NORTH FALLS

Offshore Wind Farm

ENVIRONMENTAL STATEMENT

Appendix 8.1 North Falls Wave Assessment

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NORTH FALLS
Offshore Wind Farm

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REPORT

North Falls Wave Assessment

Extreme Wave Modelling

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1 Introduction

1.1 Background

Royal HaskoningDHV has been commissioned to undertake a wave modelling study to understand the potential changes in the wave climate caused by the development of the North Falls offshore wind farm (OWF), in the North Sea off the East Coast of the UK. The location of the project site is presented in **Figure 1-1** below.

Surrounding windfarm sites (either in planning phase or constructed) are also included in the wave modelling study to understand the potential cumulative effect of multiple arrays on the wave climate.

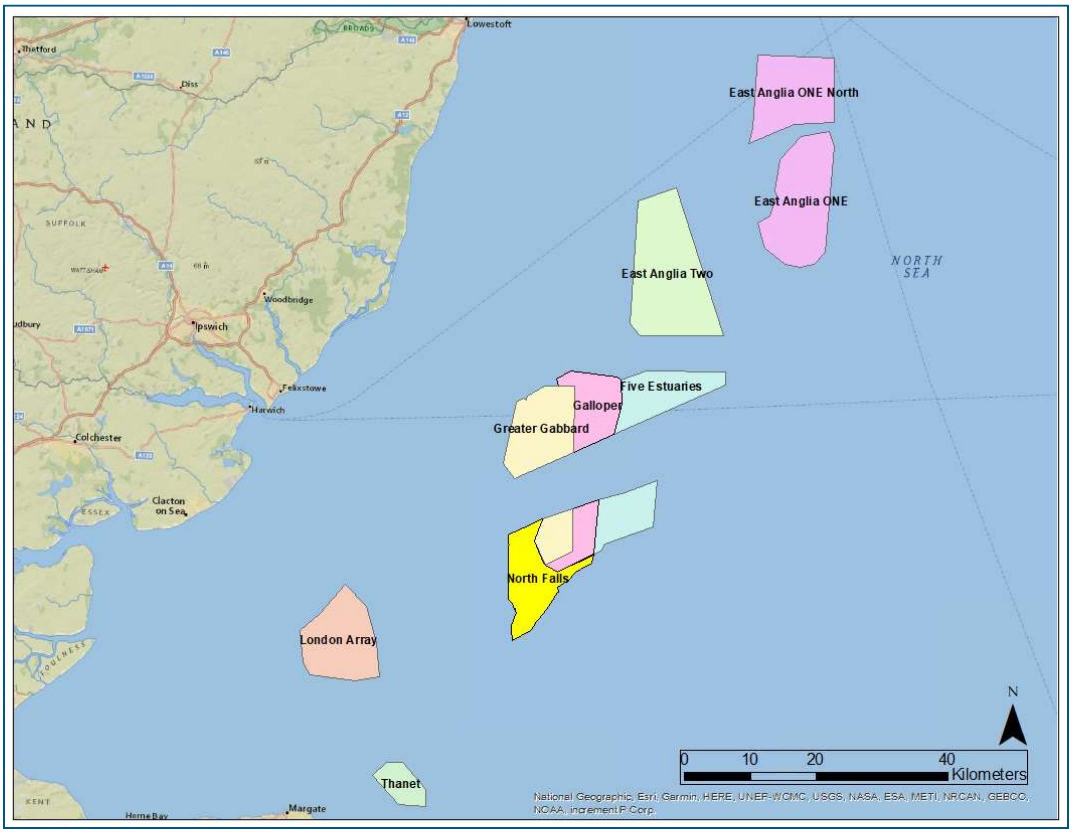

Figure 1-1: Location of project site and surrounding windfarms

1.2 Approach

The aim of the modelling study is to quantify the effect of the North Falls OWF on the surrounding wave climate. To understand this, modelling approach adopted by RHDHV is summarised below:

1. Carry out model development and model calibration of a spectral wave model (MIKE21-SW), using measured wave data close to the North Falls OWF - a detailed overview of this is provided in the technical note in **Annex D**;

2. Obtain long-term hindcast wave and wind dataset (40+ years) at the offshore model boundaries, from MetOffice and / or ERA5 reanalysis;

3. Carry out extreme value analysis of long-term hindcast wave data, to define offshore extreme wave and wind climate for a range of return periods (1 in 1 year, 1 in 50 year and 1 in 100 year) and directions (north, east and south) (**Section 2.2**);

4. Obtain reflection coefficients for turbine structures using RHDHV database of values derived from local scale 3D model, 'DIFFRACT';

5. Simulate the range of extreme wave climate scenarios (return period and directions) for 4 OWF layouts, as outlined in **Section 2.4**;

6. Present results showing the % change in significant wave height due to North Falls OWF, "North Falls OWF + existing OWF's" and "North Falls OWF + existing OWF + planned OWF's".

2 Model Development

2.1 Model Calibration

A detailed overview of the wave model calibration study is presented in the technical note in **Annex D**. A summary of model calibration results are presented in this section, which highlight the suitability of the wave model to simulate the wave climate at the North Falls project site.

The model calibration included waves from north (**Figure 2-1**), east (**Figure 2-2**), south-east (**Figure 2-3**), south (**Figure 2-4**) and south-west (**Figure 2-5**).

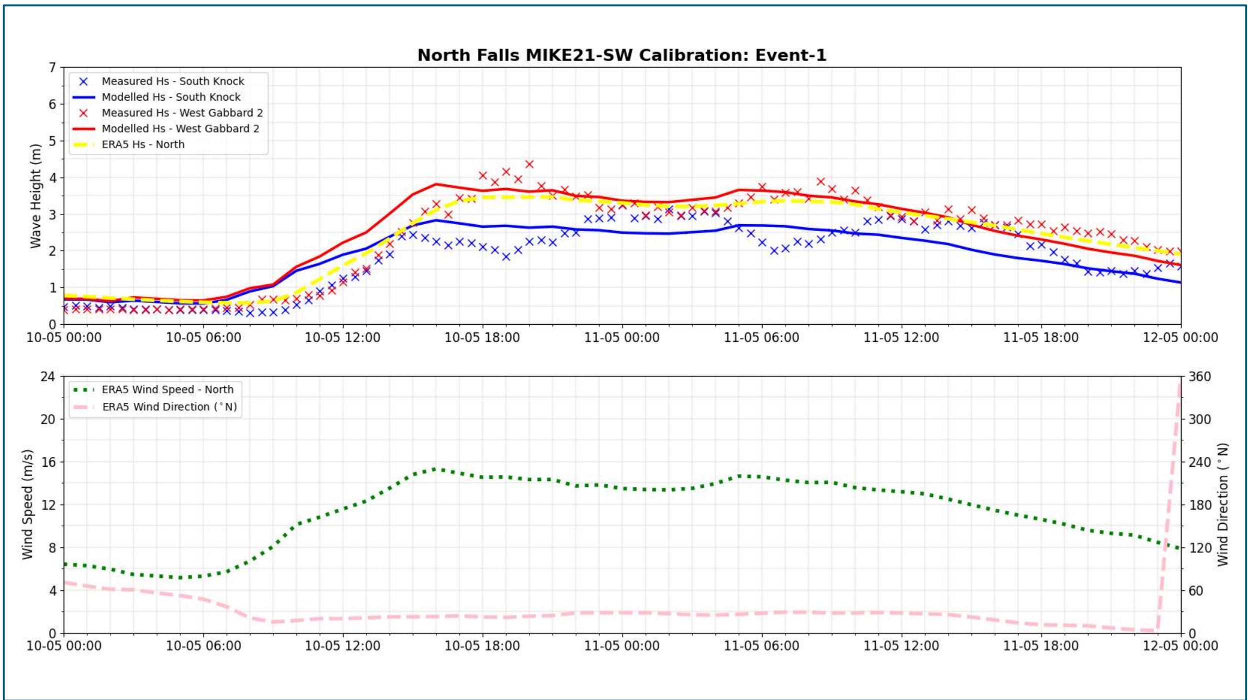

Figure 2-1: Wave model calibration - from north

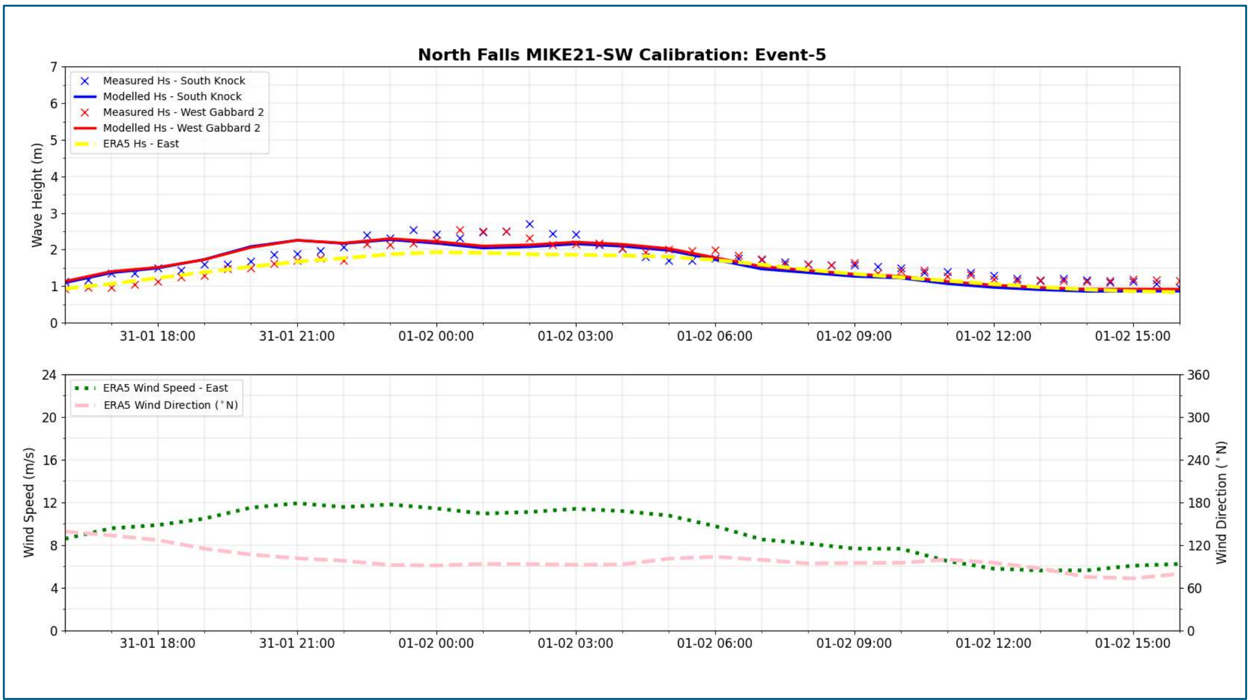

Figure 2-2: Wave model calibration - from east

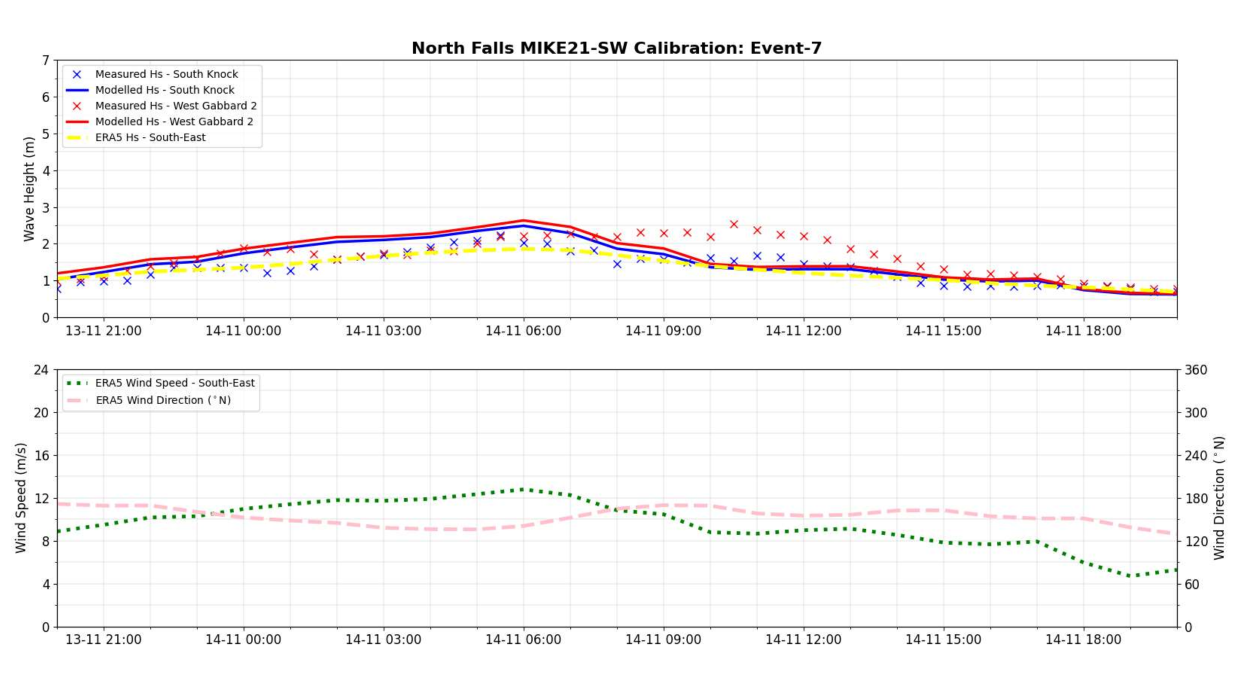

Figure 2-3: Wave model calibration - from south-east

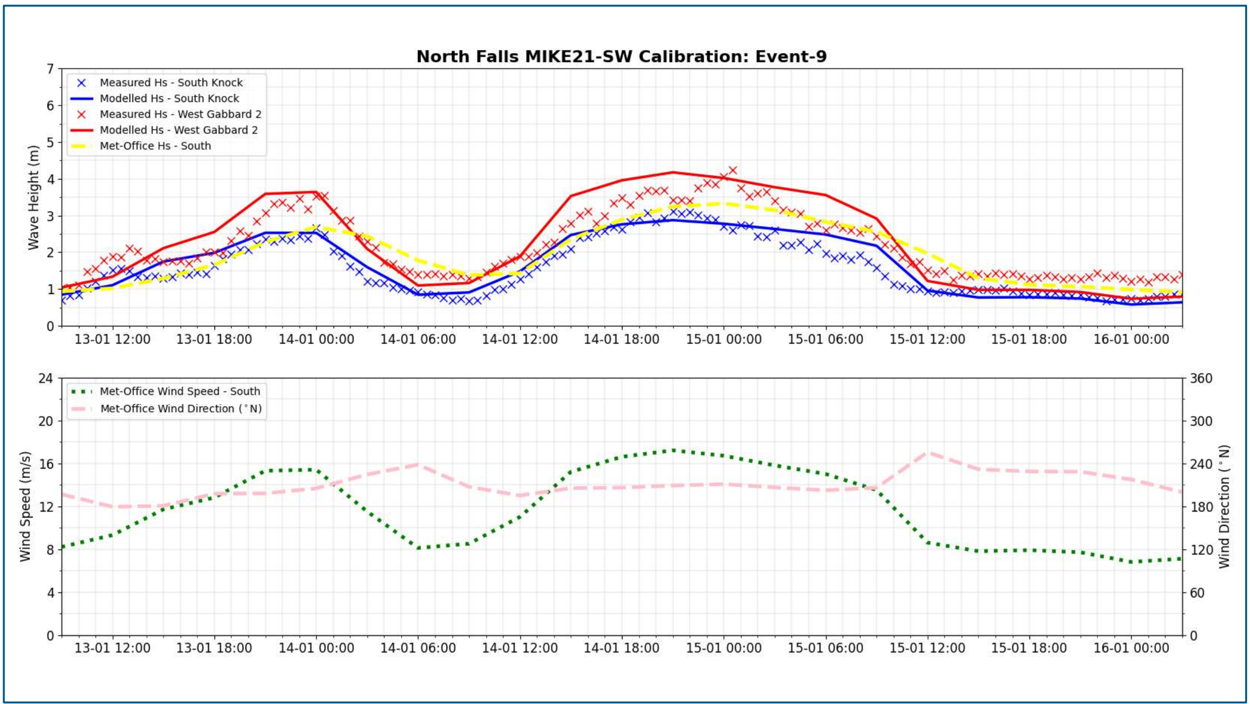

Figure 2-4: Wave model calibration - from south

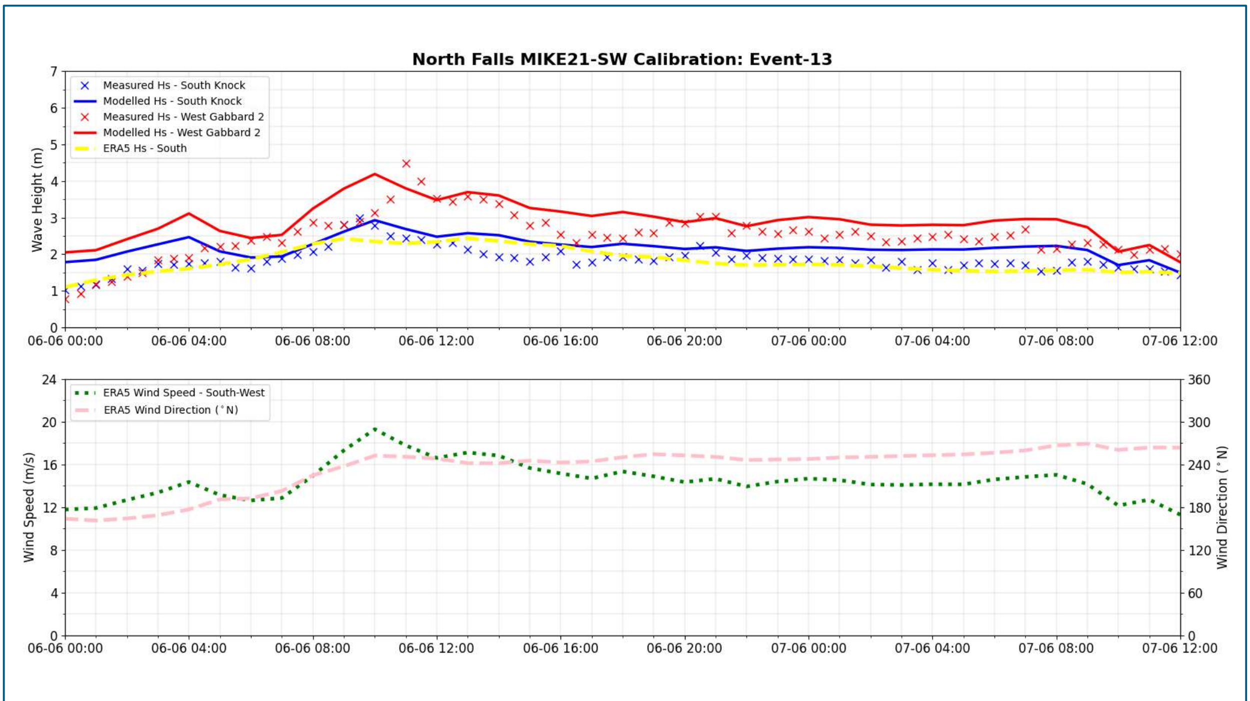

Figure 2-5: Wave model calibration - from south-west

2.2 Extreme Value Analysis

2.2.1 Data

An extreme value analysis of wave and wind climate was carried out to determine the offshore forcing conditions for the North Falls OWF wave impact assessment. To understand the cumulative effect of OWF structures on the surrounding wave climate, the offshore wave / wind direction which is of interest for the North Falls wave assessment was determined to be, north, north-east, east and south.

Models simulating waves from north, north-east and east would be forced with an offshore extreme wave condition and ‘matching’ wind speed. Model simulating waves from south which are locally generated wind waves are forced with an extreme wind speed and ‘matching’ wave conditions at the offshore boundary.

The two datasets used for the extreme analysis are the hindcast ERA5 reanalysis wave and wind dataset and the Met Office UK regional WaveWatch III hindcast model. The ERA5 reanalysis dataset is a 43 year timeseries of wave and wind climate between 1980 - 2022. The Met Office dataset is a series of three way frequency tables covering 43 years (1980 - 2022). The higher resolution Met Office UK regional hindcast wave model is used for waves approaching from east, due to the proximity of the offshore model boundary to coastline.

The input data for the extreme value analysis of each offshore wave / wind direction is summarised below and presented in **Figure 2-6**:

- From north and north-east - extreme analysis of ERA5 hindcast wave data (52.5° (lat), 2.5° (long)), along with ‘matching’ wind speed (Hs / Wind Speed) derived for each directional sector from ERA5 wind data;

- From east - extreme analysis of waves using Met Office UK regional hindcast wave data (51.770° (lat), 2.748° (long)), along with ‘matching’ wind speed (Hs / Wind Speed) derived for each directional sector from ERA5 wind data;

- From south - extreme analysis of ERA5 hindcast wind data (51.75° (lat), 1.75° (long)), along with ‘matching’ significant wave height (Wind Speed / Hs) derived for each directional sector from ERA5 wave data at the southern model boundary (51.0° (lat), 1.5° (long)).

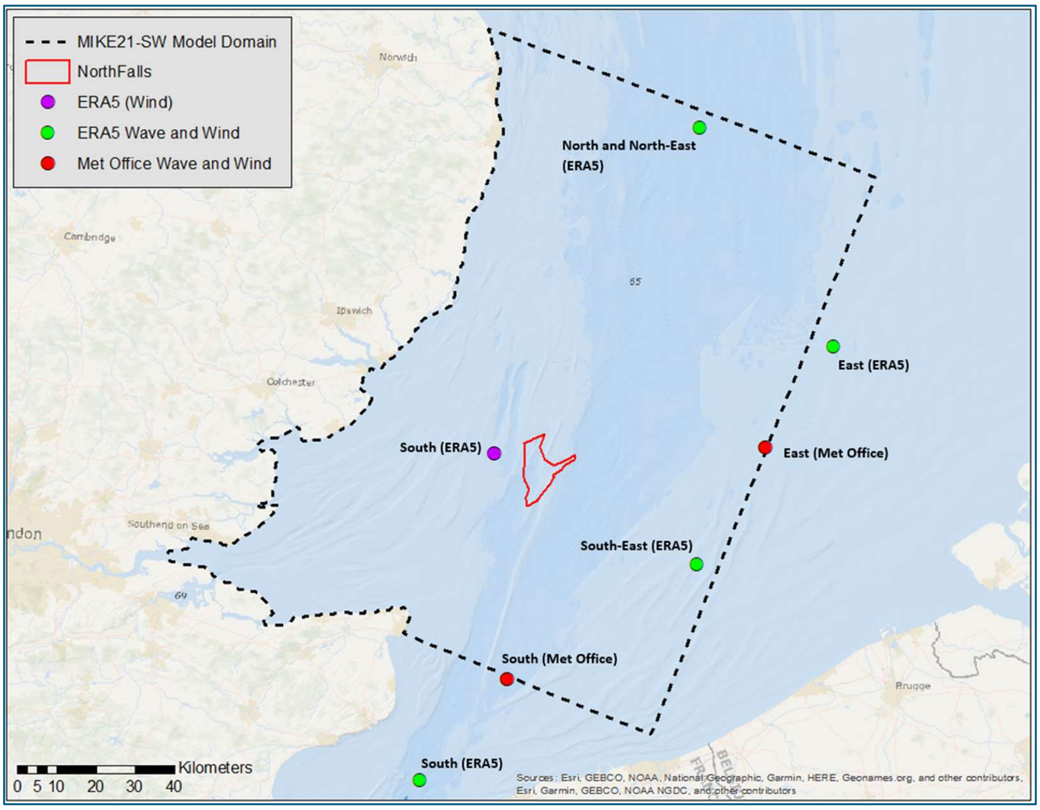

Figure 2-6: Wave model input data points

2.2.2 Method

An in-house tool 'EXTREME' was utilised for the extreme value analysis of wind and wave data. The tool requires frequency tables defining the number of occurrences of significant wave height (wind speed) at 0.5m (2m/s) bands, for each 30° directional sector. At the northern ERA5 wave data point, wave directional sectors 300° (285° - 315°), 330° (315° - 345°), 0° (345° - 15°), 30° (15° - 45°), and 60° (45° - 75°) were considered in the analysis. At the eastern Met Office point, wave directional sectors 90° (75° - 105°), 120° (105° - 135°) and 150° (135° - 165°) were considered in the analysis. Finally, at the southern ERA5 wind data point, wind directional sectors 180° (165° - 195°), 210° (195° - 225°) and 240° (225° - 255°) were considered in the analysis.

The North Falls wave assessment requires analysis for the 1 in 1 year, 1 in 50 year and 1 in 100 year extreme wave climates.

Gumbel and Weibull fitting methods were applied to the data to give a statistical distribution of wave heights for a range of return periods. In all cases, the Gumbel fitting method was preferred as a conservative estimate of extreme conditions.

To derive a peak wave period for the corresponding extreme wave heights, a series of wave period coefficients were calculated from the frequency tables at each hindcast data point. These coefficients define a relationship between wave height and wave period for a given wave height, for each directional sector. Resulting in an estimate of peak wave period.

To derive a 'matching' wind speed (or wave height for south point) and directional spreading, simple wave height / wind speed and wave height / directional spreading relationships were defined based on the long-term hindcast dataset, at each hindcast data point and for each directional sector. An example 'matching' wind speed and directional spreading relationship curve is presented in **Figure 2-7**, for the 330°N directional sector at the northern hindcast data point.

The fitting distributions for the Gumbel Method and all wave parameter relationships for the simulated directional sectors, are presented in **Annex A**.

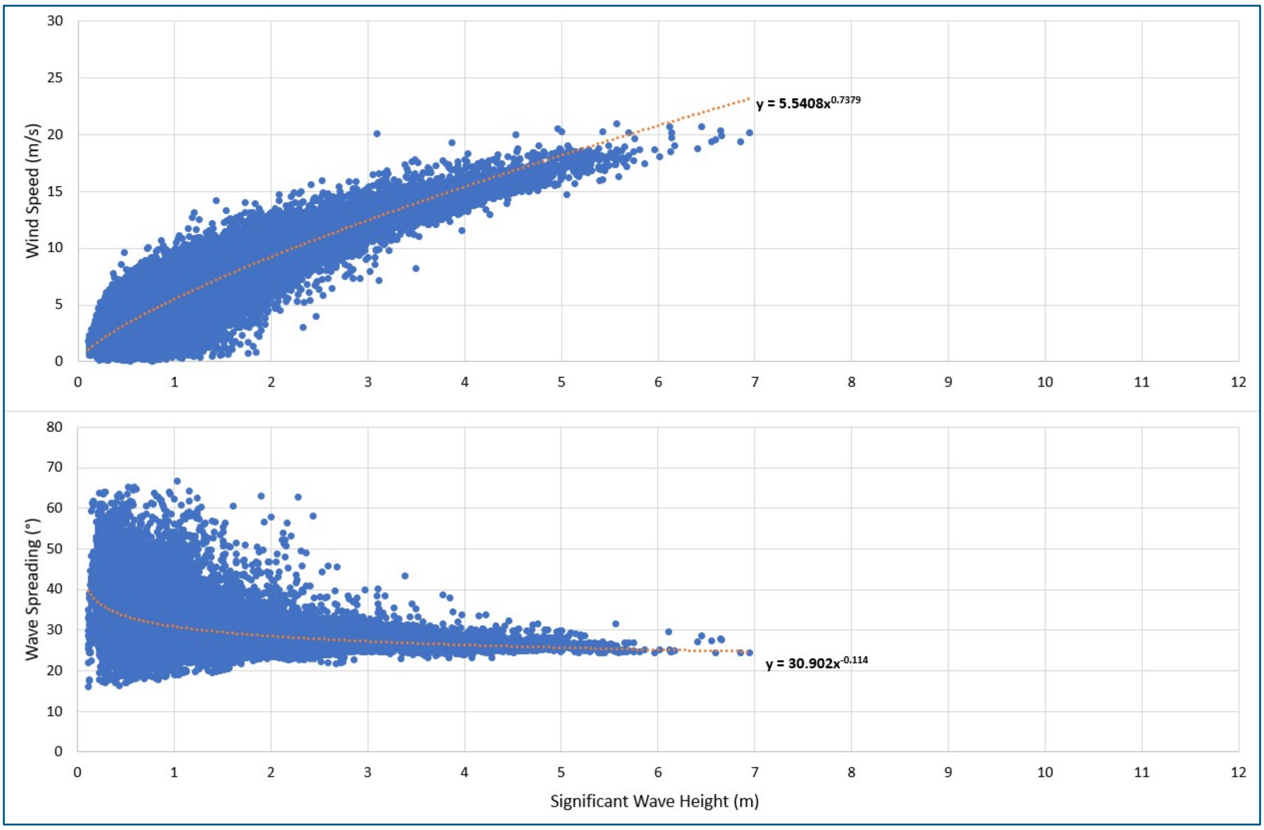

Figure 2-7: Hs / wind speed and Hs / wave spreading relationships for 330°N sector - north point

2.2.3 Results

The results from the extreme wave and wind analysis are presented in **Table 2-1**, **Table 2-2**, **Table 2-3** and **Table 2-4**, for the north (x2), east and south data points, respectively, for the 1 in 1 year, 1 in 50 year and 1 in 100 year return periods. The tables include the other parameters derived from the 'matching' relationships. The values in these tables are input into the MIKE21-SW model as boundary conditions for each scenario.

For each hindcast data point, the directional sector with the largest extreme wave height was considered for the wave assessment. Given the 330°N and 0°N directional sectors were very similar for the north hindcast data point, both were used in the wave modelling assessment.

Within the range of each 30° directional sector (+/- 15°), the modelled wave direction was selected based on the potential cumulative impact from OWF's on the surrounding sensitive areas and nearshore coastal regions. This is summarised below:

- North point - 330°N (modelled direction: 345°N) and 0°N (modelled direction: 15°N)

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- East point - 90°N (modelled direction: 105°N)
- South point - 210°N (modelled direction: 210°N)

Table 2-1: Extreme wave height (H_s) and 'matching' parameters for 330°N directional sector

Return Period (Yr)	Significant Wave Height, H_s (m)	Peak Wave Period, T_p (s)	Wave Direction (°N)	Wave Spreading (°)	Wind Speed (m/s)
1 in 1	6.09	11.23	345	25.15	21.02
1 in 50	9.02	13.10	345	24.05	28.08
1 in 100	9.54	13.47	345	23.90	29.27

Table 2-2: Extreme wave height (H_s) and 'matching' parameters for 0°N directional sector

Return Period (Yr)	Significant Wave Height, H_s (m)	Peak Wave Period, T_p (s)	Wave Direction (°N)	Wave Spreading (°)	Wind Speed (m/s)
1 in 1	5.95	11.15	15	25.57	17.94
1 in 50	8.85	13.60	15	25.10	24.08
1 in 100	9.36	13.99	15	25.03	25.10

Table 2-3: Extreme wave height (H_s) and 'matching' parameters for 90°N directional sector

Return Period (Yr)	Significant Wave Height, H_s (m)	Peak Wave Period, T_p (s)	Wave Direction (°N)	Wave Spreading (°)	Wind Speed (m/s)
1 in 1	1.96	5.89	105	28.22	9.98
1 in 50	3.36	7.45	105	27.49	14.30
1 in 100	3.61	7.73	105	27.39	15.00

Table 2-4: Extreme wind speed and 'matching' parameters for 210°N directional sector

Return Period (Yr)	Wind Speed (m/s)	Wind Direction (°N)	Significant Wave Height, H_s (m)	Peak Wave Period, T_p (s)	Wave Spreading (°)
1 in 1	23.35	210	4.79	8.18	26.40
1 in 50	32.30	210	8.45	10.08	25.49
1 in 100	33.89	210	9.19	10.39	25.35

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2.3 Model Setup

2.3.1 Software Description

The study used the MIKE21-SW (Spectral Wave) wave transformation model, developed by Danish Hydraulic Institute (DHI), a 2-dimensional spectral wind-wave model for simulating the growth, decay and transformation of wind and swell waves in offshore and coastal areas.

The MIKE21-SW model includes the following physical processes which are relevant to this study of North Falls windfarm:

- Wave growth by action of wind;
- Non-linear wave-wave interaction;
- Dissipation due to bottom friction and depth induced wave breaking;
- Wave refraction and shoaling;
- Wave diffraction; and
- Effect of time-varying water depth.

2.3.2 Model Mesh

The MIK21-SW model utilises a flexible, unstructured triangular mesh approach which enables complex geometries to be accurately resolved throughout the model domain and higher computational efficiency by setting a coarse computational grid in deeper areas offshore and reducing the resolution of the grid in areas of interest near to the project site.

The extent of the model domain is presented in **Figure 2-6**. The computational mesh within the model domain is refined around the project site, as well as other neighbouring windfarms which are of importance to this study. The coarse grid resolution (1,000m element length) is furthest away from the site and is gradually refined to a minimum resolution of (75-100m element length) at the North Falls site. The computational mesh is presented in **Figure 2-8**.

2.3.3 Boundary Conditions

For all simulations the MIKE21-SW model is run with a constant Mean High Water Springs (MHWS) water level throughout the domain of 2.4mCD, based on the Admiralty Tide Tables (2023) information at Lowestoft.

Table 2-1 to **Table 2-4** outline the wave and wind boundary conditions for each scenario. Where wind is applied as spatially constant throughout the domain and waves are applied as constant along the offshore MIKE21-SW model boundary. The required parameters for the wave and wind boundary conditions are as follows:

- Significant wave height, Hs (m);
- Peak wave period, Tp (s);
- Mean wave direction, MWD (°N); and
- Directional standard deviation, DSD (wave spreading, °)

- Wind Speed, U10 (m/s)
- Wind Direction (°N)

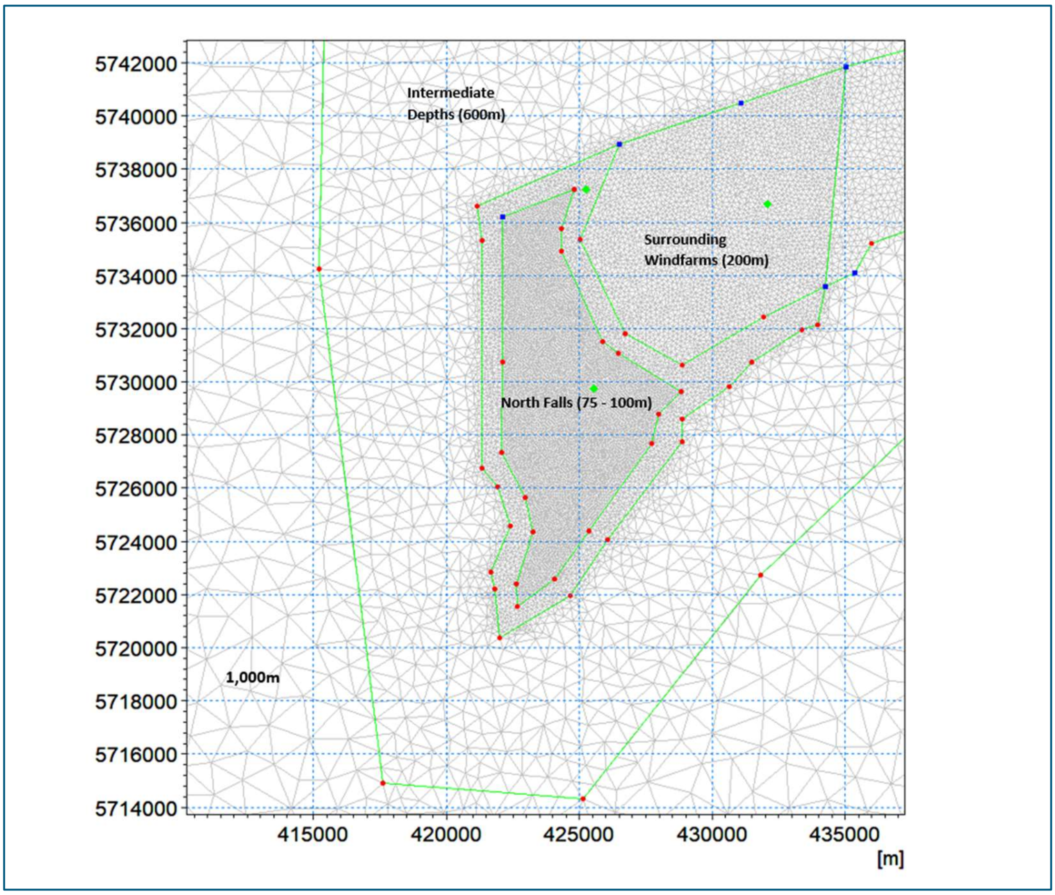

Figure 2-8: MIKE21-SW computational mesh

2.3.4 Model Settings

The key settings for the MIKE21-SW model are summarised in **Table 2-5**, these settings were established through the wave model calibration study (**Annex D**).

Table 2-5: MIKE21-SW model settings

MIKE21 Parameter	Chosen Parameter
Basic Equations	Spectral Formulation: Fully Spectral Time Formulation: Quasi Stationary
Spectral Discretization	360 degree rose: 48 directions
Solution Technique	Low order, fast algorithm Iterations: 500
Diffraction	None
Wave Breaking	Gamma: 0.8 Alpha: 1 Gamma (wave steepness): 1
Bottom Friction	Nikuradse Roughness, Kn: 0.015

MIKE21 Parameter	Chosen Parameter
Air-sea Interaction	Growth Parameter: 1.4 Type: Coupled Charnock Parameter: 0.0185
Friction Velocity	Type: Simple Cap Value: 0.06
White Capping	Cdis: 1.1 δdis: 0.5

2.4 OWF Layouts

The North Falls wave modelling assessment included a range of OWF layouts, to understand all potential implications to the surrounding wave climate. For each OWF, the model includes locations of OSP's and WTG's. These scenarios are summarised below and in **Figure 2-9**. Any offshore windfarms outside of this model domain are not included in the wave assessment.

Layout 1 - Baseline

This baseline layout includes no OWF structures within the model.

Layout 2 - Existing OWF's

For this layout, the model includes structures for existing wind farms currently in operation (*London Array, Gunfleet Sands, Thanet, Galloper, Greater Gabbard and East Anglia ONE*).

Layout 3 - North Falls + Existing OWF's

For this layout, the model includes structures for north falls wind farm and existing wind farms currently in operation (*London Array, Gunfleet Sands, Thanet, Galloper, Greater Gabbard and East Anglia ONE*).

Layout 4 - North Falls + Proposed / Consented OWF's + Existing OWF's

For this layout, the model includes structures for north falls wind farm, all proposed / consented OWF's (*Five Estuaries, East Anglia ONE North, East Anglia TWO*) and existing wind farms currently in operation (*London Array, Gunfleet Sands, Thanet, Galloper, Greater Gabbard and East Anglia ONE*).

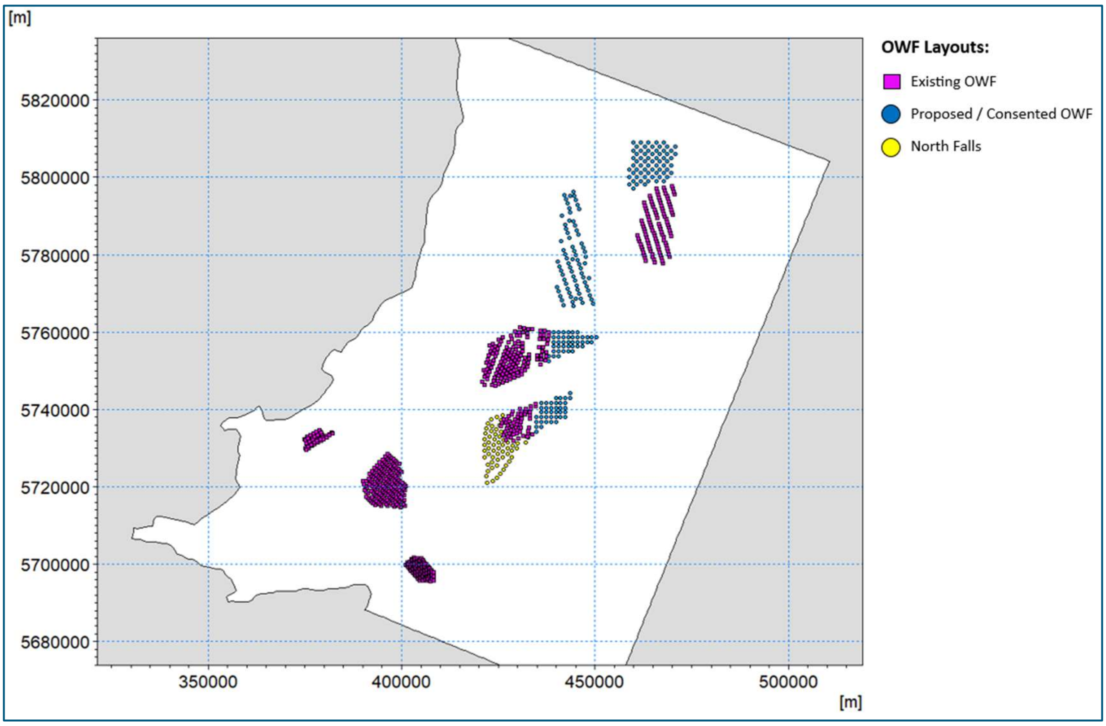

Figure 2-9: OWF layouts

2.5 OWF Structures

The dimensions of each Wind Turbine Generator (WTG) and Offshore Sub-station Platform (OSP) structure for all OWF's applied in the MIKE21-SW are summarised in **Table 2-6**.

Table 2-6: WTG and OSP dimensions for each windfarm

OWF	WTP Foundation			OSP Foundation		
	No.	Type	Dimensions	No.	Type	Dimensions
North Falls	57	GBS	65m base 15m top cone	2	GBS	65m base 15m top cone
Galloper	56	Monopile	7.5m diameter	1	Jacket	4 legs, 3m diameter
Greater Gabbard	140	Monopile	6.5m diameter	2	Jacket	4 legs, 3m diameter
Five Estuaries	79	GBS	55m base 15m top cone	2	jacket	6 legs, 3.5m diameter
East Anglia ONE	102	Monopile	6.5m diameter	2	Monopile	6.5m diameter
East Anglia ONE North	60	GBS	60m base 13m top cone	4 1 1	Electric Accomo. Met Mast	
East Anglia Two	67	GBS	60m base 13m top cone	4 1 1	Electric Accomo. Met Mast	

OWF	WTP Foundation			OSP Foundation		
	No.	Type	Dimensions	No.	Type	Dimensions
London Array	175	Monopile	5.7m diameter	2	Monopile	6m
Gunfleet Sands	50	Monopile	5m diameter	1	Monopile	5m diameter
Thanet	100	Monopile	4m diameter	1	Jacket	

2.6 3D Model - DIFFRACT

In order to determine the effects of foundation types on the near-field wave climate, a local scale wave model known as DIFFRACT was used. This model allows the foundation parameters to be digitised. An example 3D representation of a Gravity Based System (GBS) in DIFFRACT is shown in **Figure 2-10**.

The DIFFRACT model enables the relative reflection (or transmission) properties of different foundation types to be parameterised by means of controlled tests, providing numerical 'coefficients'. The sensitivity of the resultant coefficients to wave period and water depth was analysed for each foundation type tested.

The DIFFRACT study quantified reflection coefficients for GBS foundations with a base plate width of 60m and monopiles with a width of 6.5m and 12m, at a range of water depths and wave periods. A detailed summary of the study is presented in **Annex B**.

For North Falls where the base plate of the GBS foundations is 65m, a conservative approximation has been applied and the reflections coefficients are 'upscaled' from the DIFFRACT study.

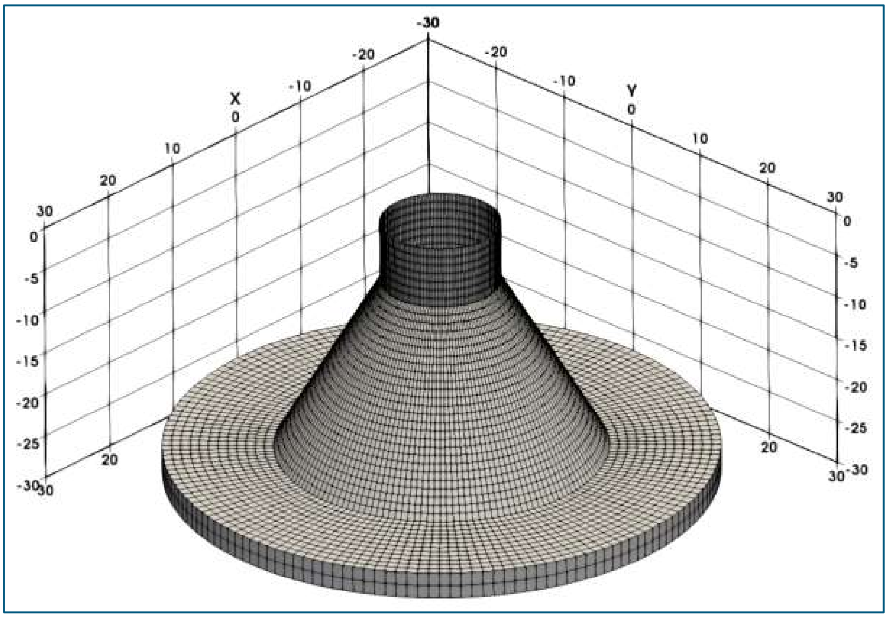

Figure 2-10: Example numerical mesh for GBS foundation in water depth of 30m.

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2.7 Structure Definition - MIKE21-SW

The reflection coefficients derived from RHDHV database of values from the DIFFRACT study, are applied via coordinates within the mesh of the MIKE21-SW model (**Figure 2-9**) at the sub-grid scale. For other monopile structures not assessed in the DIFFRACT study, default MIKE21 coefficients are applied.

2.8 Assumptions and Limitations

The key assumptions and limitations of the wave modelling approach for this study are summarised below:

1. All extreme wave model simulations are undertaken for a constant water level of MWHS at Lowestoft (2.4mCD). It is assumed that the water depth at the OWF arrays is large enough that the results are representative across the full tidal cycle;

2. Reflection coefficients within the RHDHV database which were derived from the local scale DIFFRACT-3D modelling, cover GBS up to 60m base. Therefore, for the larger North Falls GBS structures with a 65m base, reflection coefficients are derived through an extrapolation of the existing database to scale up values;

3. Reflection coefficients for other turbine structures which are not contained within the RHDHV database, are estimated using the MIKE software default approach;

4. OWF turbine layouts are extracted from a variety of online sources and previous RHDHV studies.

3 Model Results

3.1 Wave Climate

This section presents the model results of significant wave height throughout the model domain. The figures overlay the location of the North Falls OWF, although no structures were included in these model simulations.

Figure 3-1 to **Figure 3-3** present 2D contour plots of predicted significant wave height for waves from 345°N, for the 1 in 1 year, 1 in 50 year and 1 in 100 year, respectively.

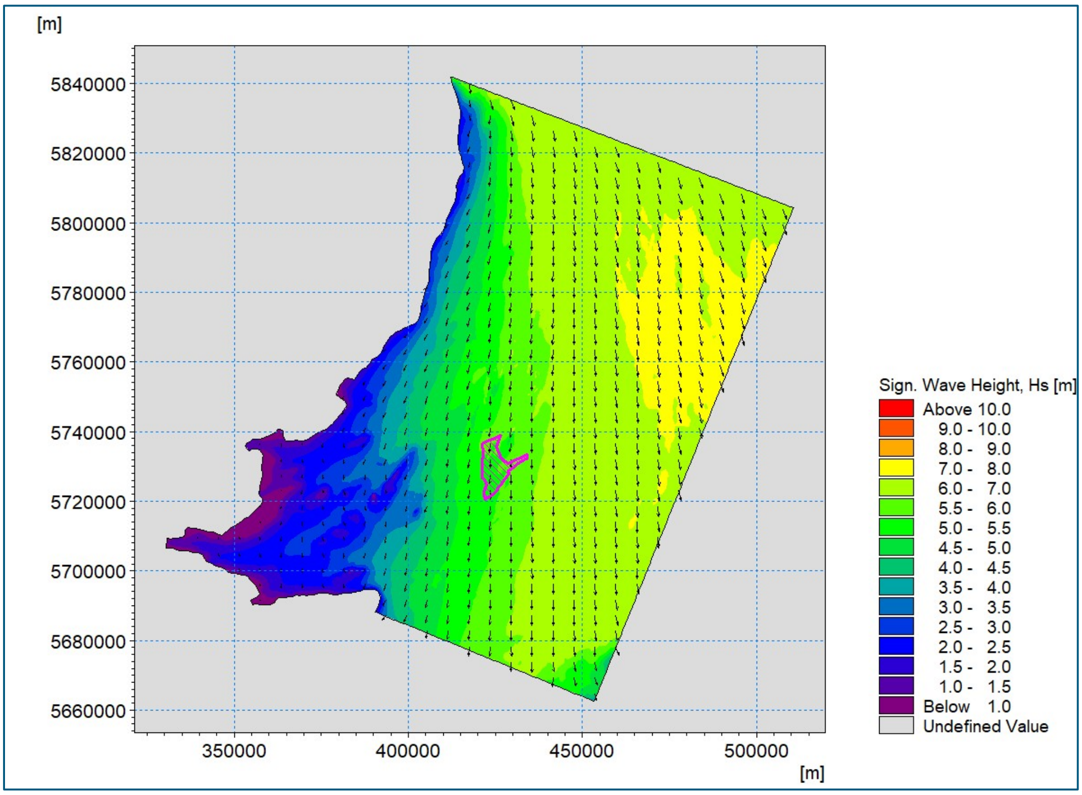

Figure 3-1: Predicted H_s for 1 in 1 year wave from 345°N

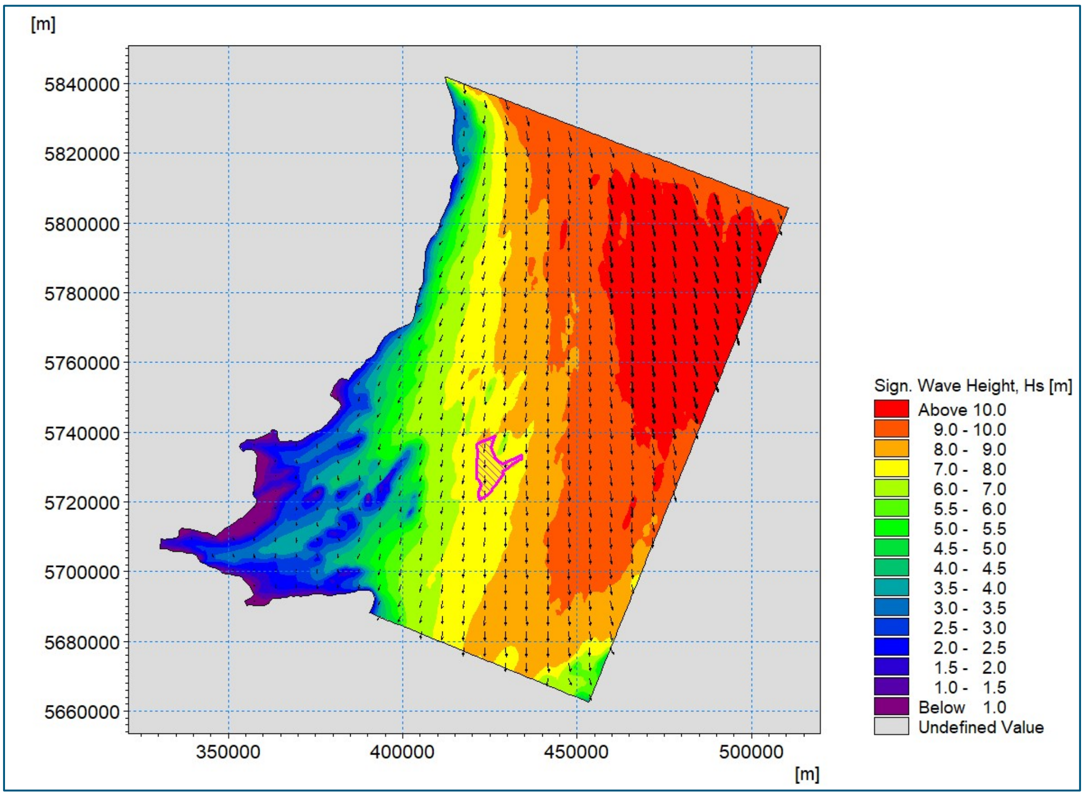

Figure 3-2: Predicted H_s for 1 in 50 year wave from 345°N

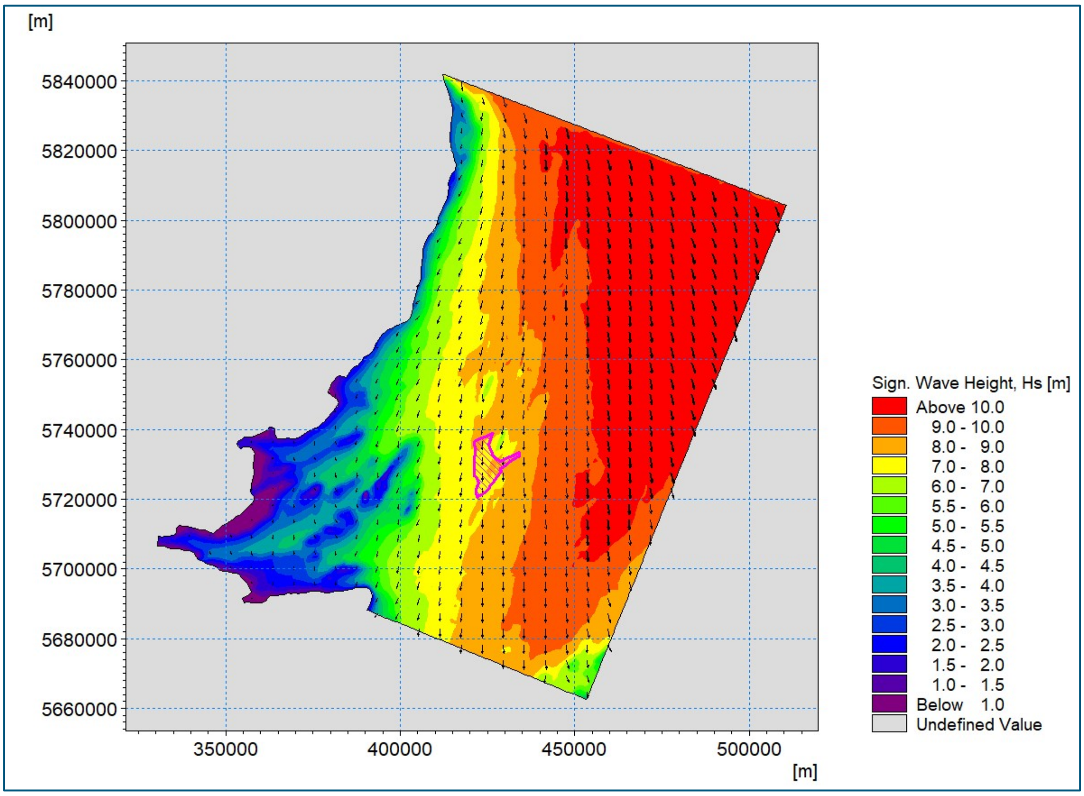

Figure 3-3: Predicted H_s for 1 in 100 year wave from 345°N

Figure 3-4 to **Figure 3-6** present 2D contour plots of predicted significant wave height for waves from 15°N, for the 1 in 1 year, 1 in 50 year and 1 in 100 year, respectively.

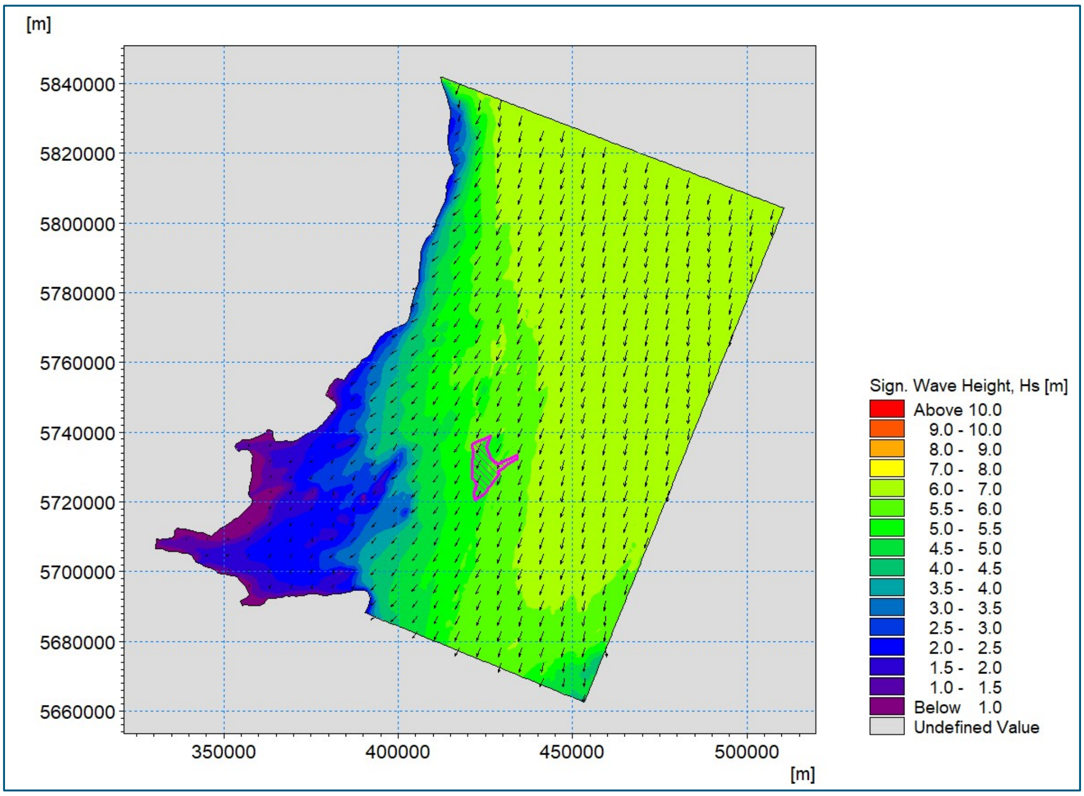

Figure 3-4: Predicted H_s for 1 in 1 year wave from 15°N

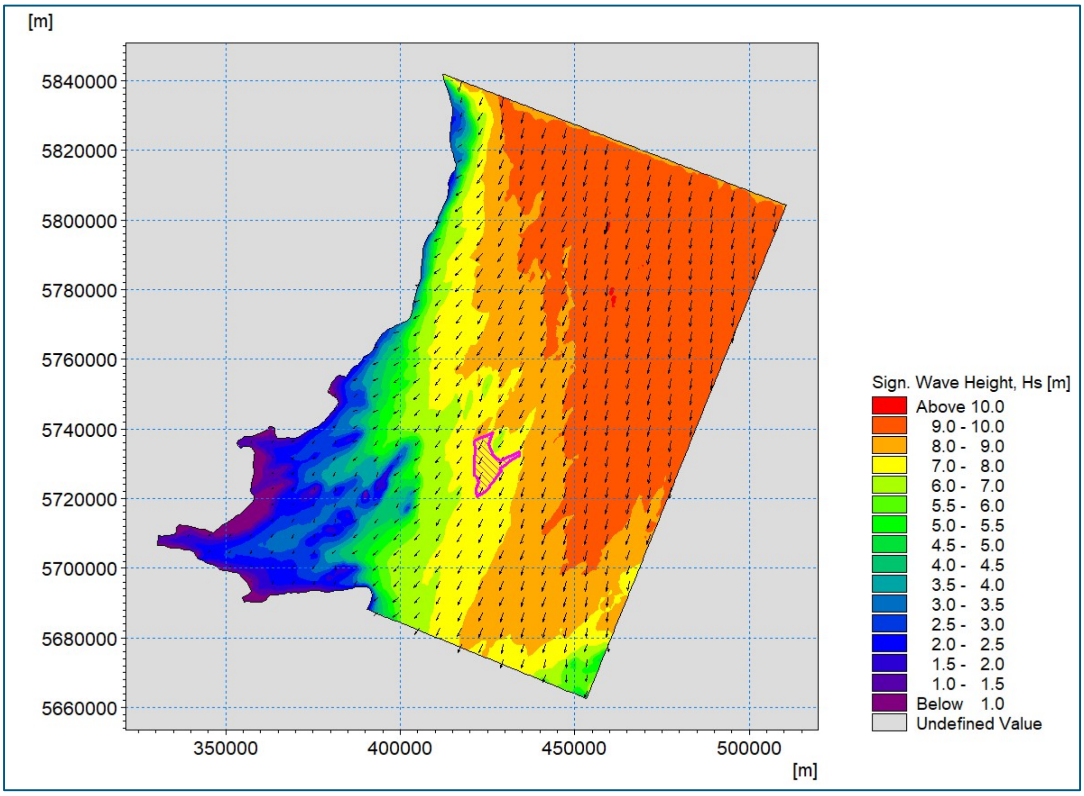

Figure 3-5: Predicted H_s for 1 in 50 year wave from 15°N

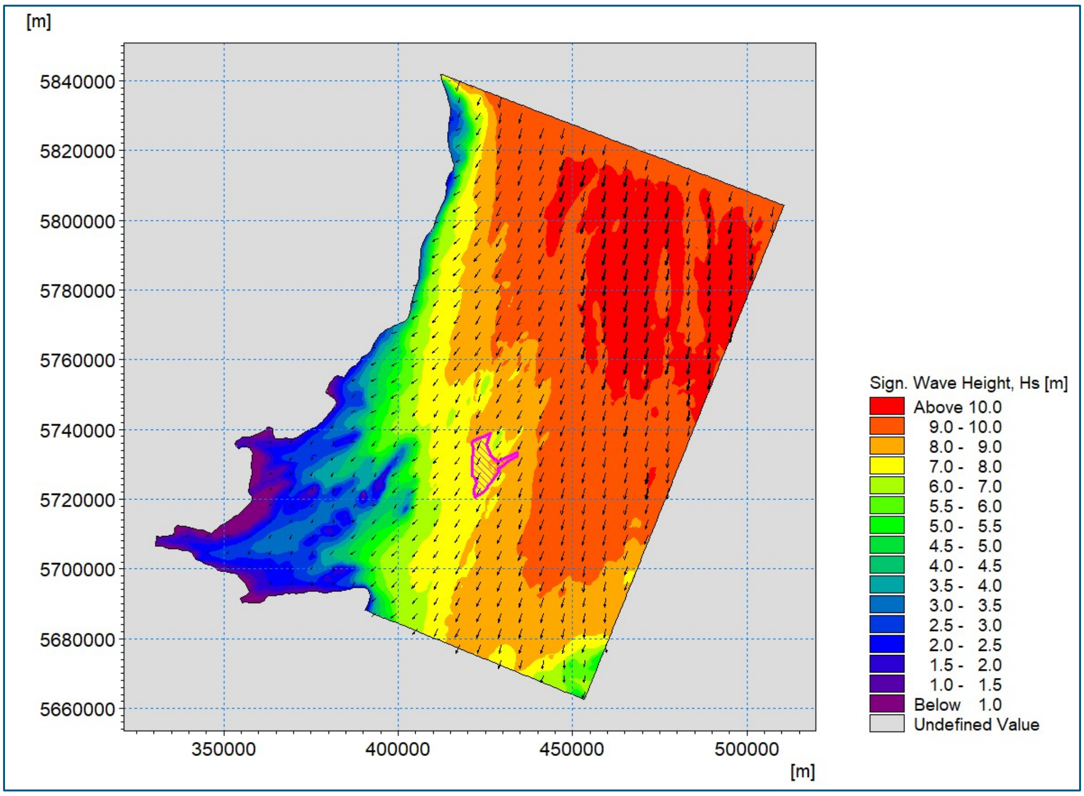

Figure 3-6: Predicted H_s for 1 in 100 year wave from 15°N

Figure 3-7 to **Figure 3-9** present 2D contour plots of predicted significant wave height for waves from 105°N, for the 1 in 1 year, 1 in 50 year and 1 in 100 year, respectively.

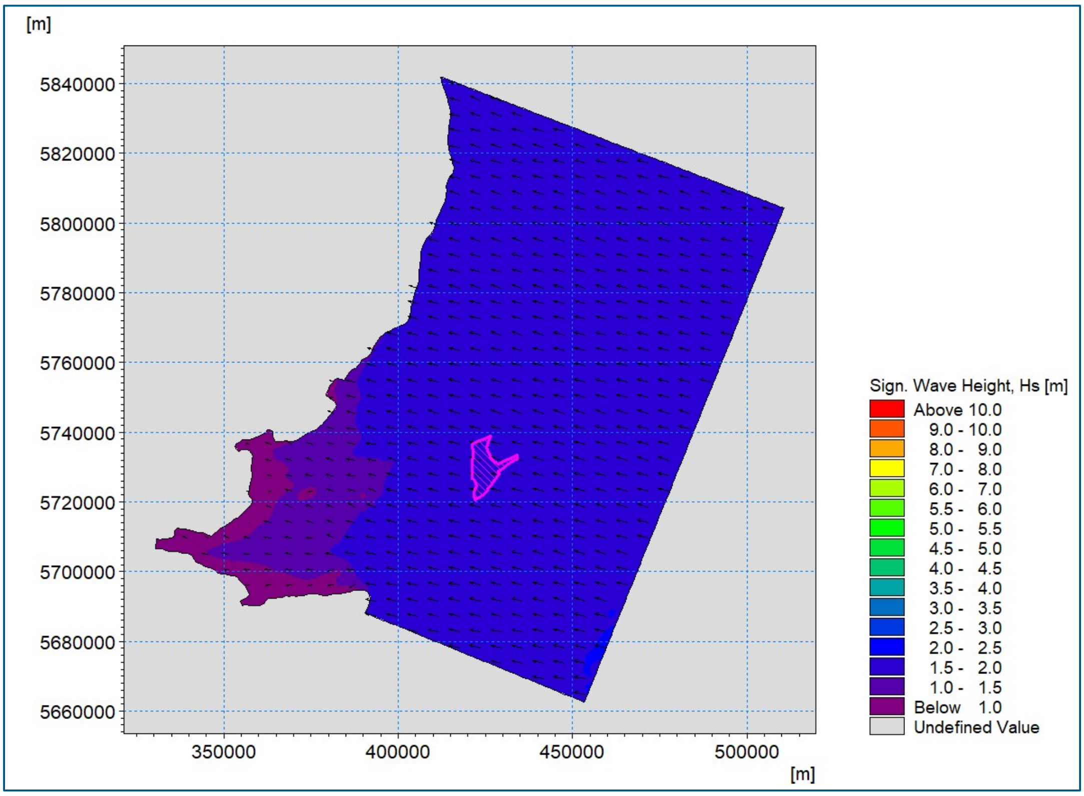

Figure 3-7: Predicted H_s for 1 in 1 year wave from 105°N

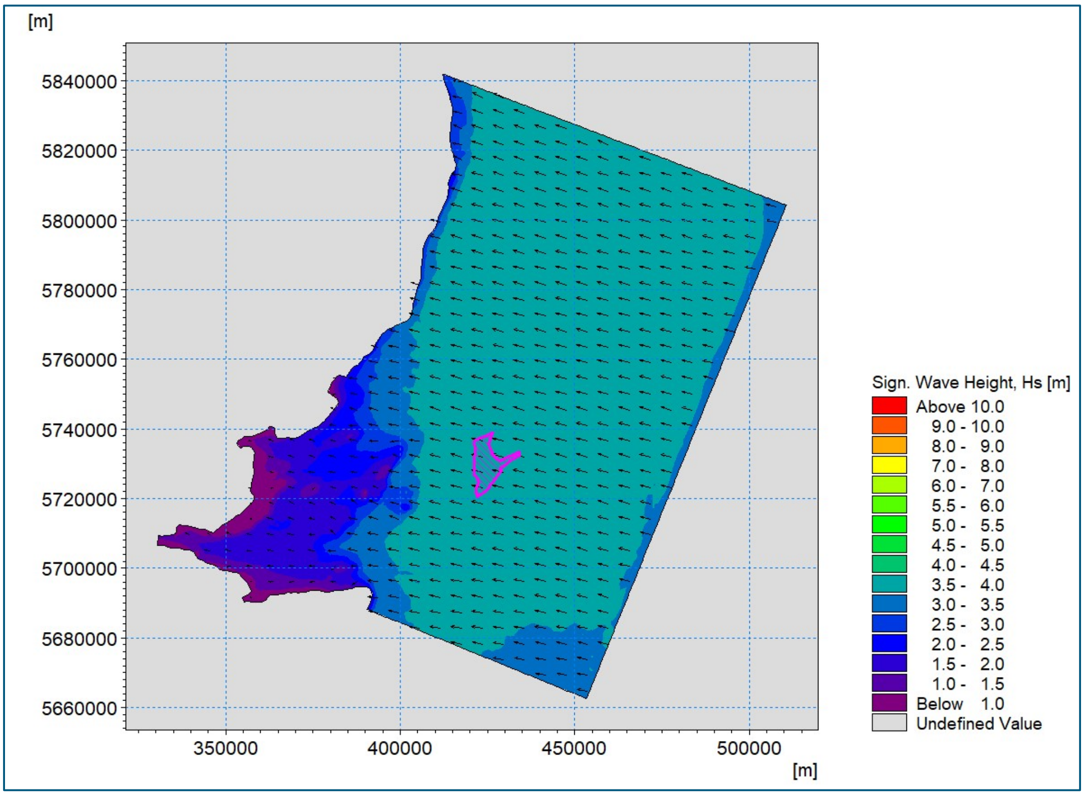

Figure 3-8: Predicted H_s for 1 in 50 year wave from 105°N

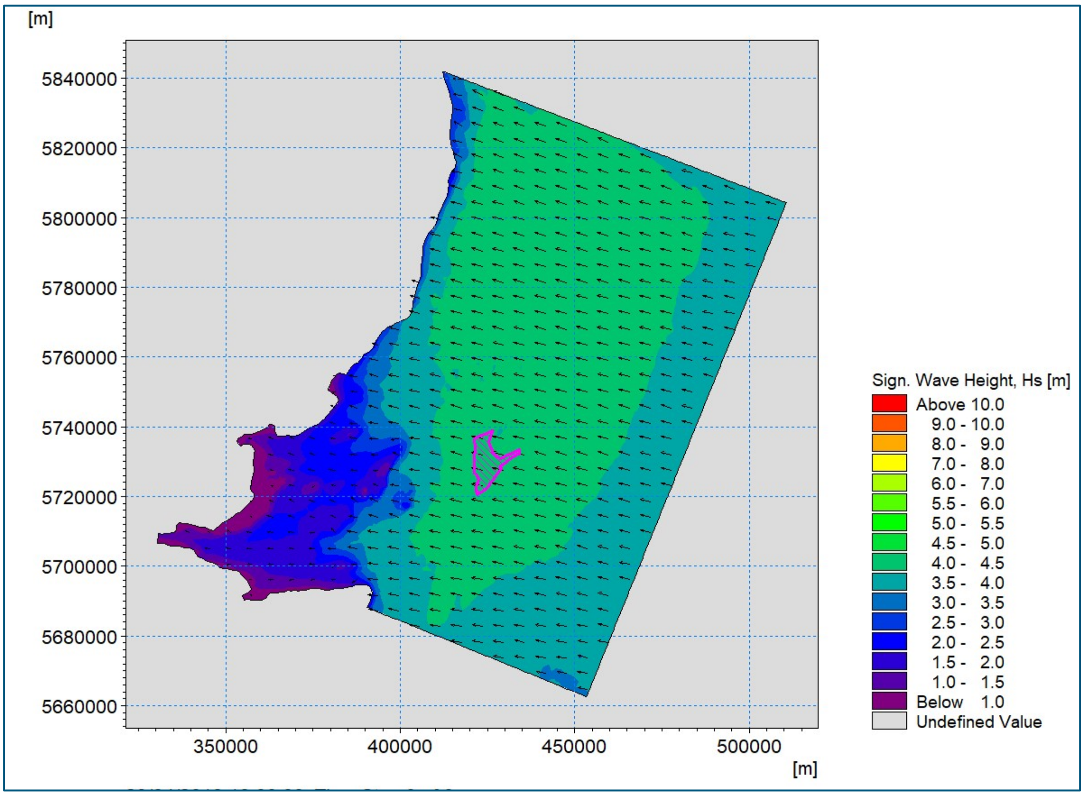

Figure 3-9: Predicted H_s for 1 in 100 year wave from 105°N

Figure 3-10 to **Figure 3-12** present 2D contour plots of predicted significant wave height for waves from 210°N, for the 1 in 1 year, 1 in 50 year and 1 in 100 year, respectively.

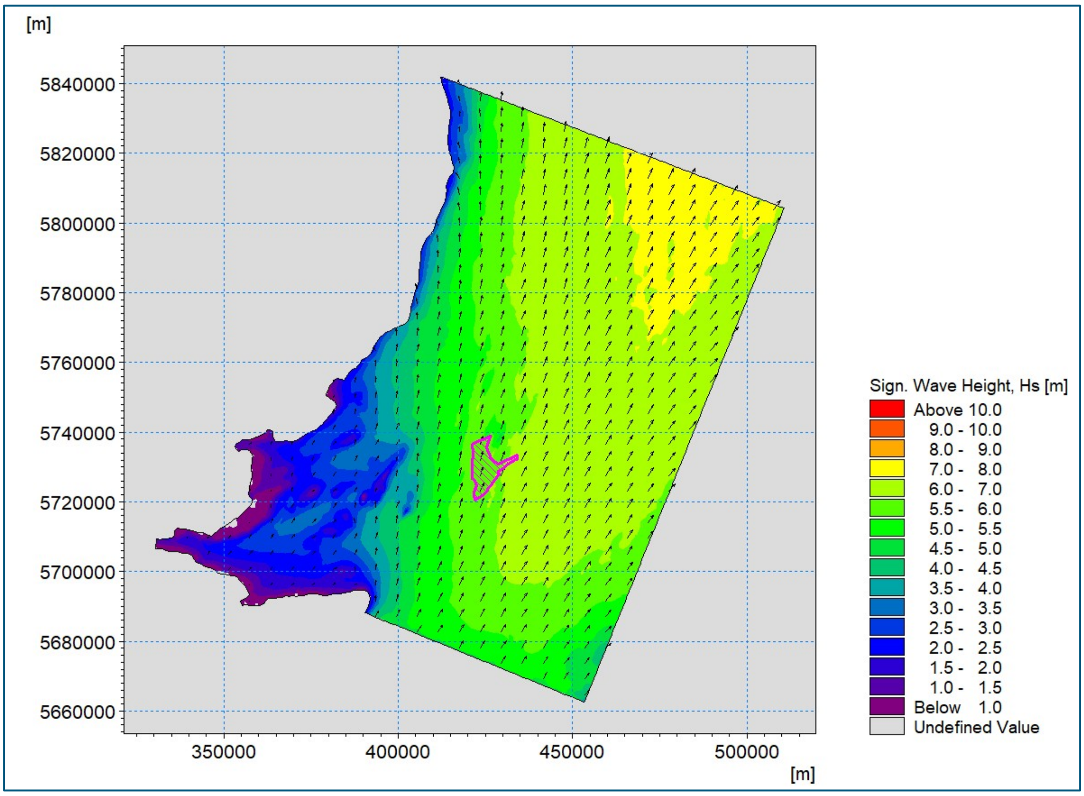

Figure 3-10: Predicted H_s for 1 in 1 year wave from 210°N

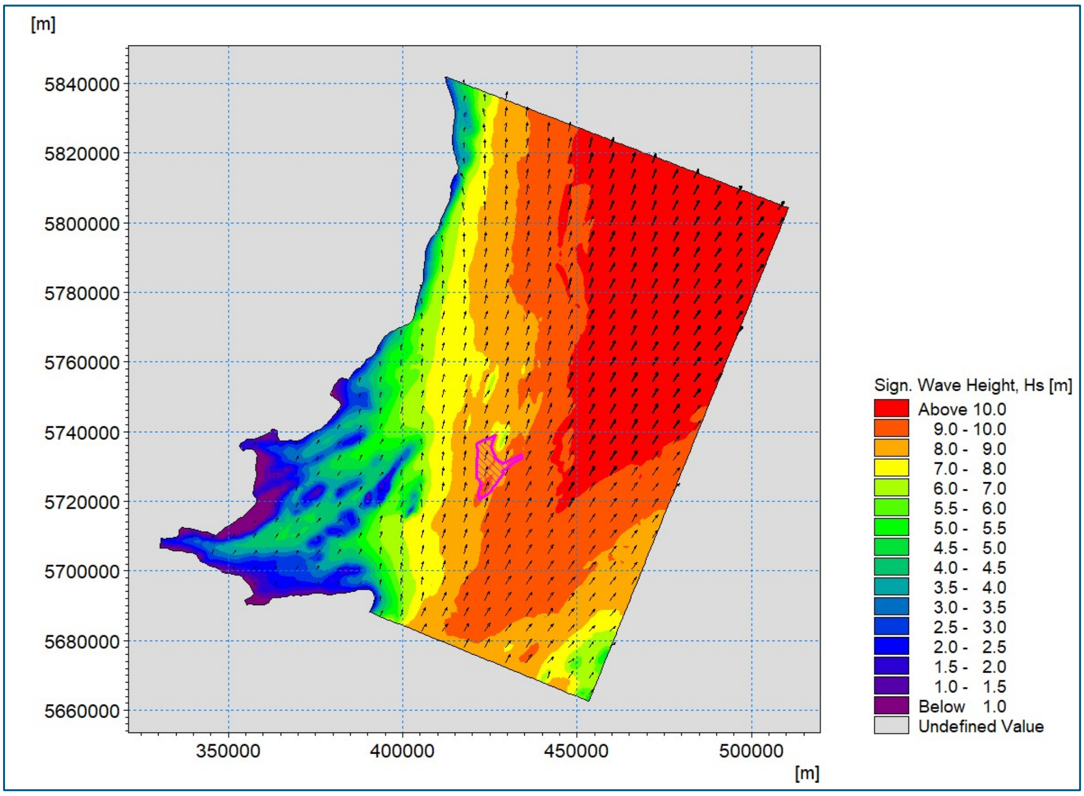

Figure 3-11: Predicted H_s for 1 in 50 year wave from 210°N

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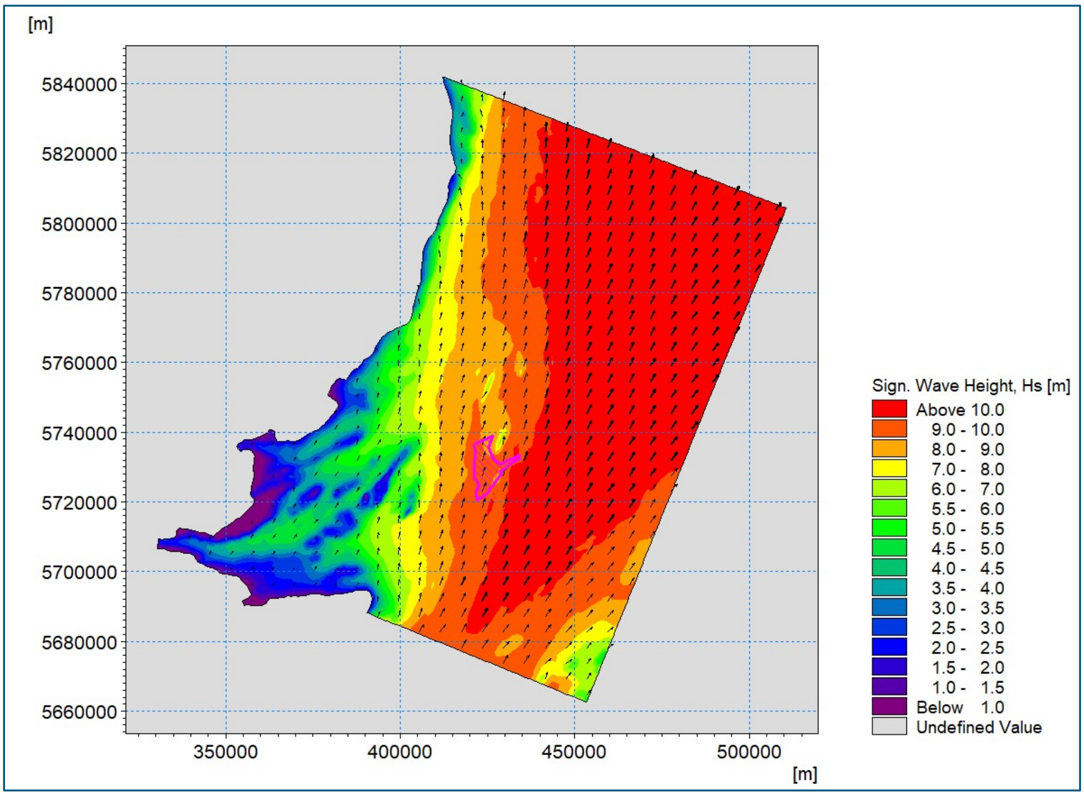


Figure 3-12: Predicted H_s for 1 in 100 year wave from 210°N

3.2 Predicted Change in Significant Wave Height

To visualise the effect of the OWF's on the surrounding wave climate, the MIKE21-SW model results are presented as a percentage change in significant wave height, where the threshold for this change in sensitive areas and coastal regions is typically 5%.

The results are presented for the worst case in terms of change in wave climate, which was the 1 in 1 year return period. For this 1 in 1 year return period, all directional sectors modelled (330°N, 0°N, 90°N and 210°N) are presented below. Change in significant wave height for other return periods (1 in 50 year and 1 in 100 year) which are less significant, are presented in **Annex C**.

3.2.1 Layout 3 - Layout 2

Figure 3-13 to **Figure 3-16** present results of this scenario (layout 3 - layout 2), showing the effect of North Falls only, on the surrounding wave climate for a 1 in 1 year return period.

The results indicate that waves from east produce the largest change in wave climate due to North Falls OWF, when compared to the other directional sectors. Despite this, the change close to the OWF is less than 2% and the >0.6 % contour does not extend to any existing other OWF's or near to the coastline. The results clearly present the effect of the structures on the wave climate, with a reduction in wave height in the lee of the array as wave energy is lost through transmission and an increase in wave height in front of the array as wave energy is reflected by the array.

Waves from south and the two north directional sectors show a very small change in the wave climate of <1.5% close to North Falls OWF.

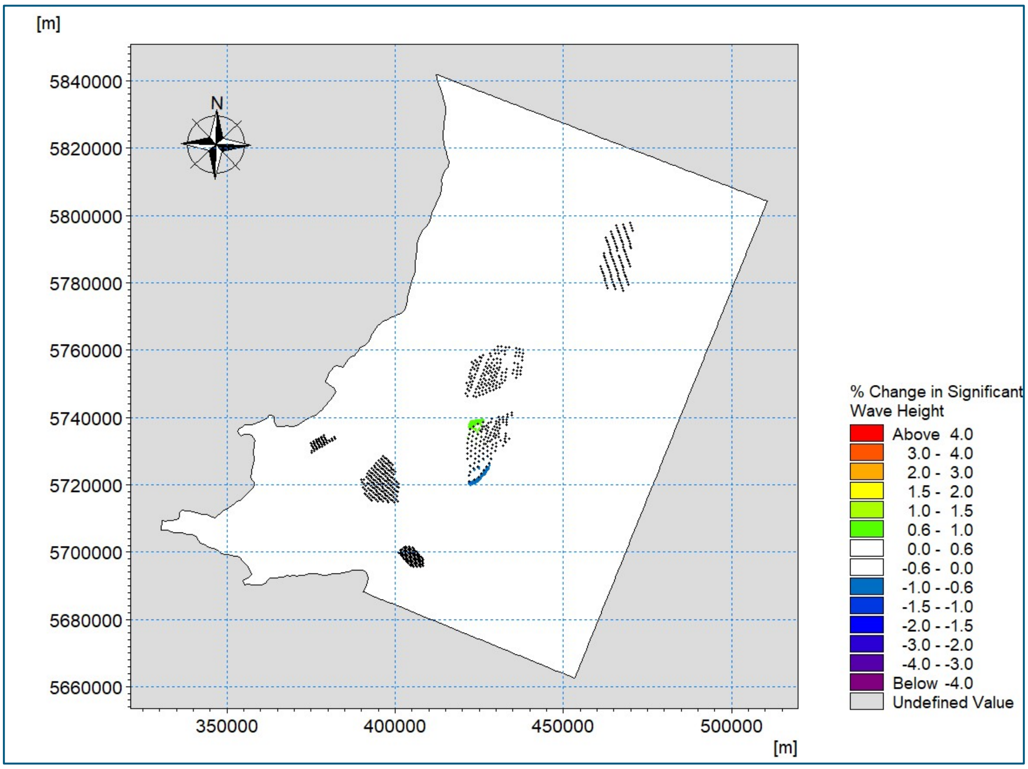


Figure 3-13: Layout 3 - Layout 2, % change in H_s for waves from 345°N - 1 in 1 year

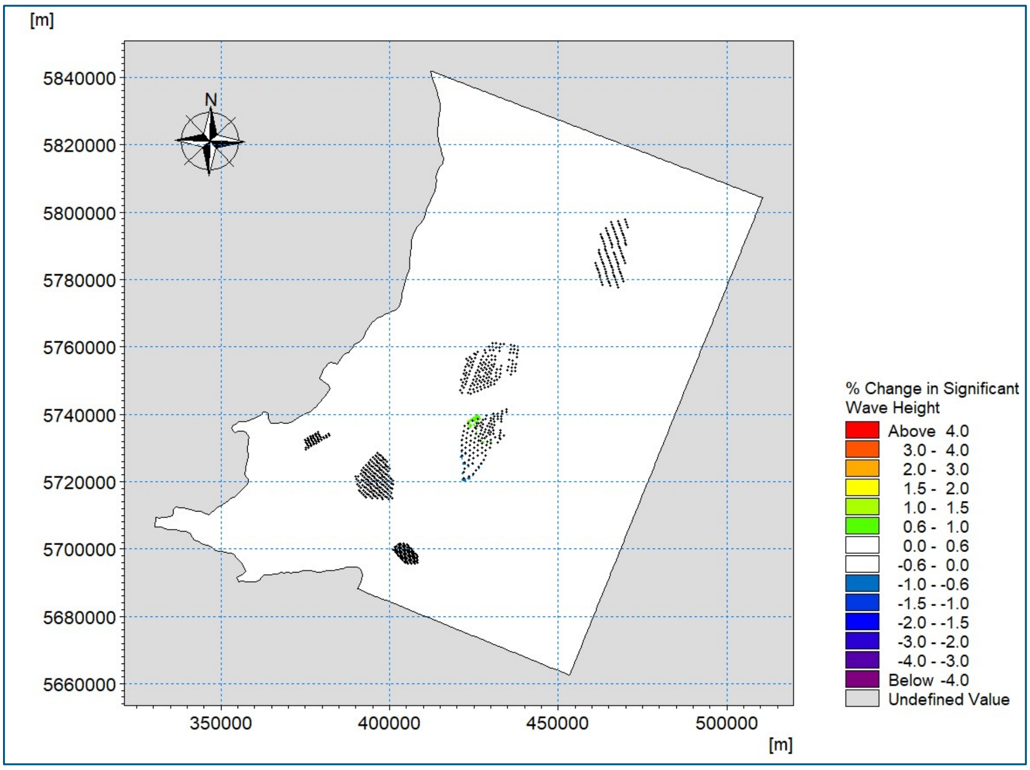


Figure 3-14: Layout 3 - Layout 2, % change in H_s for waves from 15°N - 1 in 1 year

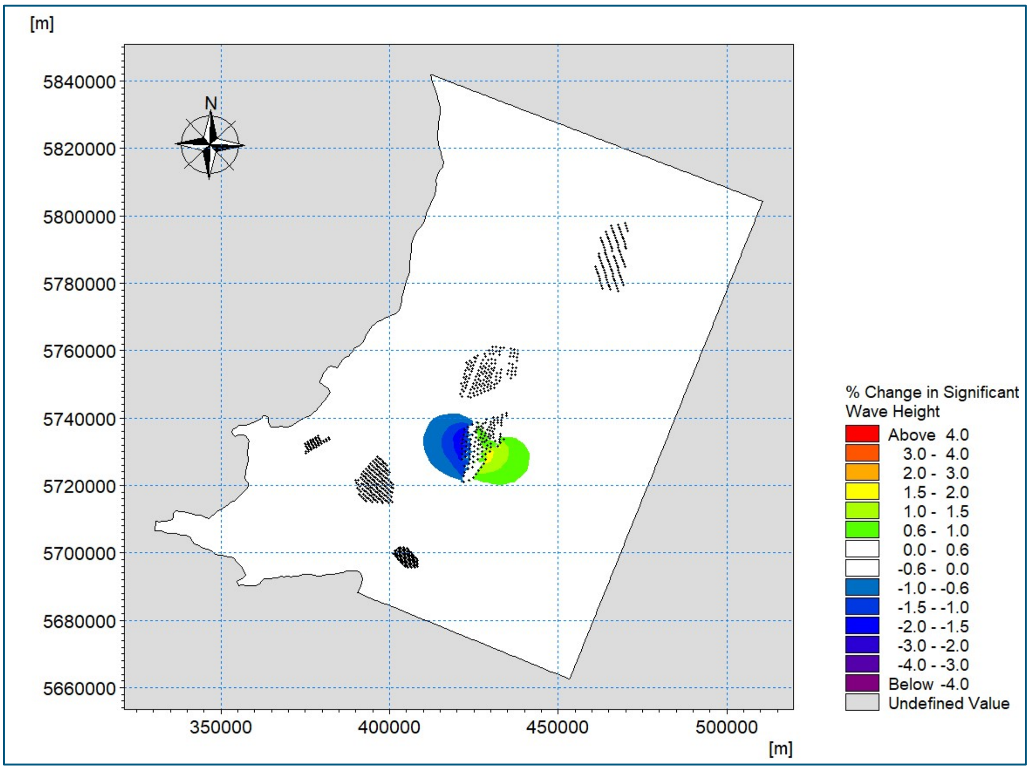


Figure 3-15: Layout 3 - Layout 2, % change in H_s for waves from 105°N - 1 in 1 year

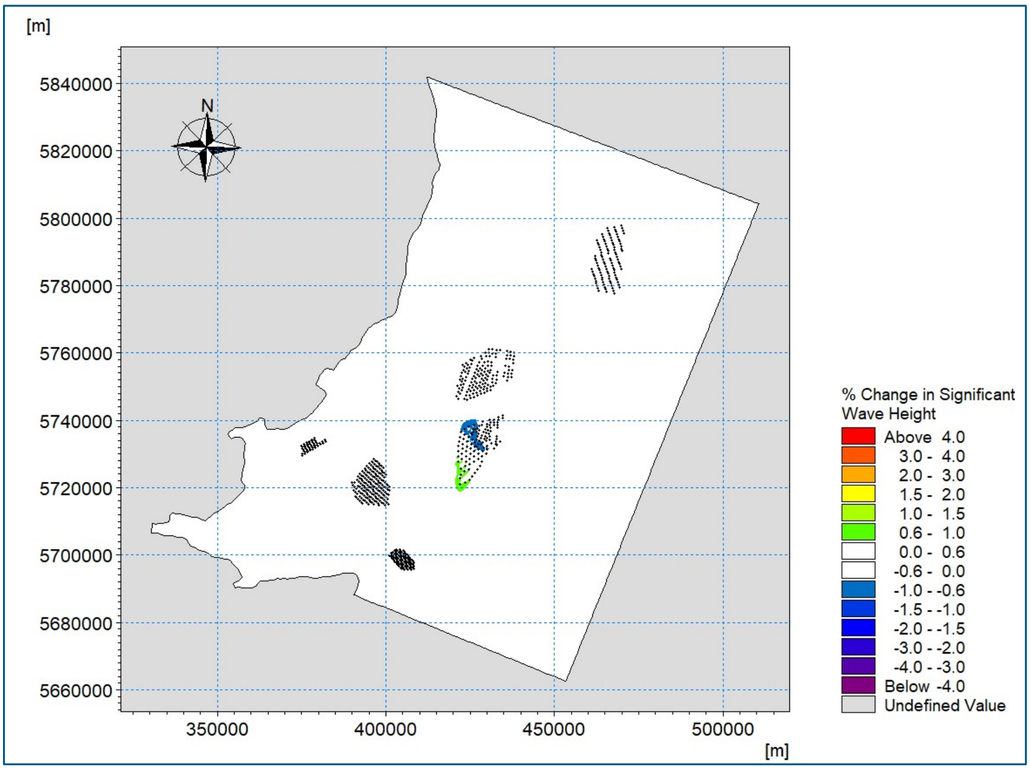


Figure 3-16: Layout 3 - Layout 2, % change in H_s for waves from 210°N - 1 in 1 year

3.2.2 Layout 3 - Layout 1

Figure 3-17 to **Figure 3-20** present results of this scenario (layout 3 - layout 1), showing the cumulative effect of North Falls and existing OWF's, on the surrounding wave climate for a 1 in 1 year return period.

The results indicate that waves from east produce the largest change in wave climate due to North Falls OWF and existing / active OWF's, when compared to the other directional sectors. Despite this, the change close to the OWF is less than 2% and the >0.6 % contour does not extend to any existing other OWF's or near to the coastline.

Waves from south and the two north directional sectors show a very small change in the wave climate of <1.5% close to North Falls OWF and other OWF's do not predict any change >0.6% apart from small, localised areas within the OWF array.

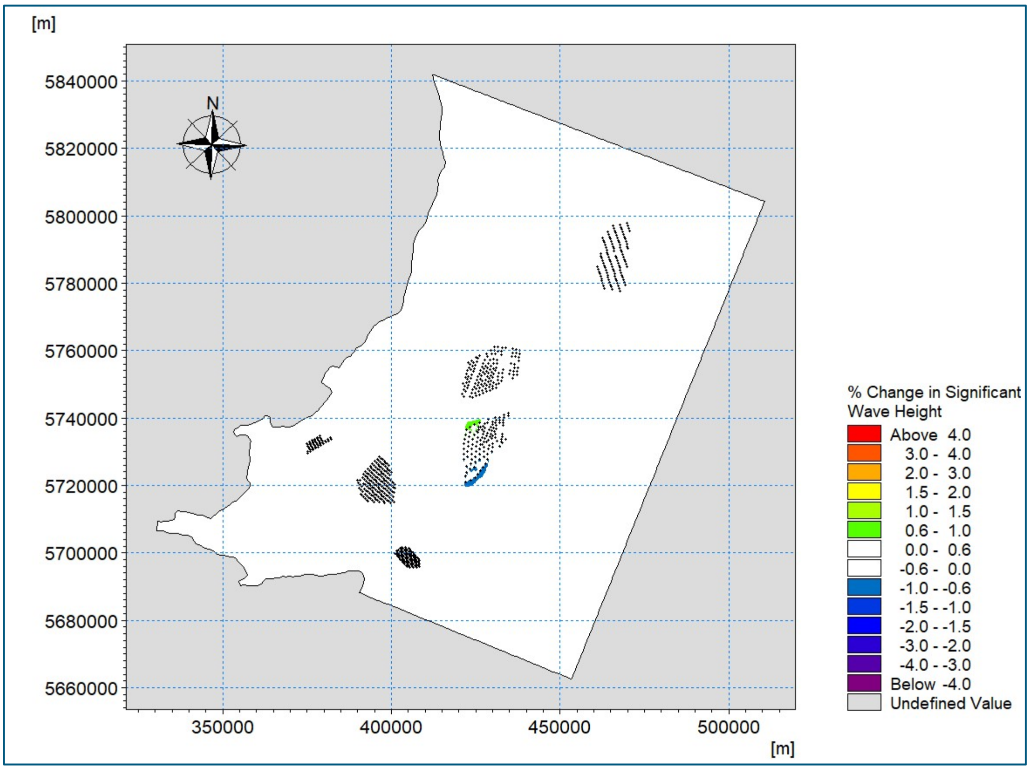


Figure 3-17: Layout 3 - Layout 1, % change in H_s for waves from 345°N - 1 in 1 year

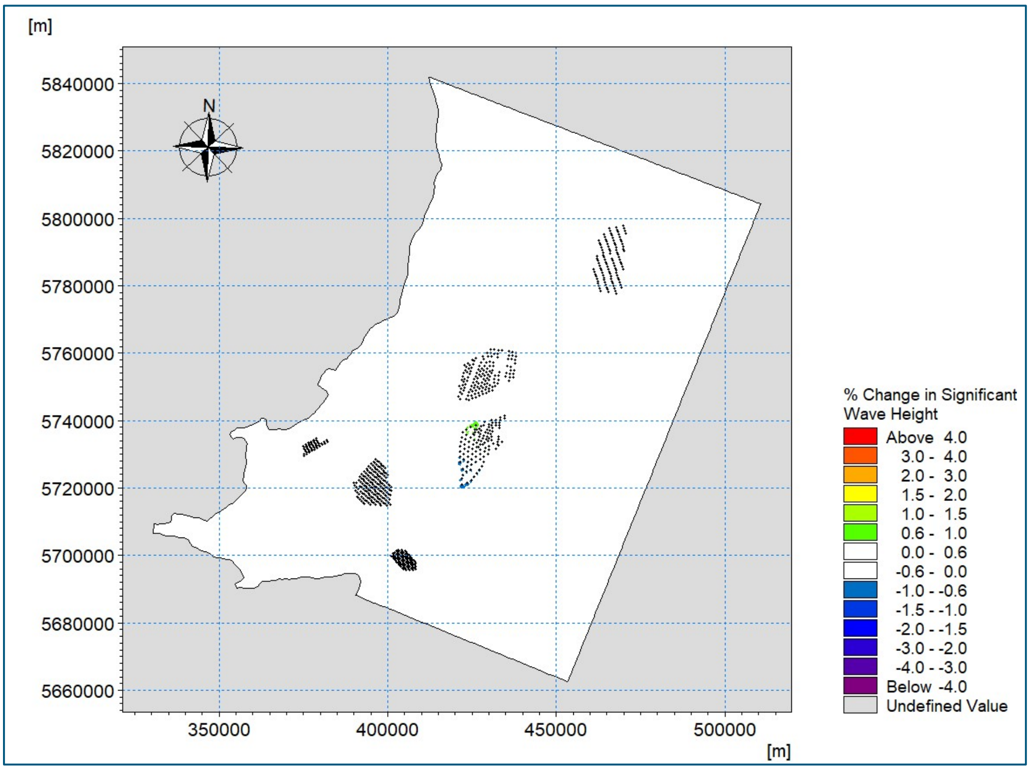


Figure 3-18: Layout 3 - Layout 1, % change in H_s for waves from 15°N - 1 in 1 year

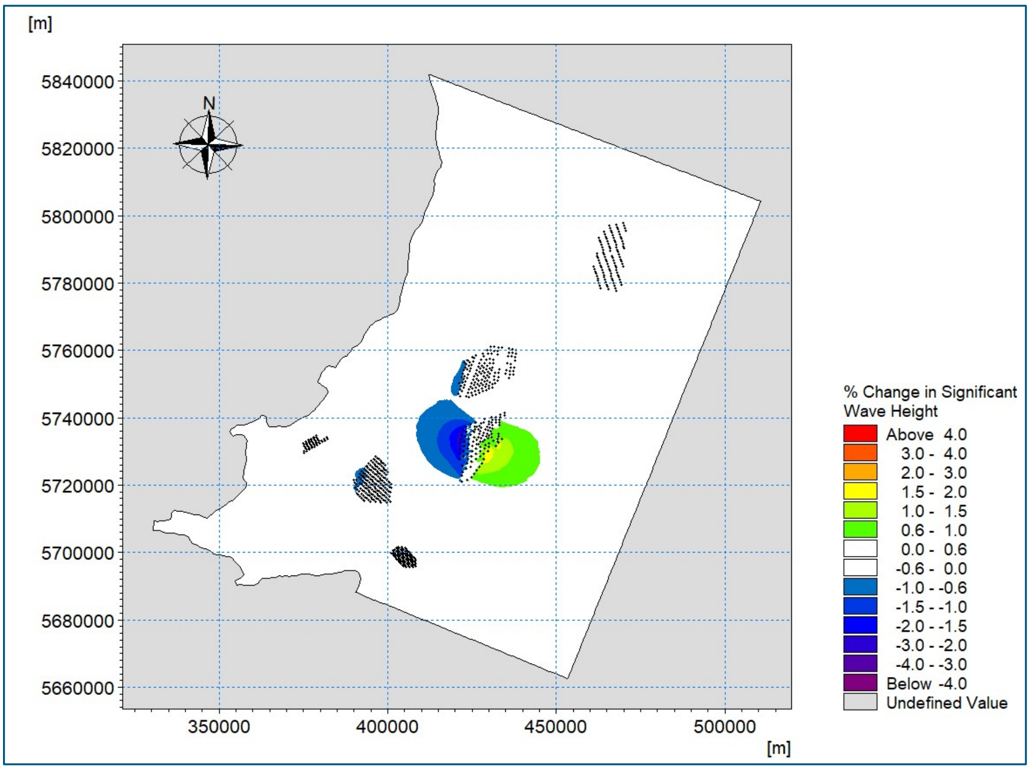


Figure 3-19: Layout 3 - Layout 1, % change in H_s for waves from 105°N - 1 in 1 year

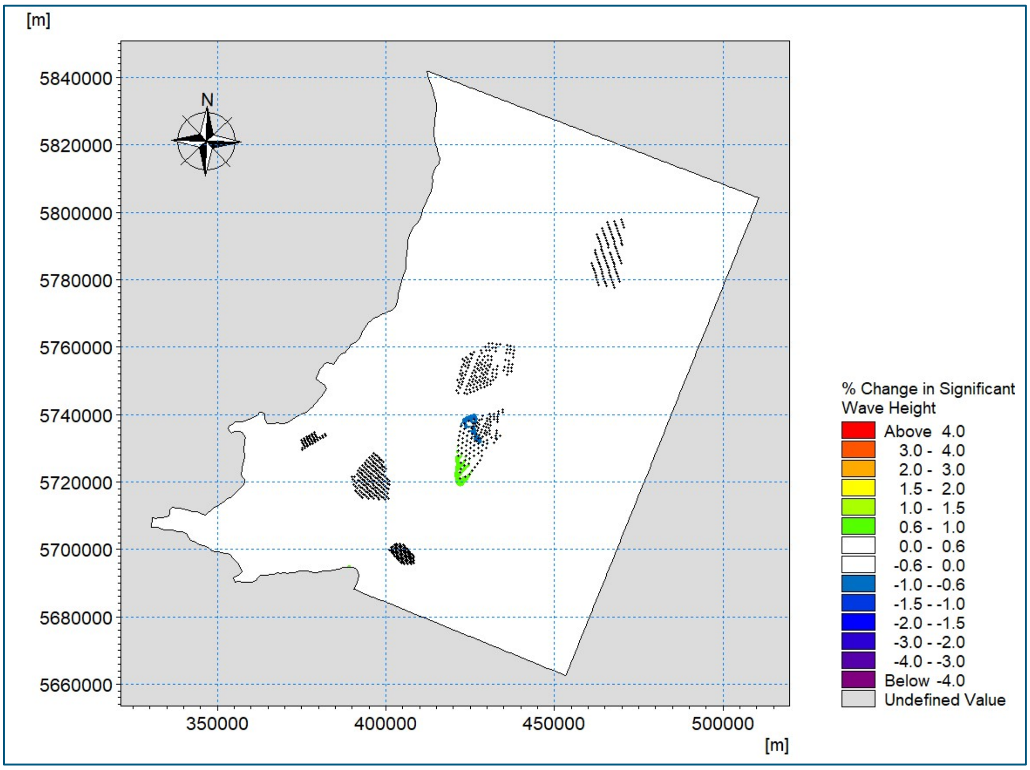


Figure 3-20: Layout 3 - Layout 1, % change in H_s for waves from 210°N - 1 in 1 year

3.2.3 Layout 4 - Layout 1

Figure 3-21 to **Figure 3-24** present results of this scenario (layout 4 - layout 1), showing the cumulative effect of all OWF's (North Falls, existing OWF's and proposed / consented OWF's) on the surrounding wave climate for a 1 in 1 year return period.

The results indicate that waves from east produce the largest change in wave climate due to the cumulative effect of all OWF's, when compared to the other directional sectors. Despite this, the change close to the OWF is less than 3% and the >0.6 % contour does not extend to the adjacent coastline.

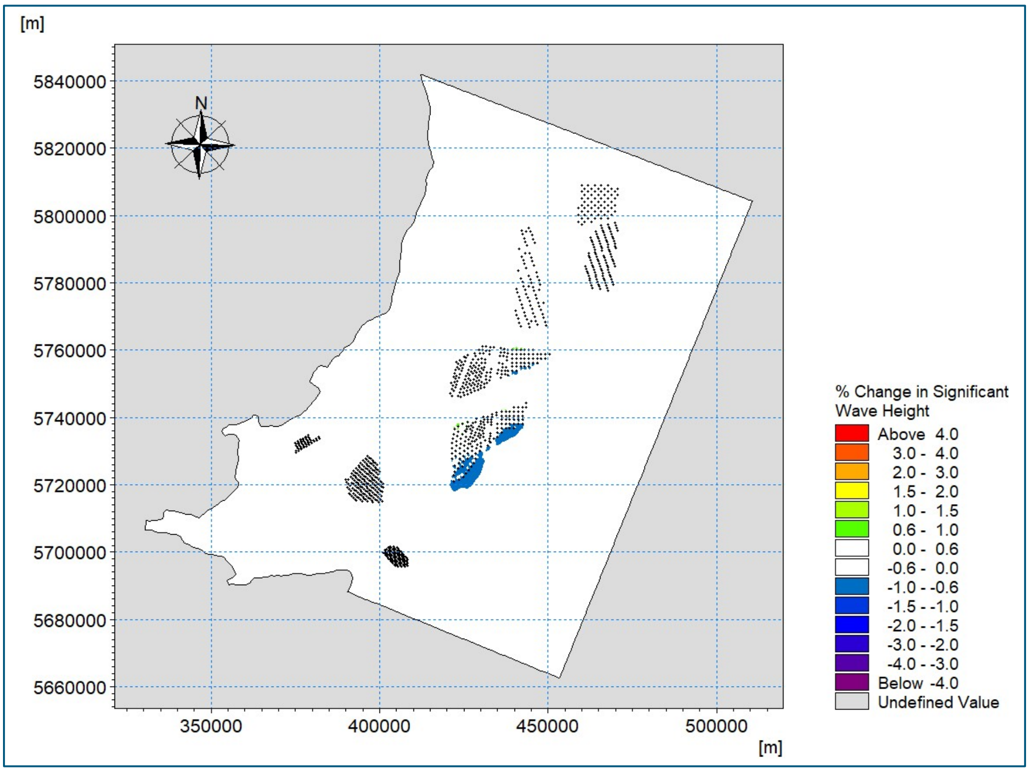


Figure 3-21: Layout 4 - Layout 1, % change in H_s for waves from 345°N - 1 in 1 year

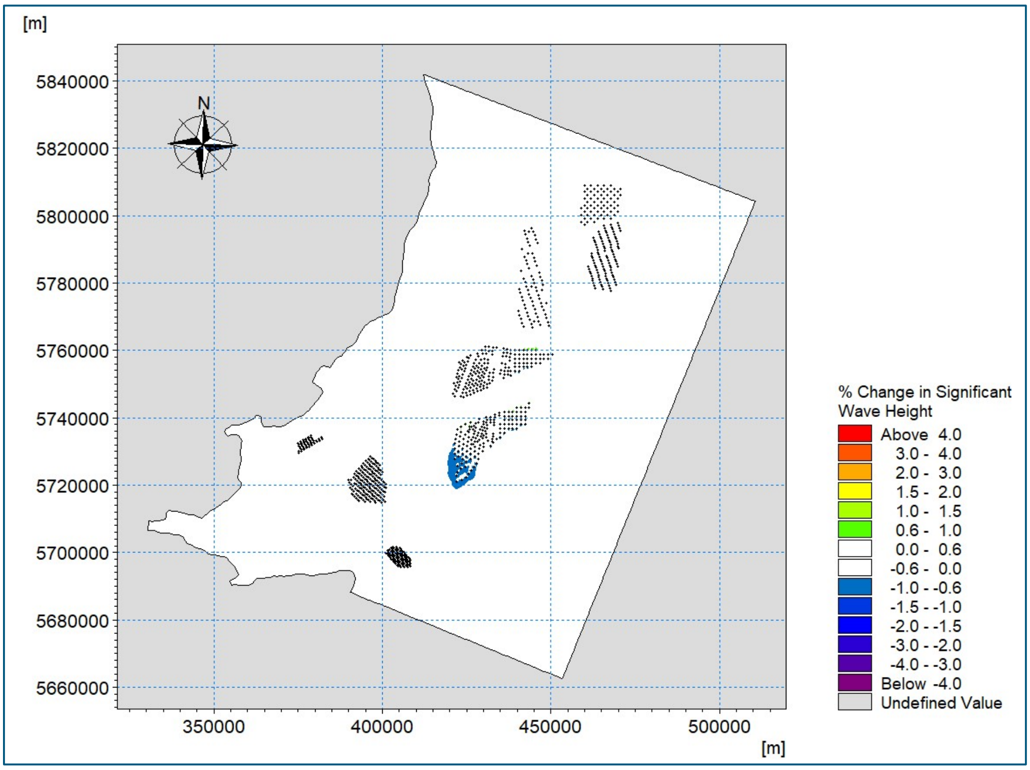


Figure 3-22: Layout 4 - Layout 1, % change in H_s for waves from 15°N - 1 in 1 year

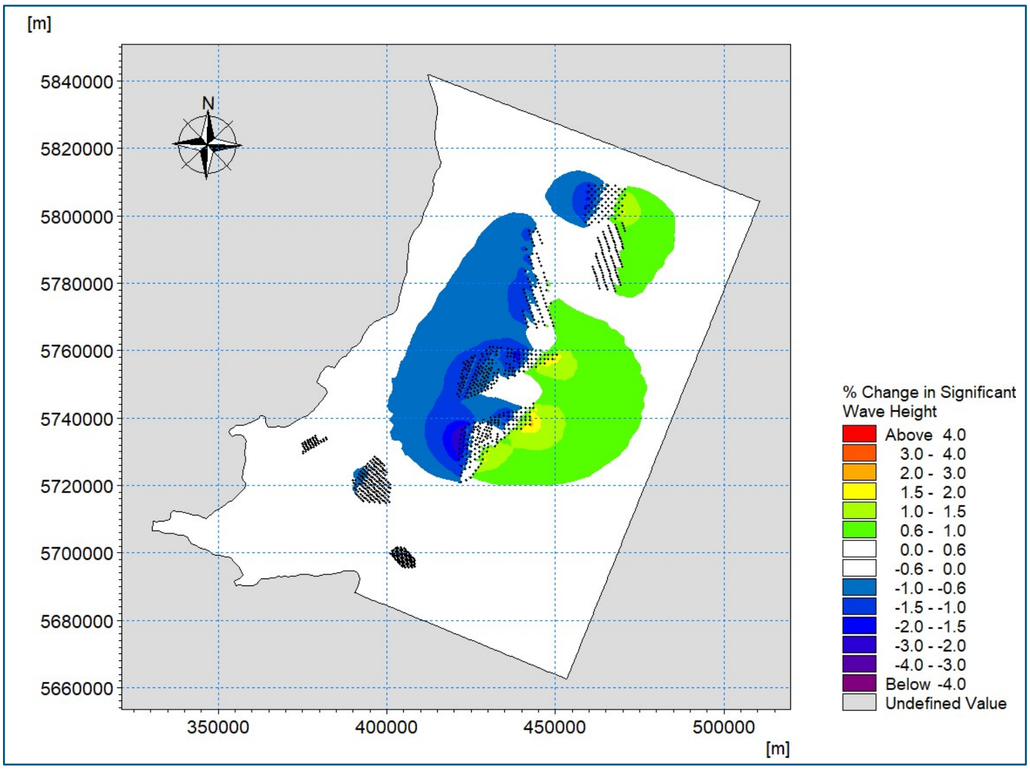


Figure 3-23: Layout 4 - Layout 1, % change in H_s for waves from 105°N - 1 in 1 year

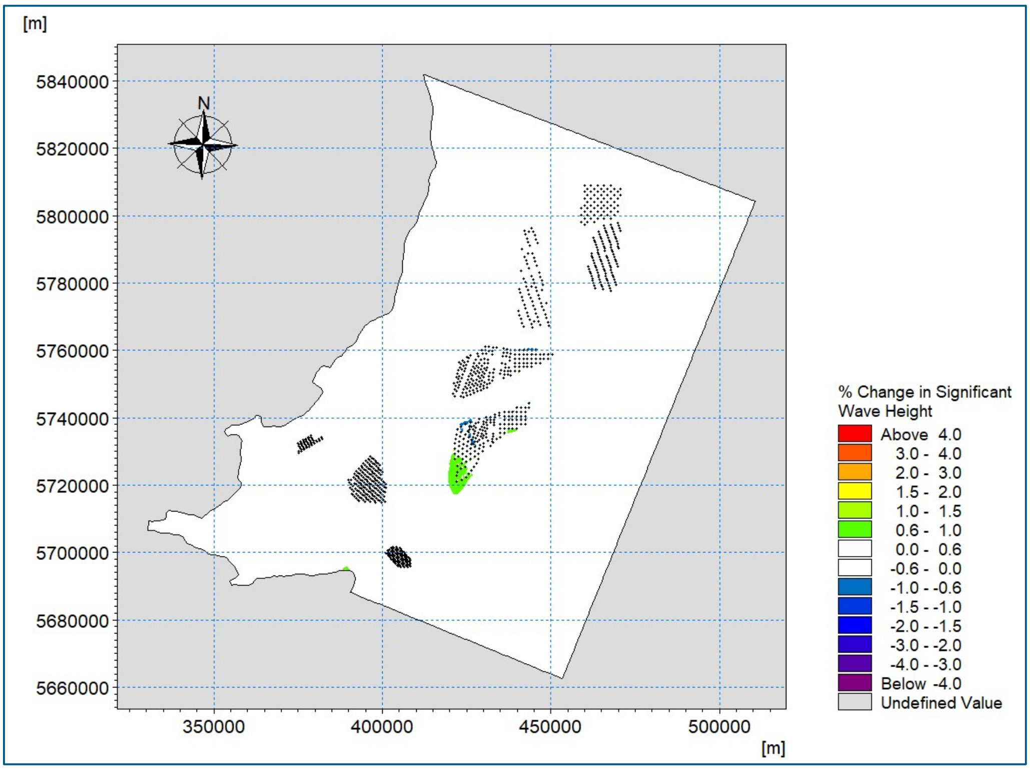


Figure 3-24: Layout 4 - Layout 1, % change in H_s for waves from 210°N - 1 in 1 year

3.3 Predicted Change in Wave Direction

As an additional sensitivity test, the predicted change in mean wave direction (MWD) due to each OWF layout is assessed, for the worst case results presented in **Section 3.2** - 1 in 1 year waves from East (105°N).

Figure 3-25 - **Figure 3-27** show the change in mean wave direction (MWD) for 1 in 1 year waves from 105°N, for layout 3 - layout 2, layout 3 - layout 1 and layout 4 - layout 1, respectively.

The results predict that the maximum change in MWD for the worst case simulation showing cumulative effect of all OWF's (layout 4 - layout 1) is less than 2°, and the >0.5° does not extend to neighbouring OWF's or the adjacent coastline.

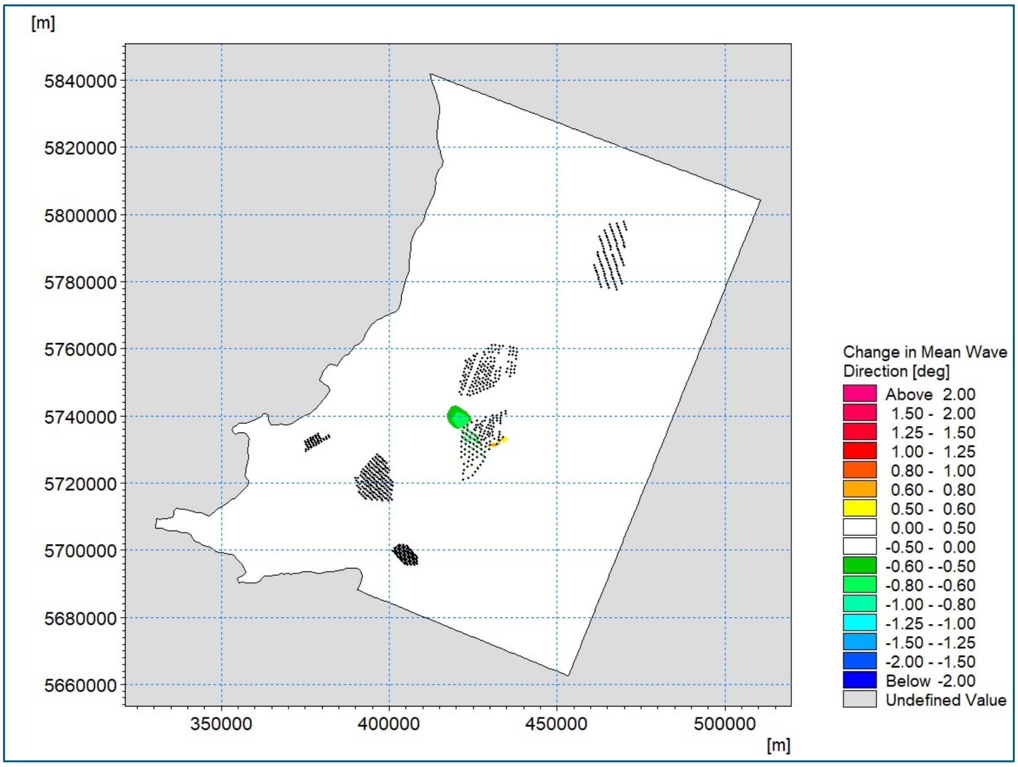


Figure 3-25: Layout 3 - Layout 2, change in MWD (°) for waves from 105°N - 1 in 1 year

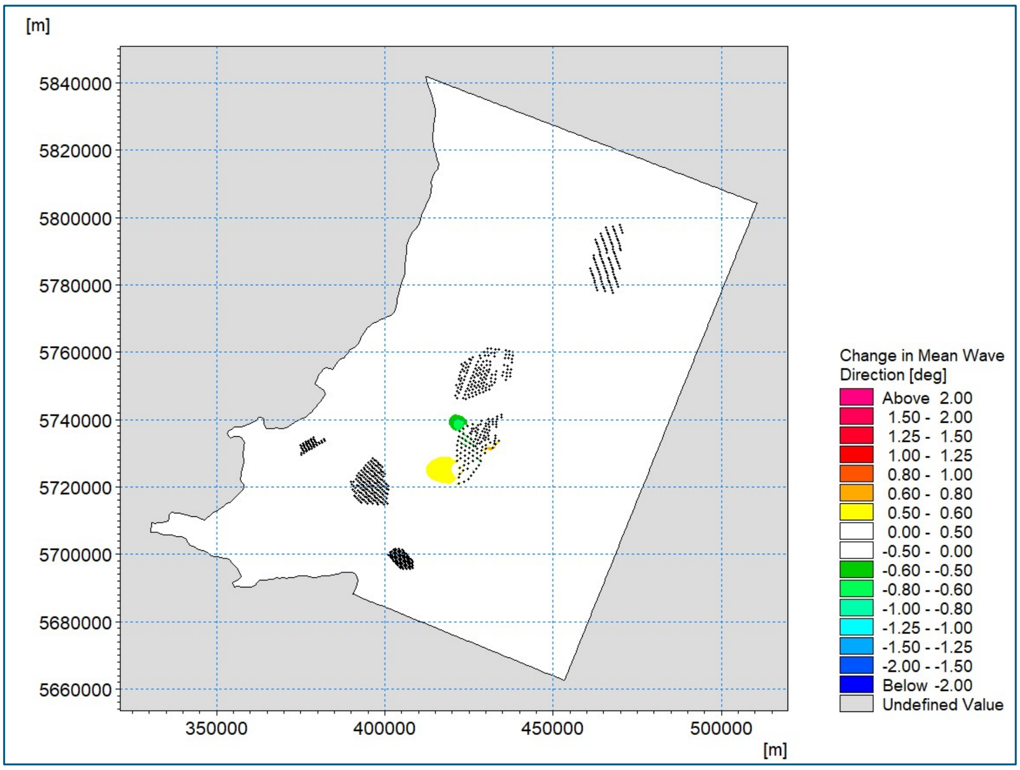


Figure 3-26: Layout 3 - Layout 1, change in MWD (°) for waves from 105°N - 1 in 1 year

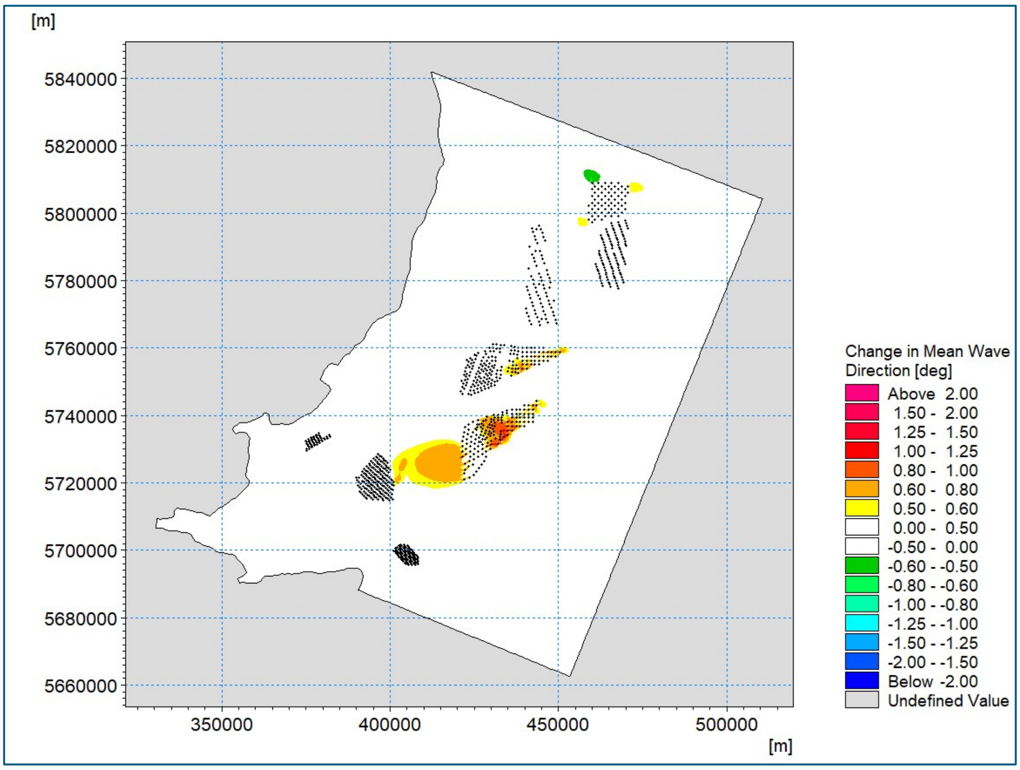


Figure 3-27: Layout 4 - Layout 1, change in MWD (°) for waves from 105°N - 1 in 1 year

4 Summary and Conclusions

A detailed wave modelling assessment has been undertaken to understand the potential effect of the North Falls OWF development on the surrounding wave climate.

The study utilised the MIKE21 Spectral Wave (SW) software, developed by Danish Hydraulic Institute (DHI), to simulate the growth and transformation of extreme waves to the North Falls site and other surrounding OWF's. The MIKE21-SW wave transformation model was first calibrated for a range of past significant storm events, approaching the project site for a range of different directions.

The boundary conditions for the extreme wave scenarios were derived from extreme value analysis of offshore wave and wind data at each model boundary, sourced from MetOffice and ERA5 hindcast models. The required return periods for the study included 1 in 1 year, 1 in 50 year and 1 in 100 year extreme wave / wind events from north, north-east, east and south-west.

The potential change in wave climate was assessed based on 3 OWF layout scenarios:

- Layout 3 - Layout 2 - North Falls OWF only
- Layout 3 - Layout 1 - North Falls OWF + existing / active OWF's
- Layout 4 - Layout 1 - North Falls OWF + existing / active OWF's + consented / pre-planning OWF's

Where the various structures for each OWF in the MIKE21-SW model, were represented using an existing RHDHV database of turbine reflection coefficients derived from local scale DIFFRACT-3D modelling.

The wave modelling results predicted that none of the OWF layout scenarios would have a significant effect on the surrounding wave climate, where a threshold for change in wave height of 5% is typically applied for these assessments.

The greatest change in wave climate due to the North Falls OWF (layout 3 - layout 2) occurred for waves from the east for the 1 in 1 year extreme event. Despite this, the % change in significant wave height reaching the surrounding wind farms and coastal regions was less than 0.6%.

The largest change in wave climate for all modelling results is predicted for the cumulative effect of all OWF's (layout 4 - layout 1) in response to a 1 in 1 year storm from east. Where % change in significant wave height exceeds 2% in areas close to some OWF arrays. Despite this, the predicted change in coastal regions is less than 0.6%.

Annex A: Extreme Analysis

Figure A. 1 to **Figure A. 4** present the Gumbel fitting distributions for the directional sectors used in the North Falls wave modelling assessment.

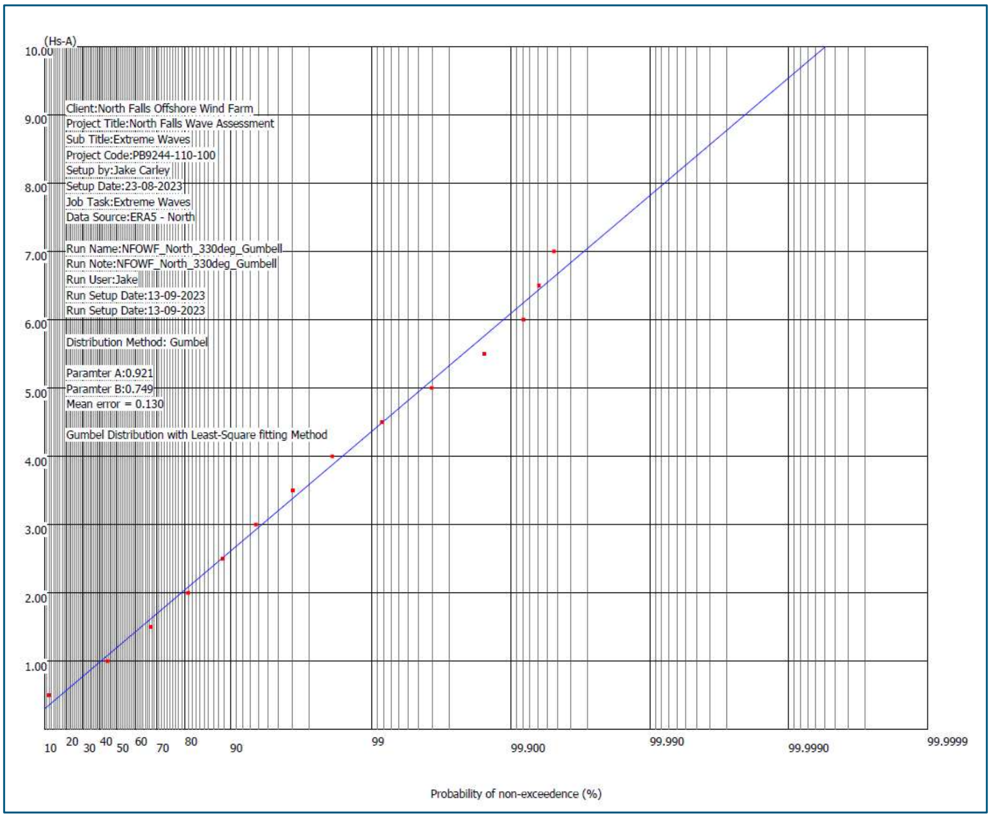


Figure A. 1: Gumbel fitting distribution - 330°N sector - north point

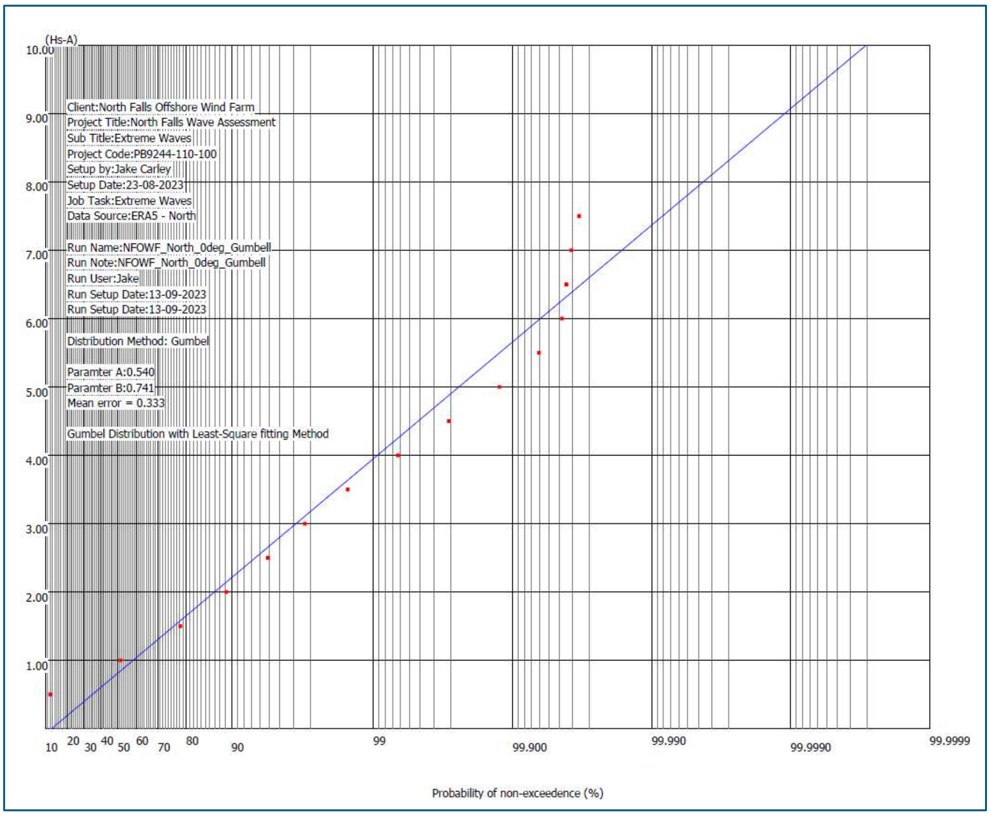


Figure A. 2: Gumbel fitting distribution - 0°N sector - north point

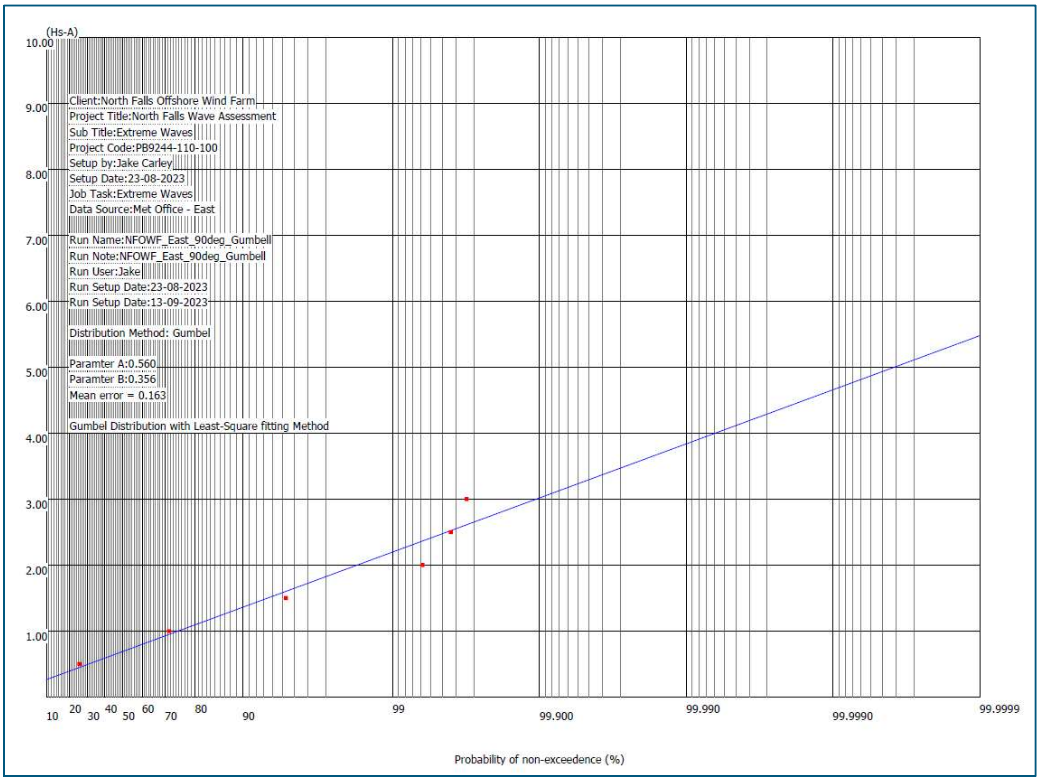


Figure A. 3: Gumbel fitting distribution - 105°N sector - east point

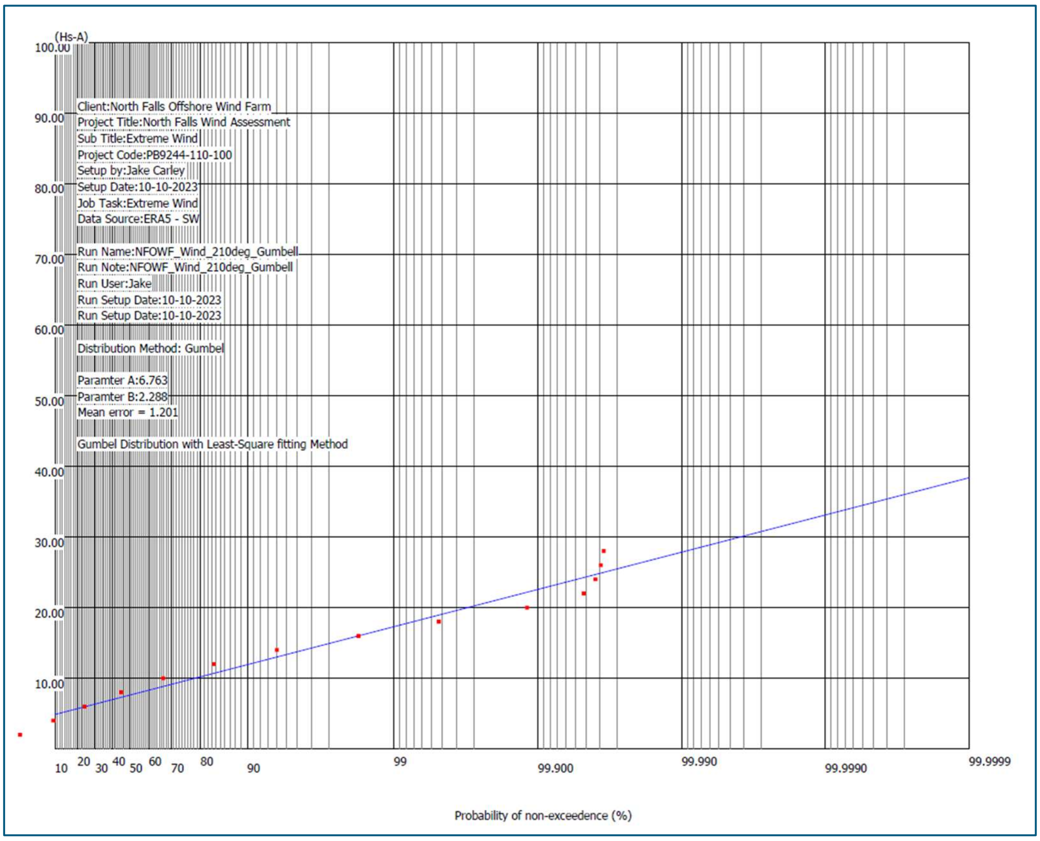


Figure A. 4: Gumbel fitting distribution - 210°N sector - south point

Figure A. 5 to **Figure A. 7** present Hs / wind speed and Hs / wave spreading relationships for each directional sector selected for the wave modelling assessment.

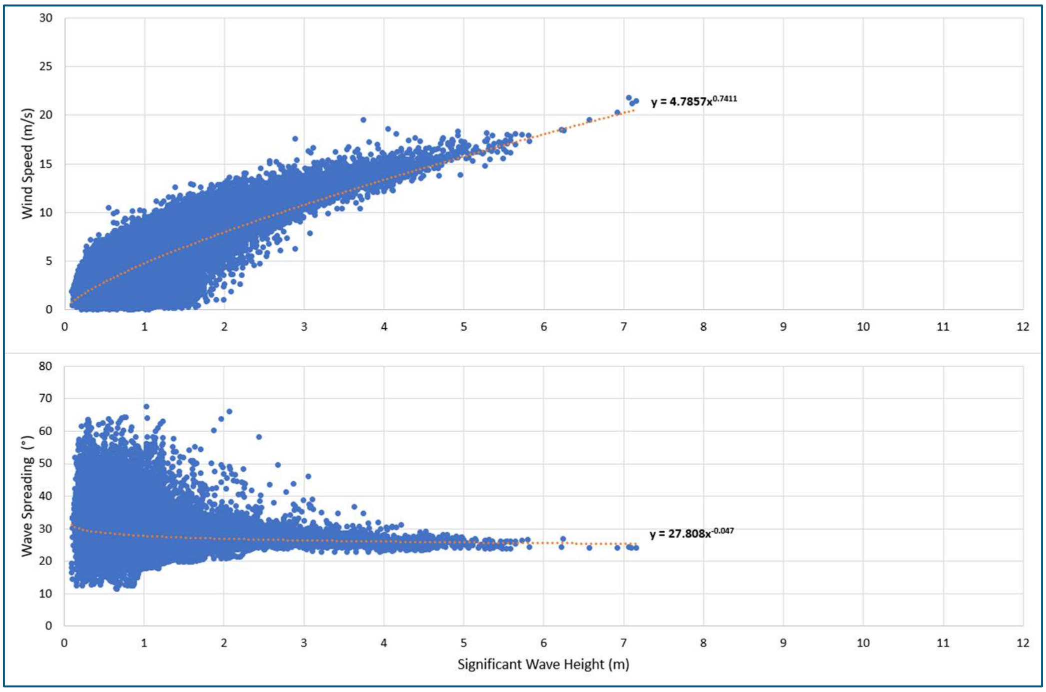


Figure A. 5: Hs / wind speed and Hs / wave spreading relationships for 0°N sector - north point

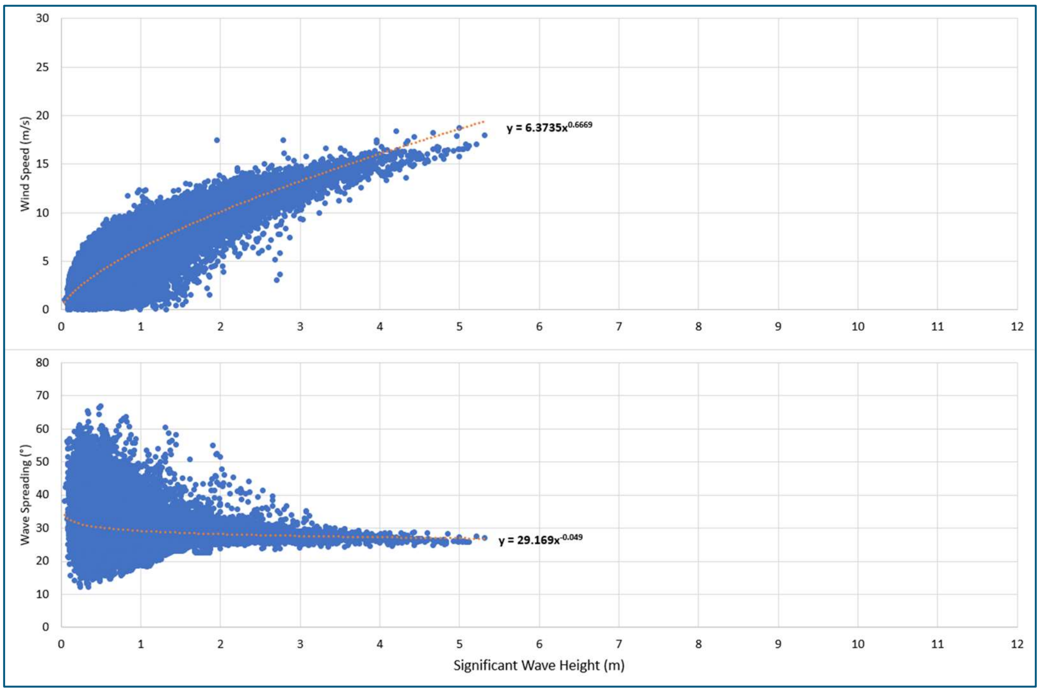


Figure A. 6: Hs / wind speed and Hs / wave spreading relationships for 105°N sector - east point

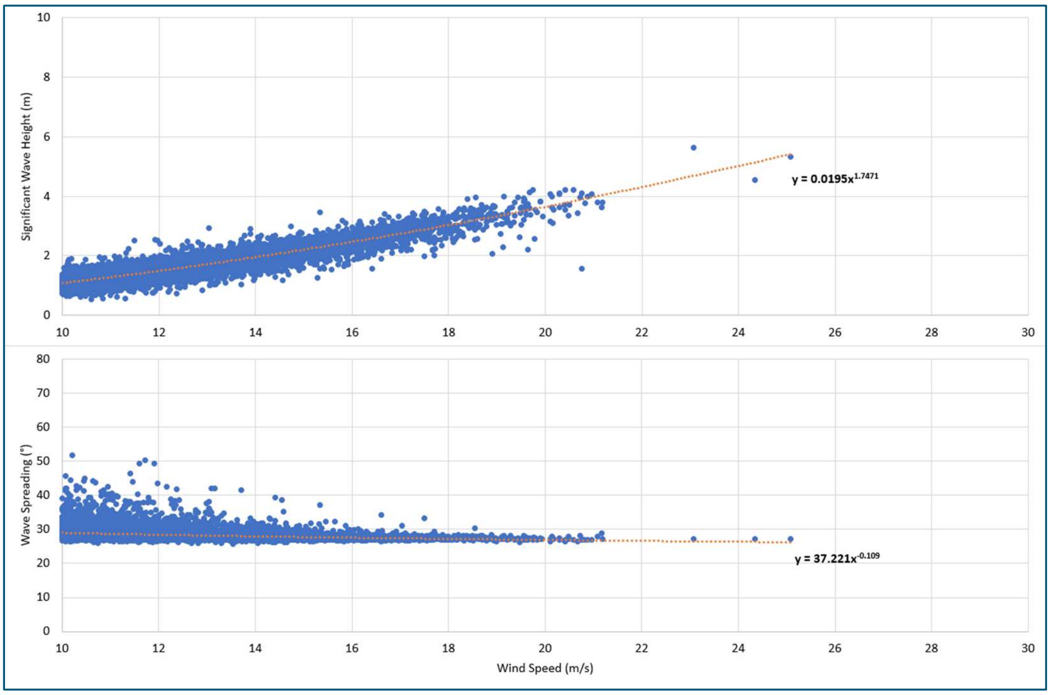


Figure A. 7: Hs / wind speed and Hs / wave spreading relationships for 210°N sector - south point

Annex B: DIFFRACT 3D Model

Background

This Annex D describes the local scale wave modelling that has been undertaken using the DIFFRACT model.

Introduction

Wave energy will be redistributed when waves interact with offshore wind turbine foundations. Usually, the dominant effects include reflection and diffraction of waves caused by the larger dimensional structures. Other causes for the redistribution/loss of wave energy are wave-structure friction and flow separation behind the structures. However, friction effects are difficult to estimate in many cases, whilst flow separation is usually assumed to be important for situations where Keulegan Carpenter (KC) numbers are greater than 6. Although it has also been argued that flow separation may occur at lower KC numbers (Trulsen and Teigen, 2002), only effects of reflection and diffraction are considered in the present report since these are deemed to be the dominant effects.

Methodology

Definition of Wave Reflection Coefficient

Considering the energy flow through the wind turbine foundations it seems reasonable to set up an energy balance based on **Figure B. 1**. The relations between incoming energy E ̂_(f,I), reflected energy E ̂_(f,R) and transmitted energy E ̂_(f,T) can be written as:

$$\hat{E}_{f,R} = \hat{E}_{f,I} - \hat{E}_{f,T} \quad (1)$$

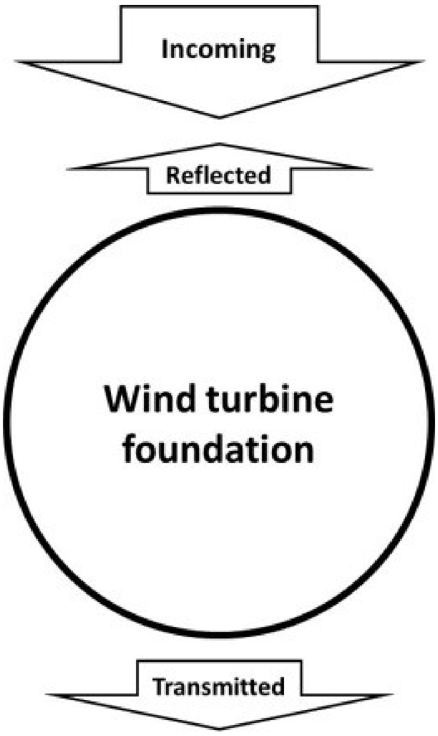


Figure B. 1: Redistributions of wave energy due to wind turbine foundation

Under first-order assumption, wave energy flux for waves over a plane seabed can be expressed by:

$$E_f = \frac{1}{T}\int_0^T \int_{-h}^0 p^+ u dz dt \quad (2)$$

Where:

u is the horizontal velocity of water particle
T is the wave period
h is water depth.

For undisturbed waves (incoming waves), the energy flux can be expressed as:

$$E_{f,I} = \frac{1}{16}\rho g H^2 c\left(1 + \frac{2kh}{\sinh(2kh)}\right) \quad (3)$$

Where:

ρ is the mass density of water
g is gravitational acceleration
H is the wave height
c is the wave celerity = ω/k (here ω=2π/T)
k is the wave number = 2π/L (here L is the wavelength)

The transmitted energy flux $\hat{E}_{f,T}$ can be calculated by integrating the wave energy flux from the foundation surface to infinity perpendicular to the wave direction, which is:

$$\hat{E}_{f,T} = \int_{-\infty}^{\infty} E_{f,T} dy \quad (4)$$

Usually, the wind turbine foundations are axisymmetric structures and only half the plane is needed in the calculations. So the transmitted energy $\hat{E}_{f,T}$ can be obtained from the integration from CL(y=0) to infinity.

$$\hat{E}_{f,T} = 2\int_{CL}^{\infty} E_{f,T} dy = 2\int_{CL}^{\infty}\left[\frac{1}{T}\int_0^T \int_{-h}^0 p^+ u dz dt\right] dy \quad (5)$$

The wave reflection coefficient can be defined as:

$$C = \frac{\hat{E}_{f,I} - \hat{E}_{f,T}}{E_{f,I}} = 2\frac{\int_{CL}^{\infty}\left\{E_{f,I} - \left[\frac{1}{T}\int_0^T \int_{-h}^0 p^+ u dz dt\right]\right\} dy}{E_f} \quad (6)$$

This parameter indicates the equivalent reflection effects of the wind turbine foundation (and it is in metres).

Calculation of Wave Reflection Coefficient

Clearly, dynamic pressure p^+ and horizontal velocity u are needed for calculating the wave reflection coefficient. Under the first-order assumption using potential flow theory, the expressions for calculating excess pressure and horizontal velocity can be written as:

$$p^+ = Re[\mathrm{i}\omega\rho\varphi e^{-\mathrm{i}\omega t}] \quad (7)$$

$$u = Re\left[\frac{\partial\varphi}{\partial x} e^{-\mathrm{i}\omega t}\right] \quad (8)$$

Where:

Re[ ] denotes the real parts of complex numbers
φ is the first-order velocity potential in fluid domain.

In wave diffraction problems, velocity potential φ can be decomposed into:

$$\varphi_I + \varphi_D \quad (9)$$

Where:

φ_I is incident potential which has analytical expression
φ_D is diffraction potential which can be obtained by solving the boundary value problem of wave-structure interactions.

A convenient way to get the diffraction velocity potential φ_D, and the total velocity potential is using potential flow solvers in frequency domain. In the present report, a potential flow solver DIFFRACT has been used to analyse wave-structure interactions.

The computational program DIFFRACT has been developed to calculate linear and second order wave diffraction from three-dimensional arbitrary-shaped fixed or floating structures under unidirectional (Walker et al., 2006; Zang et al. 2006) and directional spread input regular waves (Zang et al., 2005) and random wave groups (Walker et al. 2008; Zang et al., 2009). A wide range of benchmarking tests have been performed to validate the implemented solution algorithms and the numerical code against published results.

The mathematical background of DIFFRACT is similar to that which has also been used in the computational program WAMIT. However, there are also some different features in DIFFRACT. In this implementation of the Boundary Element Method, the body surface, internal water plane and outer free surface for both linear and second order analysis are discretized into quadratic elements (Eatock Taylor and Chau, 1992). The directional spreading can be considered for incident waves (Zang et al., 2005). In the present version of the code, partial discontinuous elements have been adopted to remove the irregular frequencies and more details of the related method can be found in the paper of Sun et al. (2008). The effects of rigid/flexible mechanical connections can be predicted for multiple floating bodies by using DIFFRACT (Sun et al., 2011 and 2012).

More details on the program and the areas that DIFFRACT has been applied to, are provided in the references.

Foundations and Corresponding Meshes

Three types/dimensions of wind turbine foundations (one GBS and two monopiles) in different water depths have been considered and more information on the scenarios considered can be found in **Table B. 1**.

The details of the GBS foundation and numerical meshes used in the diffraction calculations for 30m, 40m, 50m, 60m and 70m of water depth are shown in **Figure B. 2** to **Figure B. 11**.

Diameters of monopile #1 and #2 are D=6.5m and D=12.0m respectively. Corresponding meshes are shown in **Figure B. 12** and **Figure B. 13**.

Table B. 1: Wind turbine foundations (one GBS and two monopiles) in different water depths

Water depth (m)	GBS	Monopile #1	Monopile #2
20		●	●
30	●	●	●
40	●	●	●
50	●	●	●
60	●		
70	●		

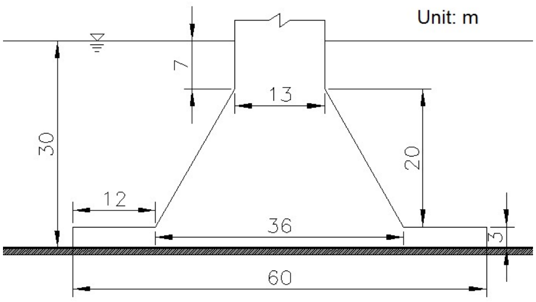


Figure B. 2: GBS foundation in water depth 30m

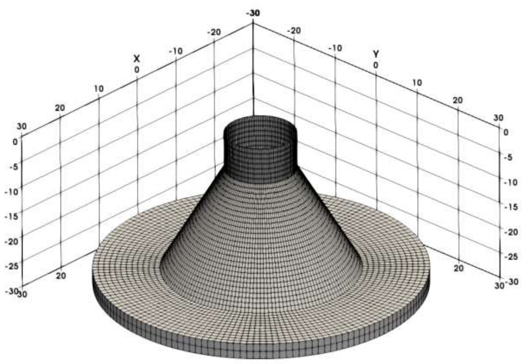


Figure B. 3: Numerical mesh for GBS foundation in water depth of 30 m

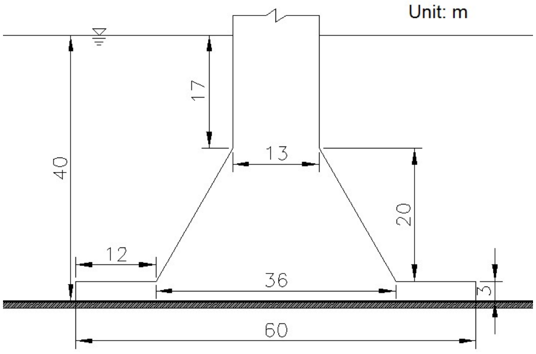


Figure B. 4: GBS foundation in water depth of 40 m

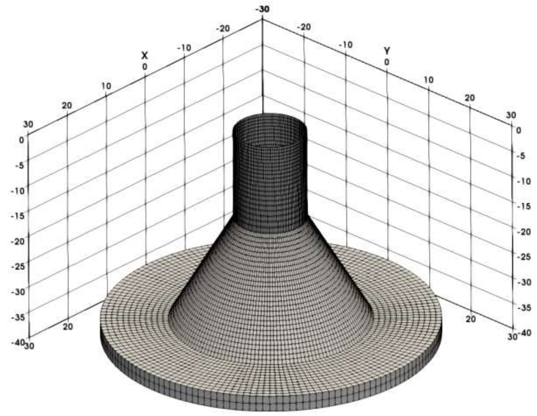


Figure B. 5: Numerical mesh for GBS foundation in water depth of 40 m

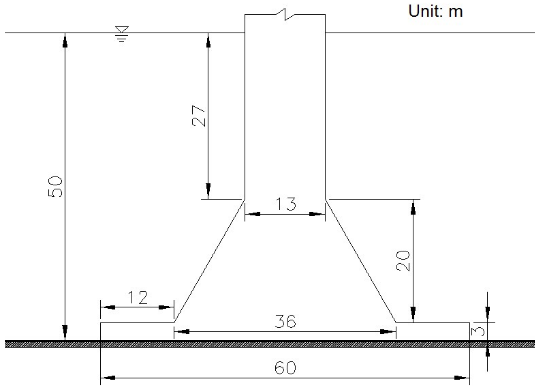


Figure B. 6: GBS foundation in water depth of 50 m

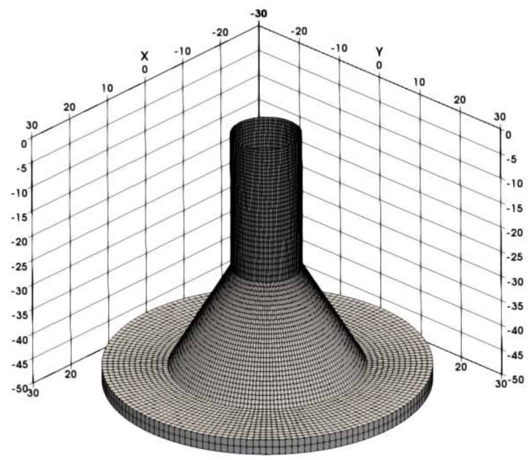


Figure B. 7: Numerical mesh for GBS foundation in water depth of 50 m

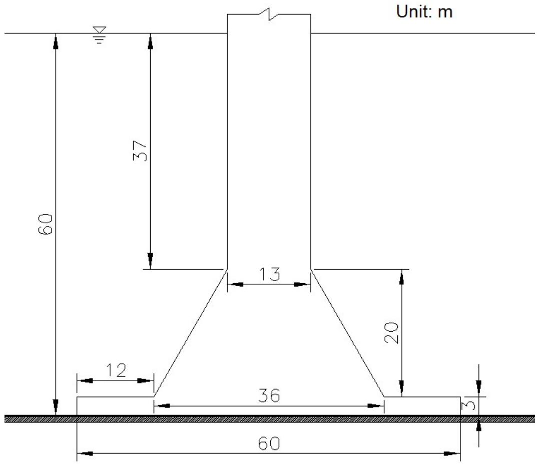


Figure B. 8: GBS foundation in water depth of 60 m

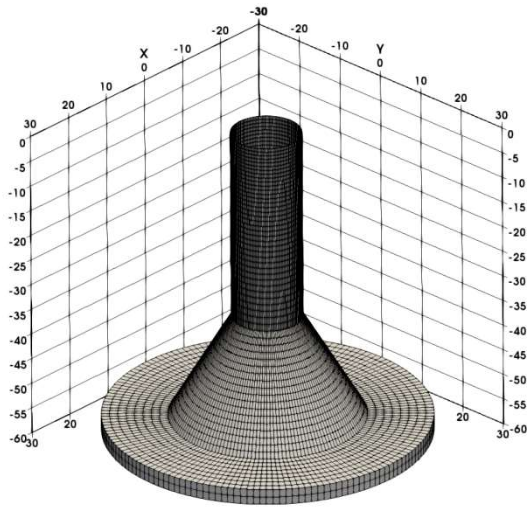


Figure B. 9: Numerical mesh for GBS foundation in water depth of 60 m

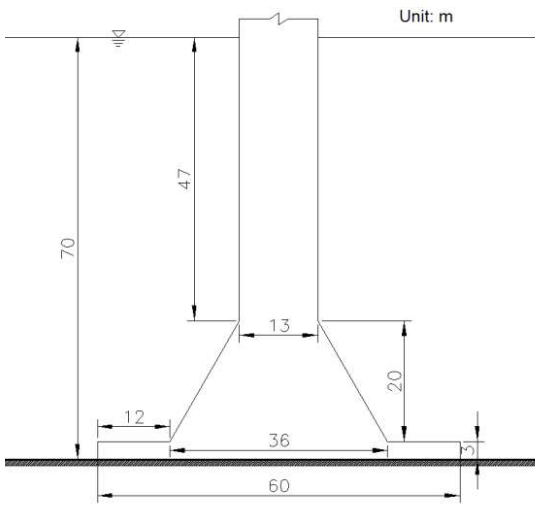


Figure B. 10: GBS foundation in water depth of 70 m

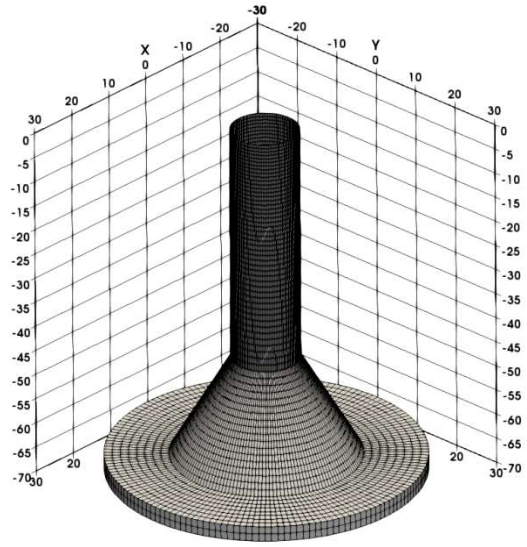
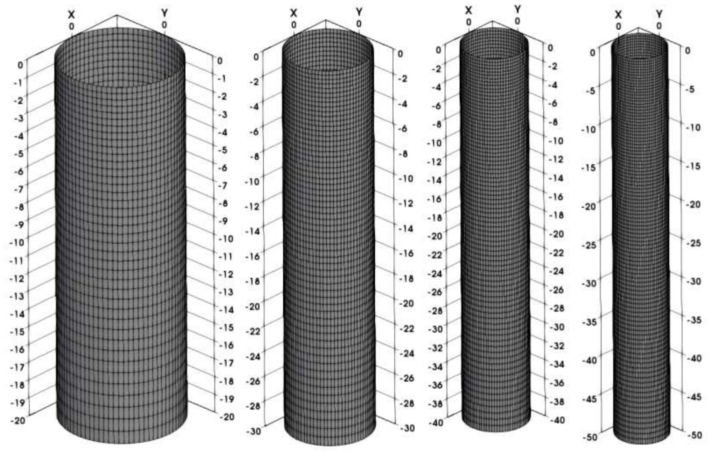


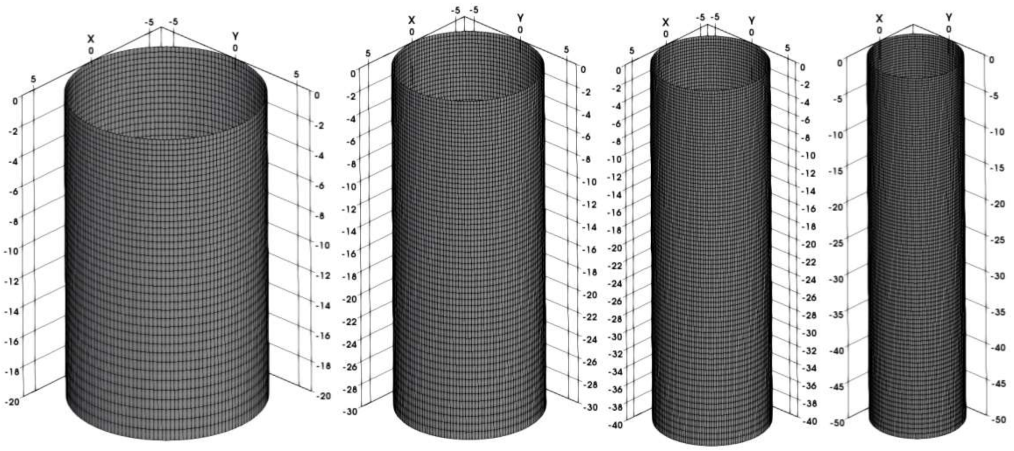
Figure B. 11: Numerical mesh for GBS foundation in water depth of 70 m



(a) (b) (c) (d)

Figure B. 12: Numerical mesh for monopile #1 (D =6.5m) in different water depths

(a) 20m (b) 30m (c) 40m (d) 50m



(a) (b) (c) (d)

Figure B. 13: Numerical mesh for monopile #2 (D =12m) in different water depths

(a) 20m (b) in 30m (c) in 40m (d) in 50m

Results of Wave Reflection Coefficients

The results of wave reflection coefficients for GBS foundation and monopiles are presented in the **Table B. 2** to **Table B. 4** and the corresponding graphs can be found in **Figure B. 14** to **Figure B. 19**.

It is reasonable that there is less reflection when longer waves pass the foundations.

Table B. 2: Wave reflection coefficients for GBS foundations in different water depths

Wave Period (s)	Water Depth (m)				
	30	40	50	60	70
2.0	8.577	8.303	8.115	7.792	7.533
3.0	8.847	8.705	8.634	8.443	8.315
4.0	9.526	9.299	9.209	9.120	9.029
5.0	10.961	10.377	10.291	10.223	10.153
6.0	9.764	8.918	8.321	8.261	8.204
7.0	6.793	5.553	5.399	5.348	5.328
8.0	4.509	3.283	3.063	2.983	2.963
9.0	3.361	2.036	1.782	1.659	1.638
10.0	2.545	1.567	1.070	0.898	0.858
11.0	2.131	1.151	0.648	0.438	0.364
12.0	1.677	0.863	0.381	0.147	0.037
13.0	1.486	0.651	0.204	0.037	0.009
14.0	1.206	0.496	0.088	0.035	0.001
15.0	0.979	0.377	0.005	0.005	0.001

Wave Period (s)	Water Depth (m)				
	30	40	50	60	70
16.0	0.798	0.287	0.001	0.001	0.001
17.0	0.542	0.217	0.001	0.001	0.001
18.0	0.416	0.162	0.001	0.001	0.001
19.0	0.272	0.117	0.001	0.001	0.001
20.0	0.237	0.083	0.001	0.001	0.001
21.0	0.215	0.050	0.001	0.001	0.001
22.0	0.152	0.028	0.001	0.001	0.001
23.0	0.093	0.103	0.001	0.001	0.001
24.0	0.077	0.034	0.001	0.001	0.001
25.0	0.027	0.018	0.001	0.001	0.001

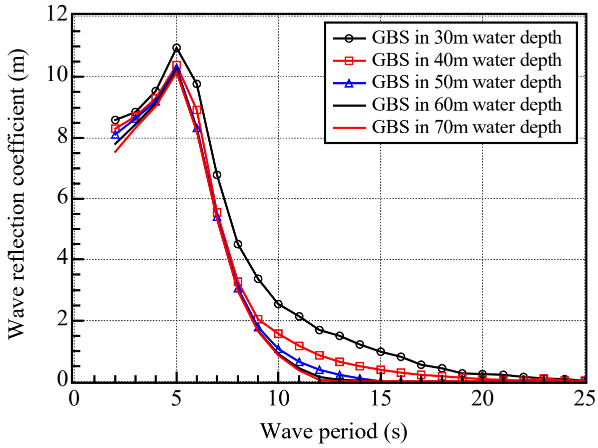


Figure B. 14: Wave reflection coefficients for GBS foundations in different water depths

Table B. 3: Wave reflection coefficients for monopile #1 in different water depths

Wave Period (s)	Water Depth (m)			
	20	30	40	50
2.0	4.234	4.147	4.057	3.969
3.0	4.786	4.726	4.665	4.604
4.0	4.747	4.711	4.662	4.611
5.0	2.621	2.406	2.383	2.345
6.0	1.148	1.140	1.061	1.055
7.0	0.705	0.636	0.645	0.509

Wave Period (s)	Water Depth (m)			
	20	30	40	50
8.0	0.437	0.334	0.322	0.340
9.0	0.299	0.182	0.139	0.142
10.0	0.223	0.099	0.032	0.008
11.0	0.174	0.051	0.010	0.002
12.0	0.141	0.018	0.002	0.001
13.0	0.114	0.009	0.001	0.001
14.0	0.091	0.001	0.001	0.001
15.0	0.069	0.001	0.001	0.001
16.0	0.045	0.001	0.001	0.001
17.0	0.018	0.001	0.001	0.001
18.0	0.005	0.001	0.001	0.001
19.0	0.001	0.001	0.001	0.001
20.0	0.001	0.001	0.001	0.001
21.0	0.001	0.001	0.001	0.001
22.0	0.001	0.001	0.001	0.001
23.0	0.001	0.001	0.001	0.001
24.0	0.001	0.001	0.001	0.001
25.0	0.001	0.001	0.001	0.001

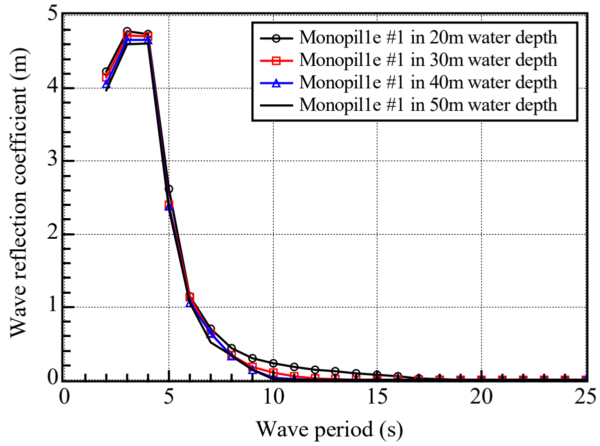


Figure B. 15: Wave reflection coefficients for monopile #1 in different water depths

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Table B. 4: Wave reflection coefficients for monopile #2 in different water depths

Wave Period (s)	Water Depth (m)			
	20	30	40	50
2.0	8.299	8.198	8.097	7.996
3.0	8.422	8.240	8.188	8.013
4.0	8.860	8.824	8.774	8.723
5.0	9.623	9.661	9.629	9.599
6.0	7.111	7.026	7.054	7.042
7.0	4.250	4.357	4.307	4.140
8.0	3.322	2.789	2.643	2.619
9.0	2.329	1.811	1.620	1.564
10.0	1.734	1.273	1.064	0.976
11.0	1.356	0.953	0.749	0.638
12.0	1.100	0.751	0.553	0.426
13.0	0.921	0.611	0.418	0.283
14.0	0.789	0.506	0.317	0.172
15.0	0.687	0.421	0.230	0.069
16.0	0.604	0.346	0.146	0.036
17.0	0.532	0.275	0.057	0.004
18.0	0.469	0.203	0.004	0.001
19.0	0.409	0.126	0.001	0.001
20.0	0.349	0.042	0.001	0.001
21.0	0.290	0.003	0.001	0.001
22.0	0.229	0.001	0.001	0.001
23.0	0.163	0.001	0.001	0.001
24.0	0.093	0.001	0.001	0.001
25.0	0.019	0.001	0.001	0.001

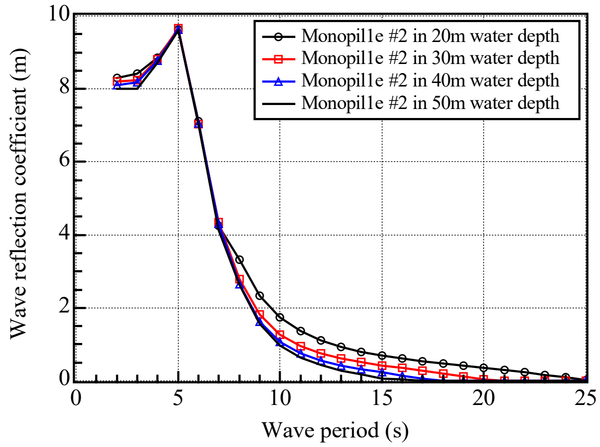

Figure B. 16: Wave reflection coefficients for monopile #2 in different water depths

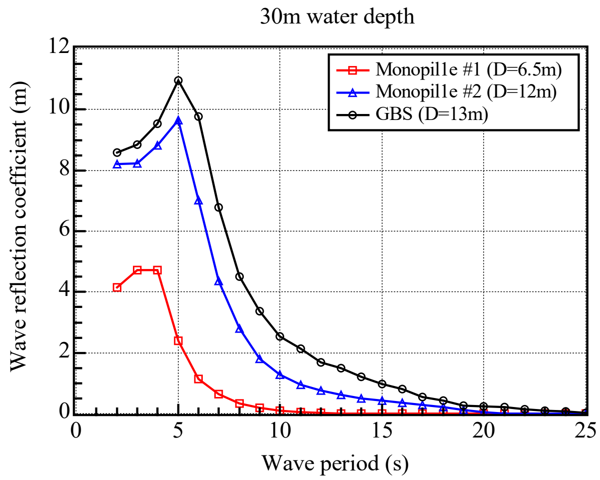

Figure B. 17: Wave reflection coefficients for 3 foundations in water depth of 30m

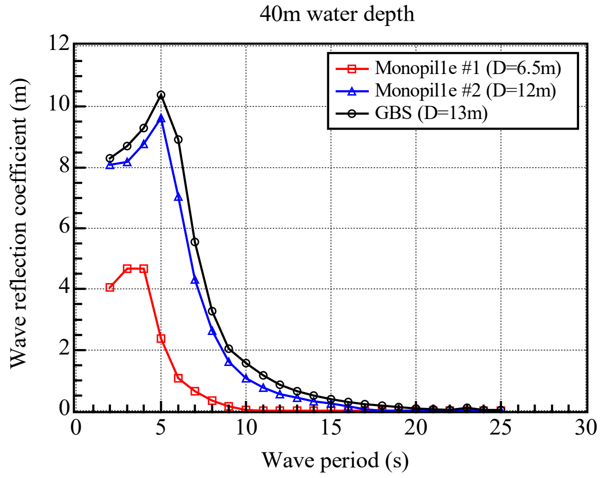

Figure B. 18: Wave reflection coefficients for 3 foundations in water depth of 40m

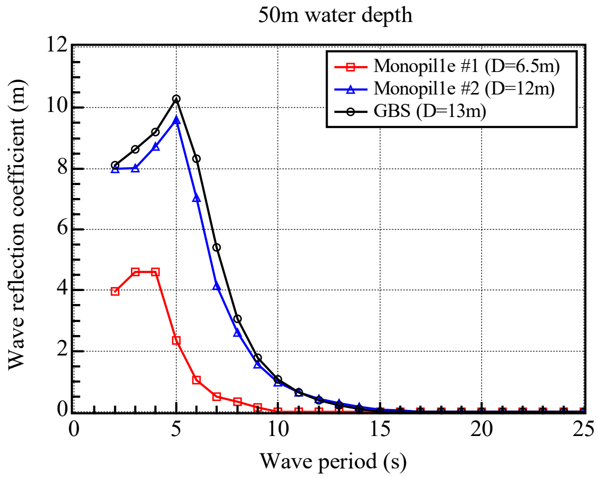

Figure B. 19: Wave reflection coefficients for 3 foundations in water depth of 50m

Concluding Remarks

In the present report, wave reflection coefficients have been calculated to indicate the near-field effects of wind turbine foundations.

Three types/dimensions of wind turbine foundations (one GBS and two monopiles) for different water depths are considered and wave reflections coefficients are plotted under wave period ranging from 2 to 25 seconds.

Reasonable results are obtained, which indicate more energy is reflected in short waves and less reflection effects are found in long waves.

It can be seen that the peak wave reflection coefficients occur around 5s for GBS foundation and monopile #2, and around 3-4s for monopile #1.

Also for the same water depth, larger wave reflection coefficients are found from GBS foundation and monopile #2, and smaller wave reflection coefficients are obtained from monopile #1.

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Annex C: Change in Significant Wave Height (1 in 50 year and 1 in 100 year return period)

Figure C. 1 to **Figure C. 8** present results of the layout 3 - layout 2 scenario, showing the effect of North Falls only, on the surrounding wave climate, for 1 in 50 year and 1 in 100 year wave events.

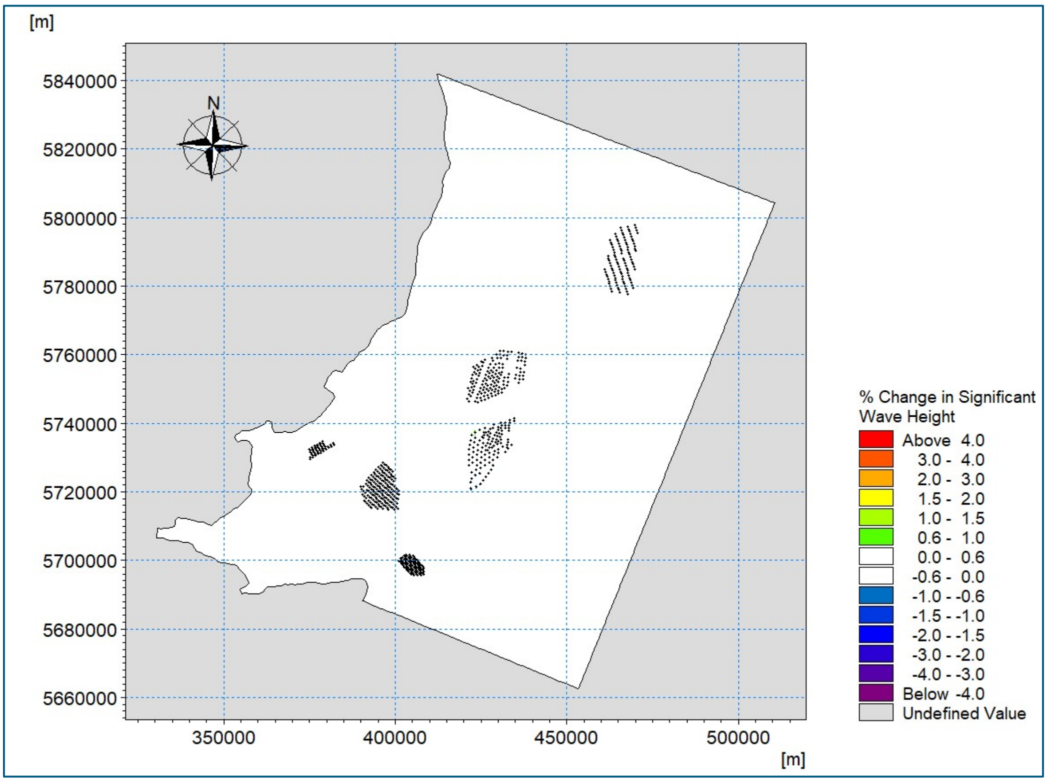

Figure C. 1: Layout 3 - Layout 2, % change in H_s for waves from 345°N - 1 in 50 year

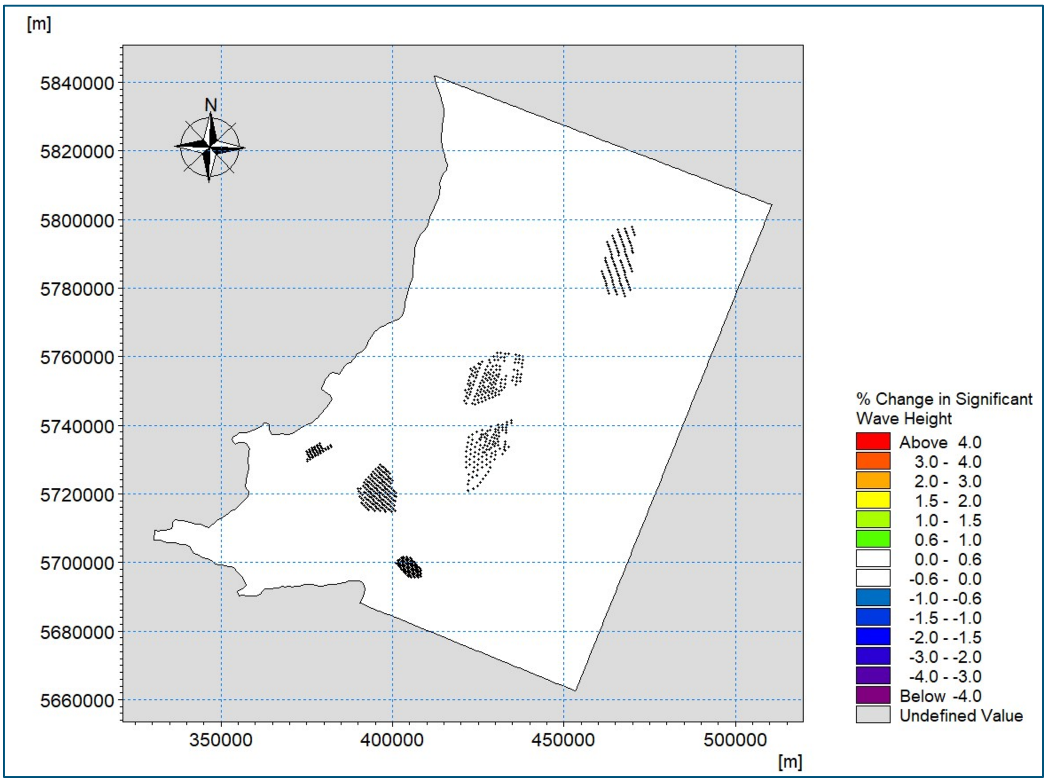

Figure C. 2: Layout 3 - Layout 2, % change in H_s for waves from 345°N - 1 in 100 year

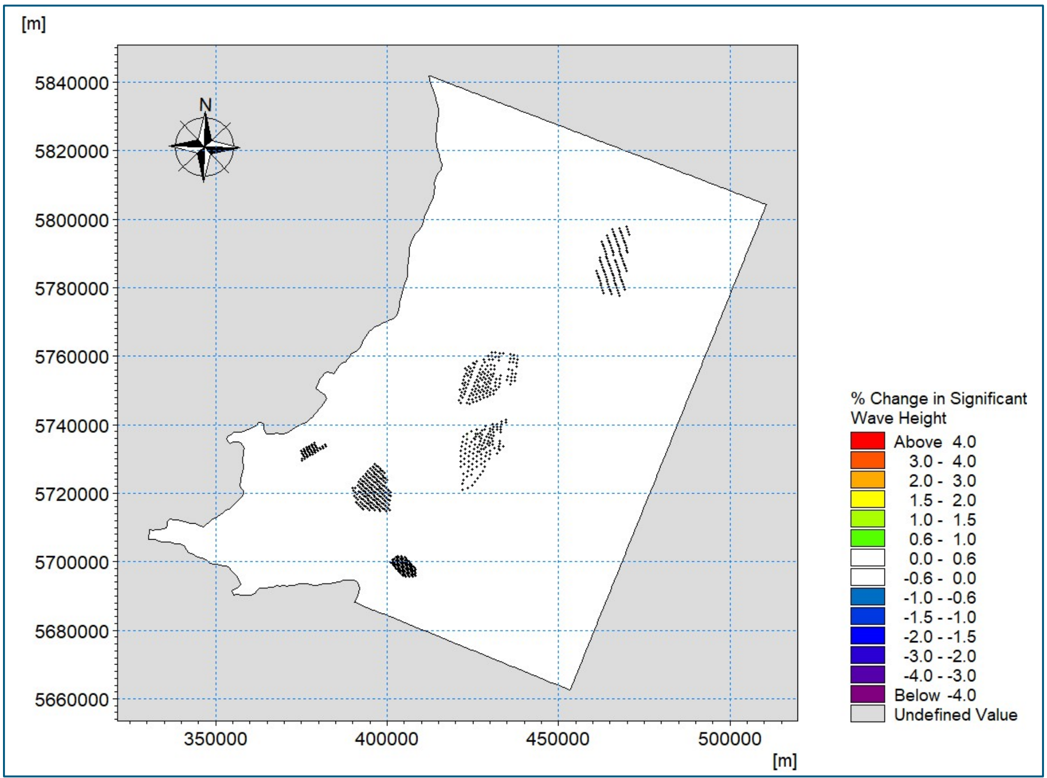

Figure C. 3: Layout 3 - Layout 2, % change in H_s for waves from 15°N - 1 in 50 year

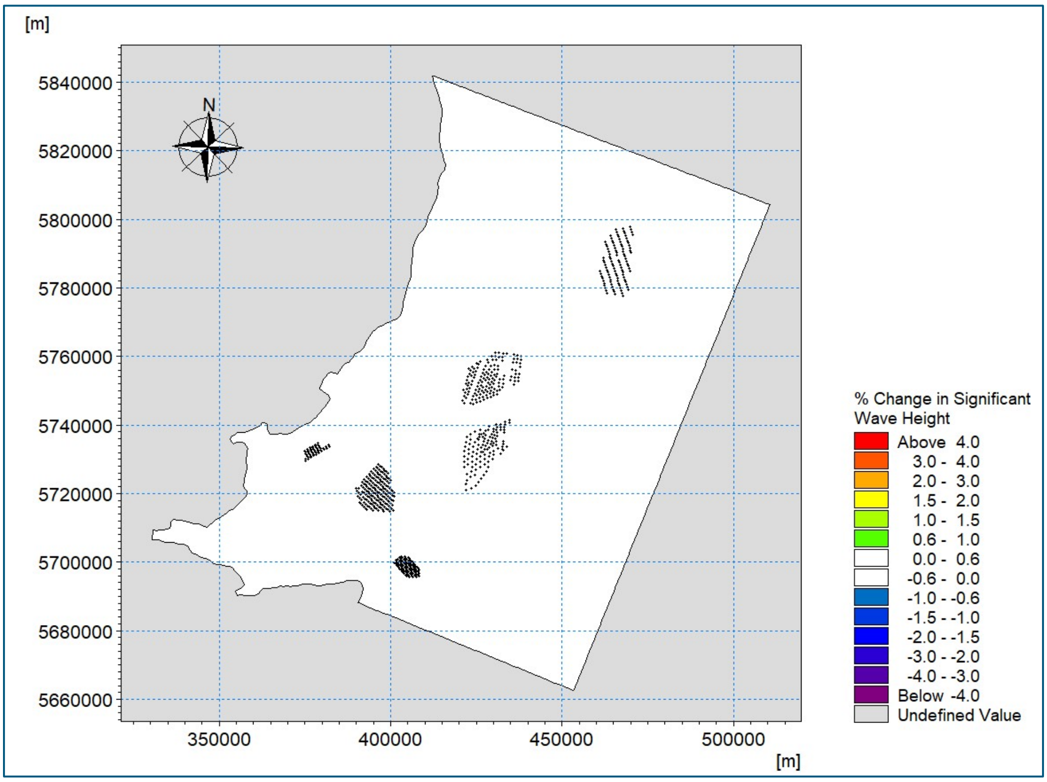

Figure C. 4: Layout 3 - Layout 2, % change in H_s for waves from 15°N - 1 in 100 year

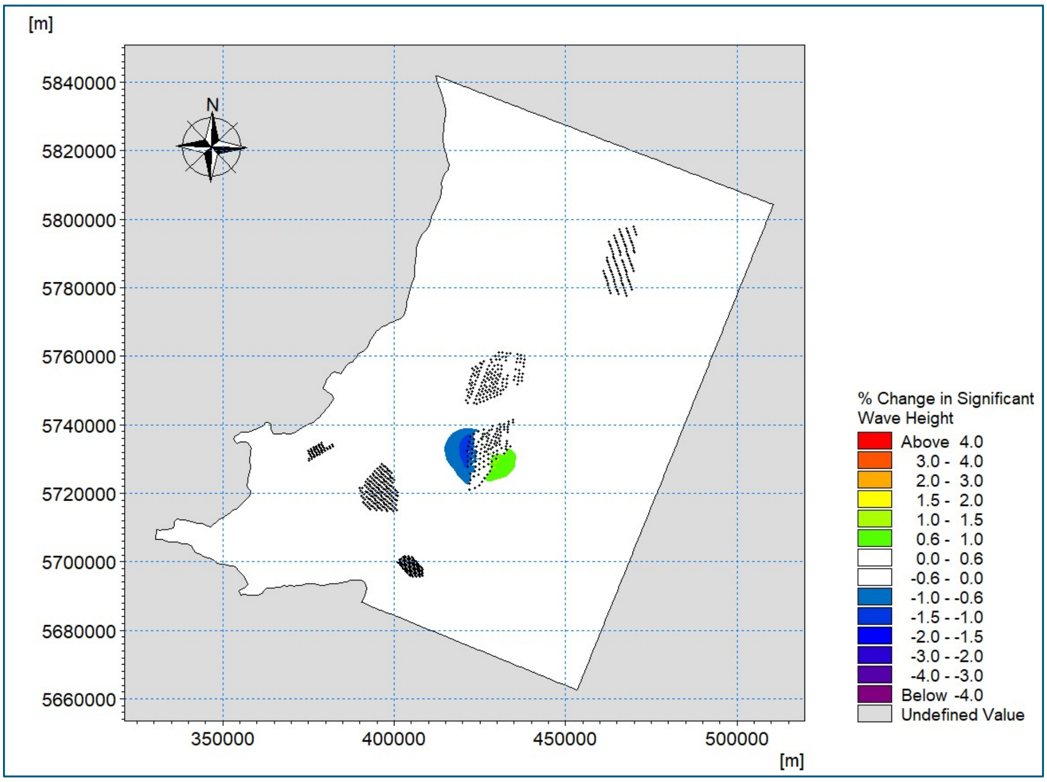

Figure C. 5: Layout 3 - Layout 2, % change in H_s for waves from 105°N - 1 in 50 year

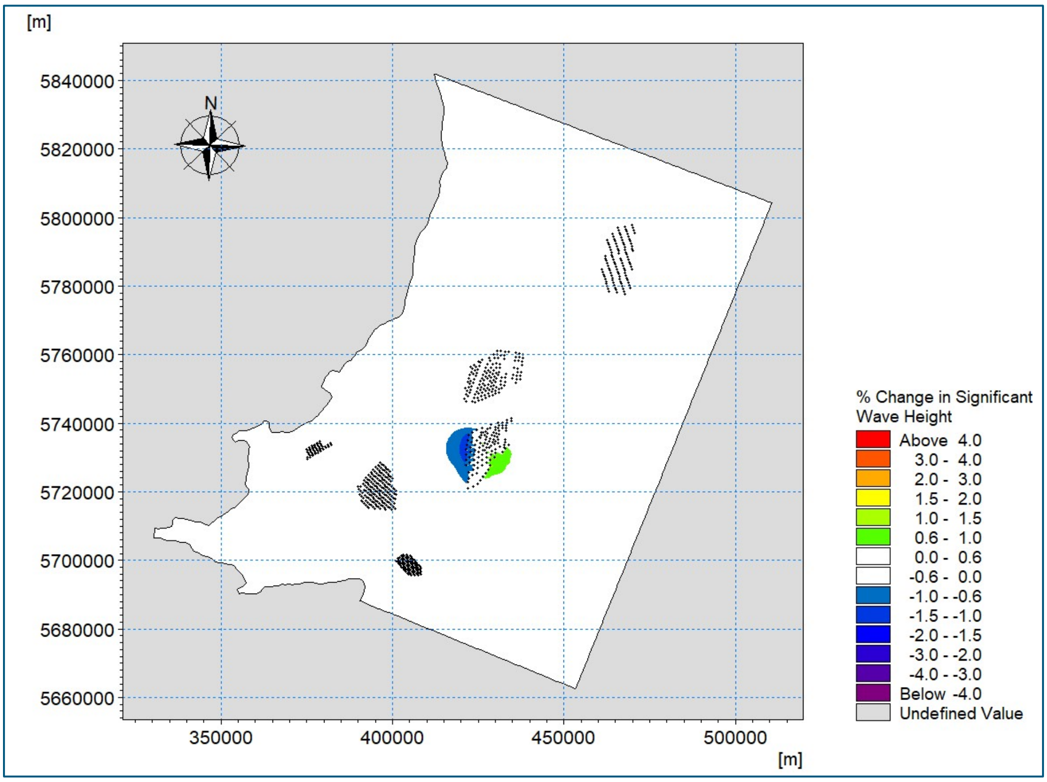

Figure C. 6: Layout 3 - Layout 2, % change in H_s for waves from 105°N - 1 in 100 year

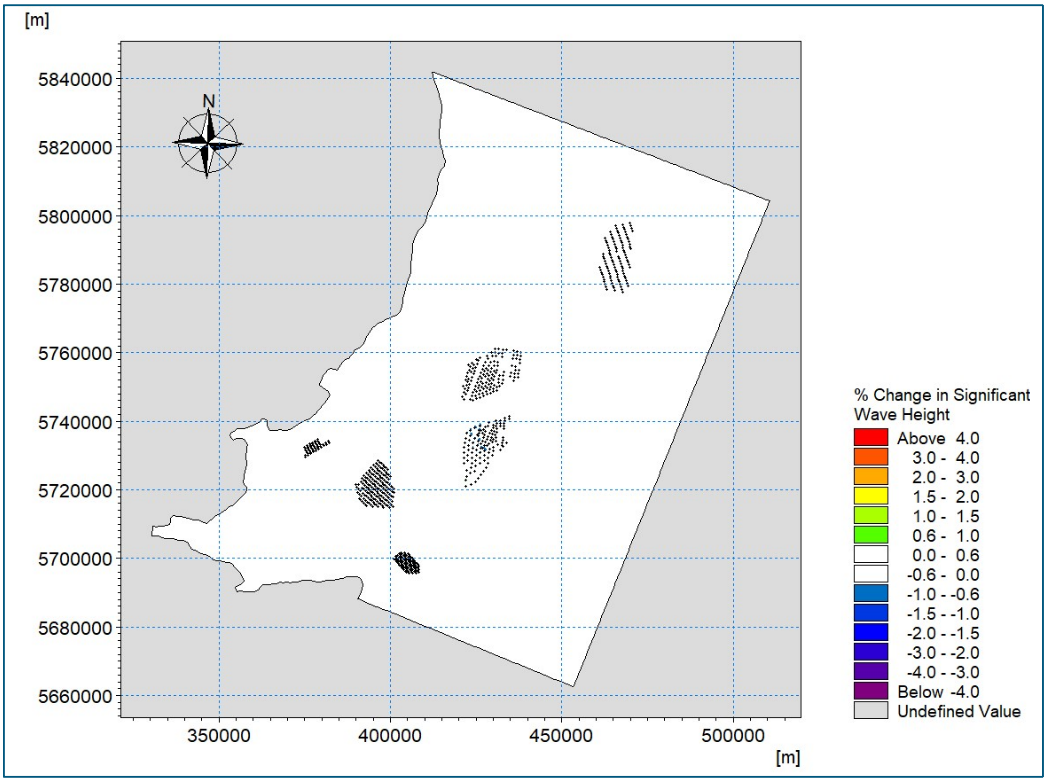

Figure C. 7: Layout 3 - Layout 2, % change in H_s for waves from 210°N - 1 in 50 year

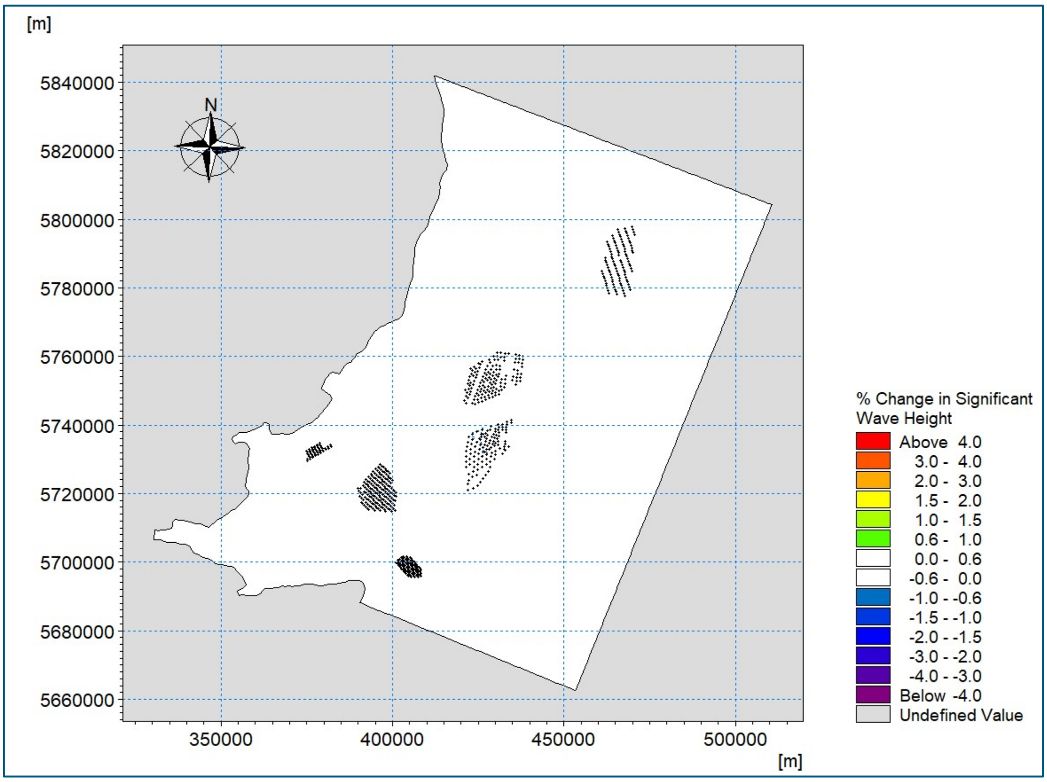

Figure C. 8: Layout 3 - Layout 2, % change in H_s for waves from 210°N - 1 in 100 year

Figure C. 9 to **Figure C. 16** present results of the layout 3 - layout 1 scenario, showing the cumulative effect of North Falls and existing OWF's, on the surrounding wave climate, for the 1 in 50 year and 1 in 100 year wave events.

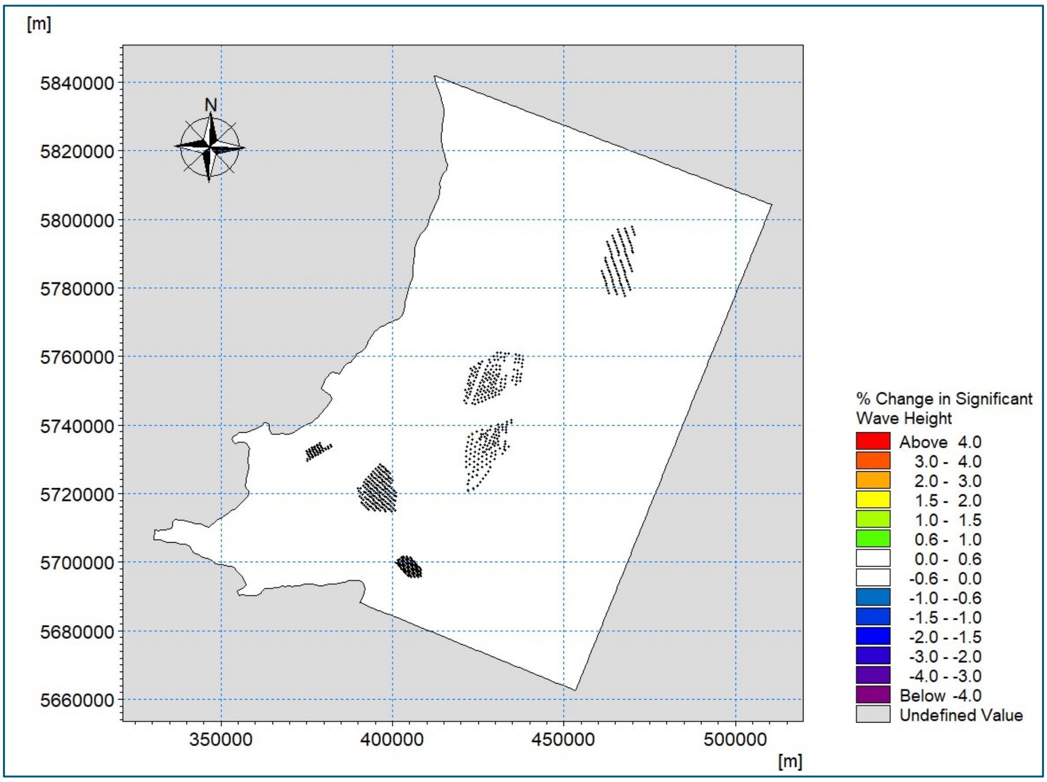

Figure C. 9: Layout 3 - Layout 1, % change in H_s for waves from 345°N - 1 in 50 year

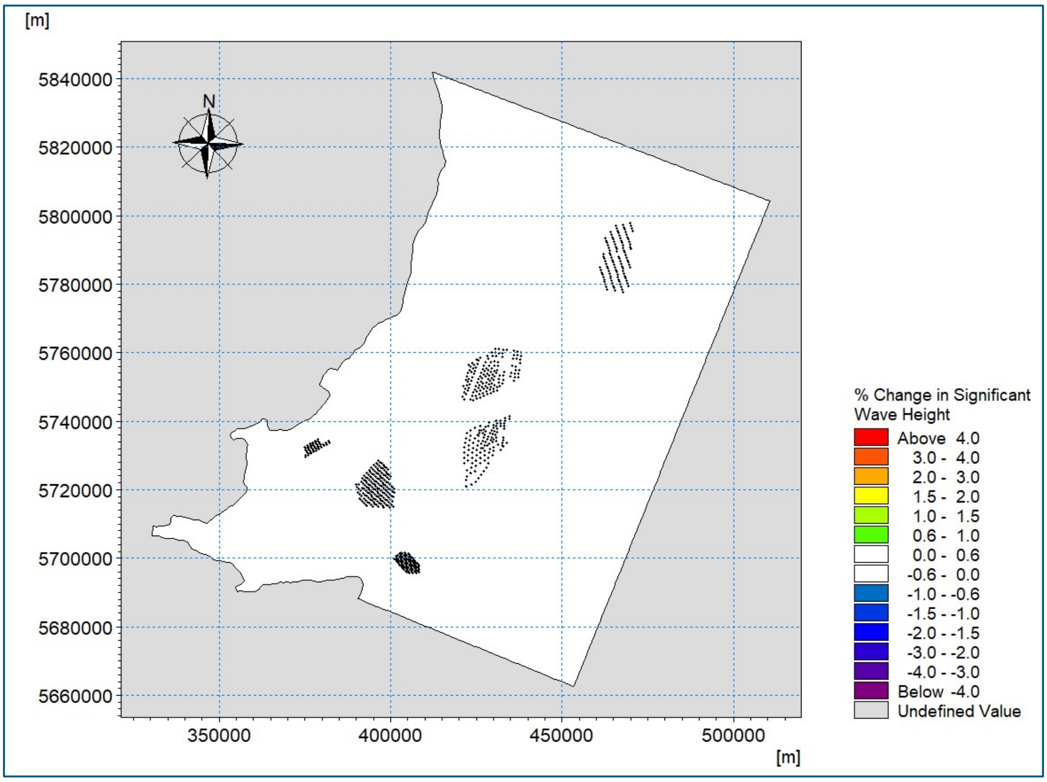

Figure C. 10: Layout 3 - Layout 1, % change in H_s for waves from 345°N - 1 in 100 year

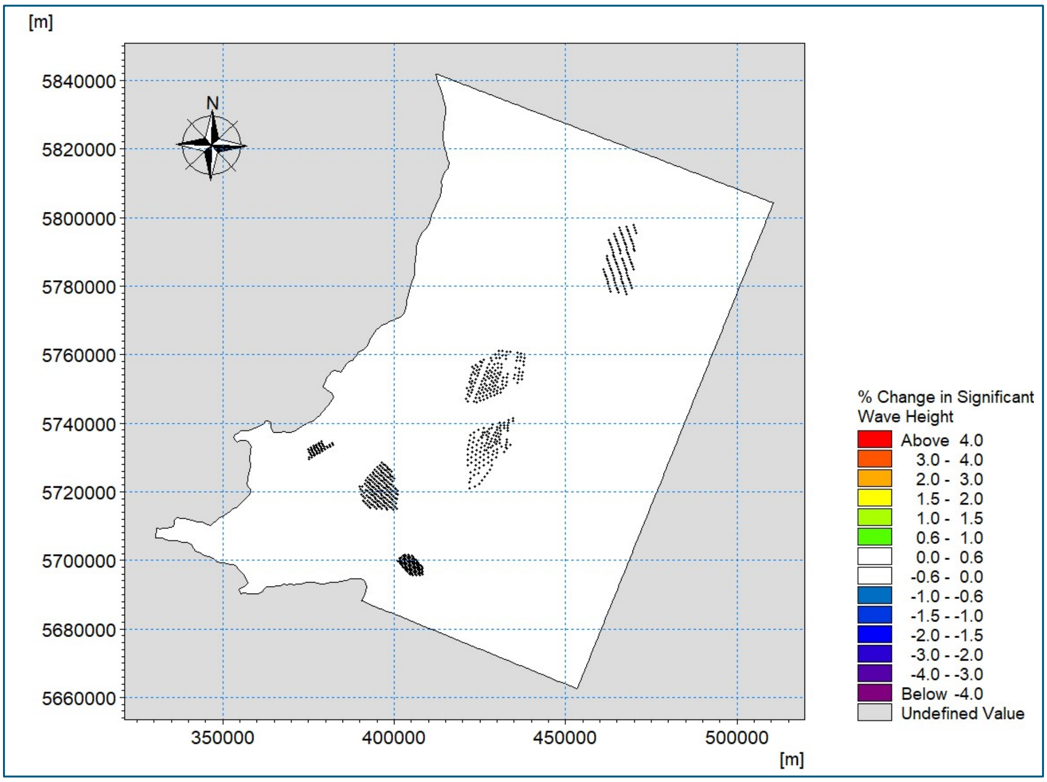

Figure C. 11: Layout 3 - Layout 1, % change in H_s for waves from 15°N - 1 in 50 year

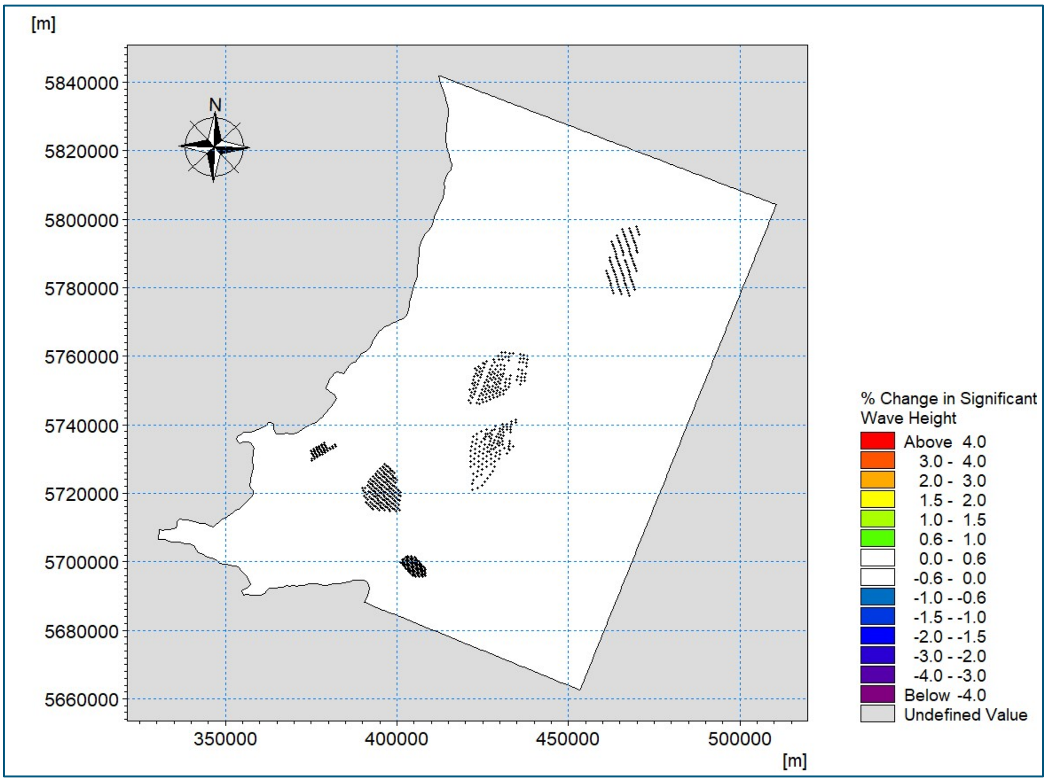

Figure C. 12: Layout 3 - Layout 1, % change in H_s for waves from 15°N - 1 in 100 year

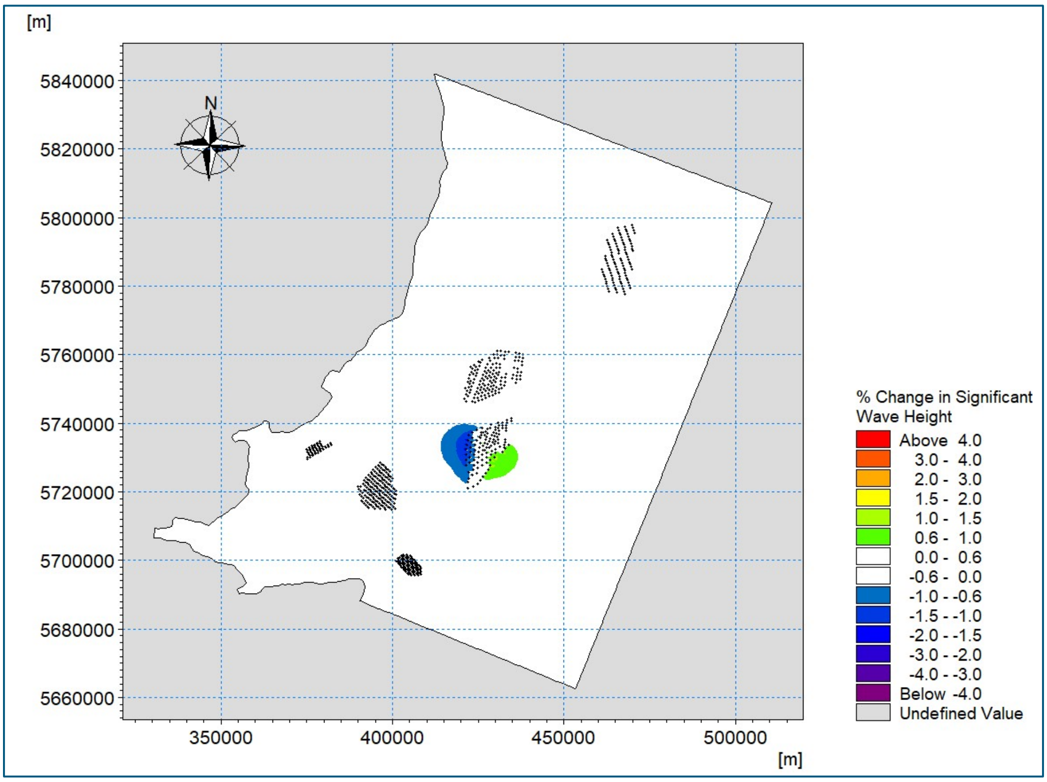

Figure C. 13: Layout 3 - Layout 1, % change in H_s for waves from 105°N - 1 in 50 year

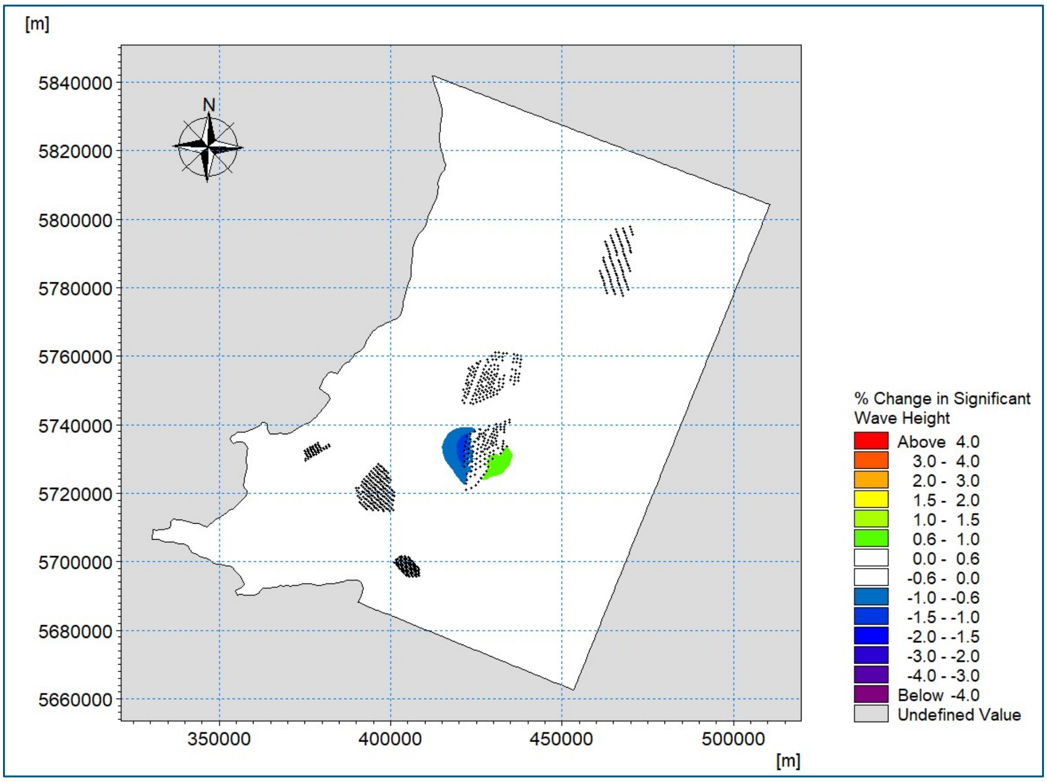

Figure C. 14: Layout 3 - Layout 1, % change in H_s for waves from 105°N - 1 in 100 year

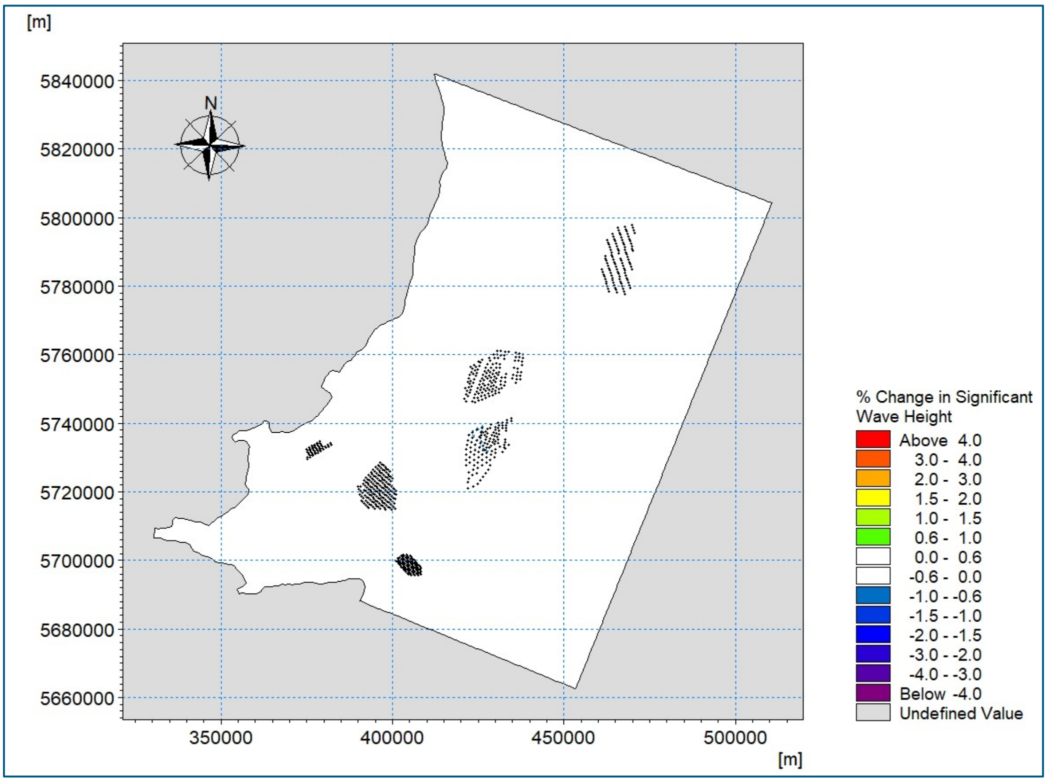

Figure C. 15: Layout 3 - Layout 1, % change in H_s for waves from 210°N - 1 in 50 year

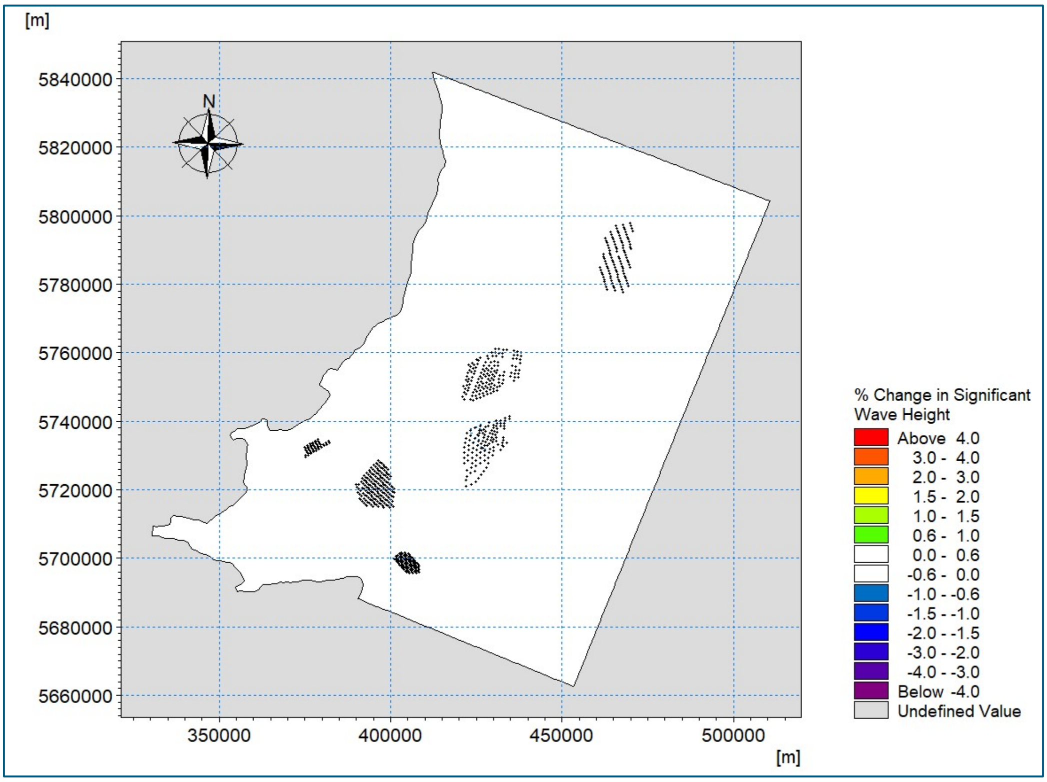

Figure C. 16: Layout 3 - Layout 1, % change in H_s for waves from 210°N - 1 in 100 year

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Figure C. 17 to **Figure C. 24** present results of the layout 4 - layout 1 scenario, showing the cumulative effect of all OWF's (North Falls, existing OWF's and proposed / consented OWF's) on the surrounding wave climate, for 1 in 50 year and 1 in 100 year wave events.

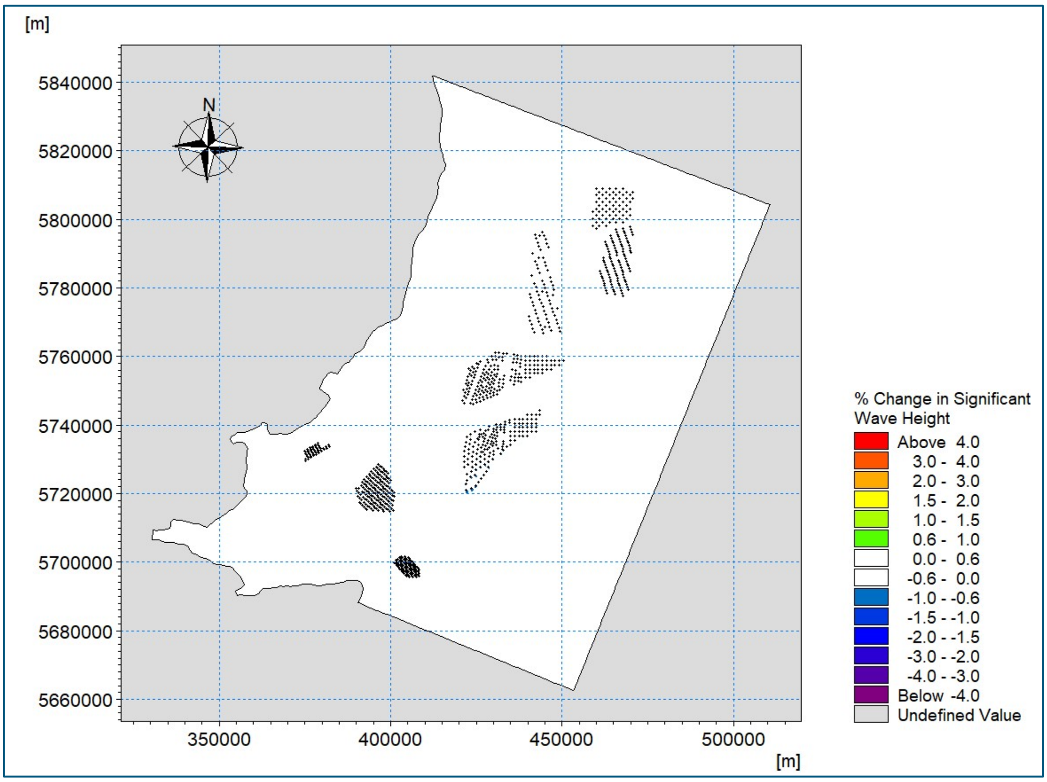

Figure C. 17: Layout 4 - Layout 1, % change in H_s for waves from 345°N - 1 in 50 year

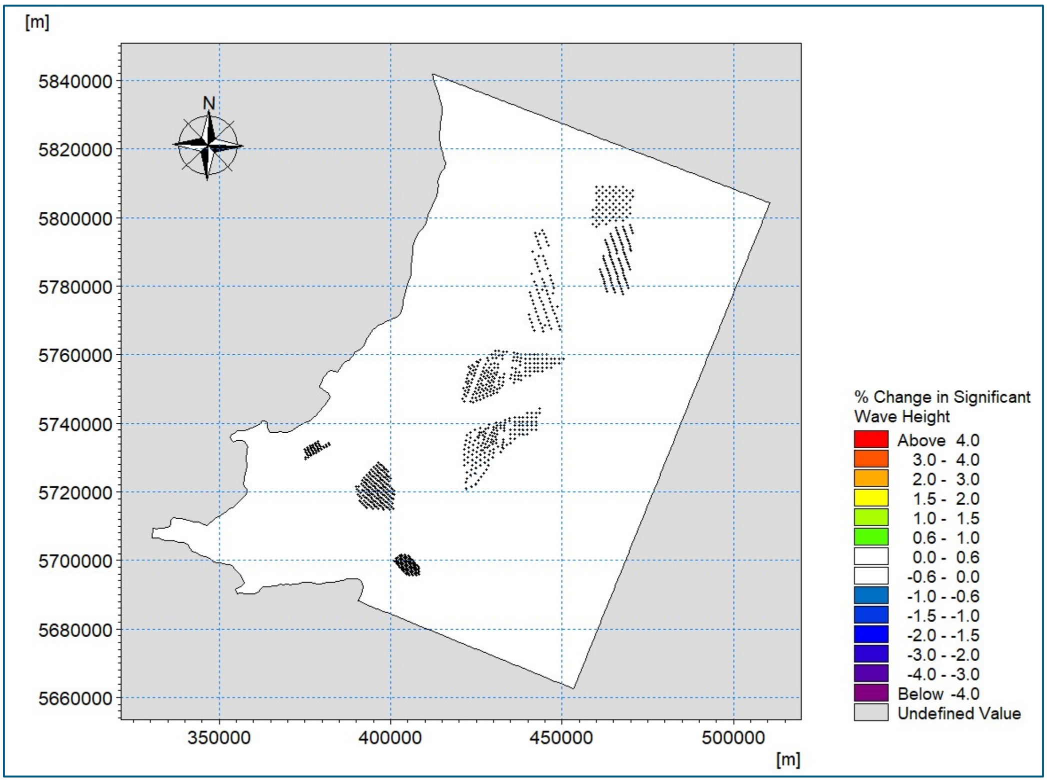

Figure C. 18: Layout 4 - Layout 1, % change in H_s for waves from 345°N - 1 in 100 year

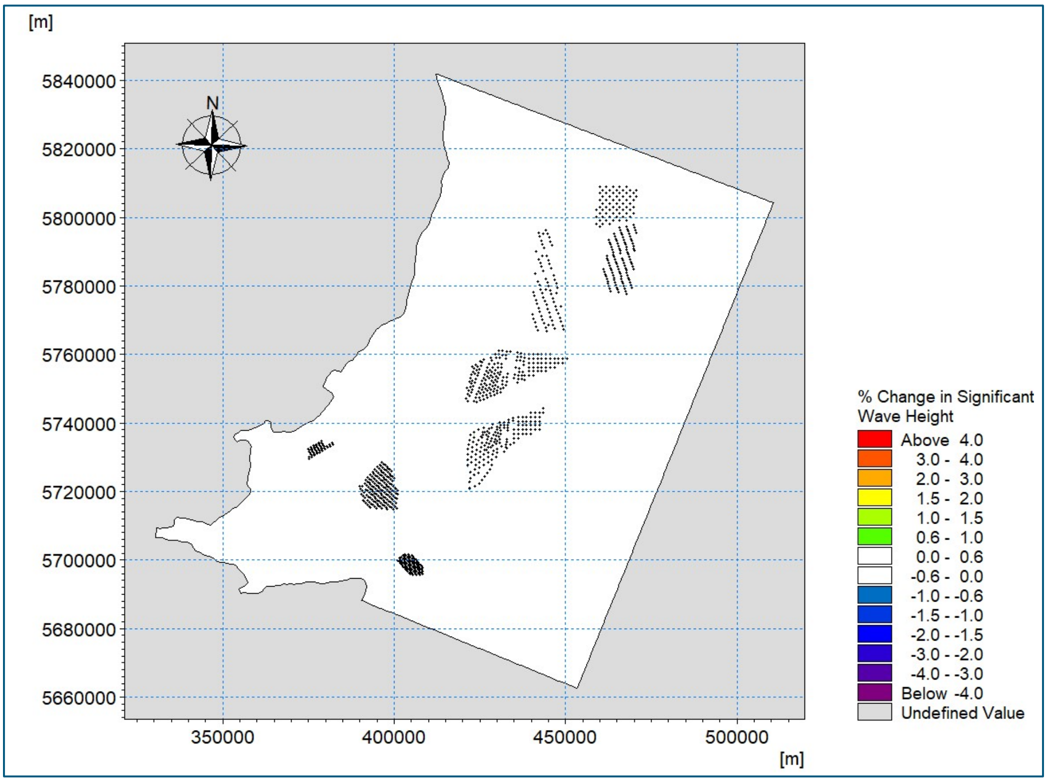

Figure C. 19: Layout 4 - Layout 1, % change in H_s for waves from 15°N - 1 in 50 year

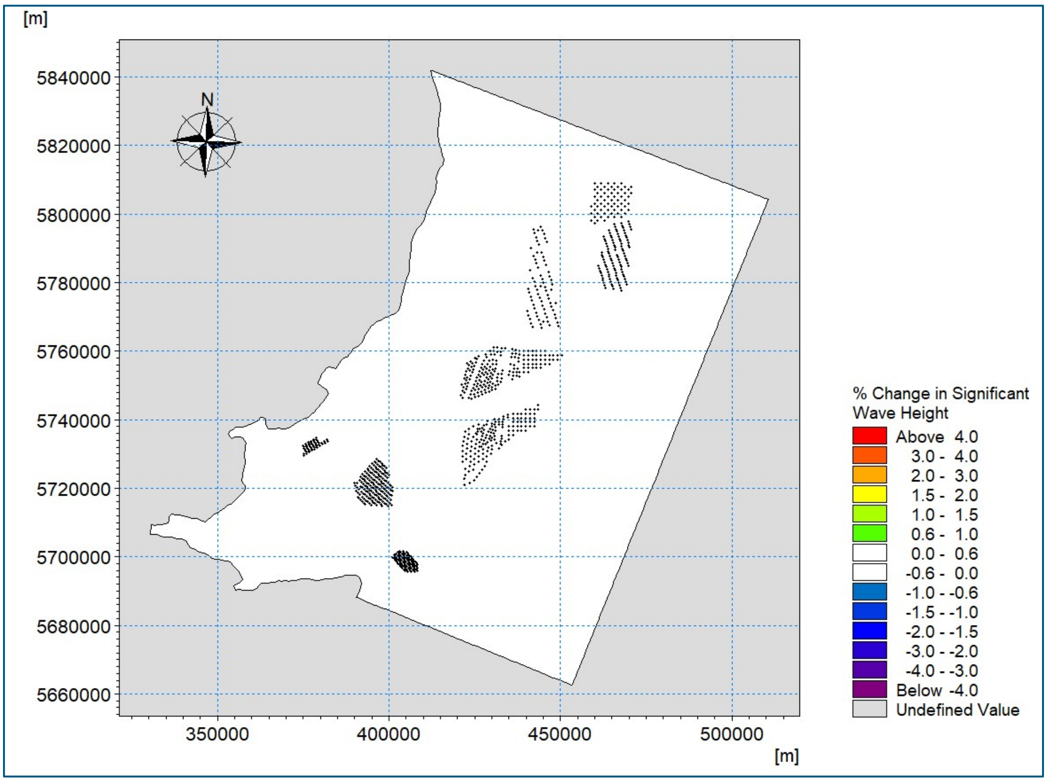

Figure C. 20: Layout 4 - Layout 1, % change in H_s for waves from 15°N - 1 in 100 year

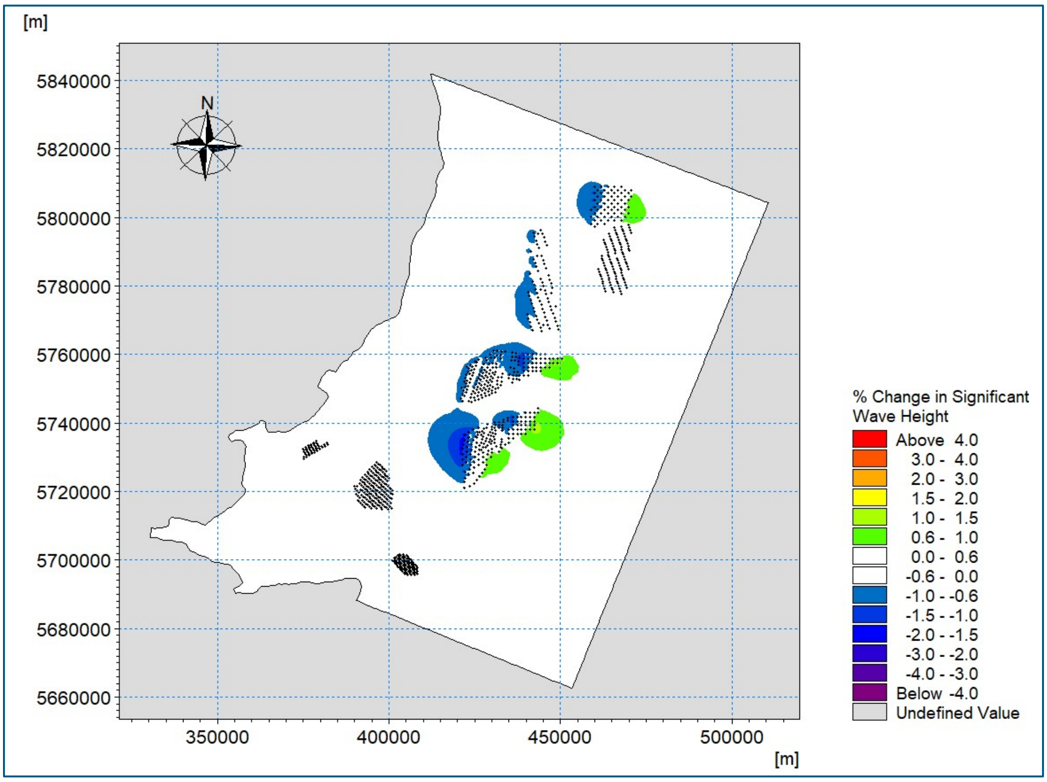

Figure C. 21: Layout 4 - Layout 1, % change in H_s for waves from 105°N - 1 in 50 year

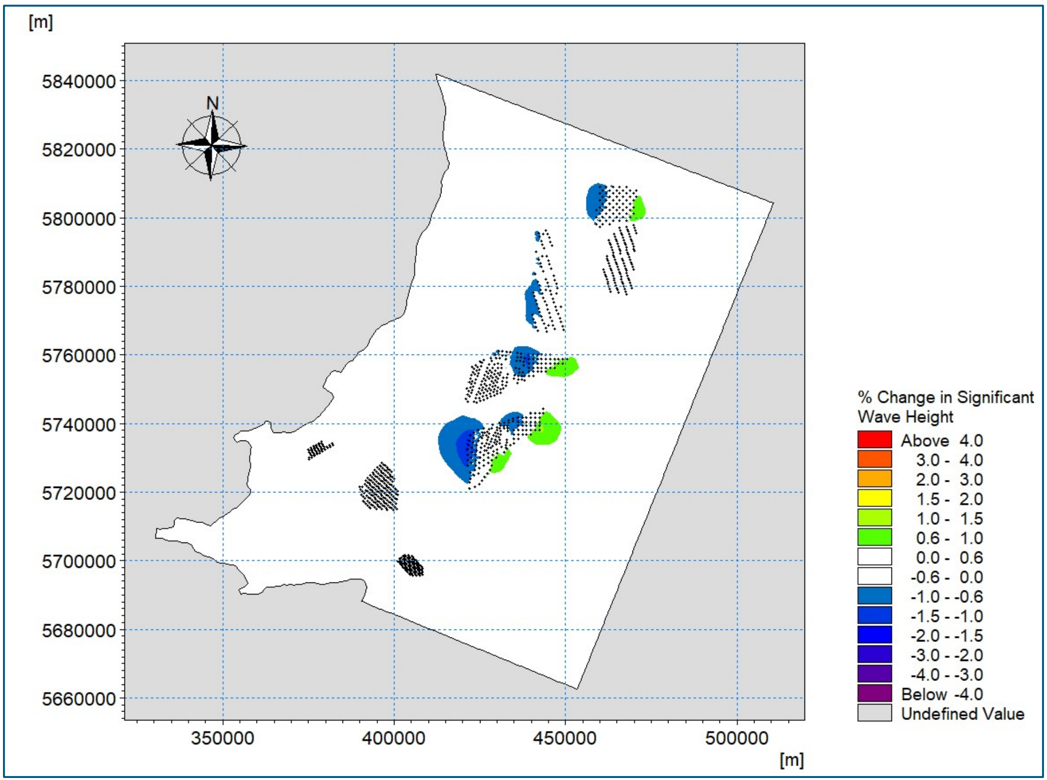

Figure C. 22: Layout 4 - Layout 1, % change in H_s for waves from 105°N - 1 in 100 year

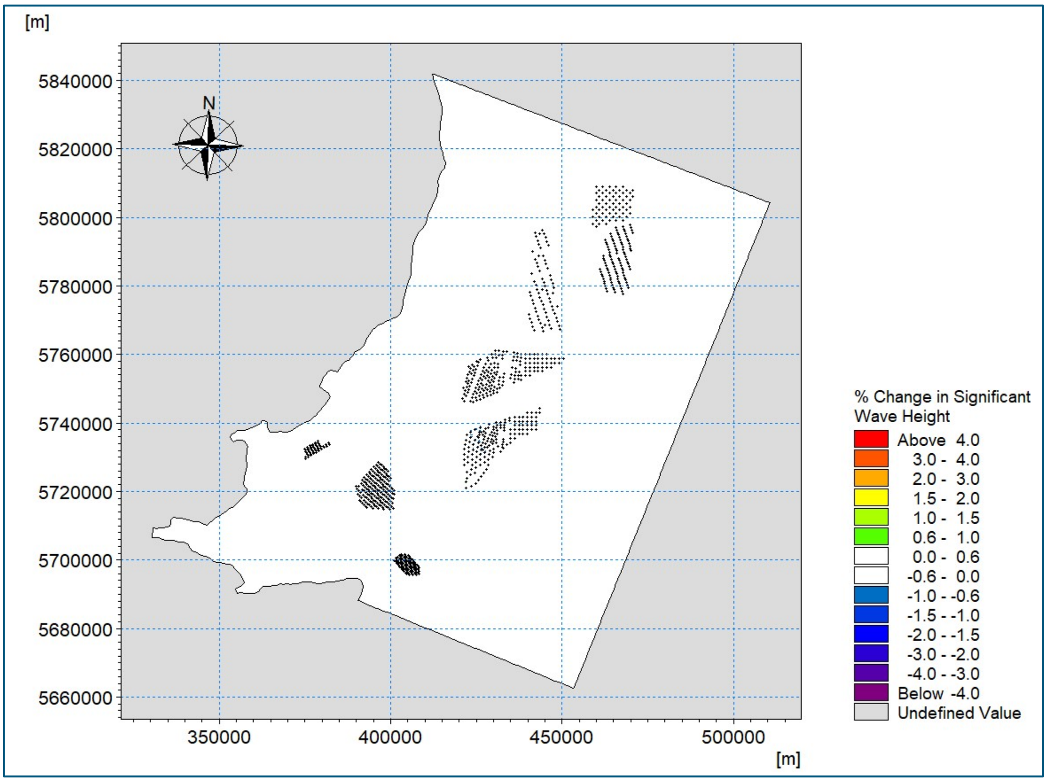

Figure C. 23: Layout 4 - Layout 1, % change in H_s for waves from 210°N - 1 in 50 year

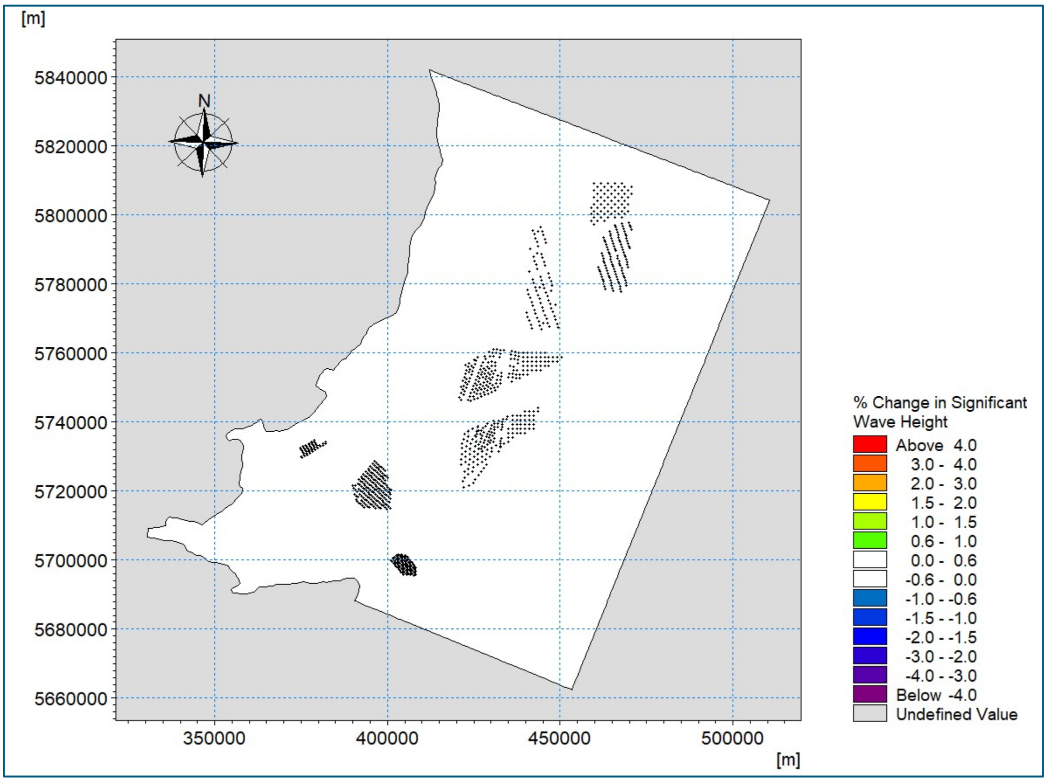

Figure C. 24: Layout 4 - Layout 1, % change in H_s for waves from 210°N - 1 in 100 year

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Annex D: Wave Model Calibration

1) Introduction

Royal HaskoningDHV has been commissioned to undertake a wave modelling study to understand the potential changes in the wave climate caused by the development of the North Falls offshore wind farm, in the North Sea off the East Coast of the UK. The location of the project site is presented in **Figure D. 1** below. Surrounding windfarm sites (either in planning phase or constructed) are also included in the wave modelling study to understand the potential cumulative effect of multiple arrays on the wave climate.

Prior to the main wave modelling study, model development and model calibration are necessary. This note presents the wave model setup and calibration against measured wave data.

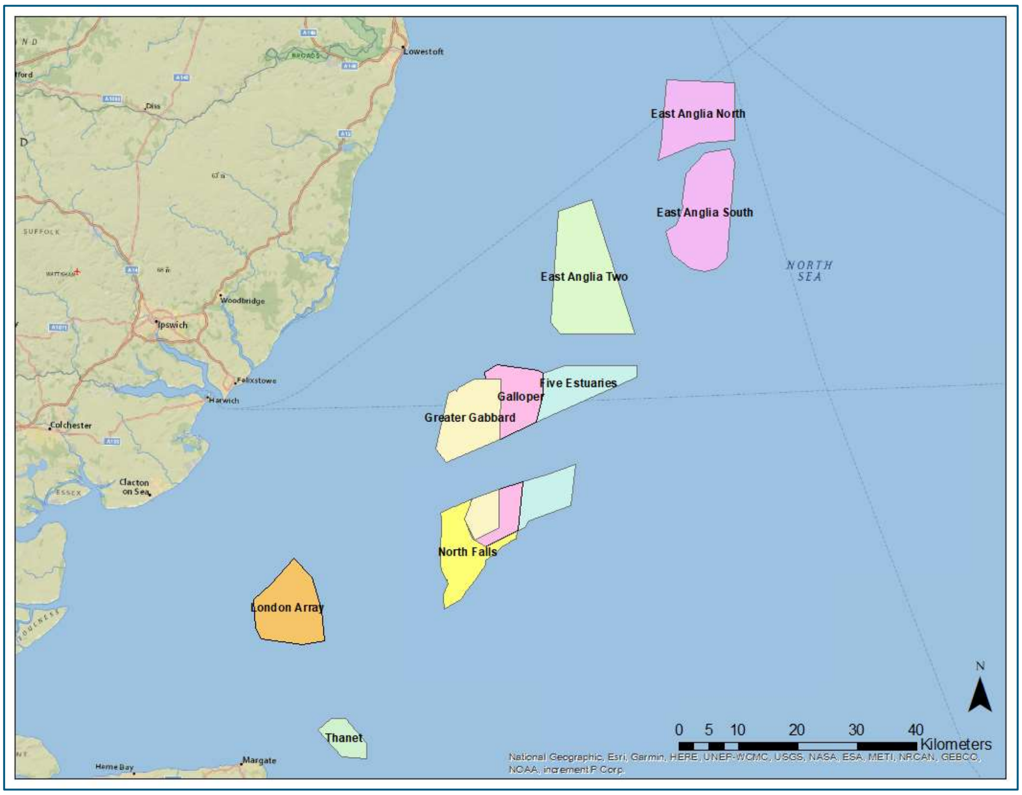

Figure D. 1: Location of project site and surrounding windfarms

2) Data Collection

For this wave modelling exercise the following data sets were collated and used in the wave model:

- Detailed 1m resolution multi beam bathymetry data has been provided by the client covering the North Falls windfarm area (**Figure D. 2**). The data covers an additional area to the North of the project site which is not contained in the updated North Falls design;
- Remaining areas throughout the model domain not covered by the detailed bathymetric survey of North Falls windfarm, EMODnet bathymetry data has been downloaded from the EMODnet

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Bathymetry Portal. The model domain and EMODnet bathymetry data are presented in **Figure D. 3**.

- Measured wave data from the Centre of Environment Fisheries and Aquaculture Science (CEFAS) wave buoys at two locations is used for model calibration. The West Gabbard 2 wave buoy (10/05/2016 - 24/08/2020) and the South Knock wave buoy (01/04/2010 - (03/02/2021) (**Figure D. 3**).

- Atmospheric hindcast wave and wind data (at approx. 10m above water surface) close to the wave model boundary has been obtained from two sources for the wave model calibration, the European Centre for Medium-Range Weather Forecasts (ECMWF) covering the time period between January 1979 and May 2023 (ERA5 reanalysis dataset) and the Met Office hindcast wave and wind covering January and February 2020.

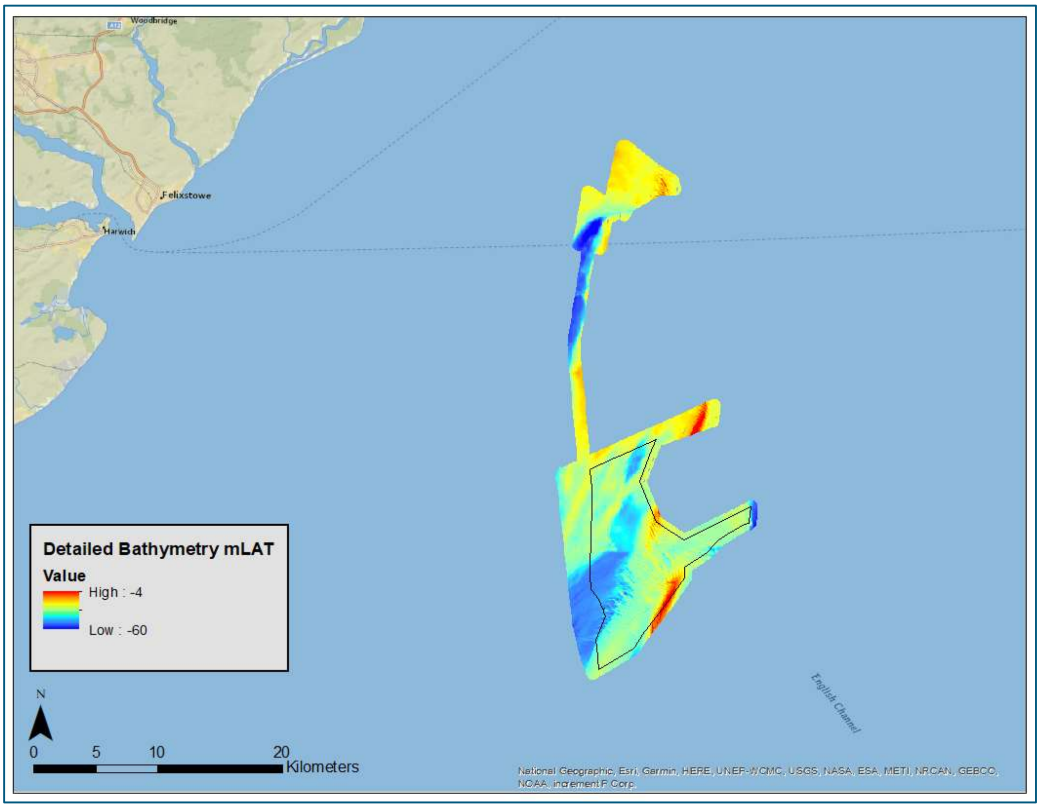

Figure D. 2: Detailed bathymetry covering North Falls (black polygon)

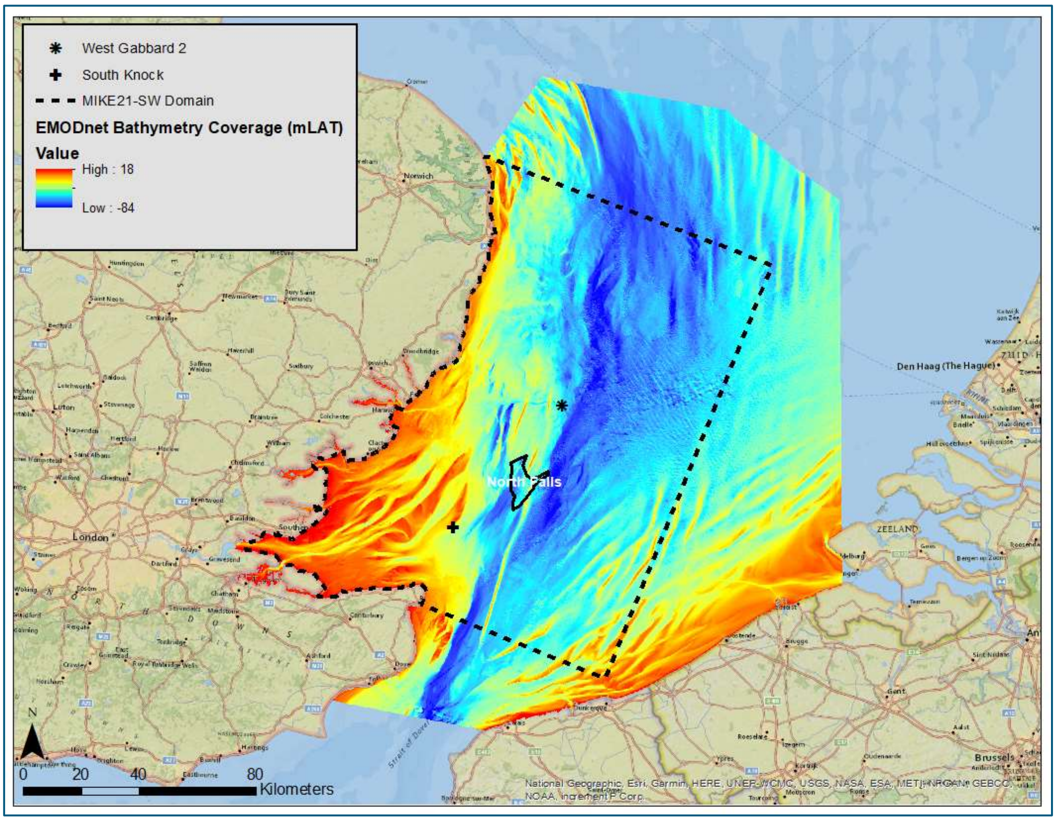

Figure D. 3: Model domain and EMODnet bathymetry data coverage

3) Model Setup

3.1) Software Description

The study used the MIKE21-SW (Spectral Wave) wave transformation model, developed by Danish Hydraulic Institute (DHI), a 2-dimensional spectral wind-wave model for simulating the growth, decay and transformation of wind and swell waves in offshore and coastal areas.

The MIKE21-SW model includes the following physical processes which are relevant to this study of North Falls windfarm:

- Wave growth by action of wind;
- Non-linear wave-wave interaction;
- Dissipation due to bottom friction and depth induced wave breaking;
- Wave refraction and shoaling;
- Wave diffraction; and
- Effect of time-varying water depth.

3.2) Model Mesh

The MIK21-SW model utilises a flexible, unstructured triangular mesh approach which enables complex geometries to be accurately resolved throughout the model domain and higher computational efficiency by setting a coarse computational grid in deeper areas offshore and reducing the resolution of the grid in areas of interest near to the project site.

The extent of the model domain is presented in **Figure D. 3**. The computational mesh within the model domain is refined around the project site, as well as other neighbouring windfarms which are of importance to this study. The coarse grid resolution (1,000m element length) is furthest away from the site and is gradually refined to a minimum resolution of (75-100m element length) at the North Falls site. The computational mesh is presented in **Figure D. 4**.

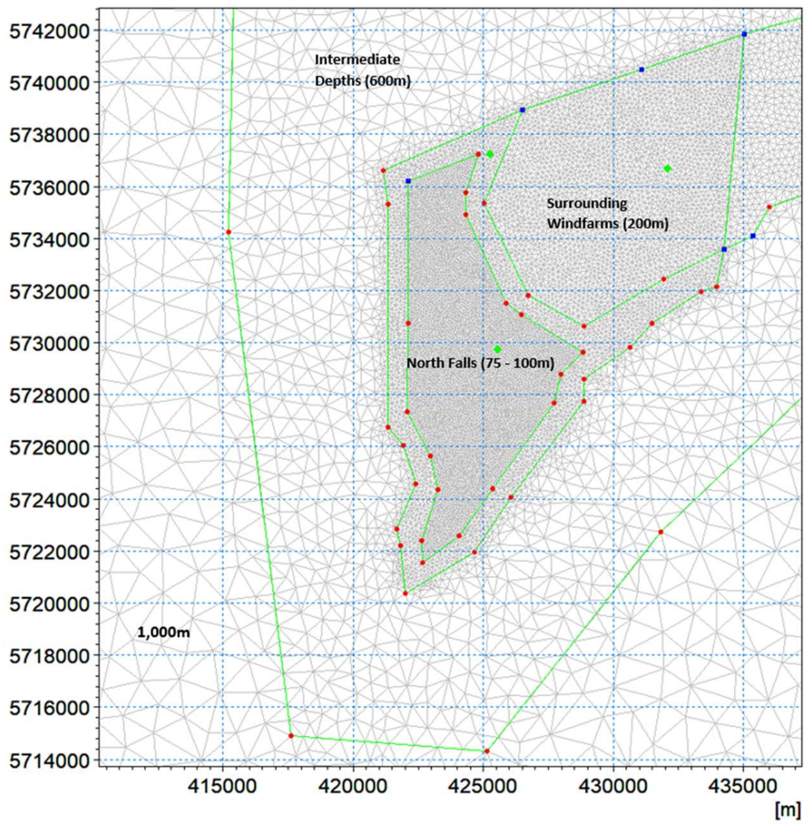

Figure D. 4: MIKE21-SW computational mesh

3.3) Boundary Conditions

For model calibration the MIKE21-SW model is run with a constant Mean High Water Springs (MHWS) water level throughout the domain of 2.4mCD, based on the Admiralty Tide Tables (2023) information at Lowestoft. Considering the deep water at the North Falls site and two CEFAS wave buoys (-24mLAT and -37.5mLAT for South Knock and West Gabbard 2, respectively), model results are not sensitive to a varying water level.

For waves approaching from north, north-east, east and south-east, ERA5 hindcast wave and wind data at 1-hour intervals provides the boundary conditions at the offshore boundary of the model. The ERA5 hindcast wave model has a spatial resolution of approximately 30km.

For waves approaching from the south out of the English Channel, this resolution of the ERA5 wave model was deemed insufficient to effectively capture wave growth, transformation and propagation through the narrow Strait of Dover (34km). Therefore, for waves from south, the Met Office hindcast wave and wind data at 3-hour intervals provides the model boundary conditions. The spatial resolution of the Met Office UK wave model is approximately 2km at the selected location of extraction.

The timeseries of ERA5 and Met Office wave parameters were applied as spatially uniform along the model boundary, which include:

- Significant wave height, Hs (m);
- Peak wave period, Tp (s);
- Mean wave direction, MWD (°N); and
- Directional standard deviation, DSD (wave spreading, °)

The timeseries of ERA5 and Met Office wind parameters were applied as spatially uniform throughout the domain, which include:

- Wind Speed, U10 (m/s)
- Wind Direction (°N)

3.4) Calibration Settings

MIKE21-SW model settings were adjusted where appropriate as part of the calibration process, to provide a suitable level of accuracy between the measured and modelled wave climate. The key model settings along with additional calibration settings (highlighted in green) applied during the final production run of the calibration process are presented in **Table D. 1**.

The model calibration focussed on two key areas to increase model performance, wave growth due to wind (‘Air-sea interaction’ and ‘friction velocity’) and wave energy dissipation throughout the model domain (‘white capping’ and ‘bed friction’).

Given the future application of the calibrated wave model, in predicting the wave climate at the site in response to extreme storm events, the success of the calibration was determined mainly on the predicted wave heights during the peak of the selected calibration storm events. However, for overall confidence in model performance it was important that either side of the peak of the storm during smaller wave heights and reduced wind speed, there was still a good comparison between measured and modelled data.

Table D. 1: MIKE21-SW model settings and calibration parameters (green)

MIKE21 Parameter	Chosen Parameter
Basic Equations	Spectral Formulation: Fully Spectral Time Formulation: Quasi Stationary
Spectral Discretization	360 degree rose: 48 directions
Solution Technique	Low order, fast algorithm Iterations: 500
Diffraction	None

MIKE21 Parameter	Chosen Parameter
Wave Breaking	Gamma: 0.8 Alpha: 1 Gamma (wave steepness): 1
Bottom Friction	Nikuradse Roughness, Kn: 0.015
Air-sea Interaction	Growth Parameter: 1.4 Type: Coupled Charnock Parameter: 0.0185
Friction Velocity	Type: Simple Cap Value: 0.06
White Capping	Cdis: 1.1 δdis: 0.5

4) Model Calibration

4.1) Run Scenarios

The location of the North Falls wind farm is exposed to significant storm events from a range of directions. Large storm waves approaching from the northern part of the North Sea, which arrive at the site between a north and north-east direction. Local wind generated storms arrive at the site from an east, south-east or south-west direction. Finally, storm waves from the English Channel arriving from a southerly direction through the Strait of Dover.

The largest storm waves approaching from these 6 primary directions form the focus of the MIKE21-SW model calibration. This is summarised by the wave rose plots in **Figure D. 5** and **Figure D. 6**, summarising the measured wave data at the South Knock (2010 - 2020) and West Gabbard 2 (2016 - 2020) wave buoys, respectively. In addition to this, the wind rose plot in **Figure D. 7**, presenting ERA5 hindcast wind data close to the project site at 52.0°, 2.0° (lat, long), between 1979 - 2019.

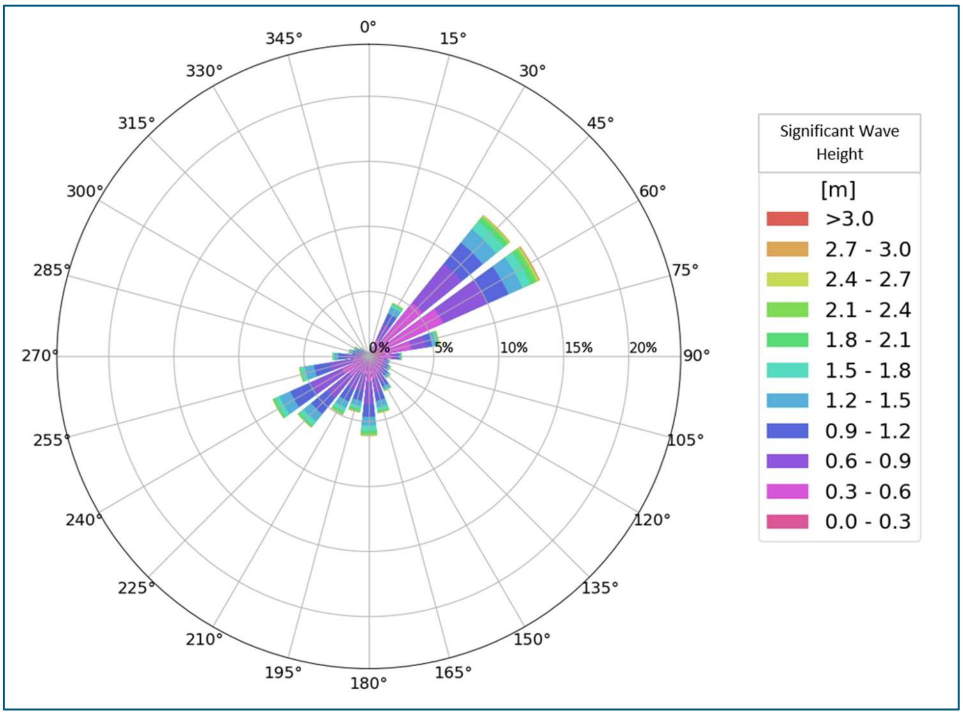

Figure D. 5: Measured wave data from CEFAS wave buoy - South Knock

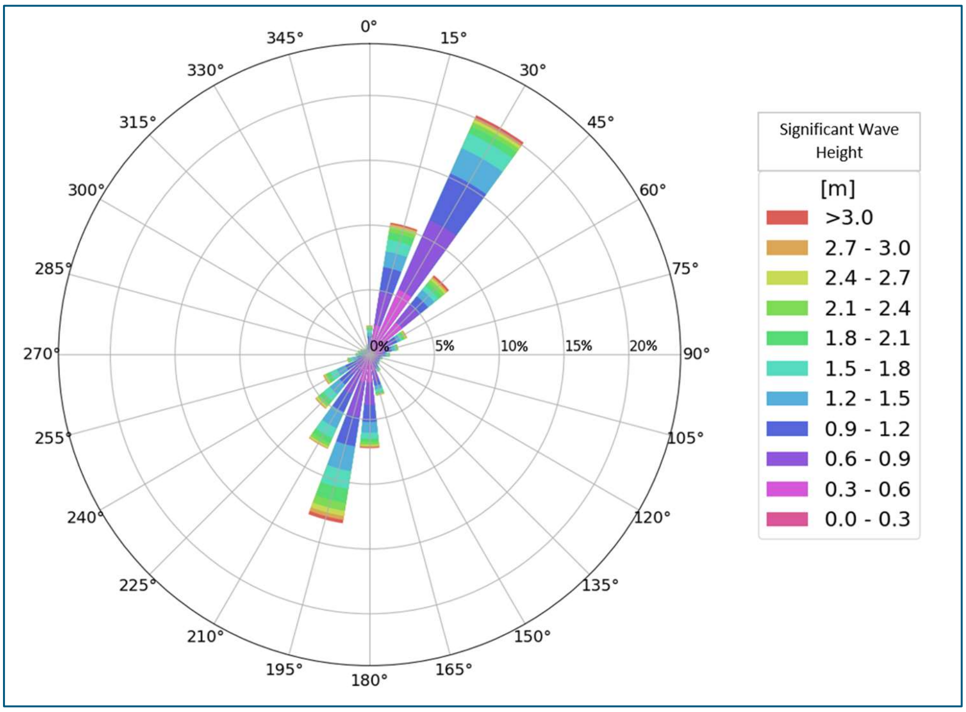

Figure D. 6: Measured wave data from CEFAS wave buoy - West Gabbard 2

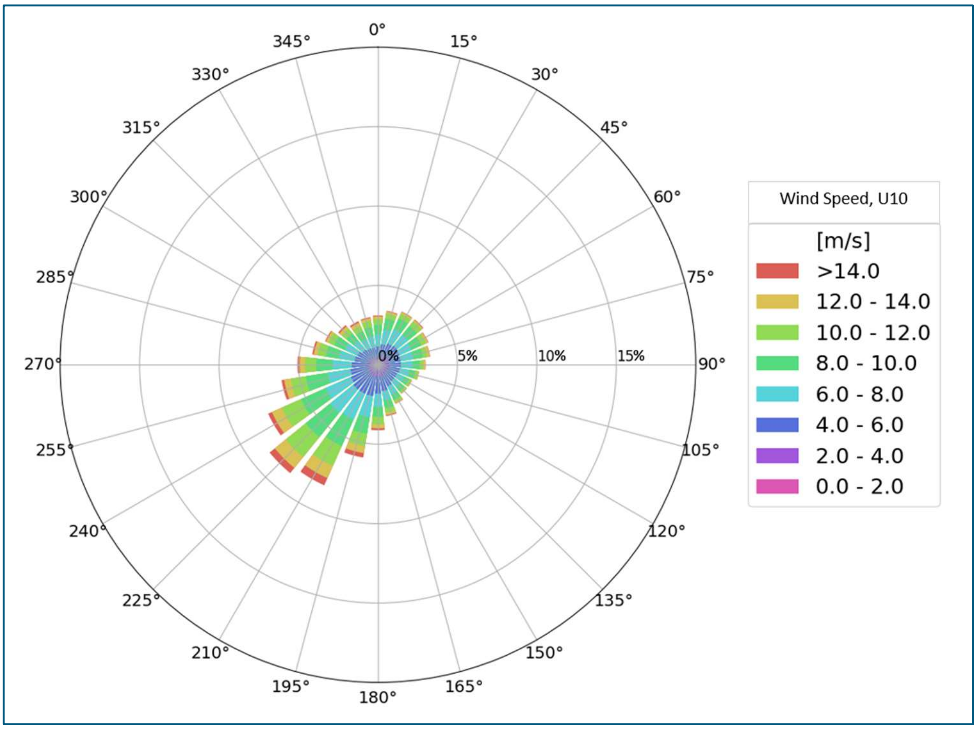

Figure D. 7: ERA5 hindcast wind data between 1979 - 2019, 52.0°, 2.0° (lat, long)

Using the overlapping time period of the two measured wave buoy datasets (West Gabbard 2,10/05/2016 - 24/08/2020 and South Knock, 01/04/2010 - 03/02/2021), a range (13) of the largest significant storm events were selected for model calibration, covering the largest storm wave events approaching from all 6 of the directions outlined above, as summarised in **Table D. 2**.

Model simulations of ‘Event-1’ to ‘Event-8’ (from N, NE, E and SE) include a significant wave height at the offshore boundary as well as wind data applied as spatially uniform across the model domain. For these cases both wave and wind data are taken from the same ERA5 data point at the most appropriate location along the offshore boundary. Where the chosen ERA5 data point is dependent on direction of storm wave approach, see **Figure D. 8**.

Model simulations ‘Event-9’, ‘Event-10’ and ‘Event-11’ (from S) include a significant wave height at the offshore boundary as well as wind data applied as spatially uniform across the model domain. For these three events, the wave model boundary conditions are from the Met Office data point at the southern model boundary. Met Office wind data is taken from the same location and applied as spatially uniform across the domain, as shown in **Figure D. 8**. As previously mentioned, for waves approaching from the south through the Strait of Dover, the spatial resolution of the ERA5 wave model is deemed insufficient, so the higher resolution UK Met Office wave model data is used.

Model simulations ‘Event 12’ and ‘Event 13’ (from SW) include significant wave height applied at the southern offshore boundary and wind in the outer Thames estuary, applied as spatially uniform throughout the domain, as shown in **Figure D. 8**. Storm waves at the project site approaching from the south-west are primarily in response to local wind generated waves from extreme wind events. Therefore, for these two events ERA5 wave data is selected at the southern model boundary.

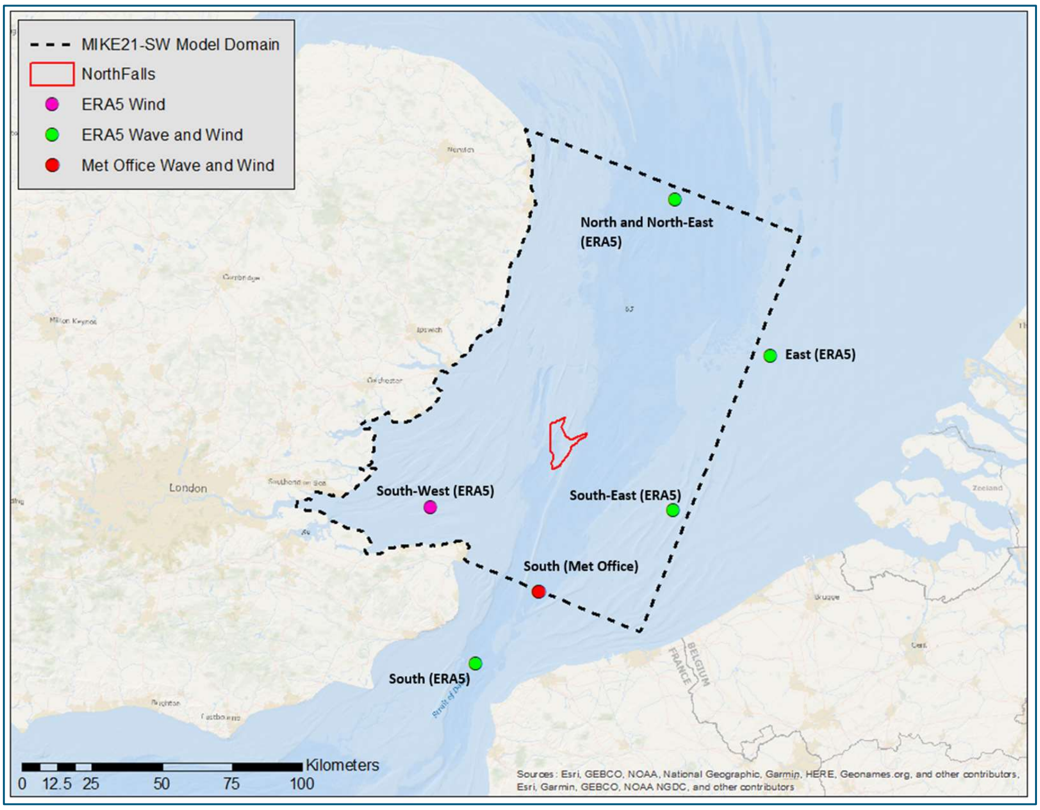

Figure D. 8: ERA5 data points for model boundary conditions

Table D. 2: MIKE21-SW model calibration storm events

ID	Date	Storm Direction (from °N)	Storm Event Type	Max Offshore Hs / Wind Speed
Event-1	10/05/2020 00:00 - 12/05/2020 00:00	N	Wave (+ wind)	Hs = 3.46m
Event-2	29/04/2018 18:00 - 01/05/2018 00:00	N	Wave (+ wind)	Hs = 3.94m
Event-3	06/11/2016 16:00 - 07/11/2016 20:00	NE	Wave (+ wind)	Hs = 3.19m
Event-4	28/02/2018 16:00 - 02/03/2018 16:00	NE	Wave (+ wind)	Hs = 4.54m
Event-5	31/01/2019 16:00 - 01/02/2019 16:00	E	Wave (+ wind)	Hs = 1.93m
Event-6	22/11/2019 17:00 - 23/11/2019 17:00	E	Wave (+ wind)	Hs = 1.82m
Event-7	13/11/2019 20:00 - 14/11/2019 20:00	SE	Wave (+ wind)	Hs = 1.86m

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ID	Date	Storm Direction (from °N)	Storm Event Type	Max Offshore Hs / Wind Speed
Event-8	15/12/2018 06:00 - 16/12/2018 08:00	SE	Wave (+ wind)	Hs = 2.76m
Event-9	13/01/2020 09:00 - 16/01/2020 03:00	S	Wave (+ wind)	Hs = 3.33m
Event-10	08/02/2020 18:00 - 12/02/2020 06:00	S	Wave (+ wind)	Hs = 4.01m
Event-11	15/02/2020 00:00 - 18/02/2020 12:00	S	Wave (+ wind)	Hs = 3.52m
Event-12	22/02/2017 18:00 - 24/02/2017 10:00	SW	Wind (+ wave)	Wind Speed = 19.57 m/s
Event-13	06/06/2017 00:00 - 07/06/2017 12:00	SW	Wind (+ wave)	Wind Speed = 19.28 m/s

4.2) Calibration Results

Figure D. 9 to Figure D. 21 present the results of the North Falls windfarm MIKE21-SW model calibration for selected storm events, 'Event-1' to 'Event-13', respectively. A brief discussion on model performance of each event is presented in **Table D. 3**. Overall, a good agreement between modelled and measured wave height has been obtained of each event, considering hindcasted wind and wave data was used for model boundary conditions.

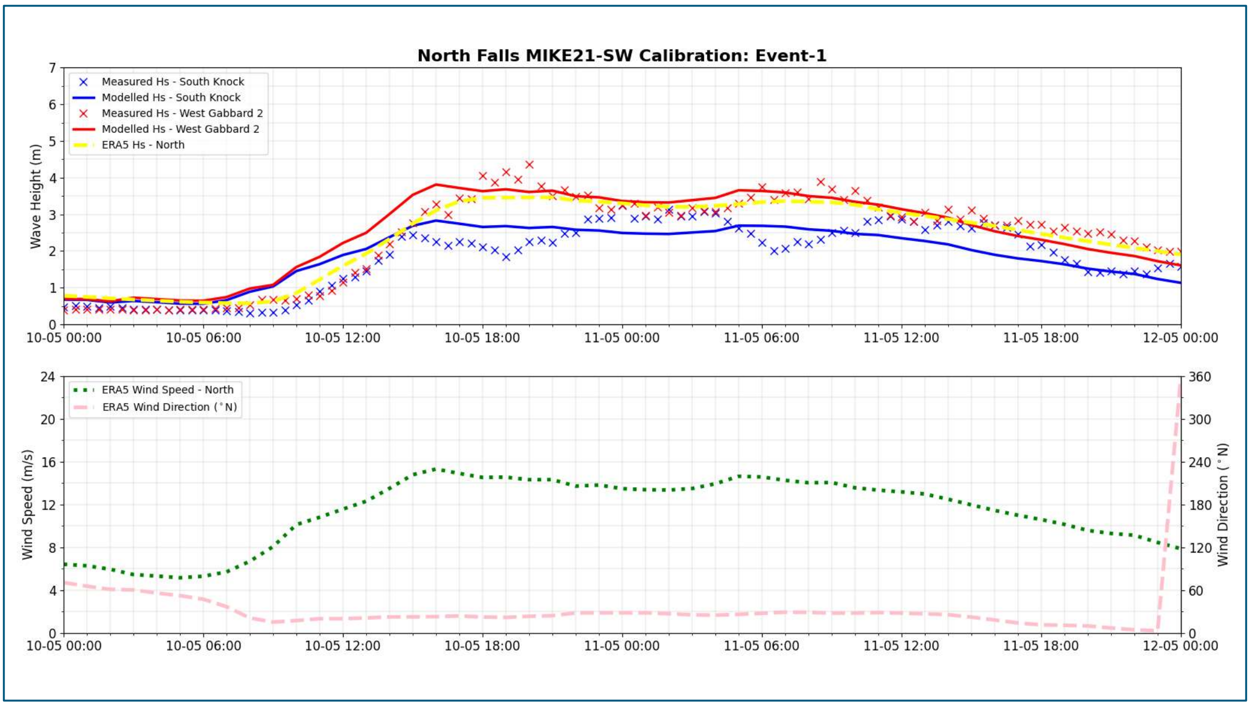

Figure D. 9: MIKE21-SW model calibration results - Event-1

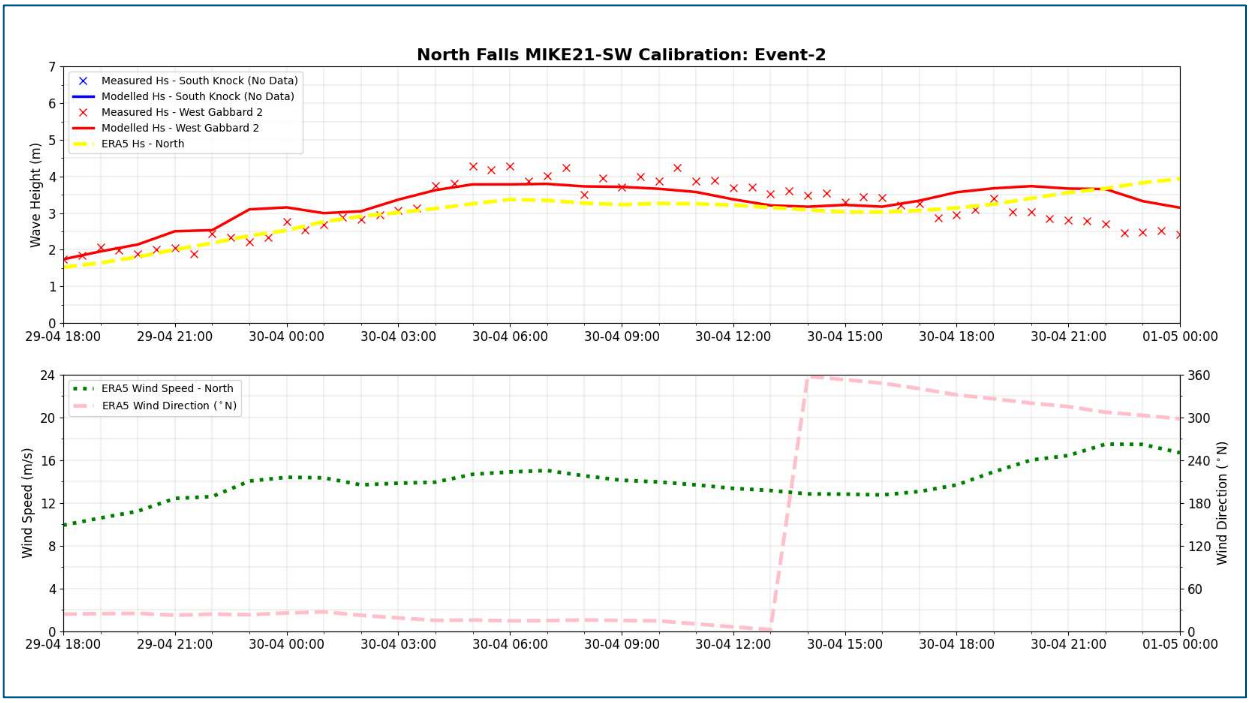

Figure D. 10: MIKE21-SW model calibration results - Event-2

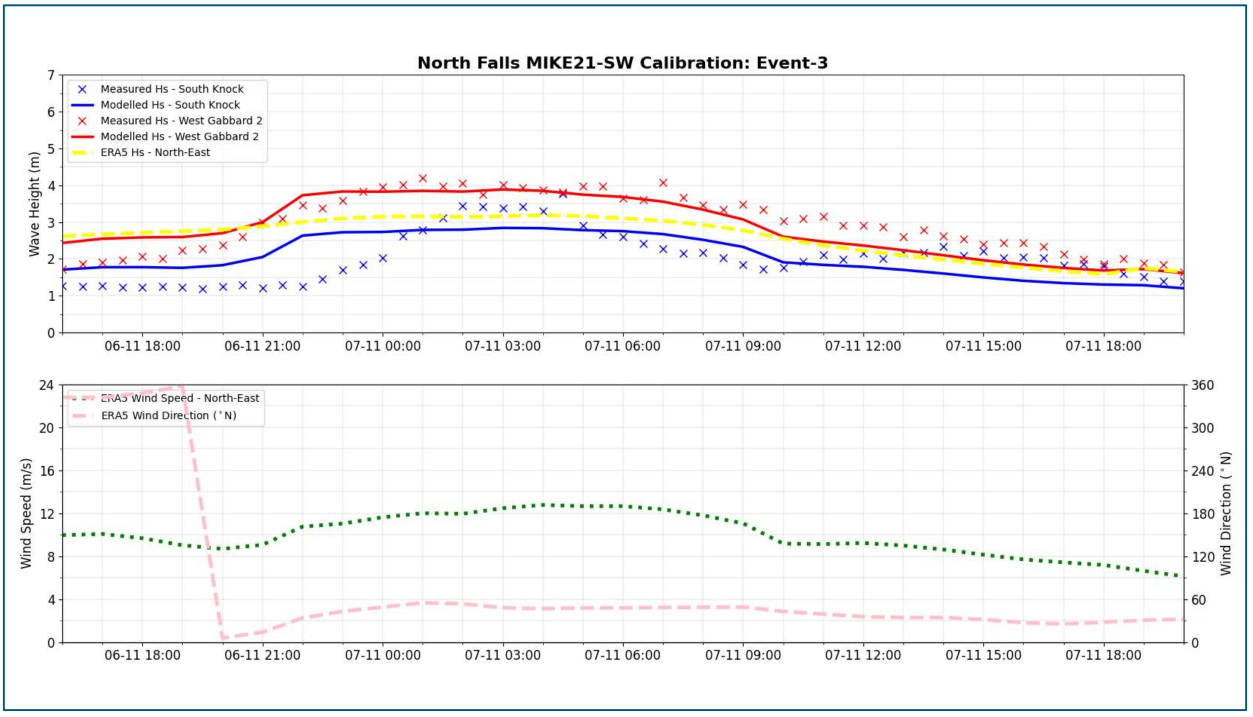

Figure D. 11: MIKE21-SW model calibration results - Event-3

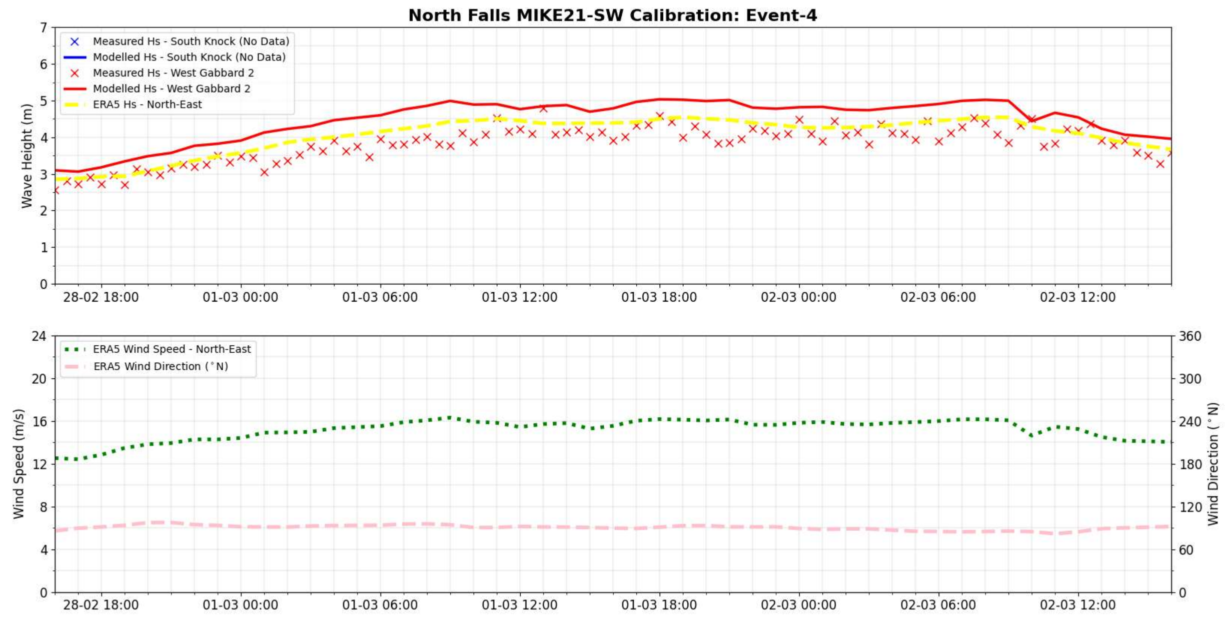

Figure D. 12: MIKE21-SW model calibration results - Event-4

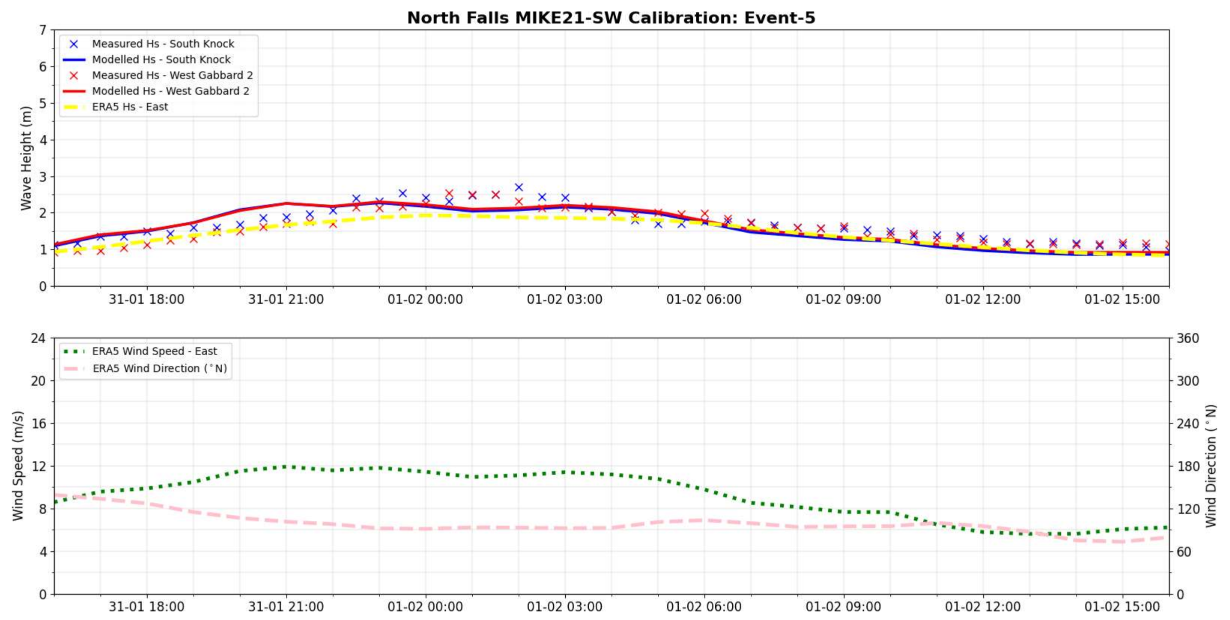

Figure D. 13: MIKE21-SW model calibration results - Event-5

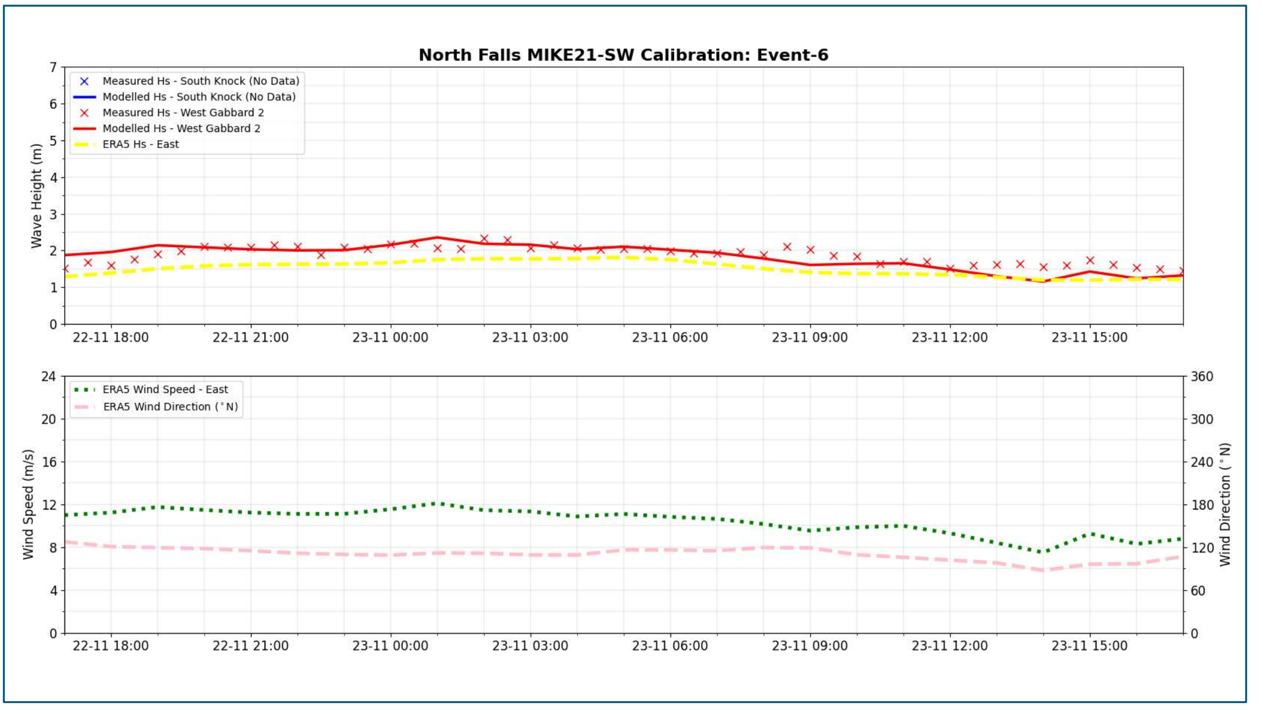

Figure D. 14: MIKE21-SW model calibration results - Event-6

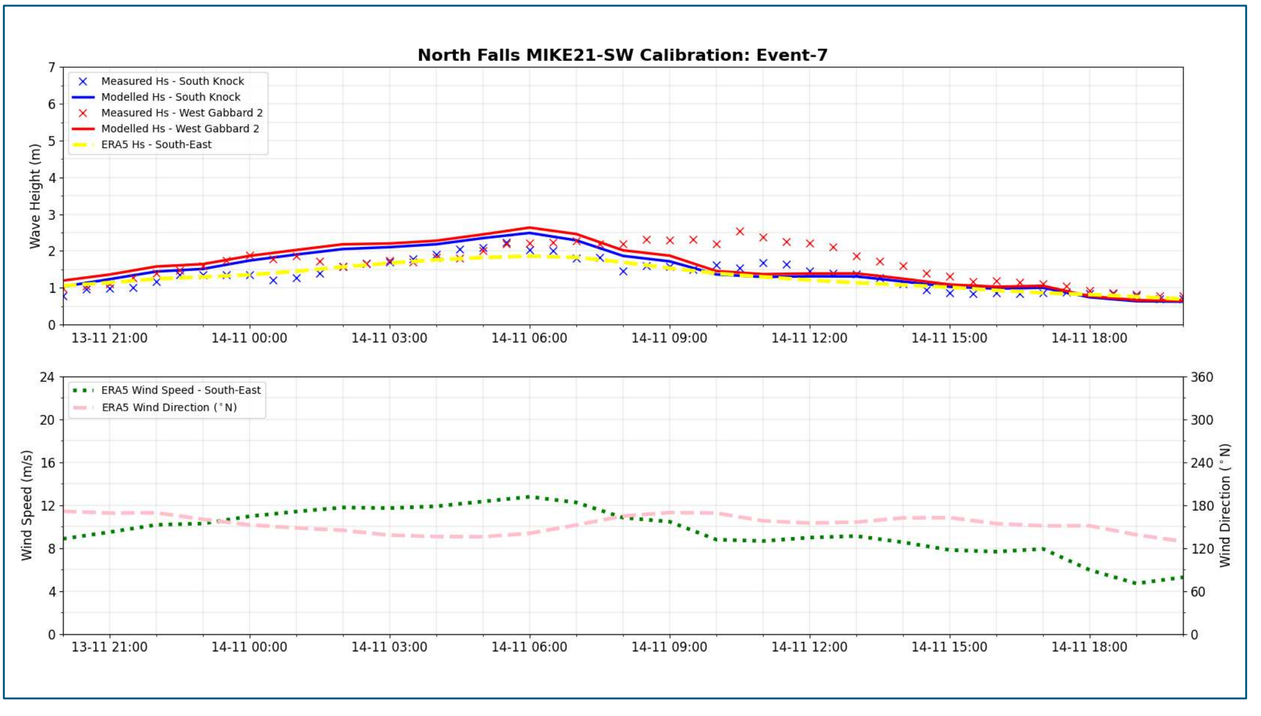

Figure D. 15: MIKE21-SW model calibration results - Event-7

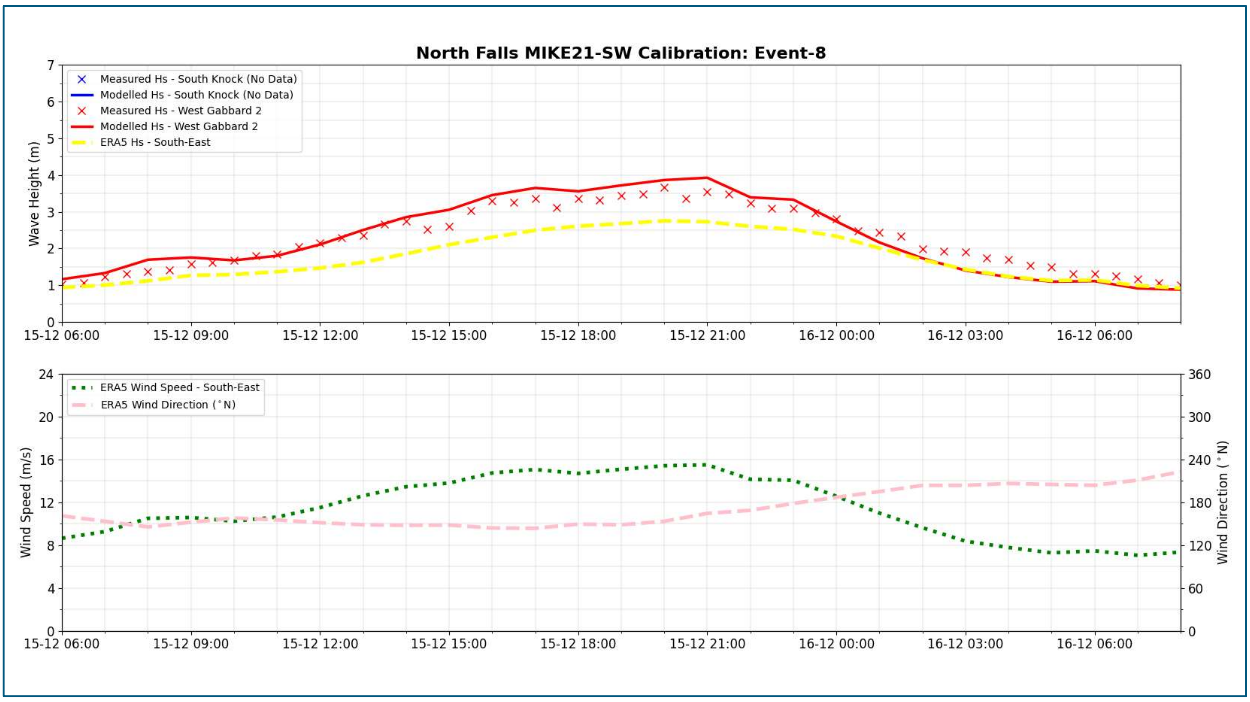

Figure D. 16: MIKE21-SW model calibration results - Event-8

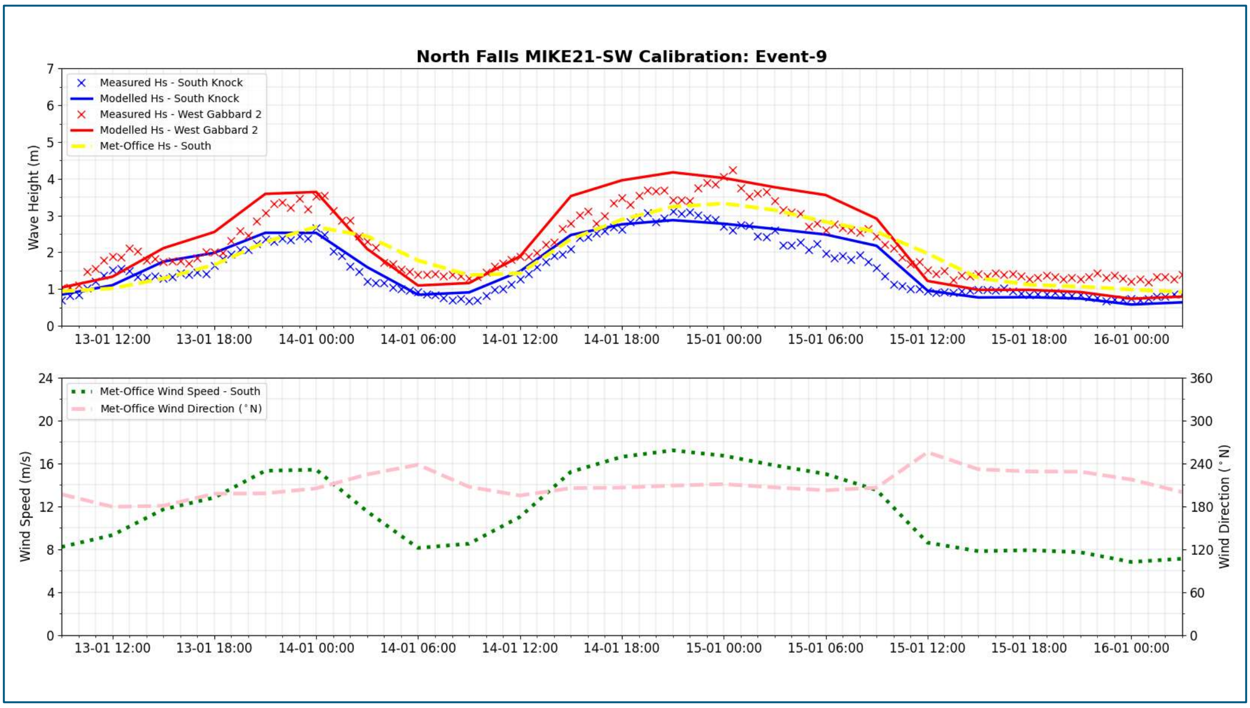

Figure D. 17: MIKE21-SW model calibration results - Event-9

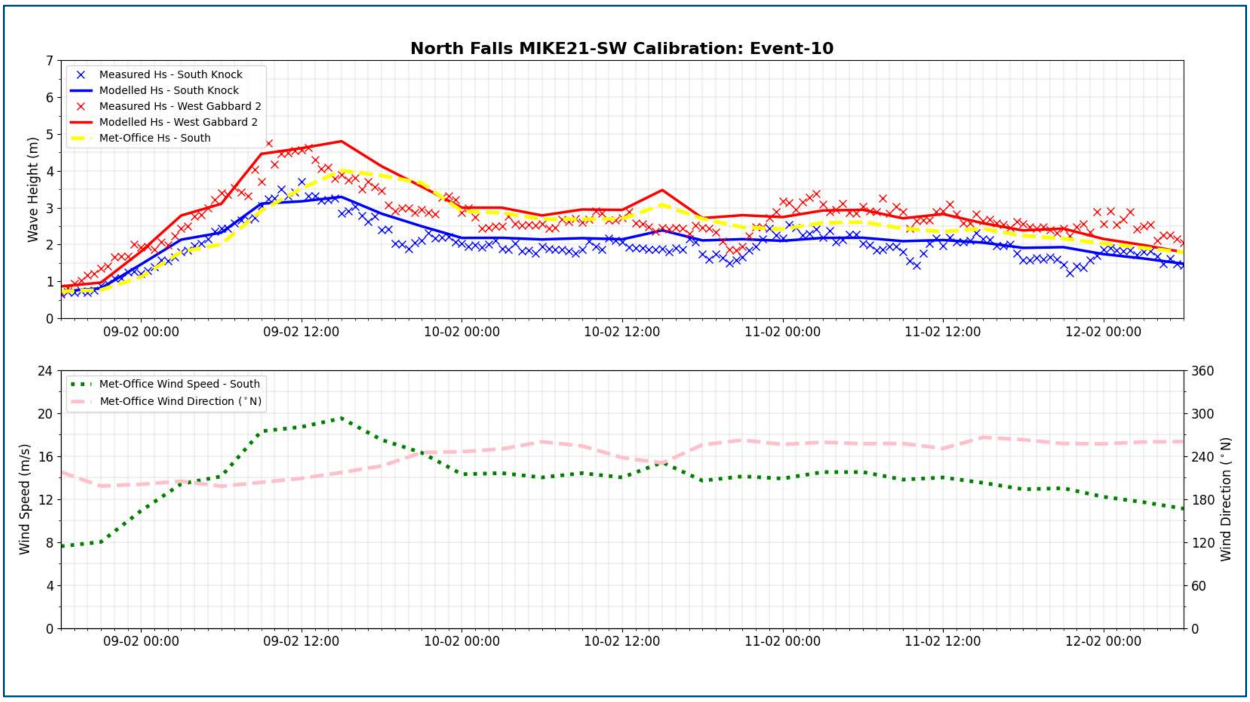

Figure D. 18: MIKE21-SW model calibration results - Event-10

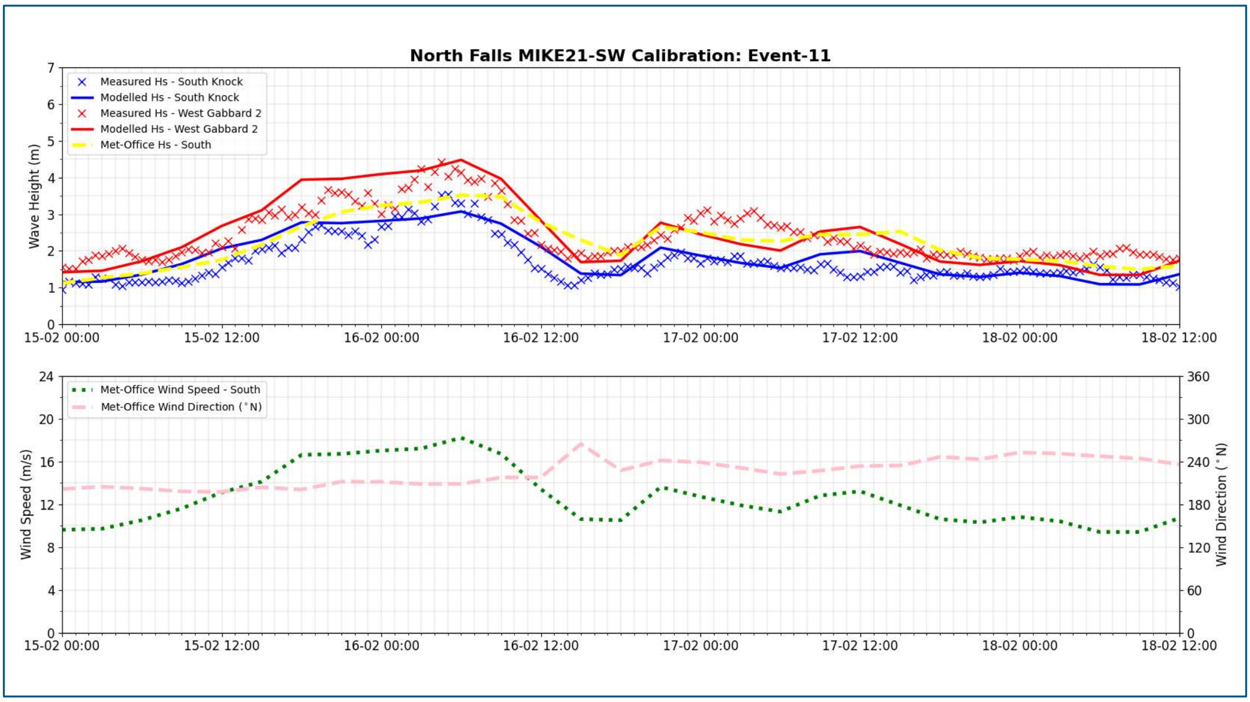

Figure D. 19: MIKE21-SW model calibration results - Event-11

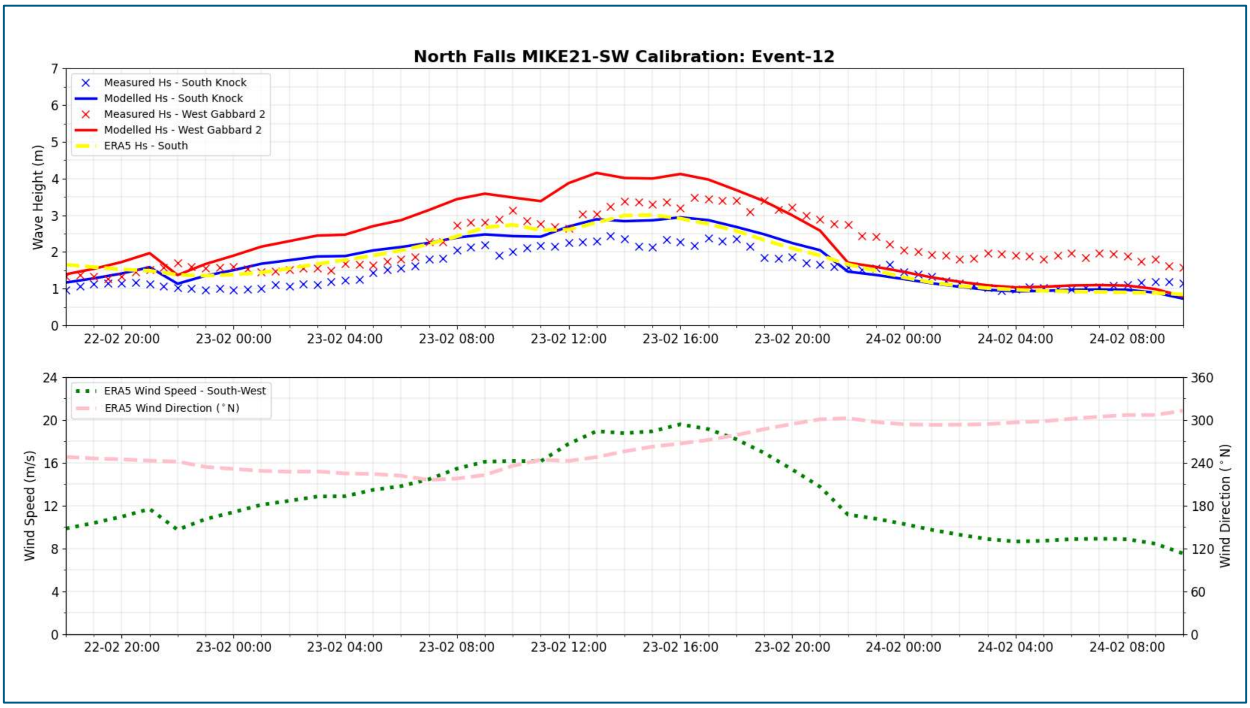

Figure D. 20: MIKE21-SW model calibration results - Event-12

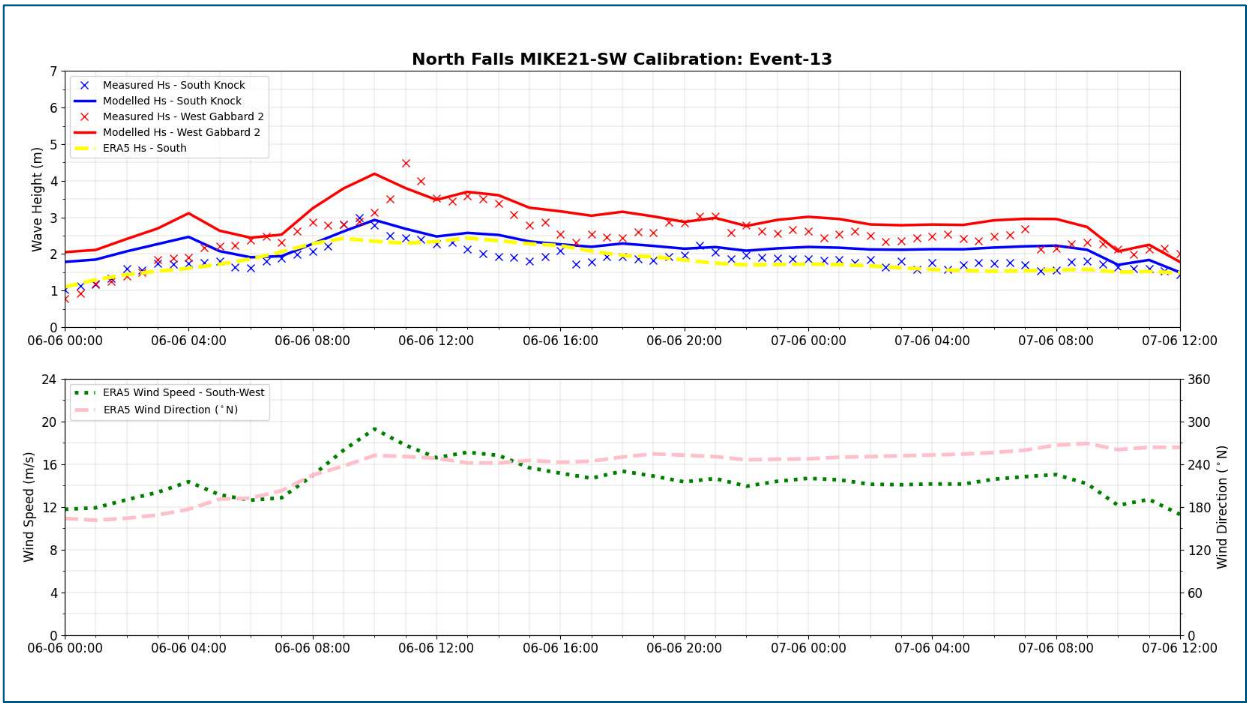

Figure D. 21: MIKE21-SW model calibration results - Event-13

Table D. 3: MIKE21-SW model calibration discussion

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Calibration Storm Event	Waves / Wind from	Discussion
Event-1	N (waves + wind)	The calibration results show reasonable agreement between measured and modelled data, although the larger measured wave heights during the peak of the storm are slightly underestimated by the MIKE21-SW model.
Event-2	N (waves + wind)	The model results show a reasonable agreement between measured and modelled wave height at West Gabbard 2. During the peak of storm event wave heights are slightly underpredicted by the model. This is likely due to the magnitude of offshore ERA5 wave and wind data not matching the measured data.
Event-3	NE (waves + wind)	At South Knock there is a reasonable agreement between the measured and modelled wave height, although during the peak of the storm events the MIKE21-SW model slightly underpredicts wave height. At West Gabbard 2 there is good agreement between measured and modelled wave height, particularly during the storm event.
Event-4	NE (waves + wind)	There is a reasonable agreement between measured and modelled wave heights at West Gabbard 2 during this storm event, with a good agreement of the largest wave height at the peak of the event.
Event-5	E (waves + wind)	The model results show good agreement between measured, modelled and input ERA5 wave heights for Event-5.
Event-6	E (waves + wind)	The model results show good agreement between measured, modelled wave heights at the West Gabbard 2 buoy during the entire storm event.
Event-7	SE (waves + wind)	The model results show good agreement between measured and modelled wave heights at the South Knock wave buoy. At the West Gabbard 2 buoy, the wave heights are underpredicted by the MIKE21-SW model during the latter half of the storm event. This is likely caused by the reduced ERA5 wind speed at the offshore boundary during this period.
Event-8	SE (waves + wind)	The model results show good agreement between measured and modelled wave heights at the West Gabbard 2 buoy, with a slight overprediction during the peak of the storm event.
Event-9	S (wave +wind)	The MIKE21-SW model results show good agreement between measured and modelled wave height at both South Knock and West Gabbard 2. Modelled wave heights match particularly well during the peak of the storm event.
Event-10	S (wave +wind)	The MIKE21-SW model results show good agreement between measured and modelled wave height at both South Knock and West Gabbard 2. Modelled wave heights during the peak of the storm event are slightly overpredicted at West Gabbard 2 and slightly underpredicted at South Knock.

Calibration Storm Event	Waves / Wind from	Discussion
Event-11	S (wave +wind)	The MIKE21-SW model results show good agreement between measured and modelled wave height at both South Knock and West Gabbard 2 during the full storm event, despite a small underprediction during the peak at South Knock.
Event-12	SW wind + S wave	The MIKE21-SW model results show reasonable agreement between measured and modelled wave heights at both sites, although during the peak of the storm event modelled wave heights are over predicted by up to 0.5m. This is likely due to the spatial resolution of the input ERA5 wave data at the southern boundary.
Event-13	SW wind + S wave	The model results show good agreement between measured, modelled and input ERA5 wave heights for Event-13.

HARNESSING THE POWER OF NORTH SEA WIND

North Falls Offshore Wind Farm Limited

A joint venture company owned equally by SSE Renewables and RWE.

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