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Shoreline Evolution and Metocean Data Behaviour in Southwest England: Is There Any Historical Link?

Temitope D. Timothy Oyedotun[1,2]

Abstract This research aims to evaluate and compare the historical morphodynamic behaviour of coastal systems (shoreline dynamics) in Southwest England in response to the historical meteorological and oceanographic (metocean) attributes. Historical geomorphological evolution of the two shoreline systems in St Ives-Hayle and Camel-Padstow were examined to evaluate morphodynamic activities through the application of shoreline analysis tools (such as Digital Shoreline Analysis System - DSAS), while the broad metocean features were investigated as the possible drivers of coastal dynamics. This study showed that low shoreline recession along southwest England coast, where sediments are present, was attributed mostly to the significant sea-level rise in this region (no significant change was observed on rocky low water shorelines). The high water shoreline, on the other hand, imposes a different pattern of change in response to constraining factors, as different percentages of erosion and accretion are observed at different sections of the study sites, principally triggered by both environmental factors and anthropogenic activities. The general overview of the regional control suggests that climatic activities (specifically wave climate and extreme wind) variably account for the persistent and progressive gradual erosion of some shorelines amidst evidence of cyclic/variable behaviour. No one specific metocean forcing, however, exerts an overarching control on these systems, but the nature of the shoreline (sedimentary vs. bedrock) is responsible for local variability.

Keywords Metocean · Coastal change · Digital Shoreline Analysis System (DSAS) · St Ives Hayle · Camel Padstow · Coastal processes

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1 Introduction

Shorelines and beaches are changing frequently in response to one or many factors which may be morphological, climatological or geological in nature. Factors which predominantly affect the evolution of coastal and marine systems include: the nature and size of the coastal zone, variable climatic patterns, nature of sedimentation in the coastal environment, and coastal hydrodynamics like waves, ocean currents and tides (Albert and Jorge 1998). Quantitative analysis of shoreline changes at historic timescales is very important for understanding of processes that drive coastal erosion and accretion (Sherman and Bauer 1993), for computing regional sediment budgets (Zuzek et al. 2003), for identification of hazard zones (Al Bakri 1996), or as a basis for modelling of morphodynamics (Maiti and Bhattacharya 2009).

The dynamic processes of shoreline erosion and accretion are mostly attributed to either hydrodynamic forces (e.g., river cycles, sea level rise, wave action), geomorphological changes (e.g., spit development), anthropogenic actions (e.g., port development, tidal power generation, construction, dredging) or other sudden forces (e.g., sudden storm events, earthquakes and tsunamis, rapid tectonic movement (Maiti and Bhattacharya 2009; Tsoukala et al. 2015). There are increasing concerns on the long-term impacts of changes in the natural physical and environmental forcing factors, as well as anthropogenic impacts of human interventions, on coastal environments (Sherman and Bauer 1993; Al Bakri 1996; Zuzek et al. 2003; Blott et al. 2006; Maiti and Bhattacharya 2009; Tsoukala et al. 2015). However, before any predictions about morphological responses to future changes can be made with strong confidence, there is the need to understand the previous changes in the system, as well as determine the envelope of natural variability about any longer-term trends.

The shoreline is perhaps the most basic indicator of changes in coastal systems and, by implication, erosion and deposition. This paper aimed to evaluate the pattern of shoreline evolution in response to meteorological and oceanographic (metocean) behaviour. Specifically, this study aimed to evaluate the importance of regional metocean forcing as a driver of historical coastal change. It is hypothesised that metocean attributes have fundamental control on coastal processes, particularly in terms of morphological changes.

2 Materials and Methods

2.1 The Study Area

Southwest England is one of the nine (9) sub-national regions of England, with an estimated area of 23,828 km^2 which forms a peninsula between the English and Bristol channels (SWRDA 2006) in the northeast Atlantic (Fig. 1). The coastal zone of Southwest England is regarded as the longest of England's regions with a total area of 1130 km^2 (SWRDA 2006). The climate of the region has been classified as oceanic (Cfb) according to Köppen climate classification, with cool and wet winters and warm summers. The wind and wave climate of the region is dominated by North Atlantic weather systems and storm activity. The 10 % exceedance significant wave height ($H_{s10\%}$) is 2.5–3 m (Draper 1991; NERC 1998) characterised by a mixture of Atlantic swell and locally generated fetch-limited wind waves (Buscombe and Scott 2008) that exhibit a Mean Spring tide Range (MSR) of 4.2 to 8.6 m (Scott et al. 2007).
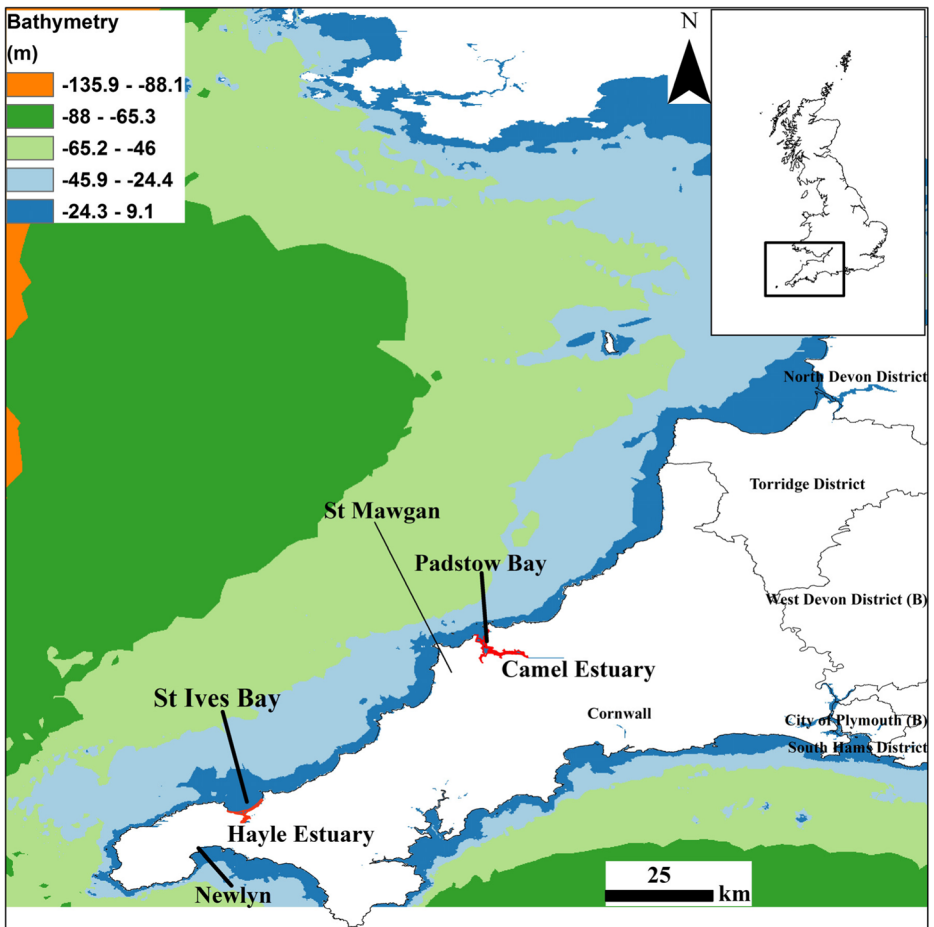
Fig. 1 Location of the selected study sites on the north coast of Cornwall, southwest England (Inset: Map of Great Britain)

The Hayle and Camel estuaries and their adjacent open-coast shorelines (Fig. 1) have been the subject of various studies in the past (e.g., Pirrie et al. 1999, 2000; Pascoe 2005; Brew and Gibberd 2009; Oyedotun et al. 2012, 2013; Pye and Blott 2014; Uncles et al. 2015 etc.) but no regional synthesis of the historical behaviour has yet been attempted. Also important is the availability of various datasets to support characterisation of coastal geomorphology and analysis of shoreline change. St Ives-Hayle and Camel-Padstow systems provide an excellent opportunity to investigate the extent to which the historical behaviour of the systems exhibits any regional coherence or dynamics in response to meteorological and oceanographic (metocean) behaviour.

2.2 Historic Trend Analysis

2.2.1 Data Sources

In most investigations of shoreline changes, the mean low and high water marks (MLW and MHW, respectively) are used to represent the shoreline, representing both a coastline position

and also a simple expression of shoreline morphology. To this end, major effort was made to identify and secure relevant maps and charts used in the analyses for this study. Table 1 lists the data acquired and utilised in the shoreline change analyses.

2.2.2 Geospatial Techniques

Historical Trend Analysis (HTA) is the principal geospatial technique adopted here to investigate historical changes in the shoreline of these systems. A GIS platform (Environmental System Research Institute (ESRI)'s ArcGIS v9.3.1) was used to delineate shorelines and evaluate dynamics in shoreline positions, shoreline morphology, erosion and deposition over specific time epochs. The Digital Shoreline Analysis System (DSAS) (Thieler and Danforth 1994a; b; Thieler et al. 2009) is a GIS tool that has been used in HTA in the examination of past and present shoreline positions or geometry (e.g., Blott et al. 2006; Oyedotun 2014). DSAS is developed as a freely available extension to ESRI's ArcGIS. The numerous recent examples of the use of DSAS in the study of coastal behaviour and shoreline dynamics, and the details of its methods of application, are reported in Oyedotun (2014). In the present study, DSAS was used to undertake:

i.   The examination of the patterns of historic configurations and morphodynamics of shoreline position over the period covered by the available historical spatial data listed in Table 1; and,
ii. The evaluation and investigation of shoreline geometry, and specifically the foreshore steepening, orientation and rotational tendencies, using the distance between mean high and low water marks (Taylor et al. 2004; Nebel et al. 2012).

The following statistical measures according to Thieler et al. (2009), and discussed extensively by Oyedotun (2014), were computed for this research:

Table 1 Datasets used for the analysis of historical shoreline change

Source	Date	Data	Scale	Accuracy
Hayle				
Ordnance Survey	1845	Old series, 1st Edition	1:2500	+/-10 m
	1908	County Series: 3rd Revision	1:2500	+/-10 m
	1936	County Series: 3rd Revision	1:2500	+/-10 m
	1948	National Grid: 1st Imperial edition	1:10,560	+/-10 m
	1963	National Grid: National Survey	1:2500	+/-10 m
	1989	Latest National Grid edition	1:10,000	+/-10 m
	2010	Master Map Vector data (Tiles)	1:2000	+/-5 m
Camel				
Ordnance Survey	1880	Padstow First Revision County series	1:2500	+/-10 m
	1907/8	County Series: 1st Revision	1:10,560	+/-10 m
	1962	National Grid Padstow	1:10,560	+/-10 m
	1973	National Grid Padstow	1:2500	+/-10 m
	1979	National Grid Padstow	1:10,000	+/-10 m
	2010	Master Map Vector data (Tiles)	1:25,000	+/-5 m

(i) Shoreline Change Envelope (SCE), which is the measure of total change in the movement of all available shoreline positions and distances, without any reference to their specific dates of data capture;

(ii) Net Shoreline Movement (NSM), which evaluates the distance between the oldest and the youngest shorelines with reference to their specific dates of capture. It is useful to compare the SCE and NSM metrics, so as to gauge the extent to which shoreline changed throughout the period considered in reflection of the net change.

(iii) End Point Rate (EPR), which is derived by dividing the distance between the oldest and youngest shoreline positions by the time elapsed between them. This metric has been shown to provide an accurate measure of the net rate of change over longer term, and it is relatively easy to apply in shoreline analyses. Further justification for the choice of this method over other methods of estimate is its ability to reliably indicate shore change irrespective of the avail-ability of intermediate shoreline dates (e.g., Milligan et al. 2010a, b).

To be able to address the data quality and accuracy issue in this study, care was taken to ensure that accurate digitisation and critical review of features were considered with the source materials. In this study, mapping errors were estimated and calibrated during the DSAS set-up as ±10 m for the pre-2000 maps and ±5 m for post-2000 maps (Anders and Byrnes 1991; Crowel et al. 1991; Thieler and Danforth 1994a; Moore 2000).

2.3 Metocean Analyses

2.3.1 Metocean Characteristics

Meteorological and oceanographic (metocean) analyses are always concerned with the supply of environmental data and models for accurate approximation of ocean's physics (Bitner-Gregersen et al. 2014). Time series (1823–2012) of winter North Atlantic Oscillation index (NAOi), wind climate, tidal conditions and sea-level rise were analysed and plotted in Microsoft Excel. These analyses aimed to evaluate the importance of physical environmental forcings as agents of change within the southwest England's coastal system. Historical time-series of wind climate based on indices for St Mawgan (indicated in Fig. 1), and the winter NAOi with 50th and 99th percentile correlation were collated to the N, E, S, W, NW and SW quadrants. The correlation at NE and SE were found to be insignificant. Also, usage of all directions, especially each 10° sector, was able to show very specific changes in directions (without obstruction of significant signature), and for this reason the historical analyses presented in this study do not follow the 90° bin.

Forcing of coastal change was further explored through the analysis of other key metocean data, focusing on wind, wave climate and sea-level change (Table 2). Wind data acquired

Table 2 Metocean datasets used in this study

Dataset	Location	Dates	Resolution
Surface wind climate BADC	St Mawgan, southwest England 5.013°W, 50.435°N	1957-2008	Hourly
NAO index CRU	n/a	1823-2013	Monthly
Mean sea level PSMSL	Newlyn 5.543°W, 50.103°N	1916-2012	Monthly Annual

through the Meteorological Office Integrated Data Archive System (MIDAS) Land and Marine Surface Stations Data was obtained from the British Atmospheric Data Centre (BADC) (http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__dataent_ukmo-midas). Due to the limitations of the temporal extent of this data, which extends back to the 1950s, the North Atlantic Oscillation index was also considered to provide a measure of wind climate extending over the full history covered by the coastal change datasets. NAO monthly indices were downloaded from the University of East Anglia Climate Research Unit (CRU) (http://www.cru.uea.ac.uk/cru/data/nao), and associations between the winter NAOi and wind climate measures were analysed following Burningham and French (2012). The monthly and annual sea-level acquired from the Permanent Service for Mean Sea Level (http://www.psmsl.org/), for Newlyn (indicated in Fig. 1, being the site where the sea-level data for southwest England could be acquired) were investigated in Microsoft Excel.

3 Results

3.1 Mesoscale Morphodynamics: Shoreline Change Analysis

This section presents findings relating to the historical evolution and the historic behaviour of the shorelines of St Ives Bay, between Porthminster Point and Godrevy Point (where the Hayle Estuary is located; Fig. 2) and at Padstow Bay between Steeper Point and Pentire Point-Widemouth (where Camel Estuary is located; Fig. 3).

3.1.1 Changes in Mean Low Water (MLW) and Mean High Water (MHW)

In most applications, the measures of shoreline change are used to make a cumulative summary of the processes that have impacted the coast through time. The spatial distribution of measures of change [Shoreline Change Envelope (SCE), Net Shoreline Movement (NSM) pattern and End Point Rate (EPR)] associated with the MLW and MHW marks are presented in Figures 2 and 3 for St Ives-Hayle Bay and Camel-Padstow Bay, respectively, while Fig. 4 presents the summary of the changes in the two systems.

St Ives-Hayle The envelope of variability in the high water shoreline (MHW) throughout the bay is relatively consistent, ranging from 50 to 100 m at over 60 % of transects (Fig. 2ai). Changes are noticeably greater around Porth Kidney Sand, on the west bank of the Hayle inlet and ebb delta, which is the point where the maximum movement in the low water (MLW) shoreline occurs. Net shoreline change, reflecting patterns of erosion and accretion are, however, spatially varied (Fig. 2aii). The MLW shoreline is predominately erosional between the Carbis Bay and Porth Kidney Sand, where 30 m to 320 m recession has occurred over 165 years. In contrast, the MHW shoreline along this stretch has been primarily accretional, although it exhibits smaller scale shifts. The eastern part of St Ives Bay is more varied in scale and direction of change. Inside and around the Hayle inlet, changes of the order ±50–100 m are shown in the MHW, but the scale of change in MLW is about half of this (±0–50 m). The MHW shoreline is more consistent (stable) along the Black Cliff to Godrevy Towans shoreline, which predominately shows small-scale accretion. The MLW here is more mixed, with pockets of accretion, but rather more evident of small-scale erosion. Rates of change (as shown by the end point rate (EPR) in Fig. 2iii) are relatively small for large stretches of the bay
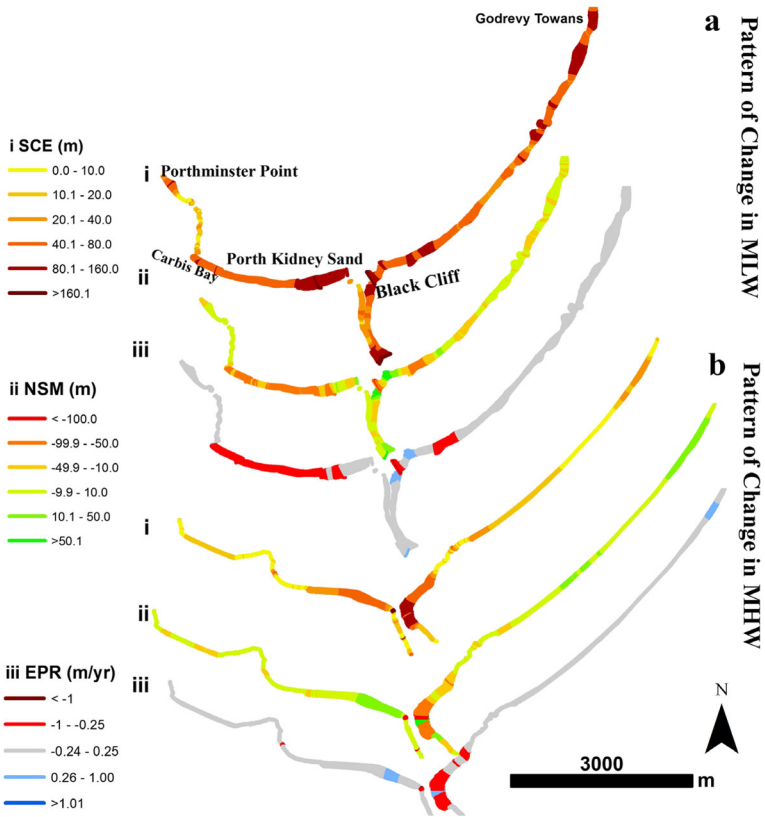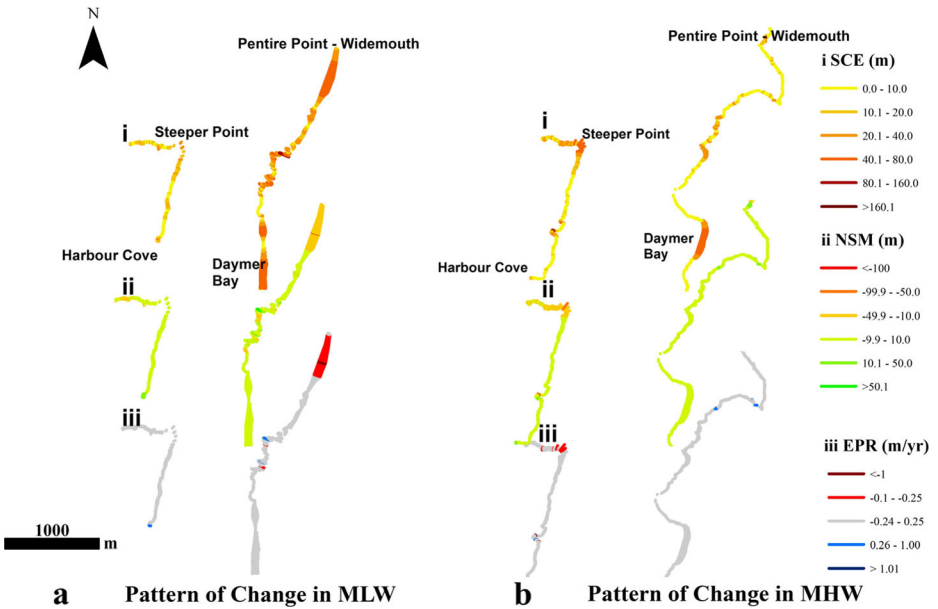
Fig. 2 St Ives Bay – Hayle estuary pattern of change (1845 – 2010): i) Shoreline Change Envelope (SCE), ii) Net Shoreline Movement (NSM) and iii) rate of change based on the earliest and most recent surveys (EPR) for Mean Low Water (MLW) and Mean High Water (MHW)

(±0.25 m yr^{-1}), but they increase significantly within the inlet region, and are also particularly high in the MLW between Carbis Bay and Porth Kidney Sand. Interestingly, the west bank of the inlet exhibits greater rates of change than the east bank.

Small scale changes (-0.24–0.25 m yr^{-1}) dominate the historical dynamics, experienced by 76.4 % of MLW transects and 90.8 % of MHW transects (Table 3). In general, greater rates of recession are expressed in the shift in MLW (22.2 %) than MHW (12 %), broadly suggesting that the intertidal zone has experienced some degree of narrowing, and assuming no change in tidal regime, has presumably steepened. However, there is not any direct spatial association between changes in the two shorelines.

Camel-Padstow Bay Historical changes in shoreline position within Padstow Bay (associated with the Camel estuary) are notably different than those illustrated in St Ives Bay and Gannel's Crantock Beach (another system in southwest England, reported by Oyedotun 2014). The Padstow Bay low water shoreline has a limited envelope of variability when compared with the other systems considered in the region (0–20 m). Figure 3 summarises the scales and rates of change in shoreline position at Padstow Bay. Changes of around 20–40 m are evident along the eastern shoreline, around Pentire Point-Widemouth and Daymer Bay (Fig. 3ai).

Fig. 3 Padstow Bay – Camel estuary pattern of change (1845 – 2010): i) Shoreline Change Envelope (SCE), ii) Net Shoreline Movement (NSM) and iii) rate of change based on the earliest and most recent surveys (EPR) for Mean Low Water (MLW) and Mean High Water (MHW)
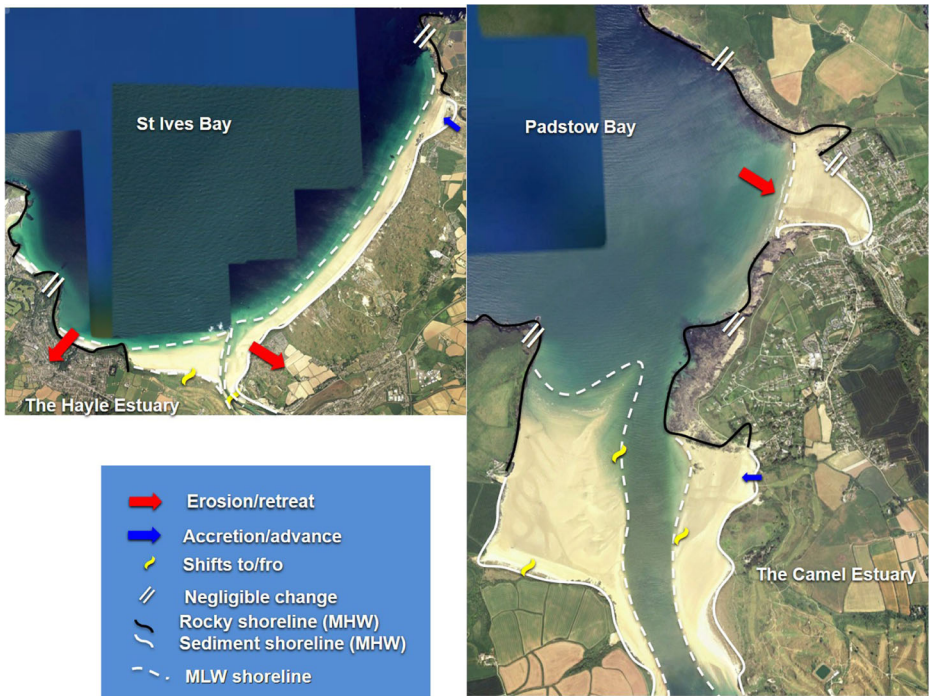
Fig. 4 Summary of historical shoreline changes in the St Ives and Padstow Bays on Google Earth aerial images showing the rocky and sediment shoreline

Table 3 Summary of MHW and MLW movements and trends in St Ives-Hayle Bay

Change rate (m yr^{-1})	No. of MLW transects	% of MLW shoreline	No. of MHW transects	% of MHW shoreline
< -1	6	0.28	3	0.2
-1 – -0.25	473	22.2	69	4.4
-0.24 – 0.25	1628	76.4	1411	90.8
0.26 – 1.00	23	1.1	72	4.6
>1.01	1	0.05	0	0.0

Transects between Stepper Point and Harbour Cove remain relatively stable with varied rates of erosion and minimal total accretion of low water position (Fig. 3aiii). Rates of change reach a maximum at Pentire Point-Widemouth where shifts of between -0.10 and -0.25 m yr^{-1} are observed (Fig. 3aiii). Padstow Bay is relatively confined in comparison to St Ives. Rock platform dominates the shorelines of the open coast around Steeper Point and Pentire Point-Widemouth, and this is responsible for the relative stability in the MLW shoreline when compared with St Ives (Fig. 4).

There is a relative stability in the shoreline change envelope of the MHW shoreline (Fig. 3b), where only Daymer Bay stands out as showing any dynamics. But net accretion here of ~10 m illustrates the minimal shoreline movement during the 132-year period considered. Rates of change (+0.24 m yr^{-1}) in the whole bay for the high water shoreline indicates a relative stability. Rocky shorelines that border the bay are certainly less responsive than sedimentary shorelines, but here also seem to provide a stabilising role, perhaps either through sheltering from the impacts of tides and waves, or simply constraining morphodynamic behaviour (Fig. 4). The orientation of the bay and estuary facilitate a more enhanced sheltering role of the Pentire Point and Steeper Point headlands (Fig. 4). Overall, the direction of change is rather more balanced here than in St Ives. Stability is experienced along 87.6 % of the MLW and 99.2 % of the MHW shorelines, although 12 % of the MLW experiences retreat (Table 4). Sediments are broadly recycled within the open coast system here, certainly much more so than in the systems further west.

3.1.2 Intertidal Steepening through MHW and MLW Movement

The pattern of change, as shown in Section 3.1.1, indicates an overall dominance of erosion along the sediment shorelines, while the rates of retreat and advancement occurring at unequal

Table 4 Summary of MHW and MLW movements and trends in Padstow Bay

| Change rate (m yr^{-1})	No. of MLW transects	% of MLW shoreline	No. of MHW transects	% of MHW shoreline
< -1	0	0	1	0.
-1 – -0.25	93	12	8	1.0
-0.24 – 0.25	679	87.6	1260	99.1
0.26 – 1.00	3	0.4	2	0.2
>1.01	0	0	0	0

levels between MHW and MLW leads to a change in foreshore geometry (beach width and beach slope; Figs. 5 and 6). Analysis of intertidal widths and slopes here again reveals considerable spatial variation in the response of the intertidal foreshore over this historical timescale. Landward shift in MLW, and seaward advance (or even relative stability) in MHW produces a narrower and steeper intertidal zone (Figs. 5 and 6), and this is evidenced at some specific locations. Sites within St Ives Bay are perhaps the most convincing, but this is largely related to the continuity of the beach environment within this system; specifically, Carbis Bay, Porth-Kidney Sand and Black Cliff show historical foreshore narrowing and steepening (Fig. 5) but the picture is more muddled in Padstow Bay (Fig. 6).

The overall historical beach width (c. 1845) at Carbis Bay was approximately 180 m while that of Porth Kidney Sand and Black Cliff areas were around 400 m and 800 m, with a slope of <3°. However, the modern beach width in Carbis Bay is currently around 120 m indicating a reduction of around 50–60 m. Beach width in Porth Kidney Sand and Black Cliff areas have remained stable while there is a reduction of around 10 m at the Hayle ebb delta (Fig. 5). Landward shifts in MLW, evident in St Ives Bay has resulted in a narrower and steeper intertidal zone. These broad, dissipative beaches still retain a low gradient morphology, so the morphodynamics of these systems have shown limited changes as they still function as dissipative intertidal zones. Steepening is evident where the MHW shoreline is rock-dominated, which precludes the recession of the high water shoreline.

In many locations, sediment shorelines are known to undergo a complete landward shift in response to sea-level rise (e.g., the Bruun rule), but the presence of bedrock or other fixed upper foreshore or supratidal feature forces the profile to respond out of equilibrium, leading to an overall steepening of the foreshore (for example, at Widemouth in Padstow; Fig. 6). In the study sites, a rather more complex signature of retreating MLW and advancing MHW suggests
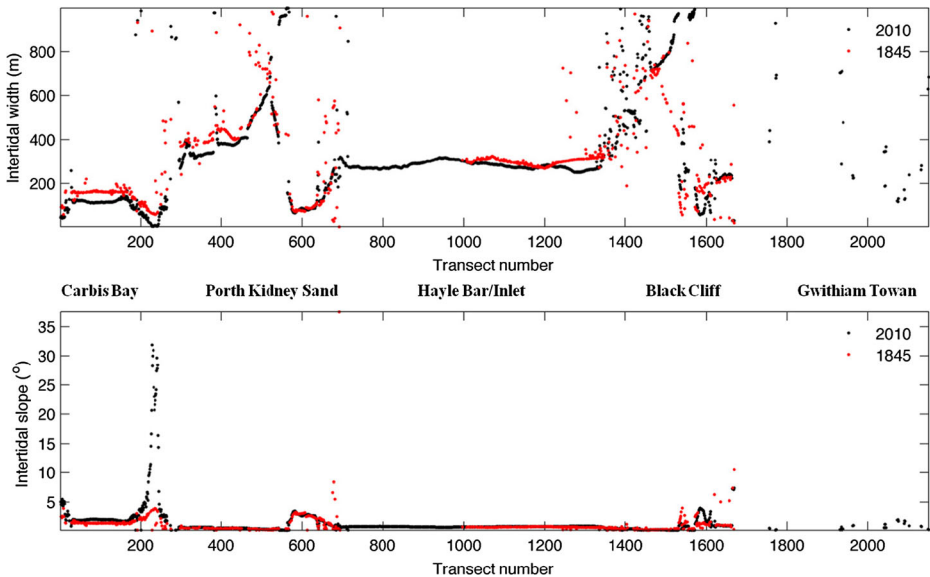
Fig. 5 Beach width (expressed as the distance between MHW and MLW) and slope (width/mean tide range) in the earliest (1845 – colour red) and most recent (2012 – colour black) mapping available for St Ives Bay and the Hayle inlet
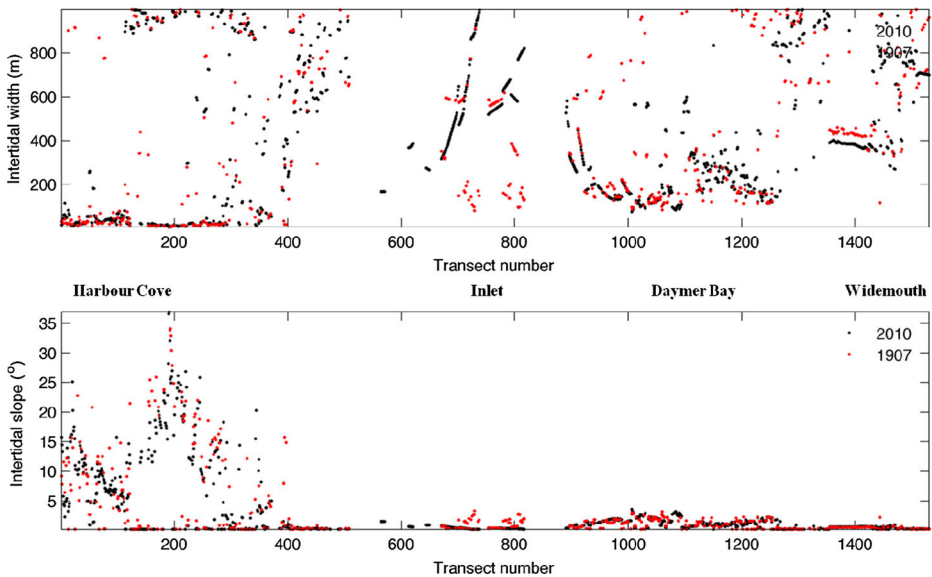
Fig. 6 Beach width (expressed as the distance between MHW and MLW) and slope (width/mean tide range) in the earliest (1907 – colour red) and most recent (2012 – colour black) mapping available for Padstow Bay and the Camel inlet

decreased sediment supply to the beach system, in addition to the vertical shift associated with metocean influence.

3.2 Metocean Changes: Historical Coastal Forcing

The forcing of coastal change is explored in this sub-section and the analyses of key metocean data focusing on historical wind, storm climate and sea-level change. The objective here is to evaluate the importance of regional forcing as the driver of historical coastal change.

3.2.1 Wind and Storm Climate

Directional frequency of winds recorded at St Mawgan show that wind direction is predominately westerly (Table 5). Low energy winds (0–10 kts) are dominated by southerlies and easterlies whereas higher energy winds (>10 kts) are more frequently from the west. High speed easterly winds are rare. Changes in wind speed, wind direction and atmospheric pressure, particularly during storms, enhance the generation of positive surges and large waves (Phillips et al. 2013). These changes can in turn increase coastal erosion risk, affect the shifting of shoreline positions and the general morphology of the coastal environment.

The winter North Atlantic Oscillation index (wNAOi) is calculated as a mean of monthly indices across the winter period: December-March is used here (Fig. 7), although a range of winter month combinations are more widely used (Burningham and French 2012). Persistent positive phases in the wNAOi occurred in the late 1880s and early 1900s, and also from the late-1970s to mid-1990s (Fig. 7). Extended periods of negative wNAOi are uncommon and relatively short in comparison to the positive phases. The winter months of 1915, 1939, 1955, 1967–1968 and 1975–1976 experienced extreme minima in wNAOi (< -1). Most recently, the

Table 5 Correlations for NAO with wind directions for St Mawgan (1957-2008): strong correlations ($|R| > 0.5$ and significant at $p < 0.01$) are highlighted in bold

Wind metric	Wind direction	Correlation (R)
Frequency	N (315-45)	-0.36
	E (45-135)	**-0.68**
	S (135-225)	0.38
	W (225-315)	**0.71**
50th percentile windspeed (kts)	N	-0.14
	E	-0.43
	S	0.13
	W	0.20
99th percentile windspeed (kts)	N	-0.05
	E	-0.36
	S	0.01
	W	0.04
Frequency	NE (0-90)	-0.18
	SE (90-180)	-0.45
	SW (180-270)	**0.76**
	NW (270-360)	0.33
50th percentile windspeed (kts)	NE	**-0.66**
	SE	-0.28
	SW	0.30
	NW	0.23
99th percentile windspeed (kts)	NE	-0.33
	SE	-0.10
	SW	0.20
	NW	0.01
50th percentile speed (kts)	All directions	0.22
99th percentile speed (kts)	All directions	0.18

winters of 1995 and 2009 experienced the most extreme lows. The pattern of change in the wNAOi does not adhere to an overall trend, but rather a cycle of shifts between positive and negative phases. There is some evidence for an increase in the range of variability in more recent years. The implications of positive phases in the NAO for the historical period explored here are increased storminess in the 1980s—early 1990s, followed by a less persistent and more variable climate in recent years.

The wind direction frequency is known to be strongly associated with NAO winter index (Burningham and French 2012), and this is evidenced in the St Mawgan dataset, which shows a strong positive correlation between the frequency of westerly winds and the wNAOi (Table 5). Furthermore, strong positive correlations exist between the strength of westerly winds and the wNAOi. Figures 8 and 9 present the time series of change in wind direction frequency, median wind speeds associated with these directions, and 99th percentile wind speeds. As highlighted in Table 5, there are strong positive correlations between the wNAOi and the frequency of westerly winds ($R = 0.71$), and strong negative relationships are observed with the easterlies ($R = -0.68$). Rotation of the direction quadrants by 45° reveals that the
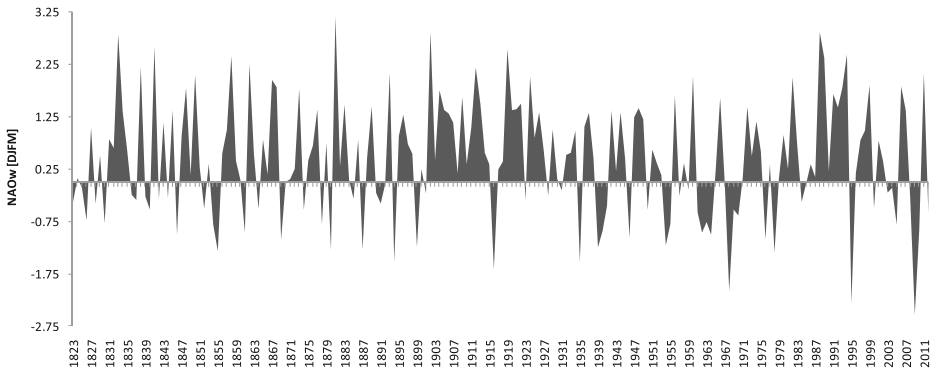
Fig. 7 Time series of winter (DJFM) NAO index

significant correlations are associated with northeasterlies (R = -0.68) and southwesterlies (R = 0.76). There was no significant linear relationship between the wNAOi and median or extreme (99th percentile) wind speeds within each of these wind direction quadrants.

Correlations between time and these wind measures, which could point to mesoscale (decadal) trends in wind climate, are summarised in Table 6. These show quite different patterns of correlations to the analysis with the wNAOi. Whereas it is the proportion of wind recorded from the southwest-west and northeast-east that are strongly associated with the temporally-variable patterns in North Atlantic pressure systems, median wind speeds show significant temporal trends over the last 50 years. The 50th percentile (median) wind speed (from NE direction) is significantly negatively correlated with time (R = -0.66) exhibiting a broad decline in speed over the last 50 years. Indeed, all correlations between wind speed measures and wNAOi are negative, suggesting that there has been a significant reduction in wind climate energy at St Mawgan over the last 50 years. The correlations with time of median wind speed from the north (R = -0.82) and west (R = -0.62) show a significant decrease over the period considered here. This is reiterated when considering the rotated quadrants; median speeds for winds recorded from the northeast, northwest and southeast all show a significant decline over time. These temporal trends are to some degree mirrored in the extreme (99th percentile) wind speeds; but it is only wind recorded from the north that achieves a correlation coefficient of |R| > 0.5. Although all correlation coefficients associated with the 99th percentiles are negative, the results suggest a rather weaker decreasing trend in the extreme wind speeds. It is particularly notable that the strong positive phase of the wNAOi during the 1980s to mid-1990s is not at all reflected in the median and extreme wind speeds recorded at St Mawgan. The far stronger signal here is the long-term trend of decreasing wind speeds.

The findings/analyses presented in this section confirm that for southwest England the NAO appears to be responsible for driving year to year changes in the frequency of westerlies and easterlies, but has had little impact on the strength of winds. It is not possible to say that the positive phases of the NAO in the late 1880s and early 1900s, and also from around 1978 to 1991, were responsible for increased climatic activity and increased energy, but these periods of increased frequency of westerlies might have driven an increase in wave energy, or possibly an increase in west-southwest to east-northeast wind-blown sediment transport across beaches in the region. Several studies have linked positive wNAOi in driving coastal geophysical processes through the occurrence of higher than average wind speeds, increased storminess and storm
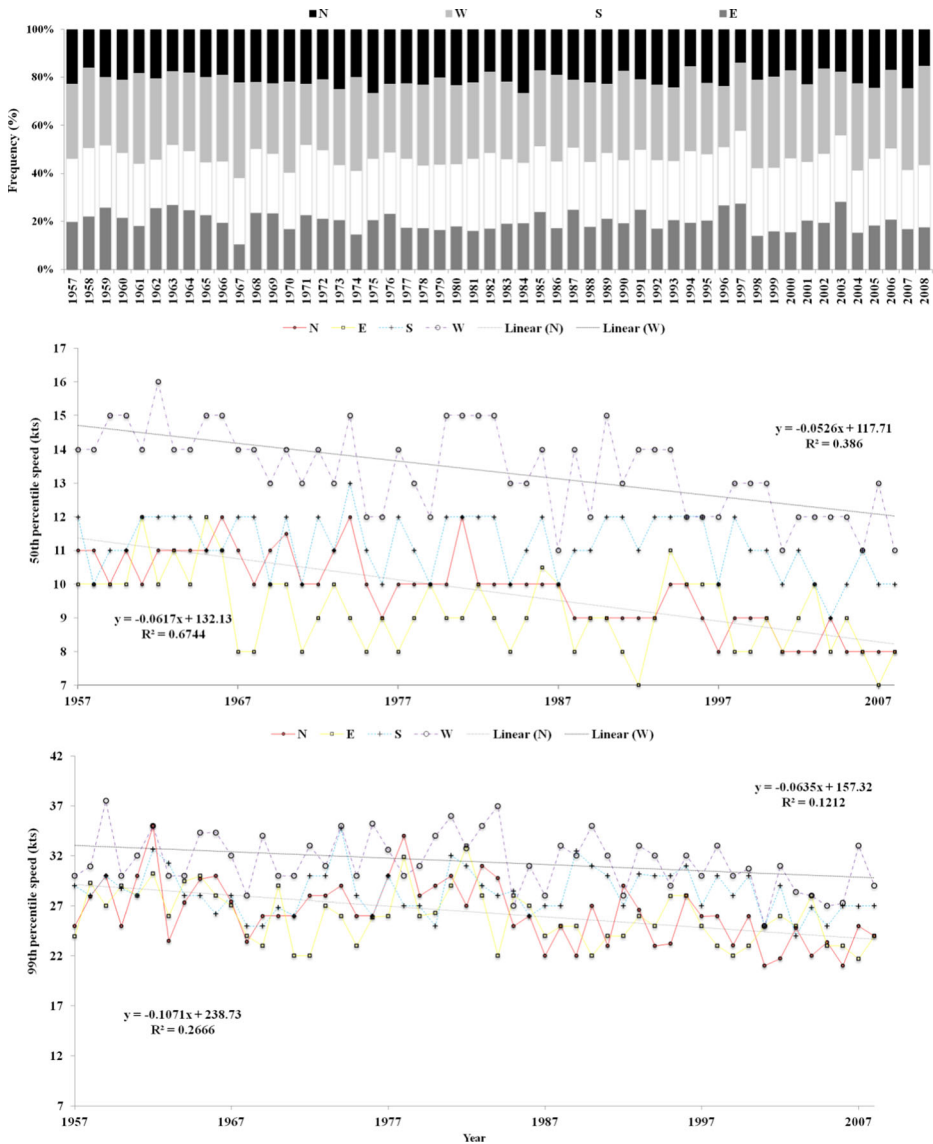
Fig. 8 Time series of wind climate based on records from St Mawgan, Southwest England, UK, showing 50th percentile and 99th percentile of wind speed and direction frequency (collated to cardinal (N, E, S, W) quadrants). Temporal correlations are reported in Table 5

frequency (e.g., Clarke and Rendell 2009). The dominant positive wNAOi phases at the first half of 20th century (also noted by Pye and Neal 1994) and the frequent stronger southwest wind speed and direction are accountable for storm and stronger climatic parameters which enforced morphological changes of shoreline positions at the study sites. Southwest England is seemingly experiencing a more complex forcing of changing wind climate which can be partly linked to the NAO (in terms of frequency of westerlies) but also comprises a more persistent trend of decreasing energy.
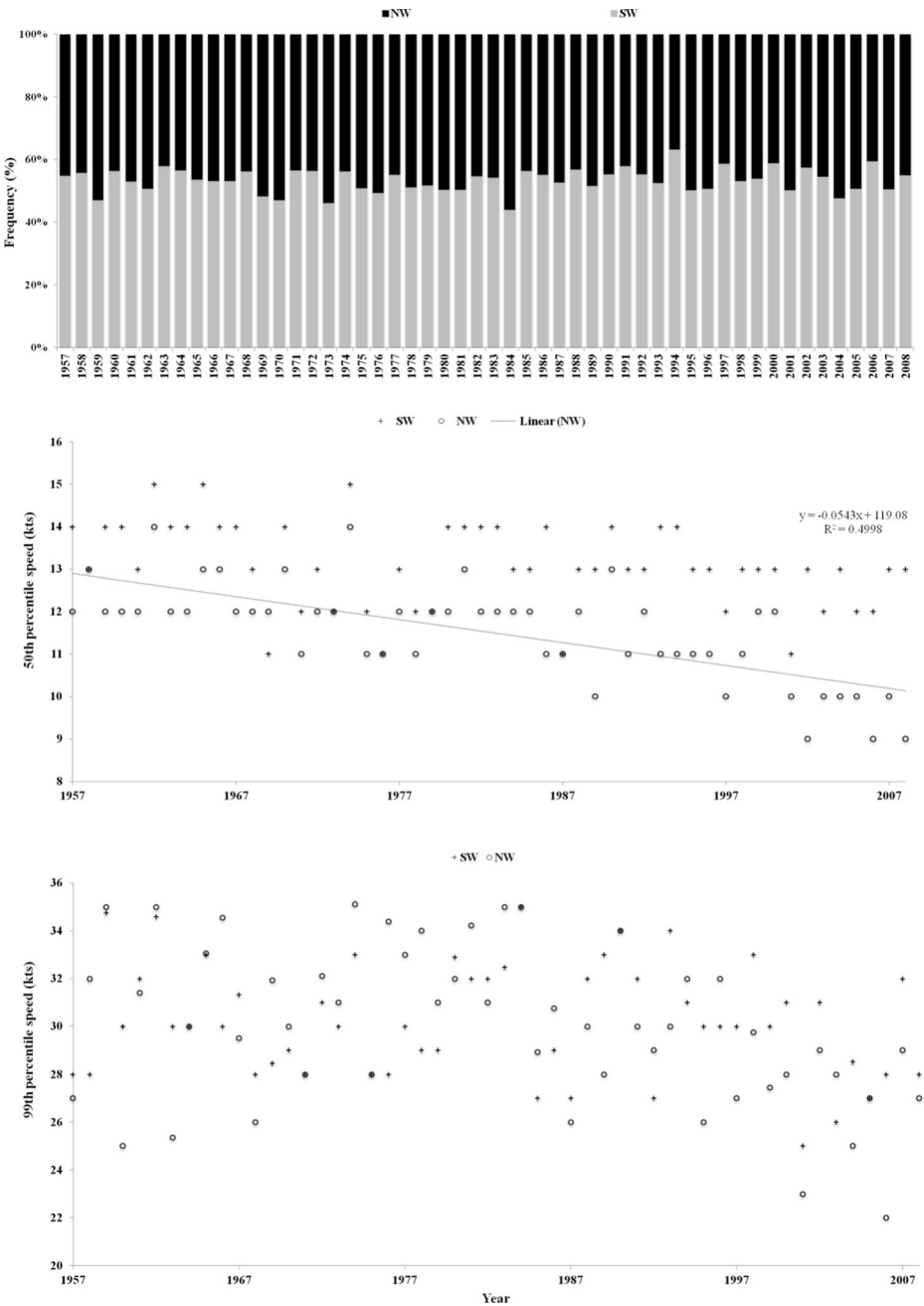
Fig. 9 Time series of wind climate based on records from St Mawgan, Southwest England, UK, showing 50th percentile and 99th percentile of wind speed and direction frequency (considering only the SW, NW quadrants as the winter NAOi at NE and SE are found to be insignificant and, therefore, the presentation of the historical analysis in N, E, S, W, NW and SW (See section 2.3.1 for more explanation). Temporal correlations are reported in Table 6

Table 6 Correlations (temporal) for the wind measures for St Mawgan (1957-2008): strong correlations ($|R| > 0.5$ and significant at $p < 0.01$) are highlighted in bold

Wind metric	Wind direction	Correlation (R)
Frequency	N (315-45)	-0.07
	E (45-135)	-0.18
	S (135-225)	0.29
	W (225-315)	0.07
50th percentile windspeed (kts)	N	**-0.82**
	E	-0.47
	S	-0.31
	W	**-0.62**
99th percentile windspeed (kts)	N	**-0.52**
	E	-0.40
	S	-0.15
	W	-0.35
Frequency	NE (0-90)	-0.18
	SE (90-180)	-0.06
	SW (180-270)	0.20
	NW (270-360)	0.03
50th percentile windspeed (kts)	NE	**-0.69**
	SE	**-0.63**
	SW	-0.34
	NW	**-0.71**
99th percentile windspeed (kts)	NE	-0.48
	SE	-0.40
	SW	-0.16
	NW	-0.39
50th percentile speed (kts)	All directions	**-0.66**
99th percentile speed (kts)	All directions	-0.36

The coastal and maritime climate of the southwest UK are noted to be largely shaped by the eastward sweep of depressions from the Atlantic coast (Phillips et al. 2013), and the analyses here show the predominance of west-southwesterlies in the wind climate of this region. The persistent phases of positive NAO do correlate with increased frequency of these west-southwesterlies, and this might drive specific morphological changes associated with direction of forcing, for example shoreline movements.

3.2.2 Sea-level Change

Figure 10 presents the historical change in mean annual sea-level for Newlyn. There has been a normal increase in Celtic sea-level from 1920, but this has shown some acceleration since the 1960s (Phillips et al. 2013). The published rate of sea-level rise for southwest England was quoted as c. 5 mm yr^{-1} in a 2004 report (DEFRA/EA 2004) but it is currently recognised as 1.77 mm yr^{-1} (Fig. 10; PSMSL 2013). The overall erosion and landward shift in the MLW shoreline positions are attributed to the rise in sea-level that this region experienced. This
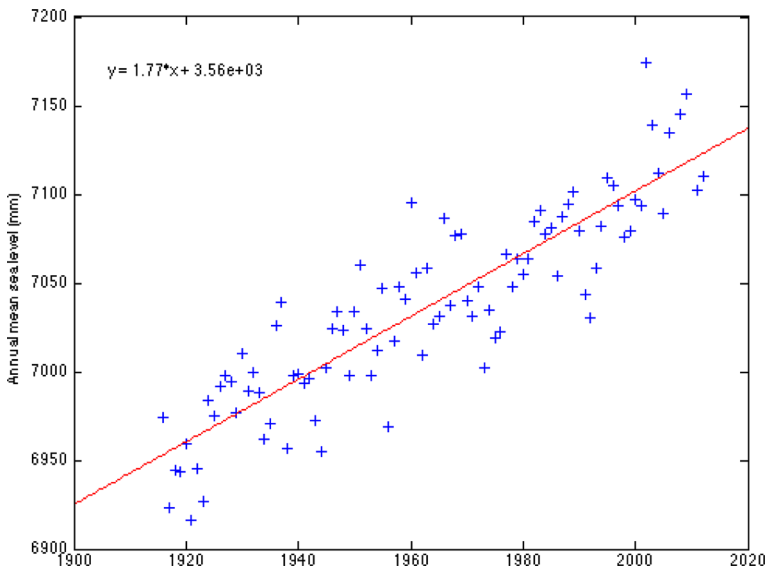
Fig. 10 Annual mean sea-level at Newlyn, exhibiting a rise over the 20th century at a rate of c. 1.77 mm yr^{-1} ($R^2 = 0.88$, $p < 0.001$) (PSMSL 2013)

parameter remains a very important phenomenon as a rise in sea-level increases the elevation at which these coastal processes (tides, surges, waves) operate, and often makes the coastal zone vulnerable to morphologic changes.

4 Discussion

The morphodynamics of coastal systems in southwest England has been shown here to be complicated at historical (century-decadal) timescales. The sensitivity of coastal landforms to experience a significant change in response to external forcing and intrinsic structural control do vary depending on the complexity of the system, the intensity and direction of controlling factors, and the time it takes for the new equilibrium to be achieved (Hansom 2001). Shoreline dynamics is a good measure of coastal sensitivity. The geomorphological evolution of the coastline in southwest England shows a combination of coherent behaviour and site-specific response. The most comparable characteristic of shoreline dynamics in the 20th Century is a retreat in the low water shoreline (MLW). The high water shoreline (MHW), however, exhibits considerable variability between systems, possibly as a result of more complex intra-estuary controls. Over decadal timescales, channel migration is evident in the patterns of change in MLW, but the mix of sedimentary and bedrock shoreline imposes a different pattern of change in the MHW. The sedimentary-dominance of the MLW shoreline in each estuary presents limited restriction on morphological change across the low intertidal as there are negligible changes in the systems (Fig. 4). The scenario observed in this study could be compared to what Taylor et al. (2004: page 181) referred to as "lateral landward retreat through non-equilibrium profile".

Quantification of morphodynamic parameters is very important in understanding the time series of change and in the comparison of regional conformity. Considering the sample coastal systems in this study, some parts of the individual systems are more clearly dynamic than

others. Specifically, in terms of MLW shoreline response, St Ives-Hayle Bay experienced landward shifts (recession) (Fig. 2), while the headlands of Camel-Padstow Bay, dominated by bedrock and rocky outcrops, have provided some degree of resistance and sheltering, leading to limited changes in the MLW shoreline. Unsurprisingly, the areas which are highly sensitive to erosion and retreat are those directly exposed to wind, wave and tide action (for example, Porth Kidney Sand, Carbis Bay and Gwithian Towan in St Ives-Hayle), while the areas with relative stability are formed in, and shielded by, rock outcrops or hard surfaces (for example, Pentire Point–Widemouth and Steeper Point in Padstow-Camel system; Fig. 4).

Although there is a broad trend in most parts of these systems of recession in the MHW shoreline, specific aspects of individual morphodynamic behaviour and character can be explained with reference to each system. The eastward extent of the Hayle inlet has experienced 30-230 m of retreat while the westward side has prograded around 130 m over the 165-year record. The response is different in Padstow Bay; the eastward extent, at Daymer Bay, is the only location that has experienced shoreline progradation (*c.* 40 m), with relative stability elsewhere, and specifically to the west (Harbour Cove). The various shifts in shoreline position in these systems have encouraged and facilitated the movement of intertidal and probably supratidal sediments. This spatial pattern in morphodynamic behaviour can be attributed to nature of the shoreline (rock vs. sediment dominated), the accommodation space and sediment availability. Shoreline movement throughout the last 120-165 years here shows that sedimentary shorelines are receding (retreating landward) while rocky shorelines remained unchanged.

The historical morphodynamics are the consequence of extrinsic coastal actions (environmental forces and anthropogenic influence) and internal properties peculiar to each individual system (for example, the inherited bedrock valley and embayment, the specific internal hydrodynamic conditions, the sedimentary estuarine environment, etc.). Therefore, both the spatial and temporal complexities in the local conditions are very important in the historical behaviour of these systems.

The consistency in the spatial pattern of shoreline positions across the systems in the region in the 20th Century suggests a high degree of regional control on the coastline character. The components exhibiting relative stability is confined to the headlands and the rocky outcrops. These trends have been ascribed to many factors among which are the relative positions within the sediment cells, the natural antecedent conditions and the range of anthropogenic/human activities (Montreuil and Bullard 2012). Although the shoreline changes derived from maps and other historical archives are likely to be inaccurate compared to recent surveys, they are, however, important in understanding the long-term/meso-scale evolutionary pattern of shorelines/coastlines. The long-term MLW shoreline recession and the overall steepening of the nearshore zone of the estuaries is primarily influenced by the presence of rocky shores and the 20th Century sea-level rise.

The average annual rate of erosion in this region (for those sites undergoing retreat) of 1.5-2 m yr^{-1} (over 150 years for the MHW mark) is in agreement with previous estimates for other studies/sites in the UK (Mason and Hansom 1988; Saye et al. 2005; Blott et al. 2006; Montreuil and Bullard 2012; Oyedotun 2014). Facing the complex dynamic interactions of marine, terrestrial and anthropogenic forces at work in the system, the specific factors responsible for this dynamic pattern in the shoreline movement cannot be directly linked to patterns of storminess or wind direction (as associated with the NAO).

The general overview of the regional controls suggests that climatic activities (specifically wave climate, extreme wind) in southwest England variably account for the persistent and progressive gradual erosion of some shorelines, evidence of growth (some of the dune systems)

and evidence of cyclic/variable behaviour (Montreuil and Bullard 2012). No one specific forcing exerts an overarching control in these systems, but the nature of the shoreline (sedimentary vs. bedrock) is mostly responsible for local variability. It is clear though that some behaviour is locally specific, and variable over the century scale. The coastal systems are responding to more than one historical climatic parameter and a combination of many climatic parameters, intrinsic controls (e.g., Allen 2004) and anthropogenic activities (e.g., Tsoukala et al. 2015).

The wider and important implication associated with natural or anthropogenic interference in any coastal systems is that the stability within the systems are changed (Thiruventakasamy and Girija 2014). This change results in changes in morphology, sediment characteristics and/ or sediment transport processes. Processes in the coastal environment are complex and their basic governing physical forcings and mechanisms are still not completely understood (López-Ruiz 2014; Thiruventakasamy and Girija 2014). Therefore, the historical link between metocean changes and shoreline changes are not expressly linked in the study presented here.

The lack of temporal conformity to change across all the coastal systems, where rates and directions of change occur differently throughout the history considered here, is an indication that other factors beyond climate change or climate forcing are responsible for site-specific response, adjustment and behaviour. These other factors could be structural, such as the shape and orientation of the bedrock valley and embayment, or anthropogenic, such as the construction of training walls or application of routine dredging.

The development of the copper and tin mining industry in Cornwall led to the advancement of a mining community around Hayle in the 18th century. The intense industrial and commercial activities led to the establishment of Hayle harbour which handled many thousands of tonnes of coastal and transatlantic shipping during the 19th century. The development of this harbour involved the construction of training walls, quays, slicing of ponds and dredging. Also, in order to maintain a navigable channel for shipping, there was a long history of sand extraction from the estuary (Noall 1984; Pascoe 2005). In the 18th and 19th centuries, Hayle harbour was a busy and very important port. Since then, there has been a progressive decline in the local engineering and metal ore mining industries, particularly since the closure of metal foundries in 1903 and the cessation of commercial shipping (Noall 1984; Pascoe 2005; Knight and Harrison 2013). These events have scaled back harbour activities to local fishing and recreational activities, which has reduced the need for constant dredging and further training wall construction. But the historical evolution of the estuary has clearly been constrained by structures put in before and during the 19th century, and these have restricted movement of the low water channel. Indeed, it is only in the inner basins of the estuary (beyond the zones of shipping activity) where any channel dynamics are observed. There is no doubt that the reduction in activity has had some impact on the system, but the estuary, ebb channel and wider open coast are still adjusting to the long 19th-20th century history of intervention, apart from the metocean behaviour discussed in this study.

The most significant anthropogenic influence in Camel estuary occurred in the pre-1930s. This was suggested to have occurred in 1929 and was a result of development of surge channels by breakers that breached the Doom Bar (within the inner estuary and outside the cover of this study), and so forming the main channel as it exists today (Brew and Gibberd 2009). Apart from this intervention, the outer channel has maintained relative stability up to date. The consideration of the wave, wind, increasing storminess and sea-level as the driver of the historical morphological behaviour do not show direct influence on the changes at the estuary, although they might have been responsible for negligible MLW shoreline changes at the outer-estuary/open-coast. But this system is so rock-dominated that the overarching morphodynamic signature here is stability, irrespective of metocean behaviour or brief anthropogenic intervention.

5 Conclusions

This paper aimed at evaluating the sensitivity of shoreline dynamics in response to meteorological and oceanographic (metocean) changes. The general overview would naturally suggest that climatic activities (metocean characteristics) in the region account for the historical morphodynamic behaviour of these coastal systems, but it is clear that some behaviour is locally specific, and variable over the decadal-to-century scale. It is of course likely that the coastal systems are responding to more than one historical climatic parameters, and probably rather to a combination of many climatic parameters, intrinsic controls and anthropogenic activities. There is also no clear conformity, or explicit role of the historical changing coastal climate in these dynamics. It is possible that coastal dynamics in this region are expressed and evident at shorter timescales, requiring consideration of spatial and temporal complexities within a contemporary context. It is hoped that such investigations, to be reported in a subsequent publication, will reveal intrinsic controls of temporal and contemporary morphodynamics. However, in the findings presented here, there is no historical link between metocean changes and shoreline changes except with sea level rise and the past anthropogenic activities in the systems.

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