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RESEARCH ARTICLE

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Formation, development and movement of ords along the Holderness coast (UK): A comparison between 1994–1998 and 2010–2020 in response to changing morphodynamic and hydrodynamic conditions

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Abstract

Sediment input from the rapidly eroding Holderness till cliffs and shore platforms forms irregularly spaced higher inter-ord and lower ord beaches. The ords, by allowing increased tidal access and wave attack on the cliff toe and cliff face, increase erosion rates. This paper compares the formation, development and movement of ords in 1994–1998 and 2010–2020. Taken in spring and autumn, stereo-aerial photographs were used in 1994–1998 and aerial LiDAR and ortho-rectified aerial photographs in 2010–2020. To compare hydrodynamic conditions in the two periods Immingham tide, Leconfield wind and Hornsea wave data were used. The main results are consistent with earlier findings that ords form near Barmston where the shelter of Flamborough Head in northerly storms ceases and causes a longshore sediment movement divide. Coastal defences had a similar effect at Hornsea and Mappleton. Ord length measurements showed ords covering 23–35% of the coast in 1994–1998 and 20–40% in 2010–2020. Average cliff toe height in the later period was 3.05, 2.24 and 3.27mAOD in the north, centre and south ord parts, respectively. This allowed all High Water Spring Tides to reach the cliff toe at the ord centres under calm conditions on the survey dates. Higher beach levels north and south provided more cliff protection. Slower annual net average ord movement southwards of 0.36 km in 1994–1998 contrasted with 1.1 km in 2010–2020. Although the storm surges over 0.9 m at Immingham increased from 12 in the earlier period to 58 in the later period, of these only four and six, respectively raised the tide level to over 4.0 mAOD, above the cliff toe height throughout the ords. No major storms occurred in 1994–1998 compared with three in 2010–2020. No rhythmic inter-tidal features closely resembling ords have been found globally in the extensive literature, but more research into morphodynamic processes within ords is needed.

KEYWORDS
aerial surveys, beach sediment input, hydrodynamic conditions, longshore sediment transport, morphodynamic processes, ords, rhythmic inter-tidal features, till cliff and shore platform erosion

1 | INTRODUCTION

The North Sea's Holderness coast, in the East Riding of Yorkshire UK, has one of the most rapidly eroding coastlines in Europe (Quinn et al., 2009). This results primarily from the interaction of the glacial till cliffs (Macfarlane, 2012; Newsham et al., 2002; Quinn et al., 2009), and the tidal and wave regimes (Brown, 2008; Mason, 1985; Pye & Blott, 2015), together with the occurrence of North Sea storm surges, which if peaking at high water (HW) can produce extremely high-water levels (Haigh et al., 2016; Pringle, 1985).

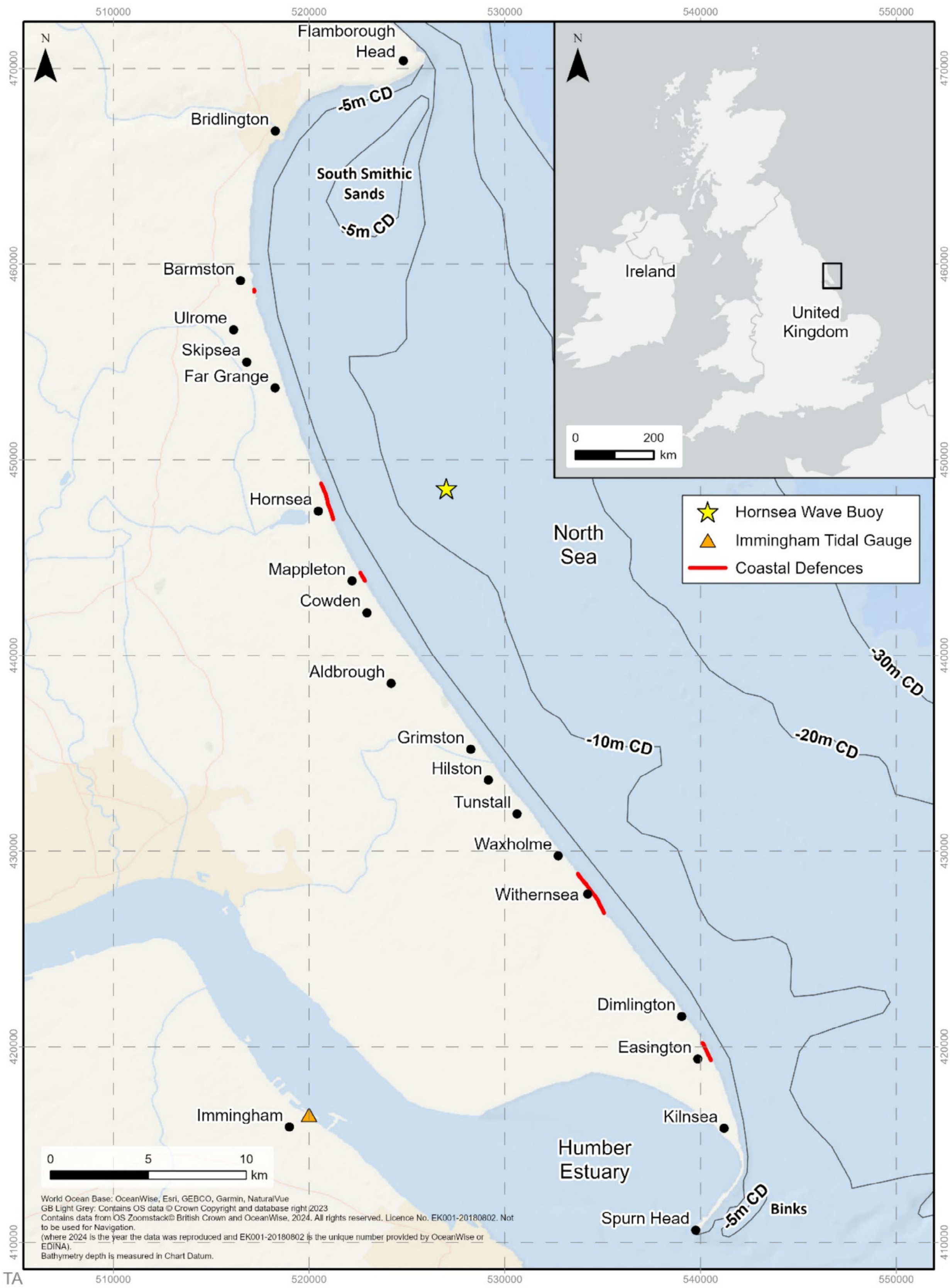


FIGURE 1 Map of the Holderness coast situated between Flamborough Head and Spurn Head in the East Riding of Yorkshire, UK. Bathymetric contours measured in chart datum (−3.90 m relative to ordnance datum).

The eroded till from the cliffs is the main source of beach sediment, which forms alternating higher and lower sections along this coast (Pringle, 1985). Whilst the higher sections provide some protection from wave attack at the cliff toe (Pringle, 1985), the lower sections, termed 'ords' (Phillips, 1962), with exposed till shore platforms at their centres, are the focus of maximum wave attack and most rapid cliff erosion (Pringle, 1985; Pye & Blott, 2015).

This paper aims to:

- investigate the formation, distribution, length and movement of ords in two time periods 1994–1998 and 2010–2020.
- compare the findings for the two periods with reference to hydrodynamic conditions and especially raised water levels resulting from storm conditions.
- relate these results to ord heights at the cliff toe, together with wave conditions for the latter period, for which wave records became available.

Ords will now be described in their locational, geological and marine setting in 1.1 The Study Area. This will be followed in 1.2 Ord Dynamics and Recent Evolution by an examination of the processes shaping ords with reference to earlier literature. Finally, Holderness ords will be considered in the wider context of rhythmic intertidal features.

1.1 | The study area

The Holderness coast extends for c 60 km south from Flamborough Head to Spurn Head. The coastline consists of a single log-spiral from the c 7.5 km east–west (E-W) aligned chalk cliffs of Flamborough Head, along the north-west (NW) to south-east (SE) aligned glacial till cliffs of Holderness, to the c 5.5 km sand and shingle spit of Spurn Head, which curves south-west (SW) into the Humber Estuary (Pringle, 1985; see Figure 1).

The construction of coastal defences at Hornsea since 1869, at Mappleton in 1991 and at Withernsea since 1875, has led to the development of sub-log-spiral coastlines south of these (Pye & Blott, 2015; see Figure 2).

Seaward of the coast, the Smithic Sands lie south of Flamborough Head and the Binks extend north-east from the tip of Spurn Head (see Figure 1). Along the rest of the coast there is a relatively gentle, featureless seaward slope.

The Holderness cliffs and shore platforms are formed mostly of Late Devensian glaciogenic deposits which thicken southwards and overlie Cretaceous chalk bedrock. Approximately 75% of the deposits visible in the cliffs are matrix-dominated with few boulders, most of which are chalk, flint, limestone and subsidiary far-travelled igneous and metamorphic clasts <0.5 m diameter (Hobbs, Jones, Kirkham, Holyoake, et al., 2019; Hobbs, Jones, Kirkham, Pennington, et al., 2019).

The Holderness Formation is a succession of Devensian diamicton, gravel, sand, silt and clay and has traditionally been subdivided into three till units: the Bridlington Member (Basement Till of e.g., Catt & Penny, 1966), the Skipsea Till and Withernsea Till members (McMillan et al., 2011). Clay, silt and sand are the dominant

FIGURE 2 The northern Holderness coast from south of Mappleton to Flamborough Head illustrating the three sub-log-spiral coastlines developing south of Flamborough Head and the Hornsea and Mappleton defences (drone photo by Craig Marriott 11 July 2020 at 14.51 hours).

components of these matrix-dominated tills as also confirmed by Bell (2002). Detailed lithological and geotechnical descriptions are given by Hobbs et al. (2015), Hobbs, Jones, Kirkham, Holyoake, et al. (2019), Hobbs, Jones, Kirkham, Pennington, et al. (2019) and Bell (2002). In short, where these tills are exposed across the cliff face and the intertidal zone, erosion is increased (Hobbs, Jones, Kirkham, Pennington, et al., 2019).

Although there is a continuous beach along the Holderness coast between Barmston and Spurn Head it varies in form with alternating higher and lower sections (Pringle, 1981). In the higher sections, the upper beach adjacent to the cliff toe is usually convex in cross-profile and composed of coarse sand (1–1.5 mm) and shingle up to 20 cm in diameter. The beach water table at its lower margin separates it from the lower beach which extends at a lower angle to low water (LW). It grades from medium sand (0.5–0.25 mm) to fine sand (0.25–0.125 mm) seawards. Commonly it is covered in a thin film of water at low tide with irregular higher patches of drier sand, which do not form into a regular sandbar. The lower sections of the beach were termed ords by Phillips (1962) using their local name and Figure 3 (Pringle, 2003) shows their characteristic features. Ords can be divided into three distinct parts, their northern, central and southern sections. At the north end, the upper beach narrows and curves in towards the till cliff toe, with lower beach sand with surface water seawards. In the ord centre, the upper beach is absent exposing the till platform seaward from the cliff toe and commonly with armoured mudballs on its surface. Seaward an asymmetric fine sandbar develops with a steeper slope landward. Towards the ord's south end, the upper beach wedges in, widening southwards, with a till platform and a water-filled channel seaward and the lower beach sandbar tapering southwards. The relatively stable lower angle cliffs at the south end are eroded to very steep in the ord centre and remain so at the north end.

Figure 4a shows cross-profiles of the northern, central and southern sections of a sample ord, with Figure 4b illustrating high tidal conditions in an ord centre which would have lasted for about four hours across HW.

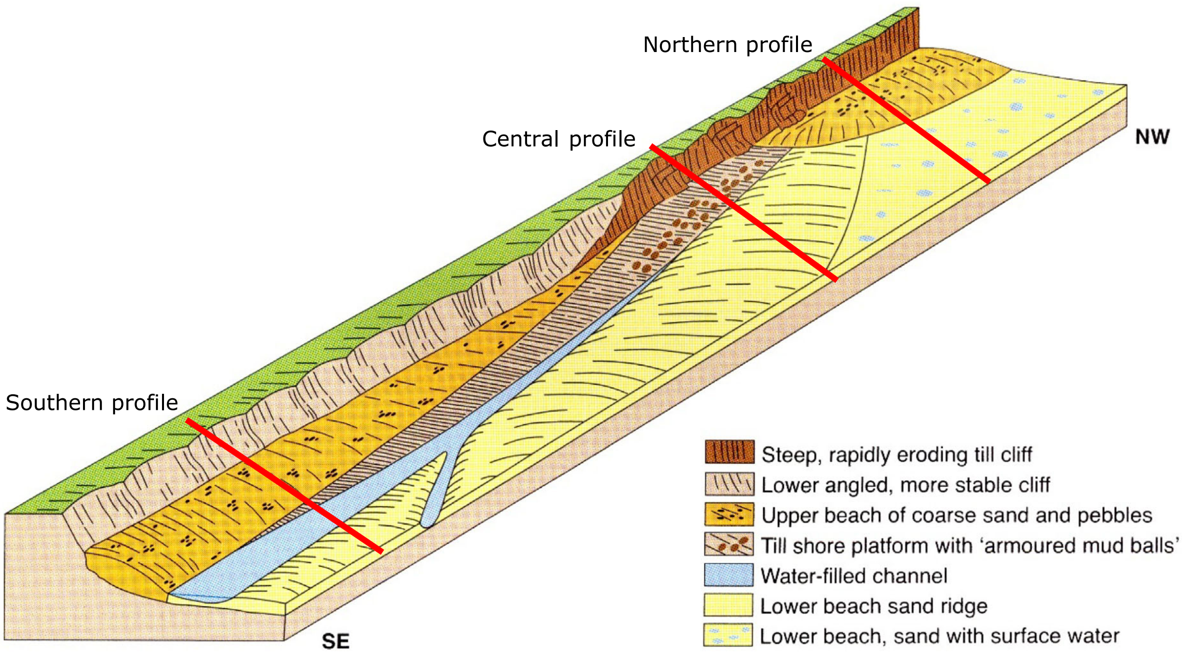


FIGURE 3 Characteristics of a Holderness Ord. Drawing by G S Pringle (Pringle, 1985, 2003. 1985 copyright John Wiley and Sons ltd, reproduced with permission). Superimposed red lines show profile positions from the LiDAR surveys 2010–2020.

Using aerial photographic evidence, Scott (1976) showed that ord lengths varied in the period 1959–1972 between 0.9 km at Kilnsea and 3.9 km at Rolston with a mean of 2.0 km. From ground surveys of a single ord which moved from Holmpton to Dimlington between 1977 and 1983, measurements of the central section with till platform exposed at the cliff toe showed variations in length between 0.27 km and 1.93 km with a mean of 1.19 km (Pringle, 1985).

The Holderness coast experiences a macrotidal regime with semi-diurnal tides. The mean spring tidal range varies between 5.0 m at Bridlington, 5.7 m at Spurn Head and 6.4 m at Immingham tide gauge (Figure 1) and between 2.4 m, 2.8 m and 3.2 m, respectively on mean neap tides (Admiralty Tide Tables, 2024). Tidal currents flow sub-parallel to the coast with the ebb running north–north-west (NNW) at a maximum rate 1.34 ms^{-1} at spring tides and 0.67 ms^{-1} at neap tides, about mid-tide. The flood current runs south–south-east (SSE) at similar maximum rates of 1.29 ms^{-1} at spring tides and 0.62 ms^{-1} at neap tides, about mid-tide (Admiralty Chart 109, 1994).

This north-east (NE) facing coast is exposed to waves generated in the North Sea from directions between north (N) and SE. Waves from N-NE are refracted around Flamborough Head before breaking on the shore (Barkwith et al., 2013; Barkwith et al., 2014; Pye & Blott, 2015). Data from the directional wave buoy, located at Hornsea since 2008 (Figure 1), indicates that the dominant wave direction is from 15 to 35 degrees and the largest waves approach the shore south of Barmston at a slightly oblique angle resulting in a net southward longshore sediment movement (Pye & Blott, 2015). The Channel Coastal Observatory (CCO) show there is a general seasonal pattern in wave heights and periods, with maximum significant wave heights (H_s) and longest wave periods (T_p) occurring between October and March.

The North Sea is prone to storm surges when a deep atmospheric low-pressure system crosses its northern area, generating strong NW-N winds and raising sea levels (Spencer et al., 2015). These strong winds also generate large waves capable of rapid cliff and beach erosion (de Boer, 1964; Dosser, 1955; Richards, 1997). When such storm surge conditions coincide with HW this may result in coastal flooding and also expose usually emerged parts of the coast to waves (Lowe & Gregory, 2005; Sistermans & Nieuwenhuis, 2013; Spencer et al., 2015).

1.2 | Ord dynamics and recent evolution

Throughout the Holocene, the interaction between the till cliffs and the tidal and wave regimes has resulted in the Holderness coast being one of the most rapidly eroding in Britain with an average annual rate of 1.2 m–2.1 m calculated in various ways by Pickwell (1878), Matthews (1905), Sheppard (1909 and 1912), Thompson (1923), Dosser (1955), Valentin (1954 and 1971) and Mason & Hansom (1988) and quoted by Pye & Blott (2015). Cliff erosion results from a combination of slumping, sliding and toppling processes strongly influenced by cliff toe wave attack and lowering of the till shore platform.

The significance of ords in cliff erosion was identified by Phillips (1962), Scott (1976) and Pringle (1981 and 1985). The reduction of the beach level in the ord centre to expose till shore platform considerably increased the frequency of wave attacks at the cliff toe. This is clearly shown between Withernsea and Easington (Pringle, 1985) as an ord moved south. The southward movement of ords along the Holderness coast, initially identified by Thompson (1824) has been well documented since. Bisat, in Catt & Madgett (1981) observed a 400 m per year southward movement between 1935 and 1952 at Dimlington. Pringle (1985) surveyed an ord's movement south from Withernsea to Easington with a 500 m average southward movement per year between 1977 and 1982. Pye & Blott (2015) showed a 600–800 m per year southward movement of ords between Cowden and Hilston from 2003 to 2013.

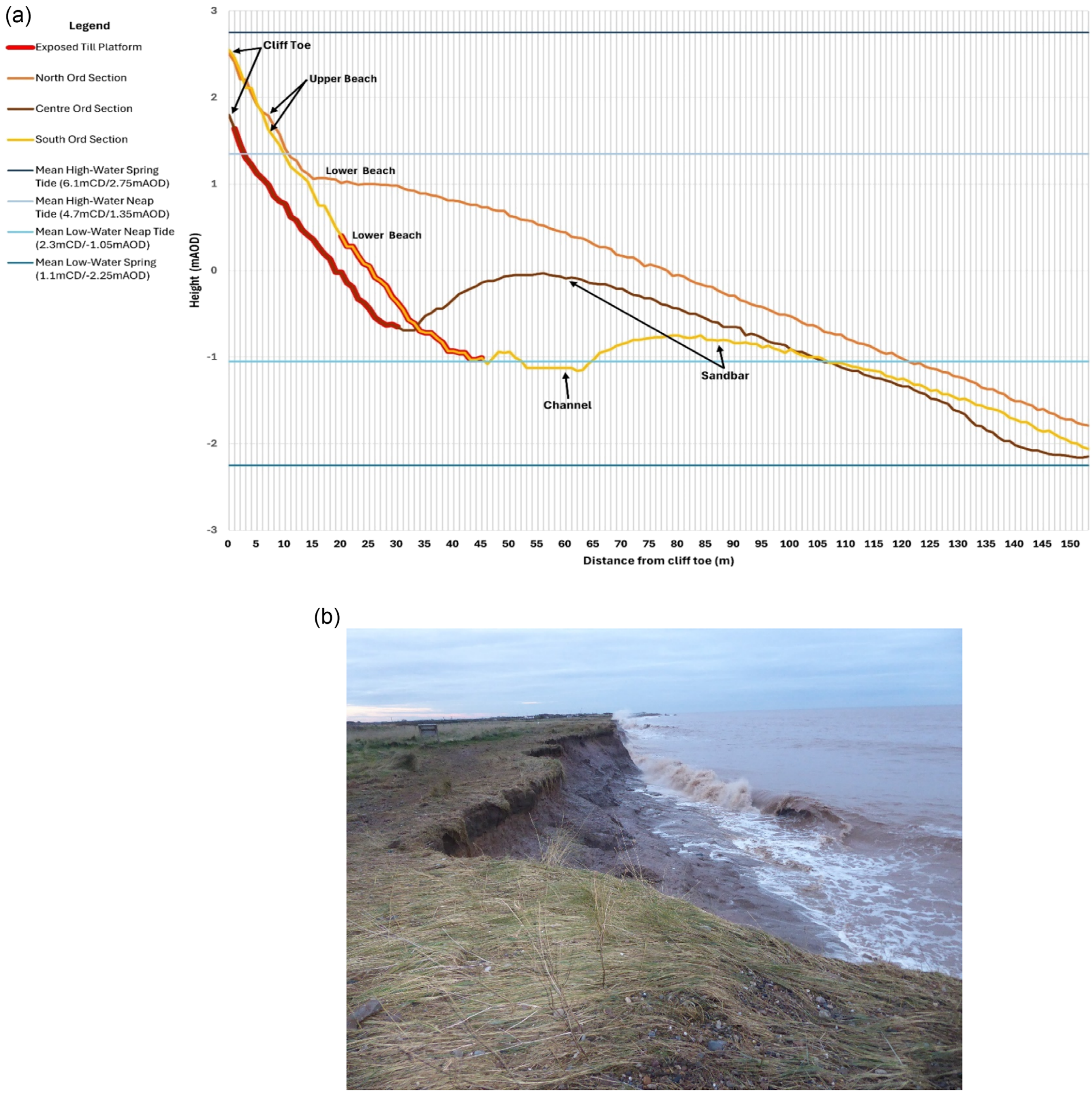


FIGURE 4 (a) Cross profiles through the north, central and southern sections of a sample Ord south of Aldbrough 25.05.17. From East Riding of Yorkshire Council LiDAR data. Bridlington mean tidal data from National Oceanography Centre. (b) Kilnsea Ord Centre 05.11.21 taken from GR 420151 at 2 hours before HW. Recorded tide height at Immingham (BODC) 6.1mACD (2.2mOD). Hornsea wave records (CCO) H_s 0.9 m, H_{max} 1.4 m, Tpeak 10.5 sec, peak wave direction 16 degrees. Waves are breaking under non-storm conditions along the Skipsea till cliff toe, sending spray above the 4–5 m high cliffs in the distance.

The main mechanism of southward movement of ords is shown in Figure 5 (Pringle, 1981, 2003). This occurs during North Sea storm surges with raised water levels and powerful northerly waves which approach the coast at a high angle of up to 40 degrees (Pringle, 2003). A tongue of upper beach sediment is drawn out from the northern end of the ord south-eastwards to lie parallel to the breaking waves. As the storm subsides, the angle of the breaking waves to the shore decreases. The tongue of sediment swings round to become increasingly parallel to the shore, which it then joins south of its pre-storm position. As the upper beach sediment in the south part of the ord was subjected to the same large obliquely arriving waves during the storm, it has been affected by a generally increased rate in southward sediment movement, resulting in the whole ord being moved south.

In recent years there has been an observed increase in intense deep atmospheric low-pressure systems crossing over the North Atlantic Ocean (Feser et al., 2014). Those tracking over the far north of the North Sea generate North Sea storm surges (Spencer et al., 2015). The Hornsea storm wave threshold as defined by the Channel Coastal Observatory is H_s 3.04 m and the swell alert threshold T_p 11.60 sec. Such waves are frequently observed during North Sea storm surges, for example, in a series of storm events between October 2013 and February 2014 (Pye & Blott, 2016), when maximum sea levels and storm surges were recorded in more than half of

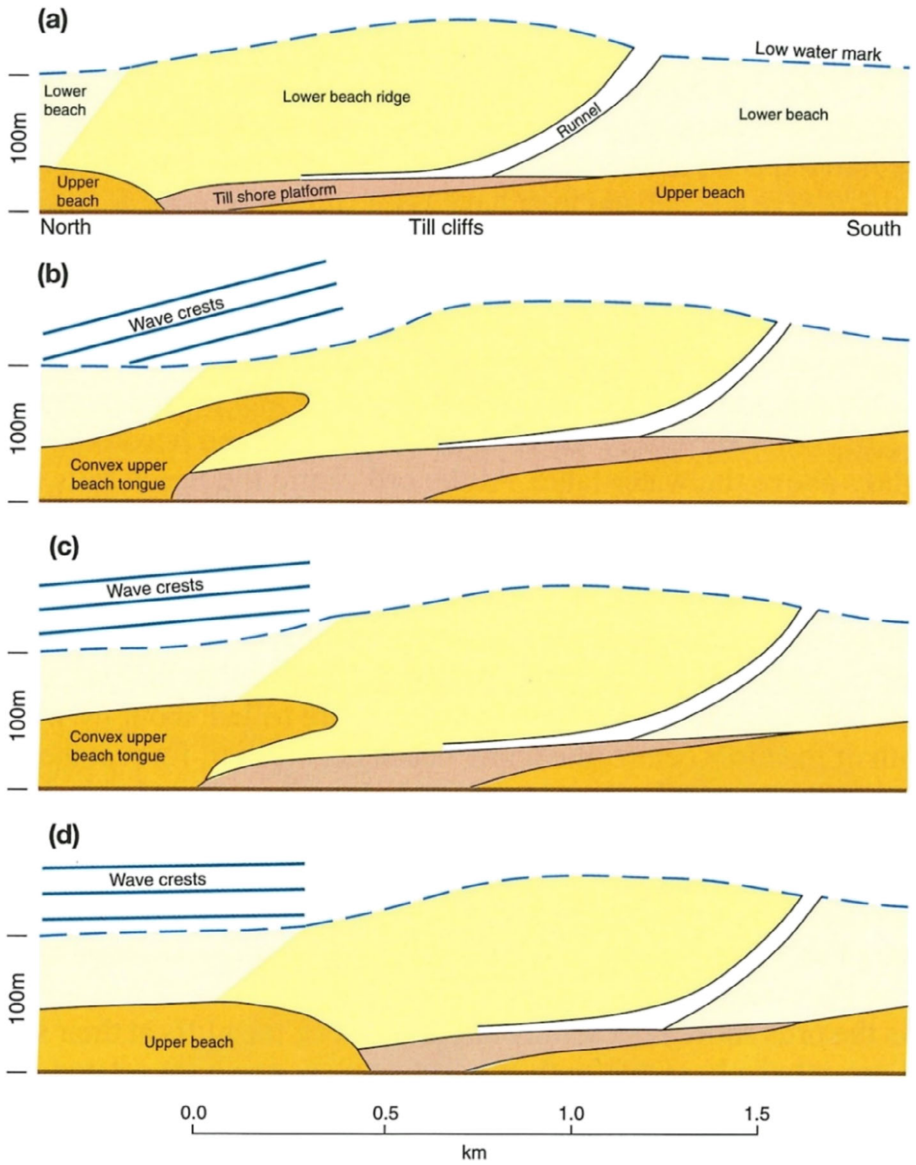


FIGURE 5 Schematic maps of Ord movements south along the Holderness coast. (from Pringle, 2003, reproduced with permission). Characteristic ord morphology: (a) After the absence of northerly storm conditions. (b) During a northerly storm with winds over 17 m/s, a positive North Sea storm surge and storm waves exceeding 3.04 m (CCO). Note the north upper beach tongue. (c) Immediately after the northerly storm as the northern upper beach tongue is pushed shoreward. (d) Several days later when the upper beach tongue has been pushed landward to the cliff toe to form a new upper beach south of its pre-storm position (Pringle, 1981, 2003).

the tidal gauges around the UK (Haigh et al., 2016). It is predicted that changes in atmospheric storminess and higher time-average sea levels are likely to increase the severity of North Sea storm surges in the future (Lowe & Gregory, 2005). In addition, under future climate scenarios, North Sea storm surge extremes and general storminess may increase along North Sea coasts towards the end of this century (Della-Marta & Pinto, 2009; Leckebusch et al., 2006; Vousdoukas et al., 2016; Woth et al., 2006).

Therefore, after examining the formation, distribution, length and movement of ords in the two time periods 1994–1998 and 2010–2020 this paper will focus on the varying water levels produced by the interaction of tides and storm surges in the earlier period and with the addition of wave effects in the latter period, for which wave data became available. This will enable an assessment of the degree of cliff exposure to wave attack, which in turn will affect cliff erosion rates.

Before turning to the detailed focus of this paper it is important to consider Holderness ords in a wider coastal context, as attempted earlier by Phillips (1962), Scott (1976) and Pringle (1981 and 1985), viewing them as a type of irregularly spaced rhythmic inter-tidal feature. No similar features have been described within the literature on the British North Sea coast. However, on the west European coast, some regular rhythmic features have been described along mainly sand beaches backed by dunes and fronted by multiple sand bars in the intertidal and surf zones. Short (1992) investigated those on the microtidal central Netherlands coast, where mean net shoreline oscillations of 59 m were relatively uniform alongshore and were related to rip currents with mean spacing of about 500 m on the inner sandbars and northward longshore movement of points of bar attachment. van der Vegt et al. (2007) modelled the formation of rhythmic mesoscale sandy coastal oscillations of up to tens of kilometres with a typical migration speed of tens of metres per year from W to E along the Dutch coast, with reference to the tidal role and influence of the Dutch and German Wadden Islands. Kaergaard et al. (2012) investigated longshore undulations on the micro-tidal W Danish coast with alongshore scale of kilometres and where one undulation migrated its own wave length in years or decades. The obliquity of the wave approach was found to be a major control.

On a global scale, the morphodynamic classification, developed initially for Australian coasts, but subsequently applied to coasts more widely (Short & Jackson, 2013) recognises rhythmic bars and troughs related to rip currents on wave-dominated and tide-modified sand coasts. The Holderness coast can be considered within this classification as a modified version of the 'Tide-modified, reflective plus low tide terrace (without rip currents)' beach type. The only rhythmic features associated with this type are small-scale beach cusps which sometimes form on the Holderness upper beaches. Although this does not help to explain the presence of ords, the morphodynamic classification provides a conceptual framework for the inter-ord beaches. Between about two hours before and after LW surf zone processes with dissipative spilling waves shape the lower beach (terrace). However, for the rest of the tidal cycle in deeper water, the waves pass over the terrace without breaking, only to collapse as plunging breakers on the steeper, coarser upper beach. Measurements taken on a similar beach type at Teignmouth (UK) showed that the dynamics of the terrace/steep beach show characteristics of separate dissipative/reflective sites although some interactions occur (Miles & Russell, 2004). The changes to these processes within ords will be considered further in the Discussion.

2 | METHODS

The methods used to analyse ords for the two survey periods will be considered separately below.

2.1 | Land-Ocean interaction study (LOIS) aerial surveys 1994–1998

As part of the Natural Environmental Research Council (NERC) LOIS project, 13 aerial surveys were flown along the Holderness coast from Bridlington to Kilnsea (Table 1). Most were flown from a height of c1,000m to produce stereo aerial photographs at a scale of c1:6,517. Two surveys were from a greater height producing larger scale photographs showing less detail. Two surveys of the entire coast were flown each year between spring and autumn, plus two additional surveys of only the southern part in 1996 and one in 1998.

Prior to the first aerial survey on 26.04.1994 an extensive ground reconnaissance was undertaken from 10 to 14.04.1994 to locate the current ord positions between Barmston and Kilnsea. From each set of aerial photographs each ord was identified and mapped onto a reduced scale OS 1:50,000 map to show its position and extent. Ground verification was undertaken on the date of each survey. From the maps, measurements of ord lengths and movements between surveys were taken.

TABLE 1 LOIS aerial surveys of the Holderness coast.

Date	Height	f (mm)	Scale
26/04/1994			Large
11/07/1994			Smaller
14/04/1995	1,000 m	153.44	1:6517
04/11/1995	3,000 m		1:c19600
31/05/1996	1,000 m	153.44	1:6517
18/06/1996	914 m	153.44	1:5959
31/08/1996	1,000 m	153.44	1:6517
26/09/1996	1,006 m	153.44	1:6555
08/04/1997	1,000 m	153.44	1:6517
19–20/09/1997	1,000 m	153.44	1:6517
27/05/1998	1,000 m	153.44	1:6517
22/07/1998	1,000 m	153.44	1:6517
06/11/1998	1,006 m	153.44	1:6555

Note: data missing for 26.04.1994 and 11.07.1994.

2.2 | 2010–2020 surveys

Orthorectified photography and aerial LiDAR data for the years 2010–2020 from the East Riding of Yorkshire Council (ERYC) were used to identify the locations of ords between Bridlington and Withernsea (Table 2). The orthorectified images displayed clear ord features including the exposed till shore platform and sand bars used to indicate ord centres. These points were mapped within ArcGIS Pro allowing the tracking of ord migration along the coastline between surveys.

Using the 1 m resolution LiDAR surveys, ord centres were identified where upper beach elevation was reduced. The northern and southern sections of each ord were mapped where upper beach elevation increased towards inter-ord levels. These sections were identified as where sediment is built up north of the ord centre and to the south where the upper beach is re-established after ord movement southwards (Pringle, 1985). The ortho-rectified photography was used to ensure the correct ord features where mapped in the north, centre and south. In ArcGIS Pro ord lengths were measured between the northern and southern points of each ord. Overall, mean averages and standard deviations of ord migration, length and upper beach elevation along ords were calculated for each survey.

TABLE 2 LiDAR surveys and orthophotography from the East Riding of Yorkshire Council (ERYC) for the years 2010–2020.

Date	Survey type
28/04/2010	LiDAR and Orthophotography
07/10/2010	LiDAR and Orthophotography
18/04/2011	LiDAR and Orthophotography
28/09/2011	LiDAR and Orthophotography
08–11/03/2012	LiDAR and Orthophotography
18/09/2012	LiDAR and Orthophotography
26/04/2013	LiDAR and Orthophotography
17/10/2013	LiDAR and Orthophotography
16/05/2014	LiDAR and Orthophotography
06/11/2014	Orthophotography
20/04/2015	LiDAR and Orthophotography
29/09/2015	LiDAR and Orthophotography
13/03/2016	LiDAR and Orthophotography
14/12/2016	Orthophotography
25/05/2017	LiDAR and Orthophotography
05–06/11/2017	LiDAR and Orthophotography
14/05/2018	LiDAR and Orthophotography
08/10/2018	LiDAR and Orthophotography
23–24/03/2019	LiDAR and Orthophotography
27/10/2019	LiDAR and Orthophotography
12/03/2020	LiDAR and Orthophotography

2.3 | Winds, waves, tides and water levels

To assess changes in the hydrodynamic conditions affecting ord formation, development and movement the following data sets were used. Meteorological Office mean hourly wind data for speed and direction was supplied by the British Atmospheric Data Centre (BADC) for Leconfield, the closest station at c20 km W of the Holderness coast. Tidal records together with residual data (difference between astronomical and recorded tide heights) for the closest station, Immingham in the Humber Estuary (Figure 1), were obtained from the National Oceanographic Data Centre (BOCD). In addition, predicted astronomical tidal data was obtained for Bridlington at the north end of the Holderness coast from the National Oceanographic Centre (NOC), but no measured tidal records were available. In 2008 the Hornsea Datawell Directional Waverider Mark 111 wave buoy was installed by the Channel Coast Observatory (CCO) at Latitude 53 degrees 55.02 minutes N; Longitude 00 degrees 03.95 minutes W, in c 12mCD water depth and c 6 km offshore. Wave data was therefore available for the 2010–2020 period.

For both studied periods, storm surge events and raised water levels were identified from monthly wind and tidal data. Graphs were used to aid visual identification. Because of a clustering of raised residuals above 0.9 m this height was selected as the base for storm surge analysis. This equated to a return period of 1:2 at Immingham (Haigh et al., 2016). As storm surges move independently of tides, they can coincide with any tidal level, having only the maximum effect at HW. As the mean cliff toe height at the ord centres in 2010–2020 was measured at 2.2mOD particular attention was paid to water levels in storm surges at this height and above.

Wave parameters such as significant wave height (Hs), maximum wave height (Hmax), peak wave period (Tp) and direction, taken between the first and last ord surveys in 2010 and 2020 were used for further analysis. The distribution of significant wave heights in relation to directions was calculated using directional intervals of 10 degrees and wave height intervals of 0.5 m between zero and three metres, with the last class including all waves higher than three metres. The moving average of the significant wave height was calculated over 14 days to include a spring and a neap tidal cycle. The storm conditions were identified using the threshold for "storm waves" of 3.04 m, determined by the CCO as the significant wave height with a return period of 0.25 years.

To illustrate the temporal intensity and direction of the longshore sediment transport, longshore component of the wave energy flux (wave power) at the Hornsea buoy was calculated with respect to the shoreline orientation, using the following equation:

$$P_l = \frac{1}{16}\rho g H_s^2 c_g \sin(\alpha)$$

Where (Ec_g) is the wave energy flux (power per unit wave crest length) (W/m), with H_s being the significant wave height (m), ρ density of seawater (kg/m^3), g gravity (m/s^2) and c_g the group velocity (m/s). The group velocity is calculated using the linear wave theory, from the measured mean wave period (T_z) and the water depth at the buoy, estimated from the measured tidal height, which includes storm surges. α is the angle with respect to shore normal. Therefore, α is positive and negative, north and south of the shore normal, respectively.

2.4 | Limitations

It is important to recall the difference in methods used to study the Holderness ords in 1994–1998 and 2010–2020 before comparing and discussing the results. Whereas in the earlier period, stereo aerial photography with extensive ground verification was used, in the latter period LiDAR (Digital Elevation Models) and orthorectified aerial photography were used without fieldwork, owing to the Covid-19 pandemic travel restrictions. Also, the entire coast between Barmston and Kilnsea was monitored in the earlier period, whereas the latter study was limited to between Barmston and north Withernsea.

Whilst the same method was used to track the ords, there could be some discrepancies between the manual method (1994–1998) and the digital method (2010–2020). However, these differences will be minimal to plus or minus one metre constrained by the one metre LiDAR resolution.

Tidal residuals rather than skew storm surges (Haigh et al., 2016) are considered in this study and there will be some difference in the height of storm surges presented here and skew surges presented elsewhere.

The longshore wave power was used to illustrate the longshore sediment transport. However, it would be more suitable to use nearshore longshore wave power which accounts for nearshore wave transformation. Tidal and wind currents have not been considered here, which will also contribute to the longshore sediment transport.

It should be noted that there were missing data in both data sets used (tidal and wave data such as 05–06.12.2013). While quality-checked data were used, both data sets were checked again for any outliers, which were not accounted for.

The results will now be presented in sequence due to the differing methodologies. For each survey period 1994–1998 and 2010–2020 they will be presented under the headings 'Ord Distribution', 'Ord Lengths', 'Ord Movements' and 'Marine influences including Storm Surges', plus 'Ord Cliff Toe Heights 2010–2020' following 'Ord Lengths'.

3 | RESULTS

3.1 | Summary of results for 1994–1998 and 2010–2020

To compare the results for the two survey periods, Table 3 summarises the main findings. Tables showing the detailed results have been placed in the Supplementary Section.

3.2 | Ord distribution

3.2.1 | 1994–1998

Ords were named according to the first location where they were identified. Ords initially formed south of Barmston (see Figure 6), with one forming at Ulrome prior to 14.04.1995 and one at Far Grange present from 14.04.1995 until the end of the survey period. No ords were present north of Barmston. At Mappleton, where new coastal

TABLE 3 Summary of results for 1994–1998 and 2010–2020.

	1994–1998 Barmston to Kilnsea 51 km	2010–2020 Barmston to N Withernsea 35 km
1. Ord Distribution		
Total Number	11 ords (includes eight north of Withernsea)	Seven to ten ords north of Withernsea
Disappeared	Two ords at Ulrome and Waxholme	Four ords at Hornsea
Appeared	Two ords at Aldbrough and Cowden	Four ords in total, one at Ulrome, Far Grange, Hornsea, Mappleton
Passage through groynes	One at Withernsea	Zero
2. Ord Lengths (km)		
Total length of ords per survey	11.5–17.6, omitting South only surveys	7.02–15.43
% of coast covered by ords	23–35	20–44
Average length per survey	1.6–2.2 overall average 1.8	1.0–1.93 overall average 1.38
Average length per ord	1.2–3.6 overall average 1.7	1.1–1.7 overall average 1.35
3. Ord Movements between Survey Dates (km)		
Total net movement South per survey	0.2–4.4	0.4–6.5
Average net movement South per survey	0.0–0.6	0.1–0.9
Northward Movement	in all except three surveys	in seven out of 20 surveys
Total net movement South per ord	0.0–3.3	1.0–9.7
Average net Movement South per year	0.0 Mappleton - 0.7 Kilnsea, overall mean average 0.36 km	0.6 Hornsea – 2.0 Barmston, overall mean average 1.11 km
4. Ord Cliff Toe Heights		
	No LiDAR available therefore ord heights not recorded.	LiDAR showed average upper beach height at cliff toe N 3.05, Centre 2.24 and S 3.27mAOD. Heights across ords did not vary seasonally.
5. Cumulative Ord Movements (km)		
	Overall net south movement at all ords except Mappleton	Overall net south movement at all ords
	North movement in all ords at some time excluding Mappleton	North movement on only seven surveys Ulrome, South of Ulrome, North of Hornsea, Cowden, Aldbrough, South of Aldbrough and Grimston
	Fastest net south movement of most ords 08.04.1997–19.09.1997	Fastest net south movement of most ords 26.04.2013–17.10.2013
	Next fastest 20.05.1996–31.08.1996. No overall seasonal pattern.	Net south movement faster north of Hornsea than Hornsea-Withernsea. No overall seasonal pattern.
	Mirror image movement Grimston and Tunstall 11.07.1994–20.05.1996	
6. Recorded Winds, Waves and Tides		
	Only winds and tides recorded	Winds, wave and tides recorded
	12 storm surges exceeded 0.9 m. Three exceeded 2.2mAOD water level at the storm surge peak, but had varying effect on HW level.	58 storm surges exceeded 0.9 m. Three exceeded 2.2mAOD water level at the storm surge peak, but had varying effect on HW level.
		There were two major storm surges on 05.12.13 and 13.01.2017 and one major storm on 28.02.18–03.03.2018 from E without storm surge.

defences were built in 1991, an ord remained on the south side throughout the whole 1994–1998 period. This ord became very long and by 14.04.1995 a new ord separated from it at Aldbrough. Similarly, another had separated at Cowden by 19–20.09.1997. Ords were identified along Spurn Head in 1994, but as Spurn was not included in many of the aerial surveys it has been omitted from this analysis. A total of 11 ords were recorded between Barmston and Kilnsea with eight located north of Withernsea.

Figure 7 shows ords at Aldbrough, Withernsea and Dimlington during the 1994–1998 period. All display the main ord features shown in Figure 3 and the actively eroding till cliffs cut into the full geological succession of beds and members at Aldbrough and Dimlington, but at Withernsea cut only into Withernsea Till.

3.2.2 | 2010–2020

In 2010–2014 (Figure 8a) ords also formed South of Barmston and migrated along the coastline south to Withernsea, where this survey ended. Less ords were seen between Hornsea and Mappleton and these disappeared before the Mappleton coastal defences, later reappearing south of them. In 2015–2020 (Figure 8b) more ords

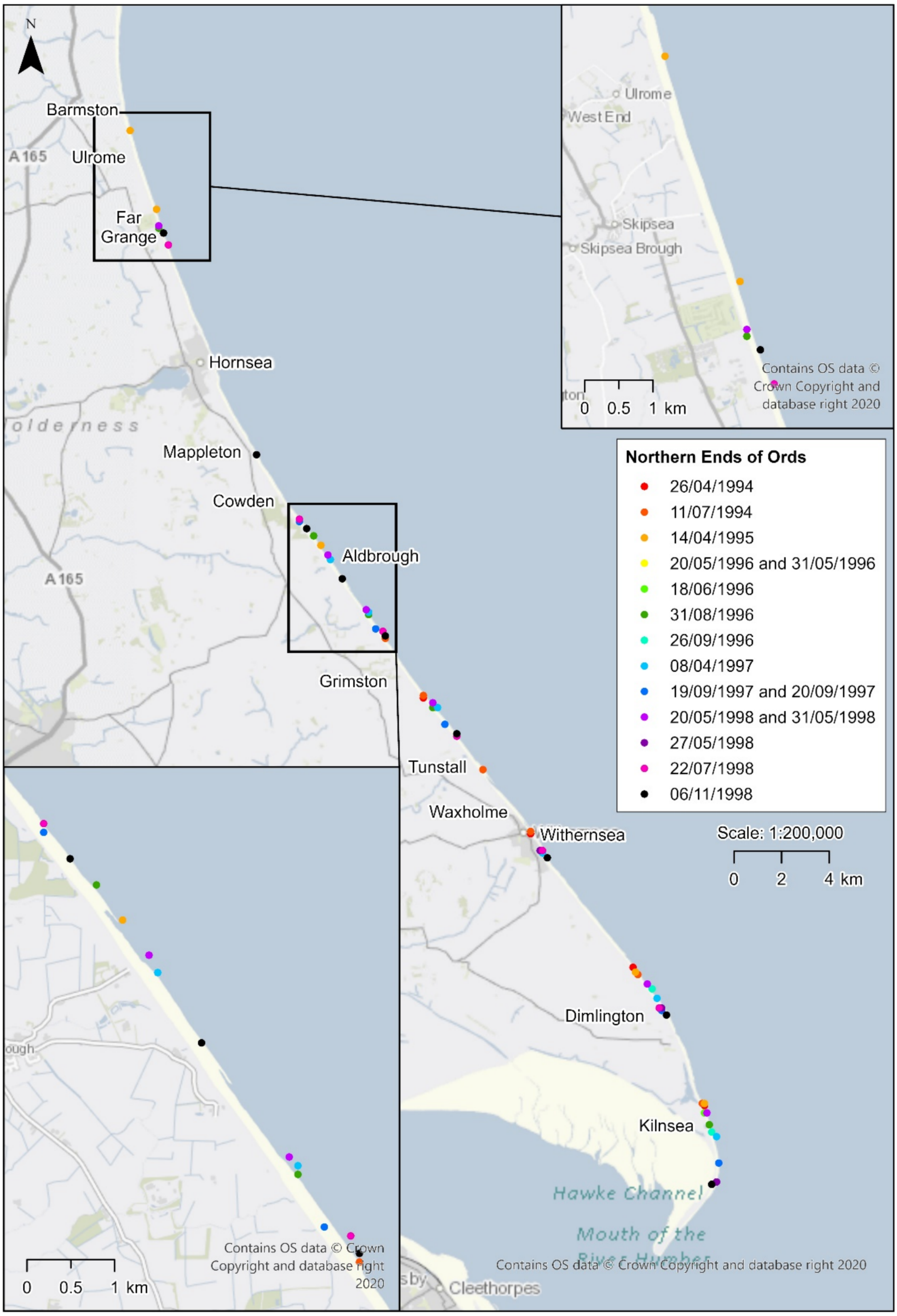


FIGURE 6 Map showing positions of ord north ends for each survey between 1994 and 1998.

appeared between Hornsea and Mappleton. The total number across all the 2010–2020 surveys ranged from seven to ten ords.

3.3 | Ord lengths

For detailed ord length data see Tables S1 and S2 in the Supplementary.

3.3.1 | 1994–1998

The date columns indicate that the total lengths of the ords per survey varied between 11.49 km on 26.04.1994 and 17.57 km on 08.04.1997. The percentage of coast with ords along the 51 km with till cliffs between Barmston and Kilnsea varied between 23 and 35%.

The average length of all ords per survey date (omitting partial surveys) was between 1.56 km on 20.05.1996 and 2.20 km on

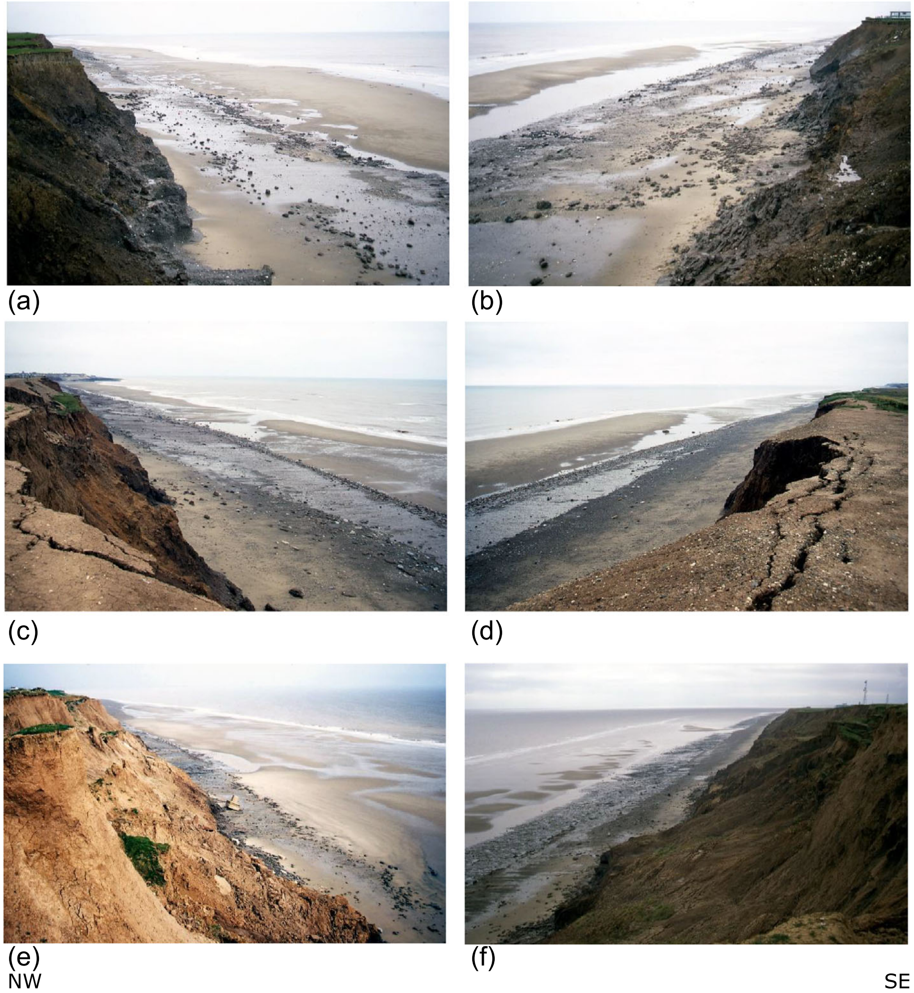


FIGURE 7 Ords during 1994–1998. **a and b Aldbrough Ord** 17.04.1995 from grid reference (GR) 257396. This shows the Ord Centre with till platform and armoured mud balls, a channel and sandbar seaward and north and south ends at the far left and right, respectively. **c and d Withernsea Ord** 20.07.1997 from GR 357262. This is taken from the ord's south section with its Centre NW and its north end in the far NW groyne field. SE the till platform, channel and sandbar wedge out as the upper beach widens. **e and f Dimlington Ord** 15.04.1995 from GR 391216. Taken from the Ord Centre showing till platform with armoured mudballs near the cliff foot. The ord's north and south ends are shown at the far left and right, respectively, with channel and sandbar wedging out southwards.

08.04.1997, with peak average lengths over 1.90 km on 11.07.1994, 04.11.1995, 31.08.1996 and 08.04.1997. The average lengths of individual ords throughout 1994–1998 were between 1.18 km at Kilnsea and 3.59 km at Mappleton. The average length of all ords present between 1994 and 1998 was 1.68 km.

3.3.2 | 2010–2020

In 2010–2020 ord lengths varied between 0.4 km on 23–24.03.2019 and 3.67 km on 12.03.2020. Coverage along the 35 km length of coast between Barmston and Withernsea ranged between 20% on 16.05.2014 with an average ord length of one kilometre and 44% on 08–11.03.2012. The overall average length of ords per survey was 1.38 km. Coastal coverage was often greater earlier in the year; however, this was not the case in 2013, 2014 and 2017.

3.4 | Ord cliff Toe Heights 2010–2020

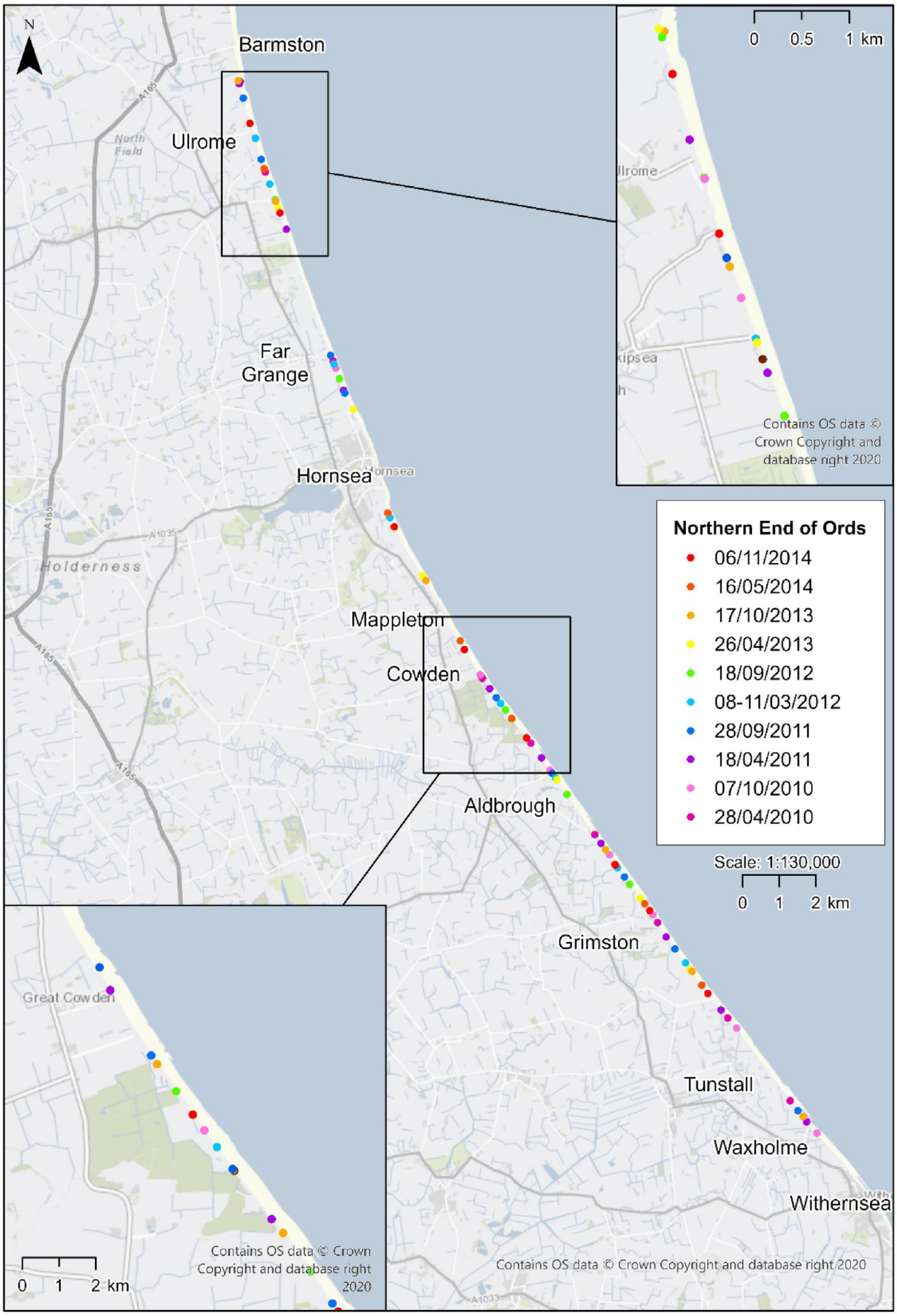
For detailed data see tables S3a, S3b and S3c in the Supplementary. Note that height data was not available for 1994–1998.

Throughout the 2010–2020 period, average ord height at the cliff toe was greater to the southern (3.27mAOD) and northern ends (3.05mAOD) of ords with a reduced upper beach elevation at their centres (2.24mAOD). The 07.10.2010, 08–11.03.2012, 18.09.2012 and 26.04.2013 surveys showed average ord centres below 2.0 m AOD.

There was no obvious seasonal trend. However, there was a small correlation between ord centre and south section heights. As ord centre height increased, so did its south section height. For example, between the surveys 14.12.2016 and 08.10.2018. On some surveys as ord centre heights increased upper beach elevation decreased across ord northern sections, and vice versa. For example, the surveys 07.10.2010, 13.03.2016, 08.10.2018 and 23–24.3.2019.

Table 4 compares the average heights of the upper beach at the cliff toe in the north, centre and south sections of the ords with the tidal HW and wave heights (CCO) for each survey. As the LiDAR surveys were undertaken across LWST level under relatively calm conditions, predicted astronomical tide data for Bridlington (NOC) were regarded as the most accurate for the Holderness coast between Barmston and Withernsea.

As the average height of the cliff toe in the ord centres was 2.2mAOD, all HWs on the survey dates would have reached the cliff toe. In contrast, in the north section, where the average cliff toe height was 3.05mAOD, HW did not reach the cliff toe on seven surveys. In the south section with an average cliff toe height of 3.27 mAOD it did not reach the cliff toe on 17 survey dates. The maximum cliff toe height variation was measured on 07.10.2010 when the north section was 1.52 m above the centre and south section 1.75 m above it. Whilst these figures contrast with an average up to 3.9 m variation between ord and inter-ord beach level at the cliff toe on a sample ord



(a) 2010-2014

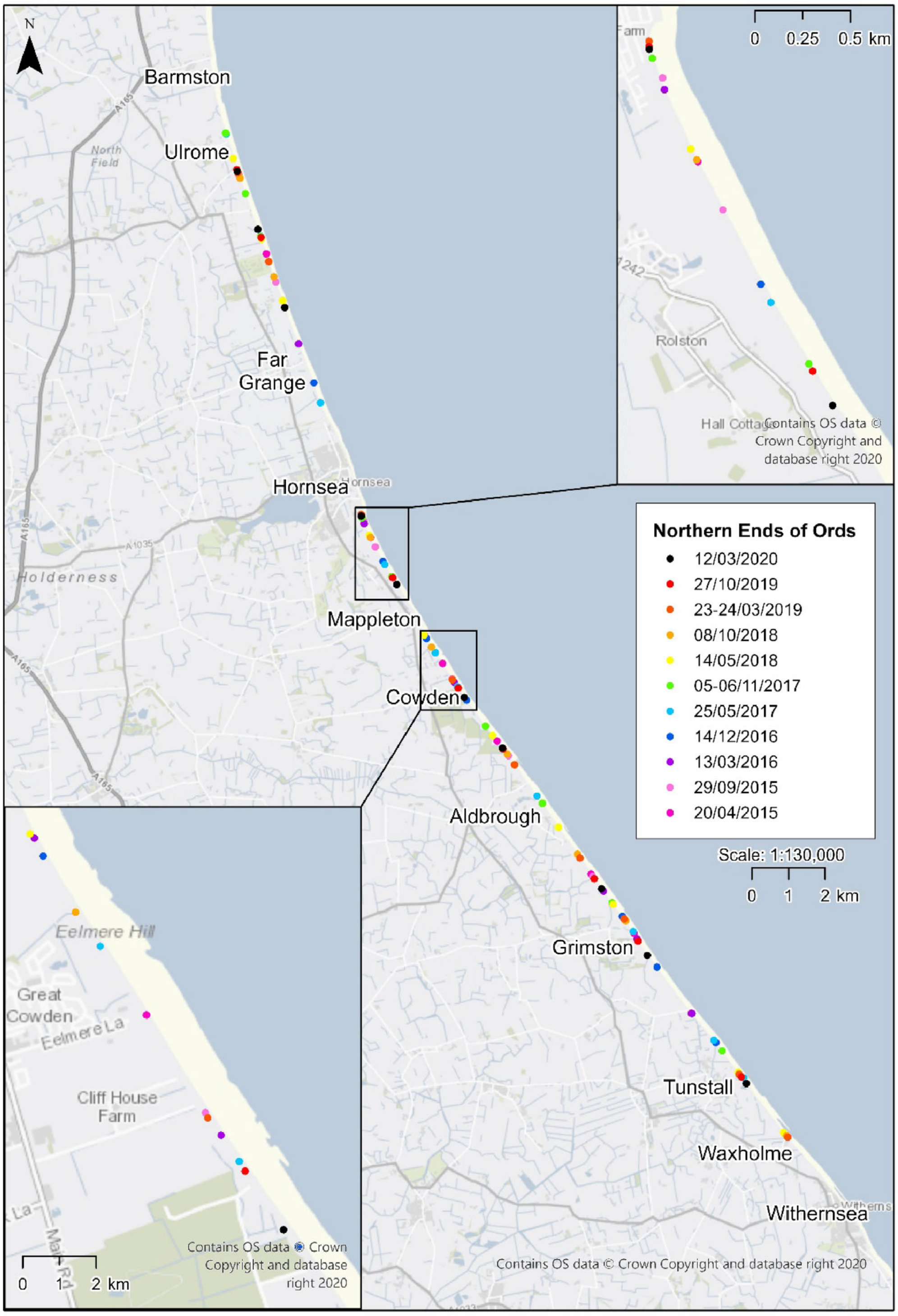
FIGURE 8 Maps showing positions of Ord north ends for each survey between 2010 and 2020.

between 1977 and 1983 (Pringle, 1985), it must be noted that the 2010–2020 data is from within the ords.

To illustrate the wave conditions on the survey days, the mean values at high water of H_s and H_{max} measured at the Hornsea wave buoy are included in Table 4. This shows that on all the survey dates H_s was below 1.0 m and H_{max} only rose above 2.0 m on three surveys to the highest level of 2.37 m. Whilst these tide and wave data relate to relatively calm conditions, storm conditions may produce much higher water levels with larger and more powerful waves as discussed later.

3.5 | Ord movement

For detailed ord movement data see Tables S4 and S5 in the Supplementary.



(b) 2015-2020

FIGURE 8 (Continued)

The dominant net movement south, but incorporating some northward movements, is shown in a cumulative graph for each period (Figures 9 and 10).

3.5.1 | 1994–1998

Figure 9 shows a net southward movement of all ords, per survey date, of between 0.22 km on 11.07.1994 and 4.36 km on 19–20.09.1997. The most rapid southward movements occurred during the summers of 1996 and 1997. The average southward movement per year between 1994 and 1998 was 0.36 km per year, ranging between zero kilometres at Mappleton and 0.74 km at Kilnsea. All dates except 26.09.1996 and 19–20.09.1997 included some northward ord movements, which reached a maximum of 1.21 km at Grimston and a joint minimum of 0.07 km at Grimston, Tunstall, Withernsea, Dimlington and Kilnsea. The average rates of net southward movement per survey date (excluding 18.06.1996) were between

TABLE 4 Comparison of Ord Beach Heights with Tidal High Water (HW) level and Wave Heights. Beach elevation data has been calculated from ERYC LiDAR surveys 2010–2020. Bridlington predicted tidal data (NOC). Hornsea wave data (CCO).

LiDAR survey date	Average Upper Beach height north of Ord Centre (mAOD)	Average Upper Beach height at Ord Centres (mAOD)	Average Upper Beach height south of Ord Centre (mAOD)	Bridlington predicted tides HW (mAOD)	Hornsea waves average Hs (m)	Hornsea waves maximum Hmax (m)
28/04/2010	2.96	2.01	3.46	2.88	0.56	1.41
07/10/2010	3.08	1.56	3.31	3.12	0.29	0.62
18/04/2011	3.03	2.55	3.49	3.13	0.28	0.74
28/09/2011	2.94	2.71	3.60	3.37	0.36	0.81
08/03/2012–11/03/2012	2.98	1.99	3.50	3.19	0.45	1.03
18/09/2012	2.70	1.91	3.36	3.26	0.48	1.04
26/04/2013	2.76	1.84	2.96	2.91	0.51	1.16
17/10/2013	2.91	2.51	2.86	2.71	0.96	2.02
16/05/2014	3.10	2.77	2.84	2.73	0.26	0.78
06/11/2014	no LiDAR	no LiDAR	no LiDAR			
20/04/2015	2.88	2.09	2.85	3.11	0.79	2.37
29/09/2015	3.33	2.14	3.08	3.47	0.24	0.49
13/03/2016	2.88	2.35	2.83	2.89	0.35	0.75
14/12/2016	3.00	2.23	3.13	3.06	0.44	1.33
25/05/2017	2.89	2.22	3.02	2.92	0.14	0.32
05/11/2017–06/11/2017	3.20	2.5	3.97	3.27	0.84	2.22
14/05/2018	3.46	2.24	3.13	2.55	0.5	1.16
08/10/2018	3.33	2.64	3.50	2.93	0.61	1.22
23/03/2019–24/03/2019	3.10	2.24	3.50	3.17	0.43	1.13
27/10/2019	3.29	2.16	3.64	3.01	0.73	1.57
12/03/2020	3.24	2.18	3.46	3.23	0.85	1.99
Overall Average	**3.05**	**2.24**	**3.27**			

Note: wave data was quality controlled by the CCO.

0.03 km on 11.07.1994 and 0.55 km on 19–20.09.1997 but note the varying time interval between surveys.

3.5.2 | 2010–2020

Figure 10 shows all ords experienced a net south movement between 2010 and 2020. The average southward movement between 2010 and 2020 was 1.11 km per year, ranging between 0.55 km at Hornsea and 1.97 km at Barmston. The greatest ord migration along the coastline occurred during the periods 26.04.2013 to 17.10.2013, 29.09.2015 to 14.12.2016, 25.05.2017 to 05–06.11.2017 and 27.10.2019 to 12.03.2020, whilst the slowest ord migration was between 08.10.2018 to 27.10.2019. The ords starting at Barmston (A) and Ulrome had the greatest average net southward movements of 0.98 km and 0.84 km, respectively, between 2010 and 2020. The lowest average net south movements per survey were 0.28 km at Hornsea and 0.33 km at Mappleton. Ords north of Hornsea experienced faster migration rates during the period 2010–2020 (see Table S6 in Supplementary for details).

3.6 | Marine influences including North Sea storm surges

3.6.1 | 1994–1998 Wind and Tidal Influences

In the absence of wave records for the Holderness coast in the 1990s, BADC wind records for Leconfield in addition to BODC tidal records for Immingham were examined. Monthly tidal and wind charts were plotted from 01.01.1993 to 31.12.1998 with the earlier start date to assess conditions before as well as during the study period. Tidal residual heights which exceeded 0.9 m (1:2 return period), are listed for 1994–1998 in Table 5 together with Leconfield wind records at the time of the storm surges.

These storm surges over 0.9 m are usually accompanied by powerful waves from a northerly quarter producing high energy conditions. From local observations when local gales from this quarter, as shown in the Leconfield wind data, coincide with such a storm surge the waves will be further heightened. Conversely, when they do not coincide, especially with winds from the prevailing SW quarter, wave heights will be lowered.

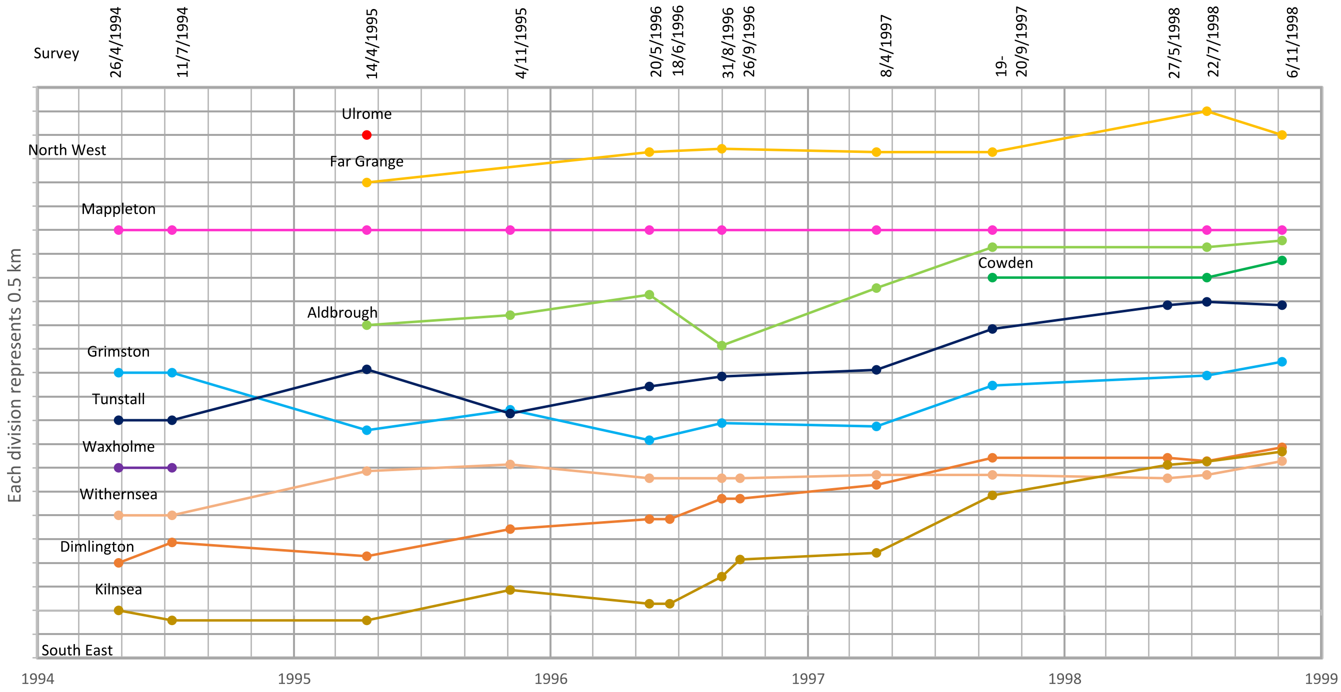


FIGURE 9 Holderness Ords 1994–1998 Cumulative Ord Movements. *Note*: south movements are positive, north movements are negative.

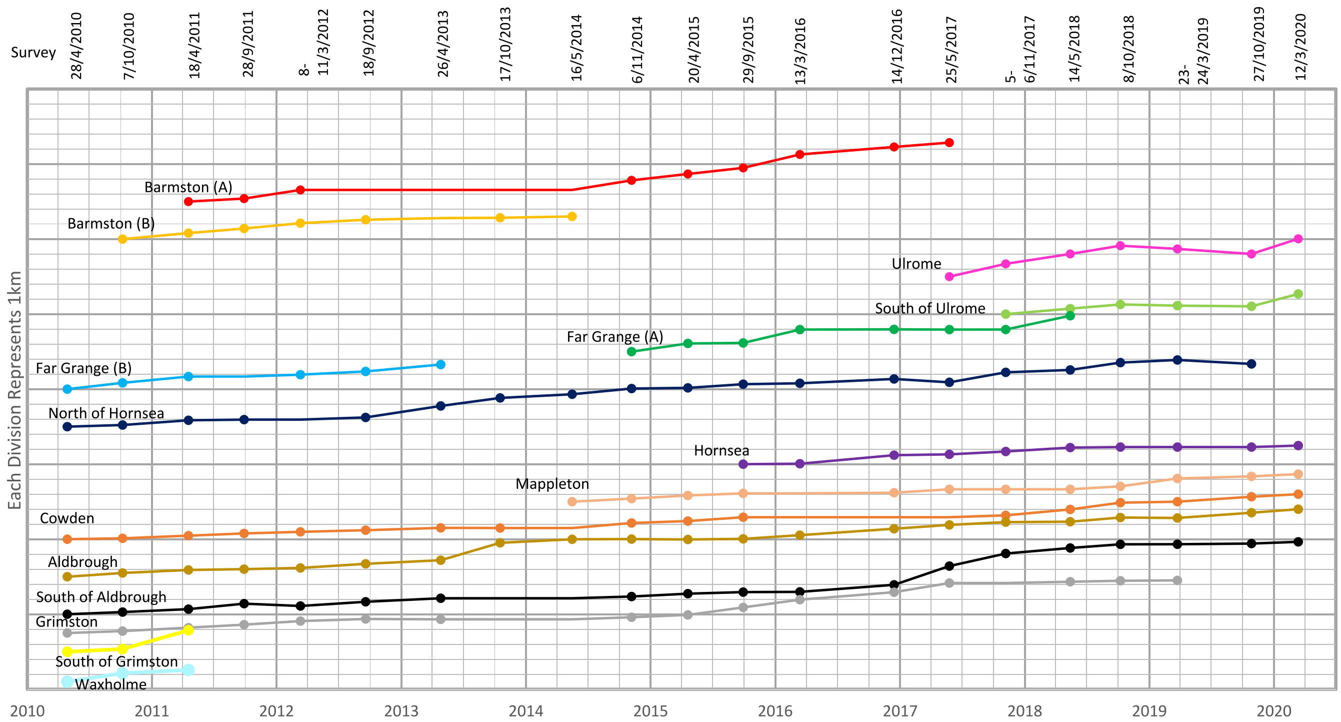


FIGURE 10 Holderness Ords 2010–2020. Cumulative Ord Movements. *Note*: south movements are positive, north are negative.

Table 5 shows that the maximum annual number of nine positive storm surges over 0.9 m occurred in 1993, with eight of them in January and February, with a maximum height of 2.13 m. During the study period in 1994, 1997 and 1998 only three comparable storm surges occurred each year reaching maximum heights of 1.03 m, 1.52 m and 1.05 m, respectively. In 1995 only one with 1.78 m height occurred and in 1996 two occurred with a maximum height of 1.53 m.

As the storm surge and tidal cycles are independent, the storm surge peak can occur at any point in the tidal cycle. Therefore, the effect of the storm surge on the maximum water level is very variable. During 1993–1998 only four storm surges raised the tide height to 8.00mACD (= 4.1mOD) or above: 11.01.93, 8.10 m; 30.01.94, 8.11 m; 06.12.94, 8.0 m; and 19.02.96, 8.0 m.

Figure 11 shows the contrasting conditions in (a) January 1993 and (b) January 1998 and indicates the height at which the water level

TABLE 5 Holderness Ords 1994–1998 Immingham storm surge records and Leconfield wind records 1993–1998.

Immingham positive storm surges over 0.9 m						Leconfield hourly mean wind records		
Date	Surge height (m)	Tide height (mACD) at surge peak	Tide height (mAOD) at surge peak	Nearest HW (mACD)	Nearest HW (mAOD)	Direction	Peak speed (knots)	Peak speed (m/s)
06/01/1993	1.19	5.85	1.95	7.08	3.18	WNW	24	12.336
11/01/1993	1.13	4.65	0.75	8.1	4.2	WSW	30	15.42
17/01/1993	1.33	4.46	0.56	6.75	2.86	SW	32	16.448
22/01/1993	1.12	3.64	−0.26	7.45	3.55	SSW	34	17.476
24/01/1993	0.99	4.77	0.87	7.38	3.48	WSW	42	21.588
25/01/1993	1.15	6.83	2.93	7.69	3.79	NNW	42	21.588
19/02/1993	1.61	3.63	−0.27	6.81	2.91	NNW	23	11.822
21/02/1993	2.13	4.32	0.42	7.92	4.02	NNW	30	15.42
19/12/1993	1.15	7.24	3.34	7.57	3.67	WSW	30	15.42
28/01/1994	1.03	2.32	−1.58	7.65	3.75	W	30	15.42
30/01/1994	0.87	2.51	−1.39	8.11	4.21	SSW	23	11.822
06/12/1994	0.94	3.99	0.09	8	4.1	SW	22	11.308
10/01/1995	1.78	4.22	0.32	6.57	2.67	NW	30	15.42
19/02/1996	1.53	2.41	−1.49	8	4.1	N	32	16.488
06/11/1996	1.03	4.3	0.4	6.54	2.64	WSW	31	15.934
18/02/1997	1.02	5.13	1.23	6.73	2.83	WSW	26	13.364
20/02/1997	1.52	3.45	−0.45	6.92	3.02	WSW	34	17.476
03/03/1997	0.93	6.14	2.24	6.67	2.77	WSW	30	15.42
02/01/1998	0.91	3.34	−0.56	7.94	4.04	WNW	27	13.878
19/01/1998	0.99	2.86	−1.04	6.74	2.84	NNW	24	12.336
11/03/1998	1.05	2.78	−1.12	6.99	3.09	N	28	14.392

Note: 1. Immingham data gap 10.09.1996–25.10.1996 due to tide gauge relocation. 2. Immingham data problem and gaps for the dates 26–30.11.1996, 24–29.03.1998, 07.04.1998, 21–22.04.1998 and 10–16.11.1998. Data from Immingham tide records (BODC), AOD above ordnance datum, ACD above chart datum = −3.90 mAOD and Leconfield wind records (BADC).

exceeded the average beach elevation measured across the ords in the later 2010–2020 period. Ord centres are frequently submerged at Mean High Water Neap (MHWN) tide level (1.88mAOD), but the upper part of the beach of the southern and northern sections are usually only submerged on High Water Spring Tides (HWST) or when storm surge peaks raise the maximum water level to such heights or above.

3.6.2 | 2010–2020 Wind, Wave and Tidal Influences

Throughout the 2010–2020 period, Immingham tide records, Hornsea wave records and Leconfield wind records were examined. With the additional availability since 2008 of wave data, the CCO H_s storm wave threshold height of 3.04 m and Tp swell alert level of 11.60 sec can be considered. For comparison with 1994–1998 all storm surges which exceeded 0.9 m high during the period 2010–2020 are listed in Table 6. The only exception that was included but did not generate a storm surge was the 'Beast from the East' storm on 28.02.2018–03.03.2018.

During the 2010–2020 period, 58 storm surges over 0.9 m occurred varying annually between 0 in 2018 and 14 in 2015. There were three major storms throughout the 2010–2020 period, on 05–06.12.2013, 13.01.2017 and 28.02.2018–03.03.18. The most powerful North Sea storm surge since 1953 occurred on 05–06.12.2013 (Spencer et al., 2015), with a surge height at Immingham of 1.97 m (skewed storm surge 1.62 m (Haigh et al., 2016)), near the top of a high spring tide. This was one of three storm surges that exceeded 2.2mAOD at the peak of the surge between 2010 and 2020. Figure 12 shows the wave conditions at Kilnsea after the peak of this storm surge had passed.

The second-highest storm surge of 1.62 m occurred on 13.01.2017. However, the water level did not exceed 2.2mAOD at its peak due to occurring around low tide.

The third major storm was the 'Beast from the East' between 28.02.2018 and 03.03.2018. Unusually this did not come from the north with an associated high positive storm surge, therefore is not listed as a storm surge in Table 6. However, Hornsea H_{max} records showed maxima for each day as 5.85 m (28.02.2018), 8.08 m (01.03.02018), 7.73 m (02.03.2018) and 5.68 m (03.03.2018).

Figure 13 shows that almost half waves in 2010–2020 came from between 15 and 35 degrees, with the maximum at 25 degrees (NNE) and that H_S was often less than 1 metre. There are also about 10% of waves coming from the ESE, with the maximum at 125 degrees. The distributions derived for the waves measured between the surveys, which are not shown here, have a similar shape. The maximum number of waves between all surveys come from 25 degrees. The

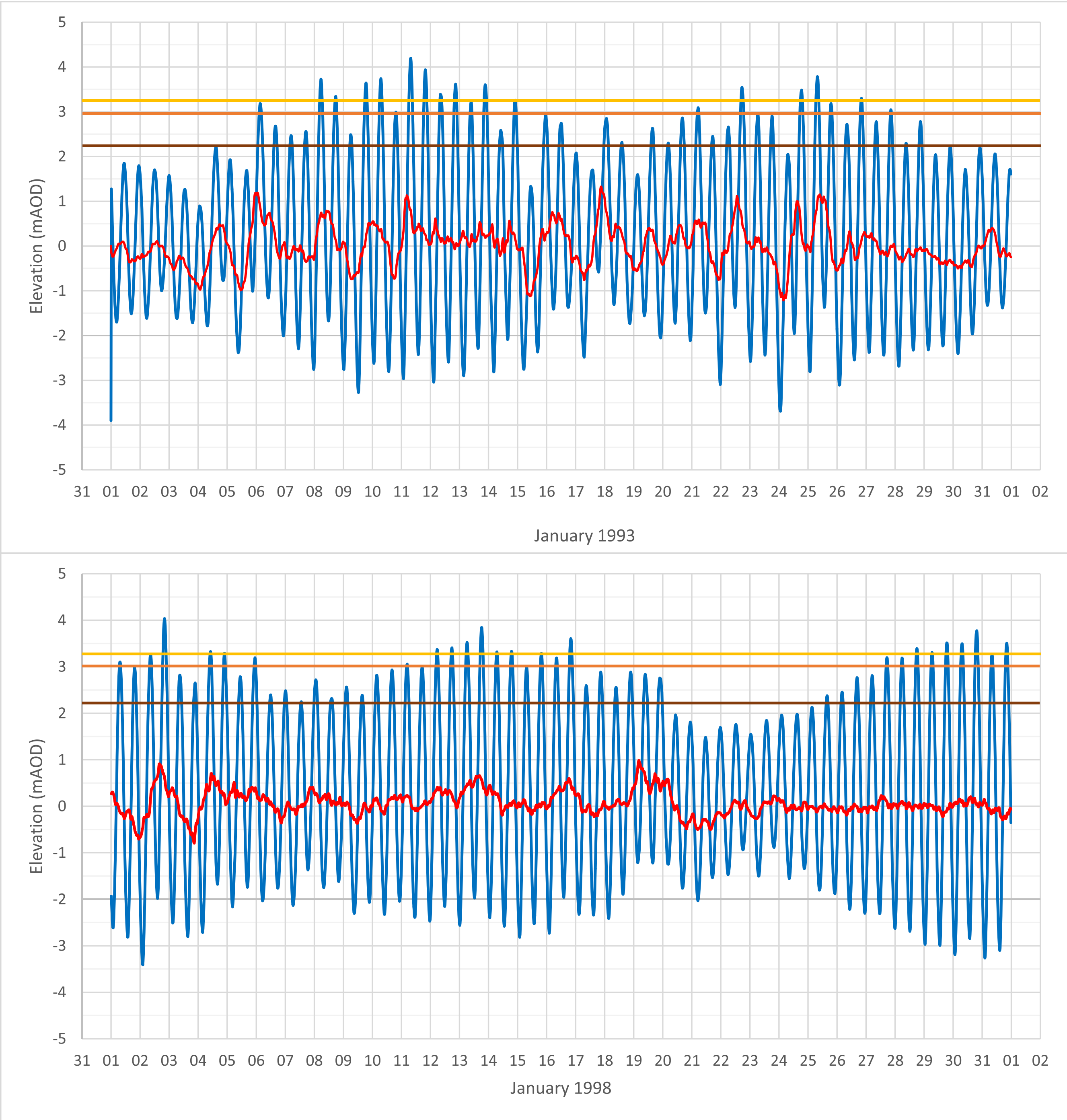


FIGURE 11 Immingham Tide Heights and residuals (a) January 1993 and (b) January 1998 (see blue line). The residuals are superimposed (red line). Data from Immingham tide records (BODC). *Note*: average mean Ord levels for 2010–2020 were calculated at 3.1 m, 2.2 m and 3.3mAOD for the ord northern (orange lines), central (brown lines) and southern sections (yellow lines), respectively.

presence of waves from E to SE, especially in the winter months, is reflected in resultant directions between 95 and 145 degrees, peaking at 125 degrees.

Figure 14 shows a) Hornsea wave H_s and moving average over 30 days, b) Immingham recorded tide height over mean high water neap elevation (1.88mAOD) and c) average upper beach cliff toe heights, throughout 2010–2020. The tide heights exceeding 2.2mAOD, submerged ords allowing waves to break at the cliff toe. There are 25 events when H_s exceeded the storm threshold (3.04 m) and the tide height exceeded 2.2mAOD. Frequently, storm surges coincided with high storm waves. The red circles in Figure 14b highlight two major storm surges on 05–06.12.2013 and 13.01.2017. An increase in average ord centre height was recorded on 10.10.2013. The next survey on 16.05.2014, following the storm on 05.12.2013, showed ord north, centre and south sections flattened out to similar elevations. Even though no storm surge occurred, following the 'Beast from the East' highlighted by the blue circles in Figure 14b, there was a shift in sediment resulting in the southern end of ords being lower than the northern end during the survey 14.05.2018.

Figure 15 illustrates cumulative longshore wave power where a positive value shows a southward orientation and a negative value

TABLE 6 Immingham tide records (BODC), Hornsea wave records (CCO) and Leconfield wind records (BADC) 2010–2020.

Date	Immingham positive storm surges over 0.9 m					Hornsea waves		Leconfield hourly mean wind		
	Surge height (m)	Tide height (mACD) at surge peak	Tide height (mAOD) at surge peak	Nearest HW (mACD)	Nearest HW (mAOD)	H_{max} at nearest HW	Direction (degrees from north)	Direction	Peak speed (knots)	Peak speed (m/s)
27/01/2010	0.95	3.66	−0.24	6.72	2.82	3.16	18	N	17	8.74
27/11/2010	1.34	6.64	2.74	6.34	2.44	1.97	30	W	28	14.39
16/12/2010	0.97	5.28	1.38	8.33	4.43	2.76	18	N	16	8.22
01/12/2011	0.99	5.71	1.81	7.29	3.39	0.82	28	W	23	11.82
03/12/2011	1.14	4.38	0.48	6.24	2.34	1.37	302	WSW	19	9.77
09/12/2011	1.41	4.95	1.05	7.52	3.62	1.33	267	W	23	11.82
26/12/2011	1.42	4.12	0.22	7.68	3.78	1.2	31	SW	19	9.77
29/12/2011	1.07	3.62	−0.28	7.25	3.35	1.24	18	W	19	9.77
04/01/2012	1.07	5.46	1.56	6.33	2.43	1.5	283	W	33	16.96
05/01/2012	1.09	6.02	2.12	7.01	3.11	2.64	13	WNW	20	10.28
12/01/2012	1.04	2.69	−1.21	7.48	3.58	1.92	25	WNW	21	10.79
10/10/2013	0.97	2.85	−1.05	7.2	3.3	5.29	21	N	20	10.28
29/11/2013	0.99	4.39	0.49	6.74	2.84	1.5	23	WNW	18	9.25
05/12/2013	1.97	7.99	4.09	9.12	5.22	2.95	28	WNW	33	16.96
15/12/2013	1.02	2.95	−0.95	6.67	2.77	1.74	132	SSW	18	9.25
19/12/2013	1.07	6.20	2.20	7.82	3.92	0.98	134	SW	14	7.20
15/03/2014	0.98	4.16	0.26	6.97	3.07	0.8	32	W	17	8.74
21/10/2014	1.35	3.31	−0.59	7.1	3.2	1.68	152	WNW	22	11.31
10/12/2014	1.29	3.73	−0.17	7.23	3.33	0.85	239	WSW	23	11.82
09/01/2015	1.44	4.19	0.29	7.64	3.74	1.27	242	SW	25	12.85
10/01/2015	1.54	3.88	−0.02	7.71	3.81	1.35	27	WSW	32	16.45
12/01/2015	1.38	4.73	0.83	7.15	3.25	0.69	18	SW	23	11.82
16/01/2015	1.09	4.71	0.81	6.52	2.62	0.89	31	WSW	27	13.88
10/03/2015	1.17	3.45	−0.45	7.19	3.29	0.54	28	WSW	11	5.65
12/03/2015	0.98	3.48	−0.42	6.76	2.86	0.88	128	NW	13	6.68
20/03/2015	1.18	2.62	−1.28	7.92	4.02	0.67	68	W	14	7.20
26/03/2015	1.15	3.05	−0.85	6.9	3	1.74	no data	WNW	18	9.25
29/03/2015	1.11	4.15	0.25	6.22	2.32	0.83	259	WSW	20	10.28
31/03/2015	1.05	3.52	−0.38	6.6	2.7	2.56	316	WNW	30	15.42
22/10/2015	1.05	5.15	1.25	6.59	2.69	0.7	241	W	17	8.74
13/11/2015	1.16	3.34	−0.56	7.64	3.74	0.83	233	WSW	20	10.28
21/11/2015	1.24	3.37	−0.53	6.46	2.56	2.65	24	N	23	11.82
30/11/2015	0.92	2.92	−0.98	7.31	3.41	0.95	28	N	17	8.74
02/02/2016	0.97	3.83	−0.07	7.5	3.6	1.39	23	WSW	25	12.85
27/01/2016	1.09	3.36	−0.54	5.8	1.9	1.44	156	WSW	24	12.34
08/08/2016	0.91	3.16	−0.74	7.21	3.31	1.05	288	WNW	17	8.74
24/12/2016	1.02	4.37	0.47	6.5	2.6	1.21	232	WSW	17	8.74
26/12/2016	0.98	5.1	1.2	6.86	2.96	1.09	263	WSW	19	9.77
26/12/2016	1.72	3.85	−0.05	6.65	2.75	1.47	291	WSW	19	9.77
04/01/2017	1	2.67	−1.23	6.9	3	5.25	24	NNW	11	5.65
13/01/2017	1.62	3.04	−0.86	7.96	4.06	5.45	35	NW	18	9.25
29/10/2017	1.41	4.34	0.44	6.08	2.18	1.55	283	N	19	9.77
08/12/2017	1.17	2.16	−1.74	7.3	3.4	1.07	8	W	15	7.71
28/02/2018						5.85	53	E	19	9.77
01/03/2018						8.08	73	E	27	13.88
02/03/2018						7.73	no data	E	25	12.85
03/03/2018						5.68	72	E	13	6.68

TABLE 6 (Continued)

Date	Immingham positive storm surges over 0.9 m					Hornsea waves		Leconfield hourly mean wind		
	Surge height (m)	Tide height (mACD) at surge peak	Tide height (mAOD) at surge peak	Nearest HW (mACD)	Nearest HW (mAOD)	H_{max} at nearest HW	Direction (degrees from north)	Direction	Peak speed (knots)	Peak speed (m/s)
01/01/2019	1.16	3.24	0.48	6.55	2.65	2.97	20	N	13	6.68
08/01/2019	1.59	3.84	1.05	7.63	3.73	4.06	28	NNW	16	8.22
08/03/2019	0.91	2.8	0.22	7.13	3.23	3.2	25	SW	18	9.25
13/03/2019	0.91	2.98	−0.28	6.41	2.51	1.9	16	NW	27	13.88
09/12/2019	1.32	3.19	1.56	6.95	3.05	3.23	18	NW	16	8.22
03/01/2020	1.08	5.3	2.12	6.45	2.55	1.29	21	N	15	7.71
08/01/2020	1.03	3.25	−1.21	6.97	3.07	0.93	120	WSW	15	7.71
14/01/2020	1.5	3.5	−1.05	7.66	3.76	1.6	131	WSW	26	13.36
17/01/2020	0.92	3.53	0.49	7.3	3.4	no data	239	SW	14	7.20
31/01/2020	0.93	3.5	4.09	6.56	2.66	0.97	149	SW	19	9.77
10/02/2020	0.98	5.61	−0.95	8.02	4.12	2.1	263	WSW	22	11.31
15/02/2020	0.93	3.11	2.18	6.93	3.03	1.48	131	SSW	26	13.36
16/02/2020	0.94	3.37	0.26	6.47	2.57	1.41	204	SSW	29	14.91
17/02/2020	0.99	3.53	−0.59	6.53	2.63	1.27	232	SW	23	11.82
11/03/2020	0.93	1.8	−0.17	7.97	4.07	no data	30	SW	21	10.79

Note: AOD above ordnance datum, ACD above chart datum = OD-3.90 m. 28.02.2018–03.03.2018 'Beast from the East' storm without storm surge. Major storms are shown in red.

FIGURE 12 Kilnsea. Major North Sea storm surge 05–06 12.2013 (Environment Agency LiDAR photo taken at 08.30 hours on 06.12.2013 one hour after HW). The Immingham tide height was 7.5mACD (3.6mAOD) (BODC), with Hornsea wave data of H_s 2.95 m, H_{max} 4.83 m, Tpeak 13.3 sec, wave direction 25 degrees (CCO). The Immingham storm surge peaked at 1.97 m around 17.30 hours on 05.12.2013. Peak tide height 9.12mACD (5.22mAOD) at 19.15 hours on 05.12.2013.

a northward orientation. Whilst this diagram may give an indication of cumulative longshore sediment transport, care should be taken when interpreting it as both wave height and wave direction will change nearshore. The arrows show the direction of change in longshore wave power for illustration purposes. The increase in cumulative wave power is gradual, except in the first year. There are sudden increases in the wave power in almost all winters, except in 2012, 2013 and 2016.

4 | DISCUSSION

4.1 | Ord distribution

This research has confirmed the earlier findings of Bisat (1940), Phillips (1962) and Scott (1976) that ords form at the north end of the Holderness coast near Barmston. Dominant N-NE waves, including those over the 3.04 m storm threshold at the Hornsea wave buoy are refracted around Flamborough Head to approach the shore south of Barmston at an oblique angle, resulting in a net longshore sediment movement southwards (Pye & Blott, 2015). They and Whitehouse (2002) showed that also during northerly storms a net northward sediment movement from near Barmston into Bridlington Bay, results in a sediment divide. This results in a depletion of upper beach sediment and exposure of the till shore platform to form an ord. In both the 1994–1998 and 2010–2020 periods two ords appeared south of Barmston, at Ulrome and Far Grange.

This research has shown that ords may form also south of coastal defences which can produce small headlands, which on a smaller scale mirror the sheltering effect of Flamborough Head from northerly storm waves. In 1994–1998 a long ord which formed south of the new Mappleton defences, built in 1991, divided to form separate ords at Cowden and Aldbrough. In 2010–2020 an ord formed south of both the Hornsea and Mappleton defences.

Once formed, ords persist in the generally southward longshore movement of beach sediment, as shown in the cumulative ord movement graphs for each period (Figures 9 and 10). In 1994–1998 there were 11 ords between Barmston and Kilnsea (eight north of Withernsea) and in 2010–2020 seven to ten north of Withernsea. Only occasionally did ords disappear: in the earlier period at Ulrome shortly after forming and at Waxholme north of the Withernsea

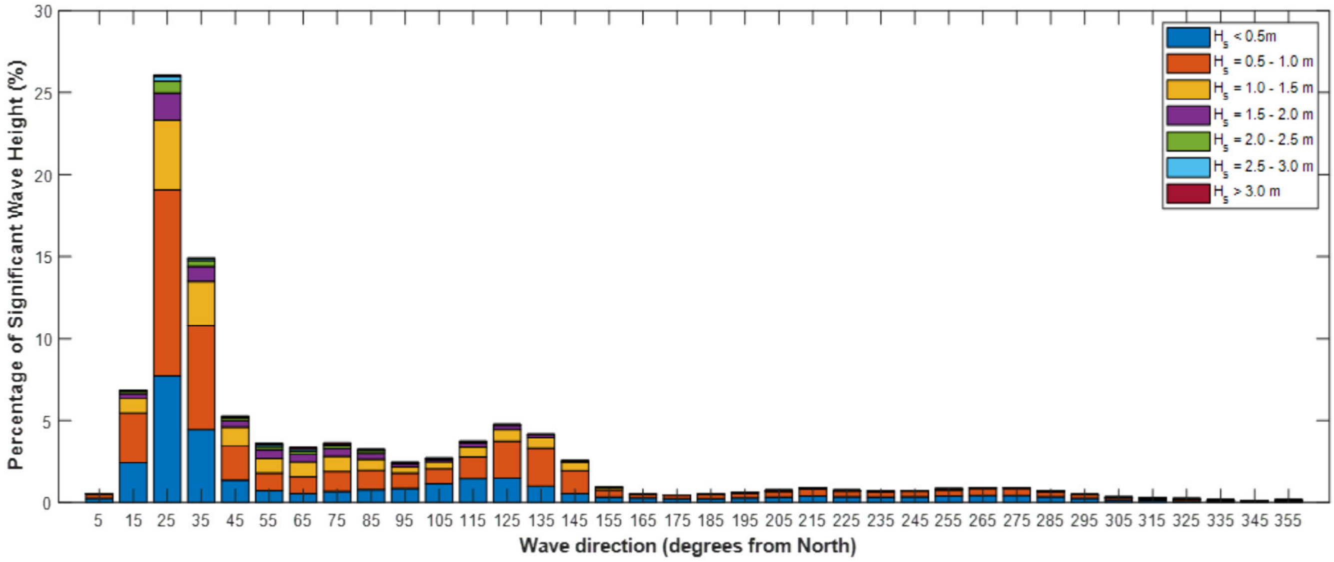


FIGURE 13 Significant wave height (H_s) and direction from north (0 degrees) between 2010 and 2020. The legend illustrates wave height (H_s) with the lowest significant wave height category being < 0.5 m and the largest > 3.0 m. Wave data from the CCO.

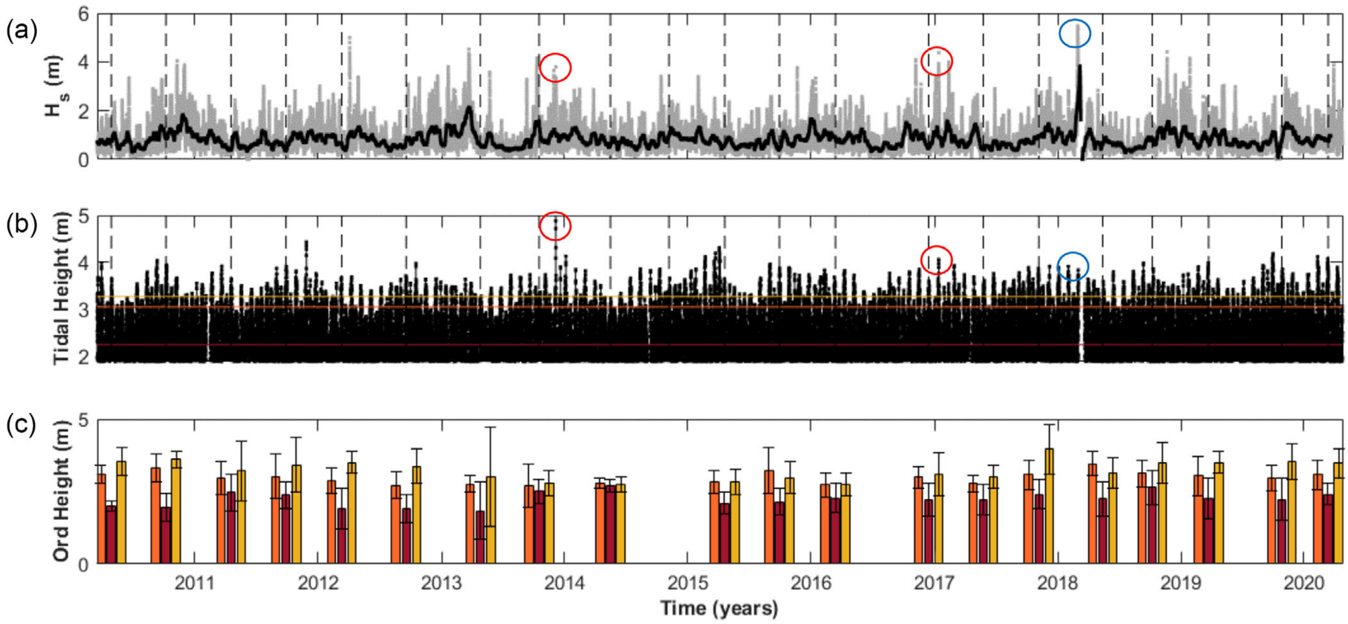


FIGURE 14 **a)** Hornsea significant wave height (m), using the significant wave height (H_s) values from the CCO data with moving average over 30 days in black. **b)** Immingham tidal height (mAOD) taken from the Immingham tidal records (above mean high water neap), incorporating storm surges. The lines show mean Ord heights in their northern (orange), southern (yellow) and central (brown) parts. **c)** Average upper beach elevations (mAOD) for ords during 2010–2020 at their northern (orange), southern (yellow) and central (brown) sections. The vertical dashed lines represented the survey dates in 2010–2020. The red circles represent the two major storm surges in 2010–2020 for the dates 05.12.2013 and 13.01.2017. The blue circles show conditions during the 'beast from the east' storm on 28.02.2018–03.03.2018. *Note*: LiDAR data was not available for 06.11.2014 therefore, upper beach elevation could not be measured.

defences, and in the later period four disappeared north of Hornsea defences and one at Waxholme. It is likely that the trapping of upper beach sediment within and updrift of groynes caused their infilling. Only one ord passed through a groyne system, at Withernsea in 1994–1998.

4.2 | Ord lengths

Ord lengths are particularly important in determining the length of the Holderness coast exposed to the higher rates of cliff erosion within them. Scott (1976) for the earlier period 1959–1972 between Barmston and Kilnsea recorded an average ord length of 2.0 km with an average coastal coverage of 34%. For 1994–1998 the same length of coast ord lengths ranged between 1.2 and 3.6 km with an average of 1.7 km, giving a coastal coverage of 23–35%. For 2010–2020, for the shorter stretch of coast between Barmston and north Withernsea, ord lengths ranged between 1.1 and 1.7 km, with a lower average of 1.35 km and a more variable coastal coverage between 20 and 44%. Overall, there was no clear seasonal trend in ord lengths for the periods in this research.

Because the coastal surveys were carried out only about six monthly in spring and autumn, it is very difficult to link changes in ord dimensions with the occurrence of storm surges and increased wave

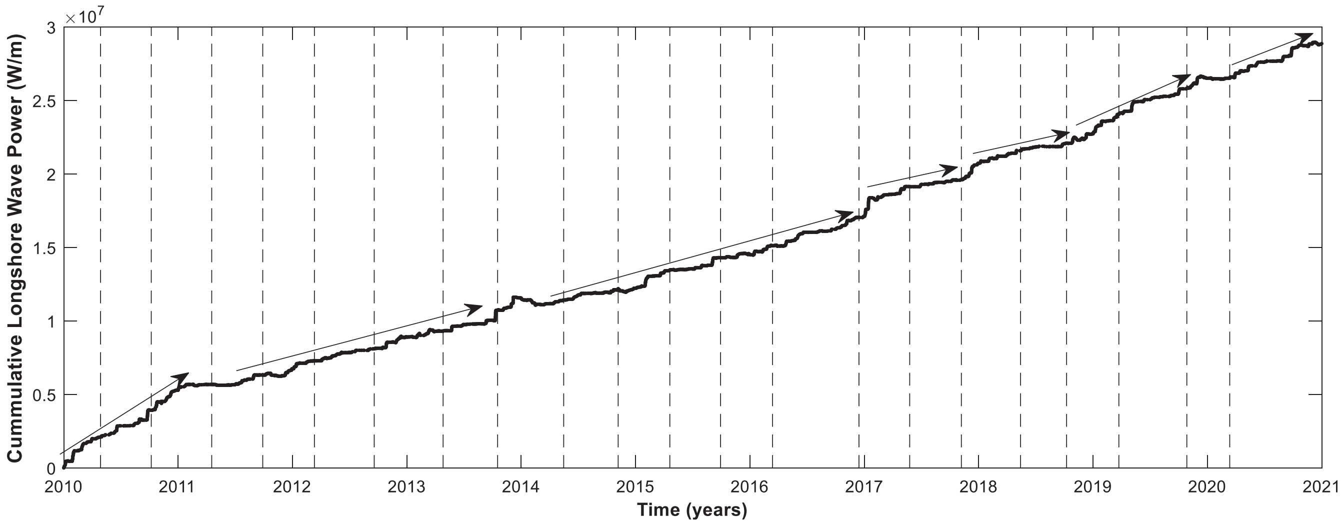


FIGURE 15 Cumulative nearshore longshore wave power measured using mean wave period (Tz) at the Hornsea buoy at tidal heights above 2.2mAOD (the average cliff toe height in the Ord Centre). The angle is the wave direction with respect to the shore normal north of Hornsea (72 degrees). Positive values indicate southward longshore wave power (W/m) with negative values indicating northward longshore wave power. The vertical lines represent each survey date between 2010 and 2020. The arrows illustrate the rate of increase of the cumulative longshore wave power.

power, which occurred often months before a survey. Further field measurements are required ideally before during and after such high-energy events.

4.3 | Ord Heights at the cliff toe

Heights within ords at the cliff toe are very important in determining the length of time in each tidal cycle that the cliff toe will be exposed to direct wave attack. Table 4 shows the average ord centre cliff toe height was 2.2 m AOD in 2010–2020. On all the surveys, carried out under relatively calm conditions, Bridlington predicted HWSTs reached that level or above. This shows that the wave attack could have been well above cliff toe height on the cliff face. Figure 4b illustrates the tide and wave conditions in a Kilnsea ord two hours before HW, which would have increased in height across HW. This research has shown also the degree of beach protection afforded to the cliff toe in the north and south ord sections, where average cliff toe heights were 3.05 and 3.27mAOD, respectively.

A greater height variation up to 3.9 m between the adjacent inter-ord beaches and the ord centres was shown by Scott (1976) and Pringle (1985). This allowed most HWN tides to reach the ord centre cliff toe, as compared to only some HWS tides along the inter-ord beaches.

4.4 | Ord movements

Dominantly, ord movement was southwards in response to the obliquely breaking waves from the NNE direction, as measured at the Hornsea wave buoy and shown in Figure 13. However, a secondary peak from the ESE does produce northward ord movement at times. In 1994–1998 the total net movement south per survey varied between 0.2 and 4.4 km, as compared with the more rapid 0.4 to 6.5 km for 2010–2020. The average rates per year were 0.36 km and 1.11 km, respectively. In the earlier period, some northward movement was recorded in 10 out of 12 surveys but only seven out of 20 surveys in the latter period. It should be noted that no ord movement occurred immediately south of the Mappleton coastal defences during either period.

Temporally, there was no clear seasonal pattern in accelerated ord movements. However, in 1994–1998 the fastest ord movements south occurred during the summers of 1996 and 1997 and in 2010–2020 during the summer of 2013. In the later period, ord migration was greater north of the Hornsea defences as compared with between Hornsea and Withernsea (Table S6 in the Supplementary). North of Hornsea the shore normal direction is 72 degrees, whereas south of Hornsea it changes to 60–64 degrees. This results in waves from the dominant NNE direction approaching the coast north of Hornsea at a higher angle, increasing overall migration rates southwards. Whitehouse (2002) modelled increased longshore sediment transport just south of Barmston and at Kilnsea, which appears to support these findings.

4.5 | Storm surges and high water levels

Storm surges with powerful waves over the Hornsea storm wave threshold of 3.04 m, especially when coinciding with high tide levels, can raise the overall water levels significantly, to well above the ord centre cliff toe height of 2.2mAOD. At these times maximum cliff and shore platform erosion is likely to occur. Using Immingham tidal residual data, rather than skew surges (Haigh et al., 2016), storm surges over 0.9 m were identified for both survey periods. During the 4.5 years 1994–1998, 12 such storm surges occurred as compared with 58 in the ten years 2010–2020. In the earlier period, the annual number varied between one in 1995 and three in each of 1994,1997 and 1998. In the 2010–2020 period, the annual range was between zero in 2018 and 14 in 2015. As storm surges can peak at any point in a tidal cycle, in 1994–1998 only four raised the tide level to 4.0 mAOD + on 30.01.1994, 06.12.1994, 12.02.1996 and 02.01.98 all during the winter. During 2010–2020 only six raised the tide height to over 4.0 mAOD (which is slightly above the average cliff toe heights in all parts of the ord in this period). No major storms occurred in 1994–1998, but three occurred in the latter period on 05.12.2013, 13.01.17 and 28.02.2018–03.03.2018. However, the latter 'Beast from the East' storm produced no storm surge. This does indicate increased storminess in the later period.

Despite the limitations of six-monthly surveys, North Sea storm surges producing high water levels and accompanied by powerful waves do seem to be linked to increased ord migration rates. For example, in the earlier period, the largest average ord movements per survey southward occurred between April and September 1997 (0.55 km) and September 1997 to May 1998 (0.27 km) following storm surges over 0.9 m since the previous surveys. In 2010–2020, for three survey periods, ord migration exceeded 1.3 km south, September 2011 to March 2012, October 2013 to May 2014 and November 2017 to May 2018. These also may have been influenced by major storm surges since the previous surveys, especially the 1.97 m surge on 05.12.2013 which was the most powerful since 1953 (Spencer et al., 2015) near the top of a high spring tide, which raised the nearest HW at Immingham to 9.12mACD (5.22mAOD) and caused the breaching of Spurn Head at the south end of the Holderness coast.

4.6 | Ords as irregular rhythmic coastal features

As considered earlier (Pringle, 1981 and 1985), ords may be viewed as inter-tidal rhythmic coastal features, but in the previous literature, it was difficult to find comparable forms elsewhere. Despite considerable expansion in research on these since, as reviewed by Coco et al. (2022), no features closely resembling ords have been described. In the Introduction, it was noted that the only other rhythmic features along North Sea coasts were found along the west European coast between the Netherlands and Denmark (Kaergaard et al., 2012; Short, 1992; van der Vegt et al., 2007). Here they were primarily associated with micro-tidal conditions or the presence of shore parallel sand ridges and rip currents in the inter-tidal and nearshore zones. None of these conditions and features are found along the Holderness coast.

It seems that ords are unique features resulting from a particular combination of conditions along the Holderness coast. Firstly, its layout, with at its north end the 7.5 km long W-E chalk Flamborough Head, to the south of which lie c60km of glacial till cliffs, which are being rapidly eroded by subaerial and marine processes. Secondly, the macro-tidal conditions and dominance of waves from the NNE are of special significance, with the latter breaking obliquely to the beaches, causing net southwards longshore sediment movement. Thirdly, the configuration of the semi-enclosed North Sea basin makes it liable to storm surges, generated in its northern part by deep atmospheric low-pressure systems and with the surges travelling south along the British east coast (Spencer et al., 2015). As discussed earlier, these conditions also generate large powerful waves which are refracted around Flamborough Head and first meet the coast near Barmston where they set up a strong upper beach longshore sediment movement south, but according to Pye & Blott (2015) also a movement northwards into Bridlington Bay. At this sediment divide an ord is formed before being moved south in the general longshore sediment movement in the inter-tidal zone. Similar conditions also may form ords south of the sheltering effect of coastal defences. The irregular spacing of ords along the Holderness coast is explained by the varying time intervals between the major northerly storms which form them. It appears, therefore, that a major control on ords is specific atmospheric events.

4.7 | Processes within Ords

Viewing the Holderness coast within the morphodynamic classification (Short & Jackson, 2013) as 'tide-modified, reflective, plus low tide terrace (without rips)' helps to indicate the processes shaping the inter-ord beaches, but not those within ords and further field research and modelling is required. Miles and Russell's (2004) measurements on a beach at Teignmouth, south Devon within the same morphodynamic type could usefully be taken to determine within a tidal cycle the percentage of time that surf zone processes, with dissipative spilling breakers affect the lower beach and sandbar in an ord. This could then be compared with the time swash zone processes affect the upper beach and till platform. Wave transformation as they break against the cliff face for up to several hours at high water levels, as shown in Figure 4b, also requires further investigation to better understand cliff erosion mechanisms.

5 | CONCLUSIONS

Investigation of the formation, distribution, length and movement of ords in 1994–1998 using stereo aerial photographs and in 2010–2020 using aerial LiDAR and ortho-rectified aerial photographs and wind, tidal and wave records reached the following main conclusions. It confirmed for both periods earlier findings that ords were formed mainly near Barmston. Here the shelter from powerful northerly storm waves provided by Flamborough Head ceases causing a sediment movement divide. After such storms, ords are carried south in the net southward beach sediment movement, driven by dominant NNE waves breaking obliquely along the Holderness coast. This research showed that ords may form also south of coastal defences which mirror the effect of Flamborough on a smaller scale. Ords are persistent southward moving features but occasionally may be infilled north of coastal defences.

Ord lengths showed that the percentage of coast exposed to the higher rates of erosion within them varied between 23 and 35% in 1994–1998 and 20–44% in 2010–2020. Average cliff toe heights within ords ranged between 3.05mAOD, 2.2mAOD and 3.27mAOD in the north, centre and south parts of the ords in 2010–2020. Comparison with HWST levels on the survey dates, under relatively calm conditions, showed that they reached the cliff toe in the ord centre on all surveys, but that the higher upper beach to north and south and in the inter-ord beaches afforded some protection against wave attack.

Rates of average annual net southward movement of ords varied between 0.36 km in 1994–1998 and the more rapid 1.11 km in 2010–2020. Some northward movement was shown in both periods. In the later period faster southward movement north of Hornsea may have resulted from higher angled waves where shore normal is 72 degrees, as compared with 60–64 degrees further south.

North Sea storm surges coupled with powerful northerly waves, especially when coinciding with high astronomical tides, can raise water levels, significantly increasing cliff and shore platform erosion. Immingham tidal residual data above 0.9 m showed 12 such surges in 1994–1998 as compared with 58 in the longer 2010–2020. However, as storm surges can peak at any stage in a tidal cycle, only four raised the tide level to 4.0 mAOD in 1994–1998 and six in 2010–2020, the height slightly above cliff toe height in all parts of the ords. No major storms occurred in the earlier period, but three in the later period including the most powerful storm since 1953 on 05.12.2013.

Relating changes within ords to specific high energy storm events with raised water levels is difficult with survey intervals of six months, in spring and autumn. However, some increased rates of ord movement after such events were suggested in both periods.

In previous studies, ords were considered as irregularly spaced rhythmic inter-tidal features, although it was difficult to find comparable features elsewhere globally. Despite considerable expansion in research on mesoscale rhythmic features in the last three decades, the same applies. Therefore, it is concluded that ords are unique to the Holderness coast. This results from the coastal layout with a prominent E-W headland north of the rapidly eroding till cliffs; a macro-tidal regime with waves dominantly from the NNE breaking obliquely on the shore; and the semi-enclosed North Sea basin being liable to storm surges with powerful northerly waves. This leads to the formation of ords south of the shelter provided by Flamborough Head from northerly storms. It is the irregular spacing in the timing of these storms that explains irregular ord spacing along this coast. However, more observations and measurements of the processes within the ords are needed to fully understand them.

AUTHOR CONTRIBUTIONS

Louise Francesca Wignall: Conceptualization; methodology; investigation; resources; software; writing—initial draft; writing—reviewing and editing. **Ada Waddon Pringle (nee Phillips):** Conceptualization; methodology; investigation; resources; writing—initial draft; writing—reviewing and editing. **Suzana Ilic:** Conceptualization; methodology; investigation; supervision; writing—reviewing and editing. **Catherine Victoria Louise Pennington:** Investigation; resources; writing—initial draft; writing—reviewing and editing. **Matthew Philip Kirkham:** Investigation; resources. **Lee Daniel Jones:** Investigation; resources.

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Figure 12 (EA DSC_0368.JPG) which was under licence from the Environment Agency.

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East Riding of Yorkshire Council who provided the orthorectified photography and LiDAR datasets for the period 2010–2020.

CONFLICT OF INTEREST STATEMENT

No author has any conflict of interest for this manuscript.

DATA AVAILABILITY STATEMENT

British Atmospheric Data Centre under licence – Leconfield wind records.

British Oceanographic Data Centre under licence – Immingham tide records https://www.bodc.ac.uk/data/hosted_data_systems/sea_level/uk_tide_gauge_network/processed/

Channel Coast Observatory and East Riding of Yorkshire Council – Hornsea wave records Data available under the Open Government Licence v3.0 © East Riding of Yorkshire Council. East Riding of Yorkshire Regional Coastal Monitoring Programme.

https://www.coastalmonitoring.org/realtimedata/?chart=72&tab=download&disp_option=

East Riding of Yorkshire Council – orthorectified aerial photographs and aerial LiDAR records. Some datasets are available at the below link. The remaining datasets were directly sourced from the East Riding of Yorkshire Council. Data available under the Open Government Licence v3.0 © East Riding of Yorkshire Council. East Riding of Yorkshire Regional Coastal Monitoring Programme.

https://www.coastalmonitoring.org/cco/

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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