

Technical Appendix 6.1

Wave Modelling

Falmouth Docks Development

Wave Modelling



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1 Introduction

1.1 Background

The Falmouth Docks is located in the Docks Basin in the Inner Harbour at Falmouth, Cornwall (see Figure 1.1).



Figure 1.1: Project location

The proposed development aims to restore and upgrade the existing facilities at Falmouth Docks, in order to reinstate and provide new alongside berth capacity, to facilitate the floating offshore wind (FLOW) renewable energy industry and accommodate cruise ships up to Excellence Class at the Docks (see Figure 1.2).

The works will include construction of new suspended deck structures (Western Wharf, Northern Wharf and FLOW Deck) with a rock revetment under the suspended decks, an area of reclamation behind the Western Wharf, an extension of Queen's Wharf and demolition of the eastern and western parts of the existing Northern Arm. Dredging of the berths will also be carried out to accommodate cruise ships up to Excellence Class and FLOW devices, as detailed in the Dredging Plan shown in Figure 1.3.

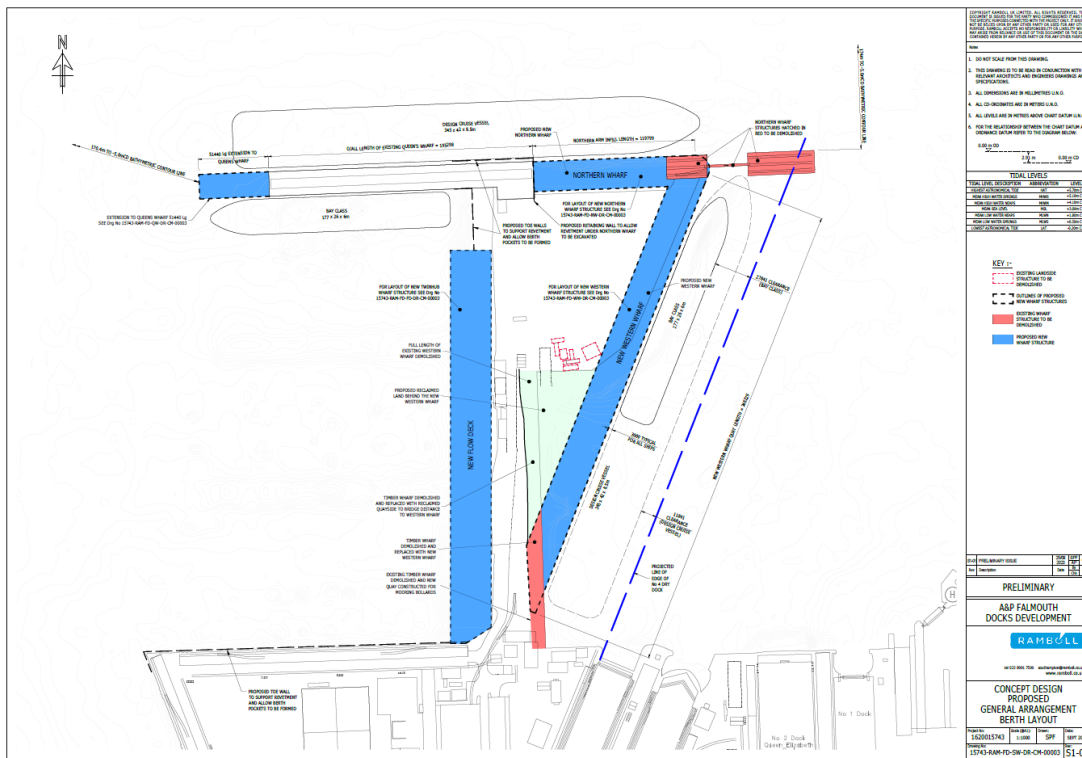


Figure 1.2: Proposed development works of Falmouth Docks

Source: Ramboll

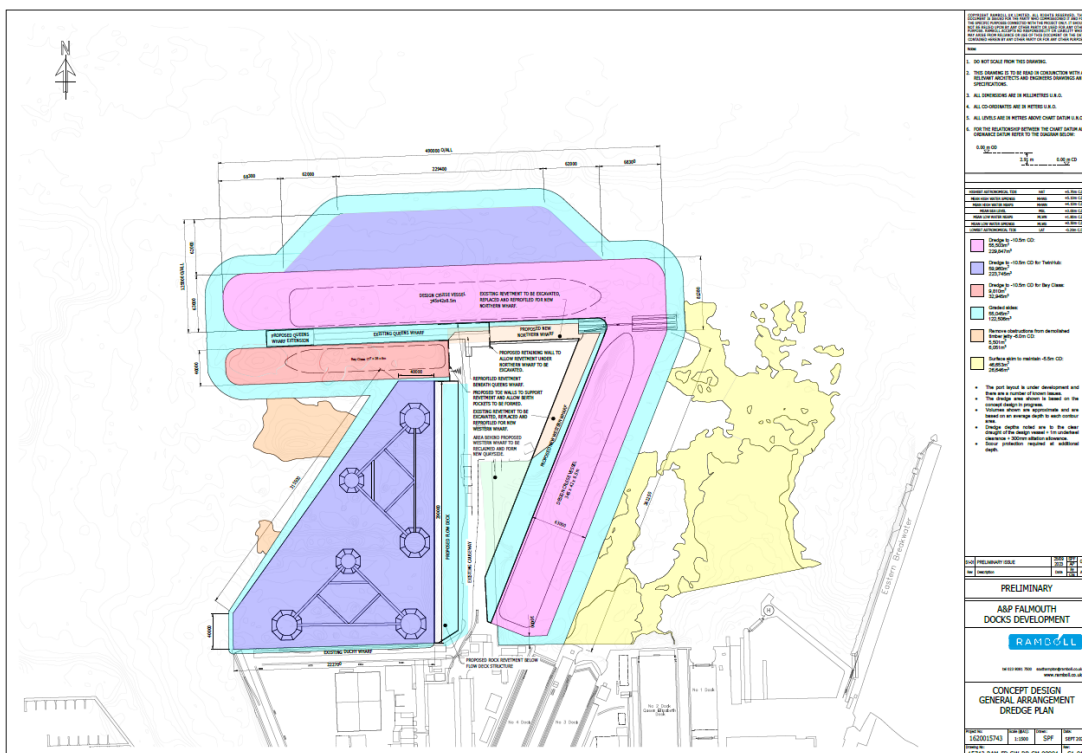


Figure 1.3: Proposed Dredging Plan

Source: Ramboll

1.2 Objectives

This study is part of a set of modelling studies (including hydrodynamics (ES Technical Appendix 6.4, sediment plumes (ES Technical Appendix 6.3, sediment transport (ES Technical Appendix 6.2) and under water noise (ES Technical Appendix 7.1) undertaken by HR Wallingford to support the Environmental Impact Assessment (EIA) for the proposed development.

This report presents the wave modelling study carried out to model the effect of the proposed development on wave conditions at the neighbouring berths and coastline, for input to the Environmental Impact Assessment and to provide information on extreme wave conditions in the inner harbour for design purposes.

1.3 Report structure

This remainder of this report is arranged as follows:

- Section 2 presents an overview of the offshore data used for the study.
- Section 3 describes the wave transformation model and its application to the present study.
- Section 4 presents the results of the wave modelling.
- Section 5 presents conclusions and recommendations.

1.4 Coordinate systems and report convention

The horizontal coordinate system used in this report is OSGB36, unless otherwise stated, with the vertical datum in Chart Datum (CD) at the site.

In accordance with normal meteorological and oceanographic conventions, wind and waves come from the specified direction while currents and water displacements are towards the specified direction, unless otherwise stated.

Table 1.1: Wave output parameters

Wave parameter	Definition	Units
Hs	Significant wave height, Hm0, from spectra	m
Dir	Mean wave direction	°N, from
Tp	Peak wave period	sec

2 Review of environmental conditions

2.1 Offshore winds and waves

Offshore wind and wave data used for this study are as follows:

- Measured winds from observations at Culdrose (1973–2023).
- Offshore wave data from the Met Office’s Atlantic –European North West Shelf Wave Physics Reanalysis model (NWS) hindcast dataset (1980–2022).

The locations of the wind measurements and the NWS wave data point used for the study are shown in Figure 2.1. The selection of the offshore NWS wave point was based on previous modelling experience of the area. This point provides good model calibration and validation against measured data in the approaches to Falmouth, as described in Section 3.3.

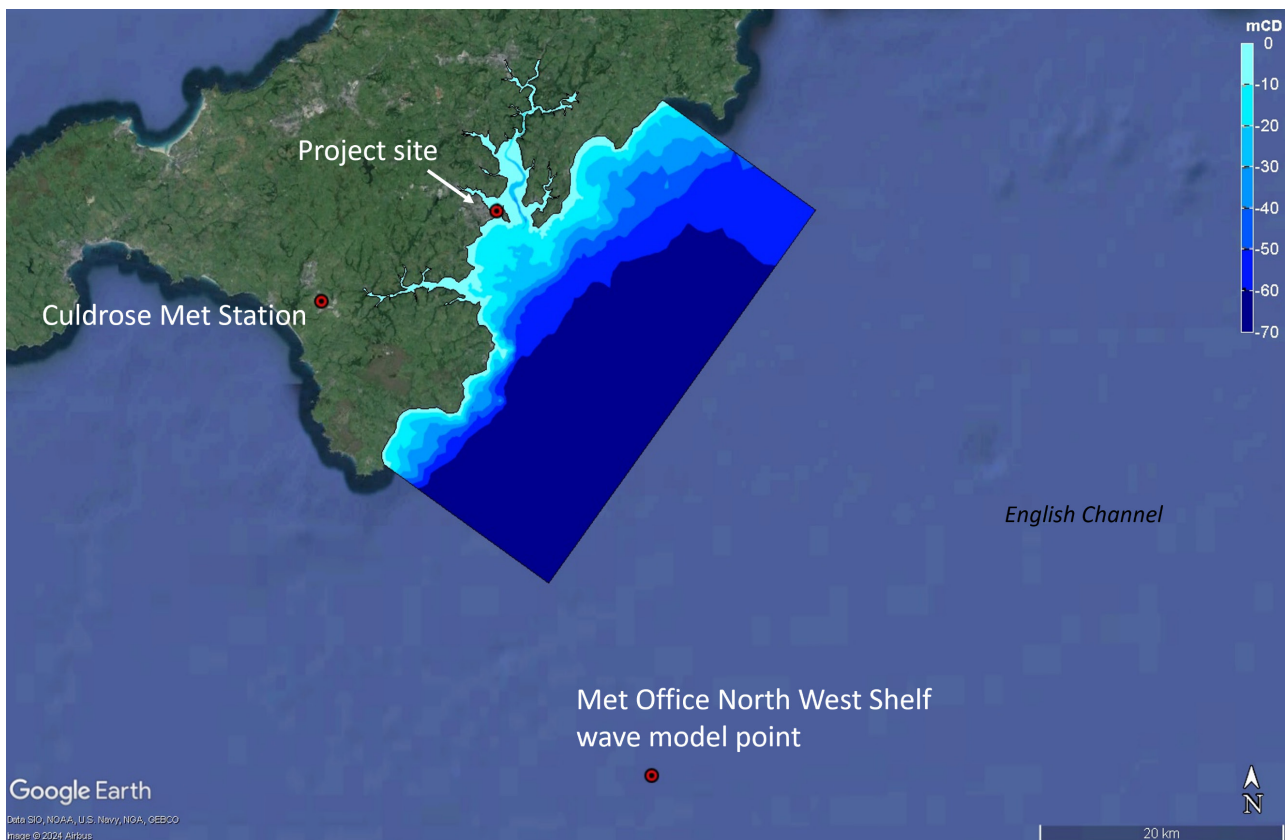


Figure 2.1: Location of wind measurements and offshore Met Office NWS hindcast wave data point

2.1.1 Wind climate

Wind conditions representative of the site have been derived from observations at Culdrose between 1973 and 2023, obtained from the National Centers for Environmental Information (NCEI) database of the United States National Oceanic and Atmospheric Administration (NOAA). The corresponding wind rose is shown in Figure 2.2. This shows that approximately 40% of the time, winds are from the W/SW, and approximately 23% from the E/NE.

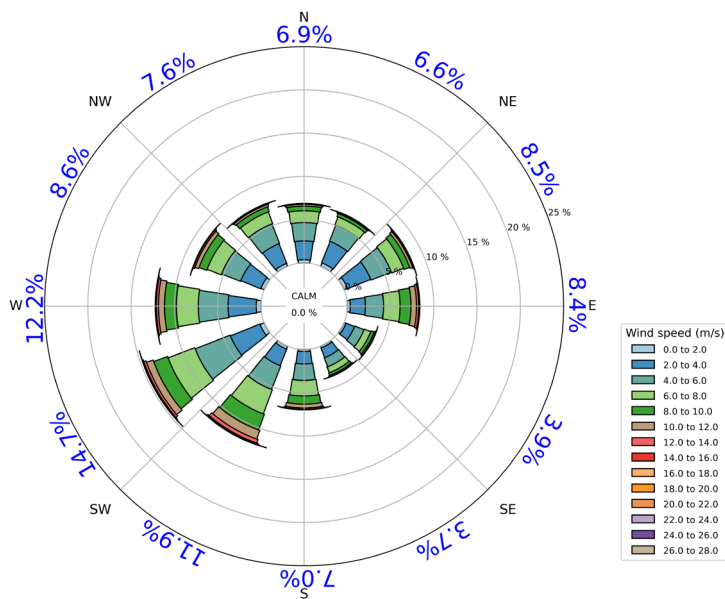


Figure 2.2: Annual wind rose at Culdrose

Source: Culdrose observed winds, 1973–2023

2.1.2 Extreme offshore winds

Extreme winds were estimated from the long term time-series of measured winds at Culdrose (1973–2023).

A list of independent peaks over a threshold were extracted from the wind time-series with a minimum separation time between neighbouring peaks of 48 hours. Extreme wind speeds conditional on the wind direction sector (30° sectors) were estimated by fitting a Weibull distribution to the independent peak wind speed values.

The 0.2 year return period winds were obtained from a count-back analysis of the data.

The derived extreme wind speeds for return periods of 0.2, 1, 10, 50 and 200 years are listed in Table 2.1. Note that these are extreme sustained winds suitable for wave prediction. They are not suitable for use in calculating wind loads on structures for which shorter duration events and gust speeds would need to be investigated separately.

Table 2.1: Extreme wind speeds (in m/s)

Return Period (years)	0°N	30°N	60°N	90°N	120°N	150°N	180°N	210°N	240°N	270°N	300°N	330°N
0.2	11.2	10.2	12.0	13.7	10.7	10.2	12.4	14.3	13.8	13.6	12.8	11.8
1	13.9	12.9	14.0	15.6	13.1	13.1	15.4	17.3	17.7	17.2	16.3	15.0
10	18.3	17.2	19.5	19.7	16.2	16.3	19.2	22.2	22.1	21.5	21.5	18.8
50	21.4	20.0	22.9	22.3	18.1	18.2	21.8	26.4	24.9	24.1	25.3	21.2
200	24.1	22.3	25.6	24.5	19.6	19.8	24.0	30.5	27.3	26.3	28.7	23.1

2.1.3 Offshore waves

The offshore wave climate was analysed in deep water at the Met office's NWS offshore point, based on the long term NWS hindcast dataset. The NWS model is forced by lateral boundary

conditions from the Met Office's global wave hindcast. The atmospheric wind forcing is given by the European Centre for Medium Range Weather Forecasts (ECMWF) numerical weather prediction reanalysis. The resolution is 1.5 km and the hindcast data are available hourly from 1980 to near present-day.

The annual wave rose at the NWS offshore point, located at 49.74°N –4.88°E, for 1980 – 2022 is presented in Figure 2.3 to summarise the offshore wave conditions. This shows that 79% of the time, the offshore waves approach from the W/SW, which includes the highest waves (with significant wave heights above 6 m). The secondary wave direction is east which represents approximately 9% of the waves, with significant wave heights up to 6 m.

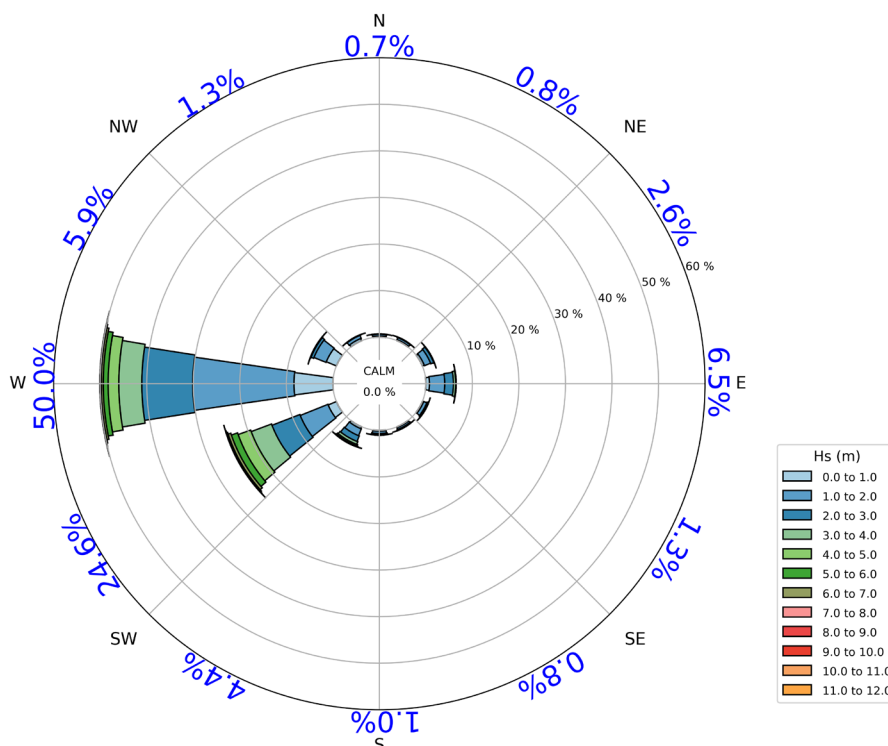


Figure 2.3: Annual average wave rose at the NWS offshore point (1980-2022)

2.1.4 Extreme offshore waves

Extreme waves were derived from the long term time-series at the NWS offshore data point.

Extreme significant wave heights conditional on the wave direction sector were estimated by fitting a Weibull distribution to the independent peak significant wave height values above a threshold, with a minimum separation time between neighbouring peaks of 48 hours.

The 0.2 year return period significant wave heights were obtained from a count-back analysis of the data.

The derived extreme offshore wave conditions are listed in Table 2.2. The peak periods listed are assigned based on the average wave steepness of the peak wave conditions in the sector in question.

Table 2.2: Extreme offshore waves

Direction sector (°N)	0.2 year		1 year		10 year		50 year		200 year	
	Hs (m)	Tp (s)	Hs (m)	Tp (s)	Hs (m)	Tp (s)	Hs (m)	Tp (s)	Hs (m)	Tp (s)
0	1.2	6.2	2.0	7.9	3.1	9.8	3.9	11.0	4.6	11.9
30	1.4	6.8	2.0	8.2	3.4	10.6	4.2	11.8	4.9	12.7
60	2.5	7.6	3.1	8.5	3.9	9.6	4.3	10.1	4.6	10.4
90	3.4	8.2	3.6	8.5	4.8	9.8	5.5	10.4	6.1	11.0
120	2.0	7.2	2.8	8.4	4.4	10.5	5.2	11.5	5.9	12.2
150	1.7	6.7	2.6	8.2	4.1	10.4	5.1	11.6	5.9	12.4
180	2.1	7.5	3.1	9.3	4.8	11.4	5.9	12.7	6.8	13.7
210	4.4	10.3	5.6	11.6	8.1	14.0	9.8	15.4	11.3	16.5
240	7.0	13.1	8.2	14.1	10.3	15.9	11.7	16.9	12.9	17.8
270	6.8	13.4	7.8	14.4	10.2	16.4	11.7	17.6	12.9	18.5
300	2.5	9.7	3.2	11.0	4.7	13.3	5.6	14.6	6.5	15.6
330	1.4	7.0	2.2	8.7	3.2	10.5	3.8	11.4	4.3	12.0

2.2 Water levels

The standard source for predicted tidal level information is UK Admiralty tide tables for 2023 (Ref 1, with information available for Falmouth). The difference between Ordnance Datum (OD) and Chart Datum (CD) at Falmouth is 2.91 m. A full set of present-day (2023) tidal levels for Falmouth is given in Table 2.3.

Table 2.3: Present-day tidal levels (2023) for Falmouth

Tidal level	Tidal level (m CD)
Highest Astronomical Tide (HAT)	5.7
Mean High Water Springs (MHWS)	5.1
Mean High Water Neaps (MHWN)	4.1
Mean Sea Level (MSL)	3.0
Mean Low Water Neaps (MLWN)	1.8
Mean Low Water Springs (MLWS)	0.5
Lowest Astronomical Tide (LAT)	-0.2

Source: UK Admiralty tide tables 2023

2.2.1 Sea level rise allowance

For the wave modelling runs, an allowance has been made for sea level rise (SLR) using the 50th percentile RCP8.5 emissions scenario (UKCP2018 – Met Office, 2018, Ref. 2). Together with 50 years of land subsidence (estimated at 0.5 mm/year), the total relative sea level rise at the site over the 50 year design life is estimated to be 0.425 m.

3 Wave modelling

3.1 Introduction

Waves at the site consist of wind waves generated over the restricted fetches of the Fal Estuary from the North to North-east together. Swell from offshore also propagates into the estuary through Falmouth Bay and enters the Docks Basin and may also reflect towards the Docks Basin from the rocky shores to the North.

As waves propagate towards the site, they will be modified by the processes of depth refraction and shoaling as they travel through increasingly shallow water. Wave models that simulate the nearshore wave transformation processes are well established and for the present study the spectral wave model SWAN (Simulating WAVes Nearshore) has been used.

SWAN is a third generation spectral wave model, which simulates the transformation of random directional waves considering the following processes:

- Wave shoaling
- Wave refraction
- Depth-induced breaking, bottom friction and whitecapping
- Wave growth due to wind
- Wave reflections from structures or rocky shorelines
- Far-field wave diffraction.

The SWAN model has been extensively validated (Holthuijsen et al 1997 (Ref 4), Booij et al., 1999 (Ref 2) and Ris et al 1999 (Ref 5)) and is ideally suited to the transformation of wave energy in relatively large coast areas. The model also includes wave generation by the wind within the model area.

The version of SWAN used in this study was 41.41.

More information on the SWAN model is available in Appendix A.

3.2 The application of SWAN at Falmouth

3.2.1 Model grid and bathymetry

A local area unstructured SWAN model was set up to represent both offshore wave propagation from the offshore data point to the site and also local wind-wave generation within the estuary.

The unstructured model grid is identical to the TELEMAC model grid applied in the flow modelling to maintain consistency. The SWAN model mesh and bathymetry extents are shown in Figure 3.1.

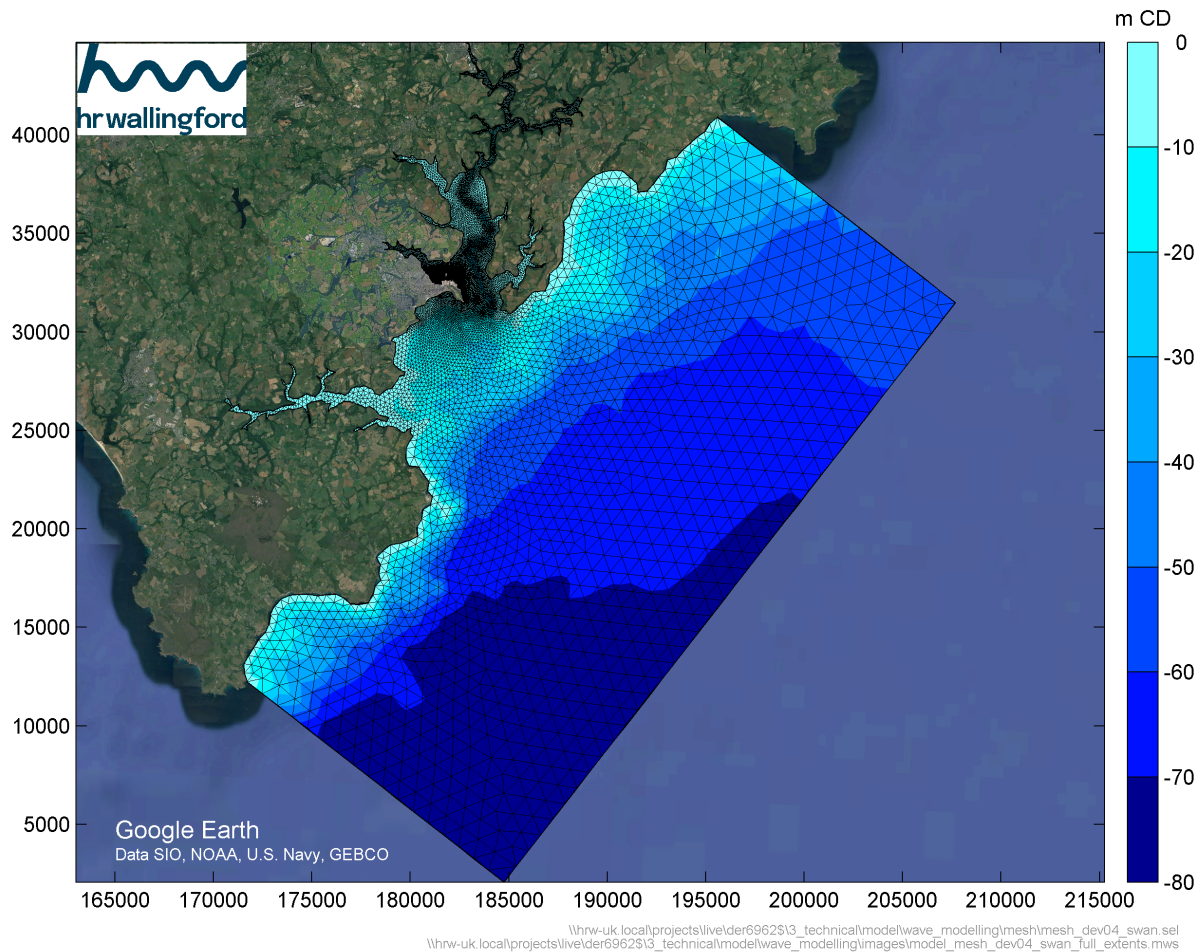


Figure 3.1: The SWAN model mesh and bathymetry

Source: Contains United Kingdom Hydrographic Office data © Crown copyright and database right

The model bathymetry was defined using bathymetric data from the United Kingdom Hydrographic Office (UKHO), supplemented with data obtained from International Hydrographic Charts from C-Map (Ref. 6), and recent local surveys carried out in 2020 and 2022, and supplied by Ramboll for the study, covering the approaches to and within the harbour (Figure 3.2). The data sets were merged to provide the bathymetry used in the wave model.

The proposed Dredging Plan (Figure 1.3) was included in the developed layout.

The model bathymetry is shown in Figure 3.1, with close up image for each layout near the study site in Figure 3.3.

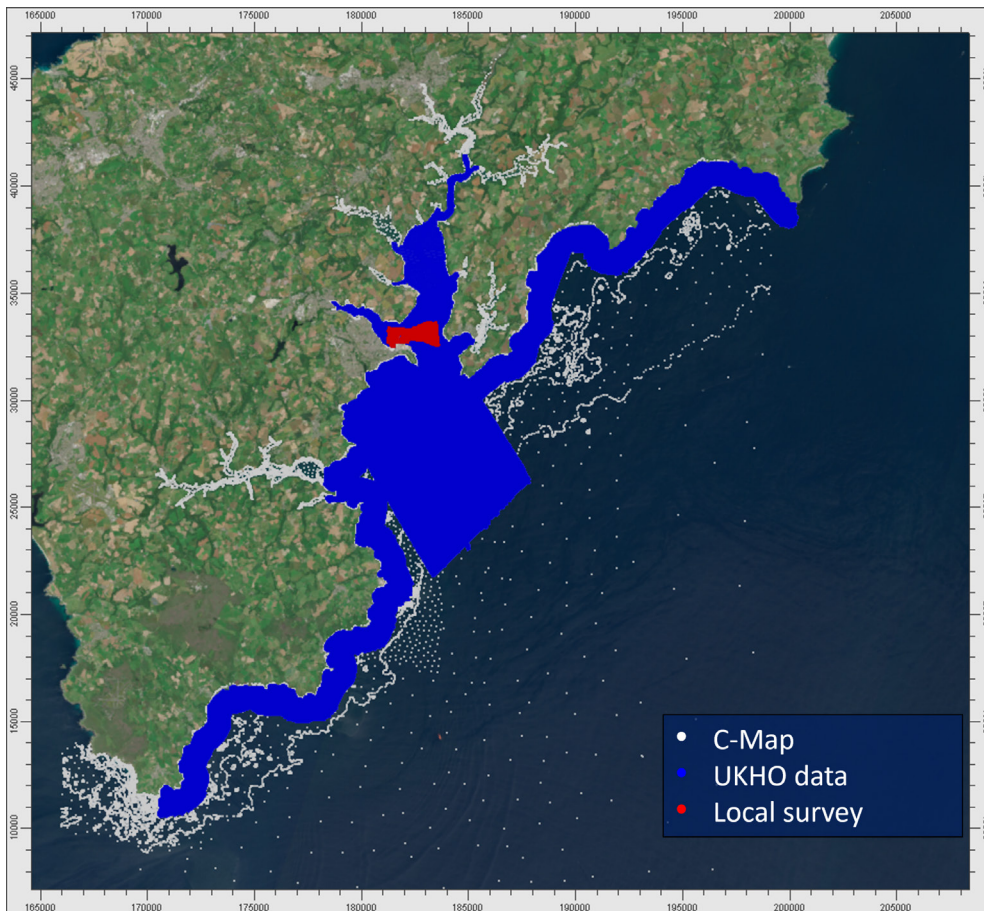


Figure 3.2: Bathymetric sources

Source: Background image Copernicus Sentinel data 2023

Baseline

Developed layout

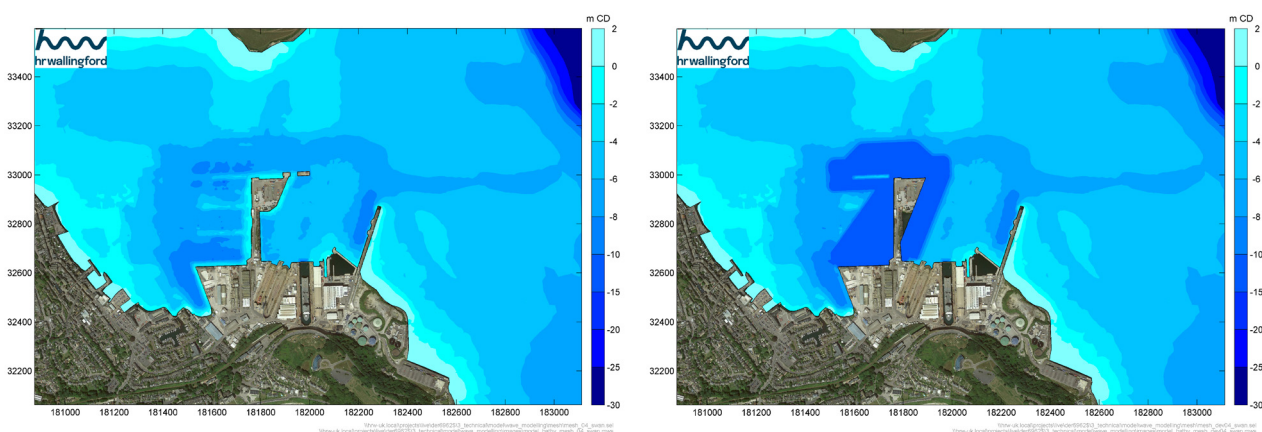


Figure 3.3: SWAN model bathymetry, local area – Baseline (left) and developed layout (right)

Source: Google Earth Imagery; contains United Kingdom Hydrographic Office data © Crown copyright and database right

The existing Queens Wharf and its extension in the developed layout are included in the model assuming no wave attenuation through the suspended deck, which, other than very localised effects around the piles, is considered to be conservative.

3.2.2 Reflection coefficients

The wave reflection properties of the coastal boundaries were represented in the SWAN model by assigning an appropriate reflection coefficient to each of the boundary types within the model. A reflection coefficient of 1.0 indicates that all the incident wave energy will be reflected, while a lower reflection coefficient indicates that some wave energy will be dissipated.

The reflection coefficients used for this study are given in Table 3.1 and in Figure 3.4.

Reflections were applied accordingly in all 3 layouts modelled.

Table 3.1: Reflection coefficients used in the SWAN model

Boundary types	Reflection coefficient	Reference
Vertical structures (quay wall)	0.95	Based on experience on similar projects
Rock revetment 1:1.5 slope	0.50	Based on Allsop's method (1990) (Ref. 7)
Low reflective rock revetment	0.45	Based on experience on similar projects
Rocky beach	0.35	Based on experience on similar projects
Slipway	0.20	Based on experience on similar projects

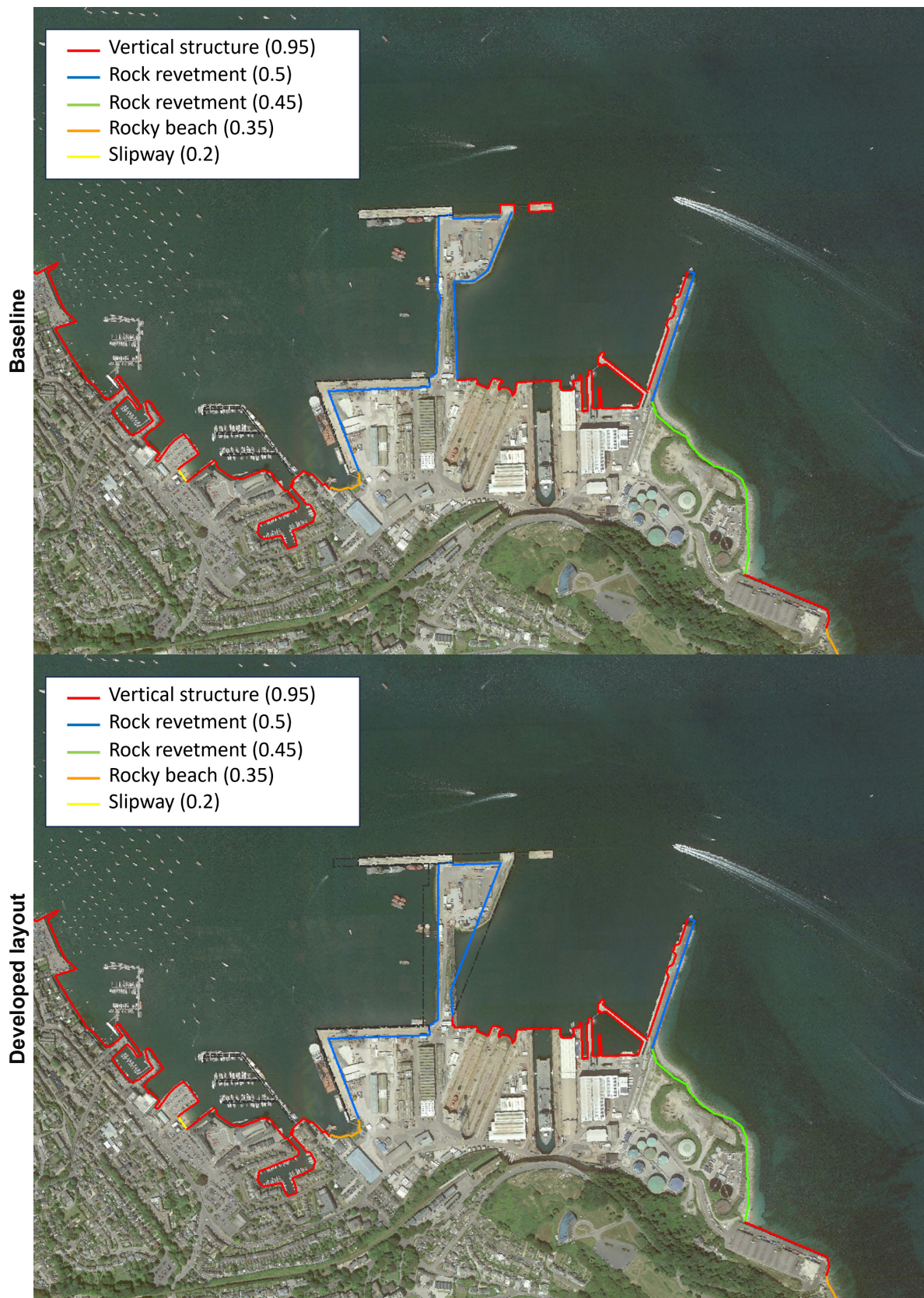


Figure 3.4: Reflection coefficients used in the SWAN model: baseline and developed layout

3.2.3 Boundary conditions

The SWAN model was run in stationary mode for a fixed set of driving conditions (offshore waves, winds and water level), by applying spatially uniform winds across the whole domain and offshore waves from the NWS offshore data point along the seaward boundary, with uniform water levels across the domain.

3.3 Model calibration and validation

Wave model calibration and validation is based on comparison of wave measurements with equivalent predictions from the wave model, for the same locations and period of time. Calibration refers to adjustments made to modelling assumptions and parameter settings required to achieve best agreement between model and measurements. Validation refers to demonstration of the agreement achieved for the chosen settings.

Wave measurements were available from two Waverider wave buoys near Falmouth, located in 45m and 7m depth (see Figure 3.5), and provided by Cefas and funded by Environment Agency, licensed under the Cefas WaveNet Licence v1.0. The data was collected between June 1984 and June 1985. More recent local wave measurements were collected for the study (between 16 June until 21 Aug 2024). This data was provided at a later stage of the study, and was used to provide a verification of the model (Section 3.3.1).

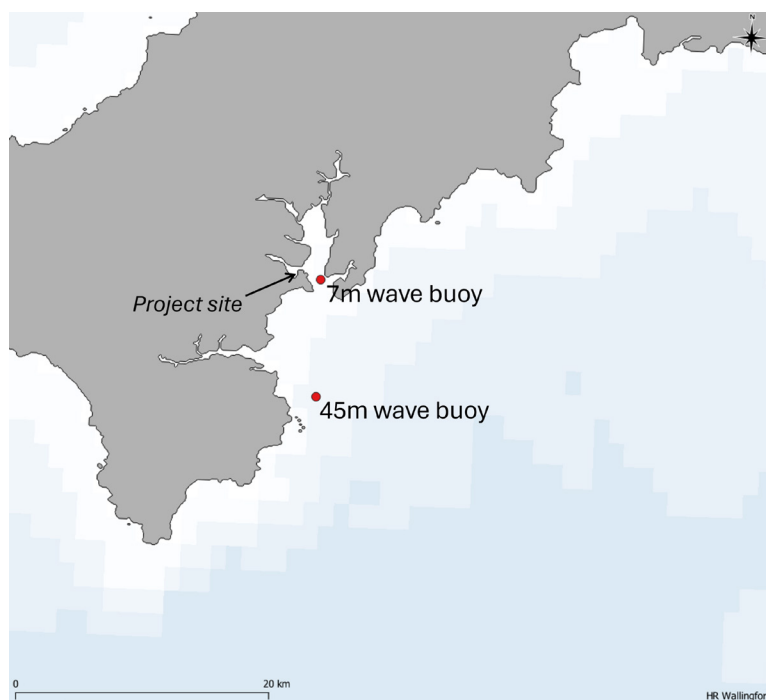


Figure 3.5: Locations of WaveNet buoys near Falmouth

The calibration and validation exercise was undertaken in two stages:

- Comparison of measured waves at the offshore 45m buoy and the Met Office NWS hindcast model at the same location and derivation of adjustment factors for the hindcast model;
- Comparison of measured waves and SWAN predictions at the two buoys for selected winter peaks.

From the analysis of the measured waves at the 45m buoy and concurrent data from the NWS hindcast model at the location of the instrument, we derived an adjustment for the NWS hindcast model.

The next stage compared the measured waves and the SWAN predictions for selected peaks during winter. In the measured datasets, an analysis was carried out of independent peaks over threshold with a 48 hour window between peaks, and obtained a list of 18 independent peaks. The selected peaks were run in the SWAN model, with the adjustment factor applied to the NWS offshore model point. Figure 3.6 shows the time-series of observed waves and the SWAN predictions of the selected peaks at both wave buoys. This shows the model generally predicts well the peaks in significant wave heights at both the 45 m and 7 m buoys. There is an underprediction of the highest peak at the 45 m buoy during mid-February 1985 of about 1 m, but slightly overpredicts at the 7 m buoy for the same event. The second highest peak is accurately predicted at the 45 m buoy, but inshore at the 7 m buoy the model noticeably over predicts the measured significant wave height. For the other conditions considered the model predictions at the 7m buoy are in good agreement with the measurements.

Based on the model calibration at the 45 m buoy and the model validation at the 45 m and 7 m buoys, the local SWAN model is considered suitable for the purposes of the present wave modelling study.

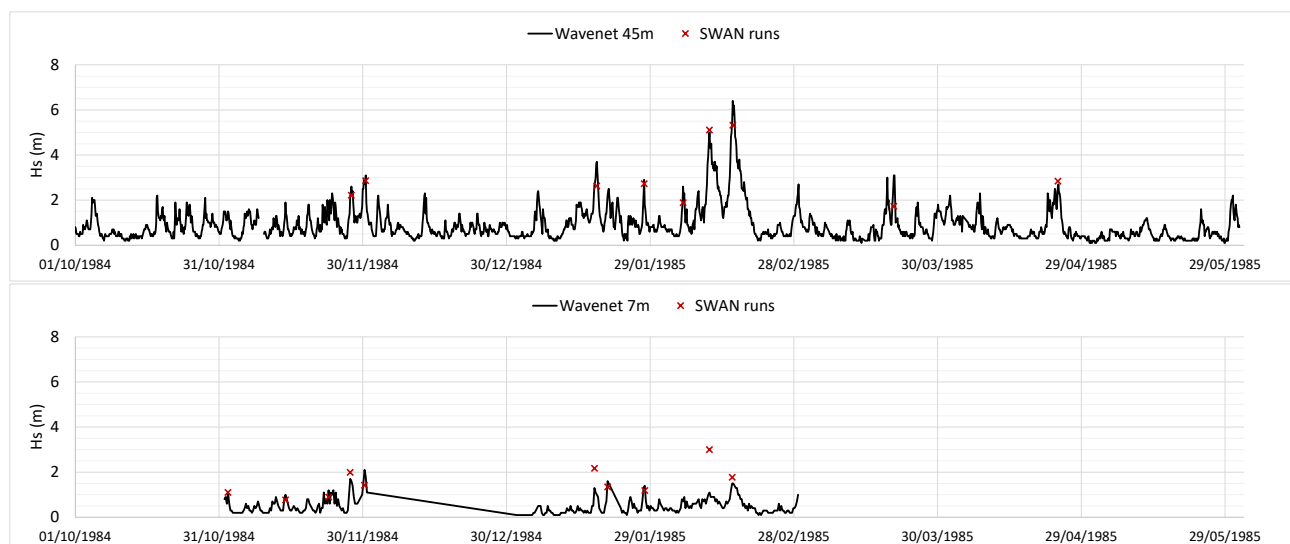


Figure 3.6: Time series of observed and predicted significant wave height (H_s) at the 45m and 7m wave buoys

Source: CEFAS WaveNet/HR Wallingford

3.3.1 Verification against site measurements

Measured waves were collected at a wave buoy located in the entrance of the docks (location: 50.16N -5.04W), for the time period between 16 June until 21 Aug 2024.

As a verification of the local wave model, the calibrated SWAN model was re-run for the highest observed peak. The model was forced with NWS offshore wave conditions data (with the same calibration applied as previously derived), winds from Cudrose and water levels from TotalTide (UK Admiralty, <https://www.admiralty.co.uk/digital-services/admiralty-digital-publications/admiralty-totaltide>) for the time close to when the highest measured waves were quoted. The comparison between the highest measured waves and the SWAN result for this time is given in Table 3.2.

Table 3.2: Comparison of model and measurements for the time of the highest quoted measured waves

	Hs (m)	Tp (s)	Wave direction (°N)
highest measured waves in the dataset (on 8/7/2024 at 19:40)	1.3	7.1	249
SWAN run for this time	1.1	5.9	144

The significant wave height (Hs) and peak period (Tp) values are in reasonable agreement, giving confidence in the model predictions. However, the measured and predicted directions are noticeably different; at this location, a wave direction of 249°N for waves of peak period of 7s seconds, i.e. relatively long, does not seem that plausible. The measured wave directions also vary noticeably between successive 10 minute timesteps. Therefore there is some uncertainty in the quoted measured directions.

Overall the recent measurements provide additional confidence in the model predictions. For the purposes of validating the model for use in design, it is recommended that further validation is performed with measurements collected, ideally, during a winter period to include more extreme storm conditions.

3.4 SWAN model runs

3.4.1 Model settings

The model settings adopted for the main runs are summarised in Table 3.3.

Table 3.3: SWAN model settings

Setting	Option/Value
Wave spectrum characteristics	JONSWAP spectrum with gamma peak enhancement parameter of 2.0
Wave Growth Formulation	Westhuysen (Komen is default)
Directional distribution and resolution	m = 2 exponent with an angular resolution of 5 degrees
Number of spectral frequencies	43
Seabed Friction	Coeff = 0.038 (default)
Wave breaking	Breaking coefficient = 0.73 (default)
Quadruplet wave-wave interactions	Switched ON

In previous studies at Falmouth (Ref. 8), HR Wallingford built a local ARTEMIS phase-resolving wave disturbance model, which was used to model complex wave interference between diffracted and reflected waves inside harbour areas. Initial tests were therefore carried out to compare the SWAN model results inside the docks area with results from the local ARTEMIS wave disturbance model. Figure 3.7 shows the model results from the two models for a wave condition from 150°N. The SWAN model gives similar results to the ARTEMIS model inside the docks area. This shows that the SWAN model is appropriate to predict waves inside the development area. It should also be noted that SWAN includes local wind wave generation, which is not represented by ARTEMIS, but is important for the other directions.

ARTEMIS model results

SWAN model results

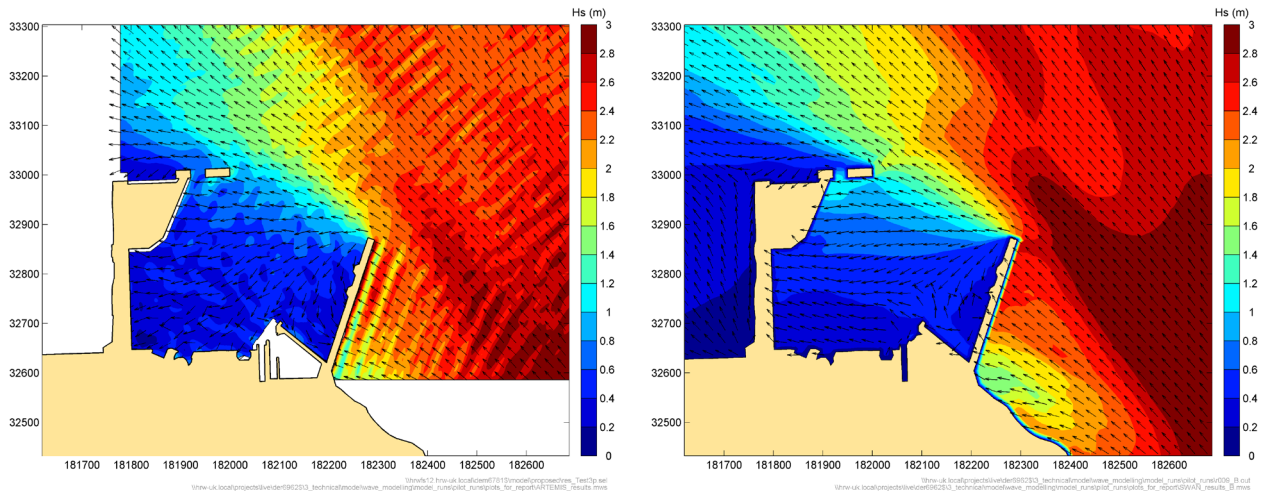


Figure 3.7: ARTEMIS and SWAN model results for a 1 year return period offshore condition from 150°N

3.4.2 Nearshore wave prediction points

Wave conditions were extracted at the prediction points shown in Figure 3.8. The coordinates of the prediction points and associated seabed levels are given in Table 3.4, as well as the type of conditions extracted at each point (either total sea, i.e. incident and reflected, or incident only on the structures).

Table 3.4: Nearshore point locations

Point	Easting	Northing	Bed level (mCD)	Conditions
WP1	181820	32666	-10.5	incident to N/S new quay
WP2	181831	32722	-10.5	incident to new western wharf
WP3	181878	32841	-10.5	incident to new western wharf
WP4	181922	32951	-10.5	incident to new western wharf
WP5	181943	32880	-10.5	total sea
WP6	181888	32742	-10.5	total sea
WP7	182033	32765	-5.5	total sea
WP8	181885	33018	-10.5	incident to new northern wharf
WP9	181815	33016	-10.5	incident to new northern wharf
WP10	181766	33014	-10.5	incident to new northern wharf
WP11	181677	33011	-10.5	total sea
WP12	181568	33007	-10.5	total sea
WP13	181599	32970	-10.5	total sea
WP14	181704	32967	-10.5	total sea
WP15	181713	32914	-10.5	incident to new flow deck
WP16	181713	32792	-10.5	incident to new flow deck
WP17	181722	32666	-10.5	incident to new flow deck
WP18	181644	32656	-10.5	incident to Duchy wharf
WP19	181574	32654	-10.5	incident to Duchy wharf
WP20	181629	32750	-10.5	total sea
WP21	181631	32871	-7.6	total sea

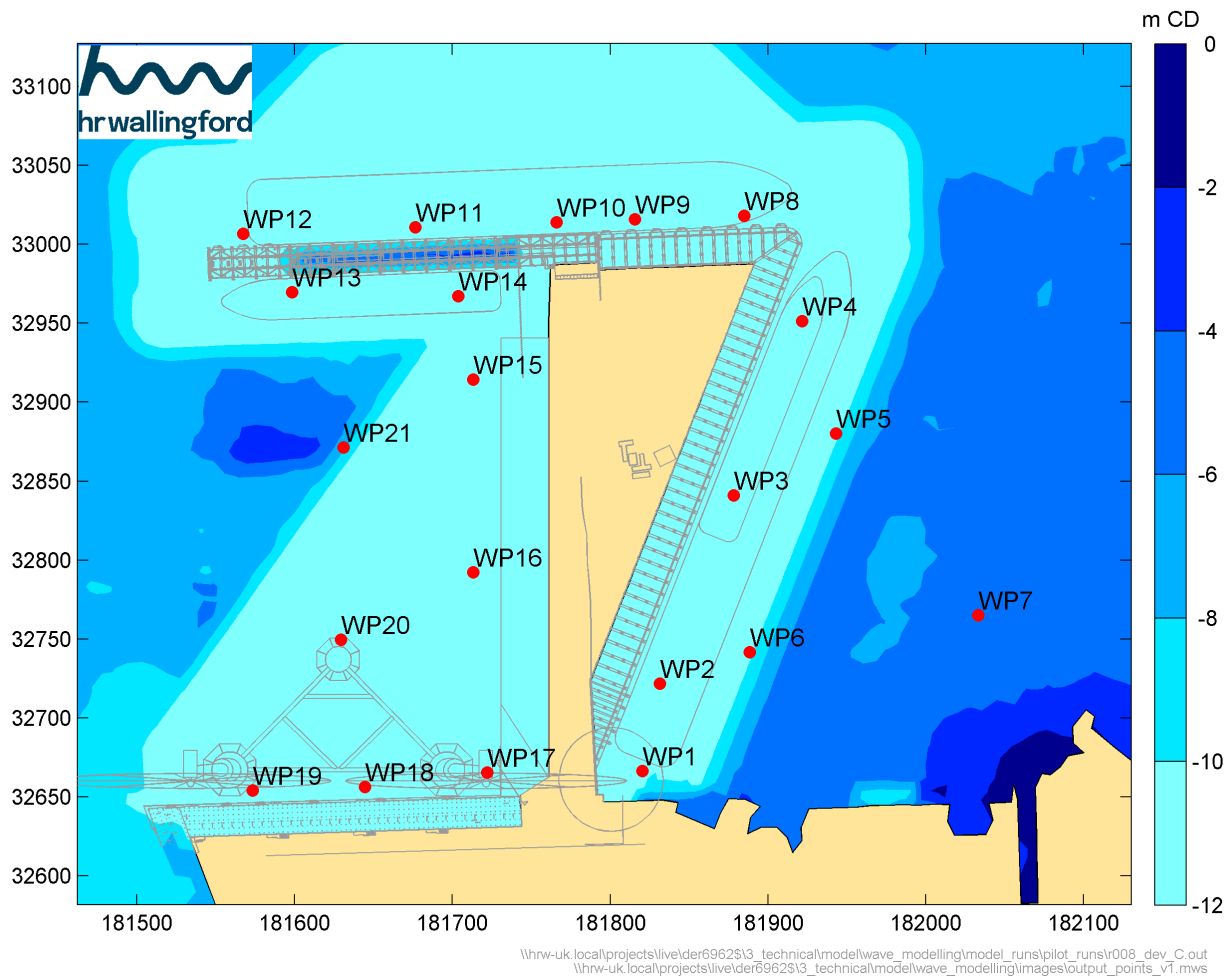


Figure 3.8: Nearshore wave prediction points

3.4.3 Run conditions

The SWAN model was run to provide wave conditions at the wave prediction points around the development for a range of return periods, different water levels and a range of wind/wave directions.

The model runs were carried out in stages:

1. The 200 year conditions were initially run in the SWAN model for the full set of present-day conditions, i.e. the full range of wind/offshore wave directions (0-360°N, every 30°), at MHWS, MSL, MLWS, in order to identify the wind/offshore wave directions and water level that lead to the worst conditions at the wave prediction points.
2. The selected conditions identified in 1) were carried forward and run for the 0.2, 1, 10 and 50 year.
3. Sensitivity to climate change and to more extreme water levels was carried out on the 1:50 and 1:200 year conditions.

Table 3.5: 200 year run conditions

Offshore sector (°N)	Return Period (years)	Wind speed (m/s)	H _s (m)	T _p (s)	Water level
0	200	26.5	–	–	MHWS, MSL, MLWS
30	200	28.1	–	–	MHWS, MSL, MLWS
60	200	27.0	–	–	MHWS, MSL, MLWS
90	200	18.5	6.1	11.0	MHWS, MSL, MLWS
120	200	18.1	5.9	12.2	MHWS, MSL, MLWS
150	200	16.8	5.9	12.4	MHWS, MSL, MLWS
180	200	16.8	6.8	13.7	MHWS, MSL, MLWS
210	200	20.2	11.3	16.5	MHWS, MSL, MLWS
240	200	18.6	12.9	17.8	MHWS, MSL, MLWS
270	200	28.9	–	–	MHWS, MSL, MLWS
300	200	31.6	–	–	MHWS, MSL, MLWS
330	200	25.4	–	–	MHWS, MSL, MLWS

For wind conditions from direction sectors 90°N to 240°N, the wave conditions in Table 2.1 were applied with the associated winds obtained by using the line of best fit (linear regression) through the scatter plot of offshore wave height and wind speed, by sector. No offshore wave conditions were applied to model runs with winds from 270°N, through North, to 60°N, as the offshore waves will be heading offshore. For these direction sectors, a 10% increase was applied to the wind speeds for conversion from land to sea.

Each condition was run at three water levels, corresponding to present-day MLWS, MSL and MHWS.

For each face (West, North and East) of the proposed layout, conditions that lead to the highest predicted waves at the nearshore points were identified, i.e.:

- Winds from 30°N or 300°N give the highest wave conditions at the site.
- As longer wave energy may penetrate from offshore through the bay, conditions from the South-East (90°N and 120°N sectors) are also selected to illustrate how offshore swells (with longer wave periods) propagate at the site.

For each of these conditions, three forcing directions were used within the sector (the central direction and 10° either side of the centre of the sector). These sensitivity tests allowed to determine the worst direction for each direction sector.

Those direction sectors were carried forward as input conditions to the other return periods considered: 0.2 to 50 years. The extreme conditions used in the SWAN model are summarised in Table 3.6. This includes the most frequent 0.2 year conditions, derived from a countback analysis of the wind and offshore wave dataset.

Table 3.6: 0.2 to 50 year return period wave conditions

Offshore direction (°N)	Return Period (years)	Wind speed (m/s)	H _s (m)	T _p (s)	Water level
30	0.2	11.2	–	–	MHWS
30	1	14.2	–	–	MHWS
30	10	18.9	–	–	MHWS
30	50	22.0	–	–	MHWS
80	0.2	11.2	3.4	8.2	MHWS
80	1	11.9	3.6	8.5	MHWS
80	10	15.1	4.8	9.8	MHWS
80	50	17.0	5.5	10.4	MHWS

Offshore direction (°N)	Return Period (years)	Wind speed (m/s)	H _s (m)	T _p (s)	Water level
130	0.2	8.0	2.0	7.2	MHWS
130	1	9.9	2.8	8.4	MHWS
130	10	14.1	4.4	10.5	MHWS
130	50	16.4	5.2	11.5	MHWS
310	0.2	14.1	-	-	MHWS
310	1	18.0	-	-	MHWS
310	10	23.7	-	-	MHWS
310	50	27.9	-	-	MHWS

4 Model results

The model was run for the baseline and the developed layout using the same model settings and boundary conditions. Model results are presented in this section as colour contour plots of significant wave heights and vectors of mean wave directions over the model area.

The results from the direction sectors that lead to the highest waves are presented in Section 4.1 for each return period. These include the effects of waves from offshore and locally generated waves due to the wind. Plots for all the 200 year conditions are presented in Appendix B.

Predicted wave conditions were also extracted at the nearshore points and tabulated for each return period in Section 4.2.1 to 4.2.3, by groups of points:

- Points WP1 to WP7, for conditions at the East of the site (Section 4.2.1);
- Points WP8 to WP12, for conditions at the North of the site (Section 4.2.2);
- Points WP13 to WP21, for conditions at the West side of the site (Section 4.2.3).

Winds from 30°N and 300°N give the highest wave conditions at the site. Significant wave heights are predicted to be of the order of 2 m in front of the Western Wharf, up to 1.4 m along the Northern and Queen's Wharf, and up to 1.4m along the new FLOW Deck on the west side of the docks, for the 200 year conditions.

Waves at the site are often a combination of wind sea and swell. Although the highest predicted wave heights are locally-generated waves from sectors 30°N or 300°N, there may also be a component of underlying swell coming from offshore reaching the site at a reduced wave height with long wave periods (see the variations in T_p in the 200 year return period tabulated results in Appendix C). Figure 4.1 shows an example of the nearshore wave spectrum at point WP7 for the 200 year return period conditions from 240°N, with a dominant wind sea component from the SW and an underlying swell component with a peak wave period of 18.7 sec from the E.

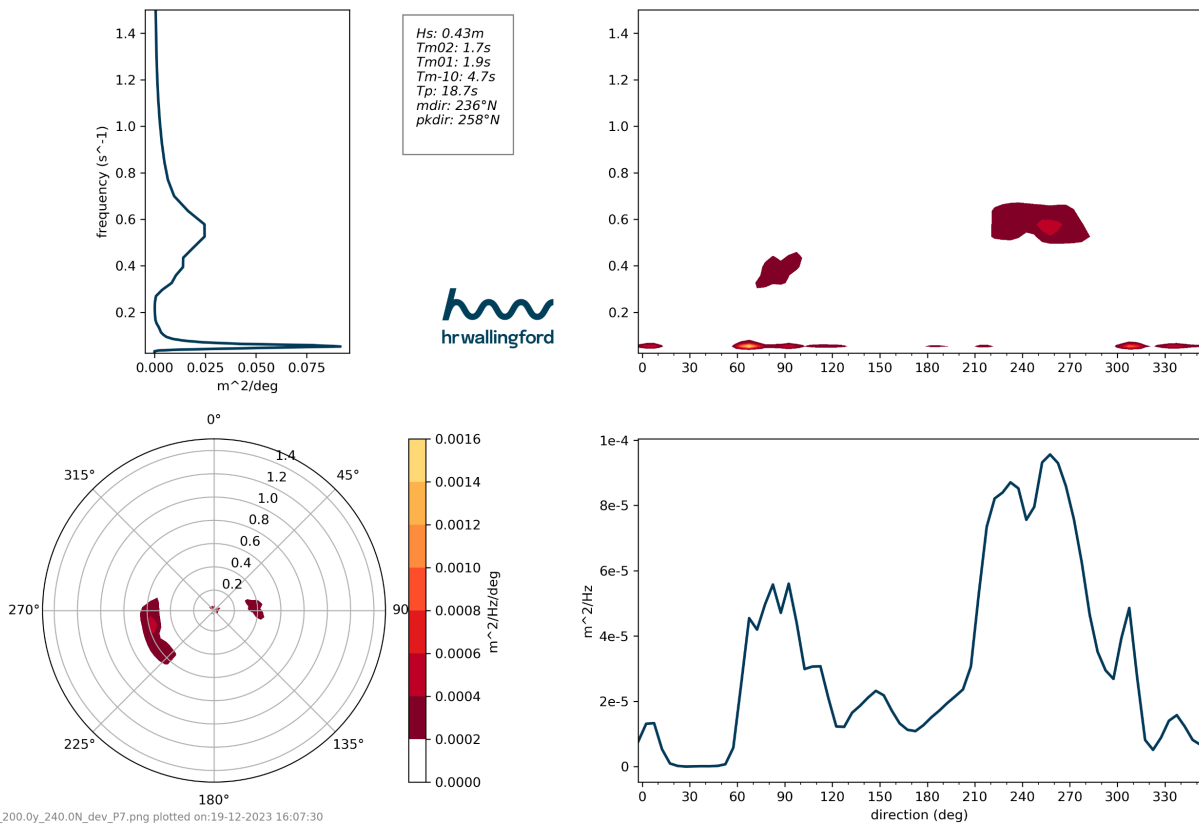
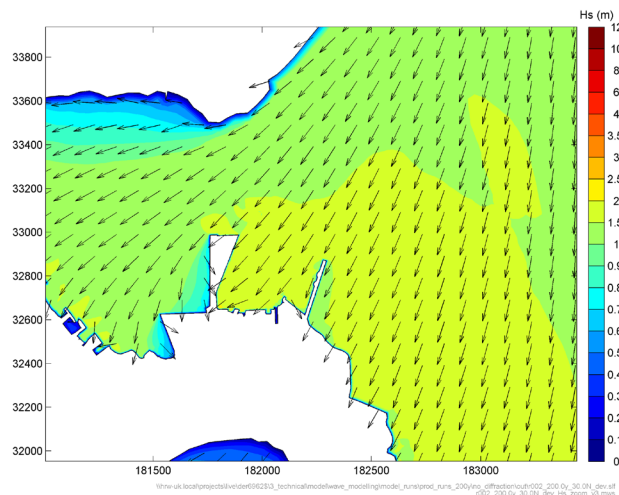


Figure 4.1: Spectral shape output illustrating the bimodal seas at the site at WP7 for the 200 year conditions from 240°N, MHWS case

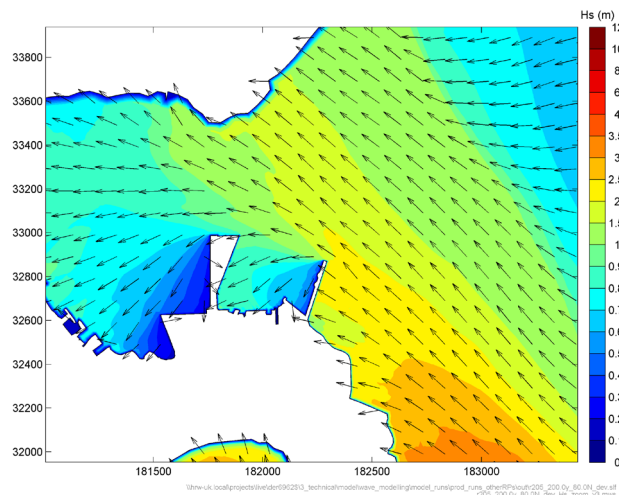
4.1 Contour plots –wave conditions for developed layout

Colour contour plots for the direction sectors leading to the highest waves are presented in Figure 4.2 for the 200 year conditions. Contour plots for the 50, 10, 1 and 0.2 year conditions are presented in Figure 4.3 to Figure 4.6.

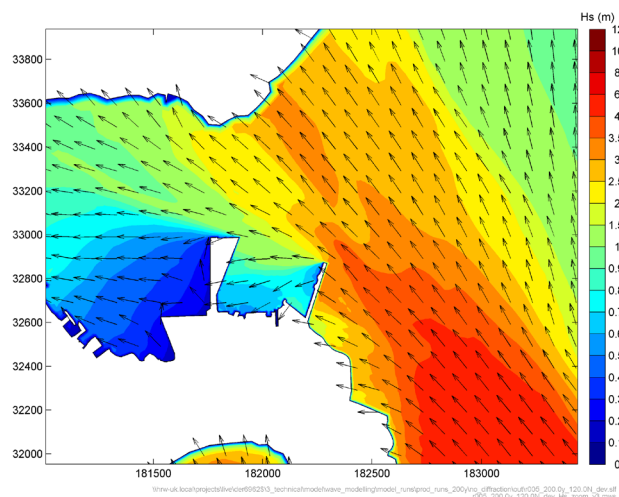
30N



90N



120N



300N

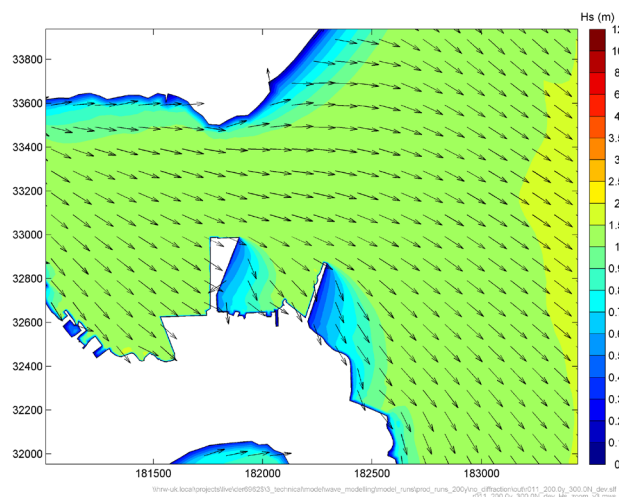
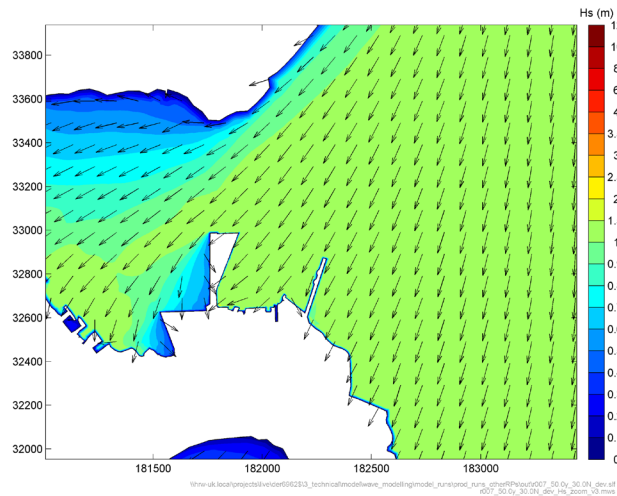
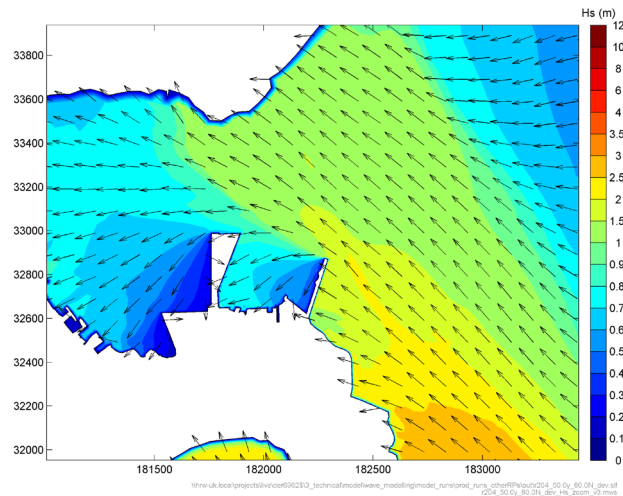


Figure 4.2: Significant wave height contours, 200 year conditions, developed layout, MHWS

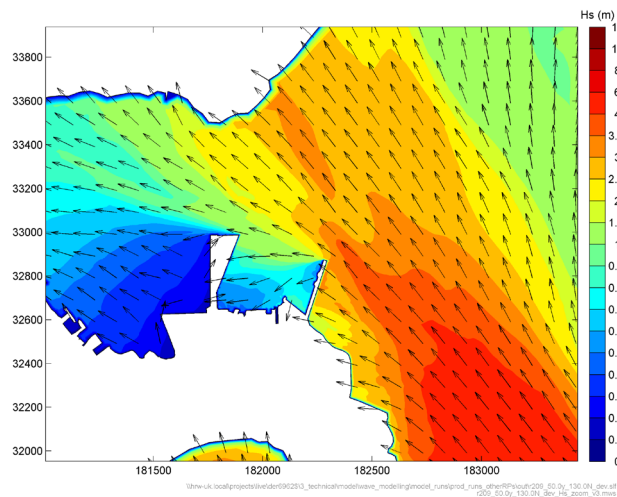
30N



90N



120N



300N

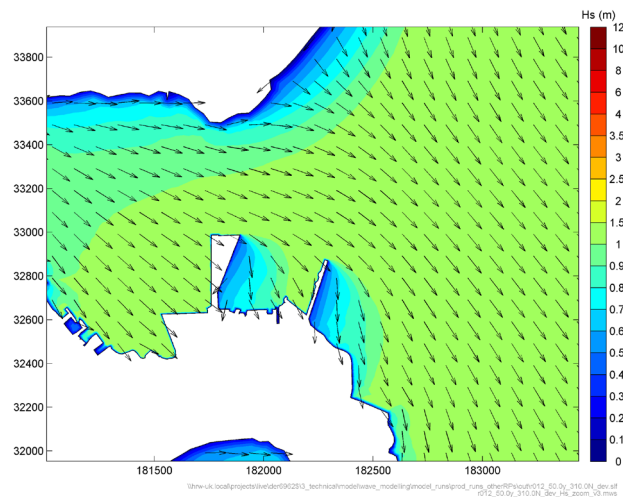
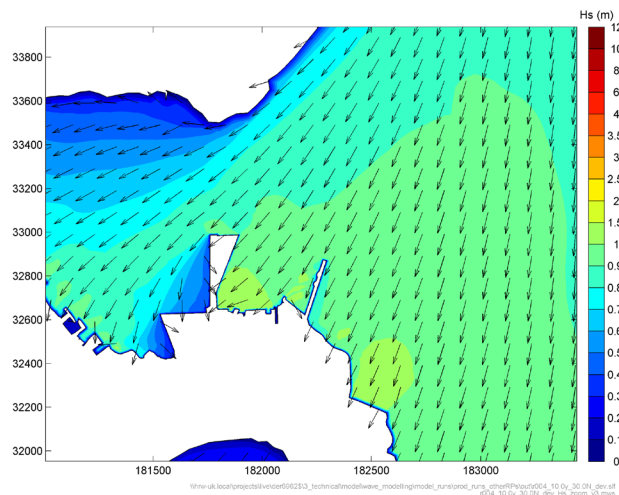
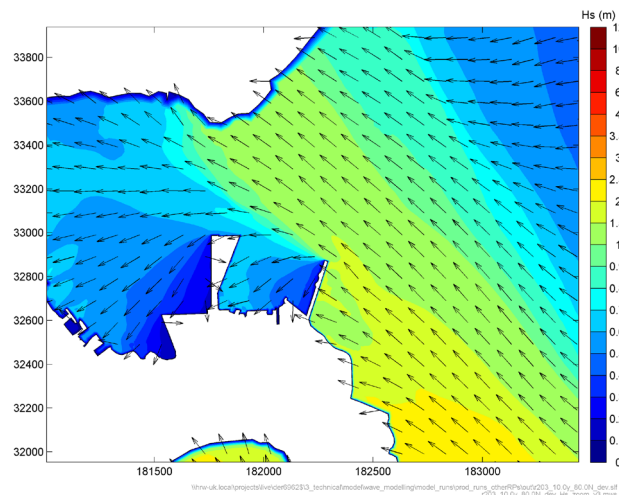


Figure 4.3: Significant wave height contours, 50 year conditions, developed layout, MHWS

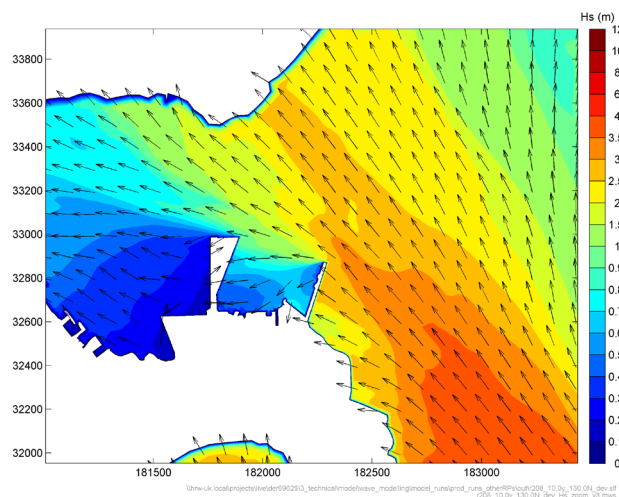
30N



90N



120N



300N

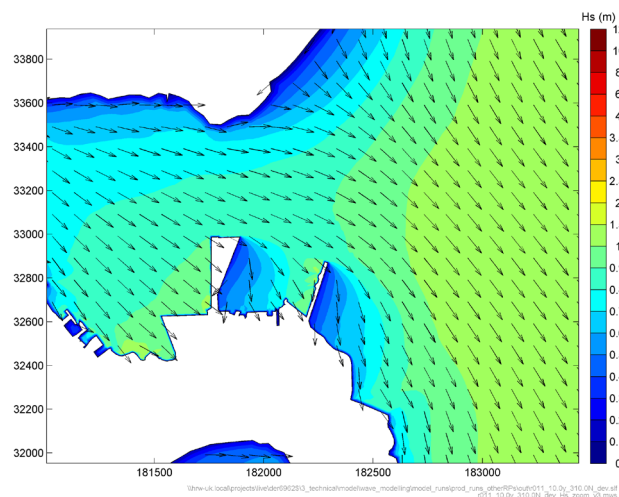
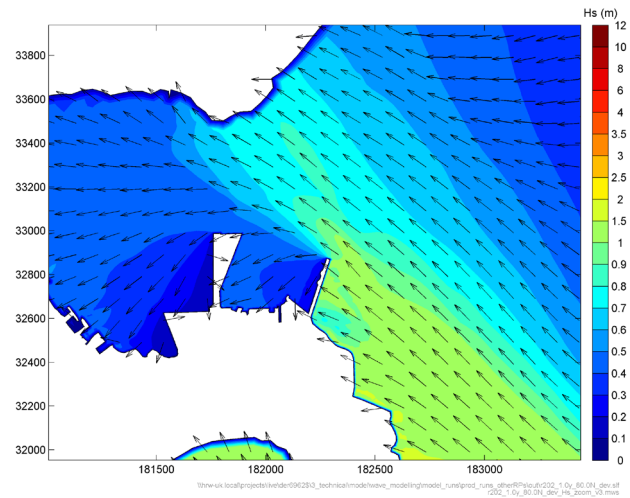
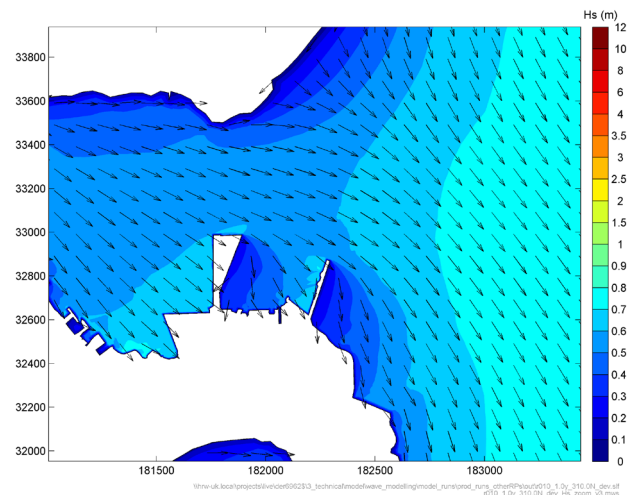


Figure 4.4: Significant wave height contours, 10 year conditions, developed layout, MHWS

90N

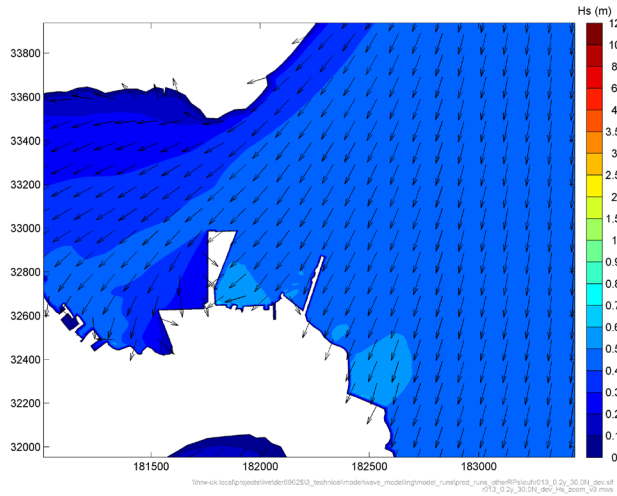


300N

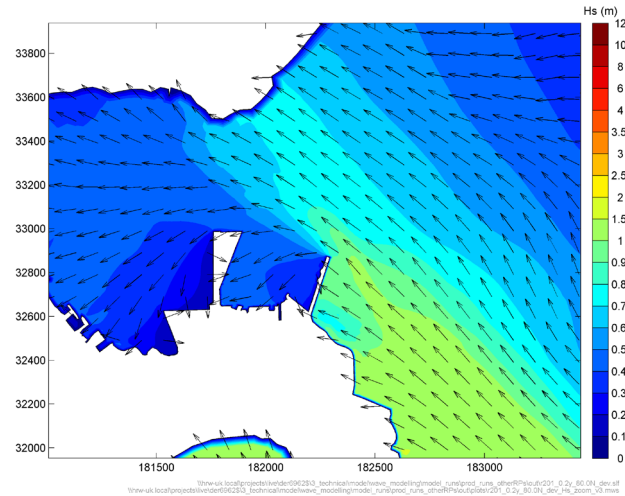


29

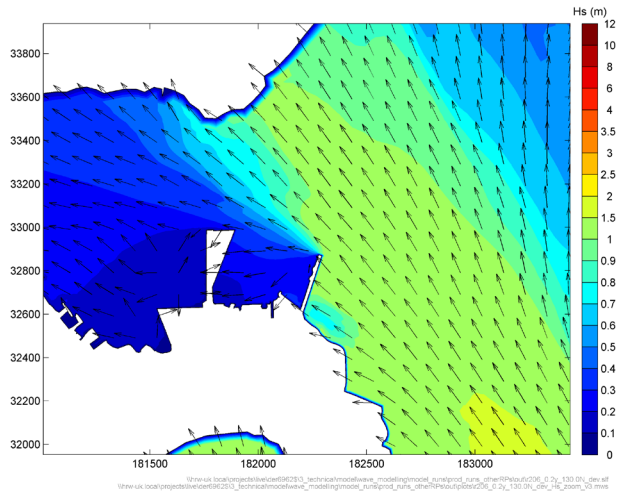
30N



90N



120N



300N

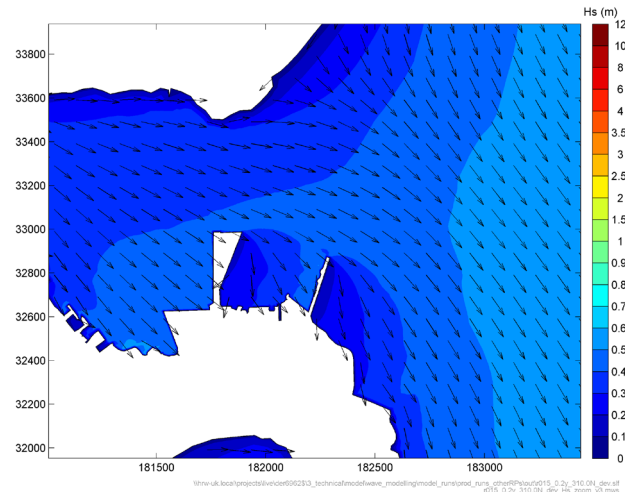


Figure 4.6: Significant wave height contours, 0.2 year conditions, developed layout, MHWS

4.2 Tabulated results – wave conditions for developed layout

Tabulated results at the nearshore points for locally generated conditions (from 30°N or 300°N) and for the conditions from the South-East (90°N and 120°N sectors) for the 200 year conditions are summarised below. For the South-East conditions, the results also include a wind sea ($H_{s,wind}$, $T_{p,wind}$) and a swell ($H_{s,swell}$, $T_{p,swell}$) component. The bimodality of the predicted conditions may be important for design when considering vessel movement at the berths or potential overtopping of the revetments or upload forces on the suspended deck. Wind sea and swell components were estimated using a wave period cut-off of 8 seconds.

Please refer to Table 3.4 for the point locations and whether results quoted below refer to incident only or total i.e. incident and reflected wave conditions.

4.2.1 Wave Prediction Points WP1 – WP7

Tabulated results for the selected direction sectors are summarised in Table 4.1 and Table 4.2 for the nearshore points WP1 to WP7.

Table 4.1: 200 year conditions, developed layout – WP1-7, locally-generated

Point	H_s (m)	$T_{m-1,0}$ (s)	T_p (s)	Mean wave direction (°N)
1	1.7	3.7	4.5	77
2	1.5	3.7	4.1	72
3	1.5	3.6	4.1	65
4	1.4	3.6	4.1	54
5	1.6	3.5	4.1	43
6	1.9	3.7	4.1	69
7	1.6	3.6	4.1	38

Table 4.2: 200 year conditions, developed layout – WP1-7, E-SE conditions

Point	H_s (m)	$T_{m-1,0}$ (s)	T_p (s)	$H_{s,wind}$ (m)	$T_{p,wind}$ (s)	$H_{s,swell}$ (m)	$T_{p,swell}$ (s)	Mean wave direction (°N)
1	0.8	2.8	3.1	0.7	3.1	0.1	11.6	79
2	0.7	2.9	3.1	0.7	3.1	0.1	11.6	78
3	0.8	3.7	3.1	0.8	3.1	0.3	11.6	78
4	1.1	9.8	12.8	0.6	7.9	0.9	12.8	101
5	0.9	9.2	12.8	0.6	7.9	0.8	12.8	80
6	0.9	3.0	3.1	0.9	3.1	0.2	11.6	81
7	0.7	9.2	12.8	0.4	7.9	0.6	12.8	76

4.2.2 Wave Prediction Points WP8 – WP12

Tabulated results for the selected direction sectors are summarised in Table 4.3 and Table 4.4 for the nearshore points WP8 to WP12.

Table 4.3: 200 year conditions, developed layout - WP8-12, locally-generated

Point	H _s (m)	T _{m-1,0} (s)	T _p (s)	Mean wave direction (°N)
8	1.4	3.4	4.1	39.2
9	1.4	3.5	4.1	41.0
10	1.4	3.5	4.1	42.3
11	1.4	3.4	4.1	45.7
12	1.4	3.3	4.1	48.4

Table 4.4: 200 year conditions, developed layout - WP8-12, E-SE conditions

Point	H _s (m)	T _{m-1,0} (s)	T _p (s)	H _{s,wind} (m)	T _{p,wind} (s)	H _{s,swell} (m)	T _{p,swell} (s)	Mean wave direction (°N)
8	0.7	3.0	3.1	0.7	3.1	0.1	11.6	49.1
9	0.7	2.9	3.1	0.7	3.1	0.1	11.6	51.1
10	0.7	2.9	3.1	0.7	3.1	0.1	11.6	52.2
11	0.8	2.9	3.1	0.7	3.1	0.1	11.6	64.2
12	0.8	2.8	3.1	0.7	3.1	0.1	11.6	66.0

4.2.3 Wave Prediction Points WP13 – WP21

Tabulated results for the selected direction sectors are summarised in Table 4.5 and Table 4.6 for the nearshore WP13 to WP21.

Table 4.5: 200 year conditions, developed layout - WP13-21, locally-generated

Point	H _s (m)	T _{m-1,0} (s)	T _p (s)	Mean wave direction (°N)
13	1.4	3.4	4.1	45.3
14	1.4	3.4	4.1	37.6
15	1.2	3.0	3.4	299.5
16	1.3	3.1	3.7	299.4
17	1.3	3.1	3.7	297.2
18	1.3	3.1	3.7	320.5
19	1.3	3.1	3.7	320.0
20	1.4	3.1	3.7	309.6
21	1.3	3.0	3.4	309.4

Table 4.6: 200 year conditions, developed layout - WP13-21, E-SE conditions

Point	H _s (m)	T _{m-1,0} (s)	T _p (s)	H _{s,wind} (m)	T _{p,wind} (s)	H _{s,swell} (m)	T _{p,swell} (s)	Mean wave direction (°N)
13	0.7	2.7	3.1	0.7	3.1	0.1	11.6	58.0
14	0.6	2.7	3.1	0.6	3.1	0.1	11.6	43.9
15	0.3	2.7	3.1	0.3	3.1	<0.1	11.6	254.6
16	0.2	2.7	3.1	0.2	3.1	<0.1	11.6	265.7
17	0.2	2.7	3.1	0.2	3.1	<0.1	11.6	293.9
18	0.3	2.1	3.1	0.3	3.1	<0.1	11.6	25.5
19	0.4	2.2	3.1	0.4	3.1	0.1	11.6	31.4
20	0.4	2.3	3.1	0.4	3.1	0.1	11.6	29.0
21	0.6	2.6	3.1	0.6	3.1	0.1	11.6	38.9

4.3 Effect of development on wave conditions

The results of the SWAN modelling at MHWS for the 0.2 and 1 year conditions from 30°N, 90°N, 120°N and 300°N sectors are shown in Figure 4.7 to Figure 4.14.

Key aspects of the changes in wave conditions predicted with the proposed development layout for the 1 year conditions are summarised below:

- Differences in significant wave heights are localised around the proposed layout and dredging areas.
- For waves from SE, 120°N, an increase in significant wave height of up to 0.3 m is predicted along the Northern Wharf. A decrease in significant wave height of up to 0.25 m is predicted in the estuary.
- For waves from NW, 300°N, an increase in significant wave height of up to 0.35 m is predicted along the Northern Wharf inside the dock area.
- For waves from N-NE, 30°N, a small increase in significant wave height of up to 0.3 m is predicted along the New Western Wharf and in the corner of the existing Western Wharf.

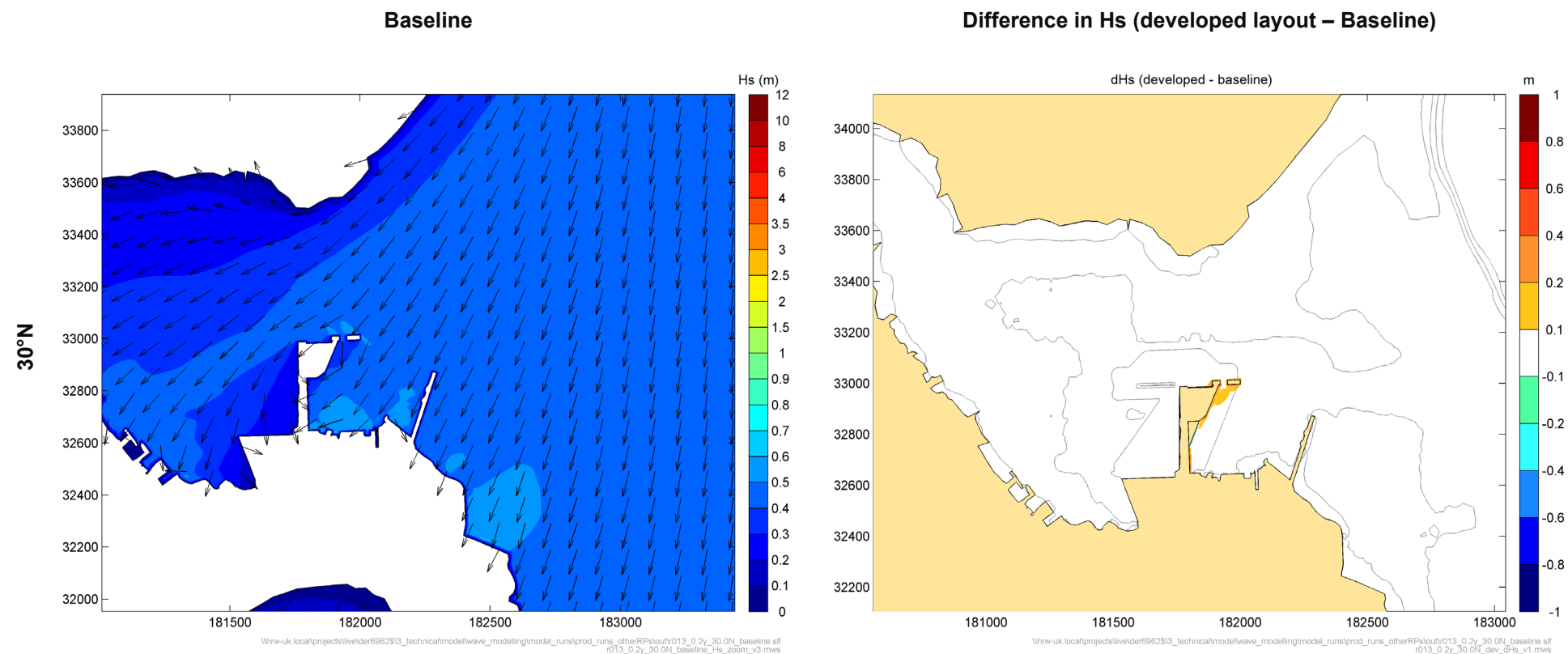


Figure 4.7: Baseline significant wave height contours (left) and difference in Hs between the developed layout and Baseline (right) – 0.2 year present day conditions from 30°N, MHWS

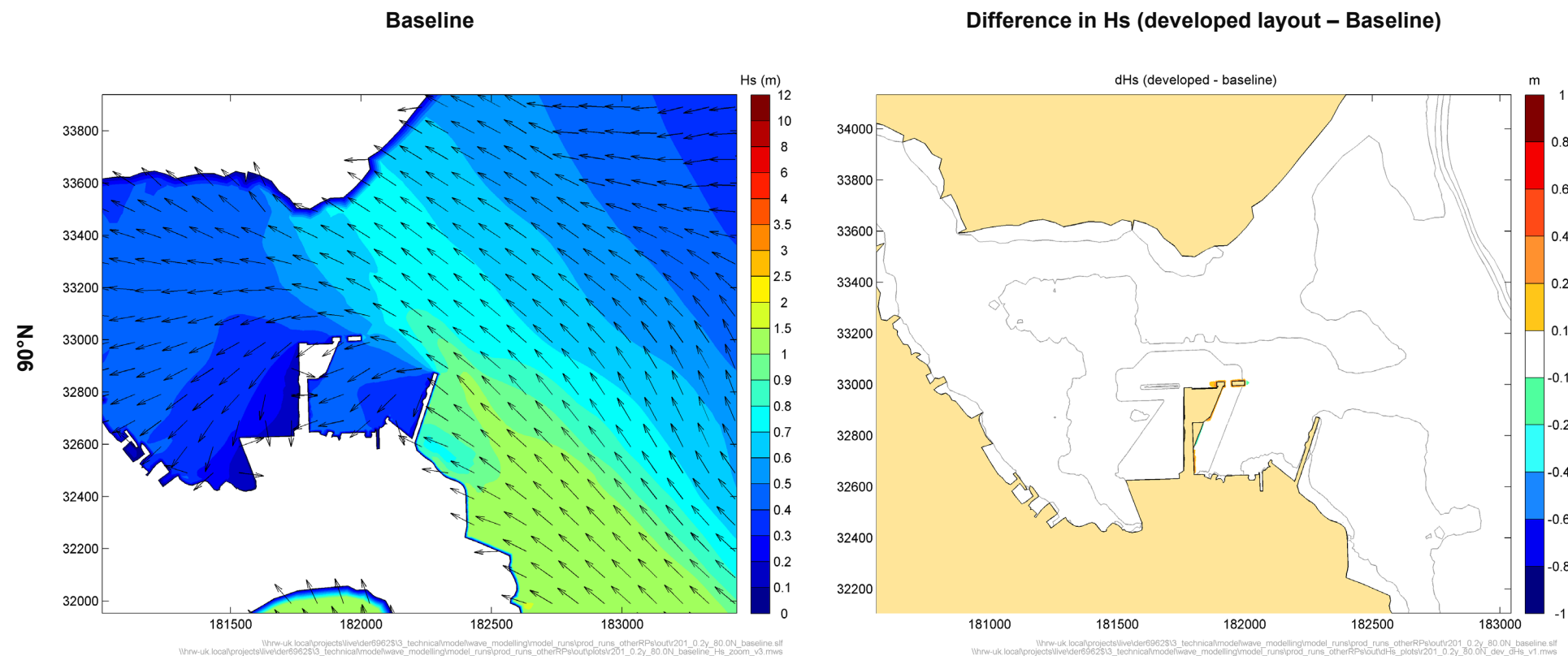


Figure 4.8: Baseline significant wave height contours (left) and difference in Hs between the developed layout and Baseline (right) – 0.2 year present day conditions from 90°N, MHWS

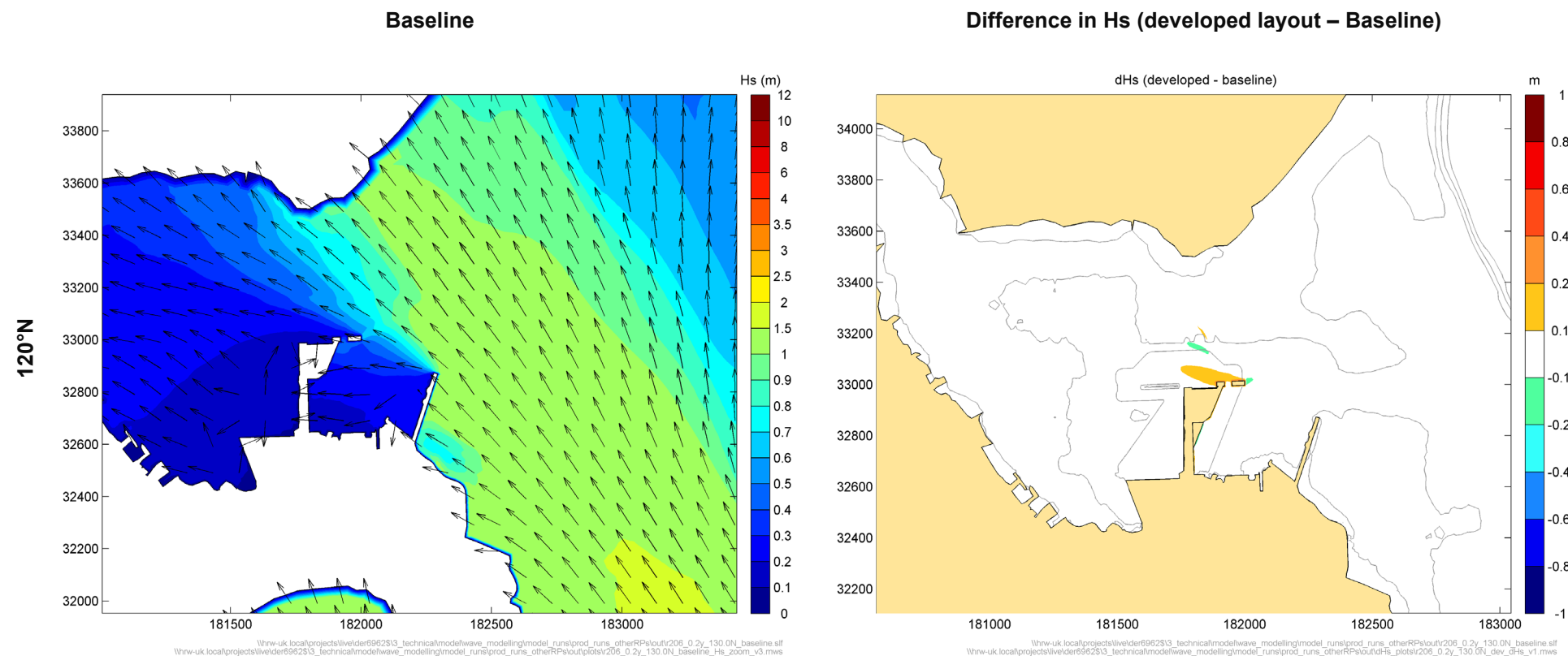


Figure 4.9: Baseline significant wave height contours (left) and difference in Hs between the developed layout and Baseline (right) – 0.2 year present day conditions from 120°N, MHWS

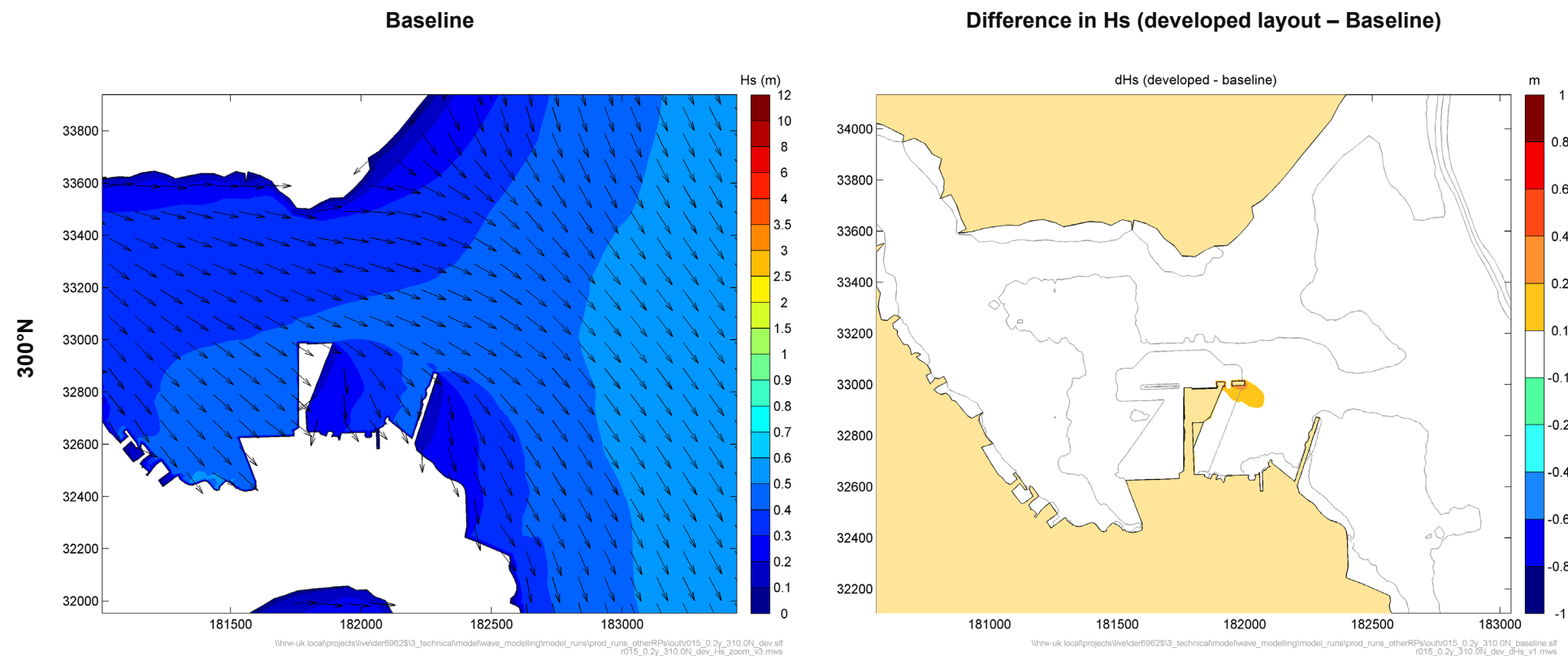


Figure 4.10: Baseline significant wave height contours (left) and difference in Hs between the developed layout and Baseline (right) - 0.2 year present day conditions from 300°N, MHWS

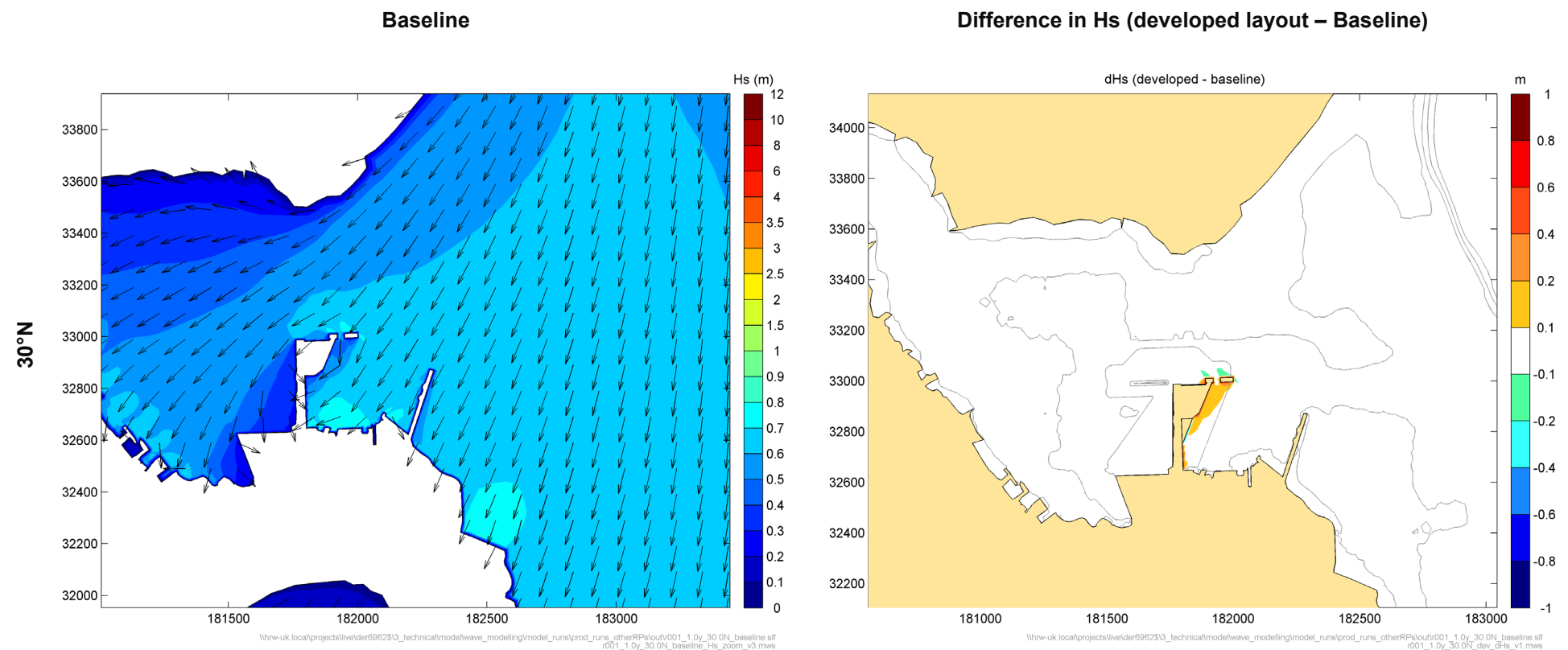


Figure 4.11: Baseline significant wave height contours (left) and difference in Hs between the developed layout and Baseline (right) - 1 year present day conditions from 30°N, MHWS

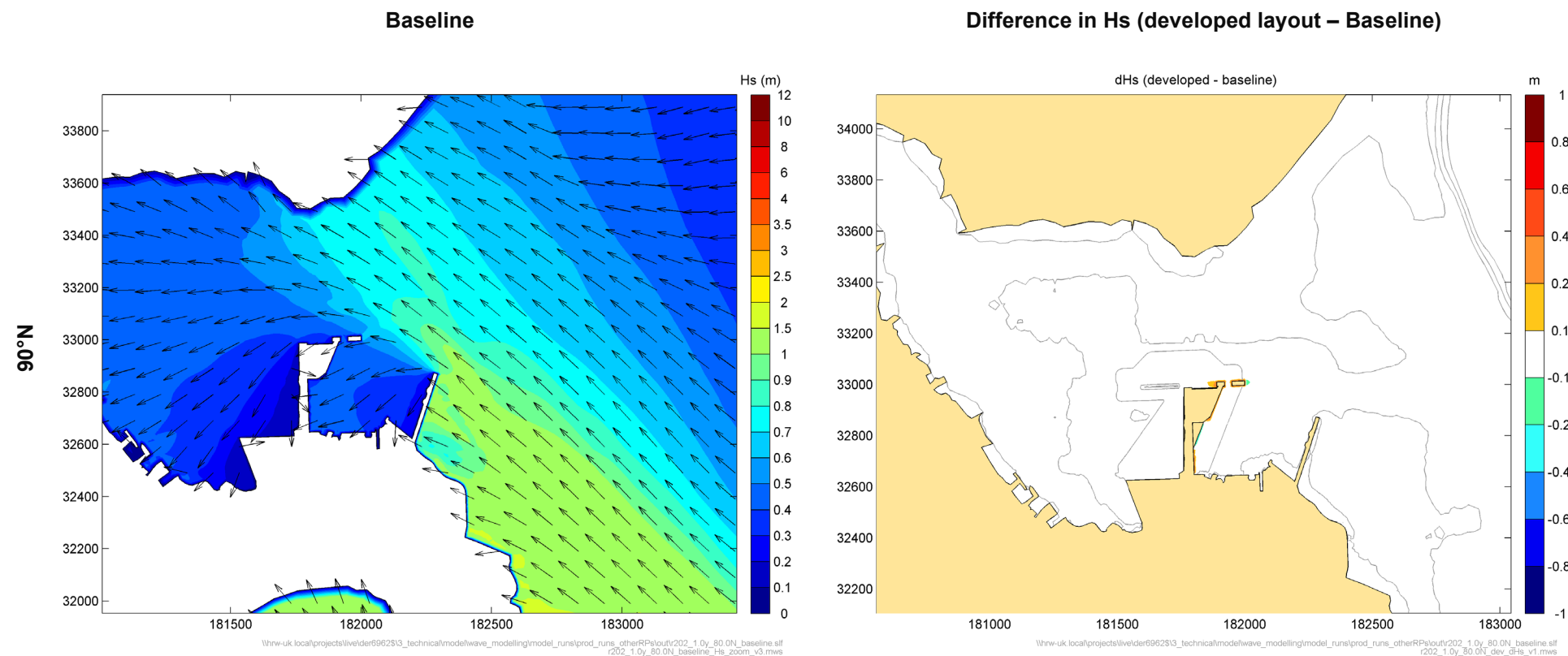


Figure 4.12: Baseline significant wave height contours (left) and difference in Hs between the developed layout and Baseline (right) - 1 year present day conditions from 90°N, MHWS

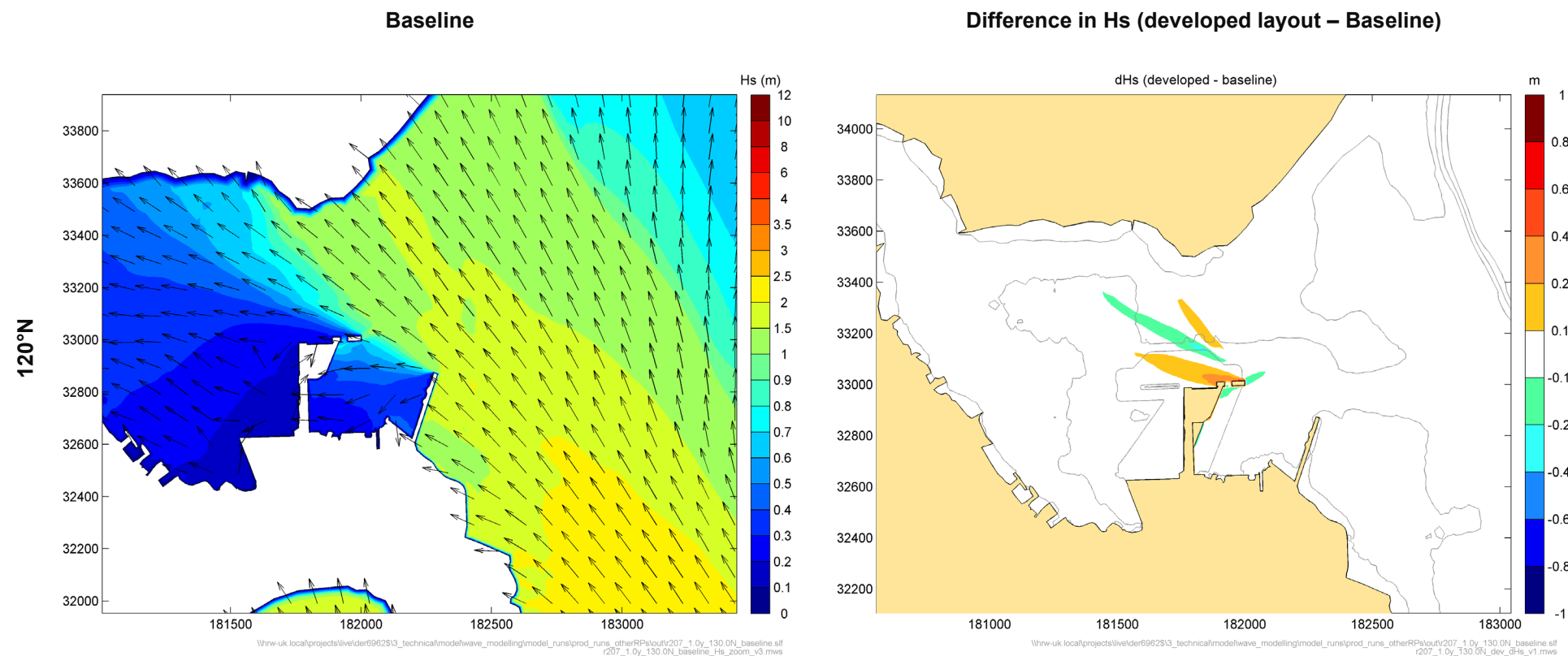


Figure 4.13: Baseline significant wave height contours (left) and difference in Hs between the developed layout and Baseline (right) - 1 year present day conditions from 120°N, MHWS

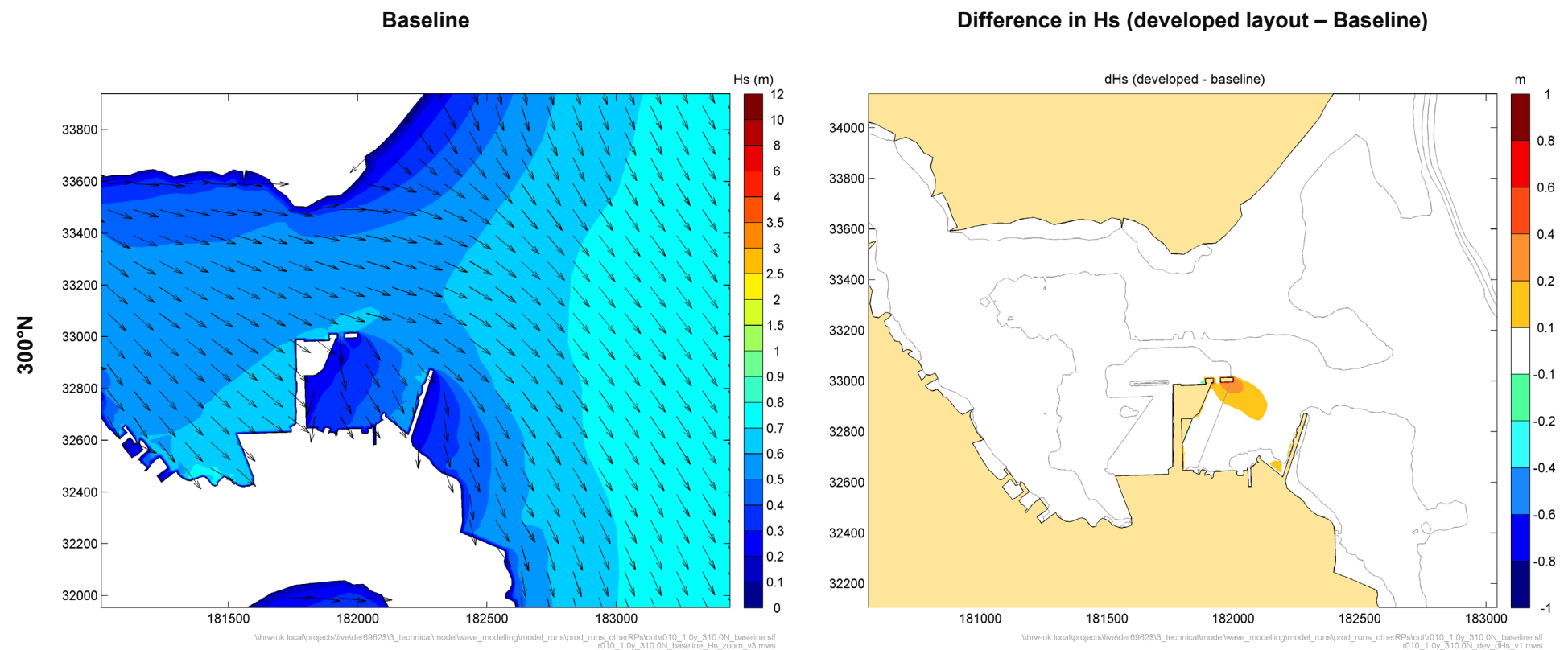


Figure 4.14: Baseline significant wave height contours (left) and difference in Hs between the developed layout and Baseline (right) - 1 year present day conditions from 300°N, MHWS

4.4 Sensitivity of results to climate change and to more extreme water level

4.4.1 Sensitivity to climate change

For the sensitivity to climate change, the 50 and 200 year conditions were run for the selected directions, accounting for future sea level rise (as defined in Section 2.2.1) and a 10% increase in offshore wind speed and significant wave height due to climate change. This allowance corresponds to the recommendations for the period 2056–2125 by the flood risk assessment guidance from the Environmental Agency (Ref. 9). Wave periods were increased accordingly to maintain the wave steepness of the present day conditions.

The defined future scenario wind and wave conditions with the estimated sea level rise are summarised in Table 4.7.

Table 4.7: Wave conditions for sensitivity to climate change

Case	Offshore sector (°N)	Return Period (years)	Wind speed (m/s)	H _s (m)	T _p (s)	Water level
1	30	200	31.0	–	–	MHWS + SLR
2	80	200	20.4	6.7	11.5	MHWS + SLR
3	130	200	20.0	6.5	12.8	MHWS + SLR
4	310	200	34.8	–	–	MHWS + SLR
5	30	50	24.2	–	–	MHWS + SLR
6	80	50	18.7	6.1	11.0	MHWS + SLR
7	130	50	18.0	5.7	12.0	MHWS + SLR
8	310	50	30.7	–	–	MHWS + SLR

Model results for the sensitivity tests are presented in Figure 4.15 and Figure 4.16. For each condition, the model results for the present-day MHWS case are also shown as reference.

Tabulated results at WP5 and WP21 are presented in Table 4.8 and Table 4.9. These show that the future conditions (including sea level rise and increase in winds and waves due to storminess) lead to an increase in significant wave height of around 0.2m for the 200 year and the 50 year conditions at WP5 and WP21.

Table 4.8: Present-day and future wave conditions, WP5, developed layout

Case	Present-day conditions				Future conditions			
	H _s (m)	T _{m-1,0} (s)	T _p (s)	Mean wave direction (°N)	H _s (m)	T _{m-1,0} (s)	T _p (s)	Mean wave direction (°N)
1	1.6	3.5	4.1	43	1.8	3.7	4.5	43
2	0.8	4.1	3.1	61	1.0	4.2	3.1	61
3	0.9	9.2	12.8	80	1.0	9.2	12.8	81
4	0.8	2.5	3.4	350	0.9	2.6	3.4	351
5	1.2	3.1	3.7	43	1.3	3.3	3.7	43
6	0.7	3.7	2.8	61	0.8	3.9	3.1	61
7	0.9	8.9	11.6	79	0.9	9.0	11.6	80
8	0.7	2.3	3.1	349	0.8	2.4	3.4	350

Note: Cases 1–4 are the 200 year return period; cases 5–8 are the 50 year return period

Table 4.9: Present-day and future wave conditions, WP21, developed layout

Case	Present-day conditions				Future conditions			
	H _s (m)	T _{m-1,0} (s)	T _p (s)	Mean wave direction (°N)	H _s (m)	T _{m-1,0} (s)	T _p (s)	Mean wave direction (°N)
1	1.2	3.2	4.1	29	1.4	3.3	4.1	29
2	0.6	2.6	3.1	39	0.6	2.7	3.4	39
3	0.4	5.6	12.8	131	0.4	5.6	12.8	139
4	1.3	3.0	3.4	309	1.5	3.2	3.7	309
5	0.9	2.8	3.4	28	1.0	3.0	3.7	28
6	0.5	2.5	2.8	39	0.6	2.6	3.1	38
7	0.4	5.7	11.6	125	0.4	5.8	11.6	129
8	1.1	2.8	3.4	309	1.3	3.0	3.4	309

Note: Cases 1-4 are the 200 year return period; cases 5-8 are the 50 year return period

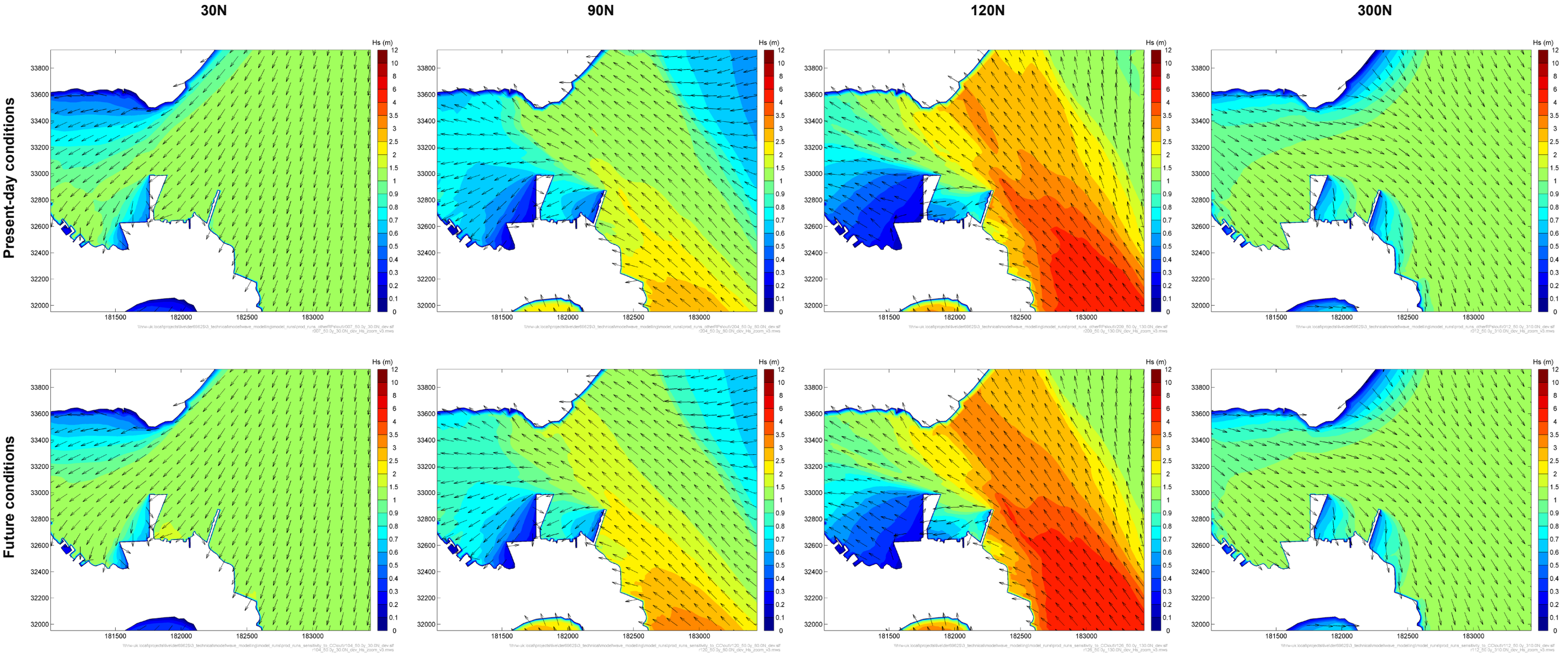


Figure 4.15: Significant wave height contours for present-day (top) and future (bottom) conditions, developed layout – 50 year conditions

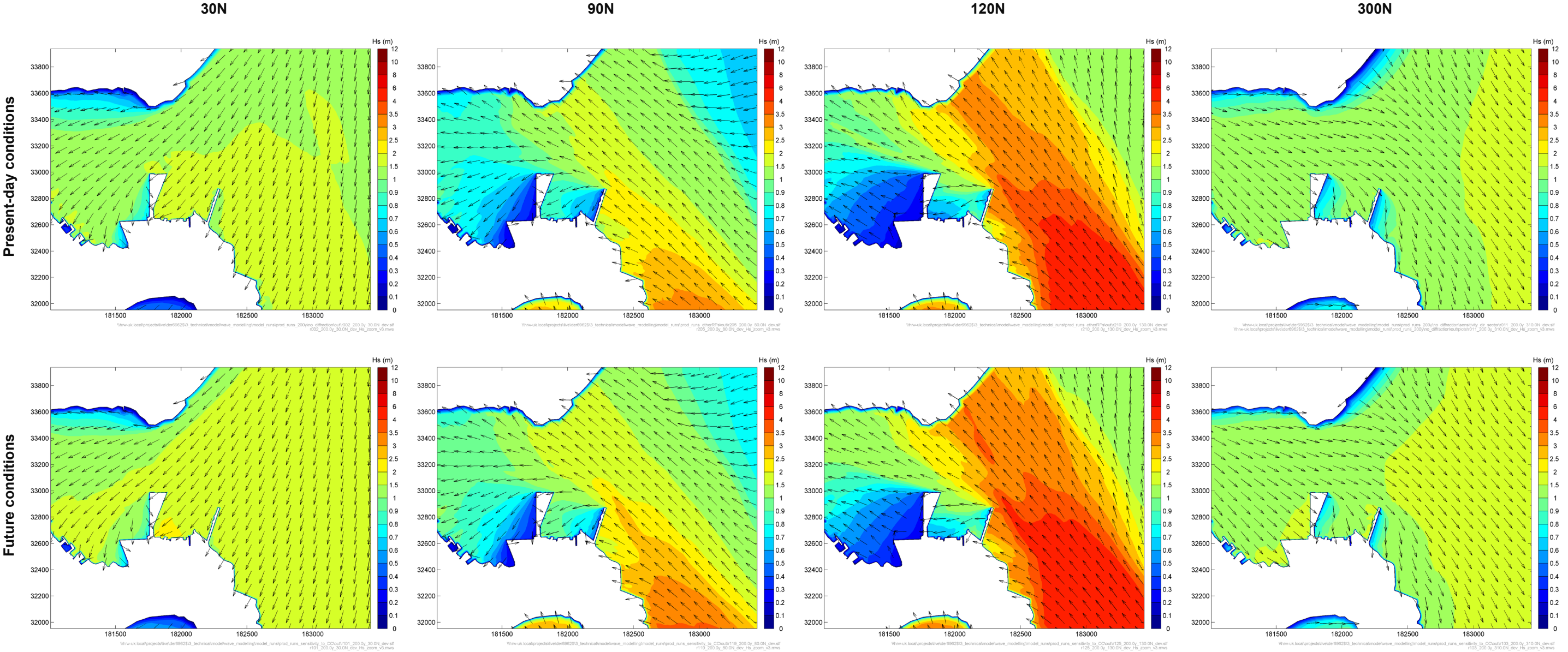


Figure 4.16: Significant wave height contours for present-day (top) and future (bottom) conditions, developed layout – 200 year conditions

4.4.2 Sensitivity to future extreme sea levels

The 50 and 200 year conditions were run with the corresponding 50 and 200 year extreme sea levels, for present-day and future conditions (including SLR and a 10% increase for storminess).

Extreme sea levels were extracted from the Environment Agency's Coastal Flood Boundary dataset which provides a consistent set of extreme sea levels around the coasts of England, Wales, Scotland and Northern Ireland (Ref. 10). The 50 and 200 extreme sea levels used in the study are summarised in Table 4.10.

Table 4.10: Estimated extreme sea levels

Return period (years)	Present-day sea level	Future sea level, including 50 year SLR
50	6.2	6.6
200	6.3	6.7

The wave conditions used for the sensitivity tests are summarised in Table 4.11.

Table 4.11: Wave conditions for sensitivity to extreme sea levels

	Case	Offshore sector (°N)	Return Period (years)	Wind speed (m/s)	H _s (m)	T _p (s)	Water level
Present-day conditions	9	30	200	28.1	–	–	6.3
	10	80	200	18.5	6.1	11.0	6.3
	11	130	200	18.1	5.9	12.2	6.3
	12	310.0	200	31.6	–	–	6.3
	13	30.0	50	22.0	–	–	6.2
	14	80	50	17.0	5.5	10.4	6.2
	15	130	50	16.4	5.2	11.5	6.2
	16	310.0	50	27.9	–	–	6.2
Future conditions	17	30.0	200	31.0	–	–	6.7
	18	80	200	20.4	6.7	11.5	6.7
	19	130	200	20.0	6.5	12.8	6.7
	20	310.0	200	34.8	–	–	6.7
	21	30.0	50	24.2	–	–	6.6
	22	80	50	18.7	6.1	11.0	6.6
	23	130	50	18.0	5.7	12.0	6.6
	24	310.0	50	30.7	–	–	6.6

Model results for the present-day conditions are presented in Figure 4.17 and Figure 4.18. Model results for the future conditions are presented in Figure 4.19 and Figure 4.20. For each condition, the model results for present-day MHWS case are also shown as reference.

Tabulated results at WP5 and WP21 are presented in Table 4.12 and Table 4.13. These show that:

- The predicted wave conditions with the extreme water levels at WP5 and WP21 are similar to the predicted waves at present-day MHWS.
- The predicted wave conditions for the future conditions with the extreme water levels (including sea level rise and increase in winds and waves due to storminess) show an increase in significant wave height of around 0.2 m for the 200 year and the 50 year conditions at WP5 and WP21 (similar to what is presented in Section 4.4.1).

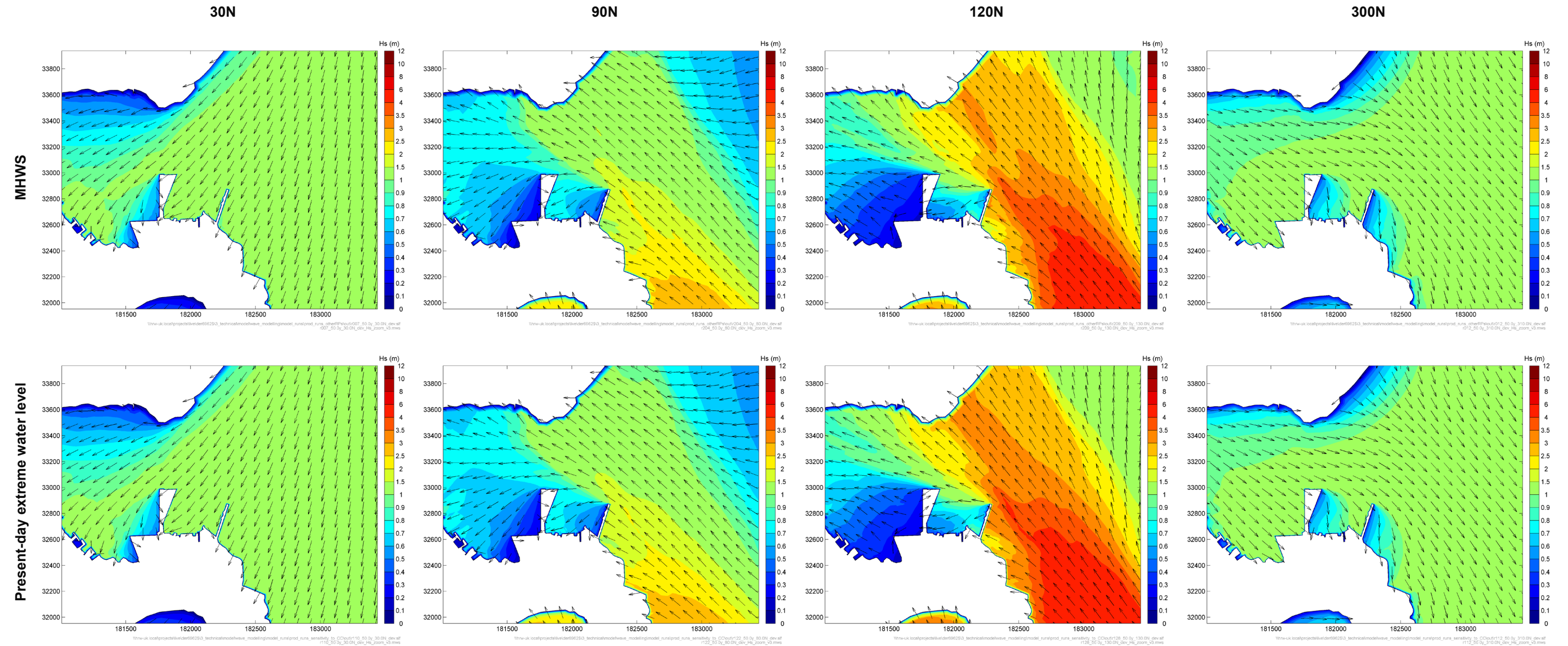


Figure 4.17: Significant wave height contours for present-day MHWS (top) and present-day extreme (bottom) water level conditions, developed layout - 50 year conditions

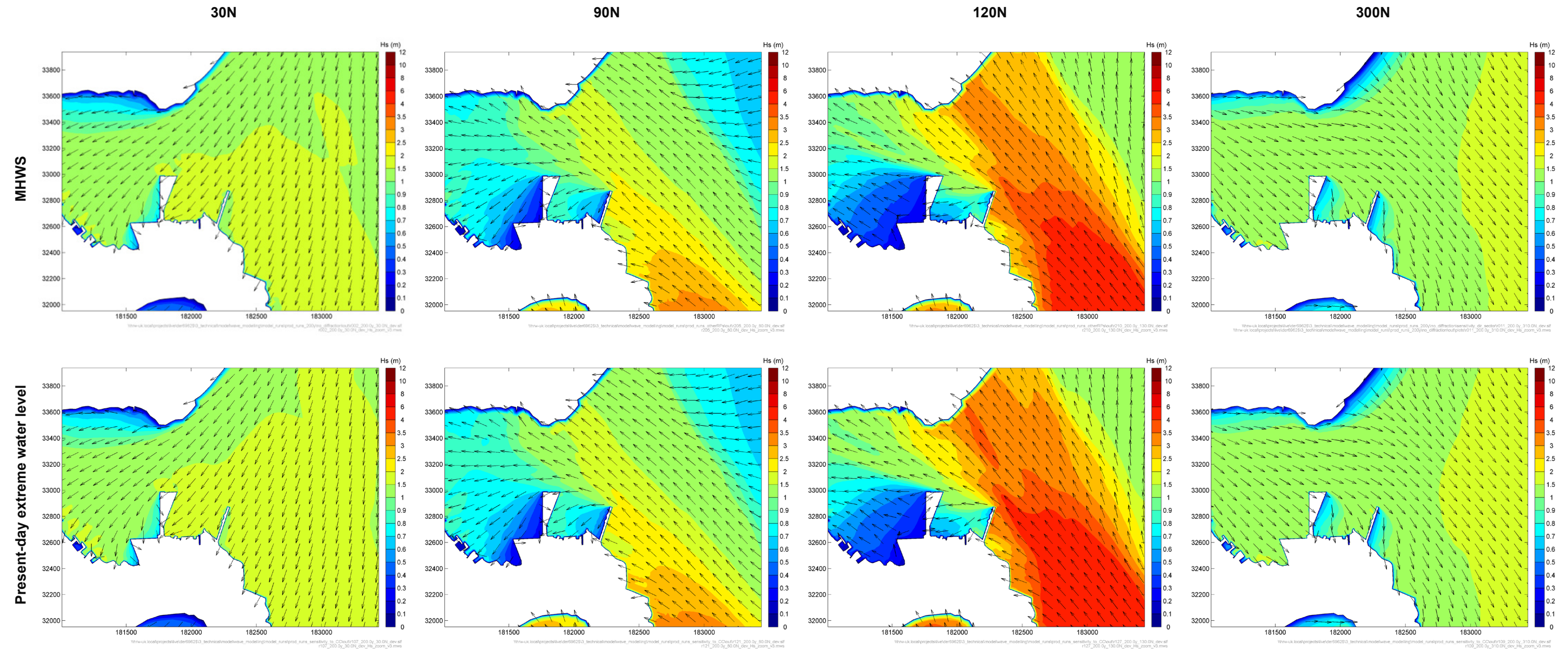


Figure 4.18: Significant wave height contours for present-day MHWS (top) and present-day extreme (bottom) water level present-day conditions, developed layout - 200 year conditions

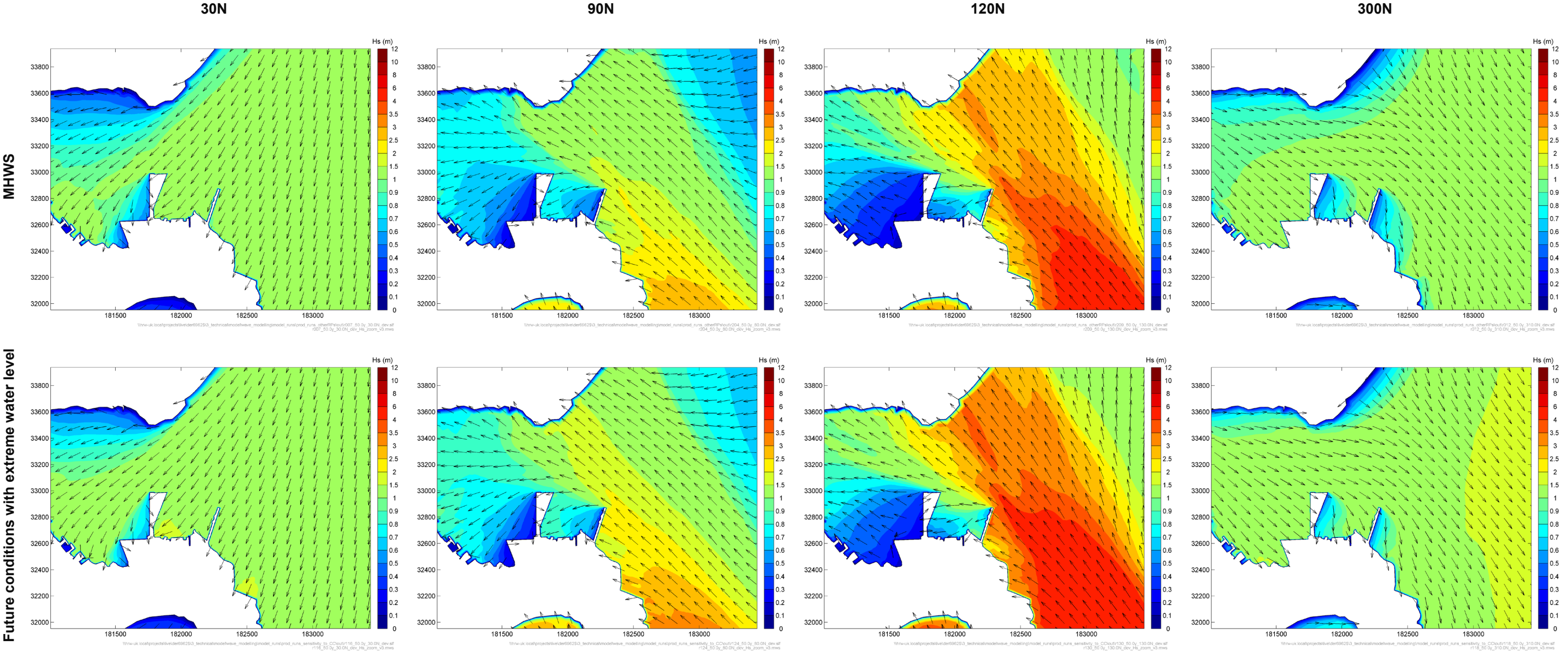


Figure 4.19: Significant wave height contours for present-day MHWS (top) and future conditions with extreme (bottom) water level, developed layout - 50 year conditions

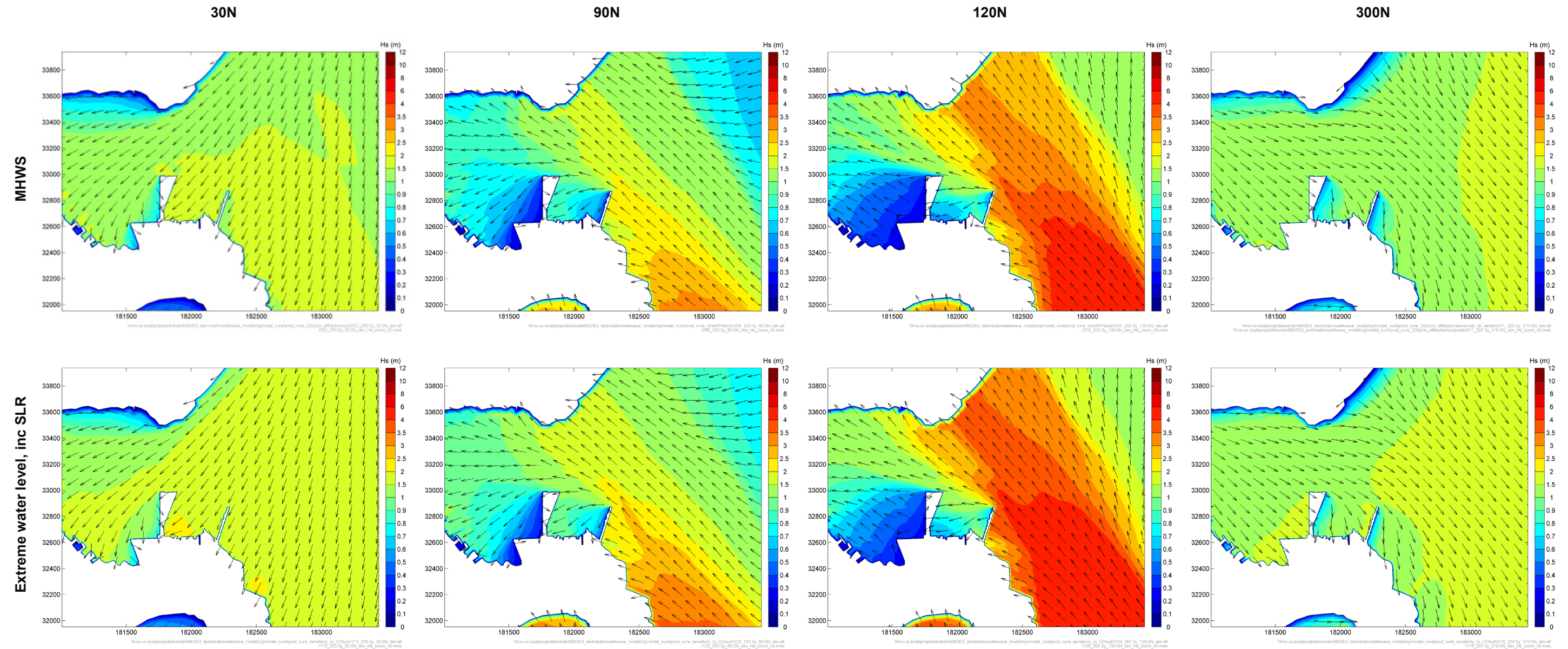


Figure 4.20: Significant wave height contours for present-day MHWS (top) and future conditions with extreme (bottom) water level, developed layout - 200 year conditions

Table 4.12: Present-day and future wave conditions, WP5, developed layout

RP	Sector	H _s (m)	Present-day MHWS			Present-day extreme sea level				Future conditions with extreme sea level			
			T _{m-1,0} (s)	T _p (s)	Mean wave direction (°N)	H _s (m)	T _{m-1,0} (s)	T _p (s)	Mean wave direction (°N)	H _s (m)	T _{m-1,0} (s)	T _p (s)	Mean wave direction (°N)
200	30	1.6	3.5	4.1	43	1.6	3.6	4.1	43	1.9	3.7	4.5	44
	90	0.8	4.1	3.1	61	0.8	3.7	3.1	61	0.9	3.9	3.1	60
	120	0.9	9.2	12.8	80	1.0	9.2	12.8	79	1.0	9.2	12.8	81
	300	0.8	2.5	3.4	350	0.8	2.5	3.4	351	0.9	2.7	3.7	353
50	30	1.2	3.1	3.7	43	1.2	3.1	3.7	43	1.4	3.3	3.7	43
	90	0.7	3.7	2.8	61	0.7	3.5	2.8	60	0.8	3.7	3.1	60
	120	0.9	8.9	11.6	79	0.9	8.8	11.6	78	0.9	8.9	11.6	79
	300	0.7	2.3	3.1	349	0.7	2.3	3.1	350	0.8	2.5	3.4	351

Table 4.13: Present-day and future wave conditions, WP21, developed layout

RP	Sector	H _s (m)	Present-day MHWS			Present-day extreme sea level				Future conditions with extreme sea level			
			T _{m-1,0} (s)	T _p (s)	Mean wave direction (°N)	H _s (m)	T _{m-1,0} (s)	T _p (s)	Mean wave direction (°N)	H _s (m)	T _{m-1,0} (s)	T _p (s)	Mean wave direction (°N)
200	30	1.2	3.2	4.1	29	1.3	3.2	4.1	29	1.4	3.4	4.1	29
	90	0.6	2.6	3.1	39	0.6	2.6	3.1	39	0.7	2.7	3.4	39
	120	0.4	5.6	12.8	132	0.4	6.4	12.8	127	0.5	6.4	12.8	131
	300	1.3	3.0	3.4	309	1.3	3.0	3.7	309	1.5	3.2	3.7	309
50	30	0.9	2.8	3.4	28	0.9	2.9	3.4	28	1.1	3.0	3.7	28
	90	0.5	2.5	2.8	39	0.5	2.5	2.8	38	0.6	2.6	3.1	39
	120	0.4	5.7	11.6	125	0.4	6.3	11.6	122	0.4	6.4	11.6	127
	300	1.1	2.8	3.4	309	1.1	2.9	3.4	309	1.3	3.0	3.4	309

5 Conclusions

A local area unstructured SWAN wave model was set up to represent both offshore wave propagation to the site and also local wind-wave generation in the estuary. The model was used to investigate the effect of the proposed development on wave conditions at the neighbouring berths and to provide extreme wave conditions in the Inner Harbour for design purposes. The modelling was carried out for a baseline case and for the proposed developed layout, incorporating the proposed development works and dredging.

For each layout, the model was run for present-day conditions representing four return periods, from 30° sectors, and for three water levels, MHWS, MSL and MLWS. Future conditions including sea level rise and a 10% increase in wind speeds and offshore waves due to climate change were also tested in the model. Sensitivity to more extreme water levels was also carried out in the model.

Winds from 30°N and 300°N give the highest wave conditions at the site. For the 200 year conditions, significant wave heights are predicted to be of the order of 2 m in front of the Western Wharf, up to 1.4 m along the Northern and Queen's Wharf, and up to 1.4 m along the new FLOW Deck on the west side of the docks. With the additional allowance for climate change (SLR and 10% increase due to storminess), the 200 year significant wave heights are predicted to be up to 2.2 m in front of the Western Wharf, up to 1.6 m along the Northern and Queen's Wharf, and up to 1.6 m along the new FLOW Deck on the west side of the docks.

Waves at the site are a combination of wind sea (short wave periods) and swell (long wave periods). Although not predicted to give the highest waves at the site, underlying swell conditions from offshore reach the site and should be considered if important for design.

Key aspects of the predicted effects of the proposed layout on wave conditions are summarised below:

- Differences in significant wave heights are localised in the area immediately around the proposed layout.
- Predicted conditions from 300°N will cause an increase in significant wave height of up to 0.3 m along the Northern Wharf for the 1 year conditions.
- Predicted conditions from 120°N will cause an increase in significant wave height of up to 0.35 m along the Northern Wharf for the 1 year conditions.
- Predicted conditions from 30°N will lead to an increase in significant wave height of up to 0.3 m along the New Western Wharf and in the corner of the existing Western Wharf.

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Appendices

A The SWAN wave transformation model

A.1 Introduction

SWAN is a computational spectral wave transformation model. It can be used to obtain realistic estimates of wave parameters in coastal areas, lakes and estuaries from given wind, seabed, and current conditions. The model has been developed by the Technical University of Delft (TU Delft).

SWAN is based on a fully spectral representation of the wave action balance equation (or energy balance in the absence of currents) with all physical processes modelled explicitly. No a priori limitations are imposed on the spectral evolution. This makes SWAN (Simulating WAVes Nearshore) a third-generation wave model.

The model has been used successfully at numerous sites around the UK and in other parts of the world. It is designed to represent the following wave propagation processes:

- refraction due to spatial variations in seabed and current;
- shoaling due to spatial variations in seabed and current;
- blocking and reflections by opposing currents;
- transmission through, blockage by or reflection from obstacles (such as coastlines or breakwaters).

The following wave generation and dissipation processes are also represented in SWAN:

- generation by wind;
- dissipation by whitecapping;
- dissipation by depth-induced wave breaking;
- dissipation by seabed friction;
- wave-wave interactions (quadruplets and triads);
- obstacles.

The SWAN wave model has been conceived to be a computationally feasible third-generation spectral wave model for waves in shallow water (including the surf zone) with ambient currents.

A.2 The SWAN wave model

The SWAN model represents the waves in terms of the two-dimensional wave action density spectrum $N(\sigma, \vartheta)$, even when nonlinear phenomena dominate (e.g., in the surf zone). The independent variables are the relative frequency σ (as observed in a frame of reference moving with the action propagation velocity) and the wave direction ϑ (the direction normal to the wave crest of each spectral component). The action density is equal to the energy density divided by the relative frequency: $N(\sigma, \vartheta) = E(\sigma, \vartheta) / \sigma$.

In SWAN, the two-dimensional wave action density spectrum may vary in time and space. Its evolution is described by the spectral action balance equation, which for Cartesian coordinates is (e.g. Hasselmann et al., 1973):

$$\frac{\partial}{\partial t} N + \frac{\partial}{\partial x} C_x N + \frac{\partial}{\partial y} C_y N + \frac{\partial}{\partial \sigma} C_\sigma N + \frac{\partial}{\partial \vartheta} C_\vartheta N = \frac{S(\sigma, \vartheta)}{\sigma} \quad (1)$$

The first term in the left-hand side represents the local rate of change of action density in time. The second and third term represent propagation of action in geographical x and y space (with propagation velocities C_x and C_y respectively). The fourth term represents shifting of the relative frequency due to variations in depths and currents in time (with propagation velocity C_σ in σ space). The fifth term represents propagation of action in ϑ space (depth-induced and current-induced refraction) with propagation velocity C_ϑ . The expressions for these propagation speeds are taken from linear wave theory. The term $S(\sigma, \vartheta)$ at the right hand side of the action balance equation is the source term representing the effects of generation, dissipation and non-linear wave-wave interactions.

The formulations for the generation, the dissipation and the quadruplet wave-wave interactions are taken from the WAM model (WAM Cycle3, WAMDI group, 1988, and optionally WAM Cycle4, Komen et al., 1994). These are supplemented with a spectral version of the dissipation model for depth-induced breaking of Battjes and Janssen (1978) and a more recently formulated discrete interaction approximation for the triad wave-wave interactions (Eldeberky and Battjes, 1995).

A.2.1 Transfer of wind energy to the waves

The transfer of wind energy to the waves is described in SWAN with a resonance mechanism (Phillips, 1957) and a feed-back mechanism (Miles, 1957). The corresponding source term for these mechanisms is commonly described as the sum of linear and exponential growth:

$$S_m(\sigma, \vartheta) = A + B \times E(\sigma, \vartheta) \quad (2)$$

in which A and B depend on wave frequency and direction, and wind speed and direction. The effects of currents are accounted for in SWAN by using the apparent local wind speed and direction. The expression for the term A is due to Cavaleri and Malanotte-Rizzoli (1981, revised by Tolman, 1992). Two optional expressions for the coefficient B are used in the model. The first is due to Snyder et al. (1981), re-scaled in terms of friction velocity by Komen et al. (1984). The second expression is due to Janssen (1991) and accounts explicitly for the interaction between the wind and the waves by considering atmospheric boundary layer effects and the roughness length of the sea surface.

A.2.2 Whitecapping

Whitecapping is primarily controlled by the steepness of the waves. In presently operating third-generation wave models (including SWAN) the whitecapping formulations are based on a pulse-based model (Hasselmann, 1974), as adapted by the WAMDI group (1988):

$$S_{ds,w}(\sigma, \vartheta) = -\Gamma \frac{\tilde{\sigma} \tilde{k}}{k} E(\sigma, \vartheta) \quad (3)$$

where Γ is a steepness dependent coefficient, k is wave number and $\tilde{\sigma}$ and $\tilde{k}$ denote a mean frequency and a mean wave number, respectively (cf. the WAMDI group, 1988). The value of Γ depends on the wind input formulation that is used. Since two expressions are used for the wind input in SWAN, two values for Γ are used. The first is due to Komen et al. (1984), and is used in SWAN when the wind input coefficient of Komen et al. (1984) is used. The second expression is an adaptation of this expression based on Janssen (1991). It is used when the wind input term of Janssen (1991) is used.

A.2.3 Depth-induced dissipation

Depth induced-dissipation may be caused by seabed friction, by seabed motion, by percolation or by back-scattering on seabed irregularities. For continental shelf seas with sandy seabeds, the dominant mechanism appears to be seabed friction, which can generally be represented as:

$$S_{ds,b}(\sigma, \vartheta) = -c_{bed} \frac{\sigma^2}{g^2 \sinh^2(kd)} E(\sigma, \vartheta) \quad (4)$$

in which c_{bed} is a seabed friction coefficient. A large number of models has been proposed. Hasselmann et al., (JONSWAP, 1973) suggested use of an empirically obtained constant. This seems to perform well in many different conditions as long as a suitable value is chosen (typically different for swell and wind sea; Bouws and Komen, 1983). A nonlinear formulation based on drag has been proposed by Hasselmann and Collins (1968), which was later simplified by Collins (1972), and is also implemented in SWAN. More complicated, eddy viscosity models have been developed by Madsen et al., (1988). The effect of a mean current on the wave energy dissipation due to seabed friction is not taken into account in SWAN.

A.2.4 Depth-induced wave breaking

Although the process of depth-induced wave breaking is still poorly understood and little is known about its spectral modelling, the total dissipation (i.e. integrated over the spectrum) can be well modelled with the dissipation of a bore applied to the breaking waves in a random field. And laboratory observations show that the shape of initially uni-modal spectra propagating across simple (barred) beach profiles is fairly insensitive to depth-induced breaking. This has led Eldeberky and Battjes (1995) to formulate a spectral version of the bore model of Battjes and Janssen (1978) which conserves the spectral shape. Their expression has been expanded in the SWAN model to include direction:

$$S_{ds,br}(\sigma, \vartheta) = \frac{D_{tot}}{E_{tot}} E(\sigma, \vartheta) \quad (5)$$

in which E_{tot} is the total wave energy and D_{tot} (which is negative) is the rate of dissipation of the total energy due to wave breaking according to Battjes and Janssen (1978). The value of D_{tot} depends critically on the breaking parameter $\gamma = H_{max}/d$ (in which H_{max} is the maximum possible individual wave height in the local water depth d). In SWAN γ has a constant value (default is 0.73 corresponding to the mean value of the data set of Battjes and Stive, 1985).

A.2.5 Wave transmission

SWAN can estimate wave transmission through a structure such as a breakwater. Since obstacles usually have a plan area that is too small to be resolved by the bathymetric grid, in SWAN, an obstacle is modelled as a line. The transmission coefficient is defined as the ratio of the (significant) wave height at the downwave side of the breakwater over the (significant) wave height at the upwave side. If the crest of the breakwater is such that waves can pass over, the transmission coefficient is taken from Goda et al. (1967) and is expressed as a function of wave height and freeboard (difference in crest level and water level).

Note that a change in wave frequency is to be expected as well as a change in wave height, since often the process above the breakwater is highly non-linear. But given the little information available, SWAN assumes that the frequencies remain unchanged over an obstacle (only the energy scale of the spectrum is affected and not the spectral shape).

A.2.6 Nonlinear wave-wave interactions

In deep water, quadruplet wave-wave interactions dominate the evolution of the spectrum. They transfer wave energy from the spectral peak to lower frequencies (thus moving the peak frequency to lower values) and to higher frequencies (where the energy is dissipated by whitecapping). In very shallow water, triad wave-wave interactions transfer energy from lower frequencies to higher frequencies often resulting in higher harmonics (Beji and Battjes, 1993; low-frequency energy generation by triad wave-wave interactions is not considered here).

A full computation of the quadruplet wave-wave interactions is extremely time consuming and not convenient in any operational wave model. A number of techniques, based on parametric methods or other types of approximations have been proposed to improve computational speed. In SWAN, the computations are carried out with the Discrete Interaction Approximation (DIA) of Hasselmann et al. (1985). Eldeberky and Battjes (1995) introduced a discrete triad approximation (DTA) for co-linear waves, obtained by considering only the dominant self-self triad interactions. Their model has been verified with flume observations of long-crested, random waves breaking over a submerged bar (Beji and Battjes, 1993) and over a barred beach (Arcilla et al., 1994). A slightly different version, the Lumped Triad Approximation (LTA) was later derived by Eldeberky (1996) and is used in SWAN.

Cycle III of SWAN is stationary and optionally non-stationary, formulated in Cartesian (recommended only for small scales) or spherical (small scales and large scales) coordinates. The stationary mode should be used only for waves with a relatively short residence time in the computational area under consideration (i.e. small travel time of the waves through the region compared to the time scale of the geophysical conditions: wave boundary conditions, wind, tides and storm surge). A quasi-stationary approach can be taken with stationary SWAN computations in a time-varying sequence of stationary conditions.

The current version of SWAN can be used on any scale relevant for wind generated surface gravity waves, as the model now uses more accurate numerical propagation schemes and can compute on spherical co-ordinates (longitude, latitude), allowing calculations in laboratory situations, coastal regions, shelf seas and oceans. However, SWAN is specifically developed for coastal applications, which would usually not require such flexibility in scale. And it must be emphasized that on oceanic scales SWAN is certainly less efficient on oceanic scales than WAVEWATCH III and probably also less efficient than WAM.

Fully implicit numerical schemes are used in the SWAN model for propagation in both geographic and spectral spaces (an iterative, forward-marching, four-sweep technique due to Ris et al., 1994). This scheme is unconditionally stable in contrast with the explicit schemes of conventional spectral wave models.

A.3 Typical results

- Colour contour plots of significant wave height, H_s , and vector plots of mean wave direction over the model area.
- Tables of H_s , T_z , T_p and mean direction at a selection of inshore locations. For example, the model can be used to investigate which offshore wave conditions lead to the worst inshore wave heights at a particular site.
- SWAN also calculates fields of wave-induced forces per unit surface area, wave orbital velocities, and a variety of other parameters. Such results can be used directly as input into a sediment transport model.
- 2D (frequency and direction) spectrum at a selection of inshore location. Information of this type would normally be required as input to a numerical harbour model or a mathematical model of beach processes. In addition this information would also be needed at the wave paddle positions in a physical model in order to generate the correct random wave sequence for design studies.

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B Contour plots – 200 year conditions (developed layout)

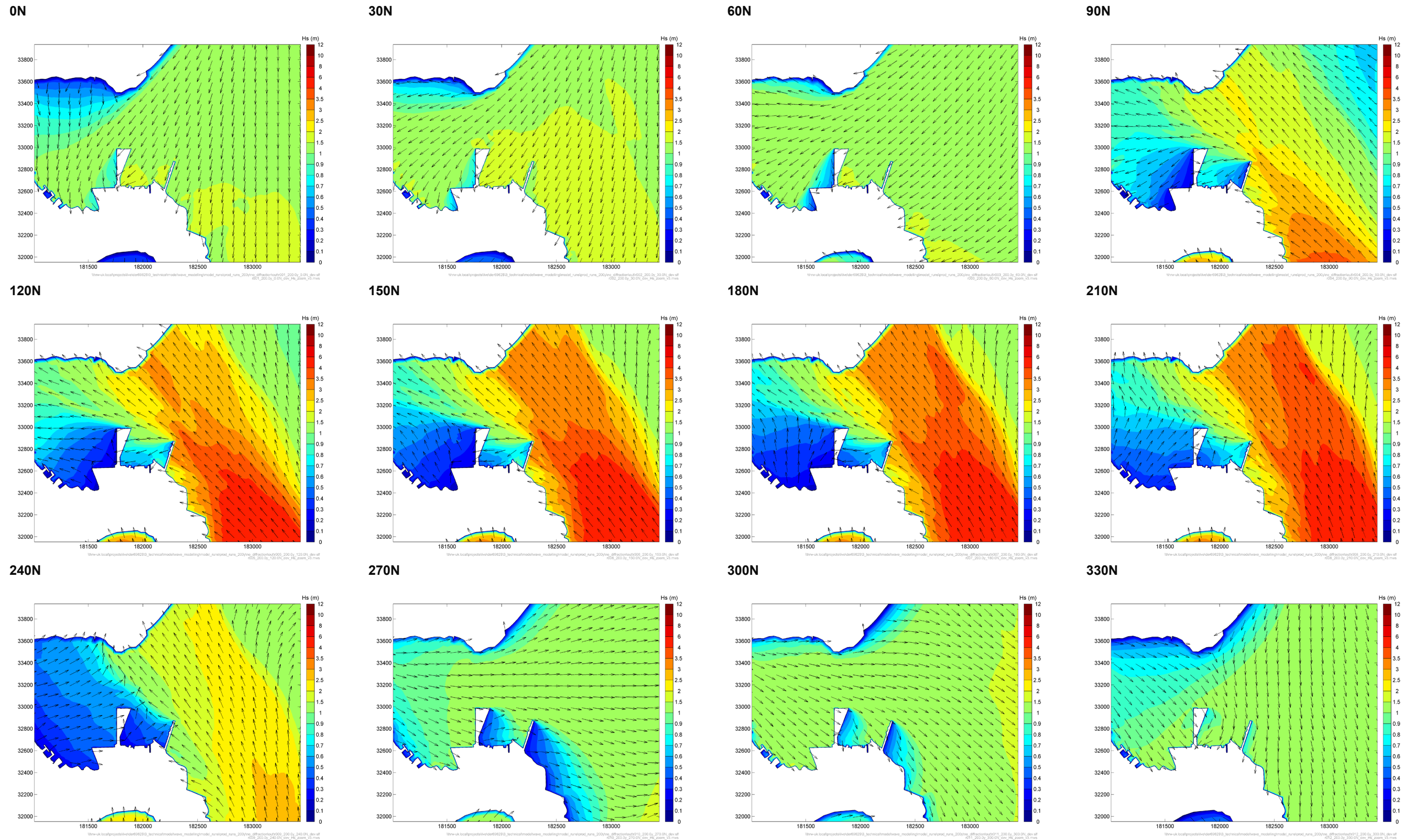
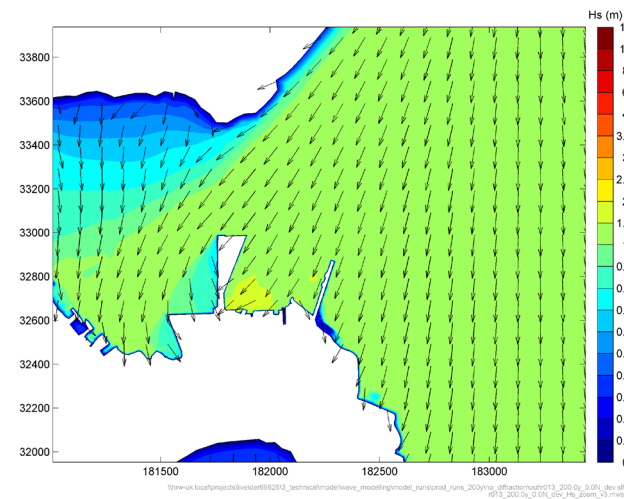
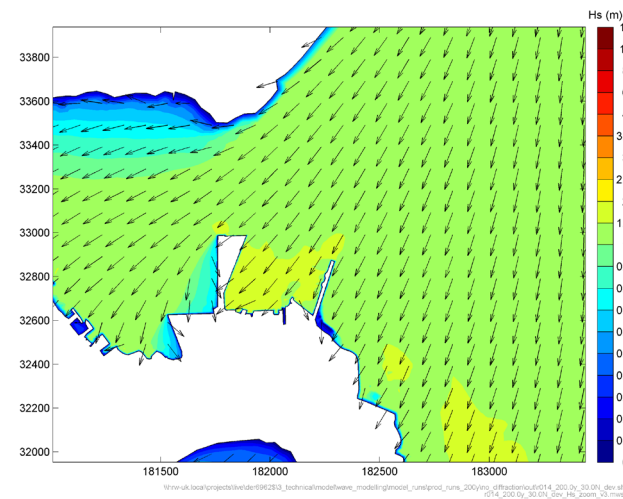


Figure B.1: Significant wave height contours, 200 year conditions, developed layout, MHWS

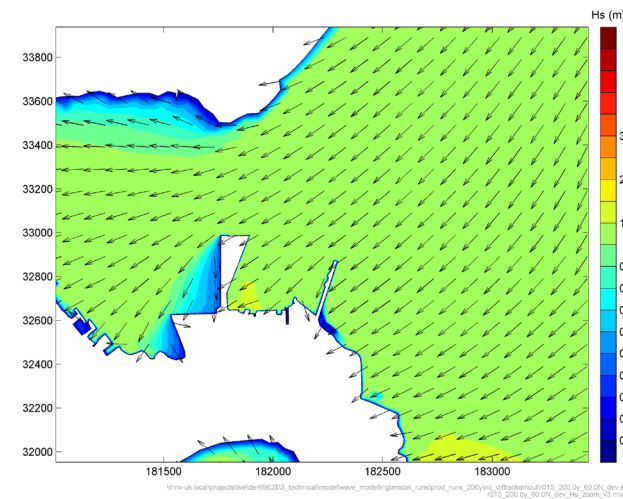
0N



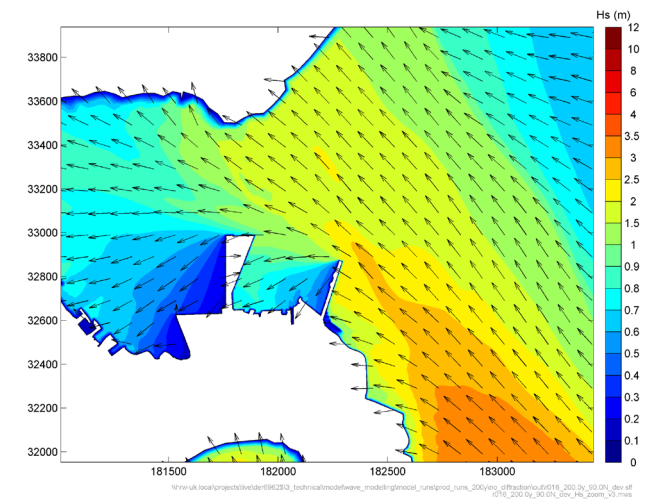
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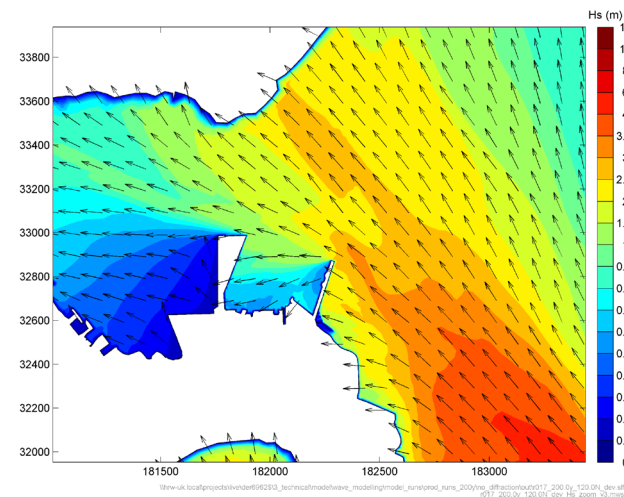
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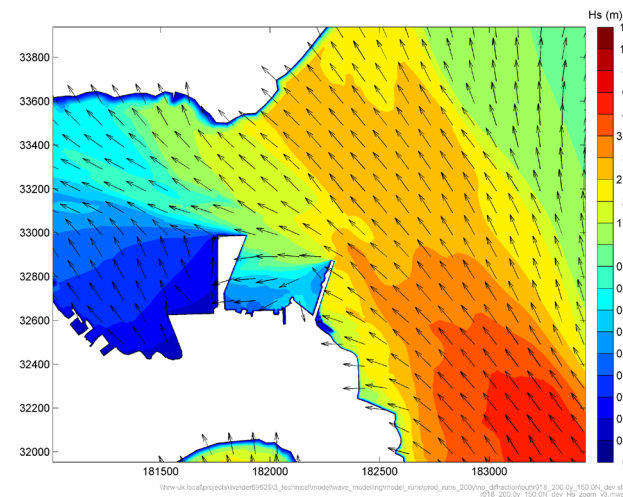
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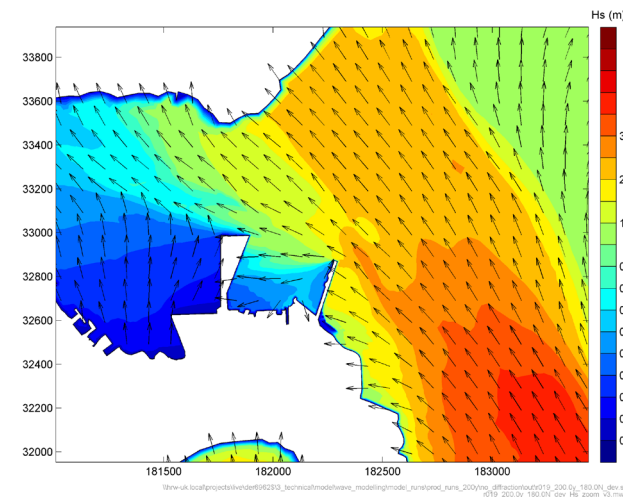
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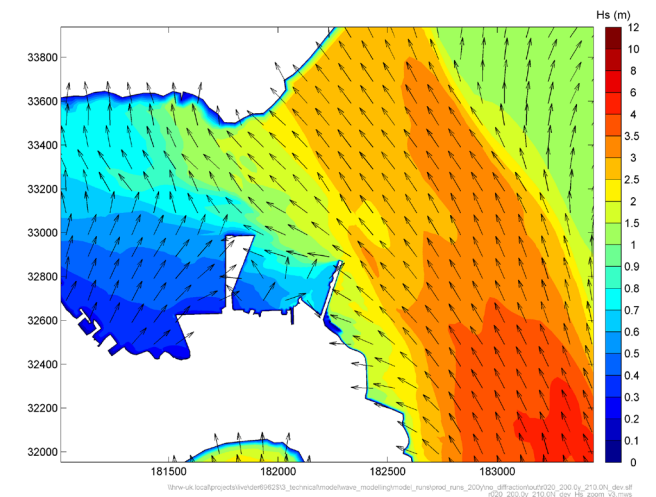
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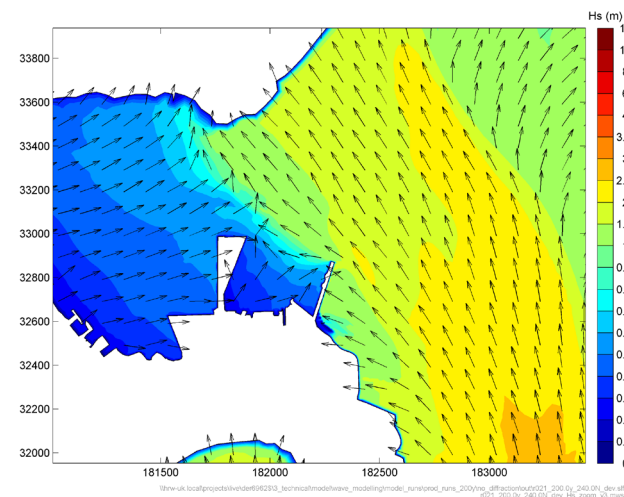
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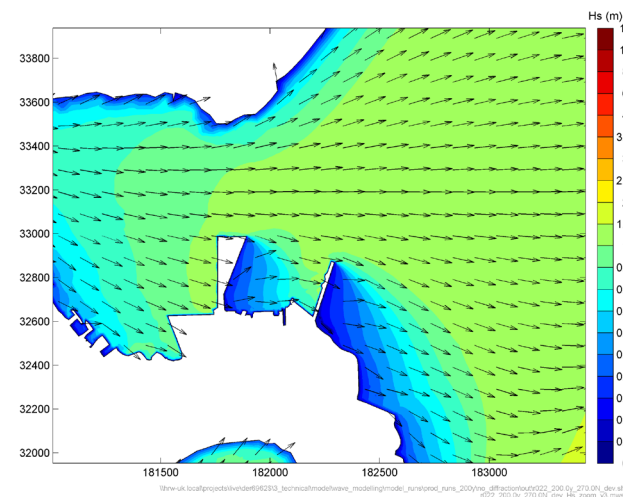
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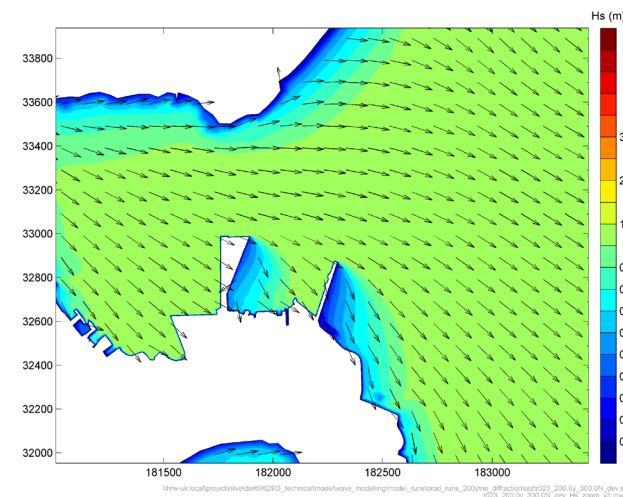
240N



270N



300N



330N

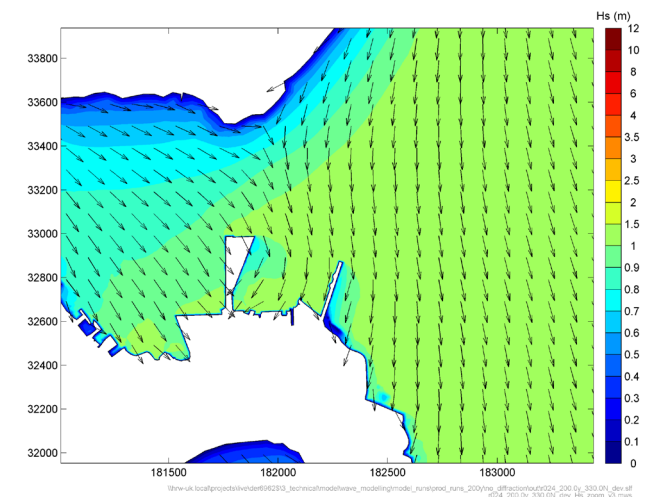
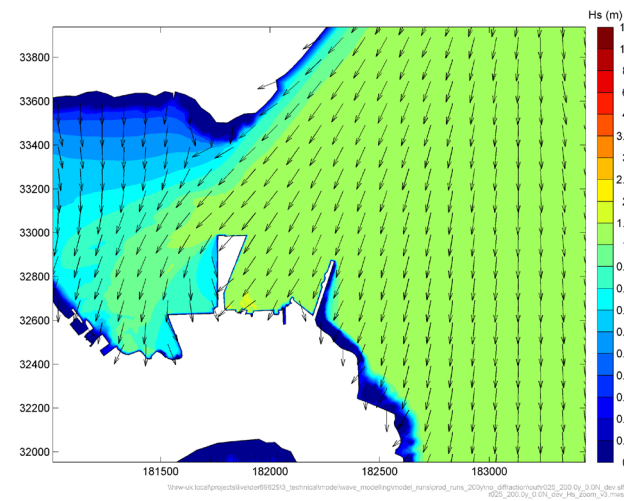
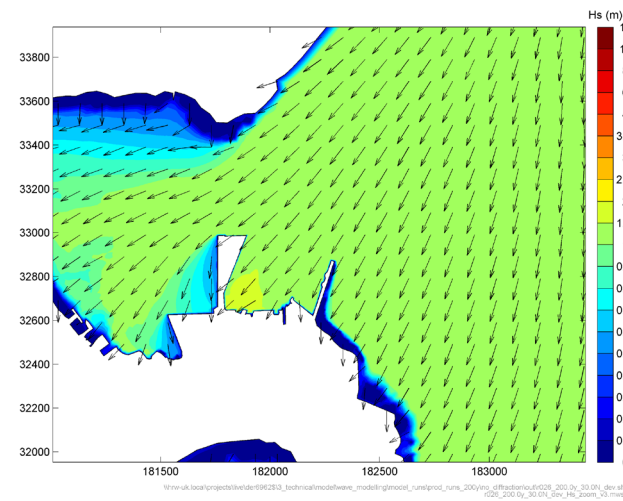


Figure B.2: Significant wave height contours, 200 year conditions, developed layout, MSL

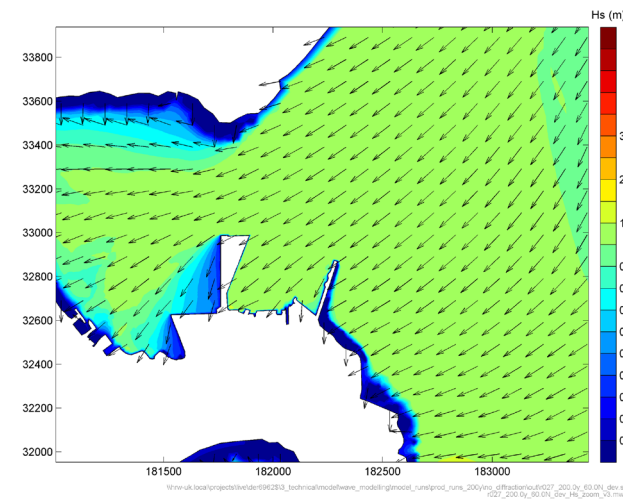
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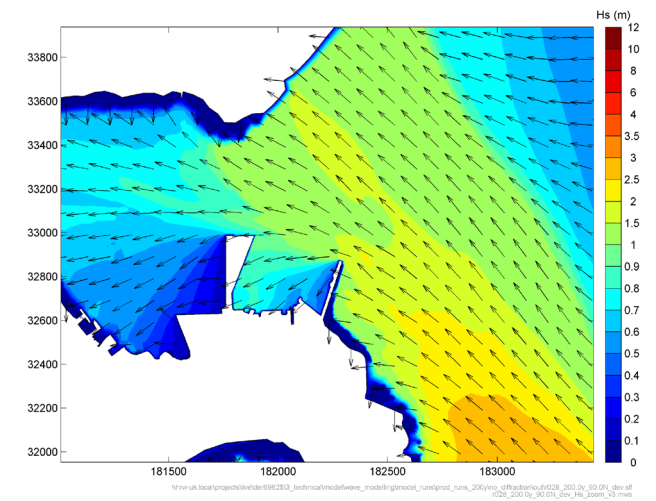
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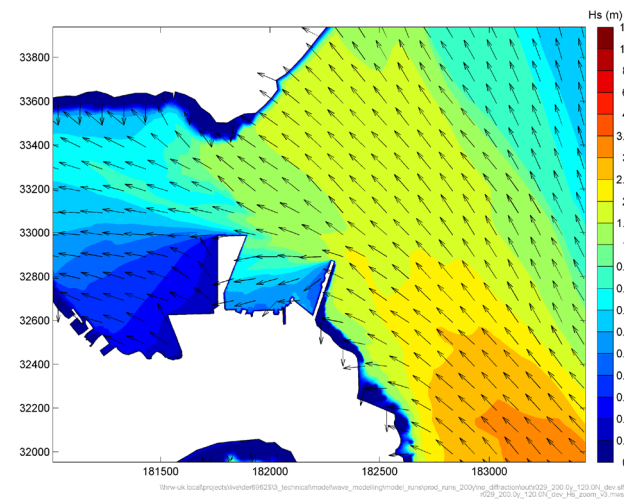
60N



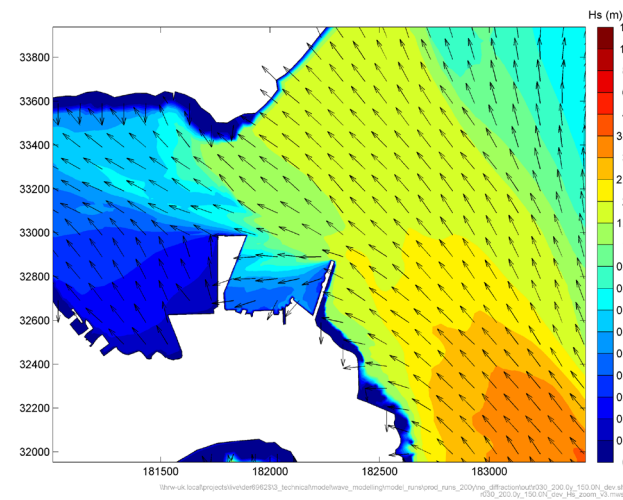
90N



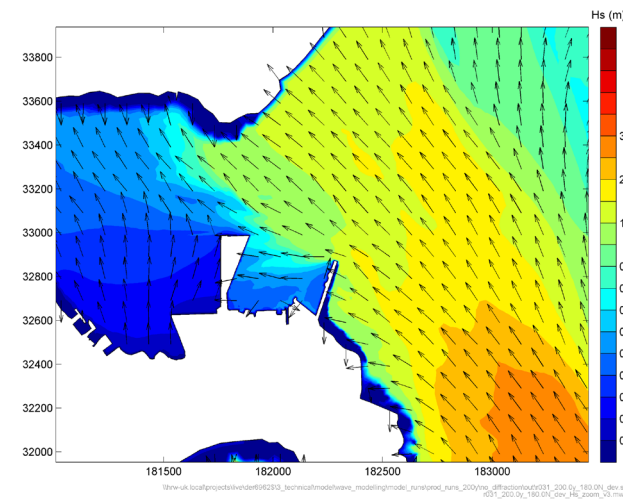
120N



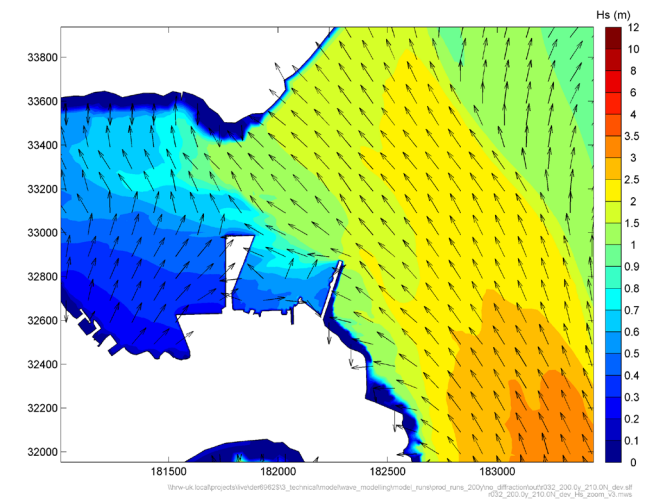
150N



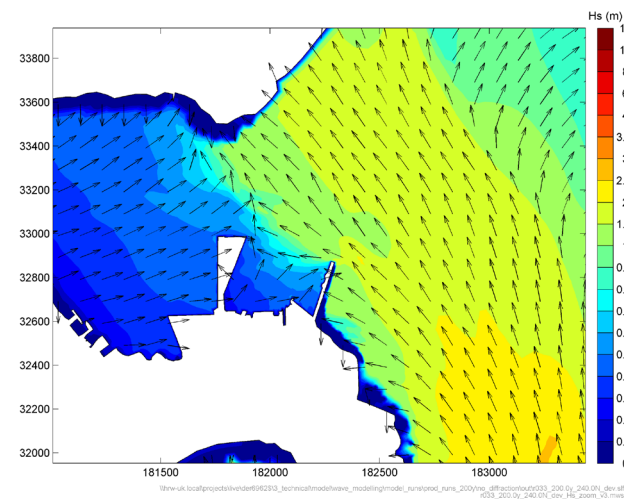
180N



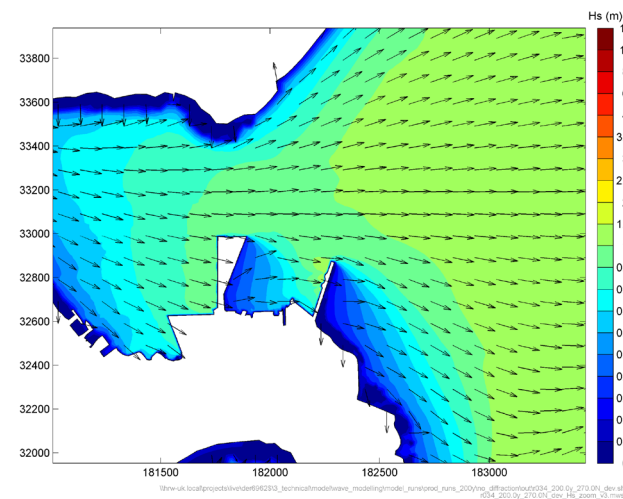
210N



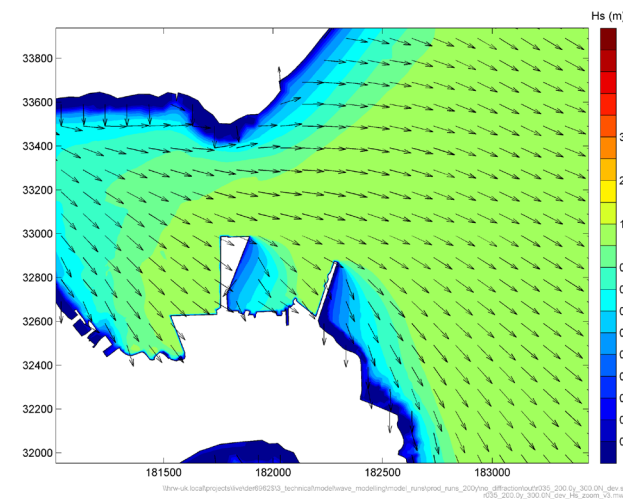
240N



270N



300N



330N

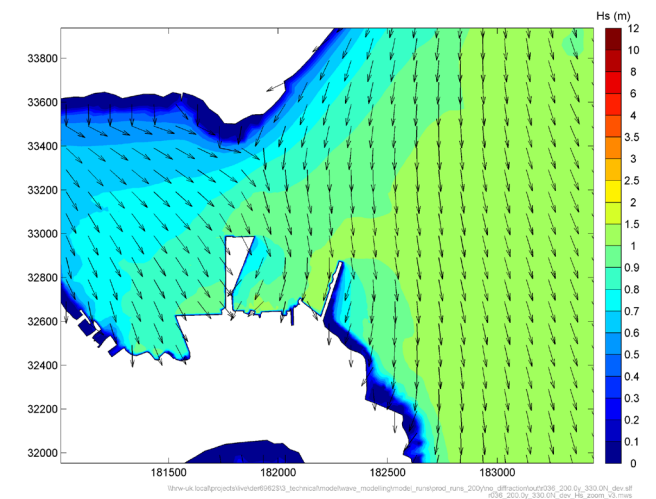


Figure B.3: Significant wave height contours, 200 year conditions, developed layout, MLWS

C Tabulated results – 200 year conditions (developed layout)

Table C.1: 200 year conditions, WP1 – developed layout

Water level	Sector	Hs (m)	Tm-1,0 (s)	Tp (s)	Mean direction (°N)
MHWS	0	1.5	3.6	4.1	77.0
	30	1.7	3.7	4.5	76.6
	60	1.4	3.3	4.1	77.2
	90	0.8	2.8	3.1	79.2
	120	0.5	7.5	12.8	86.9
	150	0.4	9.5	12.8	87.9
	180	0.3	11.5	14.1	87.6
	210	0.3	13.4	17.0	86.9
	240	0.1	9.7	18.7	87.9
	270	0.2	2.5	2.5	92.9
	300	0.6	2.6	2.8	79.2
	330	1.0	3.1	3.7	76.7
MSL	0	1.4	3.5	4.1	76.7
	30	1.6	3.6	4.1	76.4
	60	1.4	3.3	3.7	77.0
	90	0.7	3.4	2.8	80.6
	120	0.5	6.5	12.8	84.9
	150	0.4	9.6	12.8	87.0
	180	0.3	11.7	14.1	86.3
	210	0.3	13.6	17.0	86.0
	240	0.2	10.8	18.7	86.5
	270	0.2	2.4	2.3	93.3
	300	0.4	2.5	3.1	85.2
	330	1.0	3.1	3.7	76.4
MLWS	0	1.3	3.3	3.7	75.9
	30	1.5	3.4	4.1	75.7
	60	1.3	3.2	3.7	76.9
	90	0.7	3.7	2.8	80.8
	120	0.5	6.1	12.8	84.6
	150	0.4	9.5	12.8	86.4
	180	0.3	11.4	14.1	85.6
	210	0.3	13.4	17.0	84.9
	240	0.2	12.4	18.7	85.3
	270	0.1	2.3	2.3	94.0
	300	0.4	2.4	2.8	84.2
	330	0.8	2.8	3.4	75.0

Table C.2: 200 year conditions, WP2 – developed layout

Water level	Sector	Hs (m)	Tm-1,0 (s)	Tp (s)	Mean direction (°N)
MHWS	0	1.3	3.7	4.1	72.2
	30	1.5	3.7	4.1	72.0
	60	1.3	3.3	4.1	73.8
	90	0.7	2.9	3.1	77.9
	120	0.5	6.8	12.8	92.8
	150	0.4	8.8	12.8	92.4
	180	0.3	10.2	14.1	96.8
	210	0.3	12.1	17.0	96.8
	240	0.2	7.9	18.7	94.7
	270	0.2	2.5	2.5	101.4
	300	0.5	2.9	3.1	83.6
	330	0.8	3.1	3.7	61.9
MSL	0	1.3	3.6	4.1	71.6
	30	1.4	3.6	4.1	71.7
	60	1.3	3.3	3.7	73.3
	90	0.7	3.5	2.8	81.4
	120	0.6	6.1	12.8	88.7
	150	0.4	8.9	12.8	88.4
	180	0.4	10.4	14.1	92.0
	210	0.3	12.2	17.0	93.0
	240	0.2	9.2	18.7	91.1
	270	0.2	2.5	2.5	102.3
	300	0.4	2.8	3.1	97.1
	330	0.8	3.1	3.7	62.5
MLWS	0	1.1	3.3	3.7	69.2
	30	1.3	3.4	4.1	69.1
	60	1.2	3.2	3.7	72.6
	90	0.7	3.8	2.8	80.6
	120	0.5	5.8	12.8	86.3
	150	0.4	8.6	12.8	86.1
	180	0.4	10.3	14.1	86.6
	210	0.3	12.2	17.0	84.9
	240	0.2	11.0	18.7	86.3
	270	0.2	2.4	2.5	103.9
	300	0.4	2.7	3.1	97.0
	330	0.7	2.8	3.1	60.9

Table C.3: 200 year conditions, WP3 – developed layout – developed layout

Water level	Sector	Hs (m)	Tm-1,0 (s)	Tp (s)	Mean direction (°N)
MHWS	0	1.3	3.6	4.1	63.9
	30	1.5	3.6	4.1	64.7
	60	1.3	3.3	3.7	72.4
	90	0.8	3.7	3.1	77.9
	120	0.8	8.8	12.8	91.8
	150	0.7	10.0	12.8	91.9
	180	0.6	11.1	14.1	92.8
	210	0.6	12.0	17.0	101.4
	240	0.3	7.3	18.7	129.0
	270	0.3	2.5	2.5	121.1
	300	0.5	3.0	3.4	93.6
	330	0.8	3.1	3.4	53.0
MSL	0	1.2	3.4	4.1	61.2
	30	1.4	3.5	4.1	64.1
	60	1.3	3.3	3.7	71.6
	90	0.8	5.1	11.6	80.4
	120	0.8	8.4	12.8	88.0
	150	0.7	10.0	12.8	88.6
	180	0.6	10.9	14.1	91.4
	210	0.6	11.8	17.0	99.0
	240	0.3	8.8	18.7	116.8
	270	0.2	2.4	2.5	120.6
	300	0.4	2.9	3.1	105.9
	330	0.8	3.1	3.7	54.0
MLWS	0	1.0	3.2	3.7	59.4
	30	1.3	3.4	4.1	62.0
	60	1.2	3.2	3.7	69.8
	90	0.8	5.2	11.6	79.1
	120	0.7	7.5	12.8	86.6
	150	0.6	9.3	12.8	87.0
	180	0.5	9.9	14.1	92.1
	210	0.5	11.4	17.0	94.2
	240	0.3	10.3	18.7	106.1
	270	0.2	2.3	2.5	125.0
	300	0.3	2.8	3.1	106.5
	330	0.6	2.8	3.1	52.6

Table C.4: 200 year conditions, WP4 – developed layout

Water level	Sector	Hs (m)	Tm-1,0 (s)	Tp (s)	Mean direction (°N)
MHWS	0	1.2	3.6	4.1	49.2
	30	1.4	3.6	4.1	54.3
	60	1.3	3.3	3.7	64.4
	90	0.9	4.9	11.6	79.2
	120	1.1	9.8	12.8	101.4
	150	1.1	10.7	12.8	102.1
	180	1.0	11.7	14.1	102.4
	210	0.8	12.8	17.0	107.2
	240	0.4	9.4	18.7	129.3
	270	0.3	2.5	3.1	137.7
	300	0.4	3.1	3.4	87.5
	330	0.7	3.2	3.7	42.7
MSL	0	1.1	3.4	4.1	51.3
	30	1.3	3.5	4.1	55.4
	60	1.3	3.2	3.7	64.7
	90	1.0	6.6	11.6	87.6
	120	1.1	9.4	12.8	98.3
	150	1.0	10.5	12.8	100.2
	180	1.0	11.5	14.1	101.2
	210	0.8	12.3	17.0	106.7
	240	0.4	10.8	18.7	120.3
	270	0.3	2.5	3.1	134.1
	300	0.3	3.1	3.4	115.4
	330	0.7	3.2	3.7	43.4
MLWS	0	1.0	3.2	3.7	51.9
	30	1.2	3.3	3.7	55.5
	60	1.2	3.1	3.7	65.7
	90	0.9	6.1	11.6	85.9
	120	0.9	8.1	12.8	96.3
	150	0.8	9.4	12.8	98.9
	180	0.7	10.2	14.1	102.6
	210	0.7	11.5	17.0	105.1
	240	0.5	11.8	18.7	111.9
	270	0.3	2.4	2.8	139.8
	300	0.3	3.0	3.1	116.4
	330	0.6	3.0	3.4	45.9

Table C.5: 200 year conditions, WP5 – developed layout

Water level	Sector	Hs (m)	Tm-1,0 (s)	Tp (s)	Mean direction (°N)
MHWS	0	1.4	3.4	4.1	36.9
	30	1.6	3.5	4.1	42.8
	60	1.4	3.3	3.7	55.1
	90	0.8	4.1	3.1	61.0
	120	0.9	9.2	12.8	80.1
	150	0.9	10.2	12.8	80.4
	180	0.8	11.1	14.1	83.6
	210	0.8	11.1	17.0	105.0
	240	0.4	5.9	18.7	193.0
	270	0.5	2.0	1.9	252.1
	300	0.8	2.5	3.4	349.7
	330	0.9	2.9	3.7	22.6
MSL	0	1.4	3.3	4.1	35.9
	30	1.6	3.5	4.1	42.8
	60	1.4	3.2	3.7	55.4
	90	0.9	5.6	11.6	66.3
	120	0.9	8.6	12.8	78.1
	150	0.9	10.0	12.8	80.7
	180	0.8	10.8	14.1	84.9
	210	0.7	10.6	17.0	109.2
	240	0.4	6.9	18.7	180.0
	270	0.5	1.9	1.9	254.6
	300	0.7	2.2	3.1	332.6
	330	0.9	2.8	3.7	22.9
MLWS	0	1.2	3.1	3.7	33.4
	30	1.4	3.3	3.7	41.4
	60	1.3	3.1	3.7	54.5
	90	0.8	5.2	11.6	65.2
	120	0.8	7.3	12.8	77.3
	150	0.7	8.9	12.8	83.0
	180	0.6	9.4	14.1	91.3
	210	0.6	9.9	17.0	105.9
	240	0.5	8.0	18.7	163.5
	270	0.5	1.8	1.9	255.2
	300	0.6	2.1	2.3	328.9
	330	0.8	2.7	3.4	20.1

Table C.6: 200 year conditions, WP6 – developed layout

Water level	Sector	Hs (m)	Tm-1,0 (s)	Tp (s)	Mean direction (°N)
MHWS	0	1.8	3.6	4.1	73.3
	30	1.9	3.7	4.1	69.1
	60	1.6	3.4	4.1	76.4
	90	0.9	3.0	3.1	81.2
	120	0.6	7.8	12.8	75.7
	150	0.6	9.5	12.8	69.6
	180	0.5	10.0	14.1	83.9
	210	0.5	10.0	17.0	146.8
	240	0.3	4.4	18.7	230.3
	270	0.5	1.9	1.9	262.9
	300	0.8	2.5	3.1	9.8
	330	1.1	3.1	3.7	62.9
MSL	0	1.7	3.5	4.1	66.4
	30	1.8	3.6	4.1	65.9
	60	1.6	3.3	3.7	74.4
	90	0.8	3.8	2.8	76.0
	120	0.7	7.1	12.8	70.4
	150	0.6	9.5	12.8	62.5
	180	0.5	10.2	14.1	70.9
	210	0.5	10.1	17.0	129.3
	240	0.3	5.5	18.7	232.7
	270	0.5	1.8	1.7	264.5
	300	0.7	2.3	3.1	337.5
	330	1.1	3.0	3.7	59.7
MLWS	0	1.5	3.3	3.7	55.4
	30	1.6	3.4	4.1	57.9
	60	1.5	3.2	3.7	70.2
	90	0.8	4.2	11.6	70.8
	120	0.6	6.7	12.8	67.7
	150	0.5	9.1	12.8	63.4
	180	0.5	9.9	14.1	58.4
	210	0.5	10.4	17.0	43.9
	240	0.4	6.9	18.7	243.2
	270	0.5	1.7	1.7	264.8
	300	0.6	2.1	3.1	329.1
	330	0.9	2.8	3.4	43.5

Table C.7: 200 year conditions, WP7 – developed layout

Water level	Sector	Hs (m)	Tm-1,0 (s)	Tp (s)	Mean direction (°N)
MHWS	0	1.5	3.5	4.1	33.0
	30	1.6	3.6	4.1	38.2
	60	1.3	3.2	3.7	44.6
	90	0.7	3.0	3.1	48.8
	120	0.7	9.2	12.8	76.0
	150	0.7	10.1	12.8	74.0
	180	0.6	10.5	14.1	86.1
	210	0.7	10.5	17.0	204.0
	240	0.4	4.7	18.7	236.0
	270	0.7	2.2	2.3	264.3
	300	1.0	2.7	3.4	345.8
	330	1.1	3.0	3.7	20.2
MSL	0	1.4	3.4	4.1	33.4
	30	1.6	3.5	4.1	39.6
	60	1.3	3.2	3.7	46.1
	90	0.7	4.0	11.6	57.5
	120	0.7	8.2	12.8	76.0
	150	0.6	9.9	12.8	79.4
	180	0.6	10.5	14.1	88.5
	210	0.6	10.3	17.0	197.8
	240	0.5	5.5	18.7	235.2
	270	0.7	2.1	2.3	265.3
	300	0.9	2.5	2.8	316.0
	330	1.0	2.9	3.7	21.3
MLWS	0	1.3	3.1	3.7	31.4
	30	1.4	3.3	4.1	38.5
	60	1.2	3.1	3.7	46.2
	90	0.7	4.4	11.6	58.3
	120	0.6	7.5	12.8	74.0
	150	0.5	9.3	12.8	82.9
	180	0.5	9.8	14.1	103.4
	210	0.5	9.8	17.0	222.0
	240	0.5	6.7	18.7	234.8
	270	0.7	2.1	2.3	266.5
	300	0.8	2.3	2.5	313.8
	330	0.9	2.7	3.4	17.0

Table C.8: 200 year conditions, WP8 – developed layout

Water level	Sector	Hs (m)	Tm-1,0 (s)	Tp (s)	Mean direction (°N)
MHWS	0	1.2	2.6	4.1	29.3
	30	1.4	2.8	4.1	39.2
	60	1.2	2.7	3.7	46.3
	90	0.7	2.3	3.1	49.1
	120	0.4	3.0	12.8	29.3
	150	0.4	4.1	12.8	20.1
	180	0.4	7.5	14.1	31.0
	210	0.4	3.7	17.0	10.6
	240	0.4	2.0	2.5	293.0
	270	0.9	2.4	3.4	295.5
	300	1.1	2.5	3.4	305.4
	330	1.0	2.3	3.1	339.2
MSL	0	1.2	2.6	4.1	30.3
	30	1.3	2.7	4.1	40.6
	60	1.2	2.7	3.7	47.9
	90	0.6	2.3	3.1	53.4
	120	0.4	2.4	12.8	59.0
	150	0.3	3.4	12.8	53.5
	180	0.3	7.1	14.1	57.5
	210	0.3	3.3	17.0	41.3
	240	0.4	2.0	2.5	293.5
	270	0.8	2.4	3.1	294.8
	300	1.1	2.4	3.4	299.9
	330	1.0	2.3	3.1	340.7
MLWS	0	1.0	2.4	3.7	29.8
	30	1.2	2.6	3.7	42.0
	60	1.1	2.6	3.7	51.0
	90	0.6	2.2	2.8	58.5
	120	0.4	2.3	12.8	71.1
	150	0.3	3.0	12.8	76.0
	180	0.2	6.9	14.1	75.2
	210	0.3	3.0	17.0	60.3
	240	0.3	1.9	2.3	293.1
	270	0.7	2.2	3.1	293.8
	300	1.0	2.3	3.1	300.0
	330	0.9	2.2	3.1	339.3

Table C.9: 200 year conditions, WP9 – developed layout

Water level	Sector	Hs (m)	Tm-1,0 (s)	Tp (s)	Mean direction (°N)
MHWS	0	1.2	2.6	4.1	29.8
	30	1.4	2.8	4.1	41.0
	60	1.2	2.7	3.7	47.8
	90	0.7	2.3	3.1	51.1
	120	0.4	2.6	12.8	43.5
	150	0.3	3.4	12.8	34.3
	180	0.3	7.1	14.1	39.9
	210	0.3	3.6	17.0	19.4
	240	0.3	1.9	2.5	291.9
	270	0.9	2.4	3.4	296.1
	300	1.1	2.5	3.4	305.5
	330	1.0	2.3	3.1	335.1
MSL	0	1.2	2.6	4.1	31.3
	30	1.4	2.8	4.1	42.7
	60	1.2	2.7	3.7	49.3
	90	0.6	2.2	3.1	55.6
	120	0.4	2.2	12.8	64.0
	150	0.3	2.9	12.8	64.6
	180	0.2	6.7	14.1	66.0
	210	0.3	3.3	17.0	53.7
	240	0.3	1.9	2.5	291.7
	270	0.8	2.3	3.1	295.4
	300	1.1	2.4	3.4	300.7
	330	1.0	2.3	3.1	337.7
MLWS	0	1.1	2.4	3.7	31.6
	30	1.2	2.6	3.7	44.5
	60	1.1	2.6	3.7	52.2
	90	0.6	2.2	2.8	59.9
	120	0.4	2.2	12.8	73.1
	150	0.3	2.6	12.8	80.0
	180	0.2	7.5	14.1	79.7
	210	0.3	3.0	17.0	72.1
	240	0.3	1.8	2.3	289.4
	270	0.7	2.2	3.1	294.8
	300	1.0	2.3	3.1	300.8
	330	0.9	2.2	3.1	337.9

Table C.10: 200 year conditions, WP10 – developed layout

Water level	Sector	Hs (m)	Tm-1,0 (s)	Tp (s)	Mean direction (°N)
MHWS	0	1.2	2.6	4.1	29.6
	30	1.4	2.8	4.1	42.3
	60	1.2	2.7	3.7	49.0
	90	0.7	2.3	3.1	52.2
	120	0.4	2.5	12.8	50.5
	150	0.3	3.1	12.8	42.2
	180	0.3	6.8	14.1	43.2
	210	0.3	3.8	17.0	25.9
	240	0.3	1.9	2.5	292.5
	270	0.9	2.4	3.4	296.6
	300	1.2	2.5	3.4	305.9
	330	0.9	2.3	3.1	331.4
MSL	0	1.2	2.6	4.1	31.3
	30	1.3	2.8	4.1	44.1
	60	1.2	2.7	3.7	50.7
	90	0.6	2.2	3.1	56.8
	120	0.4	2.2	12.8	65.5
	150	0.3	2.7	12.8	67.7
	180	0.2	6.5	14.1	68.2
	210	0.3	3.6	17.0	60.0
	240	0.3	1.9	2.5	292.1
	270	0.8	2.4	3.1	295.9
	300	1.1	2.4	3.4	301.3
	330	0.9	2.3	3.1	333.9
MLWS	0	1.1	2.4	3.7	32.4
	30	1.2	2.6	3.7	46.4
	60	1.1	2.6	3.7	53.5
	90	0.6	2.2	2.8	60.8
	120	0.4	2.1	12.8	73.6
	150	0.3	2.5	12.8	80.7
	180	0.2	7.3	14.1	81.0
	210	0.2	3.3	17.0	76.5
	240	0.3	1.8	2.3	289.3
	270	0.7	2.2	3.1	295.8
	300	1.0	2.3	3.1	301.8
	330	0.9	2.1	2.8	335.1

Table C.11: 200 year conditions, WP11 – developed layout

Water level	Sector	Hs (m)	Tm-1,0 (s)	Tp (s)	Mean direction (°N)
MHWS	0	1.2	2.5	4.1	29.3
	30	1.4	2.8	4.1	45.7
	60	1.3	2.6	3.7	55.9
	90	0.8	2.2	3.1	64.2
	120	0.6	2.1	12.8	92.8
	150	0.5	2.1	12.8	110.6
	180	0.5	2.0	14.1	148.6
	210	0.6	2.0	17.0	204.7
	240	0.5	1.8	2.3	249.7
	270	1.1	2.2	3.1	280.2
	300	1.2	2.4	3.4	301.2
	330	0.9	2.2	3.1	323.0
MSL	0	1.2	2.5	4.1	31.5
	30	1.4	2.7	4.1	48.7
	60	1.2	2.6	3.7	58.0
	90	0.7	2.1	3.1	71.7
	120	0.6	2.1	12.8	88.2
	150	0.5	2.0	12.8	113.1
	180	0.5	1.9	14.1	157.1
	210	0.6	1.9	17.0	199.1
	240	0.5	1.7	2.3	247.8
	270	1.0	2.2	3.1	278.6
	300	1.2	2.4	3.4	295.6
	330	0.9	2.2	3.1	324.1
MLWS	0	1.1	2.4	3.7	34.5
	30	1.2	2.5	3.7	51.8
	60	1.1	2.5	3.7	60.9
	90	0.7	2.1	3.1	73.0
	120	0.6	2.0	12.8	89.3
	150	0.4	1.9	12.8	111.3
	180	0.4	1.7	14.1	161.3
	210	0.5	1.8	17.0	195.1
	240	0.5	1.7	2.1	244.7
	270	0.9	2.1	2.8	278.2
	300	1.1	2.2	3.1	297.7
	330	0.8	2.1	2.8	327.0

Table C.12: 200 year conditions, WP12 – developed layout

Water level	Sector	Hs (m)	Tm-1,0 (s)	Tp (s)	Mean direction (°N)
MHWS	0	1.1	2.5	3.7	27.1
	30	1.4	2.7	4.1	48.4
	60	1.3	2.6	3.7	58.2
	90	0.8	2.2	3.1	66.0
	120	0.6	2.0	12.8	97.2
	150	0.5	1.9	12.8	126.7
	180	0.5	1.9	14.1	169.7
	210	0.6	2.0	17.0	206.6
	240	0.5	1.7	2.3	249.6
	270	1.0	2.2	3.1	283.1
	300	1.2	2.4	3.4	303.2
	330	0.9	2.2	3.1	319.5
MSL	0	1.1	2.4	4.1	29.3
	30	1.4	2.7	4.1	51.9
	60	1.2	2.6	3.7	60.6
	90	0.7	2.1	3.1	73.7
	120	0.6	1.9	12.8	89.0
	150	0.4	1.8	12.8	125.2
	180	0.4	1.8	14.1	171.6
	210	0.6	1.9	17.0	202.8
	240	0.5	1.7	2.3	247.7
	270	1.0	2.1	3.1	281.0
	300	1.1	2.3	3.4	298.1
	330	0.9	2.1	3.1	319.7
MLWS	0	1.0	2.3	3.7	33.7
	30	1.2	2.5	3.7	56.0
	60	1.1	2.5	3.7	64.9
	90	0.6	2.0	2.8	74.5
	120	0.5	1.9	12.8	91.2
	150	0.4	1.7	12.8	121.6
	180	0.4	1.6	14.1	170.2
	210	0.5	1.7	17.0	199.4
	240	0.5	1.6	2.1	244.6
	270	0.9	2.0	2.8	280.6
	300	1.0	2.2	3.1	301.1
	330	0.8	2.0	2.8	322.2

Table C.13: 200 year conditions, WP13 – developed layout

Water level	Sector	Hs (m)	Tm-1,0 (s)	Tp (s)	Mean direction (°N)
MHWS	0	1.2	2.5	4.1	27.5
	30	1.4	2.8	4.1	45.3
	60	1.3	2.6	3.7	53.3
	90	0.7	2.1	3.1	58.0
	120	0.5	1.9	12.8	95.7
	150	0.4	1.8	12.8	142.5
	180	0.4	1.8	14.1	183.6
	210	0.6	1.9	17.0	216.9
	240	0.5	1.7	2.3	250.4
	270	1.0	2.2	3.1	283.7
	300	1.2	2.4	3.4	304.5
	330	0.9	2.2	3.1	322.3
MSL	0	1.1	2.5	4.1	29.4
	30	1.4	2.7	4.1	48.3
	60	1.2	2.6	3.7	55.5
	90	0.6	2.0	3.1	64.4
	120	0.5	1.8	2.8	85.8
	150	0.4	1.6	12.8	144.1
	180	0.4	1.6	14.1	185.1
	210	0.5	1.8	2.3	213.3
	240	0.5	1.7	2.3	248.7
	270	1.0	2.2	3.1	281.7
	300	1.2	2.4	3.4	299.2
	330	0.9	2.2	3.1	322.7
MLWS	0	1.0	2.3	3.7	31.7
	30	1.2	2.5	3.7	50.5
	60	1.1	2.4	3.7	58.0
	90	0.6	1.9	2.8	65.9
	120	0.4	1.6	2.8	88.6
	150	0.3	1.4	12.8	142.7
	180	0.3	1.5	1.7	184.5
	210	0.5	1.6	2.1	212.0
	240	0.5	1.6	2.1	245.5
	270	0.9	2.0	2.8	281.2
	300	1.0	2.2	3.1	302.0
	330	0.8	2.0	2.8	324.8

Table C.14: 200 year conditions, WP14 – developed layout

Water level	Sector	Hs (m)	Tm-1,0 (s)	Tp (s)	Mean direction (°N)
MHWS	0	1.2	2.5	4.1	25.9
	30	1.4	2.8	4.1	37.6
	60	1.1	2.5	3.7	43.2
	90	0.6	2.1	3.1	43.9
	120	0.4	1.8	12.8	94.4
	150	0.4	1.7	12.8	174.1
	180	0.4	1.7	14.1	197.9
	210	0.6	1.9	17.0	222.6
	240	0.5	1.8	2.3	250.4
	270	1.1	2.3	3.1	282.4
	300	1.3	2.5	3.4	306.1
	330	1.0	2.3	3.1	329.9
MSL	0	1.2	2.5	4.1	27.0
	30	1.3	2.7	4.1	40.1
	60	1.1	2.5	3.7	45.3
	90	0.5	1.9	3.1	48.9
	120	0.3	1.6	2.8	81.4
	150	0.3	1.4	12.8	173.1
	180	0.4	1.6	1.9	196.6
	210	0.5	1.7	2.3	218.2
	240	0.5	1.7	2.3	248.7
	270	1.0	2.2	3.1	280.5
	300	1.2	2.4	3.4	299.3
	330	1.0	2.3	3.1	331.7
MLWS	0	1.0	2.3	3.7	26.1
	30	1.1	2.4	3.7	41.3
	60	0.9	2.3	3.7	47.9
	90	0.5	1.8	2.8	52.9
	120	0.3	1.4	2.8	91.5
	150	0.2	1.2	1.6	169.1
	180	0.3	1.4	1.7	193.0
	210	0.5	1.6	2.1	215.9
	240	0.5	1.6	2.3	245.5
	270	0.9	2.1	3.1	279.4
	300	1.1	2.3	3.1	301.1
	330	0.9	2.1	2.8	333.0

Table C.15: 200 year conditions, WP15 – developed layout

Water level	Sector	Hs (m)	Tm-1,0 (s)	Tp (s)	Mean direction (°N)
MHWS	0	0.6	2.1	2.8	314.7
	30	0.6	2.4	3.7	271.1
	60	0.4	2.7	3.7	262.7
	90	0.3	2.5	3.1	254.6
	120	0.2	2.3	12.8	258.1
	150	0.2	1.9	12.8	239.2
	180	0.3	1.6	1.9	224.8
	210	0.5	1.8	2.3	236.0
	240	0.5	1.7	2.3	256.9
	270	1.0	2.3	3.4	281.6
	300	1.2	2.5	3.4	299.5
	330	0.8	2.2	3.1	304.9
MSL	0	0.6	2.0	2.8	316.1
	30	0.6	2.3	3.7	276.2
	60	0.4	2.5	3.7	259.1
	90	0.2	2.4	2.5	256.0
	120	0.1	1.9	12.8	256.3
	150	0.2	1.5	12.8	223.6
	180	0.3	1.5	1.9	221.6
	210	0.5	1.7	2.1	233.1
	240	0.5	1.7	2.3	255.6
	270	1.0	2.2	3.1	280.3
	300	1.2	2.4	3.4	296.0
	330	0.8	2.2	3.1	305.2
MLWS	0	0.5	1.9	2.5	320.8
	30	0.3	1.7	2.3	332.6
	60	0.2	1.8	3.4	314.0
	90	0.1	2.1	2.3	244.4
	120	0.1	1.3	1.4	202.4
	150	0.1	1.2	1.6	204.1
	180	0.2	1.4	1.7	216.7
	210	0.4	1.6	2.1	230.5
	240	0.4	1.6	2.1	252.9
	270	0.9	2.1	3.1	279.7
	300	1.1	2.3	3.1	299.1
	330	0.7	2.1	2.8	308.3

Table C.16: 200 year conditions, WP16 – developed layout

Water level	Sector	Hs (m)	Tm-1,0 (s)	Tp (s)	Mean direction (°N)
MHWS	0	0.7	2.2	2.8	315.2
	30	0.7	2.5	3.7	280.7
	60	0.4	2.6	3.7	281.2
	90	0.2	2.4	3.1	265.7
	120	0.2	2.4	12.8	271.0
	150	0.2	1.9	12.8	258.2
	180	0.2	1.5	14.1	233.3
	210	0.4	1.7	2.1	245.5
	240	0.5	1.7	2.3	261.8
	270	1.0	2.3	3.4	283.2
	300	1.3	2.6	3.7	299.4
	330	0.9	2.3	3.1	305.0
MSL	0	0.7	2.1	2.8	316.3
	30	0.6	2.4	3.7	285.8
	60	0.4	2.4	3.7	284.3
	90	0.2	2.3	3.1	266.0
	120	0.1	2.0	12.8	267.1
	150	0.1	1.5	12.8	243.9
	180	0.2	1.4	1.6	229.7
	210	0.4	1.6	2.1	242.2
	240	0.5	1.6	2.3	260.9
	270	1.0	2.2	3.1	282.1
	300	1.1	2.4	3.4	291.8
	330	0.9	2.3	3.1	305.3
MLWS	0	0.6	2.0	2.5	321.2
	30	0.4	1.9	2.5	336.2
	60	0.2	1.9	2.3	334.1
	90	0.1	2.1	2.5	256.3
	120	0.1	1.3	1.3	213.0
	150	0.1	1.1	1.3	206.1
	180	0.2	1.3	1.6	222.1
	210	0.3	1.5	1.9	237.0
	240	0.4	1.6	2.1	257.8
	270	0.9	2.1	3.1	280.9
	300	1.0	2.2	3.1	294.1
	330	0.8	2.2	3.1	309.2

Table C.17: 200 year conditions, WP17 – developed layout

Water level	Sector	Hs (m)	Tm-1,0 (s)	Tp (s)	Mean direction (°N)
MHWS	0	0.7	2.2	3.1	313.5
	30	0.6	2.2	2.8	321.2
	60	0.4	2.3	3.7	310.0
	90	0.2	2.2	3.1	293.9
	120	0.1	2.9	12.8	287.7
	150	0.2	2.2	12.8	283.6
	180	0.2	1.4	14.1	251.1
	210	0.3	1.6	17.0	263.7
	240	0.4	1.6	2.3	273.8
	270	1.0	2.3	3.4	286.4
	300	1.3	2.6	3.7	297.2
	330	0.9	2.4	3.1	301.5
MSL	0	0.7	2.2	2.8	314.3
	30	0.6	2.1	2.8	322.1
	60	0.3	2.2	2.3	316.8
	90	0.1	2.4	3.1	290.2
	120	0.1	2.5	12.8	291.9
	150	0.1	1.7	12.8	281.1
	180	0.1	1.2	14.1	240.1
	210	0.3	1.4	1.9	259.4
	240	0.4	1.6	2.3	273.1
	270	1.0	2.2	3.1	285.5
	300	1.1	2.4	3.4	288.8
	330	0.9	2.3	3.1	302.1
MLWS	0	0.6	2.1	2.8	318.3
	30	0.5	2.0	2.5	336.8
	60	0.3	2.0	2.3	340.3
	90	0.1	2.1	2.5	276.2
	120	0.0	1.5	12.8	266.3
	150	0.1	1.1	12.8	240.5
	180	0.1	1.0	1.1	231.4
	210	0.3	1.3	1.9	253.8
	240	0.4	1.5	2.1	270.3
	270	0.9	2.1	3.1	285.6
	300	1.0	2.2	3.1	291.2
	330	0.8	2.2	3.1	306.2

Table C.18: 200 year conditions, WP18 – developed layout

Water level	Sector	Hs (m)	Tm-1,0 (s)	Tp (s)	Mean direction (°N)
MHWS	0	0.8	2.1	3.1	350.4
	30	0.8	2.0	2.8	10.2
	60	0.6	1.9	2.5	19.4
	90	0.3	1.5	3.1	25.5
	120	0.2	2.1	12.8	358.9
	150	0.2	2.7	12.8	345.1
	180	0.1	3.9	14.1	337.1
	210	0.2	2.4	17.0	316.9
	240	0.3	1.8	2.3	305.4
	270	0.9	2.4	3.1	311.0
	300	1.3	2.6	3.7	320.5
	330	0.9	2.3	3.1	327.1
MSL	0	0.8	2.1	2.8	350.5
	30	0.8	2.0	2.8	10.8
	60	0.6	1.8	2.5	20.9
	90	0.2	1.4	3.1	30.6
	120	0.1	1.5	12.8	27.8
	150	0.1	1.9	12.8	343.7
	180	0.1	3.1	14.1	333.7
	210	0.2	1.9	17.0	299.8
	240	0.3	1.8	2.3	303.6
	270	0.8	2.3	3.1	309.8
	300	1.1	2.5	3.4	316.6
	330	0.9	2.2	3.1	327.6
MLWS	0	0.8	2.0	2.8	352.6
	30	0.7	1.9	2.5	12.7
	60	0.5	1.7	2.3	22.9
	90	0.2	1.2	1.4	45.5
	120	0.1	1.1	1.3	67.5
	150	0.1	1.2	12.8	29.8
	180	0.0	2.0	14.1	320.2
	210	0.1	1.5	1.7	284.9
	240	0.3	1.7	2.1	298.5
	270	0.8	2.2	2.8	310.6
	300	1.0	2.4	3.1	320.5
	330	0.8	2.1	3.1	331.0

Table C.19: 200 year conditions, WP19 – developed layout

Water level	Sector	Hs (m)	Tm-1,0 (s)	Tp (s)	Mean direction (°N)
MHWS	0	0.9	2.2	3.1	356.3
	30	0.9	2.2	3.1	17.9
	60	0.7	2.1	2.5	26.8
	90	0.4	1.7	3.1	31.4
	120	0.2	2.0	12.8	14.3
	150	0.2	2.5	12.8	357.8
	180	0.1	3.8	14.1	345.9
	210	0.2	2.6	17.0	331.7
	240	0.3	1.8	2.3	307.2
	270	0.9	2.4	3.1	310.1
	300	1.2	2.6	3.7	320.0
	330	0.9	2.3	3.1	327.8
MSL	0	0.9	2.1	3.1	355.5
	30	0.9	2.1	2.8	18.0
	60	0.7	2.0	2.5	27.3
	90	0.3	1.6	1.7	34.6
	120	0.2	1.5	12.8	42.3
	150	0.1	1.9	12.8	1.8
	180	0.1	3.1	14.1	340.4
	210	0.1	2.0	17.0	313.3
	240	0.3	1.8	2.3	305.2
	270	0.8	2.3	3.1	309.1
	300	1.1	2.5	3.4	316.7
	330	0.9	2.2	3.1	328.3
MLWS	0	0.8	2.0	2.8	357.2
	30	0.8	2.0	2.8	19.5
	60	0.6	1.9	2.5	28.4
	90	0.3	1.4	1.6	41.9
	120	0.1	1.2	1.4	66.6
	150	0.1	1.2	12.8	48.7
	180	0.0	2.1	14.1	331.8
	210	0.1	1.4	1.7	288.4
	240	0.3	1.6	2.1	299.5
	270	0.7	2.2	2.8	310.1
	300	1.0	2.3	3.1	321.0
	330	0.8	2.1	3.1	332.0

Table C.20: 200 year conditions, WP20 – developed layout

Water level	Sector	Hs (m)	Tm-1,0 (s)	Tp (s)	Mean direction (°N)
MHWS	0	0.9	2.2	3.1	351.7
	30	1.0	2.3	3.7	359.5
	60	0.8	2.1	3.7	20.7
	90	0.4	1.7	3.1	29.0
	120	0.3	1.6	12.8	105.2
	150	0.3	1.6	12.8	135.3
	180	0.3	1.4	14.1	212.5
	210	0.5	1.7	17.0	239.7
	240	0.5	1.7	2.3	262.4
	270	1.1	2.3	3.1	289.2
	300	1.4	2.6	3.7	309.6
	330	1.0	2.3	3.1	320.3
MSL	0	0.9	2.1	2.8	350.8
	30	1.0	2.2	3.7	2.9
	60	0.8	2.0	3.7	24.5
	90	0.3	1.5	3.1	55.1
	120	0.3	1.3	12.8	114.8
	150	0.2	1.3	12.8	148.3
	180	0.3	1.3	14.1	206.2
	210	0.4	1.6	2.1	234.2
	240	0.5	1.6	2.3	261.0
	270	1.0	2.2	3.1	287.2
	300	1.3	2.5	3.4	304.1
	330	1.0	2.2	3.1	320.5
MLWS	0	0.8	2.0	2.8	354.4
	30	0.8	2.0	2.5	20.1
	60	0.7	1.8	2.3	34.1
	90	0.3	1.3	1.4	64.8
	120	0.2	1.1	1.4	120.2
	150	0.2	1.1	1.3	150.1
	180	0.2	1.2	1.4	200.3
	210	0.4	1.4	1.9	230.1
	240	0.4	1.6	2.1	256.2
	270	0.9	2.1	2.8	285.6
	300	1.1	2.3	3.1	308.3
	330	0.9	2.1	3.1	324.4

Table C.21: 200 year conditions, WP21 – developed layout

Water level	Sector	Hs (m)	Tm-1,0 (s)	Tp (s)	Mean direction (°N)
MHWS	0	1.1	2.4	3.1	15.3
	30	1.2	2.6	4.1	29.3
	60	1.0	2.4	3.7	34.9
	90	0.6	1.9	3.1	38.9
	120	0.4	1.7	12.8	130.6
	150	0.4	1.8	12.8	167.2
	180	0.4	1.6	14.1	197.7
	210	0.6	1.8	17.0	225.8
	240	0.5	1.7	2.3	253.8
	270	1.1	2.3	3.1	286.8
	300	1.3	2.5	3.4	309.4
	330	1.0	2.3	3.1	327.7
MSL	0	1.0	2.3	3.1	14.1
	30	1.1	2.5	4.1	31.0
	60	1.0	2.3	3.7	38.3
	90	0.5	1.8	3.1	49.8
	120	0.3	1.4	12.8	115.0
	150	0.3	1.4	12.8	167.2
	180	0.3	1.5	1.9	197.8
	210	0.5	1.7	2.1	222.5
	240	0.5	1.7	2.3	252.1
	270	1.0	2.2	3.1	284.7
	300	1.2	2.4	3.4	303.0
	330	1.0	2.2	3.1	328.3
MLWS	0	0.9	2.1	2.8	11.3
	30	0.9	2.2	3.7	32.8
	60	0.8	2.1	3.7	42.4
	90	0.4	1.6	2.8	54.1
	120	0.2	1.2	1.4	120.6
	150	0.2	1.2	1.4	163.0
	180	0.3	1.3	1.7	193.3
	210	0.4	1.5	1.9	220.7
	240	0.5	1.6	2.1	248.1
	270	0.9	2.1	2.8	283.6
	300	1.1	2.2	3.1	306.8
	330	0.9	2.1	2.8	331.0

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