Hornsea Project Four

Marine Processes Supplementary Report

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Revision Summary

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Revision Change Log

Rev	*Page*	*Section*	*Description*
01	N/A	N/A	First draft submitted into Examination at Deadline 4.

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Glossary

Term	Definition
Cumulative effects	The combined effect of Hornsea Four in combination with the effects from a number of different projects, on the same single receptor/resource. Cumulative impacts are those that result from changes caused by other past, present, or reasonably foreseeable actions together with Hornsea Four.
Hornsea Project Four Offshore Wind Farm	The term covers all elements of the project (i.e. both the offshore and onshore). Hornsea Four infrastructure will include offshore generating stations (wind turbines), electrical export cables to landfall, and connection to the electricity transmission network. Hereafter referred to as Hornsea Four.
Long-term	Of several years or decades, accounting for year to year variations.
Longshore drift	Movement of (beach) sediments approximately parallel to the coastline, a process mainly driven by the oblique approach of waves.
Maximum Design Scenario	The maximum design parameters of each Hornsea Four asset (both on and offshore) considered to be a worst case for any given assessment.
Megaripples	Bedform features commonly formed of sands, defined here with crest to crest wavelengths between 0.5 to 25 m.
Mixed layer depth	Depth of positively buoyant surface mixed layer above density stratification formed by thermocline or halocline,.
Near-field	The area immediately associated with a source of change, such as around the base of a wind turbine foundation.
Nearshore	Generally, a shallow water area close to the coast.
Offshore	Generally, a more exposed and deeper water area away from any coastal influence.
Order Limits	The limits within which Hornsea Project Four (the 'authorised' project) may be carried out.
Orsted Hornsea Project Four Ltd.	The Applicant for the proposed Hornsea Project Four Offshore Wind Farm Development Consent Order (DCO).
Sandwave	A bedform feature commonly formed of sands, defined here with a crest to crest wavelength greater than 25 m, often superimposed with megaripples.
Short-term	A sub-set of a repeating cycle, e.g. likely to be a few days, weeks, or months but much less than a year.

Acronyms

Term	Definition
DCO	Development Consent Order
DGPS	Differential Global Positioning System
DGM	Digital Ground Models (DGMs)
EGA	Expert Geomorphological Assessment
EIA	Environmental Impact Assessment
ERYC	East Riding of Yorkshire Council
HTA	Historical Trend Analysis
LAT	Lowest Astronomical Tide
MCZ	Marine Conservation Zone
MMO	Marine Management Organisation
SAC	Special Area of Conservation
SPA	Special Protection Area
RIAA	Report to Inform the Appropriate Assessment
SSSI	Site of Special Scientific Interest
S-P-R	Source-Pathway-Receptor
VORF	Vertical Offshore Reference Frame

1 Introduction and Methods of Assessment

1.1 Background

1.1.1.1 Orsted is proposing to develop Hornsea Project Four (Hornsea Four), a new offshore wind farm in the North Sea approximately 65 km off the Yorkshire coast (Figure 1). The wind farm is located in the vicinity of Flamborough Front, the boundary between two distinct water masses which has a strong signature during the summer months, and the export cable corridor crosses Smithic Bank with landfall south of Bridlington.

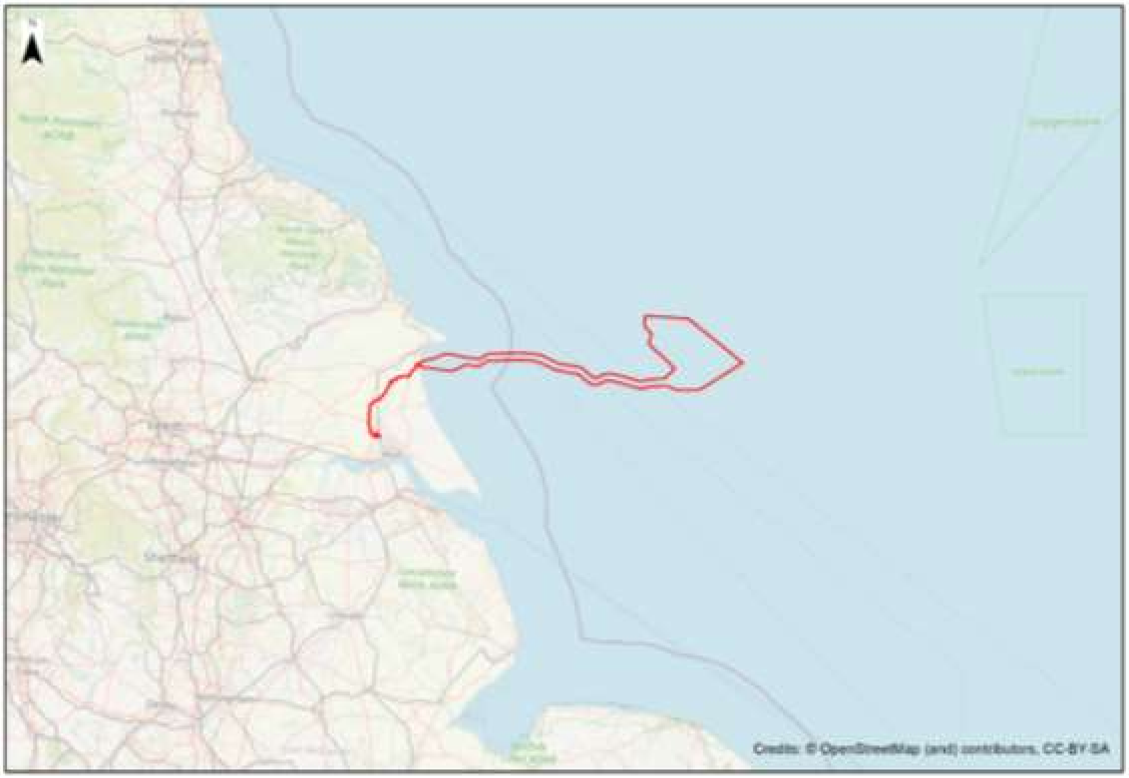


Figure 1: Hornsea Project Four Offshore Wind Order limits

1.1.1.2 This report provides supplementary information that addresses the comments from Natural England and the Marine Management Organisation (MMO) in their Relevant Representations (RR-029 and RR-020) to the Hornsea Four Development Consent Order (DCO) Application on the topic of Marine Geology, Oceanography and Physical Processes. The main issues raised by Natural England and the MMO relate to three main Marine Geology, Oceanography and Physical Processes receptors; Smithic Bank, Holderness Coast and the Flamborough Front and the relevant points from the representations made by both Natural England and then MMO are summarised in Table 1 below. For full details the reader is referred to the relevant representation by Natural England (RR-029) and MMO (RR-020) and the Applicants Response to Relevant Representations (REP1-038)

Table 1: Relevant Representations and where each point is addressed.

Relevant Rep ID	Relevant Rep	Where addressed
Smithic Bank		
RR-029-5.43	The Hornsea 4 export cable route crosses the southern part of Smithic Bank. The installation of cables and rock protection (and replenishment) in this area could result in the lowering of Smithic Bank or the alteration of its morphology. Additionally, as the Dogger Bank A& B export cables, which necessitates the placement of a substantial amount of rock protection at each of the 24 cable crossing points. Moreover, the Scotland to England Green Link 2 project has indicated a similar landfall to Hornsea 4 and will potentially cross Smithic Bank. We are concerned that a significant area of cable installation activities and the addition of any cable protection may alter the elevation/profile of the sandbank. Moderate elevation changes to the sandbank could produce significant variations in wave power at the shoreline which will, in turn, modify the shoreline response to storms, and substantially change shoreline morphology.	Section 2: Smithic Bank details the Source-Pathway-Receptor (S-P-R) model and assessment of potential effects in Section 2.4
RR-029-5.44	Natural England is concerned that the Hornsea 4 development (alone and in-combination) might adversely affect the form and function of Smithic Bank, and, in turn, affect that of other marine process receptors such as the Holderness Coast, Holderness Inshore MCZ, Dimlington Cliffs SSSI, Humber Estuary SAC/SPA/Ramsar/SSSI, Flamborough Head SAC/SSSI. Consequently, we advise that the long-term impacts of (a) cable installation and cable protection across Smithic Bank (including the proposed 25% rock replenishment during the operational phase), and (b) the presence of the HP4/Dogger Bank A&B cable crossing, need to be addressed in terms of the risk of lowering of the sandbank and affecting its associated sediment transport processes. We would also advise that these impacts be considered over the lifetime of the project, also taking into consideration the impacts of climate change.	Section 2: Smithic Bank details the S-P-R model and assessment of potential effects in Section 2.4
RR-029-5.55	Although we note and welcome the Applicant's efforts to address some of these concerns, through commitments to avoid the placement of rock protection within 350m seaward of MLWS (Co188), and the Commitment to relocate the cable crossing east of the 20m depth contour (Co189), there is insufficient evidence within the ES and supporting Annexes to show that the implementation of these measures would remove the potential for significant impacts on this sensitive receptor. Natural England would expect a commitment to avoid the placement of rock protection on Smithic Bank as a minimum (approximately 16m depth contour), but it would need to be demonstrated that this along with the placement of the cable crossing was sufficient to exclude the potential for impact.	Section 2: Smithic Bank details the S-P-R model and assessment of potential effects in Section 2.4
RR-029-APDX:E-C	Data suitability and baseline characterisation: Detailed investigation of the geomorphology of Smithic Bank, its evolution, and the impact of the proposed development on its form and function	Baseline understanding of Smithic Bank using Historical Trend

Relevant Rep ID	Relevant Rep	Where addressed
	Therefore, we do not consider the baseline characterisation to be complete at this stage.	Analysis (HTA) and Expert Geomorphological Assessment (EGA) are in Section 2.2 and Section 2.3
RR-029-APDX:E-4	In part In addition, in section 1.7.6.7, Smithic Bank is identified as a local sediment store for material supplied through cliff erosion. Consequently, Smithic Bank should be considered a receptor of the landfall works..... Given the sparsity of baseline characterisation surveys of the Holderness coastal zone and Smithic Bank, significant environmental effects on the Holderness MCZ and other designated features cannot be ruled out at this stage.	Section 2: Smithic Bank details the S-P-R model and assessment of potential effects on the Holderness Marine Conservation Zone (MCZ) in Section 2.4
RR-020-3.2.3	The MMO believes that further information should be provided to provide enough evidence on the baseline. As well as offshore physical surveys for wave and tidal currents, a number of swath bathymetry and geotechnical surveys have been undertaken. Supplementing this is a numerical modelling exercise that allows different scenarios to be explore e.g. turbidity plumes from cable excavation or seabed preparation. Whilst this gives a good overall evidence base, there are a number of areas where the evidence base is either patchy or non-existent. These include the cable route around Smithic bank and the coastline. The MMO would expect to see additional Swath Bathymetry and geotechnical surveys from just offshore of the cable crossing with Dogger Bank A+B area and the Holderness coastline.	Baseline understanding of Smithic Bank using HTA and EGA are in Section 2.2 and Section 2.3
RR-020-3.2.12	The importance here is that Smithic Bank is a "reservoir" of sediments that feeds the Holderness coast (a receptor) and the Marine Conservation Zone (MCZ), as well as the wider regional sediment transport pathways (to the Humber and Wash). An additional review is required for a realistic worst case scenario on sediment transport patterns and pathways (and magnitudes) where all the exports cables (six from Hornsea 4 and four from Dogger Bank A+B) have been constructed with excavations to the design depth of 2m and subsequent cable protection (rock dumping).	Section 2: Smithic Bank details the S-P-R model and assessment of potential effects in Section 2.4
Flamborough Head SAC, Humber Estuary European Marine Site, Greater Wash SPA, Southern North Sea SAC		
RR-029-APDX:E-7	In part ....there are a number of designated site receptors which may be influenced by impacts in the Export Cable Corridor (ECC) either directly or indirectly as a result of impacts to other marine process receptors. These therefore need to be considered. These include: • Holderness Inshore MCZ • Holderness Offshore MCZ • Flamborough and Filey Coast SPA • Flamborough SSSI	Assessment of potential effects on identified receptors is in Section 2.4

Relevant Rep ID	Relevant Rep	Where addressed
	• Humber Estuary SAC, SPA, SSSI and Ramsar • Greater Wash SPA • Southern North Sea SAC The potential for indirect impacts to the Holderness Coast from the ECC should also be explored	
Holderness coastline (including Marine Conservation Zones		
RR-029-APDX:E-D	High resolution bathymetric surveys around Smithic Bank (e.g. swath bathymetry) and accompanying geotechnical surveys (including near the Dogger Bank A&B cable crossing and along the Holderness coastline).	Baseline understanding of Smithic Bank using HTA and EGA are in Section 2.2 and Section 2.3
Flamborough Front		
RR-029-5.57	The foundation structures of the Hornsea 4 array area have the potential to generate turbulent wakes that will contribute to a mixing of the stratified water column. Mixing generated in this way could have a significant impact on the large-scale stratification of the North Sea off the coast of Flamborough Head. The presence of the Hornsea 4 array area, combined with those of Hornsea 2 and Hornsea 1, would occupy a considerable area, hence the potential large-scale impact on the Flamborough Front. Furthermore, the inclusion of Gravity Base Structures, as the MDS for turbine foundation design at Hornsea 4, significantly increases the potential for turbulence effects. Gravity bases of the size and scale proposed have not previously been deployed in the English waters, therefore, we have no evidence base on which to base understanding of their impact on marine processes and their receptors. Natural England therefore advises that the sensitivity of the Flamborough Front should be considered high, until further evidence to the contrary can be provided.	Section 4: Flamborough Front with assessment of potential effects in Section 4.2 and Section 4.3
RR-029-5.58	In part Based on the high levels of uncertainty described, Natural England is unable to rule out the potential for significant impacts to the Flamborough Front.	Assessment of potential effects on identified receptors is in Section 4.2 and Section 4.3
RR-029-APDX:E-C	Data suitability and baseline characterisation: .... Sufficient baseline characterisation and understanding of the Flamborough Front through and/in the vicinity to the HP4 array, coupled with an adequate assessment of the effects of the array on tidal flows, turbulent wakes, and mixing within the water column.	Section 4: Flamborough Front with assessment of potential effects in Section 4.2 and Section 4.3
R-029-APDX:E-D	Data Gaps: ..... Effects of the proposed foundation structures on turbulent wake-induced mixing, stratification, and, in turn, primary productivity in and around the Flamborough Front. In particular, Natural England would welcome further discussion with the	Section 4: Flamborough Front with assessment of potential effects in Section 4.2 and Section 4.3

Relevant Rep ID	Relevant Rep	Where addressed
	applicant ahead of the examination on appropriate data for Smithic Bank and Flamborough front.	
RR-020-3.2.3	The impact on Flamborough front, especially any changes (positively and negatively) to primary productively (and subsequently secondary productivity) has not yet been fully addressed. Whilst it is noted that Natural Environment Research Council ("NERC") EcoWinds (Ecological consequences of offshore wind) research project may assess this potential impact, any outcomes not likely to be within the consenting period, which is potentially three years away. Therefore, taking a pragmatic approach, all the information available should be provided and the Applicant should: a) take a full part in the research project; and b) use satellite thermal imagery to determine if cold water thermal plumes exist when the front is present (spring to autumn)	**Section 4**: Flamborough Front with assessment of potential effects in **Section 4.2** and **Section 4.3**

1.1.1.3 Natural England and the MMO consider Smithic Bank to be of high environmental value for two main reasons; it provides shelter for the Holderness Coast from wave exposure, and it acts as a sediment store that feeds the wider coastal and marine systems. Natural England has raised concerns with the proposed cable installation activities across the Smithic Bank, stating it could adversely affect the form and function (morphology) of the bank (particularly lowering) with subsequent effects on the wave climate at the coast (particularly during storms) and, in turn, change the coastal morphology. Natural England has requested long-term impacts of cable installation activities across the Smithic Bank are addressed in terms of the risk of lowering the bank and its potential effect on sediment transport processes at the site receptors (Flamborough Head Special Area of Conservation (SAC), Holderness Inshore Marine Conservation Zone (MCZ), Dimlington Cliffs Site of Special Scientific Interest (SSSI) and Humber Estuary SAC/ Special Protected Area (SPA)/ Ramsar). Natural England also suggest that the baseline assessments of Smithic Bank and the Holderness Coast, to support the assessment of potential impacts, are insufficient and would like to see detailed investigation of the historic evolution of the geomorphology of the bank and the Holderness cliffs, and potential future evolution with sea-level rise.

1.1.1.4 The MMO has concerns regarding the cumulative impact of cables crossing Smithic Bank. They indicate that although a 'high level' overview has been provided by physical monitoring surveys and bathymetry surveys, the coverage and intensity of surveys around Smithic Bank and along the Holderness Coast are sparse and that gaps exist. The MMO requested further information be provided for the baseline, including incorporation of additional bathymetry and geotechnical survey data.

1.1.1.5 Natural England and the MMO consider Flamborough Front to have high environmental value as an area of high productivity which supports concentrations of foraging fish that in turn provides a food source for high densities of seabirds and marine mammals (Please Note: This is an assertion that has not been supported by any documentary evidence and is not addressed in this report. More information on this matter will be included in the Indirect Effects: Forage Fish and Ornithology Report which will be submitted at Deadline 5). Natural England raised concerns that the potential impacts of the project alone and in-combination with other plans and projects, on disruption (turbulent wakes) to the Flamborough Front have not been adequately assessed. Natural England has requested an improvement in the baseline characterisation of the Flamborough Front, particularly in the vicinity of Hornsea Four, and its potential effect on the Flamborough Head SAC. The MMO raised concerns that impacts on the Flamborough Front, especially any changes (positively and negatively) to primary productivity (and subsequently secondary productivity) have not yet been fully addressed.

1.2 Assessment Methods

1.2.1.1 This study is divided into two main elements, as driven by the Natural England and MMO Relevant Representations (**RR-029** and **RR-020**). These are baseline environment and assessment of effects, which, in turn, are divided into specific assessment methods. For Smithic Bank and the Holderness Coast, the baseline environment is described using Historical Trend Analysis (HTA). A data review, drawing on existing models and scientific literature, is employed to describe the baseline environment of Flamborough Front (spatial and temporal extent and variability), as HTA is not applicable. The assessment of effects is driven by Expert Geomorphological Assessment (EGA) which is used to develop a Source-Pathway-Receptor (S-P-R) model for Smithic Bank and associated receptors.

1.2.2 Historical Trend Analysis

1.2.2.1 The HTA method essentially involves the interrogation of time series data to identify directional trends and rates of processes and morphological change over varying time periods. For Smithic Bank, digital bathymetry data from 1979 (Admiralty), 2011, 2016 and 2020/2021 (export cable corridor survey) is assessed in this way. Digital bathymetry data was collected across the northern half of the bank in 2011 (7th January 2011 to 5th May 2011) by the Channel Coastal Observatory (**Figure 2**). In 2016 bathymetry data (5th September 2016 to 16th December 2016) was collected across the northern half of the bank by Titan Environmental Surveys and held by East Riding of Yorkshire Council (ERYC), who has allowed its use in this study. ArcGIS is used to create Digital Ground Models (DGMs) for each of the surveys to identify features including mobile bedforms and areas of outcropping bedrock. Where they overlap, the 1979, 2011, 2016 and 2020/2021 bathymetries are compared to identify and quantify areas of morphological change (erosion and deposition of sea-bed sediment) or areas of seabed that have been static (bedrock) or in equilibrium.

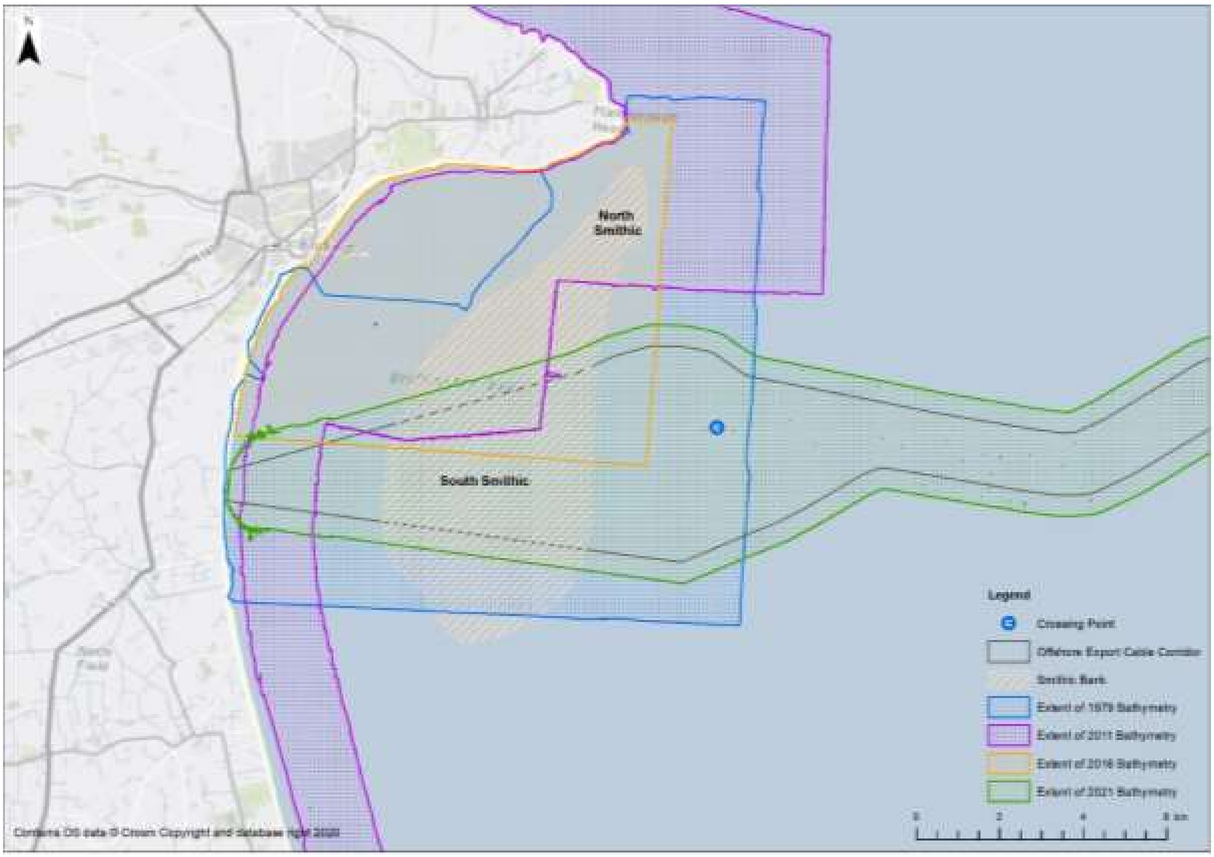


Figure 2: Location of North Smithic and South Smithic relative to the bathymetry data, the export cable corridor, and its crossing with the Dogger Bank A&B cable.

1.2.2.2 Long-term change is assessed by comparison of the 2011 data and 2020/2021 data with 1979, and short-term change by comparing 2011 with 2016. The 2011 and 2016 data are high resolution (collected using multibeam echosounder), whereas the 1979 data is lower resolution (collected using single-beam echosounder with interpolation between each survey line). Hence, the changes over an approximate 5 year period (2011-2016) are mapped in detail whereas only broad-scale changes (over several decades) are assessed between 1979, 2011 and 2020/2021. Comparison of the 2011 and 2016 data with the 2020/2021 data has not been completed because there is only limited overlap of these data across the southern part of Smithic Bank. The bathymetry interpretation is supported by cross-sections at key locations.

1.2.2.3 For the Holderness Coast, ERYC has monitored the retreat of the Holderness cliffs through a variety of techniques including historical Ordnance Survey map data (1852-1951), 123 measuring posts about 500 m apart along the length of the coast (1951-2003) and Differential Global Positioning System (DGPS) (2003 to present day). The position of the cliff-top since 1852 is derived from these data to investigate the spatial patterns of change over the past 170 years (long-term).

1.2.3 Expert Geomorphological Assessment and Source-Pathway-Receptor Models

1.2.3.1 The potential future evolution of Smithic Bank is assessed using EGA to develop a S-P-R model. EGA incorporates output from HTA but also takes into account information about current physical and sedimentary processes, geological constraints, sediment properties, and general relationships between processes and morphological responses. As part of the EGA, existing hydrodynamic, sedimentary and geomorphological data relating to the above receptors is reviewed and integrated into the assessment. The value of the EGA is two-fold:

- the potential changing morphology of Smithic Bank is used to understand the future potential implications for physical and sedimentary processes at the site receptors (Flamborough Head SAC, Holderness Inshore MCZ, Dimlington Cliffs SSSI and Humber Estuary SAC/SPA/Ramsar) and any knock-on effects on erosional or accretional trends; and
- the potential future erosion rates of the Holderness cliff tops are estimated by extrapolating the historic rates of erosion forward and applying a relative sea-level rise factor based on the 50% confidence level of the medium emissions climate change projection (RCP4.5) over the next 10, 20 and 50 years. The predictions of future cliff erosion assume that the main erosive factor is the rise of relative sea-level (the rate of cliff erosion is proportional to the change in rate of relative sea-level rise). It is assumed that the other influencing factors (e.g. wave heights) will remain constant, which given the uncertainty in their future magnitudes, is an appropriate assumption to make.

1.2.3.2 The S-P-R model links the receptors to associated impact pathways. It combines the EGA with the receptor locations and extents and maps the pathways and potential receptors that could be affected by changes in the hydrodynamic and sedimentary environment because of the proposed Hornsea Four development. The S-P-R model for Smithic Bank is used to provide additional evidence to support the impact assessments presented in the Environmental Impact Assessment (EIA) and Report to Inform the Appropriate Assessment (RIAA) relevant to the receptors and pathways.

2 Smithic Bank

2.1 Introduction

2.1.1.1 The offshore bathymetry from Flamborough Head to Fraisthorpe contains the northeast to southwest aligned offshore sand bank of Smithic Bank and associated bedforms. Smithic Bank combines the larger area South Smithic, through which the export cable corridor will pass, and the smaller area North Smithic (**Figure 2**). Smithic Bank is separated from the Flamborough Head to Fraisthorpe coast by a relatively deep area (18 m below OD), which is narrow in the north (immediately south of Flamborough Head) and relatively shallow (11 m below OD) and wide in the south (in Bridlington Bay).

2.1.1.2 The northern tip of Smithic Bank (North Smithic) is approximately 1 km from Flamborough Head and is composed of a field of sand waves and sand ridges (**Figure 3**). The wider South Smithic rises to a minimum depth of about 6 m below OD. The western inshore flank of South Smithic is about 5 km offshore from Bridlington before the bathymetry deepens down its eastern flank to its edge around 18 m below OD. The inshore flank of the bank has a much steeper slope than that of the seaward flank. The southern boundary of South Smithic was not captured by the 2011 and 2016 bathymetry data.

2.1.1.3 The distribution and migration patterns of any mobile bedforms are used to map sediment transport pathways in the vicinity of Smithic Bank. The bedforms range in size from relatively small megaripples up to large sand waves and the sand bank itself. The sand bank is a longitudinal bedform parallel or subparallel to the dominant tidal flows (northeast to southwest on the flood tide and southwest to northeast on the ebb tide) and controlled by residual tidal currents. Sand waves (which occur across North Smithic only) are typically transverse features of moderate relief, with heights around 5-10 m. They commonly occur in fields of many tens of individual sand waves with a relatively uniform spacing. The asymmetry of the sand waves is used to provide an indication of the direction of sediment transport in the area. The migration of sand waves, and hence the direction of the dominant sand transport, is in the direction in which their steeper, lee-slope faces.

2.1.1.4 This section covers the landscape-scale development of Smithic Bank and associated bedforms including areas outside where the offshore cable corridor crosses the bank. This facilitates an appreciation of bank functioning as a whole, the processes driving the morphology of the bank, and how it has and will change into the future. These changes can then be assessed within the context of the position of the export cable corridor and how its installation could potentially affect processes operating across the whole bank, not just within the vicinity of the cable.

2.2 Historical Trend Analysis

2.2.1 Interpretation and Comparison of the 1979 and 2011 Bathymetry Data

2.2.1.1 Given the lower resolution of the 1979 bathymetry (single-beam echosounder data), it is only possible to map large-scale medium-term changes of South Smithic only for the comparison of the 1979 and 2011 data. It is not possible to identify and quantify movement of the smaller bedforms including sand waves, which are present across North Smithic. For large-scale changes a comparison of 1979 and the later data is valid because the changes are likely to be greater than any inaccuracy in the 1979 data caused by the interpolation of the single-beam echosounder data.

2.2.1.2 The comparison shows that between 1979 and 2011 the crest of South Smithic Bank has migrated about 400-500 m to the northwest over this 32-year period (10-15 m per year) (**Figure 3**). The crest of South Smithic has lowered by up to 1.5 m over this period (40 mm/year) whereas parts of the northwest flank have risen by up to 3.5 m (**Figure 4** and **Figure 5**). This transfer of sand implies a net sand transport and bank migration from the crest to and down the northwest flank. The northwest and north flanks of South Smithic gained sand whereas much of the higher parts of South Smithic, including along the export cable corridor, lost sand.

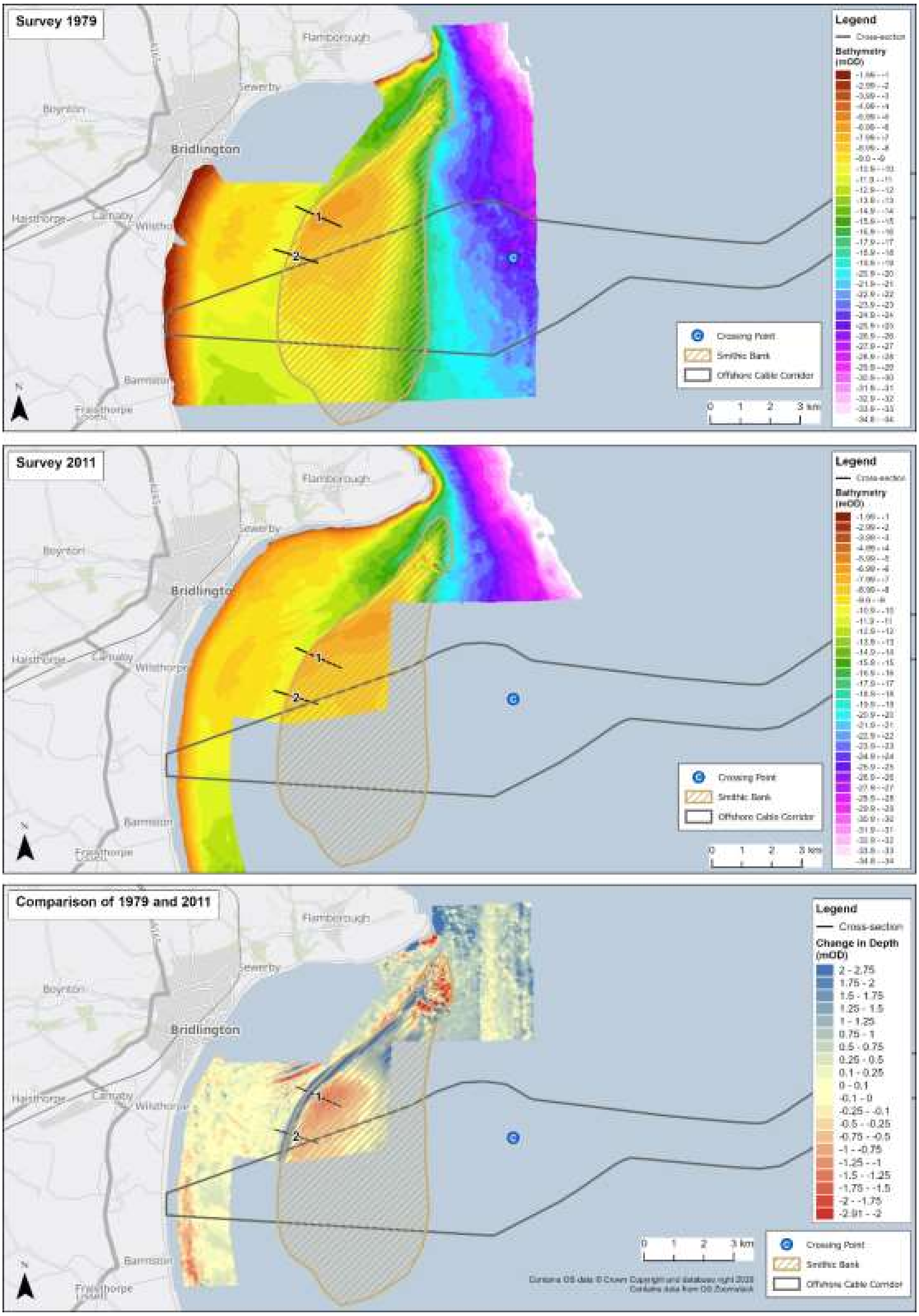


Figure 3: 1979 and 2011 bathymetries of Smithic Bank (top and middle) and a comparison of the 1979 and 2011 bathymetries (bottom).

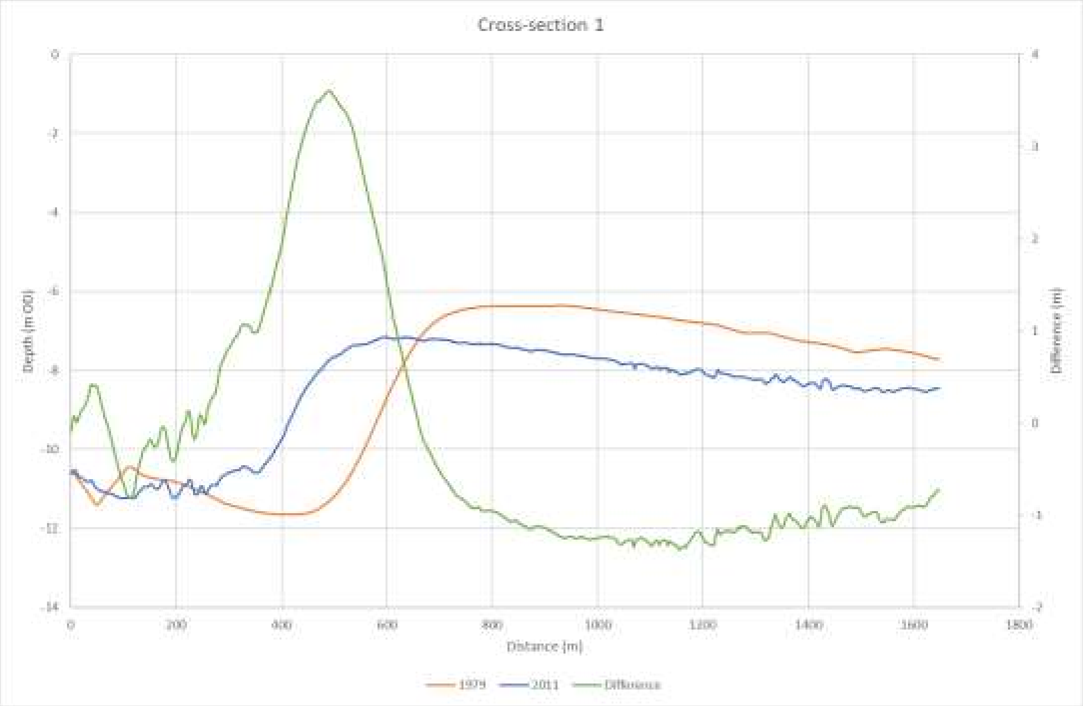


Figure 4: Cross-section of the west-northwest flank of South Smithic in 1979 and 2011 and the difference in elevation. Location of the west-northwest (left) to east-southeast (right) cross-section is shown on Figure 3.

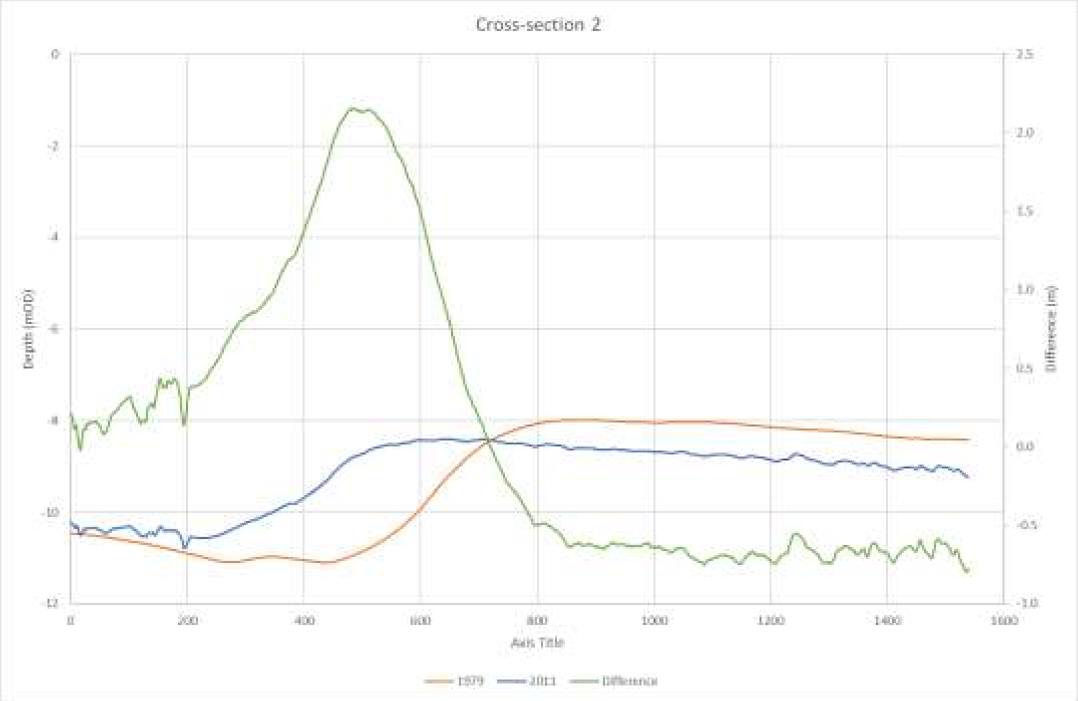


Figure 5: Cross-section of the west-northwest flank of South Smithic in 1979 and 2011 and the difference in elevation. Location of the west-northwest (left) to east-southeast (right) cross-section is shown on Figure 3.

2.2.2 Interpretation and Comparison of the 1979 and 2020/2021 Bathymetry Data

2.2.2.1 The comparison shows that between 1979 and 2020/2021 along the export cable corridor, the crest of South Smithic Bank has migrated about 500 m to the west over this 40-year period (13 m per year). The crest of South Smithic has lowered by up to 1.3 m over this period (30 mm/year) whereas parts of the west flank have risen by up to 2.0 m (**Figure 6**). This transfer of sand implies a net sand transport and bank migration from the crest to and down the west flank. The west flank of South Smithic gained sand whereas much of the higher parts of South Smithic, including along the export cable corridor, lost sand.

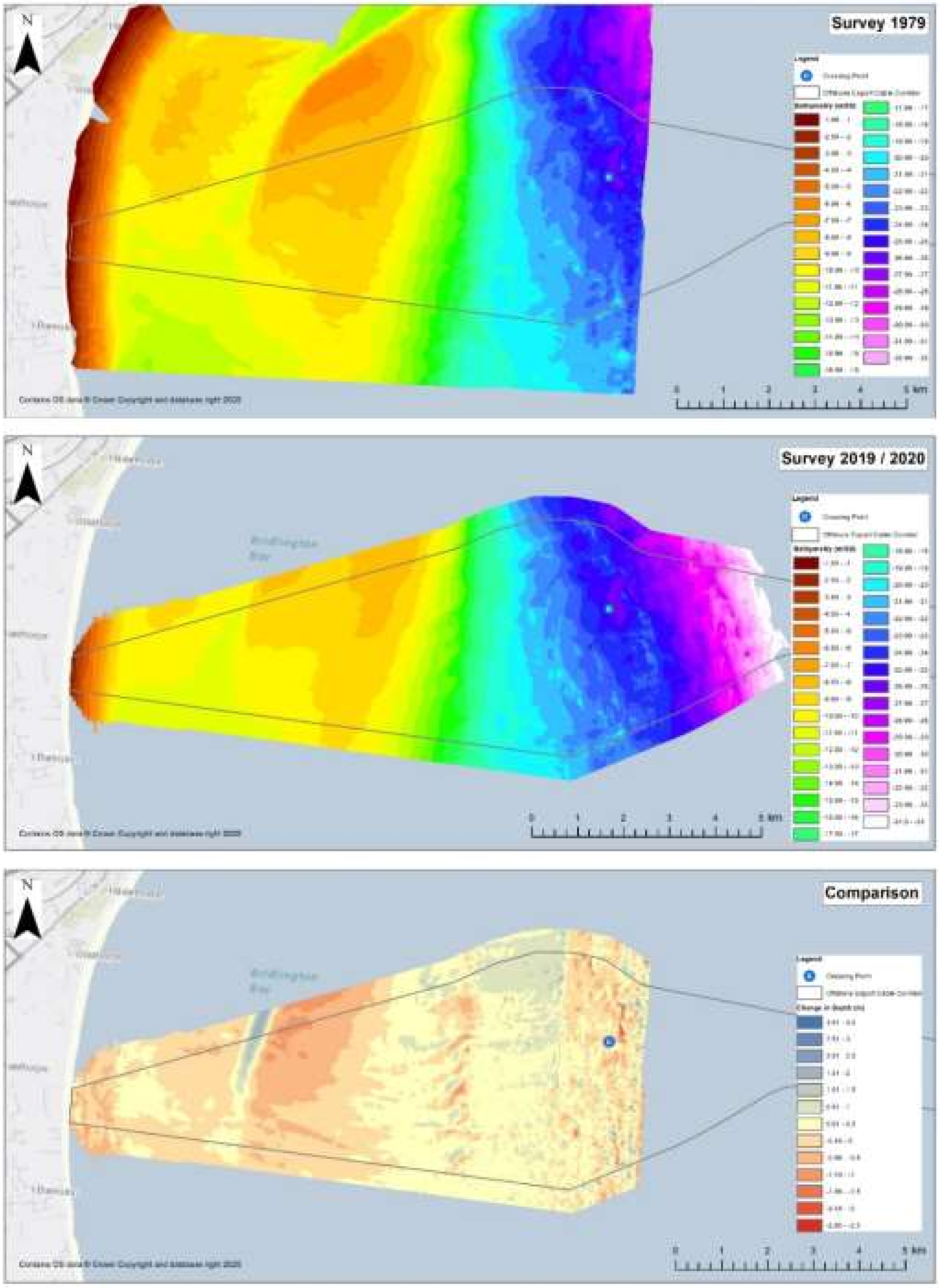


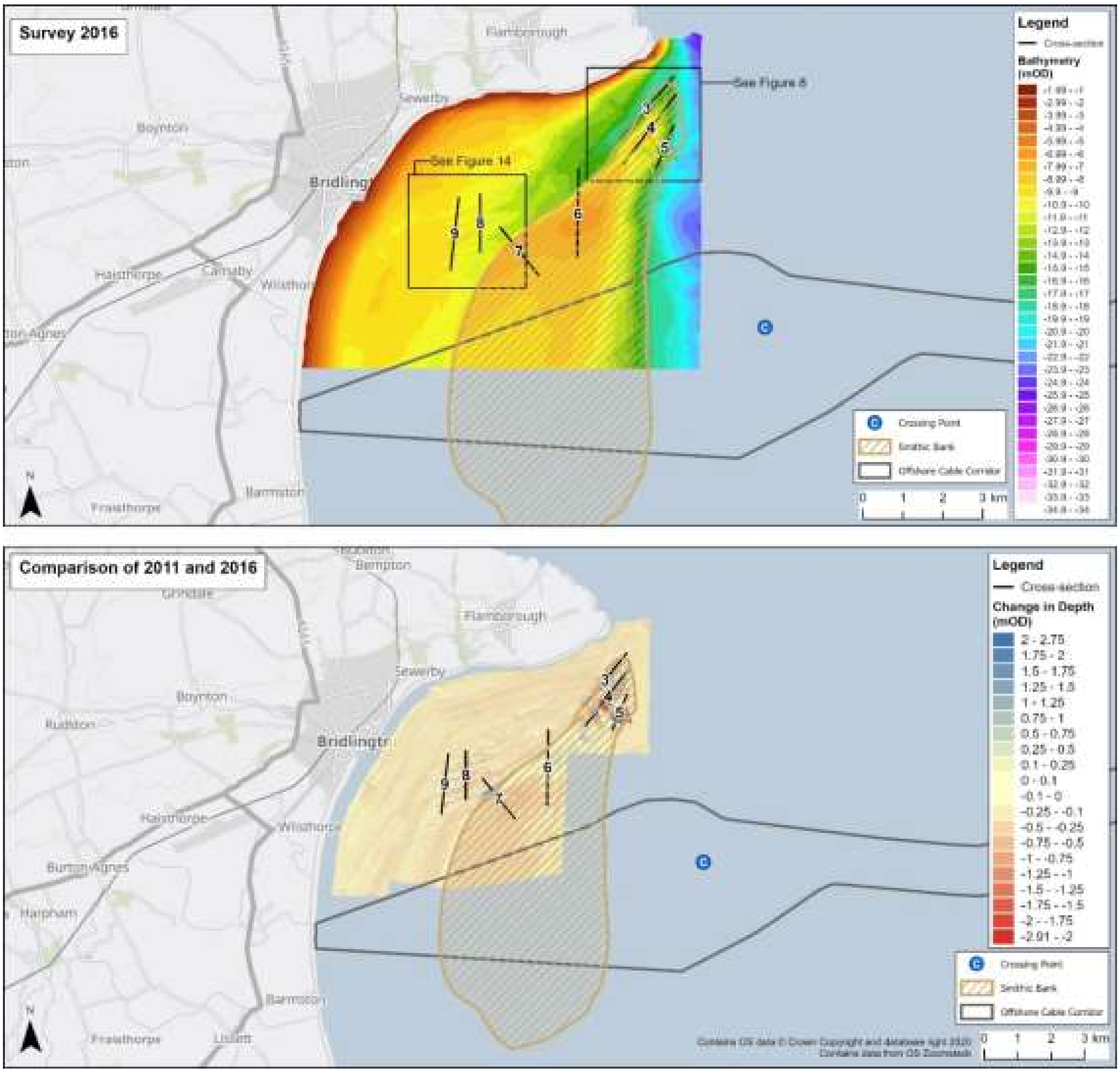
Figure 6: 1979 and 2020/2021 bathymetries of Smithic Bank along the export cable corridor (top and middle) and a comparison of the 1979 and 2020/2021 bathymetries (bottom).

2.2.3 Interpretation and Comparison of the 2011 and 2016 Bathymetry Data

2.2.3.1 A comparison of the 2016 bathymetry with the 2011 bathymetry (**Figure 7**) describes the short-term dynamic nature of Smithic Bank and its associated bedforms. Three main changes across the bank and adjacent areas are identified:

- migration of the sand waves and sand ridges across North Smithic;
- general changes in the bathymetry of South Smithic; and
- migration of the sand waves in the adjacent deeper area to the northwest of South Smithic.

2.2.3.2 The magnitude of these changes to Smithic Bank have been captured by creation of seven cross-sections across areas of significant change. To quantify the changes, the cross-sections are aligned perpendicular to the axes of maximum change.



Survey 2016

Comparison of 2011 and 2016

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Figure 7: 2016 bathymetry of Smithic Bank (top) and a comparison of the 2011 and 2016 bathymetries (bottom).

2.2.4 **North Smithic**

2.2.4.1 North Smithic is relatively narrow and sculpted into numerous sinuous sand waves with crests oriented north-south to northwest-southeast (Figure 8). The sand waves are about 1-3 m high (Figure 9 and Figure 10). In the southern part of North Smithic before the bank rises south into South Smithic, there are several larger bifurcating sand ridges, with crest lengths up to 1.2 km and heights of about 5-9 m (Figure 10). The asymmetry of the sand waves varies. The suite of sand waves on the northwest flank of North Smithic have steeper sides facing to the northeast whereas the steep sides of the sand waves through the centre of North Smithic face predominantly southwest. However, two of the larger sand ridges further southwest have steeper sides facing to the northeast (Figure 10). The sand ridges (and a sand wave) on the southeast side of North Smithic have steeper sides facing to the southwest (Figure 11).

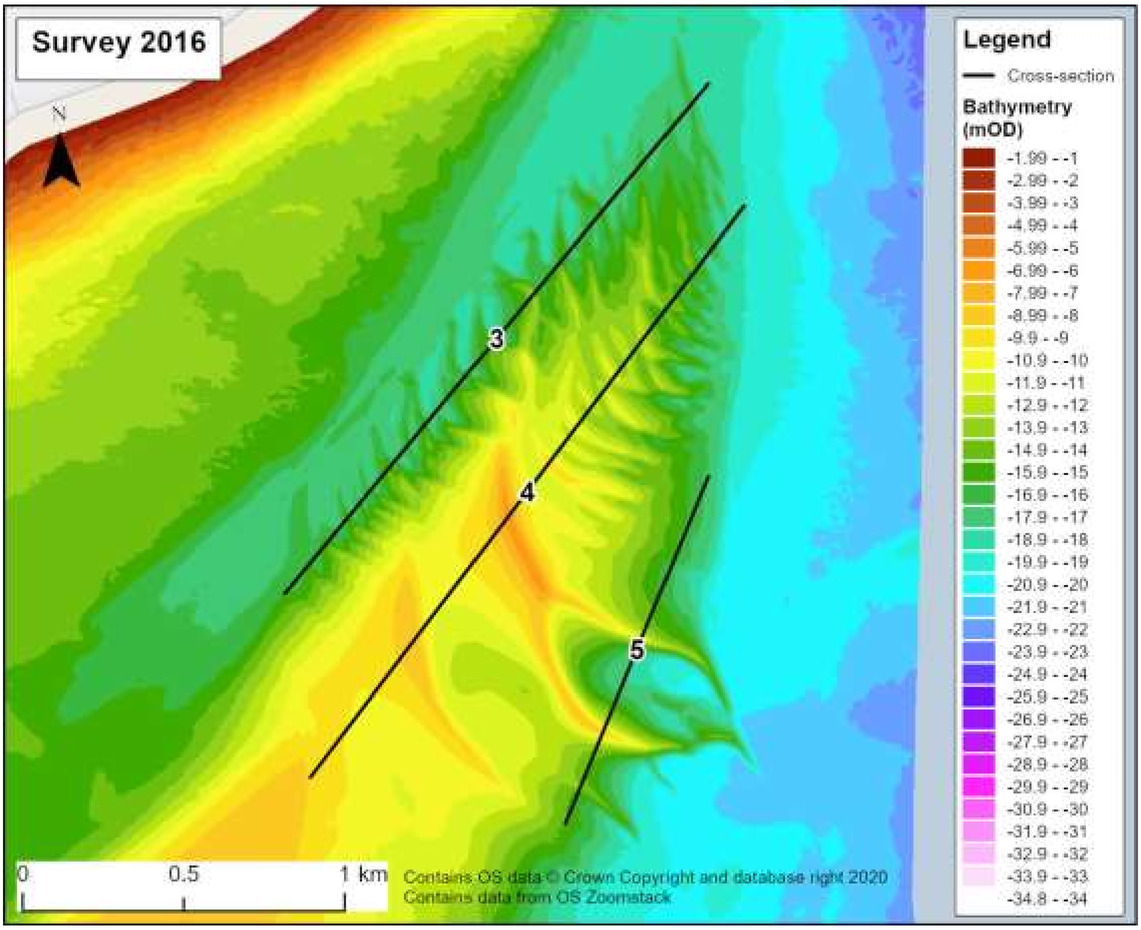

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Figure 8: Sand waves and sand ridges across North Smithic. Location is shown on Figure 7.

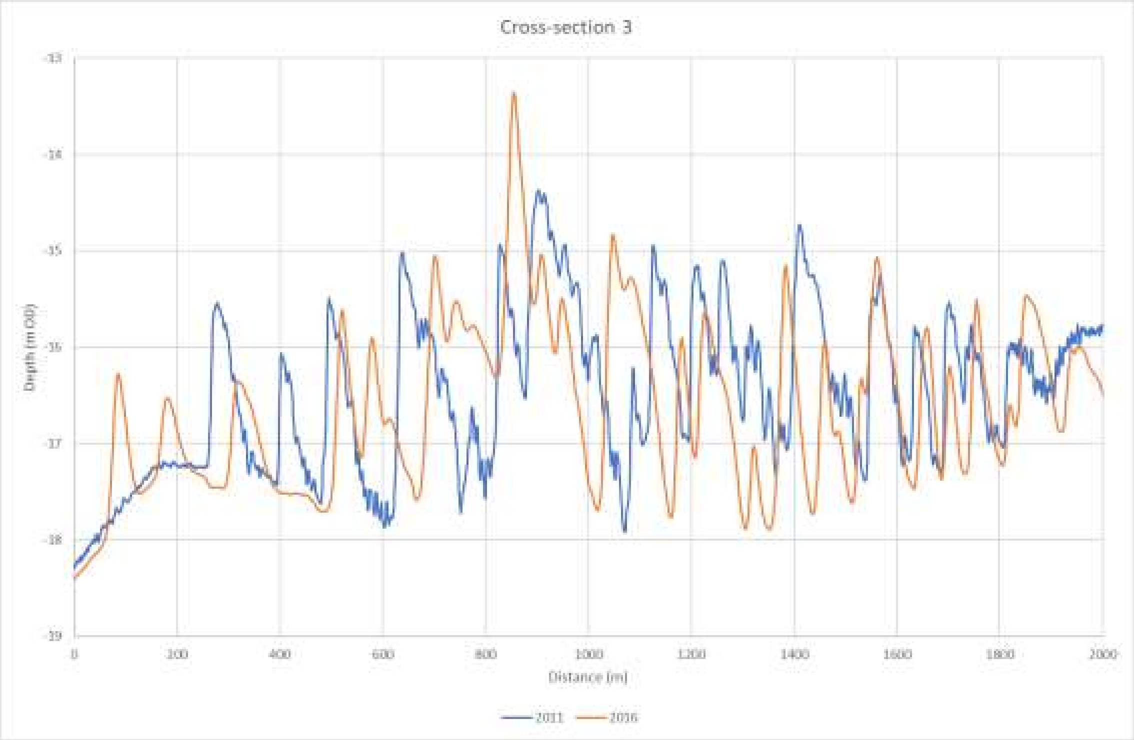


Figure 9: Cross-section of sand waves on the northwest flank of North Smithic in 2011 and 2016. Location of the northeast (left) to southwest (right) cross-section is shown on Figure 8.

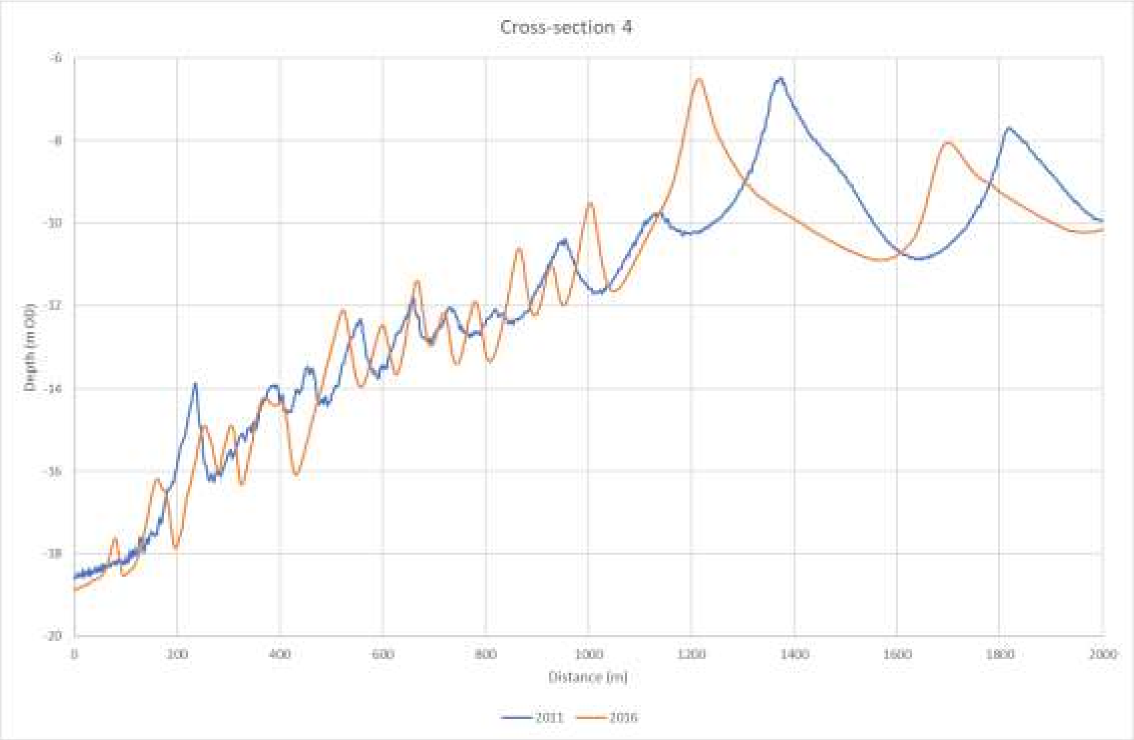


Figure 10: Cross-section of sand waves and sand ridges on central North Smithic in 2011 and 2016. Location of the northeast (left) to southwest (right) cross-section is shown on Figure 8.

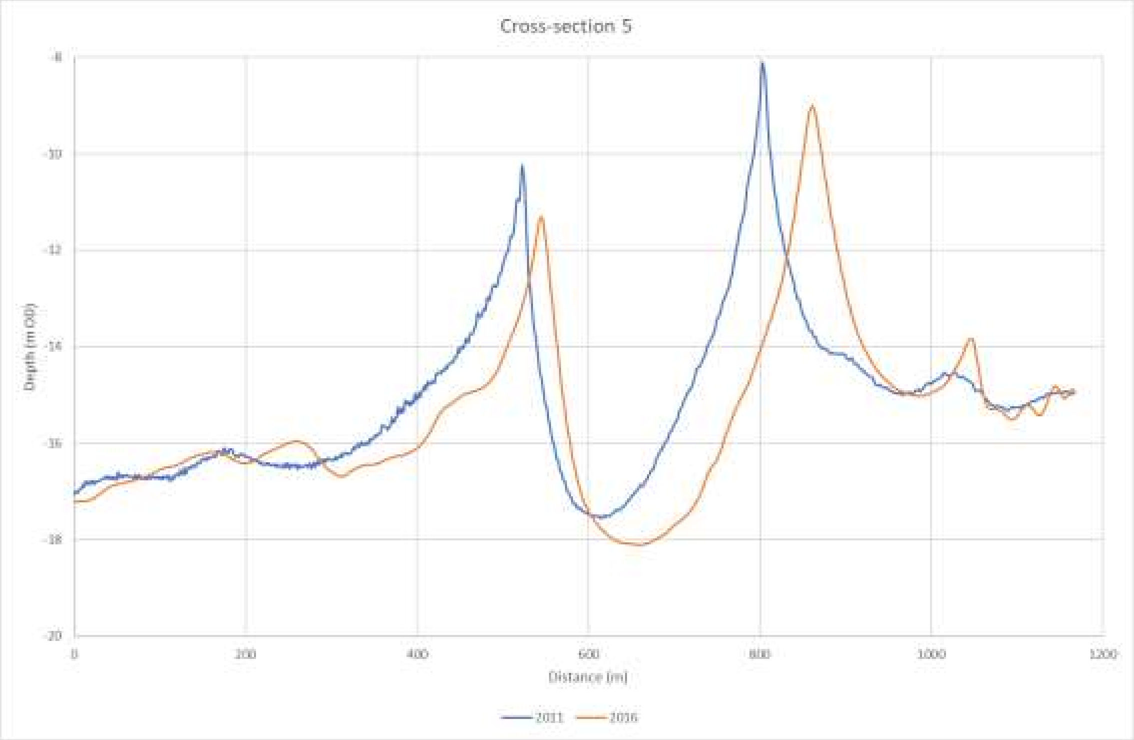


Figure 11: Cross-section of sand ridges on the southeast flank of North Smithic in 2011 and 2016. Location of the northeast (left) to southwest (right) cross-section is shown on Figure 8.

2.2.4.2 The steeper sides of the sand waves across North Smithic typically face the direction of net migration and dominant sand transport. Hence, the asymmetry of the sand waves and sand ridges imply a net clockwise circulation of bedload sand. Transport and bedform migration occurs to the northeast along the northwest flank of North Smithic (in the direction of the ebb-tide current), with a return southwest transport and bedform migration on the southeast flank (in the direction of the flood-tide current). The migration rate of the northeasterly migrating sand ridge crests varies from 120m to 160m over the five-year period equating to approximately 24m/year to 32m/year, whereas the southwesterly moving sand ridges migrated between 23m and 58m (approximately 5m/year to 12m/year). The migration rates of the more numerous sand waves are difficult to pick from the data, because it is difficult to identify the same sand wave across the two datasets.

2.2.5 South Smithic

2.2.5.1 The cross-sectional profile of South Smithic suggests a regional net movement of sand in a westerly to north-westerly direction across the bank. The crest of South Smithic has lowered by around 0.2-0.8 m over the five-year period whereas the northwest flank has risen by up to 1.5 m (Figure 12 and Figure 13). This transfer of sand implies a continuation of the longer-term change in bank orientation identified between 1979 and 2011, although there are no currently available datasets which allow a more comprehensive assessment of bank migration in its entirety.

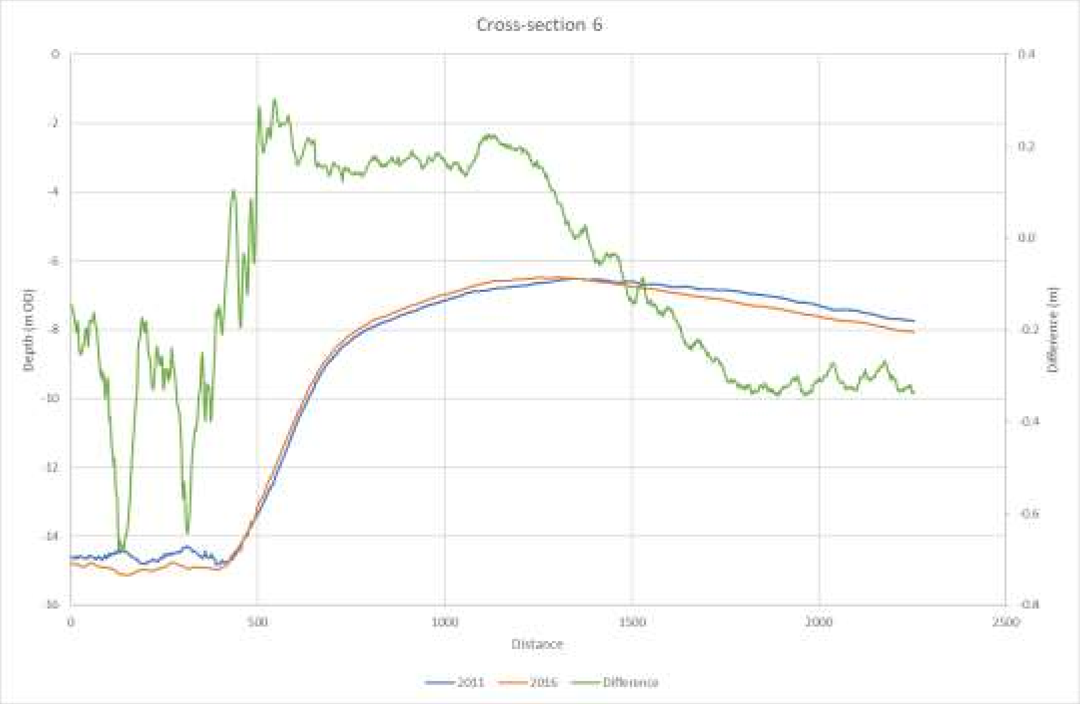


Figure 12: Cross-section of the north flank of South Smithic in 2011 and 2016 and the difference in elevation. Location of the north (left) to south (right) cross-section is shown on Figure 7.

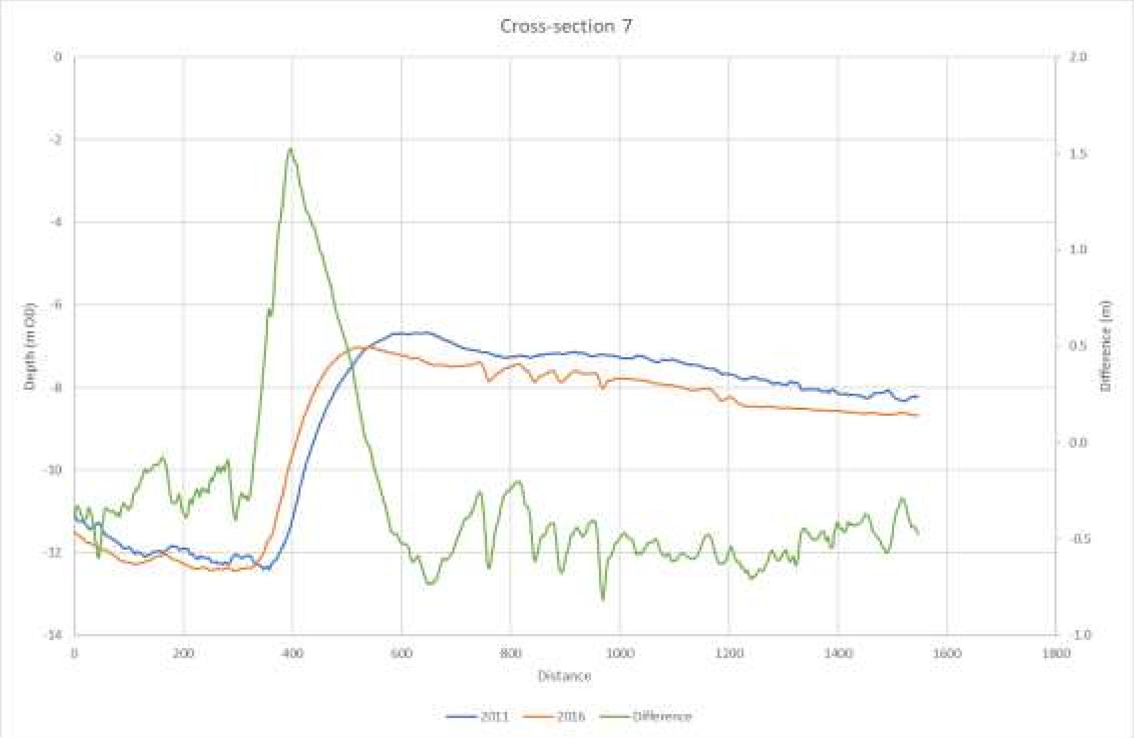
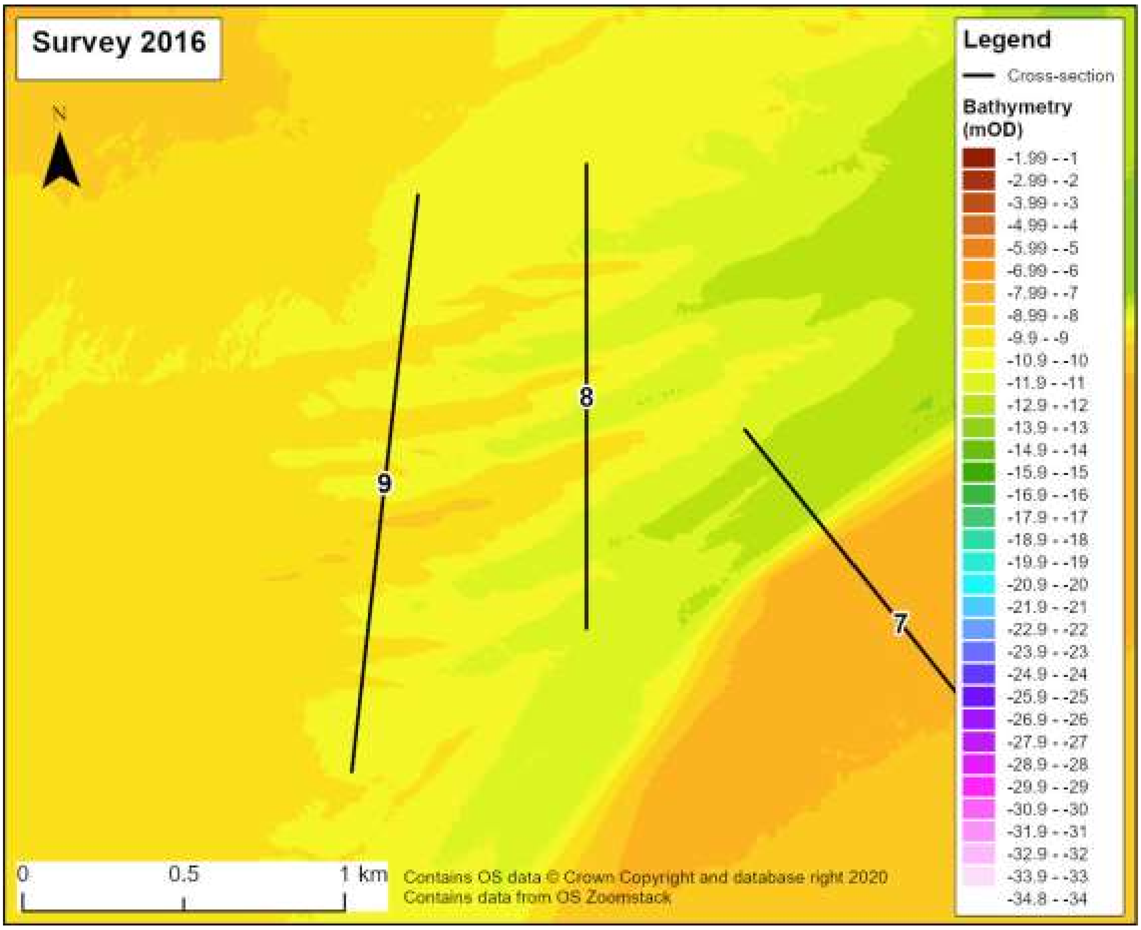


Figure 13: Cross-section of the northwest flank of South Smithic in 2011 and 2016 and the difference in elevation. Location of the northwest (left) to southeast (right) cross-section is shown on Figure 7.

2.2.6 Deeper area to the Northwest of South Smithic

2.2.6.1 There are a set of bedforms in the deeper area to the northwest of South Smithic (Figure 14). They are oriented from east-west to east-northeast to west-southwest and have heights of around 1-2 m (Figure 15 and Figure 16). They are asymmetric with their steeper sides facing north and north-northwest. This asymmetry demonstrates net sand transport and bedform migration to the north and north-northwest (towards the coast). Their migration varied from about 25 m to 43 m over the five-year period equating to an approximate rate of 5 m/year to 9 m/year.



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Contains data from OS Zoomstack

Figure 14: Sand waves in the deeper area west of South Smithic. Location is shown on Figure 7.

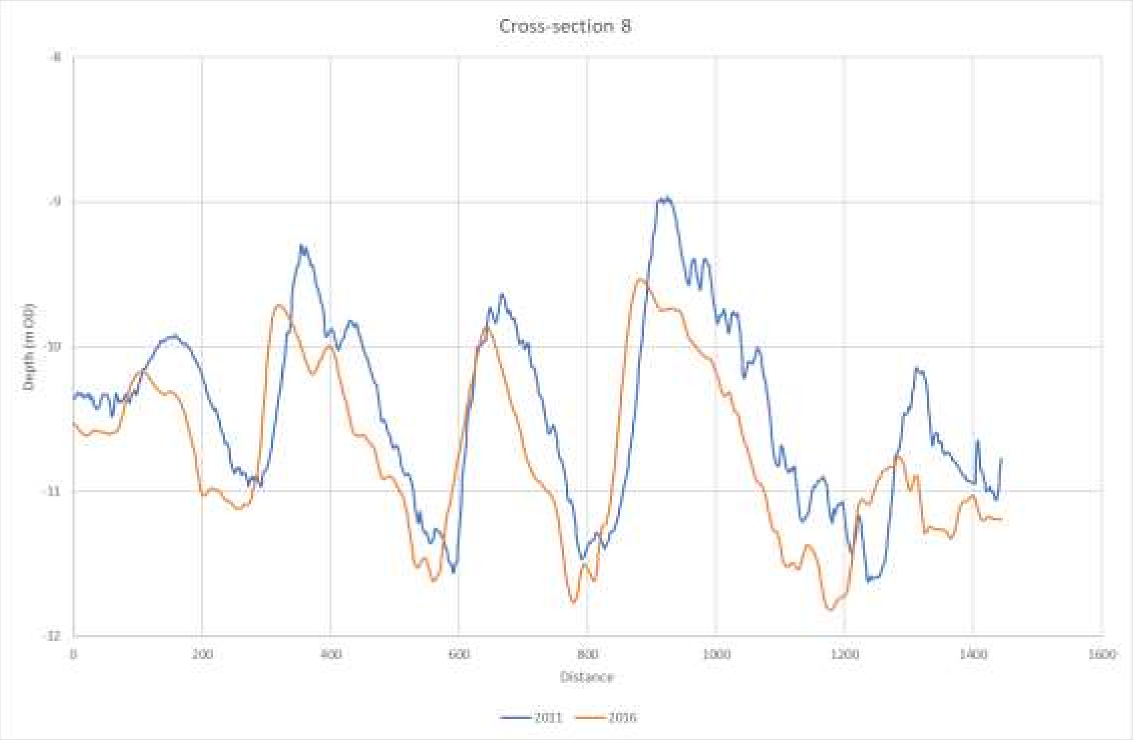

Figure 15: Cross-section of sand waves to the northwest of South Smithic in 2011 and 2016. Location of the north (left) to south (right) cross-section is shown on Figure 14.

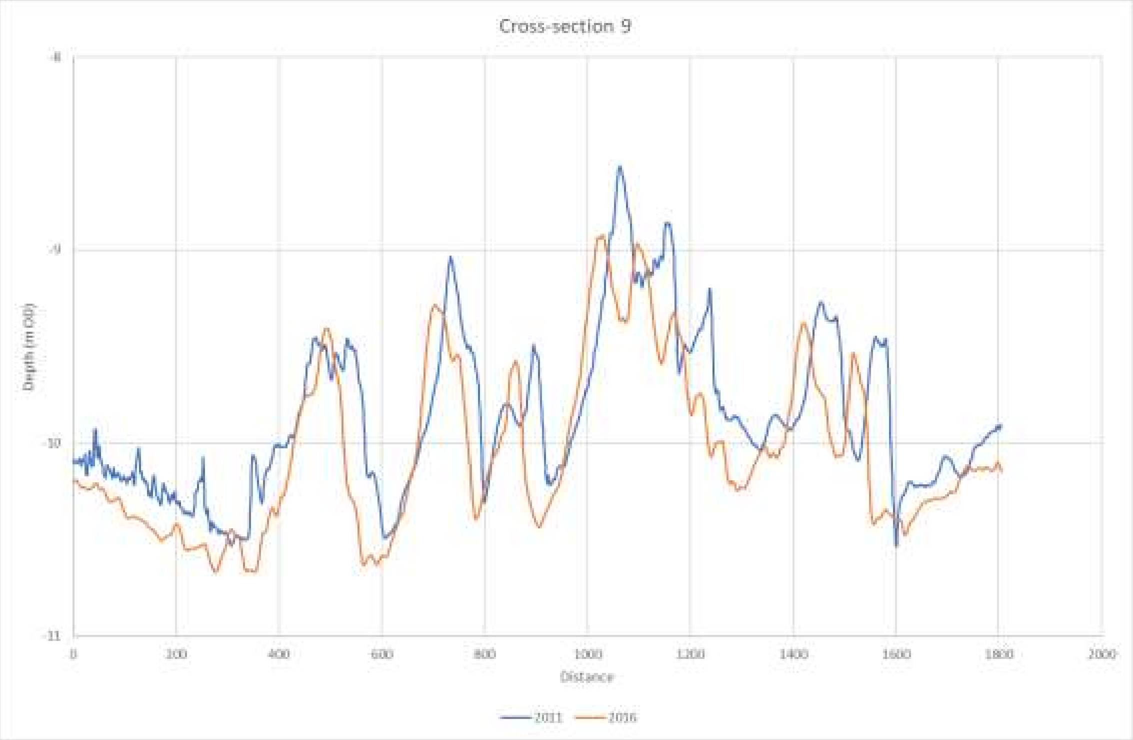

Figure 16: Cross-section of sand waves to the northwest of South Smithic in 2011 and 2016. Location of the north (left) to south (right) cross-section is shown on Figure 14.

2.2.7 Summary of baseline understanding and available evidence

2.2.7.1 Existing surveys have been examined to extend present morphological understanding of Smithic Bank, but data remains limited to partial coverage and infrequent time periods. Older data only provides reduced levels of detail (associated with single beam surveys). Assumptions made with converting to a standard vertical datum, noting Vertical Offshore Reference Frame (VORF) applies to modern surveys. It should be noted that quantification of survey accuracy is made when comparing between different surveys.

2.2.7.2 North Smithic demonstrates more dynamic behavior than South Smithic, evidenced by larger mobile sandwaves driven by strong tidal flows stemming from the influence of Flamborough Head. Distinct ebb channel separates bank from coastline at this location.

2.2.7.3 South Smithic (including the export cable corridor) more stable, flatter profile, more wave exposed than North Smithic. Ebb channel less distinctive with southern end of bank merging against the coastline (around Barmston).

2.3 Expert Geomorphological Assessment

2.3.1.1 The expert geomorphological assessment of Smithic Bank and associated receptors relates to three main elements:

- Future tidal processes driving and maintaining Smithic Bank;
- Future morphological change of Smithic Bank; and
- Future sediment transport along the Holderness Coast.

2.3.2 Future Tidal Processes Driving and Maintaining Smithic Bank

2.3.2.1 The simple north to south and south to north tidal circulation pattern along the east coast of England does not apply in Bridlington Bay because of the formation of a residual tidal gyre caused by interruption of the tidal flow by Flamborough Head. The gyre is generated by changes in water depth and tidal stream amplitude as the tidal flow curves around Flamborough Head. It has developed with the same rotational sense as the curvature of flow, resulting in a clockwise gyre on the southern side of the easterly protruding headland (and a potential anticlockwise gyre on the northern side). This headland gyre would form, and will continue to form, irrespective of the presence of Smithic Bank, but in this case the bank is present due to the gyre and occurs in the centre of gyre (headland or banner bank) with an ebb-tidal channel between Flamborough Head and the bank. This channel exhibits higher flows during the ebb phase of the tide compared to the flood, as well as over a longer duration, making the channel ebb dominant (HR Wallingford et al., 2002).

2.3.2.2 Waves help to moderate the profile of parts of Smithic Bank with larger waves dissipating some of their energy on to the bank creating a southern section (South Smithic, through which the cable corridor will pass) which is wider and smoother than the northern section

(North Smithic). North Smithic is subject to stronger tidal flows around Flamborough Head which help develop the distinct sand waves and ridges.

2.3.3 Future Morphological Change of Smithic Bank

2.3.3.1 The location and geometry of the bedforms sculpted around the periphery of Smithic Bank describe four distinct sediment transport pathways and modes of future morphological change of the bank (**Figure 17**):

- the asymmetry of a suite of sand waves on the northwest flank of North Smithic describe net sediment transport to the northeast (with the ebb-tide current);
- the asymmetry of sand ridges (and a sand wave) on the southeast side of North Smithic describe net sediment transport to the southwest (with the flood-tide current);
- the asymmetry of a suite of bedforms in the deeper area to the west of South Smithic describe net sediment transport to the north and north-northwest (towards the coast); and
- the cross-sectional profile of South Smithic suggests a regional net movement of sand in a westerly to north-westerly direction across the bank (into the ebb -tidal channel).

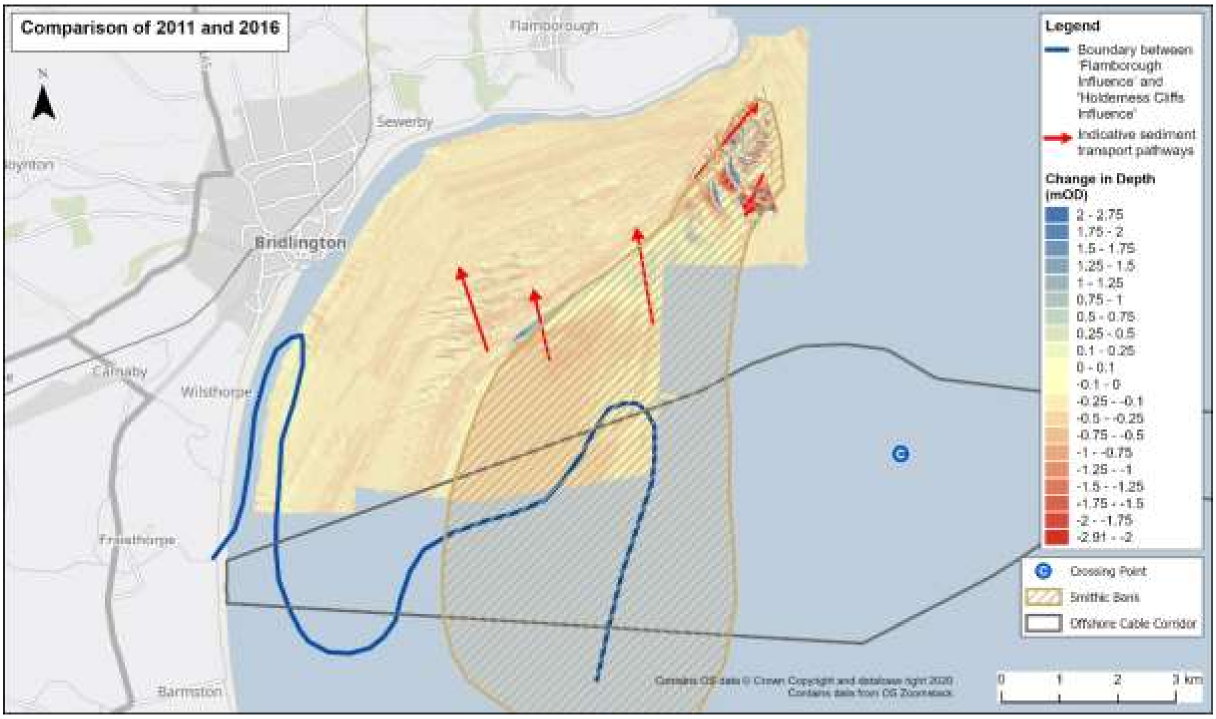

Figure 17: Indicative sediment transport pathways (red arrows) across Smithic Bank (derived from bedform geometry) and the position of the boundary between 'Flamborough Influence' and 'Holderness Cliffs Influence' of Pye et al. (2015) (blue line).

2.3.3.2 The clockwise tidally-generated gyre driving mechanism for maintenance of Smithic Bank is consistent with the orientation and asymmetry of the bedforms across North Smithic and the bedforms northwest of South Smithic. Bedforms migrate to the northeast along the inshore flank of North Smithic, to the southwest along the outer flank of North Smithic, and to the north and north-northwest in the deeper area adjacent to the inner flank of South Smithic. Thus, the clockwise movement of the tidal gyre causes sediment accumulation and provides a mechanism for deposition of Smithic Bank. Smithic Bank is a hydraulically maintained large-scale sand trap of a high order of efficiency. The constant presence of Flamborough Head and the generation of a clockwise gyre will continue to maintain Smithic Bank into the future.

2.3.3.3 The bedforms associated with Smithic Bank define sediment transport pathways that do not extend to the coast across the deeper area to the north of the bank. Apart from the bedforms to the west of South Smithic there are no other features within the deeper area and the sediment cover is thin or absent. The lack of sand within this area suggests there is likely to be little exchange of sediment between Smithic Bank and the Bridlington foreshore (across a large part of Flamborough Head SAC).However, the absence of sediment in the deeper area is not definitive evidence for limited exchange because it is governed by strong tidal currents which may transport sediment through the area without the possibility to deposit in significant volumes (hence sustaining the scoured channel) or generate bedforms.

2.3.4 Future Sediment Transport along the Holderness Coast

2.3.4.1 The rotational sand transport around Smithic Bank is likely to be contained within Bridlington Bay, with little or no transport from this source south along the Holderness Coast. Indeed, Pye et al. (2015) used sediment fingerprinting techniques to define a sediment transport boundary between a 'Flamborough Influence' to the north and a 'Holderness Cliffs Influence' to the south which intersects the coast in the Fraisthorpe-Barmston area where there is a sediment transport divide (see **Figure 17**). The longshore sediment transport divide is driven by a change in the wave climate caused by the sheltering effect of Flamborough Head. Sediment eroded from the cliffs south of Barmston-Fraisthorpe is transported south along the beach by the predominant northeast waves that are unaffected by the headland. This transport is unaffected by Smithic Bank. To the north of Barmston-Fraisthorpe, the longshore sediment transport is likely to be to the north but at low rates because of the reduced wave energy and possibly less frequent waves from the south. The exact location of the sediment transport divide may vary from year to year depending on the prevailing wave conditions and the orientation of the coast.

2.4 Source-Pathway-Receptor (S-P-R) Model

2.4.1 NE and MMO Concerns

2.4.1.1 The main concerns of NE and MMO relating to potential changes to Smithic Bank are three-fold (**Table 1**):

- the potential for an adverse effect on the form and function (morphology) of the bank (particularly lowering of the bank caused by cable installation, sand wave clearance and rock protection) and its potential to influence sediment transport processes in the nearshore and at the coast (**RR-029**-5.43);
- changes to nearshore sediment transport processes caused by the changes to wave climate and also potential for cable protection across the bank and at the Dogger Bank A&B cable crossing (**RR-029**-5.44 and **RR-029**-5.55);

- changes to erosion rates along the Holderness coast driven by changes in sediment supply from the bank to the coast (**RR-029**-5.44 and **RR-029**-5.55).

2.4.1.2 For changes to the morphology of the bank and its potential impacts, the source is the potential lowering of the crest of the bank, the pathway is the change to sediment transport driven by changes to waves and/or tidal currents, and the potential receptors of any changes in the physical and sedimentary processes are Flamborough Head SAC, Holderness Inshore MCZ, Dimlington Cliffs SSSI and Humber Estuary SAC/SPA/Ramsar. The requirement to artificially lower the sand bank through sand wave clearance was assessed as part of the Clarification Note: Justification of Offshore Maximum Design Scenarios (Ørsted, 2022). This analysis concluded that sand wave clearance would not be required along the export cable corridor across Smithic Bank and so is not a mechanism for sand bank lowering.

2.4.1.3 The potential for cable protection at the crossing zone of the Hornsea Four export cable corridor and the Dogger Bank A&B cable corridor was also a concern for NE with respect to the processes controlling the bank morphology. However, it is not considered here because the location of the crossing is outside and seaward of the boundary of Smithic Bank on a coarse sea bed in deeper water and not subject to processes driving the bank evolution (**A2.1 Marine Geology Oceanography and Physical Processes** (**APP-013**) and **A5.1.1 Marine Processes Technical Report** (**APP-067**). Section 3.3.3 and Figure 19 of **A5.1.1 Marine Processes Technical Report** (**APP-067**) clearly demonstrates that the position of the cable crossing is outside the sediment transport pathway controlling the form and function of Smithic Bank. Furthermore, commitment CO19 has already moved this crossing seaward to the 20 m contour to achieve this distinction, worth saying too Hence, the presence of any cable protection there would have no impact on bank processes because it is disconnected from them.

2.4.2 Changes to Wave Climate at the Coast

2.4.2.1 The northern section of Bridlington Bay, extending from the southern coast of Flamborough Head to Bridlington, is largely protected from extreme northerly and north-easterly storm conditions, and only waves from the northeast to southeast sectors can directly approach Bridlington. The shallow profile of Smithic Bank is considered to provide some sheltering to the coast around Bridlington, especially during storms (Scott Wilson, 2010; **A5.1.1 Marine Processes Technical Report** (**APP-067**)). Hence, it is possible that a future lowering of Smithic Bank could adversely affect the integrity of the Bridlington beaches, in terms of received wave energy.

2.4.2.2 The bathymetry evidence suggests that since 1979 the crest of Smithic Bank has been lowering naturally. Lowering has been 1.5 m between 1979 and 2011 (approximately 47 mm/year) and 0.2-0.8 m between 2011 and 2016 (40-160 mm/year). These lowering rates have occurred over large areas of the sand bank surface and constitute a significant volume loss of sand from the crest of the bank. There is no reason to think that this landscape-scale lowering of the bank will not be likely to continue into the future. The volume of the sand that will be disturbed during installation of the export cable (i.e. excavation of a trench for burial without any need for sand wave clearance) will be extremely small in comparison to the much larger (landscape-scale) volume lost due to natural physical and sedimentary processes. The continued natural loss of sand from the crest of the bank will not significantly be enhanced by any potential removal during cable installation. Also, any sand disturbed during the installation process will remain within the sediment transport system that drives changes across Smithic Bank. Hence, the cable installation processes will have negligible effect on the wave climate and sediment transport processes operating in the Flamborough Head SAC and Holderness Inshore MCZ.

2.4.3 Changes to Nearshore Sediment Pathways

2.4.3.1 The sediment transport processes controlling the development and evolution of North Smithic and South Smithic are regional in scale, both spatially and temporally. The bedforms across North Smithic can be up to 9 m high and have migrated at rates between 5 m/year and 32 m/year between 2011 and 2016. South Smithic Bank has migrated laterally 10-15 m/year between 1979 and 2011. This change in morphology has led to lowering of about 1.5 m on its crest and raising of about 3.5 m along its flank over the 32 years. Both of these sediment transport processes indicate that large volumes of sediment are being transported over a wide areas of the sea bed across and around the periphery of Smithic Bank. These large-scale natural changes to the bank are anticipated to continue into the future and would be in excess of any changes that would be incurred by local establishment of cable protection across the bank.

2.4.4 Changes to Erosion Rates along the Holderness Coast

2.4.4.1 The clockwise tidal gyre around Smithic Bank provides a mechanism by which sediment is predominantly self-contained within the bank. There is a general absence of sediment exchanged between Smithic Bank and the Holderness Coast to the south. Pye et al. (2015) argued for a sediment transport divide (divergence) immediately south of the bank. Hence, future erosion rates along the Holderness Coast will continue to be driven by wave processes and sediment supply unaffected by any changes to Smithic Bank. Climate-induced sea-level rise is likely to increase erosion rates at the coast, but this phenomena is independent of any changes to the bank. Hence, the cable installation processes, which will take place over a short period of time in a local area across the bank, will have no effect on the supply of sediment to, and sediment transport processes operating in, the Holderness Inshore MCZ and along the Dimlington Cliffs SSSI and Humber Estuary SAC/SPA/Ramsar further to the south. Historic and predicted future erosion rates along Holderness are discussed in Section 3.

2.4.5 Existing Impact Assessment

2.4.5.1 The potential impacts on wave energy at the coast (and, in turn, coastal morphology and nearshore sediment transport pathways) of a potential change in the form and function of Smithic Bank (particularly lowering) by the proposed cable installation activities were not addressed in **A2.1 Marine Geology Oceanography and Physical Processes (APP-013)**. The potential implications for erosion of the Holderness coast were also not covered in the Environmental Statement. These potential effects are covered in Section 2.4.2 to Section 2.4.4 of this supplementary report.

2.4.5.2 The potential impacts of cable protection across Smithic Bank on nearshore sediment transport pathways was considered to be negligible to minor, as they are expected to remain local to the infrastructure. The analysis completed in this supplementary report supports the original conclusion in the Hornsea Four Environmental Statement of a negligible to minor effect.

3 Holderness Coast

3.1.1.1 The following information is provided in response to a request from Natural England for more detail on the baseline characteristics of the Holderness Coast, to support the assessment of impacts. Additionally, the MMO also requested further information including incorporation of additional bathymetry and geotechnical survey data.

3.1.1.2 The coast at Flamborough Head comprises tall steep cliffs of Cretaceous chalk (up to 120 m high) with very slow rates of erosion, fronted by a chalk shore platform. These near vertical cliffs are overlain by a thin cap of till. The 60 km Holderness coast to the south of Bridlington is backed by low cliffs composed of Pleistocene glacial till fronted by highly dynamic sand and gravel beaches, which overlie a till shore platform. The sand and gravel is thin in places exposing the underlying till. The till cliffs vary in height from less than 3 m to around 35 m. This environment mainly responds to wave-driven processes which erode the cliffs providing a local supply of sediment, and transport mobile sediment along the beach.

3.1.1.3 The combination of soft till geology and a high energy wave environment makes Holderness one of the fastest eroding coasts in Europe. In addition to forming the present-day eroding Holderness cliffs, the till also forms the shore platform and the bed of the adjacent North Sea. The chalk is more resistant, and has survived large-scale erosion events, which has created the classic features of Flamborough Head. At the southern end of Holderness, the till cliffs disappear and are replaced by Spurn Head Spit, which is an outstanding example of a dynamic spit system extending across the mouth of the macro-tidal Humber Estuary.

3.2 Historical Trend Analysis

3.2.1 Cliff Erosion

3.2.1.1 The till cliffs and shore platforms of Holderness have been retreating since sea levels started to rise in the early Holocene. Since Roman times, over 30 cliff-top villages between Bridlington and Spurn Point have been lost; 26 of these since the Doomsday survey of 1086. Their previous locations suggest that around 2,000 years ago the coast was approximately 5.5 km seaward of its present position. There is extensive evidence of contemporary cliff erosion, from the presence of Second World War military pillboxes which are now at the cliff toe and roads that end at the cliff edge to detailed long term measurements of cliff-top migration.

3.2.1.2 Most of the cliff line along Holderness is not artificially defended. However, there are some defence structures, which have generally been built to protect the coastal towns and villages. Where coastal defence structures exist, particularly at Hornsea and Withernsea, the cliff toe is generally fixed. Rates of cliff erosion are locally reduced and groyne systems have been installed to capture sand and maintain beach levels by impeding longshore movement of beach sediments. The adjacent cliffs continue to erode, causing the armoured areas to protrude seaward as artificial headlands (including Barmston Holiday Park and Barmston Drain south of the landfall area). Although the defences have only been in place for short periods, there is evidence that they are causing bays to form between them, with accelerated erosion in places. Erosion is particularly severe immediately to the south or 'downdrift' of these protected frontages, where sediment starvation is most immediate.

3.2.2 Cliff Erosion Rates

3.2.2.1 Since 1951, ERYC has monitored the erosion of the Holderness cliffs through regular surveys of the cliff edge, relative to 123 measuring posts (post 1 is at Sewerby, whilst 123 is at the neck of Spurn Head) (Appendix A). Up to 1993, measurements between these posts and the cliff top were taken normal to the shore at approximately annual intervals. After 1993, the period between observations was reduced to six months. In 2003, ERYC initiated a new system of monitoring using the DGPS, every six months. These surveys are supplementary to the erosion post analyses and are being undertaken in conjunction with DGPS beach profile surveys. Prior to 1951, going back to 1852, ERYC estimated cliff erosion rates using historical Ordnance Survey map data.

3.2.2.2 The receptor of interest along the Holderness coast is Dimlington Cliffs SSSI, which is located between transects 104 and 109, immediately north of Easington Gas Terminal (**Figure 18**). This SSSI is located approximately 40 km south of the landfall. The erosion rates up to 2021 for each of these transects are shown in **Table 2**. The data includes rates of erosion spanning the record between 1852 and 1989, and the record between 1989 and 2021. The cliff heights Dimlington Cliffs SSSI are 15.2-35.4 m. Erosion rates were between 1.50 and 1.69 m/year from 1852 to 1989, and between 0.79 and 1.52 m/year between 1989 and 2021 with a maximum loss of 14.92 m in March 2008.

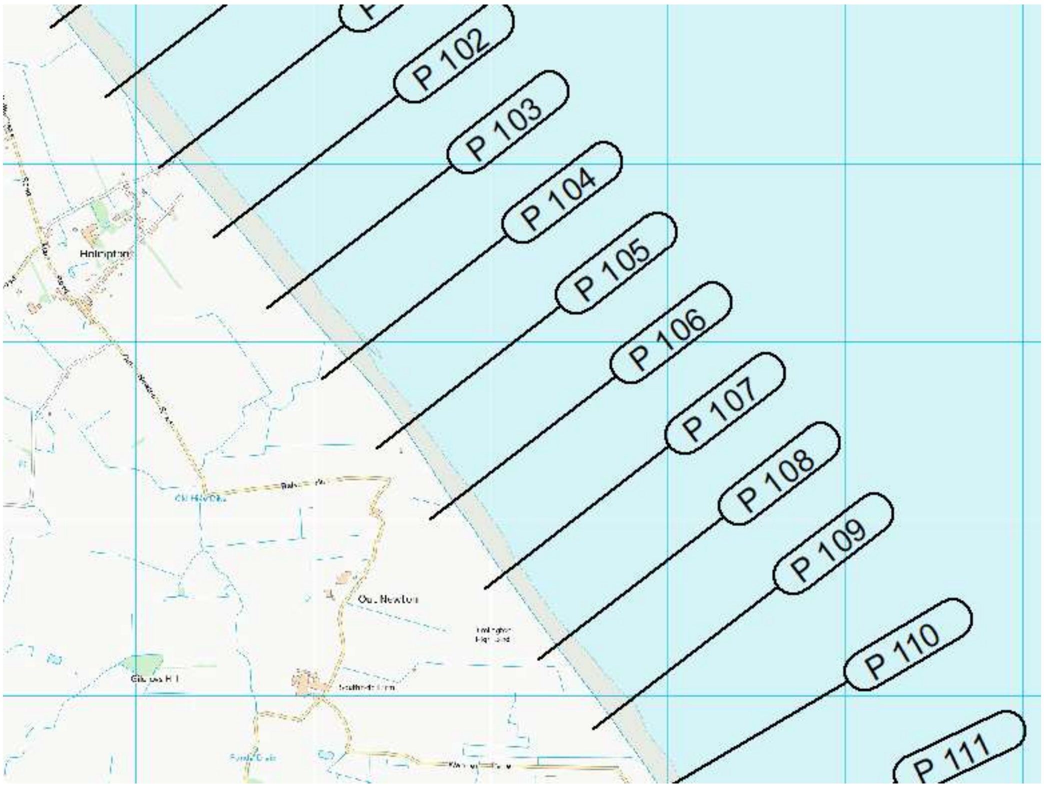

Figure 18: Location of ERYC cliff erosion measurements between 1852 and 2021 at Dimlington Cliffs SSSI.

Table 2: Average historic cliff erosion at Dimlington Cliffs SSSI for each of the coastal transects (ERYC data between 1852 and 2021).

Erosion Profile Details		Erosion rate (m/year)		Max cliff loss between profiles		
Erosion Profile	Location	Historic 1852 to 1989	Recent 1989 to 2021	Height of cliff m OD	Maximum recorded individual loss (m)	Date of max cliff loss
104	North of Out Newton	1.57	1.09	15.2	12.25	March 2020
105	Opposite Out Newton	1.58	0.54	24.5	9.31	Nov-17
106	South of Out Newton	1.62	0.81	23.4	11.74	April 2021
107	Dimlington High	1.69	0.79	35.4	14.92	March 2008
108	South of Dimlington High	1.63	1.41	27.7	14.34	May 2018
109	Between Dimlington High and Easington	1.50	1.52	23.0	12.81	May 2018

3.3 Expert Geomorphological Assessment

3.3.1.1 The following information has been provided in response to comments from Natural England (Deadline 2 Submission – Natural England review of **REP1-068 – G1.46 Clarification Note on Marine Processes Supplementary Work Scope of Works** (**REP2-084**).

3.3.2 Predicting Future Cliff Erosion

3.3.2.1 The most widely used models to forecast cliff-top erosion are empirical and use historical trend analysis from a knowledge of historic cliff erosion rates (Leatherman, 1990; Bray and Hooke, 1997; Lee and Clark, 2002; Lee 2012, 2014; Castedo et al., 2015, 2017). Two methods of historical trend analysis have typically been adopted to predict future cliff erosion:

- direct extrapolation of historic trends into the future without incorporating potential increases due to higher rates of relative sea-level rise (Lee and Clarke, 2002); and
- forward projection including potential increases to account for higher rates of relative sea-level rise (Leatherman, 1990).

3.3.2.2 The extrapolation of historic trends involves analysing past data for average cliff erosion rate and adopting this rate for future years. The forward projection equation of Leatherman (1990) predicts future cliff erosion by using projected future relative sea-level rise scenarios and measured historic cliff erosion rates. The forward projection method involves multiplying historic cliff erosion rates with a factor derived from the ratio of future and historic rates of relative sea-level rise (Equation 1): $R_P = R_H.(S_P/S_H)$. Where:

- R_P = predicted erosion rate (m/year);
- R_H = historic erosion rate (m/year) (**Table 2**);
- S_P = predicted relative sea-level rise (mm/year); and
- S_H = historic relative sea-level rise (mm/year).

3.3.2.3 The equation assumes that the main erosive factor is the rise of relative sea-level (the rate of cliff erosion is proportional to the change in rate of relative sea-level rise), the other influencing factors will remain constant, and that predictions of relative sea-level rise are reliable. The forward projection method is adopted in this study. The extrapolation method is likely to under-estimate future erosion.

3.3.3 Historic Sea-level Rise

3.3.3.1 The erosion rates at Dimlington Cliffs have been measured over the long term between 1852 and 1989, and more recently over the medium-term (1989-2021). The historic sea-level rise estimate that most closely covers this period of historic erosion is that of Woodworth (2017). Woodworth (2017) used recent mean sea level information from the UK tide gauge network along with short records of sea level measurements by the OS in 1859–1860, to estimate the average rates of sea level change around the coast since the mid-19th century. The nearest historic data to Dimlington analysed by Woodworth (2017) is at Scarborough, which includes OS data from 1859-1860 and tide gauge data for 24 of the years between 1955 and 2014 (with a central year of 1997). The estimated long-term rate of sea-level rise between mean sea level in 1859-1860 and the average mean sea level between 1955 and 2014 (1997) was 1.73 mm/year.

3.3.4 Projected Sea-level Rise

3.3.4.1 Historical data shows that the global temperature has risen since the beginning of the 20th century, and predictions are for an accelerated rise, the magnitude of which is dependent on the magnitude of future emissions of greenhouse gases and aerosols. Global changes in sea level are primarily controlled by thermal expansion of the ocean, melting of glaciers, and changes in the volume of the ice caps of Antarctica and Greenland. Observed or projected changes in global sea level take into account the elevation of the water surface, caused by changes in the volume of the oceans, and do not take into account changes in land level. At a local scale, the position and height of the sea relative to the land is known as relative sea level.

3.3.4.2 To determine a climate change sea-level allowance for Dimlington in 10, 20 and 50-years' time (to cover the 35-year operational life of the wind farm and post-operation), this study uses the data of the UK Climate Projections (UKCP18) user interface for the model grid cell that covers the area (**Figure 19**). UKCP18 relative sea-level rise estimates use 1990 as their starting year and are based on the IPCC 5th Assessment Report. They are available for low (RCP2.6), medium (RCP4.5) and high (RCP8.5) emissions scenarios and presented by UKCP18 as central estimates of change (50% confidence level) in each scenario with an upper 95% confidence level and a lower 5% confidence level. Relative sea-level rise projections for 2032, 2042 and 2072 are estimated using the 50% confidence level of the medium emissions scenario from the UKCP18 user interface. These relative sea-level rises are projected to be (**Figure 20**):

- an average rate of 4.79 mm/year over the next 10 years;
- an average rate of 4.99 mm/year over the next 20 years; and
- an average rate of 5.45 mm/year over the next 50 years.

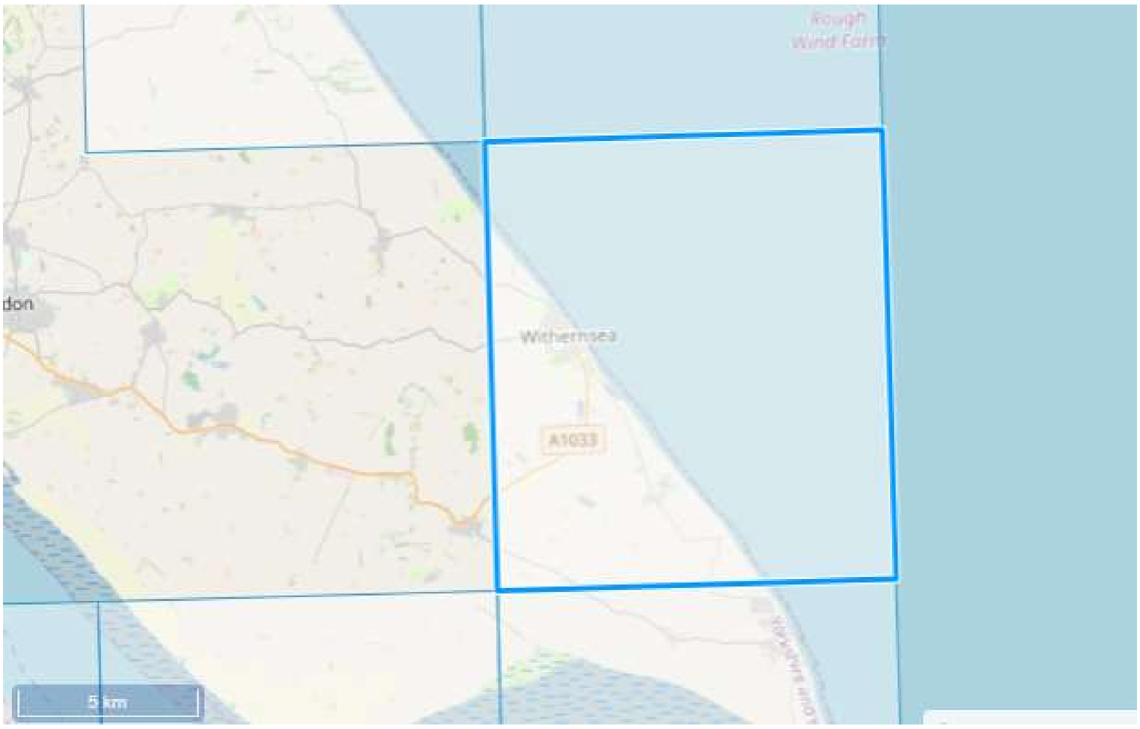

Figure 19: UKCP18 model grid used to derive sea-level rise projections for Dimlington.

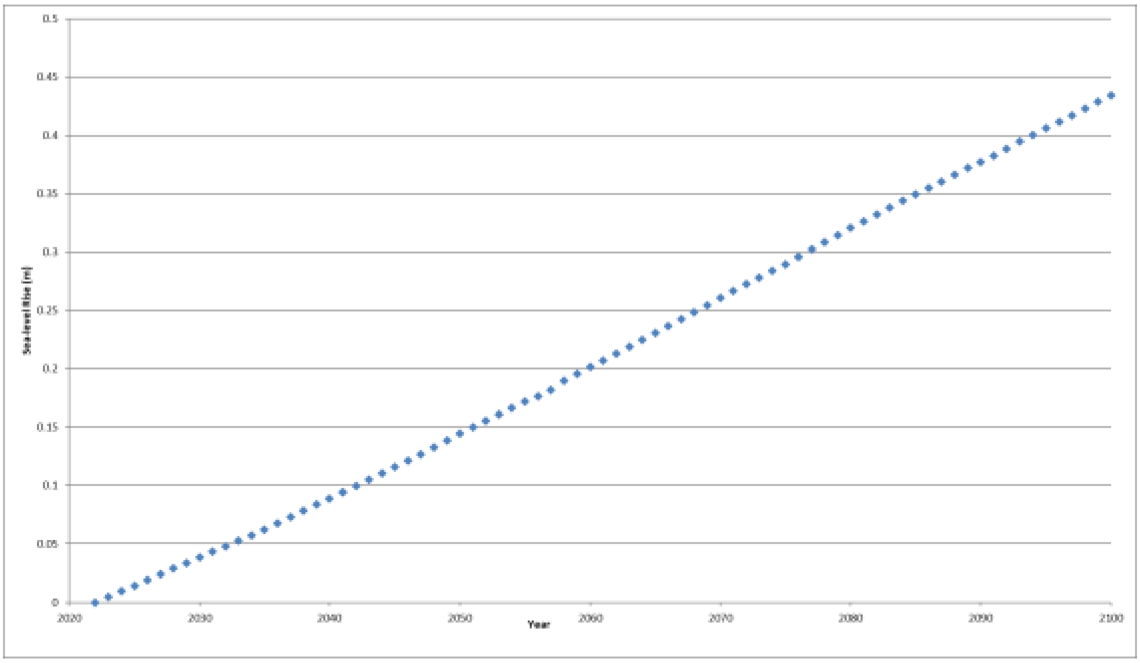

Figure 20: Projected changes in relative sea level (m) at Dimlington under the 50% confidence level of the medium emissions scenario using a 2022 baseline.

3.3.5 Predicted Future Cliff Erosion Rates

3.3.5.1 Inputting these data into Equation 1, the predicted future erosion rates at each of the transects at Dimlington Cliffs SSSI are shown in Table 3.

Table 3: Average historic cliff erosion and projected future cliff erosion at Dimlington Cliffs SSSI for each of the coastal transects (ERYC data between 1852 and 2021).

Erosion Profile Details		Erosion rate (m/year)			
Erosion Profile	Location	Historic	Future		
		1852-2021	10 years	20 years	50 years
104	North of Out Newton	1.09-1.57	3.02-4.35	3.14-4.53	3.43-4.95
105	Opposite Out Newton	0.54-1.58	1.50-4.37	1.56-4.56	1.70-4.98
106	South of Out Newton	0.81-1.62	2.24-4.49	2.34-4.67	2.55-5.10
107	Dimlington High	0.79-1.69	2.19-4.68	2.28-4.87	2.49-5.32
108	South of Dimlington High	1.41-1.63	3.90-4.51	4.07-4.70	4.44-5.13
109	Between Dimlington High and Easington	1.50-1.52	4.15-4.21	4.33-4.38	4.73-4.79

3.4 Source-Pathway-Receptor (S-P-R) Model

3.4.1.1 The drivers of future trends in cliff erosion at along the Holderness Coast, including the Dimlington Cliffs SSSI receptor (and the landfall) can be classified into two types; material and process. The material drivers include knowledge of the cliff and shore platform geology, and the process drivers include knowledge of the forcing such as variability in wave energy and direction, sediment supply and transport of sediment by waves, and sea-level rise. The average erosion rates over the long-term (1852-2021) at Dimlington Cliffs SSSI controlled by a combination of these factors are presented in Table 3. The only factors that could be affected by cable installation activities across Smithic Bank are sediment supply and transport. Section 2.4.4 of this report argues that there would be no changes to sedimentary processes along the Holderness coast caused by cable installation. The other factors (i.e. geology and sea-level rise) have no relationship to cable installation activities (i.e. they are not part of the S-P-R model), and so there can be no cause and effect related to them.

4 Flamborough Front

4.1 Data Review

4.1.1 Oceanic fronts

4.1.1.1 An oceanic front is a zone of enhanced horizontal gradients of physical, chemical and biological properties (temperature, salinity, nutrients) that separates broader areas of different vertical structure (stratification). They occur on a variety of scales, from several hundred metres up to many thousands of kilometres. Some of them are short-lived, but most are quasi-stationary and seasonally persistent, when they emerge and disappear at similar locations during the same season each year. The widths of fronts vary widely from minor fronts less than 100 m wide to major fronts up to 50-200 km wide. Many fronts extend several hundred meters in depth, with major fronts extending as deep as 2,000 m.

4.1.1.2 Fronts in the North Sea vary considerably in time and space and are strongly dependent on wind speed, current strength, and the physical properties of water masses (ICES, 2008). Oceanographic conditions in the North Sea are determined by the inflow of saline water from the Atlantic from the north (and via the English Channel to a lesser degree). This water mixes with lower salinity outflow from the Baltic Sea through the Kattegat and river run-off within coastal regions. Surface water temperatures are controlled by solar heating and heat exchange with the atmosphere, whilst the deeper waters are influenced by the inflow of Atlantic water (ICES, 2008). Episodic wind forcing can cause large-scale movement of front positions by increasing the vertical mixing power (Simpson and Bowers, 1981) or additionally, could drive dense (mixed) water over lighter stratified water and promote convective instability (Wang et al., 1990).

4.1.2 Tidal mixing fronts

4.1.2.1 The Flamborough Front is a tidal mixing front. The turbulence resulting from friction with the seabed causes vertical mixing of the water column, which can extend to the sea surface in areas where the water is shallow and/or where the tidal currents are strong enough. In other areas, where tidal currents are weaker and/or the water is deeper, less mixing occurs, and stratification of layers of different densities can develop when surface waters are warmed in summer leading to a buoyant surface layer which restricts the influence of tidal mixing from the seabed (i.e. buoyancy effects are much greater than tidal mixing effects in the surface layer).

4.1.2.2 The inclined boundaries or fronts between the contrasting areas of mixed and stratified water typically have gradients between 1 in 100 and 1 in 1,000 and are often sharply defined, with marked differences in water density on either side of the front (**Figure 21**).

4.1.2.3 Turbulent mixing of surface waters by winds and waves will break down the upper layers of stratification and will reinforce mixing by tidal currents. During winter in mid- and high latitudes, cooling and mixing by strong winds breaks down stratification completely, causing the fronts to disappear.

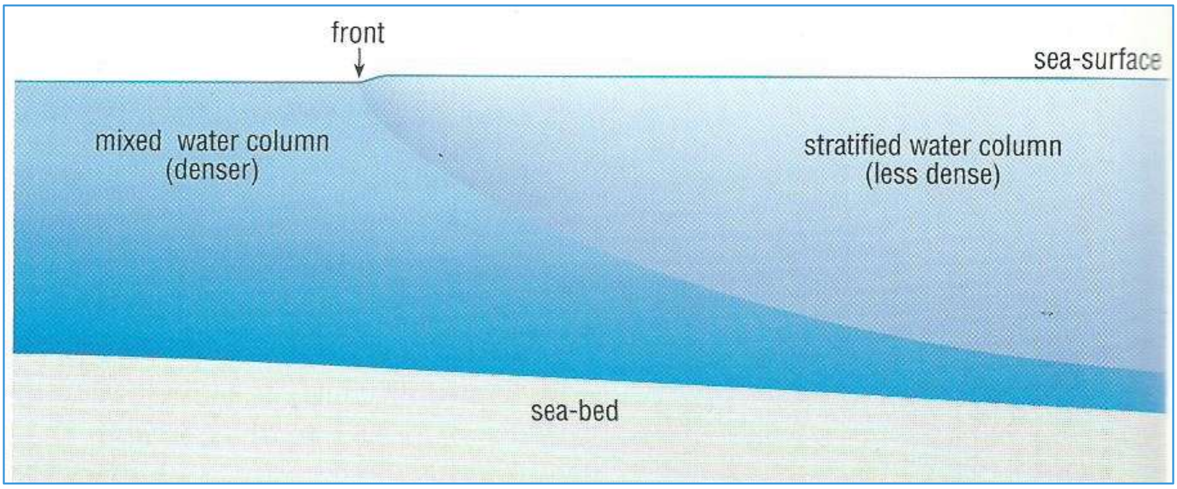

Figure 21: Schematic section with greatly exaggerated vertical scale through a tidal mixing front between stratified and tidally mixed waters in a shallow sea (such as the North Sea) (Open University, 2001).

4.1.2.4 The strength of a vertical front is also defined by the strength of the (horizontal) gradients in density (temperature and salinity) which develop positive buoyancy in the surface layer. The position and strength of the vertical front may vary on timescales of weeks to months, and from year to year, due to differences in the factors controlling stratification including:

- the rates of warming and freshwater input;
- the speed of tidal currents (neap tide versus spring tide);
- the short-term wind and wave climate; and
- the balance of these factors in conjunction with the local water depth.

4.1.2.5 The position of a vertical front is also variable on shorter timescales of hours to days as the water body containing the feature is advected back and forth by local (ebb and flood) currents.

4.1.2.6 Fronts are associated with high pelagic productivity and biodiversity (Miller and Christodolou, 2014). As the warm and cold waters mix, it creates conditions that increase plankton growth and secondary productivity which increases the seasonal availability of food to fish and shellfish species (ICES, 2008).

4.1.3 Flamborough Front

4.1.3.1 The Southern North Sea is generally a well-mixed water body. These well-mixed conditions are mainly due to relatively shallow depths and the ability of winds and waves (surface stress) and tides (bottom stress) to continually stir water sufficiently to prevent the onset of any stratification. In contrast, the Northern North Sea is relatively deep with slightly weaker currents, this helps temperature stratification develop in the spring and summer. During this period, a transition between these two water bodies develops from about 10 km offshore of Flamborough Head in the form of a front known as Flamborough Front. During autumn and winter the front dissipates due to increased wind and wave related stirring effects which are sufficient to overcome the stratification (i.e. increased mixing > buoyancy) and reestablish well-mixed conditions for this part of the Northern North Sea. The timing of the destabilisation will vary from year to year depending on the weather conditions at the time.

4.1.3.2 Hence, Flamborough Front is defined as a seasonal tidal mixing front. When present, it is a 320 km-long zone located off the East Riding of Yorkshire coast (**Figure 22**, **Figure 23** and **Figure 24**), separating the well-mixed cooler (less than 10 °C) waters to the south from the warmer (surface greater than 11 °C) stratified waters to the north (Pingree and Griffiths, 1978). The discontinuity in temperature is visible in satellite infrared imagery (Hill et al., 1993) (**Figure 23**). The Flamborough Front consists of two main parts:

- North of Flamborough Head the front lies approximately parallel with the coast about 10 km offshore; and
- Further south, the front then extends several hundred kilometres east-west within a zone offshore from Flamborough Head.

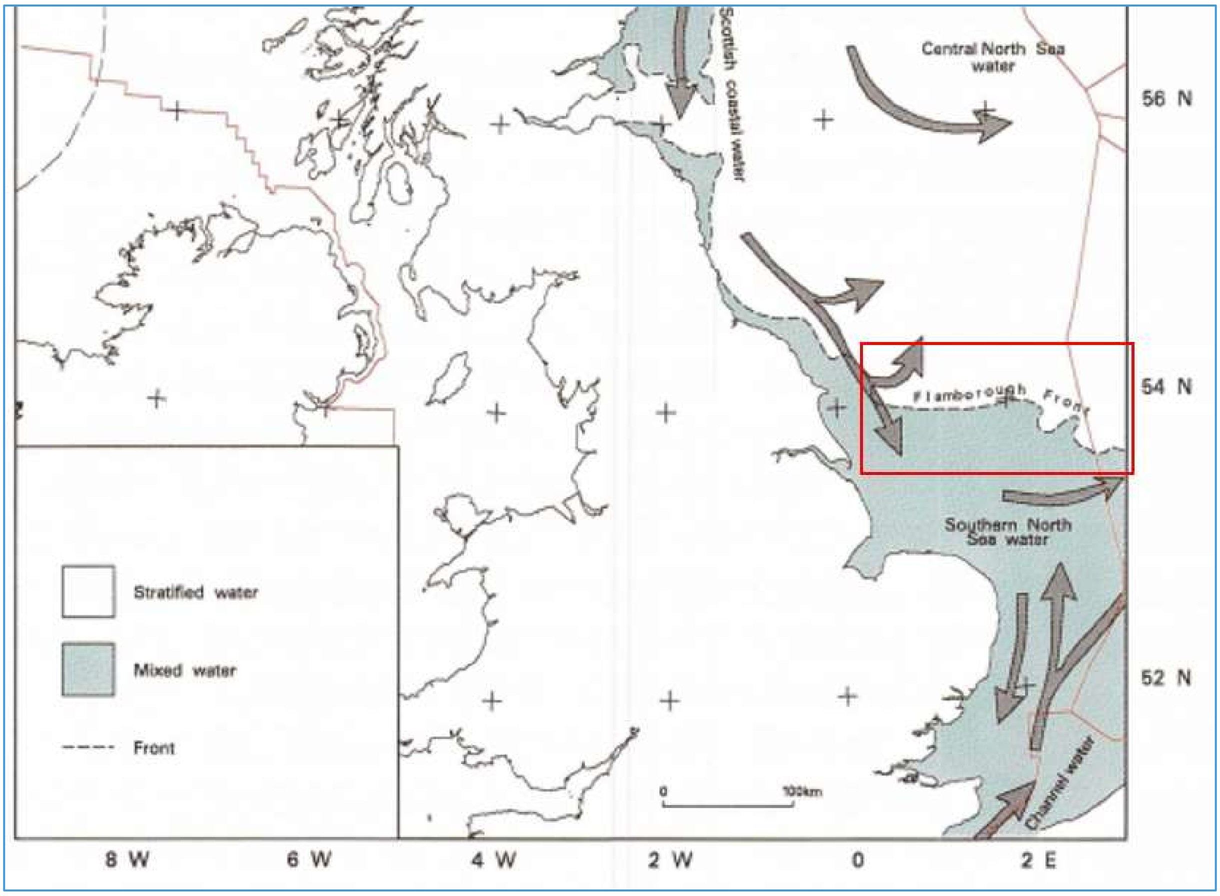

Figure 22: Location of Flamborough Front according to North Sea Task Force (1993). Flamborough Front is outlined in red box and is approximately linear and located at just south of 54°N.

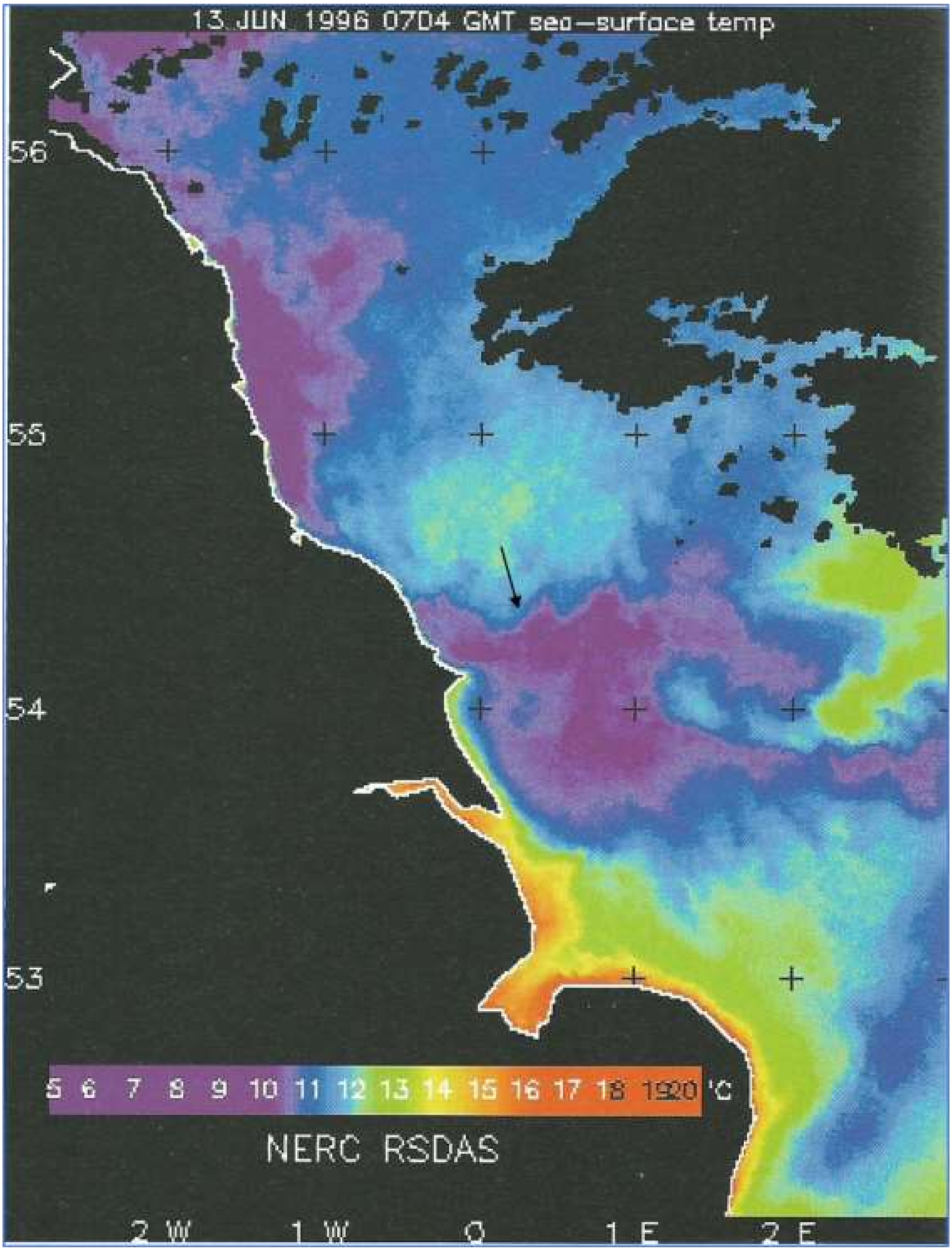

Figure 23: Location of Flamborough Front in June 1996 published by the Open University (2001). Flamborough Front is a wavy boundary zone located at approximately 54.5°N pointed to by the black arrow.

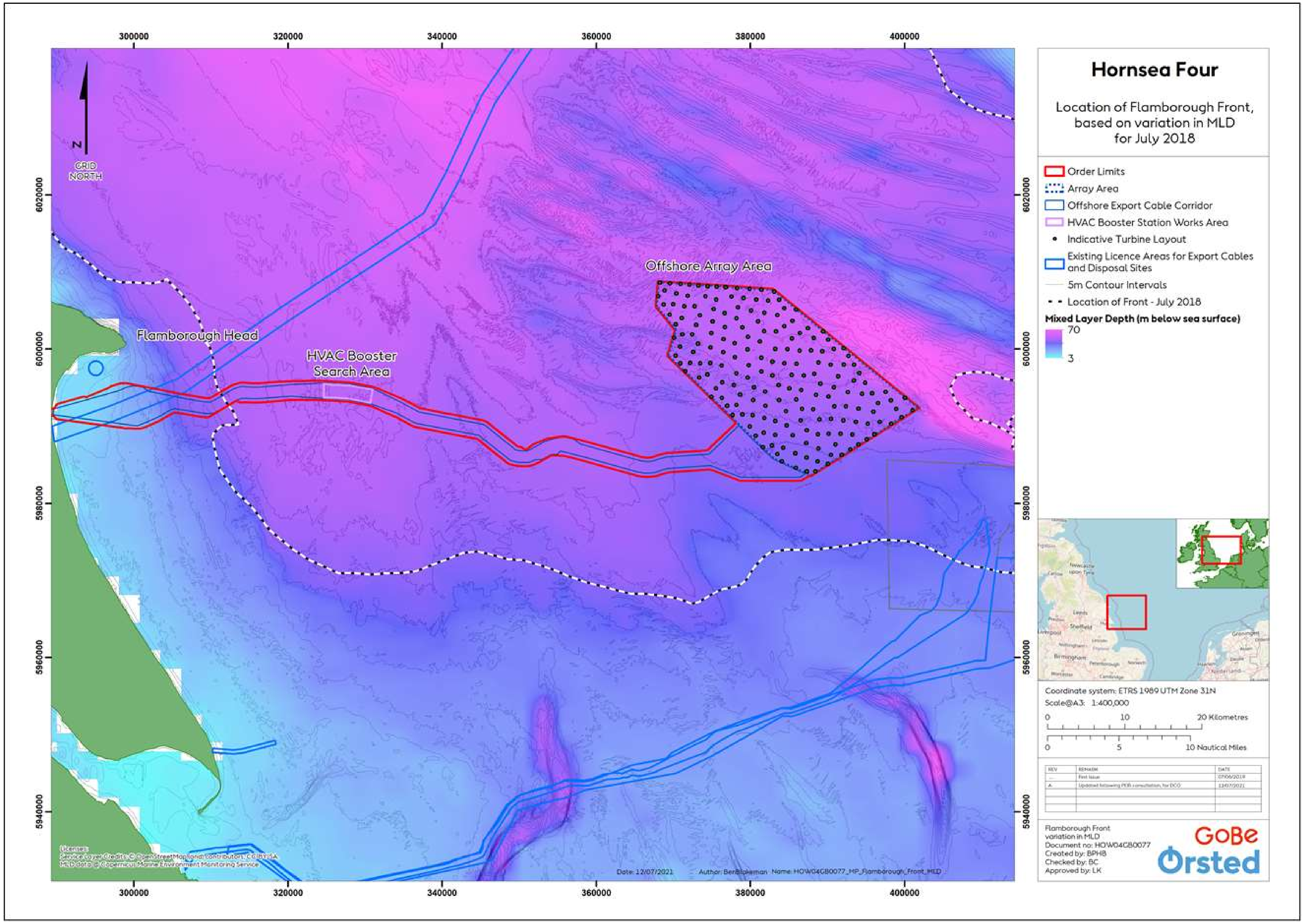

Figure 24: Location of Flamborough Front based on variation in mixed layer depth for July 2018 (Taken from APP-067). Flamborough Front undulates along the 5970000 Northing.

4.1.4 Seasonal variability in strength and depth of Flamborough Front

4.1.4.1 Miller and Christodoulou (2014) used satellite data to investigate the location of frequent thermal fronts (including Flamborough Front) in the shelf seas around the United Kingdom. The dataset contained 30,000 satellite images taken between 1999 and 2008 and was used as a proxy for pelagic diversity to support the designation of Marine Protected Areas (MPAs). Frequent front maps were created for all seasons over the ten-year period, displaying the percentage of time in which strong fronts occurred in a particular area (**Figure 25**). Seasonal inter-annual variability in frontal occurrence was also estimated (**Figure 26**).

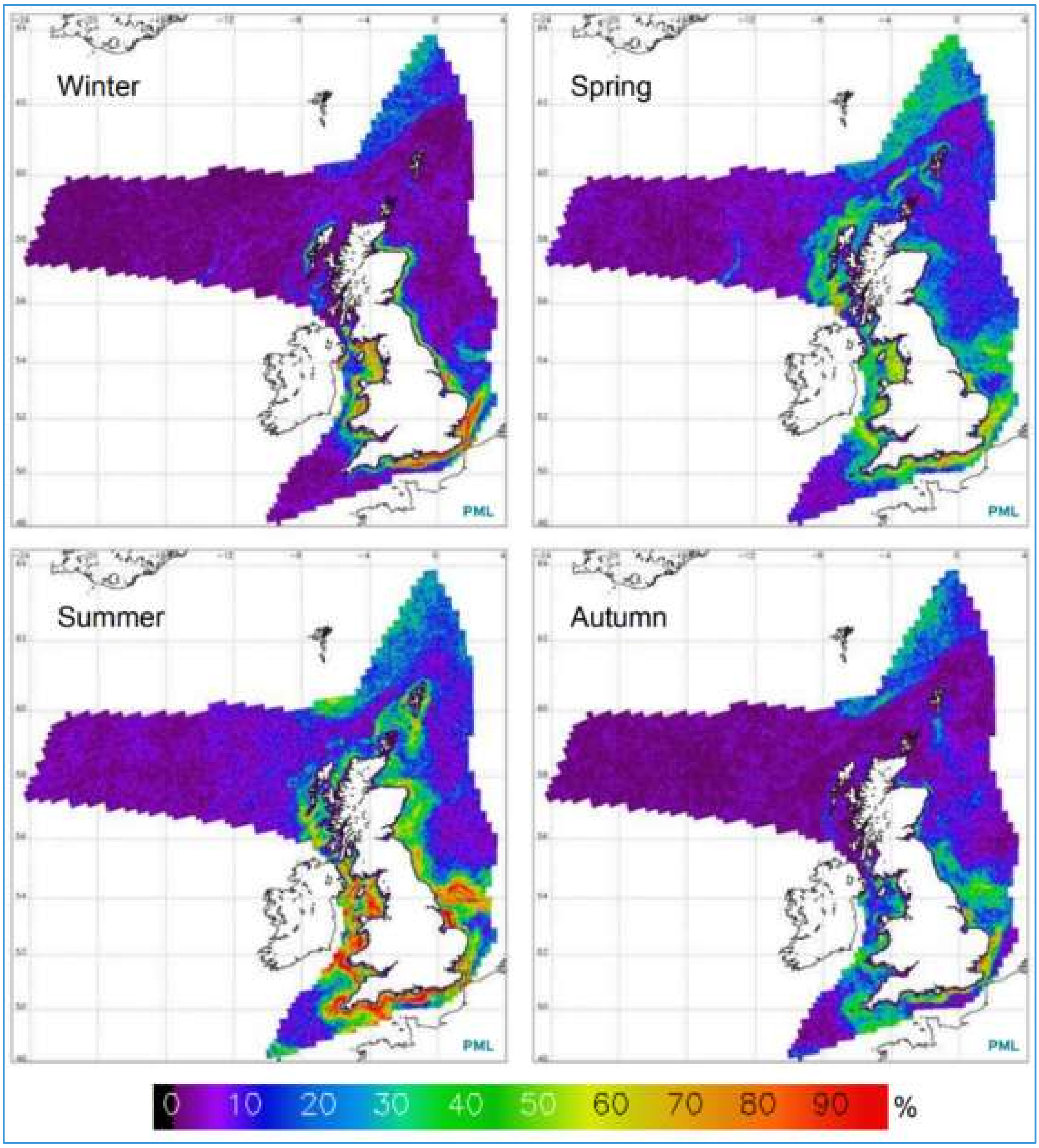

Figure 25: Seasonal frequent front maps indicating the percentage of time a strong front was observed at each location between 1999 and 2008 (Miller and Christodolou, 2014).

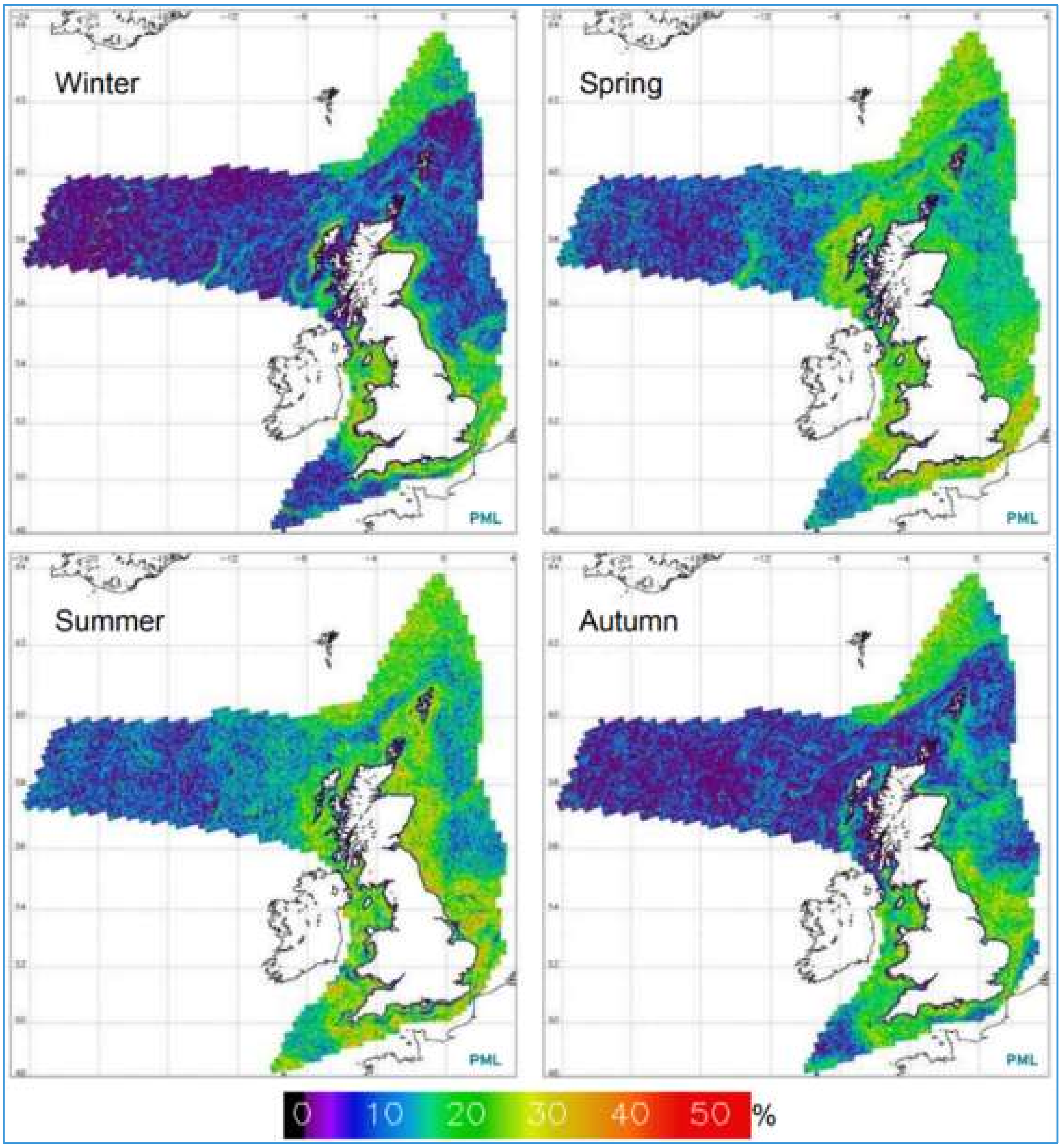

Figure 26: Seasonal inter-annual variability maps, indicating the temporal variability in frontal occurrence between 1999 and 2008 (Miller and Christodolou, 2014). Areas with a persistent front but with considerable variability in locations had a higher standard deviation value and are closer to red on the map.

4.1.4.2 The frequent front map (Figure 25) exhibits considerable spatial variability related to the tidal cycle and mesoscale processes, which is linked to predicted transitional mixed/stratified zones (Miller and Christodolou, 2014). The results show a dominant summer presence of Flamborough Front with the absence of a front at other times of the year. The summer plot shows that 70-90% of the time between 1999 and 2008, the front was in a zone east of Flamborough Head, an area that includes Hornsea Four. In autumn, the front was in the same zone approximately 30-50% of the time. The seasonal inter-annual variability maps (**Figure 26**) indicate a strong seasonal variability between the coast and the Dogger Bank region (encompassing Flamborough Front), with highly frequent fronts observed during the summer, and relatively low frequency fronts during the rest of the year.

4.1.4.3 Miller and Christodolou (2014) compared their analysis with previous analyses of fronts based on ocean models (e.g. Pingree and Griffiths, 1978) which showed that the main tidal mixing fronts (e.g. Flamborough Front) agreed very well with the observed summer distribution.

4.1.5 Inter-annual variability in the position of Flamborough Front

4.1.5.1 An assessment of the long-term variability in patterns of stratification in the North Sea was completed by van Leeuwen et al. (2015) using a long term (51-year) regional scale hydrobiogeochemical model simulation. The North Sea was delineated into five distinct regimes based on multi-decadal stratification characteristics (**Figure 27**):

- permanently stratified;
- seasonally stratified;
- intermittently stratified;
- permanently mixed; and
- Region Of Freshwater Influence (ROFI).

4.1.5.2 **Figure 27** shows the regimes which occur for the most years in each spatial grid point defined by the model. With respect to the Flamborough Front, the seasonally stratified area in the northern and central North Sea, thermally stratifies in spring when incident solar radiation starts to warm the surface of the water column and stays stratified until autumn processes remix the water column. Winter is characterized by continuous mixed conditions. The well-mixed areas in the southern North Sea are relatively shallow waters (up to 40 m) and are continuously mixed by tidal and wave action. The intermittently stratified region is characterised by long-mixed conditions during winter and repeated, short-lived thermal stratification in summer. This region is adjacent to the permanently mixed region but is distinctly separate in terms of stratification characteristics. According to van Leeuwen et al. (2015), the location of Flamborough Front can be placed at the edge of the intermittently stratified regime.

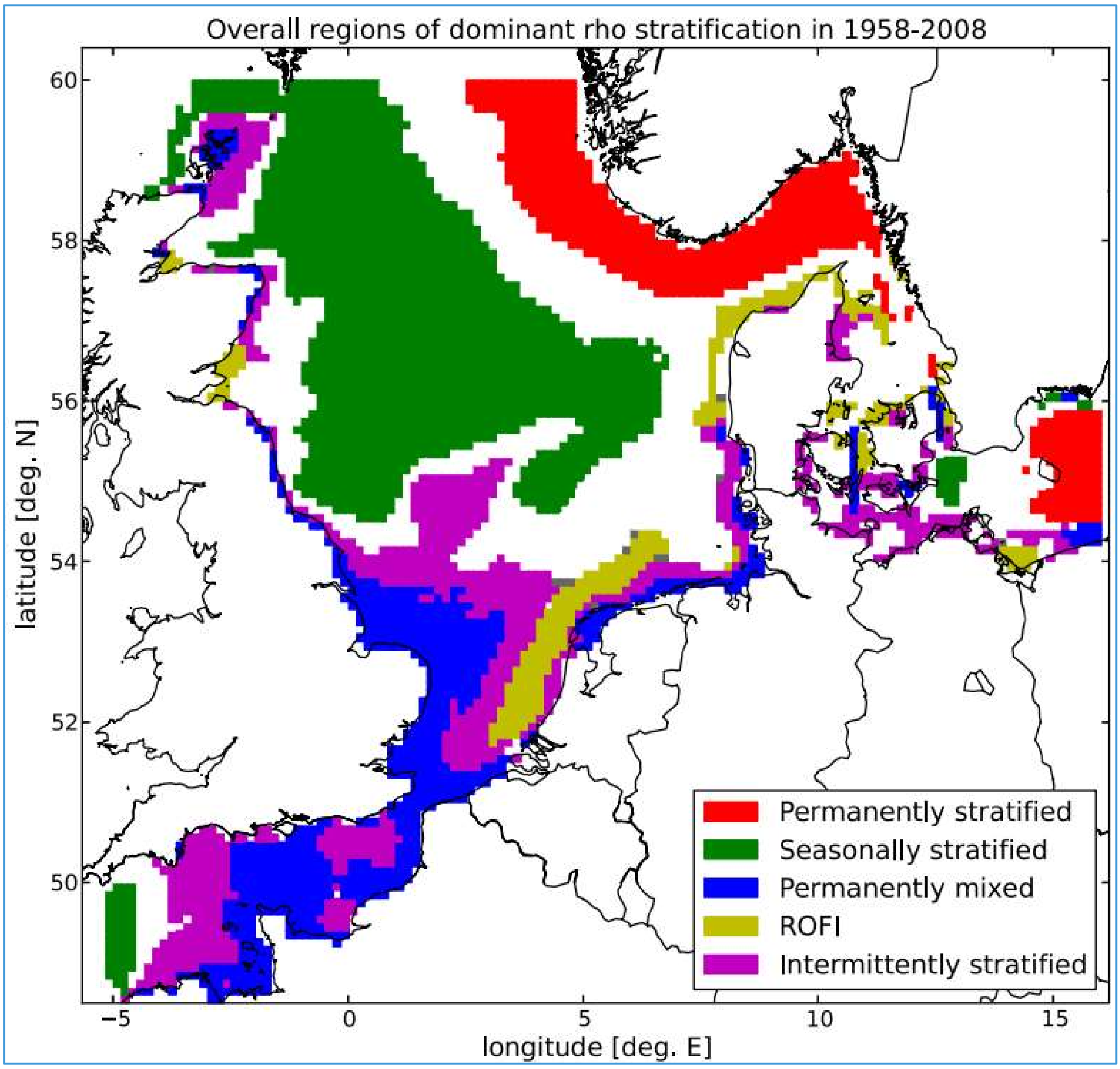

Figure 27: Time median results of the modelled, annual regions in the North Sea based on density stratification (van Leeuwen et al., 2015). Transparent areas indicate areas where the dominant regime occurs for less than 50% of the time (less visible due to minimal occurrence).

4.1.5.3 Although these areas show some inter-annual variation in geographic coverage, they are generally stable features within the North Sea. Van Leeuwen et al. (2015) demonstrated this variability by calculating the percentage of time any area can be defined according to Figure 27. The results shown in Figure 28 indicate that in the vicinity of Flamborough Front, the seasonally stratified and permanently mixed areas are well defined with small transitional areas. The intermittently stratified area is more variable.

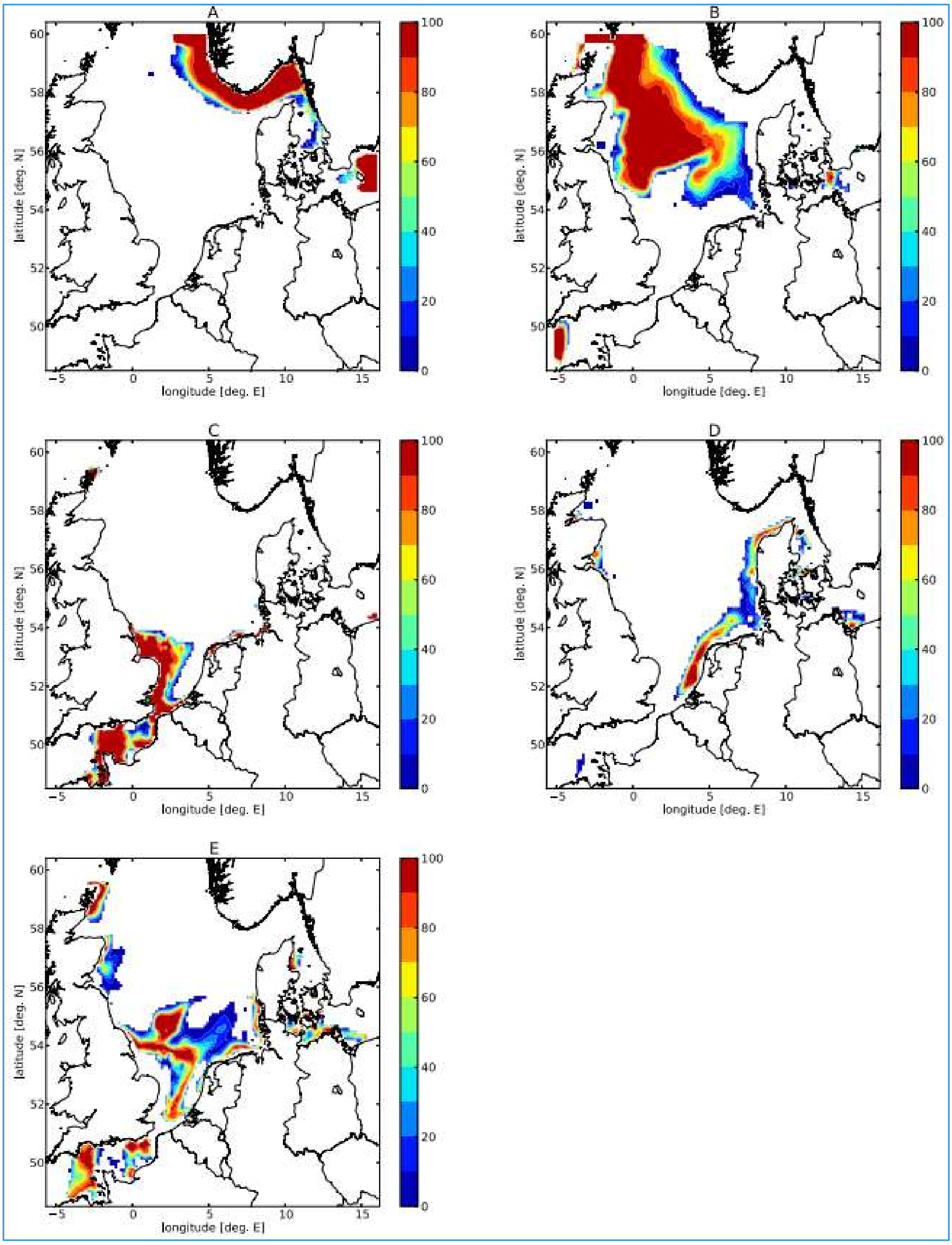

Figure 28: Spatial distribution of percentage time spent in each defined regime, over the period 1958-2008 (van Leeuwen et al., 2015). (A) Permanently stratified, (B) seasonally stratified, (C) permanently mixed, (D) ROFI, and (E) intermittently stratified.

4.1.6 Biological productivity

4.1.6.1 Wildlife Trust (2010) created a map of Areas of Additional Pelagic Ecological Importance (AAPEI), which combined the frontal data quantitatively with other pelagic metrics such as seabird foraging radii, marine mammal and basking shark hotspot, and fish spawning and nursery grounds (Figure 29). The AAPEI map approximately mirrors the front map (Figure 25) as the hotspots indicated by the other pelagic metrics coincide with frequent fronts (Miller and Christodolou, 2014). Increased abundances of animals at fronts have been observed for a range of species (Wildlife Trust, 2010), including pinnipeds, turtles, sharks, and various cetacean and seabird species. The map shows that the waters around Flamborough Head are particularly rich in marine life because of its proximity to an upwelling of nutrients and plankton caused by Flamborough Front, which provides a plentiful food supply.

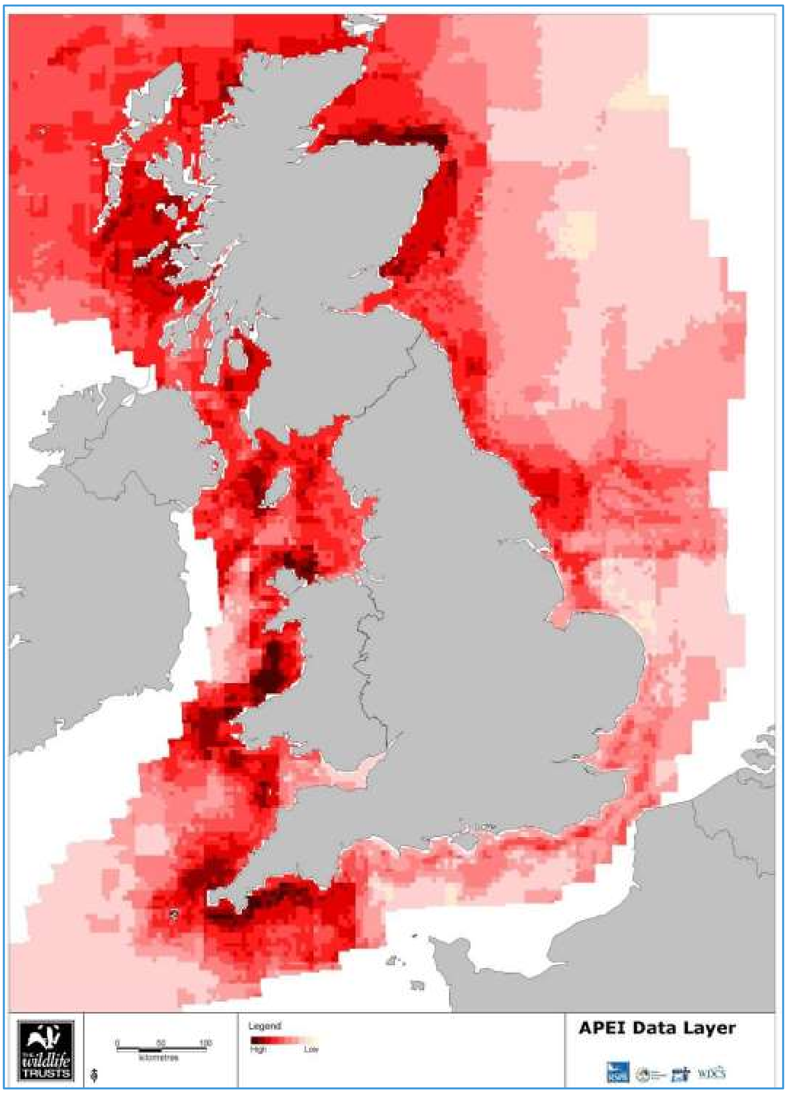

Figure 29: Areas of Additional Pelagic Ecological Importance (AAPEI) (Wildlife Trust, 2010). This map is a combination of data layers on thermal fronts, seabirds, whales, dolphins and fish.

4.1.7 Anthropogenic factors

4.1.7.1 Anthropogenic pressures, such as greenhouse gas emissions, can indirectly affect tidal mixing fronts as they are linked to meteorological forcing and water temperature. Alterations in sea-surface temperature and wind patterns could lead to changes in stratification intensity and duration, and affect frontal occurrence (Holt et al., 2010). Models have predicted an elongation of the frontal season by 10-15 days within the next 100 years (which would include the Flamborough Front) as a result of climate change (Holt et al., 2010).

4.2 Source-Pathway-Receptor (S-P-R) Model

4.2.1.1 The main potential impact on the Flamborough Front of Hornsea Four is changes to near-field mixing due to foundation wake effects and the potential for destabilsing local water column stratification (i.e. those restricted to the area inside and immediately outside the Hornsea Four array) driven by interaction of the tidal (hydrodynamic) processes with the foundation units across the offshore array. There would be a (slight) difference between the potential disturbance of the front if it crossed into the array and the potential disturbance of areas of stratification north of the front.

4.2.2 Project design

4.2.2.1 The worst-case scenario for changes to the Flamborough Front would be associated with the MDS; the greatest number of gravity base structures (GBS) in the offshore array (468 km^2) with at least the minimum spacing between turbines. The foundation considered to have the greatest blockage effect for the MDS (and hence could create the greatest amount of turbulence) is the 53 m base-diameter conical shaped GBS with a minimum separation of 810 m from their centers. The applicant has committed to up to only 110 GBS foundations plus 70 three-legged suction bucket multiple foundations. There are also up to ten large box-type offshore substation foundations.

4.2.3 Evidence base

4.2.3.1 Carpenter et al. (2016) and Cazenave et al. (2016) investigated the potential large-scale impacts of wind farm turbine foundations on shelf sea stratification. These assessments were used as the evidence base to assess impacts of Hornsea Project Three Offshore Wind Farm on Flamborough Front, and the following is taken directly from the Hornsea Three Environmental Statement and the supporting Hornsea Three Marine Processes Technical Report (Ørsted, 2018a, b).

4.2.3.2 Carpenter et al. (2016) use an idealised (conceptual) numerical model of structure induced turbulent mixing in conjunction with existing environmental hindcast data to consider the potential for large-scale change to stratification of the German Bight region of the North Sea in response to planned wind farm developments. The study showed that stratification is only gradually broken down by interaction with the wind farm. A range of 'timescale for (complete) mixing' estimates were provided (about 100 to 500 days) if the same body of initially stratified water is continually passed through the wind farm. In practice, due to non-zero residual rates of tidal advection, the same body of water will not be repeatedly passed through the same wind farm for 100 to 500 days. As a result, the mixing influence of the foundations will only lead to some partial reduction in the strength of stratification in water that passes through the wind farm.

4.2.3.3 Any increased turbulence resulting from the presence of the Hornsea Four foundation structures would be isolated to the local area of each foundation, dissipating downstream without leading to any larger array-scale effects. It is unlikely that these effects will extend to the Flamborough Front. All foundations will lead to some level of local turbulence and depending on the final design configuration of the Hornsea Four foundations, the GBS cross-section through the water column has the potential to lead to the highest level of turbulence compared to other foundation options. However, in that scenario the scale of turbulence is considered to remain localised in the form of a wake in the lee of each foundation without a larger array scale effect. The measurable distance of any wake is likely to be less than the minimum separation between foundations of 810 m. These effects are unlikely to extend to the Flamborough Front and will remain small compared to the feature in its entirety. The magnitude of any impact on the Flamborough Front is considered to be negligible because the influence from any turbulent flow wakes is likely to remain spatially distant.

4.2.3.4 Carpenter et al. (2016) conclude that no large-scale changes to stratification of the North Sea are expected at the current levels of offshore wind farm construction and that 'extensive' regions of the North Sea would need to be covered in offshore wind farms for a significant impact on stratification to occur. The study also found that the results are sensitive to the assumed type (shape and size) of foundation structure being assessed, and to the assumptions made about the evolution of the pycnocline thickness under enhanced mixing conditions.

4.2.3.5 Cazenave et al. (2016) used a regional scale 3D hydrodynamic model with a number of wind farm foundations represented as small islands in the mesh. The results showed that although wind farm foundations have some limited influence on the strength of stratification locally, it does not suggest that naturally present stratification would become completely mixed by this process. The Hornsea Three Marine Processes Technical Report (Ørsted (2018b)) noted that the model used in this study only considered time mean flow at a typical spatial resolution of 10 to 20m in the horizontal plane and more than several metres in the vertical plane. The elevation of turbulence intensity and turbulent mixing at smaller length scales in the narrow wake is important for the processes in question (as noted by Carpenter et al., 2016) but is only generally parameterised and not explicitly resolved by this model, which leads to some uncertainty in the results.

4.2.3.6 Schultze et al. (2020) used observations and high-resolution large eddy simulations to quantify the loss of stratification within the wake of a single monopile structure within four different water body stratification strengths. Their observations showed that the turbulent wake of a monopile structure is narrow and highly energetic within the first 100 m, with the dissipation of turbulence above background levels downstream of the structure. The effect of a single turbine on stratification is relatively low compared to other naturally occurring mixing mechanisms, but the effect depends on the strength of the stratification, with more impact on weakly stratified water column. Turbulent mixing is not sufficient to overcome stronger stratification, as the buoyancy of the surface layer retains a stronger influence than the increased turbulent mixing induced by the structure. Also, although the wake can persist for a long distance downstream of the structure (several 100s of metres), the energy dissipation of the wake falls rapidly away from the structure until it becomes fully dissipated/undetectable.

4.3 Updates to the Impact Assessment

4.3.1.1 The Hornsea Project Four offshore array is likely to be located within a zone bounded to the north and south by the various reported positions of the Flamborough Front (Figure 30). This means that the array could sit within the well-mixed waters to the south, the stratified waters to the north, or on the front itself. The MDS could potentially create turbulent wakes at a local foundation scale which could locally change tidal mixing processes which may locally inhibit formation of the Flamborough Front across the width of the array.

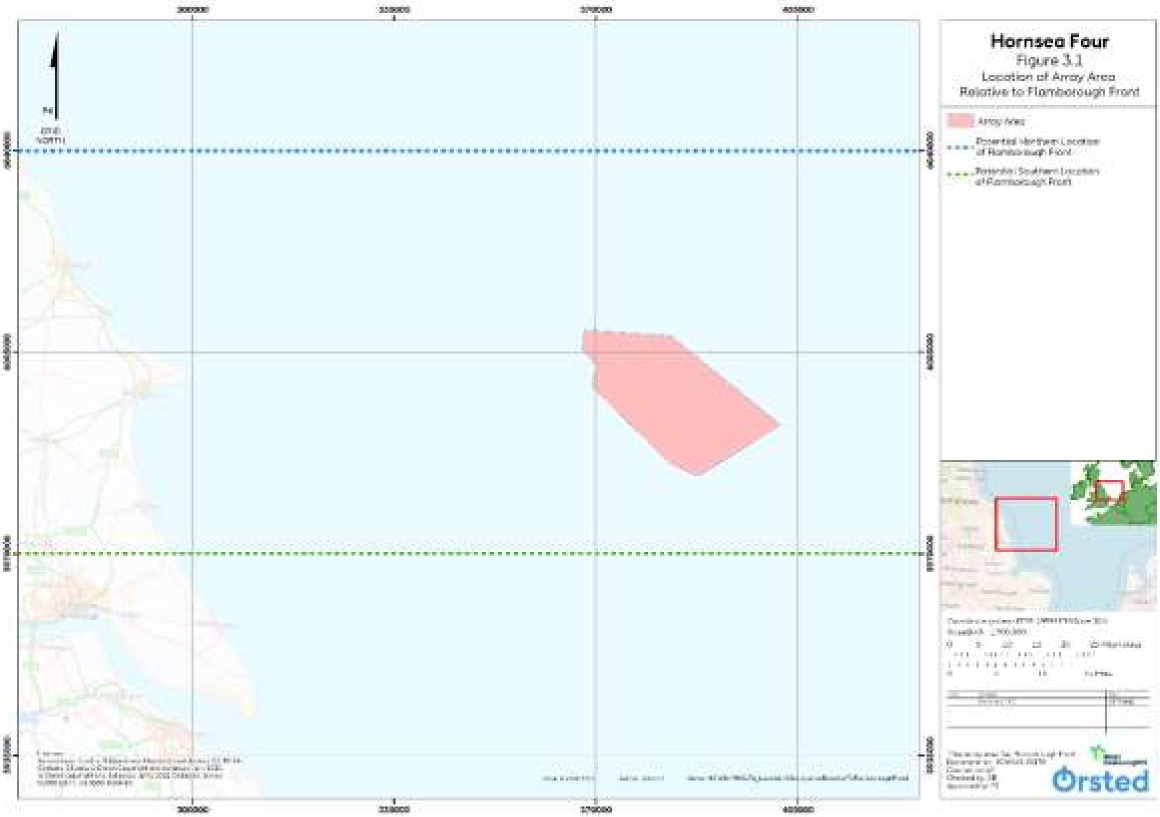

Figure 30: Location of Hornsea Project Four offshore array area relative to potential northerly and southerly positions of Flamborough Front idealised from a number of datasets (Figure 22Figure 22: , Figure 23 and Figure 24).

4.3.1.2 Both Hornsea Project Three and Hornsea Project Four Offshore Wind Farms assessed the potential impacts of the presence of foundations on destabilising the Flamborough Front, but using slightly different approaches. Hornsea Project Three assessed potential impacts by considering water passing the foundations across the array, whereas Hornsea Project Four assessed potential impacts by considering the development of turbulent wakes created in the lee of foundations causing increased mixing potential. These assessments are both considered valid and the conclusions arising from them are considered robust.

4.3.2 Hornsea Project Three

4.3.2.1 According to Ørsted (2018a), the Hornsea Project Three offshore array would be located in an intermittently stratified region based on the maps of van Leeuwen et al. (2015). Based on the evidence of van Leeuwen et al. (2015), vertical stratification (and hence the presence of Flamborough Front) is only expected to occur in or near to the Hornsea Project Four array area for less than 40 days in the year, on average. It is likely that the position of Flamborough Front close to the Hornsea Project Four array would exhibit inter-annual variability, and it could be located north, south or through the array at various times during summer months, depending on the driving forces.

4.3.2.2 Carpenter et al. (2016) and Cazenave et al. (2016) indicated that when stratification is present it is possible that foundations locally cause some minor indirect decrease in the strength of water column stratification, through increased turbulence. However, only a small proportion of the water passing through the array would actually interact with individual foundations, causing only partial and localised mixing of any stratification. It is highly unlikely that stratified water entering the array would become fully mixed, and regional scale pattern of stratification in the North Sea and the location and physical characteristics of Flamborough Front would be unaffected and would continue to be subject to natural processes and variability. Although the impact would have long-term duration it would be local in spatial extent, non-continuous and highly reversible.

4.3.3 Hornsea Four

4.3.3.1 As tidal currents flow past an individual foundation, a turbulent wake is formed as detailed within **A2.1 Marine Geology Oceanography and Physical Processes (APP-013)** and **A5.1.1 Marine Processes Technical Report (APP-067)**. Within the wake, time-averaged flow speeds are reduced and vertical mixing can be enhanced above ambient levels through increased turbulence, which has the potential to contribute to a local reduction in the strength of vertical stratification with an associated potential effect to the Flamborough Front. However, the Flamborough Front is strongly stratified regional feature in spring and summer and the high buoyancy forces associated with the stratification would not be destabilised by the local and relatively small turbulent wakes generated in the near-field of each foundation.

4.3.3.2 The most pronounced changes to the flow regime would occur immediately adjacent to and downstream of the foundation, within approximately three times the length scale of the obstacle. With minimum spacings of 810 m between foundations across the array, it is unlikely that wake to wake interactions would occur, and individual wakes would remain independent of each other and quickly dissipate away from each foundation (in the order of minutes and tens to hundreds of metres).

4.3.4 Summary

4.3.4.1 Given that the Flamborough Front is highly dynamic and ephemeral landscape-scale feature, it would not be affected by localised, small-scale changes in water column turbulence induced by individual near-field wakes at foundation locations, especially if the strength of stratification (due to buoyancy forces) was sufficient to overcome any increased mixing.

5 Concluding Remarks

Table 4 sets out the concluding remarks against the relevant points from Natural England's and the MMO's Relevant Representations.

Table 4: Conclusions in relation to each Relevant Representation item

Relevant Rep ID	Relevant Rep	Conclusions
Smithic Bank		
RR-029-5.43	The Hornsea 4 export cable route crosses the southern part of Smithic Bank. The installation of cables and rock protection (and replenishment) in this area could result in the lowering of Smithic Bank or the alteration of its morphology. Additionally, as the Dogger Bank A& B export cables, which necessitates the placement of a substantial amount of rock protection at each of the 24 cable crossing points. Moreover, the Scotland to England Green Link 2 project has indicated a similar landfall to Hornsea 4 and will potentially cross Smithic Bank. We are concerned that a significant area of cable installation activities and the addition of any cable protection may alter the elevation/profile of the sandbank. Moderate elevation changes to the sandbank could produce significant variations in wave power at the shoreline which will, in turn, modify the shoreline response to storms, and substantially change shoreline morphology.	The sediment transport processes controlling the development and evolution of North Smithic and South Smithic are regional in spatial scale. These large-scale natural changes to the bank are anticipated to continue and would be in excess of any changes that would be incurred by local establishment of cable protection across the bank. The analysis completed in this supplementary report supports the original conclusion in the Hornsea Four Environmental Statement of a negligible to minor effect.
RR-029-5.44	Natural England is concerned that the Hornsea 4 development (alone and in-combination) might adversely affect the form and function of Smithic Bank, and, in turn, affect that of other marine process receptors such as the Holderness Coast, Holderness Inshore MCZ, Dimlington Cliffs SSSI, Humber Estuary SAC/SPA/Ramsar/SSSI, Flamborough Head SAC/SSSI. Consequently, we advise that the long-term impacts of (a) cable installation and cable protection across Smithic Bank (including the proposed 25% rock replenishment during the operational phase), and (b) the presence of the HP4/Dogger Bank A&B cable crossing, need to be addressed in terms of the risk of lowering of the sandbank and affecting its associated sediment transport processes. We would	The drivers of future trends in cliff erosion at along the Holderness Coast, including the Dimlington Cliffs SSSI receptor (and the landfall) can be classified into two types; material and process. The only factors that could be affected by cable installation activities across Smithic Bank are sediment supply and transport. Section 2.4.4 of this supplementary report concludes that there would be no changes to sedimentary processes along the Holderness coast caused by cable installation or landfall activities. The other factors (i.e. geology and sea-level rise) have no relationship to cable installation

Relevant Rep ID	Relevant Rep	Conclusions
	also advise that these impacts be considered over the lifetime of the project, also taking into consideration the impacts of climate change.	activities and so there can be no cause and effect related to them.
RR-029-5.55	Although we note and welcome the Applicant's efforts to address some of these concerns, through commitments to avoid the placement of rock protection within 350m seaward of MLWS (Co188), and the Commitment to relocate the cable crossing east of the 20m depth contour (Co189), there is insufficient evidence within the ES and supporting Annexes to show that the implementation of these measures would remove the potential for significant impacts on this sensitive receptor. Natural England would expect a commitment to avoid the placement of rock protection on Smithic Bank as a minimum (approximately 16m depth contour), but it would need to be demonstrated that this along with the placement of the cable crossing was sufficient to exclude the potential for impact.	See the response to **RR-029**-5.43 (above).
RR-029-APDX:E-C	Data suitability and baseline characterisation: Detailed investigation of the geomorphology of Smithic Bank, its evolution, and the impact of the proposed development on its form and function. Therefore, we do not consider the baseline characterisation to be complete at this stage.	A baseline understanding of Smithic Bank using Historical Trend Analysis (HTA) and Expert Geomorphological Assessment (EGA) are provided in **Section 2.2** and **Section 2.3** of this supplementary report. Existing surveys have been examined to extend present morphological understanding of Smithic Bank.
RR-029-APDX:E-4	In part In addition, in section 1.7.6.7, Smithic Bank is identified as a local sediment store for material supplied through cliff erosion. Consequently, Smithic Bank should be considered a receptor of the landfall works….. Given the sparsity of baseline characterisation surveys of the Holderness coastal zone and Smithic Bank, significant environmental effects on the Holderness MCZ and other designated features cannot be ruled out at this stage.	Further information has been provided in **Section 3** on the baseline characteristics of the Holderness Coast, to support the assessment of impacts. This includes presentation of cliff erosion rates and the prediction of future cliff erosion along with historic and projected sea-level rise. The response to **RR-029**-5.44 (above) sets out that considering the information contained in this supplementary report, that no changes to sedimentary processes along the Holderness coast caused by cable installation.
RR-020-3.2.3	The MMO believes that further information should be provided to provide enough evidence on the	Existing surveys have been examined to extend present morphological

Relevant Rep ID	Relevant Rep	Conclusions
	baseline. As well as offshore physical surveys for wave and tidal currents, a number of swath bathymetry and geotechnical surveys have been undertaken. Supplementing this is a numerical modelling exercise that allows different scenarios to be explore e.g. turbidity plumes from cable excavation or seabed preparation. Whilst this gives a good overall evidence base, there are a number of areas where the evidence base is either patchy or non-existent. These include the cable route around Smithic bank and the coastline. The MMO would expect to see additional Swath Bathymetry and geotechnical surveys from just offshore of the cable crossing with Dogger Bank A+B area and the Holderness coastline.	understanding of Smithic Bank and both HTA and EGA are provided in Section 2.2 and Section 2.3. The only factors that could be affected by cable installation activities across Smithic Bank are sediment supply and transport. Section 2.4.4 of this report argues that there would be no changes to sedimentary processes along the Holderness coast caused by cable installation. Further surveys would therefore not assist helping to define any impact.
Flamborough Head SAC, Humber Estuary European Marine Site, Greater Wash SPA, Southern North Sea SAC		
RR-029-APDX:E-7	In part ….there are a number of designated site receptors which may be influenced by impacts in the Export Cable Corridor (ECC) either directly or indirectly as a result of impacts to other marine process receptors. These therefore need to be considered. These include: • Holderness Inshore MCZ • Holderness Offshore MCZ • Flamborough and Filey Coast SPA • Flamborough SSSI • Humber Estuary SAC, SPA, SSSI and Ramsar • Greater Wash SPA • Southern North Sea SAC The potential for indirect impacts to the Holderness Coast from the ECC should also be explored	The response to RR-029-5.44 (above) sets out that considering the information contained in this supplementary report, that no changes to sedimentary processes along the Holderness coast caused by cable installation.
Holderness coastline (including Marine Conservation Zones)		
RR-029-APDX:E-D	High resolution bathymetric surveys around Smithic Bank (e.g. swath bathymetry) and accompanying geotechnical surveys (including near the Dogger Bank A&B cable crossing and along the Holderness coastline).	The response to RR-029-5.44 (above) sets out that considering the information contained in this supplementary report, that no changes to sedimentary processes along the Holderness coast caused by cable installation.
Flamborough Front		
RR-029-5.57	The foundation structures of the Hornsea 4 array area have the potential to generate turbulent wakes that will contribute to a mixing of the stratified water column. Mixing generated in this way could	The MDS could potentially create turbulent wakes at a local foundation scale which could locally change tidal mixing processes which may locally inhibit

Relevant Rep ID	Relevant Rep	Conclusions
	have a significant impact on the large-scale stratification of the North Sea off the coast of Flamborough Head. The presence of the Hornsea 4 array area, combined with those of Hornsea 2 and Hornsea 1, would occupy a considerable area, hence the potential large-scale impact on the Flamborough Front. Furthermore, the inclusion of Gravity Base Structures, as the MDS for turbine foundation design at Hornsea 4, significantly increases the potential for turbulence effects. Gravity bases of the size and scale proposed have not previously been deployed in the English waters, therefore, we have no evidence base on which to base understanding of their impact on marine processes and their receptors. Natural England therefore advises that the sensitivity of the Flamborough Front should be considered high, until further evidence to the contrary can be provided.	formation of the Flamborough Front across the width of the array. However, the Flamborough Front is strongly stratified regional feature in spring and summer and the high buoyancy forces associated with the stratification would not be destabilised by the local and relatively small turbulent wakes generated in the near-field of each foundation. With minimum spacings of 810 m between foundations across the array, it is unlikely that wake to wake interactions would occur, and individual wakes would remain independent of each other and quickly dissipate away from each foundation (in the order of minutes and tens to hundreds of metres). Given that the Flamborough Front is highly dynamic and ephemeral landscape-scale feature, it would not be affected by localised, small-scale changes in water column turbulence induced by individual near-field wakes at foundation locations, especially if the strength of stratification (due to buoyancy forces) was sufficient to overcome any increased mixing.
RR-029-5.58	In part Based on the high levels of uncertainty described, Natural England is unable to rule out the potential for significant impacts to the Flamborough Front.	See response to **RR-029**-5.57 (above).
RR-029-APDX:E-C	Data suitability and baseline characterisation: .... Sufficient baseline characterisation and understanding of the Flamborough Front through and/in the vicinity to the HP4 array, coupled with an adequate assessment of the effects of the array on tidal flows, turbulent wakes, and mixing within the water column.	Further characterisation of the Flamborough Front has been set out in **Section 4.1** of this supplementary report. This includes information on inter-annual variability, biological productivity and anthropogenic factors affecting how the front may change in future years. A S-P-R is presented and commentary provided on the impact assessment.

Relevant Rep ID	Relevant Rep	Conclusions
		It is concluded that given that the Flamborough Front is a highly dynamic and ephemeral landscape-scale feature, it would not be affected by localised, small-scale changes in water column turbulence induced by individual near-field wakes at foundation locations.
R-029-APDX:E-D	Data Gaps: ….. Effects of the proposed foundation structures on turbulent wake-induced mixing, stratification, and, in turn, primary productivity in and around the Flamborough Front. In particular, Natural England would welcome further discussion with the applicant ahead of the examination on appropriate data for Smithic Bank and Flamborough front.	See response to **RR-029-APDX:E-C** (above).
RR-020-3.2.3	The impact on Flamborough front, especially any changes (positively and negatively) to primary productively (and subsequently secondary productivity) has not yet been fully addressed. Whilst it is noted that Natural Environment Research Council ("NERC") EcoWinds (Ecological consequences of offshore wind) research project may assess this potential impact, any outcomes not likely to be within the consenting period, which is potentially three years away. Therefore, taking a pragmatic approach, all the information available should be provided and the Applicant should: a) take a full part in the research project; and b) use satellite thermal imagery to determine if cold water thermal plumes exist when the front is present (spring to autumn)	Information relating to biological productivity is summarised in **Section 4.1.6**. As stated in the summary response to **RR-029-APDX:E-C** (above) it is concluded that the Flamborough Front would not be affected by localised, small-scale changes in water column turbulence induced by individual near-field wakes at foundation locations. No significant effects on biological productivity would therefore result.
RR-029-5.56	The Flamborough Front is formed where the stratified water from the northern North Sea meets the mixed water from the southern North Sea. The mixing of these two waterbodies leads to an upwelling of nutrients, which in turn leads to increased plankton growth and associated productivity, giving rise to concentrations of forage fish which in turn provide a feeding ground for other species. It is therefore perhaps of no surprise that areas around the front support high densities of seabirds and marine mammals. Consequently, it is vital that the potential impacts of the project alone	See response to **RR-020**-3.2.3 (above).

Relevant Rep ID	Relevant Rep	Conclusions
	and in-combination with other plans and projects be adequately assessed. Natural England, therefore, considers this receptor to have high environmental value and not medium as indicated in the ES.	

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Appendix A Erosion of the Holderness cliffs at 123 measuring posts (post 1 is at Sewerby, whilst 123 is at the neck of Spurn Head).

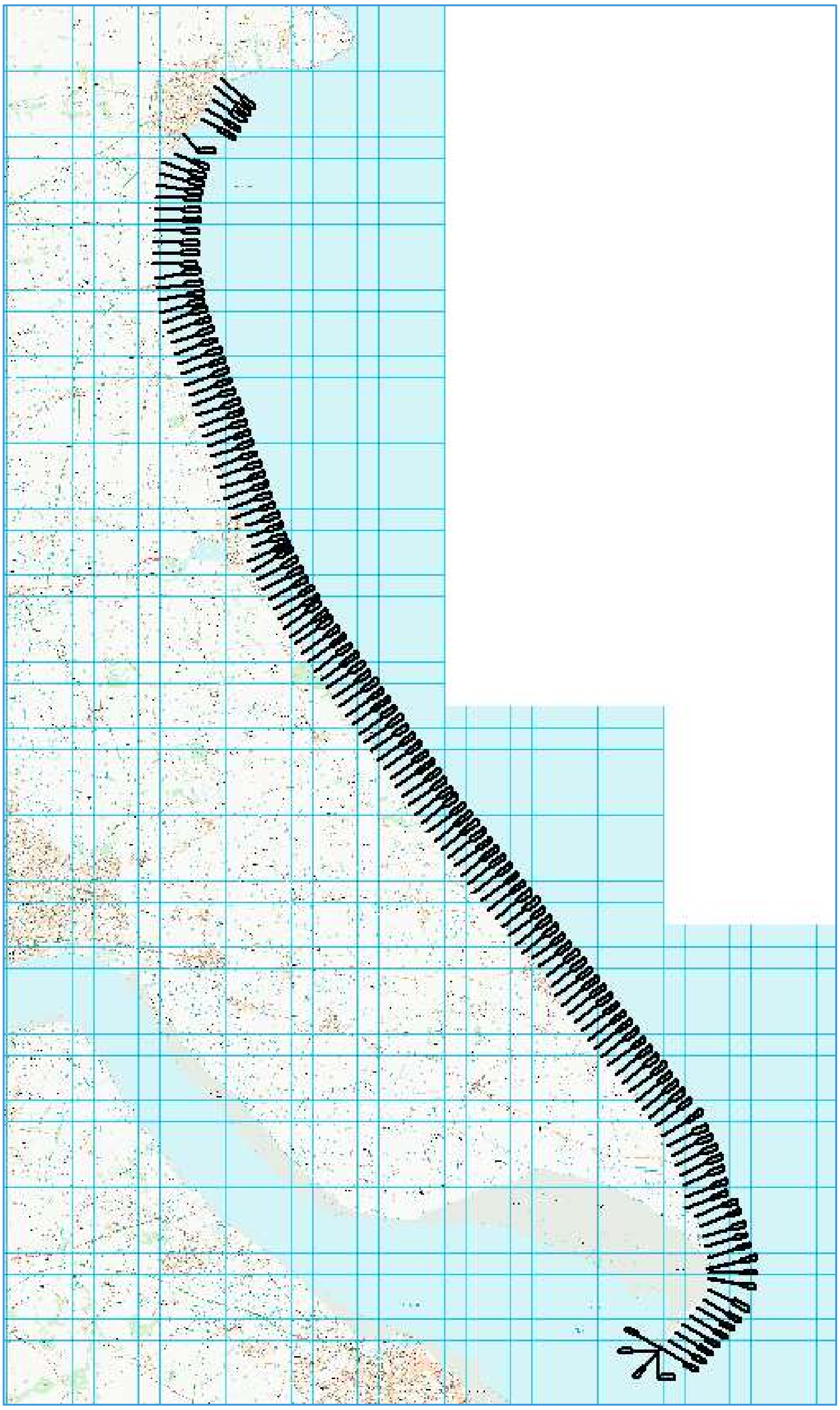

Figure A1: Location of ERYC cliff erosion measurements between 1852 and 2021 along the Holderness coast.

Table A1: Average historic cliff erosion along the Holderness coast for each of the coastal transects (ERYC data between 1852 and 2021).

Average cliff erosion between Sewerby and the neck of Spurn Head Spit for each of the coastal transects (ERYC data between 1852 and 2021)						
Erosion Profile Details		Erosion rate m/yr		Max cliff loss between profiles		
Erosion Profile	Location	Historic 1852 to 1989	Recent 1989 to 2021	Height of cliff m OD	Maximum recorded individual loss (m)	Date of max cliff loss
1	South Riviera Drive, Sewerby	No Data	No Data	25.7	5.24	April 2006
2	North of Bridlington defences	No Data	No Data	16.6	1.81	April 2011
3 to 7	Bridlington frontage	No Data	No Data	No Data	No Data	No Data
8	Within car park to south of Bridlington defences	0.59	0.00	12.2	3.60	1890 to 1907
9	Within South Shore Holiday Village, Wilsthorpe	0.41	0.02	11.2	2.47	1891 to 1907
10	South end of Wilsthorpe village	0.32	0.09	8.0	1.91	1892 to 1907
11	On Field Boundary to the North of Auburn Farm	0.20	0.38	8.1	6.40	Dec 2013
12	Opposite Auburn Farm	0.25	0.64	5.1	11.81	Dec 2013
13	On Field Boundary to the South of Auburn Farm	0.44	0.92	7.3	7.92	Dec 2013
14	North of Earl's Dyke, Barmston	0.71	1.38	6.7	9.62	May 2018
15	South of Earl's Dyke, Barmston	0.89	1.28	7.2	8.24	Dec 2013
16	Within Watermill Grounds to north of Barmston	0.95	1.43	8.3	11.29	Dec 2013
17	Opposite Hamilton Hill to north of Barmston	1.03	0.89	5.5	8.25	March 2006
18	To north of Barmston Beach caravan site, Barmston	1.18	0.87	9.8	7.54	Sept 2007

19	To south of Sands Lane, Barmston	1.37	1.58	7.0	12.25	Dec 2013
20	Opposite Barmston Outfall	1.58	0.90	9.1	12.48	March 2008
21	Opposite Brickdale to south of Barmston	1.67	1.60	5.9	9.66	March 2004
22	North Boundary of North Caravan Park, Skipsea	1.71	1.52	7.4	9.98	March 2004
23	South end of Seaside Caravan Park, Ulrome	1.70	0.85	7.1	10.04	March 2016
24	Between defences opposite Southfield Lane, Ulrome	1.56	1.16	8.2	8.83	March 2016
25	North end of Green Lane, Skipsea	1.54	1.34	8.4	9.36	March 2007
26	South of Green Lane, Skipsea	1.58	0.90	10.6	10.17	March 2008
27	Opposite Skipsea village	1.33	1.04	13.0	10.95	April 2011
28	Opposite bungalows to south of Skipsea	1.19	1.42	12.9	11.60	April 2013
29	To south of Withow Gap, Skipsea	1.10	1.41	11.6	9.82	March 2020
30	Within golf course to north of Skirlington	1.07	1.13	14.6	7.86	March 2016
31	North end of Skirlington campsite	1.07	0.95	18.3	8.34	May 2018
32	Within Low Skirlington campsite	1.02	1.26	15.4	13.02	March 2020
33	South end of Low Skirlington campsite	1.00	1.14	16.5	8.26	March 2007
34	At north end of Long Lane Atwick	1.11	0.84	14.9	11.64	April 2021
35	Opposite Long Lane, Atwick	1.06	1.17	17.4	8.13	March 2005
36	Opposite Cliff Road, Atwick	1.01	0.94	14.8	7.79	Sept 2005
37	South of Atwick	1.06	0.85	20.2	10.97	April 2013

38	Just north of Atwick Gap boat club, Hornsea	0.95	0.69	17.2	13.99	March 2008
39	Within campsite north end of Cliff Road, Hornsea	0.82	0.43	19.2	10.03	April 2011
40	Just south of Nutana Avenue, north Hornsea	0.65	0.26	16.6	5.82	Sept 2005
41	north end of Hornsea frontage	0.56	0.09	15.2	1.60	1853 to 1890
42 to 44	Hornsea frontage					
45	Within caravan park to south of defences	1.62	2.31	17.6	9.66	March 2020
46	South of Hornsea	1.86	2.78	17.5	10.83	Sept 2004
47	Within Rolston firing range	1.77	2.77	17.1	9.79	Sept 2012
48	Opposite Rolston	1.77	2.42	16.8	9.88	March 2004
49	South end of old children's camp site, Rolston	1.67	2.26	17.1	8.94	March 2020
50	North of Mappleton	1.58	1.32	17.3	9.80	May 2018
51	North of Mappleton defences	1.56	0.22	17.5	10.06	March 2020
52	South of Mappleton defences	1.54	2.04	18.5	10.25	March 2020
53	Between Mappleton and Cowden	1.58	3.21	16.2	10.28	April 2011
54	North of Ellmere Lane, Cowden	1.50	2.90	18.5	11.66	May 2018
55	South end of Cowden	1.55	3.33	18.4	15.07	April 2021
56	North end of MOD site Cowden	1.50	2.60	16.6	12.65	Dec 2013
57	Within MOD site Cowden	1.55	2.84	18.9	10.78	March 2016
58	Within MOD site Cowden	1.49	2.56	15.2	10.60	April 2005
59	Within MOD site Cowden	1.34	2.10	15.2	9.25	Sept 2012
60	South end of MOD site Cowden	1.34	2.38	16.7	14.52	Nov 2014
61	South of MOD site Cowden	1.24	2.57	19.9	13.59	Sept 2008

62	North of Aldbrough	1.10	2.80	17.8	11.01	April 2011
63	South of Aldbrough	1.07	2.15	20.3	13.55	Oct 2006
64	North of Hill Top Farm, south Aldbrough	1.06	2.55	19.8	14.92	March 2007
65	South of Hill Top Farm, south Aldbrough	1.09	2.41	20.5	16.18	March 2008
66	Opposite East Newton	1.01	2.51	16.9	11.23	Sept 2007
67	Between East Newton and Ringbrough	0.97	2.06	13.3	13.85	April 2009
68	Opposite Ringbrough	0.94	2.02	22.0	14.34	March 2006
69	South of Ringbrough	0.97	2.47	15.8	12.87	Oct 2006
70	South of Ringbrough	1.03	2.71	22.7	12.45	Sept 2012
71	North of Garton	1.14	2.45	21.1	11.55	March 2016
72	South of Garton	1.09	2.06	23.2	14.20	Sept 2004
73	Opposite Grimston Park	1.05	2.04	23.8	13.62	Sept 2007
74	South of Grimston Park	0.99	2.04	21.4	14.56	March 2020
75	North of Hilston	0.95	2.16	20.2	11.51	March 2008
76	Opposite Hilston village	0.94	2.24	19.8	9.85	April 2013
77	North of Pastures Lane Tunstall	0.95	1.67	21.3	13.10	Nov-17
78	North end of Pastures Lane Tunstall	0.92	1.74	24.1	12.49	Sept 2012
79	Opposite Pastures Lane Tunstall	0.84	1.84	16.9	10.91	April 2005
80	North of Tunstall village	0.74	1.66	10.4	11.20	March 2006
81	South of Tunstall village	0.61	1.78	14.4	10.81	March 2006
82	North of Sand Le Mere Campsite, Tunstall	0.57	2.29	16.4	11.08	Sept 2007
83	South of Sand Le Mere Campsite, Tunstall	0.54	1.68	7.4	18.38	March 2008
84	South of Sand Le Mere, Tunstall	0.69	2.52	11.9	22.68	Sept 2007

85	Opposite Redhouse Farm, south Tunstall	0.82	2.00	12.0	14.32	April 2021
86	North of Waxholm	0.87	1.35	14.3	9.95	April 2009
87	South of Waxholm	0.78	1.35	11.4	9.75	Oct 2010
88	Between Waxholm and Withernsea	0.70	1.16	14.5	14.49	April 2013
89	North of Withernsea defences	0.66	0.51	15.9	9.10	April 2013
90 to 93	Withernsea frontage	No Data	No Data	No Data	No Data	No Data
94	South of Turner Avenue at south end of Withernsea	2.14		13.5	10.49	October 2019
95	South of Golden Sands campsite Withernsea	1.81	4.22	13.3	12.65	October 2019
96	Just north of Intack Farm, Hollym	1.32	4.04	14.0	13.73	March 2006
97	Opposite sewage works off Holmpton Road	1.08	4.29	9.3	13.36	Oct 2013
98	Just north of Nevilles Farm, Holmpton	1.22	3.81	8.9	16.50	March 2007
99	Just north of The Runnell, Holmpton	1.50	1.92	7.8	18.74	Sept 2007
100	North of Holmpton Village	1.60	1.42	9.3	17.82	March 2008
101	Opposite Holmpton Village	1.56	1.41	15.8	11.16	March 2008
102	South of Holmpton Village	1.48	1.28	19.5	12.90	March 2020
103	South of Holmpton Village	1.55	1.12	17.2	10.47	March 2016
104	North of Out Newton	1.57	1.09	15.2	12.25	March 2020
105	Opposite Out Newton	1.58	0.54	24.5	9.31	Nov-17
106	South of Out Newton	1.62	0.81	23.4	11.74	April 2021
107	Dimlington High	1.69	0.79	35.4	14.92	March 2008
108	South of Dimlington High	1.63	1.41	27.7	14.34	May 2018

109	Between Dimlington High and Easington	1.50	1.52	23.0	12.81	May 2018
110	North end of gas terminal site, Easington	1.67	No Data	18.3	No Data	No Data
111	Centre of gas terminal site, Easington	1.77	Defended	12.2	No Data	No Data
112	South end of gas terminal site, Easington	1.75	No Data	12.4	No Data	No Data
113	To south of Easington defences	1.72	1.24	7.9	14.82	Oct 2010
114	Opposite Seaside Rd to south of Easington	1.73	1.23	6.8	7.67	April 2010
115 to 117	Easington/ Kilnsea Dunes	No Data	No Data	No Data	No Data	No Data
118	South end of Lagoon/Dune SSSI, Kilnsea	2.77	1.63	4.5	9.91	April 2009
119	North of old MOD site, Kilnsea	2.24	2.16	7.8	7.88	May 2010
120	South of BlueBell, Kilnsea	1.99	2.52	4.3	12.25	March 2008
121	Between Kilnsea and Spurn	2.18	2.04	6.1	13.28	March 2008
122	North end of Spurn	1.79	1.98	5.4	8.29	May 2018
123	Neck point Spurn peninsular	1.01	No Data	5.7	No Data	No Data