Hornsea Project Three
Offshore Wind Farm

# Hornsea Project Three

# Offshore Wind Farm

## Environmental Statement:
## Volume 5, Annex 1.1 – Marine Processes Technical Report

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Hornsea 3
Offshore Wind Farm

Ørsted

**Environmental Impact Assessment**

**Environmental Statement**

**Volume 5**

**Annex 1.1 – Marine Processes Technical Annex**

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# Glossary

| Term | Description |
|---|---|
| Accretion | Build-up (accumulation) of material solely by the deposition of water or airborne material through natural processes. |
| Astronomical tide | The tide levels and character which would result from the gravitational influence of the earth sun and moon without any atmospheric influences. |
| Acoustic Wave And Current Profiler (AWAC) | A Nortek instrument which measures wave height, wave direction and the full current profile. |
| Beach profile | A cross-section taken perpendicular to a given beach contour; the profile may include the face of a dune or seawall, extend over the backshore, across the foreshore, and seaward underwater into the nearshore zone. |
| Bedforms | Features on the seabed (e.g. sandwaves, ripples) resulting from the movement of sediment over it. |
| Bedload | Sediment particles that travel near or on the bed. |
| Bed shear stress | The force exerted by moving water against the bed. |
| Benthic | A description for animals, plants and habitats associated with the seabed. All plants and animals that live in, on or near the seabed are benthos. |
| British Oceanographic Data Centre (BODC) | National facility for looking after and distributing data concerning the marine environment. |
| Clay | A fine grained sediment with a typical grain size of less than 0.004 mm. Possesses electromagnetic properties which bind the grains together to give a bulk strength or cohesion. |
| Climate change | A long term trend in the variation of the climate resulting from changes in the global atmospheric and ocean temperatures and affecting mean sea level, wave height, period and direction, wind speed and storm occurrence. |
| Coastal processes | Collective term covering the action of natural forces on the coastline and adjoining seabed. |
| Cohesive sediment | Sediment containing a significant proportion of clays, the electromagnetic properties of which cause the particles to bind together. |
| Diamicton | Sediment that is unsorted to poorly sorted and contains particles ranging in size from clay to boulders, suspended in a matrix of mud or sand. |
| Diffraction | Process by which energy is transmitted laterally along a wave crest. Propagation of waves into the sheltered region behind a barrier such as a breakwater. |
| Diurnal | Having a period of a tidal day 24.84 hours. |
| European Marine Observation and Data Network (EMODnet) | EMODnet is a Directorate-General for Maritime Affairs and Fisheries (DG MARE) funded network of organisations supported by the European Union's integrated maritime policy. These organisations work together to observe the sea, process the data according to international standards and make that information freely available as interoperable data layers and data products. |
| Erosion | Movement of material by such agents as running water, waves, wind, moving ice and gravitational creep. |

| Term | Description |
|---|---|
| Geophysical survey | Activities to obtain data on the distribution and nature of geophysical properties of the seabed (e.g. bathymetry, surficial sediment type and bedforms, sub-surface geology). Geophysical survey outputs typically include multibeam bathymetry, side-scan sonar and sub-bottom profiler data. |
| Hindcast | The retrospective prediction of historical (wind and wave) conditions. |
| Hydrodynamic | Of or relating to the motion of fluids and the forces acting on solid bodies immersed in fluids and in motion relative to them. |
| Intertidal zone | The zone between the highest and lowest tides. May also be referred to as the littoral zone. |
| Lowest Astronomical Tide (LAT) | The minimum tidal level (under average meteorological conditions) which can be reached |
| Light Detecting and Ranging (LiDAR) | A surveying method that measures distance to a target by illuminating that target with a laser light. |
| Littoral drift, littoral transport | The movement of beach material in the littoral zone by waves and currents. Includes movement parallel (longshore transport) and perpendicular (onshore- offshore transport) to the shore. |
| Longshore drift | Or alongshore or littoral drift. Movement of sand and shingle along the shore. It takes place in two zones, at the upper limit of wave activity and in the breaker zone. Movement of beach (sediments) approximately parallel to the coastline. |
| Morphological | Of or relating to the form, shape and structure of landforms |
| Neap tides | Tides with the smallest range between high and low water, occurring at the first and third quarters of the moon. |
| North Atlantic Oscillation (NAO) | Weather phenomenon in the North Atlantic Ocean of fluctuations in the difference of atmospheric pressure at sea level between the Icelandic low and the Azores high. |
| Pycnocline | A layer, zone, or gradient of changing density, esp. a thin layer of ocean water with a density that increases rapidly with depth<br>Read more at http://www.yourdictionary.com/pycnocline#p1BRxpeQeHiXWbKs.99 |
| Receptor | A component of the natural or man-made environment that is affected by an impact, including people. |
| Regime | The behaviour, statistical properties and trends characterising the variability of hydrodynamic, meteorological, sedimentological and morphological parameters. |
| Return period | In statistical analysis an event with a return period of N years is likely, on average, to be exceeded only once every N years. |
| Salinity | Measure of all the salts dissolved in water. |
| Scour | Local erosion of sediments caused by local flow acceleration around an obstacle and associated turbulence enhancement. |
| Sediment transport | The movement of a mass of sedimentary material by the forces of currents and waves. The sediment in motion can comprise fine material (silts and muds), sands and gravels. Potential sediment transport is the full amount of sediment that could be expected to move under a given combination of waves and currents, i.e. not supply limited. |
| Sediment transport pathway | The routes along which net sediment movements occur. |

| Term | Description |
|---|---|
| Semi-diurnal | Having a period of approximately one half of a tidal day (12.4 hours). The predominating type of tide throughout the world is semi-diurnal with 2 high waters and 2 low waters each day. |
| Significant wave height | The average height of the highest of one third of the waves in a given sea state. |
| Spring tides | Tides with the greatest range which occur at or just after the new and full moon. |
| Seastate | The state of the sea as described using the Douglas sea scale, based on wave height and swell, ranging from 1 to 10, with accompanying descriptions. |
| Shoreline Management Plan | A Shoreline Management Plan (SMP) is a large-scale assessment of the risks associated with coastal processes. It aims to lessen these risks to people and the developed, historic and natural environments. |
| Suspended Particulate Matter (SPM) | Close to the bed, suspended matter typically consists of re-suspended mineral matter, but higher up in the water column SPM is typically in the form of flocs – loosely bound aggregates composed of mineral matter (e.g. clay minerals) as well as organic matter. |
| Storm surge | A rise in water level in the open coast due to the action of wind stress as well as atmospheric pressure on the sea surface. |
| Surficial sediments | Sediments located at the seabed surface (not necessarily of the same character as underlying sediments). |
| Surge | In water level as a result of meteorological forcing (wind, high or low barometric pressure) causing a difference between the recorded water level and that predicted using harmonic analysis, may be positive or negative. |
| Suspended load | The material moving in suspension in a fluid, kept up by the upward components of the turbulent currents or by the colloidal suspension. |
| Suspended sediment concentration (SSC) | Mass of sediment in suspension per unit volume of water. |
| Swell (waves) | Wind-generated waves that have travelled out of their generating area. Swell characteristically exhibits a more regular and longer period and has flatter crests than waves within their fetch. |
| Tidal asymmetry | 1) Relative difference in peak current speed or duration of adjacent flood and ebb half tidal cycles. 2) Relative difference in high or low water levels or duration of adjacent flood and ebb half tidal cycles. |
| Tidal excursion | The Lagrangian movement (the physics of fluid motion as an individual fluid parcel moves through space and time) of a water particle during a tidal cycle. |
| Tidal excursion ellipse | The path followed by a water particle in one complete tidal cycle. |
| Tide | The periodic rise and fall in the level of the water in oceans and seas; the result of gravitational attraction of the sun and moon. |
| Till | Collective term for the group of sediments laid down by the direct action of glacial ice without the intervention of water. |
| Topography | The form of the features of the actual surface of the earth in a particular region considered collectively. |
| Turbidity | Turbidity is a measure of the degree to which the water loses its transparency due to the presence of suspended particles. Suspended sediment concentration (SSC) refers to the mineral fraction of the suspended solids load whilst SPM includes both the in-organic and organic component. |
| United Kingdom Climate Projections (UKCP) | UKCP09 is the name given to the latest UK Climate Projections. UKCP09 provides information on plausible changes in 21st century climate for land and marine regions in the United Kingdom. |

## Acronyms

| Acronym | Description |
|---|---|
| BERR | Department for Business, Enterprise and Regulatory Reform |
| BGS | British Geological Survey |
| CEA | Cumulative Effects Assessment |
| Cefas | Centre for Environment, Fisheries and Aquaculture Science |
| COWRIE | Collaborative Offshore Wind Research into the Environment |
| DECC | Department of Energy and Climate Change |
| Defra | Department for Environment, Food and Rural Affairs |
| DHI | Danish Hydraulic Institute |
| DTI | Department of Trade and Industry |
| EA | Environment Agency |
| EIA | Environmental Impact Assessment |
| ES | Environmental Statement |
| GIS | Geographical Information System |
| HAT | Highest Astronomical Tide |
| HDD | Horizontal Directional Drilling |
| HRW | (Hydraulics Research) Wallingford |
| HV | High Voltage |
| JNCC | Joint Nature Conservation Committee |
| LAT | Lowest Astronomical Tide |
| LiDAR | Light Detection and Ranging |
| MALSF | Marine Aggregate Levy Sustainability Fund |
| MCZ | Marine Conservation Zone |
| MHWN | Mean High Water of Neap Tides |
| MHWS | Mean High water of Spring Tides |
| MIKE21SW | MIKE by DHI Spectral Wave modelling software module |
| MLWN | Mean Low Water of Neap Tides |
| MLWS | Mean Low water of Spring Tides |
| MMO | Marine Management Organisation |
| MSL | Mean Sea Level |
| MW | Megawatt(s) |
| NAO | North Atlantic Oscillation |
| ODN | Ordnance Datum Newlyn |
| REA | Regional Environmental Assessment |
| rMCZ | (Recommended) Marine Conservation Zone |
| SAC | Special Area of Conservation |
| SCI | Site of Community Importance |
| SMP | Shoreline Management Plan |
| SPA | Special Protection Area |
| SPM | Suspended Particulate Matter |
| SSC | Suspended Sediment Concentration |
| SSSI | Sites of Special Scientific Interest |
| SWAN | Simulating WAves Nearshore |
| UK | United Kingdom |
| UKCP09 | United Kingdom Climate Projections 2009 |
| UKHO | United Kingdom Hydrographic Office |
| UKMO | UK Met Office |
| ZoC | (former) Hornsea Zone Characterisation |

## Units

| Unit | Description |
|---|---|
| g | gram |
| GW | Gigawatt (power) |
| km | Kilometre (distance) |
| kV | Kilovolt (electrical potential) |
| kg | Kilogram |
| kW | Kilowatt (power) |
| m | Metre (distance) |
| MW | Megawatt (power) |
| mg/l | Milligram / litre (concentration) |
| s | Second (time) |

# 1. Introduction

## 1.1 Overview

1.1.1.1 ABPmer has been commissioned to deliver the marine processes requirements of the Environmental Impact Assessment (EIA) for the Hornsea Project Three Offshore Wind Farm (hereafter referred to as 'Hornsea Three') (Figure 1.1).

1.1.1.2 The shape of the Hornsea Three array area is approximately quadrilateral, 29 km wide in an east-west axis and 35 km north-south. Hornsea Three array area is 121 km from the UK coast (at Tringham, Norfolk). The Hornsea Three array area is located to the east of both the (consented) Hornsea Project One and (consented) Hornsea Project Two array areas and is located within the former Hornsea Zone.

1.1.1.3 The Hornsea Three offshore cable corridor is approximately 163 km long and is orientated in a broad northeast to southwest direction. The export cable landfall is located on the north Norfolk Coast, between Weybourne Hope and Kelling Hard.

1.1.1.4 This technical annex provides the findings of an assessment of the potential for change to marine processes as a consequence of the construction, operation and maintenance, and decommissioning of Hornsea Three, both on its own and in conjunction with other planned, consented and operational projects. These findings have subsequently been used to underpin the significance of effect assessments for marine processes receptors, presented in volume 2, chapter 1: Marine Processes. The results have also been used to inform assessments for other EIA receptor groups which may potentially be sensitive to changes in marine processes.

## 1.2 Approach

1.2.1.1 In order to assess the potential changes relative to the baseline (existing) coastal and marine environment, a combination of complementary approaches have been adopted for the Hornsea Three marine processes assessment. These include:

- The 'evidence base' containing monitoring data collected during the construction, and operation and maintenance of other offshore wind farm developments. The evidence base also includes results from numerical modelling and desk based analyses undertaken to support other offshore wind farm EIAs, especially that used to support the consenting processes for the nearby Hornsea Project One and Hornsea Project Two;
- Analytical assessments of project-specific data, including the use of rule based and spreadsheet based numerical models;
- Analytical and spectral wave modelling to consider potential changes to the wave regime in response to the operation of Hornsea Three, as well as the potential for cumulative changes associated with the operation of Hornsea Project One, Hornsea Project Two and Hornsea Three; and
- Standard empirical equations describing the relationship between (for example) hydrodynamic forcing and sediment transport or settling and mobilisation characteristics of sediment particles released during construction activities (e.g. Soulsby, 1997).

1.2.1.2 Consent applications for Hornsea Project One and Hornsea Project Two were made on the basis of a number of technical marine processes studies (amongst other EIA topics), which included the use of numerical modelling to quantify the environmental baseline and scheme impacts. From the outset, it should be noted that for many of the marine processes assessments, the existing evidence base from Hornsea Project One and Hornsea Project Two is used to validate and corroborate the findings of the independent quantitative analyses carried out for Hornsea Three. For instance, plume dispersion modelling was carried out to inform understanding of construction related impacts associated with Hornsea Project One and Hornsea Project Two. This information has been used to validate the findings of the independent spreadsheet based models used to inform the Hornsea Three sediment plume assessments.

1.2.1.3 The scope of the issues for assessment for marine processes is very similar (although not identical) to that previously considered for Hornsea Project One and Hornsea Project Two. The range of issues assessed in this report are summarised below whilst the specific impacts/ changes considered within volume 2, chapter 1: Marine Processes are listed in Table 1.1:

- Construction and decommissioning phase (each lasting up to eight years if the project is undertaken in two phases): short-term changes resulting from sediment disturbance activities. These will arise due to mechanical interaction with the seabed during foundation and cable laying activities, with material being transported in the water column and deposited at locations away from the source; and
- Operational and maintenance phase (25 years): persistent blockage of the passage of waves and tides due the physical presence of structures on the seabed and through the water column during the lifetime of Hornsea Three, with the potential for localised interactions leading to possible scouring around the base of individual foundations and exposed cables.

1.2.1.4 It is important to note that the spatial extent of these potential changes may differ greatly. Some (such as scour) will be operational at the structure-scale (metres to tens of metres). Others (such as changes to the wave regime) will extend away from the array area, into the far-field.

1.2.1.5 The assessment has been made with due consideration of naturally occurring variability in, or long-term changes to, marine processes during Hornsea Three lifetime (25 years). This encompasses seasonal change as well as climate change (e.g. sea level rise). This is important as it enables a reference level to be established against which the potentially modified marine processes can be compared, throughout the Hornsea Three lifecycle.

1.2.1.6 It should be recognised that in most cases, marine processes are not in themselves receptors but are, instead, 'pathways' which have the potential to indirectly impact other environmental receptors. Table 1.1 highlights which potential impacts / changes are considered as pathways and which are considered as receptors. Notwithstanding the above, three specific marine processes receptors have been identified within the Hornsea Three marine processes study area (Figure 1.1):

- The shoreline;
- Offshore sandbanks; and
- The Flamborough Front.

1.2.1.7 This annex provides the technical information underpinning each of the impacts listed in Table 1.1 and assessed within volume 2, chapter 1: Marine Processes. This annex does not:

- Provide detailed baseline information;
- Define the Maximum Design Scenarios; or
- Assign significance of effects.

1.2.1.8 Instead, all of the above information is contained within the Marine Processes chapter (volume 2, chapter 1: Marine Processes).

**Table 1.1: Summary of potential impacts/ changes considered in the marine processes assessment.**

| Potential impact/ change | Pathway/ receptor |
|---|---|
| ***Construction*** | |
| Increases in suspended sediment concentration (SSC) and deposition of disturbed sediments to the seabed due to drilling for foundation installation within the Hornsea Three array area. | Pathway |
| Increases in SSC and deposition of disturbed sediments to the seabed due to dredging for seabed preparation prior to installing gravity base foundations within the Hornsea Three array area. | Pathway |
| Increases in SSC and deposition of disturbed sediments to the seabed due to cable installation within the Hornsea Three array area. | Pathway |
| Increases in SSC and deposition of disturbed sediments to the seabed due to sandwave clearance within the Hornsea Three array area. | Pathway |
| Increases in SSC and deposition of disturbed sediment to the seabed due to drilling for foundation installation within the Hornsea Three offshore cable corridor. | Pathway |
| Increases in SSC and deposition of disturbed sediments to the seabed due to dredging for seabed preparation prior to installing gravity base foundations within the Hornsea Three offshore cable corridor. | Pathway |
| Increases in SSC and deposition of disturbed sediment to the seabed due to cable installation within the Hornsea Three offshore cable corridor. | Pathway |
| Increases in SSC and deposition of disturbed sediment to the seabed due to sandwave clearance within the Hornsea Three offshore cable corridor. | Pathway |
| Indentations on the seabed left by jack-up vessels. | Pathway |
| Removal of sandwaves impacting sandbank systems within proximity to the Hornsea Three array area and offshore cable corridor. | Pathway and receptor |
| Changes to hydrodynamics, sediment transport and beach morphology at the landfall. | Pathway and receptor |
| ***Operation and Maintenance*** | |
| Changes to the tidal regime, with associated potential impacts to sandbanks. | Pathway and Receptor |
| Changes to the wave regime, with associated potential impacts to sandbanks and along adjacent shorelines. | Pathway and Receptor |
| Scour of seabed sediments. | Pathway |
| Changes to sediment transport and sediment transport pathways with associated potential impacts to sandbanks. | Pathway and receptor |
| Changes to water column stratification with associated potential impacts to the Flamborough Front. | Pathway and receptor |
| Changes to beach morphology, hydrodynamics and sediment transport (littoral drift) at the landfall. | Pathway and receptor |

| Potential impact/ change | Pathway/ receptor |
|---|---|
| ***Decommissioning*** | |
| Increases in SSC and deposition of disturbed sediment to the seabed within the Hornsea Three array area. | Pathway |
| Increases in SSC and deposition of disturbed sediment to the seabed within the Hornsea Three offshore cable corridor. | Pathway |
| Removal of sandwaves impacting sandbank systems within proximity to the Hornsea Three array area and offshore cable corridor. | Pathway and receptor |
| Changes to hydrodynamics, sediment transport and beach morphology at the landfall. | Pathway and receptor |

## 1.3 Report structure

1.3.1.1 This report is structured around the potential impacts and effects requiring assessment, as identified during Scoping and through discussions held at the Marine Processes, Benthic Ecology and Fish and Shellfish Expert Working Group meetings (see Table 1.2 of volume 2, chapter 1: Marine Processes for further information on the consultation undertaken to date):

- Section 2: Using an evidence based approach;
- Section 3: Guidance;
- Section 4: Suspended sediment concentrations, bed levels and sediment type;
- Section 5: Turbid wakes;
- Section 6: Landfall;
- Section 7: Tidal regime;
- Section 8: Wave regime;
- Section 9: Sediment transport regime;
- Section 10: Water column stratification; and
- Section 11: Scour and seabed alteration.

1.3.1.2 In this report, the following terminology is used to characterise geographical regions of the Hornsea Three marine processes study area (Figure 1.1):

- Nearshore area (0 mLAT contour out to ~ -5 mLAT contour);
- Inshore area (~ -5 mLAT contour out to ~ -20 mLAT contour); and
- Offshore area (seaward of the ~ -20 mLAT contour).

1.3.1.3 A description of the baseline environment across the marine processes study area is provided within volume 2, chapter 1: Marine Processes. Maximum Design Scenarios used in the assessments presented in this report are also set out in volume 2, chapter 1: Marine Processes.

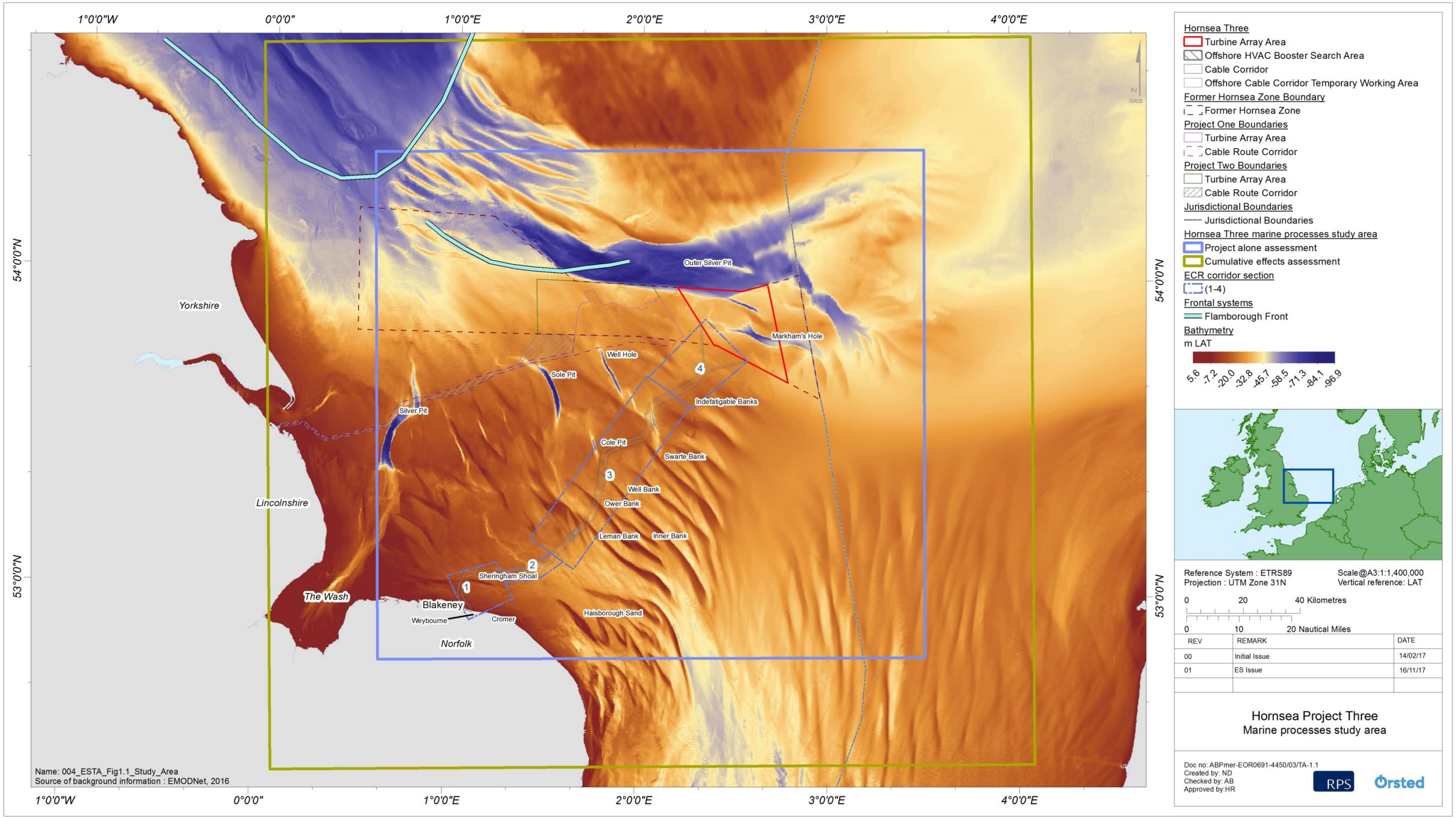


**Figure 1.1: Hornsea Three marine processes study area.**

# 2. Using an Evidence Based Approach

## 2.1 Overview

2.1.1.1 As stated in section 1, an evidence based approach has been adopted to help inform many of the assessments of changes to marine processes arising from Hornsea Three. This section provides an explanation of the approach and documents full justification for its application to Hornsea Three.

2.1.1.2 The evidence based approach to EIA utilises existing data and information from sufficiently similar or analogous studies to inform baseline understanding and/or impact assessments for a new proposed development. In this way, the evidence based approach does not necessarily require new data to be collected, or new modelling studies to be undertaken, in order to characterise the potential impact with sufficient confidence for the purposes of EIA.

2.1.1.3 An evidence based approach to marine processes can be applied where it can be demonstrated that adequate suitable information (evidence) already exists to inform the baseline characterisation and/or assessment phase of the EIA process for a given potential impact type and/or receptor:

- An evidence based approach to baseline characterisation relies upon the previous collection or development of a sufficient quantity and quality of baseline data; and
- An evidence based approach to impact assessment relies upon it being demonstrated that the aspect of the proposed development being assessed (or other developments in a cumulative sense) remains of a sufficiently similar character (e.g. operation type, foundation type and number, etc.) to an existing consented development or other close analogies, located in a similar environmental context.

2.1.1.4 An evidence based approach to EIA for marine processes issues has been successfully adopted for a number of other offshore wind farm developments where, as for Hornsea Three, development was proposed adjacent to an existing consented or operational site:

- Seagreen Phase 1 (Round 3; consented in 2014);
- Burbo (Round 2 extension; consented in 2014);
- Walney (Round 2 extension; consented in 2014); and
- Gunfleet Sands 2 and Demonstration sites (consented in 2008).

2.1.1.5 In addition to the above, the East Anglia THREE (Round 3) offshore wind farm EIA has been undertaken using an evidence based approach (East Anglia Offshore Wind, 2015) and was consented in August 2017. Key site details and project design information considered in the application are summarised below:

- The East Anglia THREE site is located in the southern North Sea, approximately 69 km offshore from Lowestoft on the Suffolk coast;
- Water depths across the East Anglia THREE site typically range from -35 m Lowest Astronomical Tide (LAT) to -45 mLAT, but the extreme depths range from a minimum of -25 mLAT to a maximum of -49 mLAT;
- The seabed across the East Anglia THREE site is characterised predominantly by sand, with some muddy sand;
- In places, surficial sediments are a thin veneer and the underlying muddy Brown Bank Formation is close to seabed;
- East Anglia THREE project would have a total capacity of 1,200 MW, with between 100 (12 MW) and 172 (7 MW) wind turbines;
- The minimum spacing between adjacent wind turbines would be 675 m within each row and a minimum spacing of 900 m between rows; and
- Gravity base foundations (gravity base foundations) (which typically cause the greatest blockage of waves and flows) with a basal diameter of up to 60 m may be used.

2.1.1.6 There are a number of close similarities between the Hornsea Three and East Anglia THREE projects, both in terms of their similarity with other consented projects within their respective Round 3 development zones as well as with each other. Key similarities include:

- Environmental setting (such as seabed sediments, water depths, wave climate);
- Project design (such as maximum foundation dimensions); and
- Availability of an extensive evidence base from an adjacent analogous development.

2.1.1.7 A more detailed project independent discussion regarding the justification for, and the application of evidence based approaches to EIA of offshore wind farms may be found in ABPmer and HR Wallingford (2009). The methods and approaches contained in this report are informed by, and consistent with, the recommendations of ABPmer and HR Wallingford (2009).

## 2.2 Justification

2.2.1.1 As stated in section 2.1, an evidence based assessment approach may applicable to either baseline characterisation and/or the impact assessment phase. In terms of baseline characterisation, a large body of new project-specific data has been collected to inform understanding of the Hornsea Three array area and offshore cable corridor baseline environment, particularly in terms of seabed morphology and seabed/sub-seabed sediment characteristics. In addition to this new data for Hornsea Three, a large body of existing metocean, geophysical, geotechnical and benthic survey data is also available from across the former Hornsea Zone, along with a number of publically available datasets and reports. All of these project and non-project specific datasets are described within volume 2, chapter 1: Marine Processes. Collectively, these combined datasets provide sufficient detail to enable robust characterisation of the Hornsea Three Project area in terms of the metocean, seabed and sub-seabed setting. The remainder of this section focuses on the justification for the application of an evidence based approach to the assessment of potential marine processes impacts.

2.2.1.2 The application of an evidence based approach to the assessment of potential changes to marine processes associated with Hornsea Three is justified given:

- The proximity of Hornsea Three to Hornsea Project One and Hornsea Project Two (see Figure 1.1) for which a large body of evidence (including numerical modelling) already exists regarding potential impacts (see SMart Wind 2013, 2015a);
- The broad similarities in environmental characteristics (Table 2.1); and
- The broad similarity with respect to the project design characteristics between Hornsea Project One, Hornsea Project Two and Hornsea Three (Table 2.2 and Table 2.3).

2.2.1.3 The applicability of an evidence based approach is further supported by the assessment outcomes for Hornsea Project One and Hornsea Project Two, which found no significant impacts for marine processes receptors (Table 2.4).

2.2.1.4 Finally, (and as stated in section 1.2), for the vast majority of the marine processes assessments presented in this report, the existing evidence base from Hornsea Project One and Hornsea Project Two (as well as other offshore wind farm developments) has not solely been relied upon to underpin the Hornsea Three marine processes assessment. Instead, independent quantitative analyses have been carried out which validate and support the evidence base.

**Table 2.1: Summary of key similarities and differences between baseline conditions within the Hornsea Project One, Hornsea Project Two and Hornsea Three array areas.**

| Theme | Comment |
|---|---|
| Tidal elevations | There is a broad northeast to southwest gradient in tidal water levels with the greatest tidal range experienced closer inshore. Within the Hornsea Three array area the mean spring range (MSR) is between approximately 2.0 and 2.5 m; in contrast the MSR across the Hornsea Project One and Hornsea Project Two array areas is between approximately 2.5 m and 3.5 m. The difference in tidal range between the sites is therefore comparable to the difference within individual sites. Moreover, the relative influence of tidal range on total water depth within the Hornsea Three array area, and the relative difference between the sites in this respect, is small. For example, a mean spring range of 2 m in variable water depths of 25-45 m (avg. depth of 35 m) represents a water level variation of approximately 5.7%. In comparison, a mean spring range of 2.5 m in the same setting represents a variation of 7.1% - i.e. a difference of only 1.4%. |
| Tidal currents | Across the former Hornsea Zone, tidal current velocities vary broadly in accordance with the observed gradients in tidal range. Peak tidal current speeds are correspondingly higher (approximately 0.9 m/s) in the Hornsea Project One and Hornsea Project Two array areas than in the Hornsea Three array area (approximately 0.7 m/s). |
| Wave climate | Significant wave heights appear well correlated across the entire area with all wave events of any significance occurring essentially simultaneously across the area. The prevailing wave direction across all three array areas is from the north-northwest. |
| Bathymetry | Across large parts of the Hornsea Three array area, water depths are comparable to those in the Hornsea Project One and Hornsea Project Two array areas (approximately -25 m to -40 mLAT). Discrete areas of relatively deeper water are present within the Hornsea Three array area along the northern boundary (up to approximately -60 mLAT, associated with Outer Silver Pit) and in central areas (up to approximately -70 mLAT, associated with Markham's Hole). |
| Geology and seabed sediments | Seabed sediments across the Hornsea Project One, Hornsea Project Two and Hornsea Three array areas are dominated by the presence of sands and gravels, with spatially varying combinations of each. However, discrete areas of relatively finer grained muddy sand are also present within the Hornsea Three array area (associated with Outer Silver Pit and Markham's Hole).<br>The underlying solid geology of the region is complex and is overlain by varying thicknesses of Quaternary sediments. These generally increase in thickness in an easterly direction and may be 200+ m thick in the east of the former Hornsea Zone. Data from the former Hornsea Zone geophysical survey confirm that the presence of the Bolders Bank Formation is extensive across the area surveyed, and it is generally mantled by varying thicknesses of recent seabed sediment. No chalk was recorded in the two existing boreholes from the Hornsea Three array area (which terminate at depths of 44 m and 47 m below the seabed).<br>It is noted here that the underlying geology (chalk) was also not found in the boreholes collected within Hornsea Project Two array area or in any of the site specific surveys carried out within the Hornsea Project One array area. |
| Suspended sediment concentrations | Variations in SSC are observed across the former Hornsea Zone. However, these variations reflect localised changes in water depths (which influence the degree of wave stirring of the bed) and seabed sediment composition. No underlying differences between the Hornsea Project One, Hornsea Project Two and Hornsea Three array areas can be identified. |
| Sediment transport | Within the Hornsea Project One and Hornsea Project Two array areas many of the mapped bedforms are symmetrical, however, where bedforms display a marked asymmetry, in general these suggest transport to the north and northwest. Existing regional scale mapping suggests a similar net transport direction within the Hornsea Three array area as elsewhere within the former Hornsea Zone (Kenyon and Cooper, 2005). |

**Table 2.2: Summary of key metrics for Hornsea Project One, Hornsea Project Two and Hornsea Three.**

| Metric | Hornsea Project One | Hornsea Project Two | Hornsea Three |
|---|---|---|---|
| Area | 407 $km^2$ | 462 $km^2$ | 696 $km^2$ |
| Max. number of turbines | 332 | 360 | 300 |
| Max. Project capacity | 1,200 MW | 1,800 MW | 2,400 MW |
| Indicative turbine density (turbines/ $km^2$) | 0.82 | 0.78 | 0.43 |

**Table 2.3: Summary of maximum design scenario metrics for Hornsea Project One, Hornsea Project Two and Hornsea Three.**

| Metric | Hornsea Project One | Hornsea Project Two | Hornsea Three |
|---|---|---|---|
| ***Maximum design scenario sediment disturbance (drill arisings)*** | | | |
| Foundation type | Monopile | Monopile | Monopile |
| Diameter | 8.5 m | 10 m | 15 m |
| Burial depth | 50 m | 50 m | 40 m |
| Number | 332 turbines | 120 turbines | 160 turbines [a] |
| Drilling rate | 3 m/hour | 3 m/hour | 0.2 – 0.5 m/hour |
| Max volume of sediment/ foundation | 2,837 $m^3$ | 3,849 $m^3$ | 7,069 $m^3$ |
| ***Maximum design scenario sediment disturbance (bed preparation)*** | | | |
| Foundation type | Gravity base | Gravity base | Gravity base |
| Base diameter | 50 m | 58 m | 53 m |
| Number | 332 turbines | 120 turbines | 160 turbines [a] |
| Depth of seabed excavation | 5 m | 5 m | 2 m |
| Max volume of sediment/ foundation | 17,839 $m^3$ | 23,892 $m^3$ | 5,845 $m^3$ |
| ***Maximum design scenario sediment disturbance (cable installation)*** | | | |
| Max. cable length | 450 km array;<br>4 x 150 km export | 675 km array;<br>8 x 150 km export;<br>300 km interconnector | 830 km array;<br>6 x 191 km export;<br>225 km interconnector |
| Target/max cable burial depth | 1 m/ 3 m | 2 m | 1 m/ 3 m |
| Width of seabed affected | 10 m | 10 m | 10 m |
| ***Worst Case Blockage*** | | | |
| Foundation type | Gravity base | Gravity base | Gravity base |

| Metric | | Hornsea Project One | Hornsea Project Two | Hornsea Three |
|---|---|---|---|---|
| Base diameter | | 50 m | 45 m | 43 m |
| Number | | 332 | 360 | 300[b] |
| Minimum spacing | | 924 m | 932 m | 1000 m |
| Max. array dimension [c] | **N-S** | 16.0 km | 19.3 km | 32.9 km |
| | **NNE-SSW** | 16.0 km | 22.5 km | 27.2 km |
| | **NE-SW** | 19.1 km | 25.9 km | 28.1 km |
| | **E-W** | 38.1 km | 41.4 km | 31.2 |

a Layout associated with maximum design scenario for a single foundation

b Conservative maximum design scenario as refers to maximum number of foundations in array

c Describes the maximum distance across the array for the defined orientation. Only those dimensions relevant to consideration of potential changes to wave conditions shown

**Table 2.4: Summary of Hornsea Project One and Hornsea Project Two marine processes EIA methodology and outcomes.**

| Activity/ potential impact | Assessed for Hornsea Project One and Hornsea Project Two? | Approach methodology for Hornsea Project One and Hornsea Project Two | Magnitude of impact | Significance of effect |
|---|---|---|---|---|
| ***Construction*** | | | | |
| Potential for disposal of drill arisings during installation of monopile foundations to increase SSC within the water column.<br>Potential for seabed preparation prior to installing gravity base foundations to increase SSC within the water column.<br>Potential for installation of cables to increase SSC within the water column. | Yes | Assessed using plume dispersion modelling (SEDPLUME-RW model) | N/A | N/A<br>*(marine processes receptors insensitive to change)* |

| Activity/ potential impact | Assessed for Hornsea Project One and Hornsea Project Two? | Approach methodology for Hornsea Project One and Hornsea Project Two | Magnitude of impact | Significance of effect |
|---|---|---|---|---|
| Disposal of drill arisings during installation of monopile foundations will deposit material on the seabed.<br>Potential for seabed preparation prior to installing gravity base foundations to result in the deposition of material on the seabed.<br>Potential for installation of cables to deposit material on the seabed. | Yes | Assessed using plume dispersion modelling (SEDPLUME-RW model). | N/A | N/A<br>*(marine processes receptors insensitive to change)* |
| Potential for the installation of the export cable at the landfall to affect beach morphology, hydrodynamics and sediment transport (littoral drift). | Yes | Desk based assessment drawing upon recent and historical beach monitoring data. | Negligible | Negligible (insignificant) |
| ***Operation and maintenance*** | | | | |
| Potential for the presence of turbines and associated offshore infrastructure to affect the tidal regime and the wave regime, with associated potential impacts along adjacent shorelines and offshore sandbanks. | Yes | Tidal flows were modelled, using TELEMAC-2D, part of the TELEMAC Modelling System.<br>The wave transformation model used was SWAN (Simulating Waves Nearshore). Wave diffraction was modelled using the ARTEMIS wave agitation model.<br>Potential changes to sediment transport at the coast were considered using empirical equations, relating changes in wave height, period and direction with changes in the (theoretical) rate of sediment transport. | Negligible/No change | Negligible (insignificant) |
| Potential for the presence of turbine foundations to result in scour of seabed sediments. | Yes | Empirical equations to enable determination of scour pit characteristics (horizontal extent and equilibrium scour depth) from foundation design. | N/A | N/A<br>*(marine processes receptors insensitive to change)* |
| Potential for the use of cable protection along the array, platform interconnector, offshore accommodation platform and export cables in deep water to affect sediment transport and sediment transport pathways. | Yes | Assessed conceptually, drawing upon the existing evidence base and empirical equations considering (for example) the extent of wave transformation for given water depths. | N/A | N/A<br>*(marine processes receptors insensitive to change)* |
| Potential for the use of cable protection along the export cable in shallow water to affect beach morphology, hydrodynamics and sediment transport (littoral drift).<br>Potential for the export cable at the landfall to affect beach morphology, hydrodynamics and sediment transport (littoral drift). | Yes | Desk based assessment drawing upon recent and historical beach monitoring data. | Negligible | Negligible (insignificant) |
| ***Decommissioning*** | | | | |
| Cutting off jacket foundations below the seabed surface has the potential to increase SSC within the water column and deposit material on the seabed.<br>Potential for removal of gravity base foundations to increase SSC within the water column and deposit material on the seabed.<br>Removal of export, array, platform interconnector or offshore accommodation platform cables has the potential to increase SSC within the water column and deposit material on the seabed. | Yes | Demonstrate that scale of impact is less than that assessed during construction/ operation phase. | N/A | N/A<br>*(marine processes receptors insensitive to change)* |
| Removal of the export cable at the landfall has the potential to affect beach morphology, hydrodynamics and sediment transport (littoral drift). | Yes | Demonstrate that scale of impact is less than that assessed during construction/ operation phase. | Negligible | Negligible (insignificant) |

# 3. Guidance

3.1.1.1 It is expected that EIA studies should apply any relevant guidance and best practice. The following guidance documents are of particular relevance to the present marine processes study:

- 'Environmental impact assessment for offshore renewable energy projects.' (BSI, 2015).
- 'Review of environmental data associated with post-consent monitoring of licence conditions of offshore wind farms.' MMO Project No: 1031. (Fugro-Emu, 2014).
- 'Advice Note Seven: Environmental Impact Assessment, Preliminary Environmental Information, screening and scoping' (The Planning Inspectorate, 2015a);
- 'Advice Note Nine: Using the Rochdale Envelope' (The Planning Inspectorate, 2012);
- 'Advice Note Twelve: Transboundary Impacts ' (The Planning Inspectorate, 2015b);
- 'Guidelines for Data Acquisition to Support Marine Environmental Assessments of Offshore Renewable Energy Projects'. (Cefas, 2011);
- 'Identifying the possible impacts of rock dump from oil and gas decommissioning on Annex I mobile sandbanks.' (JNCC, 2017);
- 'General advice on assessing potential impacts of and mitigation for human activities on Marine Conservation Zone (MCZ) features, using existing regulation and legislation' (JNCC and Natural England, 2011);
- 'National Policy Statement EN-1 - Overarching National Policy Statement for Energy' (DECC, 2011a);
- 'National Policy Statement EN-3 - National Policy Statement for Renewable Energy Infrastructure' (DECC, 2011b);
- 'Further review of sediment monitoring data'. (COWRIE ScourSed-09).' (ABPmer, HR Wallingford and Cefas, 2010);
- 'Coastal Process Modelling for Offshore Wind farm Environmental Impact Assessment: Best Practice Guide'. ABPmer and HR Wallingford for COWRIE, 2009, [http://www.offshorewindfarms.co.uk];
- 'Guidelines in the use of metocean data through the lifecycle of a marine renewables development' (ABPmer *et al.,* 2008a);
- 'Review of Cabling Techniques and Environmental Effects applicable to the Offshore Wind farm Industry.' Department for Business Enterprise and Regulatory Reform in association with Defra. (BERR, 2008);
- 'Review of Round 1 Sediment process monitoring data - lessons learnt. (Sed01)' (ABPmer et *al.,* 2007);
- 'Dynamics of scour pits and scour protection - Synthesis report and recommendations. (Sed02)' (HR Wallingford *et al.,* 2007);
- 'Offshore Windfarms: Guidance note for Environmental Impact Assessment in Respect of FEPA and CPA requirements'. (Cefas, 2004); and
- 'Potential effects of offshore wind developments on coastal processes' (ABPmer and METOC, 2002).

3.1.1.2 Monitoring evidence compiled during the construction, and operation and maintenance of earlier offshore wind farm developments is also now available. Some of this information is contained within the COWRIE ScourSed-09 publication (ABPmer *et al.,* 2010), whilst a number of monitoring reports and previous offshore wind farm Environmental Statements are hosted on the Crown Estate Marine Data Exchange website (www.marinedataexchange.co.uk/).

# 4. Suspended Sediment Concentrations, Bed Levels and Sediment Type

## 4.1 Overview

4.1.1.1 Local increases in SSC may result from the disturbance of sediment by construction related activities, most notably due to:

- Drilling of monopile foundations and pin piles for piled jacket foundations;
- Seabed preparation by dredging prior to gravity base foundation installation;
- Sandwave clearance (prior to cable burial); and
- Cable burial.

4.1.1.2 The mobilised material may be transported away from the disturbance location by the local tidal regime. According to the source-pathway-receptor model:

- Disturbance and release of sediment is considered as the source of potential changes to SSC in the water column;
- Tidal currents act as the pathway for transporting the suspended sediment; and
- The receptor is a feature potentially sensitive to any increase in suspended sediments and consequential deposition.

4.1.1.3 The magnitude, duration, rate of change and frequency of recurrence of changes to SSC and bed level are variable between operation types and in response to natural variability in the controlling environmental parameters.

## 4.2 Baseline conditions

4.2.1.1 Baseline characteristics of the hydrodynamic, sedimentological and morphological regimes within the Hornsea Three array area and along the offshore cable corridor are briefly summarised below:

- Mean spring peak current speed increases with proximity to the Norfolk coast. Peak (depth averaged) current speeds on a mean spring tide are around 0.5 m/s within the Hornsea Three array area and at the offshore terminus of the offshore cable corridor, increasing up to approximately 1.0 m/s in nearshore areas at the landfall (SMart Wind, 2012; ABPmer *et al.,* 2008). Mean neap peak current speed is approximately half that of springs;
- During winter months the concentration of suspended particulate matter (SPM), including suspended sediment and other organic matter) at the surface of the water column is typically in the range ~5 to 35 mg/l whilst during summer months, values are usually in the approximate range 1 to 10 mg/l. For both summer and winter months, SPM concentrations generally increase with greater proximity to the coast (Dolphin *et al*., 2011);
- SSC will naturally vary with height in the water column. Sediment is naturally re-suspended by the action of currents and waves at the seabed and so SSC is highest at the seabed. Sediment naturally settles downwards under gravity but is also re-suspended upwards by turbulence which is greater nearer the seabed. This results in a non-linear (power-law) profile of SSC (i.e. rapidly decreasing with height above the seabed);
- Seabed surface sediments are largely dominated by coarse grained unconsolidated material (e.g. sands/ gravels) with fine grained sediments (e.g. muds) typically comprising less than 5% of seabed sediments. However, discrete areas of relatively finer grained sediments also present within the Hornsea Three array area (up to 50% fines, associated with Outer Silver Pit and Markham's Hole) (EGS, 2016; Clinton, 2016; BGS, 1987);
- The thickness of seabed surficial sediment cover is highly variable, ranging from 0 to ~ 6 m, in the vicinity of mobile bedform features; and
- The complete succession of Quaternary deposits within the former Hornsea Zone consists of (youngest to oldest):
  - Botney Cut Formation (mainly sands);
  - Bolders Bank Formation (stiff diamictons with widely ranging grain sizes);
  - Eem Formation (very fine to medium-grained, slightly gravelly, shelly sands);
  - Egmond Ground Formation (gravelly sands interbedded with silt and clay);
  - Swarte Bank Formation (mainly glacio-fluvial sands); and
  - Yarmouth Roads Formation (characterised by a range of sediment types). (BGS, 1986; 1987; 1991; Cameron et al., 1992).
- Consideration of both the Hornsea Three specific geophysical survey data and available regional mapping information from the BGS and Humber Regional Environmental Characterisation (REC) suggests that in offshore areas the Botney Cut and Bolders Bank Formations are found either at or very close to the seabed (BGS, 1986; Tappin *et al.,* 2010; EGS, 2016; Clinton, 2016) (Figure 4.1). At the landward end of the offshore cable corridor, chalk is encountered at or very close to the seabed surface (Bibby HydroMap, 2016; Fugro, 2017) (Figure 4.2).

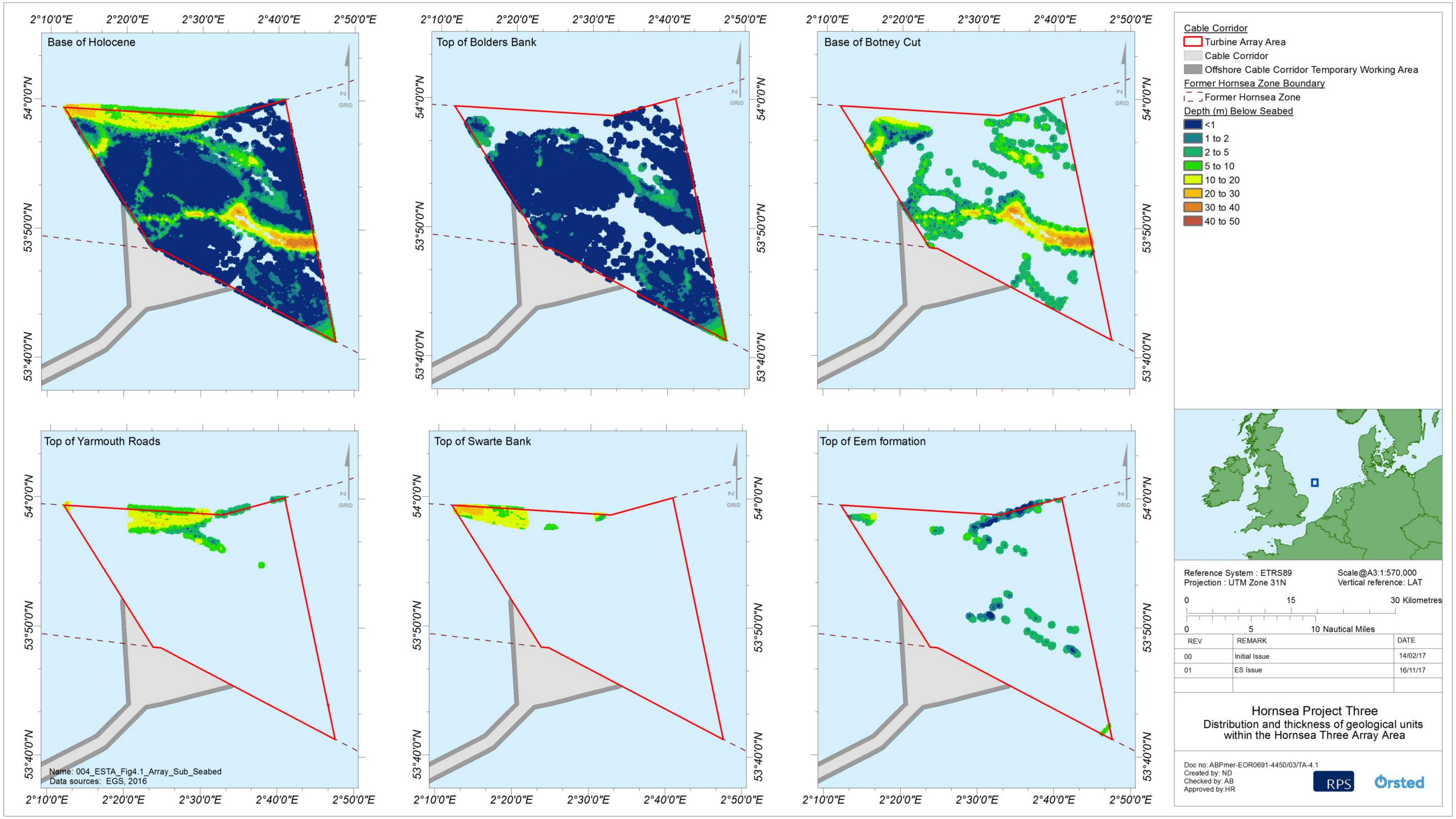


**Figure 4.1: Distribution and thickness of geological units within the Hornsea Three array area.**

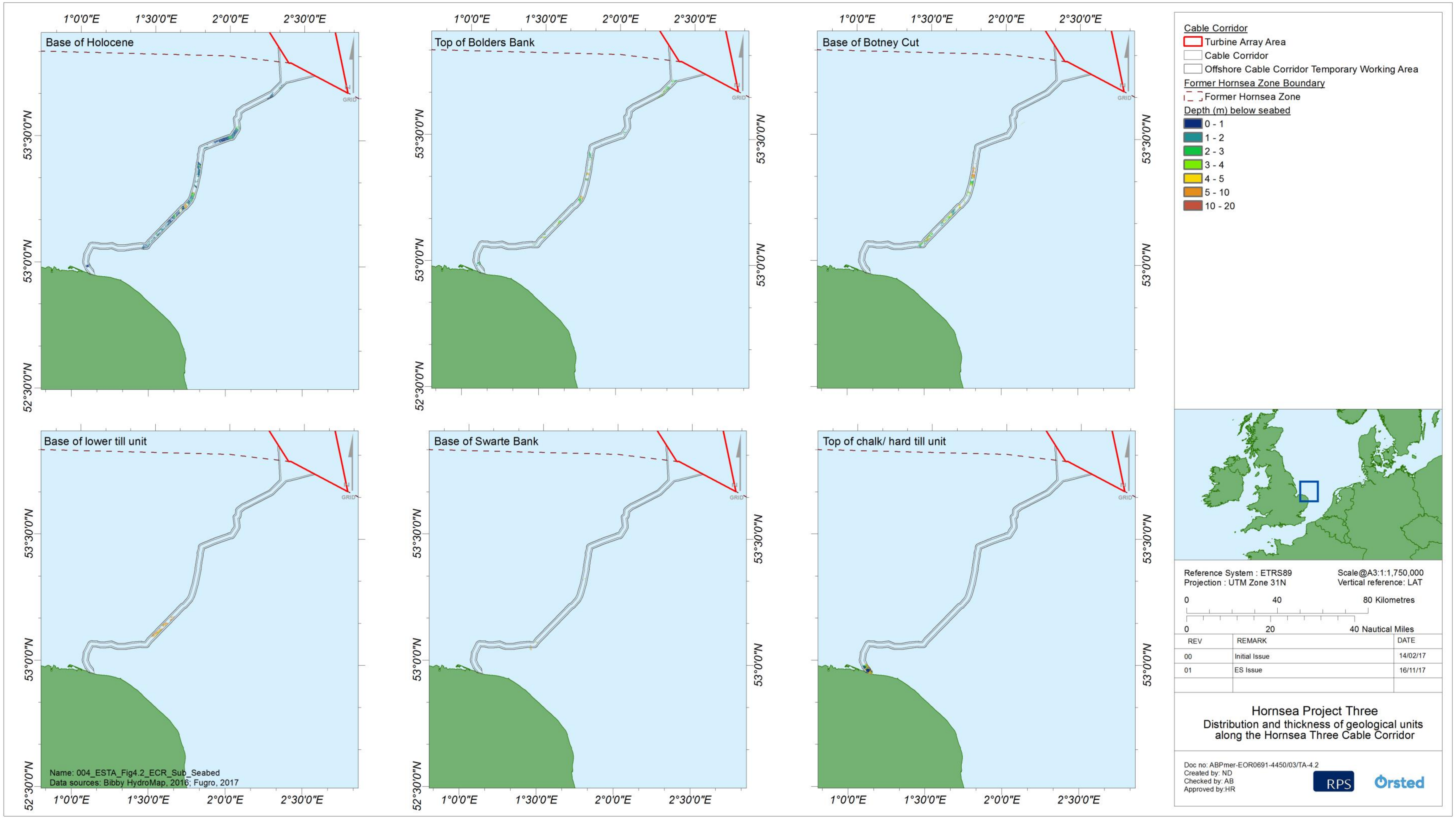


**Figure 4.2: Distribution and thickness of geological units along the Hornsea Three offshore cable corridor.**

## 4.3 Assessment

### 4.3.1 Methodology

4.3.1.1 Sediment disturbed and released into the water column during construction will settle downwards at a rate depending upon its grain size. During settling, the sediment plume will be advected away from the point of release by any currents that are present, and will be dispersed laterally by turbulent diffusion. The horizontal advection distance will be related to the flow speed and the physical properties of the sediment. The maximum near-bed level of SSC is expected to be found where the main body of the settling plume of sediment reaches the seabed.

4.3.1.2 Coarse grained sediments will behave differently to fine grained sediments when released into the water column. The disturbance of coarse grained or consolidated material is likely to give rise to high SSCs in the vicinity of the release location, but is also likely to settle out of suspension quickly (e.g. in the order of seconds to minutes) so any sediment plumes are likely to be localised. By contrast, fine grained material will tend to remain in suspension for a longer period of time (in the order of hours to days), potentially resulting in an increase in SSC over a larger area, at a progressively reduced concentration, due to advection and dispersion from the original release location. Similar differences are expected when considering any resulting changes in bed level due to resettlement of the material in suspension. Coarser material will tend to give rise to thicker but more localised changes in bed levels whereas fine grained material may give rise to smaller changes in bed levels over a wider area. The exact pattern of re-deposition of sediment to the seabed will depend on the actual combination of operational methods and environmental conditions at the time of the event which will be variable. The total volume of sediment disturbed is, however, known with greater certainty and a range of potential combinations of deposit shape, thickness and area (corresponding to the same total volume) can be more reliably provided, as a subset of all possible combinations.

4.3.1.3 In order to inform the assessment of potential changes to SSC and bed levels arising from construction related activities, a number of spreadsheet based numerical models have been developed for use. Similar models were developed and used to inform the environmental impact assessments for similar activities at Burbo Bank Extension, Walney Extension and Navitus Bay offshore wind farms (DONG Energy, 2013a,b; and Navitus Bay Development Ltd, 2014, respectively). The spreadsheet based numerical models used here are based upon the following information, assumptions and principles:

- Re-suspended coarser sediments (sands and gravels) will settle relatively rapidly to the seabed and their dispersion can therefore be considered on the basis of a 'snapshot' of the ambient conditions which are unlikely to vary greatly between the times of sediment release and settlement to the seabed. Re-suspended finer sediments may persist in the water column for hours or longer and so their dispersion is considered instead according to the longer-term residual patterns of water motion in the area, which vary both temporally and spatially in speed and direction;
- A representative current speed for the Hornsea Three array area is 0.25 m/s, which is representative of higher tidal flow conditions occurring on most flood and ebb cycles for a range of spring and neap conditions. Assuming a higher value will increase dispersion, decrease SSC and reduce the thickness of subsequent deposits and vice versa;
- Lateral dispersion of SSC in the plume is controlled by the horizontal eddy dispersion coefficient, Ke, estimated as $Ke = \kappa u^* z$ (Soulsby, 1997), where, z is the height above the seabed (a representative value of half the water depth is used), $\kappa$ is the Von Kármán coefficient ($\kappa = 0.4$) and $u^*$ is the friction velocity ($u^* = \sqrt{(\tau/\rho)}$). Where $\rho$ is the density of seawater ($\rho$ = 1027 kg/m$^3$) and $\tau$ is the bed shear stress, calculated using the quadratic stress law ($\tau = \rho \, Cd \, U^2$, Soulsby, 1997) using a representative current speed (U = 0.25 m/s) and a drag coefficient value for a rippled sandy seabed (Cd = 0.006);
- The grab sample and geophysical data from the Hornsea Three array area indicate that there are three characteristic surficial sediment types present, namely:
  - Sandy gravel (30 to 80% gravel, sand more than 90% of non-gravel fraction);
  - Muddy sandy gravel (30 to 80% gravel, sand 50 to 90% of non-gravel fraction); and
  - Muddy sand (less than 5% gravel, sand 50 to 90% of non-gravel fraction). (Based on the sediment grab samples collected in the Hornsea Three array area - where present, fines typically make up 5 to 20% of the total sediment mass, but can be up to 50% in small areas);
- To estimate the time-scale in suspension, sediment is assumed to settle downwards at a calculated (theoretical) settling velocity for each grain size fraction (0.0001 m/s for fines, 0.05 m/s for (medium) sands and 0.5 m/s for gravels and generally coarser sediments, including clastic drill arisings).

4.3.1.4 The numerical model for SSC resulting from the release of sands and gravels is constructed as follows:

- The time required for sediment to settle at the identified settling velocity through a range of total water depths representative of the site is calculated, to yield the duration for settlement;
- The horizontal distance downstream that the plume is advected is found as the product of the representative ambient current speed and the duration for settlement;
- The horizontal footprint area of the plume at different water depths is calculated from the initial dispersion area, increasing at the horizontal dispersion rate over the elapsed time for the plume to reach that depth; and
- The estimate of SSC at different elevations is found by dividing the sediment mass in suspension at a given water depth (the product of the sediment release rate and the duration of the impact, divided by the water depth) by the representative plume volume at that depth (horizontal footprint area at that depth x 1 m).

4.3.1.5 The numerical model for sediment deposition thickness resulting from the release of sands and gravels is constructed as follows:

- The area over which sediment is deposited depends on the lateral spreading of the sediment plume footprint with depth, but also with tidal variation in current speed and direction, including the possibility of flow reversal. This is an important factor if the release occurs for more than tens of minutes as it affects the distance and direction which the plume is advected from the source;
- The width of the footprint of (instantaneous) deposition onto the seabed is estimated as the square root of the near-bed plume footprint area (calculated using the model for SSC above). For monopile foundations, the point of sediment release is likely to be static and so the width of deposition is characterised directly as the footprint of deposition. For gravity base foundation and jacket foundations, the point of sediment release is likely to move within an area equivalent to the size of the jacket foundation or dredged area, in which case the overall width of deposition is characterised as the footprint of deposition plus the diameter of the gravity base foundation or size of the jacket;
- The length of the footprint of deposition onto the seabed over multiple tidal cycles is estimated as twice the advected distance of the plume at the representative current speed, representing the maximum length over consecutive flood and ebb tides. If the operation lasts less than 12.4 hours (one full tidal cycle), the length is reduced proportionally;
- The average seabed deposition thickness is calculated as the total volume of sediment released, divided by the footprint area (width times length) of deposition; and
- This model provides a conservative estimate of deposition thickness as it assumes that the whole sediment volume is deposited locally in a relatively narrow corridor. In practice, the deposition footprint on the seabed will probably be normally wider and frequently longer than is assumed, and the proportion of all sediment deposited locally will vary with the distribution in grain size (leading to a greater area but a correspondingly smaller average thickness).

4.3.1.6 The numerical model for SSC resulting from dispersion of fine sediment is constructed as per the following example:

- The vessel is likely to be stationary during precision dredging operations so the water movement relative to the vessel is dominantly tidal (at the representative current speed 0.25 m/s);
- Sediment is discharged at a representative rate (e.g. 30 kg/s for dredging over-spill) into a minimum volume of water 100 $m^3$ = 10 m x 10 m x 1m deep);
- This volume of water will be refreshed every 40 seconds (10 m / 0.25 m/s);
- The total sediment input is 40 s x 30 kg/s = 1200 kg;
- The resulting initial concentration in the receiving water is 1200 kg / 100 $m^3$ = 12 kg/$m^3$ = 12,000 mg/l;
- The initial concentration would then be subject to turbulent dispersion both laterally and vertically. Given the starting mass of sediment and water volume above, levels of SSC will vary rapidly in proportion to the dilution of the same sediment mass as the plume dimensions and volume increase; and
- Assuming a faster current speed, faster vessel motion or larger footprint of release would reduce the mass of sediment introduced to the fixed volume of the receiving waters (and so SSC) at the point of initial dispersion, and *vice versa*.

### 4.3.2 Drilling of monopile foundations and pin piles for piled jacket foundations

***Summary***

4.3.2.1 Monopile foundations and pin piles for piled jacket foundations will be installed into the seabed using standard piling techniques. In some locations, the particular geology may present some obstacle to piling, in which case, some or all of the seabed material might be drilled from within the pile footprint to assist in the piling process.

4.3.2.2 The impact of drilling operations for monopile installation mainly relates to the release of drilling spoil at or above the water surface which will put sediment into suspension and the subsequent re-deposition of that material to the seabed. The nature of this disturbance will be determined by the rate and total volume of material to be drilled, the geological conditions, and the drilling method (affecting the texture and grain size distribution of the drill spoil). These changes are quantitatively characterised in this section using the spreadsheet based numerical models described in section 4.3.1.

***Evidence base***

4.3.2.3 Sediment disturbance associated with the installation of monopiles was previously considered for Hornsea Project One and Hornsea project Two, using numerical modelling (SMart Wind, 2013, 2015a). The volume of sediment released was based on drilling 100% of the internal volume of the monopile (10 m diameter, 50 m deep, 3,927 $m^3$ per monopile, at 3m/hr, disturbing 235 $m^3$/hr) which is a smaller total volume, but a higher sediment release rate than that being considered for Hornsea Three (15 m diameter, 40 m deep, 7,069 $m^3$ per monopile, at 0.5m/hr, disturbing 88 $m^3$/hr). Taking account of these differences, the nature of the sediment disturbance, the sediment type and other environmental conditions are sufficiently similar that the previous modelling is considered to provide directly relevant evidence for Hornsea Three in this regard. The spatial pattern and magnitude of elevated SSC (and associated levels of deposition) due to drilling activities within the Hornsea Project Two array area are shown in Figure 4.3, Figure 4.4 and Figure 4.5 and summarised below:

- Predicted increases in depth averaged concentrations of more than 10 mg/l arising from monopile drilling activities were predicted to extend 2.5 to 8 km. Predicted peak increases in depth-averaged concentration in the close vicinity of the works were in the region of 90-160 mg/l;
- Peaks in suspended sediment concentration increase are typically short-lived, of the order of an hour. During monopile drilling the predicted concentration reduces to near background after approximately eight hours from the start of the release;
- Any deposition was restricted to within a few hundred metres of the location of the works;
- The simulations of works for two concurrent turbines showed that the peak predicted depth averaged SSC were reasonably similar to those for individual foundations; and
- Changes in SSC associated with drilling for jacket foundations were predicted to be much smaller compared to those of monopile drilling (SMart Wind, 2015a).

4.3.2.4 The evidence-base does not presently include many measurements of SSC resulting from drilling operations for monopile or pin pile installation. This is due to the relatively small number of occasions that such works have been necessary.

4.3.2.5 Limited evidence from the field is provided by the during- and post-construction monitoring of monopile installation using drill-drive methods into chalk at the Lynn and Inner Dowsing offshore wind farms (CREL, 2008). However, the geology of the Hornsea Three array area is different to that at Lynn and Inner Dowsing, and the foundation dimensions and drilling apparatus will likely also differ. In the Hornsea Three array area, it is also not yet known how the drilled sedimentary units will disaggregate. All of the above factors limit the extent to which the Lynn and Inner Dowsing monitoring evidence can be considered to be indicative of the proposed construction activities for Hornsea Three.

4.3.2.6 The installation of steel monopiles (4.7 m diameter and up to 20 m penetration depth) was assisted in some cases by a drill-drive methodology. The drill arisings were mainly in the form of rock (chalk) chippings that were released onto the seabed a short distance away in a controlled manner using a pumped riser. The particular concern in that case was the possibility of sub-surface chalk arisings leading to high levels of SSC of an atypical sediment type. The result of sediment trap monitoring (located as close as 100 m from the operation) was that the chalk was not observed to collect in significant quantities. However, direct measurements of SSC were not possible at the time of the operation.

4.3.2.7 The dimensions of the chalk drill arisings deposit created was measured by geophysical survey and characterised as a conical mound, approximately 3 m thick at the peak, extending laterally (from the peak to ambient bed level) up to 10 m in what is assumed the downstream direction and 5 m in the other. The volume of the partially consolidated deposit (measured as approximately 290 $m^3$) was comparable to the total volume of the drilled hole (347 $m^3$). It is noted that the deposited material is likely to be less consolidated than its original in-situ state. If all of the drilled material had been deposited into and retained in the mound, assuming a typical packing density of 0.6 (ratio of solids to voids), the mound would be expected to have a larger volume of circa 578 $m^3$, i.e. the mound is likely to contain approximately 50% of the drilled material. The drilled material not deposited in the local mound may have been subject to different patterns of initial settling or subsequent transport, leading to some material being moved away from the main deposit location. These processes are consistent with seabed photographs indicating that the material in the deposit is horizontally graded, with the largest clasts located closer to the centroid of the deposit. It is also possible that the combination of drill and drive did not necessarily release a volume of material equivalent to 100% of the internal volume of the pile, or that the full burial depth may not have been achieved in this example.

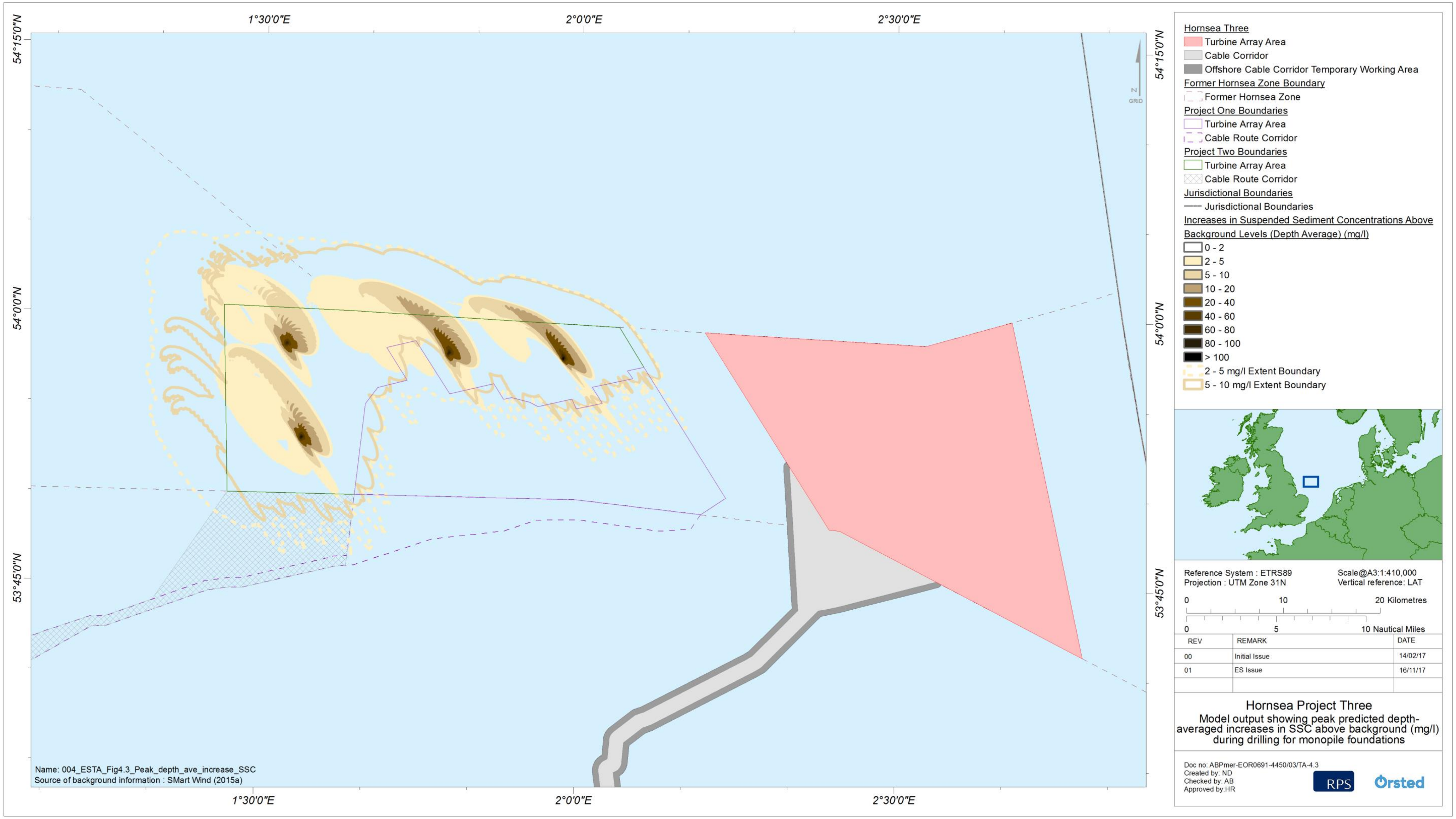


**Figure 4.3: Model output showing peak predicted depth-averaged increases in SSC above background (mg/l) during drilling for monopile foundations (reproduced from SMart Wind, 2015a).**

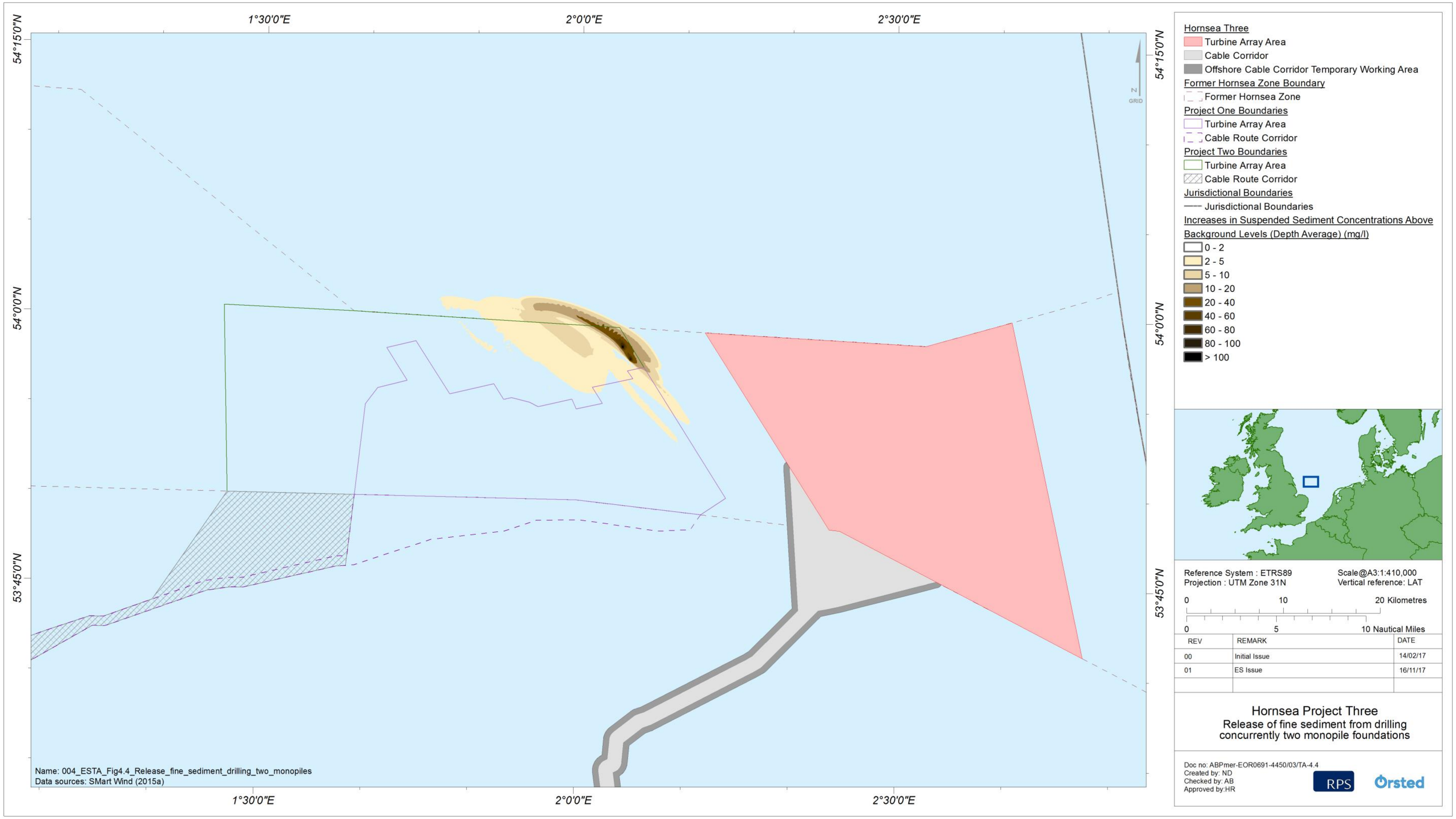


**Figure 4.4: Release of fine sediment from drilling concurrently two monopile foundations (reproduced from SMart Wind, 2015a).**

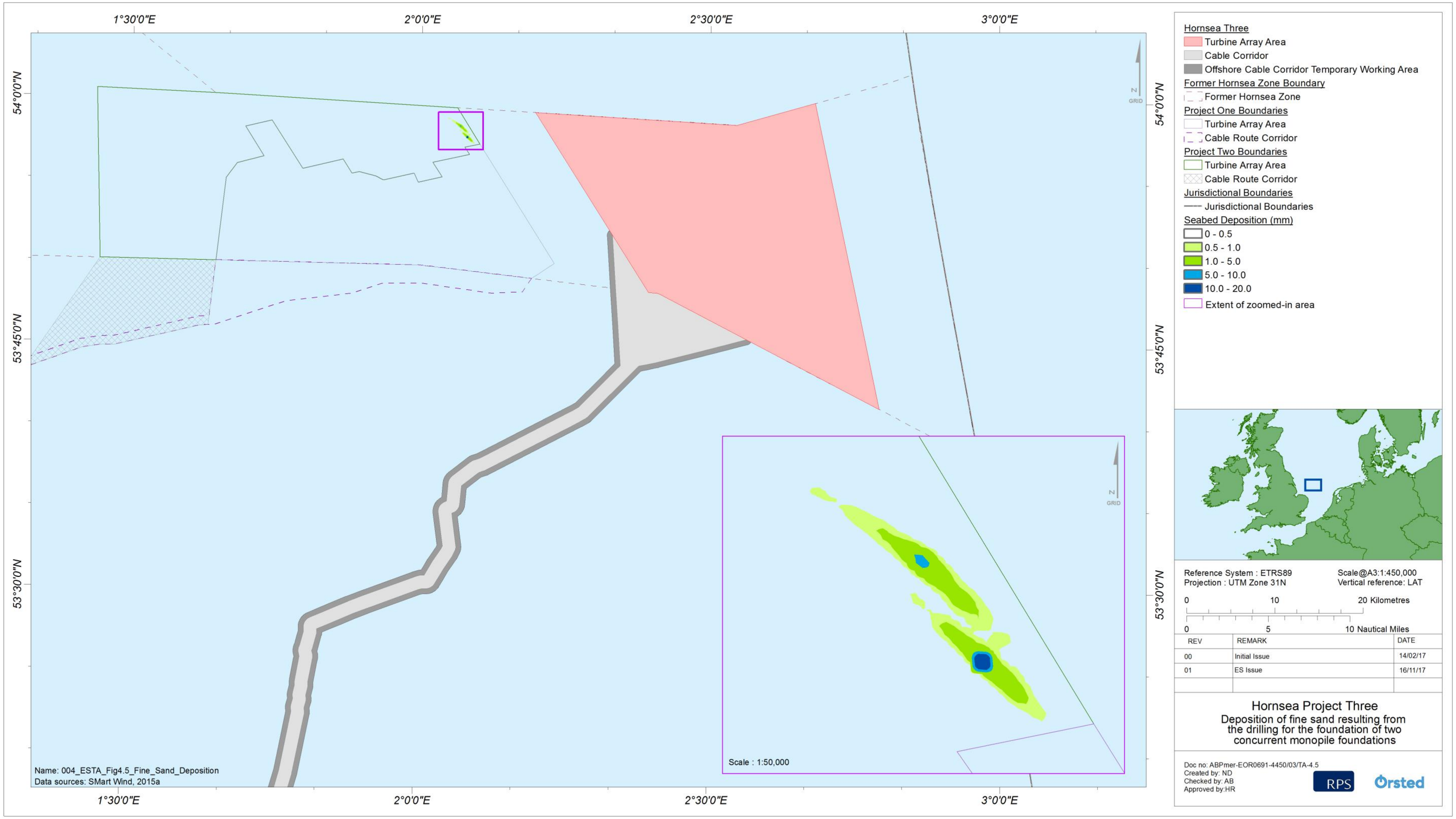


**Figure 4.5:** Deposition of fine sand resulting from the drilling for the foundation of two concurrent monopile foundations (reproduced from SMart Wind, 2015a).

*Assessment of change: Hornsea Three array area*

4.3.2.8 The greatest SSC and thickness of sediment deposition as a result of fully drilling (100% of the volume of) a single turbine monopile foundation is assessed for the largest diameter monopile (15 m, 40 m seabed penetration depth, drilling rate 0.5 m/hour). Up to 160 such turbine foundations might be installed within the Hornsea Three array area with a minimum spacing of 1000 m but, due to ground conditions, only up to 10% of the total number of turbine foundations might be fully drilled (100% of the monopile volume).

4.3.2.9 The distribution of grain/clast sizes in the drill arisings is not known in advance, so results are provided separately for scenarios where 100% of the material is assumed to be either fines, (medium) sand or (coarse) gravel sized. In practice, depending on the actual ground conditions and drilling tools used, the distribution of grain/clast size in the spoil will be some variable mixture of these with a corresponding intermediate duration, extent and magnitude of change.

4.3.2.10 The maximum design scenario for sediment release by drilling turbine monopiles is characterised in Table 4.1.

4.3.2.11 The maximum design scenario for sediment release by drilling accommodation platform monopiles is characterised in Table 4.2.

4.3.2.12 The maximum design scenario for sediment release by drilling pin piles for offshore HVAC collector substation piled jacket foundations is characterised in Table 4.3.

4.3.2.13 The maximum design scenario for sediment release by drilling pin piles for offshore HVDC converter substation piled jacket foundations is characterised in Table 4.4.

4.3.2.14 The maximum design scenario for all sediment release by drilling of 16 turbine monopiles (Table 4.1), three offshore accommodation platform monopiles (Table 4.2), 12 offshore HVAC collector substation piled jacket foundations (Table 4.3) and three HVDC substation piled jacket foundations (Table 4.4) is summarised in Table 4.5.

**Table 4.1: Maximum design scenario for sediment release by drilling turbine monopiles.**

| Parameter | Maximum design scenario | Working and other assumptions |
|---|---|---|
| Number of turbine monopiles to be drilled | 16 | Up to 10% of 160 turbine monopiles will be fully drilled |
| Diameter of monopile | 15 m | 100 % of the monopile internal area will be drilled |
| Penetration depth of monopile | 40 m | Equal to the depth of drilling |
| Total volume of drill arisings from one turbine monopile | 7,069 $m^3$ | 15 m diameter, 40 m depth |
| Total volume of drill arisings from all turbine monopiles | 113,097 $m^3$ | 7,069 $m^3$ x 16 turbine foundations |
| Sediment mineral density | 2,650 kg/$m^3$ | Assumed value for quartz sand (Soulsby, 1997). |
| Total mass of drill arisings from one turbine monopile | 18,732,850 kg | 7,069 $m^3$ x 2,650 kg/$m^3$<br>Assuming the drilled material is fully consolidated with minimal voids |
| Total mass of drill arisings from all turbine monopiles | 299,725,600 kg | 113,097 $m^3$ x 2,650 kg/$m^3$<br>Assuming the drilled material is fully consolidated with minimal voids |
| Drilling rate | 0.5 m/hour | 80 hours to install 1 monopile (40 m divided by 0.5 m/hour) |
| Sediment release rate whilst drilling | 65 kg/s | 15 m diameter, 0.5 m/hour = 88.4 $m^3$/hr = 0.025 $m^3$/s x 2,650 kg/$m^3$<br>Assuming the drilled material is fully consolidated with minimal voids |
| Consolidated packing density | 0.6 | Assumed value for a typical, medium sorted sand (Soulsby, 1997) |
| Total (consolidated) volume of drill arisings from one turbine monopile | 11,782 $m^3$ | 7,069 $m^3$ divided by 0.6 |
| Total (consolidated) volume of drill arisings from all turbine monopiles | 188,495 $m^3$ | 113,097 $m^3$ divided by 0.6 |
| Area over which sediment is released at or above the water surface | 177 $m^2$ | Assumed value – sediment is released at or above the water surface in an area approximately equal to the area of the drilled hole (15 m diameter). Using a larger value will increase initial dispersion, decrease SSC and reduce the thickness of subsequent deposits and *vice versa*. |

**Table 4.2: Maximum design scenario for sediment release by drilling accommodation platform monopiles.**

| Parameter | Maximum design scenario | Working and other assumptions |
|---|---|---|
| Number of turbine monopiles to be drilled | 3 | Up to 100% of 3 accommodation platform monopiles will be fully drilled |
| Diameter of monopile | 15 m | 100 % of the monopile internal area will be drilled |
| Penetration depth of monopile | 40 m | Equal to the depth of drilling |
| Total volume of drill arisings from one accommodation platform monopile | 7,069 m³ | 15 m diameter, 40 m depth |
| Total volume of drill arisings from all accommodation platform monopiles | 21,207 m³ | 7,069 m³ x 3 accommodation platform foundations |
| Sediment mineral density | 2,650 kg/m³ | Assumed value for quartz sand (Soulsby, 1997) |
| Total mass of drill arisings from one accommodation platform monopile | 18,732,850 kg | 7,069 m³ x 2,650 kg/m³<br>Assuming the drilled material is fully consolidated with minimal voids |
| Total mass of drill arisings from all accommodation platform monopiles | 56,198,550 kg | 21,207 m³ x 2,650 kg/m³<br>Assuming the drilled material is fully consolidated with minimal voids |
| Drilling rate | 0.5 m/hour | 80 hours to install 1 monopile (40 m divided by 0.5 m/hour) |
| Sediment release rate whilst drilling | 65 kg/s | 15 m diameter, 0.5 m/hour = 88.4 m³/hr = 0.025 m³/s x 2,650 kg/m³<br>Assuming the drilled material is fully consolidated with minimal voids |
| Consolidated packing density | 0.6 | Assumed value for a typical, medium sorted sand (Soulsby, 1997) |
| Total (consolidated) volume of drill arisings from one accommodation platform monopile | 11,782 m³ | 7,069 m³ divided by 0.6 |
| Total (consolidated) volume of drill arisings from all accommodation platform monopiles | 35,345 m³ | 21,207 m³ divided by 0.6 |
| Area over which sediment is released at or above the water surface | 177 m² | Assumed value – sediment is released at or above the water surface in an area approximately equal to the area of the drilled hole (15 m diameter). Using a larger value will increase initial dispersion, decrease SSC and reduce the thickness of subsequent deposits and *vice versa*. |

**Table 4.3: Maximum design scenario for sediment release by drilling pin piles for offshore HVAC collector substation piled jacket foundations.**

| Parameter | Maximum design scenario | Working and other assumptions |
|---|---|---|
| Number of offshore HVAC collector substation piled jacket foundations | 12 | Up to 100% of pin piles for 12 offshore HVAC collector substation piled jacket foundations will be fully drilled |
| Number of legs per foundation | 6 | |
| Number of pin piles per leg | 4 | |
| Number of pin piles per foundation | 24 | 4 pin piles per leg x 6 legs |
| Diameter of pin pile | 4 m | 100 % of the pin pile internal area will be drilled |
| Penetration depth of pin pile | 70 m | Equal to the depth of drilling |
| Total volume of drill arisings from one pin pile | 880 m³ | 4 m diameter, 70 m depth |
| Total volume of drill arisings from all pin piles for one foundation | 21,112 m³ | 880 m³ x 24 pin piles |
| Total volume of drill arisings from all pin piles for all foundations | 253,338 m³ | 21,112 m³ x 12 HVAC collector substation piled jacket foundations |
| Sediment mineral density | 2,650 kg/m³ | Assumed value for quartz sand (Soulsby, 1997) |
| Total mass of drill arisings from one pin pile for an offshore HVAC collector substation piled jacket foundation | 2,332,000 kg | 880 m³ x 2,650 kg/m³<br>Assuming the drilled material is fully consolidated with minimal voids |
| Total mass of drill arisings from all pin piles for one offshore HVAC collector substation piled jacket foundation | 55,946,800 kg | 21,112 m³ x 2,650 kg/m³<br>Assuming the drilled material is fully consolidated with minimal voids |
| Total mass of drill arisings from all pin pile for all offshore HVAC collector substation piled jacket foundation | 671,345,700 kg | 253,338 m³ x 2,650 kg/m³<br>Assuming the drilled material is fully consolidated with minimal voids |
| Drilling rate | 0.5 m/hour | 140 hours to install one pin pile (70 m divided by 0.5 m/hour) |
| Sediment release rate whilst drilling | 4.6 kg/s | 4 m diameter, 0.5 m/hour = 6.3 m³/hr = 0.00175 m³/s x 2,650 kg/m³<br>Assuming the drilled material is fully consolidated with minimal voids |
| Consolidated packing density | 0.6 | Assumed value for a typical, medium sorted sand (Soulsby, 1997) |
| Total (consolidated) volume of drill arisings from one offshore HVAC collector substation piled jacket foundation | 35,187 m³ | 21,112 m³ divided by 0.6 |

| Parameter | Maximum design scenario | Working and other assumptions |
|---|---|---|
| Total (consolidated) volume of drill arisings from all offshore HVAC collector substation piled jacket foundations | 422,230 m³ | 253,338 m³ divided by 0.6 |
| Area over which sediment is released at or above the water surface | 20 m² | Assumed value – sediment is released at or above the water surface in an area slightly larger than the area of the drilled hole (5 m diameter). Using a larger value will increase initial dispersion, decrease SSC and reduce the thickness of subsequent deposits and *vice versa*. |

**Table 4.4: Maximum design scenario for sediment release by drilling pin piles for offshore HVDC converter substation piled jacket foundations.**

| Parameter | Maximum design scenario | Working and other assumptions |
|---|---|---|
| Number of offshore HVDC converter substation piled jacket foundations | 4 | Up to 100% of pin piles for 4 offshore HVDC converter substation piled jacket foundations will be fully drilled |
| Number of legs per foundation | 18 | |
| Number of pin piles per leg | 4 | |
| Number of pin piles per foundation | 72 | 4 pin piles per leg x 18 legs |
| Diameter of pin pile | 3.5 m | 100 % of the pin pile internal area will be drilled |
| Penetration depth of pin pile | 70 m | Equal to the depth of drilling |
| Total volume of drill arisings from one pin pile | 673 m³ | 3.5 m diameter, 70 m depth |
| Total volume of drill arisings from all pin piles for one foundation | 48,490 m³ | 673 m³ x 72 pin piles |
| Total volume of drill arisings from all pin piles for all foundations | 193,962 m³ | 48,490 m³ x 4 HVDC converter substation piled jacket foundations |
| Sediment mineral density | 2,650 kg/m³ | Assumed value for quartz sand (Soulsby, 1997). |
| Total mass of drill arisings from one pin pile for an offshore HVDC converter substation piled jacket foundation | 1,784,719 kg | 673 m³ x 2,650 kg/m³<br>Assuming the drilled material is fully consolidated with minimal voids |
| Total mass of drill arisings from all pin piles for one offshore HVDC converter substation piled jacket foundation | 128,499,779 kg | 48,490 m³ x 2,650 kg/m³<br>Assuming the drilled material is fully consolidated with minimal voids |
| Total mass of drill arisings from all pin pile for all offshore HVDC converter substation piled jacket foundation | 513,999,116 kg | 253,338 m³ x 2,650 kg/m³<br>Assuming the drilled material is fully consolidated with minimal voids |
| Drilling rate | 0.5 m/hour | 140 hours to install one pin pile (70 m divided by 0.5 m/hour) |
| Sediment release rate whilst drilling | 3.5 kg/s | 3.5 m diameter, 0.5 m/hour = 4.8 m³/hr = 0.00134 m³/s x 2,650 kg/m³<br>Assuming the drilled material is fully consolidated with minimal voids |
| Consolidated packing density | 0.6 | Assumed value for a typical, medium sorted sand (Soulsby, 1997) |
| Total (consolidated) volume of drill arisings from one offshore HVDC converter substation piled jacket foundation | 80,817 m³ | 48,490 m³ divided by 0.6 |
| Total (consolidated) volume of drill arisings from all offshore HVDC converter substation piled jacket foundations | 323,270 m³ | 193,962 m³ divided by 0.6 |
| Area over which sediment is released at or above the water surface | 20 m² | Assumed value – sediment is released at or above the water surface in an area slightly larger than the area of the drilled hole (5 m diameter). Using a larger value will increase initial dispersion, decrease SSC and reduce the thickness of subsequent deposits and *vice versa*. |

**Table 4.5: Maximum design scenario for total sediment release by drilling for all foundations.**

| Parameter | Maximum design scenario | Working and other assumptions |
|---|---|---|
| Total volume of drilled sediment arisings from all foundations | 581,604 m³ | 113,097 m³ for 16 turbines, 21,207 m³ for three offshore accommodation platforms, 253,338 m³ for 12 offshore HVAC collector substations and193,962 m³ for four offshore HVDC converter substations |
| Total mass of drilled sediment arisings from all foundations | 1,541,268,966 kg | 581,604 m³ x (sediment mineral density) 2,650 kg/m³ |
| Total (consolidated) volume of drill arisings from all foundations | 969,340 m³ | 1,541,268,966 kg divided by (sediment mineral density) 2,650 kg/m³ divided by (consolidated packing density) 0.6 |

4.3.2.15 It is noted that the greatest rate of sediment release (65 kg/s) is associated with drilling of monopiles. Drilling of pin piles results in a much smaller rate of release (order of 3.5 to 4.6 kg/s).

4.3.2.16 Levels of SSC resulting from drilling of the different foundation types (with different rates of release) assuming 100% of the drill arisings are fines are shown in

4.3.2.17 Table 4.6 for the range of dispersion scenarios listed below.

- Source concentration at the point of release (total mass evenly dispersed in a volume of water 10 m wide, 10 m length, 1 m depth);
- Vertical diffusion to 5 m, 20 m lateral spread in footprint dimensions (30 seconds to one minute after release, 7.5 to 15 m downstream);
- Vertical diffusion to 15 m (from surface to approximately half water depth), 50 m lateral spread in footprint dimensions (five to ten minutes after release, 75 to 150 m downstream); and
- Vertical diffusion to 25 m (approximately full water column, so affecting the seabed), 100 m lateral spread in footprint dimensions (30 minutes after release, 450 m downstream).

4.3.2.18 The approximate timeframe and distance downstream from the point of release for each dispersion scenario is indicated, based on the representative rates of settling, lateral dispersion and current speeds previously described in paragraph 4.3.1.3.

**Table 4.6: Suspended sediment concentration as a result of drilling (100% drill arisings as fines).**

| | | | Turbine or offshore accommodation platform monopile foundations | HVAC substation piled jacket foundation Pin piles | HVDC substation piled jacket foundation pin piles |
|---|---|---|---|---|---|
| Rate of sediment release (kg/s) | | | 65 | 4.6 | 3.5 |
| Total mass released into receiving water (kg) | | | 2,600 | 184 | 140 |
| Representative current speed (m/s) | | | 0.25 | | |
| Plume width (m) | Plume depth (m) | Plume section length (m) | Resulting SSC (mg/l) | | |
| 10 | 1 | 10 | 26,000 | 1,840 | 1,400 |
| 20 | 5 | | 2,600 | 184 | 140 |
| 50 | 15 | | 347 | 24 | 18 |
| 100 | 25 | | 104 | 8 | 6 |

4.3.2.19 Levels of SSC and the estimated area and average thickness of sediment thickness resulting from drilling assuming 100% of the drill arisings are sands or gravels are shown: in Table 4.7 for a single large turbine or accommodation platform monopile foundation; in Table 4.8 for a single large offshore HVAC collector substation piled jacket foundation; and, in Table 4.9 for a single HVDC substation piled jacket foundation.

**Table 4.7: Suspended sediment concentration and sediment deposition as a result of drilling 100% of the volume of one turbine or accommodation platform monopile foundation (100% drill arisings as sands or gravels).**

| Sediment Type | Water depth (m) | Settling rate (m/s) | Duration of settlement (s) | Distance plume advected by peak current (m) | Maximum mass in suspension (kg) | Area of seabed deposition (m²) | Average thickness of seabed deposition (m) |
|---|---|---|---|---|---|---|---|
| 100% Sand | 25 | 0.05 | 500 | 250 | 32,520 | 10,972 | 1.07 |
| | 40 | | 800 | 400 | 52,033 | 25,962 | 0.45 |
| | 55 | | 1,100 | 550 | 71,545 | 47,256 | 0.25 |
| | 70 | | 1,400 | 700 | 91,057 | 74,855 | 0.16 |
| 100% Gravel | 25 | 0.5 | 50 | 25 | 3,252 | 498 | 23.63 |
| | 40 | | 80 | 40 | 5,203 | 1,063 | 11.08 |
| | 55 | | 110 | 55 | 7,154 | 1,828 | 6.45 |
| | 70 | | 140 | 70 | 9,106 | 2,791 | 4.22 |
| **Sediment type** | **Water depth (m)** | **Diameter of midwater SSC influence (m)** | **Area of midwater SSC influence (m²)** | **Midwater average SSC (mg/l)** | **diameter of near-bed SSC influence (m)** | **Area of near-bed SSC influence (m²)** | **Near-bed average SSC (mg/l)** |
| 100% Sand | 25 | 19 | 283 | 4,601 | 25 | 482 | 2,701 |
| | 40 | 27 | 588 | 2,213 | 37 | 1,053 | 1,235 |
| | 55 | 36 | 1003 | 1,297 | 48 | 1,846 | 705 |
| | 70 | 44 | 1,529 | 851 | 60 | 2,859 | 455 |
| 100% Gravel | 25 | 9 | 70 | 1,867 | 11 | 99 | 1,309 |
| | 40 | 12 | 114 | 1,137 | 15 | 177 | 736 |
| | 55 | 15 | 170 | 764 | 19 | 276 | 471 |
| | 70 | 17 | 237 | 549 | 22 | 398 | 327 |

Table 4.8: Suspended sediment concentration and sediment deposition as a result of drilling 100% of the volume of one offshore HVAC collector substation piled jacket foundation, 24 pin piles (100% drill arisings as sands or gravels).

| Sediment type | Water depth (m) | Settling rate (m/s) | Duration of settlement (s) | Distance plume advected by peak current (m) | Maximum mass in suspension (kg) | Area of seabed deposition (m²) | Average thickness of seabed deposition (m) |
|---|---|---|---|---|---|---|---|
| 100% Sand | 25 | 0.05 | 500 | 250 | 2,313 | 45,972 | 0.77 |
| | 40 | | 800 | 400 | 3,700 | 81,962 | 0.43 |
| | 55 | | 1,100 | 550 | 5,088 | 124,256 | 0.28 |
| | 70 | | 1,400 | 700 | 6,475 | 172,855 | 0.20 |
| 100% Gravel | 25 | 0.5 | 50 | 25 | 231 | 3,998 | 8.80 |
| | 40 | | 80 | 40 | 370 | 6,663 | 5.28 |
| | 55 | | 110 | 55 | 509 | 9,528 | 3.69 |
| | 70 | | 140 | 70 | 648 | 12,591 | 2.79 |
| **Sediment type** | **Water depth (m)** | **Diameter of midwater SSC influence (m)** | **Area of midwater SSC influence (m²)** | **Midwater average SSC (mg/l)** | **Diameter of near-bed SSC influence (m)** | **Area of near-bed SSC influence (m²)** | **Near-bed average SSC (mg/l)** |
| 100% Sand | 25 | 19 | 283 | 327 | 25 | 482 | 192 |
| | 40 | 27 | 588 | 157 | 37 | 1,053 | 88 |
| | 55 | 36 | 1003 | 92 | 48 | 1,846 | 50 |
| | 70 | 44 | 1,529 | 60 | 60 | 2,859 | 32 |
| 100% Gravel | 25 | 9 | 70 | 133 | 11 | 99 | 93 |
| | 40 | 12 | 114 | 81 | 15 | 177 | 52 |
| | 55 | 15 | 170 | 54 | 19 | 276 | 34 |
| | 70 | 17 | 237 | 39 | 22 | 398 | 23 |

Table 4.9: Suspended sediment concentration and sediment deposition as a result of drilling 100% of the volume of one HVDC substation piled jacket foundation, 72 pin piles (100% drill arisings as sands or gravels).

| Sediment type | Water depth (m) | Settling rate (m/s) | Duration of settlement (s) | Distance plume advected by peak current (m) | Maximum mass in suspension (kg) | Area of seabed deposition (m²) | Average thickness of seabed deposition (m) |
|---|---|---|---|---|---|---|---|
| 100% Sand | 25 | 0.05 | 500 | 250 | 1,771 | 60,972 | 1.33 |
| | 40 | | 800 | 400 | 2,833 | 105,962 | 0.76 |
| | 55 | | 1,100 | 550 | 3,895 | 157,256 | 0.51 |
| | 70 | | 1,400 | 700 | 4,958 | 214,855 | 0.38 |
| 100% Gravel | 25 | 0.5 | 50 | 25 | 177 | 5,498 | 14.70 |
| | 40 | | 80 | 40 | 283 | 9,063 | 8.92 |
| | 55 | | 110 | 55 | 390 | 12,828 | 6.30 |
| | 70 | | 140 | 70 | 496 | 16,791 | 4.81 |
| **Sediment type** | **Water depth (m)** | **Diameter of midwater SSC influence (m)** | **Area of midwater SSC influence (m²)** | **Midwater average SSC (mg/l)** | **Diameter of near-bed SSC influence (m)** | **Area of near-bed SSC influence (m²)** | **Near-bed average SSC (mg/l)** |
| 100% Sand | 25 | 19 | 283 | 250 | 25 | 482 | 147 |
| | 40 | 27 | 588 | 120 | 37 | 1,053 | 67 |
| | 55 | 36 | 1,003 | 71 | 48 | 1,846 | 38 |
| | 70 | 44 | 1,529 | 46 | 60 | 2,859 | 25 |
| 100% Gravel | 25 | 9 | 70 | 102 | 11 | 99 | 71 |
| | 40 | 12 | 114 | 62 | 15 | 177 | 40 |
| | 55 | 15 | 170 | 42 | 19 | 276 | 26 |
| | 70 | 17 | 237 | 30 | 22 | 398 | 18 |

4.3.2.20 Estimates of the area and average thickness of sediment deposition are provided in the preceding tables based on the approximate footprint of the plume and tidal advection factors. The extent, thickness and shape of sediment deposits on the seabed will be highly variable in practice. However, given the total volume of sediment, a range of potential alternative combinations can be calculated. For a given volume of sediment, a smaller area of extent will correspond to a greater thickness of accumulation, and vice versa. A steeper sided cone shape deposit will have a greater thickness and a smaller area of change than a less steep sided cone or flat deposit shape. A range of possible value combinations are provided in Table 4.10. The table demonstrates the changing spatial scale of the impact between two end members of: (i) maximum possible thickness (although also the smallest footprint or extent of impact); and (ii) the most extensive accumulation (to a smallest thickness of 0.05 m).

4.3.2.21 More concentrated and localised deposits (associated with coarse gravels and large clastic materials) are assumed to deposit naturally into a cone shape where the maximum thickness is in the centre of the deposit and decreases linearly to zero at the edges. Operationally, very thick deposits may affect safe navigation or other engineering considerations and so would not be planned or allowed to occur. The greatest possible thickness (at the central point of the cone, also corresponding to the smallest possible area) is associated with a cone that has the steepest possible slope angle (i.e. the angle of repose for such loose sediments = 32°). The height of cones with two and three times the extent of the steepest cone are provided for comparison. The largest possible areas impacted by uniformly distributed thicknesses of 0.5 m, 0.25 m and 0.05 m (more likely associated with sand sized material) are also provided (making no assumptions regarding the shape of the area).

**Table 4.10: Alternative potential extents and thicknesses of sediment deposition as a result of drilling foundations.**

| Foundation type / operation | Deposition scenario | Nominal diameter of influence (m) as a result of drilling for one foundation (and the area of influence of all foundations as a proportion of the Hornsea Three array area, 696 km$^2$) | Thickness of deposit (m) [a] |
|---|---|---|---|
| Drilling of largest monopile for 10 % of 160 turbines (7069 m$^3$ drill arisings per foundation; equivalent volume when deposited at seabed = 11,782 (based on a packing density of 0.6)). | Cone | 52 (0.00%) (steepest)<br>105 (0.02%)<br>157 (0.04%) | 16.4<br>4.1<br>1.8 |
| | Uniform thickness | 173 (0.05%)<br>245 (0.11%)<br>548 (0.54%) | 0.5<br>0.25<br>0.05 |
| Drilling for 12 HVAC substation piled jacket foundations (21,112 m$^3$ drill arisings from 24 piles per foundation; equivalent volume when deposited at seabed = 35,187 m$^3$ (based on a packing density of 0.6)). | Cone | 75 (0.01%) (steepest)<br>151 (0.03%)<br>226 (0.07%) | 23.6<br>5.9<br>2.6 |
| | Uniform thickness | 299 (0.12%)<br>423 (0.24%)<br>947 (1.21%) | 0.5<br>0.25<br>0.05 |
| Drilling for 3 HVDC substation piled jacket foundations (48,490 m$^3$ drill arisings from 72 piles per foundation; equivalent volume when deposited at seabed = 80,817 m$^3$ (based on a packing density of 0.6)). | Cone | 100 (0.00%) (steepest)<br>199 (0.02%)<br>299 (0.04%) | 31.1<br>7.8<br>3.5 |
| | Uniform thickness | 454 (0.09%)<br>642 (0.19%)<br>1,435 (0.93%) | 0.5<br>0.25<br>0.05 |
| Drilling of largest monopile for 3 accommodation platforms (7069 m$^3$ drill arisings per foundation; equivalent volume when deposited at seabed = 11,782 (based on a packing density of 0.6)). | Cone | 52 (0.00%) (steepest)<br>105 (0.00%)<br>157 (0.01%) | 16.4<br>4.1<br>1.8 |
| | Uniform thickness | 173 (0.01%)<br>245 (0.02%)<br>548 (0.10%) | 0.5<br>0.25<br>0.05 |

a Height of peak for cones and average uniform thickness. The dimensions of the steepest cone are provided here to indicate the smallest possible area that could be impacted. It is not realistically expected that cone deposits of greater thicknesses (e.g. >5 to 10 m) will be allowed to accumulate in practice. All value pairs are part of a continuous scale of possible outcomes.

4.3.2.22 The spatial pattern and magnitude of elevated SSC (and associated levels of deposition) due to drilling for foundation installation were estimated using numerical modelling for Hornsea Project One and Hornsea Project Two (SMart Wind, 2013; 2015a, see Figure 4.3, Figure 4.4 and Figure 4.5). The following observations (based on the spreadsheet based numerical model results) are consistent with the previously modelled patterns of change in Hornsea Project One and Hornsea Project Two, similarly modelled patterns of change in assessments for other wind farms, and the wider monitoring evidence base.

4.3.2.23 In summary, based on the site specific separately determined results for fines, sands and gravels, and the wider evidence base, the result of drilling for foundation installation on SCC (relative to ambient levels) is characterised as follows:

- SSC will be increased by tens to hundreds of thousands of mg/l at the point of sediment release, which is at or near the water surface;
- For fine grained drill arisings, SSC will rapidly decrease through dispersion to low tens of mg/l within the order of hundreds of meters from the point of release;
- For sand and gravel drill arisings, SSC will decrease to hundreds of mg/l locally when drilling monopiles, or only tens of mg/l when drilling pin piles, in the relatively short time before the sediment is deposited to the seabed; and
- Sands will deposit to the seabed (no longer contributing to SSC) within hundreds of metres of the source, and gravels likewise within tens of metres. The horizontal diameter of the sand or gravel plume footprint within the water column and on the seabed is likely to be in the order of tens of metres.

4.3.2.24 In summary, based on the site specific separately determined results for fines, sands and gravels, and the wider evidence base, sediment deposition as a result of drilling for foundation installation is characterised as follows:

- Deposits of mainly coarse grained and clastic sediment deposits will be concentrated within an area in the order of 25 to 100 m downstream/upstream and a few tens of metres wide from individual foundations, with an average thickness in the order of one to ten metres (limited to realistically likely values);
- Deposits of mainly sandy sediment deposits will be concentrated within an area in the order of 200 to 700 m downstream/upstream and tens to one hundred metres wide from individual foundations, with an average thickness in the order of tens of centimetres to one metre; and
- Fine grained material will be dispersed widely within the surrounding region and will not settle with measurable thickness.

4.3.2.25 Combining the separately determined results for fines, sands and gravels and the wider evidence base, and assuming that a mixture of sediment grain sizes will be present, including a significant proportion of fines, the overall spatial pattern of change due to drilling is summarised as follows:

- SSC of low tens of mg/l will be present in a narrow plume (tens to a few hundreds of metres wide, up to one tidal excursion in length (~7 km on spring tides and 3.5 km on neap tides) aligned to the tidal stream downstream from the source;
- If drilling occurs over more than one flood or ebb tidal period, the plume feature may be present in both downstream and upstream directions;
- Outside of the area up to one tidal excursion upstream and downstream of the foundation location, SSC less than 10 mg/l may occur more widely due to ongoing dispersion and dilution of material;
- The majority of gravel and sand sized sediment will be deposited to the seabed within tens to hundreds of metres from the source, respectively, resulting in seabed deposit thicknesses in the order of tens of centimetres thick in this area. A larger proportion of such material in the plume may result in SSC reducing more rapidly in this region and reducing the length or extent of the plume feature overall; and
- Sufficiently fine sediment may persist in suspension for hours to days or longer, but will become diluted to very low concentrations (<5 mg/l, indistinguishable from natural background levels and variability) within timescales of around one day. Fine grained material will be dispersed widely within the surrounding region and will not settle with measurable thickness.

4.3.2.26 If drilling, or any other activity causing sediment disturbance, is undertaken simultaneously at two or more locations that are aligned in relation to the ambient tidal streams, then there is potential for overlap between the areas of effect on SSC and sediment deposition. The effect on SSC in areas of overlap will be additive if the downstream activity occurs within the area of effect from upstream (i.e. sediment is disturbed within the sediment plume from the upstream location). The effect on SSC will not be additive (i.e. the effects will be as described for single occurrences only) if the areas of effect only meet or overlap downstream following advection or dispersion of the effects. Effects on sediment deposition will be additive if and where the footprints of the deposits overlap. Given that the minimum spacing between foundations is 1000 m, it is unlikely that sands or gravels put into suspension will be dispersed far enough (i.e. between adjacent foundation locations) to cause any overlapping effects before being redeposited to the seabed. Only relatively fine sediment is likely to be advected far enough to potentially cause overlapping effects on SCC.

***Assessment of change: Hornsea Three offshore cable corridor***

4.3.2.27 Up to four offshore HVAC booster stations may be installed within the offshore HVAC booster station search area using piled jacket foundation. Depending on the nature of the underlying geology, the jacket foundation pin piles may require drilling.

4.3.2.28 The maximum design scenario for sediment release by drilling pin piles for offshore HVAC collector substation piled jacket foundations is characterised in Table 4.11.

**Table 4.11: Maximum design scenario for sediment release by drilling pin piles for offshore HVAC booster station piled jacket foundations.**

| Parameter | Maximum design scenario | Working and other assumptions |
|---|---|---|
| Number of offshore HVAC booster station piled jacket foundations | 4 | Up to 100% of pin piles for 4 offshore HVAC booster station piled jacket foundations will be fully drilled |
| Number of legs per foundation | 6 | |
| Number of pin piles per leg | 4 | |
| Number of pin piles per foundation | 24 | 4 pin piles per leg x 6 legs |
| Diameter of pin pile | 4 m | 100 % of the pin pile internal area will be drilled |
| Penetration depth of pin pile | 70 m | Equal to the depth of drilling |
| Total volume of drill arisings from one pin pile | 880 m$^3$ | 4 m diameter, 70 m depth |
| Total volume of drill arisings from all pin piles for one foundation | 21,112 m$^3$ | 880 m$^3$ x 4 piles per leg x 6 legs |
| Total volume of drill arisings from all pin piles for all foundations | 84,448 m$^3$ | 21,112 m$^3$ x 4 HVAC booster station piled jacket foundations |
| Sediment mineral density | 2,650 kg/m$^3$ | Assumed value for quartz sand (Soulsby, 1997). |
| Total mass of drill arisings from one pin pile for an offshore HVAC booster station piled jacket foundation | 2,332,000 kg | 880 m$^3$ x 2,650 kg/m$^3$<br>Assuming the drilled material is fully consolidated with minimal voids |
| Total mass of drill arisings from all pin piles for one offshore HVAC booster station piled jacket foundation | 55,946,800 kg | 21,112 m$^3$ x 2,650 kg/m$^3$<br>Assuming the drilled material is fully consolidated with minimal voids |
| Total mass of drill arisings from all pin pile for all offshore HVAC booster station piled jacket foundation | 223,787,200 kg | 84,448 m$^3$ x 2,650 kg/m$^3$<br>Assuming the drilled material is fully consolidated with minimal voids |
| Drilling rate | 0.5 m/hour | 140 hours to install one pin pile (70 m divided by 0.5 m/hour) |
| Sediment release rate whilst drilling | 4.6 kg/s | 4 m diameter, 0.5 m/hour = 6.3 m$^3$/hr = 0.00175 m$^3$/s x 2,650 kg/m$^3$<br>Assuming the drilled material is fully consolidated with minimal voids |
| Consolidated packing density | 0.6 | Assumed value for a typical, medium sorted sand (Soulsby, 1997). |
| Total (consolidated) volume of drill arisings from one offshore HVAC booster station piled jacket foundation | 35,187 m$^3$ | 21,112 m$^3$ divided by 0.6 |
| Total (consolidated) volume of drill arisings from all offshore HVAC booster station piled jacket foundations | 140,747 m$^3$ | 84,448 m$^3$ divided by 0.6 |
| Area over which sediment is released at or above the water surface | 20 m$^2$ | Assumed value – sediment is released at or above the water surface in an area slightly larger than the area of the drilled hole (5 m diameter). Using a larger value will increase initial dispersion, decrease SSC and reduce the thickness of subsequent deposits and *vice versa*. |

4.3.2.29 The potential for increases in SSC as a consequence of drilling for similar offshore HVAC collector substation foundations in the Hornsea Three array area is described in the previous section, including specific results in Table 4.8. The overall plume characteristics described for the Hornsea Three array area will remain broadly valid for the offshore HVAC booster station search area, because:

- The number and dimensions of pin piles for HVAC collector and booster station piled jacket foundations (hence the total volume of sediment disturbed) and the assumed drilling rate is the same within the Hornsea Three array area and offshore HVAC booster station search area; and
- The analysis carried out for the Hornsea Three array area has considered a range of 'end member' sediment characteristics, capturing the full range of water depths and sediment types (fines, sands and gravels) which could be encountered (in varying proportions) at any drill location in the offshore cable corridor.

4.3.2.30 The higher peak flow speeds within the offshore HVAC booster station search area compared with the Hornsea Three array area means that it is possible that plume extents may be slightly greater than reported for the array area under certain tidal conditions. However, the greater dispersion would also mean lower overall levels of SSC within the plume.

4.3.2.31 The potential for seabed sediment deposits to accumulate as a consequence of drilling for similar offshore HVAC collector substation foundations in the Hornsea Three array area is described in the previous section, including specific results in Table 4.8 and Table 4.10. For example:

- If 21,112 m$^3$ of material were displaced during the installation of one offshore HVAC collector substation piled jacket foundation, an area measuring 703,717 m$^2$ (nominally 839 m x 839 m) could potentially be covered by an average of 0.05 m of material (assuming a packing density of the deposited material of 0.6); and
- A greater thickness of material will lead to a smaller area of impact and *vice versa*. For example, a 0.01 m average thickness deposit would affect an area five times larger than discussed above for an average deposition thickness of 0.05 m.

4.3.2.32 If drilling, or any other activity causing sediment disturbance, is undertaken simultaneously at two or more locations that are aligned in relation to the ambient tidal streams, then there is potential for overlap between the areas of effect on SSC and sediment deposition. The potential for in-combination effects on SSC and sediment deposition are discussed in paragraph 4.3.2.26.

### 4.3.3 Seabed preparation by dredging prior to gravity base installation

***Summary***

4.3.3.1 To provide a stable footing for gravity base foundations, standard dredging techniques will be used to remove or lower the level of the mobile seabed sediment veneer within a footprint slightly larger than the gravity base foundation base. Dredging has the potential to cause elevated SSC by, sediment over-spill at the water surface during dredging and by the subsequent release of the dredged material from the dredger during spoil disposal at a nearby location. The subsequent settlement of the sediment disturbed by dredging will lead to sediment accumulation of varying thickness and extent on the seabed. These changes are quantitatively characterised in this section using spreadsheet based numerical models.

***Evidence base***

4.3.3.2 Sediment disturbance associated with gravity base foundation bed preparation activities was previously considered for Hornsea Project One and Hornsea project Two using numerical modelling (SMart Wind, 2013, 2015a). The nature of the sediment disturbance, the sediment type and other environmental conditions are sufficiently similar to that being considered for Hornsea Three that the previous modelling is considered to provide directly relevant evidence in this regard. The spatial pattern and magnitude of elevated SSC (and associated levels of deposition) due to gravity base foundation bed preparation activities within the Hornsea Project Two array area are shown in Figure 4.6 and Figure 4.7, and summarised below:

- Plume extents from the dredging for gravity base foundation seabed preparation were larger than those from drilling, as a larger volume of sediment was released;
- For gravity base foundation seabed preparation, predicted increases in depth averaged concentrations of more than 10 mg/l were predicted to extend 5.5 to 13.5 km from the dredging/disposal. Predicted peak increases in depth averaged concentration in the close vicinity of the works were in the region of several hundred mg/l;
- For single gravity base foundations dredging the predicted concentration reduces to background levels within 27 hours after the start of the release;
- Deposition resulting from the dredging/disposal for gravity base foundation seabed preparation was greater than that from drilling as a larger volume of sediment was released; and
- The simulations of works for two concurrent turbines showed that the peak predicted depth averaged SSC were reasonably similar to those for individual foundations. Deposits from dredging two foundations concurrently are similar to those for individual foundations (SMart Wind, 2015a).

4.3.3.3 The evidence-base with regards to dredging and elevated levels of SSC is broad and well established through a variety of monitoring and numerical modelling studies. The following text from the UK Marine SAC Project (www.ukmarinesac.org.uk) is representative of the wider evidence base.

*"Dredging activities often generate no more increased suspended sediments than commercial shipping operations, bottom fishing or generated during severe storms (Parr et al., 1998). Furthermore, natural events such as storms, floods and large tides can increase suspended sediments over much larger areas, for longer periods than dredging operations (Environment Canada, 1994). It is therefore often very difficult to distinguish the environmental effects of dredging from those resulting from natural processes or normal navigation activities (Pennekamp et al., 1996).*

*…In general, the effects of suspended sediments and turbidity are generally short term (<1 week after activity) and near-field (<1 km from activity). There generally only needs to be concern if sensitive species are located in the vicinity of the maintained channel."*

4.3.3.4 Dredging for construction aggregates is a common marine activity on the east coast of the UK. The total mass of aggregate recovered from each region is reported annually by the British Marine Aggregate Producers Association (http://www.bmapa.org). It is reported that, in 2015, in the Humber dredging region, 1.32 million tonnes (~0.62 million m$^3$) of construction aggregate were dredged from a permitted licensed tonnage of 4.70 million (~ 2.2 million m$^3$); a further 0.20 million tonnes (~0.09 million m$^3$) were also dredged for a pipeline project and 0.63 million tonnes (~0.30 million m$^3$) were dredged for beach nourishment. During the same period in the East Coast dredging region, 4.47 (~2.11 million m$^3$) million tonnes of construction aggregate were dredged from a permitted licensed tonnage of 9.22 million (~4.35 million m$^3$).

4.3.3.5 From the above, the total volume of construction and other aggregate dredged in the Humber and East Coast regions in 2015 is ~3.12 million m$^3$ from a permitted licensed volume of ~6.55 million m$^3$. In comparison, the total volume of sediment to be dredged in the Hornsea Three array area is 2.18 million m$^3$ over the whole duration of the construction period, which will span a number of years. It is however noted that sediment dredged as part of construction activities for Hornsea Three will all be returned to the seabed nearby to the dredging location, whereas sediment dredged as part of aggregate extraction is removed permanently from the seabed.

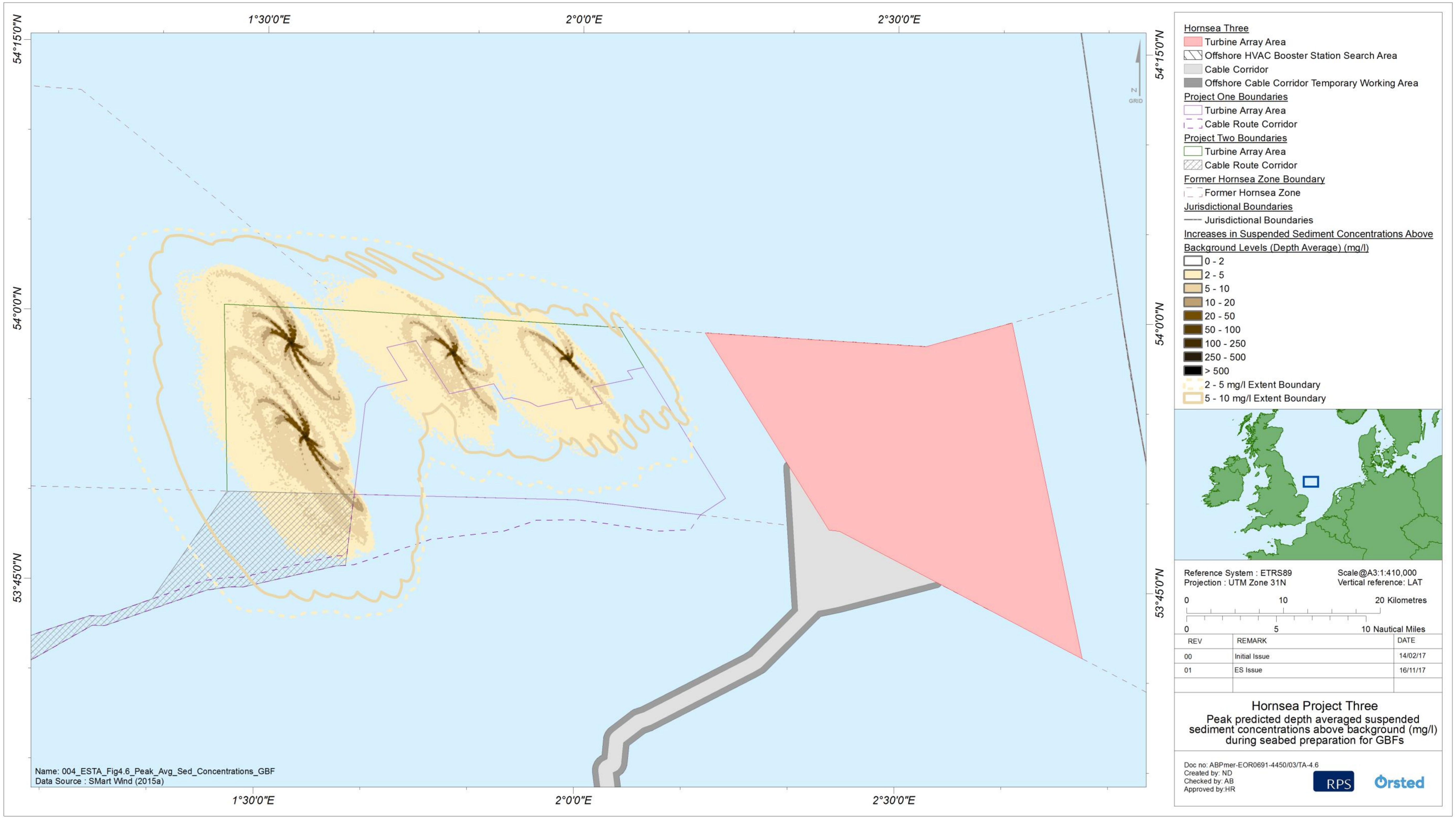


**Figure 4.6: Peak predicted depth averaged suspended sediment concentrations above background (mg/l) during seabed preparation for gravity base foundations (reproduced from SMart Wind, 2015a).**

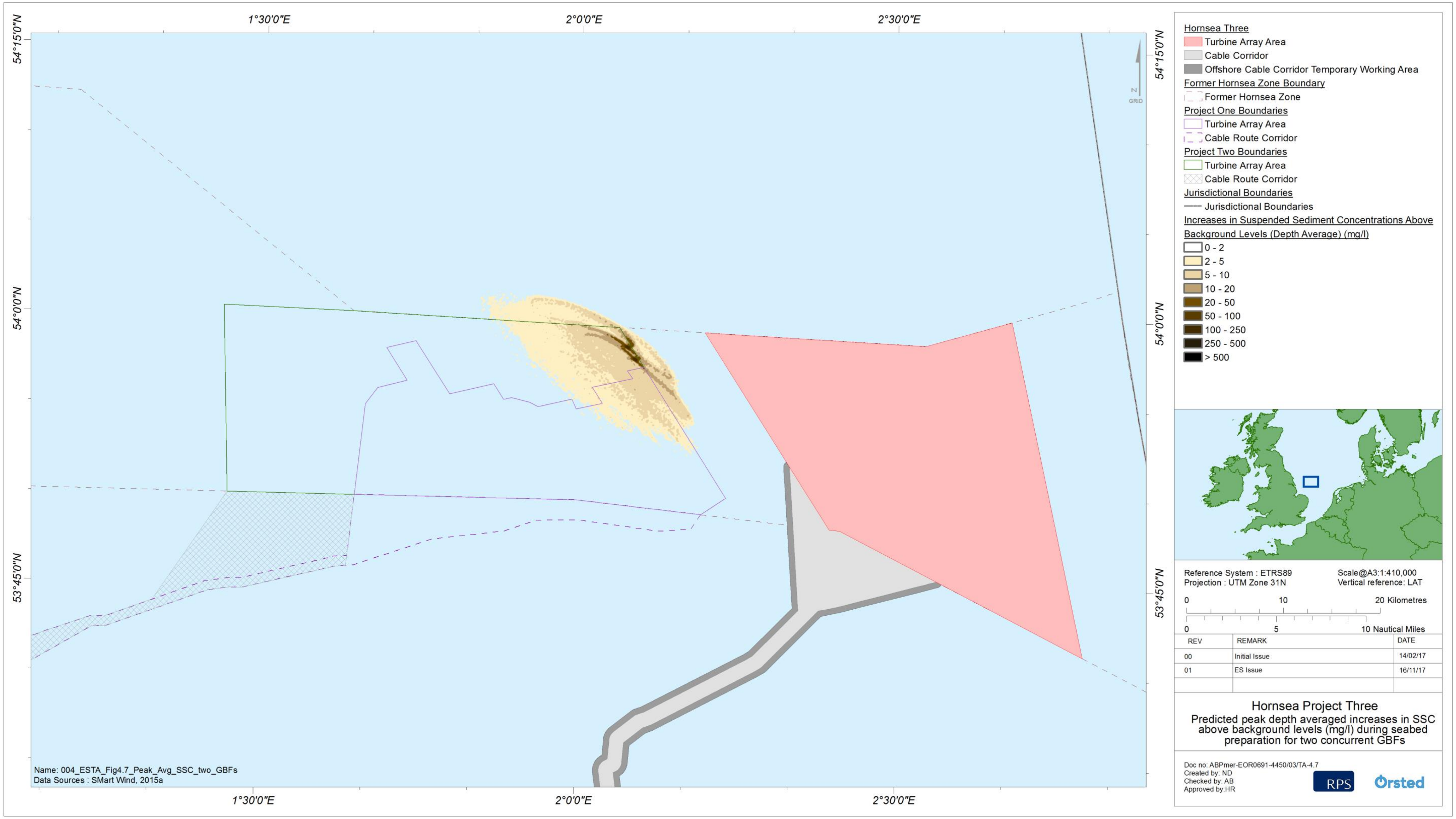


**Figure 4.7: Predicted peak depth averaged increases in SSC above background levels (mg/l) during seabed preparation for two concurrent gravity base foundations (reproduced from SMart Wind, 2015a).**

***Assessment of change: Hornsea Three array area***

4.3.3.6 The greatest SSC and thickness of sediment deposition as a result of bed preparation by dredging for a single turbine foundation is assessed for the largest diameter gravity base foundation (dredge pit dimensions 61 m diameter, 2 m depth); up to 160 such turbine foundations might be installed within the Hornsea Three array area with a minimum spacing of 1,000 m. The greatest SSC and thickness of sediment deposition as a result of bed preparation by dredging for all turbine foundations is assessed for the greatest total volume of sediment disturbance, associated with the smallest diameter gravity base foundation (dredge pit dimensions 51 m diameter, 2 m depth); up to 300 such turbine foundations might be installed within the Hornsea Three array area with a minimum spacing of 1,000 m.

4.3.3.7 The distribution of grain/clast sizes in the dredging over-spill and spoil release plumes is not known in advance, so results are provided separately for scenarios where 100% of the material is assumed to be either fines, (medium) sand or (coarse) gravel sized. In practice, depending on the actual ground conditions and dredging vessel used, the distribution of grain/clast size in the over-spill and spoil will be some variable mixture of these with a corresponding intermediate duration, extent and magnitude of change.

4.3.3.8 The maximum design scenario for sediment release by ground preparation dredging for a single large turbine gravity base foundation is characterised in Table 4.12.

**Table 4.12: Maximum design scenario for sediment release by ground preparation dredging for one large turbine gravity base foundation**

| Parameter | Maximum design scenario | Working and other assumptions |
|---|---|---|
| Number of large turbine gravity base foundations to be dredged | 1 (160) | The largest volume of sediment disturbed by ground preparation dredging for a single turbine gravity base foundation is associated with the largest turbine gravity base foundation. Up to 160 large gravity base foundations could be installed but would lead to a smaller total volume of dredging than the alternative scenario of a greater number of smaller gravity base foundations (see Table 4.14) |
| Diameter of dredged area | 61 m | |
| Depth of dredged area | 2 m | |
| Total volume of sediment to dredge for one large turbine gravity base foundation | 5,845 m$^3$ | 61 m diameter, 2 m depth |
| Sediment mineral density | 2,650 kg/m$^3$ | Assumed value for quartz sand (Soulsby, 1997). |
| Consolidated packing density | 0.6 | Assumed value for a typical, medium sorted sand (Soulsby, 1997). |
| Total mass of sediment to dredge for one large turbine gravity base foundation | 9,293,550 kg | 5,845 m$^3$ x 2,650 kg/m$^3$ x 0.6 Only a fraction of this material will be released as dredge over-spill. The remainder will be deposited to the seabed nearby, within the Hornsea Three array area |
| Dredger hopper capacity | 11,000 m$^3$ | The dredging will be undertaken by a trailer suction hopper dredger (TSHD) with an assumed representative hopper capacity of 11,000 m$^3$ |
| Equivalent number of dredging cycles to dredge one large turbine gravity base foundation | 0.5 cycles | 5,845 m$^3$ divided by 11,000 m$^3$ |
| Dredger sediment over-spill release rate | 30 kg/s | Assumed value |
| Time to fill dredger | 4 hours | Assumed value |
| Total mass of over-spilled sediment from dredging one large turbine gravity base foundation | 216,000 kg | 30 kg/s x 0.5 cycles x 4 hours x 60 min/hour x 60 s/min |
| Total (consolidated) volume of over-spilled sediment from dredging one large turbine gravity base foundation | 136 m$^3$ | 216,000 kg divided by 2,650 kg/m$^3$ divided by 0.6 |
| Area over which sediment is released at the water surface | 100 m$^2$ | Assumed value – sediment over-spill is released at the water surface in an area approximately 10 m x 10 m = 100 m$^2$. Using a larger value will increase initial dispersion, decrease SSC and reduce the thickness of subsequent deposits and *vice versa*. |

4.3.3.9 The maximum design scenario for sediment release by ground preparation dredging for offshore accommodation platform gravity base foundations is characterised in Table 4.13.

4.3.3.10 The maximum design scenario for sediment release by ground preparation dredging for all turbine gravity base foundations is characterised in Table 4.14.

4.3.3.11 The maximum design scenario for sediment released by ground preparation dredging for offshore HVAC collector substation gravity base foundations is characterised in Table 4.15.

4.3.3.12 The maximum design scenario for sediment released by ground preparation dredging for offshore HVDC converter substation gravity base foundations is characterised Table 4.16.

**Table 4.13: Maximum design scenario for sediment release by ground preparation dredging for accommodation platform gravity base foundations.**

| Parameter | Maximum design scenario | Working and other assumptions |
|---|---|---|
| Number of accommodation platform gravity base foundations to be dredged | 3 | The largest volume of sediment disturbed by ground preparation dredging for both single and all turbine gravity base foundations is associated with the largest accommodation platform gravity base foundation. |
| Diameter of dredged area | 61 m | |
| Depth of dredged area | 2 m | |
| Total volume of sediment to dredge for one accommodation platform gravity base foundation | 5,845 $m^3$ | 61 m diameter, 2 m depth |
| Total volume of sediment to dredge for all accommodation platform gravity base foundations | 17,535 $m^3$ | 5,845 $m^3$ x 3 accommodation platform gravity base foundations |
| Sediment mineral density | 2,650 $kg/m^3$ | Assumed value for quartz sand (Soulsby, 1997). |
| Consolidated packing density | 0.6 | Assumed value for a typical, medium sorted sand (Soulsby, 1997). |
| Total mass of sediment to dredge for one accommodation platform gravity base foundation | 9,293,550 kg | 5,845 $m^3$ x 2,650 $kg/m^3$ x 0.6<br>Only a fraction of this material will be released as dredge over-spill. The remainder will be deposited to the seabed nearby, within the Hornsea Three array area |
| Total mass of sediment to dredge for all accommodation platform gravity base foundations | 27,880,650 kg | 113,097 $m^3$ x 2,650 $kg/m^3$ x 0.6<br>Only a fraction of this material will be released as dredge over-spill. The remainder will be deposited to the seabed nearby, within the Hornsea Three array area |
| Dredger hopper capacity | 11,000 $m^3$ | The dredging will be undertaken by a trailer suction hopper dredger (TSHD) with an assumed representative hopper capacity of 11,000 $m^3$ |
| Equivalent number of dredging cycles to dredge one accommodation platform gravity base foundation | 0.5 cycles | 5,845 $m^3$ divided by 11,000 $m^3$ |
| Equivalent number of dredging cycles to dredge all accommodation platform gravity base foundations | 1.6 cycles | 17,535 $m^3$ divided by 11,000 $m^3$ |
| Dredger sediment over-spill release rate | 30 kg/s | Assumed value |
| Time to fill dredger | 4 hours | Assumed value |
| Total mass of over-spilled sediment from dredging one accommodation platform gravity base foundation | 216,000 kg | 30 kg/s x 0.5 cycles x 4 hours x 60 min/hour x 60 s/min |
| Total mass of over-spilled sediment from dredging all accommodation platform gravity base foundations | 691,200 kg | 30 kg/s x 1.6 cycles x 4 hours x 60 min/hour x 60 s/min |
| Total (consolidated) volume of over-spilled sediment from dredging one accommodation platform gravity base foundation | 136 $m^3$ | 216,000 kg divided by 2,650 $kg/m^3$ divided by 0.6 |
| Total (consolidated) volume of over-spilled sediment from dredging all accommodation platform gravity base foundations | 435 $m^3$ | 691,200 kg divided by 2,650 $kg/m^3$ divided by 0.6 |
| Area over which sediment is released at the water surface | 100 $m^2$ | Assumed value – sediment over-spill is released at the water surface in an area approximately 10 m x 10 m = 100 $m^2$. Using a larger value will increase initial dispersion, decrease SSC and reduce the thickness of subsequent deposits and *vice versa*. |

**Table 4.14: Maximum design scenario for sediment release by ground preparation dredging for all small turbine gravity base foundations.**

| Parameter | Maximum design scenario | Working and other assumptions |
|---|---|---|
| Number of small turbine gravity base foundations to be dredged | 300 | The greatest total volume of sediment disturbed by ground preparation dredging for turbine gravity base foundations is associated with up to 300 small gravity base foundations.<br>Small gravity base foundations individually require a smaller volume of dredging per foundation than the alternative scenario of a smaller number of larger gravity base foundations (see Table 4.12) |
| Diameter of dredged area | 51 m | |
| Depth of dredged area | 2 m | |
| Total volume of sediment to dredge for one small turbine gravity base foundation | 4,086 $m^3$ | 49 m diameter, 2 m depth |
| Total volume of sediment to dredge for all small turbine gravity base foundations | 1,225,800 $m^3$ | 4,086 $m^3$ x 300 small turbine gravity base foundations |
| Sediment mineral density | 2,650 $kg/m^3$ | Assumed value for quartz sand (Soulsby, 1997). |
| Consolidated packing density | 0.6 | Assumed value for a typical, medium sorted sand (Soulsby, 1997). |

| Parameter | Maximum design scenario | Working and other assumptions |
|---|---|---|
| Total mass of sediment to dredge for one small turbine gravity base foundation | 6,496,740 kg | 4,086 m³ x 2,650 kg/m³ x 0.6<br>Only a fraction of this material will be released as dredge over-spill. The remainder will be deposited to the seabed nearby, within the Hornsea Three array area |
| Total mass of sediment to dredge for all small turbine gravity base foundations | 1,949,022,000 kg | 1,289,847 m³ x 2,650 kg/m³ x 0.6<br>Only a fraction of this material will be released as dredge over-spill. The remainder will be deposited to the seabed nearby, within the Hornsea Three array area |
| Dredger hopper capacity | 11,000 m³ | The dredging will be undertaken by a trailer suction hopper dredger (TSHD) with an assumed representative hopper capacity of 11,000 m³ |
| Equivalent number of dredging cycles to dredge one small turbine gravity base foundation | 0.4 cycles | 4,086 m³ divided by 11,000 m³ |
| Equivalent number of dredging cycles to dredge all small turbine gravity base foundations | 111.4 cycles | 1,225,800 m³ divided by 11,000 m³ |
| Dredger sediment over-spill release rate | 30 kg/s | Assumed value |
| Time to fill dredger | 4 hours | Assumed value |
| Total mass of over-spilled sediment from dredging one small turbine gravity base foundation | 172,800 kg | 30 kg/s x 0.4 cycles x 4 hours x 60 min/hour x 60 s/min |
| Total mass of over-spilled sediment from dredging all small turbine gravity base foundations | 48,140,509 kg | 30 kg/s x 111.4 cycles x 4 hours x 60 min/hour x 60 s/min |
| Total (consolidated) volume of over-spilled sediment from dredging one small turbine gravity base foundation | 109 m³ | 172,800 kg divided by 2,650 kg/m³ divided by 0.6 |
| Total (consolidated) volume of over-spilled sediment from dredging all small turbine gravity base foundations | 30,278 m³ | 48,140,509 kg divided by 2,650 kg/m³ divided by 0.6 |
| Area over which sediment is released at the water surface | 100 m² | Assumed value – sediment over-spill is released at the water surface in an area approximately 10 m x 10 m = 100 m². Using a larger value will increase initial dispersion, decrease SSC and reduce the thickness of subsequent deposits and *vice versa*. |

**Table 4.15: Maximum design scenario for sediment release by ground preparation dredging for offshore HVAC collector substation gravity base foundations.**

| Parameter | Maximum design scenario | Working and other assumptions |
|---|---|---|
| Number of HVAC collector substation gravity base foundations to be dredged | 12 | |
| Size of dredged area | 175 m x 175 m | |
| Depth of dredged area | 2 m | |
| Total volume of sediment to dredge for one HVAC collector substation gravity base foundation | 61,250 m³ | 175 m width x 175 m length x 2 m depth |
| Total volume of sediment to dredge for all HVAC collector substation gravity base foundations | 735,000 m³ | 61,250 m³ x 12 HVAC collector substation gravity base foundations |
| Sediment mineral density | 2,650 kg/m³ | Assumed value for quartz sand (Soulsby, 1997). |
| Consolidated packing density | 0.6 | Assumed value for a typical, medium sorted sand (Soulsby, 1997). |
| Total mass of sediment to dredge for one HVAC collector substation gravity base foundation | 97,387,500 kg | 61,250 m³ x 2,650 kg/m³ x 0.6<br>Only a fraction of this material will be released as dredge over-spill. The remainder will be deposited to the seabed nearby, within the Hornsea Three array area |
| Total mass of sediment to dredge for all HVAC collector substation gravity base foundations | 1,168,650,000 kg | 735,000 m³ x 2,650 kg/m³ x 0.6<br>Only a fraction of this material will be released as dredge over-spill. The remainder will be deposited to the seabed nearby, within the Hornsea Three array area |
| Dredger hopper capacity | 11,000 m³ | The dredging will be undertaken by a trailer suction hopper dredger (TSHD) with an assumed representative hopper capacity of 11,000 m³ |
| Equivalent number of dredging cycles to dredge one HVAC collector substation gravity base foundation | 5.6 cycles | 61,250 m³ divided by 11,000 m³ |
| Equivalent number of dredging cycles to dredge all HVAC collector substation gravity base foundations | 66.8 cycles | 735,000 m³ divided by 11,000 m³ |
| Dredger sediment over-spill release rate | 30 kg/s | Assumed value |
| Time to fill dredger | 4 hours | Assumed value |
| Total mass of over-spilled sediment from dredging one HVAC collector substation gravity base foundation | 2,419,200kg | 30 kg/s x 5.6 cycles x 4 hours x 60 min/hour x 60 s/min |

| Parameter | Maximum design scenario | Working and other assumptions |
|---|---|---|
| Total mass of over-spilled sediment from dredging all HVAC collector substation gravity base foundations | 28,857,600 kg | 30 kg/s x 66.8 cycles x 4 hours x 60 min/hour x 60 s/min |
| Total (consolidated) volume of over-spilled sediment from dredging one HVAC collector substation gravity base foundation | 1,522 m³ | 2,419,200kg kg divided by 2,650 kg/m³ divided by 0.6 |
| Total (consolidated) volume of over-spilled sediment from dredging all HVAC collector substation gravity base foundations | 18,161 m³ | 28,857,600 kg divided by 2,650 kg/m³ divided by 0.6 |
| Area over which sediment is released at the water surface | 100 m² | Assumed value – sediment over-spill is released at the water surface in an area approximately 10 m x 10 m = 100 m². Using a larger value will increase initial dispersion, decrease SSC and reduce the thickness of subsequent deposits and *vice versa*. |

**Table 4.16: Maximum design scenario for sediment release by ground preparation dredging for offshore HVDC converter substation gravity base foundations.**

| Parameter | Maximum design scenario | Working and other assumptions |
|---|---|---|
| Number of HVDC converter substation gravity base foundations to be dredged | 4 | |
| Size of dredged area | 98 m x 178 m | |
| Depth of dredged area | 2 m | |
| Total volume of sediment to dredge for one HVDC converter substation gravity base foundation | 34,888 m³ | 98 m width x 178 m length x 2 m depth |
| Total volume of sediment to dredge for all HVDC converter substation gravity base foundations | 139,552 m³ | 34,888 m³ x 4 HVDC converter substation gravity base foundations |
| Sediment mineral density | 2,650 kg/m³ | Assumed value for quartz sand (Soulsby, 1997). |
| Consolidated packing density | 0.6 | Assumed value for a typical, medium sorted sand (Soulsby, 1997). |
| Total mass of sediment to dredge for one HVDC converter substation gravity base foundation | 55,471,920 kg | 34,888 m³ x 2,650 kg/m³ x 0.6<br>Only a fraction of this material will be released as dredge over-spill. The remainder will be deposited to the seabed nearby, within the Hornsea Three array area. |
| Total mass of sediment to dredge for all HVDC converter substation gravity base foundations | 221,887,680 kg | 139,552 m³ x 2,650 kg/m³ x 0.6<br>Only a fraction of this material will be released as dredge over-spill. The remainder will be deposited to the seabed nearby, within the Hornsea Three array area |
| Dredger hopper capacity | 11,000 m³ | The dredging will be undertaken by a trailer suction hopper dredger (TSHD) with an assumed representative hopper capacity of 11,000 m³ |
| Equivalent number of dredging cycles to dredge one HVDC converter substation gravity base foundation | 3.2 cycles | 34,888 m³ divided by 11,000 m³ |
| Equivalent number of dredging cycles to dredge all HVDC converter substation gravity base foundations | 12.7 cycles | 139,552 m³ divided by 11,000 m³ |
| Dredger sediment over-spill release rate | 30 kg/s | Assumed value |
| Time to fill dredger | 4 hours | Assumed value |
| Total mass of over-spilled sediment from dredging one HVDC converter substation gravity base foundation | 1,382,400 kg | 30 kg/s x 3.2 cycles x 4 hours x 60 min/hour x 60 s/min |
| Total mass of over-spilled sediment from dredging all HVDC converter substation gravity base foundations | 5,486,400 kg | 30 kg/s x 12.7 cycles x 4 hours x 60 min/hour x 60 s/min |
| Total (consolidated) volume of over-spilled sediment from dredging one HVDC converter substation gravity base foundation | 869 m³ | 1,382,400 kg divided by 2,650 kg/m³ divided by 0.6 |
| Total (consolidated) volume of over-spilled sediment from dredging all HVDC converter substation gravity base foundations | 3,451 m³ | 5,486,400 kg divided by 2,650 kg/m³ divided by 0.6 |
| Area over which sediment is released at the water surface | 100 m² | Assumed value – sediment over-spill is released at the water surface in an area approximately 10 m x 10 m = 100 m². Using a larger value will increase initial dispersion, decrease SSC and reduce the thickness of subsequent deposits and *vice versa*. |

4.3.3.13 The maximum design scenario for sediment spoil disposal by the dredger (for all foundation types) is characterised as:

- Dredge spoil will be returned to the seabed by the dredger at a nearby location within the Hornsea Three array area;
- The dredging will be undertaken by a TSHD with a split bottom release (allowing the fastest possible release of all sediment in the hopper). It is assumed that the full representative hopper capacity of 11,000 m³ is released; and
- The majority of the sediment load (up to 90% based on monitoring evidence from the aggregate industry) will descend to the seabed as a single unit, behaving as a density flow. This downward movement of material is termed the 'dynamic phase' of the plume. The rate of descent of the dynamic phase through the water column is rapid (in the order of several metres per second) relative to the normal settling rate for the individual grains that comprise it. The remaining 10% of the sediment volume released will form a more dispersed plume throughout the water column, termed the 'passive phase', that will settle at approximately the rate of the individual grains.

4.3.3.14 In summary, the maximum design scenario for all sediment release by ground preparation dredging for all 300 turbine gravity base foundations (Table 4.14), three offshore accommodation platform gravity base foundations (Table 4.13), 12 offshore HVAC collector substations (Table 4.15) and four HVDC substation piled jacket foundations (Table 4.16), is characterised as follows and in Table 4.17:

- The rate of sediment release by over-spill during dredging (30 kg/s) is determined by the performance of the dredging vessel and so is constant for all foundation scenarios;
- Spoil will be disposed of at the end of each dredging cycle from the base of the dredging vessel at a nearby location within the Hornsea Three array area. During disposal, up to 11,000 m³ of material will be released from the bottom of the vessel in a sudden event. 90% of the material will be deposited directly to the bed as a single mass and 10% of the material will be re-suspended as a plume of elevated SSC.

4.3.3.15 Levels of SSC resulting from drilling of the different foundation types (with different rates of release) assuming 100% of the drill arisings are fines are shown in Table 4.18 for the range of dispersion scenarios listed below. The approximate timeframe and distance downstream from the point of release for each dispersion scenario is indicated, based on the representative rates of lateral dispersion and current speeds previously described in paragraph 4.3.1.3.

- Source concentration at the point of release (total mass evenly dispersed in a volume of water 10 m wide, 10 m length, 1 m depth);
- Vertical diffusion to 5 m, 20 m lateral spread in footprint dimensions (30 seconds to one minute after release, 7.5 to 15 m downstream);
- Vertical diffusion to 15 m (from surface to approximately half water depth), 50 m lateral spread in footprint dimensions (five to ten minutes after release, 75 to 150 m downstream); and
- Vertical diffusion to 25 m (approximately full water column, so affecting the seabed), 100 m lateral spread in footprint dimensions (30 minutes after release, 450 m downstream).

**Table 4.17: Maximum design scenario for total sediment release by dredging for all gravity base foundations**

| Parameter | Maximum design scenario | Working and other assumptions |
|---|---|---|
| Total volume of sediment dredged while preparing all foundations | 2,117,779 m³ | 1,225,692 m³ for 300 turbines, 17,535 m³ for three offshore accommodation platforms, 735,000 m³ for 12 offshore HVAC collector substations and139,552 m³ for four offshore HVDC converter substations. |
| Total mass of sediment dredged while preparing all foundations | 3,367,268,610 kg | 2,117,779 m³ x (sediment mineral density) 2,650 kg/m³ x (consolidated packing density) 0.6. |
| Total (consolidated) volume of sediment redeposited as part of dredging while preparing all foundations | 2,117,779 m³ | Equivalent to the total volume of sediment dredged. |
| Total equivalent number of dredging cycles to dredge all foundations | 193 cycles | 2,111,557 m³ divided by (dredger hopper capacity) 11,000 m³. |

**Table 4.18: Suspended sediment concentration as a result of over-spill during dredging for any foundation (100% over-spill as fines).**

| Plume width (m) | Plume depth (m) | Plume section length (m) | Resulting SSC (mg/l) [a] |
|---|---|---|---|
| 10 | 1 | 10 | 12,000 |
| 20 | 5 | | 1,200 |
| 50 | 15 | | 160 |
| 100 | 25 | | 48 |
| a | Rate of sediment release 30 kg/s; total mass released into receiving water 1,200 kg; representative current speed 0.25 m/s. | | |

4.3.3.16 Levels of SSC as a result of overspill during dredging for any gravity base foundation type assuming 100% of the drill arisings are sands or gravels is shown in Table 4.19. The estimated area and average thickness of sediment deposition thickness for each gravity base foundation type assuming 100% of the drill arisings are sands or gravels is shown in Table 4.20.

**Table 4.19: Suspended sediment concentration as a result of over-spill during dredging for any gravity base foundation type (100% over-spill as sands or gravels).**

| Sediment type | Water depth (m) | Settling rate (m/s) | Duration of settlement (s) | Distance plume advected by peak current (m) | Maximum mass in suspension (kg) | | |
|---|---|---|---|---|---|---|---|
| 100% Sand | 25 | 0.05 | 500 | 250 | 32,520 | | |
| | 40 | | 800 | 400 | 52,033 | | |
| | 55 | | 1,100 | 550 | 71,545 | | |
| | 70 | | 1,400 | 700 | 91,057 | | |
| 100% Gravel | 25 | 0.5 | 50 | 25 | 3,252 | | |
| | 40 | | 80 | 40 | 5,203 | | |
| | 55 | | 110 | 55 | 7,154 | | |
| | 70 | | 140 | 70 | 9,106 | | |
| **Sediment type** | **Water depth (m)** | **Diameter of midwater SSC influence (m)** | **Area of midwater SSC influence (m$^2$)** | **Midwater average SSC (mg/l) [a]** | **Diameter of near-bed SSC influence (m)** | **Area of near-bed SSC influence (m$^2$)** | **Near-bed average SSC (mg/l) [a]** |
| 100% Sand | 25 | 19 | 283 | Th | 25 | 482 | Th |
| | 40 | 27 | 588 | Th | 37 | 1,053 | Th |
| | 55 | 36 | 1,003 | Th | 48 | 1,846 | Hn |
| | 70 | 44 | 1,529 | Hn | 60 | 2,859 | Hn |
| 100% Gravel | 25 | 9 | 70 | Th | 11 | 99 | Th |
| | 40 | 12 | 114 | Th | 15 | 177 | Hn |
| | 55 | 15 | 170 | Hn | 19 | 276 | Hn |
| | 70 | 17 | 237 | Hn | 22 | 398 | Hn |

a U- units(single digit); Tn – tens; Hn – hundreds; Th – thousands; TnTh – tens of thousands; HnTh – hundreds of thousands; Mn – low millions.

**Table 4.20: Sediment deposition as a result of over-spill during dredging for each gravity base foundation type (100% over-spill as sands or gravels).**

| Sediment type | Water depth (m) | Turbine or offshore accommodation platform gravity base foundation | | Offshore HVAC collector substation gravity base foundation | | HVDC converter substation gravity base foundation | |
|---|---|---|---|---|---|---|---|
| | | Area of seabed deposition (m$^2$) | Average thickness of seabed deposition (m) | Area of seabed deposition (m$^2$) | Average thickness of seabed deposition (m) | Area of seabed deposition (m$^2$) | Average thickness of seabed deposition (m) |
| 100% Sand | 25 | 6,767 | 0.02 | 96,478 | 0.02 | 84,332 | 0.01 |
| | 40 | 12,268 | 0.01 | 162,771 | 0.01 | 142,475 | 0.01 |
| | 55 | 18,849 | 0.01 | 235,369 | 0.01 | 206,275 | 0.00 |
| | 70 | 26,512 | 0.01 | 314,272 | 0.00 | 275,733 | 0.00 |
| 100% Gravel | 25 | 574 | 0.25 | 9,049 | 0.17 | 7,896 | 0.10 |
| | 40 | 964 | 0.15 | 14,744 | 0.10 | 12,872 | 0.06 |
| | 55 | 1,388 | 0.10 | 20,639 | 0.07 | 18,027 | 0.04 |
| | 70 | 1,847 | 0.08 | 26,733 | 0.06 | 23,361 | 0.03 |

a Minor differences in the results for these otherwise similar scenarios (are due to the difference in the time required to complete the dredging for one foundation (affecting the assumed length of the footprint of deposition) and due to differences in the dimensions of the dredged areas (affecting the assumed width of the footprint of deposition).

4.3.3.17 Levels of SSC in the passive phase of the plume created during dredge spoil disposal for any gravity base foundation type assuming 100% of the drill arisings are fines is shown in Table 4.21. Levels of SSC in the passive phase of the plume created during dredge spoil disposal for any gravity base foundation type assuming 100% of the drill arisings are sands or gravels is shown in Table 4.22; the resulting estimated area and average thickness of sediment deposition thickness is also provided.

**Table 4.21: Suspended sediment concentration as a result of dredge spoil disposal (passive phase only) for any foundation (100% over-spill as fines).**

| Plume width (m) | Plume depth (m) | Plume section length (m) | Resulting SSC (mg/l) [a] |
|---|---|---|---|
| 10 | 25 | 10 | 699,600 |
| 100 | 25 | 100 | 6,996 |
| 1000 | 25 | 1000 | 70 |
| 5000 | 25 | 5000 | 3 |

a Total mass fine sediment released into passive phase 1,749,000 kg (10% x 11,000 m³ x 2,650 kg/m³ x 0.6 solidity); sediment released uniformly by the active phase during descent from surface to seabed; water depth 25 m.

**Table 4.22: Suspended sediment concentration and sediment deposition as a result of dredge spoil disposal (passive phase only) for any foundation (100% as sands or gravels).**

| Sediment Type | Water depth (m) | Settling rate (m/s) | Duration of settlement (s) | Distance plume advected by peak current (m) | Maximum mass in suspension (kg) | Area of seabed deposition (m²) | Average thickness of seabed deposition (m) |
|---|---|---|---|---|---|---|---|
| 100% Sand | 25 | 0.05 | 500 | 250 | 1,749,000 | 8,978 | 0.12 |
| | 40 | | 800 | 400 | 1,749,000 | 22,771 | 0.05 |
| | 55 | | 1,100 | 550 | 1,749,000 | 42,869 | 0.03 |
| | 70 | | 1,400 | 700 | 1,749,000 | 69,272 | 0.02 |
| 100% Gravel | 25 | 0.5 | 50 | 25 | 1,749,000 | 299 | 3.68 |
| | 40 | | 80 | 40 | 1,749,000 | 744 | 1.48 |
| | 55 | | 110 | 55 | 1,749,000 | 1,389 | 0.79 |
| | 70 | | 140 | 70 | 1,749,000 | 2,233 | 0.49 |

| Sediment Type | Water depth (m) | Settling rate (m/s) | Duration of settlement (s) | Distance plume advected by peak current (m) | Maximum mass in suspension (kg) | Area of seabed deposition (m²) | Average thickness of seabed deposition (m) |
|---|---|---|---|---|---|---|---|
| **Sediment Type** | **Water depth (m)** | **Diameter of midwater SSC influence (m)** | **Area of midwater SSC influence (m²)** | **Midwater average SSC (mg/l) [a]** | **Diameter of near-bed SSC influence (m)** | **Area of near-bed SSC influence (m²)** | **Near-bed average SSC (mg/l) [a]** |
| 100% Sand | 25 | 14 | 165 | HnTh | 20 | 322 | HnTh |
| | 40 | 23 | 410 | HnTh | 32 | 810 | TnTh |
| | 55 | 31 | 767 | TnTh | 44 | 1,519 | TnTh |
| | 70 | 40 | 1,233 | TnTh | 56 | 2,448 | TnTh |
| 100% Gravel | 25 | 5 | 19 | Mn | 7 | 36 | Mn |
| | 40 | 8 | 45 | HnTh | 10 | 87 | HnTh |
| | 55 | 10 | 82 | HnTh | 14 | 159 | HnTh |
| | 70 | 13 | 130 | HnTh | 18 | 254 | TnTh |

a U- units(single digit); Tn – tens; Hn – hundreds; Th – thousands; TnTh – tens of thousands; HnTh – hundreds of thousands; Mn – low millions.

4.3.3.18 Estimates of the area and average thickness of sediment deposition are provided in the preceding tables based on the approximate footprint of the plume and tidal advection factors. The extent, thickness and shape of sediment deposits on the seabed will be highly variable in practice. However, given the total volume of sediment, a range of potential alternative combinations can be calculated. A range of alternative possible value combinations are provided in Table 4.23 for dredging overspill and in Table 4.24 for the active and passive phases of the dredge spoil disposal plume. For more details about the basis of these tables, see the previous assessment for drilling (paragraphs 4.3.2.20 and 4.3.2.21).

**Table 4.23: Alternative potential extents and thicknesses of sediment deposition as a result of over-spill during dredging.**

| Foundation type / operation | Deposition scenario | Nominal diameter of influence (m) as a result of dredging overspill for one foundation (and the area of influence of all foundations as a proportion of the Hornsea Three array area, 696 km²) | Thickness of deposit (m)[a] |
|---|---|---|---|
| Dredging overspill for 160 larger turbine gravity base foundations (144 m³ overspill per foundation). | Uniform thickness | 19 (0.01%)<br>27 (0.01%)<br>61 (0.07%) | 0.5<br>0.25<br>0.05 |
| Dredging overspill for 300 smaller turbine gravity base foundations (101 m³ overspill per foundation). | Uniform thickness | 16 (0.01%)<br>23 (0.02%)<br>51 (0.09%) | 0.5<br>0.25<br>0.05 |
| Dredging overspill for 12 offshore HVAC collector substation gravity base foundations (1,513 m³ overspill per foundation). | Uniform thickness | 62 (0.01%)<br>88 (0.01%)<br>196 (0.05%) | 0.5<br>0.25<br>0.05 |
| Dredging overspill for four HVDC converter substation gravity base foundations (756 m³ overspill per foundation). | Uniform thickness | 44 (0.00%)<br>62 (0.00%)<br>139 (0.01%) | 0.5<br>0.25<br>0.05 |
| Dredging overspill for three larger offshore accommodation platform gravity base foundations (144 m³ overspill per foundation). | Uniform thickness | 19 (0.00%)<br>27 (0.00%)<br>61 (0.00%) | 0.5<br>0.25<br>0.05 |
| Dredging overspill for three smaller offshore accommodation platform gravity base foundations (93 m³ overspill per foundation). | Uniform thickness | 15 (0.00%)<br>22 (0.00%)<br>49 (0.00%) | 0.5<br>0.25<br>0.05 |
| a Average uniform thickness. All value pairs are part of a continuous scale of possible outcomes. | | | |

**Table 4.24: Alternative potential extents and thicknesses of sediment deposition as a result of dredging spoil disposal (active and passive phases).**

| Foundation type / operation | Deposition scenario | Nominal diameter of influence (m) as a result of one spoil disposal event (and the area of influence of all events as a proportion of the Hornsea Three array area, 696 km²) | Thickness of deposit (m)[a] |
|---|---|---|---|
| Spoil disposal from the dredger, 193.5 events for all foundations (9,900 m³ in active phase, 90% of 11,000 m³). | Cone | 49 (0.05%) (steepest)<br>99 (0.21%)<br>148 (0.48%) | 15.5<br>3.9<br>1.7 |
| | Uniform thickness | 159 (0.55%)<br>225 (1.10%)<br>502 (5.51%) | 0.5<br>0.25<br>0.05 |
| Spoil disposal from the dredger, 193.5 events for all foundations (1,100 m³ in passive phase, 10% of 11,000 m³). | Uniform thickness | 53 (0.06%)<br>75 (0.12%)<br>167 (0.61%) | 0.5<br>0.25<br>0.05 |
| a Height of peak for cones and average uniform thickness. The dimensions of the steepest cone are provided here to indicate the smallest possible area that could be impacted. It is not realistically expected that cone deposits of greater thicknesses (e.g. >5 to 10 m) will be allowed to accumulate in practice. All value pairs are part of a continuous scale of possible outcomes. | | | |

4.3.3.19 The spatial pattern and magnitude of elevated SSC due to dredging were estimated using numerical modelling for Hornsea Project One and Hornsea Project Two (SMart Wind 2013, 2015a, see Figure 4.6 and Figure 4.7). The following observations (based on the spreadsheet based numerical model results) are consistent with the previously modelled patterns of change in Hornsea Project One and Hornsea Project Two, similarly modelled patterns of change in assessments for other wind farms and marine aggregate dredging activities, and the wider monitoring evidence base.

4.3.3.20 In summary, the influence of dredging overspill and spoil disposal on increasing SSC above ambient levels is characterised as follows:

- SSC levels will be highest (potentially tens to hundreds of thousands of mg/l) at the point of sediment release, which is at or near the water surface during dredging overspill and distributed through the whole water column during dredge spoil disposal. This feature will only be present during (the relatively longer) periods of active dredging or during (the relatively short) dredge spoil disposal events;
- For fine material in dredging overspill, SSC levels will decrease rapidly through vertical and horizontal dispersion to low tens of mg/l within the order of hundreds of metres from the point of release;

- For fine material released into the passive plume phase during dredge spoil disposal, SSC levels will be initially higher than for overspill (due to the sudden nature of the sediment release). SSC levels will decrease through horizontal dispersion to a few thousand mg/l within the order of low hundreds of metres and a few tens of mg/l within the order of one thousand metres distance from the source;
- For sand and gravel material in dredging overspill, local SSC levels will decrease to low thousands or hundreds of mg/l locally (low tens of mg/l in a depth mean sense) through horizontal dispersion whilst settling to the seabed;
- For sand and gravel material released into the passive plume phase during dredge spoil disposal, local SSC levels will decrease from hundreds to tens of thousands of mg/l due to horizontal dispersion whilst settling to the seabed;
- Sands will deposit to the seabed within the order of hundreds of metres of the source (taking in the order of 10 to 25 minutes to settle from surface to seabed), and gravels likewise within tens of metres (one to two minutes). The horizontal diameter of the main sand or gravel plume footprint within the water column and on the seabed is likely to be in the order of only tens of metres;
- Following cessation of dredging or spoil release, the influence of sands or gravels on SSC levels will reduce rapidly as described above and will end when all of the sediment is redeposited to the seabed (in the order of one to 25 minutes, depending on the grain size and water depth); and
- Once redeposited to the seabed, the locally dredged overspill and spoil material are essentially the same as the local sediment type. The dredged material will therefore immediately re-join the natural sedimentary environment and will not contribute further to elevated SSC above naturally occurring levels.

4.3.3.21 In summary, sediment deposition as a result of dredging for foundation installation is characterised as follows:

- Deposits of mainly gravel sized dredge overspill will be concentrated within a relatively small area in the order of tens of metres from the site of dredging, with an average thickness in the order of less than ten centimetres;
- Deposits of mainly sand sized dredge overspill sediment will be concentrated within an area in the order of 200 to 700 m downstream/upstream and tens to one hundred metres wide from individual foundations, with an average thickness in the order of less than a few centimetres;
- Spoil disposal will form more concentrated sediment deposits on the seabed. The main mass of sediment (90% of the total volume, falling as the active phase of the plume) will initially result in discrete mounds of sediment in the order of tens to hundreds of metres in diameter (depending on the pattern of settlement) and tens of centimetres to a few metres in local thickness. An area equivalent to a circle of up to 500 m in diameter might be covered to an average depth of 0.05 m. Any larger area of change would correspond to a smaller average thickness. It is possible that consecutive disposal events may overlap on the seabed, resulting in a greater local thickness of sediment but a smaller overall area of influence;
- The smaller mass of material (10% of the total volume) falling as the passive phase of the spoil disposal plume will result in a narrow deposit downstream either hundreds of metres in length and a few centimetres or less thick (for sands), or, tens of metres in length and up to tens of centimetres to a few metres thick (for gravels); and
- Fine grained material released as overspill or as the passive phase of spoil disposal will be dispersed widely within the surrounding region and will not settle locally with measurable thickness. Fine grained material in the active phase of spoil disposal will remain bound in the main sediment mass and will not be differently dispersed to that described above.

4.3.3.22 The assessments undertaken and the summaries above describe the influence of conservatively marginal scenarios where the material being dredged or disposed is entirely fines, sands or gravels. Based on these marginal cases, the following summary describes the overall influence of the same activities assuming that a mixture of sediment grain sizes is present:

- SSC of low tens of mg/l will be present in a narrow plume (tens to a few hundreds of metres wide, up to one tidal excursion in length (~7 km on spring tides and 3.5 km on neap tides) aligned to the tidal stream downstream from the source;
- If dredging occurs over more than one flood or ebb tidal period, the plume feature may be present in both downstream and upstream directions;
- Outside of the area up to one tidal excursion upstream and downstream of the foundation location, SSC less than 10 mg/l may occur more widely due to ongoing dispersion and dilution of material;
- The majority of gravel and sand sized sediment will be deposited to the seabed within tens to hundreds of metres from the source, respectively. A larger proportion of such material in the plume may result in SSC reducing more rapidly in this region and reducing the length or extent of the plume feature overall; and
- Sufficiently fine sediment may persist in suspension for hours to days or longer, but will become diluted to very low concentrations (indistinguishable from natural background levels and variability) within timescales of around one day.

4.3.3.23 If dredging, or any other activity causing sediment disturbance, is undertaken simultaneously at two or more locations that are aligned in relation to the ambient tidal streams, then there is potential for overlap between the areas of effect on SSC and sediment deposition. The potential for in-combination effects on SSC and sediment deposition are discussed in paragraph 4.3.2.26.

**Assessment of change: Hornsea Three offshore cable corridor**

4.3.3.24 Up to four offshore HVAC booster stations may be installed within the offshore HVAC booster station search area using gravity base foundations. Bed preparation would be carried out using a TSHD, assumed to be of comparable size to that for bed preparation activities within the Hornsea Three array area. Dredged material would be deposited at a nearby location, via split bottom disposal.

4.3.3.25 The maximum design scenario for sediment released by ground preparation dredging for offshore HVAC booster station gravity base foundations is characterised in Table 4.25.

4.3.3.26 The potential for increases in SSC as a consequence of bed preparation for turbines in the Hornsea Three array area is described in the previous section, including specific results in Table 4.22. The overall patterns of increase in SSC described for the Hornsea Three array area will remain broadly valid for the offshore HVAC booster station search area because elevated levels of SSC will largely be controlled by the dredging process (dredger type and volume) rather than the overall volume of material excavated.

**Table 4.25: Maximum design scenario for sediment release by ground preparation dredging for offshore HVAC booster station gravity base foundations**

| Parameter | Maximum design scenario | Working and other assumptions |
|---|---|---|
| Number of HVAC booster station gravity base foundations to be dredged | 4 | |
| Size of dredged area | 175 m x 175 m | |
| Depth of dredged area | 2 m | |
| Total volume of sediment to dredge for one HVAC booster station gravity base foundation | 61,250 m³ | 175 m width x 175 m length x 2 m depth |
| Total volume of sediment to dredge for all HVAC booster station gravity base foundations | 245,000 m³ | 61,250 m³ x 4 HVAC booster station gravity base foundations |
| Sediment mineral density | 2,650 kg/m³ | Assumed value for quartz sand (Soulsby, 1997). |
| Consolidated packing density | 0.6 | Assumed value for a typical, medium sorted sand (Soulsby, 1997). |
| Total mass of sediment to dredge for one HVAC booster station gravity base foundation | 97,387,500 kg | 61,250 m³ x 2,650 kg/m³ x 0.6<br>Only a fraction of this material will be released as dredge over-spill. The remainder will be deposited to the seabed nearby. |
| Total mass of sediment to dredge for all HVAC booster station gravity base foundations | 389,550,000 kg | 245,000 m³ x 2,650 kg/m³ x 0.6<br>Only a fraction of this material will be released as dredge over-spill. The remainder will be deposited to the seabed nearby. |
| Dredger hopper capacity | 11,000 m³ | The dredging will be undertaken by a trailer suction hopper dredger (TSHD) with an assumed representative hopper capacity of 11,000 m³ |
| Equivalent number of dredging cycles to dredge one HVAC booster station gravity base foundation | 5.6 cycles | 61,250 m³ divided by 11,000 m³ |
| Equivalent number of dredging cycles to dredge all HVAC booster station gravity base foundations | 22.3 cycles | 245,000 m³ divided by 11,000 m³ |
| Dredger sediment over-spill release rate | 30 kg/s | Assumed value |
| Time to fill dredger | 4 hours | Assumed value |
| Total mass of over-spilled sediment from dredging one HVAC booster station gravity base foundation | 2,419,200 kg | 30 kg/s x 5.6 cycles x 4 hours x 60 min/hour x 60 s/min |
| Total mass of over-spilled sediment from dredging all HVAC booster station gravity base foundations | 9,621,818 kg | 30 kg/s x 22.3 cycles x 4 hours x 60 min/hour x 60 s/min |
| Total (consolidated) volume of over-spilled sediment from dredging one HVAC collector booster gravity base foundation | 1,522 m³ | 2,419,200 kg divided by 2,650 kg/m³ divided by 0.6 |
| Total (consolidated) volume of over-spilled sediment from dredging all HVAC booster station gravity base foundations | 6,051 m³ | 9,621,818 kg divided by 2,650 kg/m³ divided by 0.6 |
| Area over which sediment is released at the water surface | 100 m² | Assumed value - sediment over-spill is released at the water surface in an area approximately 10 m x 10 m = 100 m². Using a larger value will increase initial dispersion, decrease SSC and reduce the thickness of subsequent deposits and *vice versa*. |

4.3.3.27 The higher peak flow speeds within the offshore HVAC booster station search area compared with the Hornsea Three array area means that it is possible that plume extents may be slightly greater than reported for the array area under certain tidal conditions. However, the greater dispersion would also mean lower overall levels of SSC within the plume.

4.3.3.28 The results described above are also conservatively consistent with the numerical modelling undertaken for bed preparation activities in the Hornsea Project Two array area. The modelling showed that peak increases in depth-averaged SSC of more than 2 mg/l above background levels are anticipated up to ~16 km outside of the array, whilst increases in depth-averaged SSC of more than 10 mg/l are anticipated up to ~14 km outside of the array (Figure 4.6) (SMart Wind, 2015).

4.3.3.29 The potential for seabed sediment deposits to accumulate as a consequence of bed preparation dredging for offshore HVAC collector substation foundations in the Hornsea Three array area is described in the previous section, including specific results in Table 4.22 and Table 4.24. The total extent and thickness of bed level change associated with dredging spoil disposal will be dependent on:

- If 61,250 $m^3$ of material were displaced during the installation of one gravity base structure, an area measuring 1,225,000 $m^2$ (nominally 1107 m x 1107 m) could potentially be covered by 0.05 m of material; and
- A greater thickness of material will lead to a smaller area of impact and vice versa. For example, a 0.01 m average thickness deposit would affect an area 5 times larger than discussed above for an average deposition thickness of 0.05 m.

4.3.3.30 If dredging, or any other activity causing sediment disturbance, is undertaken simultaneously at two or more locations that are aligned in relation to the ambient tidal streams, then there is potential for overlap between the areas of effect on SSC and sediment deposition. The potential for in-combination effects on SSC and sediment deposition are discussed in paragraph 4.3.2.26.

### 4.3.4 Sandwave clearance

***Summary***

4.3.4.1 Within certain sections of the offshore cable corridor, relatively large mobile bedforms are present and these may be associated with a considerable thickness (up to 6 m) of coarse grained (primarily sandy) sediment. To ensure effective burial below the level of the stable bed, it may (in places) be necessary to first remove sections of sandwaves using standard dredging techniques or through the use of a mass flow excavator tool, before trenching into the underlying bed. In addition to short term elevations in SSC and associated sediment deposition, sandwave clearance will necessarily result in localised changes to the sandwave and seabed topography. This section therefore also gives consideration to the potential for sandwave and seabed recovery and for longer term changes to sediment transport.

***Evidence base***

4.3.4.2 Sandwave clearance (via dredging and/or mass flow excavator) was previously considered for Hornsea Project Two, using numerical modelling (SMart Wind, 2015a). The nature of the sediment disturbance, the sediment type and other environmental conditions are sufficiently similar to that being considered for Hornsea Three that the previous modelling is considered to provide directly relevant evidence in this regard. The spatial pattern and magnitude of elevated SSC for jetting by mass flow excavator are shown in Figure 4.8 and summarised below:

- At the largest sandwave, predicted increases in depth-averaged SSC peak at approximately 900 mg/l above background levels; however such increases are confined to an area very close to the sandwave location; and
- High (i.e. 100's mg/l) elevated levels of SSC are predicted to occur for a very short period of time (less than one hour) (SMart Wind, 2015a).

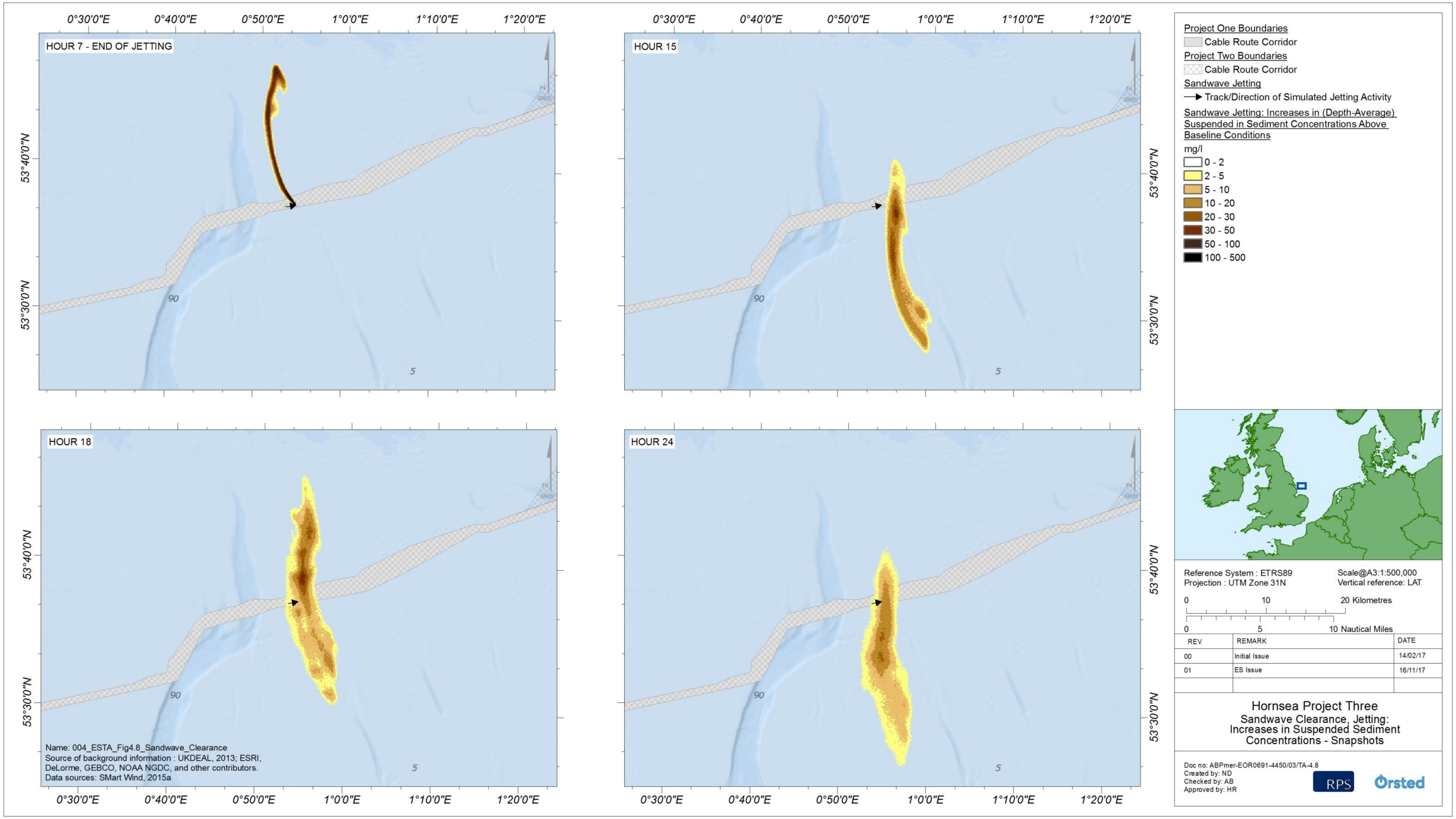


**Figure 4.8: Sandwave clearance via mass excavator tool - predicted maximum increases in depth-averaged SSC above background conditions (reproduced from SMart Wind, 2015a).**

4.3.4.3 Sandwave clearance has previously been undertaken along the Race Bank export cable corridor, using TSHD. An assessment of potential changes associated with these activities has previously been undertaken, using desk based analysis techniques (DONG Energy, 2016). Key findings are summarised below:

- Bed levelling is not considered likely to disrupt the form and function of the sandbank system as these are governed by processes that occur at a much larger scale than the proposed works;
- Dredging activities for sandwave clearance will result in sediment plumes (due to overspill and spoil disposal), causing increases in SSC above background levels and deposition of sediment onto the seabed. The magnitude, extent and duration of any particular type of influence (assessed using spreadsheet based numerical models) will be variable depending on the operational characteristics of the dredger being used, and the local water depth, sediment type and representative current speed;
- As would also logically be expected, for a given rate of dredging, a greater current speed and/or water depth typically leads to a greater extent, but progressively lower magnitude of influence on SSC due to dispersion. Coarser sediment will tend to settle to the seabed more rapidly than finer sediment, leading to a smaller extent and duration but greater magnitude of influence on SSC, and a smaller extent but greater thickness of sediment deposition. Fine sediments that take longer than a few tides to settle out of suspension will be dispersed to very low concentrations and are therefore unlikely to settle in measurable thicknesses;
- Bedform recovery will likely occur in relation to the migration and sediment transport processes across the system. Estimated recovery rates for sandwaves were in the order of several years, based on representative forcing conditions at a single water depth; and
- The proposed bed levelling is not likely to pose any barrier to ongoing sediment transport within or to locations beyond the sandbank system.

***Assessment of change***

4.3.4.4 The volume of material to be cleared from individual sandwaves will vary according to the local dimensions of the sandwave (height, length and shape) and the level to which the sandwave must be reduced (also accounting for stable sediment slope angles and the capabilities and requirements of the cable burial tool being used). Based on the available geophysical data, it is anticipated that the bedforms requiring clearance are likely to be in the range 1 to 6 m in height and located in offshore sections of the route and western parts of the Hornsea Three array area.

4.3.4.5 The nature of the planned activity and the anticipated volumes of material involved (for individual sandwaves) are broadly comparable to that encountered during sandwave clearance operations during installation of the Race Bank export cable. Sandwave clearance has been and will be undertaken for Race Bank using TSHDs to excavate trenches through sandwaves with a width of 25 to 30 m plus some allowance for side slopes. Individual sandwaves typically require dredging of about 500 to 6,000 $m^3$, but up to ~16,000 $m^3$ in the case of a few larger sandwave features. Sandwave clearance may be achieved via either dredging (using a TSHD), or through use of a mass flow excavation tool.

4.3.4.6 For Hornsea Three, the maximum design scenario sediment release caused by sandwave clearance is characterised in Table 4.26.

4.3.4.7 Changes in SSC associated with sandwave clearance by dredging will be the same as described in section 4.3.3 for gravity base foundation bed preparation. The sediments in the sandwave feature will be predominantly sand, although potentially with some small proportion of fines (<5 to 10%). Individual sandwaves typically require less than one dredging cycle per sandwave (dredge volumes 500 to 6,000 $m^3$) but between one and two dredging cycles per sandwave in the case of a few larger sandwaves (dredge volumes up to 16,000 $m^3$). Dredge spoil will be returned to the seabed in the vicinity of the dredged area and so may be less than one full hopper in volume per release. In this case, the volume of sediment entering into suspension from the disposal plume (and so the resulting SSC level), and the volume of sediment deposited to the seabed (and so the resulting extent and thickness of any deposits) is expected to be proportionally smaller.

4.3.4.8 Changes in SSC due to sandwave jetting by mass flow excavator were considered (using numerical modelling) for Hornsea Project One and Hornsea Project Two, adopting the following assumptions:

- Peak depth averaged flow speed of 0.75 to 1.0 m/s;
- The jetting device will travel at 0.05 m/s;
- The jet head will operate at 1 m above the seabed;
- The diameter of the jet head is 1.5 m;
- The jetting device draws in seawater from the side pipes and jets water out from the vertical down pipe. The bed material is shifted and trenched with the force of the jet (except in cases where the bed has high cohesive strength) and flushed away;
- Only one 'pass' will be made through each sandwave to achieve the required clearance width;
- The width of the sandwave to be cleared is 20 m;
- The depth of clearance varies for each location but the largest sandwave that may need to be cleared is 5 m in height; and
- The displaced sediment will contain up to 10% fines (i.e. <63 μm).

**Table 4.26: Maximum design scenario for sediment release by sandwave clearance for cable installation.**

| Parameter | Maximum design scenario | Working and other assumptions |
|---|---|---|
| Volume of sediment in sandwaves to be cleared in the Hornsea Three array area | 71,150 m³ | Based on the assumption that mapped 'sandwave regions cover 11.6% of the Hornsea Three array area, with sandwaves covering 33% of the mapped 'sandwave regions' (see volume 2, chapter 1: Marine Processes).<br>The average sandwave height is 0.63 m. 50% contingency factor applied to ensure estimated volumes is conservative. |
| Volume of sediment in sandwaves to be cleared for installation of export cables in the Hornsea Three offshore cable corridor | 979,090 m³ | Presently estimated value based on the Hornsea Three offshore cable corridor geophysical survey data combined with cable installation design specifications |
| Sediment mineral density | 2,650 kg/m³ | Assumed value for quartz sand (Soulsby, 1997) |
| Consolidated packing density | 0.6 | Assumed value for a typical, medium sorted sand (Soulsby, 1997) |
| Total mass of sediment to clear from sandwaves in the Hornsea Three array area | 342,776,970 kg | 215,583 m³ x 2,650 kg/m³ x 0.6<br>If dredging, only a fraction of this material will be released as dredge over-spill. The remainder will be deposited to the seabed nearby. |
| Total mass of sediment to clear from sandwaves in the Hornsea Three offshore cable corridor | 1,556,753,100kg | 979,090 m³ x 2,650 kg/m³ x 0.6<br>If dredging, only a fraction of this material will be released as dredge over-spill. The remainder will be deposited to the seabed nearby. |
| Dredger hopper capacity | 11,000 m³ | Dredging will be undertaken by a trailer suction hopper dredger (TSHD) with an assumed representative hopper capacity of 11,000 m³ |
| Equivalent number of dredging cycles to dredge sandwaves in the array area | 19.6 cycles | 215,583 m³ divided by 11,000 m³ |
| Equivalent number of dredging cycles to dredge sandwaves in the Hornsea Three offshore cable corridor | 89.0 cycles | 979,090 m³ divided by 11,000 m³ |
| Dredger sediment over-spill release rate | 30 kg/s | Assumed value |
| Time to fill dredger | 4 hours | Assumed value |
| Total mass of over-spilled sediment from dredging sandwaves in the array area | 8,466,532 kg | 30 kg/s x 19.6 cycles x 4 hours x 60 min/hour x 60 s/min |
| Total mass of over-spilled sediment from dredging sandwaves in the Hornsea Three offshore cable corridor | 38,451,535 kg | 30 kg/s x 89.0 cycles x 4 hours x 60 min/hour x 60 s/min |
| Total (consolidated) volume of over-spilled sediment from dredging sandwaves in the array area | 5,325 m³ | 8,466,532 kg divided by 2,650 kg/m³ divided by 0.6 |
| Total (consolidated) volume of over-spilled sediment from dredging sandwaves in the Hornsea Three offshore cable corridor | 24,183 m³ | 38,451,535 kg divided by 2,650 kg/m³ divided by 0.6 |
| Area over which sediment is released at the water surface | 100 m² | Sediment over-spill is released at the water surface in an area approximately 10 m x 10 m = 100 m². Using a larger value will increase initial dispersion, decrease SSC and reduce the thickness of subsequent deposits and *vice versa*. |

4.3.4.9 The results of the Hornsea Project One and Hornsea Project Two plume modelling suggest:

- Increases of approximately 900 mg/l in depth-averaged SSC above background levels in an area close to the sandwave location;
- High levels of SSC (i.e. hundreds of mg/l) near to the point of release are predicted to occur for a short period of time (less than one hour); and
- Increases of tens to a few hundreds of mg/l are observed in plumes downstream of the sandwave (in both flood and ebb directions).

4.3.4.10 Similar operational assumptions are applied for the Hornsea Three offshore cable corridor in a spreadsheet based numerical model as described in section 4.3.1. Results are presented in Table 4.27. Quantitative estimates of resulting SSC increases within the plume area are not provided due to the wide range of possible variation in the operational parameters. The mass flow excavator device is specifically designed to re-suspend and displace large volumes of sediment without local containment in a short time period. The resulting level of SSC is correspondingly very high in comparison to the natural range and will lead to a significant thickness of rapid sediment re-deposition. However, these changes (i.e. the increase in SSC and the resulting deposition of sediment) are otherwise similar to that caused by any other activity with a lesser magnitude or rate of sediment disturbance.

4.3.4.11 In summary, the majority of sandy sediment (i.e. the majority of the affected sediment volume) will form a dense plume and then be redeposited rapidly to the seabed in a manner similar to that for other cable jetting activities (described in section 4.3.5). The large total volume and rate of material displaced by mass flow excavation is expected to lead to very large increases in SSC above background levels during the operation. The plume will be limited to a relatively small spatial extent downstream (order of tens to a few hundreds of metres) and only for the duration of the activity and for a short time afterwards (order of tens to a few hundreds of seconds).

**Table 4.27: Temporal and spatial extent of the plume and thickness of sediment deposition as a result of sandwave clearance by mass flow excavator in 100% sand (settling rate 0.05 m/s)**

| Representative current speed (m/s) | Height of ejection (m) | Time for resettlement (s) | Distance plume advected by current (m) | Average thickness of seabed deposition [a] (m) |
|---|---|---|---|---|
| 0.25 | 1 | 20 | 5.0 | 10.00 |
| 0.5 | 1 | 20 | 10.0 | 5.00 |
| 0.75 | 1 | 20 | 15.0 | 3.33 |
| 1 | 1 | 20 | 20.0 | 2.50 |
| 0.25 | 5 | 100 | 25.0 | 2.00 |
| 0.5 | 5 | 100 | 50.0 | 1.00 |
| 0.75 | 5 | 100 | 75.0 | 0.67 |
| 1 | 5 | 100 | 100.0 | 0.50 |
| 0.25 | 10 | 200 | 50.0 | 1.00 |
| 0.5 | 10 | 200 | 100.0 | 0.50 |
| 0.75 | 10 | 200 | 150.0 | 0.33 |
| 1 | 10 | 200 | 200.0 | 0.25 |

Assumed total dredge volume 5000 $m^3$ (dredged channel 100 m long and 20 m wide through a sandwave crest approximately 5 m high).

a Average thickness based on the total volume of sediment released and the area formed by the distance the plume is advected by the current and the length of the dredged channel.

4.3.4.12 The resulting thickness of accumulation of sand will be relatively large (order of tens of centimetres to several metres thick) which is in proportion to the large volume of sediment being cleared and the limited area within which it is expected to settle (within tens to a few hundreds of metres).

4.3.4.13 Finer sediments will only realistically comprise a small proportion of the total disturbed sediment volume. Fines re-suspended by mass excavator will remain in suspension for longer periods of time (order of hours to days or longer). Although likely present at high concentrations at the point of release, fine sediments in suspension will rapidly become dispersed so widely that they no longer contribute to a measurable elevation in SSC and are unlikely to settle in measurable thickness locally.

4.3.4.14 If sandwave clearance, or any other activity causing sediment disturbance, is undertaken simultaneously at two or more locations that are aligned in relation to the ambient tidal streams, then there is potential for overlap between the areas of effect on SSC and sediment deposition. The potential for in-combination effects on SSC and sediment deposition are discussed in paragraph 4.3.2.26.

Recovery of sandwave features following clearance

4.3.4.15 As previously noted, the volume of material to be cleared by dredging from individual sandwaves will vary according to the local dimensions of the sandwave (height, length and shape) and the level to which the height must be reduced (accounting for stable sediment slope angles and the capabilities and requirements of the cable burial tool being used).

4.3.4.16 The potential for seabed recovery following sandwave clearance along the Race Bank export cable route as well as for wider changes to sediment transport patterns has previously been considered as a detailed desktop study to inform the HRA for the Inner Dowsing, Race Bank and North Ridge SAC (DONG Energy, 2016).

4.3.4.17 Pre and repeated post construction monitoring (at intervals of days to weeks initially, and up to four months following initial levelling) has also since become available for two offshore locations on the Race Bank offshore cable route (DONG Energy, 2017). In agreement with the conclusions of the desktop study (DONG Energy, 2016), the data show partial recovery of the sandwave crest feature occuring within the levelled corridor towards the end of the four month period for which data are presently available. Recovery was apparently achieved by naturally occuring local sediment accumulation along the previous crest line and was not obviously associated with forward migration of the sandwave crest or erosion of the surrounding non-levelled areas.

4.3.4.18 Both the Race Bank offshore wind farm export cable and Hornsea Three offshore cable corridor pass through similarly dynamic areas of seabed characterised by highly mobile sediment and migrating bedform features. The conclusions reached in DONG Energy (2016), which are supported by the monitoring described in DONG Energy (2017), are considered to be also applicable for areas of sandwave clearance within the Hornsea Three offshore cable corridor. These conclusions are summarised below. An accompanying statement of confidence (either high, medium or low) is also provided, based on expert judgement and a conceptual system understanding:

*The bedforms along which bed levelling is proposed are part of a dynamic bedform field including (in places) an active sandbank belonging to the North Norfolk Sandbank system. The patterns of processes governing the overall evolution of the systems (the flow regime, water depths and sediment availability)* *are at a much larger scale than, and so would not be affected by, the proposed local works. As a result, the proposed levelling is not likely to influence the overall form and function of the system and eventual recovery via natural processes is therefore expected (confidence:* ***medium to high****).*

*The rate of recovery would vary in relation to the rate of sediment transport processes, faster infill and recovery rates will be associated with higher local flow speeds and more frequent wave influence. The shape of the bedform following recovery might recover to its original condition (e.g. rebuilding a single crest feature, although likely displaced in the direction of natural migration) or it might change (e.g. a single crest feature might bifurcate or merge with another nearby bedform). All such possible outcomes are consistent with the natural processes and bedform configurations that are already present in the site and would not adversely affect the onward form and function of the individual bedform features, or the sandbank system as a whole (confidence:* ***high confidence*** *that the seabed will recover to a new natural equilibrium state. However, any predictions of the exact timescales of change, as well as the form of the 'new' features would have* ***low*** *confidence.****)****.*

*The levelled areas are not considered likely to create a barrier to sediment movement. Evidence drawn from aggregate dredging activities indicate that if any changes occur to the flow conditions or wave regime, these are localised in close proximity to the dredge pocket. However, the aggregate dredge pockets concerned had widths and lengths of several kilometres. The proposed works are at a much smaller scale and footprint, with trench widths of 13 m along the interlink cable, trench base widths of 25 to 30 m plus side slopes along the export cable or maximum diameter of 55 m for foundation preparation. This means there is likely to be little to no effect on the flow or wave regime, which in turn means no effect on the regional scale sediment transport processes across the array site and export cable route* ***(****confidence:* ***medium to high)****.*

4.3.4.19 Assuming that either a mass flow excavator is used for sandwave clearance, or that any material excavated via the use of a dredger is disposed of adjacent to the dredge location, no sediment volume will be removed from the sandbank systems overall. The displaced material will be of the same sediment type as the surrounding seabed and, following disposal, will be immediately available again for transport at the naturally occurring rate. Should an MMO licence for a new disposal site not be granted within the vicinity of the dredging areas, material may have to be transported some distance by vessel and therefore potentially 'lost' from the system. Although this scenario would not be preferable to local disposal, it is still considered unlikely that it would adversely affect the form and function of the designated features within the North Norfolk Sandbanks and Saturn Reef SAC. This is because the area impacted (5,760,000 $m^2$) is extremely small (<0.2 %) relative to the overall size of the SAC (circa 3,609,000,00 $m^2$). The area and volume of sediment currently present in the whole sandwave system cannot be accurately estimated, but it is reasonable to conclude that the volume of sediment being removed would also be extremely small in a relative sense (<<0.2 %).

4.3.4.20 Sandwave clearance will be limited to discrete areas of limited width to enable cable laying activities to be carried out. The sandwaves within the Hornsea Three offshore cable corridor are typically up to approximately 2 m in height but can be up to approximately 6 m. These sandwaves are located offshore (> ~8 km from the coast) in water depths of ~ -10 mLAT or greater (Bibby HydroMap, 2016). At this distance offshore and with these water depths, the clearance of limited sections of sandwaves is not anticipated to cause any change to the wave regime at the coastline.

### 4.3.5 Cable burial

***Summary***

4.3.5.1 The impact of cable burial operations mainly relates to a localised and temporary re-suspension and subsequent settling of sediments (BERR, 2008). The exact nature of this disturbance will be determined by the sediment conditions within the Hornsea Three array area and offshore cable corridor, the length of installed cable, the burial depth and burial method. These changes are quantitatively characterised in this section for export, array and substation interconnector cables using spreadsheet based numerical models.

***Evidence base***

4.3.5.2 The evidence base with respect to cable burial activities is broad and includes a range of theoretical, numerical modelling and monitoring studies considering a range of installation methodologies, sediment types, water depths and other environmental conditions. The evidence base is widely applicable as the dimensions of the cables, the installation techniques used and the target depths of burial do not vary significantly with the scale of the development (small or large wind farm arrays) or the type of cable being installed (wind farm export, array or inter-connector cables, or non-wind farm electrical and communications cables).

4.3.5.3 SSC monitoring during cable laying operations has been undertaken at Nysted Wind Farm (ABPmer *et al*., 2007; BERR, 2008). During the works, both jetting and trenching were used, where the latter method involves pre-trenching and back-filling using back-hoe dredgers. Superficial sediments within the site were predominantly medium sands, approximately 0.5 m to 3 m in thickness, underlain by clay. SSC was recorded at a distance of 200 m from jetting and trenching activities and the following values were observed:

- Trenching – mean (14 mg/l) and max (75 mg/l); and
- Jetting – mean (2 mg/l) and max (18 mg/l).

4.3.5.4 The higher sediment concentrations from the trenching activities were considered to be a result of the larger volume of seabed strata disturbed during operations and the fact that the material disturbed during trenching was lifted to the surface for inspection. This meant that the sediment was transported through the full water column before being placed alongside the trench (BERR, 2008).

4.3.5.5 Cable laying monitoring also took place at Kentish Flats where ploughing methods were used to install three export cables (EMU Limited, 2005). Cefas agreed pre-defined threshold limits against which SSC monitoring would be compared. The monitoring 500 m down-tide, i.e. where the concentrations will be greatest, of the cable laying activities showed:

- Marginal, short-term increases in background levels (approximately 9 times increase to the modal background concentrations); and
- Peak concentrations occasionally reaching 140 mg/l (equivalent to peaks in the naturally occurring background concentrations).

4.3.5.6 The observations at Nysted and Kentish Flats provide confidence that cable laying activities do not create a long-term, significant disruption to the background sediment concentrations. Furthermore, it also illustrates that there is little sediment dispersal, indicating that there is unlikely to be much deposition on the seabed other than immediately adjacent to the cable route.

4.3.5.7 Reach (2007) describes plume dispersion studies for a cable laying jetting operation in Hong Kong with an assumption that 20 per cent of a trench cross-section of 1.75 $m^2$ would be disturbed by the jetting process and the speed of the jetting machine would be 300 m/hour (0.083 m/s). ASA (2005) describes similar studies for a cable laying operation near Cape Cod in the USA and assumed that 30% of a trench cross-section of 3 $m^2$ would be disturbed by the jetting process and the speed of the jetting machine would be 91 m/hour (0.025 m/s). This latter study also assumed that any sand particles would quickly return to the bed and only the fine sediment particles (particles with a diameter less than 63 μm) would form a plume in the water column.

4.3.5.8 SeaScape Energy (2008) describes cable installation plume dispersion monitoring studies carried out at the Burbo offshore wind farm in Liverpool Bay, UK:

- Three export cables were installed to a target depth of approximately 3 m by vertical injector ploughing while array cables were installed to a similar depth by jetting assisted ploughing;
- The monitoring demonstrated clearly that both cable installation techniques had only small scale impacts on localised SSC. Changes were measurable to a few hundreds of metres only and suspended sediment levels were not elevated more than five times background. Suspended sediment levels never approached the threshold level (3,000 mg/l) agreed with regulatory authorities beforehand, even in very close proximity to the works (< 50 m); and
- Local changes in SSC over a relatively fine sediment seabed area (most likely to lead to plume impacts) was in the region of 250 to 300 mg/l within 200 m of the operation, falling to the measured baseline level (100 mg/l) by 700 m downstream. It is assumed, therefore, that coarser sediments were associated with even lower levels.

4.3.5.9 The post-burial impacts of cable burial on sandy seabed morphology were also considered by BERR (2008) with reference to a wide range of desktop and monitoring studies. The report concludes that impacts will also be limited in terms of both the thickness of re-deposited sediments and the potential for affecting the surficial sediment type:

*"The low levels of sediment that are mobilised during cable laying mean that there will be only low levels of deposition around the cable route. The finer material will generally remain in suspension for longer but will settle and remobilise on each tide with no measurable material left in place. Coarser sediments are expected to settle within a few metres of the cable route and following disturbance is likely to recover rapidly, given similar communities in the vicinity." (BERR, 2008).*

***Assessment of change***

4.3.5.10 Export, array and inter-connector cables may be installed by burial into the seabed. The Hornsea Three offshore cable corridor runs from the southwestern margin of the Hornsea Three array area to a landfall position between Weybourne Hope and Kelling Hard.

4.3.5.11 For Hornsea Three, the maximum design scenario for sediment release caused by cable burial is characterised in Table 4.28. The potential effects of sediment release due to cable burial are typically localised to the cable route or the active cable burial location. As such, the maximum design scenario information mainly considers local trench dimensions and rates of sediment disturbance. The total volume of sediment disturbance is not relevant to the assessment and so is not presented here. Likewise, the main potential effects of sediment release due to cable burial are typically of very short duration (order of seconds to minutes) and so the possibility of repeated remedial cable burial activities in the same sediment, months later is not relevant to the assessment and so is not presented here.

4.3.5.12 The vertical injection process fluidises an area of sediment within the seabed through which the cable is inserted. By design, the process is intended to bury the cable and so only a minimal proportion of the fluidised sediment is expected be actually ejected from the trench. The exact proportion ejected may vary. Values of 20 to 30% have been used in previous investigations of this type (ASA, 2005). For the purposes of this investigation, it is conservatively assumed that 50% of the disturbed material is ejected.

4.3.5.13 An assessment of potential changes to SSC and bed levels has been undertaken using the spreadsheet based numerical models introduced in section 4.3.1. The slightly larger sediment disturbance volume (by mass flow excavation) is conservatively used in conjunction with the assumption that the sub-surface sedimentary units with a different grain size distribution to surficial sediments may also be re-suspended (such as by deep vertical injection).

**Table 4.28: Maximum design scenario for sediment release by cable installation.**

| Parameter | Maximum design scenario | Working and other assumptions |
| --- | --- | --- |
| Number of export cables | 6 | |
| Minimum spacing between individual export cables | 30 m | |
| Minimum spacing between pairs of export cables | 100 m | |
| Length of individual export cables | 191 km | |
| Total length of all export cables | 1,146 km | 191 km x 6 cables |
| Maximum rate of cable burial | 5 km/day | Same for all cable types. Equivalent to 208 m/hr or 17 s per metre of cable burial. |
| Time required to install one export cable | ~38 days (917 hours) | 191 km divided by 5 km/day |
| Time required to install all export cables | ~229 days (5,501 hours) | 1,146 km divided by 5 km/day |
| Total length of all inter-array cables | 830 km | The total length of inter-array cables will be installed as multiple shorter lengths (number, length and routes to be determined as part of the cable burial design plan). |
| Time required to install all inter-array cables | ~166 days (3,984 hours) | 830 km divided by 5 km/day |
| Total length of all substation interconnector cables | 225 km | The total length of interconnector cables will be installed as multiple shorter lengths (number, length and routes to be determined as part of the cable burial design plan). |
| Time required to install all substation interconnector cables | ~45 days (1,080 hours) | 225 km divided by 5 km/day |
| Number of simultaneous cable burial operations | 3 export cables and 3 inter-array or interconnector cables | Up to three export cables and up to three inter-array or interconnector may be installed simultaneously, however, the cable installation vessels will not be operating in close proximity and therefore the potential for sediment plume interaction between cable lay operations is considered to be small. |
| Methods of cable burial | Mass flow excavation and vertical injection (i.e. jetting). | These methods have the greatest potential to energetically fluidise and eject material from the trench into suspension. By contrast, the other cable installation techniques described in the project design statement (volume 1, chapter 3: Project Description) are expected to re-suspend a smaller amount of material into the water column. Due to spatial variation in the geotechnical properties of the underlying geology within this region, it is possible that a combination of techniques may be used. |
| Dimensions of cable trench using mass flow excavation | Up to 6 m wide and 2 m deep with a 'V' shaped profile, | Mass flow excavation might be used at any location but in practice would only be used where surficial sediments are suitable. |
| Volume of sediment disturbed per metre progress using mass flow excavation | 6 $m^3/m$ | 6 m x 2 m x 0.5 (adjustment for profile)<br>Up to 100% of material is ejected from the trench. |
| Dimensions of cable trench using vertical injection | 1) For at least 95% of the cable length, trench dimensions up to 0.6 m wide and 3 m deep with a 'U' shaped profile;<br>2) For up to 5% of the cable length, trench dimensions up to 1 m wide and 10 m deep with a 'U' shaped profile. | Vertical injection might be used at any location but in practice would only be used where surficial sediments are suitable.<br>Assume up to 50% of material is actually ejected from the trench. The rest is retained as sediment cover within the trench. |
| Volume of sediment disturbed per metre progress using vertical injection | (Depending on the trench dimensions above)<br>1) 1.8 $m^3$<br>2) 5 $m^3$ | 1) 0.6 m x 3 m x 50%<br>2) 10 m x 1 m x 50%<br>Assumes up to 50% of material is actually ejected from the trench. The rest is retained as sediment cover within the trench. |
| Remedial cable burial | In localised areas, within 12 months. | Overall lengths and timescales are provided above in this table for the initial cable burial. If and where the cable is not buried sufficiently deeply during the initial burial attempt, remedial cable burial activities (one to three additional passes of the jetting tool) may also be required in localised areas. The nature and spatial dimensions of the remedial jetting disturbance will be similar or less than that for the initial cable burial. Remedial activities would be undertaken typically within a matter of months (up to 12 months) after the initial burial attempt. |

4.3.5.14 The Hornsea Three offshore cable corridor can be broadly divided into four sections that reflect regional scale spatial variation in hydrodynamic conditions and sediment characteristics (Figure 1.1, Table 4.29). The seabed and sub-seabed sediment composition along the offshore cable corridor is highly heterogeneous. In most locations, the majority of disturbed material will be coarse sand and gravels. However, when installing through the Bolders Bank formation or Cretaceous chalk units (which are present at the landward end of the Hornsea Three offshore cable corridor), some of the released material may also include some proportion of fine grained (i.e. <63 µm) sediments, depending on the degree of disaggregation.

4.3.5.15 It is impractical to capture the full detail of sediment heterogeneity in detail within the context of this assessment, which instead considers a series of maximum design scenario 'end-member' scenarios. These are:

- Mass flow excavation through 100% (coarse) gravel (15,000 µm);
- Mass flow excavation through 100% (medium) sand (375 µm); and
- Mass flow excavation through 100% (fine) silt (10 µm).

**Table 4.29: Summary of spatial variation in hydrodynamic and sedimentary characteristics along the offshore cable corridor.**

| Parameter | Section 1 | Section 2 | Section 3 | Section 4 |
|---|---|---|---|---|
| Representative spring peak current speed (m/s) | 1.0 | 1.0 | 0.75 | 0.5 |
| Sediment characteristics | Sands and gravels overlying chalk in places | Sands and gravels overlying Boulders Bank/ Botney Cut Formation | Sands and gravels overlying Boulders Bank/ Botney Cut Formation | Sands and gravels overlying Boulders Bank/ Botney Cut Formation |
| Max trench dimensions (width x depth, profile) | 6 m x 2 m, 'V' shape, 100% ejected | 6 m x 2 m, 'V' shape, 100% ejected | 6 m x 2 m, 'V' shape, 100% ejected | 6 m x 2 m, 'V' shape, 100% ejected |
| Mineral density (kg/m) | 2,650 | | | |
| Assumed sediment porosity (% void) | 40 | | | |

4.3.5.16 These three scenarios represent the full potential range of change both in terms of the duration, spatial extent of changes to SSC, and maximum thicknesses of sediment deposition. In practice, a release comprising entirely fines is very unlikely.

4.3.5.17 Cable burial through the Bolders Bank formation and Cretaceous chalk units may result in the release of a range of sediment grain sizes, depending on the local nature of the sedimentary units and cable burial method used. In practice, these sediment units are unlikely to disaggregate entirely into the finest possible constituent particle sizes due to the cable burial methods being assessed. This is particularly true for non-jetting installation methods such as ploughing which, given the density of the sub seabed sediment units along parts of the Hornsea Three offshore corridor, are more realistically expected to be used in these areas (DNV, 2014) Figure 4.9. Also, even when fully disaggregated, the Boulders Bank formation does not comprise 100% fine grained material. Ploughing (without simultaneous backfilling) would result in trench dimensions up to that described for mass flow excavation, but will result in a much lower rate of sediment resuspension, hence this method has not been explicitly assessed.

4.3.5.18 The main sources of fines within the Hornsea Three array area are from muddy sandy gravels, which are more commonly found in deep central eastern areas of the site (associated with Markham's Hole) and central northern areas (associated with Outer Silver Pit). In areas of muddy sandy gravels, the proportion of fines is expected to be typically 5 to 20%, but up to 50% in discrete areas. In other areas, the proportion of fines is expected to be much smaller (typically less than 5%).

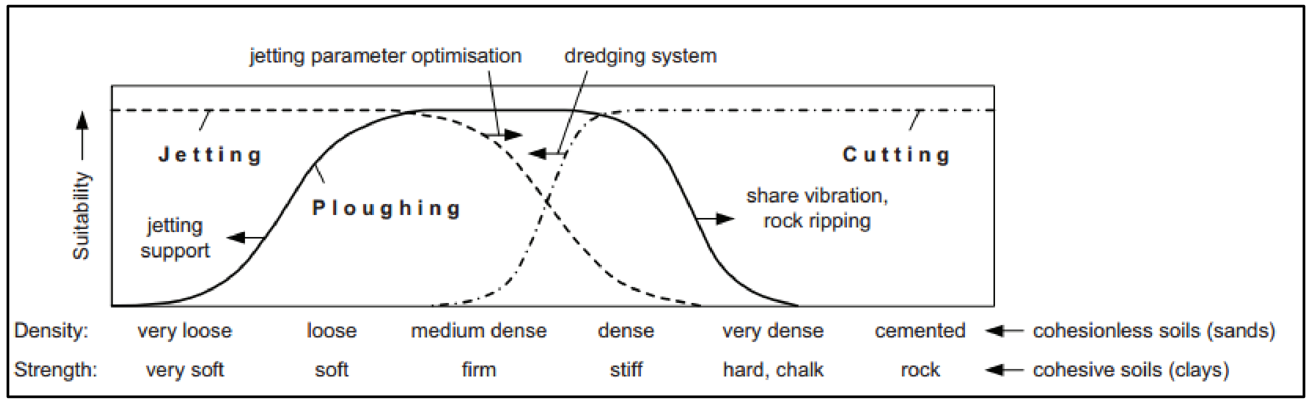


**Figure 4.9: Indicative burial tool suitability in different ground conditions (DNV, 2014).**

4.3.5.19 Results from the assessment scenarios outlined in Table 4.29 and above are presented in Table 4.30 and Table 4.31. Results are presented for a range of representative current speeds, noting that cable burial will continue through all states of the tide, including current speeds lower than the highest locally possible (peak) value. Because of the uncertainty with regards to how high into the water column from the bed material may be ejected or re-suspended, results are provided for a realistic range of heights (1, 5 and 10 m). A greater height of ejection will lead to a potentially longer plume duration and a greater distance of influence, but also a corresponding reduction in SSC and deposition thickness. Because the cable burial tool moves relatively quickly (208 m/hr, or 17 s per metre progress), any influence of the plume experienced downstream will be similarly limited in duration to approximately 17 s, after which time, the plume will have been advected downstream past the location of the receptor, or will be instead affecting an area of seabed elsewhere.

4.3.5.20 Following the same principles, changes associated with cable burial into 100% fine grained sediment will be similar to that described for sand in Table 4.31 for the predicated actual plume length in a downstream direction (4.3 to 17.3 m), the duration of change to SSC locally (17.3 s) and the average level of SSC (hundreds of thousands of mg/l) will be the same for fines in areas near to active cable burial. Fine sediment may persist in suspension for longer than sands (order of days) but the plume will be subject to significant dispersion in that time, reducing any change to SSC to tens of mg/l or less in the same timeframe. As a result of dispersion, no measurable thickness of accumulation of fine sediment is expected.

**Table 4.30: Suspended sediment concentration and thickness of sediment deposition as a result of cable burial in 100% gravel (settling rate 0.5 m/s).**

| Representative current speed (m/s) | Height of ejection (m) | Time for resettlement (s) | Distance plume advected by current (m) | Limited length of influence on SSC in downstream direction (m) | Limited duration of influence on SSC locally (s) | Average SSC in the limited length / duration of influence (mg/l) [a] | Average thickness of seabed deposition [b] (m) |
|---|---|---|---|---|---|---|---|
| 0.25 | 1 | 2 | 0.5 | 0.5 | 2.0 | Mn | 12.00 |
| 0.5 | 1 | 2 | 1.0 | 1.0 | 2.0 | Mn | 6.00 |
| 0.75 | 1 | 2 | 1.5 | 1.5 | 2.0 | Mn | 4.00 |
| 1 | 1 | 2 | 2.0 | 2.0 | 2.0 | Mn | 3.00 |
| 0.25 | 5 | 10 | 2.5 | 2.5 | 10.0 | HnTh | 2.40 |
| 0.5 | 5 | 10 | 5.0 | 5.0 | 10.0 | HnTh | 1.20 |
| 0.75 | 5 | 10 | 7.5 | 7.5 | 10.0 | HnTh | 0.80 |
| 1 | 5 | 10 | 10.0 | 10.0 | 10.0 | HnTh | 0.60 |
| 0.25 | 10 | 20 | 5.0 | 4.3 | 17.3 | HnTh | 1.20 |
| 0.5 | 10 | 20 | 10.0 | 8.6 | 17.3 | HnTh | 0.60 |
| 0.75 | 10 | 20 | 15.0 | 13.0 | 17.3 | HnTh | 0.40 |
| 1 | 10 | 20 | 20.0 | 17.3 | 17.3 | HnTh | 0.30 |

a U- units (single digit); Tn – tens; Hn – hundreds; Th – thousands; TnTh – tens of thousands; HnTh – hundreds of thousands; Mn – low millions.

b Average thickness based on the total volume of sediment released and the distance the plume is advected by the current. Large deposit thicknesses (e.g. >5 to 10 m) in combination with relatively small footprints will more realistically correspond to a broader and less thick deposit with slopes at the angle of repose for the sediment. Each row of results is part of a continuous scale of possible outcomes.

Table 4.31: Suspended sediment concentration and thickness of sediment deposition as a result of cable burial in 100% sand (settling rate 0.05 m/s).

| Representative current speed (m/s) | Height of ejection (m) | Time for resettlement (s) | Distance plume advected by current (m) | Limited length of influence on SSC in downstream direction (m) | Limited duration of influence on SSC locally (s) | Average SSC in the limited length / duration of influence (mg/l) [a] | Average thickness of seabed deposition [b] (m) |
|---|---|---|---|---|---|---|---|
| 0.25 | 1 | 20 | 5.0 | 4.3 | 17.3 | Mn | 1.20 |
| 0.5 | 1 | 20 | 10.0 | 8.6 | 17.3 | Mn | 0.60 |
| 0.75 | 1 | 20 | 15.0 | 13.0 | 17.3 | Mn | 0.40 |
| 1 | 1 | 20 | 20.0 | 17.3 | 17.3 | Mn | 0.30 |
| 0.25 | 5 | 100 | 25.0 | 4.3 | 17.3 | HnTh | 0.24 |
| 0.5 | 5 | 100 | 50.0 | 8.6 | 17.3 | HnTh | 0.12 |
| 0.75 | 5 | 100 | 75.0 | 13.0 | 17.3 | HnTh | 0.08 |
| 1 | 5 | 100 | 100.0 | 17.3 | 17.3 | HnTh | 0.06 |
| 0.25 | 10 | 200 | 50.0 | 4.3 | 17.3 | HnTh | 0.12 |
| 0.5 | 10 | 200 | 100.0 | 8.6 | 17.3 | HnTh | 0.06 |
| 0.75 | 10 | 200 | 150.0 | 13.0 | 17.3 | HnTh | 0.04 |
| 1 | 10 | 200 | 200.0 | 17.3 | 17.3 | HnTh | 0.03 |

a U- units (single digit); Tn – tens; Hn – hundreds; Th – thousands; TnTh – tens of thousands; HnTh – hundreds of thousands; Mn – low millions.

b Average thickness based on the total volume of sediment released and the distance the plume is advected by the current.

4.3.5.21 The main findings of the assessment can be summarised as follows:

- Medium to coarse sand and gravels are likely to result in a temporally and spatially limited plume affecting SSC levels (and settling out of suspension) in close proximity to the point of release. SSC will be locally elevated within the plume close to active cable burial up to tens or hundreds of thousands of mg/l. However, the change will only be present for a very short time locally, in the order of seconds to tens of seconds for sand or gravel, before the material resettles to the seabed. Depending on the height to which the material is ejected and the current speed at the time of release, changes in SSC and deposition will be spatially limited to within metres (up to 20 m) downstream of the cable for gravels and within tens of metres (up to a few hundred metres) for sands;
- Finer material will be advected away from the release location by the prevailing tidal current. High initial concentrations (similar to sands and gravels) are to be expected but will be subject to rapid dispersion, both laterally and vertically, to near-background levels (tens of mg/l) within hundreds to a few thousands of metres of the point of release. In practice, only a small proportion of the material disturbed is expected to be fines, with a corresponding reduction in the expected levels of SSC; and
- Irrespective of sediment type, the volumes of sediment being displaced and deposited locally are relatively limited (up to 6 m$^3$ per metre of cable burial) which also limits the combinations of sediment deposition thickness and extent that might realistically occur. Fundamentally, the maximum distance from each metre of cable trench over which 6 m$^3$ of sediment can be spread to an average thickness of (for example) 0.05 m is 120 m; any larger distance would correspond to a smaller average thickness. The assessment suggests that the extent and so the area of deposition will normally be much smaller for sands and gravels (although leading to a greater average thickness of deposition in the order of tens of centimetres to a few metres) and that fine material will be distributed much more widely, becoming so dispersed that it is unlikely to settle in measurable thickness locally.

4.3.5.22 If cable burial, or any other activity causing sediment disturbance, is undertaken simultaneously at two or more locations that are aligned in relation to the ambient tidal streams, then there is potential for overlap between the areas of effect on SSC and sediment deposition. The potential for in-combination effects on SSC and sediment deposition are discussed in paragraph 4.3.2.26.

## 4.4 Cumulative changes

4.4.1.1 A Cumulative Effect Assessment (CEA) has been undertaken to consider the impact associated with Hornsea Three together with other projects and plans. Each project on the CEA long list (see annex 4.5: Cumulative Effects Screening Matrix and Location of Schemes) has been considered on a case by case basis for scoping in or out of the marine processes chapter, based upon data confidence, effect-receptor pathways and the spatial/temporal scales involved.

4.4.1.2 In terms of the potential for cumulative changes to SSC, bed Levels and sediment type, the screening approach described above was informed using modelled spring tidal excursion ellipses. This is because meaningful sediment plume interaction generally only has the potential to occur if the activities generating the sediment plumes are located within one spring tidal excursion ellipse from one another and occur at the same time.

4.4.1.3 Given the length and orientation of tidal excursion ellipses in the vicinity of Hornsea Three, it is the case that the potential for sediment plume interaction would be limited to instances in which Hornsea Three construction activities within the Hornsea Three offshore cable corridor occur simultaneously with aggregate dredging activities. This potential cumulative change is discussed further below.

### 4.4.2 Hornsea Three and aggregate operations

4.4.2.1 There are three marine aggregate areas (either already licensed or under application) located within a distance of one spring tidal excursion ellipse from Hornsea Three. These are:

- Humber 3 (484);
- Humber 4 and 7 (506); and
- Humber 5 (483).

4.4.2.2 The locations of these three sites are shown on Figure 4.10.

4.4.2.3 Details of these marine aggregate areas are provided in in volume 2, chapter 1: Marine Processes. The target material at these marine aggregate areas is sands and gravels. Characteristically, the aggregate deposits in this region are understood to contain <5% fines (silt and clay) in situ and, therefore, the concentrations of this fraction in the overflow from the dredging vessels are anticipated to be relatively low.

4.4.2.4 Aggregate extraction operations may release sediment into the water column through over-spill and/or screening. The spatial extent of this plume will largely be determined by the sediments being extracted and the local hydrodynamic regime: heavier gravel-sized particles will settle rapidly at the discharge point, whilst sand-sized particles typically settle within about 250 m to 500 m, and within 5 km where tidal currents are strong (Hitchcock and Drucker, 1996; Newell *et al*., 2004). If screening is not used, the volume of discharged sand is much smaller and changes may be confined to the extraction area (Newell *et al*., 2004).

4.4.2.5 Of direct relevance to this investigation is the plume dispersion modelling results for Application Areas 483 and 484 (ABPmer, 2013). In brief:

- Dredging will create a turbid plume, in which its maximum extent is predicted to be 17.0 and 15.5 km in either a northwest or southeast direction from the dredge location (depending whether dredging occurs throughout a flood or ebb tide) for Areas 483 and 484 respectively;
- Maximum increases in near-bed concentrations could potentially exceed 600 mg/l in close proximity to the dredger within the application areas for a period of one hour, before reducing to circa 50 to 150 mg/l for the remainder of the dredging period;
- Following the cessation of dredging (i.e. following a single dredge period), SSCs will return to near background concentrations over approximately four days on spring tides, or slightly longer on neap tides; and
- The maximum sedimentation thickness predicted as a result of the dredge plumes is around 1 mm at/in very close proximity to the dredge location. These sedimentation thicknesses, however, will be transitory (i.e. come and go) with the changing flood/ebb and spring/neap tide variations in the flows.

4.4.2.6 The interaction between sediment plumes generated by construction activities along the Hornsea Three offshore corridor and those from nearby aggregate dredging could occur in two ways:

- Where plumes generated from the two different activities meet and coalesce to form one larger plume; or
- Where an aggregate dredger is dredging within the plume generated by Hornsea Three construction activities (or *vice versa*).

4.4.2.7 For two or more separately formed plumes that meet and coalesce, the physical laws of dispersion theory mean concentrations within the plumes are not additive but instead a larger plume is created with regions of potentially differing concentration representative of the separate respective plumes. In contrast, in the case of plumes formed by a dredging vessel operating within the plume created by foundation installation or bed preparation activities (or *vice versa*), the two plumes would be additive, creating a plume with higher SSC.

4.4.2.8 There is a high degree of likelihood that both forms of plume interaction described above will occur at some point during the construction phase. However of these, it is anticipated that the most common form of plume interaction during the construction phase will be associated with the coalescing of separate plumes. This scenario may result in a combined plume of slightly larger extent than envisaged on the basis of cable and foundation installation alone.

4.4.2.9 Should cable installation or offshore accommodation/ substation foundation installation be taking place within the offshore section of the Hornsea Three offshore cable corridor at the same time as dredgers are operating along the western margin of the Humber 5 aggregate area or eastern margin of Humber 7 aggregate area, it is possible that any fine sediment plumes from the respective activities would be additive. This would give rise to higher concentration (maximum a few 10's mg/l) plumes than described in section 4.3.5. However, these higher concentration plumes would not be expected to persist for much longer than a few hours.

4.4.2.10 The potential for material dispersed during cable laying activities within the Hornsea Three offshore cable corridor to deposit within aggregate dredging areas is considered to be extremely low. This is because the levels of deposition predicted during cable laying activity are minimal (< ~0.03 m within 200 m from the Hornsea Three offshore cable corridor, as described in section 4.3.5).

4.4.2.11 Finally, it is noted that spring tidal excursion ellipses are relatively rectilinear within and nearby to the aggregate sites. This means that although at times during the construction phase some plume interaction may occur, the number of occurrences is expected to be less than for an equivalent setting with more rotary tidal excursion characteristics.

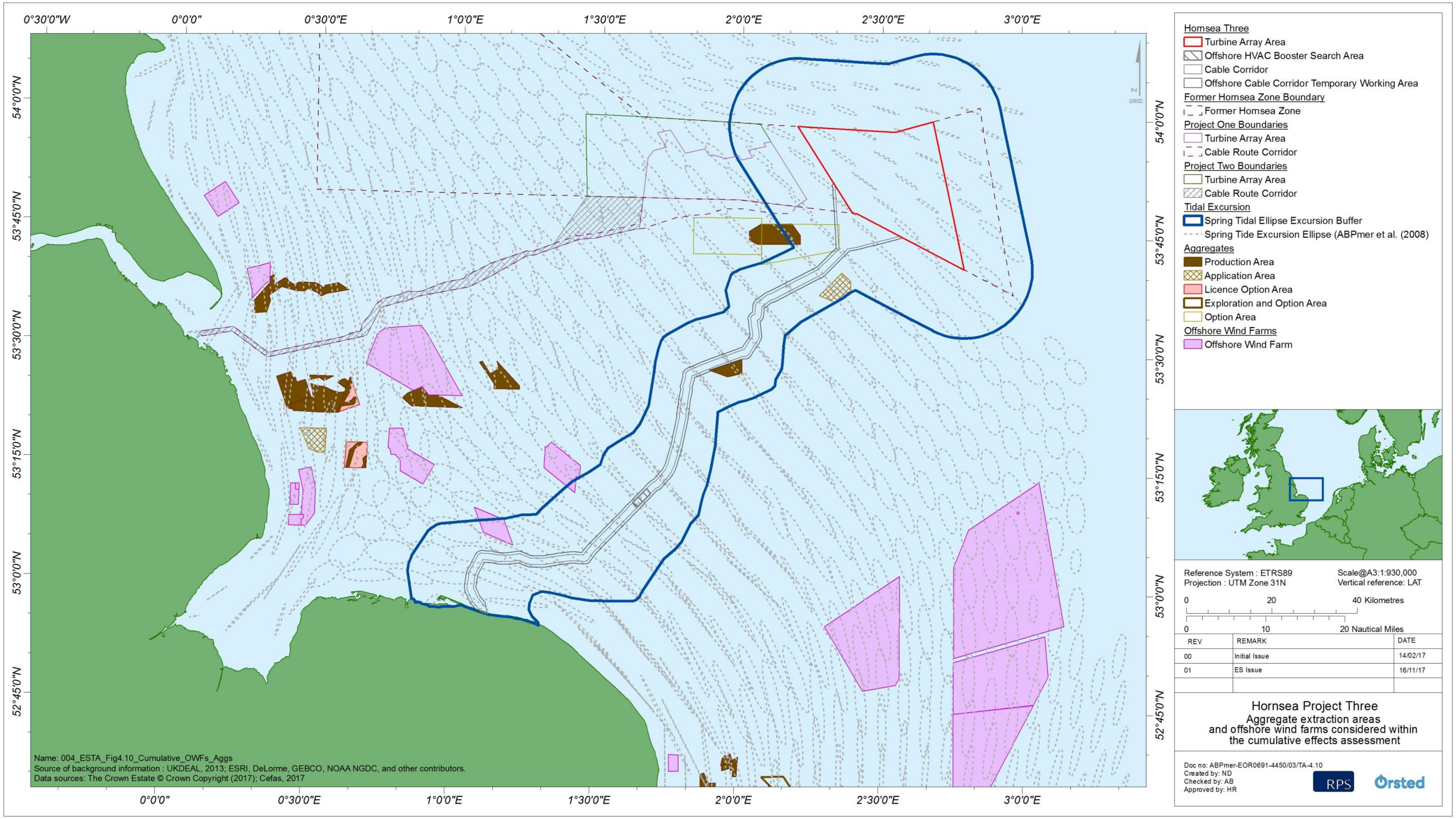


**Figure 4.10: Aggregate extraction areas and offshore wind farms considered within the cumulative effects assessment.**

# 5. Turbid Wakes Associated with Foundations

## 5.1 Overview

5.1.1.1 Recent analysis of Landsat-8 satellite imagery (Vanhellemont and Ruddick, 2014) has noted increases in SSC (turbidity) in the wakes of individual turbine foundations in the Thanet and London Array offshore wind farms in the Outer Thames Estuary (Figure 5.1) (NASA, 2016). This section considers the potential for similar features to develop within the Hornsea Three array area.

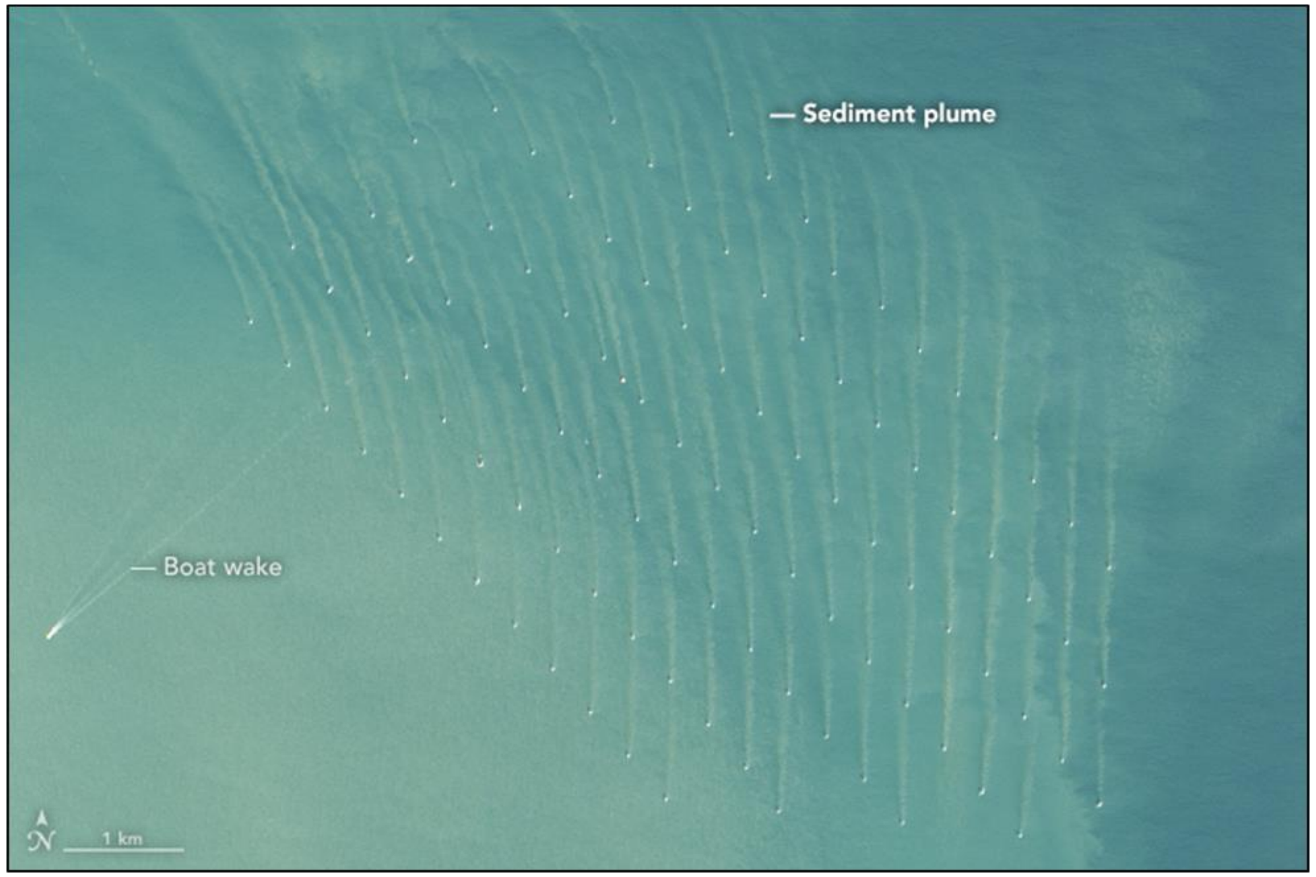


**Figure 5.1: Landsat 8 satellite imagery of Thanet offshore wind farm, acquired 30/06/2015 (NASA, 2016).**

## 5.2 Baseline conditions

5.2.1.1 Baseline conditions pertinent to the consideration of turbine wakes within the Hornsea Three array area have previously been summarised in section 4.2.

## 5.3 Evidence base

5.3.1.1 Turbid wakes have been observed at several wind farms in the outer Thames estuary (e.g. Vanhellemont and Ruddick, 2014; NASA, 2016). The turbid wake features observed at Thanet and London Array offshore wind farms are aligned with the tidal stream and their direction changes with the tide. The features are reported as being typically 30 to 150 m wide and extending 'one or more' kilometres downstream from each turbine; in one case the plumes can be seen to extend for 'more than 10 km' at Thanet offshore wind farm. The plume length is suggested to relate to the time-integrated current (i.e. the tidal excursion distance) since last flow reversal and the particle settling velocity, with absolute SPM concentrations reported as being 'probably dependent upon sea-floor sediment type and water depth' (Vanhellemont and Ruddick, 2014).

## 5.4 Assessment

5.4.1.1 The actual source of the sediment and the physical processes causing the turbid wakes observed in Thanet offshore wind farm are not addressed in detail by Vanhellemont and Ruddick (2014) although they suggest that local scour around the turbine monopile foundations is a possible cause and they note that the foundations at Thanet offshore wind farm do not have scour protection. However, no in-situ observations or investigations have been reported to date for this or any other site and there are several reasons why local scour is unlikely to be the cause, as presented below.

5.4.1.2 The satellite data used by Vanhellemont and Ruddick (2014) was collected in collected in April and September 2013 (Figure 5.2). All of the foundations at Thanet offshore wind farm were in place by June 2010, around three years before the satellite imagery in Figure 5.2 was acquired. Foundations were being installed in London Array offshore wind farm from 2011 (fully opened in 2014), so the foundations present in the 2013 satellite images will likely have been present for months or even years. Local scour is a time dependent process and will occur until an equilibrium depth is reached (section 11.4). The time taken for the equilibrium depth to be reached will vary depending upon the nature of the seabed geology but where erodible sandy sediments are present, may be achieved within a period of hours to a few days. Accordingly, the majority of scour should have already been achieved by the time the 2013 satellite imagery was acquired.

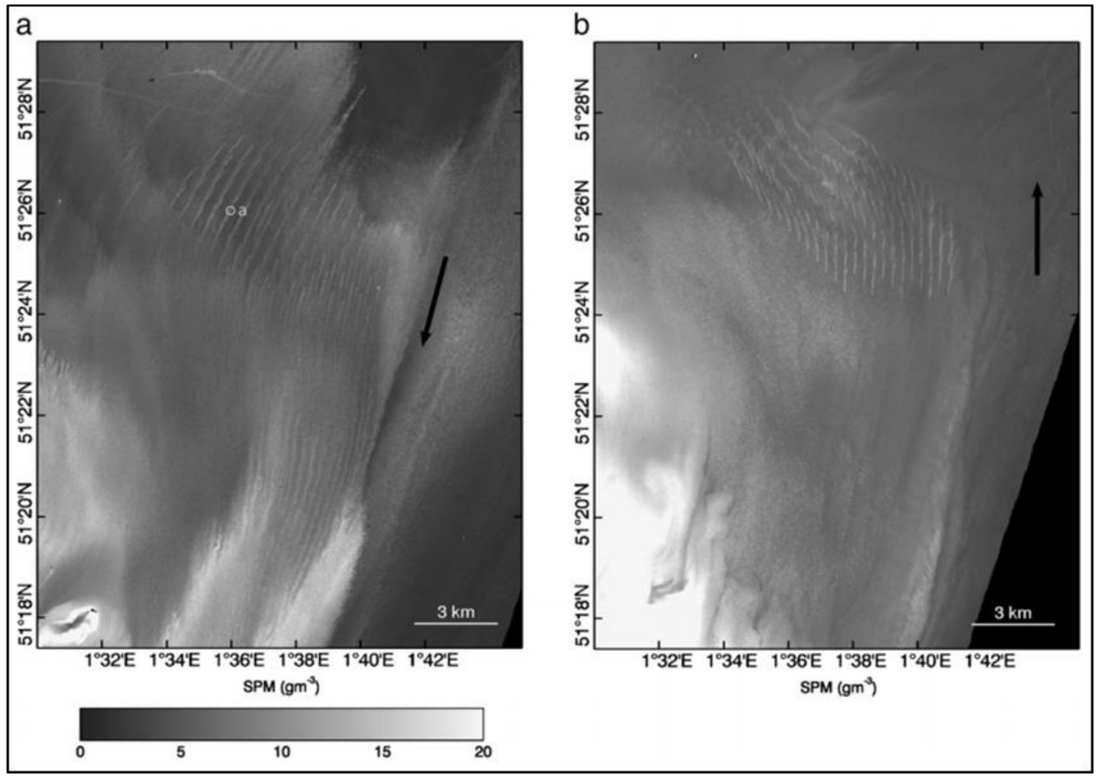


**Figure 5.2: Thanet offshore wind farm on (a) 2013-04-28 (10:54 UTC) and (b) 2013-09-03 (10:54 UTC) (from Vanhellemont and Ruddick, 2014).**

5.4.1.3 The SSC in the surface waters of the turbid wakes (estimated from the satellite data images) is between 10 and 30 g/m$^3$ (equivalent to mg/l). Using a representative water depth for the sites, the volume of water in the wake from one foundation can be estimated as 1 million m$^3$ (20 m deep x 50 m wide x 1000 m long). The total mass of sediment in suspension (assuming a representative concentration throughout the wake of 20 g/m$^3$) is 20,000 kg. Assuming a sediment density of 2,650 kg/m$^3$ and a porosity factor for seabed sediments of 0.6, this total mass equates to approximately 13 m$^3$ of seabed sediment. If 13 m$^3$ of seabed was being eroded from around each foundation every half tide (every six hours), this would cumulatively result in serious erosion in a short time scale, however, there is no such problem reported at these sites. Rather than assuming that a large volume of sediment is being eroded locally, the same mass of sediment in suspension per unit area (everywhere) can be more realistically achieved by resuspension of only 0.25 mm sediment thickness uniformly from the seabed (everywhere).

5.4.1.4 Comparing the interpreted seabed sediment type maps with the location of turbid wakes in the Thanet offshore wind farm shows that turbid wakes are also present in areas where the local seabed sediment type is not susceptible to scour. The southern margin of the array is characterised by the presence of chalk either at or very close to the seabed yet similar turbid wakes are also observed in this area (Figure 5.3). The chalk will be considerably more resistant to erosion than the unconsolidated surficial sediments found elsewhere in the site and it is therefore unlikely that active local scour is the cause of the observed turbid wake in these areas.

5.4.1.5 The satellite data also show large areas nearby but outside of the wind farm array areas that have higher (naturally controlled) surface SSC than that within the two wind farm arrays and as high as, or higher than the associated turbid wakes. These areas appear to correlate with shallower parts of the Outer Thames Estuary (where the naturally present near-bed turbidity is naturally mixed upwards to the water surface).

5.4.1.6 Therefore, rather than being the result of enhanced erosion, it is considered more likely that the turbid wakes associated with the foundations in Thanet and London Array offshore wind farms are the result of the upward turbulent mixing of naturally present suspended sediment from lower in the water column.

5.4.1.7 The sediment in the turbid wake likely originates in the naturally present near-bed layer of relatively higher SSC caused by friction between the tidal current and the seabed, potentially enhanced by wave action. Suspended sediment in this near-bed layer advecting through the array area will become entrained within the turbulent wake in the lee of individual foundation structures and mixed upwards by turbulent diffusion, becoming visible at the water surface. As the magnitude of turbulence in the wake decreases with time and distance from the foundation (order of minutes and hundreds of metres), the rate of downward settlement of the material will exceed the rate of upward dispersion by turbulence. At this point, the material in suspension will naturally tend to settle downwards and out of the surface waters, reducing the surface concentration towards ambient background values until the plume feature is no longer visible.

5.4.1.8 Relatively finer sediments have a lower settling velocity and so will remain in surface waters at lower turbulence intensities, and will take longer to settle out even when the turbulence intensity is low, resulting in a greater plume length. Coarser sediments *vice versa*. Turbid wakes are also, therefore, unlikely to occur at all where or when the sediment is too coarse or the current speed is too low to cause a sufficient rate of natural resuspension of sediment near-bed. In relatively greater water depths, it is also less likely that any near-bed suspended sediment will be carried all the way to the water surface (to form a visible wake feature); the upward mixing might still occur, but only to some lower level in the water column.

5.4.1.9 The Outer Thames Estuary is characterised by a greater abundance of finer sediment and relatively shallow water depths. The relatively coarser seabed sediment type and the greater water depths within the Hornsea Three array area make it less likely that the current wakes behind foundations in this location (described in section 7) will become visibly turbid at the water surface. Any upwards mixing of turbidity from a naturally present near-bed layer will be offset by a corresponding dilution of the near-bed concentration.

5.4.1.10 Turbid wakes are not an indication of ongoing local seabed erosion caused by the foundation. Scouring of the seabed immediately following the installation of foundations is considered separately in section 11.

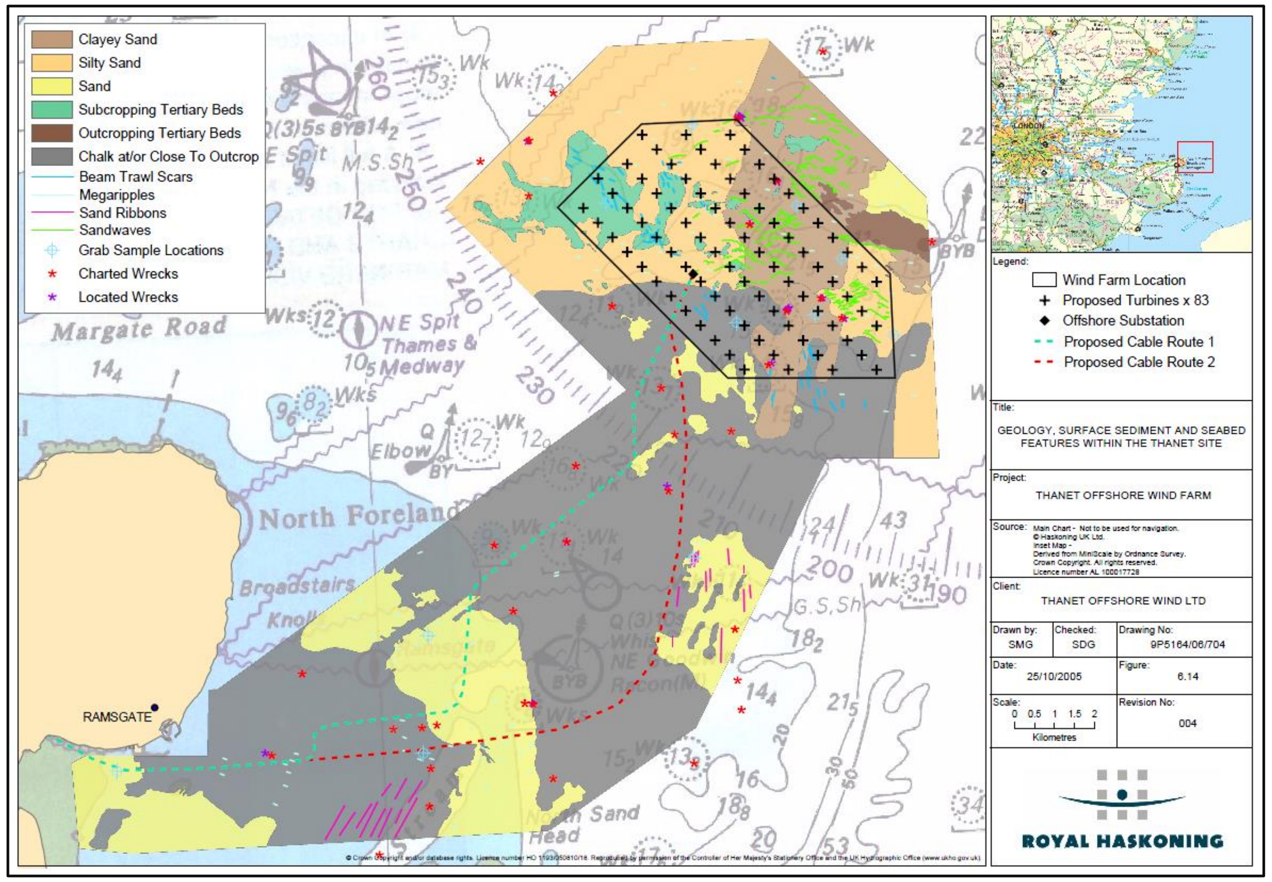


**Figure 5.3: Geology, surface sediments and seabed features within the Thanet offshore wind farm (from Royal Haskoning, 2005).**

## 5.5 Cumulative changes

5.5.1.1 As stated in section 5.4, the likelihood of current wakes behind foundations in this location becoming visibly turbid at the water surface is considered to be relatively low. Any upwards mixing of turbidity from a naturally present near-bed layer will be offset by a corresponding dilution of the near-bed concentration. However, should turbid wakes occur, the potential for cumulative interaction with wakes from Hornsea Project One and Hornsea Project Two is considered to be very limited. This is because turbid wake features will be aligned with the tidal axis which is broadly northwest to southeast across the Hornsea Three array area (i.e. parallel to rather than towards Hornsea Project One or Hornsea Project Two).

# 6. Landfall

## 6.1 Overview

6.1.1.1 The proposed Hornsea Three offshore corridor landfall is located between Weybourne Hope and Kelling Hard. For the purposes of this assessment, the landward limit of the landfall is defined by the HAT mark, whilst the offshore limit corresponds to a distance of approximately 3 km offshore from the MHWS mark (i.e. the furthest possible seaward extent of the Horizontal Directional Drill (HDD) exit location).

6.1.1.2 The preferred cable installation method at the landfall has not yet been determined although may involve HDD, thrust boring or open cut trenching.

6.1.1.3 Both the Sheringham Shoal and Dudgeon offshore wind farm export cables also come ashore at Weybourne and the various studies undertaken to support the cable landfall installation works for these separate developments have been used here to help inform the assessment.

6.1.1.4 There are several source/pathways via which the morphology of the landfall could potentially be impacted:

- Disturbance of sediments, resulting in localised elevations in SSC and associated changes to bed levels (construction);
- Excavation of the seabed could potentially enable more wave energy to propagate further inshore as waves experience less friction and shoaling/breaking effects over and in the lee of the HDD exit pits. The local change in water depth may also cause changes to patterns of wave refraction, slightly changing the direction of travel for wave crests over the excavated area;
- The HDD exit pits could potentially intercept and trap naturally occurring alongshore and cross-shore movement of sediment through passive infilling. This could theoretically lower parts of the beach outside of the initially excavated area and/or reduce the onward supply of sediment to other parts of the beach, resulting in slight changes to sediment budgets and beach morphology;
- Deposition of the excavated material would lead to an increase in local seabed elevation. If these changes are of sufficient magnitude to alter the nearshore wave regime, changes in beach morphology could potentially result;
- The presence of the cofferdams could modify the nearshore wave regime, influencing rates of alongshore sediment transport. The cofferdams could also physically block the transport of sediment locally;
- Presence of cable protection measures in the nearshore area causing changes in seabed / beach morphology (construction/ operation);
- Exposure of cables leading to changes in longshore sediment transport (operation); and
- Coastal recession, leading to exposure of jointing bay infrastructure on the beach (operation).

6.1.1.5 These are considered in turn, within section 6.4.

6.1.1.6 The assessments presented in this section have been carried out using a desk-based semi-qualitative assessment approach. There is a degree of inherent uncertainty in relation to the range of possible outcomes when making such assessments, including the exact nature of the designs and engineering approaches actually used, variability in the environmental conditions that might be experienced, and the actual interaction of processes and response of the environment to any potential changes. The assessments are considered to provide realistically likely results, although it is recognised that there is inherent uncertainty in morphological assessments of this type.

## 6.2 Baseline conditions

6.2.1.1 Baseline characteristics of the landfall are briefly summarised below, based on the findings of a nearshore geophysical survey (Fugro, 2017), an initial intertidal walk over survey (volume 5, Annex 2.1 Benthic Ecology Technical Report) and a review of the existing publicly available information:

- The shoreline in the area of the proposed landfall is formed of a steep shingle beach overlying a chalk base. In places, the beach fronts eroding cliffs comprising glacial till (Figure 6.1 and Figure 6.2);
- Outcrops of peat have been identified locally in the vicinity of the landfall (Warren, 2013);
- The landfall area is characterised by ongoing cliff retreat. Along the frontage from Kelling to Sheringham, the average rate of erosion is approximately 0.5 m/yr (Scira Offshore Energy Ltd, 2006);
- Net drift at the landfall is thought to be to the west (HR Wallingford *et al*., 2002). However, there is high potential for annual variability in drift rates, which are anticipated to reverse between years, depending on the prevailing wave conditions (HR Wallingford, 2004);
- The preferred shoreline management plan option for the proposed landfall is 'do nothing', allowing continued erosion (North Norfolk District Council, 2010);
- During winter months average SPM concentrations at the surface of the water column is typically around 30 mg/l whilst during summer months, values are usually around 10 mg/l. However, it should be noted that owing to the shallow water depths waves will regular stir the bed and in these shallow areas SSC may be in the order of hundreds to thousands of mg/l, especially during storm events; and
- Parts of the inshore/ nearshore area (i.e. between 0 mLAT and -20 mLAT) are characterised by the presence of chalk found at or very close to the seabed. Surficial coarse sediment units are typically associated with megaripple bedforms, whilst sandwaves are encountered in localised patches (Bibby HydroMap, 2016; Fugro, 2017).

**Figure 6.1: Weybourne Hope shingle ridge beach, with low cliffs in the background.**

**Figure 6.2: Eroding cliffs and steep shingle beach at the landfall.**

## 6.3 Evidence base

6.3.1.1 HDD is generally considered to cause minimal direct disturbance to the existing coastline and is an appropriate form of mitigation to avoid damage, particularly in the intertidal and landfall areas where habitats may be more sensitive (BERR, 2008). This methodology has been successfully adopted at the export cable landfalls of a number of Round 1 and Round 2 offshore wind farm developments with minimal environmental impact.

6.3.1.2 Locally, HDD has previously been used to install the export cables for both Sheringham Shoal and Dudgeon offshore wind farms, which also make landfall at Weybourne. The Sheringham Shoal offshore wind farm export cable was installed in 2009 and the Dudgeon offshore wind farm export cable was installed in 2015/16.

6.3.1.3 Open trenching and ploughing through the intertidal zone are also commonly used techniques for cable installation in a range of beach and sediment types. A wide range of different burial tools and techniques are described in BERR (2008). By design, a tool that is suitable for the beach material will achieve the required burial depth with a minimal footprint of disruption (to minimise the force required to cut the trench) and the majority of sediment will be retained in the trench (to maximise protection of the cable). When used above the water line, trenching techniques do not mix sediment with water and so result in minimal sediment resuspension impacts. The dynamic nature of beach processes will rapidly rework any locally disturbed or displaced sediment. While there are few detailed case studies publicly available, cable landfall engineering is a mature concept that is commonly undertaken with minimal adverse impacts to the local beach and coastline.

## 6.4 Assessment

### 6.4.1 Summary of landfall construction activities

6.4.1.1 Open cut trenching may be used to bury up to six cable trenches in a V-shape trench (width = 6 m; depth = 3 m). Trenches will be open for no longer than two weeks.

6.4.1.2 Alternatively, HDD may be used instead to bury the cables under the beach. An exit pit will be required at the place where each cable exits the seabed to facilitate transition jointing with the offshore section and subsequent burial of the jointed section. On the basis of the geophysical survey data collected from the landfall, the HDD exit pits will be located entirely within areas characterised by the presence of sands and gravels with a thickness of 3 m or greater. Accordingly, no chalk is expected to be disturbed during excavation.

6.4.1.3 Depending upon the final installation method, cofferdams may be required:

***HDD with cofferdam option***

- The cofferdam dimensions which will contain each exit pit are 50 m (length) x 5 m (width);
- Up to two exit pits with cofferdams may be in place simultaneously although there is the potential for up to 4 cofferdams to be present for a very short period (i.e. order of a few days) due to overlap in the cycles of cofferdam installation and removal;
- Each of the cofferdams will be in place for up to 4 months (which consists of: 1 month site setup (including cofferdam installation and pit excavation); 2 months pit fully open, drilling & duct pull-in happening; and 1 month reinstatement (including cofferdam removal and pit backfill));
- Material excavated from within the cofferdam will be side-cast to the adjacent seabed, with material subsequently used as backfill; and
- If sufficient material does not remain locally available to backfill the pits, additional material may be obtained from the disposal site or elsewhere nearby.

***HDD without cofferdam option***

- Up to eight HDD exit pits may be required;
- Exit pits likely to be located between approximately 200 m (‘short’ HDD; c. -1 mLAT) and 800 m (‘long’ HDD; c-7 mLAT) from the MHWS mark;
- Each exit pit up to 30 m (length) x 30 m (width). Depths will vary depending on surficial sediment cover but are anticipated to range from circa 2.5 m for the short HDD option to circa 6 m for the long HDD option;
- Up to two exit pits may be open simultaneously although there is the potential for up to 4 exit pits to be open for a very short period (i.e. order of a few days);
- Each of the HDD exit pits may be open for up to 4 months (which consists of: 1 month site setup (including pit excavation); 2 months pit fully open, drilling & duct pull-in happening; and 1 month reinstatement (including backfill));
- Material will be side-cast adjacent to each exit pit, with material subsequently used as backfill; and
- If sufficient material does not remain locally available to backfill the pits, additional material (diameter up to 250 mm) may be obtained from the disposal site or elsewhere nearby. Disturbance of sediments, resulting in localised elevations in SSC and changes to bed levels (construction).

6.4.1.4 Export cable installation by open cut trenching is considered to represent the maximum design scenario in terms of the potential to cause elevated levels of SSC during the construction phase and also to affect beach morphology through changes to hydrodynamic processes and interruption of littoral drift.

6.4.1.5 It is assumed that an open cut channel may be created by either jetting, trenching by use of a tracked excavator or similar, or ploughing. When and where used above the water line, none of these techniques will disturb sediment in the presence of water and so will not cause any significant sediment resuspension. When and where used below the water line, jetting has the potential to cause the greatest volume of material to enter into suspension and is therefore considered to be the maximum design scenario for sediment dispersion.

6.4.1.6 Potential changes associated with jetting activities at the landward end of the Hornsea Three offshore corridor have previously been considered in section 4.3.5 for a trench of the same width but slightly shallower than may be used at the landfall. Results are presented for the slightly shallower trench in Table 4.30 and Table 4.31, and the accompanying text, for predominantly gravel, sand and fine sediment disturbance. The slightly deeper trench profile at the landfall will slightly increase the volume of sediment displaced per metre burial, and potentially therefore also the rate of sediment disturbance for a similar rate of trenching. However, the distance over which sediment of a given grainsize will settle (and therefore the spatial extent and duration of the effect described for the shallower trench) is unaffected. Levels of SSC will be of a similar order of magnitude (potentially up to hundreds of thousands of mg/l locally, decreasing rapidly to background levels with time and distance, in the order of seconds to minutes and tens to hundreds of metres). The vast majority of coarse material (sands and gravels) displaced by the jetting activity will deposit in close proximity to the point of jetting and will not be dispersed by tidal currents. Any fines released may be held in suspension for longer and transported much further, becoming dispersed to very low concentrations. The dimensions of the exit pits, (and so the potential maximum elevated levels of SSC during their excavation), are similar to that for trenching described above.

6.4.1.7 Section 4 also includes consideration of the anticipated changes associated with the installation of cables into chalk, which may be encountered at or very close to the surface at the landward end of the Hornsea Three offshore cable corridor. In summary, cable burial into chalk will locally give rise to elevated SSC of up to hundreds of thousands of mg/l for several seconds at locations immediately adjacent (i.e. within a few tens of metres) from the cable trench. Any fine chalk arisings may persist in suspension for longer than sand sized material (order of days) but the plume will be subject to significant dispersion in that time, reducing any change to SSC to tens of mg/l or less in the same timeframe. As a result of dispersion, no measurable thickness of accumulation of fine sediment is expected.

6.4.1.8 Other than the sand and shingle that comprise the majority of the beach material, outcrops of peat have been identified locally in the vicinity of the landfall (Warren, 2013). Peat units are likely to be of weak strength and low density and as such, will readily disaggregate if subjected to jetting/ trenching. Given its low density, any disturbed peat material is likely to float and it may be transported by the action of tidal currents, waves and wind driven surface currents. On the basis of available tidal excursion ellipse information from ABPmer *et al*., (2008), the disturbed material could be carried up to 8 to 10 km along the coast from the point of release by tidal currents on a mean spring tide. However at this distance, concentrations within the water column would be very low (order of a few mg/l).

6.4.1.9 Cable installation across the beach by trenching would result in the displacement of mainly gravel material, which contains minimal fine grained material available for dispersion. This gravel material will remain in very close proximity to the trench and it is anticipated this material would then be used as backfill once the cables had been laid, thereby minimising the risk of future erosion.

6.4.1.10 Temporary changes in beach elevation due to the displacement of gravel from the trench would depend upon several factors including trench width, cable burial depth and the nature of the excavated material. For cable burial in a nominal V-shape trench measuring 6 m wide by 3 m deep, the mounds created either side of the trench would be ~2.1 m high (assuming an angle of repose for gravel of 45̊).

6.4.1.11 Importantly, the gravel mounds adjacent to the trench would only be present on the seabed/ beach for a very short period of time (up to 2 weeks) as the excavated material forming the mounds would immediately be used to backfill the trench once the cable was in place. Given that the mounds would only be present for a very short period of time, any changes to hydrodynamics and littoral transport would be highly localised, of short term duration and reversible. Accordingly, there would be no potential for long term change to coastal morphology.

### 6.4.2 Excavation of HDD exit pits causing changes in seabed/ beach morphology (construction)

6.4.2.1 The greatest potential for modification of the local wave regime in response to the HDD exit pits is expected to occur during periods of low water during storm conditions. At this time, waves could theoretically break slightly further inshore (by a distance similar to the dimensions of the HDD exit pits, (i.e. 30 m in length and limited to the width of the pit). If the HDD exit pits were located at their most inshore location (200 m from the MHWS mark at circa -1 mLAT), small changes to waves could potentially extend to the lower beach. In theory, this could cause a slight increase in wave induced sediment transport further up the beach than presently occurs. However, owing to the limited spatial extent (footprint and volume) of the HDD exit pits, the potential for significant resulting morphological change is considered to be low. It is also noted that each of the HDD exit pits will only be open for a maximum of 4 months (which consists of: 1 month site setup (including pit excavation); 2 months pit fully open, drilling & duct pull-in happening; and 1 month reinstatement (including backfill)) and therefore the potential for localised effects on beach processes and morphology immediately adjacent to each HDD exit pit will be limited to this period. The potential magnitude of effect would also progressively reduce with increasing distance of the HDD exit pit from the shoreline (up to 800 m from the MHWS mark at circa -7 mLAT).

6.4.2.2 Change across the upper beach will primarily be driven by larger (storm) waves at higher states of the tide. Such waves have the potential to transport shingle sized material which would otherwise be immobile during calmer conditions. The landfall is located in a meso tidal setting and water depths in the vicinity of the most inshore HDD exit pits will be approximately 5 m at MHWS. In such water depths, the potential for modification to storm waves as they propagate across the HDD exit pits will be very much reduced in comparison to equivalent size waves at low water. Accordingly, the wave energy reaching the upper beach is expected to remain largely unaltered with the HDD exit pits in place. Therefore, the risk of beach 'drawdown' is considered to be negligible. Again, the potential magnitude of effect would also progressively reduce with increasing distance of the HDD exit pit from the shoreline (up to 800 m from the MHWS mark at circa -7 mLAT).

### 6.4.3 Infilling of HDD exit pits causing changes in seabed/ beach morphology (construction)

6.4.3.1 The HDD exit pits could be located within those parts of the nearshore area actively involved in sediment exchange with the adjacent beach (i.e. landward of the depth of closure, which is estimated to be between approximately -4 and -5 mLAT, approximately 200 m offshore of the LAT contour). This means that during storm events, material removed from the beach may be transported across the location of the HDD exit pits. Given the relatively steep gradient of the side slopes and overall depth, it is probable that any sediment entering the HDD exit pits would likely remain there.

6.4.3.2 If a HDD exit pit were to be entirely infilled, this would represent ~1,000 to 2,500 $m^3$ of material. However, total infilling of the exit pit is generally unlikely to happen given the short duration of time that the HDD exit pits will be operational. Moreover, there will be no net loss of material volume from the local area as material excavated from the HDD exit pit will be side-cast and remain locally available for transport.

6.4.3.3 The potential magnitude of effect would progressively reduce with increasing distance of the HDD exit pit from the shoreline (up to 800 m from the MHWS mark at circa -7 mLAT). Pits located relatively further offshore within the possible range may be around or beyond the depth of closure and, therefore, would have minimal net effect on the sediment budget of the beach.

### 6.4.4 Exit pit mounds modifying wave conditions (construction)

6.4.4.1 The material dredged to excavate the exit pits would be side-cast adjacent to each exit pit and subsequently used as backfill. Depending upon the proximity of these mounds to the coast and the water depth in which they are situated, they may have the potential to modify the nearshore wave regime and therefore beach morphology at the landfall. In particular, localised changes in water depth over the pits and mounds could allow greater or differently distributed transmission of wave energy to the coast resulting in a localised morphological response.

6.4.4.2 However, for the reasons set out below any impacts to the adjacent beach are considered to be temporary and of limited spatial extent:

- The mounds would be temporary features that would only be present for a short period of time (up to 4 months) (which consists of: 1 month site setup (including pit excavation); 2 months pit fully open, drilling & duct pull-in happening; and 1 month reinstatement (including backfill));
- The footprint of the mounds will be small relative to the wave length of larger incident waves (which are likely to have the greatest influence on the adjacent beach). Accordingly, any wave refraction/ diffraction effect is expected to be limited and localised. The potential magnitude of this effect would also likely decrease with the actual distance of the exit pit location offshore (which may vary between 200 m to 800 m from the MHWS mark);
- The greatest potential for changes to the adjacent beach via modification of the wave regime will be during storm events when nearshore sands and gravels are likely be mobilised over relatively larger areas and at a relatively higher rate than in response to ‘everyday’ wave conditions. Storms only occur intermittently and storms of higher magnitude will occur relatively less frequently. There is, therefore, a limited likelihood of storms (especially larger storms) occurring during the limited time that these temporary features are present. The likelihood of larger storms occurring is also seasonal in nature;
- The excavated material in the mounds will comprise sands and gravels of the same type as the surrounding seabed so the sediments at the surface of the mound will be mobilised at the same rate and in the same manner as the surrounding seabed; and
- Mobilised sediments would be re-distributed by natural sediment transport processes. Depending on the magnitude and pattern of net sediment transport during the limited time that they are present the mounds may evolve from their initial form towards another naturally stable equilibrium shape (likely a relatively lower height and wider extent) over time (based on the response time for naturally occurring nearshore bar features this could be in the timescale of one or more large storm events or more generally in the order of days to weeks during winter months, or in the order of several months during summer).. This evolution will tend to progressively reduce any potential effect of the mound on waves and so also the rate of change in the mound shape.

### 6.4.5 Presence of cofferdams causing changes in seabed/ beach morphology (construction)

6.4.5.1 Under the maximum design scenario, cofferdams (measuring 50 m x 5 m, long axis orientated to the cable route) could be located at a minimum distance of ~200 m from the MHWS mark which is approximately 1 mLAT. Although the cofferdam structures could be situated close to the beach and will present a barrier to waves intersecting them, it is considered unlikely that they will cause widespread morphological impacts to the beach for the following reasons:

- The cofferdams will be orientated approximately perpendicular to the beach, hence they will present only a limited direct physical barrier to across-shore sediment transport (in an onshore-offshore direction). The potential magnitude of any effect would also likely decrease with the actual distance of the exit pit and cofferdam location offshore (which may vary between 200 m to 800 m from the MHWS mark);
- The majority of sediment transport on the beach is likely to occur in and around the swash zone (i.e. within the inter-tidal area). Cofferdams located closest to shore (associated with a short HDD option, up to 200m from the MHWS mark, at circa -1 mLAT) will not extend into the inter-tidal area but may extend shoreward of the depth of closure, and will therefore present only a limited direct physical barrier to along-shore sediment transport. Cofferdams located further from the shore (up to 800m from the MHWS mark, at circa -7 mLAT) will not extend shoreward of the depth of closure and so have even less potential to cause an effect.
- At lower tidal states, larger waves (which will have the greatest potential to influence beach morphology) will have broken before reaching the cofferdams;
- Individual cofferdam structures will be present for a limited duration of time only (up to 4 months, consisting of: 1 month site setup (including cofferdam installation and pit excavation); 2 months pit fully open, drilling & duct pull-in happening; and 1 month reinstatement (including cofferdam removal and pit backfill)) and only two will be present at any one time. These factors limit the potential for morphological change to the adjacent beach.

### 6.4.6 Presence of cable protection measures in the nearshore area causing changes in seabed/ beach morphology (construction/ operation)

6.4.6.1 Cable protection measures will not be used in inter-tidal areas although in theory, up to 10% of the Offshore Cable Corridor within the Cromer Shoal Chalk Beds MCZ could be associated with the use of cable protection measures. If and where cable protection measures are installed in shallow subtidal locations near to the landfall, they could potentially influence the local nearshore wave regime and patterns of sediment transport. However, it is more realistically assumed that any cable protection measures used in such areas would be installed with a sufficiently low profile and width relative to the surrounding bed so as to present minimal barrier to the passage of waves and so would cause minimal change to patterns of longshore sediment transport.

6.4.6.2 Installation of cable protection could result in a local elevation of the seabed profile by up to 2 m. Cable protection would be placed onto the seabed surface above the cable and therefore could present an obstacle to sediment transport, trapping sediment locally and thereby impacting down-drift locations through a reduction in sediment supply.

6.4.6.3 The JNCC recently commissioned an investigation into the possible impacts of rock dump from oil and gas decommissioning on Annex I mobile sandbanks in the NNSSR SAC (JNCC, 2017). Although the dimensions (i.e. height and width) of rock dump associated with oil & gas infrastructure is likely to be slightly greater for pipelines than for cables, the principles regarding the potential for interaction with naturally occurring sediment transport pathways remain the same. Accordingly, conclusions from the JNCC study are of relevance here. JNCC (2017) identified that:

*'…there is currently insufficient information to quantify or qualify the implications of rock dump in the NNSSR [SAC] from a physical (and biological) perspective. It is not possible to quantify or qualify the movement of sandbanks around or over existing or applied rock dump. Theoretically, the mobile sandbanks may cyclically cover applied rock dump and there is the potential for scour to be induced if an appropriate design is not chosen. Without further information on rock berm design, monitoring studies and numerical modelling of such behaviour, the short-term and long-term implications of both theoretical behaviours are difficult to determine.'*

6.4.6.4 No additional observational data or information has been found to inform the present study since the publication of JNCC (2017). In the absence of suitable analogous observations, the following theoretical description of the processes involved is considered to provide a conservatively realistic assessment of the potential nature and magnitude of impact.

6.4.6.5 Potential effects on sediment transport can only occur following installation of the cable protection and under conditions where sediment is being actively transported in a manner that is both susceptible to such blockage and in a direction that intersects the cable protection. The potential magnitude of any effect is correspondingly reduced if and when the rate of transport is naturally low, if the mode of sediment transport includes a larger proportion of material in high saltation or suspension, and/or where the axis of the cable protection and the local direction of sediment transport are relatively more aligned.

6.4.6.6 At worst, the obstacle presented by the cable protection will locally prevent the onward passage of all sediment in transport, causing that sediment to accumulate locally. As the accumulated sediment volume increases, any open voids in the protection would become infilled and a sediment slope would develop on the updrift side (with a maximum slope angle equal to the angle of repose for sand ~30 degrees). As the stable slope approaches the top of the protection (up to 2 m above the seabed), the blockage effect of the cable protection will be progressively reduced to near zero and sediment will subsequently be transported directly over the obstacle (via the sediment slope and/or in saltation or suspension) unimpeded, at the naturally occurring ambient rate and direction.

6.4.6.7 The maximum volume of sediment that could potentially accumulate in this way is limited by the dimensions of the protection to approximately 3.46 $m^3$ of sediment per metre of cable protection, which is small in both absolute and relative terms. Assuming that the protection has side slopes of 45° and minimal voids, this value decreases further to 1.46 $m^3$. The maximum dimensions of morphological change (seabed lowering) that might result from the maximum temporary reduction in sediment supply are therefore proportionally limited (e.g. a maximum of 0.1 m bed lowering might occur in an area up to 34.6 m downstream of the protection, or up to 0.5 m up to 6.92 m downstream, or 0.05 m up to 69.2 m downstream, etc) and is therefore unlikely to measurably affect the form and function of the seabed locally or regionally. The process of accumulating this maximum sediment volume might take place over a period of a few months or less, depending on rates of sediment transport.

6.4.6.8 It is, however, also realistically possible that the rock protection may only cause partial or no measurable blockage of sediment transport, or associated sediment accumulation. In this case, the natural modes of sediment transport (suspension, saltation and bedload locally enhanced by scour-like processes) might be sufficient to collectively allow some or all sediment to simply pass over the obstacle presented by the cable protection with limited or no overall change or interruption to the natural rate or direction.

6.4.6.9 The sediment blockage processes described above considers individual sections of cable protection. Where multiple cables with cable protection are located in relatively close proximity, each cable will undergo the processes described above. The minimum separation distance between the cables is approximately 100 m, therefore, the maximum average bed lowering that might result between a pair of cables from the maximum temporary reduction in sediment supply due to the upstream cable, (or the accumulation of sediment at the downstream cable) is approximately 0.03 m (3.46 $m^3$ / 100 m), which is very small in both absolute and relative terms, and is unlikely to change the processes and behaviour described above for individual sections of cable. Therefore, there is unlikely to be any additional additive effect for multiple cables with cable protection beyond that described for single cables.

6.4.6.10 The limited blockage effect of cable protection measures on the seabed can be considered broadly analogous to the effect of submerged shore-perpendicular coastal groynes, which act (by design in this case) to accumulate and retain a limited volume of sediment (primarily proportional to the height of the structure), with excess sediment overtopping and bypassing the structure naturally. Where a series of groynes are installed, they produce a similar effect over a larger area; however, the total number of groynes installed does not change the fundamental behaviour of the individual units.

6.4.6.11 Accordingly, for all areas in which cable protection is used (including where sandwaves are present), it is expected that the total volume of sediment supply intercepted by the protection (and so the scale of any consequential effects on seabed morphology downstream) will be very small in both absolute and relative terms. The presence of cable protection will not continue to affect patterns of sediment transport beyond the initial period of accumulation. It is also noted that cable protection measures will only be present locally where required and will not present a continuous blockage along the whole cable route corridor.

6.4.6.12 Some secondary scour may occur as a result of turbulence caused by the flow of water over the cable protection. However, the scouring action will only act to re-suspend and transport sediment over the obstacle, therefore not causing any impact in relation to sediment transport.

### 6.4.7 Exposure of cables leading to changes in longshore sediment transport (operation)

6.4.7.1 Following burial, the only way in which the cables could influence hydrodynamics and beach morphology during operation would be if they became exposed as a consequence of natural changes to beach morphology. Detailed understanding of the likely temporal variability in beach topography throughout the lifetime of Hornsea Three is therefore critical for the appropriate siting of cables as well as determination of appropriate target burial depths.

6.4.7.2 Given the general complexity of the coastal system and the long timescales and variable magnitudes of morphological processes and events, numerical modelling is unlikely to provide a reliable means by which to determine the envelope of morphological variation that might occur during the lifetime of Hornsea Three. Instead, a quantitative analysis of recent and historic beach monitoring data (including LiDAR) has been undertaken, describing the range of historical natural variability, including patterns and trends of erosion and accretion. These patterns of variability are generally anticipated to continue for the lifetime of the development. This assessment approach is followed here and has been described below.

6.4.7.3 The two primary sources of beach topographic information at the landfall are beach profile and LiDAR data. Beach profiles at the landfall (for the period 1991 to 2011) have previously been collected and analysed by the Environment Agency and are presented in the Environment Agency North Norfolk Coastal Trends Report (Environment Agency, 2012). LiDAR data (available from the Environment Agency for the period 1999 to 2014) has been downloaded and analysed for this investigation. These two datasets are complementary: the beach profile data provides a very accurate record of inter- and intra-annual change at discrete transect locations, whereas the LiDAR data describes the nature of change over the whole beach area, although on a less frequent basis (approximately every two to three years).

6.4.7.4 The LiDAR Digital Elevation Models (DEMs) were incorporated into a GIS and subject to a quality review. Data below (approximately) the MLWN tide mark were removed as they typically represent the level of the water surface rather than the beach. Elevation difference plots between selected years are presented in Figure 6.3; tidal levels for Weybourne Hope are included to aid interpretation. Changes in beach elevation between 1999 and 2014 are illustrated using water level contour plots in Figure 6.4. Maximum difference statistics (i.e. maximum level minus minimum level) for the entire LiDAR record are presented in Figure 6.5. Finally, beach profile transects extracted from the LiDAR datasets are shown in Figure 6.6. (The locations of these 4 transects are shown in Figure 6.5).

6.4.7.5 Key findings from the analysis of the LiDAR and beach topographic data are summarised below:

- The beach at the landfall is highly dynamic with local changes in beach elevation up to ~3 m occurring over the analysis period (1999 to 2014);
- There is a relatively high degree of spatial variability with regards to the magnitude of change to beach elevations, with the greatest change observed around (and landward of) the MHWS mark. Conversely, relatively limited change is seen seaward of the MSL mark;
- The position of the MHWS contour has remained relatively constant throughout the analysis period and no clear year-on year trend exists. This finding is consistent with the interpretation of coastal trends carried out by the Environment Agency for the period 1991 to 2011 which suggests very low net rates of beach erosion at the landfall (Environment Agency, 2012); and
- Given that longer term erosional and accretionary beach processes appear to be approximately in balance, the relatively large vertical changes in beach elevation observed between the LiDAR datasets are expected to be due to normal seasonal beach processes, e.g. summer beach build up and winter drawdown, and the formation and breakdown of berms (visible in Figure 6.1). This opinion is consistent with the beach profile transects extracted from the LiDAR (Figure 6.6), which evidence cross shore movement and modification of the shingle berms above and around the MHWS tide mark.

6.4.7.6 The natural processes controlling the variability in beach morphology described above will continue to act in the same way following installation of the cables and irrespective of any temporary local disturbance caused.

6.4.7.7 It is anticipated that the information on beach variability will feed into a detailed engineering assessment of cable burial depth which will minimise the risk of exposure. It may be possible to optimise the target burial depth across the beach according to the known degree of variability, with deeper burial in areas of high variability and *vice versa*. However, appropriate consideration will be given to the potential effects of climate change which is expected to lead to mean sea level rise and potentially increased rates of beach erosion and shoreline retreat.

6.4.7.8 If the export cables are buried at a sufficient depth below the base of the mobile beach material (which, on the basis of available information, is understood to be approximately the top 3 m of sediment), the cables will have no potential to influence either hydrodynamics or beach morphology. If a section of a cable does become exposed, it might locally influence beach processes and morphology at a scale proportional to the diameter of the cable (order of a few tens of centimetres) and the length of the exposed section. If the exposure occurs due to a short-term localised lowering of the beach level (e.g. in response to storm activity), it is also possible that that the cable section will become naturally reburied by similar process over time (order of hours during a storm or order of days to months during more benign conditions) as the beach returns to an equilibrium state. If the exposure is due to longer-term changes in wave climate, sediment supply or coastal morphology, the exposed cable section may need to be reburied (using similar methods to that used for the initial installation, with similar potential impacts). If more than one section of Hornsea Three cable is exposed at any one time, the potential impacts of each cable are likely to be localised to a distance much smaller than the separation between them.

### 6.4.8 Coastal recession, leading to exposure of jointing bay infrastructure on the beach (operation)

6.4.8.1 As stated in section 6.4.7, the position of the MHWS contour has remained relatively constant throughout the period 1991 to 2014, with no clear year-on year trend of erosion. However, the landfall area is characterised by ongoing cliff retreat with long-term rates of approximately 0.5 m/yr observed between Kelling to Sheringham (Scira Offshore Energy Ltd, 2006). Following consent, the latest information on cliff retreat will be used to inform appropriate set back distances for jointing bay infrastructure at the landfall. Due consideration will be given to the potential influence of climate change (especially sea level rise) on likely future rates of soft cliff erosion using quantitative assessment techniques (e.g. Bray and Hooke, 1997; Walkden and Hall, 2012).

## 6.5 Cumulative changes

6.5.1.1 The export cables for both the Sheringham Shoal and Dudgeon offshore wind farms also make landfall at Weybourne (which at their closest point, are approximately 300 m to the east of the Hornsea Three landfall). All of the cables were installed using HDD. The cables for Sheringham Shoal offshore wind farm were installed in 2009 and the cables for Dudgeon offshore wind farm were installed in 2015/16. Both cables were installed via HDD and therefore the risk of future exposure is considered to be minimal. Provided these cables remain buried, there is no potential for them to influence hydrodynamics or beach morphology and therefore there is no potential for cumulative impacts with the Hornsea Three export cables. If a section of cable from another wind farm were to become exposed at the same time as a section of a Hornsea Three cable, the potential impacts of each cable are likely to be localised to a distance much smaller than the separation between them, and so any impacts will not interact cumulatively.

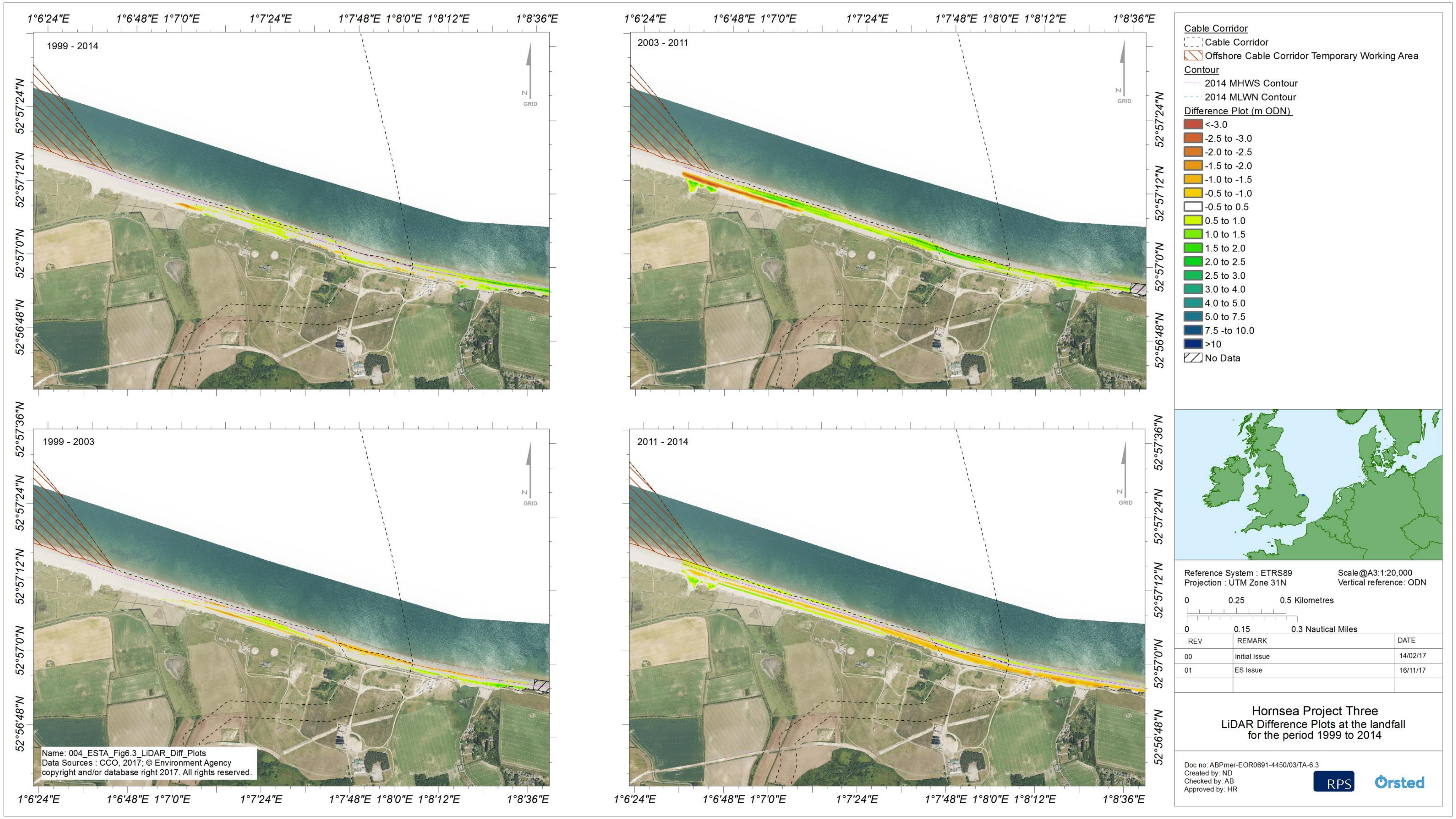


**Figure 6.3: LiDAR difference plots at the landfall for the period 1999 to 2014.**


**Figure 6.4: MHWS and MLWN contours at the landfall established from LiDAR for the period 1999 to 2014.**

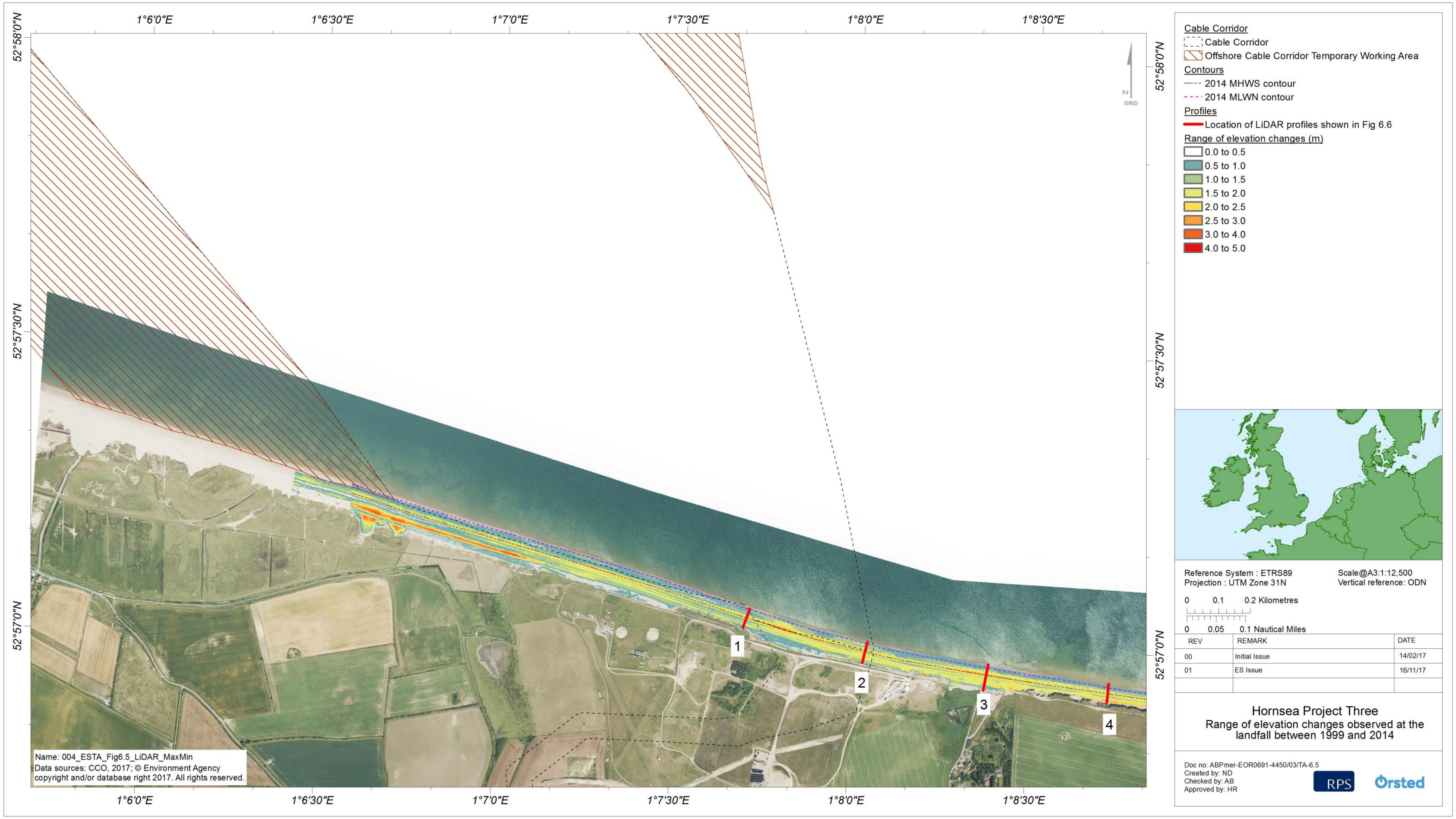


**Figure 6.5: Range of elevation changes observed at the landfall between 1999 and 2014.**

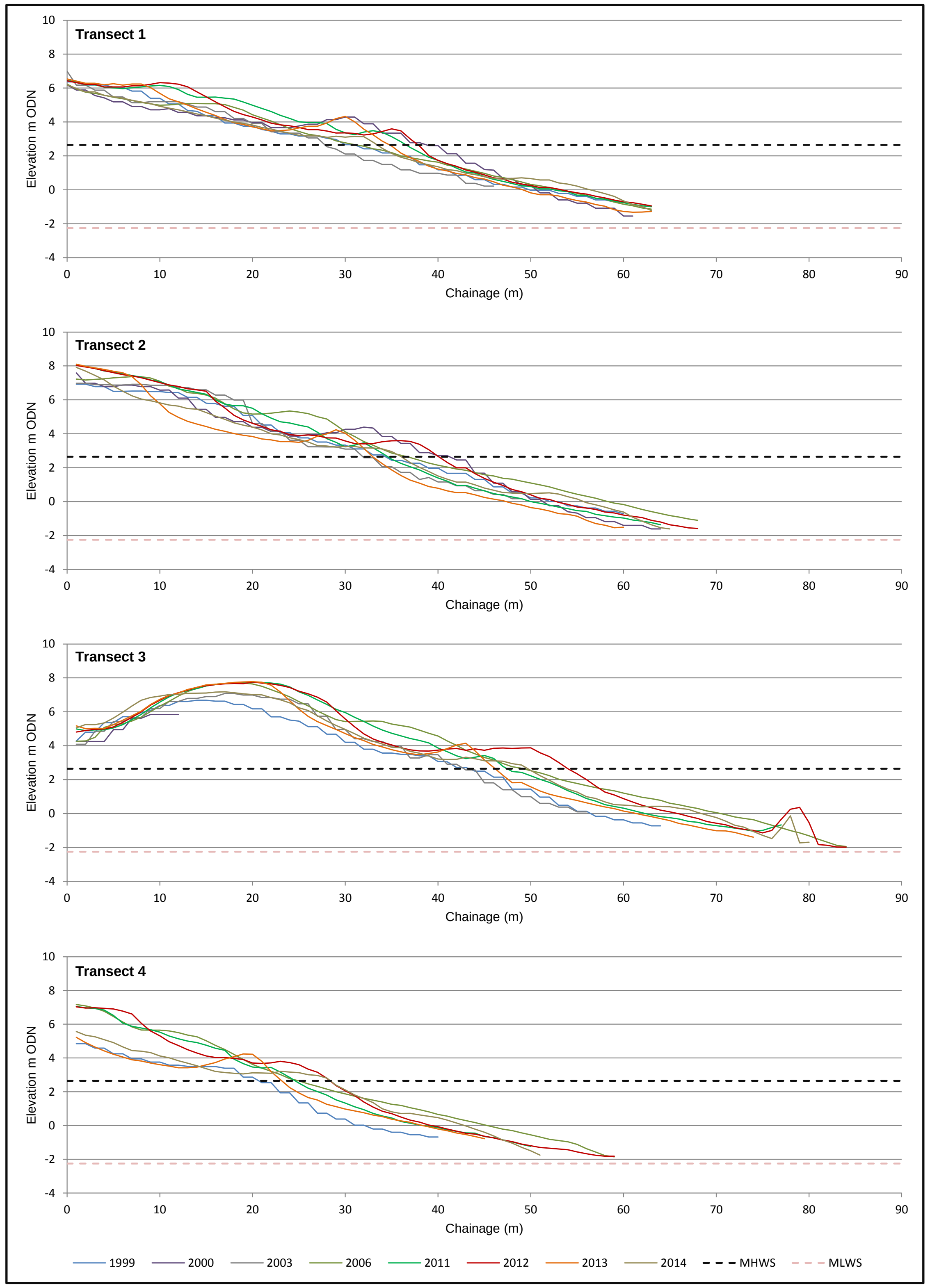


**Figure 6.6: Topography (m ODN) along profile transects 1 to 4 during the period 1999 to 2014, based on LiDAR data.**

# 7. Tidal Regime

## 7.1 Overview

7.1.1.1 The interaction between the tidal regime and the foundations of the wind farm infrastructure will result in a general reduction in current speed and an increase in levels of turbulence locally due to frictional drag and the shape of the structure. Resistance posed by the array (due to the sum of all foundation drag) to the passage of water at a large scale may distort the progression of the tidal wave, also potentially affecting the phase and height of tidal water levels.

7.1.1.2 Within the extent of the Hornsea Three array area, the modification of tidal currents will be evident as a series of narrow and discrete wake features extending downstream along the tidal axis from each foundation. The wake signature naturally dissipates to near background levels by a distance in the order of ten to twenty obstacle diameters downstream, and the maximum extent of any possible direct change to currents from the whole array is one tidal excursion from the outermost foundation locations (in the direction of flow).

7.1.1.3 Changes to the tidal regime may potentially influence seabed morphology in a number of ways. In particular, there exists a close relationship between flow speed and bedform type (e.g. Belderson *et al.*, 1982) and thus any changes to flows have the potential to alter seabed morphology over the lifetime of Hornsea Three. More generally, changes in flow may alter the balance between sediment erosion and deposition as well as the rate and direction of sediment transport. These potential changes to the sediment transport regime are discussed separately, in section 9.

## 7.2 Baseline conditions

7.2.1.1 Baseline characteristics of the tidal regime within the marine processes study area have previously been described in within volume 2, chapter 1: Marine Processes. Key aspects are very briefly summarised below:

- Ebb tidal currents are to the northwest; flood tidal currents are to the south-east. Tidal current speeds increase with an east to west gradient across the Hornsea Three array area;
- Mean spring tidal current velocities within the site are ~0.5 m/s, with equivalent neap velocities of ~0.25 m/s (SMart Wind, 2012); and
- Spring tidal excursion ellipses (which show the approximate path that a package of water would follow over the course of a mean spring tide) are relatively rectilinear in nature across the Hornsea Three array area and are typically between ~6 and 8 km in length (ABPmer *et al.*, 2008).

## 7.3 Evidence base

7.3.1.1 Changes to tidal flows were previously considered for Hornsea Project One using numerical modelling (SMart Wind, 2013). The spatial pattern and magnitude of change are discussed further in section 7.4.

7.3.1.2 No monitoring evidence from developments directly analogous to Hornsea Three is available (ABPmer *et al*., 2010). However, on the basis of (i) post construction monitoring of wake fields (e.g. from Burbo and Lincs offshore wind farms (ABPmer *et al*., 2010); and (ii) numerical modelling results available from other offshore wind farm project Environmental Statements, it is apparent that changes to flow speeds as a result of flow blockage are greatest in the immediate vicinity of the foundation structures, reducing quickly in magnitude with increased distance from the foundations. As such, the largest flow speed changes are anticipated to occur within the Hornsea Three array area itself. Outside of the array area, changes in flow speed are typically confined to within the order of hundreds of metres of individual wind turbines and therefore also the site boundary.

## 7.4 Assessment

### 7.4.1 Changes to flows

7.4.1.1 Hydrodynamic flow modelling using TELEMAC-2D was carried out in support of the Environmental Impact Assessment for Hornsea Project One. Details of the model calibration and validation are provided in (SMart Wind, 2013).

7.4.1.2 As Hornsea Project Two shares a similar seabed area and baseline flow regime to Hornsea Project One and the number and size of turbines is similar for Hornsea Project One and Hornsea Project Two (Table 2.1 and Table 2.2), the flow modelling work carried out for Hornsea Project One was previously applied in an evidence based approach to the assessment of currents in Hornsea Project Two (SMart Wind, 2015a).

7.4.1.3 As the Hornsea Three array area also shares a similar seabed area and baseline flow regime to the Hornsea Project One array area and the number and size of turbines is conservatively similar for Hornsea Project One and Hornsea Three, the flow modelling work carried out for Hornsea Project One is also applicable to Hornsea Three. Table 7.1 shows that the maximum design scenario for Hornsea Three presents a smaller mean and maximum blockage density than that modelled for Hornsea Project One and considered for Hornsea Project Two. The results of the modelling for Hornsea Project One are summarised in this section and have been interpreted to conservatively assess the likely influence of Hornsea Three on the tidal regime.

7.4.1.4 The Hornsea Project One tidal modelling simulated 332 conical gravity base foundations with a spacing of 924 m and a foundation base diameter of 50 m (with scour protection extending an additional 20 m from the foot of the gravity base foundation – 90 m diameter in total). The greatest mean and maximum blockage density in the Hornsea Three array area is associated with up to 300 conical gravity base foundations with a spacing of 1,000 m and a foundation base diameter of 43 m. Hornsea Project Two comprises 360 conical gravity base foundations with a minimum spacing of 932 m (810 m spacing along the dense perimeter) and a foundation base diameter of 58 m (with scour protection extending an additional 20 m from the foot of the gravity base foundation – 98 m diameter in total.

7.4.1.5 The Hornsea Project One modelling also simulated five offshore HVAC collector substations, two offshore HVDC converter stations (all within the area of Hornsea Project One), two offshore accommodation platforms and one offshore HVAC reactive compensation substation, all with gravity base foundations. The Hornsea Three array area maximum design scenario includes offshore 12 HVAC collector substations, four HVDC converter substations and three offshore accommodation platforms (all within the Hornsea Three array area). The Hornsea Project Two maximum design scenario includes six substations and two offshore accommodation platforms (all within the area of Hornsea Project Two).

7.4.1.6 The flow modelling for Hornsea Project One simulated the largest number of turbines (332) with the largest gravity base foundation size (90 m in total). In practice this layout is a highly conservative representation of the development as the largest turbine sizes would be associated with a smaller overall number of turbines. The modelling scenario for Hornsea Project One is, therefore, highly conservative as a worst case.

7.4.1.7 The foundations will be exposed to both currents and waves. The 2D tidal current modelling for Hornsea Project One (SMart Wind, 2013) provides an approximation of the drag effect of the turbines and their associated foundation structures. It does not represent the detailed turbulent flows associated with the structural elements. In open coastal waters turbulence will exist regardless of the presence of turbine structures; the structures will act to locally enhance these ambient turbulent flows.

7.4.1.8 Across the Hornsea Project One array area, modelled peak current speeds vary from approximately 0.6 m/s (at High Water) to 1 m/s (at Low Water) for mean spring tides Figure 7.1 (reproduced from the Hornsea Project One Environmental Statement, (SMart Wind, 2013)) show the predicted changes to current speeds resulting from the operational presence of Hornsea Project One, at high water and low water, respectively. These figures clearly illustrate that the changes in current speed occur within Hornsea Project One itself and a narrow region just outside of the boundary (up to about 4 km).

**Table 7.1: Comparison of cross sectional area (blockage) of foundations per unit area in Hornsea Project One, Hornsea Project Two and Hornsea Three.**

| Project | Number of turbines | Representative blockage width per foundation [a] (m) | Total Array Area ($km^2$) | Minimum turbine spacing (m) | Blockage density ($m/km^2$) | |
|---|---|---|---|---|---|---|
| | | | | | Mean [b] | Maximum [c] |
| Hornsea Project One | 332 | 18.5 | 407 | 800 | 15.1 | 28.9 |
| Hornsea Project Two | 360 | 18.5 | 462 | 800 | 14.4 | 28.9 |
| Hornsea Three | 300 | 18.5 | 696 | 1000 | 8.0 | 18.5 |

a See text for more details

b [Mean blockage density] = ([Number of turbines] x [Representative blockage width per foundation])/ [Total Array Area]. The mean blockage density assumes that turbines are distributed approximately evenly through the array area (but not necessarily in any particular layout).

c [Maximum blockage density] = [Representative blockage width per foundation]/ [Minimum turbine spacing]$^2$. The maximum blockage density can only realistically occur in a small part of the total array area, in order to not exceed the maximum number of turbines.

7.4.1.9 The predicted changes in peak current speeds for Hornsea Project One vary from +0.04 m/s to -0.10 m/s. Current speed is decreased in a narrow wake extending downstream from each foundation. The relatively regularly gridded layout of foundations modelled for Hornsea Project One is aligned to the tidal current axis and results in the wake from foundations upstream intersecting and combining with the wake from turbines downstream. Conversely, current speed is increased (by a lesser magnitude but in a slightly wider corridor than the area of decreased flow) between the rows of foundations which results in limited net difference in the total flow rate of water through the array area.

7.4.1.10 The flow modelling undertaken for Hornsea Project One indicates that changes to tidal currents resulting from the presence of turbines and associated infrastructure are very small and limited to the immediate vicinity of the Hornsea Project One array area. Given the similarities between Hornsea Project One and Hornsea Three in terms of the tidal regime (water depth, flow speeds, etc.) and the project scope (location and similar number of foundations, but of a smaller size and at a greater minimum spacing within the Hornsea Three array area than Hornsea Project One), it is considered that a similar pattern and a similar or smaller magnitude of change to tidal flows will be observed for Hornsea Three.

7.4.1.11 The maximum changes to current speeds resulting from the operational presence of Hornsea Three are therefore predicted to be in the order of +0.04 m/s to -0.10 m/s, spatially limited to within the Hornsea Three array area and a narrow region just outside of the boundary (in the order of 4 km).

7.4.1.12 The above magnitudes assume the maximum design scenario layout for Hornsea Three which is a regular grid aligned to the tidal axis, providing the greatest potential for interaction of individual wakes. The particular layout of foundations in the Hornsea Three array area is however not fixed in this assessment and so the foundation layout might not necessarily be regularly gridded, and/or aligned to the tidal current axis. Where adjacent foundations are not locally aligned to the tidal axis, the same pattern of wake feature will be generated from each individual foundation, but it would be less likely that wakes will overlap or interact cumulatively between foundations. The likelihood of corridors of increased current speed developing is also reduced. The overall influence of a less regular or less tidally aligned layout will therefore be to reduce the magnitude of the predicted decreases and increases in current speed from that described above.

### 7.4.2 Changes to water levels

7.4.2.1 Foundations in the array area have been shown to cause some redistribution of currents speed including local increases and decreases in flow speed, but with a minimal overall net change in the rate at which water passes through the array area. As such, patterns of natural variability in local and regional water levels are not expected to be affected by Hornsea Three. This includes both tidal and non-tidal (surge) contributions to water levels. This assertion is entirely consistent with numerical modelling undertaken to inform a wide range of other Round 3 developments (e.g. East Anglia Offshore Wind, 2012; Moray Offshore Renewables Ltd, 2012, Navitus Bay Development Ltd, 2014).

## 7.5 Cumulative changes

7.5.1.1 As discussed in section 7.4, changes to the tidal regime as a result of Hornsea Three are predicted to largely be localised to the array area. Indeed, on the basis of the numerical modelling carried out for Hornsea Project One (which is analogous to Hornsea Three in terms of foundation number and dimensions), the only changes in current speed are anticipated to occur within the array itself and a narrow region just outside of the boundary (up to about 4 km), and local to foundation structures.

7.5.1.2 Owing to the alignment of the tidal axis in this region, the greatest changes are anticipated to occur to the northwest and southeast of the Hornsea Three array, with minimal change to the east and west (Figure 7.1). Given that The Hornsea Three array is located to the east of the Hornsea Project One and Hornsea Project Two arrays, the potential for cumulative interaction is considered to be very low.

7.5.1.3 All other operational offshore wind farms are located at a sufficient distance away from Hornsea Three that interactions will not occur. As such, cumulative changes to the tidal regime resulting from interactions between Hornsea Three and other operational wind farms are not predicted.

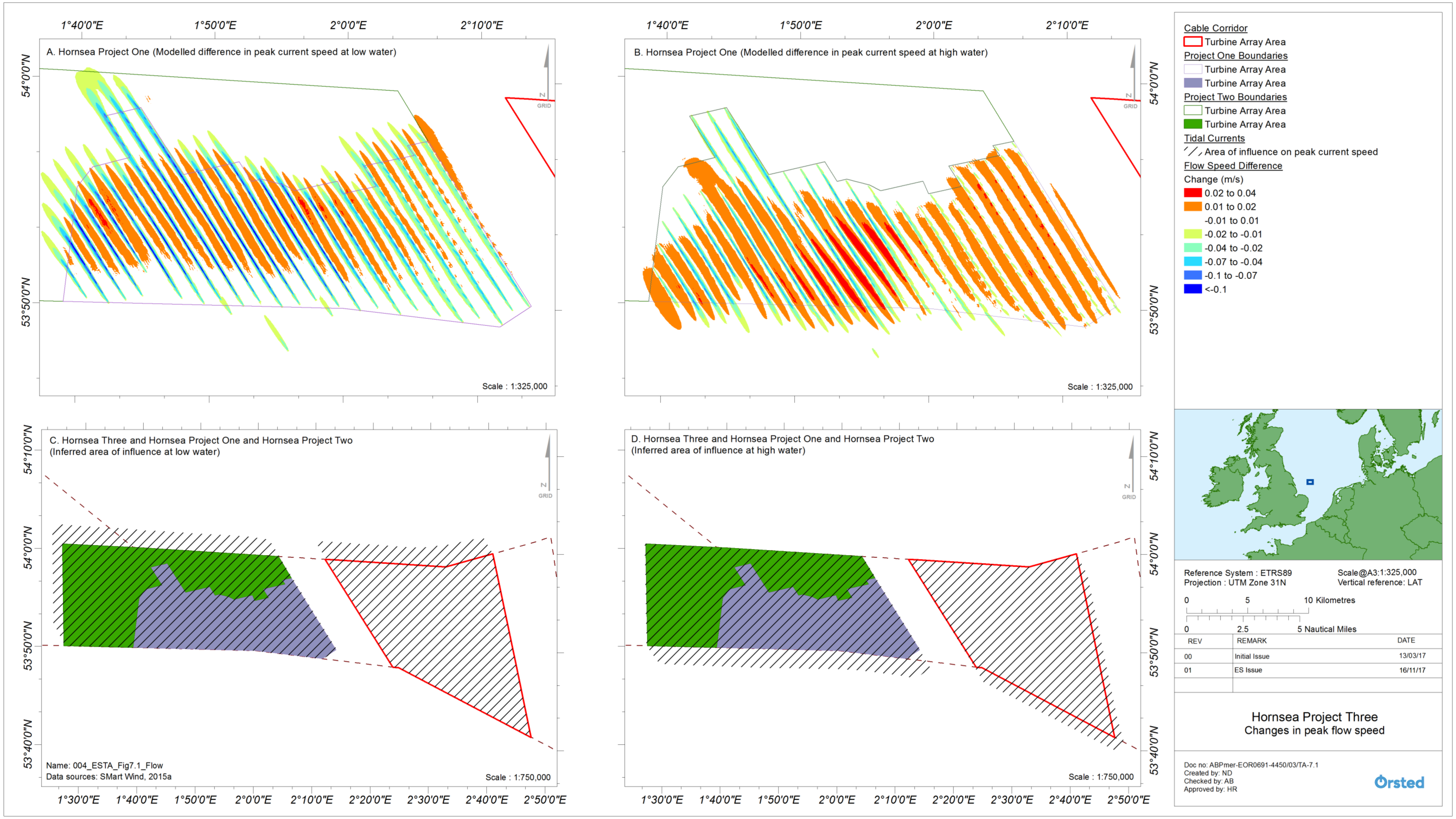


**Figure 7.1:** Model output from Hornsea Project One showing changes in modelled peak current speed at (a) low water; and (b) high water due to turbine foundations in the Hornsea Project One array area (reproduced from SMart Wind, 2013). Also shown are the likely pattern, magnitude and extent of influence predicted in the Hornsea Three and Hornsea Project Two array areas at (c) low water; and (d) high water.

# 8. Wave Regime

## 8.1 Overview

8.1.1.1 The interaction between waves and foundation infrastructure may result in a local reduction in wave energy potentially extending into the far-field. The influence of a single structure on individual waves is not easily measurable in practice but the cumulative change of many structures is generally accepted to be a slight reduction of wave energy (height and period).

8.1.1.2 Where the wave climate is persistently modified, these changes may potentially alter the frequency of sediment mobilisation and rates of transport and deposition (section 9).

8.1.1.3 In order to undertake the assessment of potential changes to the wave regime, a rule based numerical model has been used to simulate the patterns of reduction of wave height through the array area and the subsequent recovery of wave height downwind. The model setup is informed by and validated against the results of spectral wave modelling previously undertaken by HR Wallingford in support of EIA of the Hornsea Project One and Hornsea Project Two developments, both alone and in combination (SMart Wind, 2013; 2015a). A full description of the set-up and validation of the rule based numerical model used in the present assessment is set out in Appendix A. The validity of the rule based modelling approach has also been independently confirmed through separate spectral wave modelling of Hornsea Three, both alone and acting cumulatively with Hornsea Project One and Hornsea Project Two. The results of this separate assessment are presented in Appendix B.

## 8.2 Baseline conditions

8.2.1.1 Baseline characteristics of the wave regime are very briefly summarised below:

- The dominant wave direction within the array is from the northwest to north although there is also a large contribution of waves from southerly sectors;
- The 90$^{th}$ percentile significant wave height (representing the wave height value that 90% of the offshore record are either less than or equal to) is between approximately 1.7 m to 1.9 m during summer months and between 2.5 m and 2.7 m in winter months. Associated values for wave periods are between 5.8 s and 6.6 s (for summer months) and between 6.6 s and 7.1 s (for winter months) (SMart Wind, 2012); and
- On the basis of the former Hornsea Zone metocean survey, the 1:1 year significant wave height is calculated as 5.9 m, whereas equivalent values for the 1:10 year and 1:50 year event are 6.9 m and 7.5 m, respectively (SMart Wind, 2012).

## 8.3 Evidence base

8.3.1.1 Changes to waves were previously considered for Hornsea Project One and Hornsea Project Two using numerical modelling (SMart Wind, 2013; 2015a). The spatial pattern and magnitude of change are discussed further in section 8.4.

8.3.1.2 Due to their large profile, gravity base foundations impart a greater blockage to waves than other foundation types and, therefore, would represent the realistic maximum design scenario. The majority of observational information contained within the present evidence-base is related to monopile arrays and no monitoring evidence from developments directly analogous to Hornsea Three is available (ABPmer *et al.,* 2010). However, a large number of other offshore wind farm project Environmental Statements are now in the public domain and provide some useful supporting evidence with respect to the potential changes of an installed wind farm array upon wave regimes. In particular, the following general patterns are noted:

- The primary influence of gravity base foundations is a reduction in wave height;
- The magnitude of the change increases approximately linearly with distance through the wind farm (given a regular layout of wind turbines), subsequently recovering at a similar (linear) rate beyond the down-wave edge of the site;
- The change outside the wind farm site is generally confined to the down-wave direction but with a small degree of spreading at the edges (in the order of 20°, due to naturally present spreading of wave energy in the wave spectrum); and
- The largest changes to wave energy occur within the array, adjacent to the down-wave boundary, i.e. at the point with the longest fetch through the wind farm array.

## 8.4 Assessment

8.4.1.1 A rule based numerical model has been used to simulate patterns of wave height attenuation due to the maximum design scenario blockage presented by foundations within the Hornsea Three array area. The conceptual and mathematical basis for the rule based numerical model is described in Appendix A. The model combines rates of wave height attenuation and wave height recovery with maps of distance travelled through and beyond the array area for given wave directions to estimate the local net attenuation in wave height. These results are weighted and then integrated over a range of wave directions, about the peak direction, to account for wave spreading. The model has been calibrated and validated (also shown in Appendix A) to provide very similar results to the spectral modelling previously undertaken for Hornsea Project Two (SMart Wind, 2015a,c), including cumulative effects with Hornsea Project One. The model setup and results for the new scenarios including Hornsea Three, both alone and in combination with Hornsea Project One and Hornsea Project Two, are also validated against the results from a new spectral wave model in Appendix B.

8.4.1.2 Simulated patterns of wave height reduction from the rule based model for Hornsea Three alone are shown in Figure 8.1 to Figure 8.5. Results are provided for the 50% non-exceedance wave height condition for five wave direction scenarios (waves from north, north-northeast, northeast, east-northeast and east) representing the range of directions most likely to result in a change in wave height at adjacent coastlines. Waves come from these modelled directions (between north and east) for approximately 26% of the time in total, and only for approximately 5% of the time from each of the individually assessed directions in this sector (SMart Wind, 2013; 2015a).

8.4.1.3 The relative wave height attenuation (as a proportion of the baseline condition) was previously found to greatest for the (lower) 50% non-exceedance wave height condition tested due to greater blockage of smaller period waves. For any larger wave height condition (e.g. storm waves), the relative wave height attenuation will be similar or less than that reported for the 50% non-exceedance wave height. Results are provided: 1) using the direction specific calibrated rate of attenuation; 2) using the maximum calibrated rate of attenuation (associated with the north wave condition) for all directions (see below and in Appendix A for more details).

8.4.1.4 The original spectral wave modelling for Hornsea Project One and Hornsea Project Two deliberately varied the rate of attenuation (via the 'transmission coefficient') by direction to reflect differences in the baseline wave period and subtle differences in the grid alignment of Hornsea Project One and Hornsea Project Two. The same assumptions are applied in the results using the direction specific calibrated rates of attenuation.

8.4.1.5 The results using the maximum rate of attenuation for all directional scenarios provides an additional, more conservative result for Hornsea Three where the exact foundation layout is not specified, and to account for conditions where the dominant wave period might be smaller and so more readily attenuated.

8.4.1.6 The effect of Hornsea Three alone on local and regional patterns of wave height can be summarised as follows:

- The magnitude and extent of the change associated with Hornsea Three alone is similar to that previously modelled for Hornsea Project One and Hornsea Project Two (shown in Appendix A and Appendix B). Due to the underlying similarities in baseline wave condition, the foundation type, dimensions and density, and the general dimensions of the array areas, such similarities are realistic and expected and are considered to further validate the results of the rule based model;
- The results describe the maximum expected proportional change in wave height for a range of wave conditions from low magnitude, high frequency events (i.e. 50% non-exceedance, typical waves) to high magnitude, low frequency events (i.e. storms);
- The maximum reduction in wave height for a given wave direction scenario occurs around the centre of the downwind edge of the array area. Considering the more conservative results for a constant (maximum calibrated) rate of attenuation, the maximum wave height reduction magnitude is relatively similar at 13 to 15% for all directions;
- The maximum reduction in wave height and the width of the footprint of change is controlled by the relative length and width of the array area in the orientation of the wave coming direction, which remain broadly similar through the range of directions tested for Hornsea Three. As a result, assuming a constant (maximum calibrated) rate of attenuation, the downwind extent of change is also relatively similar between the scenarios;
- In practice, localised areas of wave height reduction will also occur in the immediate lee of individual foundations (length scale in the order of tens of metres); and
- For any given location, a reduction in wave height will only be experienced for a relatively small proportion of the time. As previously stated, waves only come from the modelled directions (between north and east) for approximately 26% of the time in total, and only for approximately 5% of the time from each of the individually assessed directions in this sector (SMart Wind, 2013; 2015a).

8.4.1.7 There will be no measurable reduction in wave height (>2.5%) at adjacent coastlines as a result of Hornsea Three alone.

8.4.1.8 The effect of Hornsea Three alone on patterns of wave height at other offshore locations (e.g. sandbanks or other designated areas) can be summarised as follows:

- The potential reduction in wave height at other offshore locations will be variable depending on the orientation and distance of the location from the array area (as shown in Figure 8.1 to Figure 8.5). The location must be aligned with the array area in the incoming wave direction to be affected. Based on the patterns of difference, locations more than approximately 30 km from the array area will typically not experience a reduction in instantaneous wave height greater than 5%.

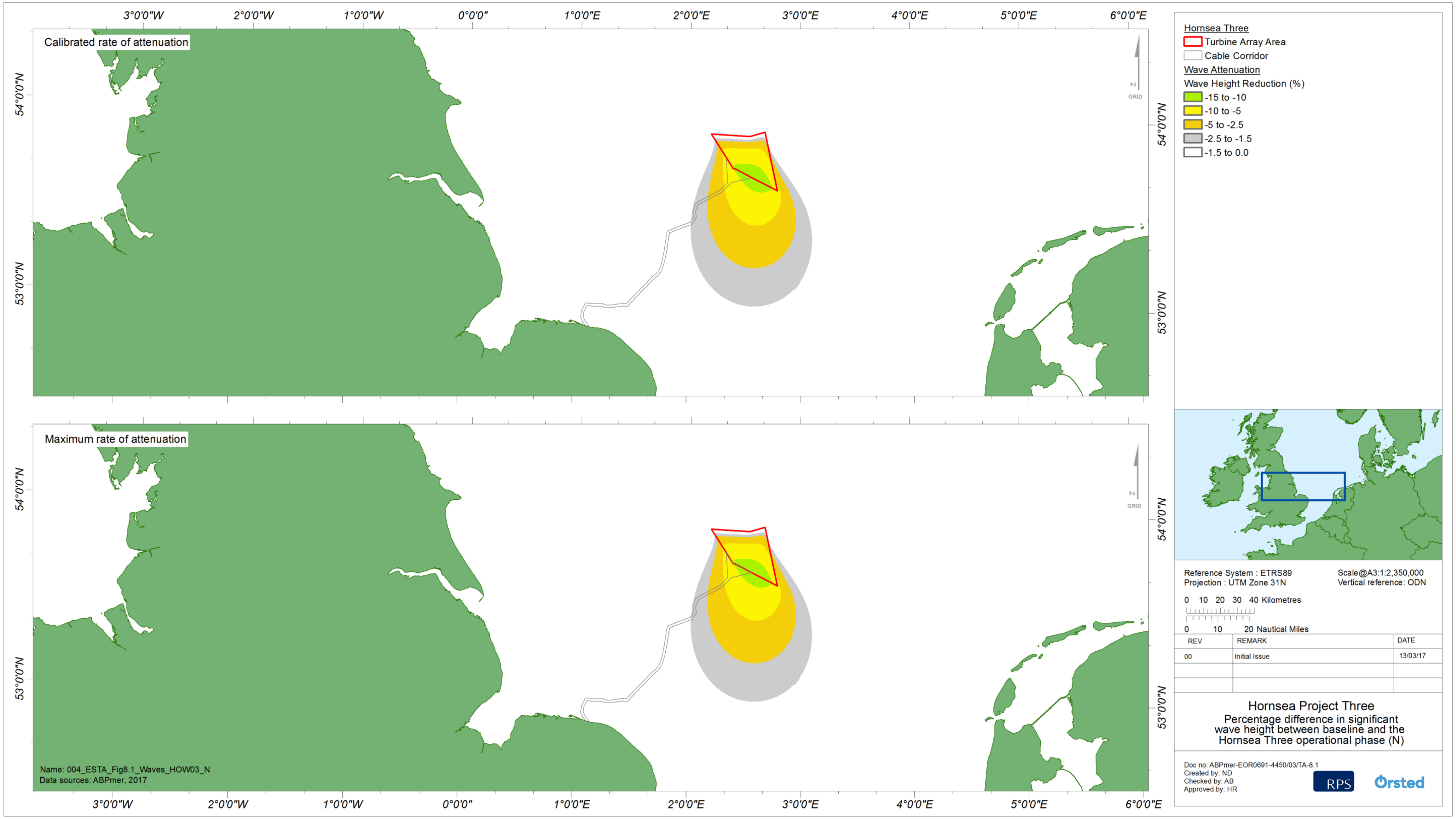


**Figure 8.1: Percentage difference in significant wave height between baseline and the Hornsea Three operational phase, 50% no exceedance, wave direction North: (top) calibrated rate of attenuation; (bottom) maximum rate of attenuation.**

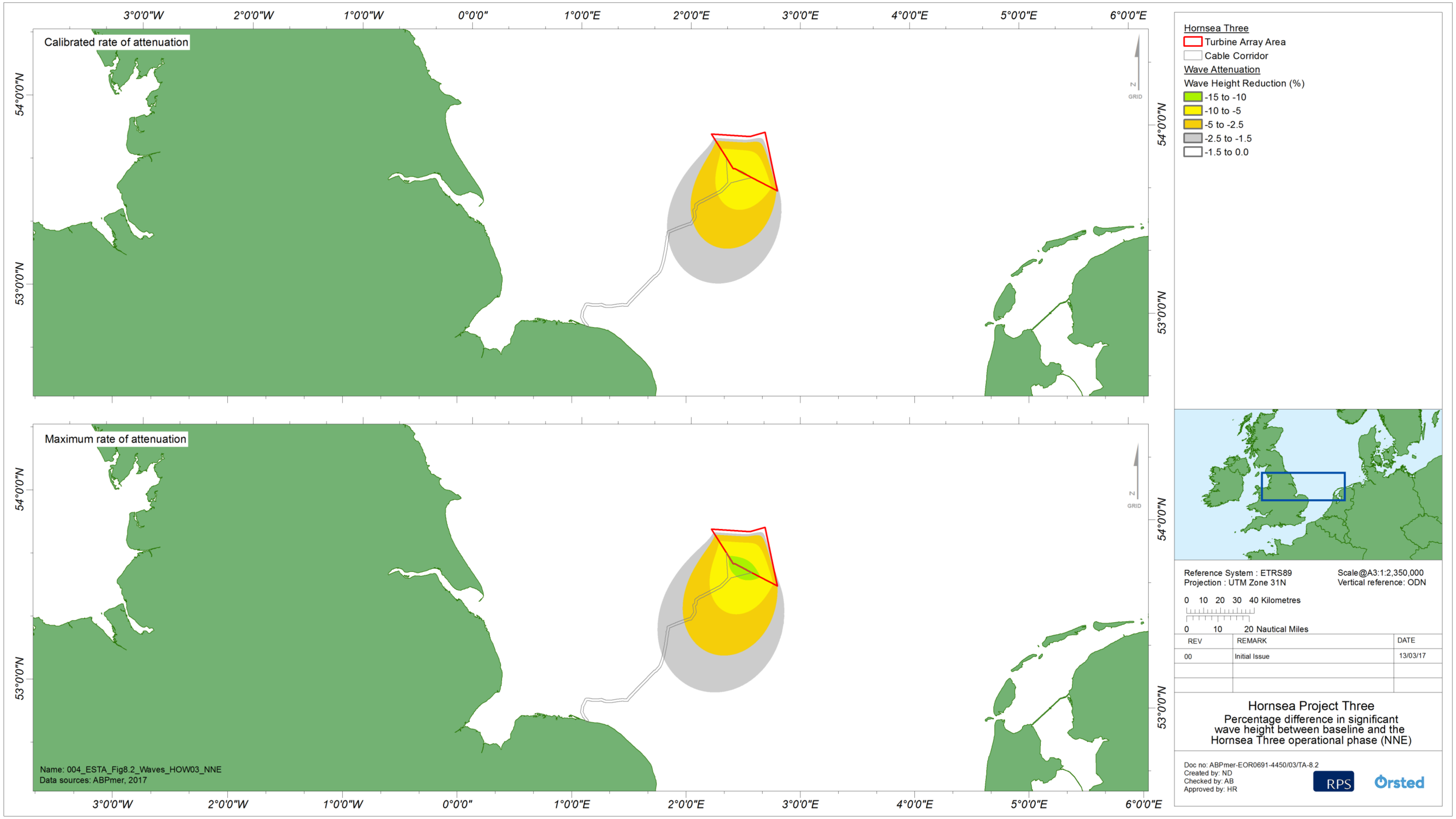


**Figure 8.2:** Percentage difference in significant wave height between baseline and the Hornsea Three operational phase, 50% no exceedance, wave direction North-northeast: (top) calibrated rate of attenuation; (bottom) maximum rate of attenuation.

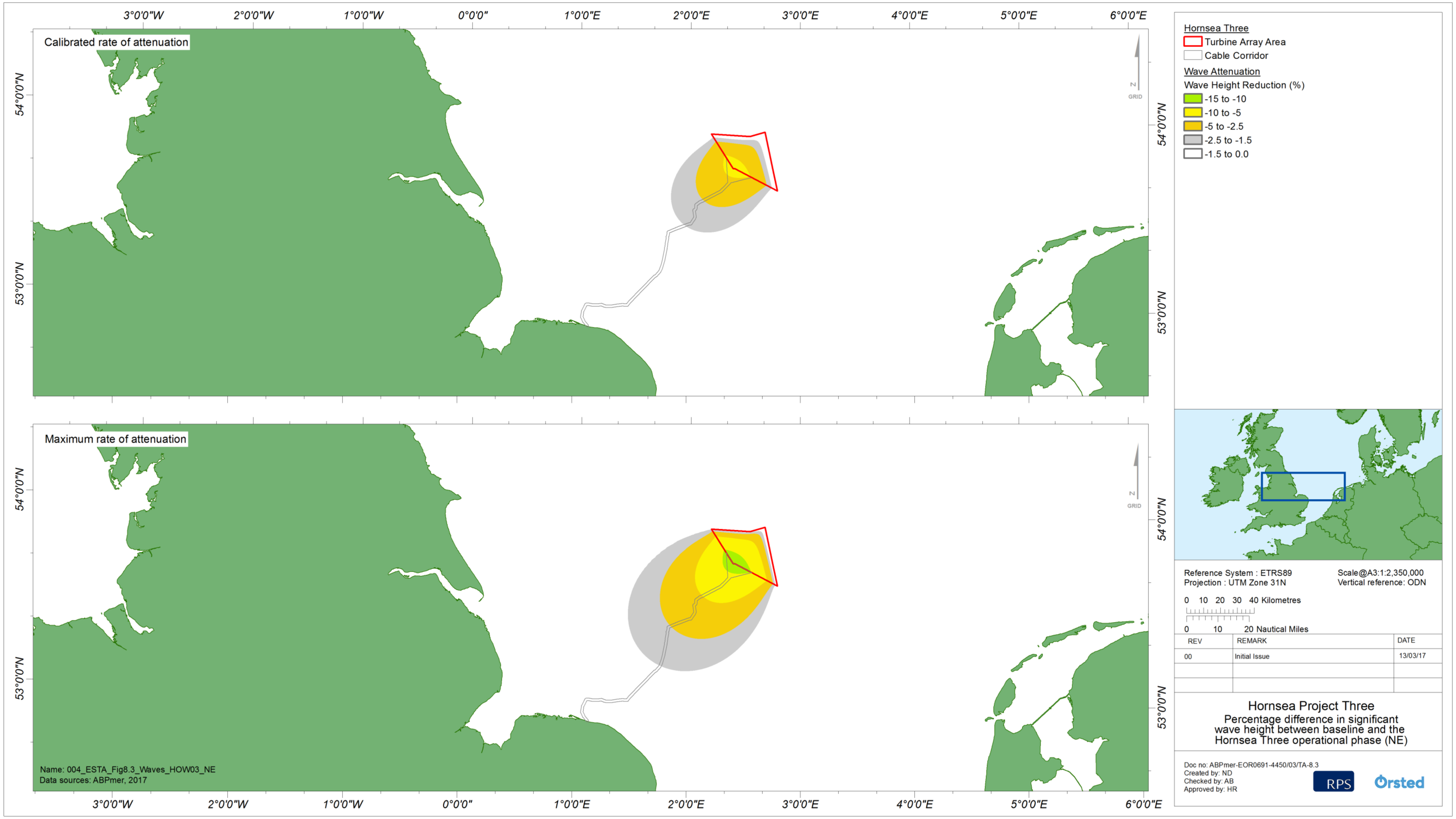


**Figure 8.3: Percentage difference in significant wave height between baseline and the Hornsea Three operational phase, 50% no exceedance, wave direction Northeast: (top) calibrated rate of attenuation; (bottom) maximum rate of attenuation.**

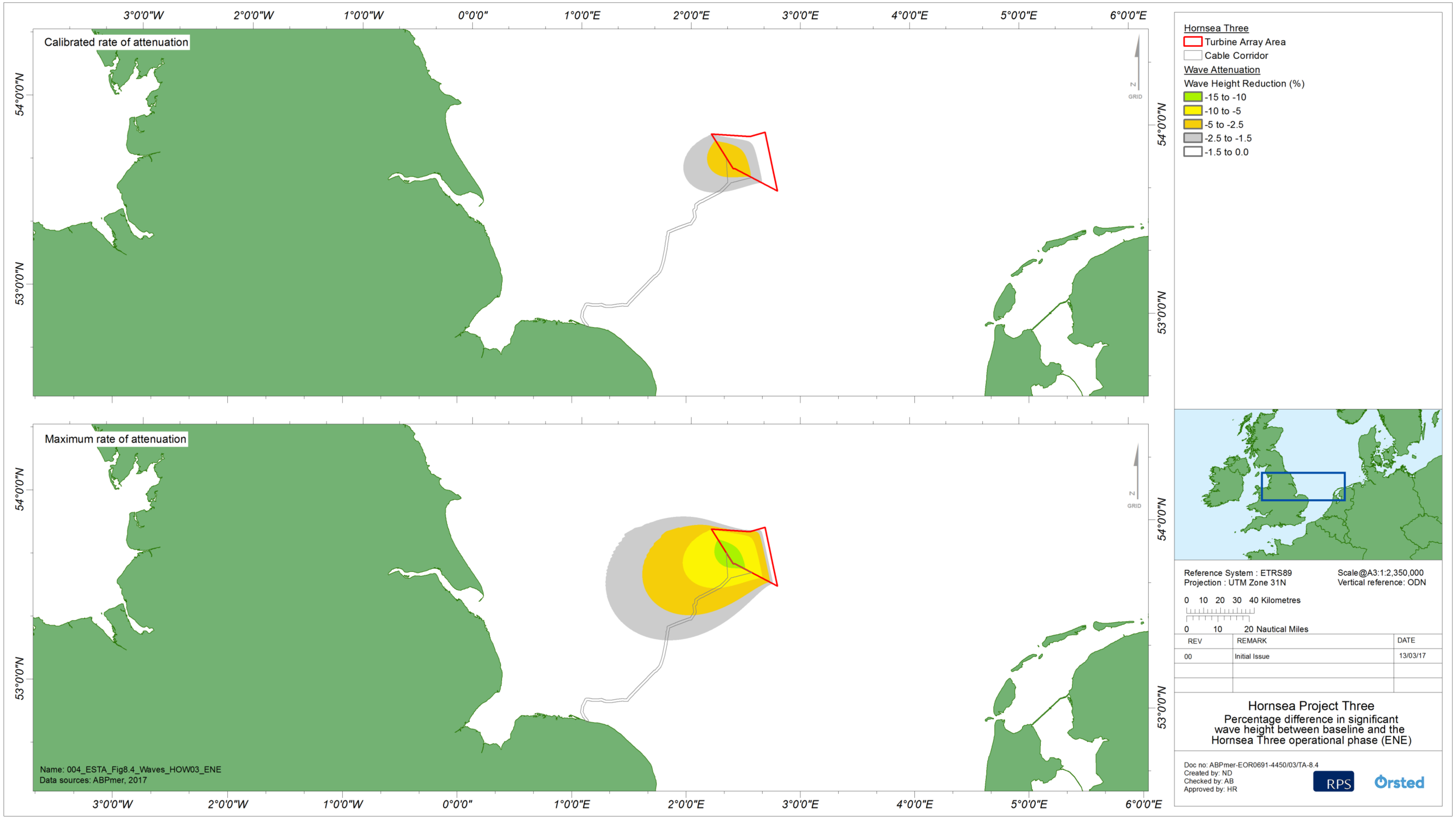


**Figure 8.4: Percentage difference in significant wave height between baseline and the Hornsea Three operational phase, 50% no exceedance, wave direction East-northeast: (top) calibrated rate of attenuation; (bottom) maximum rate of attenuation.**

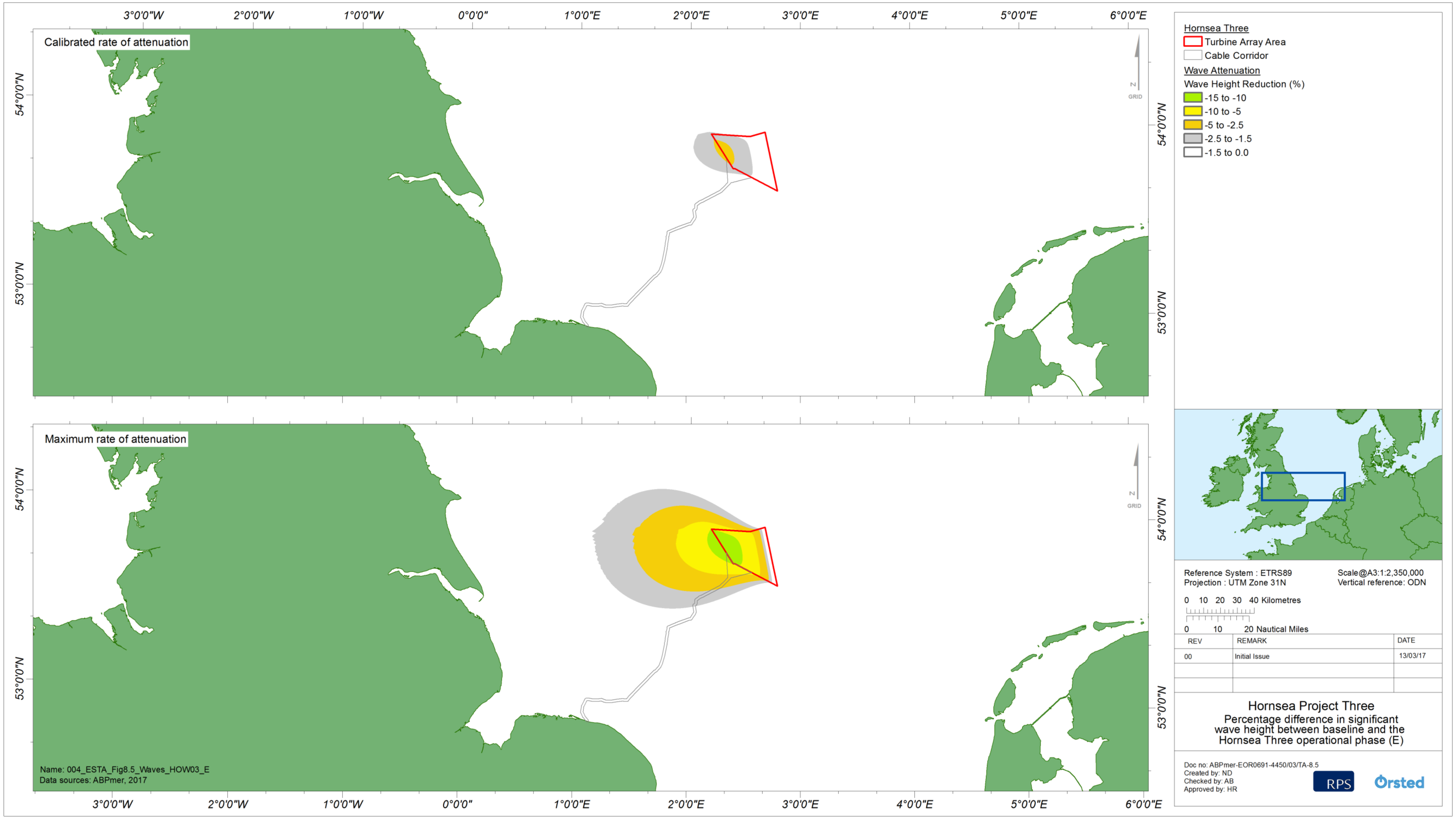


**Figure 8.5: Percentage difference in significant wave height between baseline and the Hornsea Three operational phase, 50% no exceedance, wave direction East: (top) calibrated rate of attenuation; (bottom) maximum rate of attenuation.**

## 8.5 Cumulative changes

### 8.5.1 Hornsea Project One, Hornsea Project Two and Hornsea Three

8.5.1.1 For the cumulative assessment scenario, the final approved layout for the smaller number of smaller monopile foundations being built in Hornsea Project One (174 turbines with monopile foundations, diameter 8.1 m), and the consented indicative layout scenarios for the maximum number of gravity base foundations (360 turbines with gravity base foundations, equivalent monopile diameter 32.9 m) in Hornsea Project Two (described in SMart Wind 2015), are used to realistically describe the potential distribution and dimensions of foundations within these array areas.

8.5.1.2 The description of Hornsea Project One used in the new cumulative scenario assessment (174 monopiles) is therefore different to (much less blockage than) the scenario modelling for the Hornsea Project One and Hornsea Project Two ES', which assessed Hornsea Project One based on a maximum design scenario of the greatest number of 332 gravity base foundations. However, as Hornsea Project One has now confirmed its layout and foundations, these have been carried into the assessment to provide a more realistic assessment. Given the project has now commenced construction, the confirmed layout and foundations for Hornsea Project One are referred to throughout as the 'final approved' definition of the project.

8.5.1.3 Simulated patterns of cumulative wave height reduction from the rule based model for Hornsea Three, Hornsea Project One (final approved) and Hornsea Project Two (as consented) are shown in Figure 8.6 to Figure 8.10. As previously discussed for Hornsea Three alone, two results are provided for each wave direction scenario: 1) using the direction specific calibrated rate of attenuation; 2) using the maximum calibrated rate of attenuation (associated with the north wave condition) for all directions. (See Appendix A for a discussion about the difference between these assumptions and associated results.)

8.5.1.4 The results show that, for Hornsea Three interacting cumulatively with Hornsea Project One (final approved) and Hornsea Project Two (as consented):

- Where the three array areas (Hornsea Three and Hornsea Project One and Hornsea Project Two) are not aligned with the incoming wave direction, the magnitude and patterns of change are the same as for each array alone;
- Where the three array areas are not aligned with the incoming wave direction but there is overlap of the footprints of change, the magnitude of change locally can increase beyond that calculated for either array alone, but is not a simple additive change;
- Where the three array areas are aligned with the incoming wave direction, wave height is initially reduced by the upwind array (as if alone). There is some (limited) wave height recovery in the gap between the arrays. Further wave height attenuation within the downwind array is relative to the pattern of already reduced (and slightly recovered) wave height entering at the upwind edge which can lead to a greater maximum reduction in wave height than either array alone;
- The maximum reduction in wave height for a given wave direction scenario occurs around the centre of the downwind edge of each array area. Considering the results for a constant (maximum calibrated) rate of attenuation, the maximum reduction magnitude is 28% in the Hornsea Project Two array area, which is associated with waves from the east (the longest axis passing through both array areas). The Hornsea Project One and Hornsea Project Two array areas are not closely aligned with Hornsea Three in directions other than east to west (occurring only approximately 5% of the time), so the maximum reduction in wave height for directional scenarios from north to east-northeast is similar to or the same as each array alone, but with a wider overall footprint of change;
- In practice, localised areas of wave height reduction will also occur in the immediate lee of individual foundations (length scale in the order of tens of metres);
- There will be no measurable reduction in wave height (>5%) at adjacent coastlines; and
- Considering the more conservative results for a constant (maximum calibrated) rate of attenuation, slight reductions in wave height (~2.5% or less) potentially occurring at adjacent coastlines are so small in both relative and absolute terms that they are not measurable in practice and would be indistinguishable from normal short term natural variability in wave height (both for individual wave heights and in terms of the overall seastate).

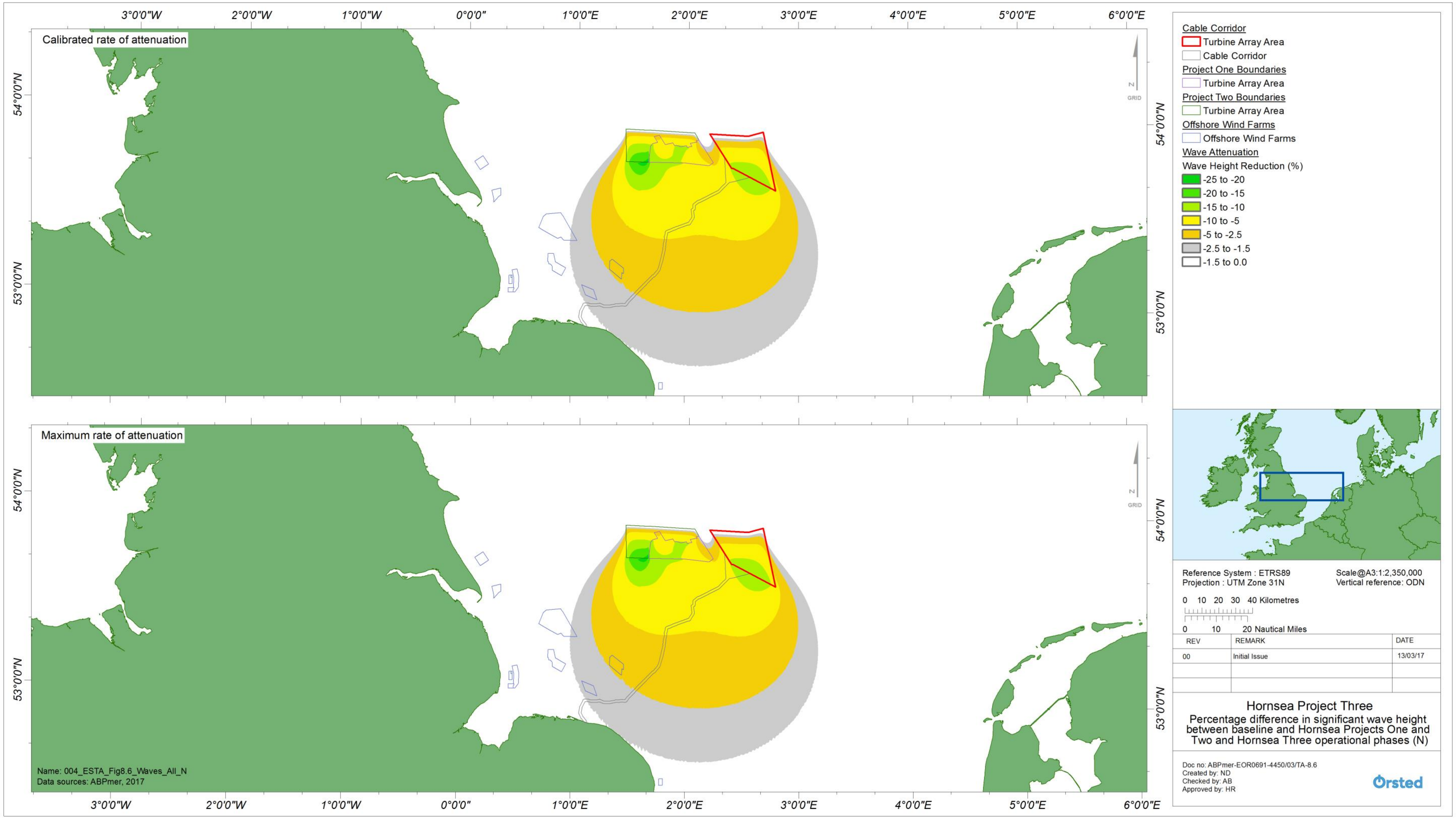


**Figure 8.6: Cumulative percentage difference in significant wave height between the baseline and the Hornsea Project One, Hornsea Project Two and the Hornsea Three operational phase, 50% no exceedance, wave direction North: (top) calibrated rate of attenuation; (bottom) maximum rate of attenuation.**

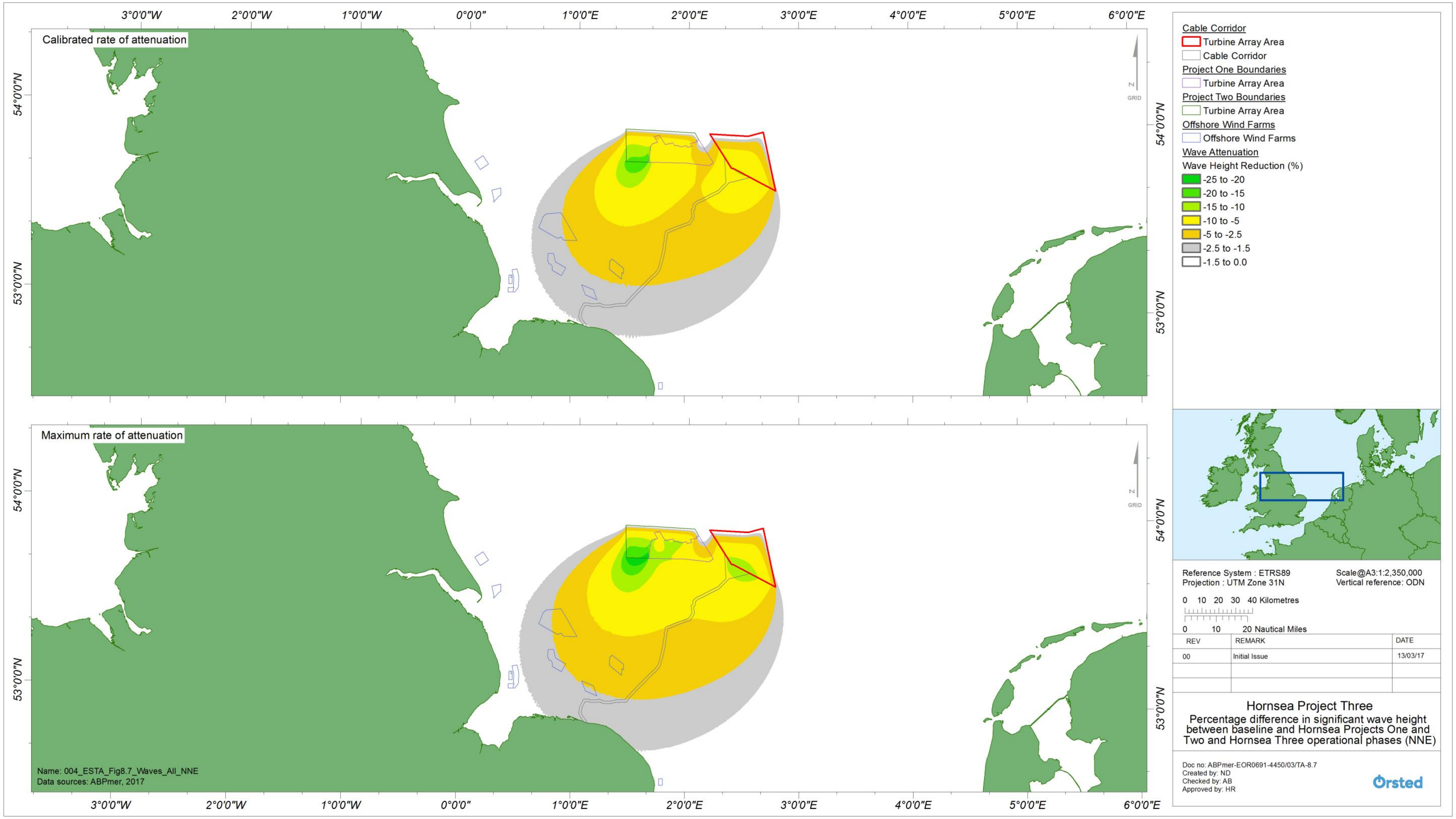


**Figure 8.7: Cumulative percentage difference in significant wave height between the baseline and the Hornsea Project One, Hornsea Project Two and the Hornsea Three operational phase, 50% no exceedance, wave direction North-northeast: (top) calibrated rate of attenuation; (bottom) maximum rate of attenuation.**

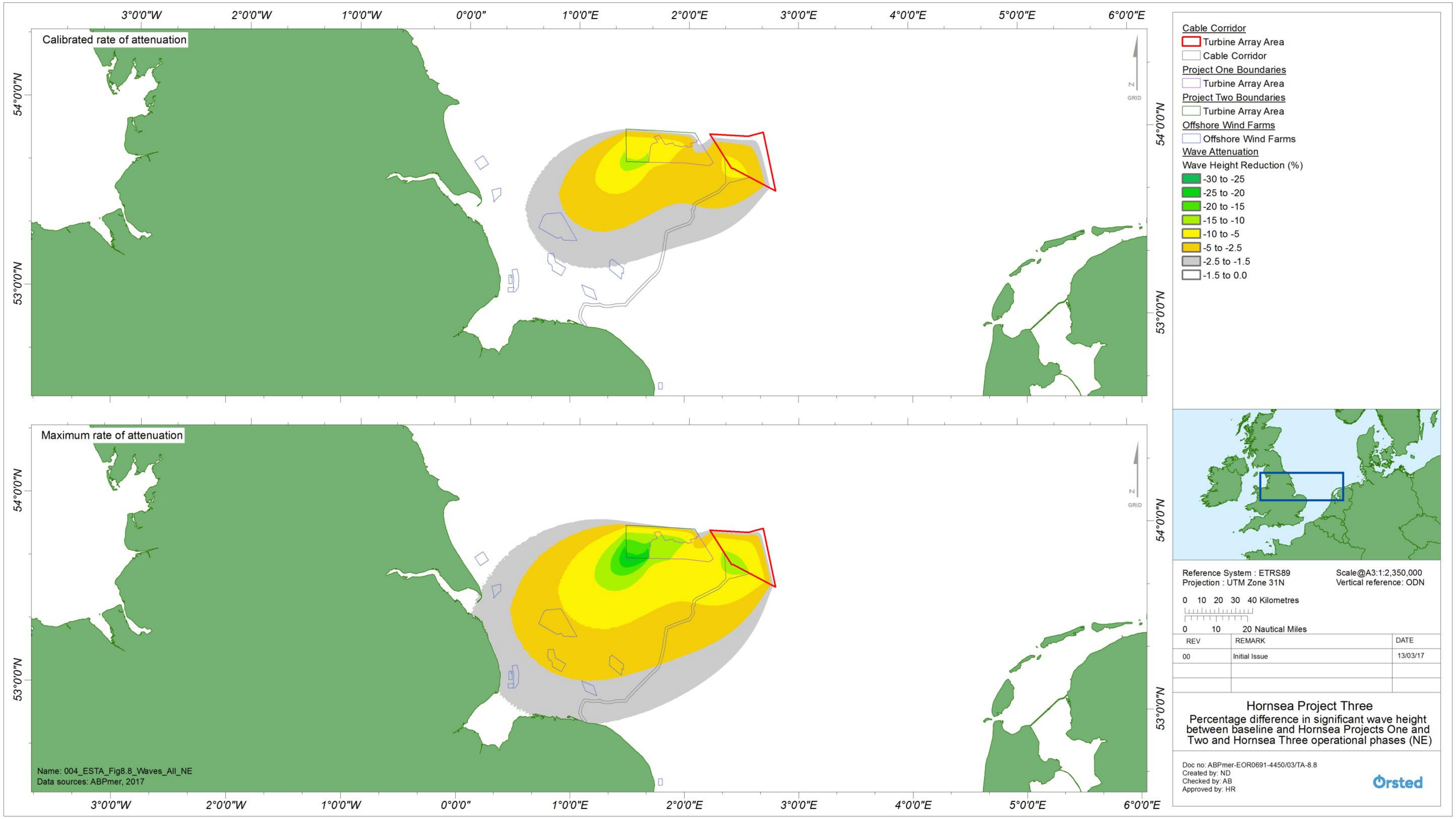


**Figure 8.8: Cumulative percentage difference in significant wave height between the baseline and the Hornsea Project One, Hornsea Project Two and the Hornsea Three operational phase, 50% no exceedance, wave direction Northeast: (top) calibrated rate of attenuation; (bottom) maximum rate of attenuation.**

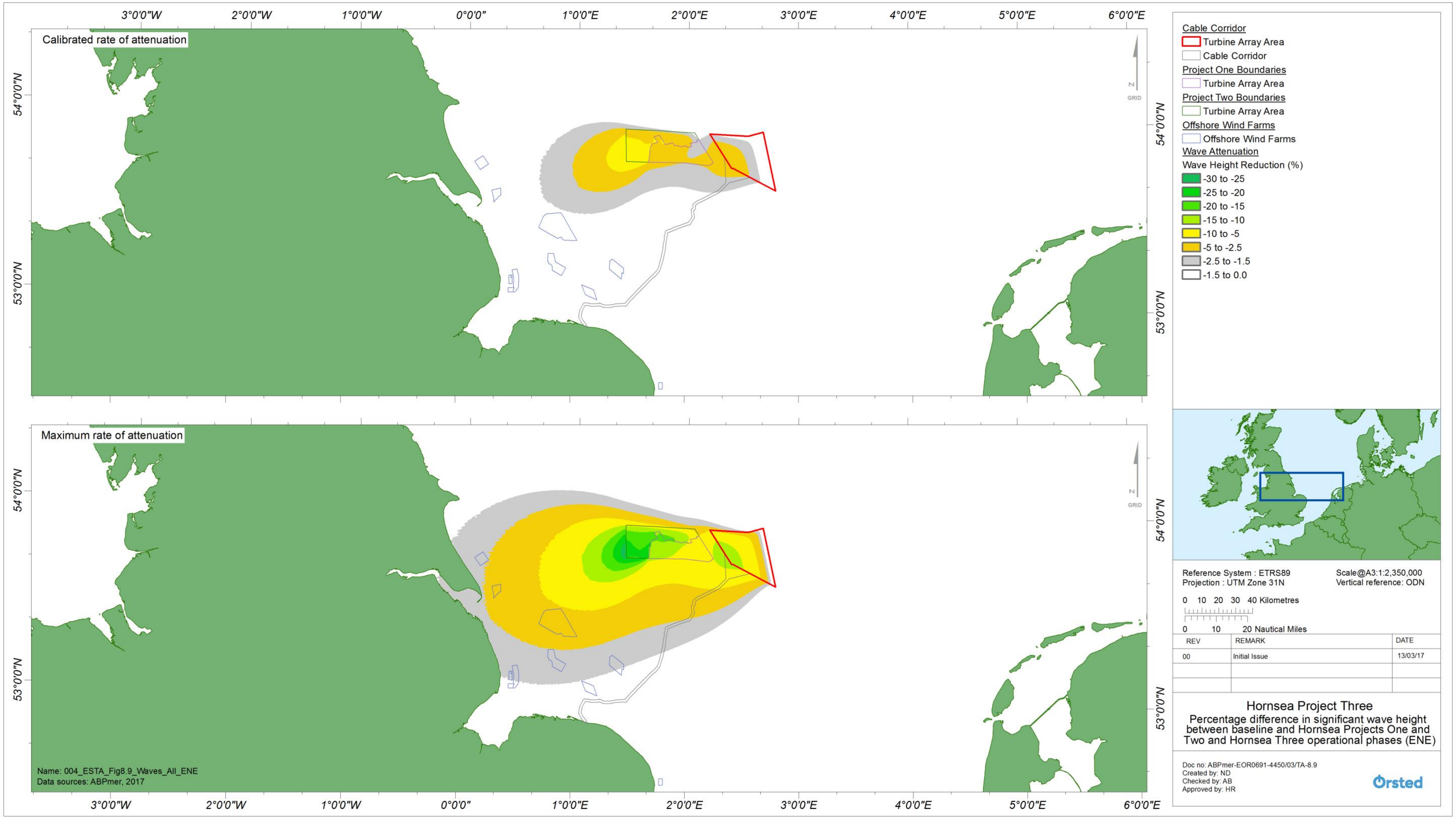


**Figure 8.9: Cumulative percentage difference in significant wave height between the baseline and the Hornsea Project One, Hornsea Project Two and the Hornsea Three operational phase, 50% no exceedance, wave direction East-northeast: (top) calibrated rate of attenuation; (bottom) maximum rate of attenuation.**

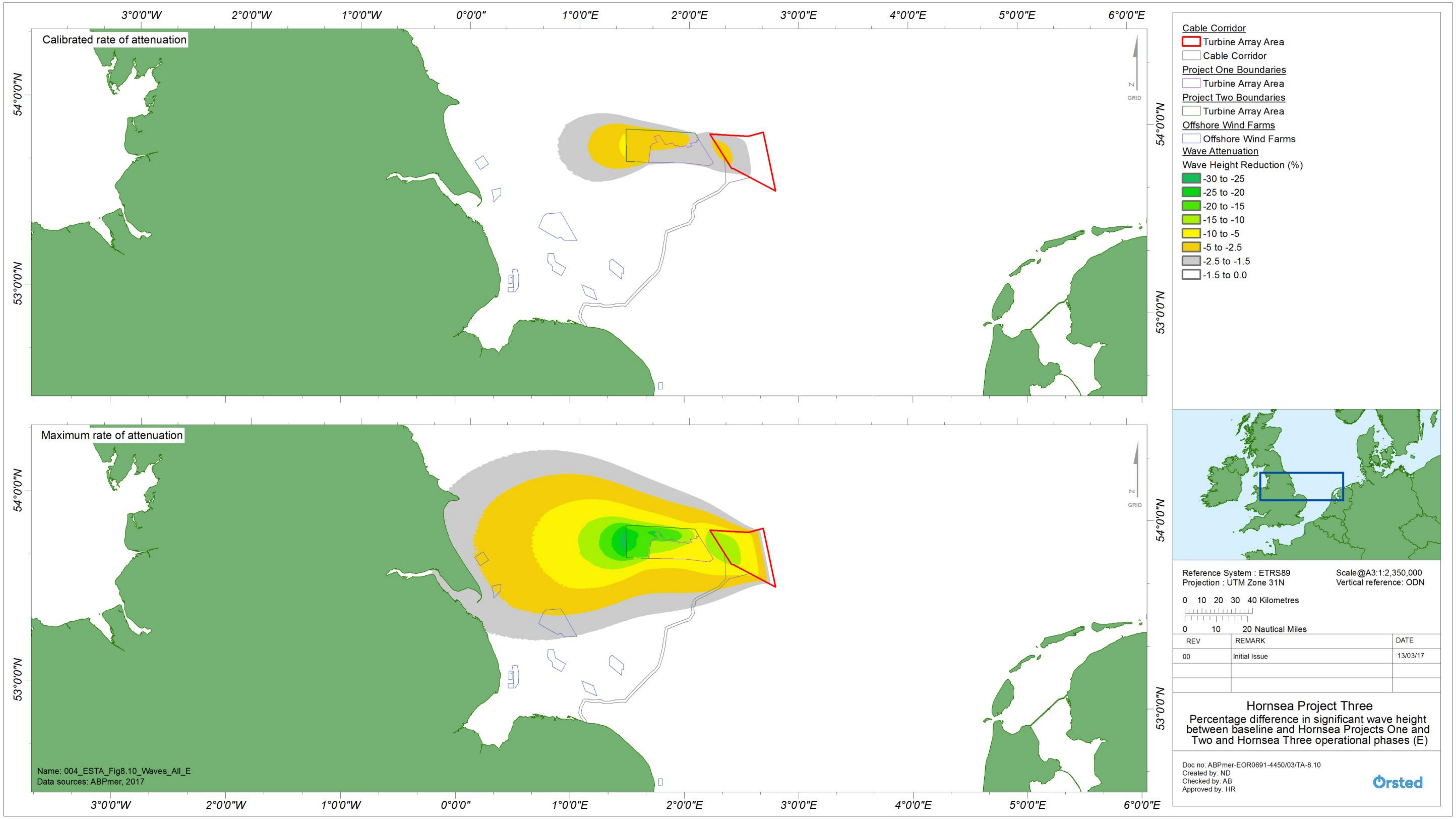


**Figure 8.10: Cumulative percentage difference in significant wave height between the baseline and the Hornsea Project One, Hornsea Project Two and the Hornsea Three operational phase, 50% no exceedance, wave direction East: (top) calibrated rate of attenuation; (bottom) maximum rate of attenuation.**

8.5.1.5 Drawing also on the results of the spectral wave modelling undertaken for Hornsea Three (see Appendix B) and other spectral wave modelling previously undertaken for Hornsea Project One and Hornsea Project Two, and other offshore wind farm wave height impact assessments:

- The maximum proportional impact on wave height is associated with the 50% non-exceedance condition (for which results have been provided above). The proportional impact on larger wave height (longer return period) conditions will be equal to or less than that reported above;
- The primary impact of the wind farm is a reduction in wave height. Wave period and wave direction will not be measurably affected (e.g. Moray Offshore Renewables Ltd, 2012, Navitus Bay Development Ltd, 2014);
- Differences in wave height of less than 5% are small in both relative and absolute terms. Such small differences are not measurable in practice and would be indistinguishable from normal short term natural variability in wave height (both for individual wave heights and in terms of the overall seastate);
- The maximum extent of a 5% reduction wave height is approximately 60 km, associated with the easterly wave condition for the cumulative Hornsea Three, Hornsea Project One and Hornsea Project Two scenario. The closest UK coastline in this direction is North Norfolk, approximately 90 km from the former Hornsea Zone. The closest coastline of any other European nation to the south is much further away, approximately 270 km to Belgium. Therefore, no measurable impact on wave height (>5%) is expected at any coastline as a result of the operational presence of Hornsea Three, either alone or in combination; and
- As previously noted in the Hornsea Project One and Hornsea Project Two Environmental Statements (SMart Wind, 2013; 2015a):

*Winds blow from the north through east quadrants only about 20% of the time and it is from this direction range that the presence of the wind farms in the Hornsea Zone is capable of exerting an influence on the nearshore wind-wave climate. The dominant wind regime interacts with wind farms in the Hornsea Zone from directions that can affect the inshore wave climate relatively infrequently. Around 80% of the time, the winds are directed away from, or parallel to, the coastline. The results presented here therefore have to be viewed in the context of being a worst case scenario, extracted from a considerably larger and generally more benign data set, as far as the effects upon the nearshore wave climate are concerned.*

8.5.1.6 The effect of Hornsea Three in combination with Hornsea Project One and Hornsea Project Two on patterns of wave height at other offshore locations (e.g. sandbanks or other designated areas) can be summarised as follows:

- The potential reduction in wave height at other offshore locations will be variable depending on the orientation and distance of the location from the array area (as shown in Figure 8.6 to Figure 8.10). The location must be aligned with the array area in the incoming wave direction to be affected. Based on the patterns of difference, locations more than approximately 60 km from the array area will typically not experience a reduction in instantaneous wave height greater than 5%.

### 8.5.2 Other offshore wind farm projects

8.5.2.1 There are nine offshore wind farms (either operational, under construction or consented) which have been scoped into the assessment. These are:

- Westermost Rough;
- Humber Gateway;
- Lynn and Inner Dowsing;
- Lincs;
- LID6-1;
- Sheringham Shoal;
- Triton Knoll;
- Dudgeon; and
- Race Bank.

8.5.2.2 Westermost Rough and Humber Gateway offshore wind farms are situated to the west of Hornsea Three, as shown on Figure 4.10. The Westermost Rough Environmental Statement (DONG Energy, 2009) concluded that changes in wave height along the shore resulting from the presence of the wind farm would be limited in magnitude. Similarly, the Humber Gateway Environmental Statement (E.ON, 2009) considered potential changes to waves and concluded that wave heights will only be slightly reduced by the Humber Gateway project.

8.5.2.3 As can be seen from Figure 8.6 to Figure 8.10. predicted changes to wave heights resulting from the operational presence of Hornsea Project One, Two and Three are expected to be very small (no greater than ~2.5%) as far west as Humber Gateway and Westermost Rough for any of the wave directions tested. Moreover, potential wave interactions between the wind farms in the former Hornsea Zone, Westermost Rough offshore wind farm and Humber Gateway offshore wind farm will only occur for waves coming from an easterly direction. Based on available 36 year wave hindcast from the Hornsea Three array area, waves from this sector only occur for approximately 15% of the record and the majority of these waves are shorter period wind waves which will have recovered in height before reaching the Humber Gateway and Westermost Rough wind farms. Accordingly, the duration of time over which potential wave interaction could occur is very small.

8.5.2.4 Lynn and Inner Dowsing, Triton Knoll, Race Bank, Dudgeon, Sheringham Shoal, Lincs and LID6 offshore wind farms are all situated to the southwest of Hornsea Three, as shown on Figure 4.10. When waves are coming from the north, north northeast and northeast (approximately 15% of time), the footprint of predicted changes to wave heights resulting from Hornsea Project One, Hornsea Project Two and Hornsea Three overlaps with the location of Lynn and Inner Dowsing, Triton Knoll, Race Bank, Dudgeon, Sheringham Shoal and Lincs offshore wind farms (Figure 8.6, Figure 8.7 and Figure 8.8 respectively).

8.5.2.5 The Lynn and Inner Dowsing Environmental Statement (Royal Haskoning, 2003) found that percentage reduction in wave heights in the lee of the wind farms is in the range 3 to 5%. The Triton Knoll Environmental Statement (RWE npower renewables, 2012) considered the changes to the wave regime of Triton Knoll with the Lincs, LID, Race Bank and Docking Shoal offshore wind farms during the operational phase for the wave regime. The low magnitude of wave height reductions (greatest reduction of 0.02 m) and the small directional changes (<0.54 degrees) were deemed to be of negligible significance.

8.5.2.6 The Environmental Statements for the Race Bank (Centrica Energy, 2009), Dudgeon (Dudgeon Offshore Wind Farm Ltd., 2009), Sheringham Shoal (Scira Offshore Energy Ltd, 2006) and Lincs (Centrica Energy, 2007) offshore wind farms predicted only minor changes in the wave regime, restricted to the wind farm sites themselves.

8.5.2.7 The cumulative reduction in wave heights predicted due to the operational presence of the offshore wind farms presented above are considered to be of very small magnitude. This is the case, even though the assessments of potential change to the wave regime presented in the Environmental Statements for the aforementioned wind farms in the Greater Wash have typically considered an array comprising gravity base foundation structures. These structures will represent the greatest blockage of waves. However, steel monopiles are either the installed foundation option (for those sites which are operational) or typically the preferred the preferred foundation option (for sites not yet constructed who have selected a foundation option). Monopile structures will result in considerably less blockage than that described for gravity base foundation structures for the purposes of EIA;

8.5.2.8 The implications of these small changes in wave characteristics for sediment transport at the coast is considered in section 9.4.

# 9. Sediment Transport Regime

## 9.1 Overview

9.1.1.1 Potential changes to the sediment transport regime could occur in response to the presence of:

- turbine foundations and sub-stations; and
- Cable protection measures.

9.1.1.2 It has been shown in section 7 and section 8. that the interaction between the naturally present oceanographic regime (currents and waves) and the wind turbine foundations may result in a reduction in current speed and wave energy, and locally an increase in levels of turbulence. These modifications to either the tidal regime and / or the wave regime may result in changes to the sediment transport regime.

9.1.1.3 The influence on patterns of sediment transport immediately adjacent to individual foundations is to cause scour (considered in section 11), the majority of which may occur in relatively short timescales (order of hours to days from installation). Persistent changes to wave and currents over larger areas may cause changes to patterns of net sediment transport (rates and directions) that might also result in a morphological change over longer time scales of weeks to months or years. The sensitivity of morphological features to these patterns of change would depend upon the relative importance of currents and / or waves, the magnitude and extent of any change to them and the degree to which the system is presently in balance.

9.1.1.4 There are no marine processes receptors present within the wider marine processes study area that are directly sensitive to a short term difference in the instantaneous rate of sediment transport (provided that the modified condition remains within the baseline range of natural variability). However, persistent changes in sediment transport patterns over longer timescales (years to decades) may have the potential to cause alterations to seabed and coastal morphology. The potential for such changes to occur is assessed in this section, with the influence of foundation infrastructure and cable protection measures considered separately.

## 9.2 Baseline conditions

9.2.1.1 Baseline characteristics of the sediment transport regime are briefly summarised below:

- Rates of sediment transport are anticipated to be variable across the marine processes study area;
- Within the array area, on the basis of the known tide and wave regimes and range of water depths present, net bedload sediment transport rates are estimated (calculated, e.g. using the relationships in Soulsby, 1997) to be generally low, with no clear associated direction.;
- In contrast, in parts of the Hornsea Three offshore cable corridor (especially in the vicinity of sandbanks) bedload sediment transport rates are expected to be greater. This is especially the case in the shallower nearshore areas where tidal current speeds are relatively faster and the influence of waves is more pronounced;
- The above theoretical observations are consistent with the orientation, size and relative symmetry of sedimentary features visible in the geophysical survey data. Regional-scale mapping in conjunction with analysis of the 2016/17 Hornsea Three offshore cable corridor geophysical survey suggests that, net bedload sediment transport is broadly directed to the northwest at the offshore end of Hornsea Three offshore cable corridor near to the array area, but towards the south/southeast at the landward end of the Hornsea Three offshore cable corridor in inshore/nearshore areas. The two regions of different net sediment transport direction are separated by a bedload parting zone (in which sediment is mobile but without a clearly associated direction) which runs in an approximately shore parallel direction, at a distance of approximately 15 km from the coast; and
- Net drift at the landfall is thought to be to the west (HR Wallingford *et al.,* 2002). However, there is high potential for annual variability in drift rates, which are anticipated to reverse between years, depending on the prevailing wave conditions HR Wallingford (2004).

## 9.3 Evidence base

9.3.1.1 Relatively little observational evidence is available with regard to the impacts of wind farm foundations on patterns of bedload sediment transport and potential associated changes to bathymetry. Where information is available, it is typically associated with the short to medium impacts of monopile foundations which are located in areas of sandy seabed, not directly analogous to the Site.

9.3.1.2 Cefas (2005) describe the results of post construction monitoring at Scroby Sands offshore wind farm which was undertaken to investigate the impacts of monopiles on coastal processes. It was found that at Scroby Sands, the impacts on sediment transport are probably limited to local scour pits and scour wakes. Any ensuing bathymetric impacts are probably limited to the order of 100 m around each monopile. It was further noted that given monopile spacings of over 300 m, such bathymetric impacts are unlikely to be cumulative between monopiles and across the turbine array.

## 9.4 Assessment

### 9.4.1 Turbine foundations and sub-stations

9.4.1.1 The sediment transport regime has been described within the baseline in terms of sediment transport at the bed (bed load transport), sediment transport within the water column (suspended sediment transport) and sediment transport at the coast (longshore drift). These elements of the sediment transport regime are discussed below, with particular focus on the presence of foundation infrastructure within the Hornsea Three array area. This is because the small number (up to four) of offshore HVAC collector substations located within the Hornsea Three offshore cable corridor will have very limited potential to influence sediment transport, with any change in potential transport rates restricted to a distance of (approximately) up to a few hundreds of metres from each structure (i.e. the area anticipated to experience measurable changes to flow speed).

***Potential changes to sediment transport at the coast***

9.4.1.2 Using the rule based numerical model to assess potential changes in wave conditions arising from the operational presence of Hornsea Three, it is found that there will be no measurable reduction in wave height (>2.5%) at adjacent coastlines (section 8.4). Differences in wave height of this magnitude are small in both relative and absolute terms. Such small differences are not measureable in practice and would be indistinguishable from normal short term natural variability in wave height (both for individual wave heights and in terms of the overall seastate). Accordingly, these changes are not predicted to have any measurable influence on sediment transport.

9.4.1.3 This assertion is entirely consistent with the quantitative analysis of potential changes to littoral drift rates in response to modification of the wave regime previously undertaken to inform the Hornsea Project Two assessment (SMart Wind, 2015a). Estimated changes in annual drift rate resulting from similarly limited reductions in wave heights were predicted to be very small at all locations along the north Norfolk and Lincolnshire coast, reaching a maximum reduction of just 0.7% in the vicinity of Cromer.

9.4.1.4 It is important to note here that actual rates of longshore sediment transport will vary temporally, on a seasonal and annual basis in response to inter and intra-annual variations in average wave height and direction. Indeed, inspection of the hindcast wave records from the Hornsea Three array area reveals that during the 36 year period of the record, annual variability in wave height and period deviated by up to ~10% from the average for this period. Changes in wave characteristics of this magnitude are considerably greater than those predicted to occur from Hornsea Three at the coast. It follows from this that any associated changes in the rate of longshore sediment transport resulting from the presence of the array will be less than those which have occurred naturally in the past.

9.4.1.5 In addition to the above, past changes in significant wave height are known to have occurred in response to changes in the North Atlantic Oscillation (NAO) (e.g. Leggett, 2007). It is probable that these changes will have manifest in some change in rates of longshore sediment along the Lincolnshire and north Norfolk coastlines.

9.4.1.6 Finally, in this region future changes to the wave climate as a consequence of climate change are predicted to occur as an increase of ~+0.25 m of the mean annual maxima significant wave height (between 1960 and 1990, to 2070 and 2100) (Lowe *et al.,* 2009). These changes, as well as alterations to the directional wave climate driven by changes in large scale climate variability have the potential to result in spatial modifications (erosion and accretion) to coastlines due to deviations in longshore sediment transport supply (Splinter *et al*., 2012). Importantly, the predicted future changes to the wave climate due to climate change are counter-directional to those predicted to occur as a consequence of Hornsea Three (i.e. larger storm waves are expected as a consequence of climate change whereas very slightly smaller storm waves may reach the coast with Hornsea Three in place).

***Potential changes to sediment transport at designated offshore locations***

9.4.1.7 A number of sandbanks are present within the vicinity of the Hornsea Three array area and offshore cable corridor, including those designated sandbanks belonging to the North Norfolk Sandbanks and Saturn Reef SAC. Sandbanks are tidally induced bedforms, with sandbank formation principally governed by sediment availability and the prevailing tidal current regime.

9.4.1.8 Waves primarily influence sandbanks by determining the maximum height to which they can accumulate (Kenyon and Cooper, 2005). The quantitative assessment of potential changes to the wave regime (sections 8.4 and 8.5) suggests that when waves are coming from the north, north northeast and northeast (approximately 15% of time), there may be a reduction in wave height of up to approximately 15% within the vicinity of the Indefatigable bank system and up to ~2% in the vicinity of banks closer inshore (e.g. Ower Bank). However, for the following reasons it is considered extremely unlikely that these changes to wave conditions would result in a corresponding morphological change to the banks in the form of a small increase in crest elevation:

- The wave events that are likely to cause the greatest effects on offshore sandbanks occur during low-frequency high-intensity storm conditions (e.g. 1 in 10 year return period). The numerical modelling undertaken for Hornsea Project One and Hornsea Project Two has demonstrated that whilst some reductions in wave heights under calm conditions (high-frequency low-intensity wave events; 50% no exceedance) may be expected, larger storm waves will be comparatively less affected. Accordingly, the key wave events that control sandbanks do not correspond to the wave events anticipated to undergo the greatest change (SMart Wind, 2015);
- The Indefatigable Banks (which are the closest banks to the Hornsea Three array area) are understood to be largely relict features. Accordingly, even if wave stirring of the bed were to be slightly reduced across the crest of the banks (which even at their shallowest point are approximately -15 mLAT), the crest elevation would not be expected to increase. This is because the banks are not actively being modified and 'built up' by tidal processes; and
- The banks closer inshore are understood to be highly dynamic bedforms subject to natural changes under baseline conditions. Even if very small reductions in the heights of northerly/ north-easterly waves were to occur across these banks, it is extremely unlikely these would manifest in changes to bank crest elevation. This is because these banks are also influenced by large waves from the southerly quadrant which will also contribute to flattening of the crests, thereby maintaining their existing (baseline) elevation.

***Potential changes to sediment transport at the bed***

9.4.1.9 Bed load transport across the Hornsea Three array area and offshore sections of the Hornsea Three offshore cable corridor is dominated by the action and asymmetry of tidal currents. The hydrodynamic modelling undertaken to inform the Hornsea Project One Environmental Statement (described in section 7) has demonstrated that:

- The only changes in current speed are anticipated to occur within the array itself and a narrow region just outside of the boundary (up to about 4 km), and local to foundation structures;
- The predicted changes in peak current speeds for Hornsea Project One vary from +0.04 m/s to -0.10 m/s; and
  Current speed will be reduced in a narrow wake extending downstream from each foundation (section 7); Conversely, current speed is increased (by a lesser magnitude but in a slightly wider corridor than the area of decreased flow) between the rows of foundations which results in limited net difference in the total flow rate of water through the Hornsea Three array area.

9.4.1.10 Very similar patterns of current modification to that described for Hornsea Project One are anticipated for the Hornsea Three array area.

9.4.1.11 The extent to which these small changes in flow speed could influence rates of bedload transport within and nearby to the Hornsea Three array area will depend upon the magnitude of change relative to sediment mobilisation thresholds. Within the wake of individual foundations, localised time mean current speed reductions (order of 0.10 m/s on a spring tide) might lessen the rate or frequency with which sediment is mobilised and transported; however, this reduction might be offset to some extent by the corresponding increase in turbulence also expected in the wake. Marginally increased rates of sediment transport might be experienced in the gap between foundations where small magnitude and localised acceleration of time mean current speed (order of 0.04 m/s on a spring tide) may occur.

9.4.1.12 The potential changes to sediment transport are localised and are of a different (opposite) nature inside and outside of the current wake from individual foundations. The direction of tidal currents passing through the Hornsea Three array area is relatively rectilinear (aligned closely to one direction) and minimal tidal rotation will be experienced during each flood and ebb cycle. As a result, the narrow wake downstream of individual foundations may be positioned over (and so affect) the same areas of seabed during each tidal cycle. Any effect will therefore be focussed upon, but also limited to, the narrow footprint of the wake from individual foundations.

9.4.1.13 The overall result of these slight changes in flow speed could potentially be a very small reduction in the net volume of material transported as bedload through the Hornsea Three array area. Baseline rates of sediment transport across the Hornsea Three array area are predicted to be low and any absolute changes in the net overall volume of sediment transport will therefore also be small. Accordingly, the potential for wider morphological change to the surrounding seabed is considered to be very limited.

9.4.1.14 The regional sediment transport pathways described by Kenyon and Cooper (2005) are aligned with the tide in an approximate southeast to northwesterly direction. These transport pathways therefore do not connect the Hornsea Three array area with nearby designated seabed areas, in particular the North Norfolk Sandbanks and Saturn Reef SAC (located ~10 km to the south) and Klaverbank SAC and Site of Community Importance (SCI) (located ~10 km to the east).

***Potential changes to sediment transport in the water column***

9.4.1.15 In theory, changes to the hydrodynamic regime caused by Hornsea Three have the potential to change:

- The concentration of sediment suspended in the water column;
- The rate at which suspended sediment is transported; and
- The direction in which material is transported.

9.4.1.16 Changes to tidal currents (which control the rate and direction in which suspended sediment is transported) due to the operational presence of the Hornsea Three array area are assessed in section 7 to be limited in absolute magnitude and spatially restricted to the array area plus a few kilometres downstream in the main flood and ebb directions. Potential changes to waves (which can influence the rate at which sediment is re-suspended) passing through the Hornsea Three array area to adjacent coastlines are assessed in section 8 to be of relatively greater extent but similarly limited magnitude.

9.4.1.17 The main source of naturally present sediment in suspension in the area is the East Anglia Plume, a region of elevated turbidity extending across the Southern Bight of the North Sea, primarily originating from the Thames Estuary, Humber Estuary and other areas of active coastal erosion on the southeast coast of the UK. The limited potential influence of the wind farm described above is unlikely to have any influence on the development of the East Anglia Plume and therefore on regional patterns of SSC.

9.4.1.18 During large storm events, waves may also stir the seabed within shallower parts of the Hornsea Three array area, naturally causing an additional short-term contribution to SSC levels locally. The maximum design scenario layout will potentially cause a reduction in wave heights within and nearby to the site and it is therefore possible that there will be a corresponding reduction in the rate at which sediment is locally re-suspended from the seabed. The change would only be apparent during larger storm events and would potentially slightly reduce SSC from that which would have occurred in the baseline condition. Levels of SSC will remain dominated by regional scale inputs that are not affected by the presence of the wind farm. No measureable changes to SSC outside the range of natural variability are expected to occur within or nearby to the Hornsea Three array area.

### 9.4.2 Cable protection measures

9.4.2.1 Export, array and substation interconnector cables will be buried into the seabed. Normal engineering best practice will be followed to ensure that cables are buried to a suitable depth that minimises the risk of exposure during the operational lifetime of the development. Additional cable protection measures may be required for approximately 10% of all cables (within both the Hornsea Three array area and the offshore cable corridor). The form of cable protection will be made by the contractor and will depend upon local seabed and hydrodynamic conditions and the outcome of the cable burial design plan (to be developed at a later date).

9.4.2.2 Installation of cable protection could result in a local elevation of the seabed profile by up to 2 m (volume 1, chapter 3: Project Description). Cable protection would be placed onto the seabed surface above the cable and therefore could, in theory, influence marine process in two ways:

- The cable protection could directly block the transport of sediment, impacting sediment supply to down-drift locations; and
- Cable protection measures could, in theory, modify the transmission of waves, indirectly impacting patterns of longshore sediment transport locally.

9.4.2.3 These potential impacts are discussed further below.

***Blockage of seabed sediment transport***

9.4.2.4 A detailed description of the potential changes to sediment transport associated with the installation of cable protection measures is provided in Section 6.4.6.

9.4.2.5 Accordingly, for all areas in which cable protection is used (including where sandwaves are present), it is expected that the presence of the cable protection measures will not affect patterns of sediment transport, following an initial period of small scale sediment accumulation. It follows that any changes on seabed morphology away from the protection devices will also be very small and any associated impacts on benthic habitats and other sensitive ecological receptors will be similarly limited.

***Modification of the wave regime***

9.4.2.6 In terms of the potential for the cable protection to modify the wave regime, it is considered that any interruption of inshore and nearshore wave processes would be minimal and highly localised. As stated in section 6.4.2, this is because the cable protection would likely occupy a low profile within the water column relative to the water depth. As such, the cable protection would present a minimal cross section of interference to the passage of incoming waves.

## 9.5 Cumulative changes

### 9.5.1 Cumulative changes associated with the presence of turbine foundations and sub-stations

9.5.1.1 The only other projects of sufficient scale and proximity to Hornsea Three that could potentially give rise to cumulative changes to the sediment transport regime are the Hornsea Project One and Hornsea Project Two wind farms. The potential for cumulative changes to bedload and suspended sediment transport are considered separately, below.

***Potential changes to sediment transport at the coast***

9.5.1.2 The wave modelling undertaken to inform the Hornsea Project Two Environmental Statement found that there would be no measurable reduction in wave height (>5%) at adjacent coastlines. The analyses presented in section 8.5 have demonstrated that this finding remains, even with the Hornsea Three array area in place. It follows therefore, that the quantitative estimates of potential change to annual drift rates presented in the Hornsea project Two Environmental Statement and summarised in section 9.4 will remain broadly the same with the Hornsea Three array area in place as well.

9.5.1.3 As discussed in section 9.4.1, changes of this magnitude are small in comparison to the range of natural variability and are very unlikely to be measurable or result in significant morphological changes at the coast.

***Potential changes to sediment transport at the bed***

9.5.1.4 Bed load transport in the Hornsea Three array area and offshore sections of the offshore cable corridor is dominated by the action and asymmetry of tidal currents. Owing to the alignment of the tidal axis in this region, the greatest changes to tidal currents are anticipated to occur to the northwest and southeast of the Hornsea Three array area, with minimal change to the east and west (see section 7). Given that the Hornsea Three array area is located to the east of the Hornsea Project One and Hornsea Project Two arrays, the potential for measurable cumulative interaction with respect to current speed is' considered to be very low. Given that the potential for a cumulative reduction in current speed is very low, it follows that any cumulative changes to bed load transport will be similarly limited.

***Potential changes to sediment transport in the water column***

9.5.1.5 A reduction in wave heights within and nearby to the Hornsea Three array area could theoretically cause a reduction in the rate at which sediment at the bed is mobilised and re-suspended by wave action during larger storm events, thereby reducing concentrations of sediment in the water column. It has been shown in section 8 that when the Hornsea Project One, Hornsea Project Two and Hornsea Three array areas are aligned with respect to the incoming wave direction (from the east), there is the potential for a cumulative reduction in wave heights in the Hornsea Project One and Hornsea Project Two array areas. On this basis, it follows that there could theoretically be a cumulative reduction in concentrations of sediment in the water column at these times.

9.5.1.6 However as previously stated, the principal sources of suspended sediments in this region are from the Humber, Wash and Thames, as well as the eroding East Anglia coastline. The relative contribution of material eroded locally from the seabed is negligible by comparison. Accordingly, no detectable changes are expected to occur to SSC as a consequence of cumulative changes to the wave regime.

### 9.5.2 Cumulative changes associated with the presence of cable protection measures

9.5.2.1 As discussed in section 9.4.2, changes in rates of sediment transport as a consequence of the presence of cable protection measures are anticipated to be largely short term and localised. There are no other projects of sufficient scale and/or proximity to Hornsea Three that could potentially interact cumulatively with the proposed cable protection measures to cause a greater change than that described in section 9.4.2.

# 10. Water Column Stratification

## 10.1 Overview

10.1.1.1 Stratification is a naturally occurring seasonal hydrodynamic feature related to the distribution of sea water temperature and salinity, which influences the availability of nutrients, and the distribution and growth rates of pelagic flora and fauna.

10.1.1.2 During the summer, increased heat input from solar radiation and higher air temperatures preferentially warms the upper part of the water column. Temperature differences of up to 10 C between the warmer (and so more buoyant) surface waters and colder (denser) bottom waters can be established in the North Sea, with a relatively steep vertical gradient in temperature between the two layers. The gradient in temperature (sometimes enhanced by vertical gradients in salinity) corresponds to a gradient in water density (the pycnocline), which acts as a physical barrier to vertical mixing and diffusion processes within the water column. Where stratification is present, depending on the strength of the density gradient, the availability of nutrients can be enhanced or reduced in certain parts of the water column, affecting the distribution of pelagic flora and fauna and leading to complex cycles and patterns of ecosystem development.

10.1.1.3 The tendency for stratification to develop is balanced against the ambient rate of turbulent mixing across the density gradient. Turbulence is developed at the seabed by friction with currents, and at the water surface by friction with winds (and any wave breaking). As a result, stratification is more likely to develop in relatively deeper areas, but may also occur in shallower areas with sufficiently low current speeds and exposure to winds and waves.

10.1.1.4 Stratification (as described above) is a horizontally orientated feature, characterised by vertical gradients in temperature, salinity and/or density. Fronts are vertically orientated features that develop at the transition between areas of stratified and non-stratified water. Fronts are also associated with (typically relatively enhanced) local patterns of nutrient distribution and ecosystem development. They are relatively widespread features within the North Sea and (at certain times during the year) may extend for a distance of several hundred kilometres (e.g. Hill et al., 1993; 2005). The strength of a vertical front is also defined by the strength of the (horizontal) gradients in density (temperature and salinity). 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 fresh water input; the speed of tidal currents (neap vs spring); the short term wind and wave climate; and the balance of these factors in conjunction with the local water depth. The position of the 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.

10.1.1.5 As currents move water past the individual offshore wind farm foundations, a turbulent wake is formed (see section 7.4.1). Within the turbulent wake, vertical mixing can be enhanced above ambient levels (section 4.3.4 considers this change in relation to SSC). The increase in turbulence intensity might potentially contribute to a local reduction in the strength of vertical stratification. This section considers the potential for foundations within the Hornsea Three array area to influence regional-scale patterns of stratification and any resulting change in the location of fronts.

## 10.2 Baseline conditions

10.2.1.1 A brief summary of the nature of water column stratification and frontal regions in the marine processes study area is summarised as follows:

- The North Sea is characterised by significant spatial and temporal variation in the vertical distribution of temperature and salinity. An assessment of intra-annual patterns of stratification in the North Sea has been undertaken using a long term (51 year) regional scale hydrobiogeochemical model simulation by van Leeuwen *et al*. (2015);
- The Hornsea Three array area is located in an area described by van Leeuwen *et al*., (2016) as being 'intermittently stratified', defined as <40 days in the year where the water column is stratified and between 120 to 250 days in the year where the water column is fully mixed. To the south and west of the Hornsea Three array area (i.e. closer to the UK coastline), shallow water depths and higher current speeds result in areas described as 'permanently mixed' (<20 days stratified and >345 days mixed in the year). To the north of the Hornsea Three array area are areas of deeper water and lower current speeds described as 'seasonally mixed' (>120 days stratified and >40 days mixed in the year);
- The Flamborough Front forms in the vicinity of the former Hornsea Zone during summer months (Figure 10.1). The Flamborough Front extends for a distance of several hundred kilometres offshore in an approximately east-west axis from Flamborough Head and represents the transition between stratified water to the north and mixed waters to the south;
- The Flamborough Front is characterised by a distinct temperature gradient between the waters north and south of the Flamborough headland (Pingree and Griffiths, 1978). It is predominantly a near bottom feature but has a weak surface signature and is visible in satellite infrared images (Hill *et al.,* 2005);
- Circulation patterns at the Flamborough Front are complex. The most pronounced feature is an along-front jet driven by the cross-front density-induced pressure gradient. This current is expected to be in the order of 0.15 m/s, occurring in an offshore direction (east) towards Dogger Bank (Hill *et al.,* 2005). Secondary circulation perpendicular to the front, of the order <0.05 m/s, is predicted to be driven by pressure field instabilities causing upwelling of cold bottom water on the mixed front (Simpson *et al.,* 1978); and

- There is likely to be significant inter-annual variability with regards to the position of the Flamborough Front in response to climatic variation in solar insolation and wind forcing. In addition, over the spring-neap cycle modulation of the level of tidal stirring causes periodic, non-linear advance and retreat of the mean frontal position. The position of the front will also be displaced by shorter distances by semi-diurnal tidal advection (in the order of 7 to 14 km on neap and spring tides, respectively).

## 10.3 Evidence base

10.3.1.1 The potential for wind turbine foundations to influence alter column stratification has previously been considered by Carpenter *et al*. (2016) and Cazenave *et al*. (2016), using numerical modelling analyses. These two studies are considered further in section 1.1.

## 10.4 Assessment

10.4.1.1 As described in section 7.4.1 and section 4.3.4, where an obstruction is introduced to a flow, complex three-dimensional interaction creates a wake with reduced time-mean current speed and increased turbulence intensity. The most pronounced changes to the flow regime occur immediately around but primarily downstream of the obstruction, within approximately three times the length scale of the obstacle. The wake effect recovers towards ambient levels of time-mean flow speed and turbulence with time and distance downstream (in the order of minutes and tens to hundreds of metres). The potential for turbine wakes to enhance vertical mixing and decrease stratification within the water column is discussed below.

10.4.1.2 The potential impacts of wind farm turbine foundations on shelf sea stratification have been the focus of two recent investigations by Carpenter *et al*. (2016) and Cazenave *et al.* (2016).

10.4.1.3 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 shows that stratification is only gradually broken down by interaction with the wind farm. A range of 'timescale for [complete] mixing' estimates are provided (in the order of 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, mixing due to the foundations will only lead to some partial reduction in the strength of stratification in water that passes through the wind farm. They conclude that no large scale changes to stratification of the North Sea are expected at the current levels of offshore wind farm construction and 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.

10.4.1.4 Cazenave *et al*. (2016) use a regional scale 3D hydrodynamic model with a number of wind farm foundations represented as small islands in the mesh. The mesh has a variable resolution of 2.5 to 20 m in the vicinity of the obstacles. Patterns of depth and time mean flow speed reduction in the wake are consistent with that described in section 7.4.1. Patterns of slightly downwards and upwards inclined time mean flow, upstream and downstream of each turbine are presented as a possible mechanism for mixing across the pycnocline. The resulting vertical distributions of temperature and salinity are used to calculate the local energy anomaly (a measure of water column stratification stability). Maps of this parameter are compared for scenarios with and without the wind farms present showing a change equivalent to 5 to 15% of the strength of stratification. It is noted that the change is both positive and negative, and is localised to the wind farm array areas.

10.4.1.5 The general results of Cazenave *et al.,* (2016) are that wind farm foundations may have some limited influence on the strength of stratification locally but it does not suggest that naturally present stratification would be completely mixed by this process. It is noted that the model used in this study only considers time mean flow at a typical spatial resolution of 10 to 20 m 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.

10.4.1.6 Based on the available evidence, vertical stratification (and so also the presence of the Flamborough Front) is only expected to occur in or near to the Hornsea Three array area for less than 40 days per year on average. When stratification is present, it is possible that foundations in the Hornsea Three array area may cause some minor decrease in the strength of water column stratification within the array area. Only a small proportion of water passing through the array area will actually interact with individual foundations, causing only partial and localised mixing of any stratification. Numerous repeat passes through the array area would be needed for an initially stratified body of water to become mixed; however, this is unlikely to happen due to displacement of the water body out of the array area over shorter time periods by residual tidal currents. It is therefore unlikely that water which is stratified entering the Hornsea Three array area will become fully mixed. Regional scale patterns of stratification in the North Sea will be unaffected and will continue to be subject to natural processes and variability. The location and physical characteristics of the Flamborough Front are therefore unlikely to be measurably affected and will remain within the range of natural variability.

## 10.5 Cumulative changes

10.5.1.1 Based on the available evidence (section 10.2), vertical stratification (and so also the presence of the Flamborough Front) is only expected to occur in or near to the former Hornsea Zone for less than 40 days in the year on average (van Leeuwen *et al*. 2015) (Figure 10.1). When stratification is present, it is possible that foundations in the Hornsea Three array area and other wind farm array areas within the former Hornsea Zone may locally cause some minor decrease in the strength of water column stratification; however, it is very unlikely that water which is stratified entering the array areas will become fully mixed. The Hornsea Three array area is not aligned with Hornsea Project One or Hornsea Project Two along the tidal axis and so there is no potential for cumulative impacts on stratification. As such, regional scale patterns of stratification in the North Sea will be unaffected and will continue to be subject to natural processes and variability under a cumulative scenario considering these projects. The location and physical characteristics of the Flamborough Front are therefore also unlikely to be measurably affected and will remain within the range of natural variability.

10.5.1.2 All other proposed wind farms are located much more than one tidal excursion from the Hornsea Three array area and from other wind farms in the former Hornsea Zone, so there is no potential for cumulative impacts on stratification.

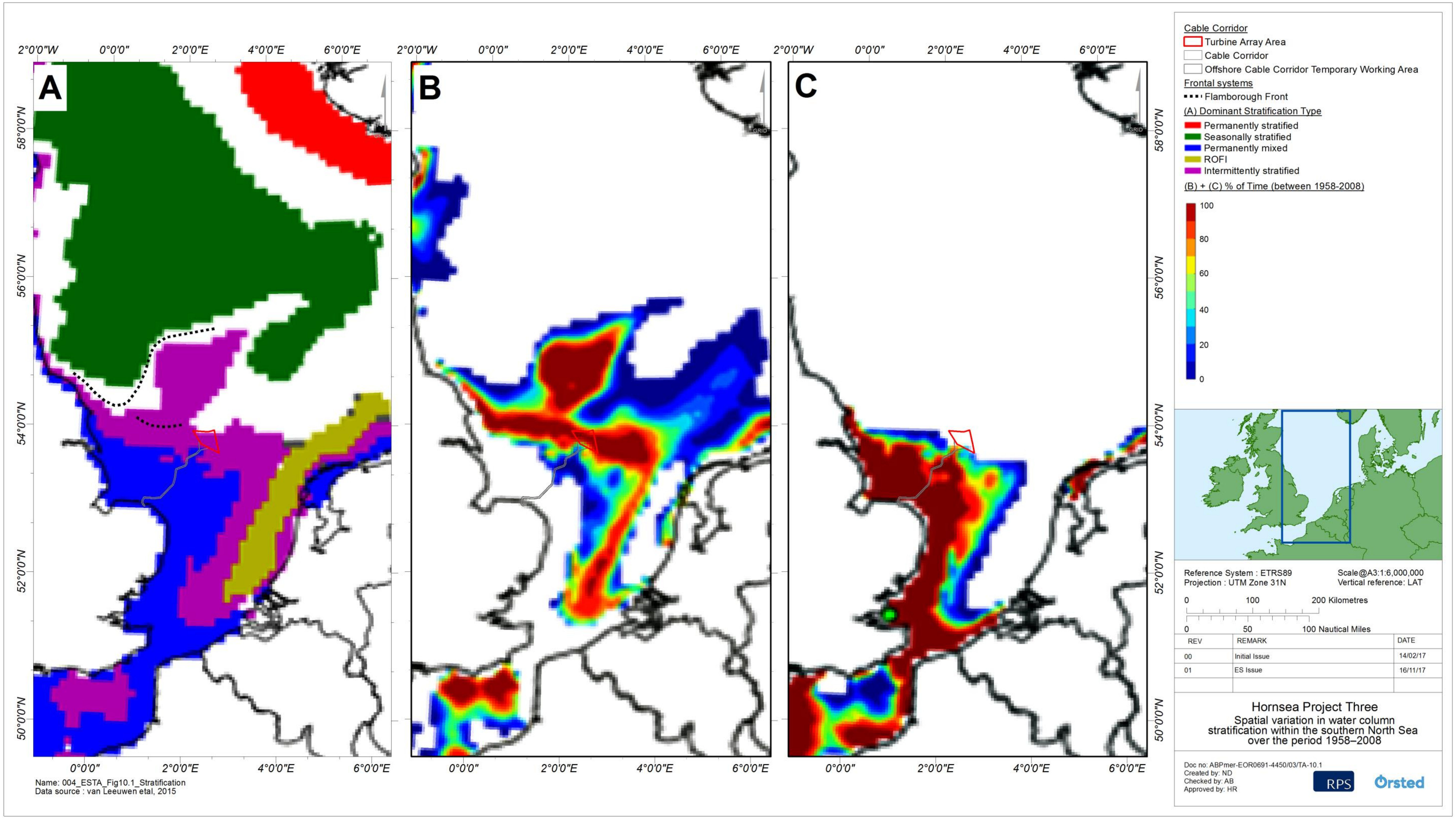


**Figure 10.1: Spatial variation in water column stratification within the southern North Sea over the period 1958 to –2008 (reproduced from van Leeuwen *et al*., 2015).**

# 11. Scour and Seabed Alteration

## 11.1 Overview

11.1.1.1 The purpose of this section is to conservatively and quantifiably estimate the area of seabed that will altered during the operational phase of the wind farm as a result of sediment scour that may develop adjacent to turbine foundations (in the absence of any scour protection).

11.1.1.2 The term scour refers here to the development of pits, troughs or other depressions in the seabed sediments around the base of turbine foundations. Scour is the result of net sediment removal over time (typically in the order of hours to days from installation in mobile sediments) due to the complex three-dimensional interaction between the foundation and ambient flows (currents and/or waves). Such interactions result in locally accelerated time-mean flow and locally elevated turbulence levels that enhance sediment transport potential in the area of influence. The resulting dimensions of the scour features and their rate of development are, generally, dependent upon the characteristics of the:

- Obstacle (dimensions, shape and orientation);
- Ambient flow (depth, magnitude, orientation and variation including tidal currents, waves, or combined conditions); and
- Seabed sediment (geotextural and geotechnical properties).

11.1.1.3 Based on the existing literature and evidence base, an equilibrium depth and pattern of scour can be empirically approximated for given combinations of these parameters. Natural variability in the above parameters means that the predicted equilibrium scour condition may also vary over time on, for example, spring-neap, seasonal or annual time-scales. The time required for the equilibrium scour condition to initially develop is also dependant on these parameters and may vary from hours to years.

11.1.1.4 Scour assessment for EIA purposes is considered here for three foundation types: monopiles; piled jacket foundations (a four legged version); and gravity base foundation structures. Each foundation type may produce different scour patterns therefore monopiles, gravity base foundations and jacket foundations have all been considered. Suction caisson foundations (for monopods and jackets) have not been considered in the assessment below because these will fall within the envelope of change associated with the other three foundation types.

11.1.1.5 The concerns under consideration include the seabed area that may become modified from its natural state (potentially impacting sensitive receptors through habitat alteration) and the volume and rate of additional sediment resuspension, as a result of scour. The seabed area directly affected by scour may be modified from the baseline (pre-development) or ambient state in several ways, including:

- A different (coarser) surface sediment grain size distribution may develop due to winnowing of finer material by the more energetic flow within the scour pit;
- A different surface character will be present if scour protection (e.g. rock protection) is used;
- Seabed slopes may be locally steeper in the scour pit; and
- Flow speed and turbulence may be locally elevated.

11.1.1.6 The magnitude of any change will vary depending upon the foundation type, the local baseline oceanographic and sedimentary environments and the type of scour protection implemented (if needed). In some cases, the modified sediment character within a scour pit may not be so different from the surrounding seabed; however, changes relating to bed slope and elevated flow speed and turbulence close to the foundation are still likely to apply. No direct assessment is offered within this document as to the potential impact on sensitive ecological receptors.

11.1.1.7 The assessment presented here is not intended for use in detailed engineering design. However, methodologies similar to those recommended for the design of offshore wind foundations (e.g. DNV, 2016) have been used in some cases where they are applicable. The methods applied to assess scour are set out in Appendix B.

## 11.2 Baseline conditions

11.2.1.1 Where obstacles are not present on the seabed, normal sediment transport processes can cause spatial and temporal variations in seabed level and sediment character in the baseline environment. Scour is a similar but localised change resulting from particular local patterns of sediment transport. Scour may also occur in the baseline environment in response to natural obstacles such as rocky outcrops or boulders. Key features of the baseline environment pertinent to the assessment of scour due to the presence of wind farm infrastructure are summarised below:

- Surficial sediments in the Hornsea Three array area and offshore cable corridor are typically characterised coarse grained and unconsolidated, with both sand and sandy gravel sediment types particularly prevalent. Where present, fines typically make up 5 to 20% of the total sediment mass, but can be up to 50% in some small areas;
- Surficial sediment units are typically less than 1 m thick across large areas of the Hornsea Three array area. Considerably greater thicknesses of mobile material are present in places along the Hornsea Three offshore cable corridor (Fugro GeoConsulting Limited, 2012; Clinton, 2016; EGS, 2016; Bibby HydroMap, 2016). Surficial sediment units typically overlie more consolidated, and therefore erosion resistant, geological units; and
- Locally, the seabed level is expected to vary naturally on hourly timescales in the order of centimetres to decimetres, due to the migration of small scale bedforms due to the action of tidal currents and waves. Larger natural variation in bed level over longer timescales might be associated with regional scale bed level change and the migration of larger sandwave or sandbank features.

## 11.3 Evidence base

11.3.1.1 Whitehouse (1998) provides a synthesis of a range of research papers, industry reports, monitoring studies and other evidence available at that time, describing the patterns and dimensions of scour that result from a variety of obstacle shapes, sizes and environmental conditions. Building upon a theoretical understanding of the processes involved, the accepted methods for the prediction of scour mainly rely on stochastic relationships and approaches (i.e. relationships that are based on and describe the available evidence). As such, scour analysis is an evidence based science where suitable analogues provide the most robust basis for prediction.

11.3.1.2 Since the publication of Whitehouse (1998), evidence continues to be collected and other predictive relationships have been developed and reported by the research community. In general, more recent observations have confirmed the approaches (and associated ranges of uncertainty) presented in Whitehouse (1998). As the evidence base has grown, additional approaches and relationships have been developed to better predict scour for a wider range of more specific obstacle shapes, sizes and environmental conditions.

11.3.1.3 Monitoring evidence regarding scour development around unprotected wind farm monopile installations is provided by HR Wallingford *et al*. (2007) and ABPmer *et al*., (2010) in a series of monitoring data synthesis reports for DTI and COWRIE. HR Wallingford *et al*., (2007) note that the available data support the view that scour is a progressive process that can occur where the seabed sediment is potentially erodible and there is an adequate thickness of that sediment for scouring to occur. Where the seabed comprises consolidated pre-Holocene sedimentary units (such as that encountered within many areas of the Hornsea Three array area), the scour will be slower to develop and limited in depth. For instance, geotechnical surveys at Kentish Flats offshore wind farm (Outer Thames) show that the seabed consists of non-cohesive sands over more resistant London Clay. The post construction monitoring evidence generally indicates that maximum scour rates around the monopiles (of diameter 4.3 m) occurred during the first year from installation and then rapidly slowed with near stability occurring by the third anniversary of the works. Scour depths ranged from 1.5 to 1.9 m at the monitoring locations and the results indicate that the scour depth is restricted by the cohesive underlying clay formation.

11.3.1.4 A research paper by Whitehouse *et al*., (2011) provides a summary of the field evidence for scour around gravity base foundations in the North Sea used in oil and gas projects. This review emphasized the sensitivity of scour to foundation shape, with foundations in very close proximity sharing similar hydrodynamic/ sedimentary environments displaying markedly different scour characteristics. This review also described field evidence for scour around a rectangular gravity base foundation (75 m by 80 m by 16 m high) located within the North Sea in 42 m water depth. Scour was measured as 2.5 to 3.5 m deep in 0.15 mm (i.e. fine) sand. Although not a direct analogue for the Hornsea Three turbine gravity base foundations, the structure described above is anticipated to be broadly similar to the box gravity base foundations which may be used to support offshore HVAC collector substations/ HVDC converter sub-stations (volume 1, chapter 3: Project Description).

11.3.1.5 Scour protection is evidently a mature engineering concept and by design will both prevent primary scour and minimise secondary scour. The evidence base supporting the design of scour protection is therefore strong but is not relevant to this assessment. The evidence base concerning the environmental impacts of scour protection is more limited. Although multi-layered gravel and rock scour protection is being successfully used at the Thornton Bank offshore wind farm in conjunction with six gravity base foundations in a sandy environment with water depths (28 m, similar to depths in the shallower parts of the Hornsea Project Three array area) (ABPmer *et al.,* 2010).

## 11.4 Assessment

### 11.4.1 Outline of structures considered in assessment

11.4.1.1 The following foundation structures have been considered within the assessment presented in this section:

- Monopile foundations:
  - 15 m diameter (largest) and 10 m diameter (smallest);
- Jacket foundations:
  - 40 m x 40 m base with four 4.6 m diameter legs (largest) and 32 m x 32 m base with four 3.3 m diameter legs (smallest); and
- Gravity base foundations:
  - 53 m diameter base (largest) and 43 m diameter base (smallest).

11.4.1.2 For each foundation type, both the largest and smallest structures have been considered. This is because the former has the potential to cause the greatest extent of scour at the scale of individual foundations whereas the latter may potentially be associated with the greatest extent of scour at the array scale, owing to the larger number of structures.

### 11.4.2 Factors affecting equilibrium scour depth

11.4.2.1 As summarised in Whitehouse (1998), a number of factors are known to influence equilibrium scour depth for monopiles, contributing to the range of observed equilibrium scour depths. These factors include the:

- Frequency and magnitude of ambient sediment transport;
- Ratio of monopile diameter to water depth;
- Ratio of monopile diameter to peak flow speed;
- Ratio of monopile diameter to sediment grain size; and
- Sediment grain size, gradation and the geotechnical properties of sedimentary units.

11.4.2.2 The influence of these factors where they do apply is to generally reduce the depth, extent and volume of the predicted scour, hence providing a less conservative estimate. For example, a greater frequency and magnitude of sediment transport can actually reduce the equilibrium scour depth, as the scour hole is also simultaneously being (partially) in-filled by ambient sediment transport.

11.4.2.3 The above factors have been considered in the context of the Hornsea Three array area and were not found to significantly or consistently reduce the predicted values for the purposes of EIA.

11.4.2.4 The greatest influence on local scour depth would arise from the installation of scour protection. If correctly designed and installed, scour protection will essentially prevent the development of local primary scour as described in this section. The dimensions and nature of scour protection may vary between designs but, given its purpose, would likely cover an area of seabed approximately similar to the predicted extent of the scour.

11.4.2.5 Interaction between ambient currents and the scour protection may lead to the development of secondary scour at its edges. The local dimensions of secondary scour are highly dependent upon the specific shape, design and placement of the protection. These parameters are highly variable and so there is no clear quantitative method or evidence base for accurately predicting the dimensions of secondary scour. However, as for foundations, the approximate scale of the scour depth and extent is likely to be proportional to the much smaller size of the individual elements comprising the protection.

### 11.4.3 Time for scour to develop around the foundation options

11.4.3.1 Scour depth can vary significantly under combined current and wave conditions through time (Harris *et al*. 2010). Monitoring of scour development around monopile foundations in UK offshore wind sites suggest that the time-scale to achieve equilibrium conditions can be of the order of 60 days in environments with a potentially mobile seabed (Harris *et al.,* 2011). However, as previously stated in section 11.3, equilibrium scour depths may not be reached for a period of several months or even a few years where erosion resistant sediments/ geology are present. These values account for tidal variations as well as the influence of waves. (Near) symmetrical scour will only develop following exposure to both flood and ebb tidal directions.

11.4.3.2 Under waves or combined waves and currents an equilibrium scour depth for the conditions existing at that time may be achieved over a period of minutes, whilst typically under tidal flows alone equilibrium scour conditions may take several months to develop (SMart Wind, 2015d).

### 11.4.4 Spatial extent of scour

11.4.4.1 At the Scroby Sands offshore wind farm, narrow, elongated scour features have been observed to extend over tens or hundreds of metres from individual foundations, leading to a more extensive impact than would normally be predicted. The development of elongate scour features at Scroby Sands is considered to have occurred due to the strongly rectilinear nature of the tidal currents (a very well defined tidal current axis with minimal deviation during each half tidal cycle) which allows the narrow turbulent wake behind each foundation to persist over the same areas of seabed for a greater proportion of the time, leading to net erosion in these areas. Due to a relatively higher rate of tidal rotation, the development of elongate scour features is not considered likely to occur within the Hornsea Three array area and offshore HVAC booster station search area.

### 11.4.5 Results

11.4.5.1 Table 11.1 and Table 11.2 summarize the key results of the first-order scour assessment undertaken using the methodological approach set out in Appendix B. Results conservatively assume maximum equilibrium scour depths are symmetrically present around the perimeter of the structure in a uniform and frequently mobile sedimentary environment with unlimited seabed thickness. Local scour extent is measured from the edge of the monopile, pin pile or gravity base foundation base; 'global scour' extent is measured from the centroid of the jacket foundation location. Global scour refers to a region of shallower but potentially more extensive scour associated with a multi-member foundation resulting from the change in flow velocity through the gaps between members of the structure and turbulence shed by the entire structure. Global scour does not imply scour at the scale of the wind farm array.

**Table 11.1: Summary of predicted maximum scour dimensions for largest individual turbine foundation structures.**

| Parameter | | Foundation type | | |
|---|---|---|---|---|
| | | Monopile (15 m diameter) | 4 Legged Jacket (40 m x 40 m base, 4.6 m legs) | Gravity Base (53 m base diameter) |
| Equilibrium Scour Depth (m) | Steady current | 19.5 | 6.0 | 1.6 |
| | Waves | Insufficient for scour | Insufficient for scour | 2.1 |
| | Waves and current | 19.5 | 6.0 | 3.4 |
| | Global scour | N/A | 1.8 | N/A |
| Extent from foundation [a] (m) | Local scour | 31.2 | 9.6 | 2.5 |
| | Global scour | N/A | 40.0 | N/A |
| Footprint [a] ($m^2$) | Structure alone | 177 | 50 | 2,206 |
| | Local scour (exc. structure) | 4,530 | 1,632 | 444 |
| | Global scour (exc. structure) | N/A | 4,976 | N/A |
| Volume [a] ($m^3$) | Local scour (exc. structure) | 34,224 | 3,948 | 347 |
| | Global scour (exc. local scour and structure) | N/A | 9,156 | N/A |
| | Drill arisings or bed preparation | 7,069 | 2,765 | 5,845 |

a Based upon the scour depth for steady currents. Footprint and volume values are per foundation.

**Table 11.2: Total seabed footprint of the different turbine foundation types with and without scour.**

| Parameter | Monopiles | | 4 Legged Jacket | | Gravity Base | |
|---|---|---|---|---|---|---|
| | (10.7 m diameter) | (15 m diameter) | (33 m base length) | (40 m base length) | (43 m diameter) | (53 m diameter) |
| Maximum number of foundations | 300 | 160 | 300 | 160 | 300 | 160 |
| Seabed footprint of all foundations ($m^2$) | 26,976 | 28,274 | 7,926 | 8,042 | 435,660 | 352,989 |
| Proportion of Hornsea Three array area [a] (%) | 0.00 | 0.00 | 0.00 | 0.00 | 0.06 | 0.05 |
| Seabed footprint of all local scour ($m^2$) | 691,520 | 724,801 | 265,957 | 261,109 | 79,474 | 70,988 |
| Proportion of Hornsea Three array area [a] (%) | 0.10 | 0.10 | 0.04 | 0.04 | 0.01 | 0.01 |
| Seabed footprint of all foundations + local scour ($m^2$) | 718,496 | 753,075 | 273,883 | 269,151 | 515,135 | 423,977 |
| Proportion of Hornsea Three array area [a] (%) | 0.10 | 0.11 | 0.04 | 0.04 | 0.07 | 0.06 |
| Seabed footprint of all global scour ($m^2$) | N/A | N/A | 1,018,432 | 796,205 | N/A | N/A |
| Proportion of Hornsea Three array area [a] (%) | N/A | N/A | 0.15 | 0.11 | N/A | N/A |
| Seabed footprint of all scour protection ($m^2$) | 647,426 | 678,584 | 190,230 | 193,019 | 1,187,522 | 733,876 |
| Proportion of Hornsea Three array area [a] (%) | 0.09 | 0.10 | 0.03 | 0.03 | 0.17 | 0.11 |
| Seabed footprint of all foundations + scour protection ($m^2$) | 674,402 | 706,858 | 198,156 | 201,062 | 1,623,182 | 1,086,865 |
| Proportion of Hornsea Three array area [a] (%) | 0.10 | 0.10 | 0.03 | 0.03 | 0.23 | 0.16 |

All scour dimensions are based upon the scour depth for steady currents.
a Corresponding proportion of the Hornsea Three array area (696 $km^2$).

11.4.5.2 Scour footprints exclude the footprint of the structure. Scour pit volumes for monopiles and gravity base foundation structures are calculated as the volume of an inverted truncated cone, minus the structure volume; scour pit volume for the jacket foundations are similarly calculated but as the sum of that predicted for each the corner piles. Key findings are summarised below:

- Overall, scour development within the Hornsea Three array area is expected to be dominated by the action of tidal currents;
- Of all of the turbine foundation options under consideration, a 15 m diameter monopile foundation has the potential to cause the greatest equilibrium local scour depth (19.5 m), footprint (4,530 $m^2$) and volume (34,224 $m^3$), but only in areas where the seabed is potentially erodible by the action of scour to that depth;
- The greatest individual turbine foundation global scour footprint is associated with the larger (40 m base length) piled jacket foundation (4,976 $m^2$), although with a relatively small average depth (1.8 m);
- For the Hornsea Three array area as a whole, the greatest total turbine foundation local scour footprint is associated with an array of 160 larger (15 m diameter) monopile foundations (724,801 $m^2$, equivalent to only approximately 0.1% of the array area);
- For the Hornsea Three array area as a whole, the greatest total turbine foundation global scour footprint is associated with an array of 300 smaller (43 m base diameter) piled jacket foundations (1,018,432 $m^2$, equivalent to only approximately 0.15% of the array area);
- In practice, the thickness of easily erodible surficial sediment overlying the more erosion resistant Quaternary units (primarily Bolders Bank Formation across most of the array area Figure 4.1) is

limited to around one metre. This is likely to lead to a natural limitation of scour depth and a related reduction in the footprint and volume of seabed affected by scour, both for individual foundations and for the array as a whole; and

- Scour protection may be used to protect the stability of foundations if necessary. Where scour protection is used, primary scour is unlikely to occur, although a small amount of secondary scour may develop at the edges of the scour protection. For monopile and piled jacket foundation types the footprint area of scour protection is similar to (or smaller than) the predicted footprint of local scour. For gravity base foundations, the footprint area of scour protection is larger than the predicted footprint of local scour for this foundation type (due to a relatively smaller predicted depth of scour) but more similar to that for monopiles. At most, the maximum footprint of scour protection is equivalent to only approximately 0.19% of the array area (0.25% including the footprint of the foundations also).

## 11.5 Cumulative changes

11.5.1.1 Scour around all structures will be confined to the Hornsea Three array area and offshore HVAC booster station search area. Accordingly, there is no potential for cumulative changes arising from interactions with other projects.

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# Appendix A Rule Based Wave Modelling

## A.1 Overview

A.1.1.1 Both in reality and in a spectral wave model, waves that are present in a local seastate do not come from only one direction. The reported wave direction is more specifically the peak (or mean) coming direction of wave energy, considering the whole seastate. Waves will also come from directions either side of the peak direction; typically, the contribution of such waves to the total seastate energy becomes progressively smaller with increasing angle from the peak direction.

A.1.1.2 As waves pass through the wind farm array area, they interact with the foundations of the wind turbines and other infrastructure. In practice, individual foundations will block or absorb wave energy through a combination of local wave reflection, wave breaking and friction. The exact mechanisms and proportion of wave energy affected will vary depending on the dimensions of the foundation and the length and height of the individual waves present.

A.1.1.3 The combined influence on waves of varying height and period within a range of characteristic spectral seastates for the Hornsea Project One and Hornsea Project Two array areas was computed using the ARTEMIS wave modelling software by HR Wallingford (SMart Wind, 2013; 2015a) for gravity base foundations in a relatively uniform density gridded layout. The ARTEMIS modelling approach is relatively spatially detailed and is able to simulate the scattering and blockage of wave energy by structures. This higher-resolution local-scale model was used initially to determine the rate of wave energy reduction caused by small groups of foundations. The resulting 'transmission coefficient' was then applied within the array area in a lower-resolution regional-scale SWAN spectral wave model to represent the sub grid-scale influence of the same foundation type and layout density.

A.1.1.4 For shorter period waves, the transmission coefficients determined by the ARTEMIS model are directly representative of the blockage presented by the total cross sectional area of the obstacles in the area of the model domain. The rates of attenuation determined during calibration of the rule based model are therefore representative of the maximum design scenario blockage density for Hornsea Project One and Hornsea Project Two, but may need to be adjusted to provide a realistic representation of the maximum design scenario for Hornsea Three. To inform this adjustment, the cross sectional area (blockage) of foundations per unit area in each array area is compared in Table A.1 and in Table 7.1 (within the main report).

A.1.1.5 A representative blockage width ('equivalent monopile diameter') of 32.9 m for each foundation was previously used when modelling gravity base foundations in Hornsea Project One and Hornsea Project Two (summarised in Table A.1 and reported in the Hornsea Project Two wave modelling appendices, SMart Wind (2013b and 2015b)). The equivalent monopile diameter is a representative vertically averaged value based on gravity base foundations with column diameters 8.5 and 10 m and base diameters 50 and 58 m, considering a representative range of water depths in Hornsea Project One and Hornsea Project Two respectively. Taking account of the maximum design scenario number of turbines present, the area of each array, and the minimum turbine spacing, Table A.1 also provides a summary of the resulting mean and maximum blockage density represented by the transmission coefficients described above.

A.1.1.6 Corresponding values for the maximum design scenario for Hornsea Three (turbines only) are also provided in Table A.1. The maximum design scenario blockage density for Hornsea Three is associated with the largest number of smaller gravity base foundations in the Hornsea Three array area column width (300 turbines, column diameter 15 m and base diameter 43 m). The representative blockage width (29.4 m) for individual turbines is only slightly smaller than that considered for Hornsea Project One and Hornsea Project Two, but the layout density (turbines/ $km^2$) is lower, leading to approximately half the mean blockage density.

A.1.1.7 Blockage density estimates for the larger number of smaller gravity base foundations for turbines plus up to 19 auxiliary structures (e.g. OSPs and accommodation platforms) in the Hornsea Three array area are also shown in italics for comparison in Table A.1. This scenario corresponds to an indicative layout of foundations at the minimum possible spacing throughout the Hornsea Three array area and therefore provides a more conservative (slight overestimate) of the total blockage and blockage density. This scenario is used to characterise the maximum design scenario for Hornsea Three in relation to impacts on waves and is also used for consistency to inform the new spectral wave modelling (used to further validate this rule based model) described in Appendix B.

A.1.1.8 Blockage density estimates for a smaller number of larger gravity base foundations in the Hornsea Three array area (160 turbines, column width 15 m and base diameter 53 m) are also shown in italics for comparison in Table A.1. The representative blockage width per foundation is slightly larger that for Hornsea Project One and Hornsea Project Two, but the resulting mean blockage density is even lower due to the lower number and layout density of turbines within Hornsea Three. The maximum blockage density is not shown as it is not realistically possible for this smaller number of turbines to fill the whole Hornsea Three array area at the minimum turbine spacing.

**Table A.1: Comparison of cross sectional area (blockage) of foundations per unit area in Hornsea Project One, Hornsea Project Two and Hornsea Three.**

| Project | Number of turbines | Representative blockage width per foundation [a] (m) | Total Array Area ($km^2$) | Minimum turbine spacing (m) | Blockage density ($m/km^2$) | |
|---|---|---|---|---|---|---|
| | | | | | Mean [b] | Maximum [c] |
| Hornsea Project One (as consented) | 332 | 32.9 | 407 | 800 | 26.8 | 51.4 |
| Hornsea Project One (final approved) | 174 | 8.1 | 407 | 800 | 3.5 | 12.7 |
| Hornsea Project Two (as consented) | 360 | 32.9 | 462 | 800 | 25.6 | 51.4 |
| Hornsea Three (WTG only) | 300 | 29.4 | 696 | 1000 | 12.7 | 29.4 |
| Hornsea Three (all foundations) | 300 +19 aux | 29.4 | 696 | 1000 | 13.5 | 29.4 |
| *(Hornsea Three)* | *160* | *34.4* | *696* | *1000* | *7.9* | - |

a See text for more details

b [Mean blockage density] = ([Number of turbines] x [Representative blockage width per foundation])/ [Total Array Area]. The mean blockage density assumes that turbines are distributed approximately evenly through the array area (but not necessarily in any particular layout).

c [Maximum blockage density] = [Representative blockage width per foundation]/ [Minimum turbine spacing]$^2$. The maximum blockage density can only realistically occur in a small part of the total array area, in order to not exceed the maximum number of turbines.

A.1.1.9 When scaled up to the whole array, the overall mean and maximum blockage density for the largest number of gravity base foundations in the Hornsea Three array area is approximately half that previously considered for Hornsea Project One and Hornsea Project Two (as shown in Table A.1). This is due to the larger total array area in conjunction with a similar (slightly smaller) blockage width per foundation. Utilising transmission coefficients based on Hornsea Project One and Hornsea Project Two model results would therefore provide an overestimate of the maximum influence of Hornsea Three (by up to a factor of two for the maximum design scenario larger number of smaller gravity base foundations, and by up to a factor of four for the smaller number of larger gravity base foundations). The transmission coefficient used in the rule based model for Hornsea Three, both alone and in combination with Hornsea Project One and Hornsea Project Two, is therefore reduced in proportion to the difference in overall mean blockage density (see Section A.3.2 for more details of the new scenarios including Hornsea Three).

A.1.1.10 The transmission coefficient used in the rule based model for Hornsea Project One is also reduced in proportion to the difference in overall mean blockage density (as shown in Table A.1) to reflect the 'final approved' design details of this wind farm (see Section A.3.2 for more details of the new scenarios including Hornsea Three).

## A.2 Assumptions

A.2.1.1 The following assumptions are implemented in the rule based numerical model:

- Wave energy is normally distributed (i.e. follows a Gaussian distribution) about the peak or mean wave coming direction. The standard deviation of wave spreading about the mean is 30°, which is broadly representative of a fully developed wind sea condition;
- The magnitude of the change on total wave energy is proportional to the change in wave height (i.e. there is no significant influence of the foundations on the distribution of wave period within the seastate). This assumption is consistent with the findings of previous spectral numerical modelling studies (e.g. Moray Offshore Renewables Ltd, 2012);
- Within the array area(s), wave height is reduced at an approximately linear rate, proportional to the distance travelled through the array. The rate of wave height attenuation for each model scenario is determined by calibration against the corresponding results of the previous Hornsea Project One and Hornsea Project Two spectral wave modelling. Variation in the rate of reduction used (by scenario direction) in the rule based model is thereby consistent with the magnitude of (and reasons for) variation in the transmission coefficient between the previous Hornsea Project One and Hornsea Project Two spectral wave model directional scenarios; and
- Outside of the array area, reduced wave heights recover asymptotically towards the background condition at a non-linear rate as a function of the distance travelled from the array. The coefficient of wave height recovery for each model scenario is also determined by calibration against the corresponding results of the previous Hornsea Project One and Hornsea Project Two spectral wave modelling. The same coefficient was found to apply to all scenarios.

## A.3 Model construction

A.3.1.1 The rule based wave model is constructed as follows:

- The model utilises a regular spatial grid (resolution 1 km) sufficiently large to encompass the wind farm(s) being assessed and the extent of measurable change to wave height (the minimum reduction reported/considered magnitude of change is 2.5%); and
- For every location (x, y) in the grid, for 360 wave coming directions (dir = 0, 1, 2… 359 °N), the following distances are determined:
  - (La), the distance travelled through the wind farm array area by a wave arriving at location = x, y, coming from direction = dir. La=0 for locations where the upwind wave path does not pass through the array area. Down-wind of the array area, along any given transect line, La is constant and equal to the width of the array area in that orientation. Within the array area, along any given transect line, La is proportional to the distance travelled through the full width of the array area in that orientation; and
  - (Lb), the distance travelled from the down-wind edge of the array area by a wave arriving at location = x, y, coming from direction = dir. Lb = 0 for locations where the upwind wave path does not pass through the array area.
- The probability distribution function (PDF) for wave energy in the baseline situation (prior to including the influence of the wind farm) at all locations is described by a standard normal (Gaussian) distribution (shown below) in intervals of 1° in the range dir ± 90° (±3 standard deviations, σ = 30°). The area under this slightly truncated PDF is normalised, so that the distribution describes the proportional contribution from each coming direction to the total wave energy.

$$PDF(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/(2\sigma^2)}$$

Where:

x = direction;

μ = peak wave coming direction; and

σ = wave spreading standard deviation.

- For every location (x, y) in the grid, for each wave coming direction in the relevant subset (e.g. for a northerly wave scenario dir = 270, 269,… 359, 0,… 89, 90 °N):
  - The total reduction of wave height (as a proportion of the baseline wave energy, by direction) and the total recovery of wave height (as a proportion of the reduction, by direction) are calculated using the rate of attenuation (Ra) and the coefficient of recovery (Cb) in conjunction with distances La and Lb;
  - The net wave energy reduction (as a proportion of the baseline wave energy, by direction) is found as the product of the total reduction and total recovery (by direction); and
  - To account for the varying proportional contribution of waves coming from each direction to the total local wave energy, the local PDF is modified by the net wave energy reduction (by direction). The area of the modified PDF gives the modified total wave energy (as a proportion of the baseline wave energy), which is equivalent to the modified total wave height (as a proportion of the baseline wave height).

- For individual array areas, the net wave energy reduction (as a proportion of the baseline wave energy, by direction) is obtained using:

$$Reduction_{(x,y,dir)} = \left(L_{a(x,y,dir)} \times R_a\right) \times {C_b}^{-L_{b(x,y,dir)}}$$

- For the cumulative change associated with two array areas, the net wave energy reduction (as a proportion of the baseline wave energy, by direction) is obtained using:

$$\boldsymbol{Reduction_{(x,y,dir)}} = \left(\left(\left(\boldsymbol{L_{a1(x,y,dir)}} \times \boldsymbol{R_a}\right) \times \boldsymbol{C_b}^{-\left(\boldsymbol{L_{b1(x,y,dir)}}-\boldsymbol{L_{a2(x,y,dir)}}\right)}\right) + \left(\boldsymbol{L_{a2(x,y,dir)}} \times \boldsymbol{R_a}\right)\right) \times \boldsymbol{C_b}^{-\boldsymbol{L_{b2(x,y,dir)}}}$$

- For the cumulative change associated with three array areas, the net wave energy reduction (as a proportion of the baseline wave energy, by direction) is obtained using:

$$Reduction_{(x,y,dir)} = \left(\left(\left(\left(\left(L_{a1(x,y,dir)} \times R_a\right) \times C_b^{-\left(L_{b1(x,y,dir)}-L_{a2(x,y,dir)}-L_{a3(x,y,dir)}\right)}\right) + \left(L_{a2(x,y,dir)} \times R_a\right)\right) \times C_b^{-\left(L_{b2(x,y,dir)}-L_{a3(x,y,dir)}\right)}\right) + \left(L_{a3(x,y,dir)} \times R_a\right)\right) \times C_b^{-L_{b3(x,y,dir)}}$$

- Where, the additional numerical subscripts indicate the La(x,y,dir) and Lb(x,y,dir) pair for the array area which is [1] furthest from and (progressively) [2] then [3] closest to the position x, y, based on the value of Lb(x,y,dir).

## A.3.2 Scheme Representation of Wind Farm Foundations

***Previously modelled cumulative effect of Hornsea Project One and Hornsea Project Two (as consented)***

A.3.2.1 The optimum values of the rate of wave attenuation, Ra, and the coefficient of wave recovery, Cb, (shown in Table A.2) were determined iteratively by difference minimisation between the simulated patterns of wave height reduction from the previous cumulative Hornsea Project One and Hornsea Project Two (as consented) spectral wave modelling and the rule based wave model, for all wave directions.

A.3.2.2 The values shown in Table A.2 (for Hornsea Project One and Hornsea Project Two (as consented)) are used to validate the rule based model against the results of the previous cumulative Hornsea Project One and Hornsea Project Two SWAN spectral wave modelling in Section A.4, and against the results of the new MIKE21SW spectral wave model for the same scenario in Section B.5.

**Table A.2: Rates and coefficients used by the rule based model.**

| | 50% Non-Exceedance Return period Directional Wave Model Scenario | | | | |
|---|---|---|---|---|---|
| **Parameter** | **N** | **NNE** | **NE** | **ENE** | **E** |
| Ra (%/km) | | | | | |
| Hornsea Project One and Hornsea Project Two (as consented) | -1.080 | -0.900 | -0.530 | -0.320 | -0.225 |
| Hornsea Three | -0.555 | -0.463 | -0.272 | -0.164 | -0.116 |
| Hornsea Project One (final approved) | -0.072 | -0.060 | -0.035 | -0.021 | -0.015 |
| Hornsea Project Two (as consented) | -1.080 | -0.900 | -0.530 | -0.320 | -0.225 |
| Cb (all scenarios) | 1.010 | | | | |

***New scenarios including Hornsea Three***

A.3.2.3 The results of the rule based model for new assessment scenarios including Hornsea Three alone and the cumulative effect of Hornsea Three, Hornsea Project One and Hornsea Project Two, are reported in Section 8.4 and 8.5, respectively.

A.3.2.4 The realistic maximum adverse scenario effect of Hornsea Three alone includes:

- The maximum number (300 WTG + 19 auxiliary, 319 total) of 43 m base diameter, 15 m pylon diameter gravity base foundations (equivalent monopile diameter 29.4 m) in the Hornsea Three array area (696 $km^2$).

A.3.2.5 For the cumulative assessment scenario, the final approved layout for the smaller number of smaller monopile foundations being built in Hornsea Project One (174 turbines with monopile foundations, diameter 8.1 m), and the consented indicative layout scenarios for the maximum number of gravity base foundations (360 turbines with gravity base foundations, equivalent monopile diameter 32.9 m) in Hornsea Project Two (described in SMart Wind 2015), are used to realistically describe the potential distribution and dimensions of foundations within these array areas.

A.3.2.6 The potential realistic worst case effect of Hornsea Three, Hornsea Project One (final approved) and Hornsea Project Two (as consented) includes:

- The maximum number (300 WTG + 19 auxiliary, 319 total) of 43 m base diameter, 15 m pylon diameter gravity base foundations (equivalent monopile diameter 29.4 m) in the Hornsea Three array area (696 $km^2$).
- The final approved number (174) and layout of 8.1 m diameter monopile foundations (equivalent monopile diameter 8.1 m) in the Hornsea Project One array area (407 $km^2$); and
- The maximum number (360) of 50 m base diameter, 15 m pylon diameter gravity base foundations (equivalent monopile diameter 32.9 m) in the Hornsea Project Two array area (462 $km^2$).

A.3.2.7 The description of Hornsea Project One to be used in the new cumulative scenario assessment (174 monopiles) is therefore different to (much less blockage than) the scenario modelling for the Hornsea Project One and Hornsea Project Two ES', which assessed Hornsea Project One based on a maximum design scenario of the greatest number of 332 gravity base foundations. However, as Hornsea Project One has now confirmed its layout and foundations, these have been carried into the assessment to provide a more realistic assessment. Given the project has now commenced construction, the confirmed layout and foundations for Hornsea Project One are referred to throughout as the 'final approved' definition of the project.

A.3.2.8 The wave height attenuation rates (Ra) used for each wind farm in conjunction with the different directional 50% non-exceedance return period conditions was objectively determined as the calibrated attenuation rate for Hornsea Project One and Hornsea Project Two (for each directional return period condition) scaled by the ratio of the previous and new mean blockage density ([equivalent monopile diameter x foundation number] / site area), as follows:

- Hornsea Three – for a lower density of gravity base foundations of slightly smaller dimensions in Hornsea Three, the adjustment ratio is ([29.4 m x 319 foundations] / 696 $km^2$) / ([32.9 m x 332+360 foundations] / 407+462 $km^2$) = 0.514;

- Hornsea Project One (final approved) - for a smaller number of smaller monopile foundations in Hornsea Project One, the adjustment ratio is ([8.1 m x 174 foundations] / 407 km$^2$) / ([32.9 m x 332 foundations] / 407 km$^2$) = 0.129; and
- Hornsea Project Two (as consented) – There is no change in the assumed foundation density, dimensions, or overall blockage density. The adjustment ratio is ([32.9 m x 360 foundations] / 462 km$^2$) / ([32.9 m x 360 foundations] / 462 km$^2$) = 1.

A.3.2.9 The resulting values of Ra are also shown in Table A.2. The same coefficient of wave height recovery (Cb) is used in all cases.

## A.4 Model validation

A.4.1.1 The rule based model results are validated in several ways:

- The simulated patterns of wave height reduction from the rule based model are validated by direct comparison to the results of the previous SWAN cumulative Hornsea Project One and Hornsea Project Two spectral wave modelling (described below).
- A new (MIKE21 SW) spectral wave model has been developed and separately validated against the previous cumulative Hornsea Project One and Hornsea Project Two SWAN spectral wave modelling (described in Appendix B). In Section B.5, the rule based model is also validated by comparison with the results of the new MIKE21SW wave model for:
    - The previous cumulative Hornsea Project One and Hornsea Project Two spectral wave modelling scenario;
    - The maximum design scenario for Hornsea Three (in isolation); and
    - Hornsea Three, Hornsea Project One (final approved) and Hornsea Project Two (as consented).

A.4.1.2 The simulated patterns of wave height reduction from the rule based model are validated by comparison to the results of the previous cumulative Hornsea Project One and Hornsea Project Two spectral wave modelling in Figure A.1 to Figure A.5. The figures provide a like-for-like visual comparison of the pattern of wave height reduction predicted by the previous spectral modelling and the calibrated rule based model. Contours of wave height reduction from the rule based model are superimposed onto the spectral model results to enable direct spatial comparison. For each directional scenario, the previously modelled baseline wave height map is also reproduced for information. A scatter plot comparison of the results is also provided.

A.4.1.3 The figures show that the rule based model provides a close representation of the main features of the cumulative influence of the Hornsea Project One and Hornsea Project Two wind farms on wave height, including:

- The rate and pattern of wave height reduction within the array areas;
- The maximum magnitude of wave height reduction in the array areas; and
- The rate and pattern of wave height recovery outside of the array areas, from the local maxima immediately downwind, to magnitudes of -5%.

A.4.1.4 The scatter plots collectively demonstrate that the rule based model reproduces the results of the spectral wave model to an accuracy of ±2.5% or better, for all wave direction scenarios. The rule based model is therefore validated to provide a similar assessment of impacts on wave height for the consented version of Hornsea Project One and Hornsea Project Two wind farms.

A.4.1.5 The extent of very small magnitudes of wave height reduction (less than 5%, i.e. the position of the 2.5% contour) is generally well represented by the rule based model but is somewhat more detailed in the previous spectral wave model results. This is likely due to the additional detail of local wave processes accounted for in the spectral model, e.g. influence of relatively shallower water depth in the nearshore, rates of wind-wave energy transfer, etc. By also accounting for the additional extent of wave height reduction up to -1.5%, the results of the rule based model can also provide a conservative indication of the spatial extent of very small magnitude impacts on wave height at adjacent coastlines.

A.4.1.6 Comparison of the new MIKE21SW and rule based model scheme impact results in Section B.5 demonstrates that the two model types produce a very similar prediction of the magnitude and extent of scheme effects on wave height due to the effect of Hornsea Three alone and in combination with other wind farms.

A.4.1.7 The rule based model is therefore validated for use in the assessment of impacts on wave height for Hornsea Three both alone and in combination with the final approved version of Hornsea Project One and the consented version of Hornsea Project Two wind farms.

## A.5 References

SMart Wind. (2015a). Hornsea Round 3 Offshore Wind Farm. Project Two Environmental Statement: Vol 2 – Chapter 1 Marine Processes. PINS Document Reference 7.2.1.

SMart Wind. (2015b). Hornsea Round 3 Offshore Wind Farm. Project Two Environmental Statement: Vol 5 – Offshore Annexes. Annex 5.1.2 Wave Modelling.

SMart Wind. (2013). Hornsea Round 3 Offshore Wind Farm. Project One Environmental Statement: Vol 2 – Chapter 1 Marine Processes. PINS Document Reference 7.2.1.

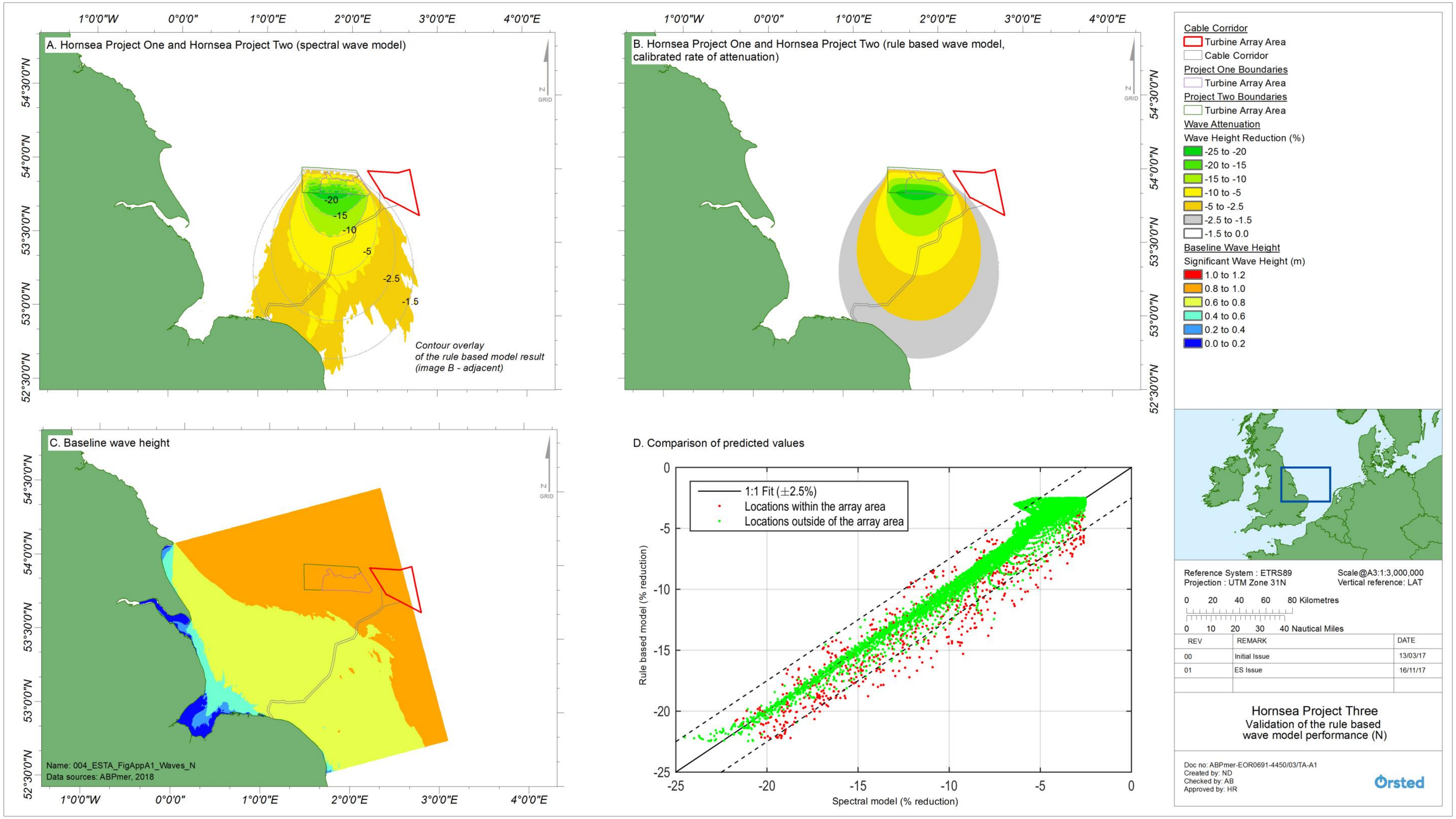



**Figure A.1:** Validation of the rule based wave model performance, 50% no exceedance, wave direction North. Percentage difference in significant wave height between baseline and both the Hornsea Project One and Hornsea Project Two operational phases for (a) previous spectral wave model results and (b) calibrated rule based wave model results; (c) Baseline significant wave height; and (d) scatter plot comparison of results from the previous spectral wave model and the calibrated rule based wave model.

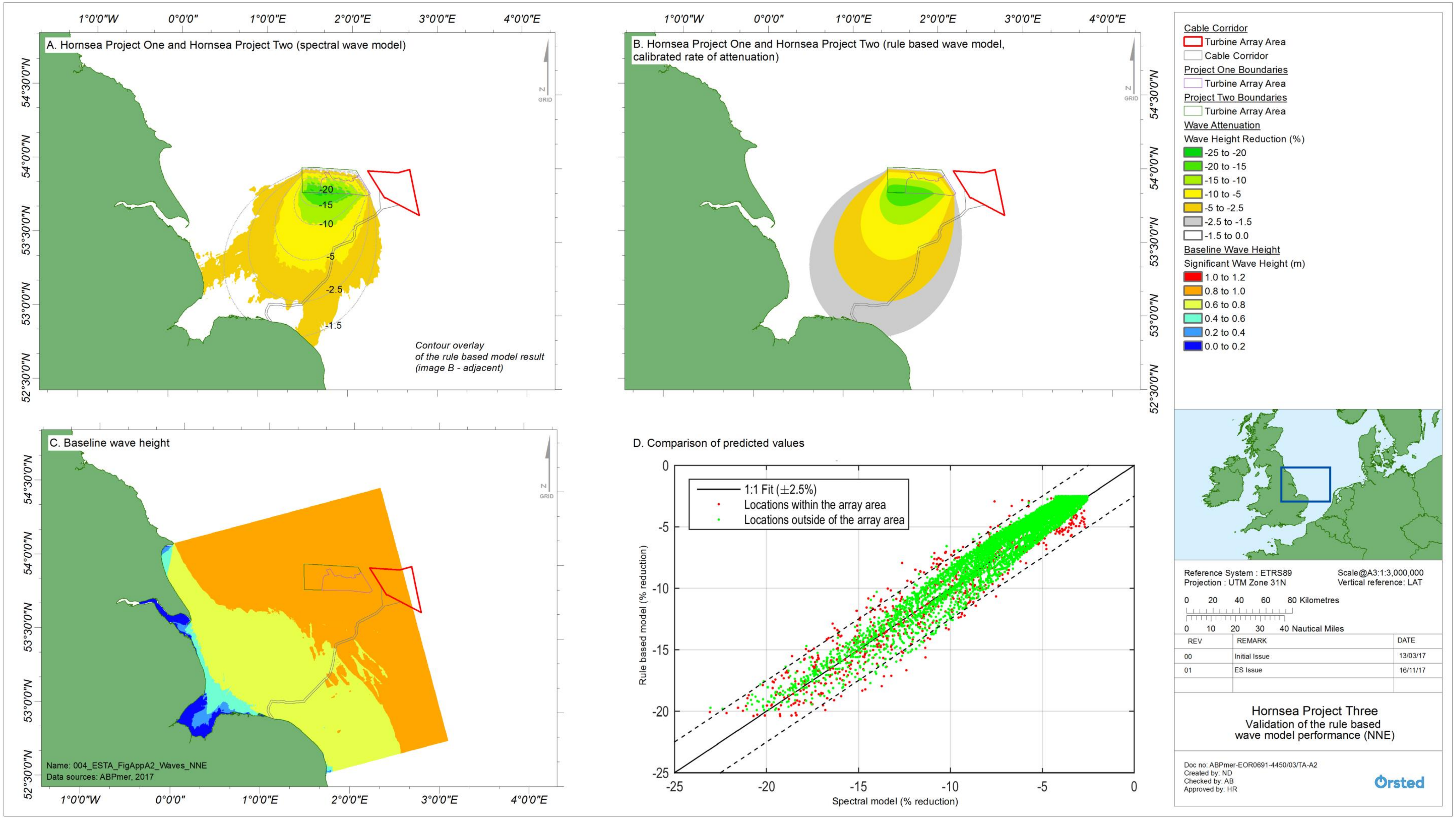



**Figure A.2: Validation of the rule based wave model performance, 50% no exceedance, wave direction North-northeast. Percentage difference in significant wave height between baseline and both the Hornsea Project One and Hornsea Project Two operational phases for (a) previous spectral wave model results and (b) calibrated rule based wave model results; (c) Baseline significant wave height; and (d) scatter plot comparison of results from the previous spectral wave model and the calibrated rule based wave model.**

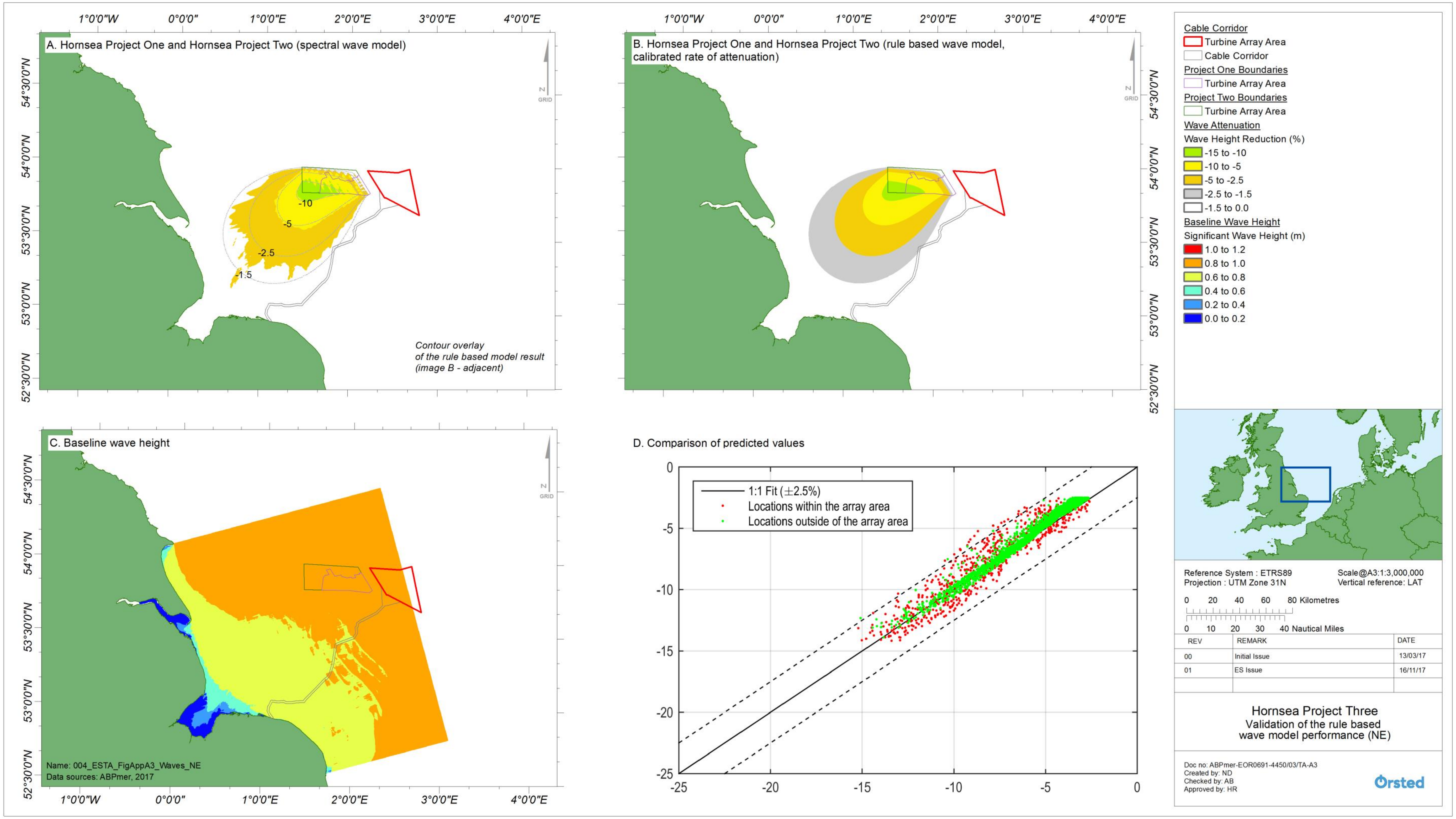



**Figure A.3: Validation of the rule based wave model performance, 50% no exceedance, wave direction Northeast. Percentage difference in significant wave height between baseline and both the Hornsea Project One and Hornsea Project Two operational phases for (a) previous spectral wave model results and (b) calibrated rule based wave model results; (c) Baseline significant wave height; and (d) scatter plot comparison of results from the previous spectral wave model and the calibrated rule based wave model.**

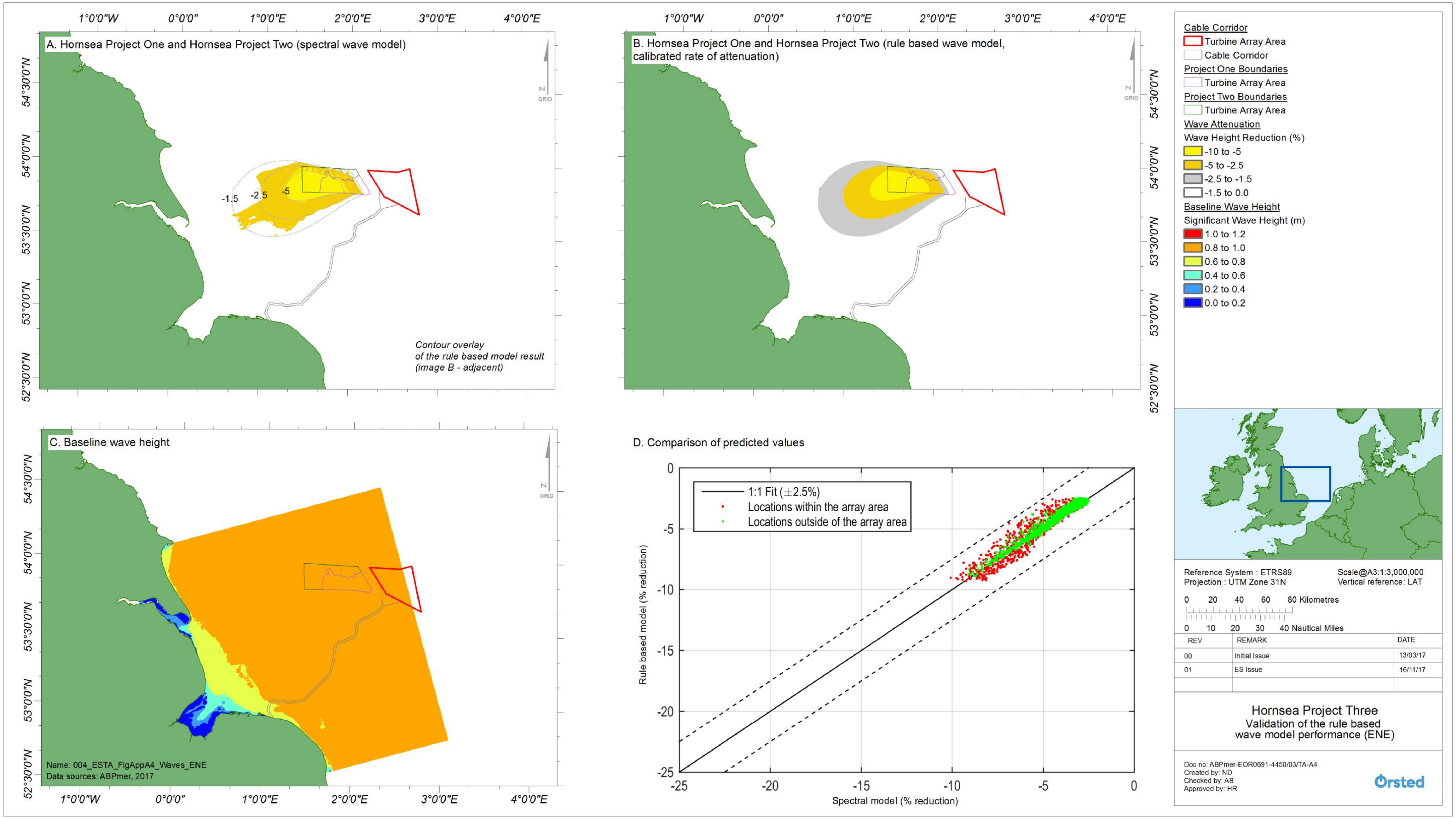



**Figure A.4: Validation of the rule based wave model performance, 50% no exceedance, wave direction East-northeast. Percentage difference in significant wave height between baseline and both the Hornsea Project One and Hornsea Project Two operational phases for (a) previous spectral wave model results and (b) calibrated rule based wave model results; (c) Baseline significant wave height; and (d) scatter plot comparison of results from the previous spectral wave model and the calibrated rule based wave model.**

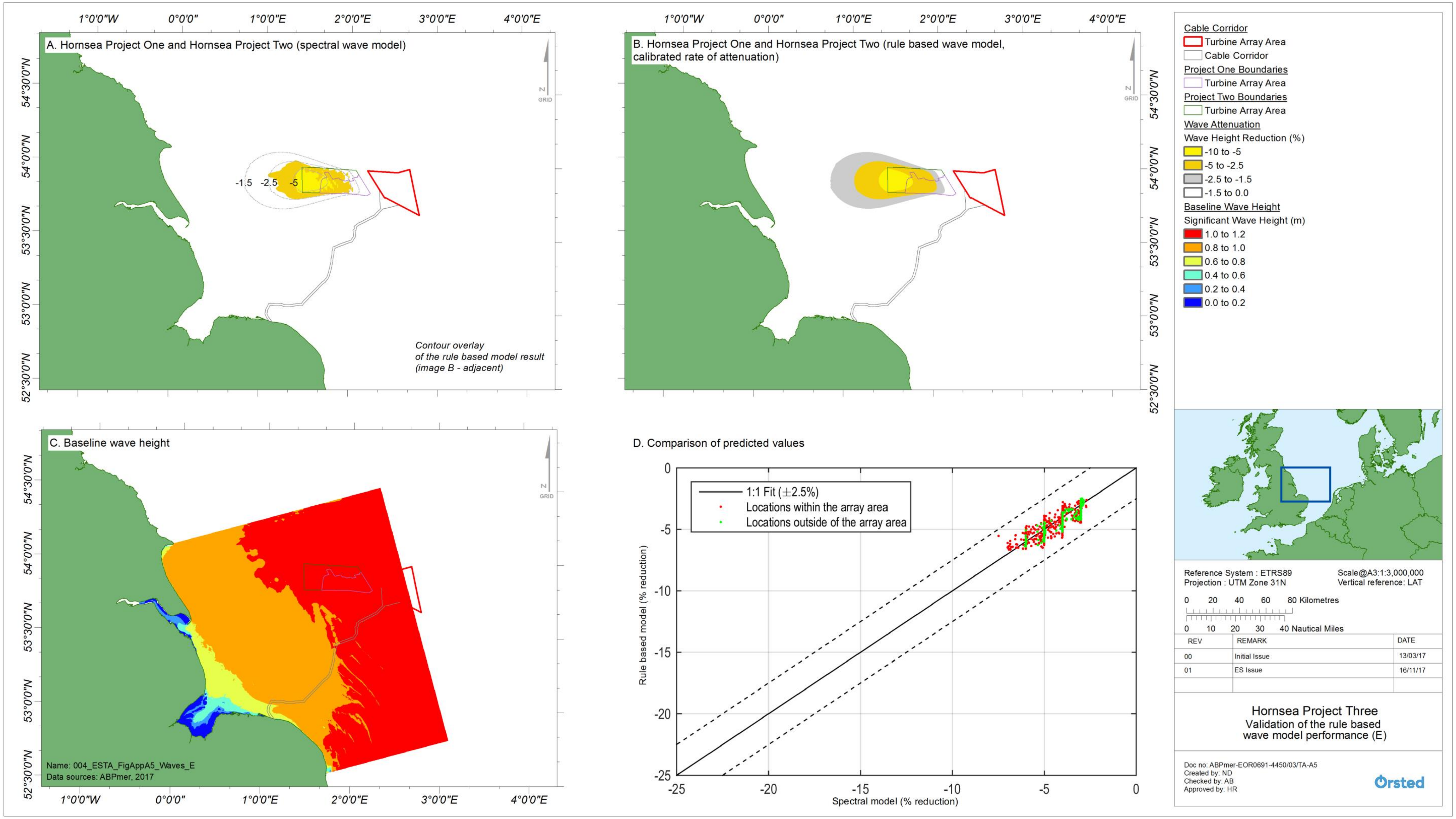



**Figure A.5: Validation of the rule based wave model performance, 50% no exceedance, wave direction East. Percentage difference in significant wave height between baseline and both the Hornsea Project One and Hornsea Project Two operational phases for (a) previous spectral wave model results and (b) calibrated rule based wave model results; (c) Baseline significant wave height; and (d) scatter plot comparison of results from the previous spectral wave model and the calibrated rule based wave model.**

# Appendix B Spectral Wave Modelling

## B.1 Introduction

### B.1.1 Overview

B.1.1.1 This technical appendix provides a description of the set-up, calibration and validation of a new spectral wave model used to simulate the potential impact of wind farm foundations on waves passing through the array area and onwards to designated offshore areas and adjacent coastlines. This appendix then details how this wave model has been used to validate the 'rule based' wave model used within the main wave assessment.

B.1.1.2 The new spectral wave model is calibrated and validated with respect to similar modelling previously undertaken for the assessment of Hornsea Project One and Hornsea Project Two wind farms. The new model scenarios consider the potential impacts of Hornsea Three, both on its own and in conjunction with the final approved design of Hornsea Project One and the consented design of Hornsea Project Two.

B.1.1.3 Hornsea Project One and Hornsea Project Two wind farms were identified for explicit assessment of potential cumulative effects on waves with Hornsea Three due to their close proximity, their location relative to each other and the adjacent coastlines, and their proposed foundation design (i.e. Hornsea Project Two is consented with gravity base foundations). Other wind farms in the wider region are considered within the cumulative effects assessment presented within volume 2, chapter 1: Marine Processes, but not explicitly included in the cumulative wave modelling assessment as they are either comparatively small, constructed using much smaller profile monopile foundations, or are not aligned with Hornsea Three in relation to adjacent coastlines, and are therefore very unlikely to measurably contribute to cumulative effects on waves.

B.1.1.4 The results of the new spectral wave modelling validate the results of the rule based wave model (described in Appendix A of this report) as a suitable tool for the assessment of potential effects on waves. The results of the rule based wave model are in turn used to inform the marine processes assessments presented in volume 2, chapter 1: Marine Processes.

### B.1.2 Wave Modelling

B.1.2.1 A numerical model has been built using the spectral wave module (MIKE21SW) of the MIKE by DHI environmental modelling software package from the Danish Hydraulic Institute (DHI). MIKE by DHI is a commercial standard product for use in complex applications within oceanographic, coastal and estuarine environments. MIKE21SW is a third generation spectral wave model based on unstructured mesh which simulates the growth, decay and propagation of the swell and wind generated waves in offshore and coastal areas.

B.1.2.2 Hornsea Project One and Hornsea Project Two (both alone and in combination) have previously been modelled by HR Wallingford (HRW) using a calibrated SWAN (Simulating WAves Nearshore) spectral wave model. The exact format of the original SWAN model (described in SMart Wind, 2013) was not used directly in the present study as it would also have required updates to assess the design of Hornsea Three and the final approved design of Hornsea Project One. For consistency, the MIKE21SW model developed here utilises the same model extent, bathymetry, most setup parameters and baseline scenario definitions as the previous SWAN model. The new MIKE21SW model is also then calibrated and validated against the baseline and scheme impact results from the previous SWAN model.

B.1.2.3 This appendix provides a description of the MIKE21SW wave model developed to inform the assessment of Hornsea Three (see Section B.2). Details are provided of the validation process that was undertaken to demonstrate that the MIKE21SW wave model can accurately reproduce representative baseline and scheme effect simulations, consistent with previous studies (see Section B.3). Additional model outputs are also provided describing the effect of Hornsea Project Three, both alone and in combination with Hornsea Project One and Hornsea Project Two (See Section B.4). The further validation of the rule based with reference to the new MIKE21SW wave model outputs is presented in Section B.5.

## B.2 MIKE21SW Spectral Wave Model Configuration

B.2.1.1 The following description of the new MIKE21SW wave model setup provides a summary of the key parameters and choices made relevant to the present study. For more detailed information about the mathematical basis of the model, or the available user options, please refer to the associated documentation (DHI, 2016a,b), available from the MIKE by DHI software website (www.mikepoweredbydhi.com/).

### B.2.2 Mesh Design

***Mesh extent***

B.2.2.1 For consistency, the MIKE21SW model extent (shown in Figure B.1), is the same as that used in the previously developed SWAN model, incorporating more than 50,000 km$^2$ of the southern North Sea. The projection and coordinate system used is WGS84 UTM Zone 31N.

B.2.2.2 The model domain extends from Whitby on the North Yorkshire coast, east-northeast offshore to Dogger Bank, south-southeast to Brown Ridge and back to the Suffolk coast around Ipswich. The coastline within the model domain includes all parts of the Norfolk coastline, the Wash, the Humber Estuary and the Holderness coastline with an aspect facing Hornsea Three.

B.2.2.3 As with previous modelling studies, only wave scenarios coming from north through to east are considered in this study, as these are the only conditions likely to potentially result in a measurable effect on wave heights at adjacent coastlines after passing through the Former Hornsea Zone. The extent of the mesh (and the distribution of mesh resolution within it, described below) is therefore optimised for the simulation of these wave conditions and potential impacts.

***Mesh resolution***

B.2.2.4 A flexible mesh design is used (as shown in Figure B.1), i.e. the mesh comprises a series of interlocking triangular elements of varying size. A nominal mesh resolution (typical distance between element centers) of 500 m is used within an area encompassing Hornsea Three, Hornsea Project One and Hornsea Project Two, i.e. slightly larger than the former Hornsea Zone. An 'intermediate' resolution of 1 km is used between the former Hornsea Zone and the adjacent coastlines, i.e. in the direction that any impacts on wave height are anticipated to extend. For efficiency, a coarser resolution of 2 km is used in areas 'upwind' of the wind farm (for the range of conditions being simulated) which are therefore not expected to experience or need to resolve any impacts on wave height.

B.2.2.5 The finest resolution of 500 m in the former Hornsea Zone (in and around the wind farm array areas) provides at least one mesh element separation between the elements containing the individual foundations in the wind farms and is sufficient to resolve the progressive development of the array scale blockage effect (i.e. the combined effect of all the individual foundations at the scale of the whole array area) (see Section B.2.4 for more information about the simulation of the blockage effect from structures). The relatively coarser resolution of 1 km used elsewhere downwind of the array area is similarly sufficient to resolve the transmission and recovery of the array scale effects on wave height in the far field.

B.2.2.6 Sensitivity tests were undertaken using higher resolutions of 200 m, 500 m and 1 km in the former Hornsea Zone, 'intermediate' and 'upwind' areas, respectively. The higher resolution model presented practical difficulties in relation to model run time and stability, but showed no significant difference or improvement in either the accuracy of the baseline wave simulation, or the spatial patterns or magnitude of effect on wave height due to scheme effects.

B.2.2.7 In comparison, the previous SWAN modelling used a regular grid layout with a 200 m resolution in most areas and a 1 km resolution in offshore/upwind areas. The different (flexible mesh) approach and (relatively coarser) resolution of the new MIKE21SW wave model is not considered to be a limitation or weakness and it is demonstrated (in Section B.3) that the SWAN and MIKE21SW models produce very similar results in terms of both the magnitude and spatial patterns of baseline wave conditions and potential scheme effects.

B.2.2.8 The model land boundary to the west is defined by the coastline (approximating the location of mean high water springs). There are three open offshore boundaries in the model (on the northern, eastern and southern edges of the model domain) at which pre-determined return period wave conditions are applied, explained further in Section 2.3.2.

***Mesh bathymetry***

B.2.2.9 For consistency, the gridded bathymetry of the previous SWAN model was interpolated directly onto the MIKE21SW wave model grid using a natural neighbour method (a method of spatial interpolation where surrounding data values are weighted according to their relative distribution and distance from the new location of interest). The resulting distribution of interpolated bathymetry is shown in Figure B.1. All bathymetry in the mesh is referenced to Mean Sea Level (MSL).

B.2.2.10 The original bathymetry comprised regional scale data 'based on existing bathymetry files held by HRW that cover almost the entirety of the North Sea and the English Channel'. In addition, bathymetric survey data of the Hornsea Project One and array area (EMU, 2011) and the cable route close to the entrance to The Humber (Fugro, 2011) were also used.

B.2.2.11 The model bathymetry has been compared to the regional and site specific bathymetry data sets presently available to this study for Hornsea Three. No consistent large differences were found within or around the Hornsea Three array area and so the model bathymetry is used without adjustment.

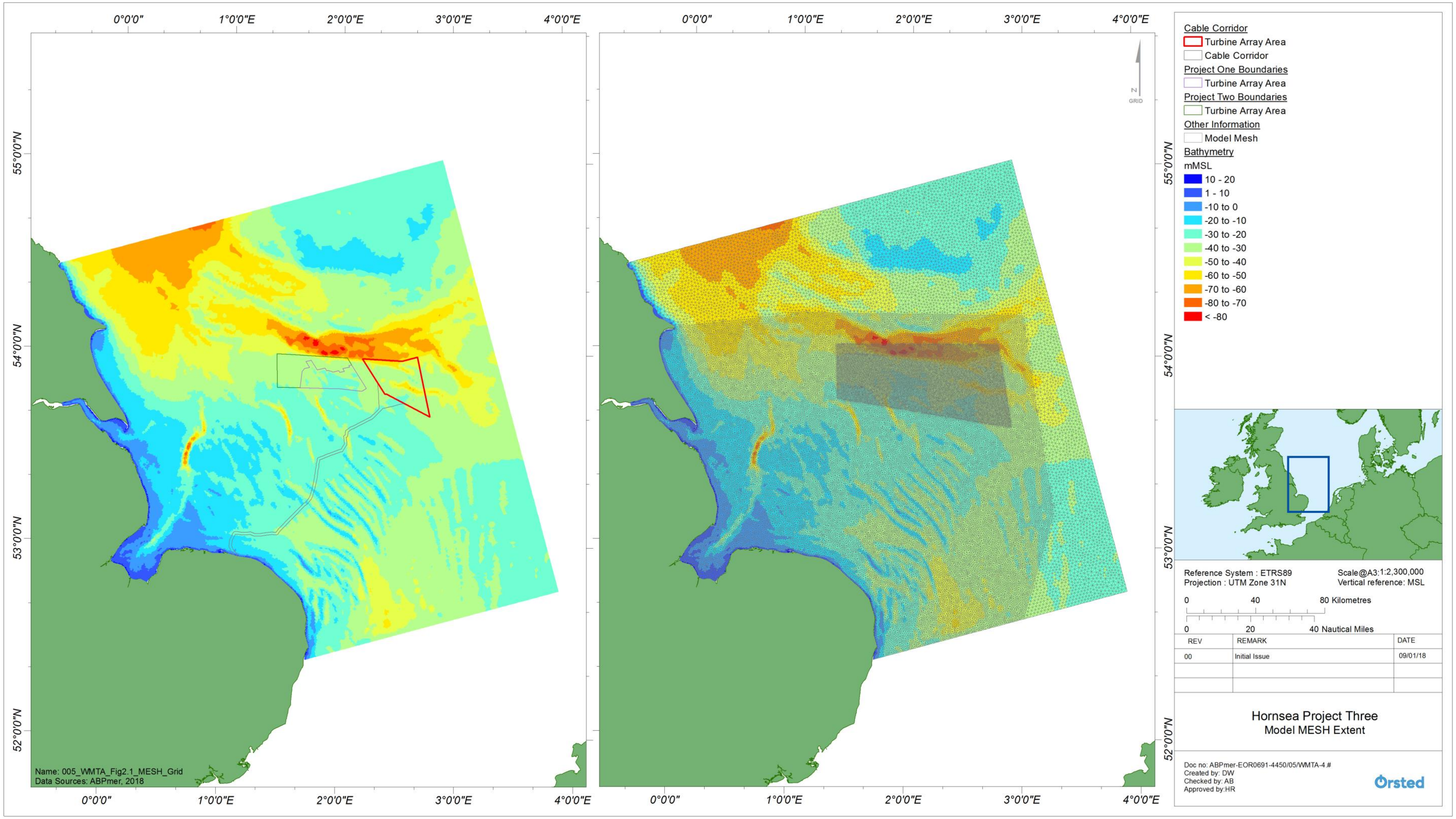



**Figure B.1: MIKE21SW Model mesh extent, resolution and bathymetry.**

## B.2.3 Baseline Model Setup Parameters

B.2.3.1 As waves propagate from the open boundaries throughout the model domain, the local seastate changes in terms of wave height, period, and direction distribution due to the combined spatially integrated influence of wind forcing, refraction, shoaling, bottom friction and wave breaking. The following sections present the choices of key parameters used, affecting these properties of the MIKE21SW wave model.

***Spectral and time formulations***

B.2.3.2 A fully spectral formulation is used. The fully spectral formulation is based on a wave action conservation relationship where the directional-frequency wave action spectrum is the dependent variable. Of the available choices, this formulation is the most appropriate for the relatively large domain being modelled.

B.2.3.3 A quasi-stationary time formulation is used. Time is removed as an independent variable and a steady state solution is calculated at each time step (in this case corresponding to each directional return period wave condition).

B.2.3.4 A logarithmic distribution of 25 spectral frequencies are resolved, equivalent to wave periods in the approximate range from 1.8 to 18 s with smaller intervals at smaller wave periods (this is the default setting).

B.2.3.5 Directional calculations are made using 32 directional sectors (11.25°). This is more than the default number (16 directional sectors, 22.5°) in order to reduce the occurrence of small magnitude 'radial artefacts' in the scheme effect results. The baseline wave maps are largely unaffected by the difference.

B.2.3.6 Based on the available descriptions of model setup and the good level of agreement in results, the original SWAN modelling was likely also undertaken using a similar fully spectral quasi-stationary approach and related frequency and directional parameterisation.

***Wave and wind boundary conditions***

B.2.3.7 The model is driven by wave forcing at the three offshore wave boundaries at the north, east and south extent of the model grid, and a wind field forcing over the whole domain. The wave and wind boundary conditions used in the MIKE21SW wave model are the same as those applied in the previous SWAN model (with only minor adjustment of wind speed to optimise results) and were derived by HRW from analysis of a long timeseries of hindcast offshore wave and wind conditions from the UK Met Office (UKMO) European Wave Model (described in SMart Wind, 2013 and 2015). The data and methods used in the original determination of baseline boundary conditions by HRW has been reviewed and found to remain suitable for application in the new MIKE21SW wave model.

B.2.3.8 Directional spectral wave conditions are applied uniformly along the three offshore wave boundaries, defined by significant wave height (Hs), peak wave period (Tp), mean wave direction and directional standard deviation (DSD). The directional return period values of Hs, Tp and mean wave direction used are shown in Table B.1 As would be expected, the values are different for each coming direction and return period. The DSD value used in the previous SWAN modelling was not explicitly reported; a value of 23.3° (corresponding to the suggested default value in MIKE21SW) was therefore used for all scenarios in the MIKE21SW wave model.

B.2.3.9 Wind boundary conditions are applied uniformly across the whole domain area. The directional return period values of wind speed (at 10 m above sea level) and direction used are shown in Table B.1. In order to fully optimise the comparison between the SWAN and MIKE21SW directional return period baseline condition results (due to small differences in the underlying details of the modelling packages), wind speed inputs (only) were modified slightly (in the range ±5%) from the originally used values.

**Table B.1: Wave and wind boundary conditions for each of the tested directional return period condition.**

| Directional Sector | Case (Return Period) | Significant Wave Height (Hs, m) | Peak Wave Period (Tp, s) | Mean Wave Direction (degN) | Wind Speed @10 m (m/s) | Wind Direction (deg N) |
|---|---|---|---|---|---|---|
| N | 50% no exc | 1.1 | 5 | 0 | 4.32 | 0 |
| | 0.1 yr RP | 2.9 | 8.1 | 0 | 10.40 | 0 |
| | 1 yr RP | 4.15 | 9.6 | 0 | 16.06 | 0 |
| | 10 yr RP | 5.39 | 11 | 0 | 21.68 | 0 |
| | 50 yr RP | 6.23 | 11.8 | 0 | 24.50 | 0 |
| | 100 yr RP | 6.58 | 12.2 | 0 | 25.77 | 0 |
| NNE | 50% no exc | 1.1 | 5 | 22.5 | 4.52 | 22.5 |
| | 0.1 yr RP | 2.4 | 7.4 | 22.5 | 9.52 | 22.5 |
| | 1 yr RP | 3.91 | 9.4 | 22.5 | 17.17 | 22.5 |
| | 10 yr RP | 5.35 | 11 | 22.5 | 23.24 | 22.5 |
| | 50 yr RP | 6.34 | 11.9 | 22.5 | 26.30 | 22.5 |
| | 100 yr RP | 6.76 | 12.3 | 22.5 | 27.19 | 22.5 |
| NE | 50% no exc | 1.1 | 5 | 45 | 4.15 | 45 |
| | 0.1 yr RP | 2.7 | 7.9 | 45 | 10.74 | 45 |
| | 1 yr RP | 4 | 9.6 | 45 | 17.53 | 45 |

| Directional Sector | Case (Return Period) | Significant Wave Height (Hs, m) | Peak Wave Period (Tp, s) | Mean Wave Direction (degN) | Wind Speed @10 m (m/s) | Wind Direction (deg N) |
|---|---|---|---|---|---|---|
| | 10 yr RP | 5.05 | 10.7 | 45 | 22.12 | 45 |
| | 50 yr RP | 5.67 | 11.4 | 45 | 23.96 | 45 |
| | 100 yr RP | 5.92 | 11.6 | 45 | 24.79 | 45 |
| ENE | 50% no exc | 1.2 | 5.2 | 67.5 | 5.00 | 67.5 |
| | 0.1 yr RP | 2.9 | 8.1 | 67.5 | 9.61 | 67.5 |
| | 1 yr RP | 4.72 | 10.4 | 67.5 | 14.69 | 67.5 |
| | 10 yr RP | 6.21 | 11.9 | 67.5 | 18.41 | 67.5 |
| | 50 yr RP | 7.16 | 12.8 | 67.5 | 20.20 | 67.5 |
| | 100 yr RP | 7.56 | 13.1 | 67.5 | 20.86 | 67.5 |
| E | 50% no exc | 1.3 | 5.4 | 90 | 6.02 | 90 |
| | 0.1 yr RP | 3.2 | 8.5 | 90 | 11.24 | 90 |
| | 1 yr RP | 4.69 | 10.3 | 90 | 17.46 | 90 |
| | 10 yr RP | 5.91 | 11.6 | 90 | 22.14 | 90 |
| | 50 yr RP | 6.66 | 12.3 | 90 | 24.50 | 90 |
| | 100 yr RP | 6.96 | 12.5 | 90 | 25.43 | 90 |

B.2.3.10 The presence of a sufficiently high concentration of sea ice could affect the transfer of wind energy to the water surface and therefore patterns of wave growth and propagation. No sea ice is simulated in the present study.

***Wave breaking, bottom friction and other wave transformation parameters***

B.2.3.11 Wave breaking and bottom friction coefficients were varied from the default settings in order to achieve consistency in setup and results in comparison to the previous SWAN model.

B.2.3.12 Depth-induced wave breaking is the process by which waves dissipate energy when the waves are too high to be supported by the water depth, i.e. reach a limiting wave height/depth-ratio. Wave breaking is described in both SWAN and MIKE21SW by standard equations that are scaled by a coefficient 'Gamma'. A constant Gamma value of 0.73 was used; the same value was used in the previous SWAN modelling.

B.2.3.13 Bottom friction is relevant where, as waves propagate into shallow water, the orbital wave velocities penetrate throughout the full water depth and the source function due to wave-bottom interaction becomes important. A large part of the model domain (towards the adjacent coastlines) is shallow enough relative to the waves being simulated to be affected by choices relating to the implementation of bottom friction. The dissipation source function used in the spectral wave module is based on the quadratic friction law and linear wave kinematic theory. The dissipation coefficient depends on the hydrodynamic and sediment conditions. The settings used in the previous SWAN modelling were not explicitly reported. Sediment roughness is characterised in the MIKE21SW wave model by the Nikuradse Roughness length and the distribution of baseline wave heights in the domain was optimised in comparison to the results of the previous SWAN wave model by using a value of 0.01 m.

B.2.3.14 The MIKE21SW wave model also takes account of the following wave transformation processes (using default settings):

- White capping (Dissipation coefficients, constant Cdis = 4.5, constant DELTAdis = 0.5);
- Quadruplet-wave interaction (included); and
- Triad-wave interaction (not included).

***Currents and water levels***

B.2.3.15 The potential effects of spatial and temporally varying currents and water levels are not explicitly tested, but are considered likely to cause only minor deviation from the (no current, mean water level) conditions modelled.

### B.2.4 Scheme Representation of Wind Farm Foundations

B.2.4.1 As waves pass through a wind farm array area, they interact with the foundations of the wind turbines and other infrastructure. In practice, individual foundations will block or absorb wave energy through a combination of local wave reflection, wave breaking and friction. The exact mechanisms and proportion of wave energy affected will vary depending on the dimensions of the foundation and the length and height of the individual waves present.

***Previous ARTEMIS and SWAN wave models***

B.2.4.2 The combined influence of the wind farm foundations was initially computed for local array areas within Hornsea Project One and Hornsea Project Two using the ARTEMIS wave modelling software (SMart Wind, 2013; 2015). The ARTEMIS modelling approach is relatively spatially detailed and can be better suited than a spectral wave model approach to the detailed simulation of the scattering and blockage caused by obstacles to individual waves in a given seastate. Models such as ARTEMIS are used in conjunction with spectral model types such as SWAN to provide a description of the effect of obstacles that are smaller than the grid resolution of the spectral model. Other methods may be used by other modelling software or approaches, e.g. in MIKE21SW, the planned distribution of individual structures with an equivalent monopile diameter are included directly in the spectral wave model simulation (see paragraph B.2.4.8 onwards).

B.2.4.3 Indicative foundation layouts were created for the consented maximum adverse scenarios for Hornsea Project One (332 turbines) and for Hornsea Project Two (360 turbines) as described in SMart Wind (2013 and 2015). The ARTEMIS model considered the effect of various characteristic local layout orientations and densities from these indicative layouts, on waves of varying height and period, within a range of characteristic spectral seastates.

B.2.4.4 The realistic worst case foundation tested by the previous modelling was a gravity base foundations, described as a large solid conical structure with a base diameter of 50 m at the seabed, tapering gradually to an upper pylon diameter of 15 m at the water surface. The blockage presented by the individual gravity base foundations represented in the ARTEMIS software is rather described as an ‘equivalent monopile diameter’, which is the diameter of a cylindrical obstacle with uniform diameter from the seabed to the water surface, that would produce the same overall drag force as the gravity base foundation. SMart Wind (2013) states an equivalent monopile diameter of 32.9 m is used.

B.2.4.5 The relatively high-resolution ARTEMIS model is only suitable for local-scale applications and cannot be practicably applied at the scale of the whole wind farm array area, or to model the recovery of waves in the far field. The ARTEMIS model results were, therefore, used to determine a rate of wave energy transmission / attenuation caused by small groups of foundations.

B.2.4.6 The resulting ‘transmission coefficient’ was then applied as a series of partially transmissive walls within the array area in a lower-resolution regional-scale SWAN spectral wave model to represent the sub grid-scale influence of the same foundation type and layout density.

B.2.4.7 The degree to which an individual wave will interact with an obstacle of finite width depends on the ratio of the obstacle width and the wave length. A wave that is very long in comparison to the width of the obstacle will experience relatively little resistance other than friction due to the orbital motion of the water; in this case, energy loss is minimal and the transmission coefficient is high. A wave that is short in comparison to the width of the obstacle is more likely to result in wave breaking or wave reflection from the face of the obstacle, resulting in greater energy loss (within the width of the obstacle) and a lower transmission coefficient. The ARTEMIS modelling considered a range of directional return period conditions where the wave period (and therefore the wave length) varies in relation to the fixed obstacle width. As a result, the transmission coefficient used and the resulting relative array scale effect on wave height also varied by direction and return period.

***New MIKE21SW wave model***

B.2.4.8 Blockage due to individual foundations is simulated directly within the MIKE21SW wave model as ‘cylindrical pier’ point structures. The location and diameter of discrete obstacle(s) is included in the model setup.

B.2.4.9 Wave energy is removed from elements containing obstacles through the use of a transmission coefficient which is determined locally based on the diameter of the obstacle as a proportion of the width of the mesh element. This method conservatively assumes that the wave experiences full blockage within the width of the obstacle (i.e. irrespective of the wavelength to obstacle width ratio for individual waves).

B.2.4.10 The maximum adverse scenario for potential effects on waves by Hornsea Three is the greatest total blockage presented by foundations within the Hornsea Three array area. The maximum total blockage is associated with the largest number of gravity base foundations for turbines (up to 300 at 43 m diameter) and offshore accommodation platforms (up to three 41 m diameter) and the largest dimensions of gravity base foundation for offshore HVAC collector substations (up to 12 at 75 m length scale) and offshore HVDC converter substations (up to four 75 m length scale) in the array area. An indicative layout for these 319 foundations in Hornsea Three is used to realistically describe the potential distribution of gravity base foundations within the Hornsea Three array area. The equivalent monopile diameter for the associated gravity base foundation (base diameter 43 m, pylon diameter 15 m) is calculated to be 29.4 m, which is applied at all 319 locations.

B.2.4.11 For cumulative scenario assessments, the final approved layout for the smaller number of smaller monopile foundations being built in Hornsea Project One (174 turbines with monopile foundations, diameter 8.1 m), and the consented indicative layout scenarios for the maximum number of gravity base foundations (360 turbines with gravity base foundations, equivalent monopile diameter 32.9 m) in Hornsea Project Two (described in SMart Wind 2015), are used to realistically describe the potential distribution and dimensions of foundations within these array areas.

B.2.4.12 The description of Hornsea Project One to be used in the new cumulative scenario assessment (174 monopiles) is therefore different to (much less blockage than) the scenario modelling for the Hornsea Project One and Hornsea Project Two ES', which assessed Hornsea Project One based on a maximum design scenario of the greatest number of 332 gravity base foundations. However, as Hornsea Project One has now confirmed its layout and foundations, these have been carried into the assessment to provide a more realistic assessment. Given the project has now commenced construction, the confirmed layout and foundations for Hornsea Project One are referred to throughout as the 'final approved' definition of the project.

B.2.4.13 The obstacle diameter that is used in conjunction with different directional 50% non-exceedance return period conditions was objectively determined according to the following principles:

- To calibrate the scheme model (Hornsea Project One and Hornsea Project Two), the MIKE21SW equivalent monopile diameter was initially estimated for each directional return period on the basis of the stated ARTEMIS wave model equivalent monopile diameter and the relative magnitude of the associated SWAN wave model transmission coefficient. This value was then adjusted if needed to further optimise agreement with the available SWAN wave model results;
- The equivalent monopile diameter for each directional return period condition for gravity base foundations of different dimensions in Hornsea Three is determined as the calibrated equivalent monopile diameter for Hornsea Project One and Hornsea Project Two (for each directional return period condition) scaled by the ratio in equivalent monopile diameter (29.4 / 32.9 = 0.907); and
- The equivalent monopile diameter for each directional return period condition for monopile foundations to be built in Hornsea Project One is determined as the calibrated equivalent monopile diameter for Hornsea Project One and Hornsea Project Two (for each directional return period condition) scaled by the ratio in equivalent monopile diameter (8.1 / 32.9 = 0.246).

## B.2.5 Comparison of the processes considered in the previous SWAN and new MIKE21SW wave model

B.2.5.1 A summary of the similarities and differences between the previous SWAN and new MIKE21SW wave model features and processes relevant to the present study is provided in Table B.2. Other processes and features may also be available but are not relevant to the present study (e.g. effect of sea ice coverage or diffraction within harbours).

B.2.5.2 Both the SWAN and MIKE21SW spectral wave models are considered to be well-known, proven, commercial grade software packages, which are commonly and interchangeably used for studies of this kind. The mathematical basis or approach used by each model type may be slightly different in terms of the exact formulations and methods used and the choices available to or made by individual users. However, both modelling packages have been developed to include a range of methods and options that are similarly likely to provide a robust description of the relevant processes, and to provide results within a reasonably expected range of accuracy.

B.2.5.3 The suitability and accuracy of any given model (irrespective of the intended application and the software used) is also dependant on the appropriate design and application of the model by the model operator, including the quantity and quality of data used to build, calibrate and validate the model, and the choice of settings made.

B.2.5.4 Full technical details regarding the range of processes included in each software type may be found in the corresponding scientific documentation (SWAN, www.tudelft.nl; MIKE21SW www.mikepoweredbydhi.com).

**Table B.2: Summary comparison of the previous SWAN and new MIKE21SW wave model features and processes relevant to the present study.**

| Feature / Process | Previous SWAN wave model | New MIKE21SW wave model |
|---|---|---|
| Model software | SWAN, a third generation spectral wave model by Delft University of Technology (TU Delft). | MIKE21FM SW, a third generation spectral wave model by the Danish Hydraulic Institute (DHI). |
| Mesh extent | The same overall mesh extent is used for both models (see Figure B.1). | |
| Mesh resolution | 200 m regular grid for the Hornsea Project One and Hornsea Project Two array areas, extending to most of the adjacent coastlines; 1000 m regular grid in Hornsea Three array area and offshore. | 500 m flexible mesh encompassing the Hornsea Project One, Hornsea Project Two and Hornsea Three array areas; 1000 m flexible mesh to most of the adjacent coastlines; 2000 m flexible mesh in offshore areas (see Figure B.1). |
| Mesh bathymetry | The same bathymetry is used for both models (see Figure B.1). | |
| Spectral discretisation | The exact settings used are not known but are assumed to be similar to those for the MIKE21SW model. The nature of some results suggests that directional calculations are made using 16 equal size directional sectors (22.5°). | A fully spectral formulation is used. A logarithmic distribution of 25 spectral frequencies are resolved. Directional calculations are made using 32 equal size directional sectors (11.25°). |
| Temporal discretisation | The exact settings used are not known but are assumed to be similar to those for the MIKE21SW model. | A quasi-stationary time formulation is used (the results represent the duration independent equilibrium seastate resulting from the given boundary conditions). Sufficient iterations are allowed in order to allow each scenario to converge on a numerically stable solution. |
| Boundary conditions | The same wind and wave boundary conditions are used for both models (see Table B.1). Minor adjustments to the wind speed (<±5%) were made in the MIKE21SW model to optimise agreement in the simulation of baseline wave height patterns within the domain as a whole and in terms of magnitude within the former Hornsea Zone area. | |
| Wave breaking | The same settings are used for both models (a constant Gamma value of 0.73). | |
| Bottom friction | The exact settings used are not known but are assumed to be similar to those for the MIKE21SW model. | A Nikuradse roughness length of 0.01 m was used. |
| White capping | The exact settings used are not known but are assumed to be similar to those for the MIKE21SW model. | Dissipation coefficients: constant Cdis = 4.5; constant DELTAdis = 0.5. |

| Feature / Process | Previous SWAN wave model | New MIKE21SW wave model |
|---|---|---|
| Quadruplet-wave interaction | Included in software, assumed to be used in the simulation. | Included in software and used in the simulation. |
| Triad-wave interaction | Included in software, assumed to be used in the simulation. | Included in software but not used in the simulation as only relevant in shallow water and not considered relevant in the present study. |
| Currents and water levels | The same settings are used for both models (zero current speed and fixed mean sea level throughout the model domain for all scenarios). | |
| Effect of structures | Simulated indirectly as partially transmissive walls. The transmission coefficient for different local layout options and seastates (wave height, period and direction), was determined in advance using a separate ARTEMIS model (see paragraph B.2.4.2 onwards for more details). This method takes account of the reduced blockage effect when the wave length becomes large in comparison to the length scale of the obstacle. | Simulated directly as 'cylindrical pier' point structures. The location and diameter of discrete obstacle(s) is included in the model setup. Wave energy is removed from elements containing obstacles through the use of a transmission coefficient which is determined locally based on the diameter of the obstacle as a proportion of the width of the mesh element. This method conservatively assumes that the wave experiences full blockage within the width of the obstacle (i.e. irrespective of the wavelength to obstacle width ratio for individual waves). |

## B.3 Calibration and Validation

### B.3.1 Baseline

B.3.1.1 The purpose of calibrating and validating the baseline MIKE21SW model is to ensure that it provides a representative basis for the assessment of relative changes in waves. The validation target in the present study is that the new MIKE21SW wave model provides a similar magnitude and pattern of significant wave height to that previously provided by the SWAN wave model for each return period and direction.

B.3.1.2 In order to calibrate the model, the parameters described in Section B.2.3 were systematically and objectively varied in order to identify the response of the model result. The results from the MIKE21SW wave model were compared with previously reported data from the SWAN wave model, including maps of baseline significant wave height for the 50% no-exceedance and 1 year return period wave conditions, and local values at three discrete locations within the Former Hornsea Zone for all return periods and directions. The comparison between the model results was optimised through the use of particular non-default settings as described in Section B.2.3. The following text and figures describe the relative similarity of the models in terms of baseline conditions following calibration.

B.3.1.3 Previously modelled maps of baseline significant wave height for the 50% no-exceedance condition (all directions) were provided in SMart Wind (2015). The underlying data for these maps was obtained and are replicated in Figure B.2, with the original source data extent and colour scale. The corresponding map result from the new MIKE21SW wave model is shown for comparison with the same extent and colour scale. The overall magnitude and patterns of significant wave height are shown to be reproduced with good accuracy for all directions for this return period.

B.3.1.4 Previously modelled maps of baseline significant wave height for the 1 year return period condition (all directions) were provided in SMart Wind (2013). The underlying data for these maps was not available but the images are reproduced in Figure B.7, with the original source data extent and colour scale. The corresponding map result from the new MIKE21SW wave model is shown for comparison with the same extent and colour scale. The overall magnitude and patterns of significant wave height are shown to be reproduced with reasonable accuracy (within tens of centimetres) for all directions for this return period. Apparent differences in the extent of certain wave height categories reflect relatively small differences in absolute wave height of less than 0.5 m, as shown by the following comparison.

B.3.1.5 Metocean data were collected by AWAC (Acoustic Wave And Current) devices at three locations within and near to the Hornsea Project One, Hornsea Project Two and Hornsea Three array areas (see SMart Wind, 2013 and 2015 for more details). The position of these devices is shown in Figure B.2 and Figure B.7. SMart Wind (2013 and 2015) provide tables of the baseline significant wave height from the previous SWAN wave model at these locations for all return periods and directions; these are compared with coincident values from the new MIKE21SW wave model results in Figure B.8. The MIKE21SW wave model is shown to closely replicate the previously modelled baseline significant wave height (typically within ±0.2 m) at these AWAC locations across the full range of return periods and directions modelled.

B.3.1.6 On the basis of the comparisons described above, the new MIKE21SW model is validated to adequately reproduce the magnitude and spatial patterns of baseline significant wave height, as previously reported in SMart Wind (2013 and 2015).

### B.3.2 Scheme (Hornsea Project 1 and Hornsea Project 2)

B.3.2.1 The purpose of calibrating and validating the MIKE21SW scheme model is to ensure that it provides a similar representation of the blockage effect of foundations within the Hornsea Project One and Hornsea Project Two array areas, and therefore a representative basis for the assessment of relative changes in waves that is consistent with the previous SWAN wave modelling. The validation target in the present study is that the new MIKE21SW wave model provides a similar magnitude and pattern of effect on significant wave height to that previously provided by the SWAN wave model, for each return period and direction, for the realistic worst case Hornsea Project One and Hornsea Project Two operational phases as described in the original ES (SMart Wind, 2015).

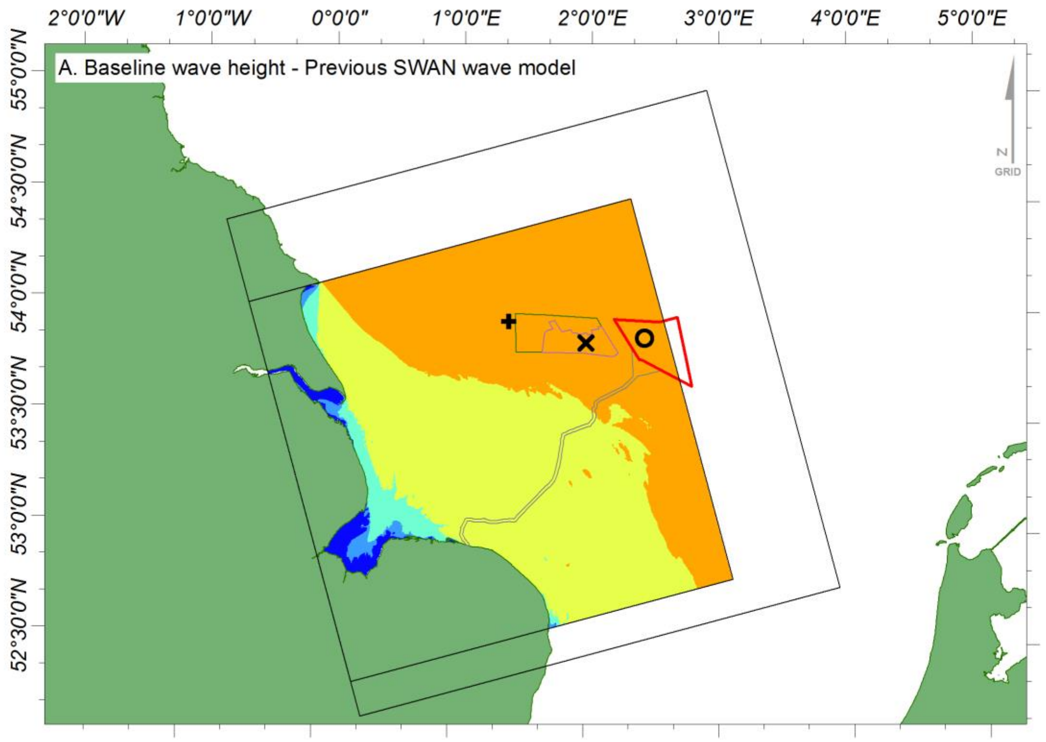
B.3.2.2 In order to calibrate the model, the parameters described in Section B.2.3 were systematically and objectively varied in order to identify the response of the model result. The results from the MIKE21SW wave model were compared with previously reported data from the SWAN wave model, including maps of percentage difference in significant wave height for the 50% no-exceedance condition, and local difference values at the three AWAC locations within the Former Hornsea Zone for all return periods and directions. The comparison between the model results was optimised through the choice of representative monopile diameter, as described in Section B.2.4. The following text and figures describe the relative similarity of the models in terms of scheme effects following calibration.

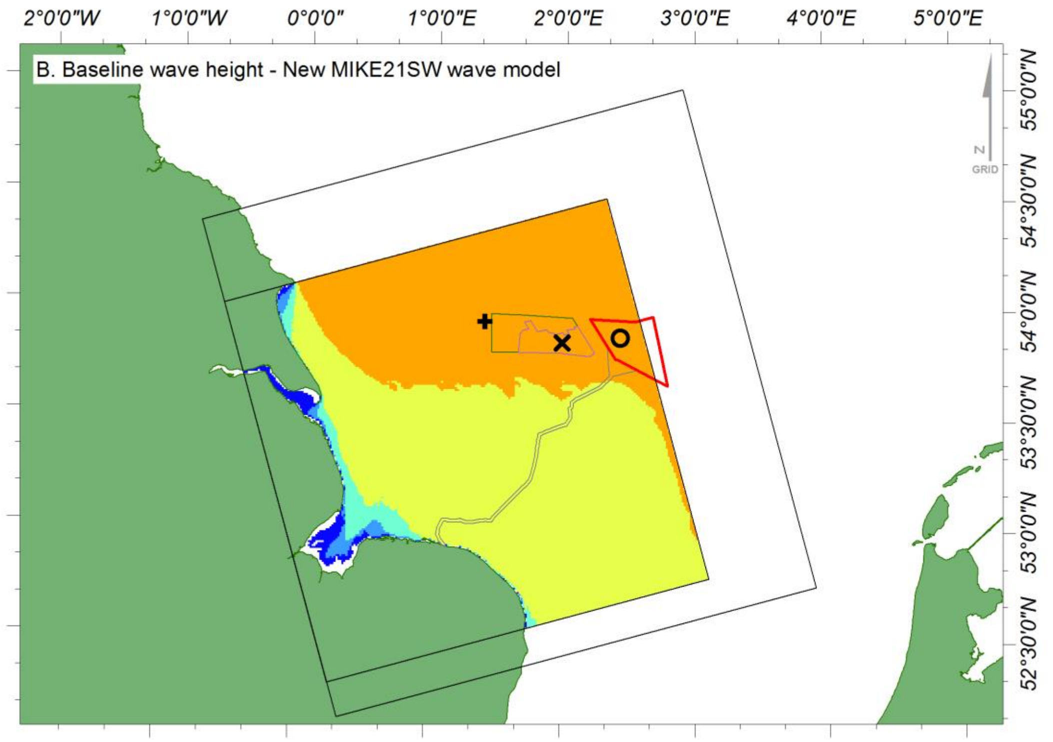
B.3.2.3 Previously modelled maps of percentage difference in significant wave height were provided in SMart Wind (2015). The underlying data for the 50% no-exceedance condition (all directions) maps were obtained and are replicated in Figure B.9 to Figure B.13, with the original source data extent and colour scale. The corresponding map result from the new MIKE21SW wave model is shown for comparison with the same extent and colour scale. The overall magnitude and patterns of difference in significant wave height are quantitatively shown to be reproduced with good accuracy for all directions for this return period.

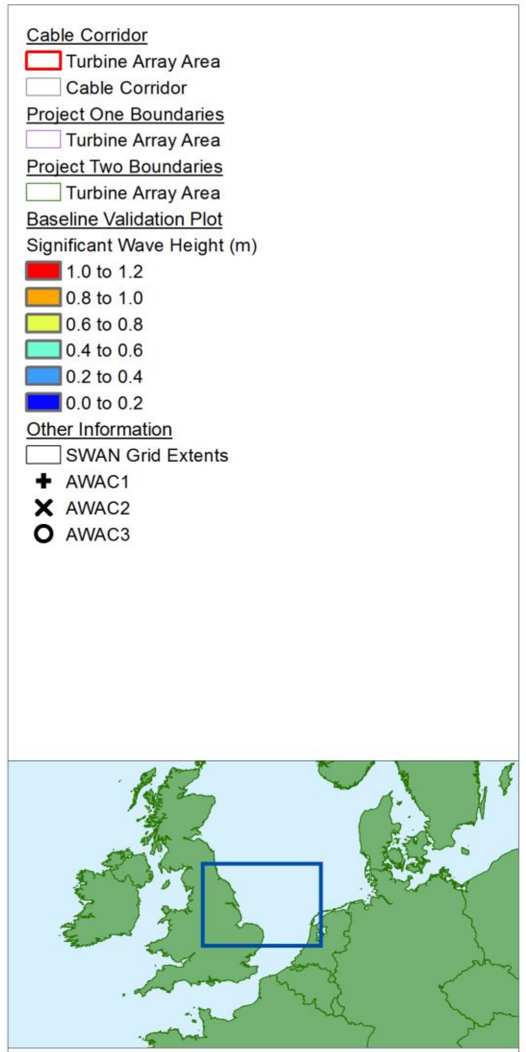
B.3.2.4 Images for all directional return periods are reproduced in Figure B.14 to Figure B.19, with the original source data extent and colour scale. The corresponding map result from the new MIKE21SW wave model is shown for comparison with the same extent and colour scale. The overall magnitude and patterns of difference in significant wave height are qualitatively shown to be reproduced with good accuracy for all directions for this return period.

B.3.2.5 SMart Wind (2015) provides tables of the difference in significant wave height, from the previous SWAN wave model, due to the effect of Hornsea Project One and Hornsea Project Two, at the three AWAC locations for all return periods and directions. However, the difference in the spatial pattern of how the blockage effect of the foundations is applied (a series of more widely spaced lines in the SWAN model versus more evenly distributed points in the MIKE21SW model) means that the development of the effect within the array area is different. This leads to apparently large differences between the models in terms of differences to wave heights at specific locations within the wind farms, which are not related to overall performance of simulating array scale effects. Therefore, these are not explicitly compared here with coincident values from the new MIKE21SW wave model results.

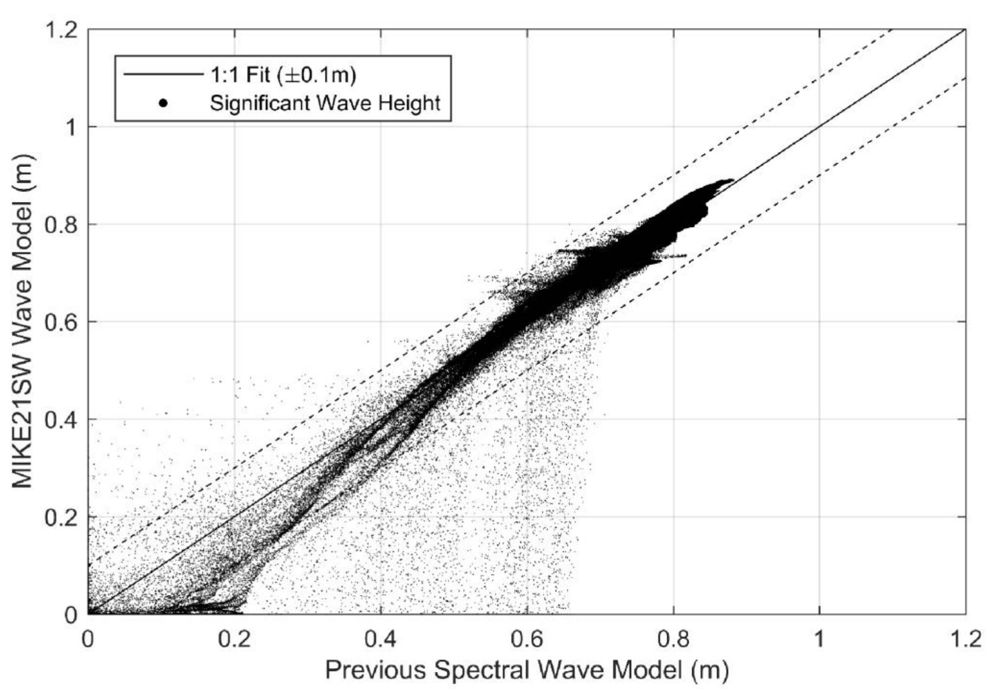
B.3.2.6 On the basis of the comparisons described above, the new MIKE21SW model is validated to adequately reproduce the magnitude and spatial patterns of differences in significant wave height due to the presence of Hornsea Project One and Hornsea Project Two, as previously reported in SMart Wind (2015).




C. Comparison of predicted values




The underlying data for the previous SWAN model results were obtained from SMart Wind (2015b).

The data extent shown is the same as the figures in the original report.

The colour scale used is consistent with that in the original source report and is suitable for the range of values, considering all directions for this return period condition.

Symbols '+', 'x' and 'o' show the position of AWAC (metocean survey) device deployments. SMart Wind (2015b) provides tables of baseline significant wave height at these locations for all return periods and directions from the previous SWAN wave model; these are compared with coincident values from the new MIKE21SW wave model in Figure 3.7.

Name: 005_WMTA_Fig3.1_BslnValidation_50pc_N
Data sources: ABPmer, 2018

Reference System : ETRS89
Projection : UTM Zone 31N

Scale@A3:1:3,804,026
Vertical reference: LAT

0 40 80 120 160 Kilometres
0 20 40 60 80 Nautical Miles

| REV | REMARK | DATE |
|---|---|---|
| 00 | Initial Issue | 09/01/18 |

Hornsea Project Three
Validation of the MIKE21SW
baseline wave model performance (N)

Doc no: ABPmer-EOR0691-4450/05/WMTA-3.1
Created by: DW
Checked by: AB
Approved by: HR

Ørsted

**Figure B.2: Validation of the MIKE21SW spectral wave model performance, 50% no-exceedance, wave direction N. Comparison of baseline significant wave height distribution.**

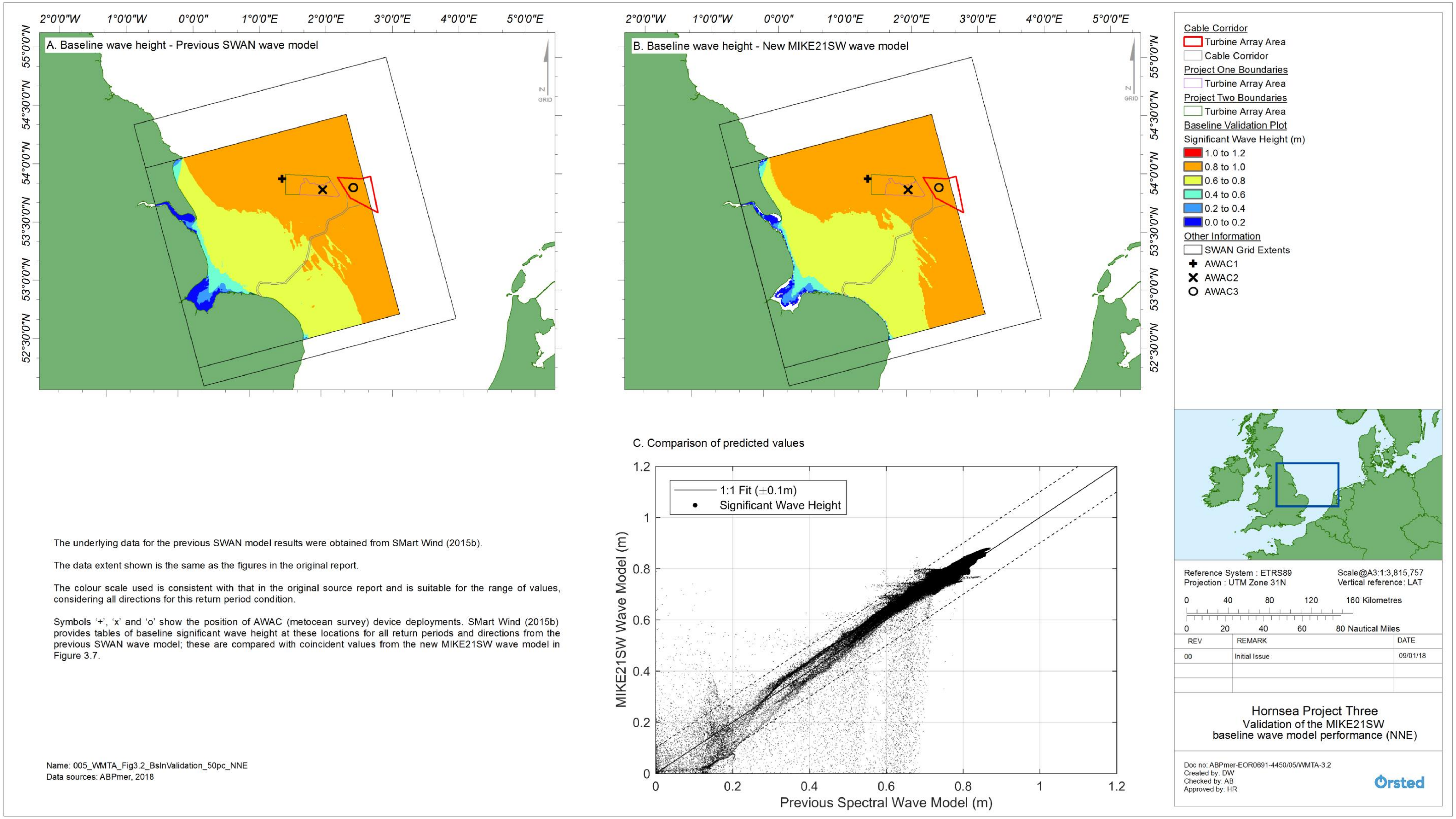



**Figure B.3: Validation of the MIKE21SW spectral wave model performance, 50% no-exceedance, wave direction NNE. Comparison of baseline significant wave height distribution.**

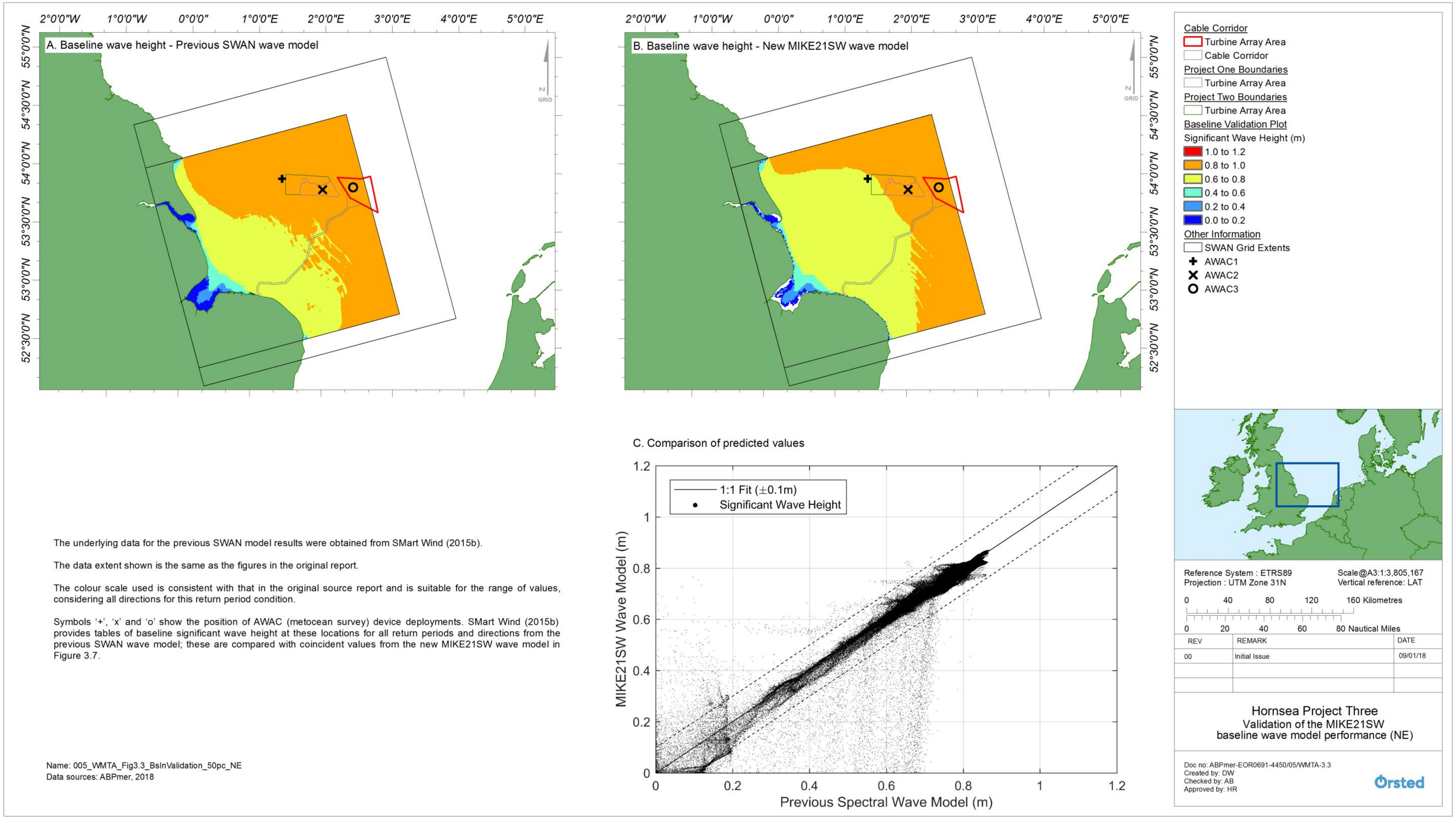
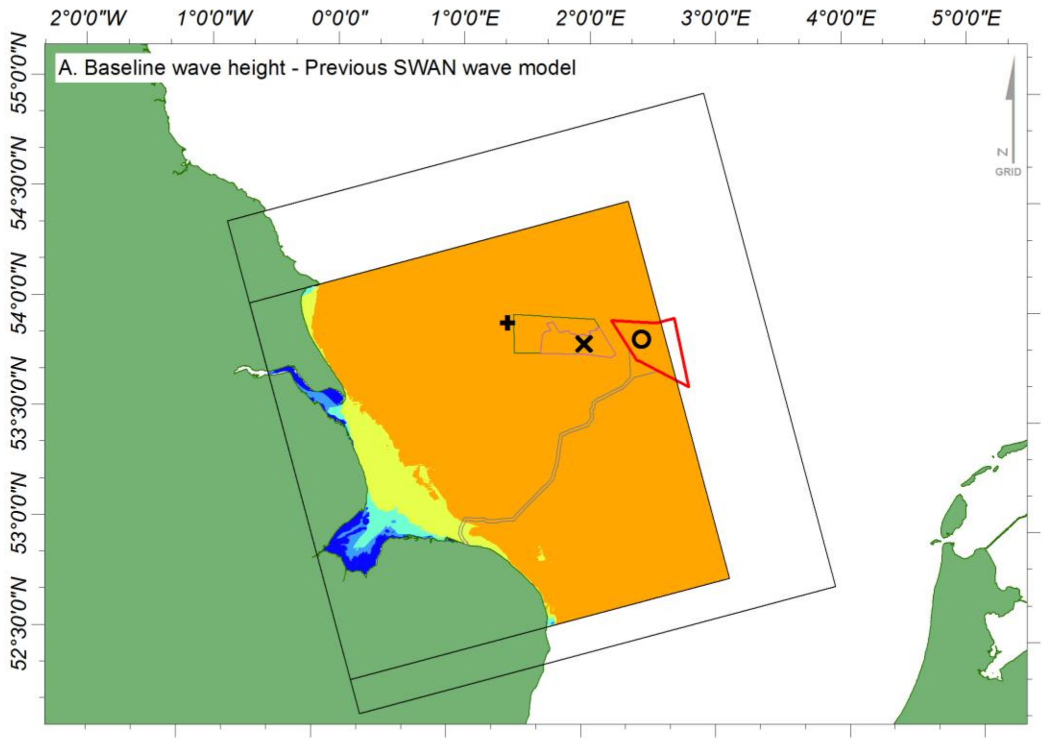
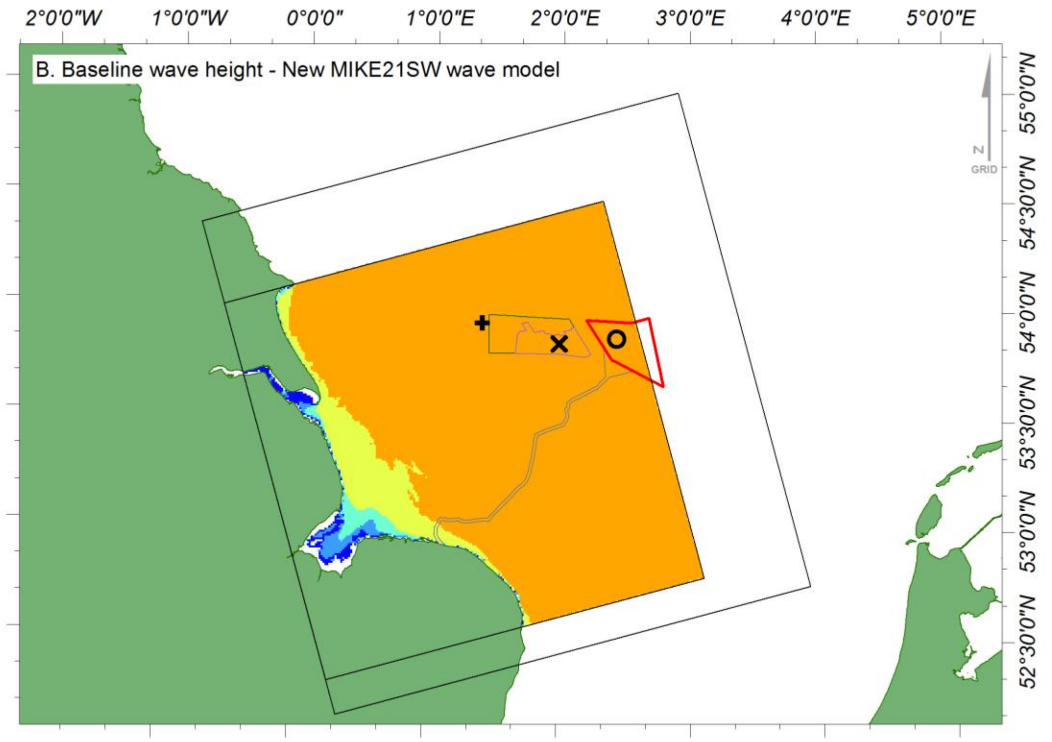


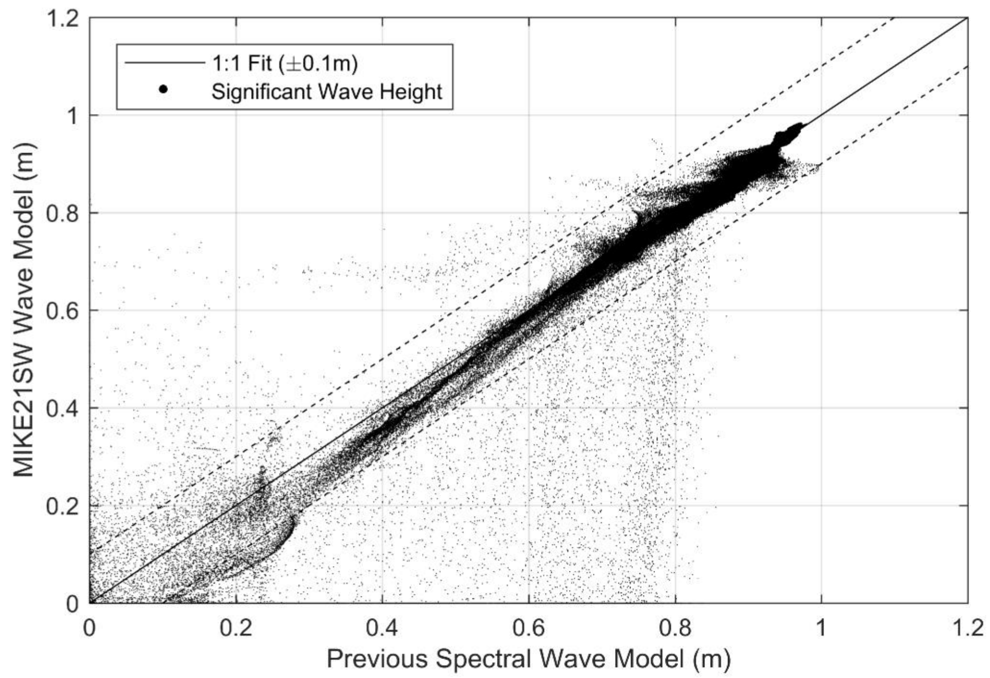

**Figure B.4: Validation of the MIKE21SW spectral wave model performance, 50% no-exceedance, wave direction NE. Comparison of baseline significant wave height distribution.**




Cable Corridor
Turbine Array Area
Cable Corridor
Project One Boundaries
Turbine Array Area
Project Two Boundaries
Turbine Array Area
Baseline Validation Plot
Significant Wave Height (m)
1.0 to 1.2
0.8 to 1.0
0.6 to 0.8
0.4 to 0.6
0.2 to 0.4
0.0 to 0.2
Other Information
SWAN Grid Extents
AWAC1
AWAC2
AWAC3

C. Comparison of predicted values




The underlying data for the previous SWAN model results were obtained from SMart Wind (2015b).

The data extent shown is the same as the figures in the original report.

The colour scale used is consistent with that in the original source report and is suitable for the range of values, considering all directions for this return period condition.

Symbols '+', 'x' and 'o' show the position of AWAC (metocean survey) device deployments. SMart Wind (2015b) provides tables of baseline significant wave height at these locations for all return periods and directions from the previous SWAN wave model; these are compared with coincident values from the new MIKE21SW wave model in Figure 3.7.

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Reference System : ETRS89
Projection : UTM Zone 31N

Scale@A3:1:3,839,163
Vertical reference: LAT

0 40 80 120 160 Kilometres
0 20 40 60 80 Nautical Miles

| REV | REMARK | DATE |
|---|---|---|
| 00 | Initial Issue | 09/01/18 |

Hornsea Project Three
Validation of the MIKE21SW
baseline wave model performance (ENE)

Doc no: ABPmer-EOR0691-4450/05/WMTA-3.4
Created by: DW
Checked by: AB
Approved by: HR

Ørsted

**Figure B.5: Validation of the MIKE21SW spectral wave model performance, 50% no-exceedance, wave direction ENE. Comparison of baseline significant wave height distribution.**

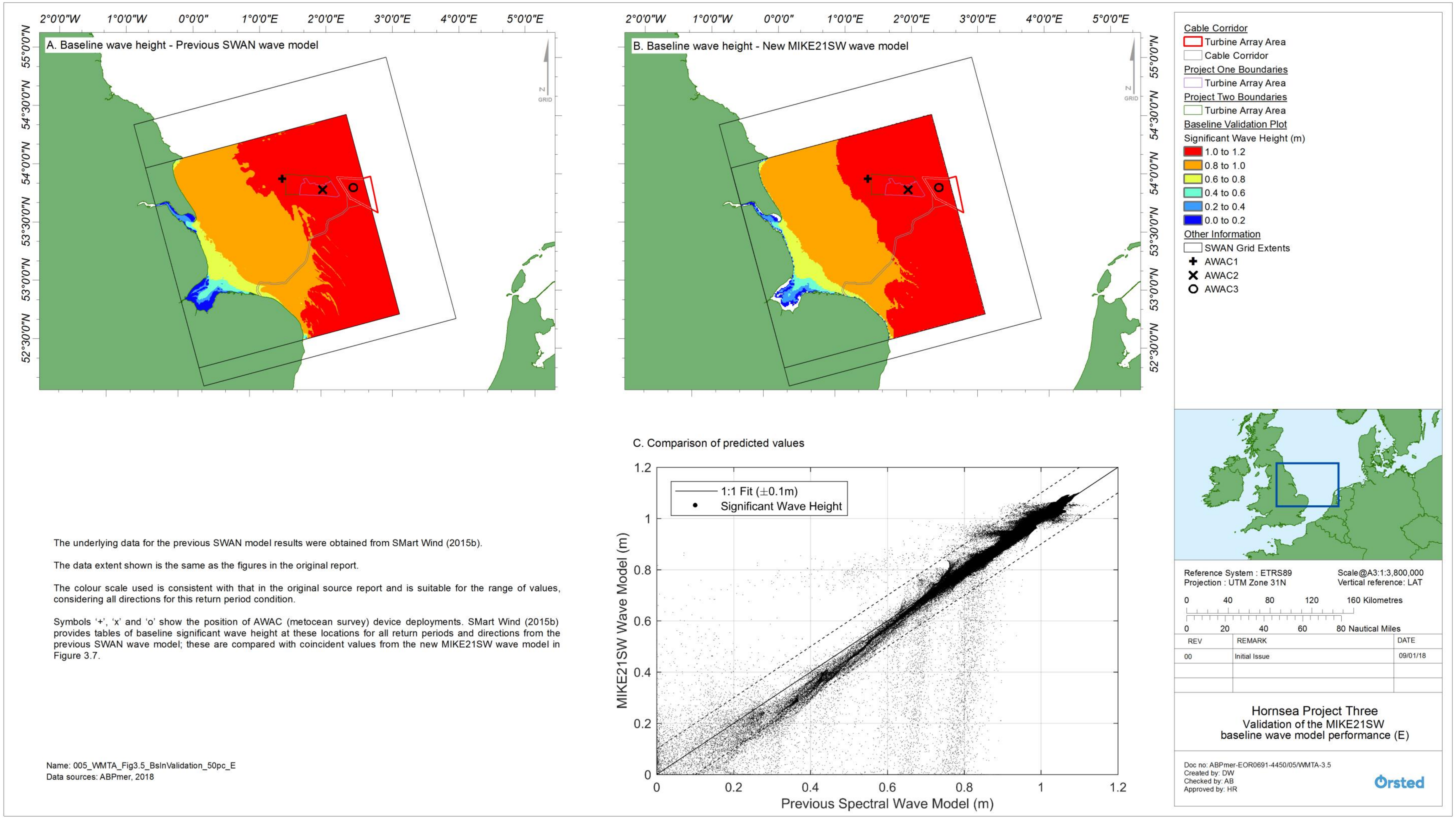


**Figure B.6: Validation of the MIKE21SW spectral wave model performance, 50% no-exceedance, wave direction E. Comparison of baseline significant wave height distribution.**

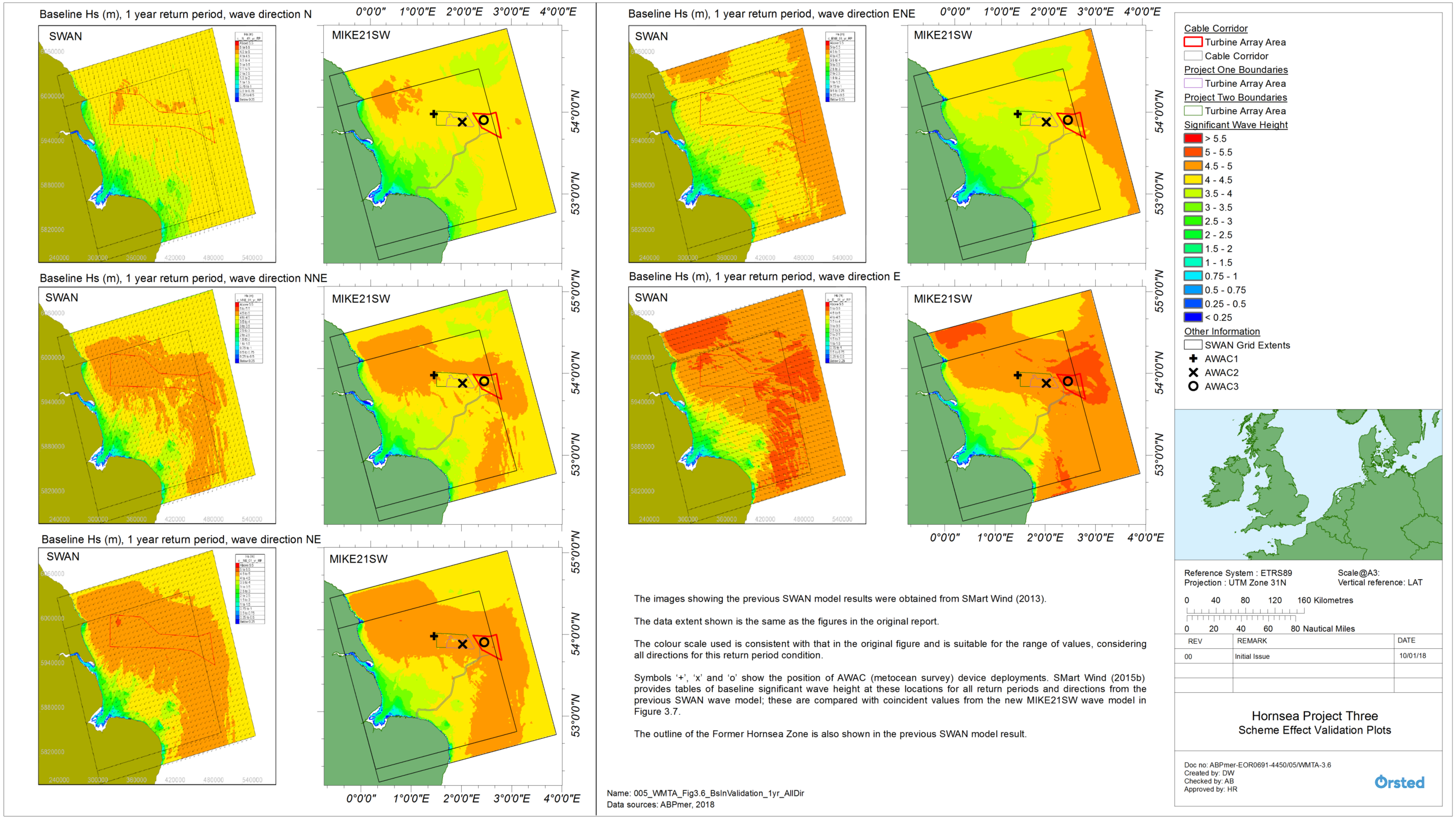


**Figure B.7: Validation of the MIKE21SW spectral wave model performance, 1 year return period, all directions. Comparison of baseline significant wave height distribution.**

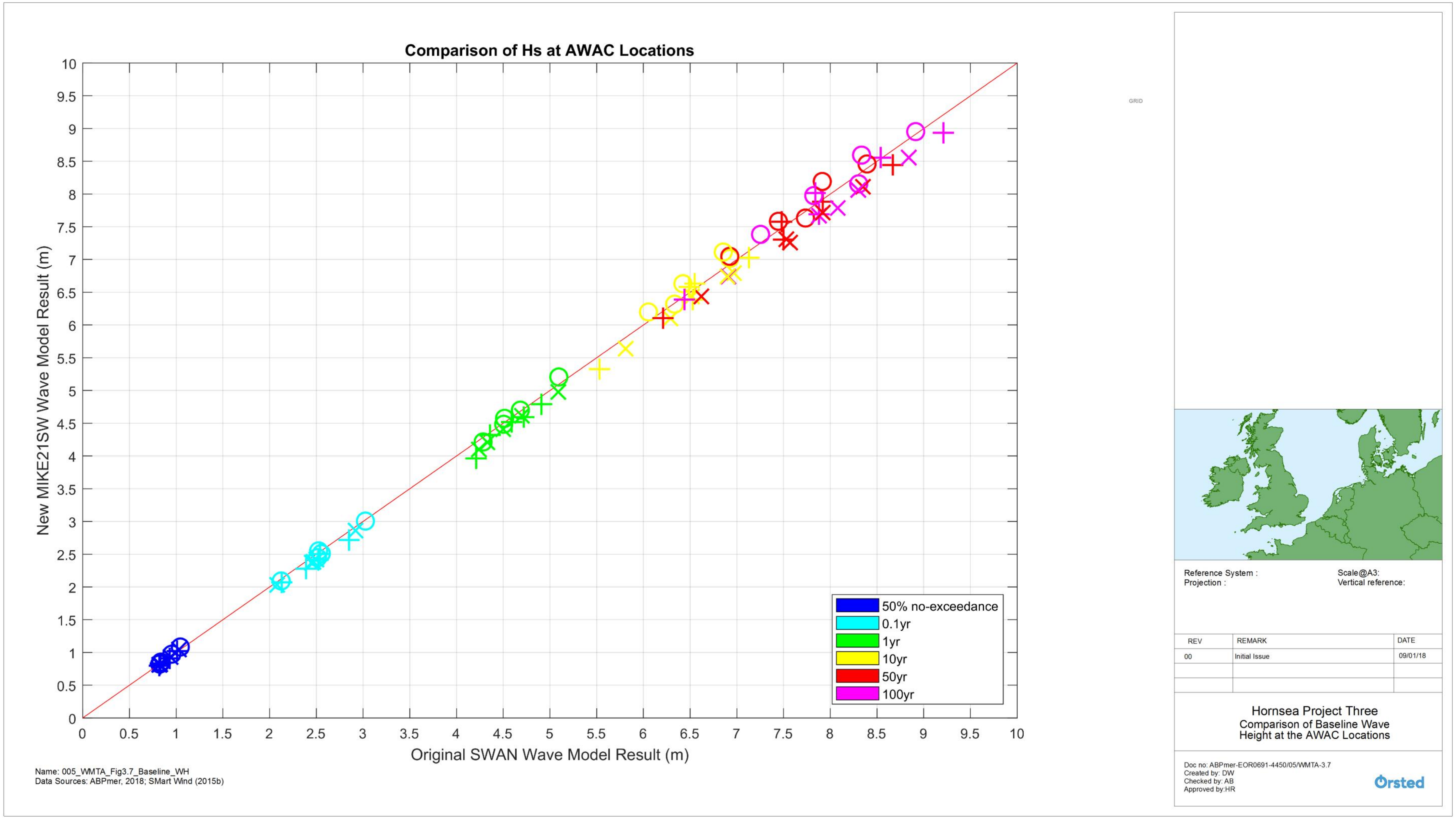


**Figure B.8: Validation of the MIKE21SW spectral wave model performance, all return periods, all directions. Comparison of baseline significant wave height at the position of the AWACs.**

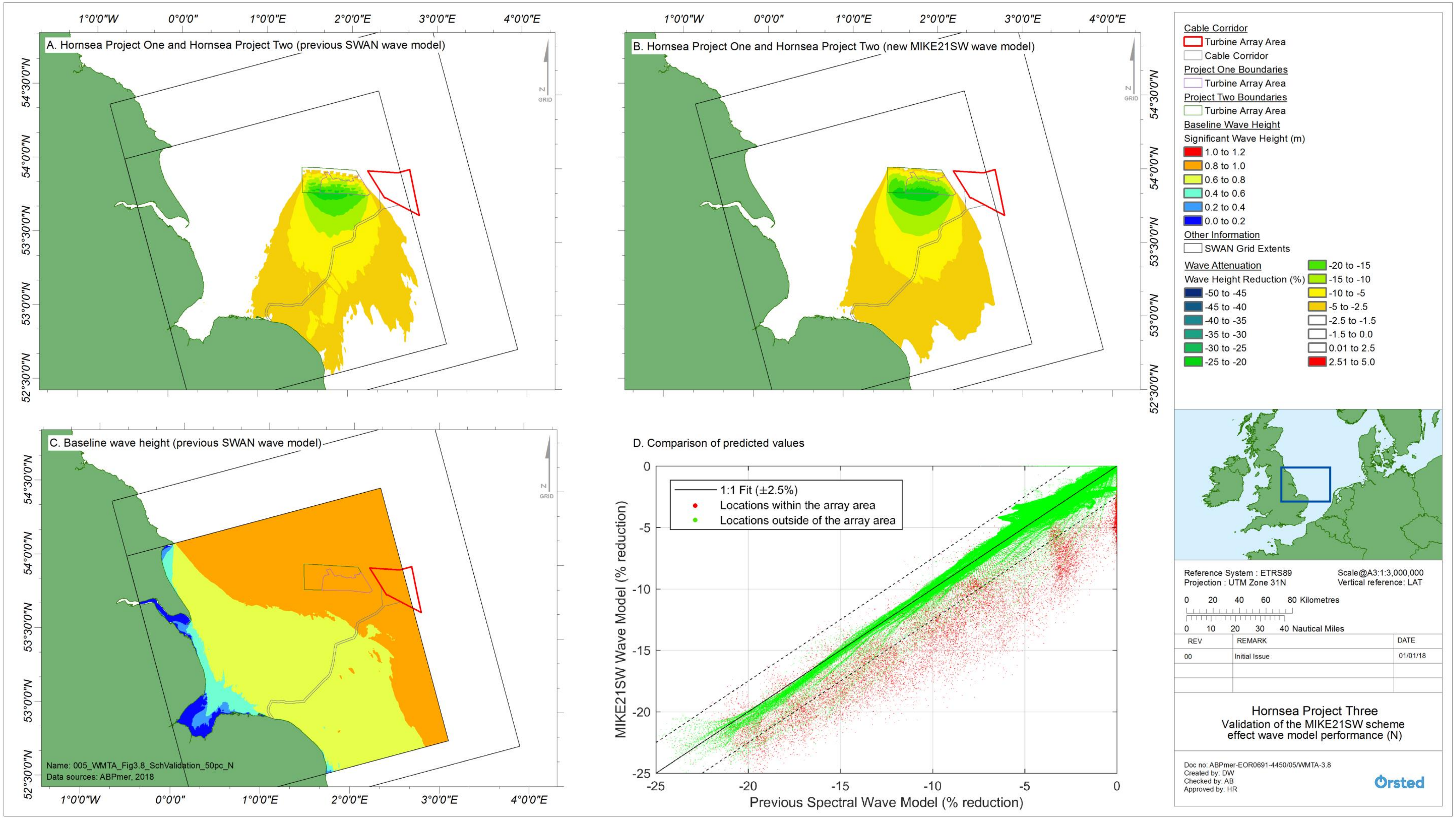


**Figure B.9: Validation of the MIKE21SW spectral wave model performance, 50% no exceedance, wave direction N. Absolute difference in significant wave height between baseline and both the Hornsea Project One and Hornsea Project Two operational phases.**

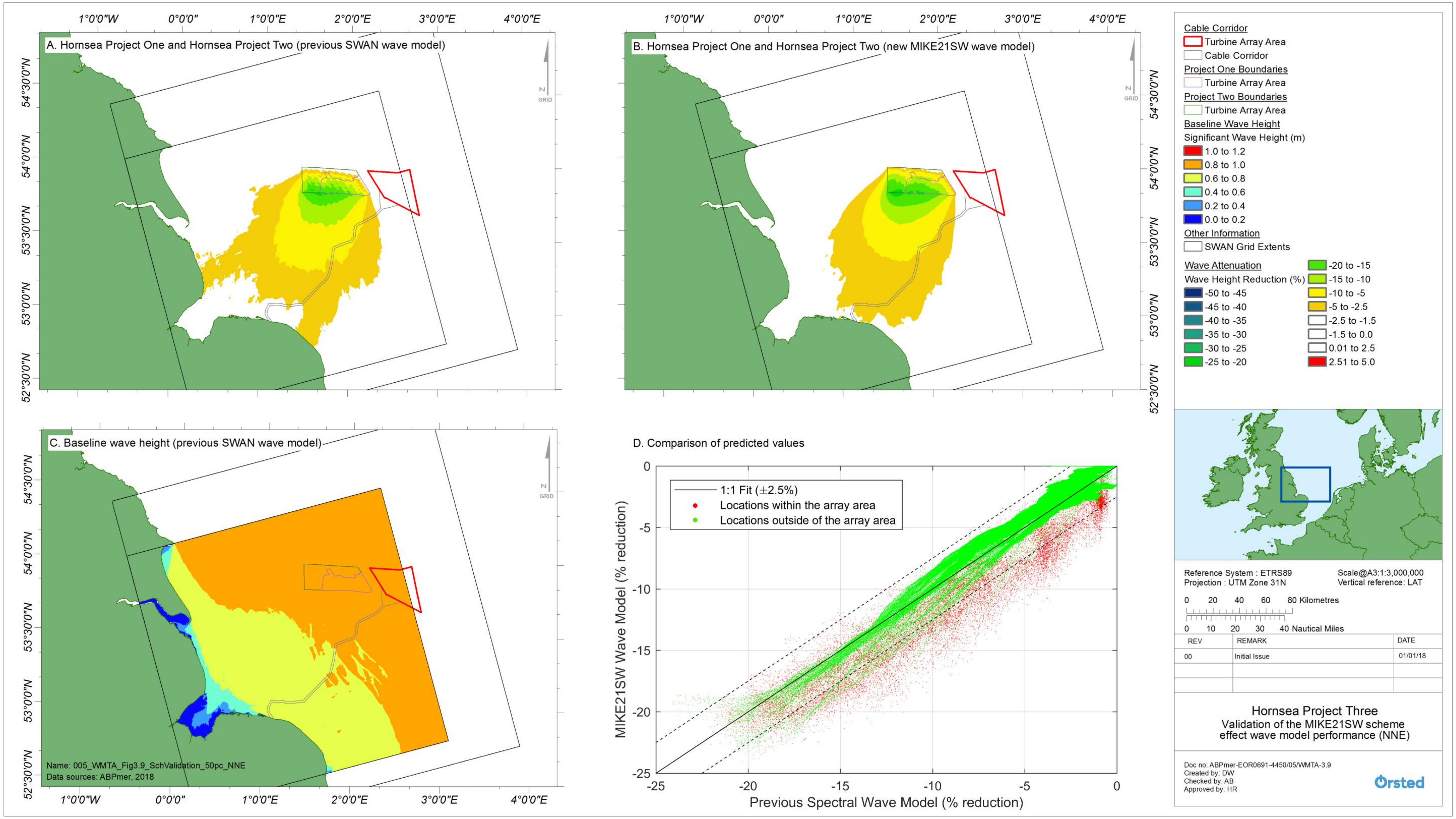


**Figure B.10: Validation of the MIKE21SW spectral wave model performance, 50% no exceedance, wave direction NNE. Absolute difference in significant wave height between baseline and both the Hornsea Project One and Hornsea Project Two operational phases.**

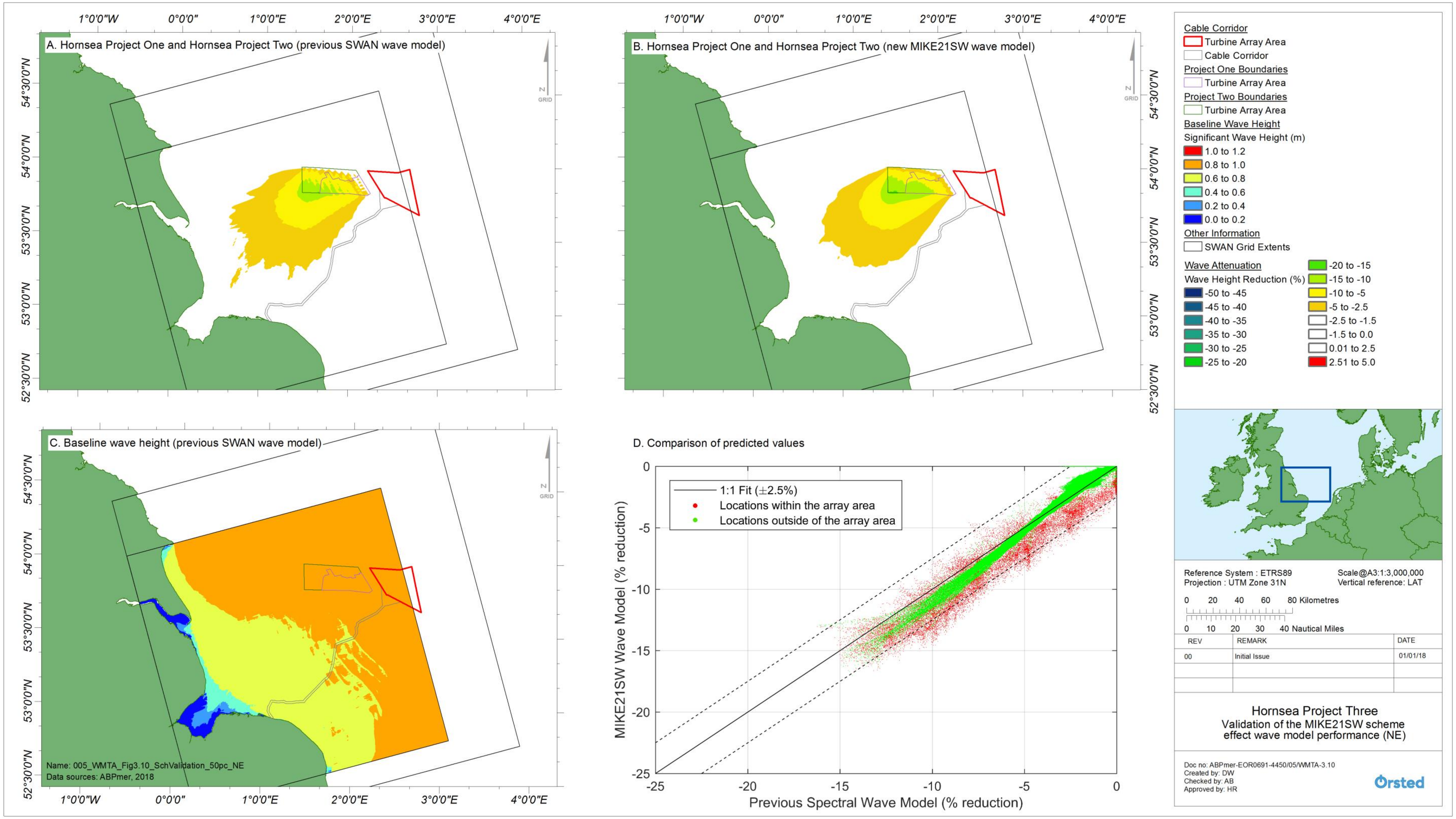


**Figure B.11: Validation of the MIKE21SW spectral wave model performance, 50% no exceedance, wave direction NE. Absolute difference in significant wave height between baseline and both the Hornsea Project One and Hornsea Project Two operational phases.**

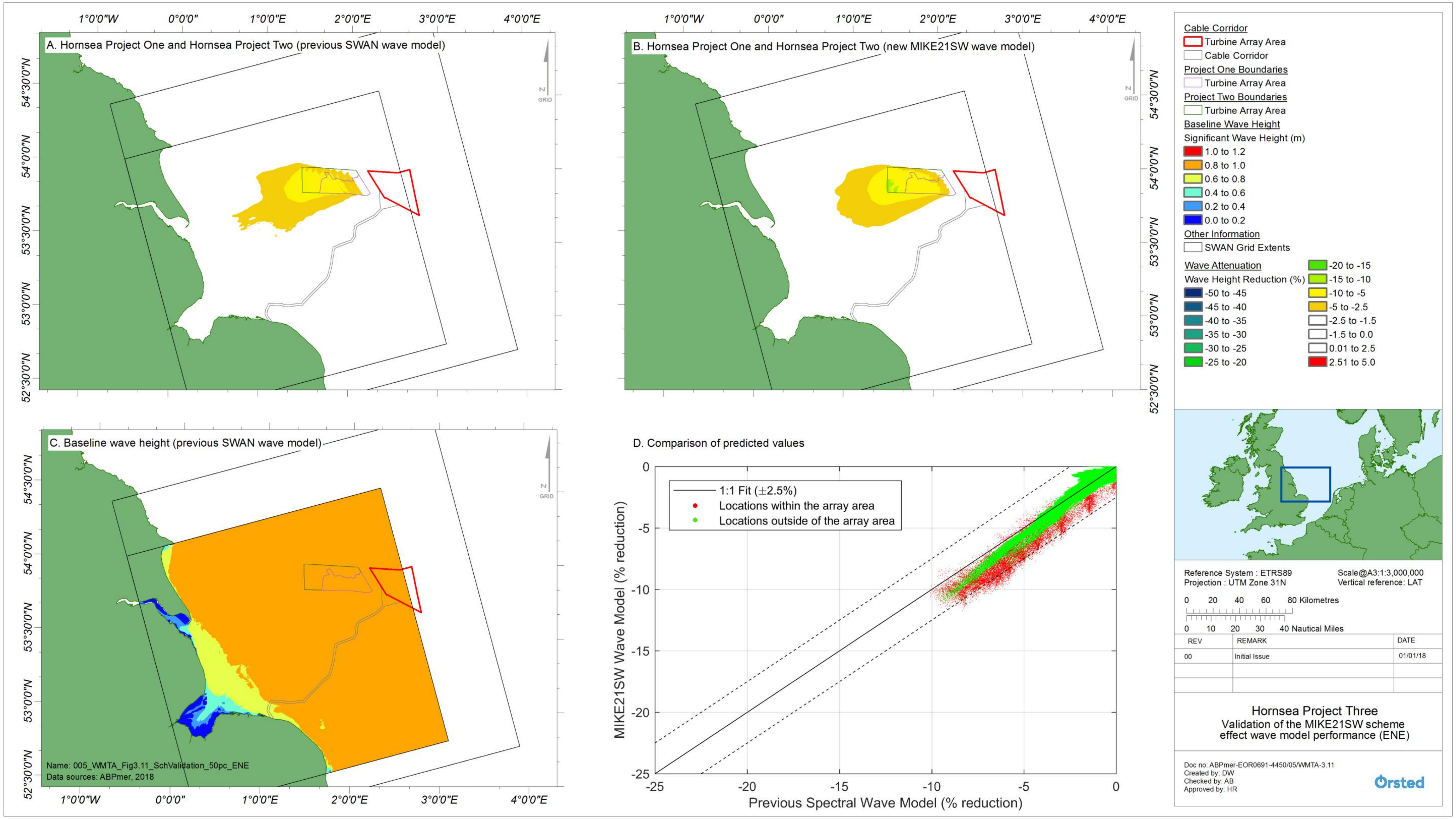


**Figure B.12: Validation of the MIKE21SW spectral wave model performance, 50% no exceedance, wave direction ENE. Absolute difference in significant wave height between baseline and both the Hornsea Project One and Hornsea Project Two operational phases.**

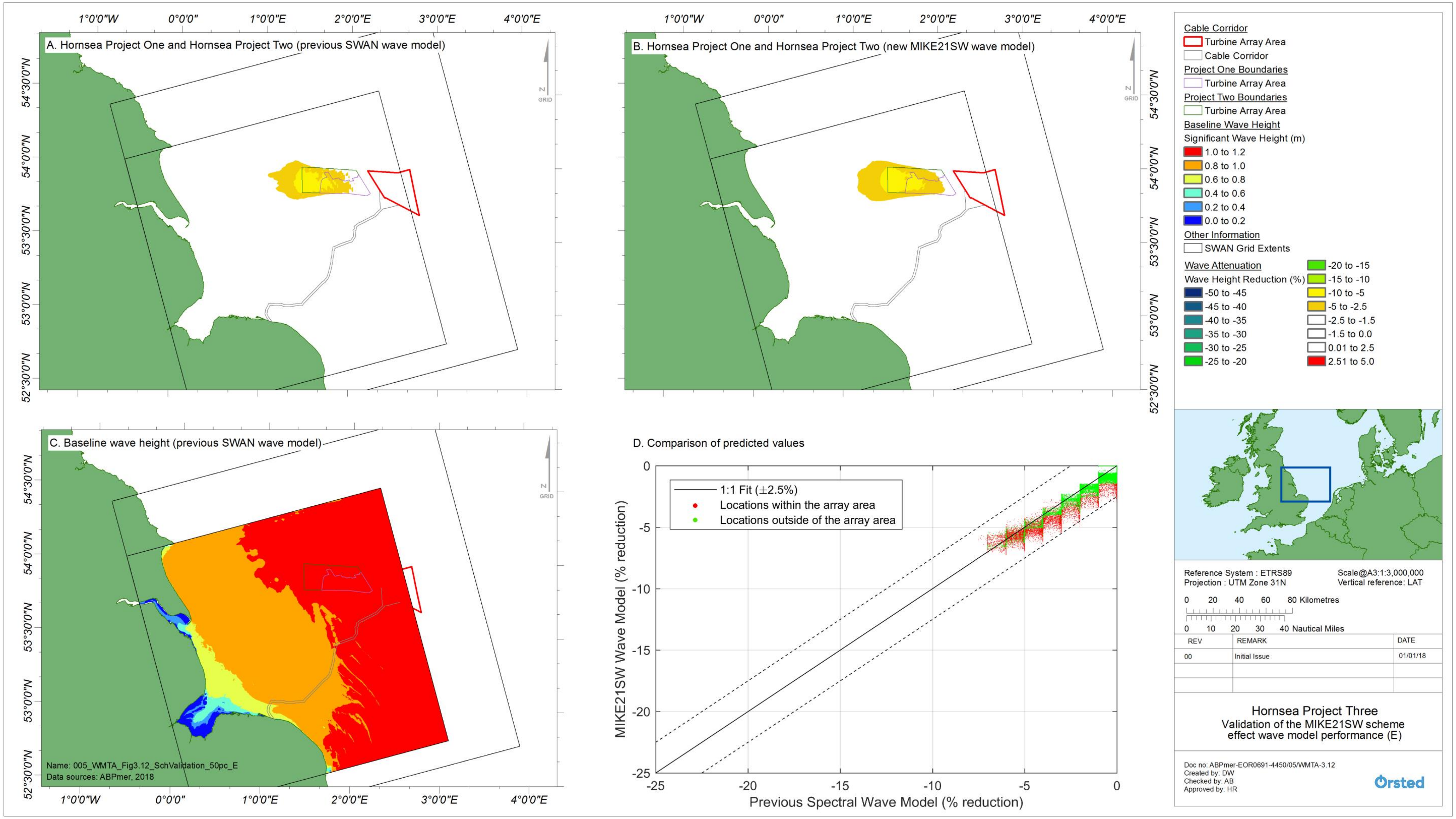


**Figure B.13: Validation of the MIKE21SW spectral wave model performance, 50% no exceedance, wave direction E. Absolute difference in significant wave height between baseline and both the Hornsea Project One and Hornsea Project Two operational phases.**

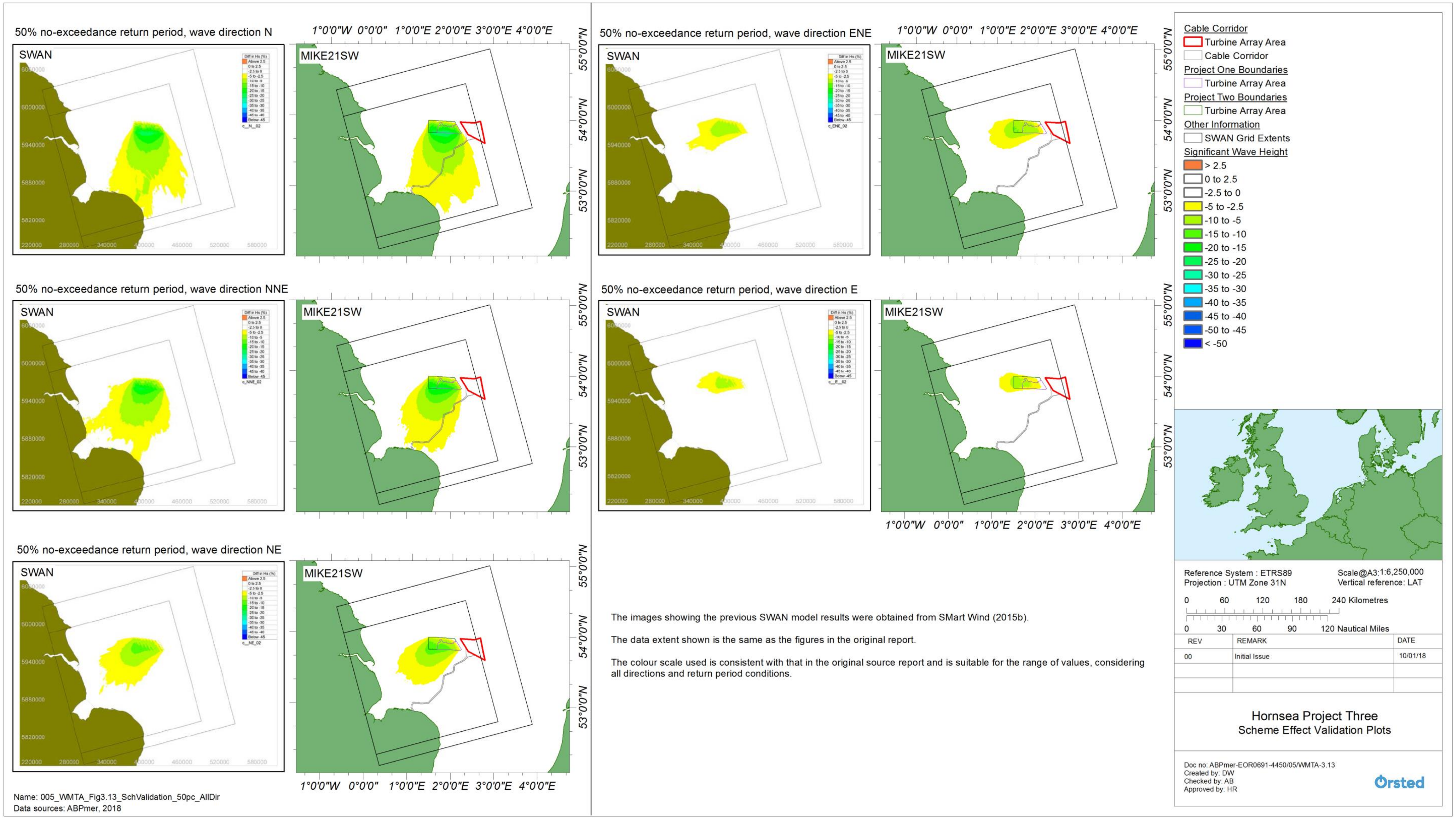


**Figure B.14: Validation of the MIKE21SW spectral wave model performance, 50% no exceedance, all wave directions. Comparison of percentage difference in significant wave height between baseline and both the Hornsea Project One and Hornsea Project Two operational phases.**

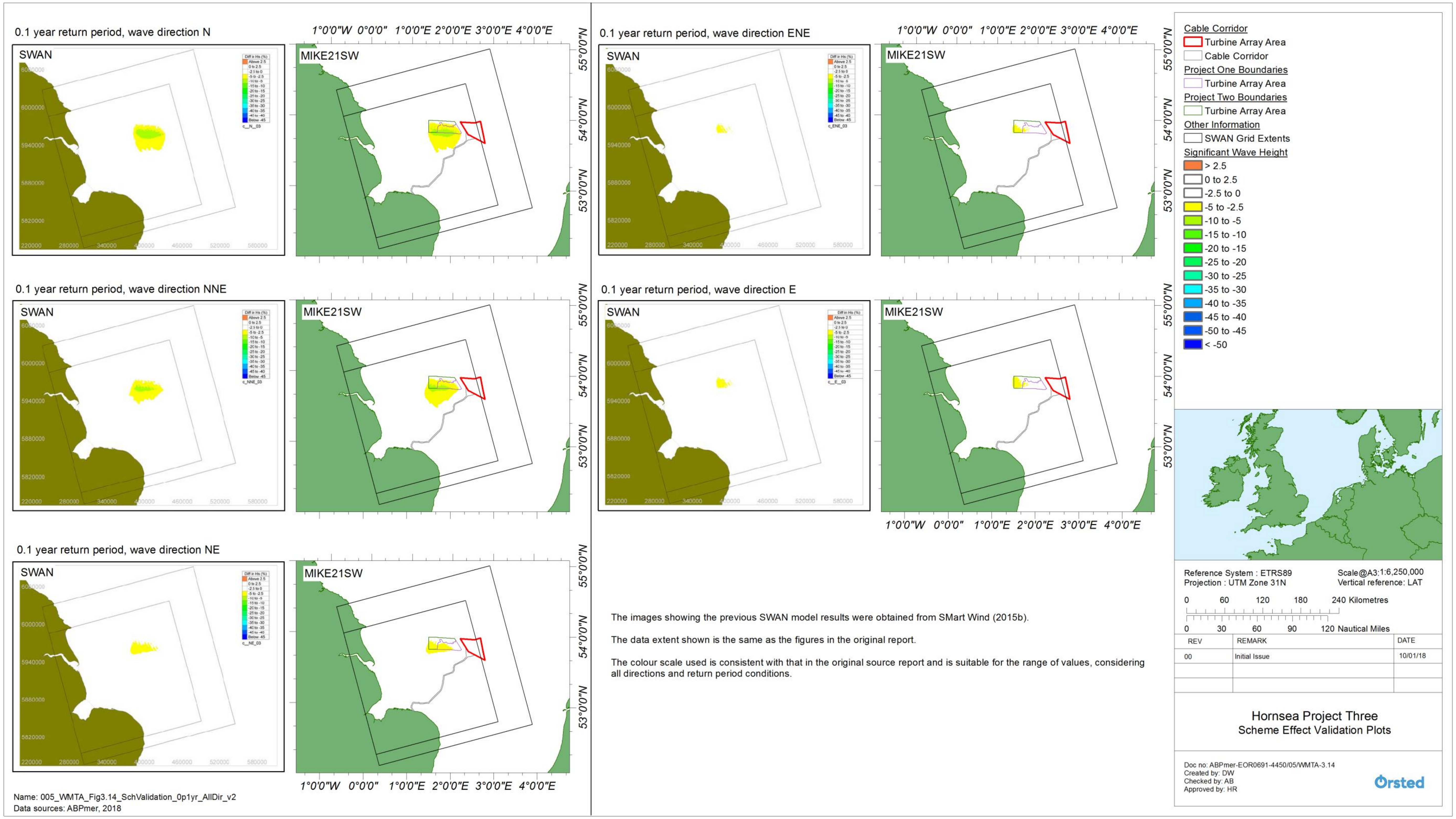


**Figure B.15: Validation of the MIKE21SW spectral wave model performance, 0.1 year return period, all wave directions. Comparison of percentage difference in significant wave height between baseline and both the Hornsea Project One and Hornsea Project Two operational phases.**

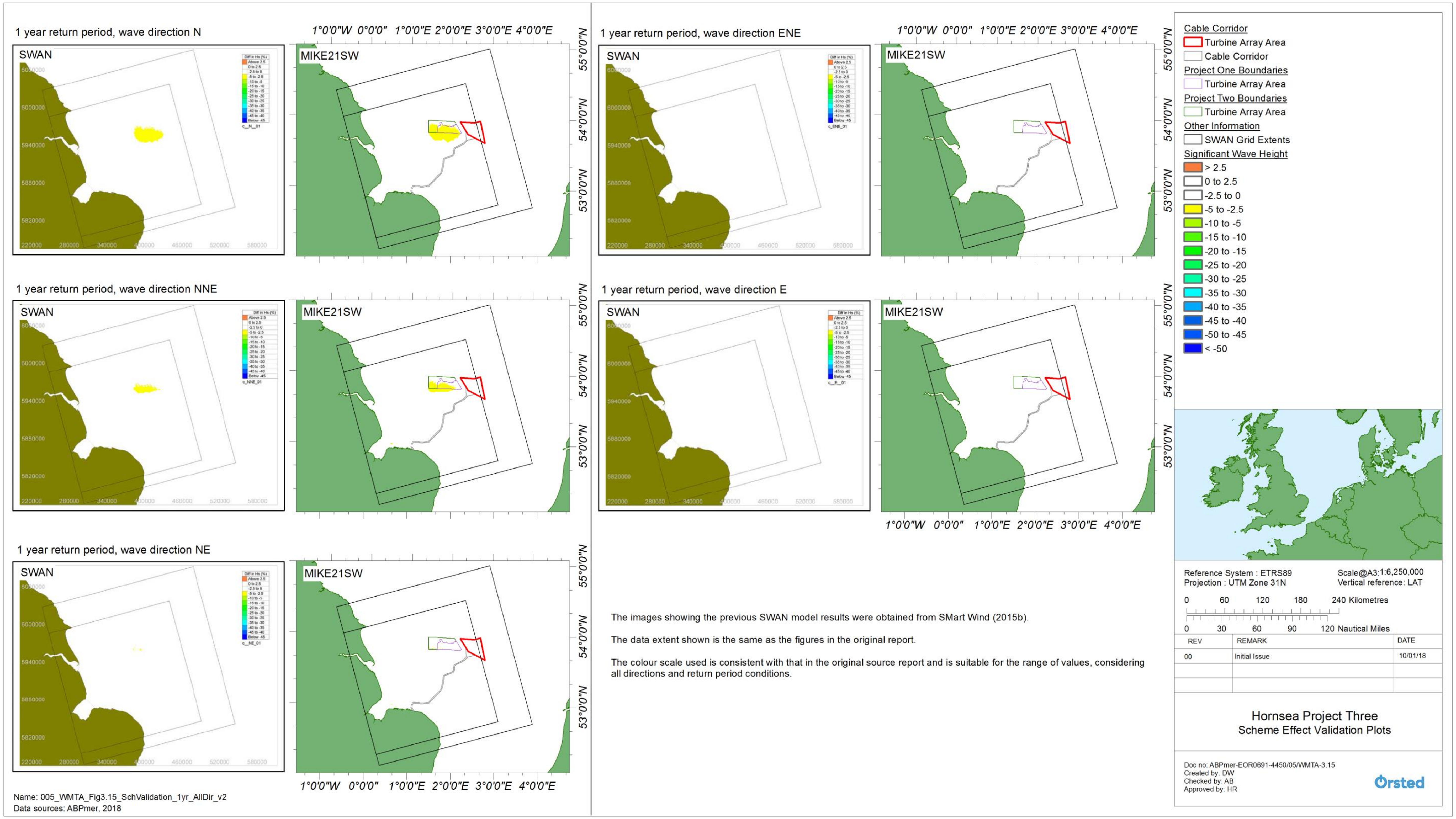


**Figure B.16: Validation of the MIKE21SW spectral wave model performance, 1 year return period, all wave directions. Comparison of percentage difference in significant wave height between baseline and both the Hornsea Project One and Hornsea Project Two operational phases.**

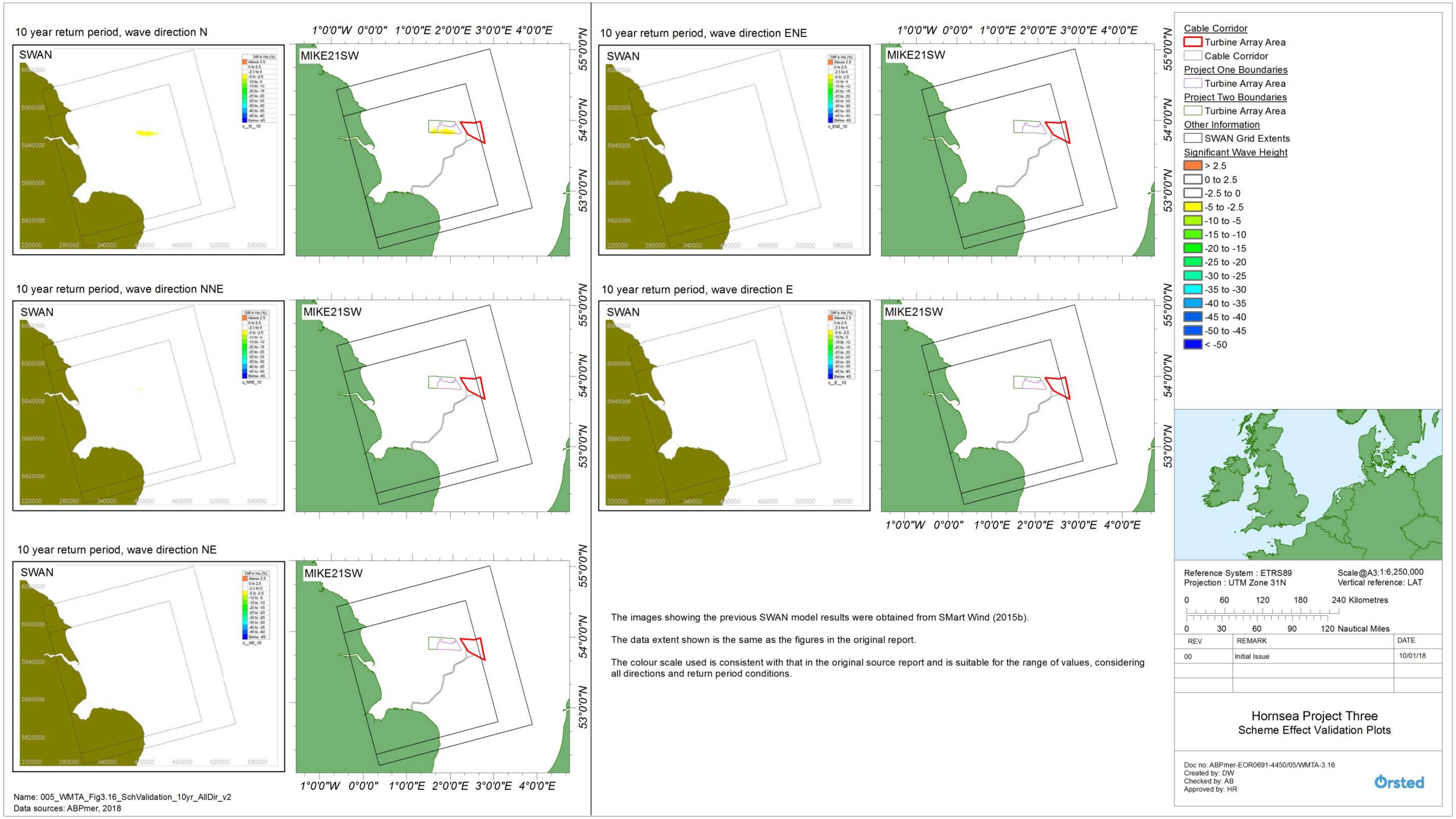


**Figure B.17: Validation of the MIKE21SW spectral wave model performance, 10 year return period, all wave directions. Comparison of percentage difference in significant wave height between baseline and both the Hornsea Project One and Hornsea Project Two operational phases.**

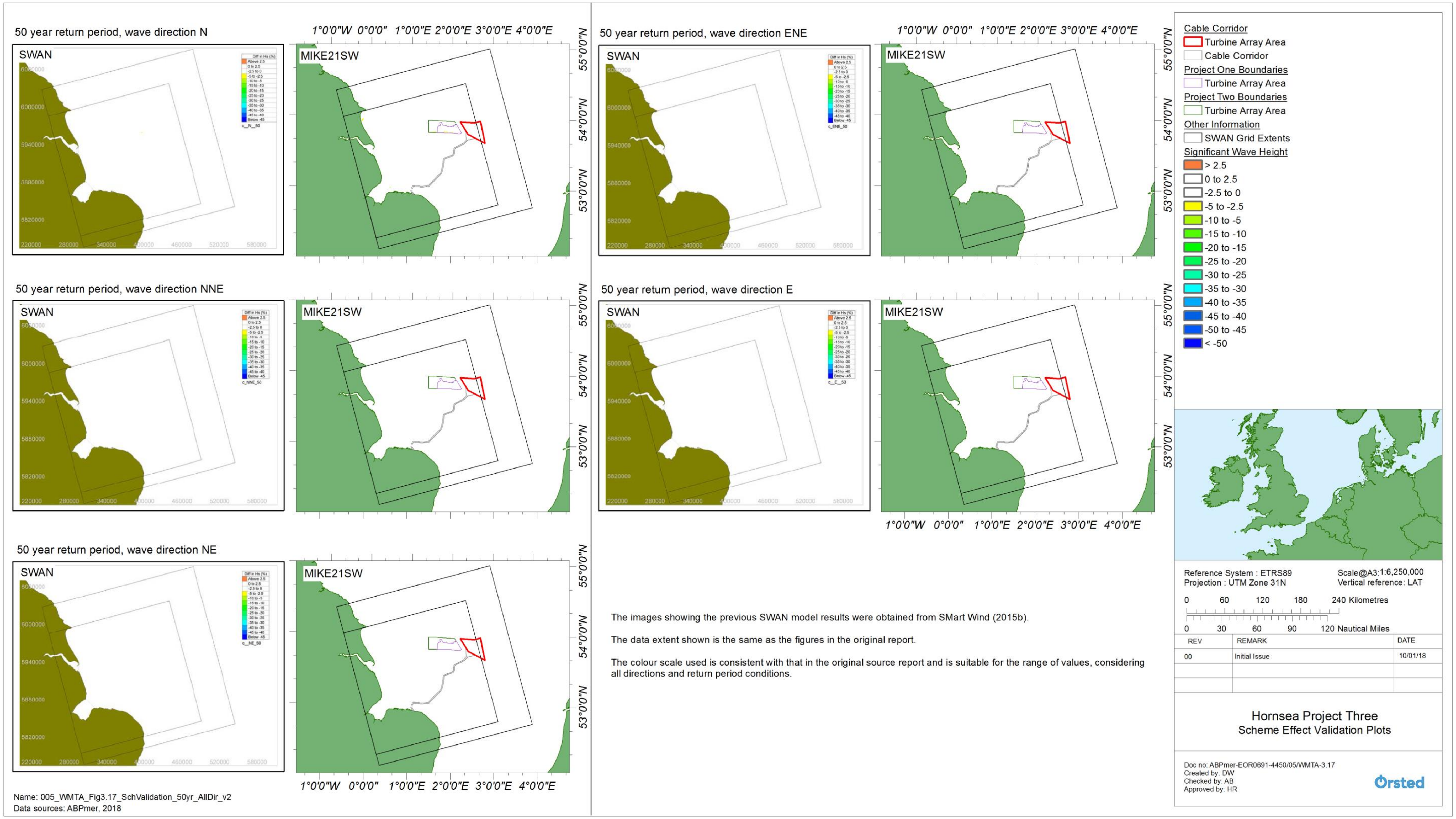


**Figure B.18: Validation of the MIKE21SW spectral wave model performance, 50 year return period, all wave directions. Comparison of percentage difference in significant wave height between baseline and both the Hornsea Project One and Hornsea Project Two operational phases.**

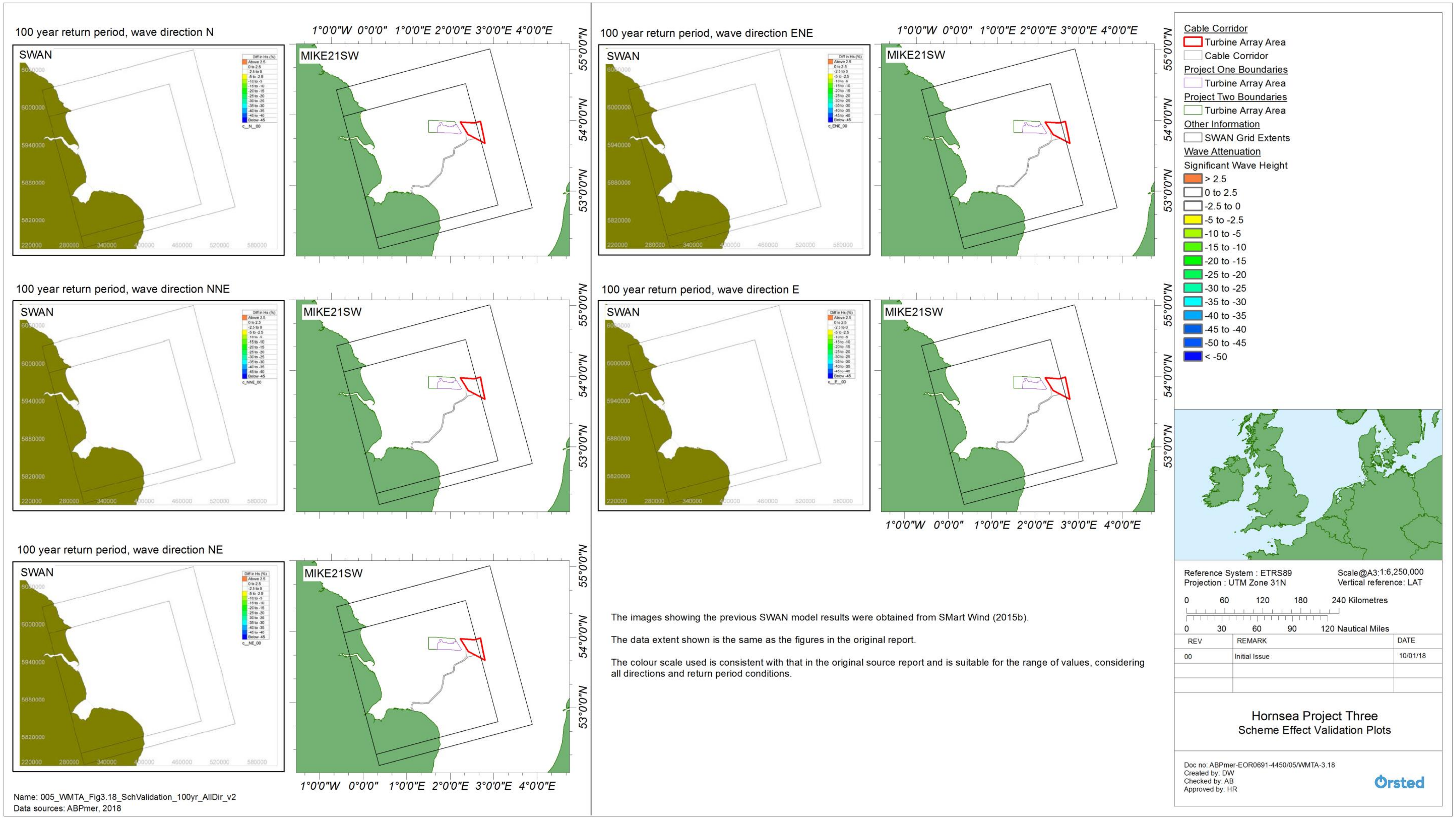


**Figure B.19: Validation of the MIKE21SW spectral wave model performance, 100 year return period, all wave directions. Comparison of percentage difference in significant wave height between baseline and both the Hornsea Project One and Hornsea Project Two operational phases.**

## B.4 MIKE21SW Assessment of Hornsea Three Scheme Impacts on Wave Height

### B.4.1 Hornsea Three (in isolation)

B.4.1.1 The potential realistic maximum design scenario effect of Hornsea Three alone is shown in Figure B.20. This scheme includes:

- The maximum number (300) of 43 m base diameter, 15 m pylon diameter gravity base foundations in the Hornsea Three array area, and 19 other ancillary foundations (319 gravity base foundations in total).

B.4.1.2 Results are shown as the percentage reduction in significant wave height for the 50% no-exceedance wave condition for all directions. This is the worst case effect for any given direction; higher return period scenarios yield a lesser magnitude and smaller extent of (proportional) effect.

### B.4.2 Hornsea Three, Hornsea Project One (final approved) and Hornsea Project Two (as consented)

B.4.2.1 The potential realistic worst case effect of Hornsea Three, Hornsea Project One (final approved) and Hornsea Project Two (as consented) is shown in Figure B.21. This scheme includes:

- The maximum number (300) of 43 m base diameter, 15 m pylon diameter gravity base foundations in the Hornsea Three array area, and 19 other foundations (319 gravity base foundations in total);
- The final approved number (174) and layout of 8.1 m diameter monopile foundations in the Hornsea Project One array area; and
- The maximum number (360) of 50 m base diameter, 15 m pylon diameter gravity base foundations in the Hornsea Project Two array area.

B.4.2.2 Results are shown as the percentage reduction in significant wave height for the 50% no-exceedance wave condition for all directions. This is the worst case effect for any given direction; higher return period scenarios yield a lesser magnitude and smaller extent of (proportional) effect.

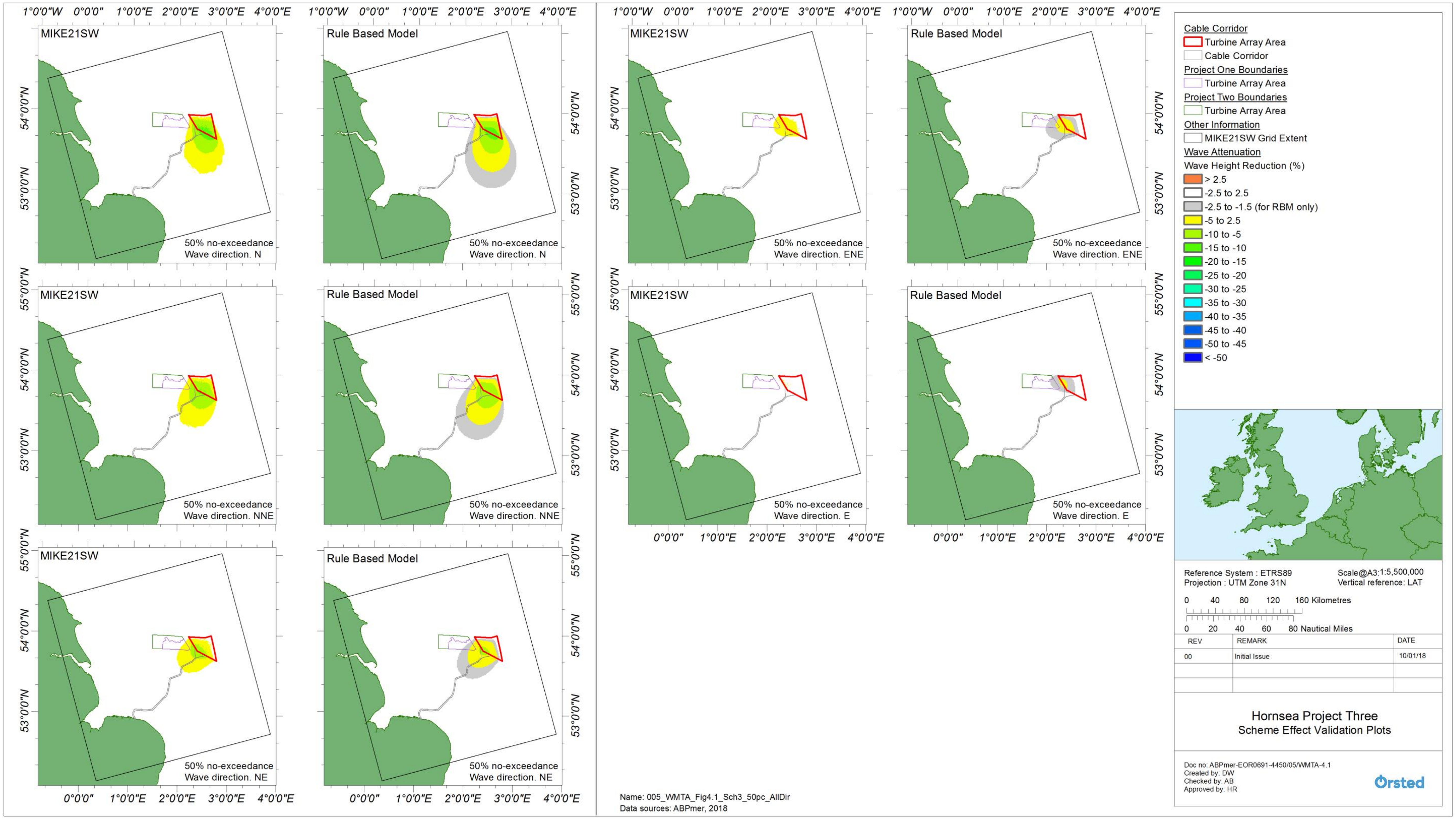


**Figure B.20: Percentage difference in significant wave height between baseline and scheme (Hornsea Three) operational phase, 50% no exceedance, all wave directions, from the MIKE21SW wave model. Also providing comparison with and validation of the rule based wave model.**

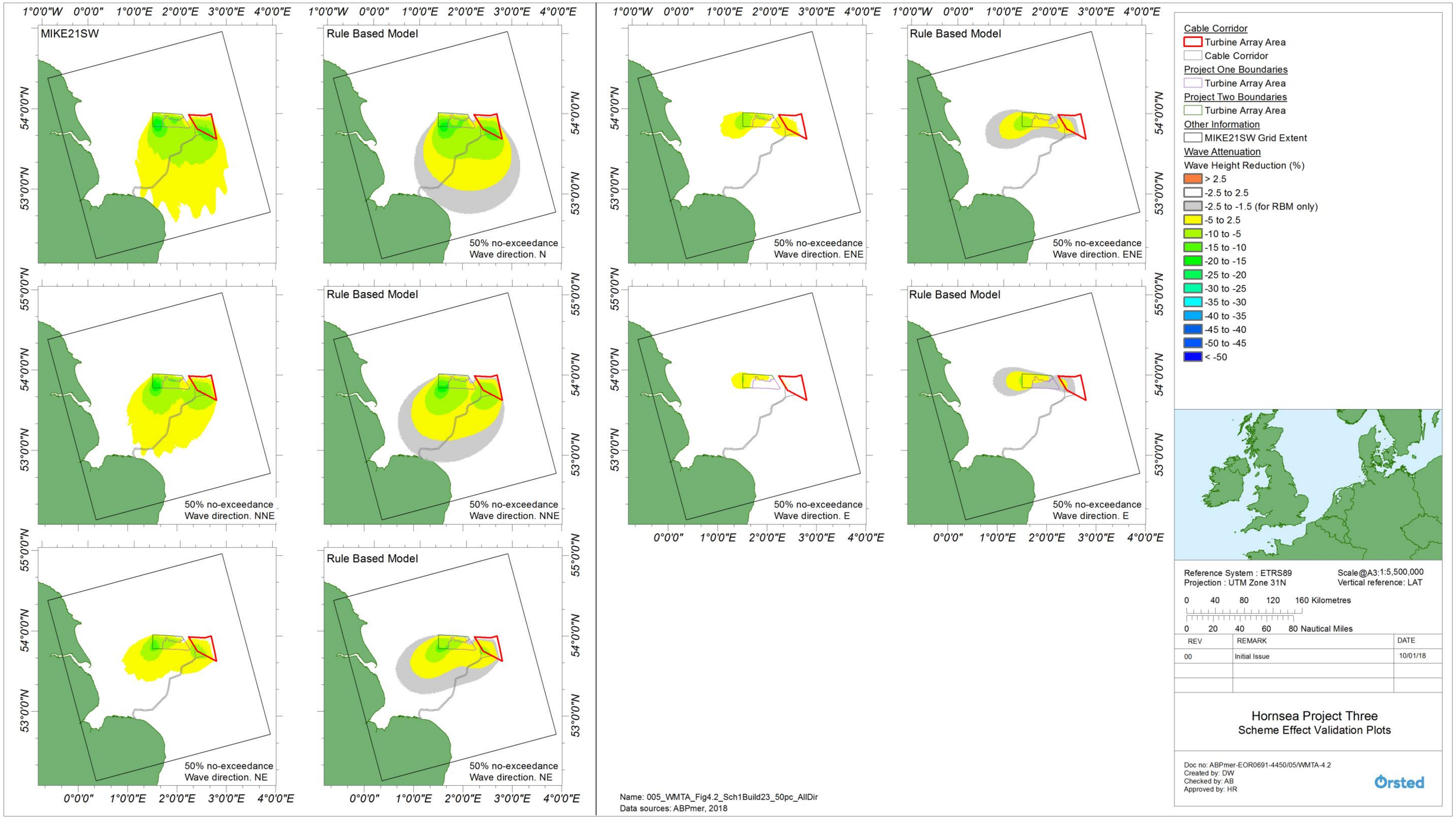


**Figure B.21: Percentage difference in significant wave height between baseline and scheme (Hornsea Three and Hornsea Project One (final approved) and Hornsea Project Two (as consented)) operational phase, 50% no exceedance, all wave directions, from the MIKE21SW wave model. Also providing comparison with and validation of the rule based wave model.**

## B.5 Further Validation of the Rule Based Wave Model

B.5.1.1 The rule based wave model, used for the main assessment of impacts on wave height, is described and validated against the previous SWAN wave model with respect to the potential realistic worst case effect of Hornsea Project One and Hornsea Project Two in Appendix A.

B.5.1.2 This section provides further validation of the rule based model for assessment of new scenarios (including Hornsea Three) that were not considered by the previous SWAN modelling. This is achieved by comparing the relative performance and consistency of the rule based and MIKE21SW wave model results for a range of previously and newly modelled scheme scenarios. Only the 50% no-exceedance wave condition is considered, as it consistently provides the most conservative (highest and most extensive) estimate of percentage effect on wave height, for all wave directions.

B.5.1.3 The calibration and validation of the previous SWAN model is described in Smart Wind (2015a and 2015). The MIKE21SW wave model has been validated in this Appendix B with respect to the results of the previous SWAN wave model, including the magnitude and spatial pattern of baseline significant wave height (Section B.3.1) and differences in wave height as a result of the potential realistic worst case effect of Hornsea Project One and Hornsea Project Two (Section B.3.2). Both the SWAN and MIKE21SW models are considered to be suitably validated for use and provide similar results for the previously modelled scheme scenario.

B.5.1.4 The rule based wave model does not simulate the underlying baseline wave field, so this is not compared with the results of the SWAN or MIKE21SW wave models.

B.5.1.5 The MIKE21SW and rule based wave model scheme effect results for the consented designs of Hornsea Project One and Hornsea Project Two are compared directly in Figure B.22. The two new model types are shown to produce a very similar prediction of the magnitude and extent of scheme effects on wave height for this previously modelled scenario.

B.5.1.6 The extent of very small magnitudes of wave height reduction (less than 5%, i.e. the position of the 2.5% contour) is generally well represented by the rule based model but can be somewhat more detailed or extensive in some of the MIKE21SW wave model results. This is likely due to the additional detail of local wave processes accounted for in the MIKE21SW model, e.g. influence of relatively shallower water depth in the nearshore, rates of wind-wave energy transfer, etc. By also accounting for the additional extent of wave height reduction up to -1.5%, the results of the rule based model (shown in the images by an additional grey colour contour) can also provide a conservative indication of the spatial extent of very small magnitude impacts on wave height at adjacent coastlines.

B.5.1.7 New, not previously modelled, scheme impact scenarios for Hornsea Three (both alone and in combination with the final approved version of Hornsea Project One and the consented version of Hornsea Project Two) were tested using the MIKE21SW model in Section B.4.

B.5.1.8 Assessments of the same new scheme impact scenarios using the rule based model are also presented for direct comparison with the MIKE21SW results in Figure B.20 for Hornsea Three alone, and in Figure B.21 for the cumulative scenario. Again the -1.5% contour is also shown for the rule based model results.

B.5.1.9 Comparison of the new MIKE21SW and rule based model scheme impact results demonstrates that the two model types produce a very similar prediction of the magnitude and extent of scheme effects on wave height due to the effect of Hornsea Three alone and in combination with other wind farms.

B.5.1.10 The rule based model is therefore validated for use in the assessment of impacts on wave height for Hornsea Three both alone and in combination with the final approved version of Hornsea Project One and the consented version of Hornsea Project Two wind farms.

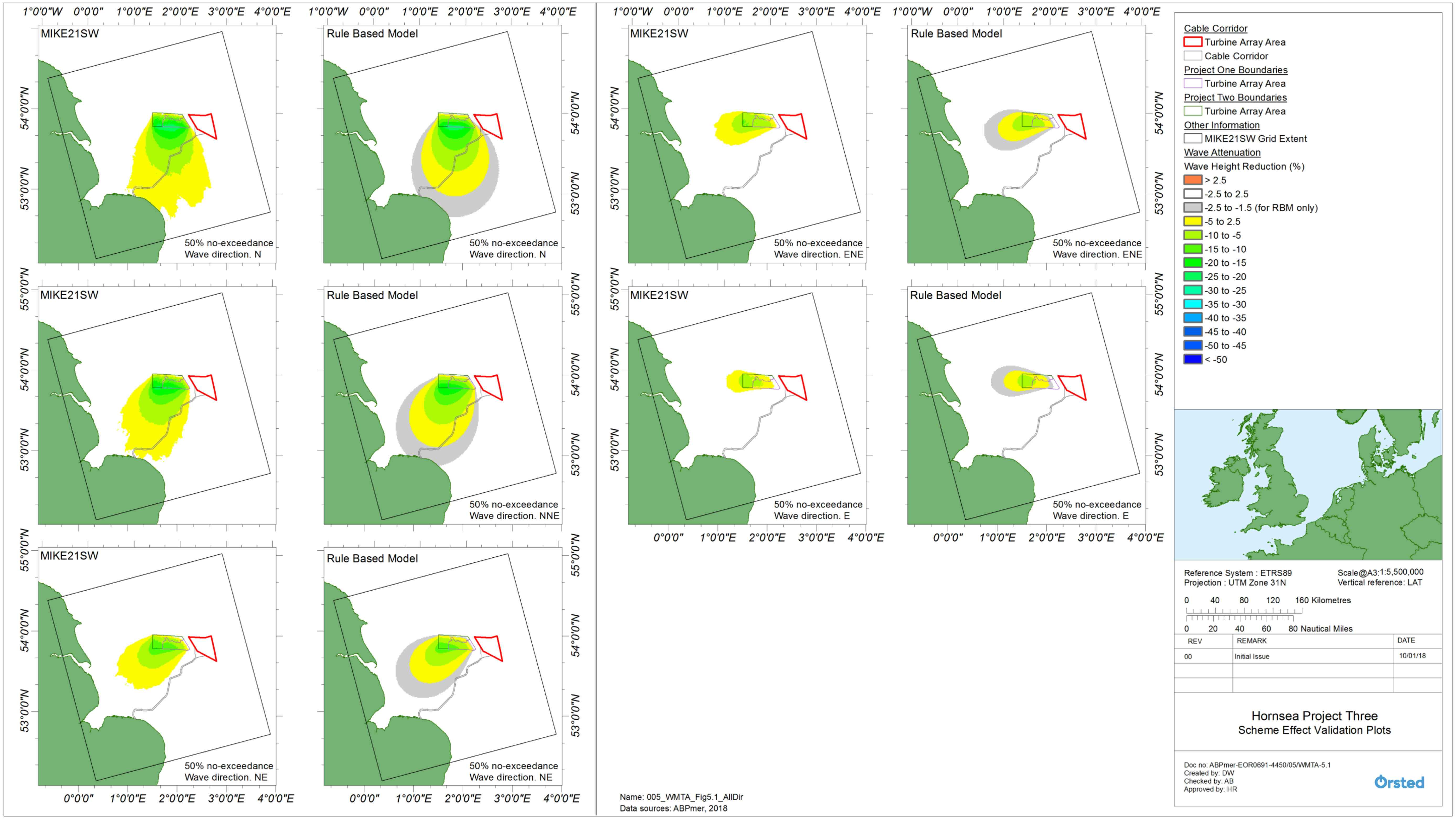


**Figure B.22: Validation of the rule based wave model against the MIKE21SW wave model, 50% no exceedance, all wave directions. Comparison of percentage difference in significant wave height between baseline and both the Hornsea Project One and Hornsea Project Two (consented designs) operational phases.**

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# Appendix C Scour

## C.1 Overview

C.1.1.1 In order to quantify the area of seabed that might be affected by scour (either the footprint of scour or scour protection), estimates of the theoretical maximum depth and extent of scour are provided below. Estimates are made of the primary scour, i.e. the scour pit directly associated with the presence of the main obstacle. The equilibrium primary scour depth for each foundation type has been conservatively calculated assuming the absence of any scour protection, using empirical relationships described in Whitehouse (1998). This analysis considers scour resulting from the characteristic wave and current regime, both alone and in combination.

C.1.1.2 The project description (volume 1, chapter 3: Project Description) provides maximum design scenario extents of scour protection for each foundation type. Scour protection might be applied around the base of some or all foundations depending upon the seabed conditions and other engineering requirements. By design, scour protection will largely prevent the development of primary scour, but may itself cause smaller scale secondary scour due to turbulence at the edges of the scour protection area.

## C.2 Assumptions

C.2.1.1 The following scour assessment for Hornsea Three reports the estimated equilibrium scour depth, which assumes that there are no limits to the depth or extent of scour development by time or the nature of the sedimentary or metocean environments. As such, the results of this study are considered to be conservative and provide an (over-) estimation of the maximum potential scour depth, footprint and volume. Several factors (discussed in section 11.4.1) may naturally reduce or restrict the equilibrium scour depth locally, with a corresponding reduction in the area and volume of change.

C.2.1.2 This study makes the basic assumption that the seabed comprises an unlimited thickness of uniform non-cohesive and easily eroded sediment. The Hornsea Three specific surveys indicate that whilst unconsolidated surficial sediment is present in many areas, this unit is typically thin (generally less than ~1 m thick) across much of the array. In practice, once exposed by initial scouring, the more erosion resistant sub-surface sedimentary units are expected to either reduce or prevent further scour, limiting the depth, extent and volume of scour accordingly.

C.2.1.3 The foundation types, dimensions and numbers used in the assessment are consistent with the project design information provided in volume 1, chapter 3: Project Description.

C.2.1.4 Reported observations of scour under steady current conditions (e.g. in rivers) generally show that the upstream slope of the depression is typically equal to the angle of internal friction for the exposed sediment (typically 32° in loose medium sand; Hoffmans and Verheil, 1997) but the downstream slope is typically less steep. In reversing (tidal) current conditions, both slopes will develop under alternating upstream and downstream forcing and so will tend towards the less steep or an intermediate condition. For the purposes of the present study a representative angle of internal friction (32°) will be used as the characteristic slope angle for scour development.

## C.3 Equilibrium scour depth

C.3.1.1 The maximum equilibrium scour depth (Se) is defined as the depth of the scour pit adjacent to the structure, below the mean ambient or original seabed level. The value of Se is typically proportional to the diameter of the structure and so is commonly expressed in units of structure diameter (D).

C.3.1.2 Scour depth decreases with distance from the edge of the foundation. The scour extent (Sextent) is defined as the radial distance from the edge of the structure (and the point of maximum scour depth) to the edge of the scour pit (where the bed level is again equal to the mean ambient or original seabed level). This is calculated on the basis of a linear slope at the angle of internal friction for the sediment, i.e.:

$$S_{extent} = \frac{S_e}{\tan 32^\circ} \approx S_e \times 1.6$$

(Eq. 1)

C.3.1.3 The scour footprint ($S_{footprint}$) is defined as the seabed area affected by scour, excluding the foundation's footprint, i.e.:

$$S_{footprint} = \pi\left(S_{extent} + \left(\frac{D}{2}\right)\right)^2 - \pi\left(\frac{D}{2}\right)^2$$

(Eq. 2)

C.3.1.4 The scour pit volume is calculated as the volume of an inverted truncated cone described by Equations 1 and 2 above, accounting for the presence of the foundation but excluding its volume.

## C.4 Scour assessment method: monopiles

C.4.1.1 The outline design of the proposed monopile structure is shown in Figure C.1. Compared to other more complex foundation types, scour around upright slender monopile structures in steady currents is relatively well-understood in the literature and is supported by a relatively large empirical evidence base from the laboratory and from the field. The maximum equilibrium scour depth, adjacent to the structure, below the mean seabed level ($S_c$), is typically proportional to the diameter of the monopile and is therefore expressed in units of monopile diameter (D).

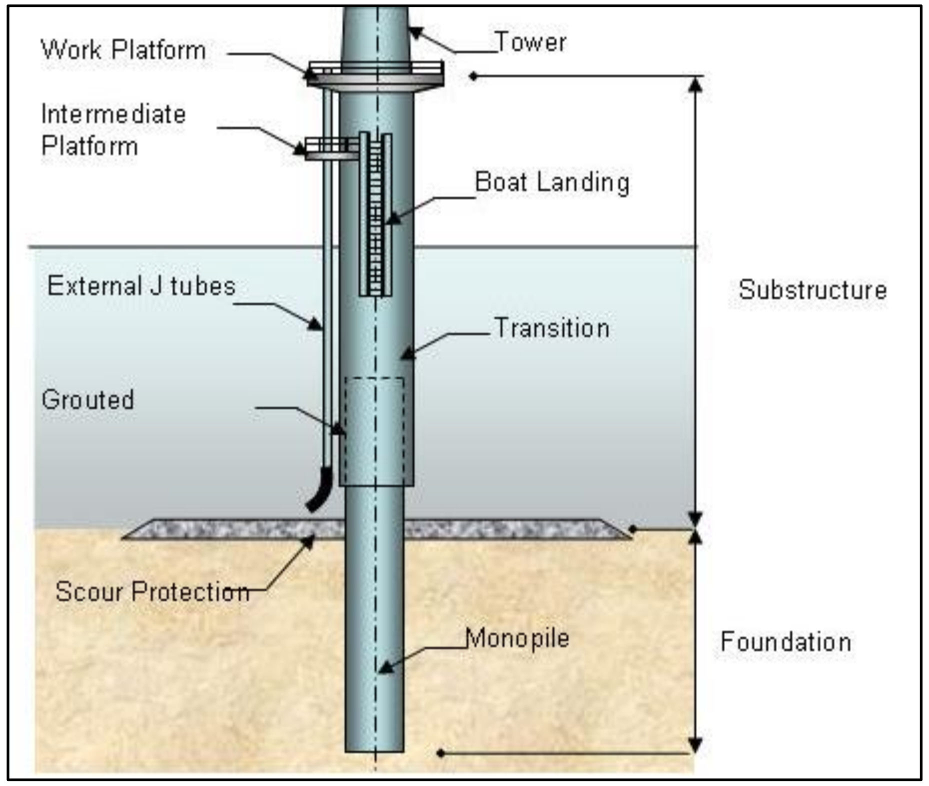


**Figure C.1: Outline design of a typical steel monopile foundation (with scour protection) (reproduced from SMart Wind, 2015d).**

***Under steady currents***

C.4.1.2 Breusers *et al*. (1977) presented a simple expression for scour depth under live-bed scour (i.e. scour occurring in a dynamic sediment environment) which was extended by Sumer *et al*. (1992) who assessed the statistics of the original data to show that:

$$\frac{S_c}{D} = 1.3 \pm \sigma_{Sc/D}$$

(Eq. 3)

C.4.1.3 Where $\sigma_{Sc/D}$ is the standard deviation of observed ratio $S_c$ /D. Based on the experimental data, $\sigma_{Sc/D}$ is approximately 0.7, hence, 95 % of observed scour falls within two standard deviations, i.e. in the range 0 < $S_c$/D < 2.7. Based on the central value $S_c$ = 1.3 D (as also recommended in DNV, 2016), the maximum equilibrium depth of scour for the largest diameter monopile (15 m) is estimated to be 19.5 m. The equivalent value for the smallest diameter monopile (10 m) is 13.0 m.

***Under waves and combined wave-current forcing***

C.4.1.4 The mechanisms of scour associated with wave action are limited when the oscillatory displacement of water at the seabed is less than the length or size of the structure around which it is flowing. This ratio is typically parameterised using the Keulegan-Carpenter (KC) number:

$$KC = \frac{U_{0m} T}{D}$$

(Eq. 4)

C.4.1.5 Where $U_{0m}$ is the peak orbital velocity at the seabed (e.g. using methods presented in Soulsby, 1997) and T is the corresponding wave period. Sumer and Fredsøe (2001) found that for KC < 6, wave action is insufficient to cause significant scour in both wave alone and combined wave-current scenarios.

C.4.1.6 Values of KC are < 6 for monopiles in the Hornsea Three array area, for a range of extreme wave conditions (see Table B.3) and for the full expected range of tidally affected water depths across the site (approximately -26.6 mLAT to -72.7 mLAT). Therefore, it is predicted that waves do not have the potential to contribute to scour development around monopiles in the Hornsea Three array area.

**Table B.3: Extreme omni-directional wave conditions considered.**

| Return period (years) | Significant wave height, Hs (m) | Zero crossing period, Tz (s) |
|---|---|---|
| 1:1 | 4.7 | 8.0 |
| 1:10 | 6.2 | 9.2 |
| 1:50 | 7.2 | 9.8 |

C.4.1.7 The value of $U_{0m}$ for given (offshore or deep water) wave conditions depends upon the local water depth, which varies between approximately -26.6 mLAT to -72.7 mLAT within the array due to variations in absolute bathymetry and relative water level; the influence of shoaling and wave breaking have been ignored in the present study (a conservative assumption).

## C.5 Scour assessment method: jacket foundations

C.5.1.1 The outline design of the proposed four legged jacket foundation for turbines is shown in Figure C.2. Above the seabed jacket foundations comprise a lattice of vertical primary members and diagonal cross-member bracing, up to 4 m in diameter; it is assumed that either no near-bed horizontal cross-member bracing is required, or that it is sufficiently high above the bed to not induce significant local scour. The four legged jacket foundation will have a nominally square plan view cross-section with base edge dimensions of between 32 m and 40 m (Volume 1, Chapter 3: Project Description). bed horizontal cross-member bracing is required, or that it is sufficiently high above the bed to not induce significant local scour. The four legged jacket foundation will have a nominally square plan view cross-section with base edge dimensions of between 32 m and 40 m (Volume 1, Chapter 3: Project Description).

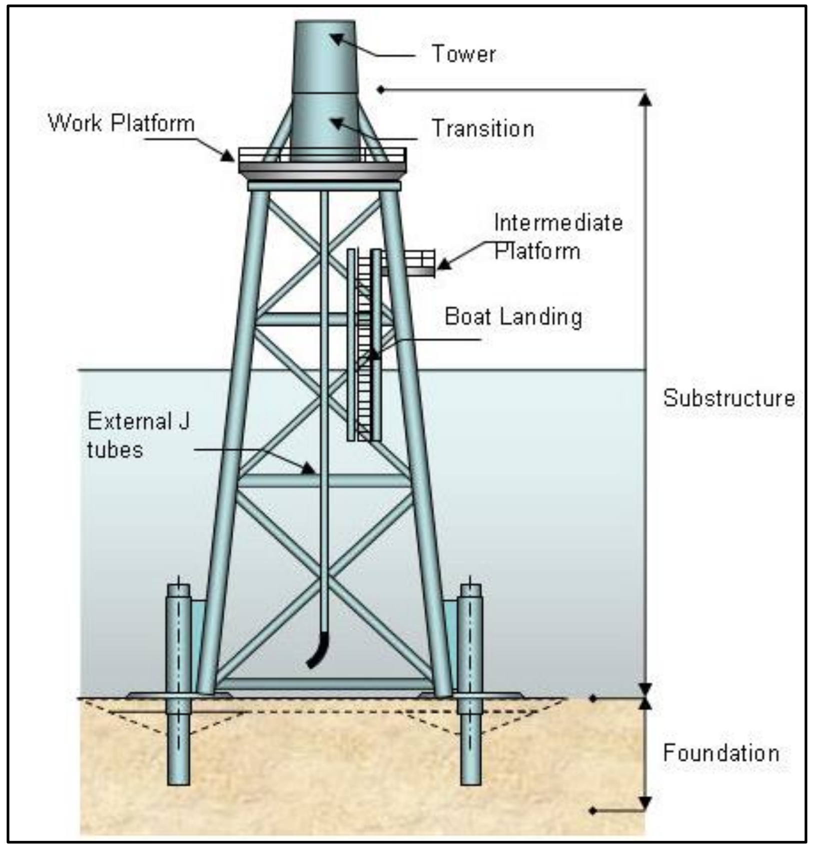


**Figure C.2: Outline design of a typical jacket foundation (reproduced from SMart Wind, 2015d).**

C.5.1.2 The jacket foundation is anchored to the seabed at each corner by a pile driven into the seabed, between 3.3 and 4.6 m in diameter. A jacket foundation structure may result in the occurrence of both local and group or global scour. The local scour is the local response to individual structure members.

***Under steady currents***

C.5.1.3 Under steady currents alone, the equilibrium scour depth around the vertical members of the structure base can be assessed using the same methods as for monopiles, unless significant interaction between individual members occurs. The potential for such interaction is discussed below.

C.5.1.4 The main scour development will be in proportion to the size of the largest exposed member near to the seabed. In this case, the largest exposed member will be the jacket leg: for the largest jacket foundation this will have a diameter of 4.6 m. Using equation 3, the scour depth for the largest jacket foundation is therefore estimated as 6.0 m. The equivalent value for the smallest jacket foundation (leg diameter of 3.3 m) is 4.3 m.

C.5.1.5 In the case of currents, inter-member interaction has been shown to be a factor when the gap to pile diameter ratio (G/D) is less than 3. In this case limited experiments by Gormsen and Larson (1984) have shown that the scour depth might increase by between 5 % and 15%. However, in the case of the present study the gap ratio for members at the base of the jacket foundation structure is much greater than 3, and so no significant in-combination change is expected.

C.5.1.6 Empirical relationships also presented in Sumer and Fredsøe (2002) indicate that the depth of group scour (measured from the initial sediment surface to the new sediment surface surrounding local scour holes) for an array of piles similar to a jacket foundation (2x2) can be approximated as 0.4D (i.e. approximately 1.8 m based on 4.6 m diameter jacket leg). On the basis of visual descriptions of group scour pits, their extent from the edge of the structure is estimated as half the width of the structure and following a broadly similar plan shape to that of the jacket foundation (i.e. square).

C.5.1.7 Together, the predicted maximum scour depth at the corner piles (6.0 m) and the group scour (1.8 m) is conservatively consistent with evidence from the field reported in Whitehouse (1998), summarising another report that scour depths of between 0.6 m and 3.6 m were observed below jacket structures in the Gulf of Mexico (although these could potentially be constrained from the maximum possible equilibrium scour depth by environmental factors and could also be subject to uncertainties in the seabed reference datum against which to measure the scour).

C.5.1.8 On the basis of the proposed jacket design, the diagonal bracing members are not predicted to induce seabed scouring due to the distance of separation from the seabed.

***Under waves and combined wave-current forcing***

C.5.1.9 Values of the KC parameter (Eq. 4) were calculated for a 4.6 m diameter jacket leg from the extreme wave conditions found at the site (Table B.1)). Values of KC are less than 6 over the full expected range of tidally affected water depths across the site (approximately -26.6 mLAT to -72.7 mLAT) and so it is predicted that waves do not have the potential to contribute to scour development around the base of the jacket foundations.

C.5.1.10 The diagonal bracing members will have a smaller diameter and so a larger KC value. However, they are again not predicted to induce seabed scouring due to the distance of separation from the seabed. For moderate KC numbers a sufficient distance to avoid scour is approximately one diameter for a horizontal member, increasing to approximately three diameters under increasing KC numbers.

C.5.1.11 As such, little or no significant additional scour is predicted to result from waves, either alone or in combination with currents.

## C.6 Scour assessment method: gravity base foundations

C.6.1.1 The outline design of the proposed gravity base foundation is shown in Figure C.3. The foundation is characterised as a round base plate upon which sits a circular cross-section cone with a base diameter of between 41 m (for the smallest option) and 53 m (for the largest).

C.6.1.2 The evidence base for scour associated with gravity base foundation installations is relatively limited in comparison to that for monopiles and typically refers to oil and gas platforms which have a wide range of shapes and designs. Attempts to produce empirical relationships are complicated by this diversity of gravity base foundation structures.

C.6.1.3 The pattern and extent of scouring and the location of the point of maximum scouring may also vary depending upon the gravity base foundations relative size and shape. For the purposes of the present assessment, scour is assumed to be equally present at the predicted depth around the whole perimeter of the gravity base foundation, decreasing in depth with distance from the base edge to the ambient bed level at the angle of internal friction for the sediment (32°).

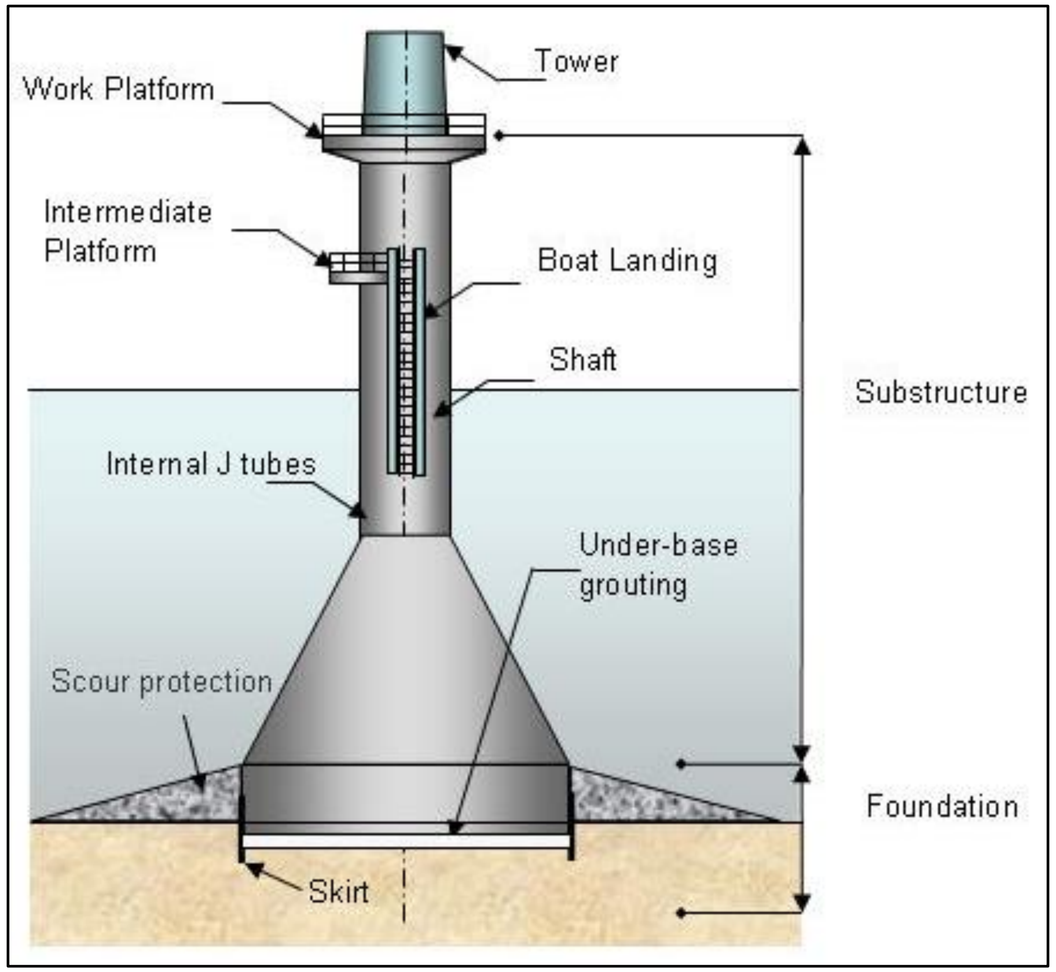


**Figure C.3: Outline design of a gravity base foundation (reproduced from SMart Wind, 2015d).**

***Under steady currents***

C.6.1.4 Hoffmans and Verheij (1997) presented the Khalfin (1983) current-only scour predictor for a gravity base foundation with the following modified features:

- The pile diameter was replaced by a characteristic length, $D_c$, taken as the average of the length and breadth of the gravity base foundation;
- The flow depth, h, in the water depth to diameter ratio $h/D_c$ was replaced by the gravity base foundation height, $h_c$; and
- The undisturbed depth-averaged flow velocity was multiplied by $\alpha_c/2$ with $\alpha_c$ = 2 for a circular structure, and $\alpha_c$ = 2.3 for a rectangular gravity base foundation expressing the additional turbulence generated at the corners of the structure. The coefficient $\alpha_c$ is an influence factor that represents the flow enhancement near the structure caused by the structure.

C.6.1.5 The equilibrium scour depth, S, is then given by:

$$\frac{S}{D_c} = 8.96\left(2\frac{0.5a_cU}{U_{cr}} - 1\right)\left(\frac{h_c}{D_c}\right)^{1.43}\left(\frac{(0.5a_cU)^2}{gh}\right)^N$$

With $U/U_{cr} = 1$ for $U>U_{cr}$

And $$N = 0.83\left(\frac{h_c}{D_c}\right)^{0.34}$$

Where: $U_{cr}$ is the value of depth-averaged flow velocity for initiation of sediment motion (m/s); and

g is the gravitational acceleration constant (9.81 m/s$^2$)

(Eq. 5)

C.6.1.6 Assuming $h_c$ = h = 40.8 m and $U>U_{cr}$, the maximum equilibrium depth of scour for the largest diameter gravity base foundation ($D_c$ = 53 m) is estimated to be 1.59 m. The equivalent value for the smallest diameter gravity base foundation ($D_c$ = 41 m) is 1.09 m.

***Under waves and combined wave-current forcing***

C.6.1.7 The large scale of the gravity base foundation structures in relation to both water depth and wave orbital excursion length mean that the processes governing structure-flow interaction and scour are different from that described in relation to monopile and jacket structures. As such, relationships for scour associated with a shallow conical top gravity base foundation for waves alone are also not readily available from the literature. However, Whitehouse (2004) provides a relationship for a 'girder top' gravity base foundations, predicting equilibrium scour depth in response to waves alone of:

$S_e$ = 0.04D

(Eq. 6)

C.6.1.8 Yielding a value of between 1.6 m and 2.1 m for a 41 m and 53 m diameter gravity base foundation, respectively. Empirical results from physical model testing by Whitehouse (2004) suggest that the maximum scour depth around a conical top gravity base foundation (broadly similar to that proposed here) under combined wave-current conditions will be:

12.1.1.1 $S_e$ = 0.064D

(Eq. 7)

C.6.1.9 Yielding a value of between 2.6 m and 3.4 m for a 41 m and 53 m diameter gravity base foundation, respectively.

## C.7 References

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