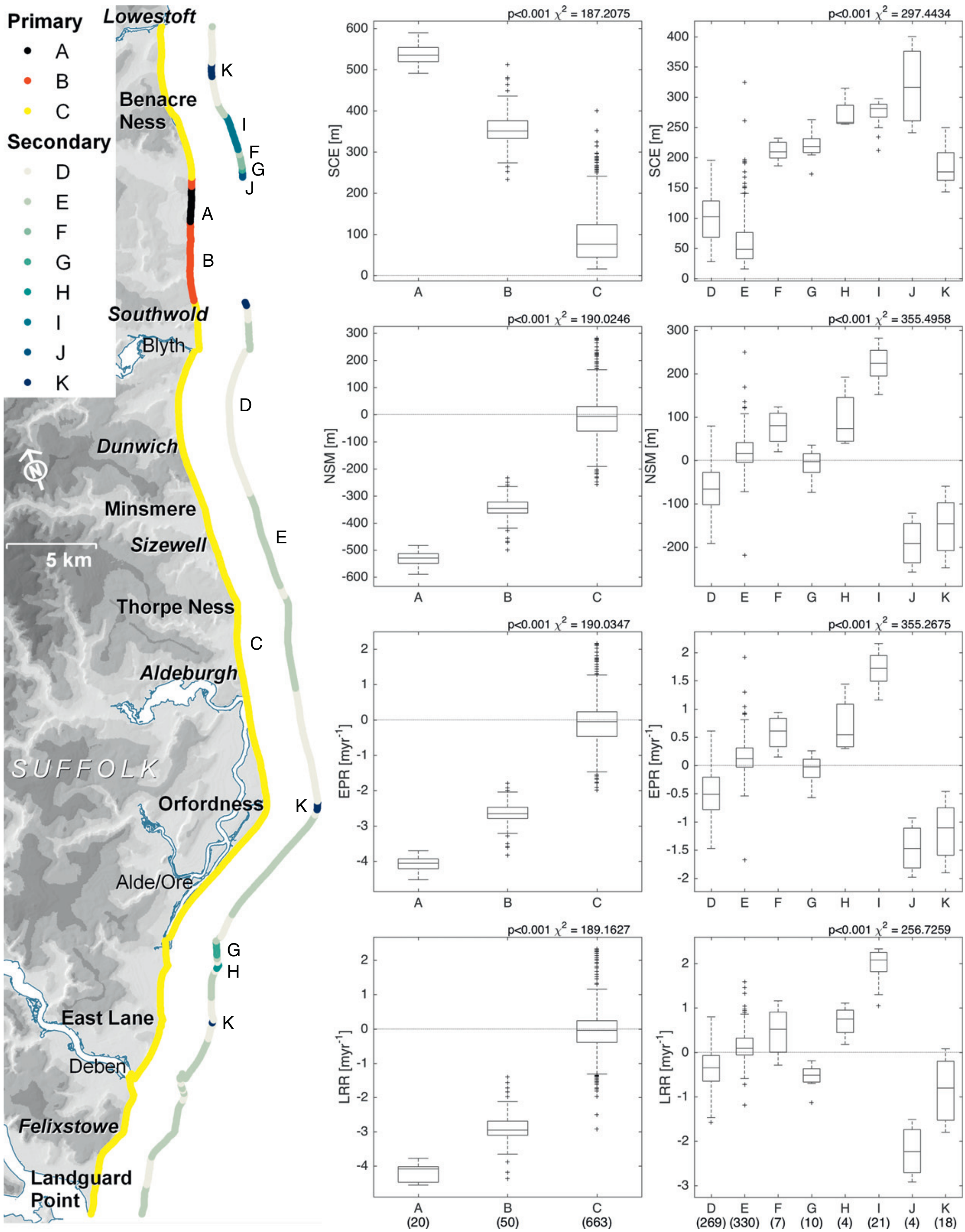

Fig. 6. Classification of shoreline behaviour between 1881 and 2015 (multi-decadal timescale): shoreline transects are classified spatially (left) and the shoreline change statistics for each cluster are summarised (centre – primary clusters; right – secondary clusters). Clusters D to K are derived through a cluster analysis of those transects grouped in C of the primary cluster analysis. Time series of relative shoreline position for these clusters in shown in Fig. 7.

represented by cluster A and B (primary clusters), and are non-linear. Sites in cluster K (Orfordness, East Lane and north of Benacre Ness) show varying rates of recession whereas those in cluster J show advance followed by recession.

Cluster analysis applied to intra-decadal shoreline changes since 1990 also yields a primary classification of three clusters (Fig. 8). Again, extreme shoreline changes are the basis for the first level clustering, but the recent behaviour is dominated by large-scale accretion (Table 3). Clusters A and B pick out significant progradation (>5 ± 0.05 m year^{-1}) at sites that exhibit non-linear trends. The clusters are differentiated by the intra-decadal rates of change (cluster A – progressive; cluster B – recent and rapid) and timing of maximum seaward

Table 2
Classification of multi-decadal (covering 1881 to 2015) shoreline behaviour of Suffolk derived from hierarchical cluster analysis, where % shows the proportion of coastline classified in each cluster and Δ expresses the direction of change (+ve is accretional and −ve is erosional). See Figs. 6 and 7 for supporting analysis.

	Cluster i	Cluster ii	Location	%	Coastal behaviour	Δ
Primary	A		Benacre Broad/cliffs	3%	Progressive, significant, large-scale (>500 m) retreat since the 1880s. Rates of retreat are in the order of 4–4.6 m $year^{-1}$, which are statistically significant negative linear trends ($\|r\| > 0.5$; $p < 0.05$).	−ve
	B		North Suffolk cliffs-barriers (Southwold to Benacre)	7%	Progressive, significant, recession of 300–500 m since the 1880s. Rates of retreat are in the order of 3–4 m $year^{-1}$, which are statistically significant negative linear trends ($\|r\| > 0.5$; $p < 0.05$).	−ve
	C		Remaining coast	90%	Variable, but notably smaller-scale change. This grouping is explored further in the secondary classification.	~
Secondary		D	Several including Dunwich, Aldeburgh to Orfordness, N/S of East Lane	36%	Quite variable scales of change, with some reversals in shoreline change direction, but at the centennial scale, notably erosional with rates in the order of around 0.5 m $year^{-1}$.	−ve
		E	Remaining coast	45%	Small-scale change, resulting in little net shift in shoreline position over historical time-scales. Limited evidence for statistically significant trends; rates of change are less than ± 0.5 m $year^{-1}$.	~
		F	Benacre Ness	1%	Significant mid-20th century shoreline advance followed by more recent reversal, resulting in $\|NSM\| < SCE$. Behaviour is almost opposite of F, with similar NSM but smaller envelope of change. Century-scale progradation is in the order of 0.5–1 m $year^{-1}$.	+ve
		G	Benacre Ness, Shingle Street	1%	Similar envelope of change to F, but the maxima in shoreline advance had occurred by 1950, with persistent erosion since, leading to limited EPR rates of change, but an average negative trend over the century with rates in the order of 0–1 m $year^{-1}$.	−ve
		H	Shingle Street	1%	Relatively small rates of positive change (0.5–1 m $year^{-1}$) owing to cycles of advance, retreat, advance, leading to much larger envelope of change (250–300 m) than net movement (50–150 m).	+ve
		I	Benacre Ness	3%	Significant shoreline advance, with some evidence of temporally variable rates and directions of change. These sites exhibit net historical progradation by 150–275 m. Statistically significant positive ($\|r\| > 0.5$; $p < 0.05$) linear trends in the order of 1.5–2.5 m $year^{-1}$.	+ve
		J	Benacre Ness	1%	Mid-20th century advance followed by more recent retreat resulting in a large envelope of change (250–400 m) in shoreline position, and average retreat rates in the order of 2–3 m $year^{-1}$, despite the reversal in direction of change.	−ve
		K	Benacre Ness, Orfordness	2%	Similar net change to J; distinctly erosional with limited reversals but non-linear trends and a reduced envelope of change (150–250 m) leading to smaller average historical trends of 0.5–1.5 m $year^{-1}$.	−ve

progradation (cluster A – 1995 to 2005; cluster B – 2005 to present) (Fig. 9A, B). As at the centennial-scale, clusters A and B resolve aspects of the alongshore movement of the Benacre Ness foreland. Cluster C, which represents 98% of the remaining coast, covers a range of behaviours. A second level cluster analysis on sites included in cluster C generated four further clusters that identified primarily erosional stretches of coast (cluster D), shorelines exhibiting minimal change (cluster E), stretches with progradation at a smaller scale than clusters A and B (cluster F), and a final 'cluster' comprising just the North Weir Point shoreline at the mouth of the Alde/Ore estuary (cluster G).

Just 7% of the Suffolk coast as a whole shows significant progressive retreat at rates of 4 to 5 ± 0.08 m $year^{-1}$ at this intra-decadal time-scale (Fig. 9A, B). As with the centennial-scale analysis, this rapid erosion category captures most of the north Suffolk cliff-barrier shoreline. Unlike the longer-term perspective, however, it also incorporates Orfordness (where the beach ridge foreland has recently retreated) and East Lane (where the rate of erosion into the low cliffs to the south has rapidly increased since extension of rock armour protection here). Most of the Suffolk shoreline (90% represented by cluster E) has experienced small-scale shifts in position since 1990 that display no significant trend or cyclicity (Fig. 9E). Smaller scale coastal advance captured in cluster F again reflect alongshore movement and reshaping of the sedimentary forelands, notably at Benacre Ness and Shingle Street (Fig. 9F). Cluster G, where large-scale recession has occurred since 2005, describes the southern tip of Orford Spit that has historically experienced significant episodes of growth, recession and breaching (Fig. 9G) (Burningham, 2015).

5. Discussion

5.1. Attribution of large-scale coastal behaviour

Broad-scale analysis of changes in shoreline position has the potential to highlight the role of regional forcing on large-scale coastal behaviour (e.g. long-term tidal cycles (Gratiot et al., 2008) or sea-level rise (Zhang et al., 2004)) in addition to identifying distinct 'hotspots' of contrasting behaviour (e.g. McNinch, 2004; Hapke et al., 2010). These insights are more readily achieved through analysis at high temporal as well as spatial resolution. The Suffolk shoreline dataset examined here allows an unusually comprehensive synthesis of historical shoreline change, supported by a good distribution of evidence spanning the last 135 years, and more frequent surveys over the last 25 years. Moreover, the data can be analysed at high spatial resolution (100 m alongshore interval) along the entirety of a 74 km shoreline.

The evidence for strong met-ocean forcing is ostensibly compelling (Fig. 10). The highly bimodal wave climate has clearly exerted a strong control on sediment movement alongshore, with the multi-century development of Orford Ness and Orford Spit driven by sediment supply from the north and a net southerly drift (Burningham, 2015). Although there is no direct evidence for significant long term trends in wave climate (Fig. 10A, B), the relative frequency of northeasterlies and southwesterlies (Fig. 10C) closely follows that in the local wind climate (Fig. 10D), the southwesterly component of which is to some extent comparable to the NAO index (Fig. 10E). This implies at least some degree of regionally coherent forcing that could lead to phases of south- or north-directed sediment transport associated with the large-scale shifts in North Atlantic weather systems. Sea-level rise is also an obvious factor to consider and the multi-decadal trend recorded at Lowestoft since the 1950s averages 2.5 mm $year^{-1}$, with some suggestion of an increase in the rate to 3.4 mm $year^{-1}$ since 1980 (Fig. 10F). Surge events are important on this coastline (Fig. 10G), and the 1953 North Sea storm surge is a well documented example of the potential of elevated water levels on the coasts of the southern North Sea (Baxter, 2005). A similar event in 2013 raised water levels at Lowestoft by 2.18 m on top of the predicted high water causing some erosion and extensive flooding (Spencer et al., 2015), although erosion was limited by the relatively calm wave conditions associated with this event. Nevertheless, elevated surge water levels are known to be important drivers of longer term dynamics on sedimentary shorelines (Chaverot et al., 2008).

As the preceding analysis has shown, there is relatively little regional coherence in the behaviour of the Suffolk shoreline. On the basis of a localised analysis, it might be tempting to link the rapid erosion in

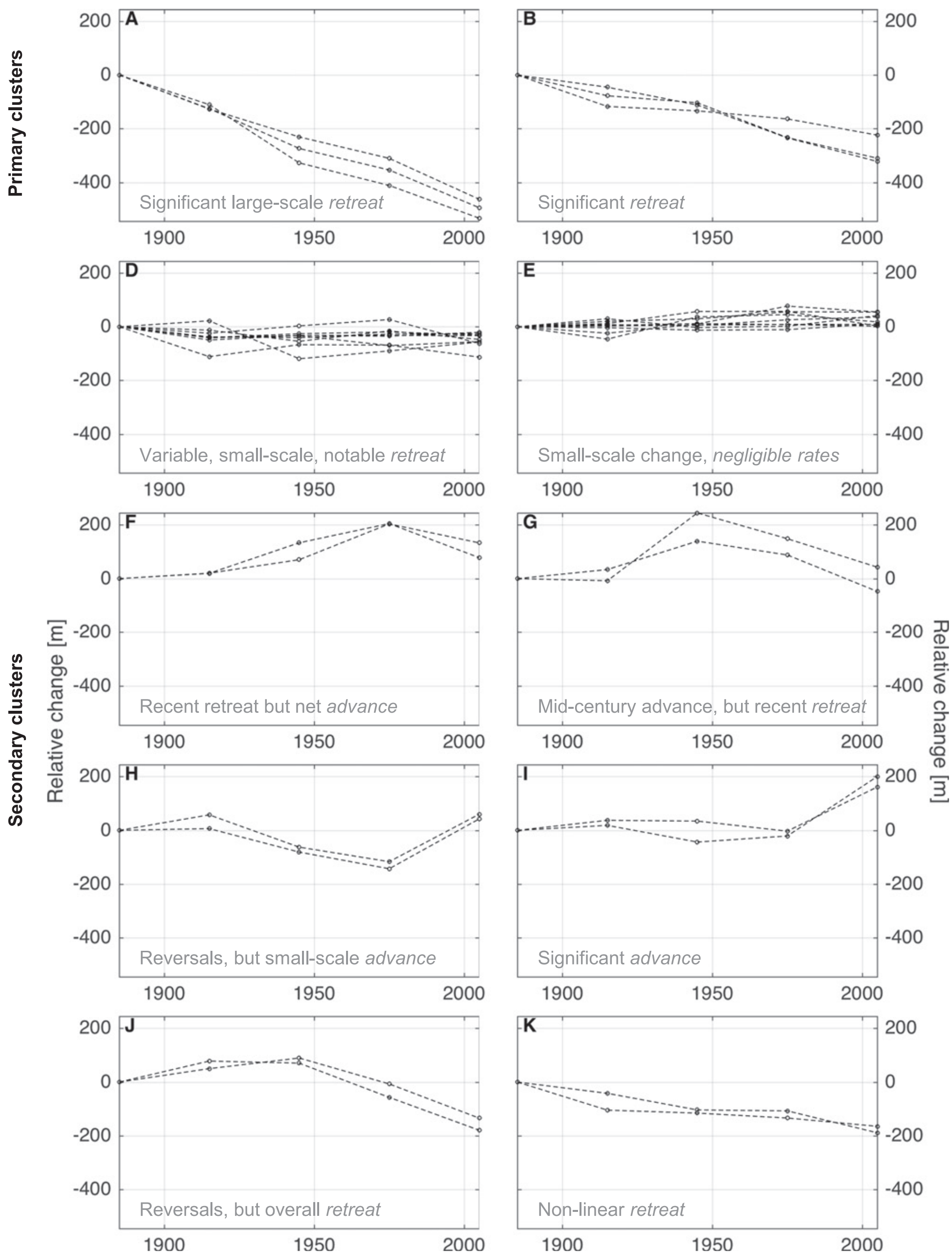

Fig. 7. Time series of relative shoreline position that characterise the primary (A and B) and secondary (D to K) clustering of multi-decadal-scale (1881–2015) shoreline behaviour as defined in Fig. 6.

north Suffolk to a rising sea level, but such a direct causal linkage between forcing and coastal behaviour is not consistently manifested throughout the region. Similarly, although Brooks and Spencer (2014) allude to a direct link between the NAO and rate of recession in the cliffs of Norfolk and Suffolk, the analysis presented here suggests that this association is neither regionally consistent nor significant. As the cluster-based segmentation reveals, a large proportion of the coast is characterised by variable, but small-scale change at the centennial timescale. Even at the level of detail attainable in this analysis, there is insufficient spatial or temporal structure to the signature of shoreline change to support attribution to specific external forcings. Rather, cluster analysis reveals a broader suite of long-term behaviours that include persistent erosion or accretion at different rates, as well as trend reversals over time. At a recent intra-decadal time-scale, a different suite of behaviour is evident, suggesting that the forcing of coastal change at the centennial scale is somewhat different to that at the intra-decadal scale. This might be interpreted as a form of time-dependent complex response of the kind envisaged by Schumm and Lichty (1965), whereby changes over shorter timescales are inherently associated with tighter cause-effect linkages at smaller spatial scales, and broader trends emerge over longer time-scales. Equally, differences in centennial and intra-decadal behaviour might reflect a shift in forcing over the last 135 years, perhaps linked to an increase in the rate of sea-level rise, or a change in storminess. But the timescale dependence also varies spatially, which might reflect an interweaving of climate and anthropogenic (management and intervention) factors.

The fact that contrasting modes of behaviour can be found in such close proximity suggests that local influences may be particularly important in Suffolk. Where prograding stretches are adjacent to retreating stretches, alongshore movement of sediment is often implied. This is most evident along the Easton Bavents (retreat) to Benacre Ness (advance) section, but also seems to be the case at Orfordness (retreat)

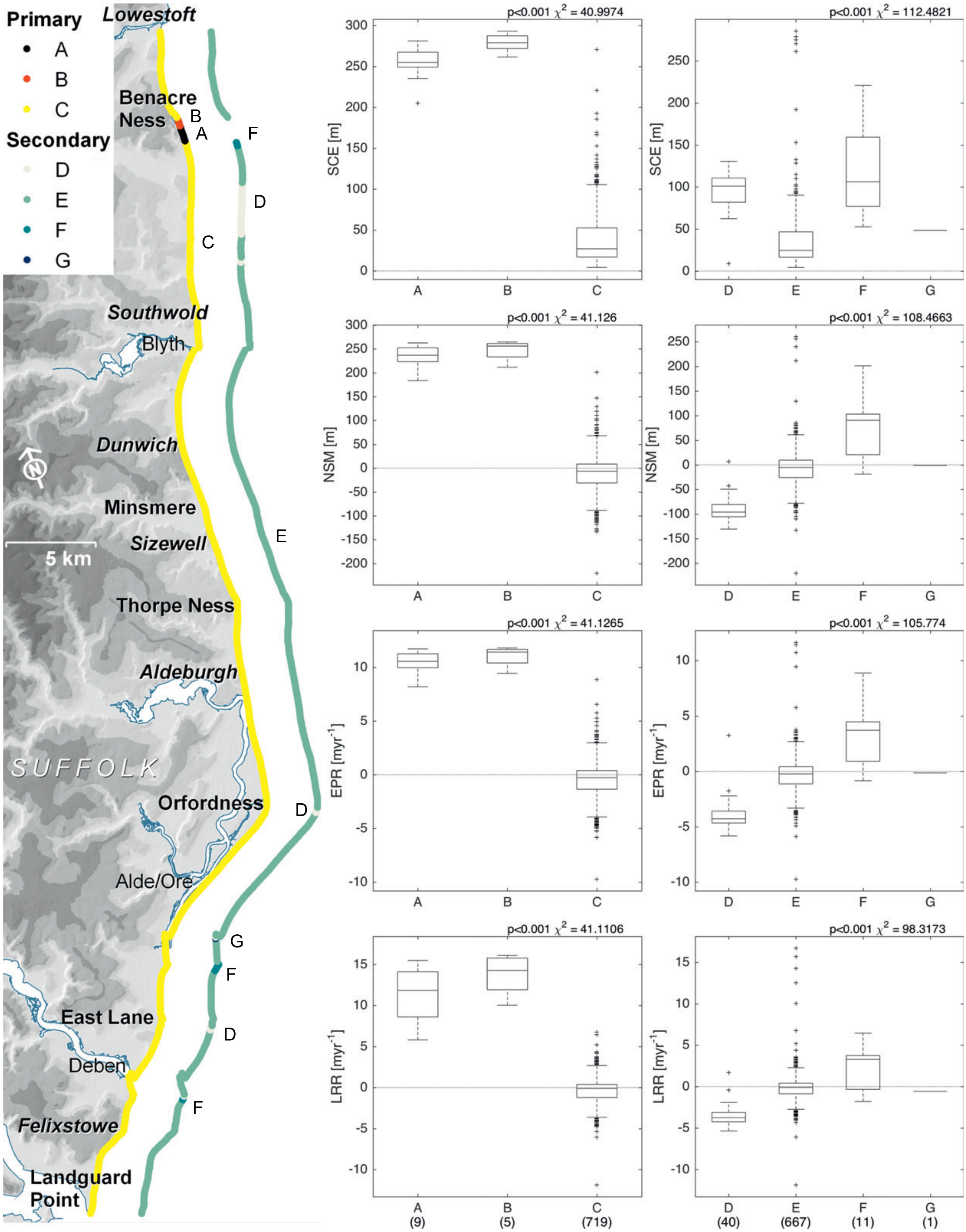

Fig. 8. Classification of shoreline behaviour between 1990 and 2015 (intra-decadal timescale): shoreline transects are classified spatially (left) and the shoreline change statistics for each cluster are summarised (centre – primary clusters; right – secondary clusters). Clusters D to G are derived through a cluster analysis of those transects grouped in C of the primary cluster analysis. Time series of relative shoreline position for these clusters in shown in Fig. 9.

and just to the north (advance). Both these transitions in behaviour suggest localised net littoral fluxes of sand and gravel to the north, in contrast to the more prevalent flux to the south (SNSSTS, 2002; Burningham and French, 2016). These localised instances of coupled behaviour have led to a distinct net change in regional shoreline planform over the last century. As shown in Fig. 11A and B, large stretches of the shoreline exhibit distinct rotation at a centennial timescale. At Orfordness the relatively sharp apex of the 1880s cuspate foreland has been rounded, and the shoreline to the south has consequently rotated anti-clockwise whilst the shoreline to the north has rotated similarly clockwise. Rotation is also apparent around estuary mouths, where progradation has preferentially occurred on the updrift margin of inlets.

Table 3
Classification of recent, intra-decadal (covering 1990 to 2015) shoreline behaviour of Suffolk derived from hierarchical cluster analysis, where % shows the proportion of coastline classified in each cluster and Δ expresses the direction of change (+ve is accretional and −ve is erosional). See Figs. 8 and 9 for supporting analysis.

	Cluster I	Cluster ii	Location	%	Coastal behaviour	Δ
Primary	A		Benacre Ness	1%	Large-scale advance that has been more progressive over the last 25 years than that experienced in (B). Rates of progradation are in the order of 5–15 m year^{-1} ($|r| > 0.5$; $p < 0.05$) with some evidence of very recent small-scale retreat.	+ve
	B		Benacre Ness	1%	Significant, very large-scale advance over the most recent decade following near stability for the previous 15 years. Rates of progradation are in the order of 10–15 m year^{-1} ($|r| > 0.5$; $p < 0.05$).	+ve
	C		Remaining coast	98%	Variable, but notably smaller-scale change. This grouping is explored further in the secondary classification.	~
Secondary		D	North Suffolk cliffs-barriers, Orfordness, East Lane	5%	Progressive, significant, large-scale (c. 100 m) retreat since 1990. Rates of retreat are in the order of 4–5 m year^{-1}, which are statistically significant negative linear trends ($|r| > 0.5$; $p < 0.05$).	−ve
		E	Remaining coast	90%	Small-scale change, resulting in little net shift in shoreline position over historical time-scales. Limited evidence for statistically significant trends; rates of change are less than ± 0.5 m year^{-1}.	~
		F	Shingle Street, Benacre Ness	2%	Distinctly advancing shorelines where most of the growth occurred between 1995 and 2005, followed by some reversals in trend. Despite the reversals, rates of growth are in the order of 2–4 m year^{-1}.	+ve
		G	North Weir Point (Alde/Ore)	1%	Localised, rapid and large-scale recession of > 10 m year^{-1}, here caused by recession of the tip of Orford Spit, at the mouth of the Alde/Ore estuary, over the last 10 years.	−ve

Most of the inlet-margin offsets imply north to south transport, but progradation at Shingle Street (south of the Alde/Ore inlet) and erosion of the southern end of Orford Spit (North Weir Point) illustrates northward transport over recent decades. Sediment transport field experiments from the 1950s–1970s similarly indicate that sediment transport directions are spatially and temporally variable (Kidson et al., 1958; Robinson, 1966; McCave, 1978), and it is likely that significant reversals occur at the decadal timescale.

On the eastern U.S. coast, Lazarus and Murray (2007) analysed 80 km of the northern North Carolina Banks and found that diffusive behaviour dominated decadal-scale shoreline change. Their intra-decadal analysis using spatial smoothing windows of 100–3000 m showed that, along a relatively linear sand-dominated coast, shoreline convexities tended to recede and concavities to accrete. The Suffolk shoreline is more complex in planform but also comprises a number of distinctly convex (positive) seaward protrusions and concave (negative) embayments. Using various alongshore windows to disaggregate regional from local curvature for the 1880s shoreline (Fig. 11C), it seems clear that, in Suffolk, there is no consistent association between planform and centennial-scale coastal behaviour (Fig. 11D). Evidence of diffusive behaviour is found at Orfordness and at the late 19th century location of Benacre Ness (both contribute to regional-scale alongshore convexity, and the former represents significant curvature at small and large scales), which are both foci of historical erosion and have decreased in

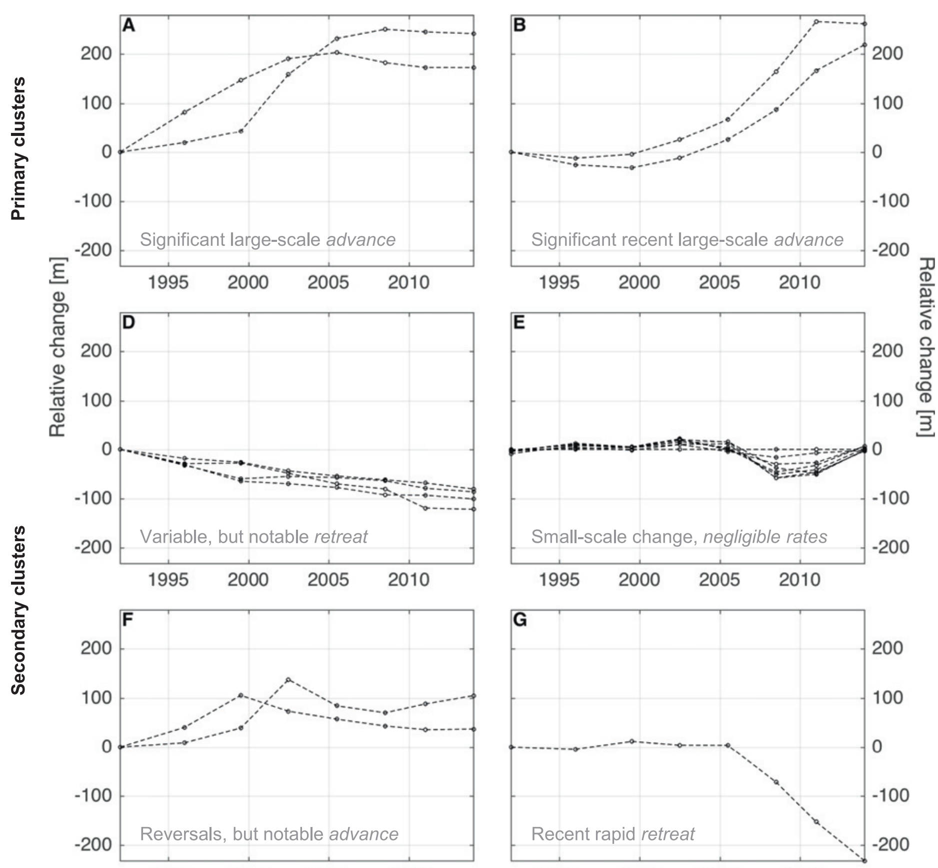

Fig. 9. Time series of relative shoreline position that characterise the primary (A and B) and secondary (D to G) clustering of intra-decadal-scale (1990–2015) shoreline behaviour as defined in Fig. 8.

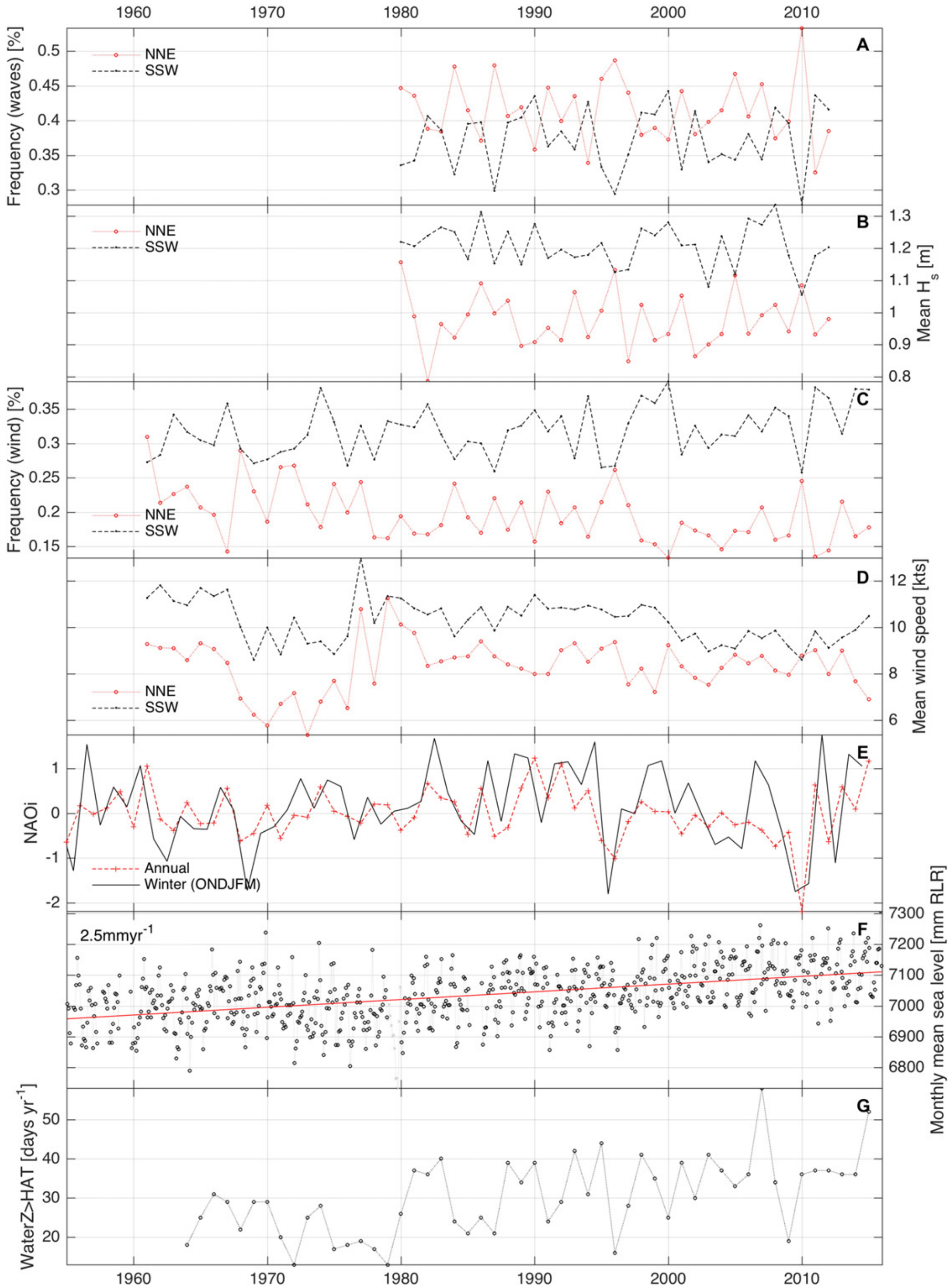

Fig. 10. Temporal variation in available met-ocean parameters: offshore wave frequency (A) and height (B) for the primary direction modes NNE and SSW, wind frequency (C) and speed (D) for the primary direction modes NNE and SSW at Wattisham [c. 33 km northwest of Felixstowe], the North Atlantic Oscillation index [crudata.uea.ac.uk/cru/data/nao] (E), and sea level (F) and surge frequency (G) at Lowestoft.

convexity. However, some concave stretches of shoreline (e.g. Dunwich to the Blyth and Benacre Ness to Lowestoft) exhibit erosional signatures, whilst others (e.g. Aldeburgh to Thorpe Ness) are accretional. Over the more recent history, the regionally convex locations are still associated with sedimentary forelands (Fig. 11E) that continue to show erosional trends (Fig. 11F) but alongshore variability persists. Recent research has shown that variability in the relative dominance of opposing modal wave directions in Suffolk, and their high-angle interaction with the regional shoreline planform can lead to individual years that are variously dominated by either north or south directed sediment transport (Burningham and French, 2016). It is highly probable, given the varying alongshore relationship between wave approach and shoreline bearing, that both diffusive and anti-diffusive ('unstable') behaviour will occur (Ashton and Murray, 2006), and that these will likely change as the shoreline planform adjusts in response to the consequent patterns of erosion and deposition. It is in this aspect of coastal change where the NAO is more likely to impose significant control. Although positive phases of the NAO can promote strong winds (Burningham

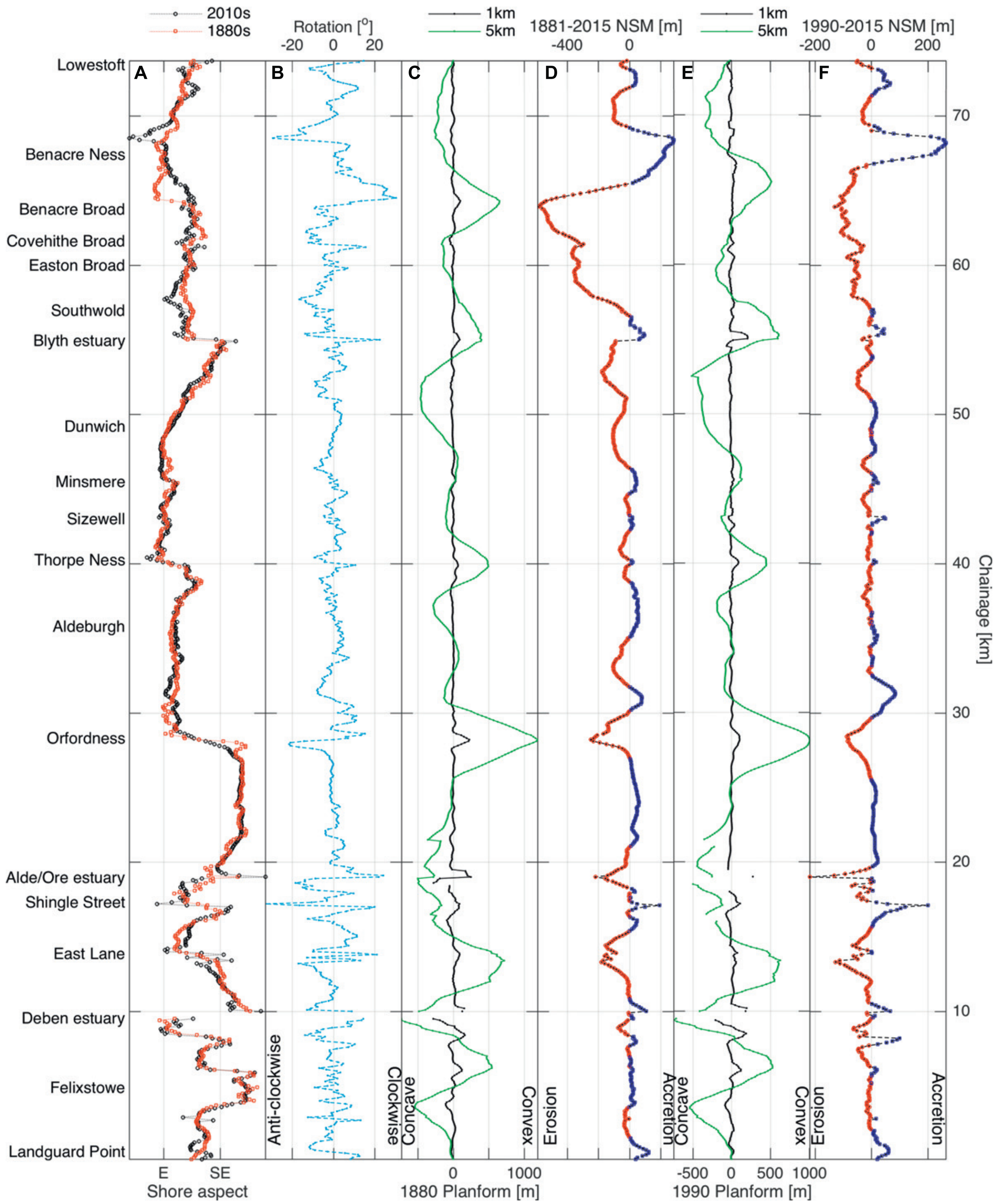

Fig. 11. Centennial-scale change in shoreline aspect (A) and associated shoreline rotation (B) in the context of alongshore planform (calculated over 1 km and 5 km windows) and net shoreline movement 1881 to 2015 (C,D) and 1990 to 2015 (E,F). Accretion and erosion are highlighted as blue and red respectively in subplots D and F.

and French, 2013), high waves (Dodet et al., 2010) and elevated surge levels (Woodworth et al., 2007), it is the relative frequency of northeasterlies and southwesterlies, driving phases of south- or northward dominance in alongshore sediment transport that is perhaps more important for coastal change in Suffolk and elsewhere (see, for example, Dodet et al., 2010; Le Cozannet et al., 2011).

5.2. Importance of geological controls

There is also evidence for longer-term geological control on shoreline behaviour. Unlike the other sedimentary forelands (locally called *nesses*), the beach ridge foreland at Thorpe Ness lies at the base of a small rock headland formed in Pliocene Coralline Crag that outcrops in the nearshore as a subtidal platform (Lees, 1980; Balson et al., 1993). The weak net trends here mask subtle variations in the shape of the foreland, which has become increasingly pronounced (Fig. 12A). This is picked up to some extent in the cluster analysis, which places Thorpe Ness and the coastline immediately to the north, into different clusters (clusters E and D respectively; Figs. 6, 7) that resolve a slightly erosional signature just to the north. Although perhaps not an influence on decadal scale behaviour, it seems likely that the bedrock and nearshore platform provide some degree of anchoring and shelter that controls longer-term behaviour and certainly the very presence of this shoreline protrusion.

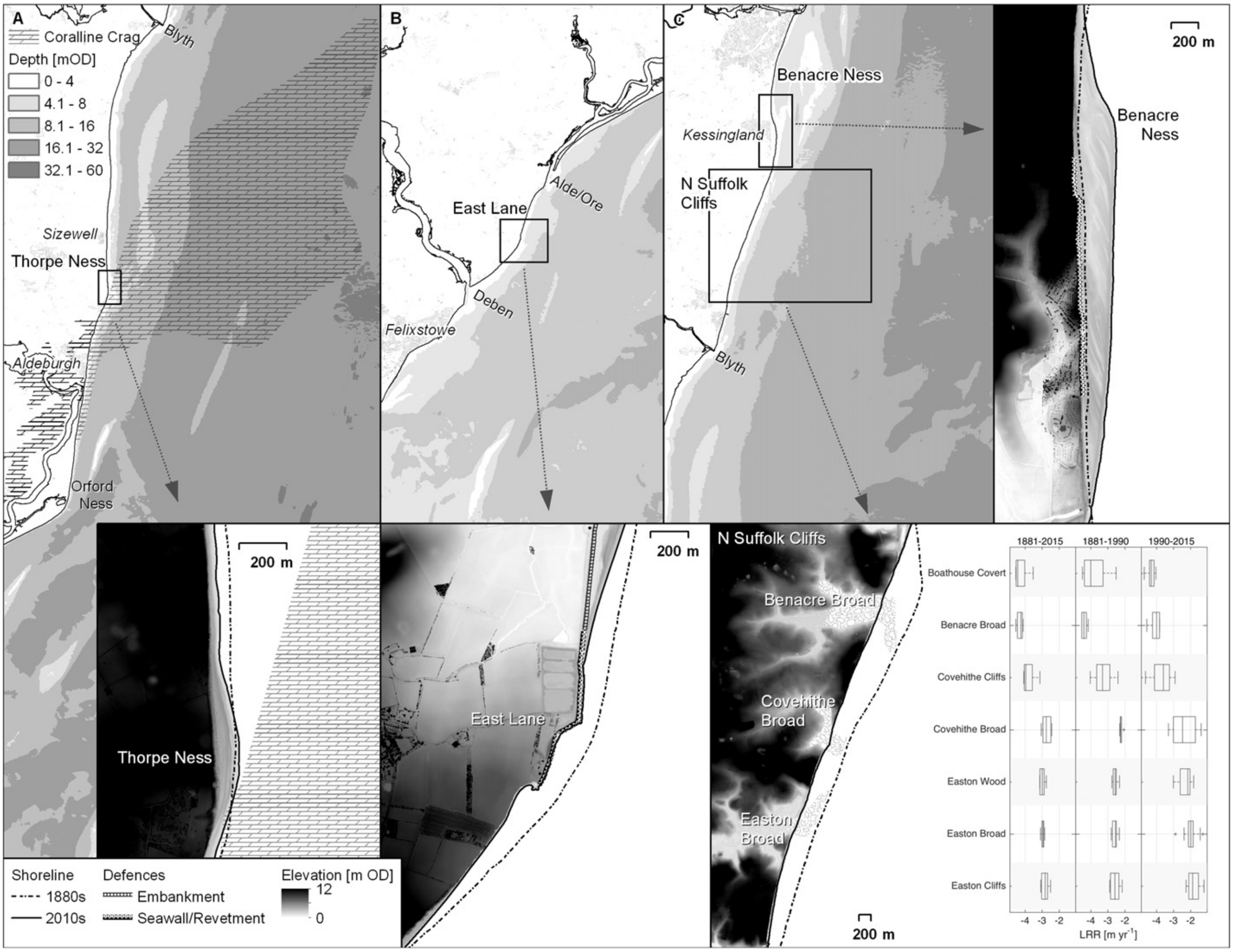

Fig. 12. Shoreline change and structural (geological/defence) context at selected sites: A) Thorpe Ness, B) East Lane and C) Benacre Ness and the north Suffolk cliffs.

5.3. Anthropogenic influences

Coastal defences emerge as a key structural control on coastal dynamics. Much of the developed shoreline around Felixstowe is defended. Groynes have been present since the 1880s, with sea wall construction commencing in the 1900s and several phases of extension, maintenance and re-construction in the decades since to combat declining beach volumes. Shoreline change here has been minimal, which translates into cluster E (negligible change) in both the centennial and intra-decadal analyses. It seems evident that continued retreat around East Lane, midway between the Deben and Alde/Ore estuary inlets, would have initiated a bay had sea defence structures not been deployed from the early 20th century (Fig. 12B). Reports from the mid-19th century describe '*two large 'fulls'* [beach ridges or storm berms], *with fine shingle below, and a solid sandy foreshore*' (Redman, 1864: 197), corroborated by the 1880 maps that depict a 100 m shingle backshore and upper foreshore fronted by 40–50 m of sandy lower foreshore. Groynes were installed in the late 19th/early 20th century along approximately 600 m, but by the 1920s they were supplemented with revetments that have subsequently been modified and extended to protect low-lying farmland and a gun emplacement constructed during WWII (Kelly and Hawkins, 2009). Currently, around 850 m of the shoreline at East Lane is defended with rock armour, fixing the shoreline about 80 m landward of its 1880 position. Retreat continues apace to the north and south of the defences (prompting successive extensions to the revetment), classified as distinct behaviour from the adjacent shoreline (cluster K (non-linear recession) at the centennial scale and cluster D (retreat) over the more recent period (Figs. 7, 9)).

In contrast, north of Benacre Broad at Kessingland, a seawall initially constructed in the 1930s, in response to erosion, has since been covered by the migrating Benacre Ness foreland (Fig. 12C). As already noted, the shoreline immediately north of the foreland erodes in advance of foreland migration and progradation, picked up as a distinct behaviour at both centennial (cluster I in Figs. 6, 7) and recent intra-decadal (cluster B in Figs. 8, 9) scales. The erodibility of the unprotected north Suffolk cliffs has facilitated high rates of retreat, which has potentially fed sediment to Benacre Ness. Retreat rates do vary along this cliff-barrier shoreline (Fig. 12C), not least in that the northern stretch, where Benacre Ness was positioned in the 19th century, show increased rates of retreat that incorporate the loss of the foreland and subsequent hinterland recession (multi-decadal cluster A; Fig. 7A). Compacted peat exposed on the lower foreshore and subtidal by barrier rollover, may have locally reduced the rate of erosion. However, the net longer-term effect of these variations must be minimal based on the maintenance of a near linear planform.

The range of behaviours exhibited along the Suffolk coast effectively illustrates the difficulty of attributing observed shoreline change to specific mechanisms of forcing. Studies of the drivers of coastal change increasingly suggest that, although short-term erosion is often directly linked to storm frequency and intensity, the role of storms in controlling longer-term behaviour is less clear-cut (e.g. List et al., 2006; Chaverot et al., 2008). Multi-decadal behaviour is seemingly driven more by variations in sediment budget and in particular alongshore responses to energy and flux gradients (Lazarus and Murray, 2007). Del Río et al. (2013) found that the regional variability in shoreline change across the Gulf of Cadiz was primarily a product of sediment supply, determined secondarily by coastal geomorphology and anthropogenic intervention. Similarly, Hapke et al. (2013) showed that despite the dominance of historical erosion, significant regional variability was evident, largely controlled by geomorphology and human development. Despite the need to seek direct associations between met-ocean forcing, including the effects of climate change, and coastal change, it is clear that much of the behaviour observed over decadal time scales is a product of a geological and geomorphological legacy that is often substantially shaped by humans. Elucidating the timing of human forcing of coastal dynamics is pertinent to a broader debate within geomorphology on how to define and characterise the Anthropocene (Brown et al., 2016).

5.4. Implications for shoreline management

Quantitative information on shoreline position is vital to underpin varied aspects of coastal management, including flood and coastal defence (Nicholls et al., 2013), climate change adaptation (Dawson et al., 2009; Nicholls and Cazenave, 2010; Woodroffe et al., 2014; Sánchez-Arcilla et al., 2016) and coastal hazard and economic zoning (Ferreira et al., 2006; Rodríguez et al., 2009; Gopalakrishnan et al., 2011). Hitherto, the emphasis of most coastal change analyses has been on quantifying rates of shoreline position change with reference to historical data, and the extrapolation of indicative future changes. Additional sophistication has come through the implementation of probabilistic frameworks (e.g. Cowell et al., 2006; Ranasinghe et al., 2011; Spirandelli et al., 2016), or the use of historic data to constrain morphodynamic models that can resolve the inherent non-linearities in coastal landform response to external forcings (e.g. Walkden and Hall, 2011; Castedo et al., 2015). Management also depends on fundamental understanding and, as we demonstrate here, a range of coastal behaviours exist that are not particularly well captured by a simple net shoreline movement or linear rate of change. Theoretical frameworks for coastal behaviour at the decadal and centennial scales most relevant to management and climate change adaptation have evolved considerably from the mapping of relatively large littoral sediment cells, to the identification of more complex hierarchies of landform and sediment systems (Cowell et al., 2003; Burgess et al., 2004), and the human interventions that constrain them (French et al., 2016a). Such frameworks tend to be highly idealised and practical tools are required to aid their implementation in practice. In the analysis presented here, the use of cluster analysis to segment the coastline into specific groups of time-varying behaviour is shown to be very effective at revealing the subtleties of coastal change and identifying coherent behavioural, and potentially management, units. Pilkey and Cooper (2004) advocated the extrapolation of past rates of shoreline retreat with an "expert eye" (to encompass consideration of sediment budget, engineering and geological context) as more appropriate than modelling approaches such as the "Bruun rule". Whilst there is inevitably a degree of subjective judgement in the choice of algorithms employed, cluster analysis can provide an objective element of this "expert eye" in its ability to recognise qualitatively distinct modes of shoreline change.

6. Conclusions

Trends and magnitudes calculated from the analysis of relative shoreline positions over different periods in time provide the basis for management decisions and understanding of coastal behaviour worldwide. These metrics adequately capture the nature of change in systems that show systematic recession or advance, but are less appropriate where cyclic, non-linear and/or episodic behaviour are involved. Cluster analysis of relative shoreline position at a high alongshore spatial resolution provides an objective basis for segmenting the coast to capture a broad suite of dominant modes of behaviour. When used in combination with conventional shoreline change metrics, this provides a more robust approach for the analysis of large-scale coastal behaviour that can supplement expert geomorphological assessment as basis for identifying appropriate management units.

A regional application of this methodology to 74 km of Suffolk coast, eastern England, reveals multiple modes of shoreline change. These include, inter alia, progressive erosion and recession at long-term rates of up to 5 m year^{-1}; cyclic behaviour where reversals in trend are evident; and persistent but non-linear erosion or accretion. The use of a 100 m alongshore sampling interval is effective in resolving localised subtleties in behaviour and disaggregating the influences of met-ocean forcing, geological control and engineered structures more effectively than a basic shoreline change analysis.

Regional-scale shoreline change analyses at different temporal scales have the potential to highlight primary mechanisms of forcing and the evolving interplay of climatic variability and change, and anthropogenic interventions. However, in the Suffolk case study presented here, there is little immediate evidence for regionally coherent forcing at neither centennial (post-1880s) nor intra-decadal (post-1990s) timescales. Indeed, the range of behaviours revealed by cluster-based segmentation points to a more complex interaction between met-ocean forcing and antecedent factors that are spatially and temporally variable. Whilst it is likely that continuing (and possibly accelerating) sea-level rise drives erosional and steepening along the coast as a whole, the alongshore variability in the presence of structural control (in the form of both anthropogenic interventions and geological features) exerts a complex influence on the efficacy of erosion processes and the movement of sediment. The coastline is also responsive to high energy events, but the longer-term consequence of such change is much reduced. The relative importance of wave direction, and the potential variability in this associated with regional climate signatures such as the NAO, appears to exert an important control on sediment transport direction alongshore that can explain some of the linked behaviour.

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