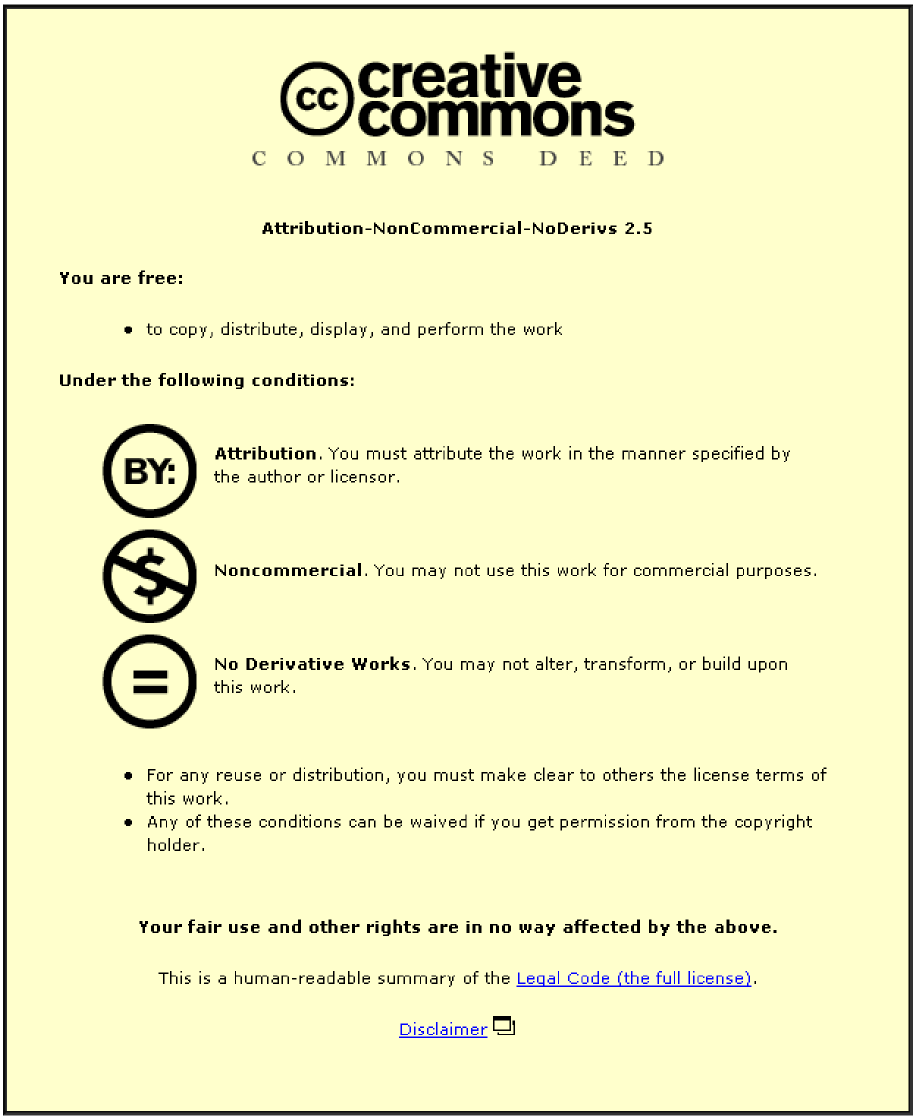

A 150-year record of coastline dynamics within a sediment cell: eastern England.

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Abstract

Coastal sediment cells reflect processes operating at a range of scales, but it is the medium spatial and temporal scales (decades to centuries) that are of greatest interest for coastal management. This paper focuses on coastline position change within a single sediment cell over 150 years where the geomorphology includes cliffs, beaches and saltmarshes. The focus is the east coast of England from Flamborough Head to Gibraltar Point. Although the updrift sector of this sediment cell has been studied for well over a century, the downdrift sector has attracted significantly less attention. Using topographic profiles, bathymetric profiles, aerial photographs and historical maps we mapped coastline erosion and accretion using the Digital Shoreline Analysis System (DSAS) and calculated volumetric changes for different morphometric units. Rapid erosion of the updrift Holderness cliffs has been counterbalanced with accretion on beaches along the downdrift Lincolnshire coast. The amount of accretion in Lincolnshire corresponds to around 29% of the volume of sediment eroded from Holderness. Much of the eroded cliff material is likely to be deposited temporarily into nearshore and offshore sand banks before being redistributed by cross-shore currents. An exploration of storm surge impact on long-term erosion and accretion rates showed no clear relationship between storm surge frequency and change in coastline position, however this may be in part due to the relative timing of storm occurrence and data acquisition. The Jenkinson Daily Weather Type classification was found to be a reasonable proxy for the occurrence of strong onshore winds which may offer scope for further investigation of the role of forcing factors over time periods beyond the length of the meteorological and tidal station records. Winter North Atlantic Oscillation phase was not a good indicator of storminess on the east coast of England but may be a useful proxy for quiescence.

Keywords Sediment cell, Coastline change, sediment budget, storm surge, Jenkinson Weather Types

Highlights

1) Trends in the balance of sediment supplies and sinks in a littoral cell are examined.

2) Long-term erosion dominates cliffs updrift and reaches rates of up to 2 m year^{-1}

3) Accretion up to 2.7 m yr^{-1} dominates on sandy beaches at the centre of the cell.

4) The Jenkinson Daily Weather Type is a useful proxy for UK east coast storminess.

1. Introduction

Coastlines are inherently dynamic landscape components and significant alterations in their position and alignment have been documented worldwide. These changes occur in response to factors such as sea-level change (Orford et al.,1995), large-scale morphological self-organization (Cooper et al., 2007), changes in sediment budget associated with sources (e.g. rivers, cliff erosion), sinks (e.g. sand banks, submarine canyons) and longshore transport (Pye, 1983; Aagaard et al., 2004), variations in storminess and wave climate (Zhang et al., 2001; Pye and Blott, 2008), and coastal management (Iskander et al., 2007; Kaminsky et al., 2010). Along any stretch of coastline, variations in the rate and direction (erosion or accretion) of change are common, associated with local sediment budget and coastal characteristics such as the distribution of headlands, cliffs and beaches; records of such dynamics are typically used to plan coastal management strategies. The importance of littoral sediment budget as a control on the direction of coastline movement is widely recognized and is typically linked to the concept of the sediment (or littoral) cell. Ideal sediment cells are sections of coast that are relatively self-contained and include defined sources, transport pathways and sinks of sediment. The concept was first applied to the California coast (Bowen and Inman, 1966; Inman and Frautschy, 1966) but is now widely used in countries such as the USA, Canada, New Zealand and the UK for coastal management planning, where cell boundaries define the planning units (e.g. Motyka and Brampton, 1993; Hooke and Bray, 1995; Cooper and Pontee, 2006).

The delimitation and operation of sediment cells reflect processes interacting at a range of spatial and temporal scales, and in many areas coastal morphology and dynamics still reflect and are recovering from the impact of Holocene sea-level changes and deglaciation (May and Hansom, 2003). It is the medium spatial (≥10 km) and temporal (decades to centuries) scales that are usually of greatest interest for coastal management and forward planning

(Cooper et al., 2001; Pethick, 2001; Orford and Pethick, 2006; Gelfenbaum and Kaminsky, 2010), but there is often a lack of systematic information concerning decadal-scale changes in interacting landforms within a single cell (e.g. Lee, 2001; Ruggiero et al., 2005; Pye et al., 2007). The aim of this paper is to quantify the spatial and temporal variability in coastline position, rate of change and sediment budget within a single sediment cell. Particular attention has been given to six areas of interest characterised by different coastal landforms (e.g. cliffs, beaches) or management intervention. We use complementary data sources including maps, aerial photographs and topographic profiles to document change over timescales up to 150 years. A preliminary examination of the relationship between morphological change and forcing factors is also presented. The area of interest is the east coast of England between Flamborough Head and Gibraltar Point. Whilst the northern part of this region has been widely-studied, the downdrift, southern sector has attracted significantly less attention.

2. Regional setting

Prior to the 1980s, coastal management in Britain was typically local in focus and determined by administrative bodies such as local authorities. Increasing recognition in the 1980s that management at one location can impact the coastline elsewhere led to various authorities combining interests to develop more integrated coastal management plans (Hooke and Bray, 1995). These coastal groups recognised the importance of understanding sediment transport patterns for effective management (e.g. Hooke and Bray, 1995; Hooke et al., 1996). Since the 1990s, the coastline of England and Wales has been divided in to eleven coastal cells (Motyka and Brampton, 1993) (Fig. 1). Each of these cells represents a defined natural sedimentary system and for each there is a Shoreline Management Plan (SMP) used to guide sustainable coastal defence decision-making processes (MAFF, 1994; DEFRA, 2006). SMPs involve numerous partner organisations and stakeholders including local authorities, government agencies and business and community groups, and their introduction marked a strategic step towards integrated management of the coastline within natural rather than purely administrative boundaries that is both long term and considers the impact of local-scale coastal management elsewhere (Hooke and Bray, 1995; O'Connor et al., 2009).

2.1. Geomorphology of the coastal cell

This paper focuses on sediment cell 2 along the East Riding and Lincolnshire coastlines, which is divided into three sub-cells (2a Flamborough Head to Spurn Head; 2b Outer Humber Estuary; 2c Donna Nook to Gibraltar Point: Fig. 1). Net longshore sediment transport is from north to south. The concept of sediment cells focuses on wave-driven transport of non-cohesive sediments (Motyka and Brampton, 1993) and is harder to apply to fine sediments in suspension (Hooke and Bray, 1995). However, many sediment cells include a variety of landforms including both those formed from non-cohesive sediments (such as sandy beaches) and those dominated by cohesive material such as saltmarshes. In the study area, coastal geomorphology within the cell is varied and includes chalk and glacial till cliffs, wide sandy beaches, saltmarshes, sand dunes, coastal spits and nearshore and offshore sand banks. Coastal management strategies include engineered defences built over the last two centuries and beach nourishment programmes, although large stretches of the coastline have no man-made defences. The main cell boundaries are Flamborough Head to the north, a fixed chalk headland, and Gibraltar Point spit in the south, which is a partial boundary with sediment transfer continuing in to The Wash and southern North Sea.

<Fig. 1>

In the north of the sediment cell, glacial till cliffs 3-40 m high extend 60 km along the Holderness coast and are rapidly retreating (recently reviewed by Quinn et al., 2009). The cliff erosion occurs through repeated landslide activity, caused mainly by waves undercutting the base of the cliffs and removing beach material (Dossor, 1955; Quinn et al., 2009). Sea defences are present near some coastal towns. Sediment eroded from these cliffs and the shore platform are transported southwards to Spurn Head and to offshore sand banks by littoral drift and wave currents. Spurn Head is a narrow sand and gravel spit that extends 5.5 km into the mouth of the Humber Estuary (sub-cell 2b). The Humber Estuary mouth stretches from Spurn Head to Donna Nook and is influenced both by the tide and flow from the river. Strong tidal flows intersect the north-south sediment transport pathway along the open coast, limiting the entry of gravels and sands into the estuary mouth.

In contrast, the low-lying Lincolnshire coast, south of the Humber, comprises superficial deposits left by retreating ice sheets (Swinnerton and Kent, 1949; Brampton and Beven, 1987) and is characterized by sandy beaches and saltmarshes (sub-cell 2c). Offshore sand banks are present from Donna Nook to Mablethorpe, and not only protect the shore against wave attack, but also provide a source of sand to the beaches which are up to 3.5 km wide and backed by dunes (van Houwelingen et al., 2006). Extensive saltmarshes at Saltfleetby are sheltered by broad beaches. This section of the Lincolnshire coastline is typically accreting (HR Wallingford, 2002). South of Mablethorpe the sediment budget changes and coastal erosion dominates in part due to the absence of offshore sand banks (Dugdale and Vere, 1993). Sea defences have been built to protect against coastal flooding and, following a severe storm surge in 1953, extensive ‘hard’ defences were built such as seawalls, groynes and revetments particularly near Skegness. Historically, during high storms, the thin sand cover on the beach moved seaward and the underlying glacial till was exposed and eroded. To counter this erosion, a major beach renourishment plan began in 1994 and continues to date (Environment Agency, 2004). Just south of Skegness, the coastline changes orientation slightly providing a sheltered coast for the development of coastal dunes and saltmarshes at Gibraltar Point (National Nature Reserve).

2.2. Marine and climatic setting

Along this coast, tides are semi-diurnal and macro-tidal, with a mean spring tidal range of 6 m; tidal currents flow southward during the flood and northward during the ebb (Table 1). The dominant incident wave approach is from the north to east quadrant (corresponding to the longest wind fetch). Offshore significant wave conditions are characterized by a 50% exceedence significant wave height of 0.5 m and a modal wave period of 4s, but wave heights can reach 2.5 m in winter (van Houwelingen et al., 2008). Wave-driven processes and flood residual tidal currents are the main drivers of alongshore sediment transport which is directed towards the south (Pye, 1995; van Houwelingen et al., 2006). Storm surges are relatively rare, but the most severe recent events occurred in 1953 (Barnes and King, 1953; Brampton and Beven, 1987) and in 1978, and significantly affected the Lincolnshire coast (Steers et al., 1979; Blott and Pye, 2004). Severe storm surges are the result of combined high tidal level and energetic wave activity, caused by deep depressions tracking eastward toward the North Sea and moving around the North Sea basin in an anticlockwise circulation (Dolata et al., 1983). Consequently, surge levels increase southwards along the east coast of England caused by the funnelling effect of the narrowing North Sea. Winds prevail from the southwest (i.e. offshore) and wind speeds are modest (<8 $m.s^{-1}$) for the majority of the time (73%). During winter months, however, the development of high pressure systems over the British Isles and the North Sea can lead to prolonged strong northwesterly and easterly winds (Steers, 1966).

<Table 1>

Global average sea level rose at approximately 1.8 mm year^{-1} between 1961 and 2003, but has accelerated to 3.1 mm year^{-1} over recent years (IPCC, 2007). Along the east coast of England, sea-level rise is lower than this global average at c.1 mm year^{-1} (HECAG, 2009, Woodworth et al., 2009). For the purposes of this study sea level is considered to have been negligible from 1850 to 2010.

3. Methods and Approach

Changes in coastline position (section 3.2) from the mid-1990s for the whole sediment cell were determined using cross-shore topographic surveys. From these, we identified 6 specific areas of interest (AOIs) within the sediment cell representing a range of coastal geomorphological features (Table 2). These 6 AOIs were examined in more detail to determine:

1. the changing position and relative rate of retreat or accretion of the coastline from the mid- to late-1800s to date;
2. changes in the volume of sediment in backshore and beach/foreshore from the mid-1990s to date;
3. changes in nearshore bathymetry from 1999 (for AOIs 3-6 only).

A preliminary exploration of the key environmental factors affecting rates of coastline change was made using climate and tidal data, including the potential for using a proxy dataset to explain long-term geomorphological changes.

<Table 2>

3.1. Geomorphological data sources

3.1.1. Topographic and bathymetric profiles

The temporal frequency of cross-shore topographic surveys around the UK is variable and for this study dates were selected that were: a) available for all AOIs, b) corresponded to aerial photograph coverage, and c) maximized the length of the record. Surveys were used from the mid-1990s (one of 1994, 1996 or 1997), 1999, 2005, 2008 and 2010 and were supplied for the Holderness coast by the East Riding of Yorkshire Council, and for Lincolnshire by the UK Environment Agency. For each year, a total of 160 profiles, surveyed in summer or early autumn, was analysed (profile spacing 0.5 km and 1 km along the East Riding and Lincolnshire coasts, respectively). Initially surveys were conducted using a standard total station (horizontal accuracy ±0.1 m and vertical accuracy ±0.01 m) located over Ordnance Survey (OS) control points and referenced to the ODN datum. However, since 1999 and 2003 (East Riding and Lincolnshire, respectively), surveys have been made using a RTK-GPS system. Detailed topographic airborne laser surveys have been undertaken along the East Riding coast since 2008 (horizontal accuracy ±1 m; vertical accuracy ±0.15 m). From these we extracted cross-shore topographic profiles along the same lines used in earlier surveys.

Nearshore changes were determined using bathymetric surveys made as seaward extensions of the terrestrial cross-shore topographic profiles, and carried out by Gardline under contract to the UK Environment Agency in 1999, 2005 and 2008 along the Lincolnshire coast only. The surveys employed single multi-beam echo-sounders, the accuracy of which has been estimated to be ±1 m in the horizontal and ±0.005 m in the vertical (Gardline, 2008).

3.1.2. Maps and Aerial Photographs

For each AOI, coastline change was estimated over a ~150-year period using historic OS maps (1854-1951: Table 3) and aerial photographs (1953-2010: Table 3 - available data vary by site). Analysis of the historical OS maps can often experience a delay between field survey dates and the publication dates, so that it is difficult to establish specifically when surveys were undertaken. Aerial survey acquisitions were generally during summer months. The use of historical data and combining different data sources can be subject to uncertainties and errors (Thomas et al., 2011; James et al., 2012) which were minimized where possible. Aerial photographs were individually registered against the 2010 ortho-rectified photographs using the British National Grid (OSGB36) reference system, and ArcMap 9.3 software. Registration was based upon eight stable ground control points (e.g. buildings, road junctions) visually identifiable on all photographs; an average error of ±1.5 m is considered acceptable (Dolan et al., 1991; Chaverot et al., 2008). The root mean square error (RMSE; Maune, 2007) associated with the geo-referencing process was less than 3.5 m for each aerial photograph. Independent error estimates were also undertaken by measuring the positional difference of six additional ground control points, on every map and aerial photograph and the same features on the 2010 ortho-rectified photograph. The average difference for the OS maps ranges between 6.6 m and 7.3 m, while the errors of ortho-photographs are estimated to be 3.4 m in 1953, and below 2 m for all others and deemed to be within acceptable limits (Longley et al., 2005).

<Table 3>

The coastline (section 3.2) on each map and aerial photograph was digitized using ArcView 9.3 software. The Digital Shoreline Analysis System (DSAS) enables calculation of rate of change statistics from multiple shoreline positions (Thieler et al., 2009; Brooks and Spencer, 2010;) and was used in combination with ArcView to calculate coastline change between consecutive maps and aerial photographs. For this study, transects were generated every 100 m perpendicular to the reference coastline, defined as 1854 and 1891 for the East

Riding and Lincolnshire coast AOIs respectively (Table 2). At Saltfleetby, the number of transects was reduced due to a lack of ground control points in part of the AOI and historical coastal change was only estimated from ortho-photographs. This is because when measured using the above technique there was a difference in the coastline position depicted on the 1951 OS map and that interpreted from the 1953 aerial photographs of 625 m. In the context of other coastline changes, such high rates of accretion are highly unlikely and are attributed to errors and uncertainties in the mapping process (James et al., 2012). Within DSAS, the End Point Rate (EPR) method, determining the distance between the earliest and the most recent coastlines divided by the time between surveys, was used to obtain rates of coastline change. This also reduces the potential problem of image quality over time (Dolan et al., 1991).

3.2. Definition of morphological parameters

Defining a consistent reference point along a dynamic coastline is challenging due to variations in tide levels, meteorological or marine conditions (Pajak and Leatherman, 2002; Thieler and Danforth, 1994), and limitations of spatial resolution during data acquisition (Cracknell, 1999). Here, the coastline was defined from the topographic profiles using a fixed reference plane at HAT (highest astronomical tide) level for the sandy beaches along Spurn Head and the Lincolnshire coast; for precision, cross-shore profiles were linearly interpolated to 0.1 m. The HAT level often coincides with the seaward limit of vegetated coastal foredunes and can provide an objective, repeatable way of identifying morphological sub-unit boundaries (Guillén et al., 1999). However, along the East Riding coast the top of cliff/cliff base position identified from field or airborne surveys was assumed to provide a better representation of the coastline (Brooks and Spencer, 2010). Coastline changes were investigated relative to the initial survey if profiles did not reach the HAT level (with first measureable survey being the zero, or reference, line).

The topographic profiles were also used to quantify sediment budget changes in the AOIs (1997-2010 East Riding; 1994-2010 Lincolnshire). Cross-shore profiles were divided into three morphological units - backshore, foreshore and nearshore – and sediment volume was determined using simple trapezoidal area calculations under the survey line for one unit length (m^3 m^{-1}) of coastline. The reference base for the backshore was +MHWS (mean high water spring) height (Fig. 2), and thus corresponds to the sediment unit which is only affected by marine processes during energetic events. The boundaries of the foreshore unit are MHWS and ODN heights ($z=0$ m). In both these units volume is calculated above ODN. The nearshore zone was divided using ODN to MLWS (sub-unit 1) and from MLWS to $z = -5$ m (sub-unit 2). The baseline of $z = -5$ m was used to compute the sediment volume (Fig. 2).

<Fig. 2>

Although it has been argued that the HAT level gives a good approximation of coastline (Halcrow, 1988; Saye et al., 2005; Pye et al., 2007), it is worth noting that across different data sources (aerial photographs, topographic profiles) there is no significant correlation between the coastline and HAT level positions (Table 4). There are several possible reasons for this; first the coastline derived from aerial photographs corresponds to the crest of the foredune on sandy beaches, while the HAT level often represents the foredune slope-toe, which is likely to be a more dynamic morphologic feature (Ruessink and Jeuken, 2002). Second, the terrestrial and airborne surveys were not carried out simultaneously so some morphological change may have occurred between survey periods. Coastline position is related to the sand volume of the backshore and, unsurprisingly, there is a negative relationship between sand volume in the backshore and in the foreshore. Recent studies elsewhere in the North Sea Basin have suggested that significant quantities of sand can be supplied from the nearshore zone to the shoreface during energetic hydrodynamic conditions (Aagaard et al., 2004; Anthony et al., 2006).

<Table 4>

3.3. Climate and tidal data sources

Coastline position reflects processes operating at a range of magnitudes and frequencies. It has been demonstrated, for example, that the coastline can recover relatively rapidly following a single storm event, however sequences of storm events can cause major and sustained alterations due to insufficient recovery time (Douglas and Crowell, 2000; Morton and Sallenger, 2003; Stockdon et al., 2007). Detailed examination of the impact of climate and tidal conditions on the coastline would require continuous records of all variables including coastline position. Whilst coastline position data are only available every few years over the long term and every few months more recently, there are higher temporal resolution records of wind and water level and atmospheric conditions. These data can be used to identify the occurrence and frequency of high magnitude events, such as storms, that are likely to have a significant influence on the coastline.

3.3.1. Modern records

Wind and water level records were examined from 1994 to 2010 to investigate the causes of temporal and spatial variability in coastline dynamics. Hourly mean wind speed and direction were obtained from Donna Nook weather station and fifteen-minute measurements of the water level at Immingham tide gauge were supplied by the British Meteorological Data Centre and the British Oceanographic Data Centre (BODC) respectively. Data relating to water levels obtained in Chart Datum were converted to Ordnance Datum using the conversions at Spurn Head and Skegness given by BODC (www.bodc.ac.uk). Within macro-tidal environments, the primary factor controlling storm impacts is the water level reached during storm surges, and it must be associated with both wind speed and direction, and amplitude of surge (Vasseur and Héquette, 2000). Storm surge impact will only occur during high tides. To identify energetic events with potential impact on the coastline a storm surge was defined as the occurrence of onshore winds (i.e. winds from 350° to 150°) ≥ 14 m s^{-1} combined with a water level ≥ 3.5 m (ODN). Offshore winds are in the range 180° to 320°, with all other winds defined as alongshore. The mean of the monthly extreme water levels from 1994 to 2010 was 3.88 m and 3.74 m (ODN) at Spurn Head and Skegness, respectively. However, tide gauge measurements do not always reflect the hydrodynamic processes operating near the coast (Masselink and Hughes, 2003; Parker and Foden, 2009), particularly the run-up (set-up and wave up-rush) which can reach tens of centimetres along a macro-tidal beach during a storm surge. Therefore, a threshold of 3.5 m, slightly lower than the mean monthly extreme water level, was selected. This also corresponds approximately to the height of the interface between the foredune toe and the gentle beach slope along the Lincolnshire coast.

3.3.2. Proxy records of wind strength

The lack of long, continuous wind records has limited exploration of the impacts of long-term variations in storminess. However, given that the passage of synoptic scale storms is associated with strong winds due to intense pressure gradients (Carnell et al., 1996) it may be possible to use historical records of synoptic conditions to estimate long-term storminess (Alexandersson et al., 2000; Wang et al., 2009; Donat et al., 2010). Studies have suggested that the North Atlantic Oscillation (NAO) may control the occurrence of storm surge in the Atlantic and thus potentially influence coastal morphological changes (Woolf et al., 2002; O'Connor et al., 2011; Thomas et al., 2011). However, no clear associations have been found between NAO and the extreme wind and water climate in the North Sea (Woolf et al., 2003; Tsimplis et al., 2005), probably due to the sheltering effect of the British Isles land mass.

A method of classifying the daily circulation patterns of the British Isles (50°–60°N, 2°E–10°W) was developed by Lamb (1972) and has been applied to a range of west European climatological and environmental studies (El-Kadi and Smithson, 1992; Wilby et al., 1997; Buchanan et al., 2002). Lamb's subjective classification used daily atmospheric pressure charts to examine the surface airflow pattern and steering of the circulation system. Eight main directional types are recognized as the cardinal points, and there are three main non-directional types: anticyclonic, cyclonic, and unclassified. Days not characterized by a single weather type can be classified into one of nineteen hybrid combinations of the main types. Jenkinson and Collinson (1977) subsequently designed an objective, automated version of Lamb's classification (Jones et al., 1993) to produce the Jenkinson daily weather type (JWT) catalogue (also known as Circulation Weather Type; CWT). JWT is based on a 16-point grid of mean sea level pressure data over the British Isles to determine numerical values or indices of geostrophic wind total flow (F) and cardinal direction (D) at 0.1° intervals.

In this study, the Jenkinson daily synoptic indices from 1871 to 2010 were used as a climate proxy (provided by the Climate Research Unit, University of East Anglia, UK). Wind flow expressed in pressure units was converted to m s^{-1} (1 unit = 0.617 m s^{-1}) and the JWT was then used to determine the number of days when onshore, offshore, and alongshore winds exceeding 14 m s^{-1} occurred. These records were used to evaluate the annual variability in wind storminess at the synoptic scale.

4. Results

4.1. Coastal morphological changes

4.1.1. Flamborough Head to Gibraltar Point

Topographic profiles clearly highlight recent changes in coastline position (Fig. 3). There is a marked contrast between the eroding Holderness cliffs of East Riding, and the accreting Lincolnshire coast. Retreating sectors account for ~50.1 km out of 98.5 km (50.8%) of the coastline, whereas naturally accreting sectors extend for ~25.4 km (25.8%) and artificially (nourished) accreting or stable sectors represent ~23 km (23.4%).

<Fig. 3 >

On average, the Holderness cliffs retreated -28 m between the initial survey (mid-1990s) and 2010, but changes along this stretch of the coast varied from cliff retreat (erosion) of -89.8 m at the P97 profile to an advance (accretion) of +36.9 m at the P127 profile near Spurn Head between 1997 and 2010. In the north (P8-9) the coastline is near-stable due to sea defences (Fig. 3: where positive values indicate accretion or seawards extension and negative values indicate retreat or erosion). The mean short-term rate of retreat of the Holderness cliffs is 1.88 m year^{-1} but this varied over the survey period from -1.67 m year^{-1} (1990s-2005), followed by more rapid erosion of -2.65 m year^{-1} (2005-2008) then slowing to -1.71 m year^{-1} (2008-2010). Along Spurn Head, parts of the spit extended seawards (e.g. profile P127 showed accretion of +37 m) and other parts eroded (narrowed). The mean rate of change along Spurn Head varied from +2.84 m year^{-1} at P127 (centre of the spit) to -3.14 m year^{-1} at P131 (south) between 1997 and 2010.

Along the Lincolnshire coast, coastline change (1994-2010) varied from retreat of -11.3 m at the L2A5 profile to an advance of +191.3 m at the L2E4 profile due to the extension of the saltmarsh at Saltfleetby (Fig. 3). At Donna Nook the greatest seawards advance was +17.6 m (L1A4) whilst at Theddlethorpe it was +37.3 m (L2D1). Further south, changes range from -2.9 m at the profile L2B7 to +54.6 m at the L2C6 (just north of Skegness) between 1994 and 2010.

4.1.2. Specific areas of interest – trends in coastline position 1800s-2010

Within the sediment cell, the AOIs have very different spatial and temporal dynamics. Over the past 150 years the Easington cliffs have been eroding (Fig. 4). Mean cliff retreat rate is -2 m year^{-1} but it exceeded -3 m year^{-1} for the periods 1854-1890, and 1969-2005. The annual rate of cliff erosion decreased to -1.36 m year^{-1} between 2005 and 2010. The highest rates of retreat occur along the southern urbanized coastal sections and locally reached -3.9 m yr^{-1} from 2008-2010 and -5.6 m yr^{-1} from 1952 to 1969. Over the long-term North Spurn Head is eroding with a mean rate of coastline change of -1.56 m year^{-1} for the period 1854-2010 (Fig. 4). As at Easington, the highest rate of erosion measured (-4.9 m year^{-1}) occurred between 1951 and 1969. Since 1969, data from the aerial photograph analysis indicate that the mean annual rate of retreat is slowing down.

<Fig. 4>

The downdrift sector of the sediment cell (2c – Lincolnshire) is dominated by sandy beaches and saltmarshes (Table 2). At Donna Nook map and aerial photograph analyses indicate a seaward advance of the coastline of 2.7 m year^{-1} (Fig. 5A). Since 1951 the rate of accretion has been relatively constant. This AOI stretches 5.1 km alongshore but coastline advance since 1891 has varied from +46 m in the north to +449 m at the southern end of the site.

<Fig. 5>

At Saltfleetby, coastline evolution was only investigated between 1994 and 2010 (section 3.1.2). Results indicate erosion of -1.1 m year^{-1} between 1994 and 2008, followed by a more recent phase of accretion (Fig. 5E). The Saltfleetby AOI is characterized by extensive saltmarsh partially bounded on the seaward side by sand dunes. These dunes have been very dynamic and their development appears to be linked to that of the saltmarsh. Aerial photograph analysis indicates both an inland migration and decrease in size of these dunes. Taking the Saltfleetby AOI as a whole, the overall erosion trend reflects the morphological changes of these coastal dunes. By excluding transects intersecting the dunes, the results indicate that where saltmarsh dominates it is accreting at a rate of +1.15 m year^{-1}. A gradual increase in the rate of accretion was also observed from +1.36 m year^{-1} (1999-2005) to +2.64 m year^{-1} (2008-2010).

South of Saltfleetby, at the Theddlethorpe AOI there is no saltmarsh, but a wide beach with well-developed dunes. Within the AOI overall coastline position advanced +126 m in the north increasing to c..+185 m in the south. Here the coastline is accreting rapidly at a mean rate of 2 m year^{-1} (1891-2010). As with the other AOIs, the rate of coastline change has varied through time and between 1951 and 1953 an accretion rate as high as +7.67 m year^{-1} is suggested by our analysis; however this may be over-estimated due to the change in data source from the OS map (1951) to aerial photographs (1953). From the photo-interpretation analysis, the rate of accretion varied with a mean annual rate from c.+3.1 m year^{-1} for 1976-

1983 to just +0.97 m year^{-1} over the period 2005-2008. By considering the photo-interpretation results only, the mean rate of coastline accretion was of +1.9 m year^{-1} between 1953-2010, which is similar to the average estimated for the 119-year study period.

No detailed analyses of the coastline changes were undertaken along the Skegness coast because it has been protected by sea defences which were installed following the 1953 floods and are well maintained (HECAG, 2009). Sea defences prevent or alter interactions between inland and tidal zones, however since 1994 the data show accretion seaward of the defences along a vegetated line which has extended both alongshore and towards the sea (Fig. 6). This may be a response to a major sand nourishment programme undertaken just to the north along the beach at the L2B6 profile of 210,000 m^3 in 1994, with subsequent replenishment in 2006 and 2007 (Environment Agency, 2008).

<Fig. 6>

4.1.3. Specific areas of interest – changes in sediment budget 1990s-2010

Tables 5 and 6 present the net sediment budget calculated individually for the backshore, foreshore and nearshore (bathymetric) units in each of the AOIs (Fig. 2). The data shown are the total gain (+) or loss (-) of sediment in m^3 x 10^3 between successive surveys, and cumulative change through time. Annual rate of change in m^3 year^{-1} is also estimated.

<Table 5>

<Table 6>

At Easington, from 1997 to 2010 there was a cumulative sand loss of c. -66.9×10^3 m^3 for the combined backshore and foreshore units (Table 4). The majority of this is accounted for by cliff erosion in the backshore which is twenty-two times greater than losses from the foreshore unit. North Spurn Head was also affected by overall sand loss with an erosion rate of c. -1.5×10^3 m^3 $year^{-1}$ although during specific periods both the backshore (1997-1999) and foreshore (1999-2005) did gain sediment (c. -8.3×10^3 m^3 and $0.8 \text{ x } 10^3$ m^3 respectively).

As might be expected from the long-term coastline trends described above, the Lincolnshire coast overall gained sediment from 1994-2010. At Donna Nook the results indicate an annual positive budget of 49.9×10^3 m^3 $year^{-1}$. The backshore displayed the greatest mean accretion rate of 30.5×10^3 m^3 $year^{-1}$, however net volume gain has fallen since 2005 with sand losses between 2005 and 2008. Similarly at Saltfleetby there were volumetric gains in both the backshore and foreshore from 1994 to 2005 followed by overall sediment losses from 2005 to 2010. Overall Theddlethorpe gained on average c. 47.6×10^3 m^3 $year^{-1}$ from 1994 to 2010 but all of the increase in sediment volume was on the backshore (c. $63. \times 10^3$ m^3 $year^{-1}$) whilst the foreshore actually lost c. -15.4×10^3 m^3 $year^{-1}$. At Skegness there was a total mean accretion of c. 21.5×10^3 m^3 $year^{-1}$ with the greatest changes recorded in the backshore unit.

For the nearshore units (Table 5) there were overall sediment gains at Donna Nook and Skegness but sediment losses at Saltfleetby (-6.3×10^3 m^3 $year^{-1}$) and Theddlethorpe (-35.1×10^3 m^3 $year^{-1}$). At Theddlethorpe, interestingly the nearshore sub-unit 1 from ODN to MLWS experienced a significant sand loss, whilst accretion took place in the seaward nearshore unit. At Skegness the nearshore zone gained sediment in sub-unit 1 but lost sediment in sub-unit 2.

4.2 Forcing factors

4.2.1. Twenty-year record

Strong onshore winds occurring during astronomical high tides result in storm surges that could be responsible for coastline erosion and retreat. The analysis of forcing factors for the period 1993-2009 shows water levels above 3.5 m are infrequent and no storm surge events were recorded in 1994-1995 and 2002-2003 (Fig. 7). Although storm surge frequency was variable, the mean rate of coastline retreat at Easington was relatively constant from 1994-2010. At North Spurn Head storm activity (1-5 events yr^{-1}) from 1997-2001 coincided with a phase of accretion (Fig. 7) whilst from 2002-2006 storms were less frequent and this included a phase of coastline erosion of up to -1.3 m yr^{-1}.

<Fig. 7>

Along the Lincolnshire coast, at Donna Nook (Fig. 7C) up to 8 storm surges per year occurred between 1994 and 1998 and this coincided with coastline accretion of c. +4 m year^{-1}. Coastal propagation subsequently continued at a slower but relatively constant rate. A stormy phase from 1996-1998 coincided with saltmarsh retreat at Saltfleetby AOI of -2.3 m year^{-1} however this slowed down to less than -0.3 m year^{-1} between 1999 and 2004 before accelerating back to -2.3 m year^{-1} from 2005-2007, another storm phase. However, where it is unconstrained by the coastal dunes, the saltmarsh shows significant seaward advance over the last twelve years, with no clear relationships with the occurrence of storm surge events. At Theddlethorpe the highest rates of coastline accretion (+2.5 m year^{-1}) occurred between 1994 and 1998 (Fig. 6E) when up to 8 storms per year were recorded. The rapid coastline advance continued in the absence of frequent storm events between 1999 and 2004 and continued, but at a slower rate until 2010. This decrease in the rate of advance coincided with a period of slightly higher storm surge activity. At Skegness from 1999-2004 the coastline (HAT level) prograded at a rate of +1 m year^{-1} but changed to a retreat of -2 m year^{-1} between 2008 and 2010, possibly in response to storms in 2008.

4.2.2. Long-term record

Fig. 8 shows the occurrence of days with high wind speeds (storms) from 1871 to 2010 over the British Isles indicated by JWT. The most frequent winds are offshore, coinciding with strong westerly winds in winter. The long-term trend of strong offshore winds appears relatively stable although with a slight fall in frequency in the 1960s. However, offshore winds are not likely to be associated with significant storm surges. Rather storm surge will be associated with strong onshore winds. From 1871-2010 the annual frequency of onshore winds ≥14 m s^{-1} varies from zero in 1932 to 19 in 1917. The 5-year running mean indicates three peaks in the onshore storm event record in 1876, 1878, and 1883. This last peak was followed by a relatively stable period of 35 years. Three distinct stormy periods occurred in 1955-1970, 1975-1988 and 1994-2000 (Fig. 8). Strong alongshore winds typically occur on fewer than 6 days per year.

<Fig. 8>

To assess the utility of the Jenkinson weather catalogue as a proxy for storm surge, a correlation analysis was undertaken between the frequency of storm surges predicted per year using recorded wind and tide data from 1994 to 2010 and the incidence of onshore wind events exceeding 14 m s^{-1} predicted by JWT records for the same period. The temporal patterns of storm frequency are broadly similar (Fig. 9) and high correlation coefficients are obtained for both Skegness ($r=0.52$, $p<0.05$) and Spurn Head ($r=0.58$ $p<0.05$) suggesting the Jenkinson weather catalogue may be a useful proxy for long-term storminess.

<Fig. 9>

5. Discussion

An examination of detailed records over the past two decades and longer historical records demonstrates clear trends in erosion and accretion along the Flamborough Head to Gibraltar Point coast. These trends can be ascribed to factors such as natural antecedent conditions, relative position within the sediment cell (i.e. updrift/downdrift) and human activities. In this discussion, we consider the short-term changes in coastline position and sediment budget and their relationships with environmental forcing factors, the long term historical coastline changes and finally possible response of the coastline to sea level rise.

5.1. Coastline changes from mid 1990s-2010

Unsurprisingly, the topographic profile data indicate rapid and significant erosion of the Holderness cliffs since the mid-1990s. Spatially-averaged retreat rates suggest more rapid erosion from 2005-2008 (>2.6 m yr^{-1}) compared with preceding and following years (c. 1.7 m yr^{-1}). However, rates of cliffline recession are spatially very variable (Fig. 3). This reflects localised occurrence of landslips, which typically cause a few years of increased recession followed by a period of below average retreat (Pringle, 1985; Posford Duvivier, 1992), such as described for profiles P78 and P95 by Quinn et al. (2009), the location of intertidal sandbars which accelerate cliff erosion rates (Pringle, 1985; Pethick, 1996; Moore et al., 1998) and the presence or absence of offshore sand banks which reduce inshore wave energy and hence slow retreat rates (Eurosion, 2003). Changes in the HAT level indicate that, downdrift of Holderness, the north Lincolnshire beaches are accreting. Leggett et al. (1998) also documented accreting beach profiles along the north Lincolnshire coast with a positive change of 2% (by volume) from 1991-1996. Between Mablethorpe and Skegness, the coastline has been affected by beach nourishment since 1994, and overall the HAT level has undergone seaward extension. The UK Environment Agency (2011) suggests accretion of the upper-beach in this location can be attributed to retention of renourishment material blown up the beach.

Using topographic profiles for all the cliffed sections of the East Riding coast, we calculated that the retreating cliffs have lost 1,004,755 m^3 yr^{-1} (1000x10^3 m^3 yr^{-1}) of sediment since the initial survey in the mid-1990s. This rate is comparable to the estimate of 1000×10^3 m^3 $year^{-1}$ (from 1852-1952) by Valentin (1971). ABP (1996) predicted a slightly higher cliff erosion rate of up to 1400×10^3 m^3 $year^{-1}$. The combined sediment losses from both the cliffs and the shoreface along the Holderness coast are estimated to be in the region 2500-3000 ×10^3 m^3 $year^{-1}$ (ABP, 1996; Balson et al., 1996, 1998; Eurosion, 2003), which increases to 3900-4700 x10^3 m^3 $year^{-1}$ if the lower seabed to the limit of erosion is included (Wingfield and Evans, 1998). Of this eroded material 60-80% is clays and silts, while the rest is predominantly sand and gravels (Balson and Harrison, 1988; Blewett and Huntley, 1998; Townend and Whitehead, 2003). Balson et al. (1998) estimated that 33% of the sediment is eroded from the cliff, and 67% from the shorefaces and seabed.

Calculations for the AOI at Easington for this paper suggest the cliffs here have yielded approximately 66.9×10^3 m^3 $year^{-1}$ (Table 5). Posford Duvivier (1992) modeled the wave-driven littoral drift at Easington (including both sediments being transported from the northern cliffs and input from Easington itself) and predicted a southward longshore sand transport of 157-310×10^3 m^3 $year^{-1}$ from this area. Easington marks the point at which the southwards travelling sand derived from erosion along the total length of the cliffs moves offshore (Halcrow and Geosea, 1990), although the precise transport pathways of eroded sediments will depend on their mineralogy and grain size (Newsham et al., 2002). This offshore transport is a result of a combination of the change in both the orientation of the coast and the direction of the tidal currents at this point. Previous studies suggest 3-6% of the eroded cliff material is transported to the southern end of Holderness and incorporated in to the Spurn Head spit whilst the remainder is deposited in the nearshore and offshore zones (Valentin, 1971; Ciavola, 1997).

Whilst the littoral drift may input 30-60 x 10^3 m^3 yr^{-1} to the spit (Valentin, 1971; Ciavola, 1997), our results show that erosion from North Spurn Head has the potential to supply 1.5×10^3 m^3 $year^{-1}$ to areas downdrift (Table 5). The principal pathway of bedload sediment material is southwards towards the nearshore sand banks of The Binks, which act as a sand reservoir for Spurn Head and a buffer to erosion under energetic hydrodynamic conditions. The littoral cell of interest has three sub-cells, the central one (2b; Fig. 1) being defined by the Humber Estuary. The sediment budget of the Humber Estuary is complex but whilst total sediment flux through the estuary mouth is very high, the net exchange between the estuary and the North Sea is low (Townend and Whitehead, 2003) with estimates of sediment input to the North Sea ranging from 100-255 kt yr^{-1} (compared with 1400-2610 kt yr^{-1} eroded from Holderness; McCave, 1987; HR Wallingford, 1992). Only around 1% of the total sediment is estimated to enter and circulate into the Humber estuary before being expelled back in to the North Sea (Halcrow and GeoSea, 1990; Black and Veatch, 2004). Fine sediments eroded from the updrift Holderness cliffs are transported into the estuary by the flood tide and coarser sand-sized materials are moved in to the marine environment (ABP, 2000). Strong tidal flows can prevent gravels and sands from crossing the Humber Estuary (HECAG, 2009), however, Robinson (1968) released seabed drifters from The Binks near Spurn Head, 60% of which were recovered from the south shore confirming a sediment transport pathway across the mouth. Medium and fine sands can be transported across the estuary mouth especially during storm conditions and build up in offshore sand banks at Donna Nook (Steers, 1966; Tonk, 2000; HECAG, 2009). This deposition is reflected in this study through the dominance of accretion in both the back/fore shore and nearshore zones at Donna Nook where the volume of accretion is equivalent to 5.8% of the total estimated Holderness cliff erosion (Tables 5, 6). Additional sediment supply to this area can come from The Binks during storm surge conditions (HR Wallingford, 2002).

From the mid-1990s to 2010 the back and fore shore units at Saltfleetby and Theddlethorpe have been accreting, while erosion has characterized the nearshore zone (Tables 5, 6). The total annual sediment supply at Saltfleetby and Theddlethorpe is equivalent to 4.7% of that eroded from the East Riding coast. At Mablethorpe, the coastline switches from accretion to erosion (Schans et al., 2001) driven by a combination of exposure to wave activity (Dugdale and Vere, 1993) and anthropogenic pressures (Robinson, 1964; Pye, 1995). The artificially nourished coastal section from Mablethorpe to Skegness was assumed not to accumulate sediment from the Holderness cliffs. Data from topographic and bathymetric profiles at Gibraltar Point indicate that sediment input has been approximately 181.9×10^3 m^3 $year^{-1}$. Assuming no additional sources, this quantity would represent 18.7% of the cliff material eroded to the north. Again assuming no additional sediment sources or sinks along the coastline, when combined with the 5.8% input to Donna Nook and 4.7% input at Saltfleetby-Theddlethorpe, this suggests that only 29% of the material eroded in sediment sub-cell 2a is transported ‘directly’ by the littoral drift to the Lincolnshire coast (sub-cell 2c). The majority of sand material eroded from the Holderness cliffs can therefore be assumed to move offshore, however the division is likely to be less clear-cut as material transported offshore to the Binks and other sand banks along the Lincolnshire coast, will be redistributed by cross-shore wave currents (Halcrow, 1988; ABP, 1996). Sediments introduced to the system during the nourishment programme may also form some of the inputs to Gibraltar Point.

Over the short-term there were few storm surges where wind speed was ≥14 m s^{-1} and water level was ≥3.5 m ODN, but the highest frequencies occurred between 1996-2001. This was followed by two very calm years and then by a period of medium activity between 2004-2010 (Fig. 7). At Easington, retreat rates were remarkably constant whereas they varied far more at North Spurn Head and along the Lincolnshire coast. Our data show a positive correlation between storm surge occurrence and coastline position and between storm surge and sand volume in the backshore, whereas there is a negative relationship with the sand volume in the foreshore (Table 4). However, there are no clear relationships between coastline change and storminess. A limitation of our data set is the relative timing of data acquisition in that it rarely includes the coastline position recorded immediately before or after a storm surge, however it may represent the beach morphology in calm weather conditions, and thus the post-storm recovery state.

5.2. Coastal evolution from the 1800s to 2010

Although coastline changes determined from maps and historical aerial photographs are likely to be less reliable than recent field surveys, they are necessary to determine the long-term evolutionary tendency of the coastline. The changes that have taken place in the northern part of this sediment cell (2a) along the Holderness coast have been the subject of numerous previous studies (e.g. Reid, 1885; Valentin, 1954, 1971; Dosser, 1955; Steers, 1966; Mason and Hansom, 1988; HECAG, 2009; Quinn et al., 2009), and beach development in the far south around Gibraltar Point has also received some attention (e.g. King, 1964, 1968, 1973; Barnes and King 1955; King and Barnes, 1964). There has, however, been considerably less research in the south-central sector of the cell along the north Lincolnshire coast.

In the north of the sediment cell, we determined that the southern Holderness cliffs have, on average, been eroding at 2 m yr^{-1} since 1854 (Fig. 11). This is in agreement with previous estimates of 1-2 m yr^{-1} over 150 years (Valentin, 1954; Mason and Hansom, 1988; Quinn et al., 2009). Some research indicates that towards Flamborough Head, parts of the north of the Holderness coast underwent aggradation from 1852-1952 (Valentin, 1954; Bird, 1984) but analysis of recent topographic profiles (1994-2010) suggest that currently erosion is taking place along the whole cliffed coastline albeit at a much more rapid rate towards the south. Spurn Head has long been recognized as a very dynamic feature undergoing cyclic breaching, destruction and reformation (De Boer, 1964). This paper has reported significant variability in rates of erosion on North Spurn Head ranging from nearly -5 m yr^{-1} (1951-1969) to <-0.7 m yr^{-1} (1890-1951 2005-2010). This most recent decrease in rates of erosion was also observed by Saye et al. (2005).

In contrast, the beaches of north Lincolnshire have undergone accretion up to +2.7 m $year^{-1}$ over the past 120 years (Fig. 11). The result agrees with the study by Halcrow (1988) which indicated accretion from the late 19th century to 1970. Robinson (1984) also reported that by the early 19th century the Saltfleetby-Theddlethorpe coastline was characterized by an accreting coastline. One of the sediment sources for these beaches is, as mentioned above, material eroded from the Holderness coast (Steers, 1946), but in addition there is onshore movement of material from sand banks (Halcrow, 1988; ABP, 1996; HR Wallingford, 2002). Our analysis did not indicate any general coastline retreat caused by the severe 31st January-1st February 1953 North Sea storm surge, however the intervals between maps and aerial photographs probably hides some short-term coastline recession. The storm surge impacts in 1953 are also likely to have been reduced by the presence of coastal dunes and the higher, wide beach along the North Lincolnshire coast (Robinson, 1953; Brampton and Beven, 1987).

<Fig. 11>

5.3 Proxies for storminess

Pressure-based circulation weather types, such as the JWT used here, have been widely used to examine general trends and variability in long-term storminess in Europe (e.g. Alexandersson et al., 2000; Donat et al., 2011; Wang et al., 2011) and are generally more reliable proxies over sea than over land (Krueger et al., 2012). We suggest JWT may provide a reasonable proxy for storminess on the east coast of England. Frequencies of storm events identified using JWT data are much higher than those of measured storm surges (Fig. 9); this is because we have not differentiated onshore energetic events associated with high tides, where storm surges would be likely, from those associated with low tides where little or no impact would be expected due to the lower overall water level (Chaverot et al., 2008). Accounting for water level over the longer term is something that could be explored in future. Over long time periods other studies have successfully used similar proxy measures of storminess, such as variations in the NAO, to explain temporal patterns of coastline evolution (Vespremeanu-Stroe et al., 2007; Thomas et al., 2011; O’Connor et al., 2011) which suggests analysis of the JWT data set may be worth pursuing further.

Overall temporal patterns of storminess (all directional sectors) in the NE Atlantic and North Sea since the 1870s determined using the JWT/CWT approach have shown variable, but typically low, levels of storminess in the late nineteenth century and first half of the twentieth century (Alexandersson et al., 2000; Wang et al., 2009) although in the central North Sea (55°N 5°E) total gale days indicate high storminess in the early twentieth century (Donat et al., 2011). Minimum storm activity has been put at around 1960 with maximum storminess during the 1990s followed by a decline to long-term average conditions in the early 2000s (Wang et al., 2009; Donat et al., 2011). This is broadly in accordance with patterns determined in this paper, however due to the geomorphological research questions being addressed we deconstructed the total record into specific directional sectors (onshore, offshore and alongshore) and events meeting specific wind speed conditions, and these components show some differences to the overall pattern. For example, the frequency of JWT onshore wind storms was variable from 1871 to the 1920s (1-19 events per year), but was slightly higher than the long term mean of 7 events per year. This was followed by a relatively calm period of up to 35 years (Fig. 10A). Peak periods of onshore wind storm events occurred during 1955-1970, 1975-1988, and from the mid-1990s to 2000. The first of these peak periods contrasts with more widely-observed low levels of overall storminess (which can be seen in the offshore record in Fig. 8). These peaks indicate an increase in wind speeds likely to generate greater significant wave heights and these energetic periods are broadly coincident with the highest rates of coastal erosion recorded between 1854-1890 and 1951-1969 at Easington and North Spurn Head (Fig. 10). The JWT storm event frequency decreased after 2005, which coincides with a decrease of coastline recession rates at these sites. Within a littoral sediment cell with a defined sediment budget, erosion of material in one part of the cell should lead to accretion elsewhere within the cell; accordingly high recession rates along the Easington cliffs between 1891-1910 and 1976-1983 were concomitant with the highest rates of coastline accretion recorded at Donna Nook (1891-1910) and Theddlethorpe (1976-1983), and from 1994-2005 at both sites (Fig. 10). In contrast, the recent decrease in cliff retreat from 2005-2010 may be the cause of the lower rates of seaward accretion along the North Lincolnshire sandy beaches over the same period. In the study region our long-term data set only provides reliable information concerning longshore coastal changes, however, as discussed in section 5.1, the short-term (decadal) data indicate cross-shore sediment transport to and from offshore stores such as sand banks is substantial. As with other regions, such as the Columbia River Littoral Cell (Ruggiero et al., 2005), lack of cross-shore transport data makes it difficult to make long-term sediment budget calculations.

Within our data, one particular period of interest is that between the 1900s and 1951 where rates of coastline change throughout the sediment cell were very low. This broadly coincides with a long period of low frequencies of annual wind storms (1920-1955). Both the geomorphological and climatological records suggest there was a period of quiescence lasting ~35 years in the first half of the 20th century. Previous research has identified strong correlations between storminess in the NE Atlantic (including the North Sea) and NAO (e.g. Wang et al., 2009), but in the methods we indicated that winter NAO was not a good indicator of storminess on the east coast of England. Positive winter NAO phase leads to enhanced westerlies due to a stronger than usual sub-tropical high pressure centre and a deeper than normal Icelandic low (Hurrel, 1995) and most storms identified using CWT are associated with westerly flow (Donat et al., 2010). Between 1900s and 1950, winter NAO phase was positive with consecutive strong positive phases between 1900-1915 and 1915-1930 (Fig. 10B). Over this period, the occurrence of storm events, affecting the North Atlantic west-facing coast would be expected to have increased, whereas the east coasts would be relatively sheltered. It can be suggested, therefore, that although positive NAO phase may not indicate storminess on the east coast of England, it could provide a useful proxy for quiescence. The advantage of using JWT/CWT data sets is that they can be focused on specific directional sectors (in this case winds from the north and the eastern sector (N, NE, E, SE) which is important in the context of understanding the impact of events on the coastline. Although the JWT approach was originally developed for the British Isles (Lamb, 1972) it has been successfully applied to other regions including the Netherlands (Buishandt and Brandsma, 1997), Spain (Goodess and Palutikof, 1998, Lorenzo et al., 2008), Portugal (Trigo and Dacamara, 2000) and Morocco (Born et al., 2010) in research focusing primarily on precipitation and catchment scale flooding. This paper, and other recent studies using circulation weather types to examine wind storms (e.g. Wang et al. 2009; Donat et al., 2011), suggest that they could provide a valuable data source for interpreting long-term coastal geomorphological change throughout northwest Europe.

The use of JWT/CWT data merits further exploration but low levels of storminess are not likely to explain fully the relatively static nature of the coastline from 1900 to 1950. Other possibilities are a redistribution of sediments, for example there was a natural extension of a barrier located seaward of the centre of the Spurn spit during the 18th and 19th centuries (Halcrow, 2002) which may have lead to a reduction in sand volume reaching beaches in north Lincolnshire as the barrier extended (Pye and Blott, 2010). In addition, this coast has a long history of defence. Hard coastal defences were built on sections of the Holderness coast such as Hornsea, Mappleton, Withernsea and Easington in the late 19th century and may have temporarily reduced or stopped the cliff retreat; the construction of a groyne field is also likely to have impeded the littoral drift of sediment (Pye and Blott, 2010). In 1883/84, further groynes and timber revetments were built to prevent breaching and erosion along Spurn Head. Spurn Head was a military stronghold during the second world war and coastal defences were built along the seaward side (De Boer, 1981), which are likely to have reduced alongshore sand transport to the south. These were abandoned and fell in to disrepair in the 1960s.

5.4. Response of the coastline to sea-level rise

There are number of challenges associated with predicting the response of sediment cell and landform dynamics to climate change and sea-level rise. One of the most important is obtaining historical records over sufficiently long time periods for accurate change detection, particularly given that in many littoral cells short-term changes can occur at a very different rate, or even show the opposite trend, to long-term change (Ruggiero et al., 2005; Brooks and Spencer, 2012). In addition, as demonstrated here, because both cliff and beach systems can exhibit considerable alongshore variability in rates of change, and because sediment processes acting over a larger area can influence local scale change, the spatial scale needs to extend over at least the sub-cell and ideally the whole coastal cell (Ruggiero et al., 2005; Neill et al., 2008; Quinn et al., 2009). In this study, the time interval between data sets (years to decades) and the length of time between the earliest and the most recent data set (>110 years) means the impact of short-term change is minimised; there are clear directional changes at most of the AOIs examined (with the exception of Spurn Head). Over the historical period coastline dynamics in the downdrift sector of the sediment cell (2c) have been controlled by the supply of sand material from the updrift section of the cell (2a), the eroding Holderness coast. During periods of more rapid cliff retreat, rates of coastline progradation have been higher on the Lincolnshire coast; when cliff retreat is slowed, such as during the early twentieth century, rates of accretion downdrift are reduced. For the central sub-cell (2b) historical data used to reconstruct changes in the volume of the Humber estuary since 1851 suggest an overall period of infilling prior to 1940 followed by erosion up to 2000 (although data sources prior to 1936 were incomplete) however there has been no significant change in average flow rates over the last century (Townend et al., 2007).

A number of studies has examined and modelled the likely response of other sectors of the east coast of England (notably sediment cell 3; East Anglia) to future environmental change (Dickson et al., 2007; Dawson et al., 2009; Brooks and Spencer, 2012). Sea level is predicted to rise at an accelerated rate in future (IPCC, 2007) and there is a range of possible responses of cliffs to sea-level rise varying from increased retreat rate to decreased retreat rate or no change (Ashton et al., 2011), but sea-level rise is not the only controlling factor on cliff retreat (e.g. Lim et al., 2010). Storm frequency and magnitude are also predicted to increase and will probably heighten coastal erosion as well as flooding on low-lying coasts (Webster et al., 2005; Bindoff et al., 2007; Chini et al., 2010). Dickson et al. (2007) and Brooks and Spencer (2012) used historical data for retreating sectors of the East Anglian coast (Norfolk and Suffolk respectively; both sediment cell 3) to test models for predicting coastline response to sea level rise. Brooks and Spencer (2012) found that the longer the time period for which historical (baseline) data were available, the better the predictions, but importantly found that a single spatially-averaged estimate of retreat performed poorly because the alongshore variation in retreat rates was not accounted for. On the Norfolk coast, models of historical change captured the measured patterns of erosion in the cliffed sectors (e.g. from Weybourne to Eccles) and deposition along the unconsolidated coastline from Eccles to Winterton Ness, and a similar pattern of cliff recession and beach volume increase is predicted under a variety of sea level change and management scenarios (Dickson et al., 2007). In sediment cell 2, it could be assumed that the future rate of cliff erosion and sediment supply will be similar to present day rates (Newsham et al., 2002; Black and Veatch, 2004), although whilst this may be an appropriate assumption at Easington where rates of erosion have been relatively stable for 150 years, at sites such as Spurn Head future behaviour is likely to be harder to predict (Scott and Wilson, 2009). Spurn Head above the upper-intertidal zone is expected to migrate westward, but it is unlikely to extend further south due to the forcing effects of tidal flows and overwashing events that occur during storm surges (East Riding Council, 2004). Models applied to cell 3 suggest that broad spatial patterns of erosion and retreat are likely to continue over the twenty-first century and, similarly; in cell 2 sand eroded from the Holderness cliffs is likely to continue to supply the North Lincolnshire coastline causing ongoing accretion. At present, whilst the Holderness coast has some coastal defences these are insufficient to prevent cliff erosion and the current Shoreline Management Plan recommends letting natural processes continue except in localised areas where town frontages and infrastructure require protection (HECAG, 2009). Similarly, along the Lincolnshire coast defences are minimal north of Mablethorpe and continued coastal progradation will likely allow this to continue during the current century even under predicted sea-level rise. A largely unknown factor, and one for which there are fewer long-term historical records from which to make predictions, is the impact of cross-shore sediment transport to and from the offshore sand banks. As indicated in section 5.1 offshore sediment transport is substantial and the offshore sand banks play an important role not only in supplying sand to the coastline, but also in reducing wave energy (Steers, 1966; Motyka and Brampton, 1993; Blott and Pye, 2004, Brooks and Spencer, 2012) which may impact both coastline recession and progradation rates.

6. Conclusions

Spatial and temporal variability in coastline position, rate of change and sediment budget were assessed within a single sediment cell. There have been clear trends in erosion and accretion from Flamborough Head to Gibraltar Point over the past 150 years and the different parts of the sediment cell are clearly connected. High rates of erosion updrift (2a) are associated with high rates of accretion downdrift (2c) and periods of relative stability in these two sections of the sediment cell are broadly coincident. The volume of sediment incorporated in to the accreting beaches represents around 29% of that eroded from the Holderness cliffs. The results highlight the importance of understanding the variable dynamics of different types of landform occurring within a single sediment cell (e.g. cliffs, dune-backed beaches). Erosion on sandy beaches is often an outcome of storm surges, however where the storm causes the release of large quantities of sediment updrift within the sediment cell, this erosion may be mitigated or, in the case of north Lincolnshire, result in accretion due to the increased sediment supply to areas downdrift.

Overall temporal patterns of storminess in the north Atlantic and North Sea can be identified using pressure-based continental weather types. An exploration of the use of the Jenkinson Daily Weather Type as a proxy for storm surges over the historical record suggests that by deconstructing the data into specific directional sectors, to account for onshore-, offshore- and alongshore-directed events, useful information on long-term patterns of storminess and its potential impacts on specific coasts can be obtained. The performance of such weather type data for predicting the geomorphological impacts of storm surges would probably be improved by incorporating information about water level with the wind record.

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Table Captions

Table 1 Tidal levels and tidal ranges, expressed in metres above Ordnance Datum Newlyn (ODN). Tide level for East Riding coast derived from Spurn Head data taken from Admiralty Tide Tables (Admiralty, 2009) and from tidal statistics at Skegness derived from POLTIPS 3 software developed by the National Oceanography Centre Liverpool (NOC, 2009). Abbreviations: HAT – Highest Astronomical Tide; MHWS – Mean High Water Spring; MHWN – Mean High Water Neap; MLWN – Mean Low Water Neap; MLWS – Mean Low Water Spring; LAT – Lowest Astronomical Tide.

Table 2 Summary characteristics of the six areas of interest (AOIs) examined in detail. Profile labels correspond to original data sources (East Riding Yorkshire Council or UK Environmental Agency).

Table 3 Summary of map and aerial photograph source documents and characteristics for each AOI. Abbreviations: B&W – black and white, EA – UK Environment Agency. For AOI information, see Table 2.

Table 4. Correlation table between morphology parameters and forcing factors at the sandy beaches between surveys (AOIs 2, 3, 5): CI - Relative coastline position, C_{HAT} - HAT level position, V_B - sand volume in backshore, V_F – sand volume in foreshore, SS - storm surge. Correlation values above ±0.5 are in bold.

Table 5 Estimated inter-survey and cumulative sediment volume changes for the periods 1994/97-1999, 1999-2005, 2005-2008, 2008-2010, by shore units (see Fig. 2). Positive values indicate accretion, and negative values erosion.

Table 6 Estimated inter-survey and cumulative volumetric changes for the periods 1994/97-1999, 1999-2005, 2005-2008, 2008-2010, by nearshore sub-unit (see Fig. 2). Positive values indicate accretion, and negative values erosion.

Figure Captions

Figure 1	Inset: Distribution of coastal cells around the coast of England and Wales, Main figure: Boundaries and major features of sediment cell 2, east coast of England.
Figure 2	Schematic diagram defining the limits of the backshore, foreshore and nearshore zones used to calculate sediment budget.
Figure 3	Changes in coastline position within sediment cell 2 from Flamborough Head (P1) to Gibraltar Point (L2A7) over the period from mid-1990 to 2010 (longshore spacing not to scale). Coastline represented by the cliff base (East Riding; P1-121) or HAT (Spurn Head; P122-P134 and Lincolnshire coast; L1A1-L2A7). Zero line represents the initial survey in 1994/96/97 along East Riding coast and 1997 along Lincolnshire coast. Profile labels correspond to original data sources (East Riding Yorkshire Council or UK Environmental Agency). Notation of AOIs is indicated - see Table 2. Profiles perpendicular to coastal defences and lagoons are excluded (P3-P7, P42-P44, P90-P93, P115-P118, P133, L2A4).
Figure 4	Position of coastlines from 1854/91 to date for: A) Easington, B) North Spurn Head superimposed on ortho-photographs in 2010. Evolution of the coastline position (line curve) relative to OS maps in 1854 at C) Easington, D) North Spurn Head. Dashed line corresponds to mean long-term rate of shoreline evolution (1854-2010).
Figure 5	Position of coastlines from 1891 to date for: A) Donna Nook, B) Saltfeetby, C) Theddlethorpe superimposed on ortho-photographs in 2010. Evolution of the coastline position (line curve) relative to OS maps in 1891 at D) Donna Nook, F) Theddlethorpe and in 1994 at E) Saltfeetby. Dashed line corresponds to mean long-term rate of shoreline evolution over the timeframe.
Figure 6	Position of coastline from 1891 to date for Skegness: A) North, B) South.
Figure 7	Annual frequency of storm surge and coastline evolution between 1994/97-2010 at: A) Easington, B) North Spurn Head, C) Donna Nook, D) Saltfleetby, E) Theddlethorpe, and F) Skegness.
Figure 8	Time series of JWT annual strong wind events and storm surge measured at tide gauges between 1994 and 2010

Figure 9	Time series of JWT annual storm wind events between 1871-2010 for A) onshore winds, B) alongshore winds and C) offshore winds. In each case daily frequency and 5-year running mean are shown. Note: vertical scales differ.
Figure 10	Time series of: A) JWT annual strong onshore wind events between 1871-2010, B) winter NAO values (Dec-March) between 1850-2010 and coastline evolution at C) Easington, D) North Spurn Head, E) Donna Nook, and F) Theddlethorpe from 1854/91 to 2010.
Figure 11	Long-term morphodynamic trends in the coastal cell along East Riding and Lincolnshire coasts at the studied AOIs since 1850/81.

Table 1 Tidal levels and tidal ranges, expressed in metres above Ordnance Datum Newlyn (ODN). Tide level for East Riding coast derived from Spurn Head data taken from Admiralty Tide Tables (Admiralty, 2009) and from tidal statistics at Skegness derived from POLTIPS 3 software developed by the National Oceanography Centre Liverpool (NOC, 2009). Abbreviations: HAT – Highest Astronomical Tide; MHWS – Mean High Water Spring; MHWN – Mean High Water Neap; MLWN – Mean Low Water Neap; MLWS – Mean Low Water Spring; LAT – Lowest Astronomical Tide.

Coastal region	HAT	MHWS	MHWN	MLWN	MLWS	LAT
East Riding	3.80	3.00	1.60	-1.20	-2.70	-3.70
Lincolnshire	4.09	3.20	1.70	-1.09	-2.59	-3.57

Table 2 Summary characteristics of the six areas of interest (AOIs) examined in detail. Profile labels correspond to original data sources (East Riding Yorkshire Council or UK Environmental Agency).

AOI	Sediment cell	Location	Geomorphology		Alongshore length (km)	Profiles	No. Transects used in DSAS
			Landward features	Near/ Offshore features			
1	2a	Easington (E)	Clay strata and cliff from 9m to 5.3m high		5.2	P113-P121	43
2	2a	North Spurn Head (NSP)	Sand spit of c. 5km length	Glacial ridge of clay banks	1.4	P122-P124	17
3	2b	Donna Nook (DN)	Coastal dunes and clay embankment	Sand banks of morainic material	5.1	L1A1-L1A6	34
4	2c	Saltfleet-by (SA)	Saltmarsh	Sand banks of morainic material	4.1	L2E1-L2E4	30
5	2c	Theddle-thorpe (TH)	Coastal dunes	Sand banks of morainic material	4.9	L2E5-L2D1	44
6	2c	Skegness (SK)	Engineering defences Erosive clay strata		5	L2B6-L2A3	57

Table 3 Summary of map and aerial photograph source documents and characteristics for each AOI. Abbreviations: B&W – black and white. For AOI information, see Table 2.

AOI	Year	Type	Source	Document type	Scale
EA, NSH	1854, 1890, 1951	OS map	Edina	Geo-referenced	1:10 560
DN, SA, TH, SK	1891, 1910, 1951	OS map	Edina	Geo-referenced	1:10 560
EA, NSH	1966	B&W Aerial photo	English Heritage and EA	Scan from print photograph (600dpi)	1:7 500
EA, NSH	2005, 2008, 2010	Colour Aerial photo	East Riding Yorkshire Council	Digital ortho-georeferenced	1:5 000
DN	1970	B&W Aerial photo	English Heritage	Scan from print photograph (600dpi)	1:7 500
TH	1953, 1966, 1976, 1983	B&W Aerial photo	Natural England	Scan from print photograph (600dpi)	1:7 500
DN, SF, TH, SK	1994, 1999	B&W Aerial photo	Environment Agency	Scan from print photograph (600dpi)	1:5 000
DN, SF, TH, SK	2005, 2008, 2010	Colour Aerial photo	Environment Agency	Digital ortho-georeferenced	1:5 000

Table 4. Correlation table between morphology parameters and forcing factors at the sandy beaches between surveys (AOIs 2, 3, 5): Cl - Relative coastline position, C_{HAT} - HAT level position, V_B - sand volume in backshore, V_F – sand volume in foreshore, SS - storm surge. Correlation values above ±0.5 are in bold.

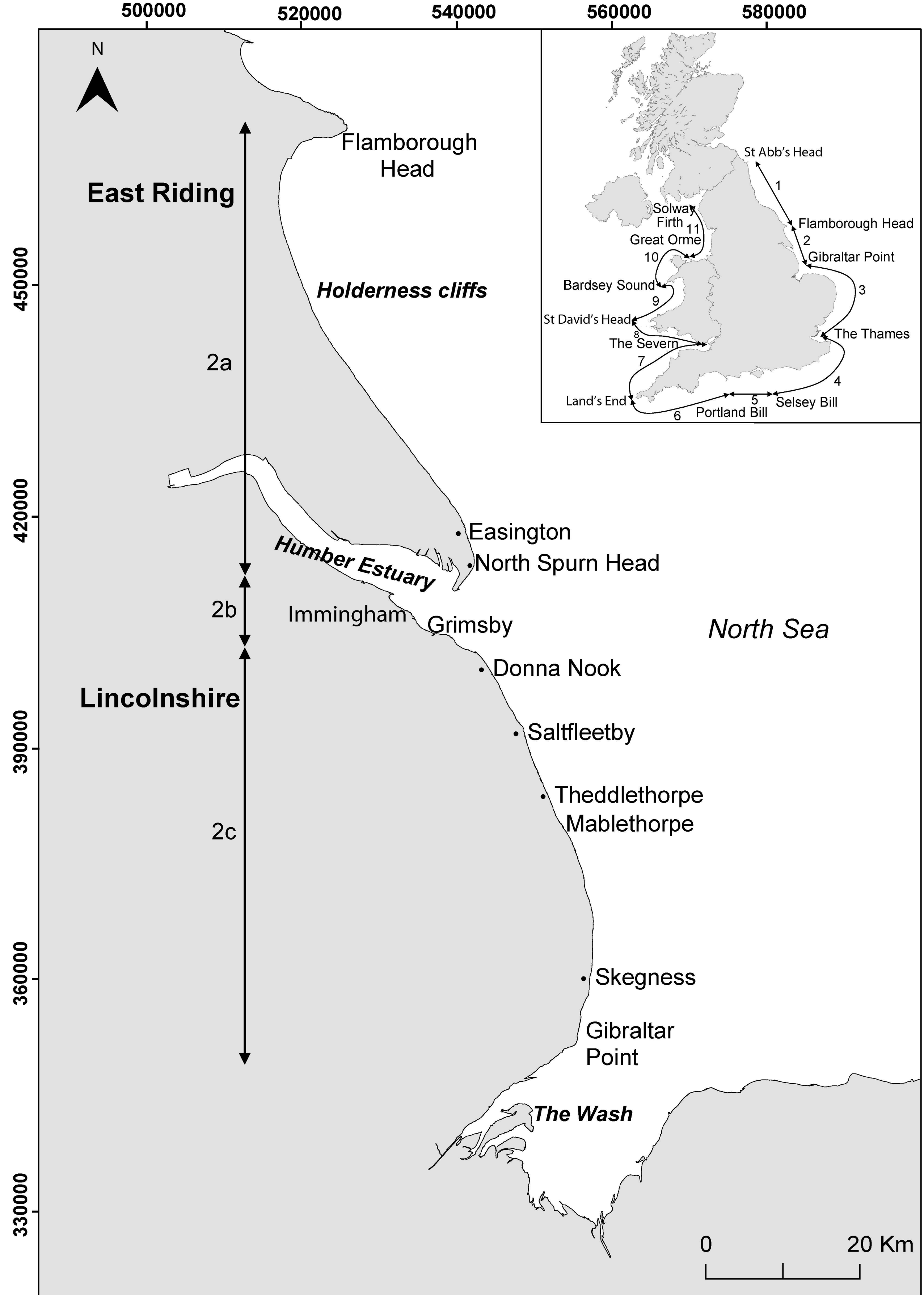
	Cl	**C_{HAT}**	**V_B**	**V_F**	**SS**
Cl		-0.112	**0.538**	-0.011	**0.733**
C_{HAT}			0.073	0.072	-0.019
V_B				**-0.528**	**0.656**
V_F					**-0.508**

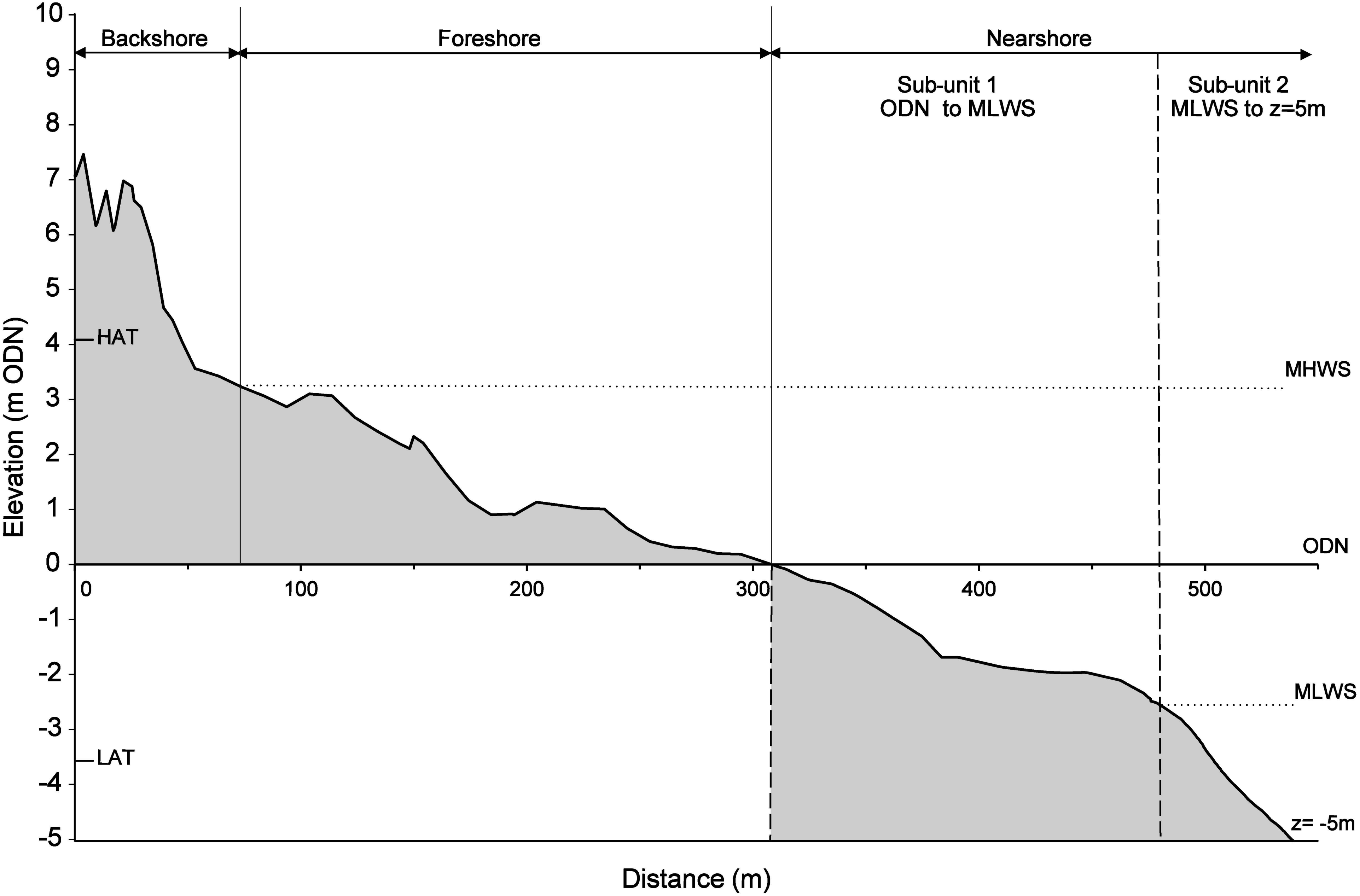
Table 5 Estimated inter-survey and cumulative sediment volume changes in backshore and foreshore units (see Figure 2). Positive values indicate accretion, and negative values erosion.

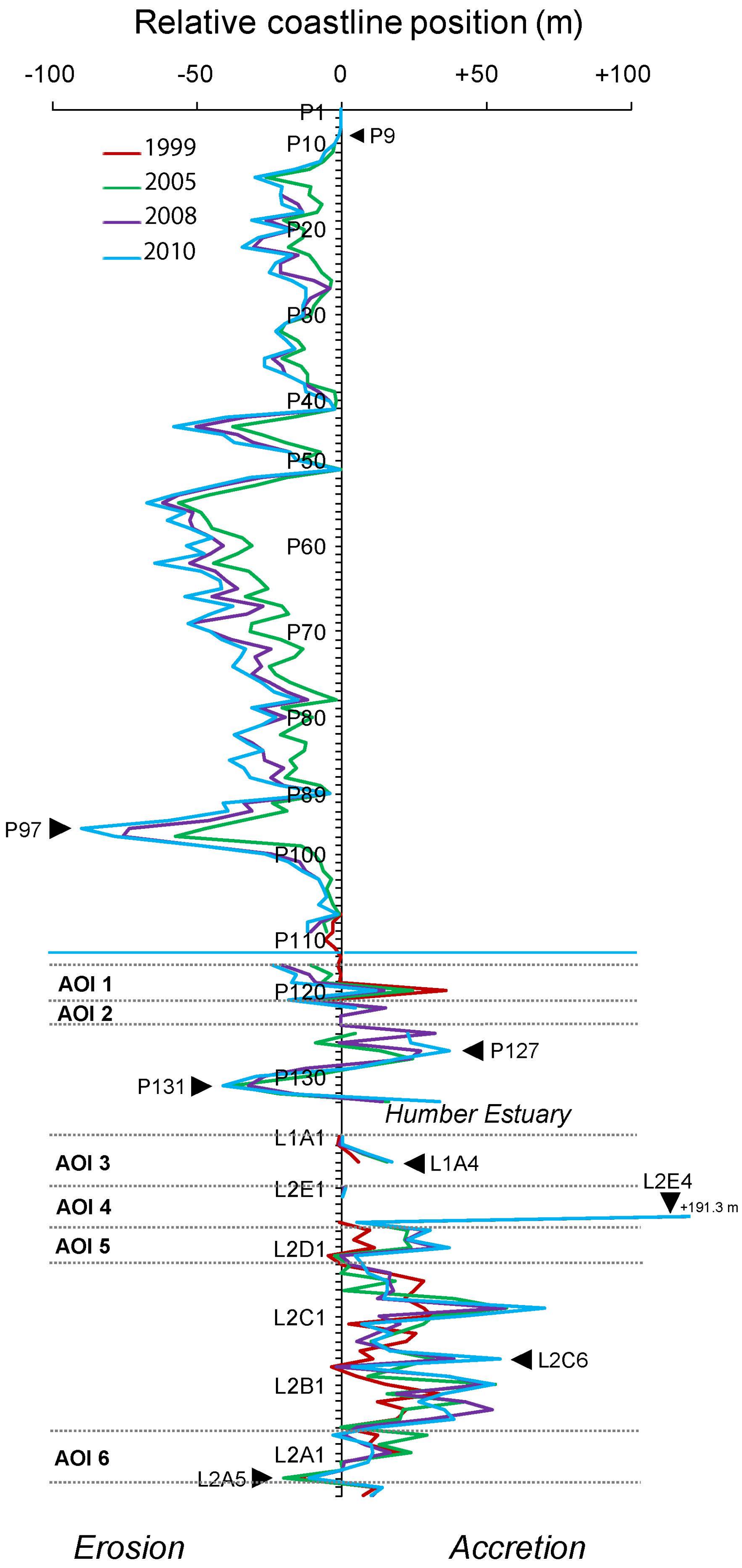
		Inter-survey change (m^3 x 10^3)			Cumulative change (m^3 x 10^3)		
AOI	Period	Backshore	Foreshore	Total	Backshore	Foreshore	Total
Easington	1997/1999	-161.3	-20.8	-182.1	-161.3	-20.8	-182.1
	1999/2005	-175.9	-60.0	-235.9	-337.2	-60.0	-397.2
	2005/2008	-367.8	-59.3	-427.1	-705.0	-59.3	-764.3
	2008/2010	-127.2	-37.8	-165.0	-832.3	-37.8	-870.0
		Rates of change (m^3 year^{-1})			-64.0	-2.9	-66.9
North Spurn Head	1997/1999	8.4	-1.9	6.5	8.4	-1.9	6.5
	1999/2005	-11.0	0.8	-10.2	-2.7	-1.9	-4.5
	2005/2008	-13.0	-22.8	-35.9	-15.7	-1.9	-17.6
	2008/2010	-1.4	-0.3	-1.7	-17.1	-1.9	-19.0
		Rates of change (m^3 year^{-1})			-1.3	-0.1	-1.5
Donna Nook	1994/1999	96.3	91.2	187.5	96.3	91.2	187.5
	1999/2005	497.5	-109.0	388.6	593.8	-17.7	576.1
	2005/2008	-132.1	-105.3	-237.4	461.7	-123.0	338.6
	2008/2010	26.5	432.7	459.2	488.1	309.7	797.8
		Rates of change (m^3 year^{-1})			30.5	19.4	49.9
Saltfleetby	1994/1999	349.5	129.6	479.1	349.5	129.6	479.1
	1999/2005	66.4	173.7	240.1	415.9	303.3	719.2
	2005/2008	-21.2	-26.6	-47.8	394.7	276.7	671.4
	2008/2010	-24.2	12.7	-11.5	370.6	289.4	659.9
		Rates of change (m^3 year^{-1})			23.2	18.1	41.2
Theddlethorpe	1994/1999	681.8	-435.4	246.4	681.8	-435.4	246.4
	1999/2005	276.0	358.2	634.1	957.8	-77.3	880.5
	2005/2008	423.0	-330.3	92.7	1380.8	-407.6	973.3
	2008/2010	-372.1	160.6	-211.5	1008.8	-247.0	761.8
		Rates of change (m^3 year^{-1})			63.0	-15.4	47.6
Skegness	1994/1999	153.1	-51.6	101.5	153.1	-51.6	101.5
	1999/2005	48.6	107.6	156.2	201.7	56.0	257.7
	2005/2008	-7.8	65.1	57.3	193.8	121.2	315.0
	2008/2010	67.9	-38.3	29.6	261.7	82.9	344.6
		Rates of change (m^3 year^{-1})			16.4	5.2	21.5

Table 6 Estimated inter-survey and cumulative volumetric changes by nearshore sub-unit (see Figure 2). Positive values indicate accretion, and negative values erosion.

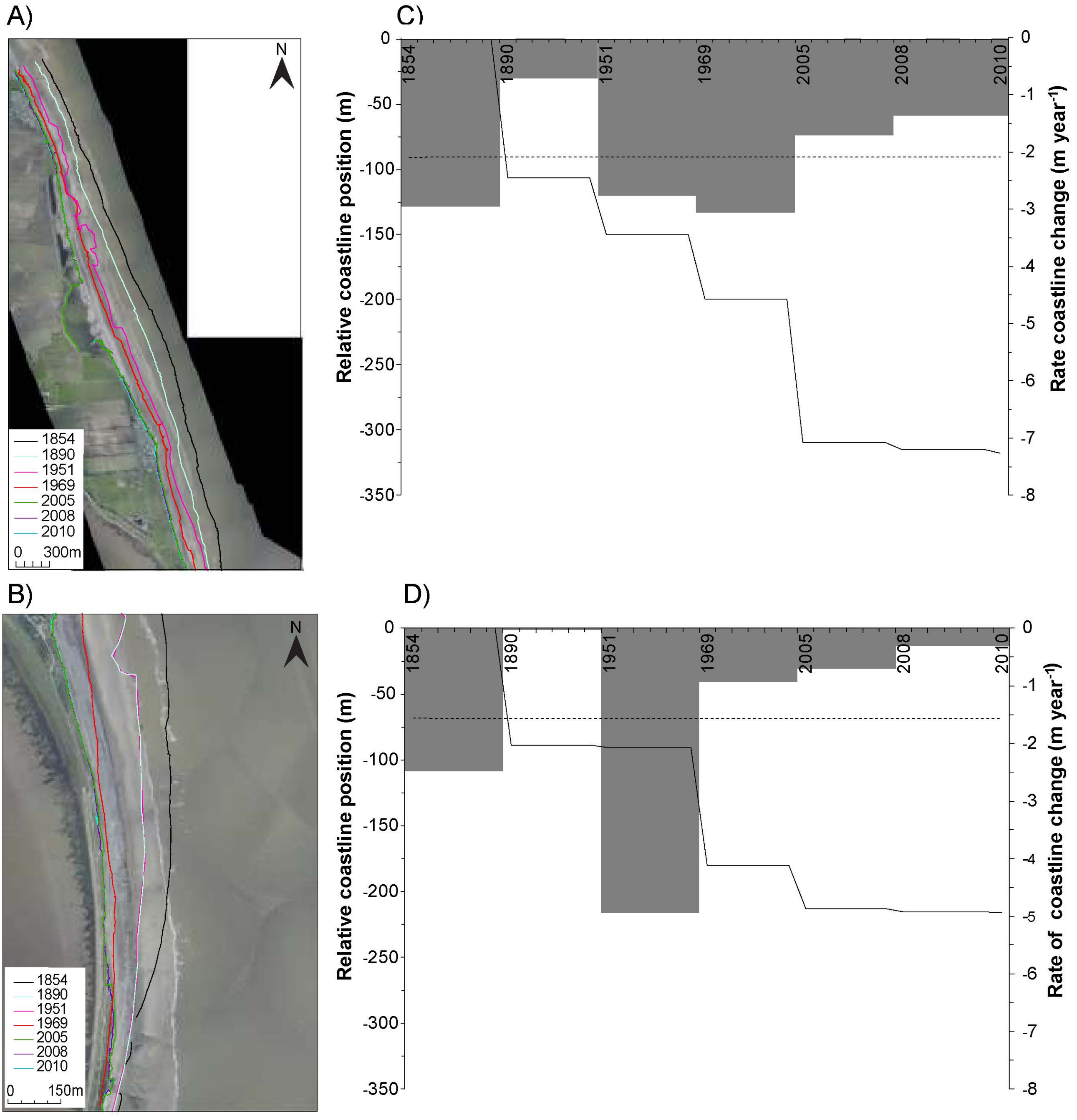
		Nearshore inter-survey change (m^3 x 10^3)			Nearshore cumulative change (m^3 10^3)		
	Period	Sub-unit1	Sub-unit2	Total	Sub-unit1	Sub-unit2	Total
Donna Nook	1999/2005	219.5	112.8	332.3	219.5	112.8	332.3
	2005/2008	-187.6	-73.0	-260.6	31.9	39.8	71.8
		Rates of change (m^3 year-$^{1)}$			3.5	4.4	8.0
Saltfleetby	1999/2005	140.3	-223.4	-83.1	140.3	-223.4	-83.1
	2005/2008	-3.9	30.2	26.3	136.3	-193.1	-56.8
		Rates of change (m^3 $year^{-1}$)			15.1	-21.5	-6.3
Theddlethorpe	1999/2005	-286.3	128.2	-158.1	-286.3	128.2	-158.1
	2005/2008	-14.3	70.8	56.4	-572.7	256.5	-316.2
		Rates of change (m^3 $year^{-1}$)			-63.6	28.5	-35.1
Skegness	1999/2005	116.7	12.9	129.6	116.7	12.9	129.6
	2005/2008	25.3	-34.2	-8.9	142.0	-21.3	120.7
		Rates of change (m^3 $year^{-1}$)			15.8	-2.4	13.4

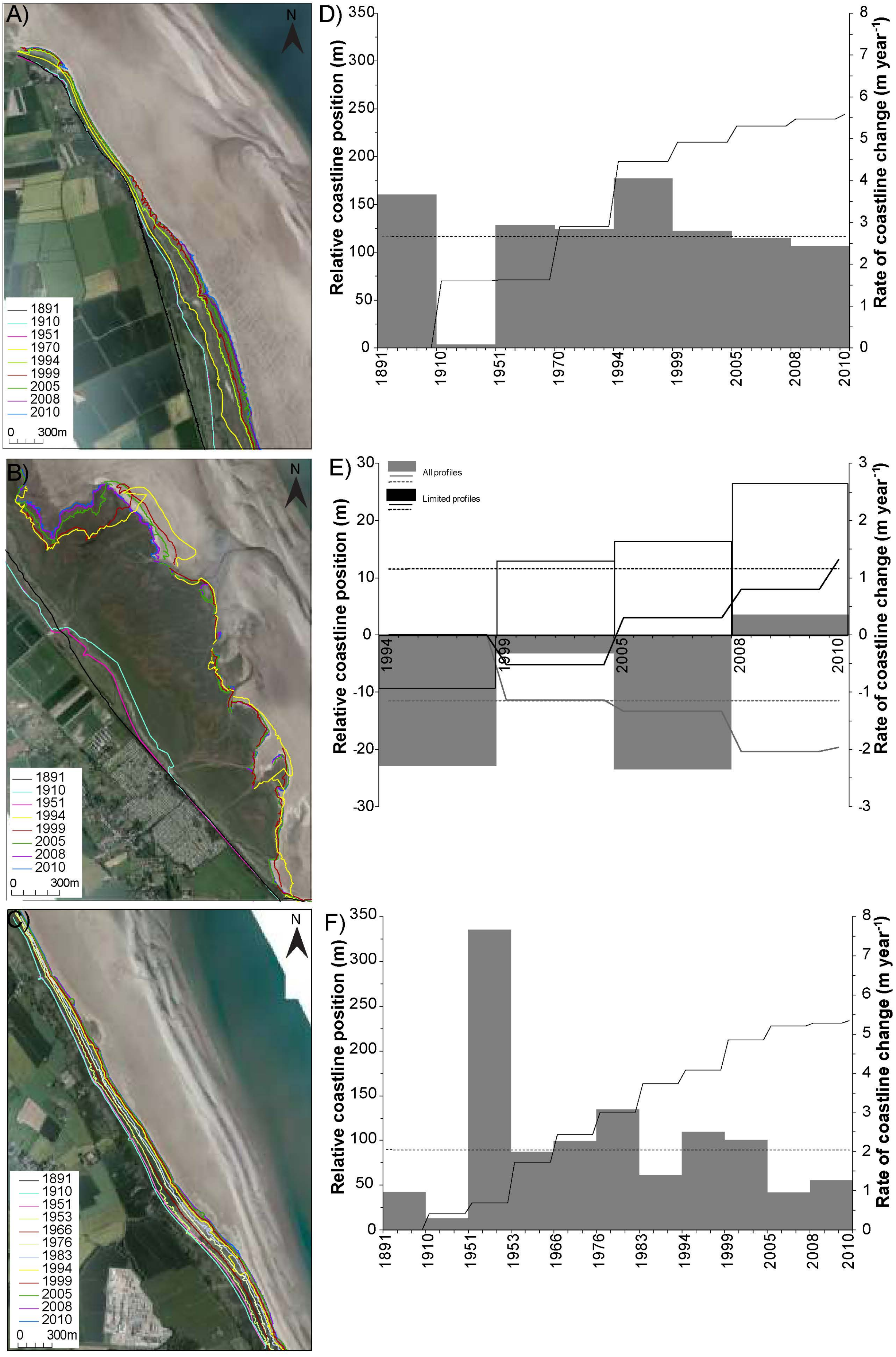

500000
520000
540000
560000
580000
450000
420000
390000
360000
330000
N
Flamborough Head
East Riding
Holderness cliffs
2a
Easington
Humber Estuary
North Spurn Head
2b
Immingham
Grimsby
North Sea
Donna Nook
Lincolnshire
Saltfleetby
Theddlethorpe
Mablethorpe
2c
Skegness
Gibraltar Point
The Wash
0
20 Km
St Abb's Head
1
Flamborough Head
2
Gibraltar Point
3
The Thames
4
Selsey Bill
5
Portland Bill
6
Land's End
7
The Severn
8
St David's Head
9
Bardsey Sound
10
Great Orme
11
Solway Firth

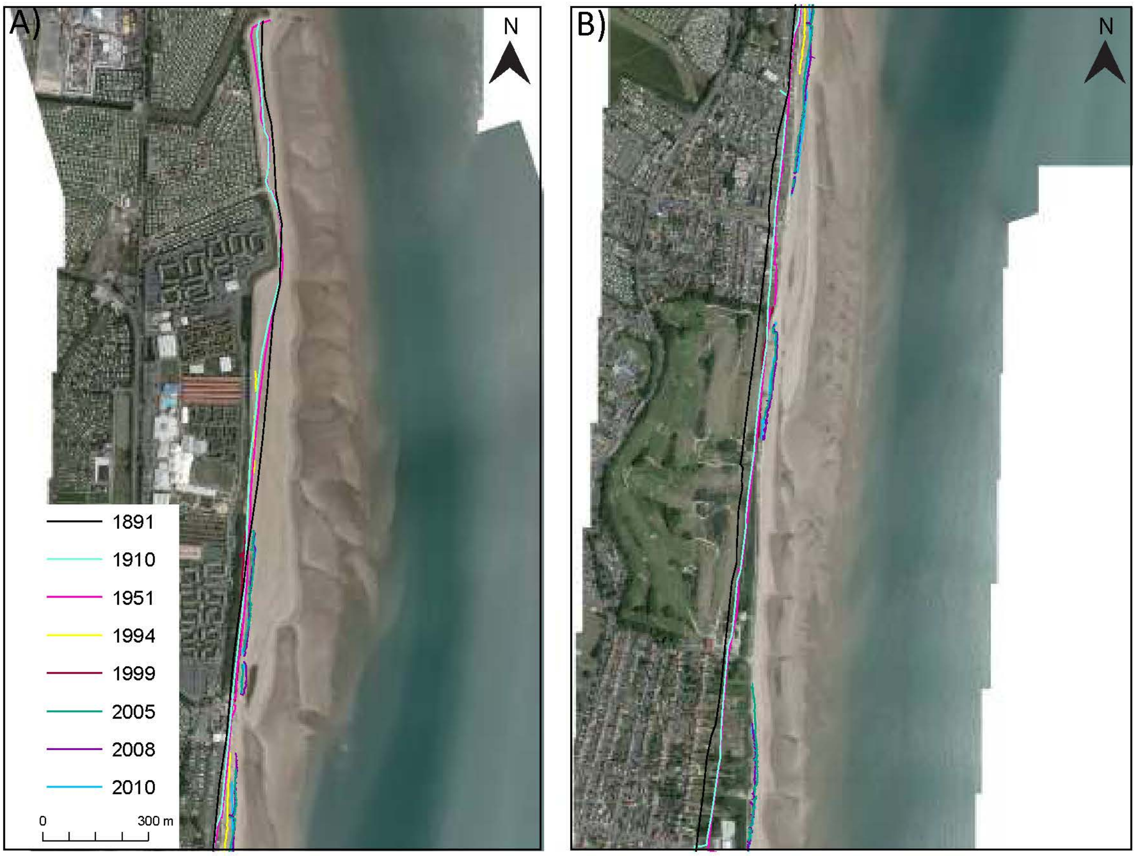

Backshore
Foreshore
Nearshore
Sub-unit 1
ODN to MLWS
Sub-unit 2
MLWS to z=5m
HAT
MHWS
ODN
MLWS
LAT
z= -5m
Elevation (m ODN)
Distance (m)
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
0
100
200
300
400
500

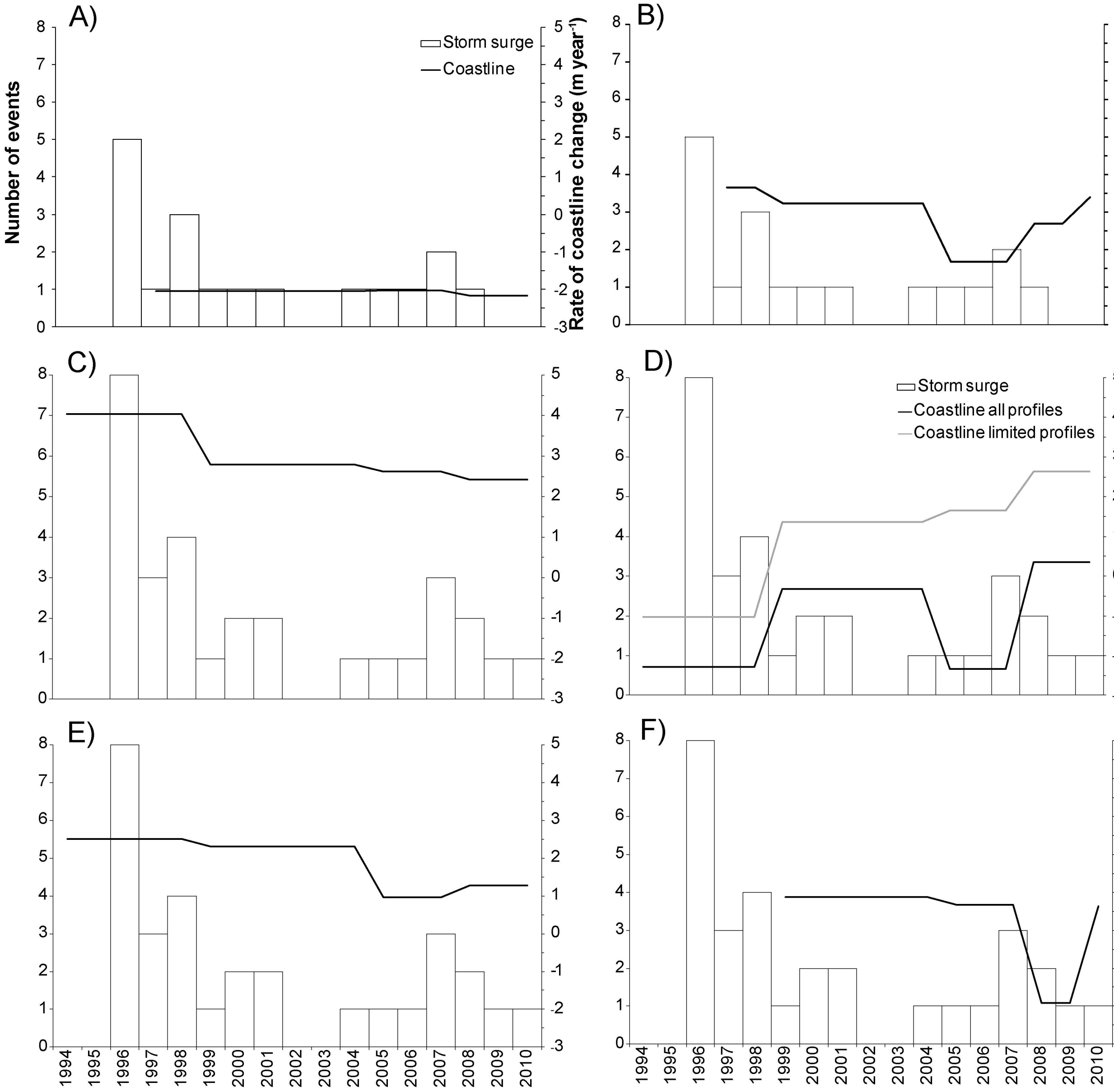


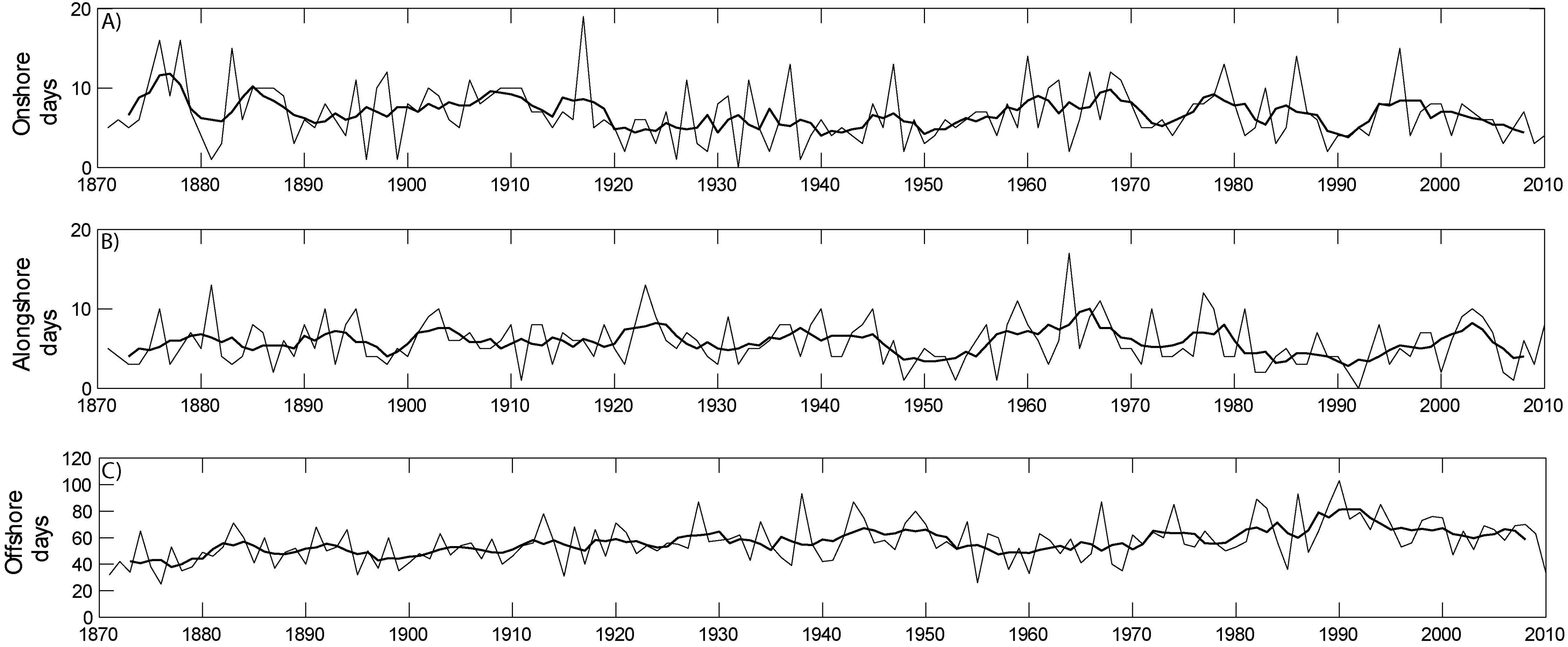
Relative coastline position (m)
-100
-50
0
+50
+100
1999
2005
2008
2010
P1
P9
P10
P20
P30
P40
P50
P60
P70
P80
P89
P97
P100
P110
AOI 1
P120
AOI 2
P127
P130
P131
Humber Estuary
L1A1
AOI 3
L1A4
L2E1
L2E4
+191.3 m
AOI 4
AOI 5
L2D1
L2C1
L2C6
L2B1
AOI 6
L2A1
L2A5
Erosion
Accretion

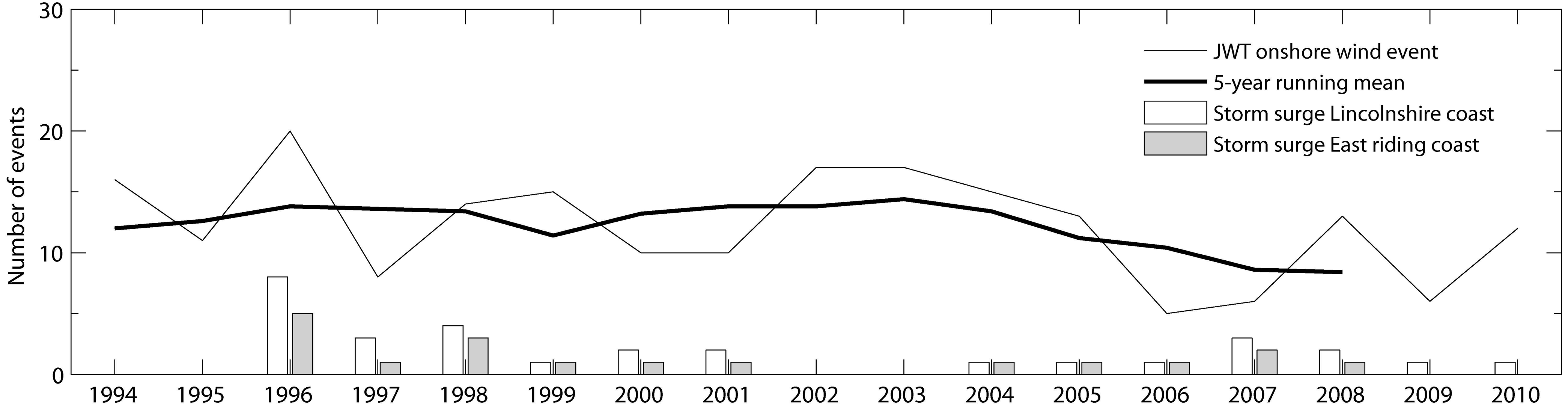

A)
N
1854
1890
1951
1969
2005
2008
2010
0 300m
B)
N
1854
1890
1951
1969
2005
2008
2010
0 150m
C)
Relative coastline position (m)
Rate coastline change (m year^{-1})
0
-50
-100
-150
-200
-250
-300
-350
0
-1
-2
-3
-4
-5
-6
-7
-8
1854
1890
1951
1969
2005
2008
2010
D)
Relative coastline position (m)
Rate of coastline change (m year^{-1})
0
-50
-100
-150
-200
-250
-300
-350
0
-1
-2
-3
-4
-5
-6
-7
-8
1854
1890
1951
1969
2005
2008
2010

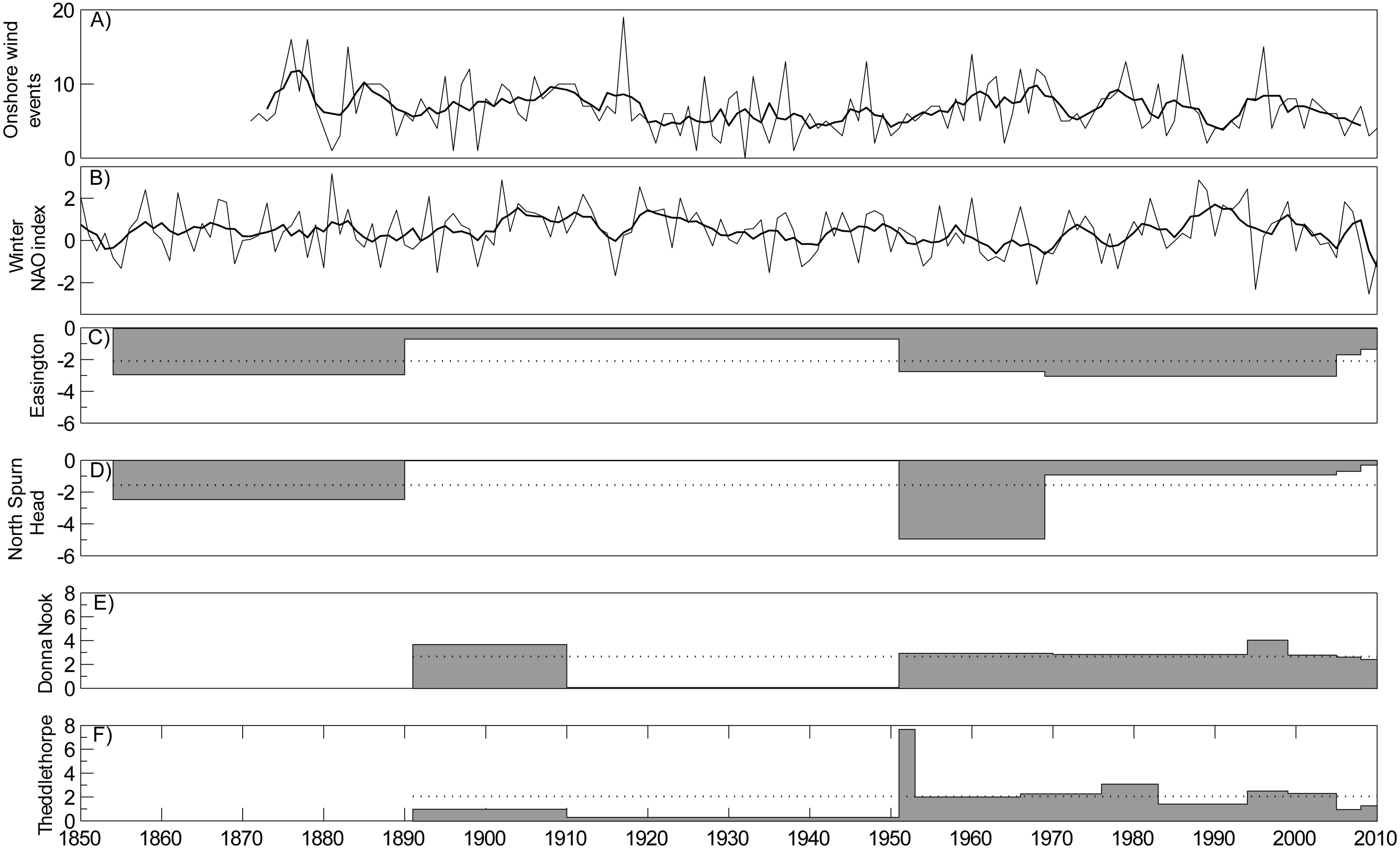

A)
N
1891
1910
1951
1970
1994
1999
2005
2008
2010
0 300m
D)
Relative coastline position (m)
Rate of coastline change (m year-1)
0
50
100
150
200
250
300
350
0
1
2
3
4
5
6
7
8
1891
1910
1951
1970
1994
1999
2005
2008
2010
B)
N
1891
1910
1951
1994
1999
2005
2008
2010
0 300m
E)
All profiles
Limited profiles
Relative coastline position (m)
Rate of coastline change (m year-1)
30
20
10
0
-10
-20
-30
3
2
1
0
-1
-2
-3
1994
1999
2005
2008
2010
C)
N
1891
1910
1951
1953
1966
1976
1983
1994
1999
2005
2008
2010
0 300m
F)
Relative coastline position (m)
Rate of coastline change (m year-1)
0
50
100
150
200
250
300
350
0
1
2
3
4
5
6
7
8
1891
1910
1951
1953
1966
1976
1983
1994
1999
2005
2008
2010

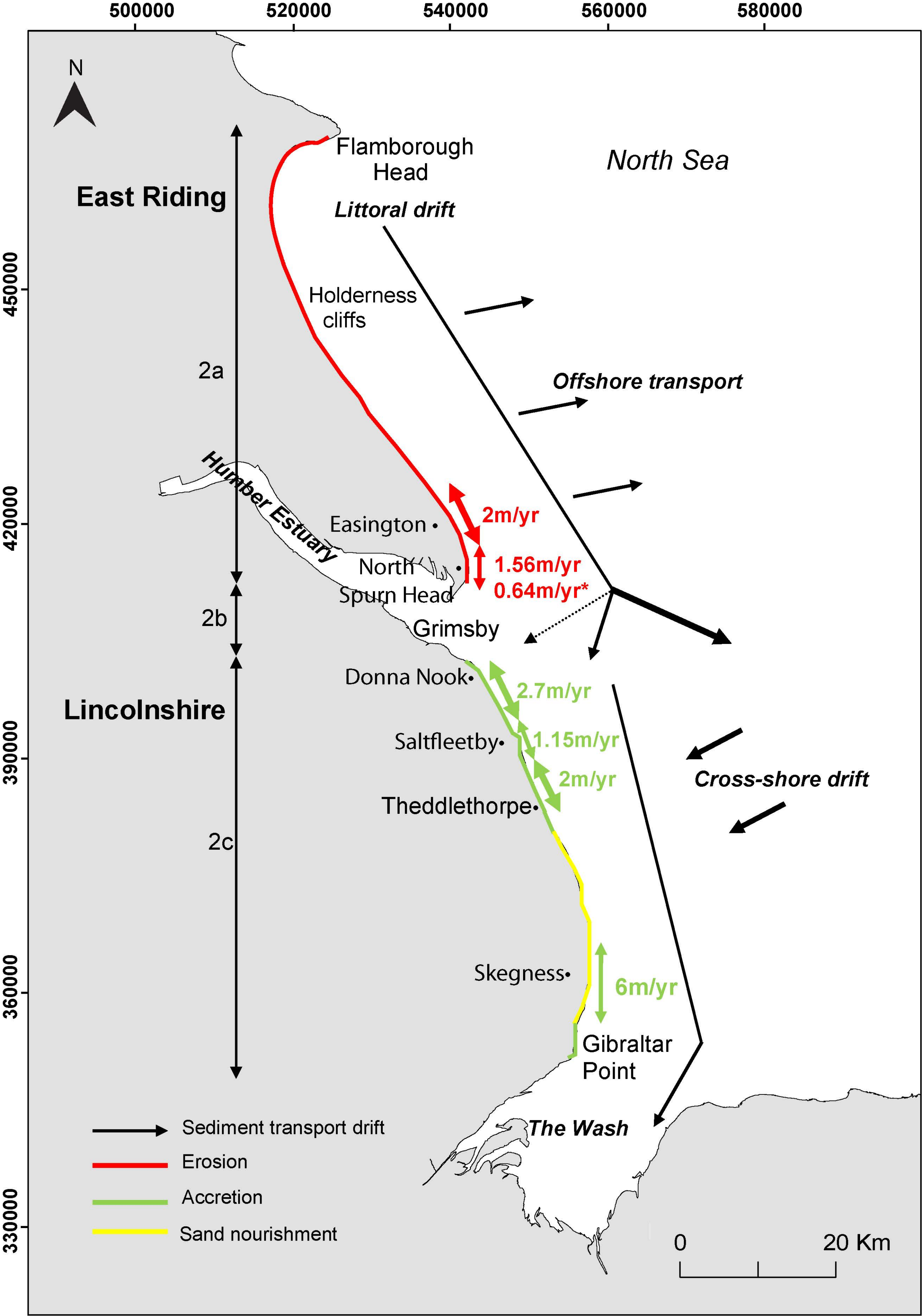

A)
B)
N
N
1891
1910
1951
1994
1999
2005
2008
2010
0
300 m


A)
B)
C)
D)
E)
F)
Storm surge
Coastline
Coastline all profiles
Coastline limited profiles
Number of events
Rate of coastline change (m year^{-1})
0
1
2
3
4
5
6
7
8
-3
-2
-1
0
1
2
3
4
5
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010


A)
Onshore days
0
10
20
B)
Alongshore days
0
10
20
C)
Offshore days
0
20
40
60
80
100
120
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010


JWT onshore wind event
5-year running mean
Storm surge Lincolnshire coast
Storm surge East riding coast
Number of events
0
10
20
30
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010


A)
Onshore wind events
20
10
0
B)
Winter NAO index
2
0
-2
C)
Easington
0
-2
-4
-6
D)
North Spurn Head
0
-2
-4
-6
E)
Donna Nook
8
6
4
2
0
F)
Theddlethorpe
8
6
4
2
0
1850
1860
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010



500000
520000
540000
560000
580000
450000
420000
390000
360000
330000
N
Flamborough Head
North Sea
East Riding
Littoral drift
Holderness cliffs
2a
Offshore transport
Humber Estuary
Easington
2m/yr
North
1.56m/yr
0.64m/yr*
Spurn Head
2b
Grimsby
Donna Nook
2.7m/yr
Lincolnshire
Saltfleetby
1.15m/yr
2m/yr
Cross-shore drift
Theddlethorpe
2c
Skegness
6m/yr
Gibraltar Point
The Wash
Sediment transport drift
Erosion
Accretion
Sand nourishment
0
20 Km