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Volume 7B Proposed Development (Offshore) Appendices

Appendix 2-2 Marine and Coastal Processes Numerical Modelling Report

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Volume 7B Appendix 2-2 Marine and Coastal Processes Numerical Modelling Report

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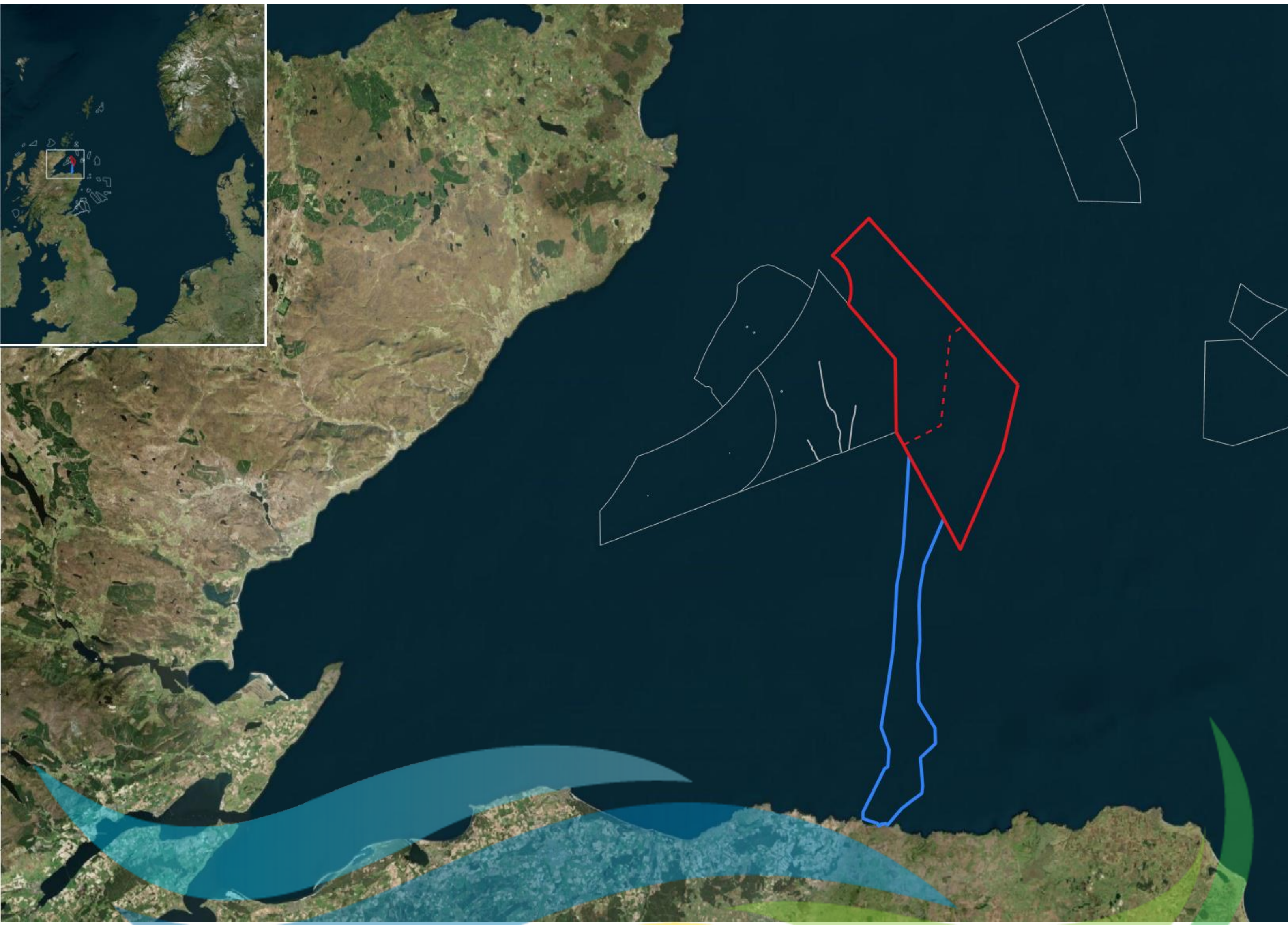
This document contains the following report: 'Caledonia Offshore Windfarm. Numerical Modelling Report' as prepared by Ports and Coastal Solutions Ltd. in October 2024. For the purpose of Consent Application, the document has been retitled to: 'Volume 7B, Appendix 2-2: Marine and Coastal Processes Numerical Modelling Report', alongside the addition of a new front cover.

Caledonia Offshore Wind Farm

Numerical Modelling Report

Report No. PU031_R02D04



GoBe
Numerical Modelling Report
October, 2024

Caledonia Offshore Wind Farm

Numerical Modelling Report

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PORT & COASTAL SOLUTIONS

CONTENTS

ACRONYMS AND ABBREVIATIONS

ARI	Annual Recurrence Interval
DHI	Danish Hydraulics Institute
EIA	Environmental Impact Assessment
EIAR	Environmental Impact Assessment Report
HD	Hydrodynamic (model)
HDD	Horizontal Directional Drilling
H_s	Significant Wave Height
HW	High Water
LW	Low Water
MDS	Maximum Design Scenario
MPA	Marine Protected Area
MSL	Mean Sea Water
OECC	Offshore Export Cable Corridor
OSP	Offshore Substation Platform
OWF	Offshore Wind Farm
PCS	Port and Coastal Solutions Ltd
PE	Peak Ebb
PF	Peak Flood
PSD	Particle Size Distribution
PT	Particle Tracking (model)
SSC	Suspended Sediment Concentration
SW	Spectral Wave (model)
TLP	Tension Leg Platform
T_p	Peak Wave Period
UTC	Coordinated Universal Time
WTG	Wind Turbine Generator

Executive Summary

In support of the Environmental Impact Assessment (EIA) for the Proposed Development (Offshore), which includes both the Caledonia Offshore Export Cable Corridor (OECC) and Caledonia OWF, GoBe commissioned Port and Coastal Solutions Ltd (PCS) to develop and apply a suite of numerical modelling tools to characterise the existing environmental conditions and to assess the effect of the Proposed Development (Offshore) on the marine and coastal environment. The models included a hydrodynamic (HD) model to simulate tidal flows, a Spectral Wave (SW) model to simulate waves and a Particle Tracking (PT) model to simulate the dispersion of sediment released during construction activities.

In the following, a summary of results is presented separately for Caledonia North, Caledonia South and for the Proposed Development (Offshore) (which includes Caledonia North and Caledonia South in combination).

Caledonia North

Results from the characterisation of the existing environment metocean conditions in the area showed that:

- Water levels are relatively uniform across the Caledonia North Site with a mean spring tidal range of 2.8 m, and a mean neap tidal range of 1.4 m;
- The peak tidal flows occur close to the time of high water and low water rather than at mid-tide level;
- Within the Caledonia North Site, flood currents are to the south and ebb currents are to the north, while in the southern part of the Caledonia North OECC flood currents are to the west and ebb currents are to the east (i.e. parallel with the adjacent shoreline);
- Current speeds within the Caledonia North Site are up to around 0.5 m/s on spring tides and less than 0.3 m/s on neap tides;
- The residual currents are generally low during both mean spring and neap tides and over a 14.5 day spring neap tidal cycle, with slowest residual flows in the northern half of the Caledonia North Site and fastest residual flows of up to 0.03 m/s in the southern half of the Caledonia North Site;
- There is a south to south-westward flow residual in the Caledonia North Site and an eastward flow residual along most of the Caledonia North OECC. The HD model is expected to slightly under predict the magnitude of the eastward flow residual along the Caledonia North OECC (PCS, 2024);
- The largest waves are from a north easterly direction and the smallest waves are from a north westerly direction;
- For the Annual Recurrence Interval (ARI) conditions modelled, significant wave heights (H_s) range from 5.0 m (1 in 1 year ARI from the northwest) to 8.4 m (1 in 50 year ARI from the northeast);
- H_s is relatively uniform across the Caledonia North Site with variations of around 0.5 m, increasing to more than 1 m when waves are from the north to west sectors; and
- The peak wave period (T_p) for the 1 in 1 year ARIs range from 8.7 to 13.2 seconds, increasing to more than 14 seconds for the 1 in 50 year ARIs, with longest period waves from the offshore directional sectors.

Potential construction related impacts arising from the disturbance and dispersion of sediment in the marine environment were assessed for cable installation, Horizontal Directional Drilling (HDD) and pile drilling of the Wind Turbine Generator (WTG) foundations. For inter-array cable installation and pile drilling the modelling assessment released sediment from within the Caledonia South Site. There are some small differences between the array areas of Caledonia South and Caledonia North which will affect the volumes of sediment disturbed during construction activities at these two sites and how any disturbed sediment may disperse.

In particular, the seabed in the Caledonia South Site has a higher percentage of fines than the seabed in the Caledonia North Site and, as such, a higher volume of fine sediment will be dispersed in the marine environment during cable installation within the Caledonia South Site than for cable installation within the Caledonia North Site. In addition, the flow speeds in the Caledonia North Site are slightly faster than those in the Caledonia South Site. Despite these differences, the modelling results presented for inter-array cable installation and pile drilling as part of Caledonia South are expected to give a good indication of how sediment will disperse in the marine environment for inter-array cable installation and pile drilling for Caledonia North, albeit with a shift in plume centroid.

Results from the modelling of the construction related impacts suggested that:

- Impacts for all construction activities (both in terms of suspended sediment concentrations (SSC) and sedimentation) were predicted to mainly be confined to occur within the Caledonia North Site and/or along the Caledonia North OECC;
- Cable installation:
  - The dispersion of fine sediment released during cable installation with a jet trencher was predicted to result in a plume with a peak SSC of more than 50 mg/l, but the area with elevated SSC was very localised to where the activity was being undertaken with very limited transport of the suspended sediment predicted. This is a result of the low tidal currents combined with the sediment being released relatively close to the seabed;
  - Increases in SSC were predicted to be short lived with increases of more than 25 mg/l occurring for less than 7.2 hours and increases of more than 5 mg/l occurring for less than six days; and
  - Sedimentation of more than 10 mm was predicted in parts of the Caledonia North Site, but more typically sedimentation of 2-3 mm was predicted along the Caledonia North OECC and interconnector cable routes, reducing to values of less than 0.1 mm at a short distance from where the sediment release was applied in the model.
- HDD:
  - The dispersion of fine sediment from muds and cuttings released at pop-out during HDD was predicted to result in a short lived, localised plume, with SSC above 0.5 mg/l extending over an area approximately 2.5 km west of the release point and 4 km to the east and higher SSC of more than 50 mg/l constrained to an area of approximately 1 km x 0.5 km. Given the models tendency to underpredict the magnitude of the eastward flow dominance in this area (PCS, 2024) it is possible that the plume would not extend as far west and would extend further to the east than predicted by the model;
  - The plume was predicted to disperse within three days of the sediment release, although some areas of higher SSC were predicted to remain along the shallow coastal areas including at the Inverboyndie bathing water. However, these increases were predicted to be low (typically less than 2 mg/l) and short lived; and
  - Sedimentation of more than 0.1 mm was predicted to be highly localised and constrained to an area of less than 2 km east-west and less than 1 km north-south.
- Foundation installation:
  - Sediment released during drilling of monopile foundations was predicted to result in a low concentration sediment plume, with increases in SSC of more than 5 mg/l constrained to within 5 km of the release location in a north-south direction and to within 1 km in an east-west direction. The SSC plume dispersed longer distances from the sediment release location than the plumes from cable installation and HDD

  due to the modelled release being in the surface layer, allowing a longer period for dispersion as the sediment settled to the bed;
  - Predicted sedimentation was less than 1 mm at distances of more than 1 km from the release location; and
  - Areas of increased SSC and sedimentation from pile drilling were predicted to extend over an area which is greater than the distance between WTG foundations. The drilling of all WTG foundations in the Caledonia North Site are therefore expected to result in sedimentation at greater depths than shown for the limited number of piles drilled in the modelling simulation.

Operational impacts of Caledonia North, specifically in relation to the presence of WTG foundations, were assessed in the HD and SW models. Results from the modelling of the blockage effect during operation showed that:

- The WTG foundations did not result in any notable changes in water levels;
- The WTG foundations resulted in localised neighbouring areas of increased and reduced flows, the magnitude of these changes were less than 0.002 m/s;
- Changes in residual flows were constrained to a small area and represented a small change of less than 0.002 m/s; and
- The bottom-fixed WTG foundations resulted in small changes to H_s, predicted to be less than ±0.05 m and with changes constrained to be within the Caledonia North Site.

Caledonia South

Results from the characterisation of the existing environment metocean conditions in the area showed that:

- Water levels are relatively uniform across the Caledonia South Site with a mean spring tidal range of 2.8 m, and a mean neap tidal range of 1.4 m;
- The peak tidal flows occur close to the time of high water and low water rather than at mid-tide level;
- Within the Caledonia South Site, flood currents are to the south and ebb currents are to the north, while in the southern part of the Caledonia South OECC flood currents are to the west and ebb currents are to the east (i.e. parallel with the adjacent shoreline);
- Current speeds within the Caledonia South Site are up to around 0.4 m/s on spring tides and less than 0.2 m/s on neap tides;
- The residual currents are generally low during both mean spring and neap tides and over a 14.5 day spring neap tidal cycle, with slightly faster residuals (of up to 0.035 m/s) in the northern half of the Caledonia South Site.
- There is a southward (to south-westward) flow residual in the Caledonia South Site and an eastward flow residual along most of the Caledonia South OECC. The HD model is expected to slightly under predict the magnitude of the eastward flow residual along the Caledonia South OECC (PCS, 2024);
- The largest waves are from a northerly direction and the smallest waves are from a southerly direction;
- For the ARI conditions modelled, significant wave heights (H_s) range from 4.8 m (1 in 1 year ARI from the south) to 8.2 m (1 in 50 year ARI from the northeast);
- H_s is relatively uniform across the Caledonia South Site with variations of around 0.5 m, increasing to more than 1 m when waves are from the north to west sectors; and
- The peak wave period (T_p) for the 1 in 1 year ARIs range from 8.6 to 13.3 seconds, increasing to more than 14 seconds for the 1 in 50 year ARIs, with longest period waves from the offshore directional sectors.

Potential construction related impacts arising from the disturbance and dispersion of sediment in the marine environment were assessed for cable installation, HDD and pile drilling of the WTG foundations. Results from the modelling of the construction related impacts showed that:

- Impacts for all construction activities (both in terms of SSC and sedimentation) were predicted to mainly be confined to occur within the Caledonia South Site and/or along the Caledonia South OECC;
- Cable installation:
  - The dispersion of fine sediment released during cable installation with a jet trencher was predicted to result in a plume with a peak SSC of more than 50 mg/l, but the area with elevated SSC was very localised to where the activity was being undertaken with very limited transport of the suspended sediment predicted. This is a result of the low tidal currents combined with the sediment being released relatively close to the seabed;
  - Increases in SSC were predicted to be short lived with increases of more than 25 mg/l occurring for less than 7.2 hours and increases of more than 5 mg/l occurring for less than six days; and
  - Sedimentation of more than 10 mm was predicted in parts of the Caledonia South Site, but more typically sedimentation of 2-3 mm was predicted along the Caledonia South OECC and interconnector cable routes, reducing to values of less than 0.1 mm at a short distance from where the sediment release was applied in the model.
- HDD:
  - The dispersion of fine sediment from muds and cuttings released at pop-out during HDD was predicted to result in a short lived, localised plume, with SSC above 0.5 mg/l extending over an area approximately 2.5 km west of the release point and 4 km to the east and higher SSC of more than 50 mg/l constrained to an area of approximately 1 km x 0.5 km. Given the models tendency to underpredict the magnitude of the eastward flow dominance in this area (PCS, 2024) it is possible that the plume would not extend as far west and would extend further to the east than predicted by the model;
  - The plume was predicted to disperse within three days of the sediment release, although some areas of higher SSC were predicted to remain along the shallow coastal areas including at the Inverboyndie bathing water. However, these increases were predicted to be low (typically less than 2 mg/l) and short lived; and
  - Sedimentation of more than 0.1 mm was predicted to be highly localised and constrained to an area of less than 2 km east-west and less than 1 km north-south.
- Foundation installation:
  - Sediment released during drilling of monopile foundations was predicted to result in a low concentration sediment plume, with increases in SSC of more than 5 mg/l constrained to within 5 km of the release location in a north-south direction and to within 1 km in an east-west direction. The SSC plume dispersed longer distances from the sediment release location than the plumes from cable installation and HDD due to the modelled release being in the surface layer, allowing a longer period for dispersion as the sediment settled to the bed;
  - Predicted sedimentation was less than 1 mm at distances of more than 1 km from the release location; and
  - Areas of increased SSC and sedimentation from pile drilling were predicted to extend over an area which is greater than the distance between WTG foundations. The drilling of all WTG foundations in the Caledonia South Site are therefore expected to result in sedimentation at greater depths than shown for the limited number of piles drilled in the modelling simulation.

Operational impacts of Caledonia South, specifically in relation to the presence of WTG foundations, were assessed in the HD and SW models. Results from the modelling of the blockage effect during operation showed that:

- The WTG foundations did not result in any notable changes in water levels;
- The WTG foundations resulted in localised neighbouring areas of increased and reduced flows, the magnitude of these changes were less than 0.002 m/s;
- Changes in residual flows were constrained to a small area and represented a small change of less than 0.002 m/s;
- The bottom-fixed WTG foundations resulted in small changes to H_s, predicted to be less than ±0.05 m and with changes constrained to be within the Caledonia South Site;
- The floating WTG substructures resulted in larger changes to H_s than the bottom-fixed WTG foundations with a reduction in H_s of more than ±0.05 m extending close to the northern Moray Firth coastline. This change of 0.05 m at the coast is small in relative terms (with H_s of more than 7 m for the existing wave environment), being less than a 1% change; and
- Larger reductions in H_s of more than 0.25 m also occur but these are mainly constrained to the Caledonia South Site.

Proposed Development (Offshore)

An in-combination assessment of the operational blockage effect of the Proposed Development (i.e. Caledonia North and Caledonia South) on flows and waves showed that:

- the combined changes in peak flow and residual flow from Caledonia North and Caledonia South are broadly similar to the changes from the Caledonia OWF (i.e. presence of infrastructure within the array areas for Caledonia North and Caledonia South) indicating that in-combination effects are small; and
- the combined changes in wave height from Caledonia North and Caledonia South individually are smaller than the changes from the Caledonia OWF indicating that there is some in-combination effect.

An in-combination assessment of Caledonia South, Caledonia North and other adjacent OWF developments (including Stromar, Broadshore, Sinclair and Scaraben) was also undertaken to assess the blockage effect on waves. The in-combination blockage of the OWFs increases the area where H_s is reduced by more than 0.05 m so that it extends to the adjacent coastlines when the waves are from offshore sectors. Further, for waves from the east, the in-combination effect reduces wave heights by more than 0.1 m along the northern Moray Firth coastline, although this change remains small in relative terms (1-2%).

Overall, the modelling results have predicted that the construction and operational impacts of the Proposed Development (Offshore) are relatively small and are predominantly constrained to occur within the Caledonia OWF and along the Caledonia OECC. The construction works were predicted to have the potential to result in increases in SSC of more than 50 mg/l, but these were typically shown to be very localised to where the construction activity was being undertaken (i.e. within the Caledonia OWF or along the Caledonia OECC). The persistence of elevated concentrations will depend on the duration of the activity.

Although plots of predicted changes in tidal flows and waves due to the proposed structures have been presented, these changes have typically been shown by plotting the changes down to a very small difference. Based on the scale of the changes, it is considered unlikely that any measurable changes will occur, except potentially within the Caledonia South Site where floating WTGs could result in measurable reduction in wave heights. In-combination effects with other nearby OWFs could extend the area of measurable change to wave heights beyond the footprint of the Caledonia OWF.

PORT & COASTAL SOLUTIONS

1. Introduction

GoBe Consultants is supporting Caledonia Offshore Wind Farm Limited (the Applicant) in the preparation of the Environmental Impact Assessment Report (EIAR) to support the two applications (Caledonia North and Caledonia South) that make up the Proposed Development (Offshore) in the Moray Firth as part of the Environmental Impact Assessment (EIA) process. GoBe Consultants is undertaking a marine and coastal processes technical study to inform the EIA and has commissioned Port and Coastal Solutions Ltd (PCS) to undertake a numerical modelling study to directly inform elements of the marine and coastal processes technical study. The modelling work will also inform other relevant elements of the EIA such as marine water and sediment quality.

The primary requirements of the numerical modelling study are to:

- Develop hydrodynamic and spectral wave models covering the coastal and marine regions of the study area and the Moray Firth;
- Characterise the existing environmental conditions in the study area based on the numerical modelling results and other available information;
- Apply the developed models to assess the effects of installation (for structures and cables) on water quality; and
- Apply the developed models to assess the operational effects of the offshore infrastructure on hydrodynamics and waves.

This report provides a summary of the results from the modelling work undertaken. The development of the modelling tools was reported separately in the model calibration report (PCS, 2024). A brief overview of the modelling approach is provided in Section 1.2 of this report.

1.1. Project Background

The Proposed Development (Offshore) is located within the Moray Firth in relatively close proximity to the operational Moray West, Moray East and Beatrice OWFs (referred to collectively in this report as the 'Moray OWFs') (Figure 1). For the consenting application, the Proposed Development (Offshore) is being split into two areas, referred to as Caledonia North and Caledonia South.

The key elements of the Proposed Development (Offshore) which are relevant to the modelling study are detailed below:

- Up to 77 wind turbine generators (WTGs) with bottom-fixed foundations and associated support structures in the Caledonia North Site (Array Area) and up to 78 WTGs with either all bottom-fixed foundations or a mixture of bottom-fixed and floating foundations and associated support structures in the Caledonia South Site (Array Area) (noting that the total number of WTGs resulting from the two phases will not exceed 140).
- Two offshore substation platforms (OSPs) in Caledonia North and two OSPs in Caledonia South;
- Up to 360km of inter-array caling in Caledonia North and 365 km of inter-array cabling in Caledonia South;
- 30 km of interconnector cabling in both Caledonia North and Caledonia South; and
- Up to 180 km of export cabling along the Caledonia North Offshore Export Cable Corridor (OECC) and into the Caledonia North Site (total for two cables), and up to 150 km of export cabling along the Caledonia South OECC and into the Caledonia South Site (total for two cables).

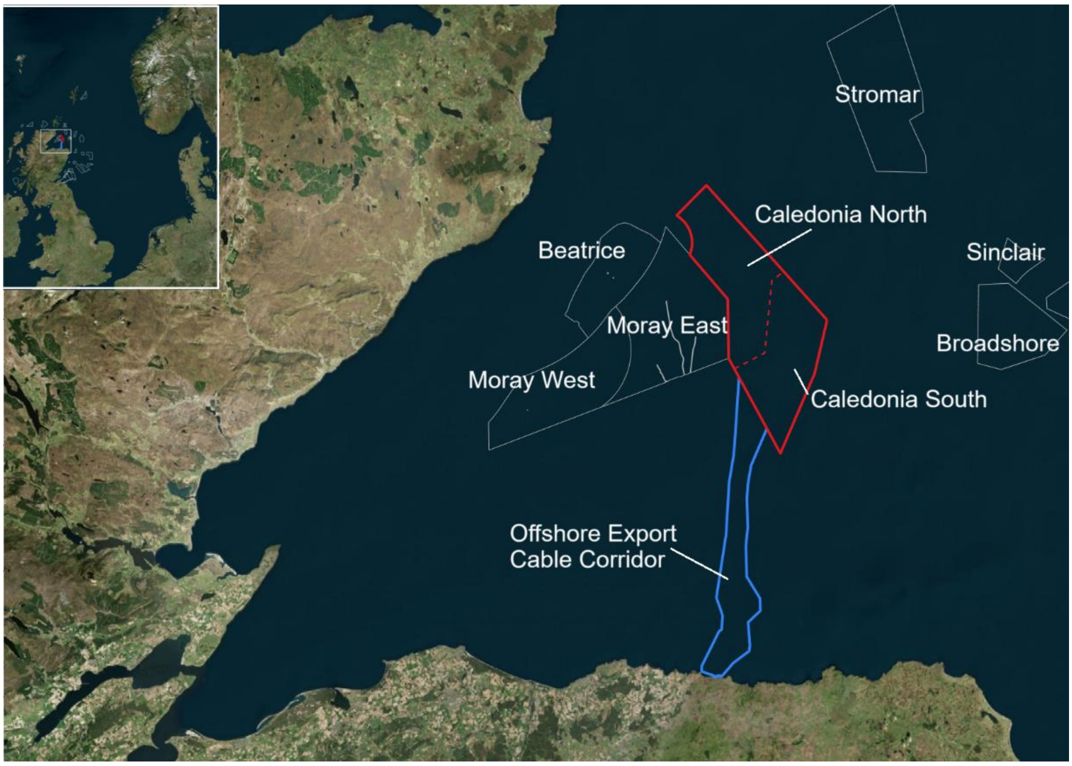


Figure 1. Study Area.

For the purposes of this report, the Caledonia OWF refers spatially to all infrastructure within the Array Area, and thus the combined Caledonia North Site and Caledonia South Site, while the Proposed Development (Offshore) includes all offshore aspects across both applications (thus spatially the array areas and OECCs).

1.2. Overview of modelling approach

To provide consistency with assessments undertaken during the consenting process for the Moray OWFs (ABPmer, 2012; Moray OWF, 2018), the modelling approach applied for these developments has been adopted in the present study. In particular this has dictated the choice of modelling software and model extents.

Numerical models of the North Sea off the east Scottish coast were configured in the MIKE software, which is developed by the Danish Hydraulics Institute (DHI). The MIKE suite is internationally recognised state of the art software which has previously been adopted in the UK and internationally for similar projects, including Marine Scotland's Pentland Firth and Orkney Water's climatology (Wolf *et al.*, 2015) and a number of other UK OWF developments including the Moray OWFs. The MIKE suite includes hydrodynamic (HD), spectral wave (SW) and particle tracking (PT) modules which allows all necessary processes relevant to the coastal processes assessment to be simulated. In particular, the modules include the following:

- The MIKE HD model simulates water level variations and flows in response to a variety of forcing functions in marine, coastal and estuarine regions;
- The MIKE SW model allows for the growth, decay and transformation of wind-generated and swell waves in both offshore and coastal environments; and

- The MIKE PT model simulates the transport of mud (cohesive sediment) and sand driven by flows and waves and the interaction of sediment with the bed, including settling, deposition and erosion. The model can be run in 3-dimensional mode which is critical for the assessment of construction impacts required for the study.

1.3. Report Structure

The report herein is set out as follows:

- An introduction to the study is provided in Section 1;
- Details on the Proposed Development (Offshore) are provided in Section 2;
- The characterisation of the existing environment is summarised in Section 3;
- The construction impacts are detailed in Section 4;
- The operational impacts are presented in Section 5;
- A summary of the key findings from the study are discussed in Section 6; and
- Additional plots (impacts to waves) are provided in Section 7.

Unless stated otherwise, levels are reported to Mean Sea Level (MSL) and times are quoted relative to Coordinated Universal Time (UTC).

Wind and wave directions are reported as the direction the wind and waves are coming from in degrees clockwise from True North. Current direction is reported as the direction the current is going to in degrees clockwise from True North.

2. Proposed Development (Offshore)

The Proposed Development (Offshore) is being brought forward under two separate applications: Caledonia North and Caledonia South. The construction periods for the two application sites will most likely be sequential, with a gap of up to five years between construction periods, although there is the potential for a concurrent construction scenario (whereby both Caledonia North and Caledonia South are built at the same time).

The Caledonia North OECC extends southward from the Caledonia North Site, through the and to the Landfall Site, while the Caledonia South OECC extends southward from the Caledonia South Site to the Landfall Site. The Caledonia, Caledonia North and Caledonia South OECCs largely follow the same route for the two applications and their array areas are immediately adjacent to each other. The assessment of construction impacts therefore considers the impact for Caledonia South, with the impacts at this site also providing an assessment of the impact for Caledonia North.

The assessment of operational impacts considers:

- Caledonia North on its own;
- Caledonia South on its own; and
- The Proposed Development (Offshore) (Caledonia North and Caledonia South in-combination).

The baseline case for the model setup represents the existing environment and therefore includes a representation of the adjacent Moray West, Moray East and Beatrice OWFs. This includes the blockage effects of the WTG foundations. The following structures are represented in the model setup for the existing environment:

- 60 x 10 m diameter monopiles for Moray West OWF;
- 100 x 3 legged jacket structures (with 2.2 m diameters piles for the primary members) for Moray East OWF; and
- 84 x 4 legged jacket structures (with 2.2 m diameters piles for the primary members) for Beatrice OWF.

2.1. Construction

A range of construction methods are being considered for site preparation, structure foundation installation and cable installation. Further details are provided in the following subsections.

2.1.1. Site Preparation

Site preparation activities are likely to include removal of boulders and Unexploded Ordnance. Survey data collected to date indicates that only relatively small bedforms (~50 cm high ripples) are present across the Caledonia OWF (including the Caledonia North Site and Caledonia South Site) and along the Caledonia OECC, Caledonia North OECC and Caledonia South OECC. These bedform features would not require pre-sweeping. Site preparation activities could occur across both the Caledonia OWF and along the Caledonia OECC, Caledonia North OECC and Caledonia South OECC. The required activities typically disturb only small volumes of sediment, much less than during cable installation and therefore they have not been assessed using numerical modelling tools.

2.1.2. Cable Installation

Cable installation is required for export cables along the Caledonia OECC, Caledonia North OECC and Caledonia South OECC and inter-array and interconnector cables within the Caledonia OWF. The following cable lengths are to be installed:

- Up to 150 km of export cabling for Caledonia South (two export cables) and up to 180 km of export cabling for Caledonia North (two export cables);
- Up to 360 km of inter-array cabling in Caledonia North and up to 365km of inter-array cabling in Caledonia South; and
- Up to 30 km of interconnector cabling in both Caledonia North and Caledonia South (one cable per application).

A number of options are being considered for cable installation including the use of:

- A plough, which uses mechanical force to make a trench;
- A jet trencher, which fluidises the bed layer by injecting water into the seabed; and
- A mechanical trencher, which uses a wheel or cutting chain to form a trench.

Of the potential options, jet trenching is likely to be a worst case with respect to the potential for the formation and dispersion of a sediment plume. This is because the sediment release is likely to be at a greater height above the seabed than the other options.

Assuming a v-shaped trench with a width of 2 m and a depth of 3 m, and adopting the highest potential installation rate of 700 m/hour, a volume of 2,100 m^3 will be disturbed per hour. This is equivalent to a dry sediment release of 1,050 kg/s assuming a dry bed density of 1,800 kg/m^3 (the upper range of expected densities along the cable route). Much of the disturbed sediment will be moved along the bed to form berms either side of the trench. Assuming 30% of the sediment removed from the trench is suspended in the water column as a passive plume (Intertek, 2017; Gooding *et al*., 2012), the rate of sediment disturbance will be 315 kg/s (worst case assuming the maximum installation rate).

The coarser sediment fractions will rapidly settle back to the bed adjacent to the trench while the finer sediment has the potential to remain in suspension and be dispersed away from the area of disturbance. The model only considers the release and dispersion of the fine sediment fractions. To characterise the sediments, grab samples were obtained from numerous sites across the Caledonia OWF and along the Caledonia OECC (see Volume 7B, Appendix 4-1: Environmental Baseline Report (Array Area) and Volume 7B, Appendix 4-2: Environmental Baseline Report (Offshore Export Cable Corridor)). A total of 72 samples were analysed for Particle Size Distribution (PSD), of which 16 were in the Caledonia North Site, 18 were in Caledonia South Site and 38 were along the Caledonia OECC, Caledonia North OECC and Caledonia South OECC (noting the 18 samples within the Caledonia South Site also form part of the Caledonia North OECC).

Sediment across the Caledonia OWF was classified as muddy sand to sandy gravel under modified Folk (1954) with sand typically being the dominant fraction accounting for between 49 and 97%, except for one site where gravel was dominant. The percentage of fines varied across the Caledonia OWF with a higher percentage of very fine sand and silt (<125 µm) in the Caledonia South Site (Table 1). On average 14.4% of the sediment was finer than 125 µm in the Caledonia North Site, compared to 25% of the sediment in the Caledonia South Site. The higher percentage of fines in the Caledonia South Site results from a high percentage of finer sediment in the deeper southern section.

Sediment along the Caledonia OECC was classified as sandy gravel to muddy sand under modified Folk (1954). Generally, sand was the dominant fraction accounting for between 55% and 99% of the sediment. On average 11.3% of the sediment was finer than 125 µm, although this varied from less than 1% to 24% along the route. The lower percentage of fines typically occur in the shallower areas close to the Landfall Site and the higher percentage of fines occur in the deeper areas.

Table 1. Average percentage of fine-grained sediment present in the Caledonia OWF and Caledonia OECC.

Region	Very Fine Sand (63-125µm)	Coarse/Medium Silt (16-63µm)	Fine Silt (4-16µm)	Clay (<4µm)	All Fines (<125µm)
Caledonia North Site	8.7	2.4	1.9	1.4	14.4
Caledonia South Site	13.4	4.9	4.1	2.7	25.0
Caledonia OECC	3.6	4.7	1.8	1.1	11.3
Average	7.2	4.2	2.4	1.6	15.4

Considering the percentage of fines in the Caledonia OWF and along the Caledonia OECC (Table 1) the source terms given in Table 2 are applied in the model to simulate the passive plume dispersion during cable installation in the different areas.

Given the higher percentage of fine sediment in the Caledonia South Site, the source terms are highest for interconnector and inter-array cable installation as part of Caledonia South (up to 79.0 kg/s) and lowest for export cable installation (35.8 kg/s).

Four different representative grain sizes are applied in the model (90 µm representing very fine sand, 40 µm representing coarse to medium silt, 10 µm representing fine silt and 2 µm representing clay). Overall, these modelled source terms account for 3.4 to 7.5% of the total sediment disturbance.

Table 2. Source terms for cable installation.

Activity	Array Area Source Term (kg/s)		Export Cable Source Term (kg/s)
	North	South	
Cable Installation	45.4	79.0	35.8

A moving source term is applied in the model to simulate the cable installation at the appropriate cable installation rate. To provide a conservative assessment, the source term is applied at a height of 5 m above the seabed.

The model simulates the dispersion of sediment during 29.5 days of cable installation activity, with no sediment release during the last 12 hours (totalling the installation of 495.6 km of cable which is 86% of the total maximum expected cable length). Based on the construction approach and considering the higher percentage of fines in the Caledonia South Site compared to in the Caledonia North Site, the installation of the export cables and interconnector and inter-array cables for Caledonia South is simulated in the model, as this presents a worst case for the two developments. The disturbance of fine sediment during installation of the export cable would be the same for Caledonia North as for Caledonia South, while the disturbance of fine sediment during installation of the interconnector and inter-array cables would be lower (by around 40%) for Caledonia North compared to Caledonia South.

The inter-array cable layout or interconnector cable routes are not known at this stage. The route applied in the model is therefore indicative, selected to give the cable lengths as outline above. The export cable installation in the model follows two tracks from the Landfall Site to indicative OSP locations within the Caledonia South Site. The interconnector cable then runs between the two OSP locations and inter-array cables run from each WTG location to one or other of the OSPs.

In reality, there will be some downtime due to weather, equipment and vessel maintenance and repositioning. However, the continual installation adopted in the model provides a worst-case assessment.

2.1.3. Horizontal Directional Drilling

Horizontal directional drilling (HDD) will be used to install the export cables across the shallower subtidal areas along (indicatively) 1.2 km of the Caledonia OECC at the Landfall Site. Each export cable will require a single 0.86 m bore (for a 0.63 m duct).

HDD across the shallower subtidal areas close to the Landfall Site will release some sediment to the marine environment, although the majority will be recovered at the entry point and sent for disposal on land. The loss of soil to the sea is expected to be around 47 m^3 per cut, equating to a mass in the range of 70,500 kg to 117,500 kg per cut (depending on whether drilling through surficial sediments of sands and clays with a density of 1,500 kg/m^3 or through the underlying bedrock layer which has a density of 2,500 kg/m^3). In addition, 450 m^3 of bentonite (drilling muds used as lubricant) is also expected to be released per cut. The density of the bentonite is 2,200 kg/m^3, assuming this is a mix of muds and freshwater yields a sediment mass of 1,927 kg/m^3 of bentonite, equating to a dry sediment mass of 867,000 kg.

The HDD works are estimated to take around 56 days per cut assuming 12 hours operation per day. This totals approximately 672 hrs for HDD ducting for a single line. However, the release of sediment to the marine environment is only expected to occur at ‘pop-out’ (i.e. where the duct connects with the offshore trench) and as such the sediment release would occur over a short period of time. Assuming all sediment is released in one hour and adopting a conservative assumption that all sediment is bedrock which is completely broken down to fines by the drilling would yield a source term of 32.6 kg/s for the cuttings and an additional 240.9 kg/s for the drilling muds.

Some of the sediment released will rapidly fall to the seabed as a dynamic plume. The far field model cannot simulate this process and as such the inclusion of the full sediment release in the model would not be appropriate. Becker *et al*. (2015) provided estimates of source terms of sediment available for passive transport as a percentage of sediment disturbed by different dredging methods. These are typically in the range of 3 to 20% being highest for overflow from a trailing suction hopper dredger. Adopting the most conservative value of 20% of the sediment release initially remaining in suspension as a passive plume yields a sediment release rate of 6.5 kg/s for drill cuttings (with an even split between the three representative grain sizes for clay, fine silt and coarse silt) and 48.2 kg/s for drilling mud. The actual PSD of the bentonite is not known but is simulated in the model as 50% clay (with a representative grain size of 2 µm), 30% fine silt (with a representative grain size of 10 µm) and 20% coarse silt (with a representative grain size of 40 µm).

This source term is applied at a single location approximately 1.2 km from the Landfall Site in a water depth of 23.4 m below MSL. The model simulation only considers the release of sediment from the pop-out release from one cut.

2.1.4. Foundation Installation

For foundation installation the two options under consideration are drilling and piling. Of these two options, drilling has the potential to release larger volumes of fine sediment into the water column.

Several structure options are being considered including monopiles and jackets (with the latter considering both pin piles and suctions caissons) for Caledonia North and Caledonia South. In addition, fully restrained platforms and floating structures (including semi submersible and tension leg platforms (TLP)) are being considered for the deeper area of the Caledonia South Site (the area to the south of the yellow boundary shown in Figure 1). The volume of sediment disturbed would vary with structure type. The drilling of the foundation for the monopile structures (which would have up to a 14 m diameter on the bed) results in the highest sediment disturbance rate and for the longest duration compared with all other bottom-fixed and floating foundation types. The drilling of the monopile foundations has therefore been considered in the modelling assessment of construction related impacts.

The monopile foundations will be drilled to a depth of 50 m below the seabed at a rate of 0.25 m per hour. This yields a volume of 7,700 m^3 for each monopile WTG foundation, with the drilling expected to take approximately 200 hours (8.3 days) for each WTG. Only one foundation will be drilled at a time. It is unknown whether the spoil from the drilling would be released at the seabed or at the surface of the water column. Based on this, the worst case assumption of the drill arisings being released at the surface of the water column has been adopted.

The composition of the drill arisings will depend on the properties of the layer being drilled through. For the surface layer (assumed to be the upper 5 m), the drill arisings will have the composition of the surficial sediments.

For the underlying bedrock, the composition of the drill arising will depend on how the bedrock breaks up during drilling, which in turn depends on the properties of the bedrock. Areas of chalk and mudstone occur across the site. Monitoring of drill arisings from drilling through chalk at the Lynn and Inner Dowsing wind farm site indicated that around 50% of samples obtained during drilling had a diameter of less than 63 µm (Centric Renewable Energy Ltd, 2007). Assuming that 50% of the chalk breaks into fines during drilling and adopting the upper density value of 1,850 kg/m^3 for chalk and upper drilling rate of 0.25 m/hr gives a fine sediment disturbance rate of 9.9 kg/s. No studies have been identified which have monitored drill arisings for drilling through mudstone and it therefore conservatively assumed that all of the mudstone will breakdown into fines during drilling. Based on this and adopting the upper density value of 2,200 kg/m^3 for mudstone and upper drilling rate of 0.25 m/hr gives a fine sediment disturbance rate of 23.5 kg/s. The model therefore considers drilling through mudstone rather than through chalk, as this is a worst case for sediment release rates.

The exact PSD of the mudstone is not known but a conservative assumption is that 100% is mud-sized particles and in lieu of detailed lab analysis, an even split is assumed for three representative particle sizes (40 µm, 10 µm and 2 µm).

Some of the sediment released will rapidly fall to the seabed as a dynamic plume. Considering only the sediment which will initially remain in suspension in a passive plume by adopting a conservative value of 20%, a source term of 1.0 kg/s and 4.7 kg/s has been applied in the model to represent the passive plume dispersion associated with drilling through surficial sediments and mudstone, respectively. This modelled release accounts for just under 19% of the total sediment volume disturbed by drilling for each foundation.

For the purposes of modelling it is assumed that drilling will be continuous during the installation of each foundation and that there will be a 16 hour gap between drilling subsequent foundations. The model simulation is 30 days in duration allowing the simulation of the drilling of three complete foundations and three days of a fourth foundation. Four WTGs located within the Caledonia South Site have been selected for consideration in the modelling (see Figure 2). These locations were selected as lying in an area of higher peak tidal and residual flows and for their proximity to the Southern Trench Marine Protected Area (MPA). Drilling at more southerly WTG locations could result in a sediment release in closer proximity to the Southern Trench MPA than simulated in the model but the extent of any plume would be expected to be smaller than predicted for the selected locations.

2.2. Operation

The blockage effect of the WTG foundations during operation results in local changes to flows and waves. The blockage will depend on the size and spacing of the structures. As noted in Section 2.1.4 several foundation options are being considered.

For bottom-fixed foundations it is widely accepted that jacket structures exert a smaller influence on flows and waves than solid structures such as gravity base or monopiles. However, one option within the design envelope is a jacket structure with a suction caisson foundation. The suction caissons have a cylindrical shape with a 15 m diameter while the primary members of the jacket have a diameter of 5 m. There are up to four suction caissons per jacket structure (one per leg). The height of the caisson above the bed level will depend on the penetration into the bed; the caisson has a height of 45 m and between 15-30 m of this will be below the seabed. Assuming the caissons extend to 30 m above the seabed and taking account of the primary and secondary members of the jacket structure the blockage is equivalent to that of an 11.5 m diameter pile throughout the full depth (in a water depth of 60 m), with up to four of these per structure. Sensitivity testing with the hydrodynamic and wave models found that the jackets with suction caissons resulted in a slightly larger impact on the flows and waves than monopiles. The jackets with suction caissons therefore represent the Maximum Design Scenario (MDS) for impacts on flows and waves and these are represented in the model to assess the operational effect of the OWF for all bottom-fixed WTG locations.

For Caledonia South, structures will either all be bottom-fixed, or a mixture of bottom-fixed and floating (with up to 39 floating WTGs). Foundations would be bottom-fixed only in the shallower parts of the Caledonia South Site, while the deeper southern area could include bottom-fixed or floating foundations. The blockage effect of floating WTG foundations is mainly constrained to the upper part of the water column. The semi-submersible design has a draught of 20 m, with three columns of 17.2 m diameter, while the TLP design has a 15 m diameter central column with a draught of 30 m plus three radial arms with a height of 14 m (from 16 m below to 30 m below water line), 11 m wide and 48.5 m long.

Based on the design envelope dimensions noted above, the TLP would have a greater operational impact on flows and waves than the semi-submersible (with a greater cross sectional area obstructing flows and waves).

Sensitivity testing with the hydrodynamic (HD) and Spectral Wave (SW) models found that the jackets with suction caissons resulted in a slightly larger impact on the flows but that the TLP’s had a larger impact on the waves. The larger impact of the TLP on waves results from wave energy being greatest at the surface where the floating structures present a larger blockage, although the method adopted to represent the TLP in the SW model may also be a factor. The SW model accounts for the effect of the structures by the addition of a decay term to reduce wave energy in the lee of the structure. This decay term is the difference in the significant wave height upstream and downstream of the structure (also known as the wave transmission). The transmission of fixed structures for slender piles such as for bottom-fixed WTG foundations is calculated using Morison’s equation. This approach accounts for the blockage effect at differing depths in the water column for waves of a given periodicity and height. The Morison equation is not applicable to structures such as TLP (since they have large dimensions relative to the wavelength and they float so are not slender piles) and the derivation of suitable transmission values for such structures is complex and is likely to be sensitive to the orientation of the structure relative to the wave direction. A review of transmission theories for different structure types was undertaken by Biescheuvel (2013). Of the theories considered, that of Macagno (1954) is the most applicable to the TLP, although a number of Macagno’s assumptions remain invalid. The transmission was calculated using both Morison’s equation and the approach of Macagno (1954) and results from the two approaches were compared. The Morison’s equation provided lower transmission values than the approach of Macagno for longer period swell waves (such as occur for the storm conditions modelled from offshore directions) and similar transmission for the shorter period waves (as would occur from offshore for more typical wave conditions and for the storm conditions modelled from the onshore directions). For conservatism the transmission derived from the Morison's equation was therefore adopted throughout.

The MDS for flows is for jackets with suction caissons, while the MDS for waves is for a mixture of jackets with suction caissons and TLP, with the maximum possible number (39) of TLP.

The locations of the WTGs are influenced by:

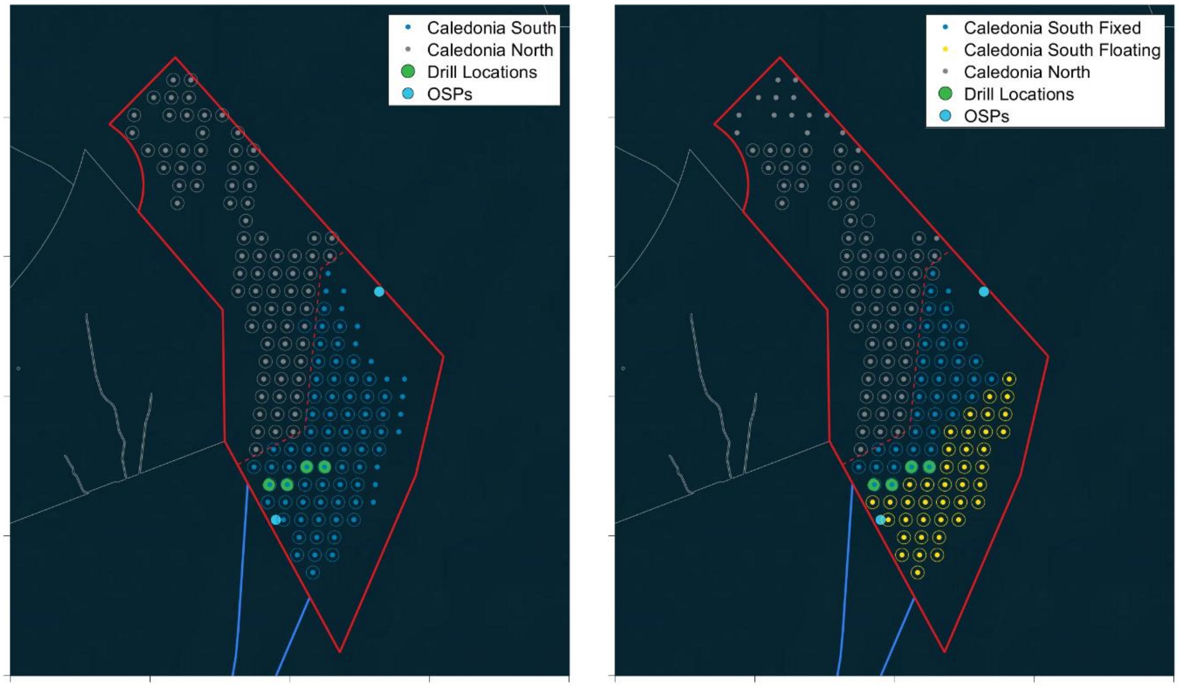
- The turbine number;
  - Caledonia North application will include up to 77 WTGs;
  - Caledonia South application will include up to 78 WTGs; and
  - The Caledonia OWF will include up to a maximum of 140 WTGs, with a potential split of 63:77 WTGs between the two applications; and
- The turbine spacing – this is assumed to be around 4 to 6 times the rotor diameter. The minimum array spacing would provide a worst case for blockage (i.e. 4 times rotor diameter). It is noted that minimum WTG spacing within the design envelope is 944 m; however, if the final WTG layout was based on this spacing, the overall coverage and area of (potentially slighter larger magnitude) impacts through blockage effects would be constrained to a smaller spatial impact. Therefore, it has been assumed that used of 4 times rotor diameter presents a realistic worst case assumption to inform modelling.

Local constraints such as proximity to existing OWF developments, relict wells, subsea cables, water depths and seabed features will also influence the actual layout of the Proposed Development (Offshore). Considering the spacing and the known local constraints, potential WTG locations were identified and used to develop MDS layouts (Figure 2), which were adopted in the modelling assessment of operational impacts. The MDS layout for flows selected locations in the shallowest water depths and with the lowest spread (i.e. to give the highest concentration of structures) to give the highest potential impact. The selection of other WTG locations, for example in the deeper water to the south of the Caledonia South Site, would be expected to result in a smaller operational impact in both magnitude and extent, but would change the location of the area of the impact (by up to 8.5 km to the south and 3.6 km to the east). This potential for a shift in impacted area should be considered when assessing the potential impact on receptors.

The Greater Gabbard OWF EIA (ABPmer, 2005) reported that; "*It has been previously agreed with both DEFRA and CEFAS that it is the greater number of smaller sized, smaller spaced structures that represent the 'worst-case' arrangement rather than the lower number of larger, bigger spaced turbines*". However subsequent studies (for example the East Anglia One OWF EIA (Royal Haskoning DHV, 2019) reported that "*For the windfarm site as a whole, it is not possible to quantify whether a larger number of smaller rated wind turbines would cause worse blockage than a smaller number of larger rated wind turbines (or some combination in between) without detailed numerical modelling. As a conservative approach, the largest dimensions for a GBS (the 300m wind turbine foundation) together with the greatest number of wind turbines (the 250m layout) have been adopted as a worst case scenario. Whilst these arrangements would not be used in practice, their consideration avoids potential uncertainty if different combinations were considered*".

Consistent with the approach applied for East Anglia One OWF the modelling assessment for the Proposed Development (Offshore) considers the largest dimensions along with the greatest number of WTGs to ensure full flexibility in the consented design.

In addition, an in combination assessment, which includes a representation of structures from other nearby proposed floating OWFs, has been undertaken. The in combination scenario includes the blockage effect of floating structures for the Stromar (71), Broadshore (60), Sinclair (6) and Scaraben (6) OWF's, with the number in brackets being the number of WTGs included (based on published scoping reports or estimated from the site capacity). All structures are assumed to be TLP with the same dimensions and spacing as adopted for the Proposed Development (Offshore), with layouts developed to provide the smallest distance from the Caledonia Site.



Circled WTG locations are included in modelling for the Proposed Development (Offshore).

Figure 2. Indicative layout for Caledonia North and Caledonia South for flows (left) and waves (right) used to inform modelling

The Caledonia OWF will consist of fifteen fewer WTGs than the combination of Caledonia North and Caledonia South modelled and assessed in isolation, with a total number for the two application areas combined not exceeding 140 WTGs. Indicative layouts have been developed for Caledonia North, Caledonia South and Caledonia OWF to reflect these WTG numbers. Different turbine locations were included in the flow and wave models, with the flow model including the more northerly locations in shallower water (to give a larger impact on flows) and the wave model including the deeper southerly locations where floating structures could be used (to give a larger impact on waves).

PORT & COASTAL SOLUTIONS

3. Characterisation of the Existing Environment

This section provides an overview of the existing hydrodynamic and wave conditions in the study area to provide a characterisation of these key metocean conditions for the existing environment.

3.1. Hydrodynamic Conditions

Plots of the modelled water level across the Caledonia OWF, Caledonia, Caledonia North and Caledonia South OECCs and the surrounding region are shown at the time of peak flood (PF), high water (HW), peak ebb (PE) and low water (LW), for mean neap and spring tides in Figure 3 and Figure 4, respectively. The times of PF, HW, PE and LW vary across the model domain and the selected model timesteps are based on the timing of the tide within the Caledonia OWF as follows:

- PF: the time at which flows are at a maximum before HW on the selected tide;
- HW: the time at which water level is at a maximum on the selected tide;
- PE: the time at which flows are at a maximum after HW on the selected tide; and
- LW: the time at which water level is at a minimum on the selected tide.

Plots of the minimum and maximum water levels over a mean spring tide are also shown in Figure 5 to demonstrate the tidal range in the wider region, as the timing of the tide changes away from the Caledonia OWF.

The plots show the following:

- The similar levels at PF and HW and at PE and LW indicate that the fastest flows occur close to the time of HW and LW rather than at mid-tide level;
- Water levels are relatively uniform across the Caledonia OWF;
- The Caledonia OWF has a mean spring tidal range of 2.8 m, and a mean neap tidal range of 1.4m;
- The tidal range increases into the Moray Firth;
- The largest tidal range (i.e. lowest low water and highest high water) occurs in the inner Moray Firth and to the west of the Orkney Islands; and
- Comparing the plots at HW and LW during a mean spring tide to the plots of the maximum and minimum water level over the spring tide shows notable differences in water levels to the west of the Orkney Islands, indicating that there is a phase difference between the timing of HW and LW to the west and east of the Orkney Islands.

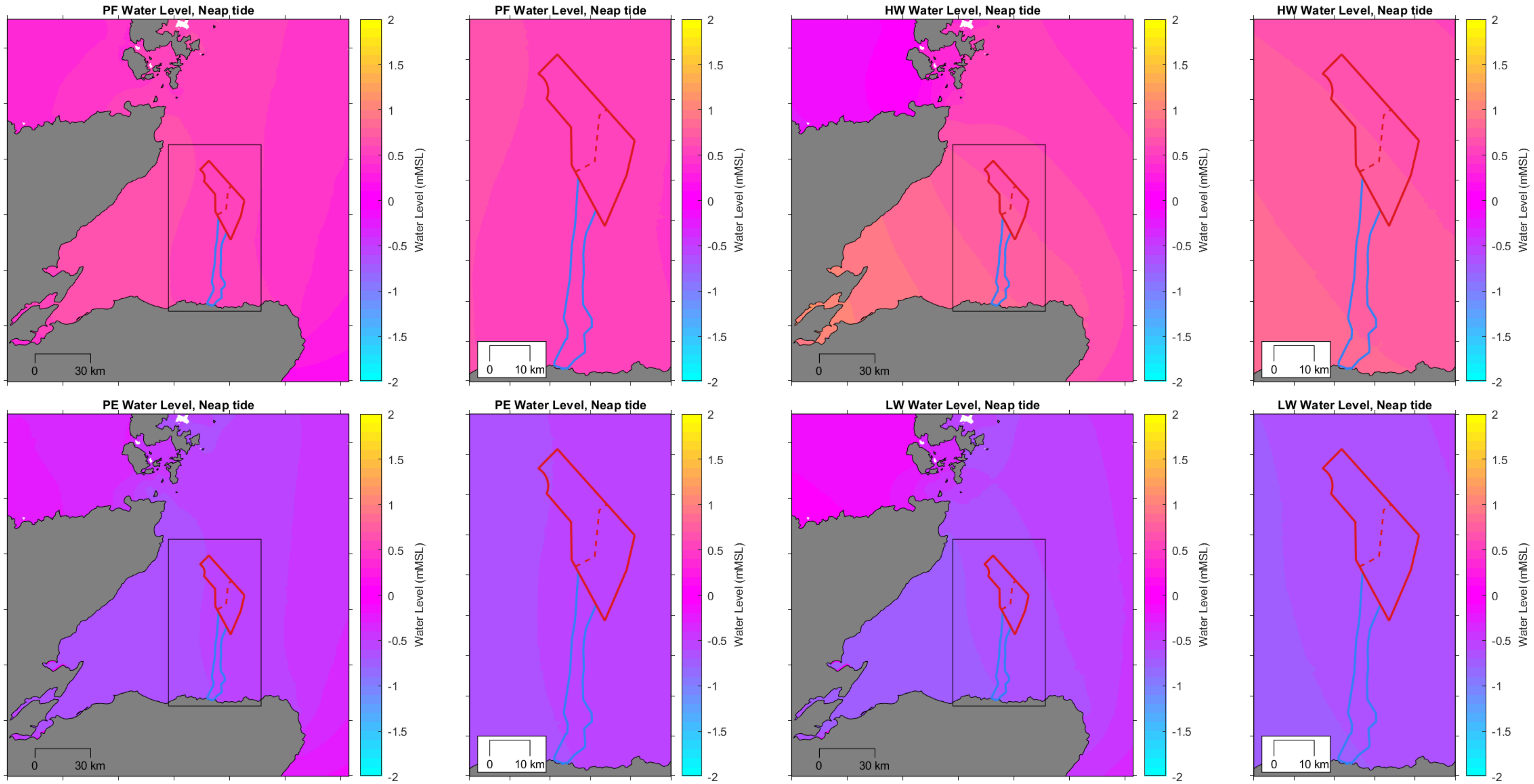


Figure 3. Modelled water levels at varying tidal stages across the Proposed Development (Offshore) during a mean neap tide.

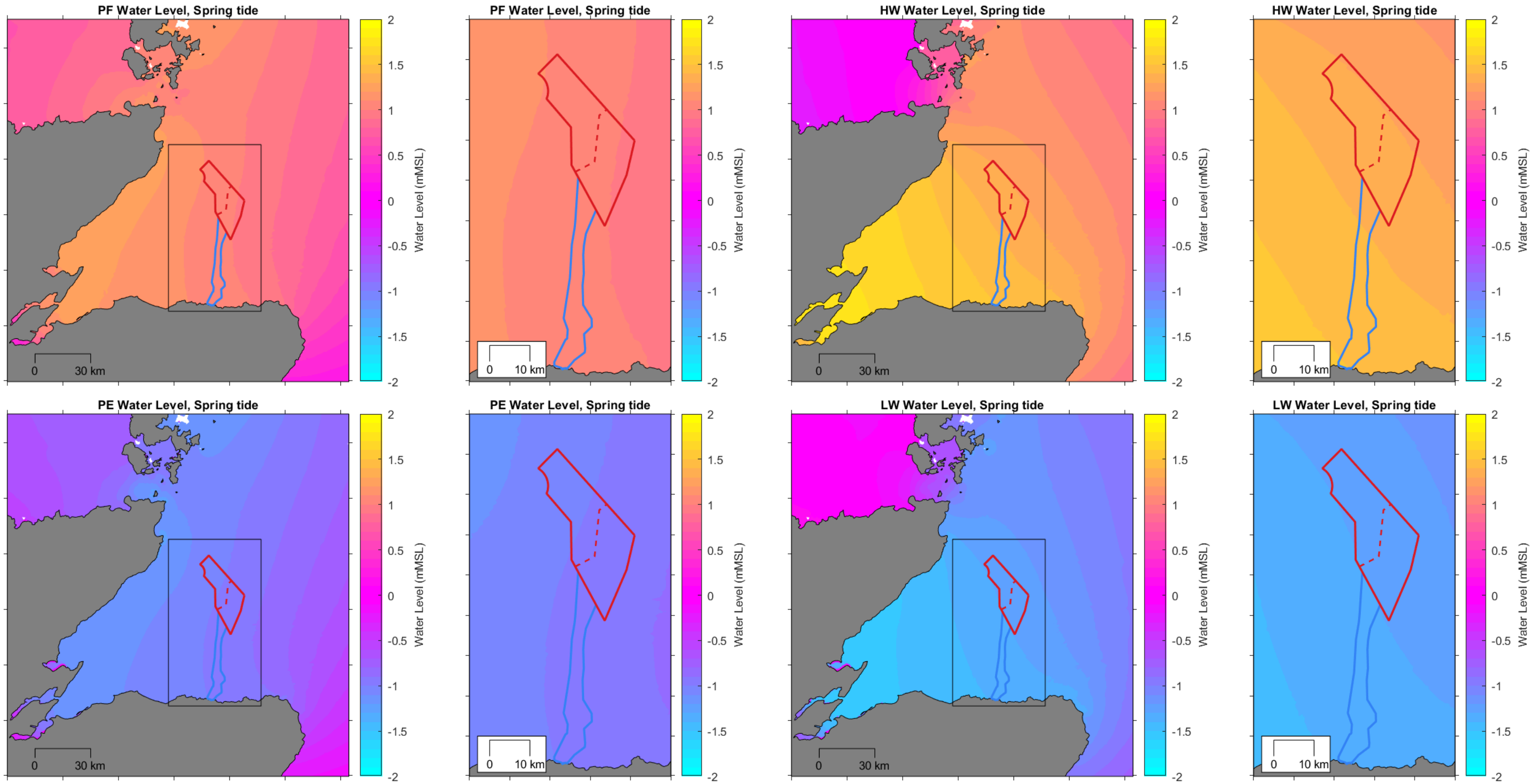


Figure 4. Modelled water levels at varying tidal stages across the Proposed Development (Offshore) during a mean spring.

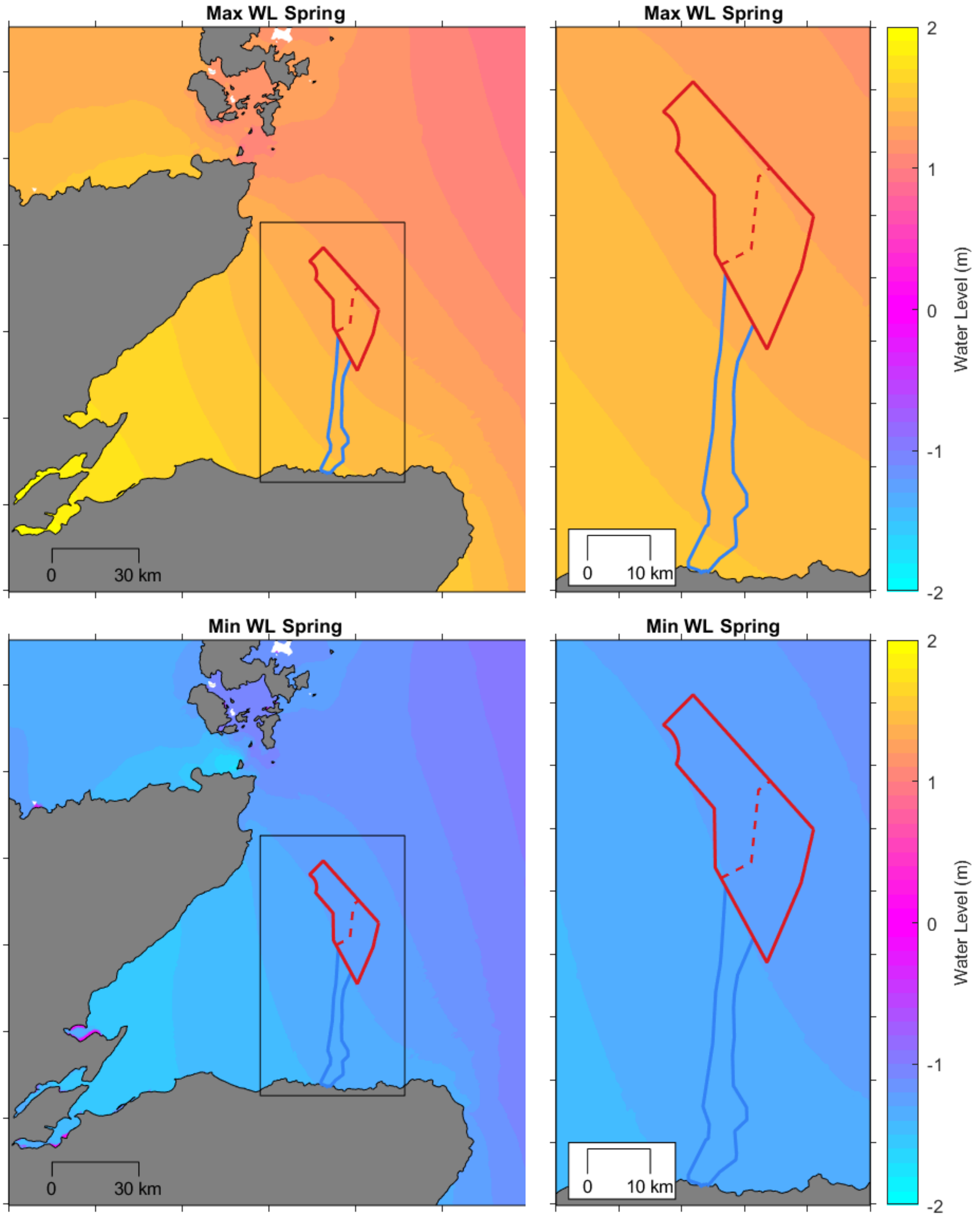


Figure 5. Modelled maximum and minimum water levels across the Proposed Development (Offshore) during a mean spring tide.

Map plots of the current speed across the study area are shown in Figure 6 for the times of PF and PE during mean neap and spring tides. As for the water level plots, the times relate to the timing of the tide within the Caledonia OWF. More detailed flow plots of mean spring PE and PF conditions are also shown for the Caledonia OWF and Caledonia OECC. Due to the lower flows at the Caledonia OWF, compared to those from the wider model domain, the flows in the local scale plot adopt a different colour scale to wider scale flow plots. Plots of the residual tidal flows across the study area are shown for mean neap and spring tides in Figure 7 and over a 14.5 day spring neap tidal cycle in Figure 8.

The plots show the following:

- The highest current speeds in the model domain occur in the Pentland Firth, with speeds of more than 2 m/s at the time of PE and PF in the Caledonia OWF. As noted, there is a phasing difference across the model domain and as a result the peak flood and ebb flows at the time of peak flow in the Pentland Firth are higher than those shown in the figures here (as they are relative to the time of PF and PE in the Caledonia OWF);
- Within the Caledonia OWF the flood currents are to the south and the ebb currents are to the north;
- Peak current speeds within the Caledonia OWF are less than 0.7 m/s on spring tides and less than 0.4 m/s on neap tides, with the highest current speeds occurring in the Caledonia North Site;
- The residual currents are generally low during both mean spring and neap tides and over a 14.5 day spring neap tidal cycle, being less than 0.05 m/s throughout the Caledonia OWF; and
- There is a southward (to south westward) residual in the Caledonia OWF and an eastward residual along most of the Caledonia OECC.

Timeseries plots showing the water levels and flows at two sites within the Caledonia OWF (labelled as CalNorth and CalSouth for Caledonia North and Caledonia South, respectively) and three sites along the Caledonia OECC (OECC-North, OECC-Mid and OECC-South) are shown in Figure 10 to Figure 12 (see Figure 9 for site locations). Figure 10 shows the slight increase in water levels and later timing of HW from the CalNorth location in a southward direction to the OECC-South location, while Figure 11 shows the reduction in flow speed from the Caledonia North (CalNorth) location in a southward direction to the OECC-Mid location (current speeds at OECC-South are higher than at OECC-Mid due to the shoreline).

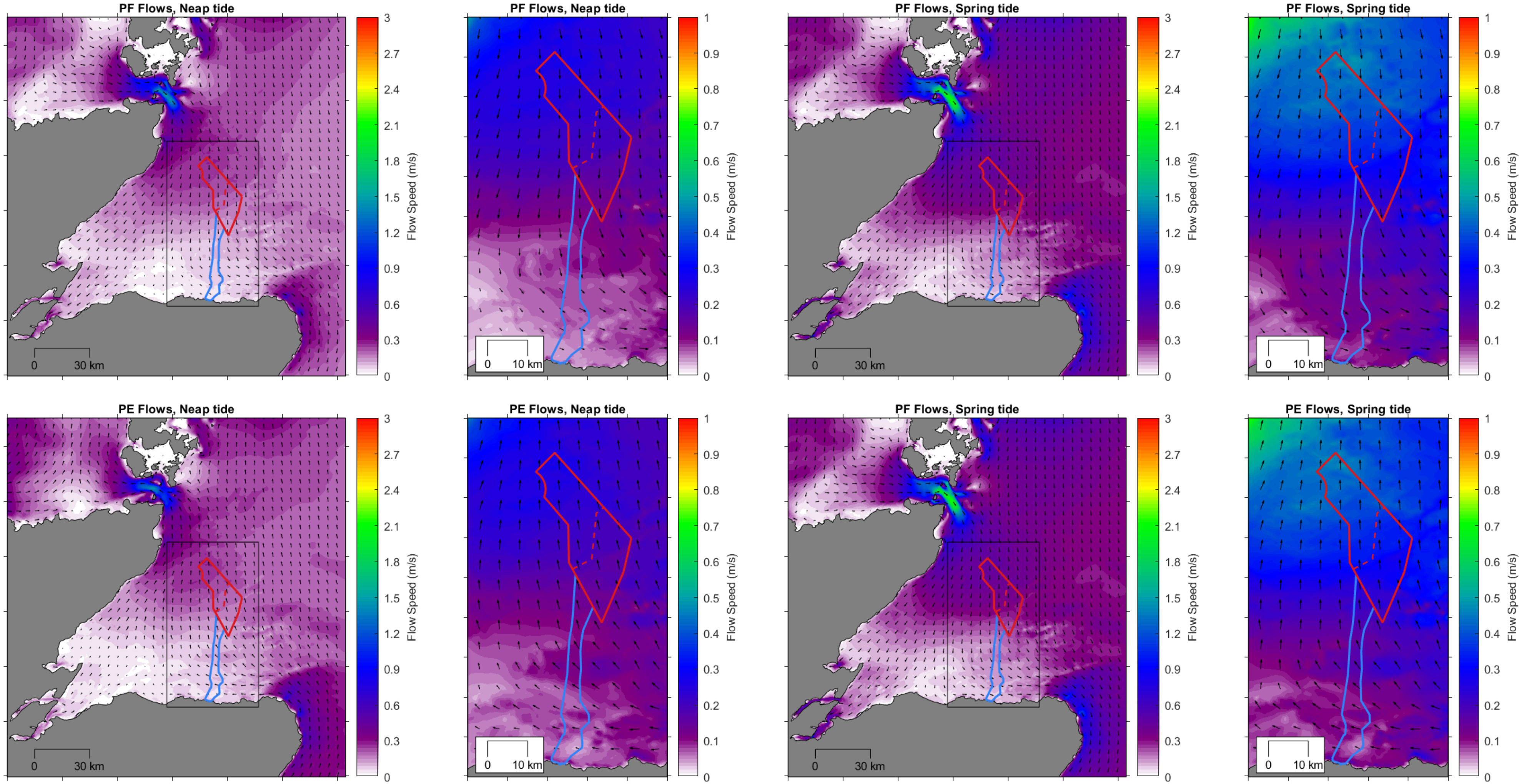


Figure 6. Modelled peak flood (PF) and peak ebb (PE) tidal flows during mean neap (left) and spring tides (right).

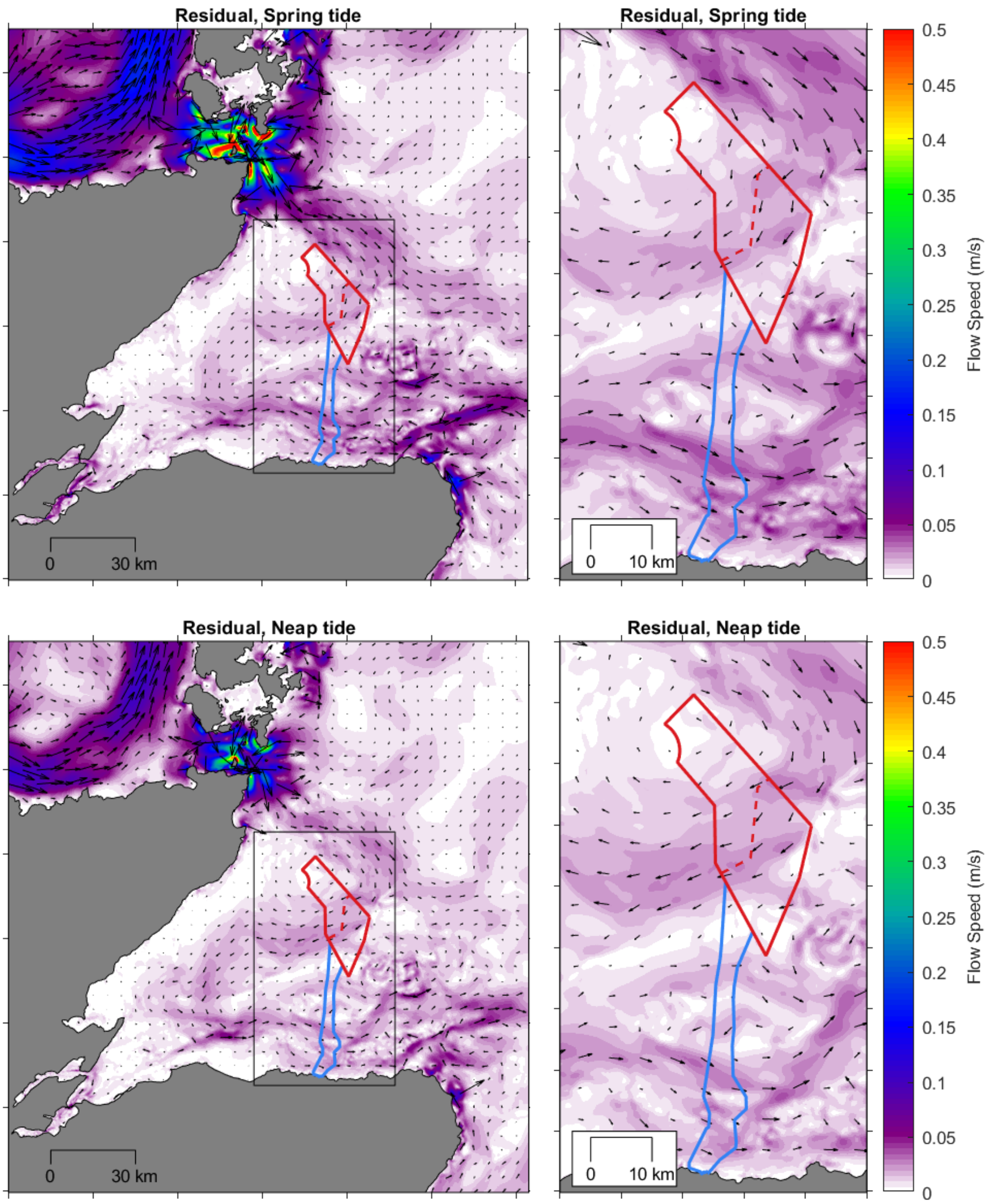


Figure 7. Residual tidal flow on mean spring (upper) and mean neap (lower) tides.

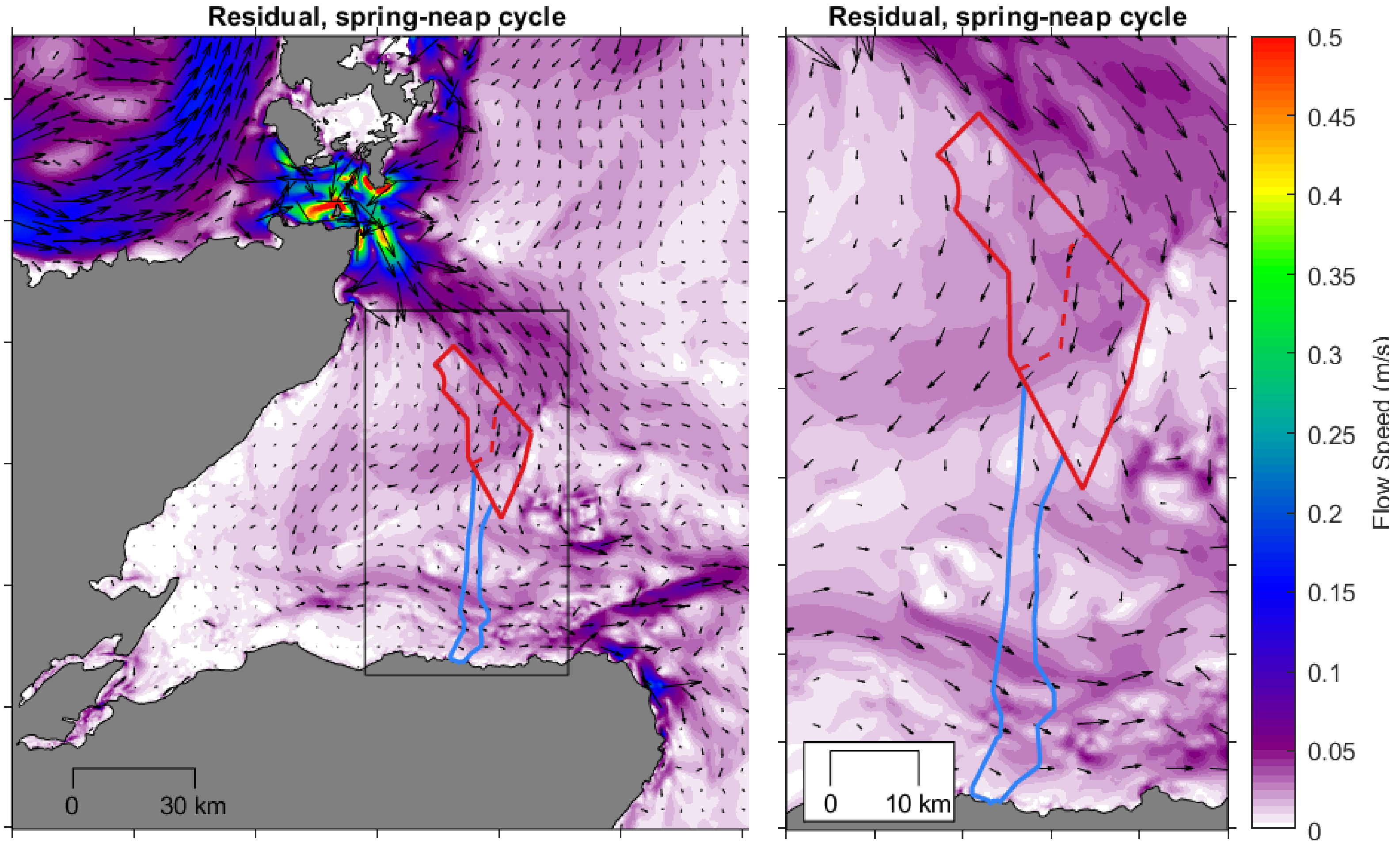


Figure 8. Residual tidal flow over a 14.5 day spring neap tidal cycle.

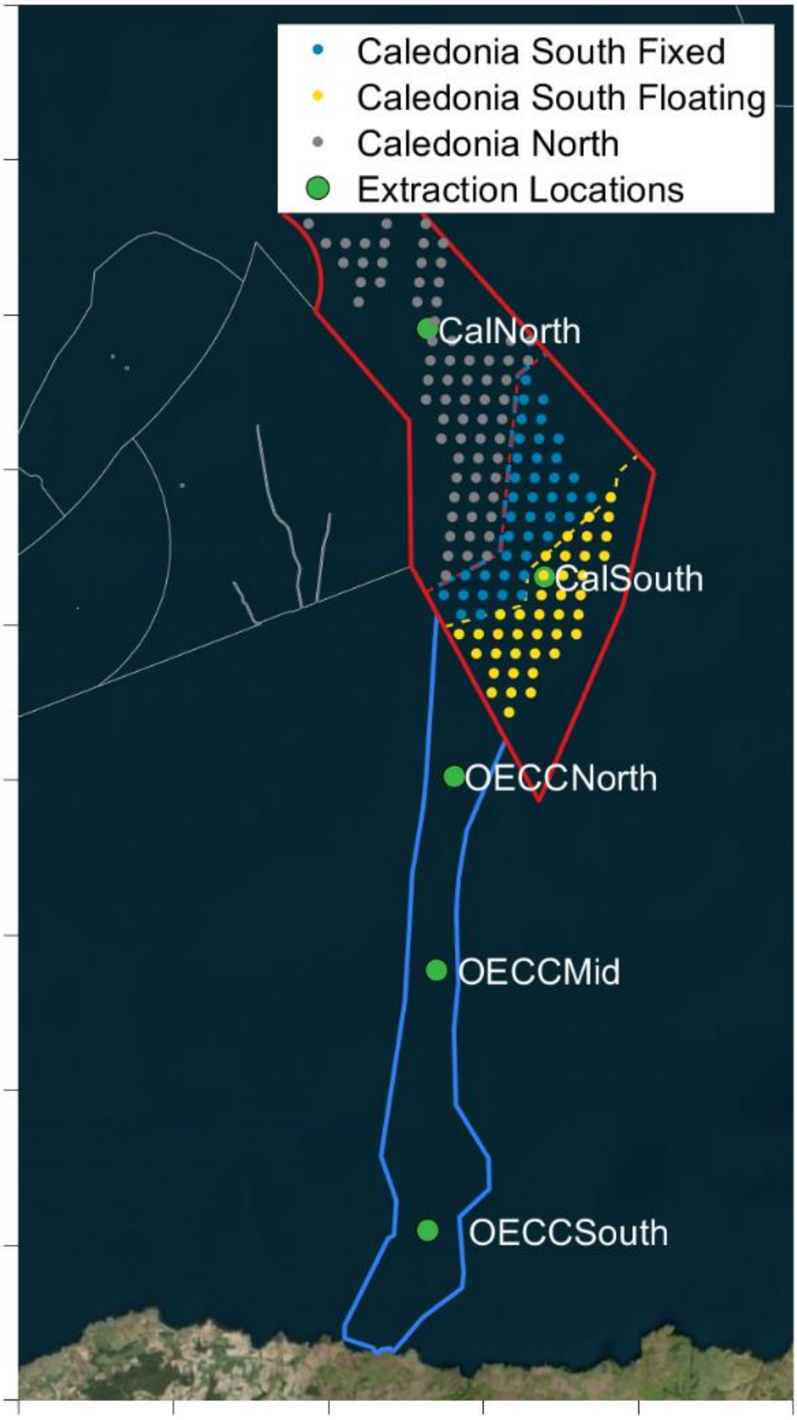


Figure 9. Extraction Locations.

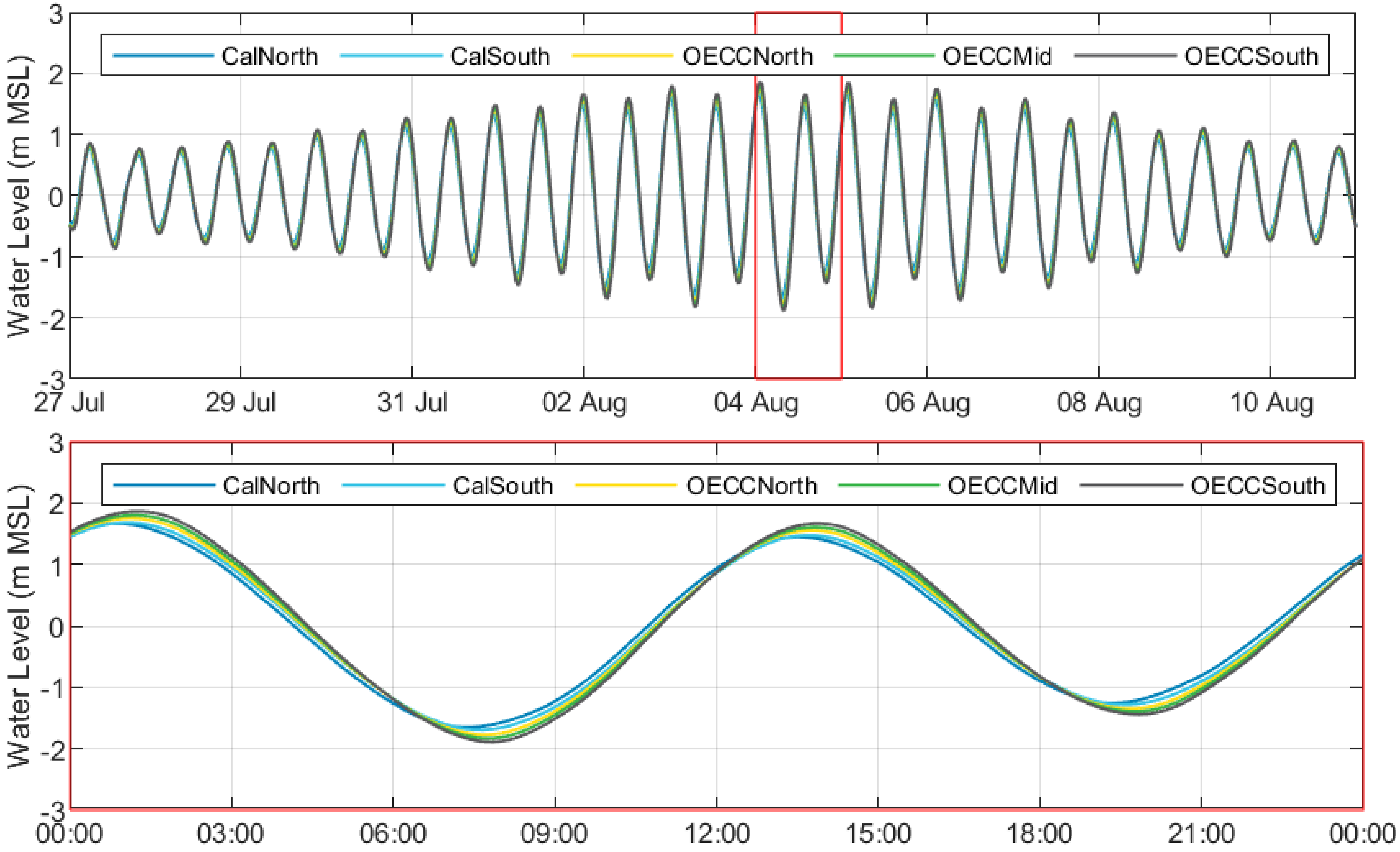


Figure 10. Timeseries plot of water levels at selected locations within the Caledonia OWF and along the Caledonia OECC.

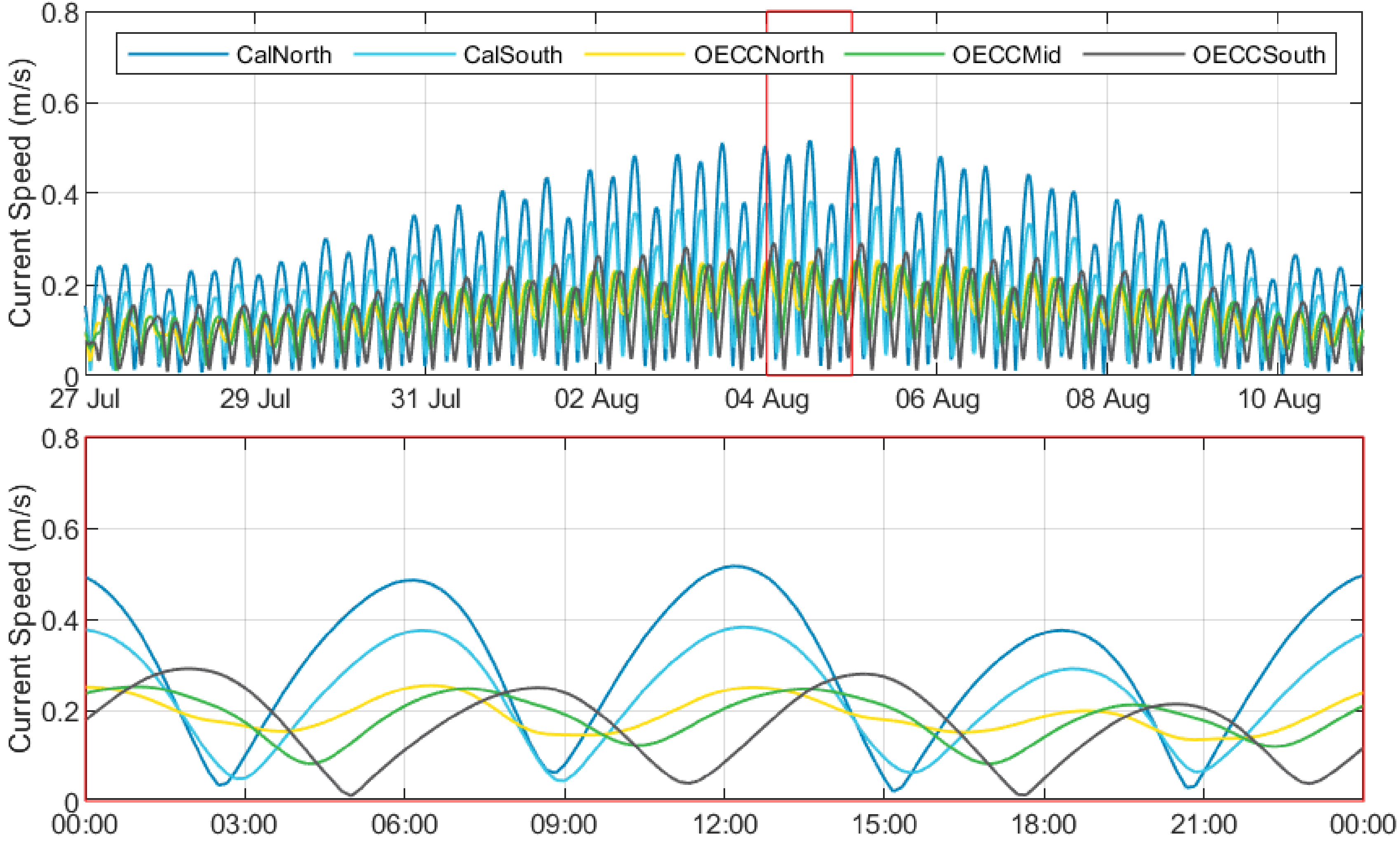


Figure 11. Timeseries plot of flow speeds at selected locations within the Caledonia OWF and along the Caledonia OECC.

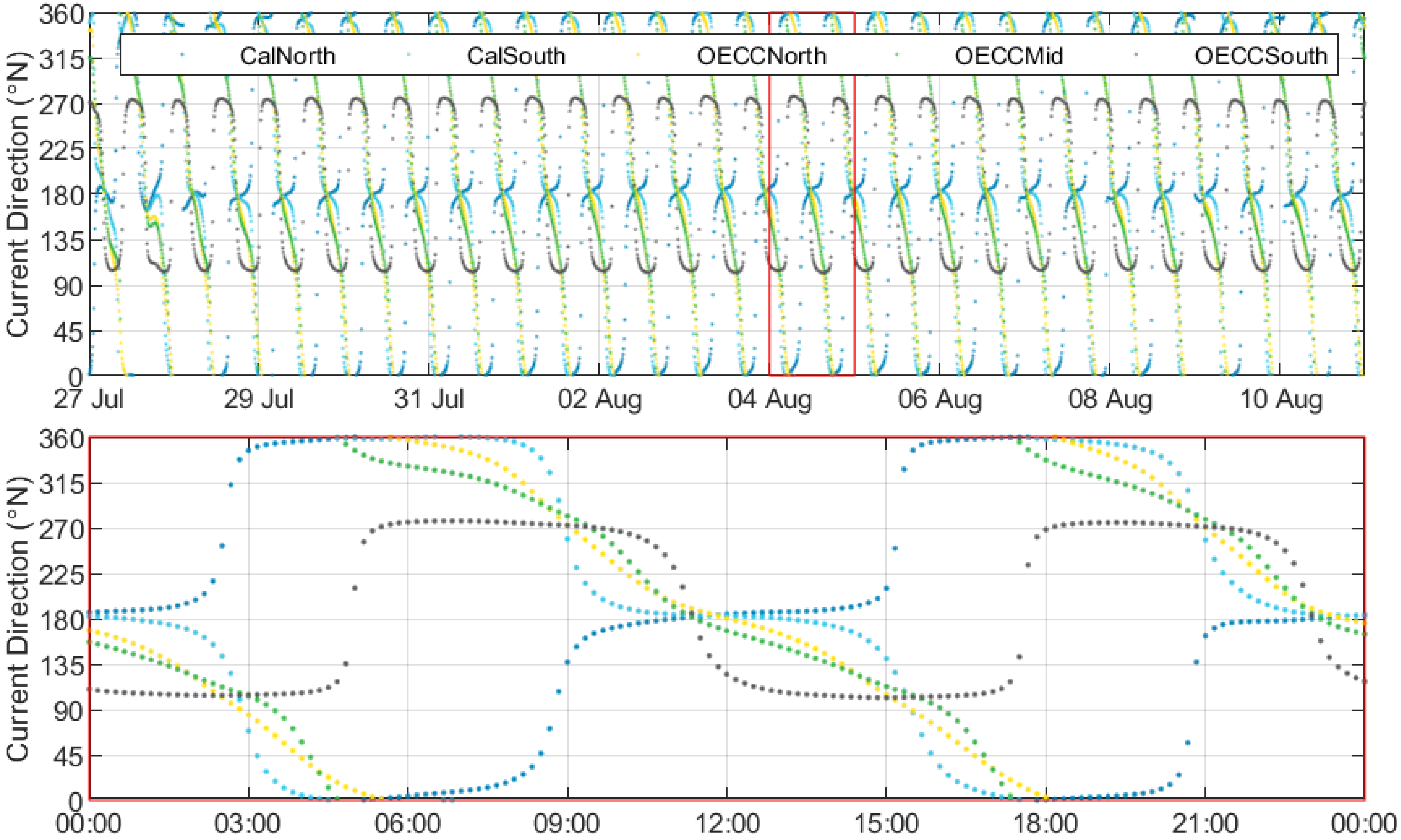


Figure 12. Timeseries plot of flow directions at selected locations within the Caledonia OWF and along the Caledonia OECC.

3.2. Wave Conditions

The SW model was setup to simulate the waves during extreme wave events including the 1 in 1, 1 in 10 and 1 in 50 year Annual Recurrence Interval (ARI) for eight cardinal directions (north, northeast, east, southeast, south, southwest, west and northwest). The significant wave height (H_s) is shown across the study area in Figure 13, Figure 14 and Figure 15, for the 1 in 1, 1 in 10 and 1 in 50 year events respectively. The plots show the following:

- H_s is relatively uniform through the Caledonia OWF for offshore generated waves (North, Northeast, East and Southeast), while for waves generated in the Moray Firth (South, Southwest, West and Northwest), waves build across the Caledonia OWF, and are higher in the eastern half (due to the increased fetch);
- H_s reduces at the landward end of the Caledonia OECC in response to reducing water depths; and
- The largest waves are from a northerly direction and the smallest waves are from a southerly direction.

Wave conditions (H_s, peak wave period (T_p) and mean wave direction) have been extracted from the model at five locations (see Figure 9), two within the Caledonia OWF (CalNorth and CalSouth) (Table 3), and three within the Caledonia OECC (OECCNorth, OECC-Mid and OECC-South) (Table 4). The results show the following:

- H_s ranges from 4 m (1 in 1 year ARI from south) to 8.6 m (1 in 50 year ARI from the northeast) at the CalNorth extraction location;
- H_s at the CalNorth and CalSouth extraction locations are typically within 0.5 m, except when waves are from the north to west sectors when differences are more than 1 m;
- T_p for the 1 in 1 year ARIs range from 8.7 to 13.2 seconds at the CalNorth extraction point, with the largest period from offshore sectors. T_p for the 1 in 1 year ARIs range from 8.6 to 13.3 seconds at the CalSouth extraction location;
- T_p increases for the higher return periods, with the highest period waves being 14.2 seconds at both the CalNorth and CalSouth extraction locations;
- Wave conditions are broadly consistent between the OECC-North and OECC-Mid extraction locations with H_s typically within 0.5 m, T_p within 0.2 seconds and mean wave directions within 10°, except when waves are from the south and southwest sectors;
- For waves from the south, H_s at the OECC-North extraction location is up to 1 m higher than H_s at the OECC-Mid extraction location; and
- Wave conditions change more notably at the OECC-South extraction location where shallower water depths dissipate wave energy and generally reduce the H_s (except when waves are from the north and northwest sectors).

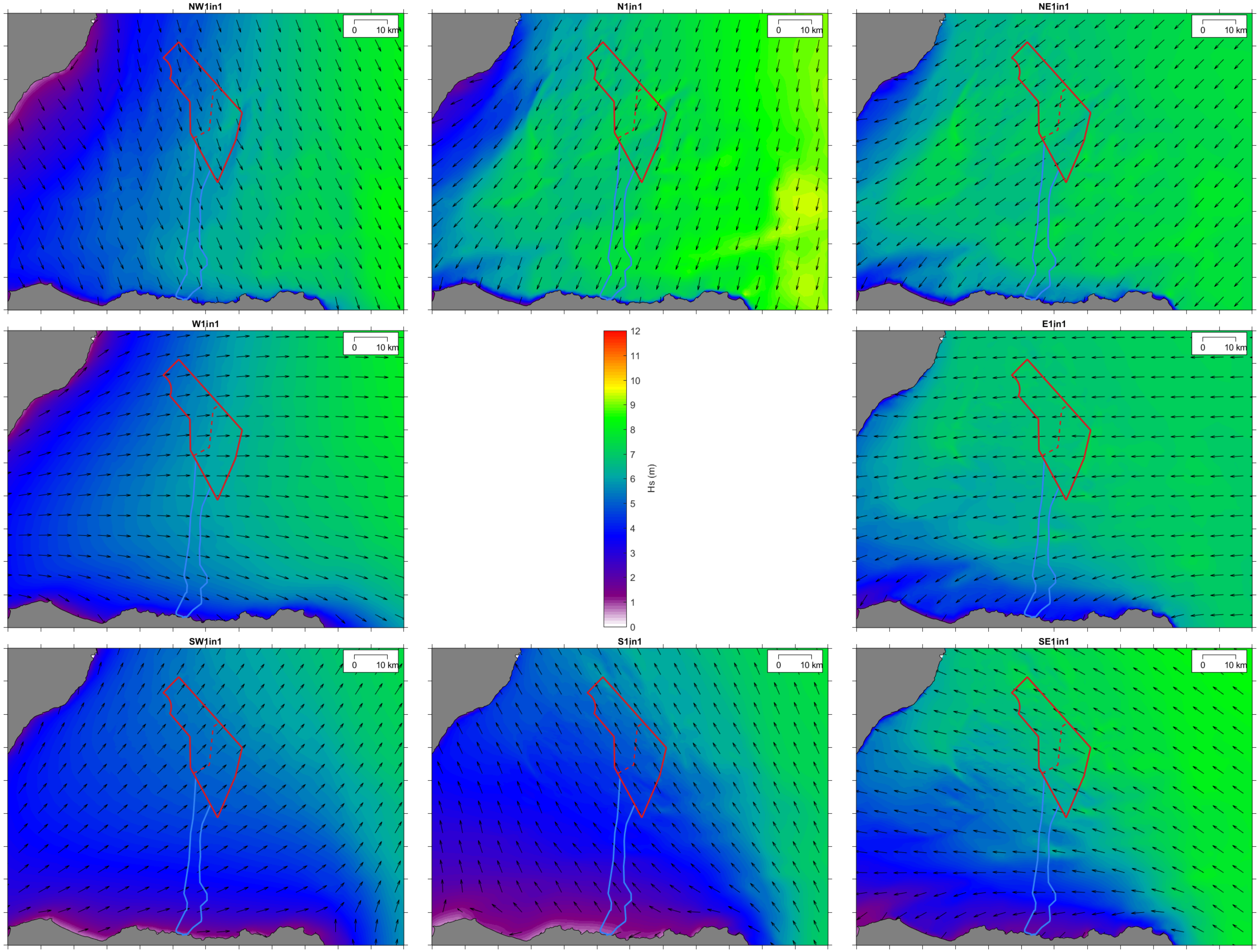


Figure 13. Modelled wave height and direction for the 1 in 1 year ARI events.

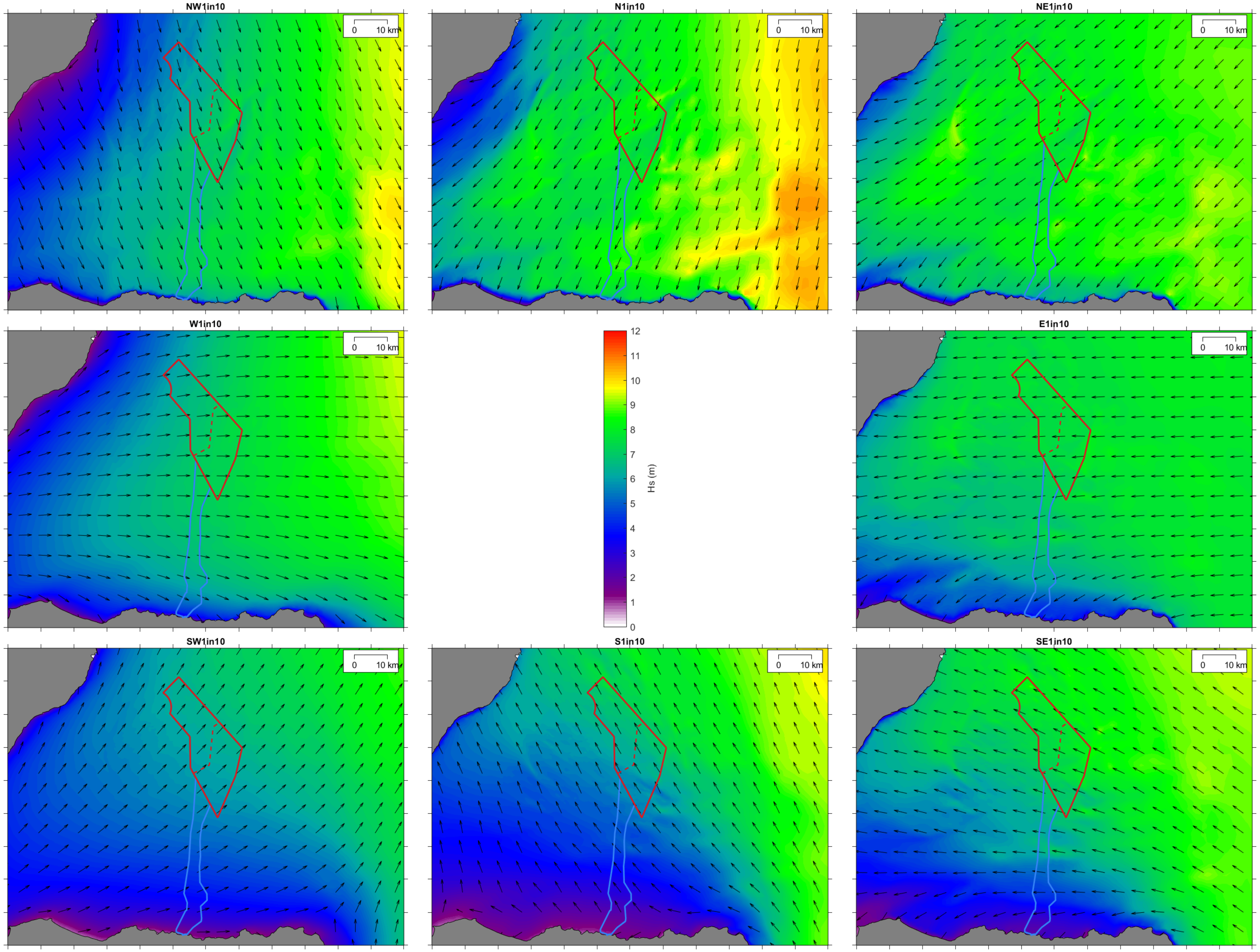


Figure 14. Modelled wave height and direction for the 1 in 10 year ARI events.

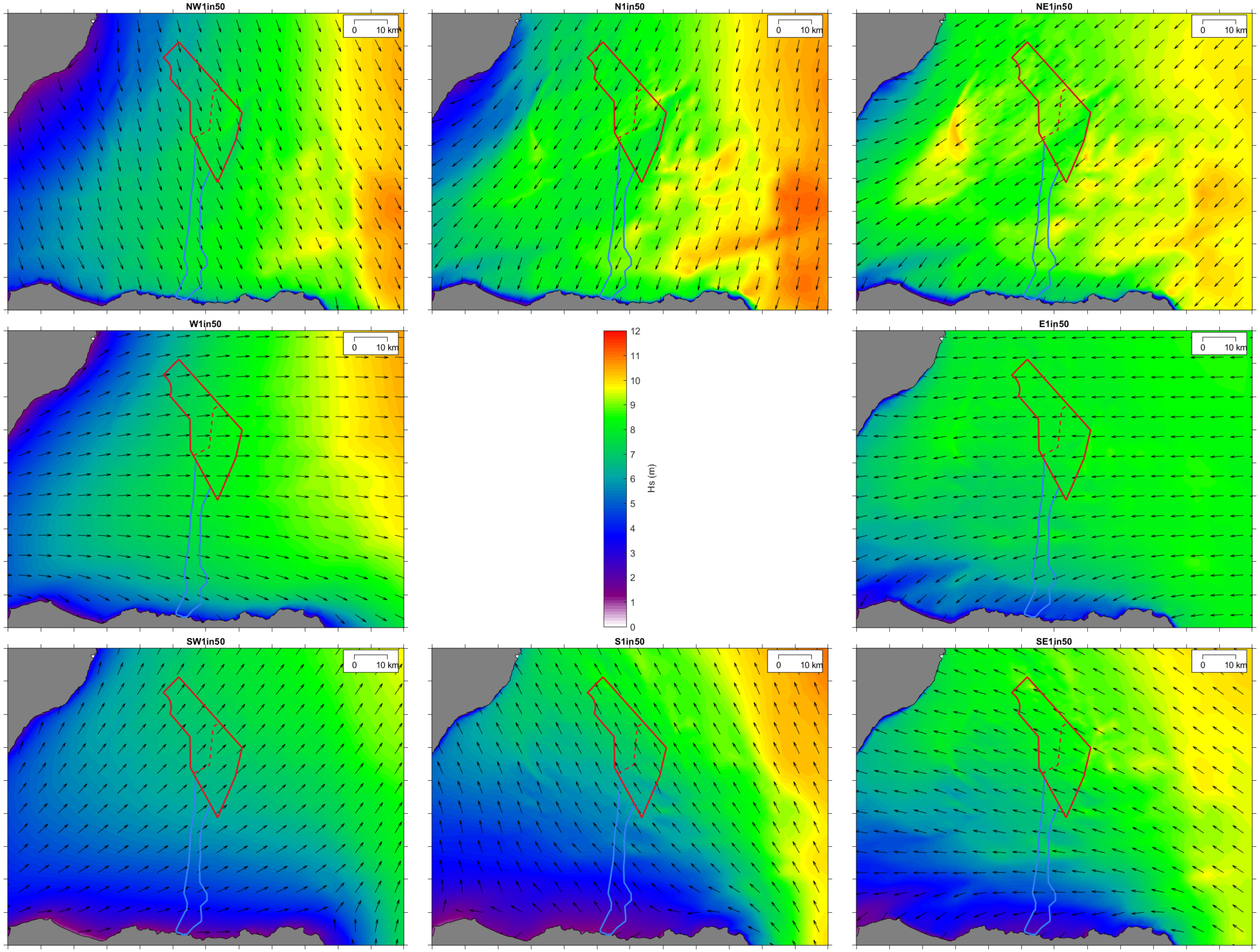


Figure 15. Modelled wave height and direction for the 1 in 50 year ARI events.

Table 3. Wave model results within the Caledonia OWF.

Wave Condition	CalNorth (526403; 6459119 UTM30N)			CalSouth (533934; 6443104 UTM30N)		
	H_s (m)	T_p (s)	Dir (º)	H_s (m)	T_p (s)	Dir (º)
North 1in1	6.5	12.6	27	6.9	12.7	22
North East 1in1	6.5	13.2	55	6.5	13.3	54
East 1in1	6.8	13.2	88	6.7	13.2	89
South East 1in1	6.9	13.2	113	6.8	13.3	111
South 1in1	5.2	10.8	150	4.8	10.5	147
South West 1in1	5.3	8.8	220	5.1	8.6	228
West 1in1	5.5	8.7	263	6.1	9.2	270
North West 1in1	5.0	9.4	340	6.0	10.4	344
North 1in10	7.3	13.0	27	7.7	13.1	22
North East 1in10	7.6	13.8	56	7.5	13.9	55
East 1in10	7.5	13.6	88	7.5	13.6	89
South East 1in10	7.8	13.6	113	7.7	13.7	110
South 1in10	6.8	11.6	150	6.2	11.3	147
South West 1in10	6.3	9.3	220	6.1	9.1	227
West 1in10	6.6	9.2	263	7.3	9.7	271
North West 1in10	6.1	10.0	341	7.2	11.0	344
North 1in50	7.7	13.2	27	8.1	13.2	22
North East 1in50	8.4	14.2	56	8.2	14.2	55
East 1in50	8.0	13.8	88	7.9	13.9	89
South East 1in50	8.4	13.8	113	8.2	14.0	110
South 1in50	7.5	11.9	150	6.9	11.6	147
South West 1in50	6.9	9.6	220	6.7	9.4	227
West 1in50	7.3	9.5	263	8.0	10.0	271
North West 1in50	6.7	10.3	341	7.9	11.3	344

Table 4. Wave model results within the Caledonia OECC.

Wave Condition	OECC-North (528119; 6430235 UTM30N)			OECC-Mid (526975; 6417746 UTM30N)			OECC-South (526403; 6400968 UTM30N)		
	H_s (m)	T_p (s)	Dir (º)	H_s (m)	T_p (s)	Dir (º)	H_s (m)	T_p (s)	Dir (º)
North 1in1	6.9	12.7	24	7.0	12.8	23	7.5	13.1	24
North East 1in1	6.7	13.2	55	6.9	13.3	53	6.6	13.5	44
East 1in1	6.5	13.1	84	6.6	13.2	79	5.0	12.9	63
South East 1in1	5.9	12.8	106	5.5	12.7	97	3.0	10.9	84
South 1in1	4.0	9.4	144	3.2	8.4	141	1.7	5.5	146
South West 1in1	4.7	8.1	232	4.1	7.5	239	2.7	6.1	251
West 1in1	6.0	9.0	272	5.8	8.8	278	5.0	8.5	293
North West 1in1	5.8	10.0	336	5.8	9.9	332	6.0	10.3	339
North 1in10	7.7	13.1	25	7.9	13.2	23	8.4	13.5	24
North East 1in10	7.8	13.8	56	8.1	13.9	54	7.6	14.1	44
East 1in10	7.2	13.5	84	7.3	13.5	79	5.4	13.3	62
South East 1in10	6.6	13.2	105	6.2	13.1	97	3.3	10.8	84
South 1in10	5.2	10.1	145	4.3	9.2	139	2.2	5.9	149
South West 1in10	5.6	8.6	232	4.8	7.9	238	3.2	6.4	251
West 1in10	7.1	9.5	272	6.9	9.3	278	5.9	9.0	293
North West 1in10	6.9	10.5	336	6.9	10.5	332	7.2	10.9	339
North 1in50	8.1	13.3	25	8.2	13.4	23	8.8	13.7	24
North East 1in50	8.6	14.2	56	8.9	14.3	55	8.3	14.5	45
East 1in50	7.6	13.8	83	7.7	13.8	79	5.7	13.5	62
South East 1in50	7.1	13.4	105	6.7	13.3	96	3.5	10.8	84
South 1in50	5.8	10.4	145	4.8	9.5	138	2.5	6.0	150
South West 1in50	6.1	8.9	232	5.3	8.2	238	3.5	6.6	251
West 1in50	7.8	9.8	272	7.6	9.7	278	6.5	9.3	294
North West 1in50	7.5	10.8	336	7.6	10.8	332	7.8	11.2	340

4. Construction Impacts

This section provides details of the potential construction impacts resulting from the installation of the infrastructure associated with the Proposed Development (Offshore). As detailed in Section 2.1 the construction processes which have been assessed in the model include the cable installation (burial by jet trencher and HDD) and monopile drilling. These activities disturb the seabed and have the potential to release suspended sediment into the water column. The MIKE 21 PT model was setup to provide a realistic representation of the sediment disturbance as a result of these activities over a 30 day period covering two spring-neap tidal cycles to capture the full range of potential impacts. The model included the 50th percentile wave conditions from the northeast (the direction with the longest fetch length) throughout the simulation to include the influence of typical wave conditions on sediment dispersion. As the construction works will occur for a longer duration than the model simulation (particularly for drilling) the model results only provide a snapshot of the likely impacts for selected locations, but similar impacts will occur elsewhere during the full construction programme. Results showing the predicted impacts to SSC and sedimentation from the PT model simulations are presented in the following sections, with results for the cable burial and pile drilling given in different sections for clarity. The results from each of the PT model simulations are presented in the form of:

- Spatial maps of statistical representations of the predicted increase in SSC due to the sediment released by the construction activities, including the maximum SSC in each model grid cell and percentile plots of the SSC calculated for the period over which construction activities were simulated;
- Spatial maps of the sedimentation depth at the end of the model simulation due to the sediment released by the construction activities; and
- Time series plots of the predicted SSC and sedimentation depth due to the sediment released by the construction activities.

The plots shown vary depending on the results from the model simulation, with the plots aimed at providing an understanding of the key results from each simulation/construction activity.

While the PT model simulates the dispersion of the sediment plume at sub-grid scale avoiding artificial numerical dispersion, the calculated SSC and sedimentation are output as average values over grid cells. Due to the large model domain and to enable a thirty day simulation with varying hydrodynamic forcing at a 5 minute timestep it was not feasible to include the high resolution (200 m) area across the Caledonia OWF. Instead, a uniform resolution of 500 m across the study area was applied (although the higher 200 m resolution was maintained at landfall to capture the more complex flows near the landfall).

It is important to note that the spatial maps of the maximum SSC and percentiles do not show an actual representation of the SSC at any point in time, rather they are duration-based plots which show statistical summaries of the SSC over the entire model simulation. The maximum SSC demonstrates the maximum concentrations that can be expected to occur at the given grid cell across the simulation period. The percentile plots show the value which the SSC is below for a given percentage of time over a defined period. The statistics are calculated over a 30 day period for cable installation and for drilling. Due to the short duration of the HDD release it was considered more appropriate to calculate the statistics over a shorter duration of 15 days. The 99th percentile plot for cable installation therefore shows the value that the SSC is exceeded for 1% of the time, or 7.2 hours. For reference the number of hours that the SSC is exceeded for different calculation periods and percentiles is provided in Table 5.

For all construction related impacts, the model does not simulate the dispersion of any sediment which is moved along the bed or any sediment which will rapidly settle to the bed (either in a dynamic plume or the larger grain sizes). Sedimentation close to the sediment release locations will therefore be larger than from the settling of the fine grained passive plume simulated in the model.

Table 5. Hours of exceedance for different calculation periods and percentiles.

Percentile	Hours that SSC shown is exceeded when calculated over different periods	
	30 days	15 days
50th	360	180
80th	144	72
90th	72	36
95th	36	18
99th	7.2	3.6

4.1. Cable Installation

The 80th percentile, 99th percentile and maximum SSC for the 30 day period over which cable installation activities were simulated are shown in Figure 16 and the sedimentation at the end of the model simulation is shown in Figure 17. When interpreting the plots it is important to note that the model simulates the dispersion of the fine sediment suspended in the water column, accounting for less than 10% of the overall sediment disturbance during cable installation. The remainder of the sediment is expected to settle within close proximity to the disturbance site and as such sedimentation thickness immediately adjacent to the trench will be higher than that shown from the modelling.

The plots show the following:

- The peak SSC is more than 50 mg/l, but the area with elevated SSC remains very localised to where the activity is being undertaken with very limited transport of the suspended sediment predicted. This is a result of the low tidal currents combined with the sediment being released relatively close to the seabed;
- Highest increases in SSC along the Caledonia OECC occur at the landward end of the route. These higher concentrations are an artefact of the way in which the PT module calculates concentrations - all particles are assigned a mass and the concentration is calculated as the mass per cell volume. As a result, a particle in a cell with a smaller volume (either due to higher resolution or shallower water depths) returns higher peak concentrations than the same particle in a cell with a larger volume. Grid cell volumes are smaller at the landward end of the Caledonia OECC both due to the higher resolution of the model (to resolve small scale flow patterns) and the shallower water depths, resulting in higher peak concentration in the sediment release cells;
- Highest increases in SSC within the Caledonia OWF occur close to the assumed OSP locations. In lieu of detailed design information and to achieve the maximum expected length of inter-array cabling it was necessary to assume that each WTG was connected directly to one of the two OSPs per application. Therefore, the model simulates cable installation along multiple trenches radiating out from the two indicative OSP locations, resulting in repeated releases of sediments in many of the cells close to the OSPs, driving the elevated SSC in these areas;
- The difference between the 99th percentile and maximum SSC shows that increases in SSC above 25 mg/l due to the cable installation only occurred for a short duration of time (less than 7.2 hours). The 99th percentile increase in SSC from the cable installation is typically less than 10 mg/l except for small patches within the Caledonia OWF.

- The 80th percentile increase in SSC from the cable installation shows that increases in SSC above 5 mg/l occurred for less than six days;
- Increases in SSC from the cable installation above 1 mg/l are mainly constrained within the footprint of the Caledonia OWF and Caledonia OECC; and
- Sedimentation of more than 10 mm is predicted in the area around the OSPs, and sedimentation of 2-3 mm is typically predicted along the Caledonia OECC and interconnector cable routes. Sedimentation of more than 0.1 mm is mainly predicted to occur within the Caledonia OWF and Caledonia OECC.

Time series plots of the SSC and sedimentation are shown over the 30-day model simulation at a series of extraction points in Figure 18 to Figure 23. Two of the locations (A1 and A2 shown in Figure 18 and Figure 19, respectively) are at the indicative OSP locations and therefore have sediment releases within the cell in which they lie for several hours (almost 3 hours and 13 hours at A1 and A2, respectively with a higher release time in the cell which A2 lies compared to the cell in which A1 lies due to the relative location of the OSP within the cell). These releases are intermittent and result in the high spikes (of more than 20 mg/l) in SSC, but with SSC quickly reducing to values of less than 5m/l once the jet trencher has moved away.

The sedimentation is predicted to be up to 35 mm at A1 and 62 mm at A2, although this sediment will compact and reduce in thickness over time. The sedimentation is predicted to reduce away from the OSP locations at A1 and A2 to less than 1 mm at A4, A5 and A6.

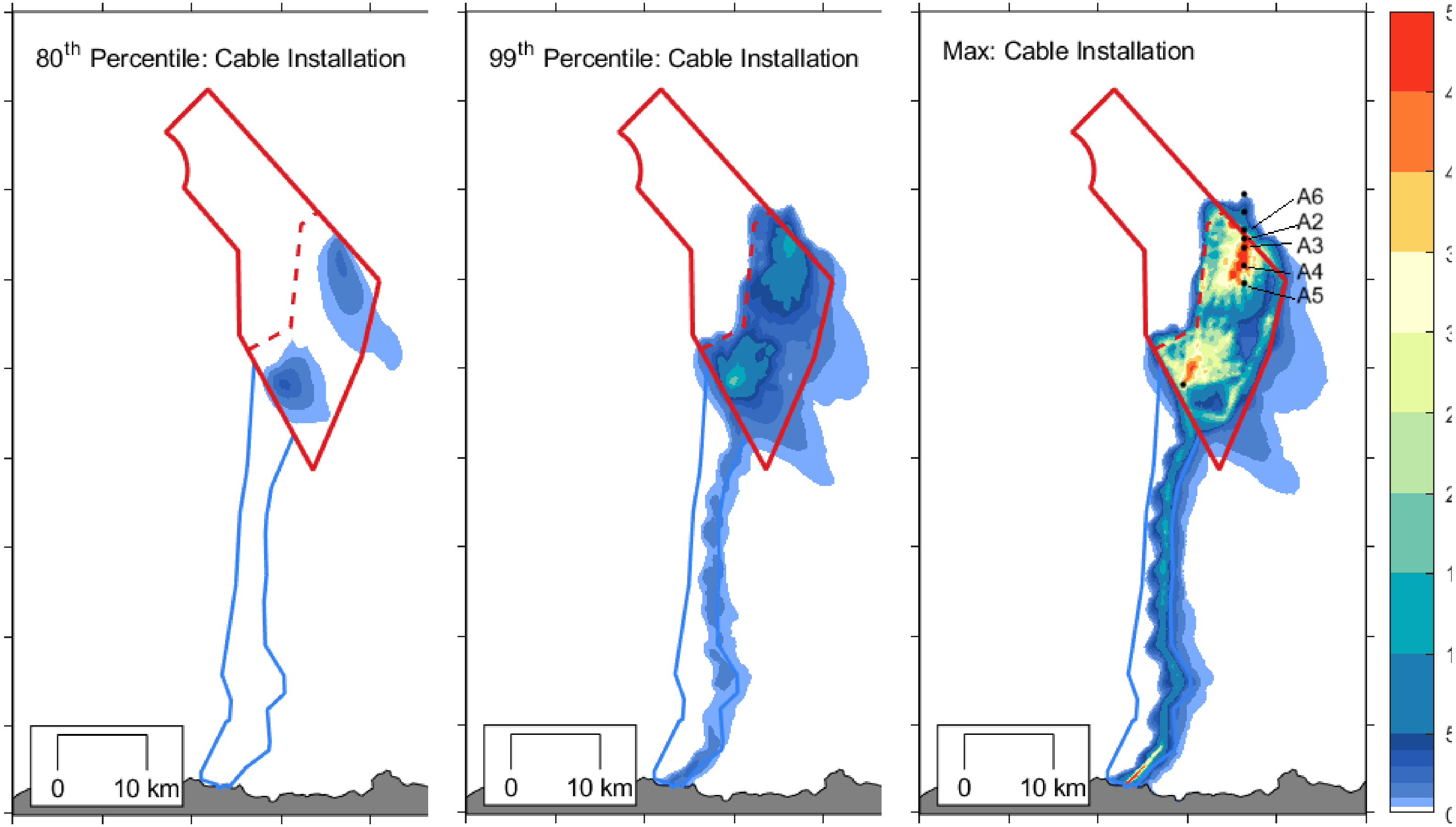


Figure 16. **Modelled 80th (left), 99th percentile (middle) and maximum (right) SSC from the PT model simulation for cable installation using the jet trencher.**

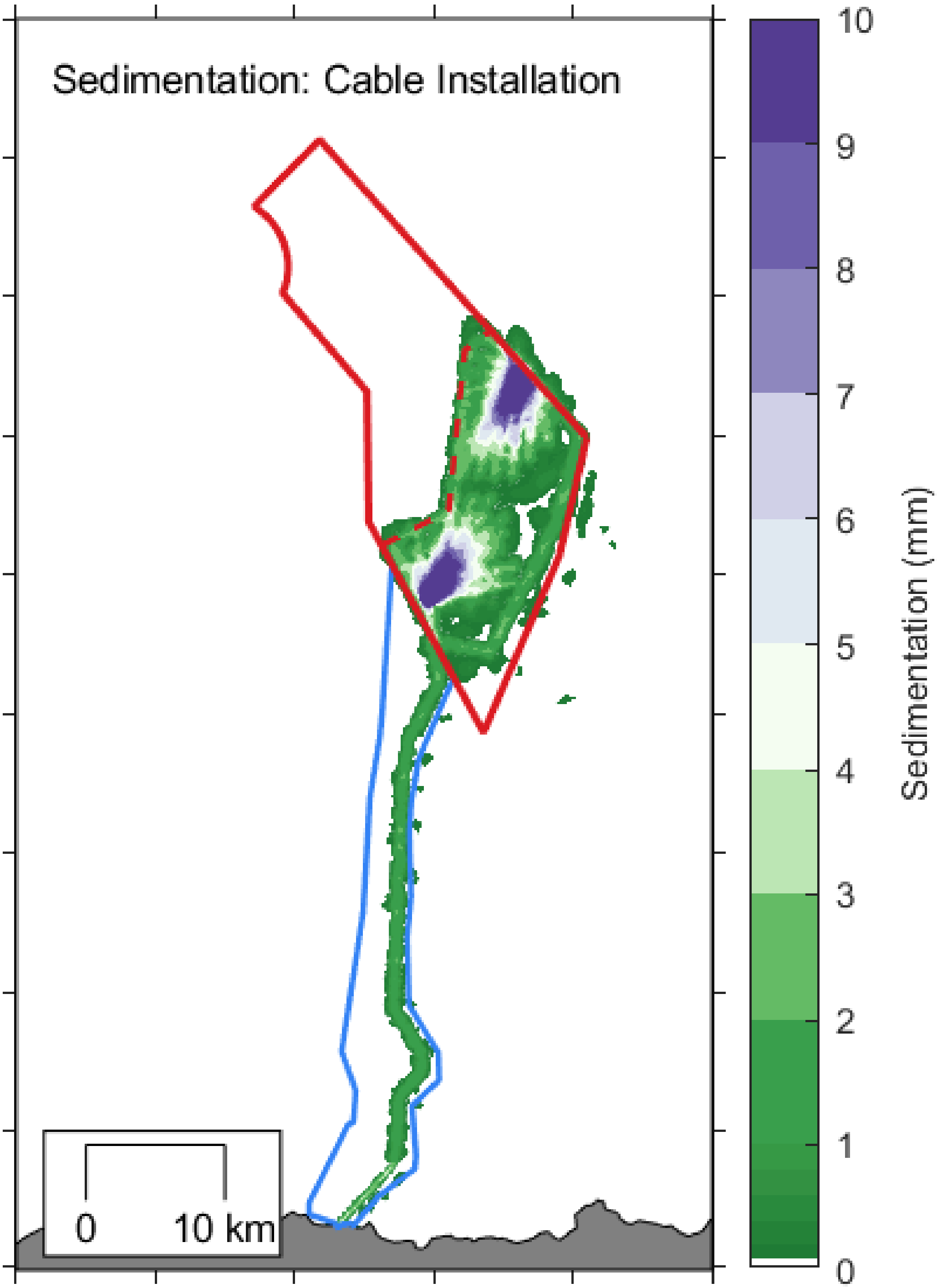


Figure 17. Modelled sedimentation from the PT model simulation for cable installation using the jet trencher.

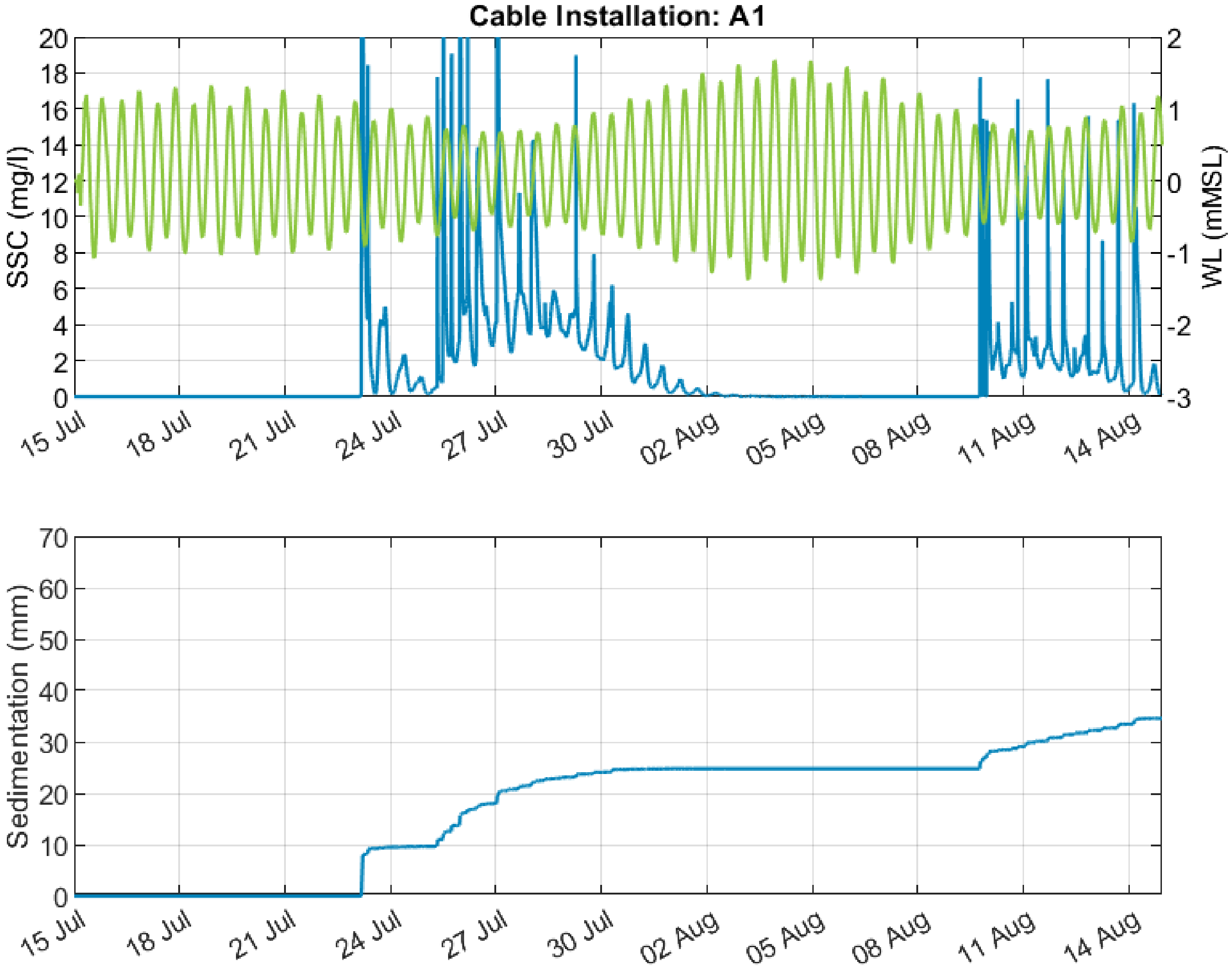


Figure 18. Modelled SSC and sedimentation at A1 for cable installation using the jet trencher.

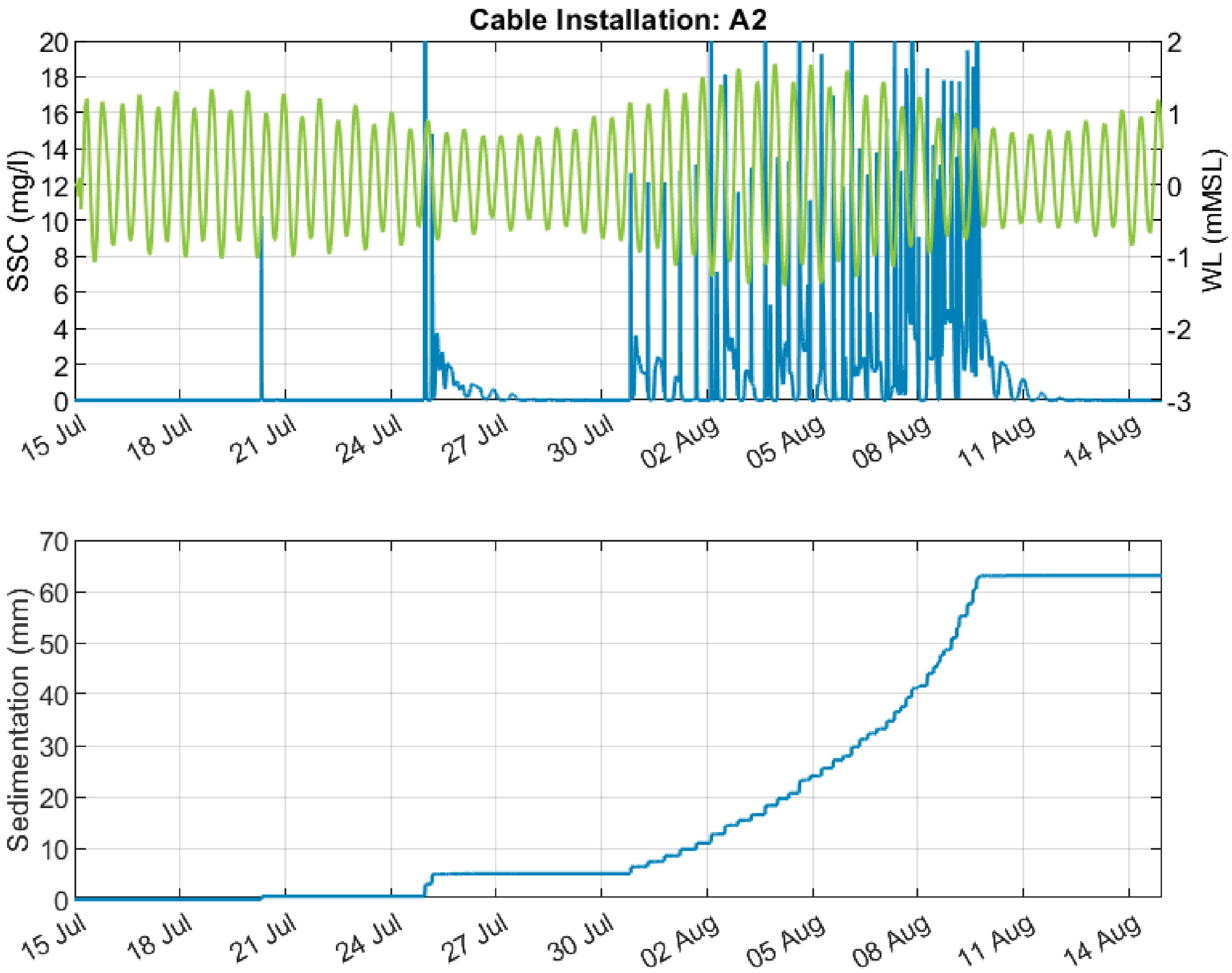


Figure 19. **Modelled SSC and sedimentation at A2 for cable installation using the jet trencher.**

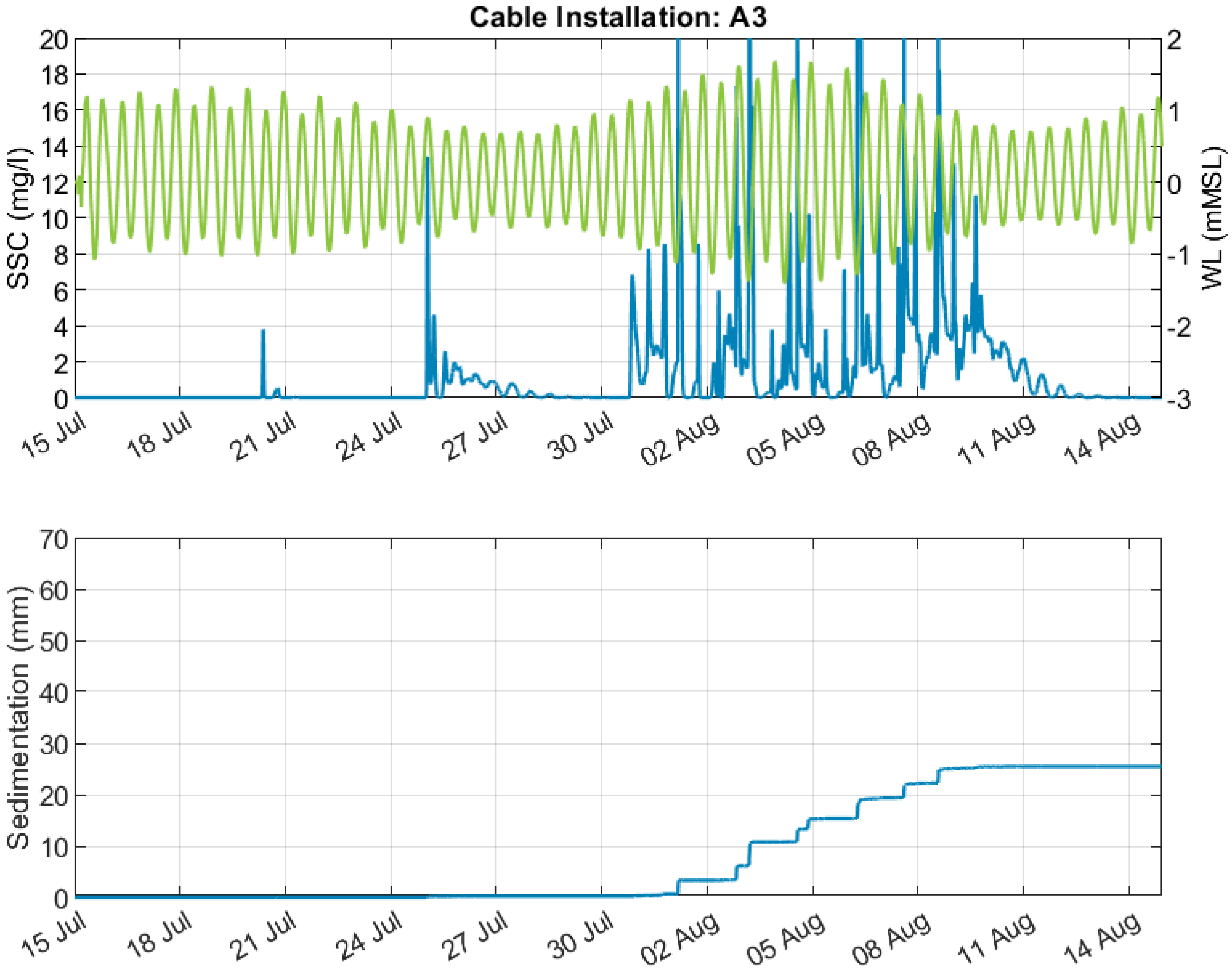


Figure 20. Modelled SSC and sedimentation at A3 for cable installation using the jet trencher.

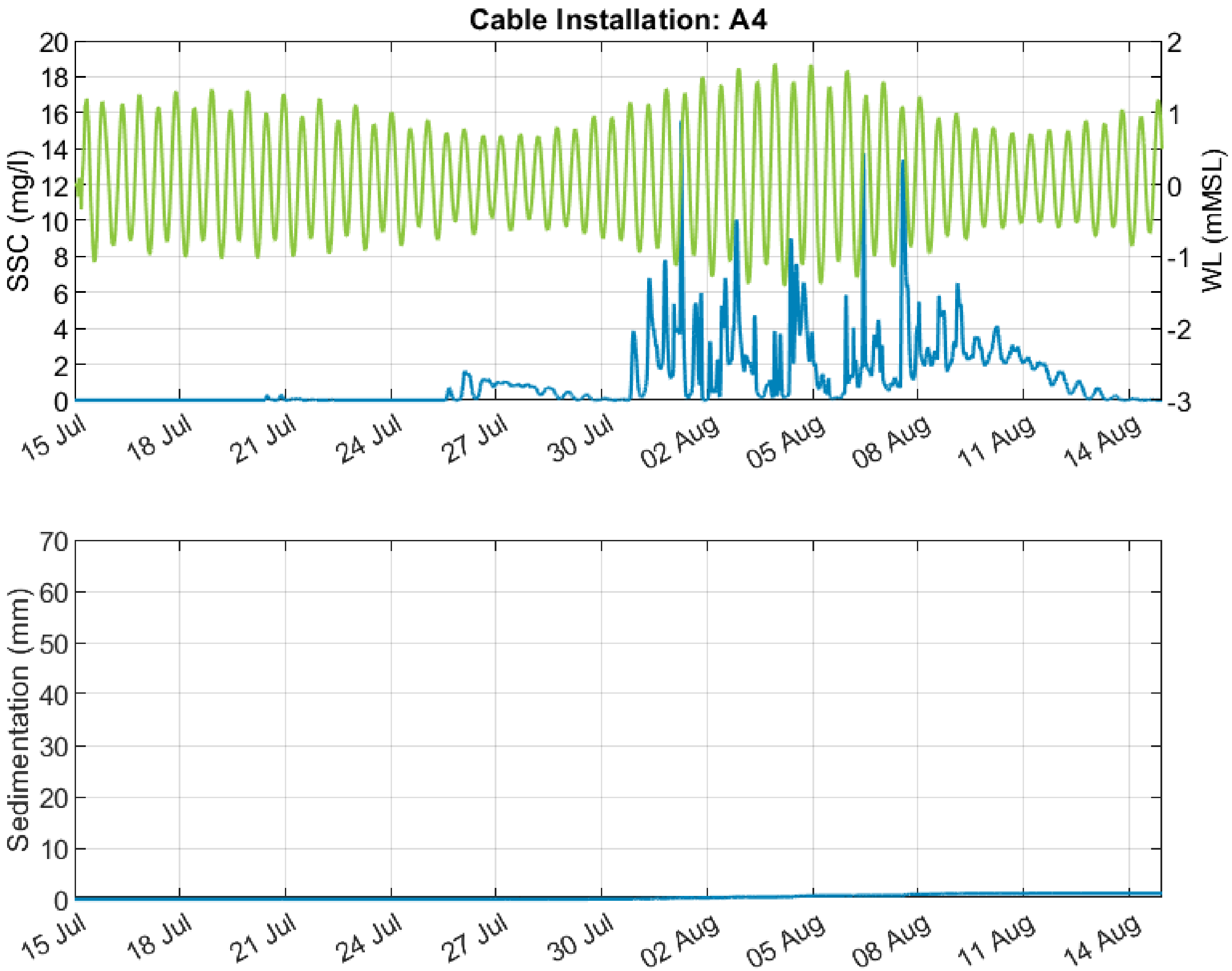


Figure 21. Modelled SSC and sedimentation at A4 for cable installation using the jet trencher.

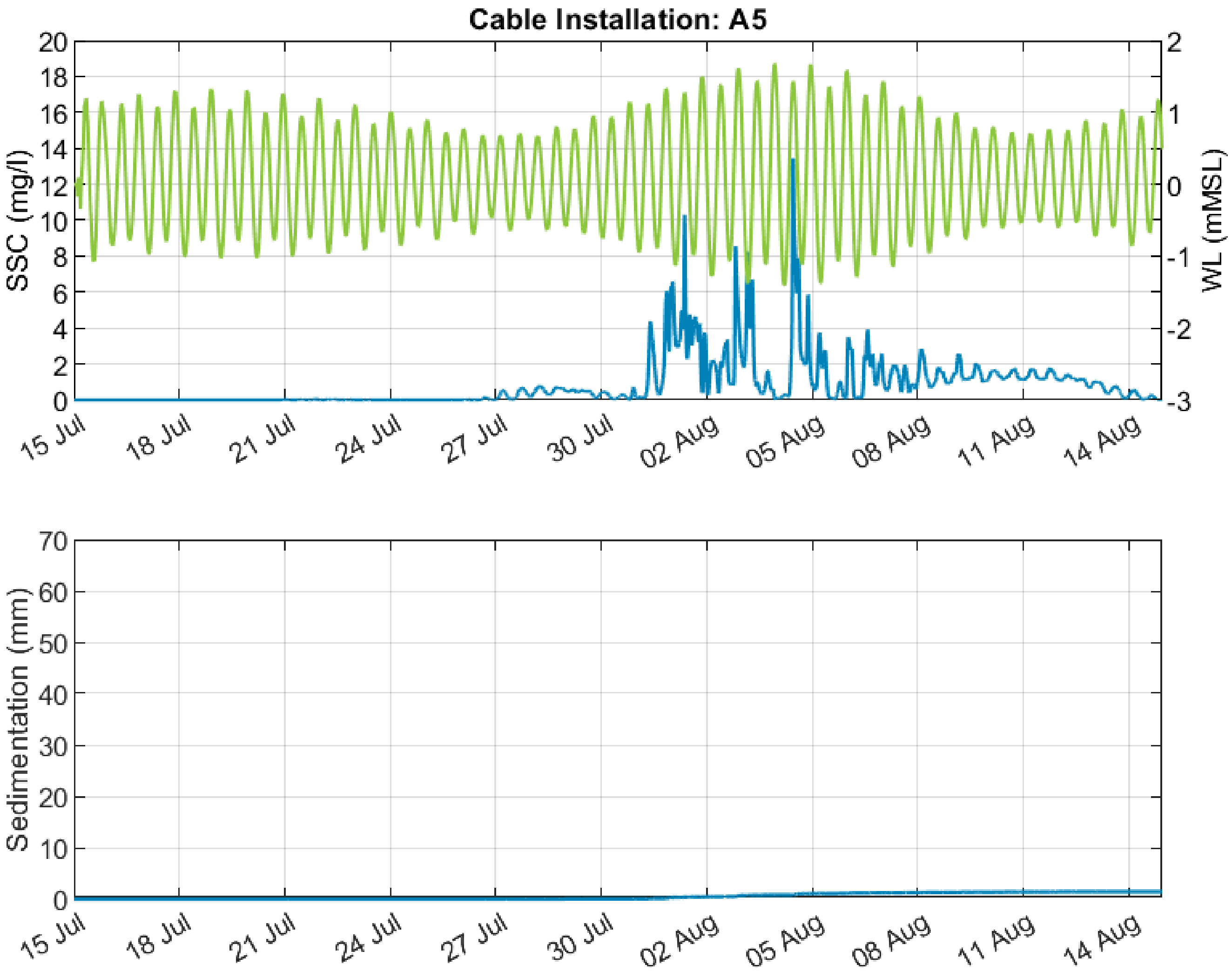


Figure 22. Modelled SSC and sedimentation at A5 for cable installation using the jet trencher.

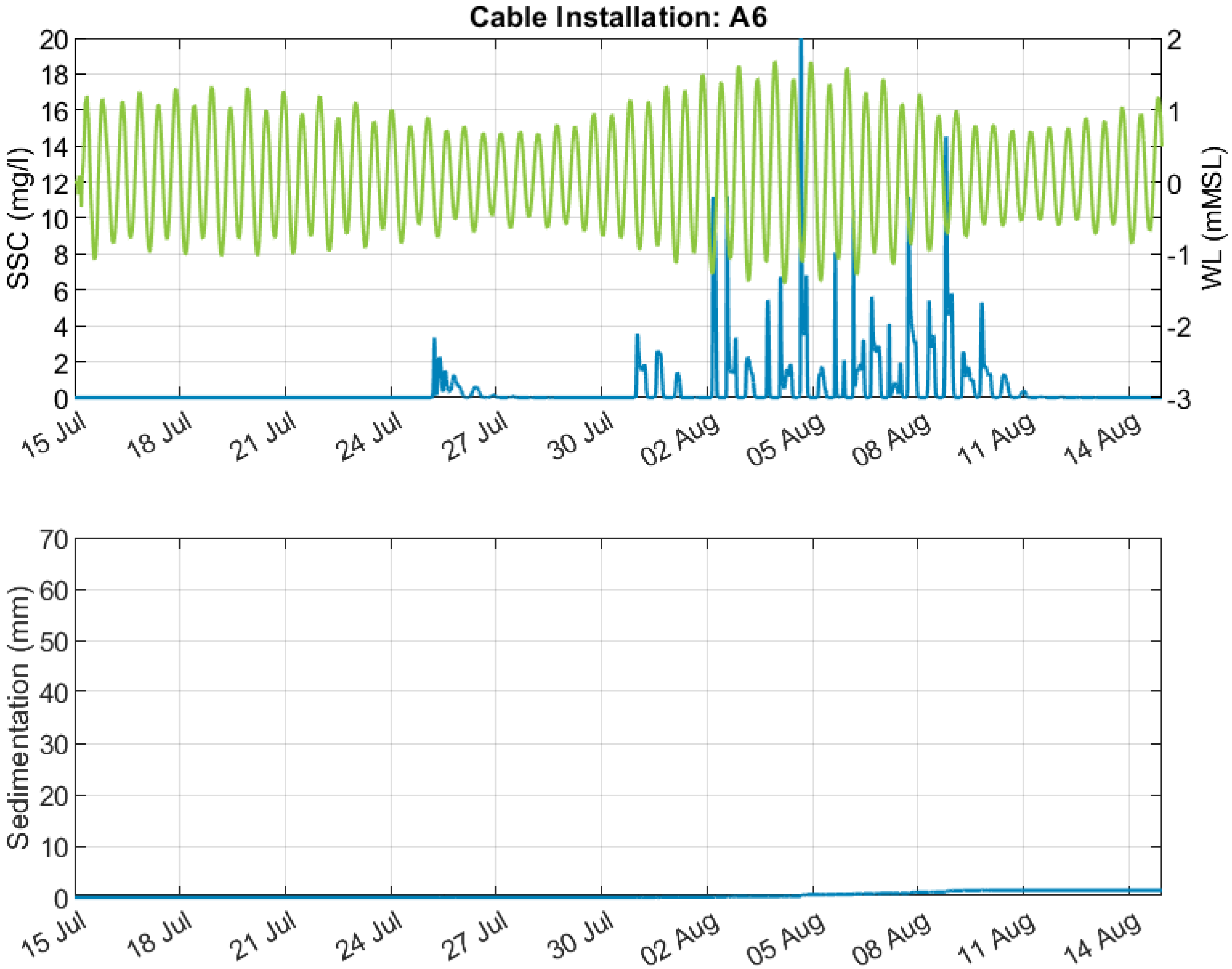


Figure 23. Modelled SSC and sedimentation at A6 for cable installation using the jet trencher.

4.2. Horizontal Directional Drilling

The maximum SSC during the 15 day period over which the statistics were calculated for the HDD model simulation are shown in Figure 24. The plot shows increased SSC of more than 0.5 mg/l is constrained to an area extending approximately 2.5 km west of the release point and 4 km to the east. Higher concentrations of more than 50 mg/l occur over an area of less than 1 km x 0.5 km. Given the models tendency to underpredict the magnitude of the eastward flow dominance in this area (PCS, 2024) it is possible that the plume would not extend as far west and would extend further to the east than predicted by the model.

There are areas of increased SSC along the coastline including at the Inverboyndie bathing water. However these increases are low (typically less than 2 mg/l) and short lived (see 99th and 90th percentile SSC plots during the 15 day period for which the statistics were calculated in Figure 25 and Figure 26, respectively).

The sedimentation from the release of sediment from HDD is shown in Figure 27. When interpreting the plot it is important to note that the model simulates the dispersion of the fine sediment suspended in the water column, accounting for 80% of the overall sediment disturbance from HDD from a single cut. The area where deposits are more than 0.1 mm is highly localised and constrained to an area of less than 2 km east-west and less than 1 km north-south. Local to pop-out deeper sedimentation thicknesses will occur from the deposition of the dynamic plume (not simulated in the model).

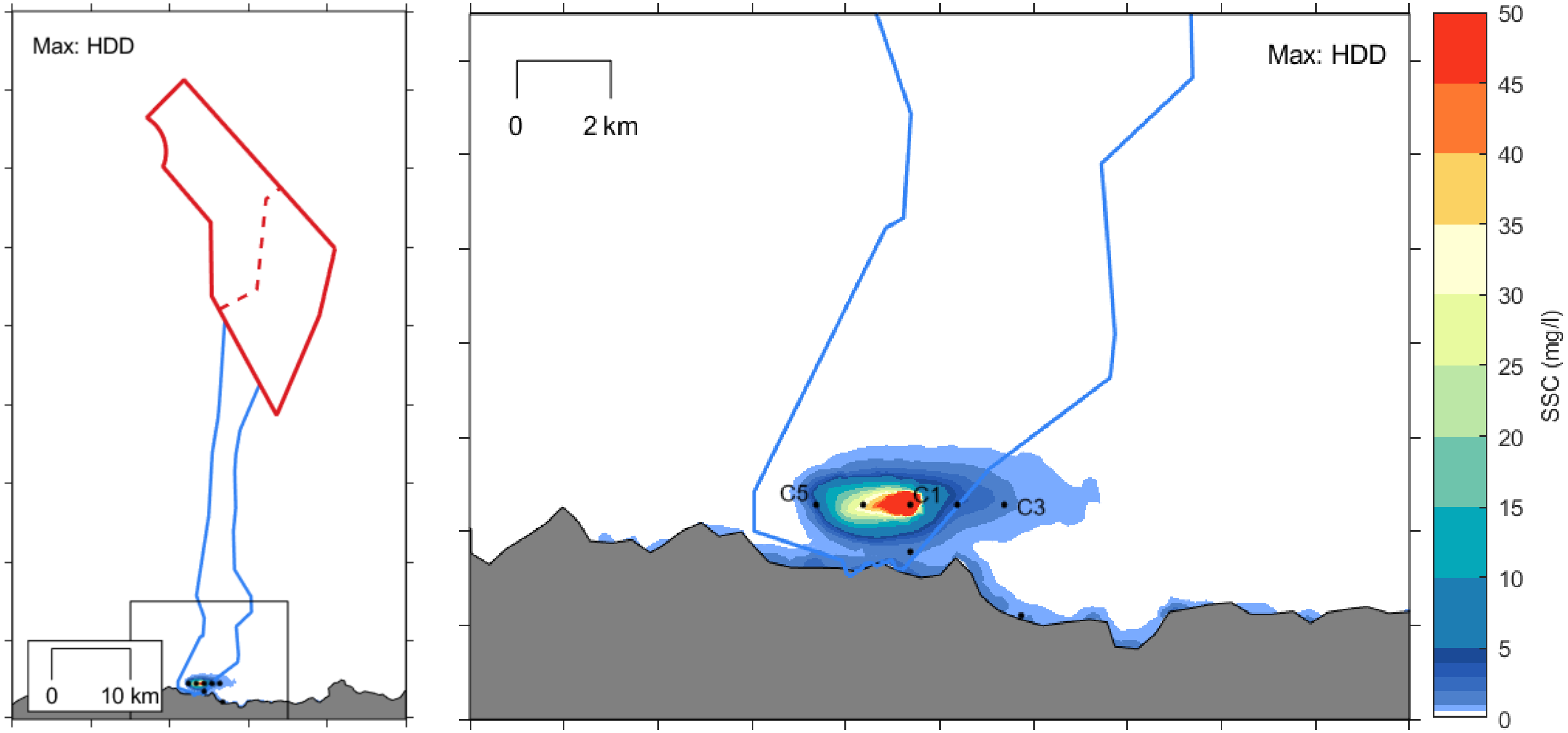


Figure 24. **Maximum SSC from the PT model simulation for HDD.**

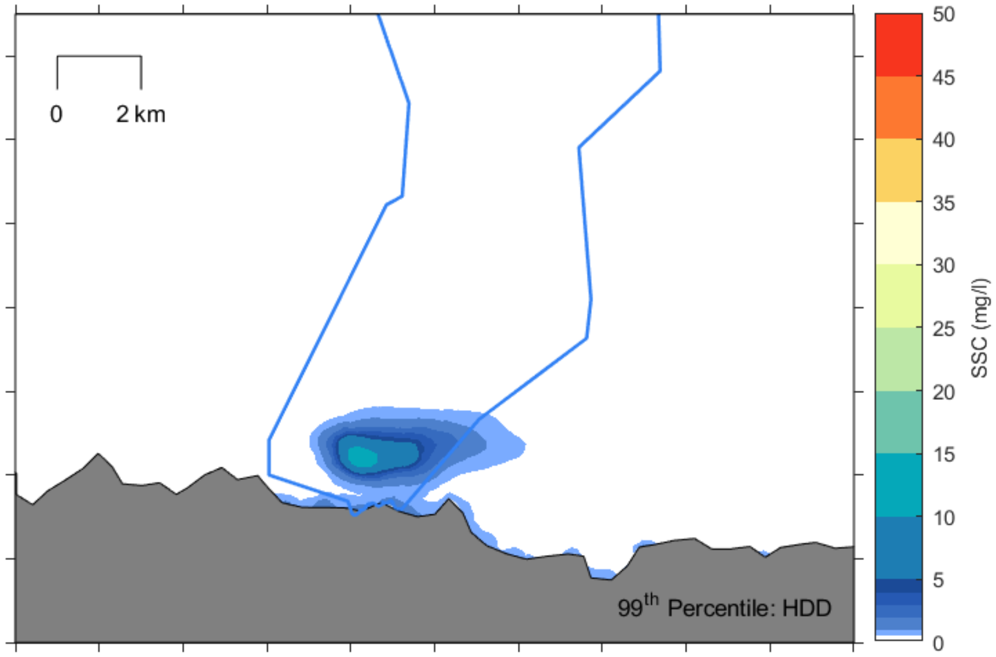


Figure 25. Modelled 99th percentile SSC from the PT model simulation for HDD.

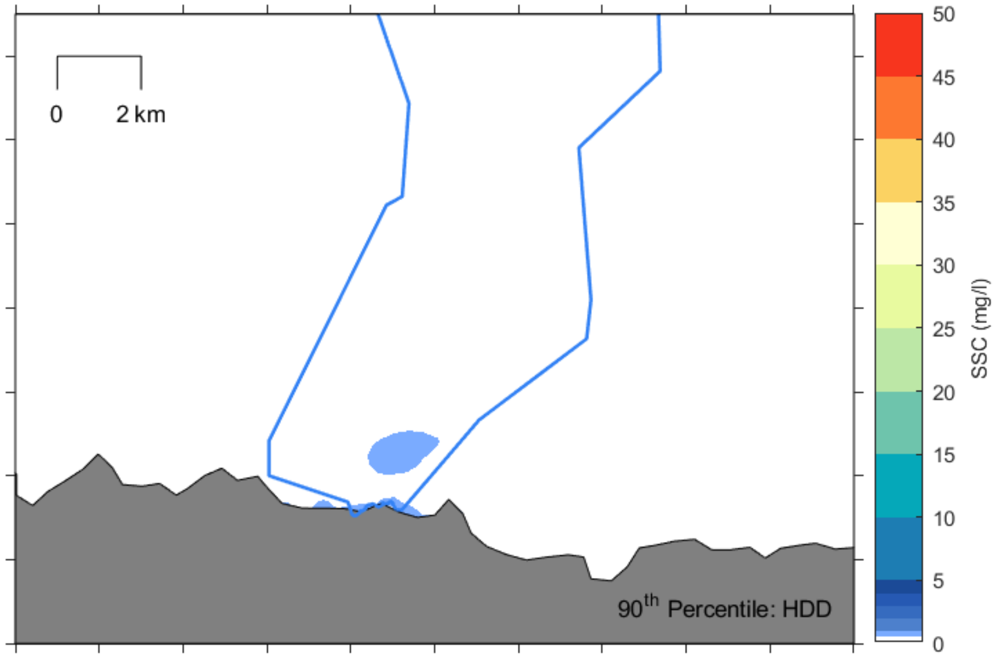


Figure 26. Modelled 90th percentile SSC from the PT model simulation for HDD.

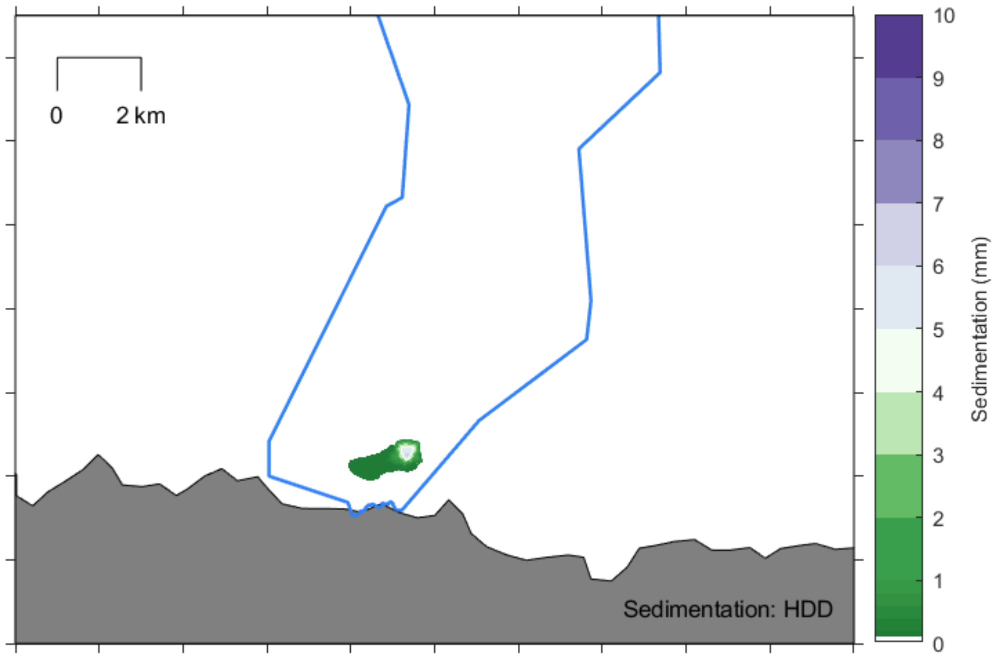


Figure 27. Modelled sedimentation from the PT model simulation for HDD.

Timeseries plots are shown at locations around the release location in Figure 28 to Figure 31. As for the percentile plots, the timeseries plots show the short period of enhanced SSC with values returning to close to zero within three days of the release at locations C1 to C3. Conversely, increases in SSC do not occur at the Inverboyndie bathing water until more than two days after the release and these continue for the rest of the 15 day period shown. The model was run on for another 15 days after the period shown, during this period there were some small increases in SSC for up to another five days, although these were very short duration and at levels of less than 1 mg/l. The total time that SSC increases exceeded zero at the bathing water was 81 hours (3.4 days).

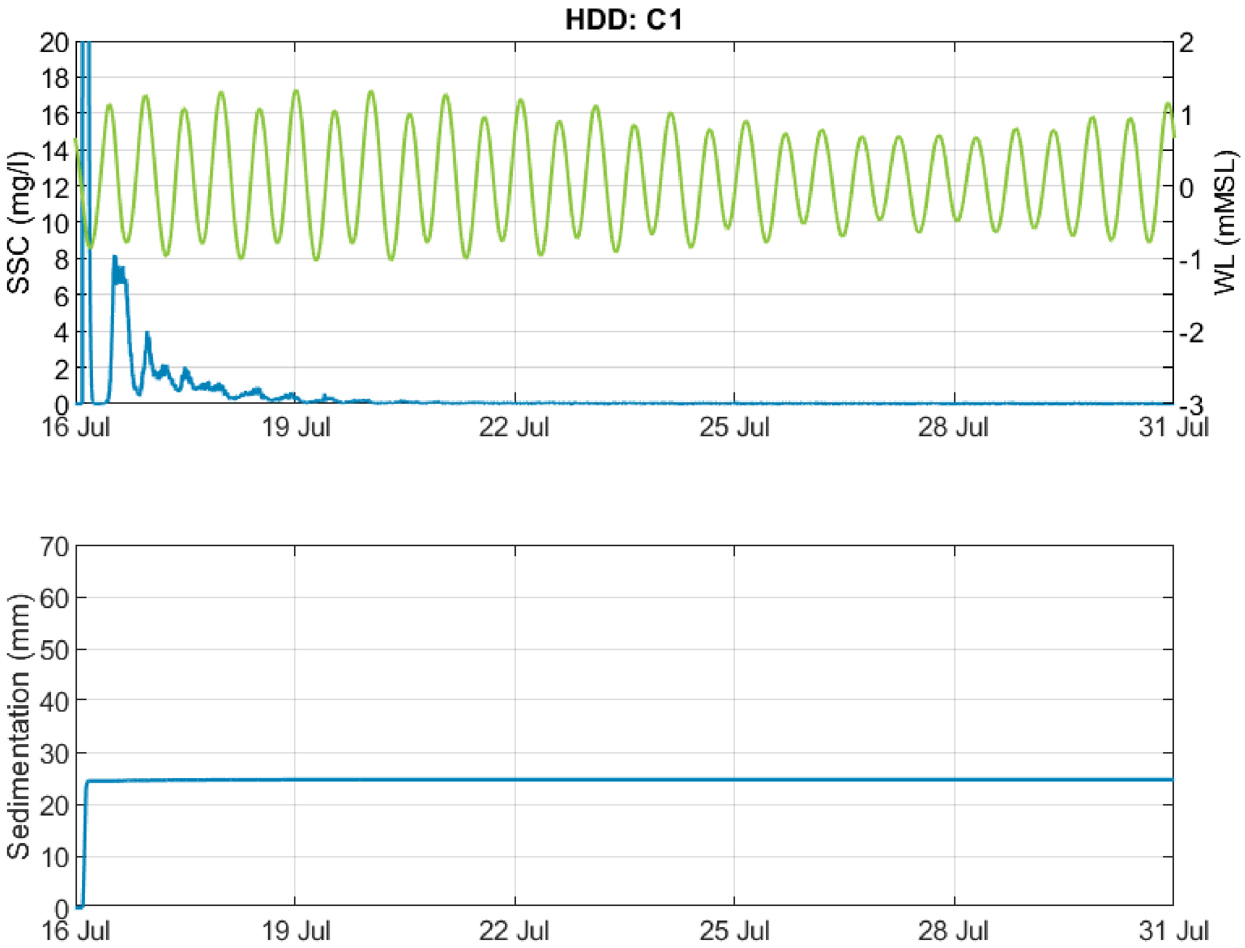


Figure 28. Modelled SSC and sedimentation at C1 for HDD.

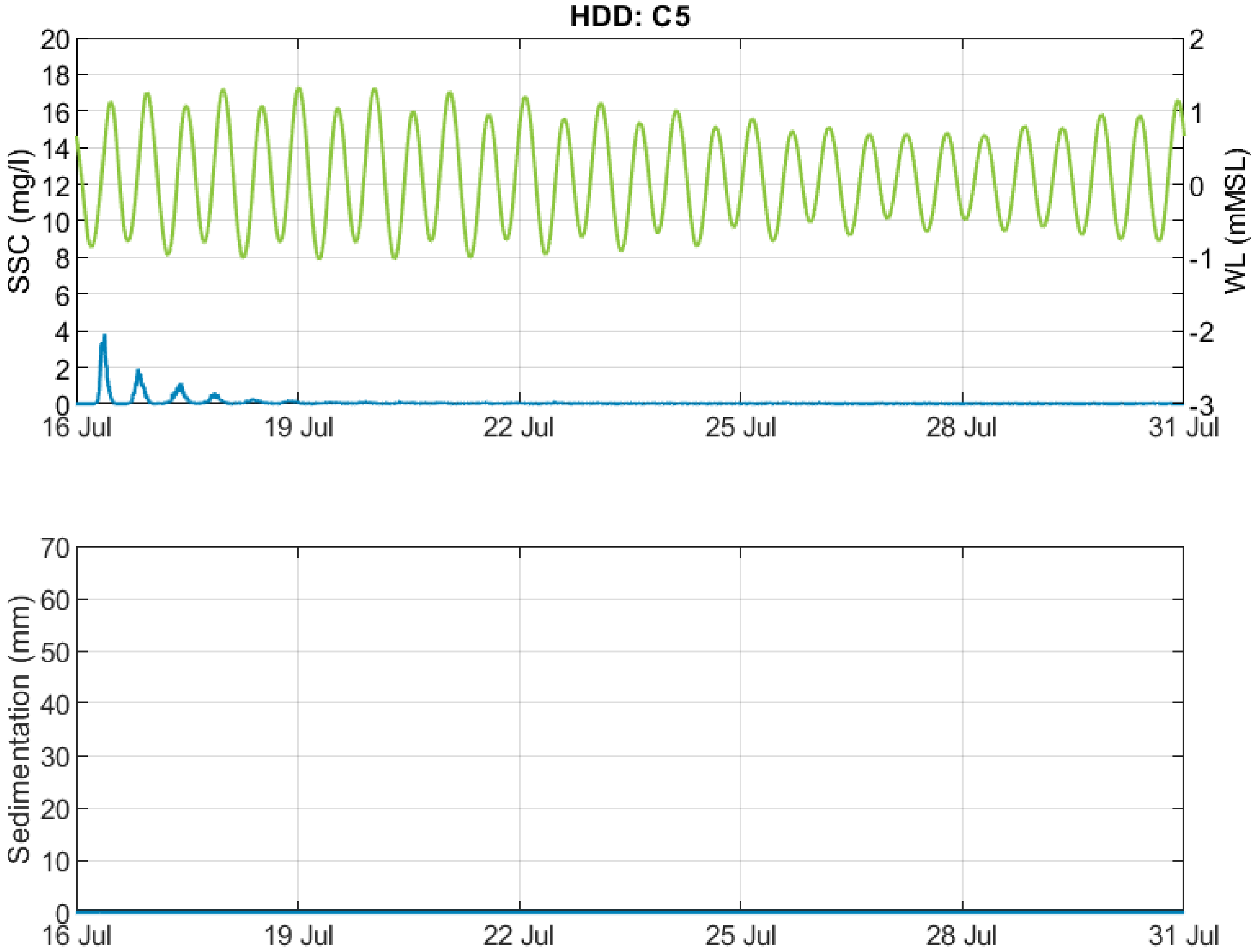


Figure 29. Modelled SSC and sedimentation at C5 for HDD.

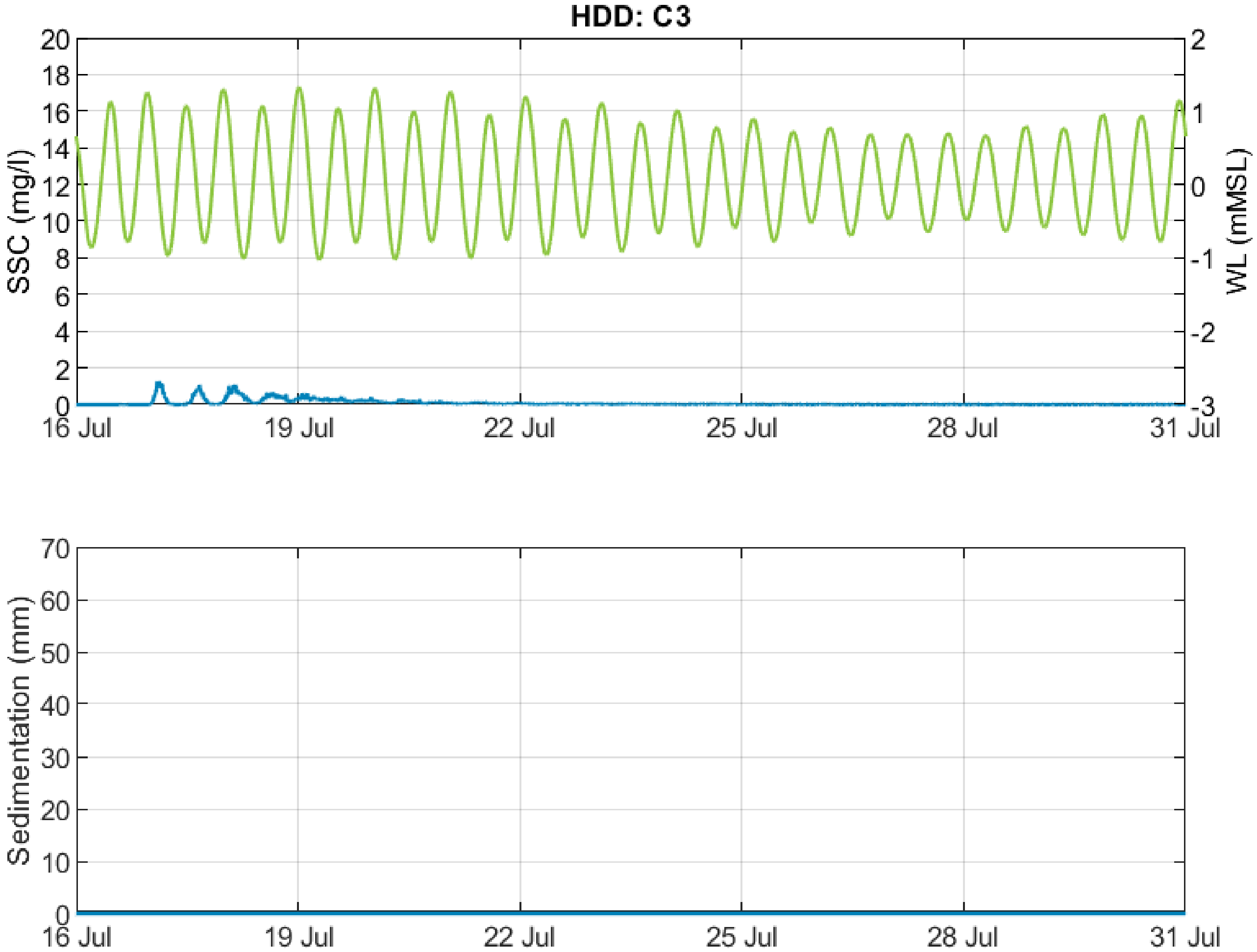


Figure 30. Modelled SSC and sedimentation at C3 for HDD.

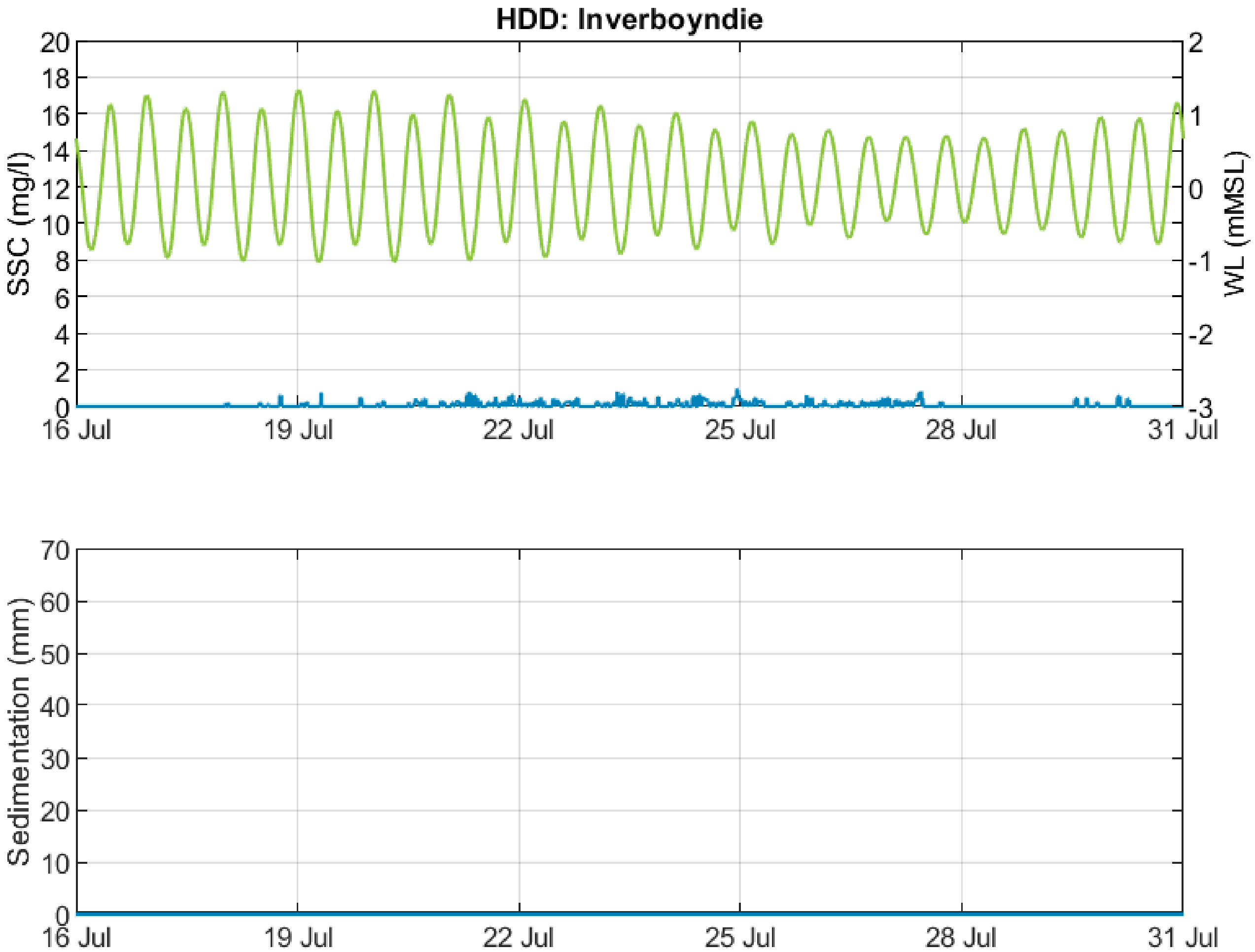


Figure 31. Modelled SSC and sedimentation at the Inverboyndie bathing water for HDD.

4.3. Foundation Installation

The maximum SSC over the 30 day period over which foundation installation activities were simulated are shown in Figure 32 while the 80th and 99th percentile increases in SSC are shown in Figure 33 and the sedimentation at the end of the model simulation is shown in Figure 34. Timeseries plots of SSC and sedimentation at selected extraction locations are also shown in Figure 35 to Figure 39. When interpreting the plots it is important to note that the model simulates the dispersion of the fine sediment in the water column, accounting for less than 10% of the overall sediment disturbance during foundation installation for all WTG locations. Sediment plumes and deposits across the Caledonia OWF would occur during drilling at other WTG locations during construction.

The plots show the following:

- The maximum SSC plot shows that increases in SSC of more than 5 mg/l are constrained to within 5 km of the release location in a north-south direction and to within 1 km in an east-west direction;
- Maximum SSC is more than 1 mg/l above background up to 30 km to the southeast of the release location;
- The maximum SSC plot is similar to the 99th percentile plume plot (since there is a continual release from each location for approximately 200 hours), while the 80th percentile plot shows a notable reduction in SSC. This suggests that the peak concentrations occur cyclically at particular tidal states (since if the plume were to persist for the full 200 hours the 80th percentile plot would also be similar to the maximum SSC plot). This is confirmed by the time series plots which show a series of spikes in SSC varying between peak values of around 16 mg/l to less than 2 mg/l at B1 during the drilling of the foundation that lies at B1 (between the 16th and 24th July);
- There are spikes in SSC at B1 even after the completion of drilling the foundation at B1, although to much lower peak levels of 4 mg/l (corresponding to the times when drilling was ongoing at B2) and around 1 mg/l (corresponding to drilling ongoing at location B4). There were no peaks in SSC at B1 during drilling at B3 which is likely to be due to the faster spring flows which coincided with drilling at this location dispersing the plume. Should the drilling of upstream or downstream foundations have been simulated by the model (rather than those across stream) the peaks associated with drilling other foundations would be expected to be higher;
- Sedimentation is approximately 1-2 mm adjacent to the release locations and less than 1 mm at distances of more than 1 km from the release locations; and
- Given the WTG spacing and the extent of the area experiencing elevated SSC and sedimentation, as additional structures are drilled the period of exposure to elevated SSC and the depth of sedimentation will increase.

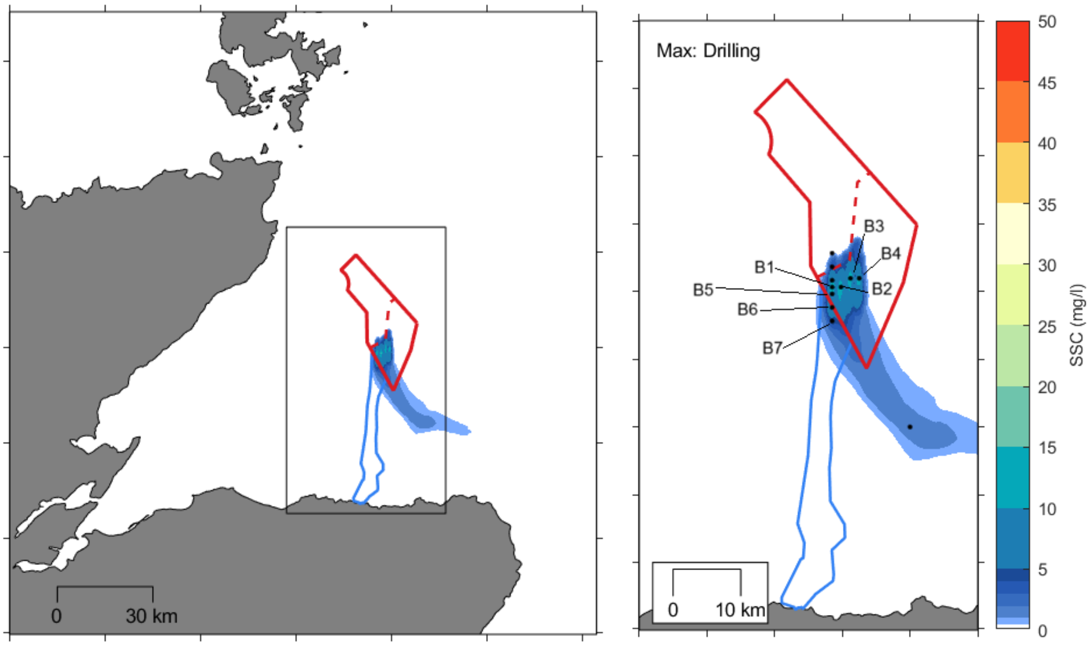


Figure 32. Maximum SSC from the PT model simulation for foundation installation by drilling.

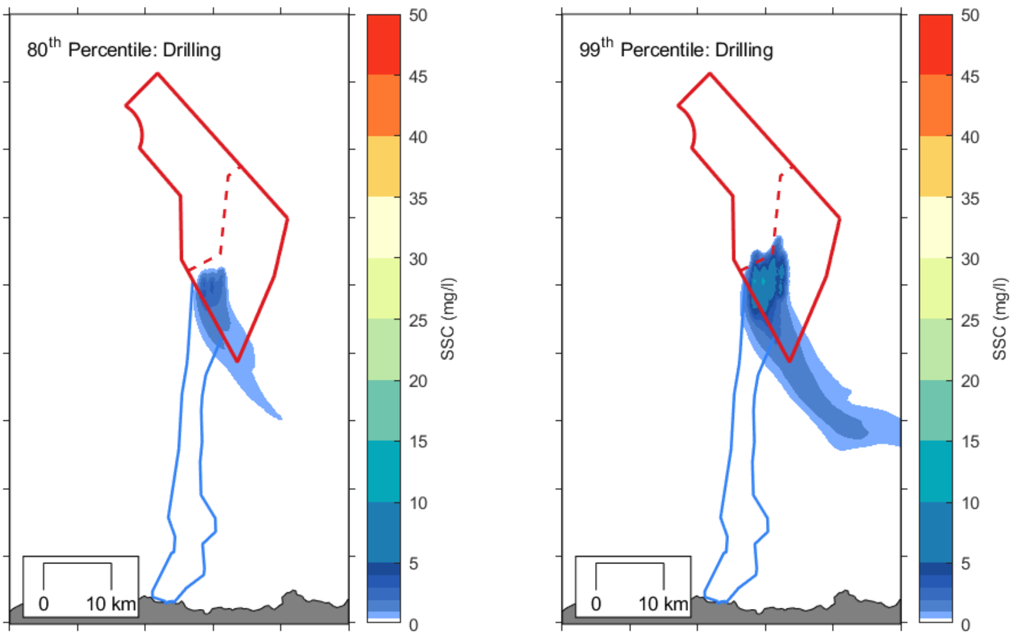


Figure 33. Modelled 80th (left) and 99th (right) percentile SSC from the PT model simulation for HDD.

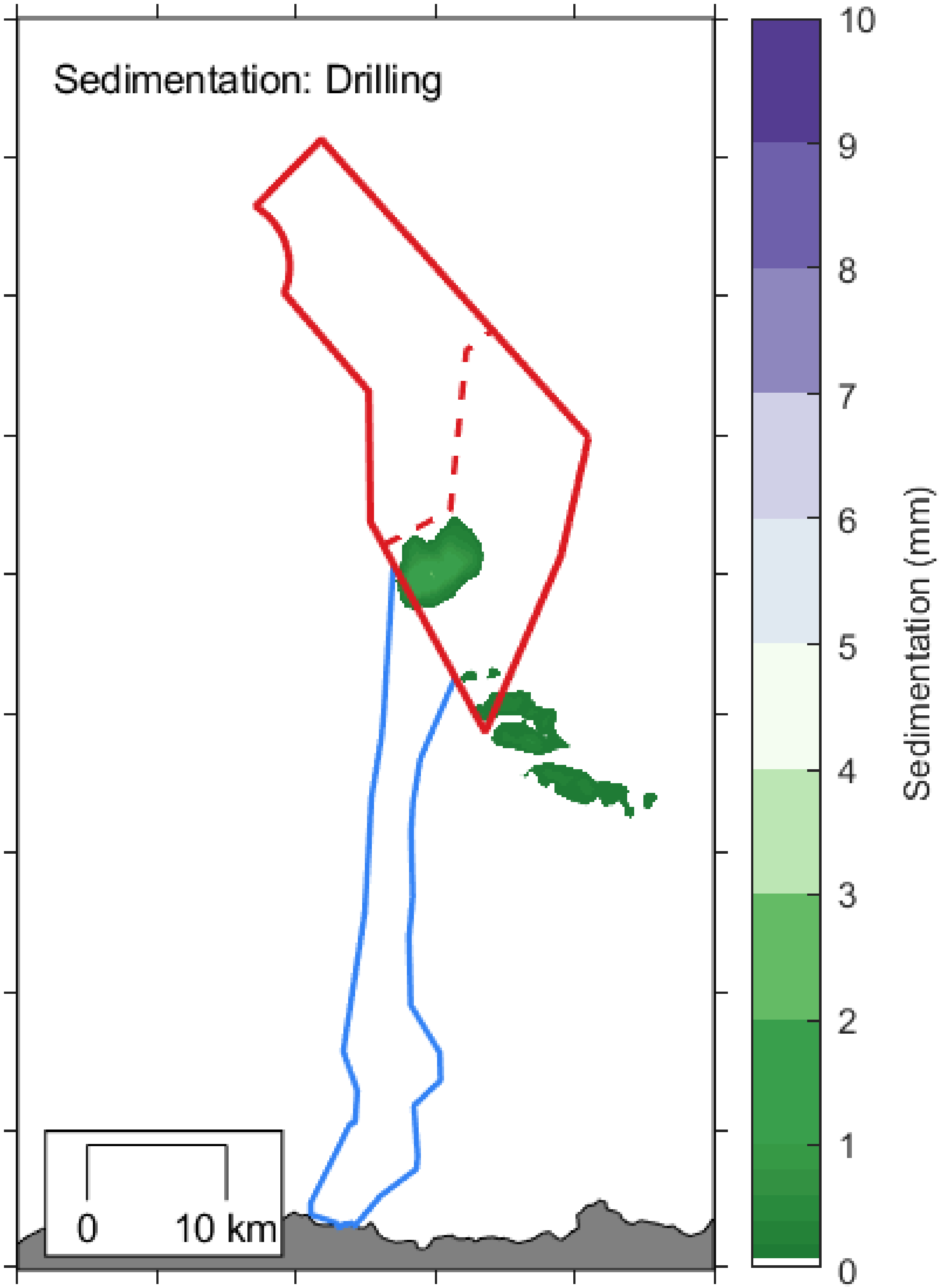


Figure 34. Modelled sedimentation from the PT model simulation for foundation installation by drilling.

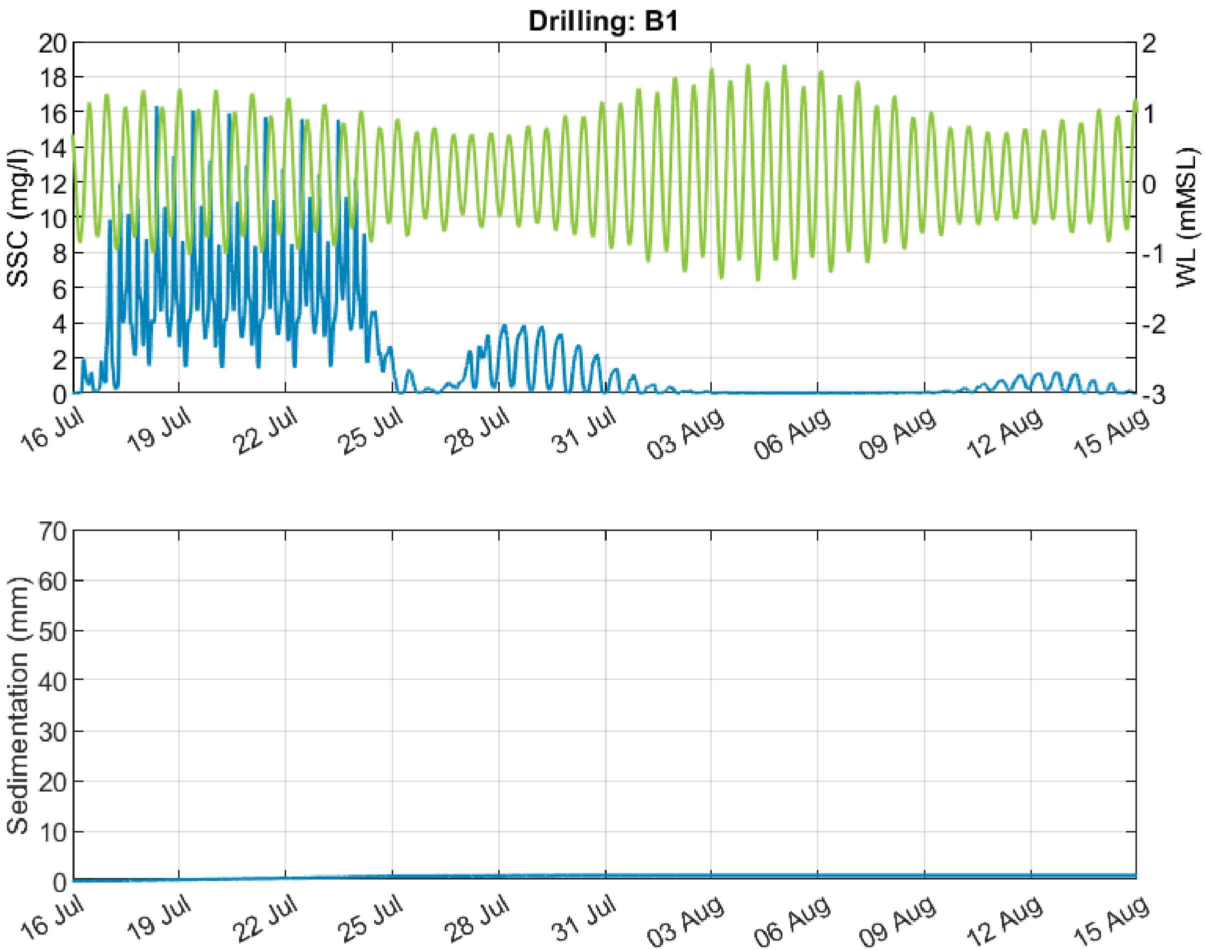


Figure 35. Modelled SSC and sedimentation at B1 for foundation installation.

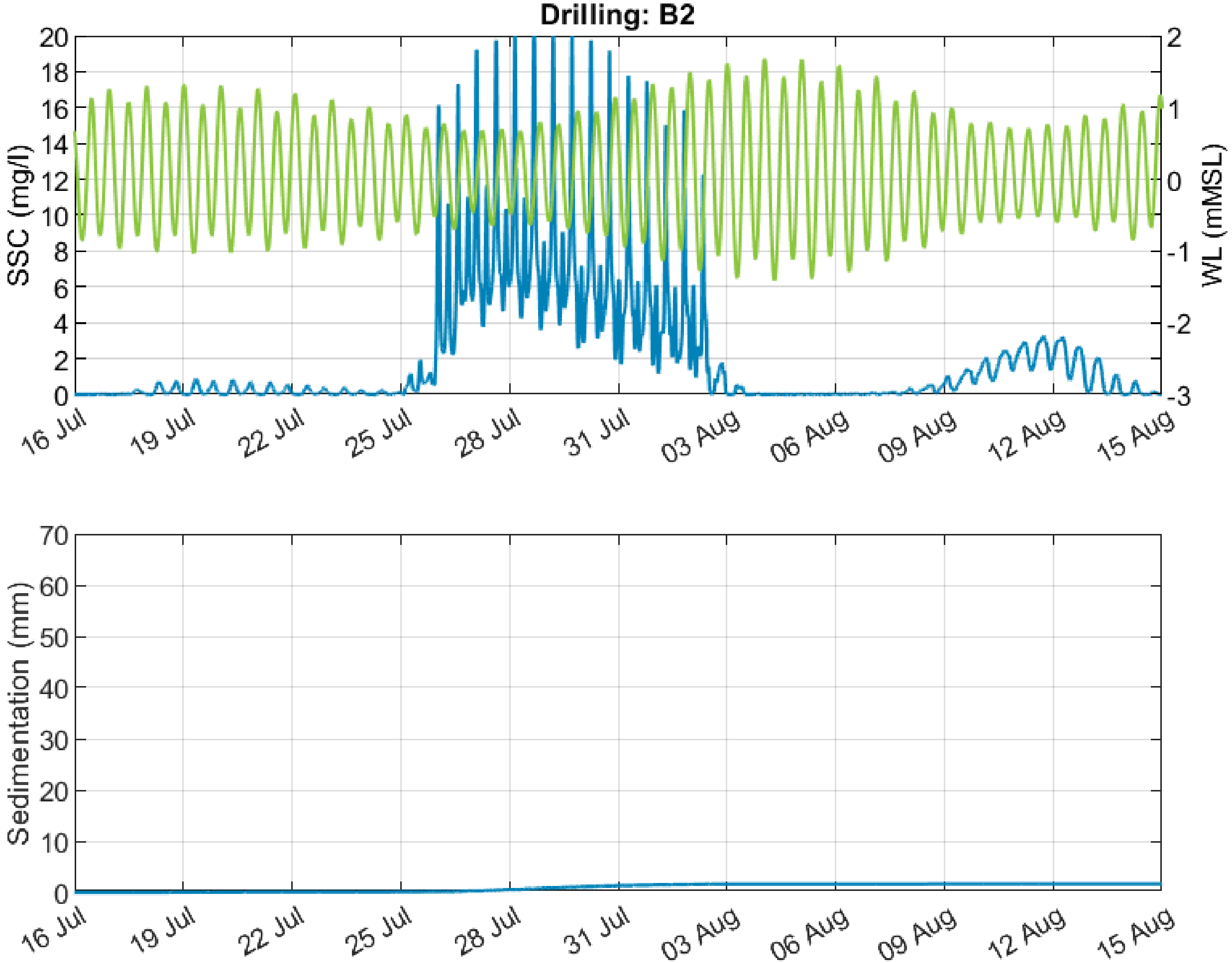


Figure 36. Modelled SSC and sedimentation at B2 for foundation installation.

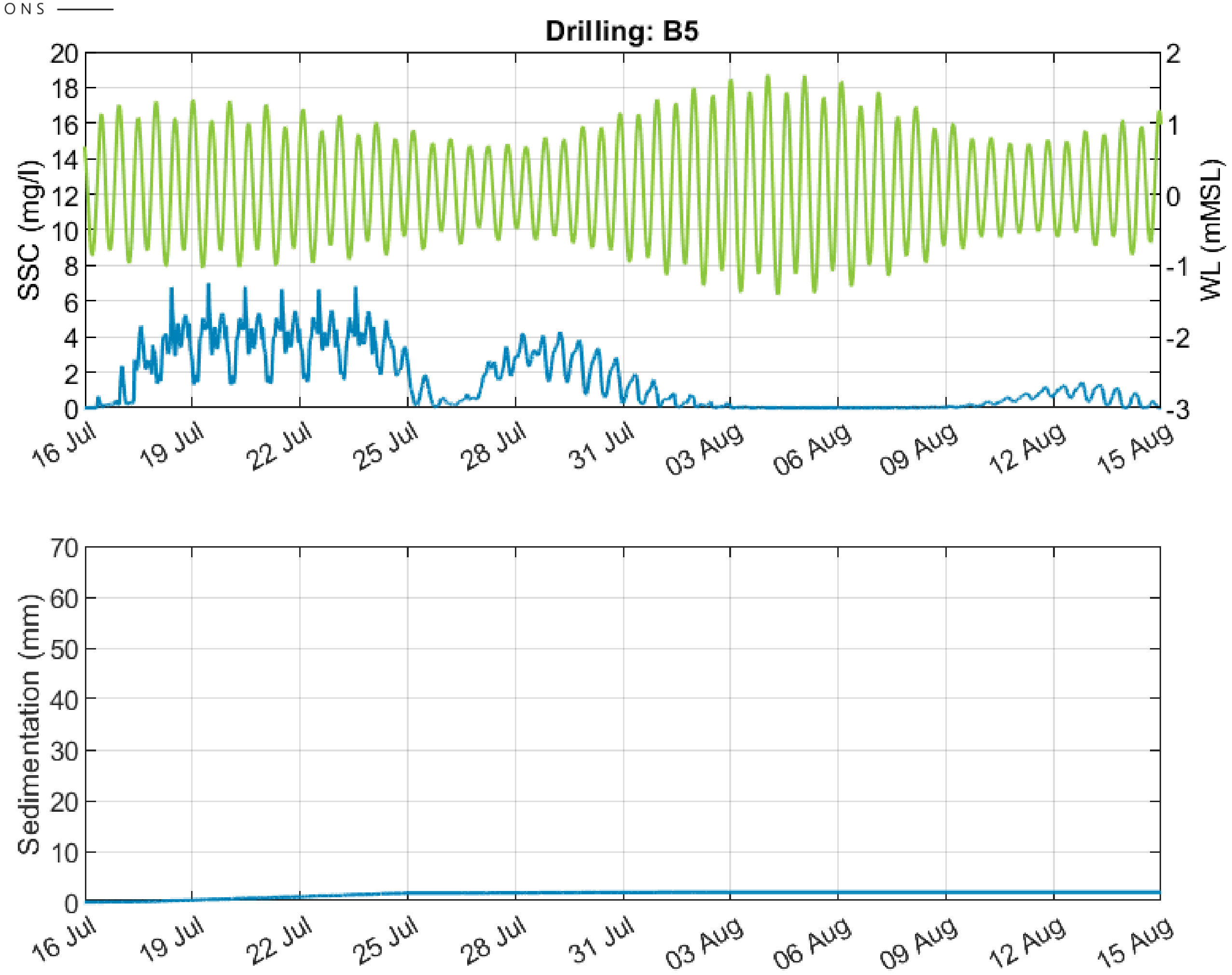


Figure 37. Modelled SSC and sedimentation at B5 for foundation installation.

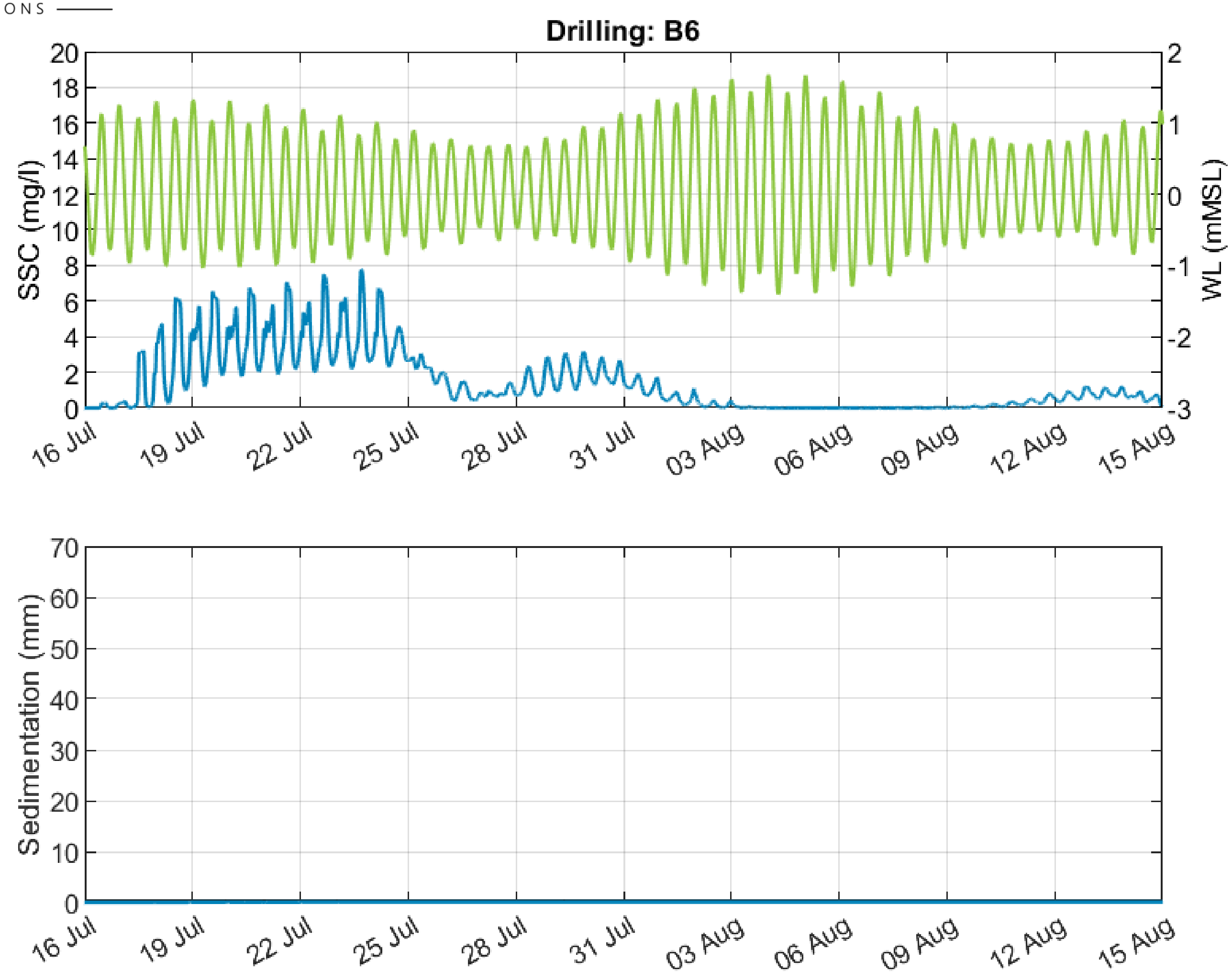


Figure 38. Modelled SSC and sedimentation at B6 for foundation installation.

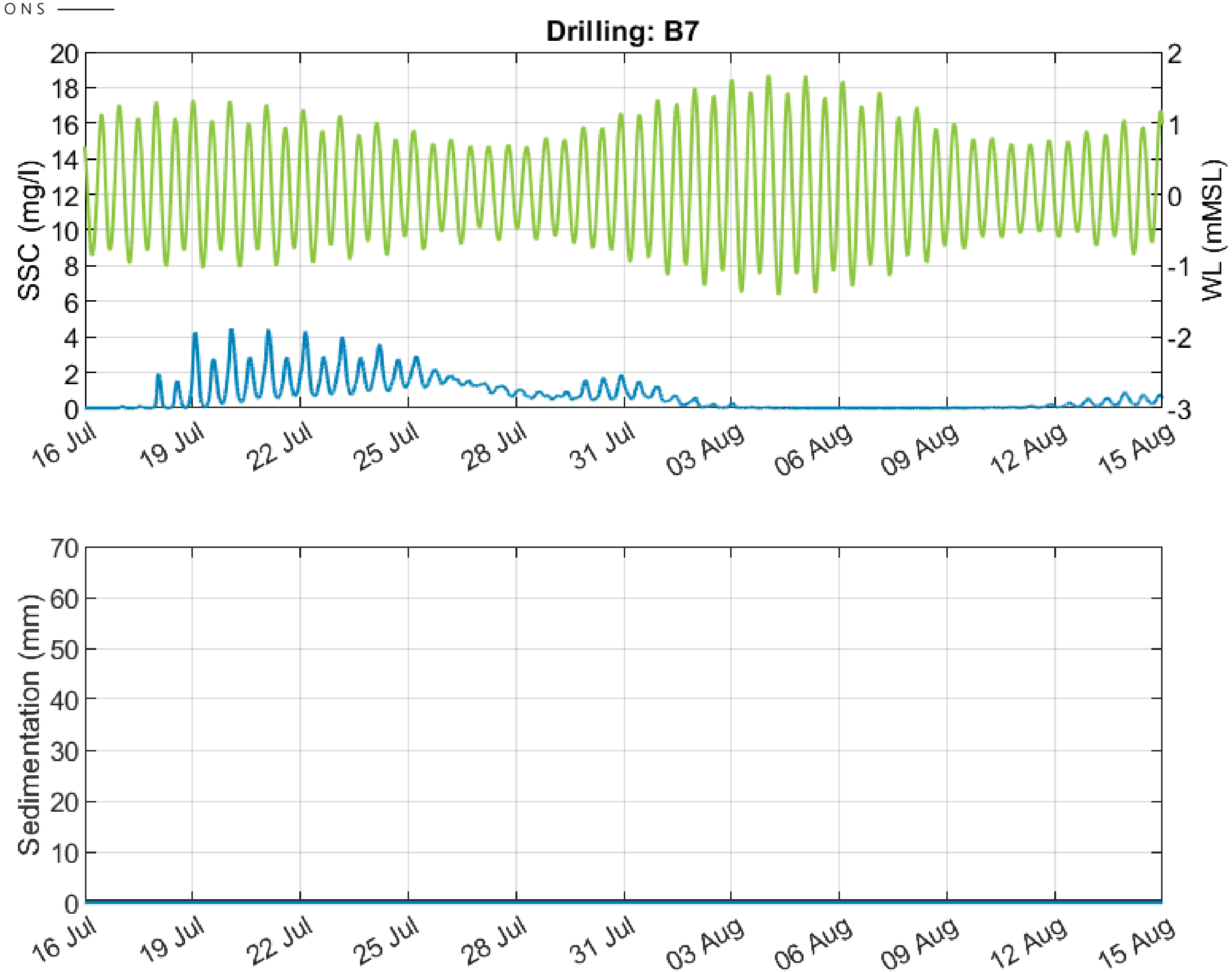


Figure 39. Modelled SSC and sedimentation at B7 for foundation installation.

5. Operational Impacts

This section provides details of the potential operational impacts resulting from the WTG and OSP foundations. Results showing the predicted impacts of the structures on water levels and currents from the HD model simulations and on waves from the SW model simulations are presented in the following sections.

5.1. Hydrodynamic Impacts

The HD model was setup to simulate hydrodynamics for a 15 day spring-neap period for the following scenarios:

- The existing environment (i.e. including a representation of structures in the existing Moray OWFs);
- Caledonia North;
- Caledonia South; and
- The Caledonia OWF.

Comparisons between the results from the scheme model setups (i.e. those including Caledonia OWF) and the existing environment model setup have been made to determine the potential impacts of the Caledonia OWF on water levels and currents. Given the low magnitude and extent of impacts of the Caledonia OWF on the hydrodynamics it is not considered necessary to undertake an in-combination assessment with other proposed OWF developments in the wider area.

5.1.1. Impact on water levels

The maximum change in the water level in each model element over the model simulation was calculated for each scheme model setup but the results showed no changes of more than ±0.001 m, which would be indiscernible from natural variation. Therefore, the Caledonia OWF is not predicted to result in any changes in the water level at any stage of the tide under spring and neap conditions.

5.1.2. Impact on flows

The changes in flow speed at the time of PF, HW, PE and LW on a spring and neap tide are shown in Figure 40 and Figure 41, respectively. The changes are shown down to very low differences in flow speed (± 0.001 m/s or 1 mm/s). Plots of the change in peak flow speed (Figure 42) and residual flow speed (Figure 43) are also shown for the Caledonia OWF, for Caledonia North and for Caledonia South. Timeseries plots of flow speed differences at the CalNorth and CalSouth sites are also shown in Figure 44 and Figure 45, respectively. The results show the following:

- Changes in flows of more than 0.001 m/s are predominantly constrained to within the Caledonia OWF;
- Changes in flows show adjacent areas of increased and decreased flows with localised decreases in the lee of the structures and localised increases adjacent to the structures as the flow accelerates around them;
- Increases and decreases in flows are typically less than 0.02 m/s and 0.03 m/s, respectively on spring tides and less than 0.005 m/s and 0.01 m/s, respectively on neap tides;
- The largest reduction in flows occurs on the flood tide in the middle of the Caledonia North Site, corresponding to an area where the WTGs align with the tidal flow direction;

- The combined changes in peak flow and residual flow from the Caledonia North Site and Caledonia South Site are broadly similar to the changes from the Caledonia OWF indicating that in-combination effects are small;
- Changes to peak flows and residual flows are broadly similar to changes described at individual timesteps with flow decreases in the lee of the structures and with flow increases adjacent to the structures; and
- Changes in direction are typically less than a couple of degrees, although greater diversions in flow will occur directly adjacent to the structures.

PORT & COASTAL SOLUTIONS

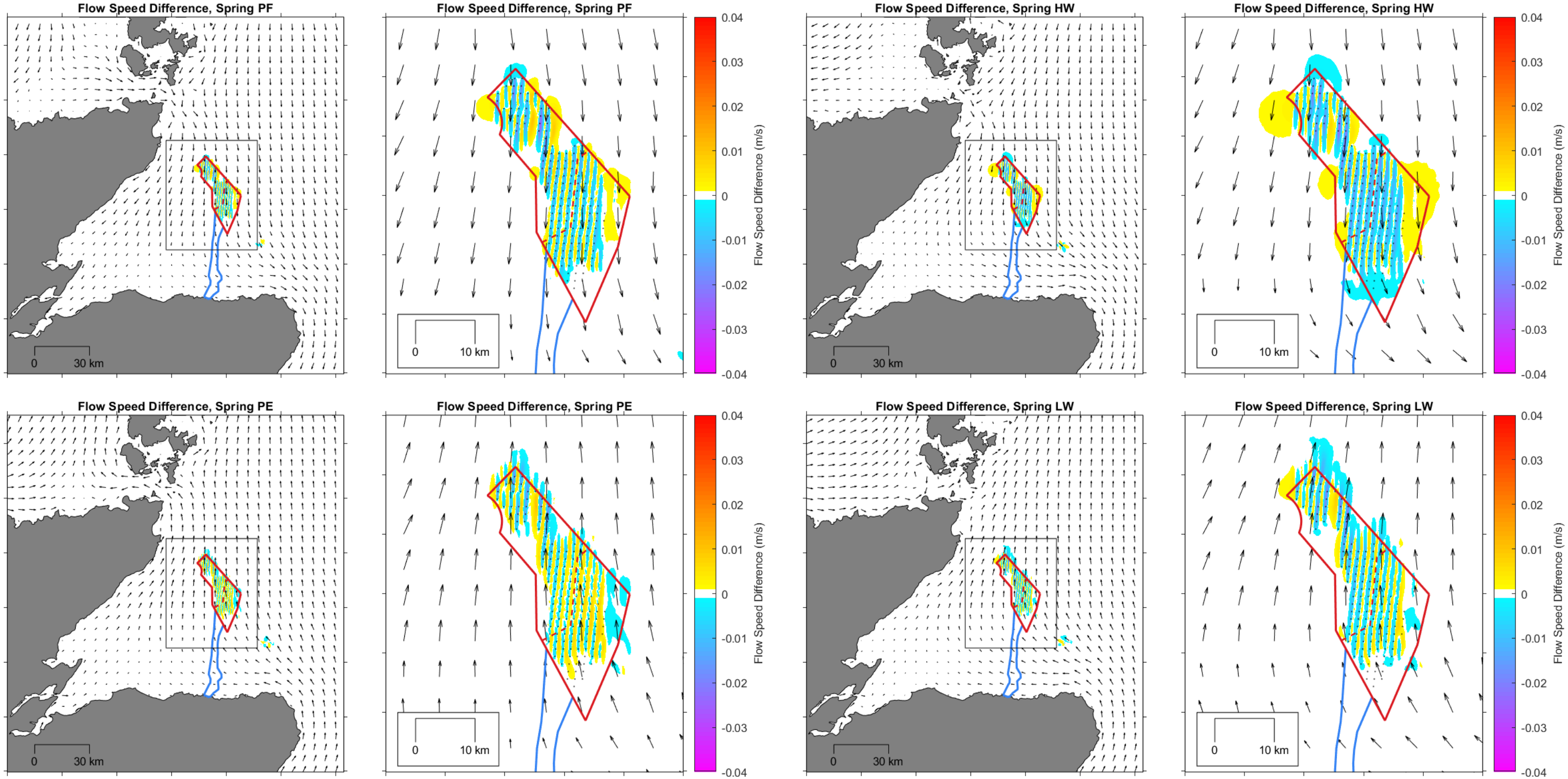


Figure 40. Modelled change in current speed at varying tidal stages on a mean spring tide - Caledonia OWF.

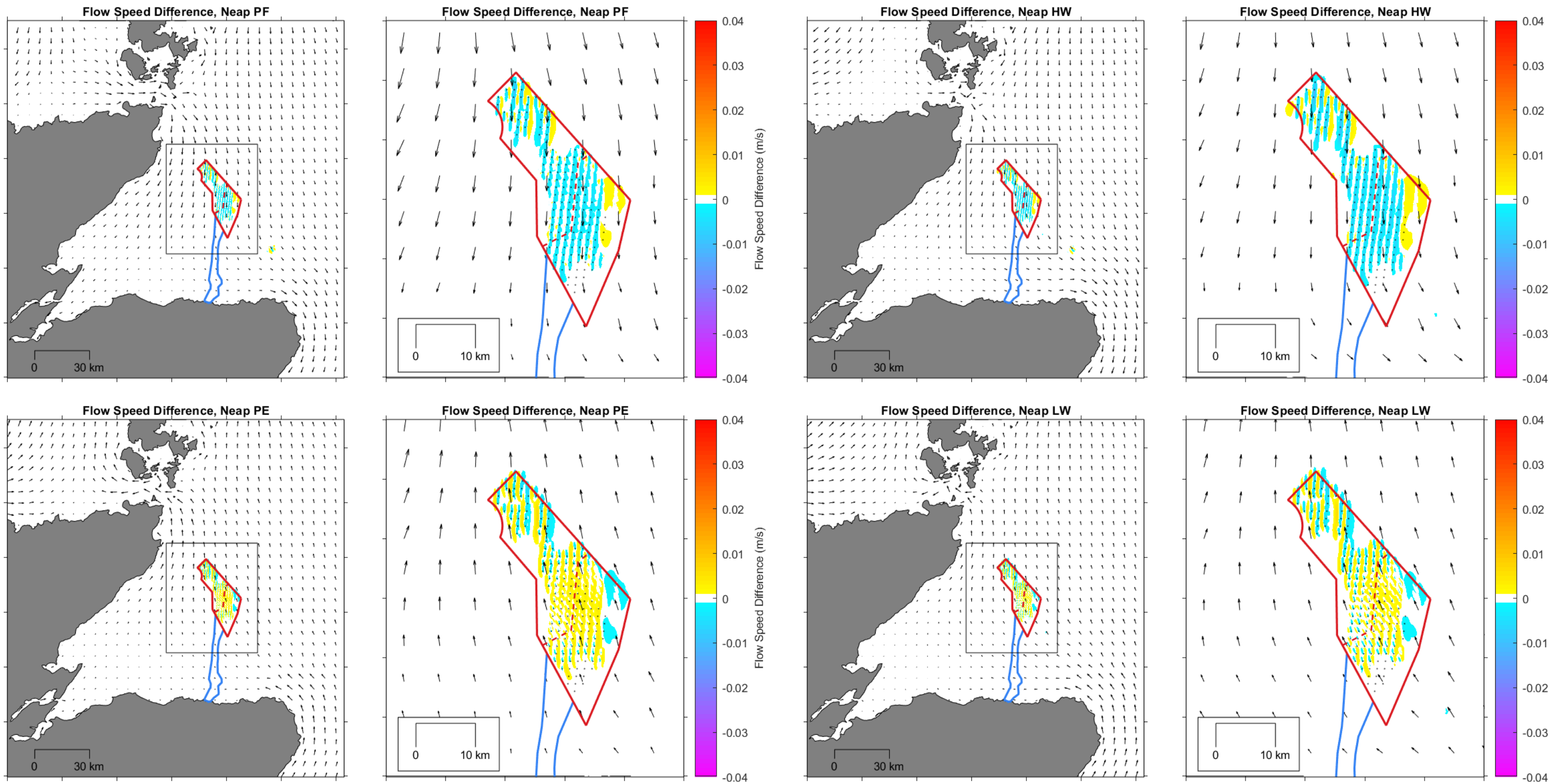


Figure 41. Modelled change in current speed at varying tidal stages on a mean neap tide – Caledonia OWF.

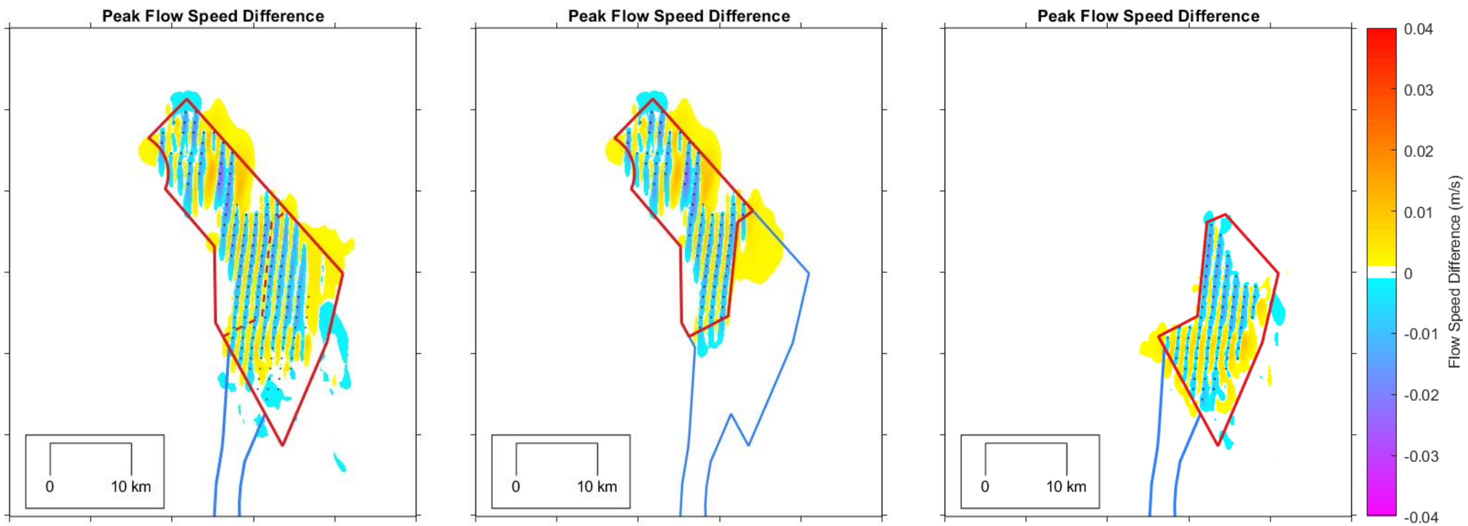


Figure 42. Modelled change in maximum flow speed – Caledonia OWF (left), Caledonia North (middle) and Caledonia South (right).

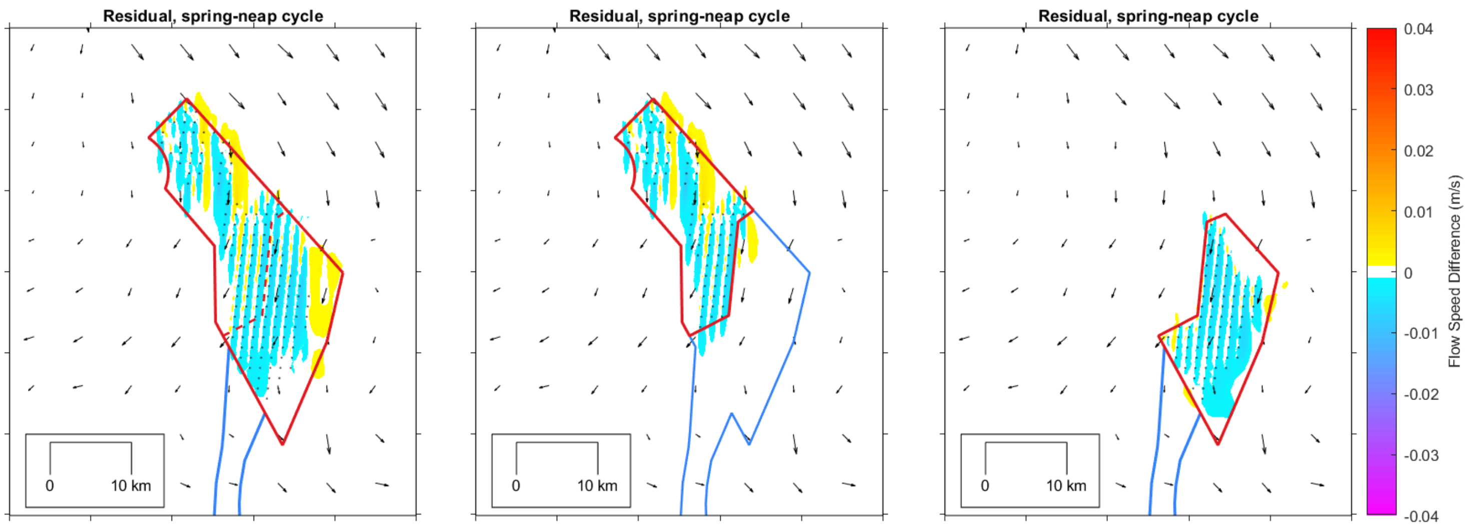


Figure 43. Modelled change in residual flow speed – Caledonia OWF (left), Caledonia North (middle) and Caledonia South (right).

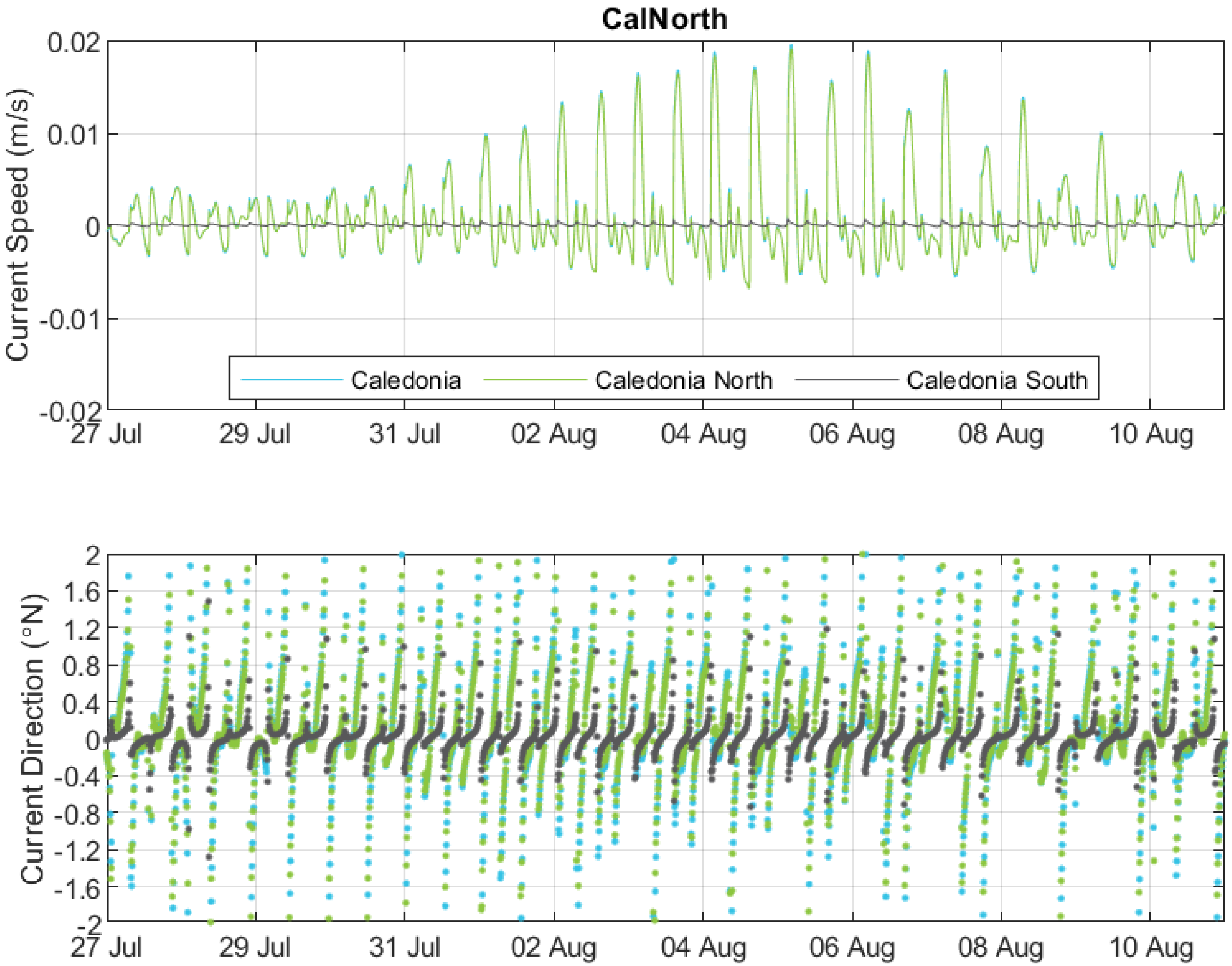


Figure 44 . Modelled change in current speed and direction at the CalNorth extraction location.

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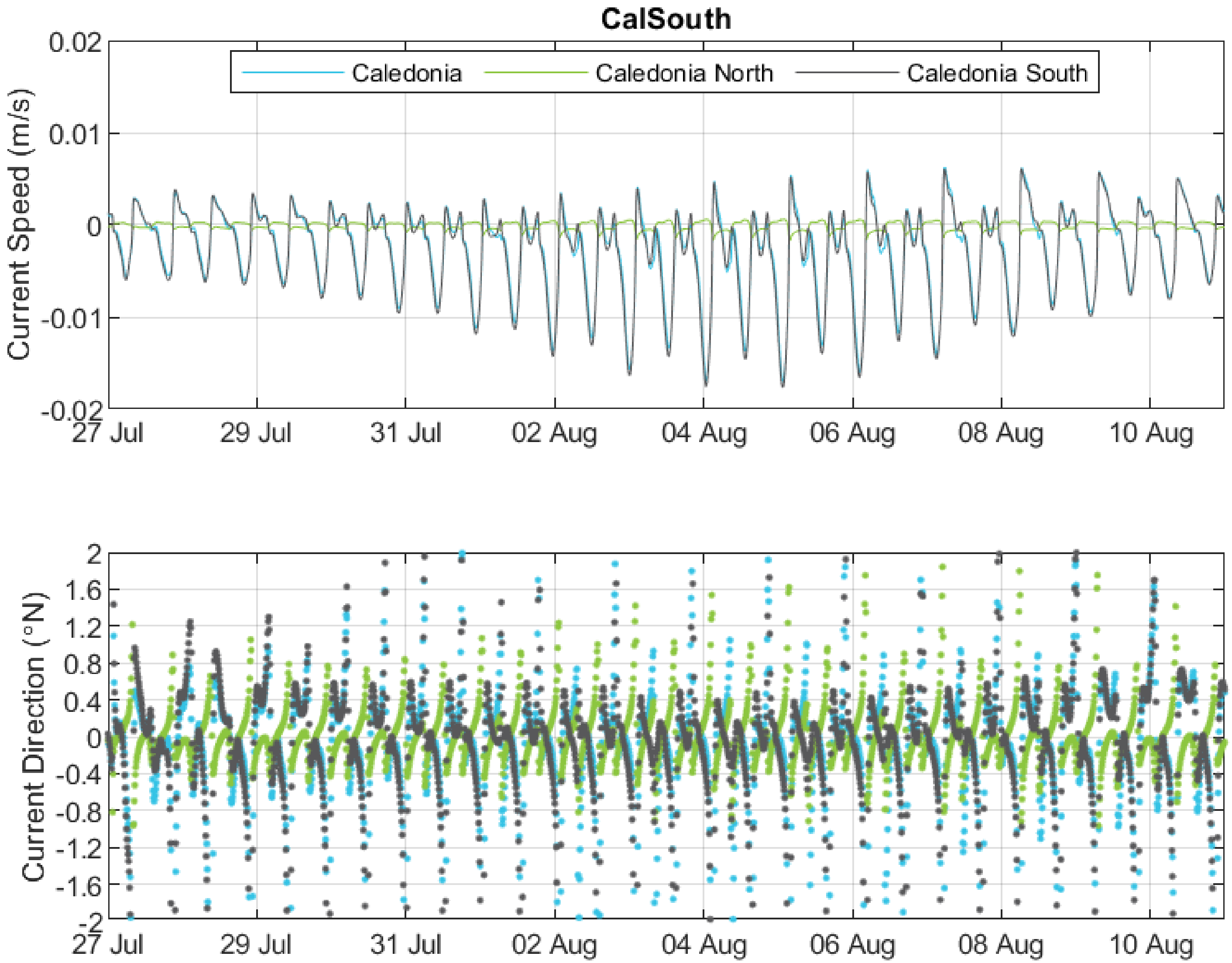

Figure 45. Modelled change in current speed and direction at the CalSouth extraction location.

5.2. Wave Impacts

The SW model was setup to simulate extreme wave conditions. Eight cardinal directions were modelled for the 1 in 1, 1 in 10 and 1 in 50 year ARIs. As for the HD model, the SW model was configured for the existing environment (i.e. including a representation of structures in the existing Moray OWFs) and for the Caledonia OWF, Caledonia North and Caledonia South. In addition, an in-combination assessment which includes a representation of structures from the proposed Stromar OWF (71 floating structures), Broadshore OWF (60 floating structures), Sinclair OWF (six floating structures) and Scaraben OWF (six floating structures) has been undertaken. All structures are represented as TLP with the same dimensions and with the same spacing as those applied for Caledonia South.

Comparisons between the results from the scheme model setups (i.e. those including Caledonia OWF) and the existing environment model setup have been made to determine the potential impacts of the Caledonia OWF on the local wave conditions. Changes in H_s for each modelled direction are shown for the 1 in 1 year ARI in Figure 46, for the 1 in 10 year ARI in Figure 47 and for the 1 in 50 year ARI in Figure 48. Results are shown for the Caledonia OWF, while results for Caledonia North and Caledonia South are included in Section 7. In addition, where changes are above 0.05 m, the change is also shown as a percentage change relative to the wave height for the existing environment (Figure A7 to Figure A18).

The plots show that the blockage effect of the WTG foundations reduces wave heights in the lee of the OWF. Reductions in H_s of more than 0.25 m are mainly constrained to within the Caledonia OWF, while reductions in H_s of 0.05 m extend more than 50 km from the Caledonia OWF, but only extend as far as any neighbouring coastlines for the 1 in 50 year wave from the southeast. This change of 0.05 m at the coast is small in relative terms (with H_s of more than 7 m for the existing wave environment), being less than a 1% change. As noted in Section 2.2, the WTG locations considered in the model were selected in deeper waters as those in the shallower water depths to give a maximum impact. The selection of other WTG locations, for example in the deeper water to the south of the Caledonia OWF (i.e. within Caledonia South), would be expected to result in a smaller operational impact in both magnitude and extent, but would change the location of the area of the impact by around 5 km to the south and the area of impact for the northerly ARI events could therefore extend to the southern Moray Firth coastline.

Comparisons of the impacts of the Caledonia OWF against that for Caledonia North and Caledonia South are made for the 1 in 50 year ARI from the northwest in Figure 49. The results show that the effect of Caledonia North on the wave climate is very small, with only a very localised reduction in wave heights of more than 0.05 m. This is because the bottom-fixed jacket structures with suction caissons are ‘slender piles’ (with a diameter of less than half the wavelength) and as such the impact on the waves is minimal. Comparatively, the effect of Caledonia South on the wave climate is more extensive with reductions in wave height of more than 0.05 m extending more than 20 km from the Caledonia South Site. This is because the floating structures in Caledonia South are much larger relative to the wavelength, resulting in a dampening of the wave energy. The combined changes in wave height from Caledonia North and Caledonia South individually are smaller than the changes from the Caledonia OWF development indicating that there is some in-combination effect.

In addition to an assessment of in-combination effects between Caledonia North and Caledonia South, an in-combination assessment of the impact of the Caledonia OWF and other nearby OWFs has been undertaken and results are presented in Figure 50 to Figure 52. The figures show that the in-combination blockage of the OWFs increases the area where H_s is reduced by more than 0.05 m so that it extends to the adjacent coastlines when the waves are from offshore sectors. Further, for waves from the east, the in-combination effect reduces wave heights by more than 0.1 m along the northern Moray Firth coastline, although this change remains small in relative terms (1-2%).

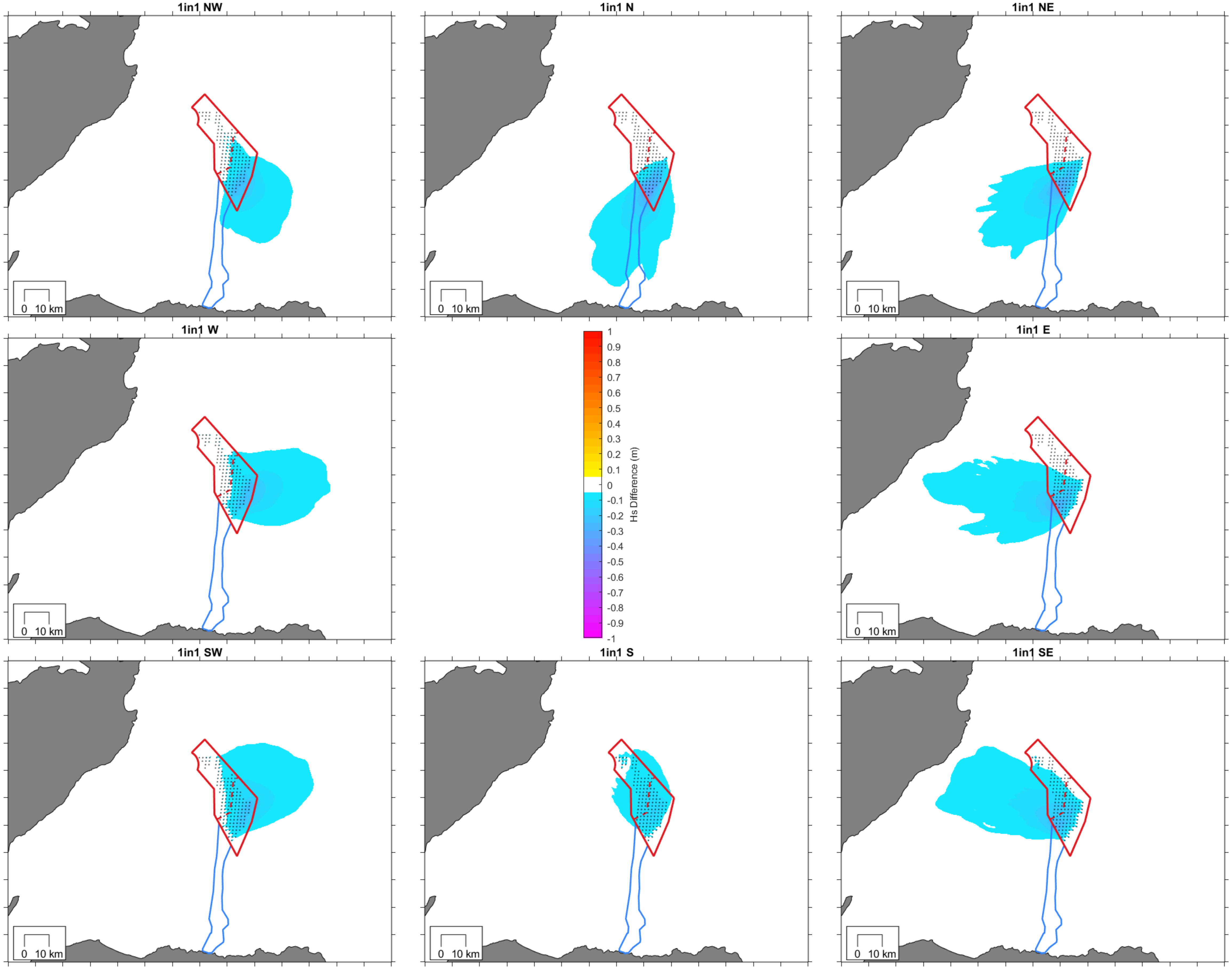

Figure 46. Difference in modelled H_s for the 1 in 1 year ARI events – Caledonia OWF.

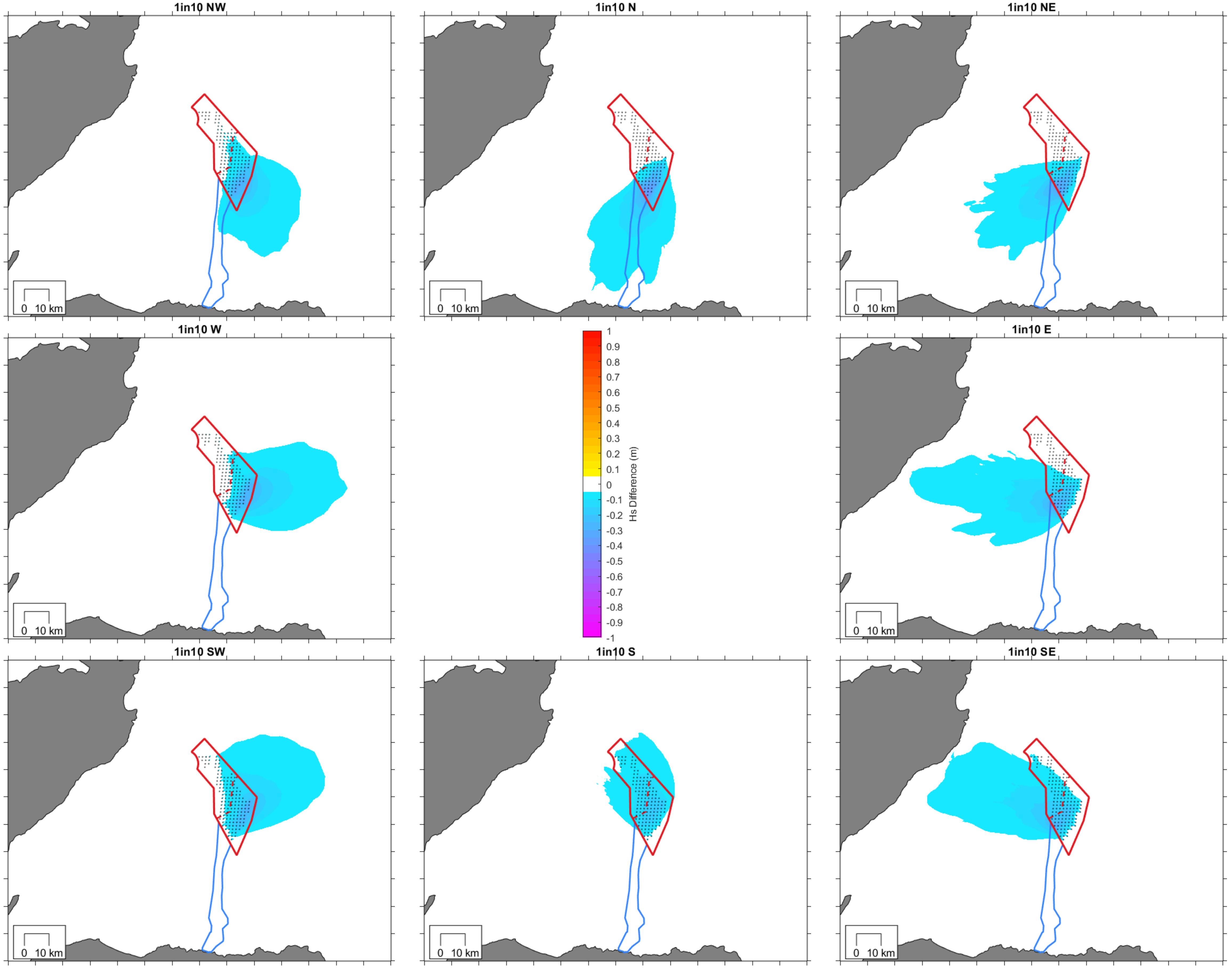

Figure 47. Difference in modelled H_s for the 1 in 10 year ARI events – Caledonia OWF.

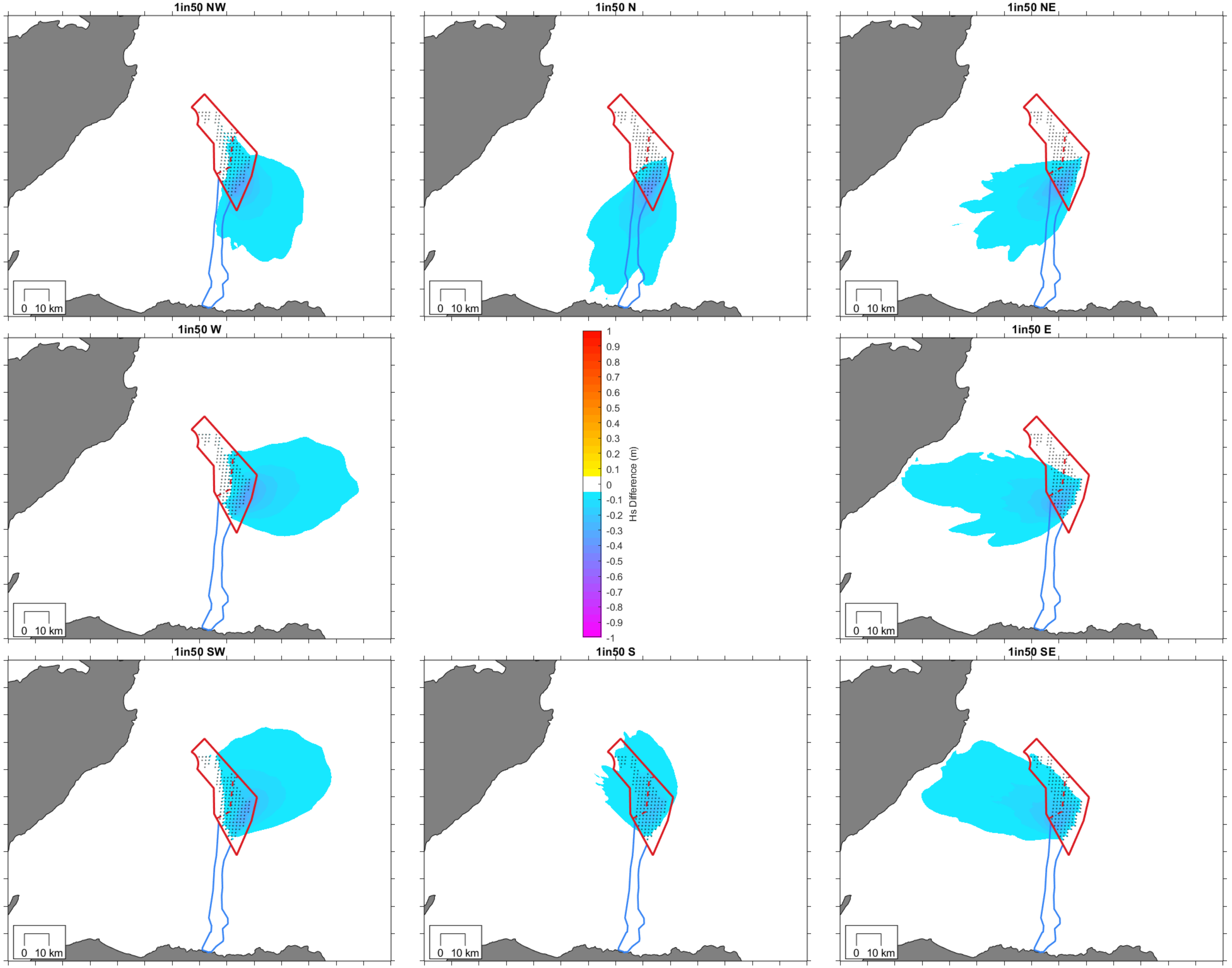

Figure 48. Difference in modelled H_s for the 1 in 50 year ARI events – Caledonia OWF.

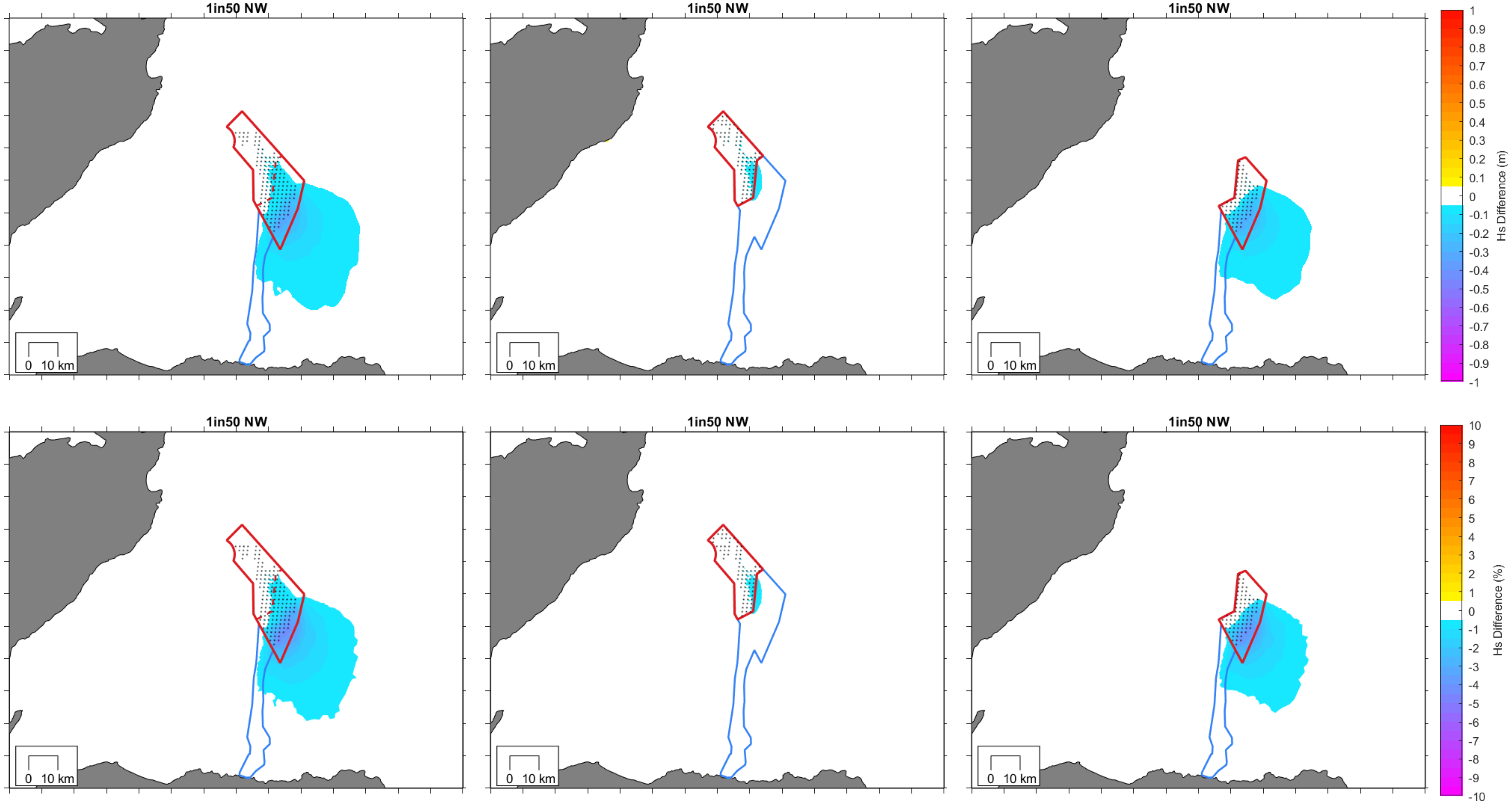

Figure 49. Absolute (upper) and percentage (lower) difference in H_s for the 1 in 50 year ARI event from the northeast for Caledonia OWF (left), Caledonia North (middle) and Caledonia South (right).

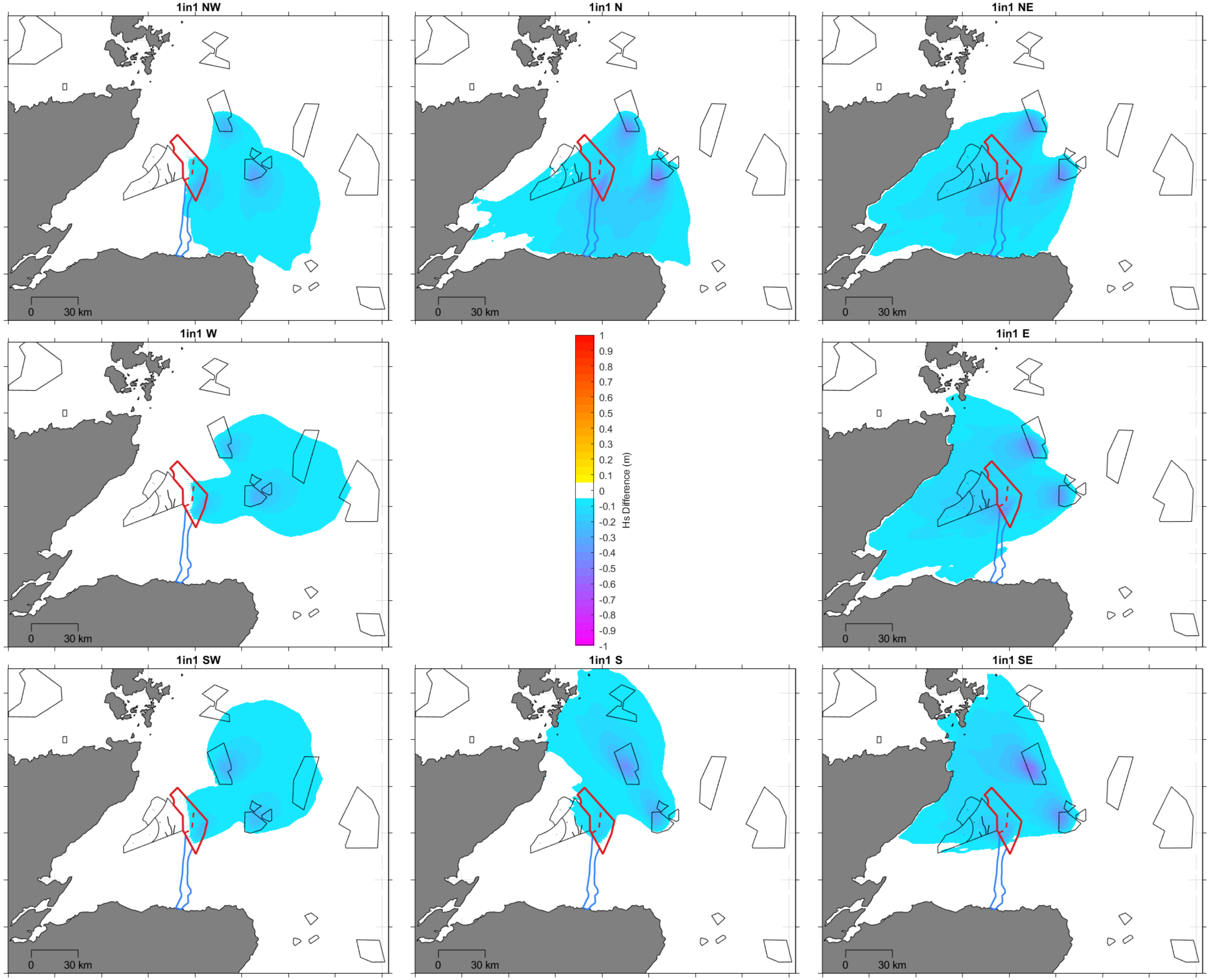

Figure 50. Difference in modelled H_s for the 1 in 1 year ARI events – Caledonia OWF in-combination with other adjacent OWFs.

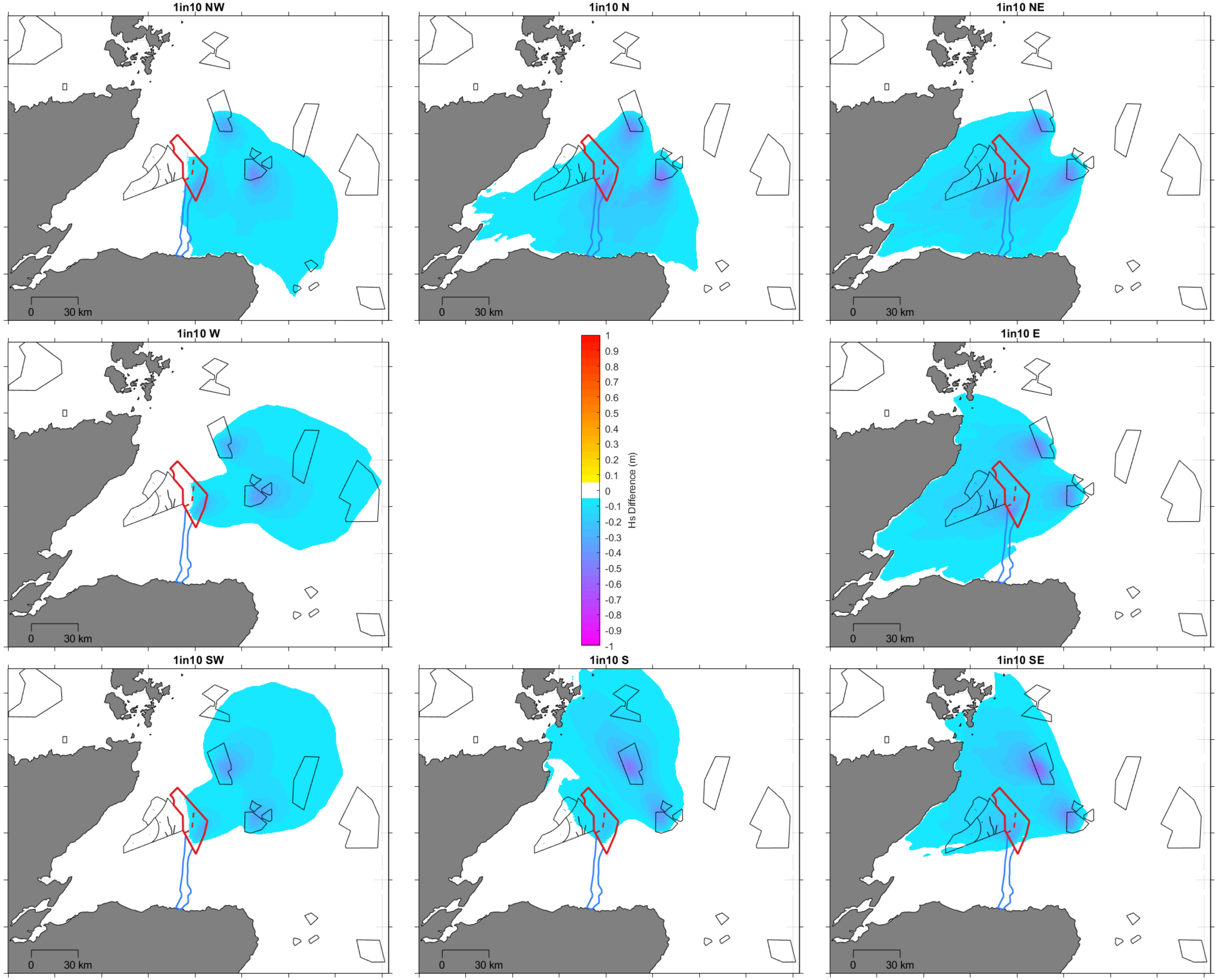

Figure 51. Difference in modelled H_s for the 1 in 10 year ARI events – Caledonia OWF in-combination with other adjacent OWFs.

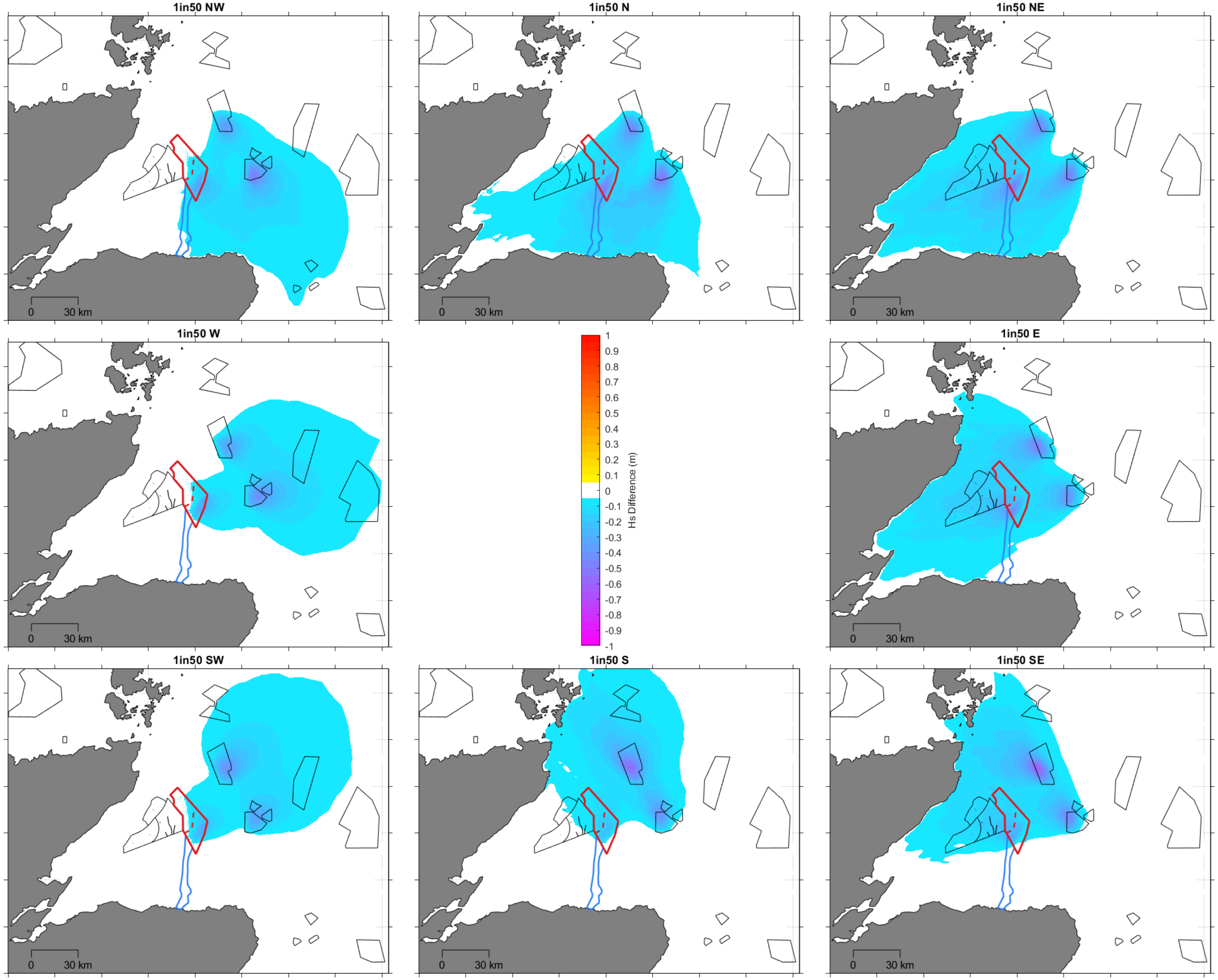

Figure 52. Difference in modelled H_s for the 1 in 50 year ARI events – Caledonia OWF in-combination with other adjacent OWFs.

6. Summary

This technical report presents results from a suite of numerical models to inform a number of topics for two applications that make up the Proposed Development (Offshore). Results from numerical models which simulate tidal flow, waves and sediment dispersion have been presented to characterise the existing environmental conditions and to assess the construction and operational impacts of the Proposed Development (Offshore) on marine and coastal environment. In the following, results are presented separately for Caledonia North, Caledonia South and for the Caledonia OWF (which includes Caledonia North and Caledonia South in combination).

6.1. Caledonia North

Results from the characterisation of the existing environment metocean conditions in the area showed that:

- Water levels are relatively uniform across the Caledonia North Site with a mean spring tidal range of 2.8 m, and a mean neap tidal range of 1.4 m;
- The peak tidal flows occur close to the time of high water and low water rather than at mid-tide level;
- Within the Caledonia North Site, flood currents are to the south and ebb currents are to the north, while in the southern part of the Caledonia North OECC flood currents are to the west and ebb currents are to the east (i.e. parallel with the adjacent shoreline);
- Current speeds within the Caledonia North Site are up to around 0.5 m/s on spring tides and less than 0.3 m/s on neap tides;
- The residual currents are generally low during both mean spring and neap tides and over a 14.5 day spring neap tidal cycle, with slowest residual flows in the northern half of the Caledonia North Site and fastest residual flows of up to 0.03 m/s in the southern half of the Caledonia North Site;
- There is a south to south-westward flow residual in the Caledonia North Site and an eastward flow residual along most of the Caledonia North OECC. The HD model is expected to slightly under predict the magnitude of the eastward flow residual along the Caledonia North OECC (PCS, 2024);
- The largest waves are from a north easterly direction and the smallest waves are from a north westerly direction;
- For the Annual Recurrence Interval (ARI) conditions modelled, significant wave heights (H_s) range from 5.0 m (1 in 1 year ARI from the northwest) to 8.4 m (1 in 50 year ARI from the northeast);
- H_s is relatively uniform across the Caledonia North Site with variations of around 0.5 m, increasing to more than 1 m when waves are from the north to west sectors; and
- The peak wave period (T_p) for the 1 in 1 year ARIs range from 8.7 to 13.2 seconds, increasing to more than 14 seconds for the 1 in 50 year ARIs, with longest period waves from the offshore directional sectors.

Potential construction related impacts arising from the disturbance and dispersion of sediment in the marine environment were assessed for cable installation, HDD and pile drilling of the WTG foundations. For inter-array cable installation and pile drilling the modelling assessment released sediment from within the Caledonia South Site. There are some small differences between Caledonia South and Caledonia North which will affect the volumes of sediment disturbed during construction activities at these two sites and how any disturbed sediment may disperse.

In particular, the seabed in the Caledonia South Site has a higher percentage of fines than the seabed in the Caledonia North Site and as such a higher volume of fine sediment will be dispersed in the marine environment during cable installation within the Caledonia South Site than for cable installation within the Caledonia North Site. In addition, the flow speeds in the Caledonia North Site are slightly faster than those in the Caledonia South Site. Despite these differences, the modelling results presented for inter-array cable installation and pile drilling as part of Caledonia South are expected to give a good indication of how sediment will disperse in the marine environment for inter-array cable installation and pile drilling for Caledonia North, albeit with a shift in plume centroid.

Results from the modelling of the construction related impacts showed that:

- Impacts for all construction activities (both in terms of SSC and sedimentation) were predicted to mainly be confined to occur within the Caledonia North Site and/or along the Caledonia North OECC;
- Cable installation:
  - The dispersion of fine sediment released during cable installation with a jet trencher was predicted to result in a plume with a peak SSC of more than 50 mg/l, but the area with elevated SSC was very localised to where the activity was being undertaken with very limited transport of the suspended sediment predicted. This is a result of the low tidal currents combined with the sediment being released relatively close to the seabed;
  - Increases in SSC were predicted to be short lived with increases of more than 25 mg/l occurring for less than 7.2 hours and increases of more than 5 mg/l occurring for less than six days; and
  - Sedimentation of more than 10 mm was predicted in parts of the Caledonia North Site, but more typically sedimentation of 2-3 mm was predicted along the Caledonia North OECC and interconnector cable routes, reducing to values of less than 0.1 mm at a short distance from where the sediment release was applied in the model.
- HDD:
  - The dispersion of fine sediment from muds and cuttings released at pop-out during HDD was predicted to result in a short lived, localised plume, with SSC above 0.5 mg/l extending over an area approximately 2.5 km west of the release point and 4 km to the east and higher SSC of more than 50 mg/l constrained to an area of approximately 1 km x 0.5 km. Given the models tendency to underpredict the magnitude of the eastward flow dominance in this area (PCS, 2024) it is possible that the plume would not extend as far west and would extend further to the east than predicted by the model;
  - The plume was predicted to disperse within three days of the sediment release, although some areas of higher SSC were predicted to remain along the shallow coastal areas including at the Inverboyndie bathing water. However, these increases were predicted to be low (typically less than 2 mg/l) and short lived; and
  - Sedimentation of more than 0.1 mm was predicted to be highly localised and constrained to an area of less than 2 km east-west and less than 1 km north-south.
- Foundation installation:
  - Sediment released during drilling of monopile foundations was predicted to result in a low concentration sediment plume, with increases in SSC of more than 5 mg/l constrained to within 5 km of the release location in a north-south direction and to within 1 km in an east-west direction. The SSC plume dispersed longer distances from the sediment release location than the plumes from cable installation and HDD due to the modelled release being in the surface layer, allowing a longer period for dispersion as the sediment settled to the bed;
  - Predicted sedimentation was less than 1 mm at distances of more than 1 km from the release location; and
  - Areas of increased SSC and sedimentation from pile drilling were predicted to extend over an area which is greater than the distance between WTG foundations. The drilling of all WTG foundations in the Caledonia North Site are therefore expected to

result in sedimentation at greater depths than shown for the limited number of piles drilled in the modelling simulation.

Operational impacts of Caledonia North were assessed in the HD and SW models. Results from the modelling of the blockage effect during operation showed that:

- The WTG foundations did not result in any notable changes in water levels;
- The WTG foundations resulted in localised neighbouring areas of increased and reduced flows, the magnitude of these changes were less than 0.002 m/s;
- Changes in residual flows were constrained to a small area and represented a small change of less than 0.002 m/s; and
- The bottom-fixed WTG foundations resulted in small changes to H_s, predicted to be less than ±0.05 m and with changes constrained to be within the Caledonia North Site.

6.2. Caledonia South

Results from the characterisation of the existing environment metocean conditions in the area showed that:

- Water levels are relatively uniform across the Caledonia South Site with a mean spring tidal range of 2.8 m, and a mean neap tidal range of 1.4 m;
- The peak tidal flows occur close to the time of high water and low water rather than at mid-tide level;
- Within the Caledonia South Site, flood currents are to the south and ebb currents are to the north, while in the southern part of the Caledonia South OECC flood currents are to the west and ebb currents are to the east (i.e. parallel with the adjacent shoreline);
- Current speeds within the Caledonia South Site are up to around 0.4 m/s on spring tides and less than 0.2 m/s on neap tides;
- The residual currents are generally low during both mean spring and neap tides and over a 14.5 day spring neap tidal cycle, with slightly faster residuals (of up to 0.035 m/s) in the northern half of the Caledonia South Site;
- There is a southward (to south-westward) flow residual in the Caledonia South Site and an eastward flow residual along most of the Caledonia South OECC. The HD model is expected to slightly under predict the magnitude of the eastward flow residual along the Caledonia South OECC (PCS, 2024);
- The largest waves are from a northerly direction and the smallest waves are from a southerly direction;
- For the Annual Recurrence Interval (ARI) conditions modelled, significant wave heights (H_s) range from 4.8 m (1 in 1 year ARI from the south) to 8.2 m (1 in 50 year ARI from the northeast);
- H_s is relatively uniform across the Caledonia South Site with variations of around 0.5 m, increasing to more than 1 m when waves are from the north to west sectors; and
- The peak wave period (T_p) for the 1 in 1 year ARIs range from 8.6 to 13.3 seconds, increasing to more than 14 seconds for the 1 in 50 year ARIs, with longest period waves from the offshore directional sectors.

Potential construction related impacts arising from the disturbance and dispersion of sediment in the marine environment were assessed for cable installation, HDD and pile drilling of the WTG foundations. Results from the modelling of the construction related impacts showed that:

- Impacts for all construction activities (both in terms of SSC and sedimentation) were predicted to mainly be confined to occur within the Caledonia South Site and/or along the Caledonia South OECC;
- Cable installation:
  - The dispersion of fine sediment released during cable installation with a jet trencher was predicted to result in a plume with a peak SSC of more than 50 mg/l, but the area with elevated SSC was very localised to where the activity was being undertaken with very limited transport of the suspended sediment predicted. This is a result of the low tidal currents combined with the sediment being released relatively close to the seabed;
  - Increases in SSC were predicted to be short lived with increases of more than 25 mg/l occurring for less than 7.2 hours and increases of more than 5 mg/l occurring for less than six days; and
  - Sedimentation of more than 10 mm was predicted in parts of the Caledonia South Site, but more typically sedimentation of 2-3 mm was predicted along the Caledonia South OECC and interconnector cable routes, reducing to values of less than 0.1 mm at a short distance from where the sediment release was applied in the model.
- HDD:
  - The dispersion of fine sediment from muds and cuttings released at pop-out during HDD was predicted to result in a short lived, localised plume, with SSC above 0.5 mg/l extending over an area approximately 2.5 km west of the release point and 4 km to the east and higher SSC of more than 50 mg/l constrained to an area of approximately 1 km x 0.5 km. Given the models tendency to underpredict the magnitude of the eastward flow dominance in this area (PCS, 2024) it is possible that the plume would not extend as far west and would extend further to the east than predicted by the model;
  - The plume was predicted to disperse within three days of the sediment release, although some areas of higher SSC were predicted to remain along the shallow coastal areas including at the Inverboyndie bathing water. However, these increases were predicted to be low (typically less than 2 mg/l) and short lived; and
  - Sedimentation of more than 0.1 mm was predicted to be highly localised and constrained to an area of less than 2 km east-west and less than 1 km north-south.
- Foundation installation:
  - Sediment released during drilling of monopile foundations was predicted to result in a low concentration sediment plume, with increases in SSC of more than 5 mg/l constrained to within 5 km of the release location in a north-south direction and to within 1 km in an east-west direction. The SSC plume dispersed longer distances from the sediment release location than the plumes from cable installation and HDD due to the modelled release being in the surface layer, allowing a longer period for dispersion as the sediment settled to the bed;
  - Predicted sedimentation was less than 1 mm at distances of more than 1 km from the release location; and
  - Areas of increased SSC and sedimentation from pile drilling were predicted to extend over an area which is greater than the distance between WTG foundations. The drilling of all WTG foundations in the Caledonia South Site are therefore expected to result in sedimentation at greater depths than shown for the limited number of piles drilled in the modelling simulation.

Operational impacts of Caledonia South were assessed in the HD and SW models. Results from the modelling of the blockage effect during operation showed that:

- The WTG foundations did not result in any notable changes in water levels;
- The WTG foundations resulted in localised neighbouring areas of increased and reduced flows, the magnitude of these changes were less than 0.002 m/s;

- Changes in residual flows were constrained to a small area and represented a small change of less than 0.002 m/s;
- The bottom-fixed WTG foundations resulted in small changes to H_s, predicted to be less than ±0.05 m and with changes constrained to be within the Caledonia South Site;
- The floating WTG substructures resulted in larger changes to H_s than the bottom-fixed WTG foundations with a reduction in H_s of more than ±0.05 m extending close to the northern Moray Firth coastline. This change of 0.05 m at the coast is small in relative terms (with H_s of more than 7 m for the existing wave environment), being less than a 1% change; and
- Larger reductions in H_s of more than 0.25 m also occur but these are mainly constrained to the Caledonia South Site.

Proposed Development (Offshore)

An in-combination assessment of the operational blockage effect of the Caledonia OWF (i.e., Caledonia North and Caledonia South) on flows and waves showed that:

- The combined changes in peak flow and residual flow from Caledonia North and Caledonia South are broadly similar to the changes from Caledonia OWF indicating that in-combination effects are small; and
- The combined changes in wave height from Caledonia North and Caledonia South individually are smaller than the changes from the Caledonia OWF indicating that there is some in-combination effect.

An in-combination assessment of Caledonia South, Caledonia North and other adjacent OWF developments (including Stromar, Broadshore, Sinclair and Scaraben OWFs) was also undertaken to assess the blockage effect on waves. The in-combination blockage of the OWFs increases the area where H_s is reduced by more than 0.05 m so that it extends to the adjacent coastlines when the waves are from offshore sectors. Further, for waves from the east, the in-combination effect reduces wave heights by more than 0.1 m along the northern Moray Firth coastline, although this change remains small in relative terms (1-2%).

Overall, the modelling results have predicted that the construction and operational impacts are relatively small and are predominantly constrained to occur within the Caledonia OWF and along the Caledonia, Caledonia North and Caledonia South OECCs.

The construction works were predicted to have the potential to result in increases in SSC of more than 50 mg/l, but these were typically shown to be very localised to where the construction activity was being undertaken (i.e. within the Caledonia North Site and Caledonia South Site or along the Caledonia, Caledonia North and Caledonia South OECCs). The persistence of elevated concentrations will depend on the duration of the activity.

Although plots of predicted changes in tidal flows and waves due to the proposed structures have been presented, these changes have typically been shown by plotting the changes down to a very small difference and based on the scale of the changes it is considered unlikely that any measurable changes will occur, except potentially within the Caledonia South Site where floating structures could result in measurable reduction in wave heights. In-combination effects with other nearby OWFs could extend the area of measurable change to wave heights beyond the footprint of the Caledonia South Site.

7. Additional Plots: Impacts to Waves

The following section contains a number of additional plots which present the impact of Caledonia North and Caledonia South upon the wave regime.

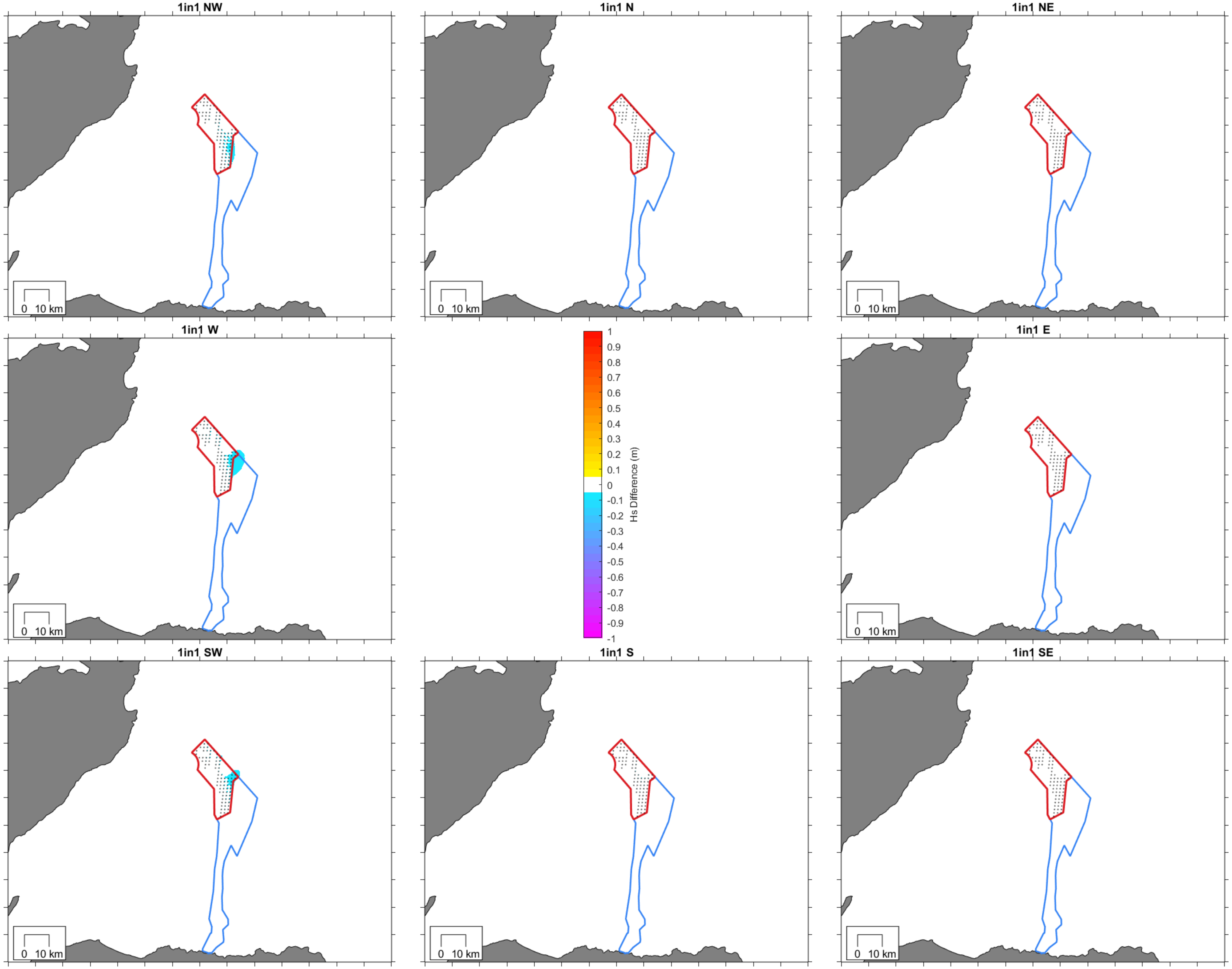

Figure A1. Difference in modelled wave height and direction for the 1 in 1 year ARI events – Caledonia North.

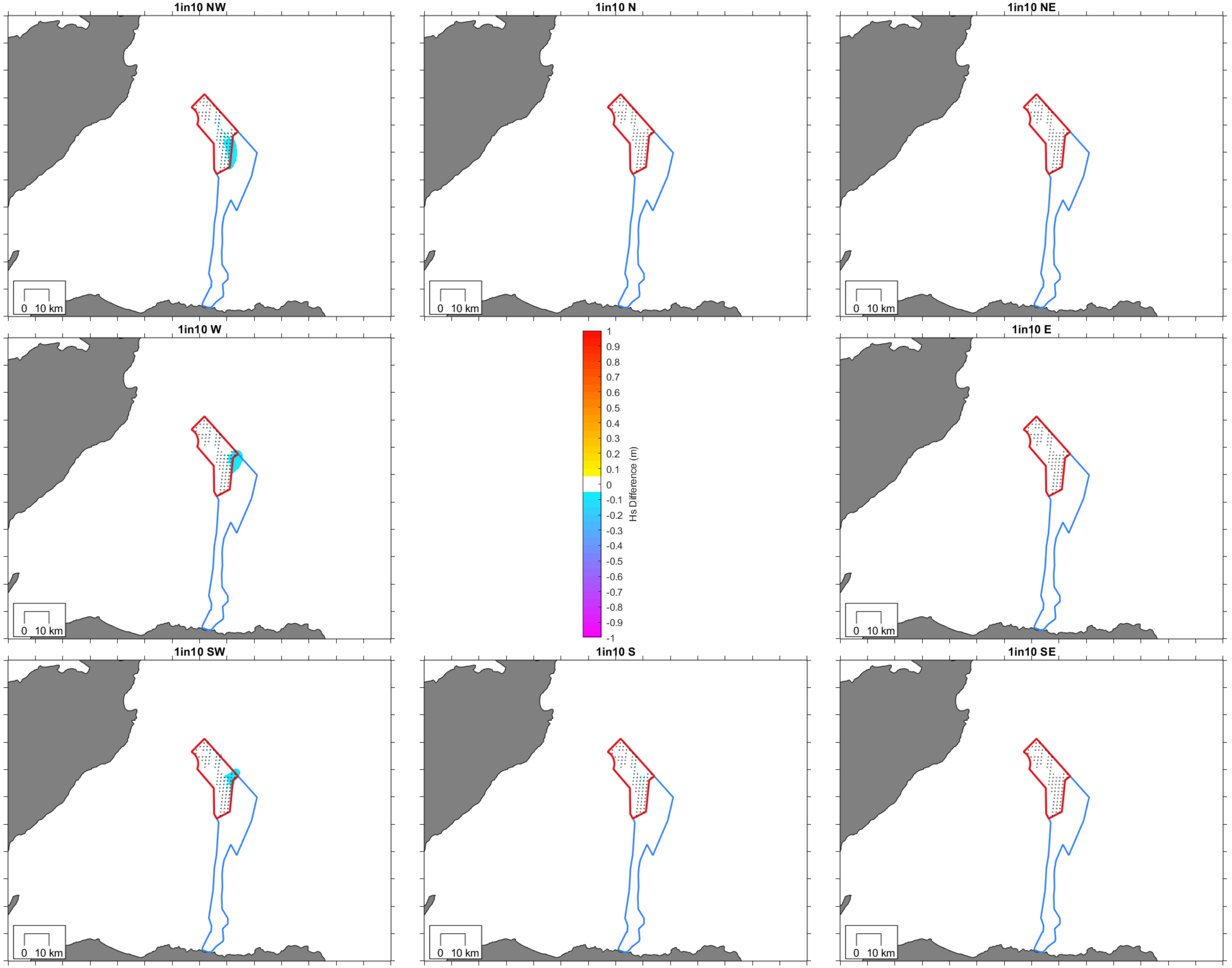

Figure A2. Difference in modelled wave height and direction for the 1 in 10 year ARI events – Caledonia North.

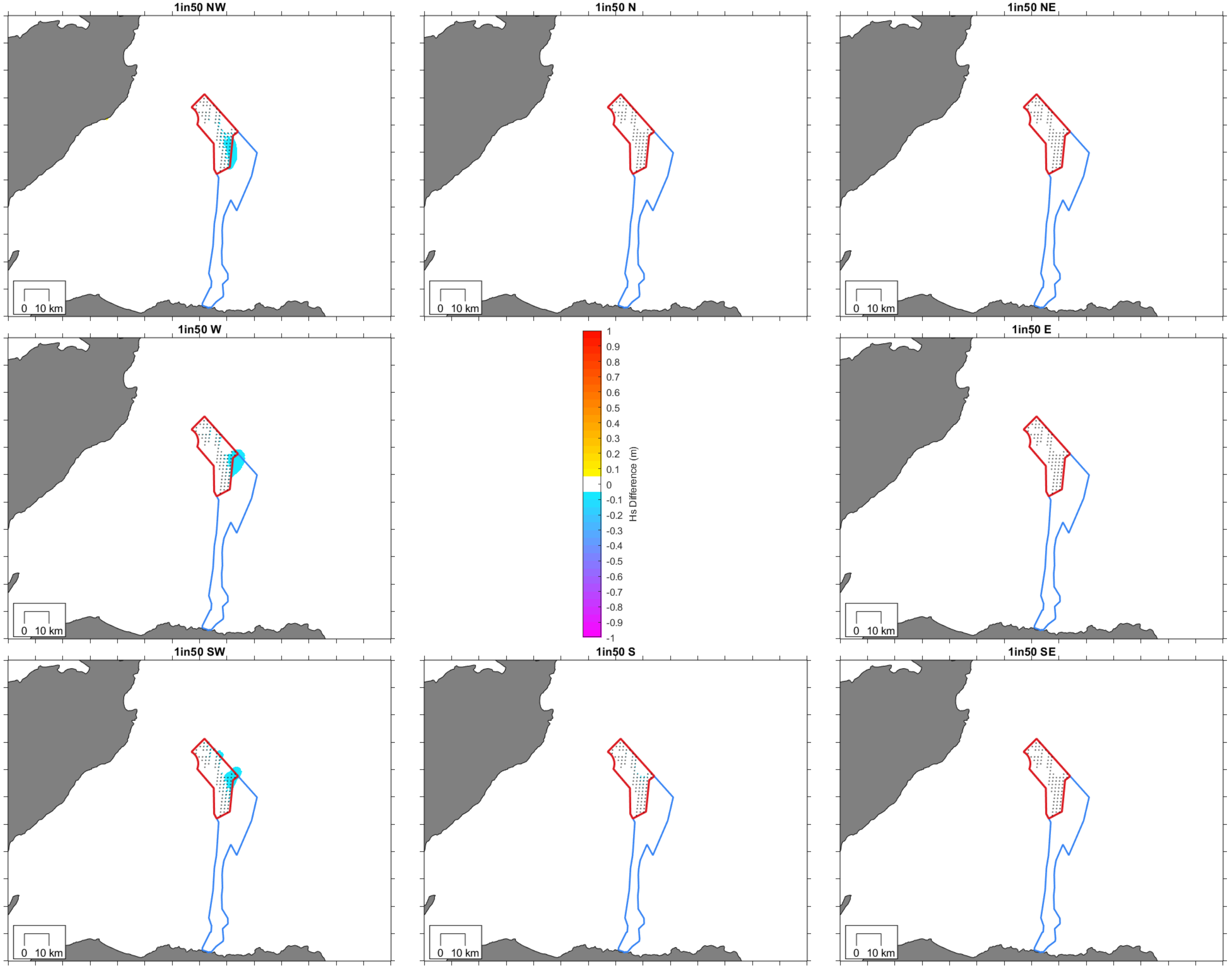

Figure A3. Difference in modelled wave height and direction for the 1 in 50 year ARI events – Caledonia North.

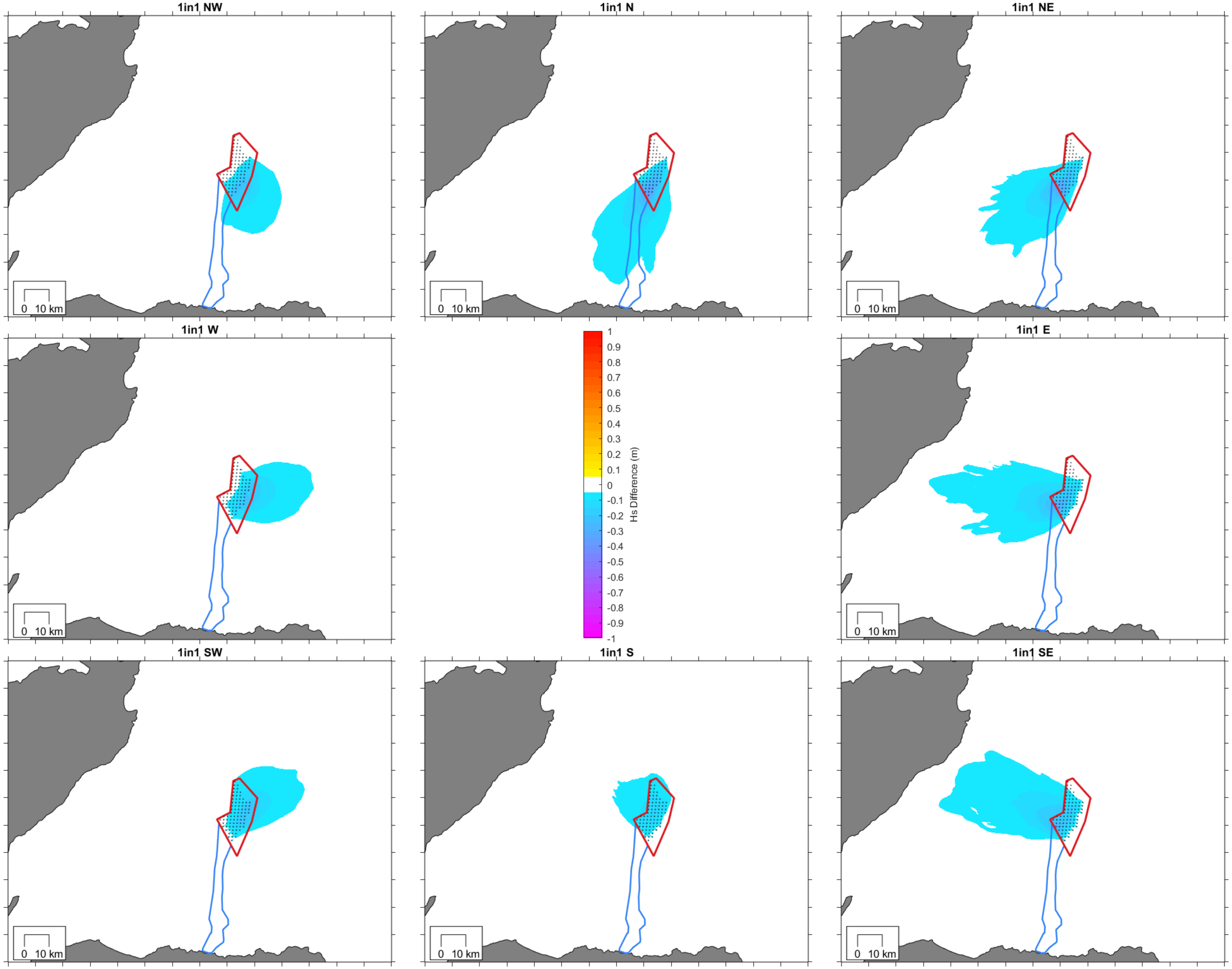

Figure A4. Difference in modelled wave height and direction for the 1 in 1 year ARI events – Caledonia South.

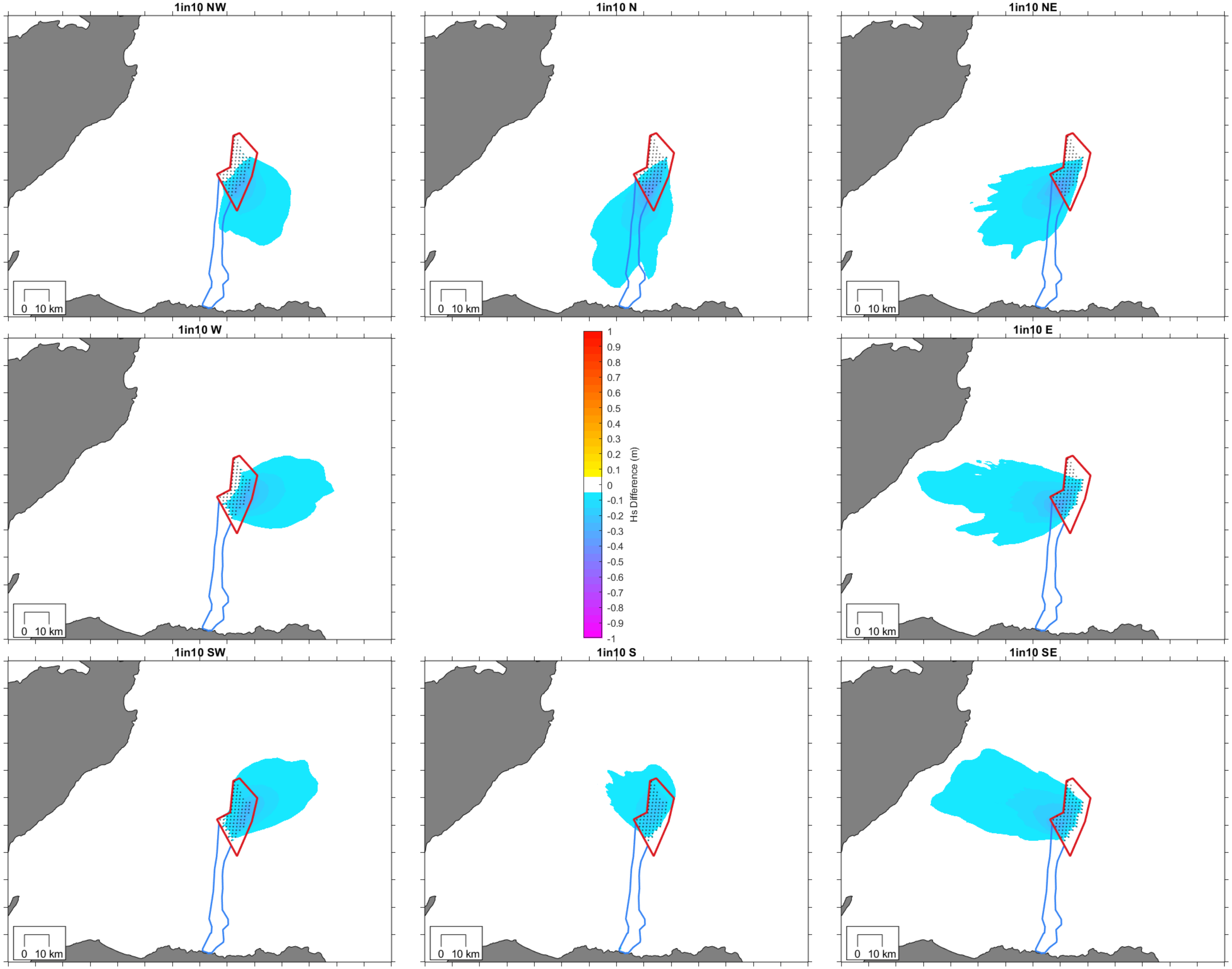

Figure A5. Difference in modelled wave height and direction for the 1 in 10 year ARI events – Caledonia South.

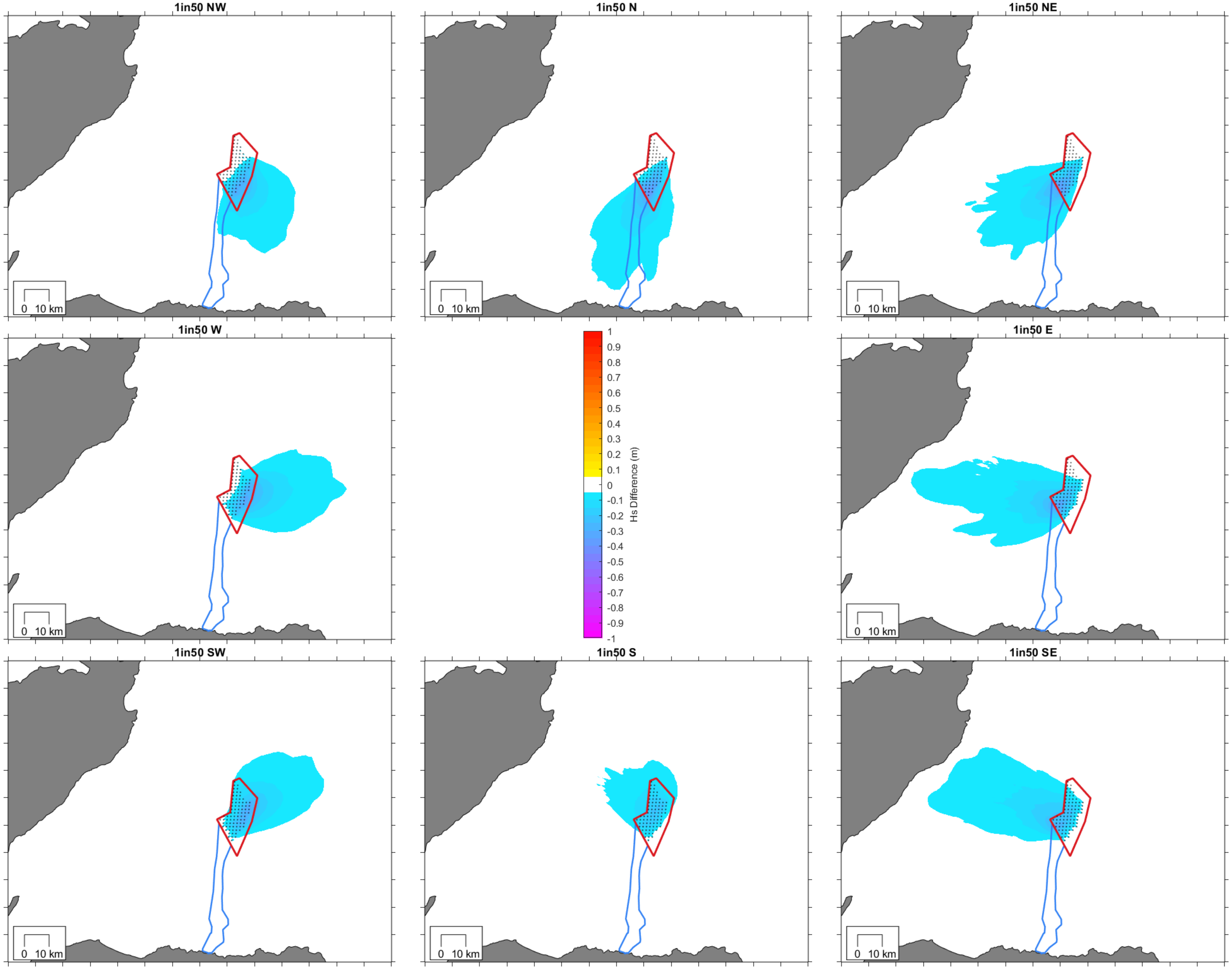

Figure A6. Difference in modelled wave height and direction for the 1 in 50 year ARI events – Caledonia South.

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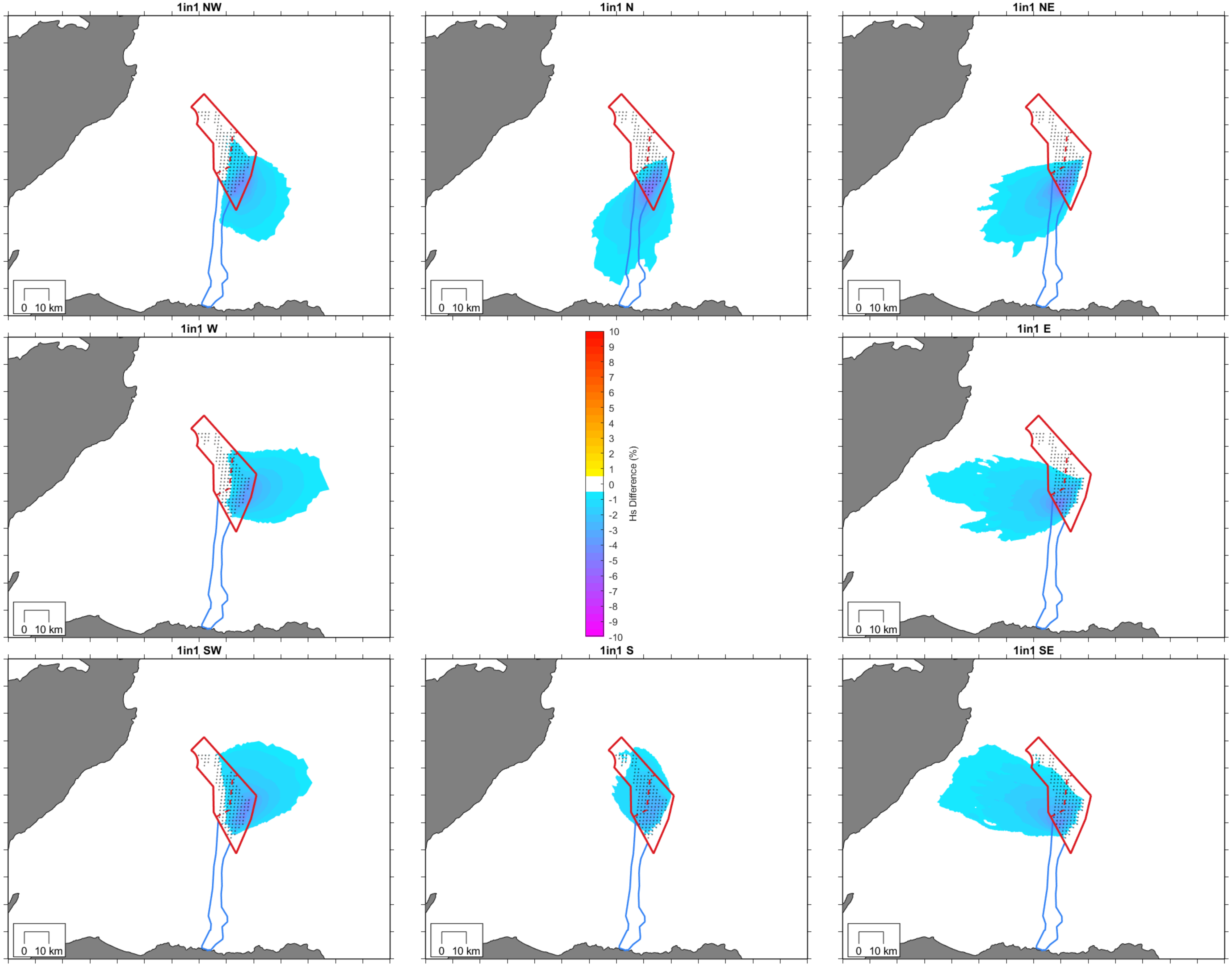

Figure A7. Percentage difference in modelled Hs for the 1 in 1 year ARI events – Caledonia OWF.

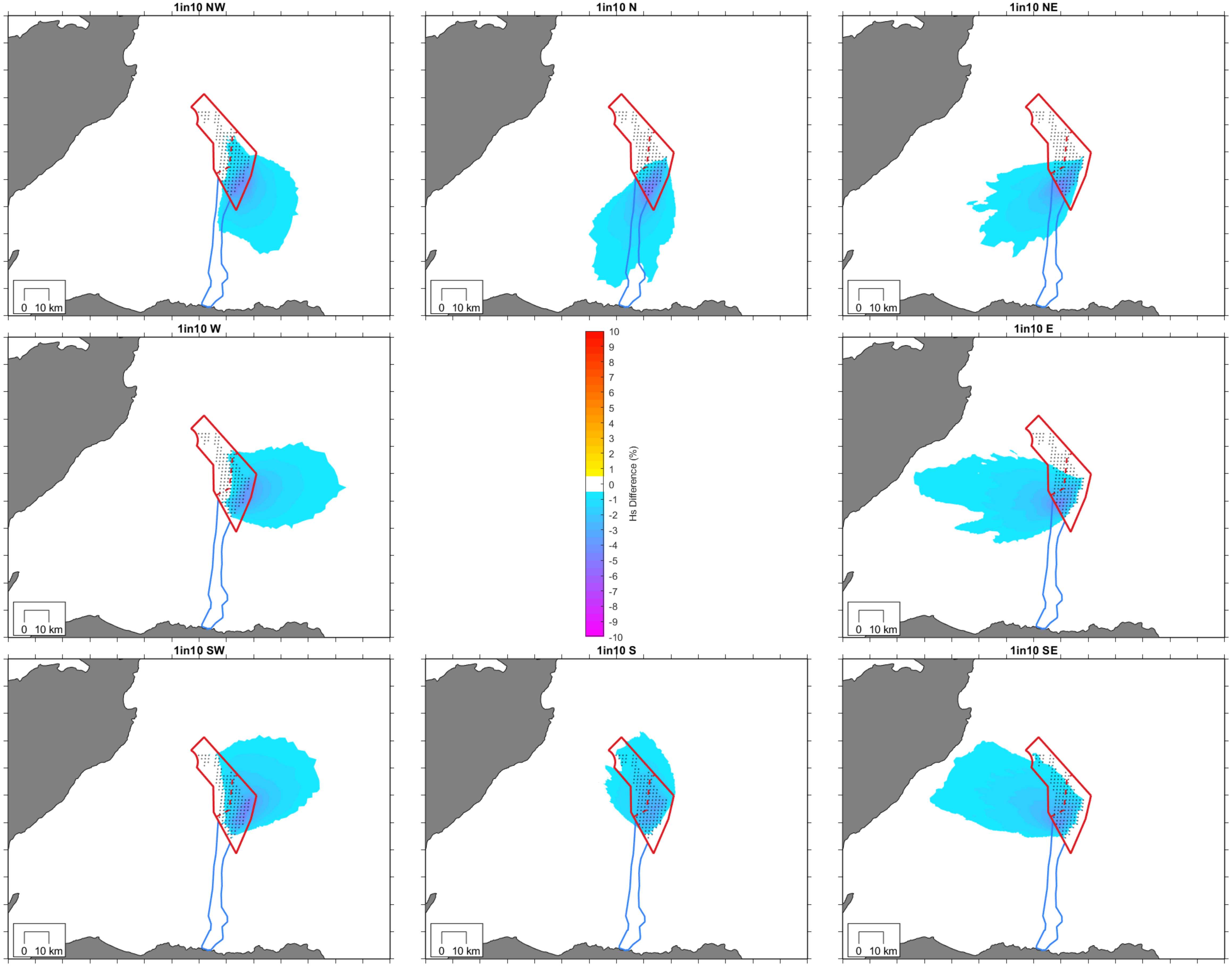

Figure A8. Percentage difference in Hs for the 1 in 10 year ARI events – Caledonia OWF.

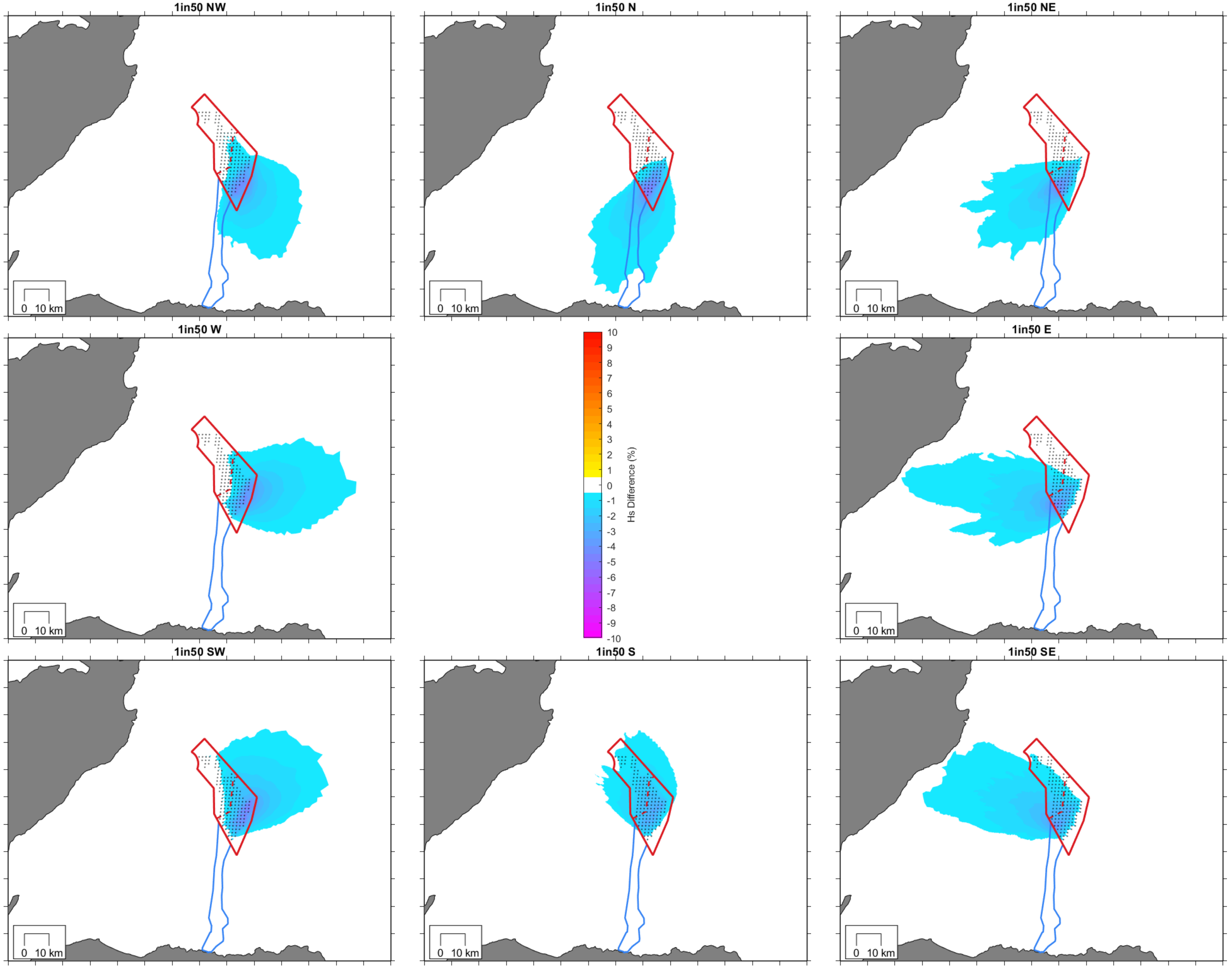

Figure A9. Percentage difference in Hs for the 1 in 50 year ARI events – Caledonia OWF.

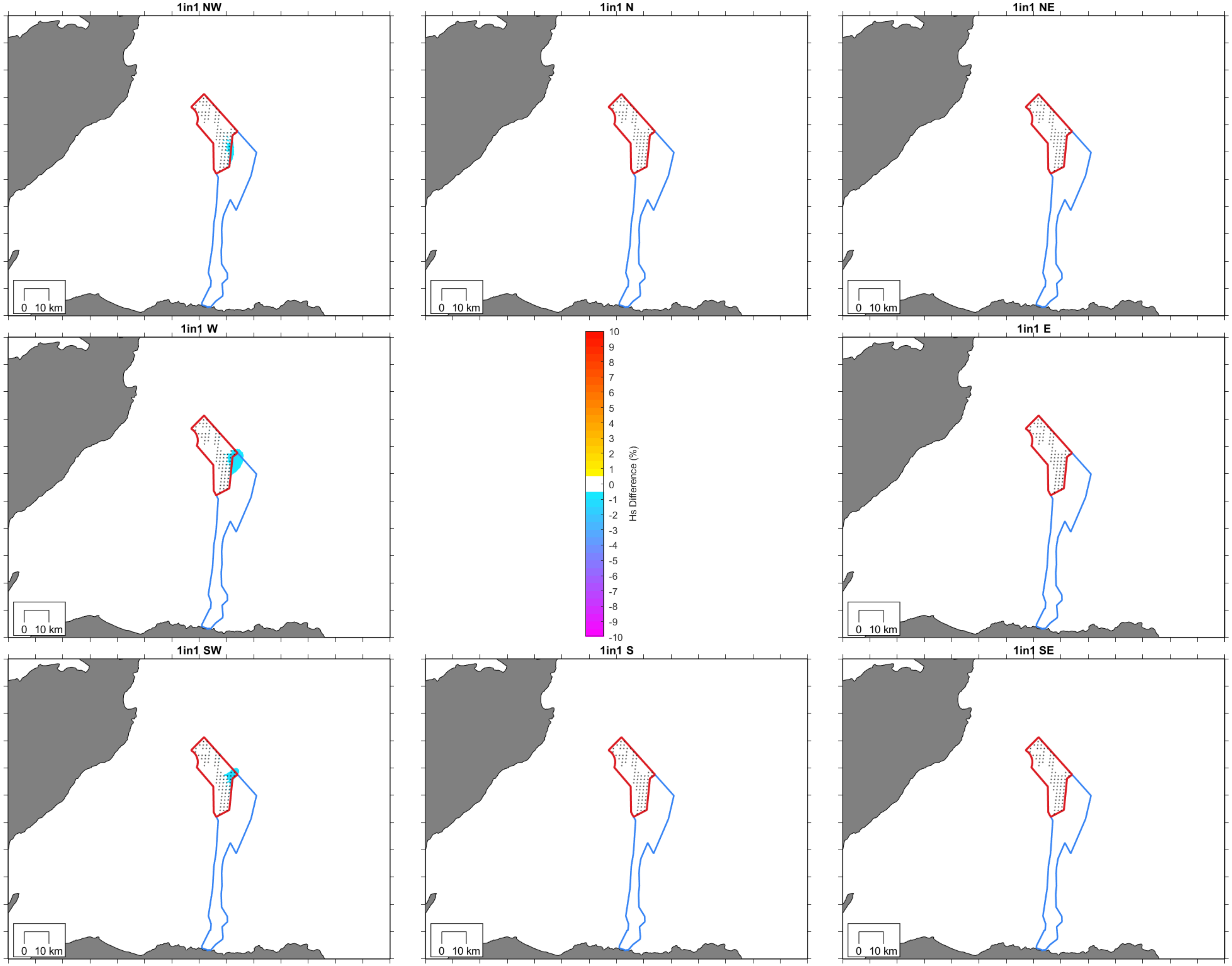

Figure A10. Percentage difference in modelled Hs for the 1 in 1 year ARI events – Caledonia North.

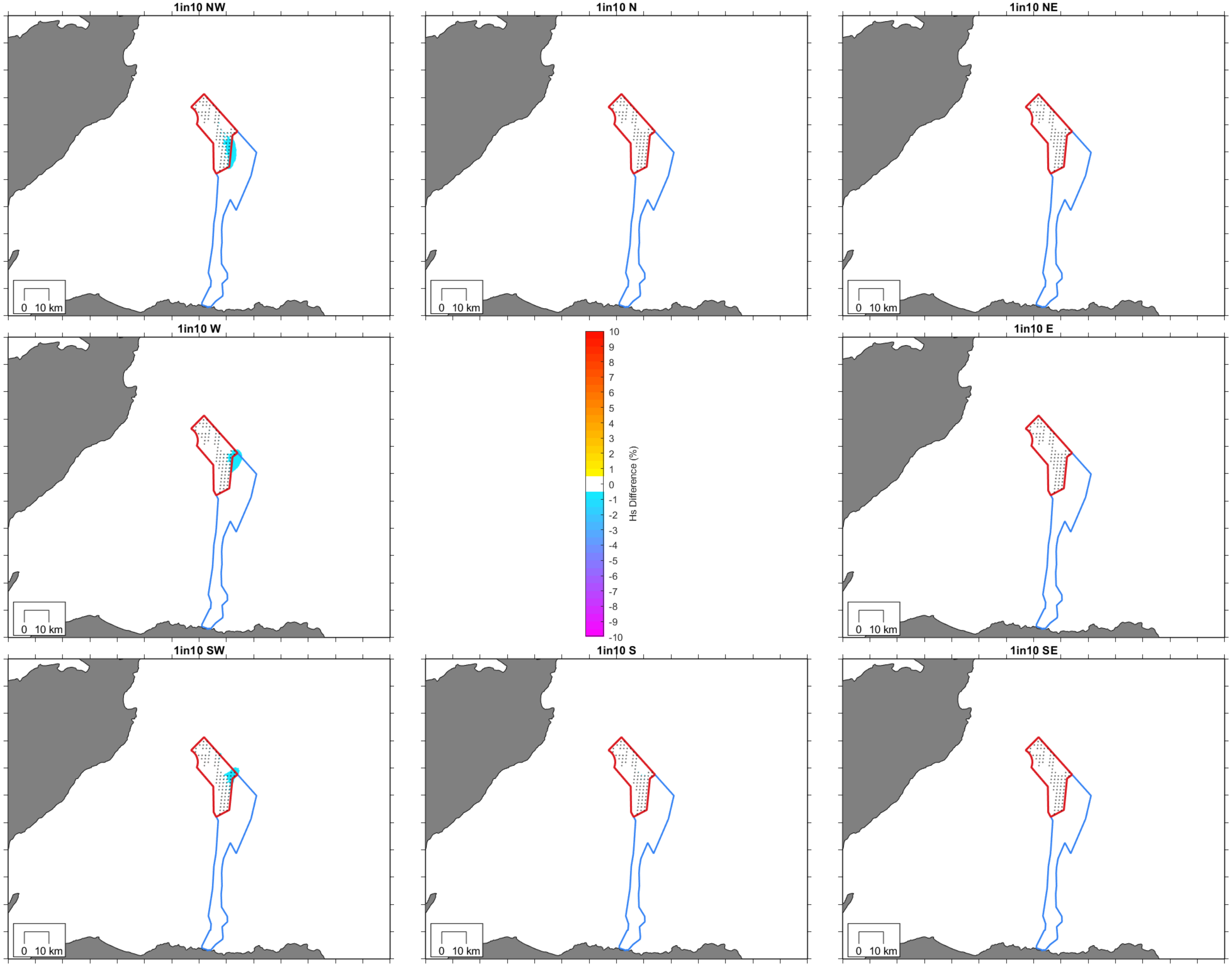

Figure A11. Percentage difference in Hs for the 1 in 10 year ARI events – Caledonia North.

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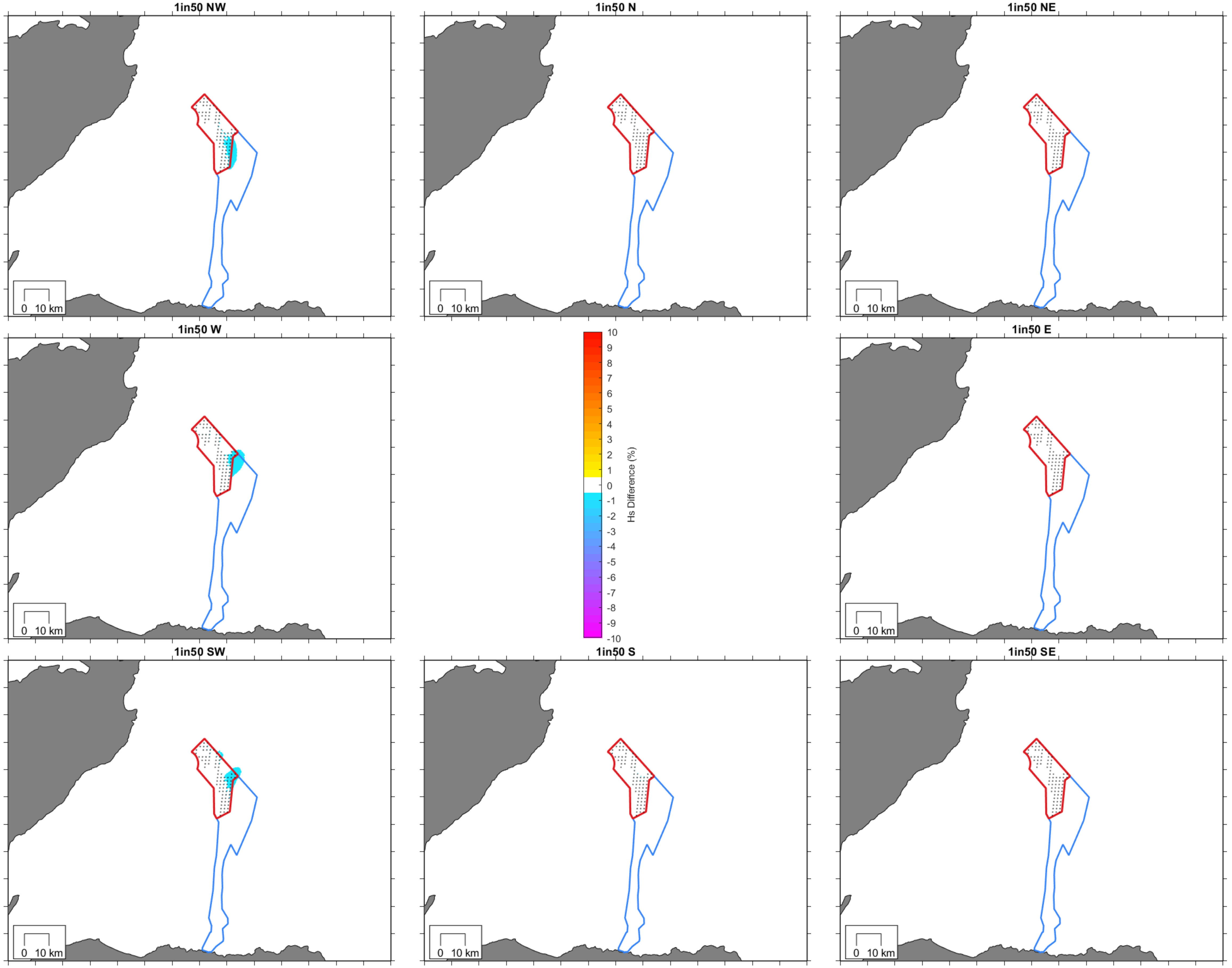

Figure A12. Percentage difference in Hs for the 1 in 50 year ARI events – Caledonia North.

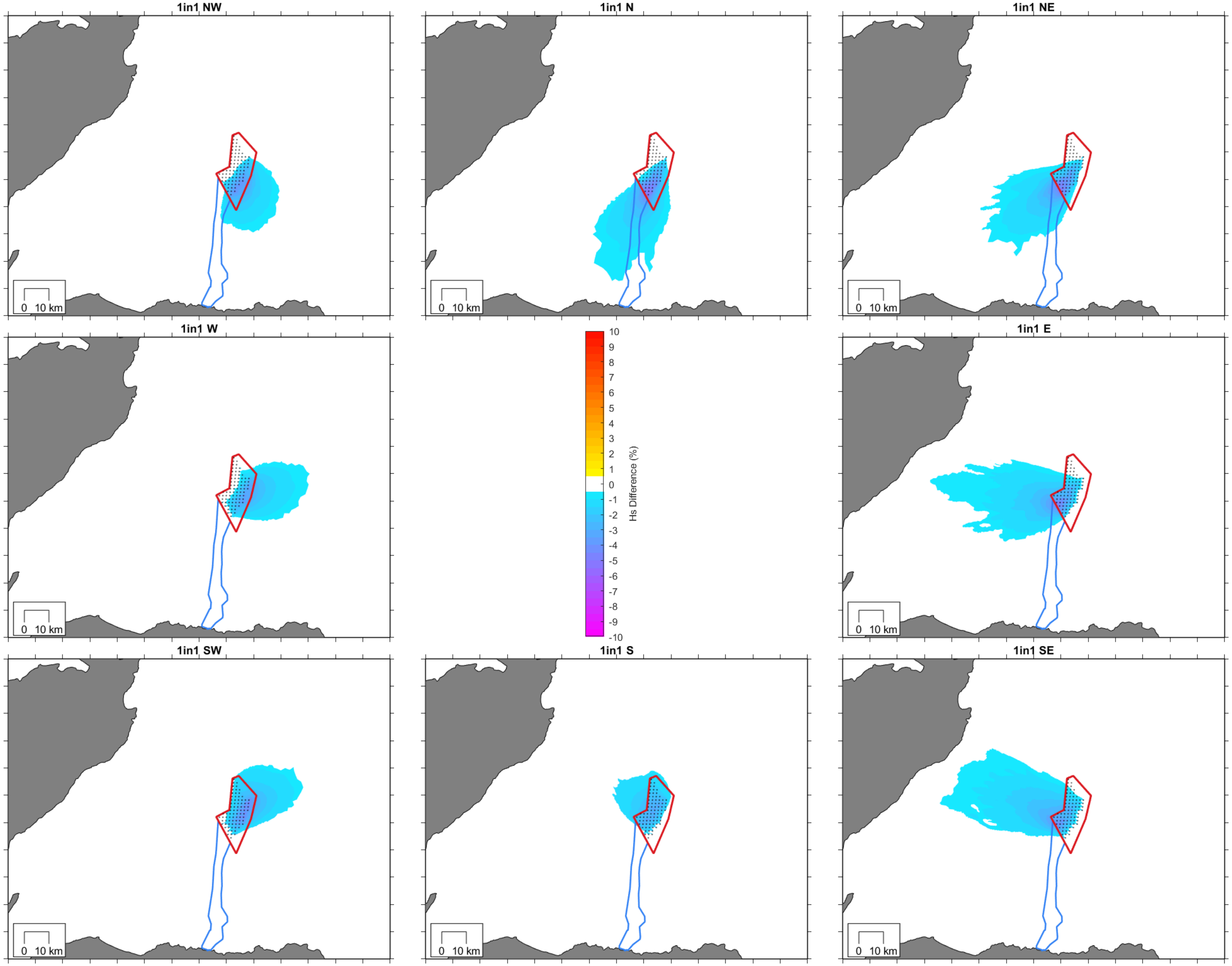

Figure A13. Percentage difference in modelled Hs for the 1 in 1 year ARI events – Caledonia South.

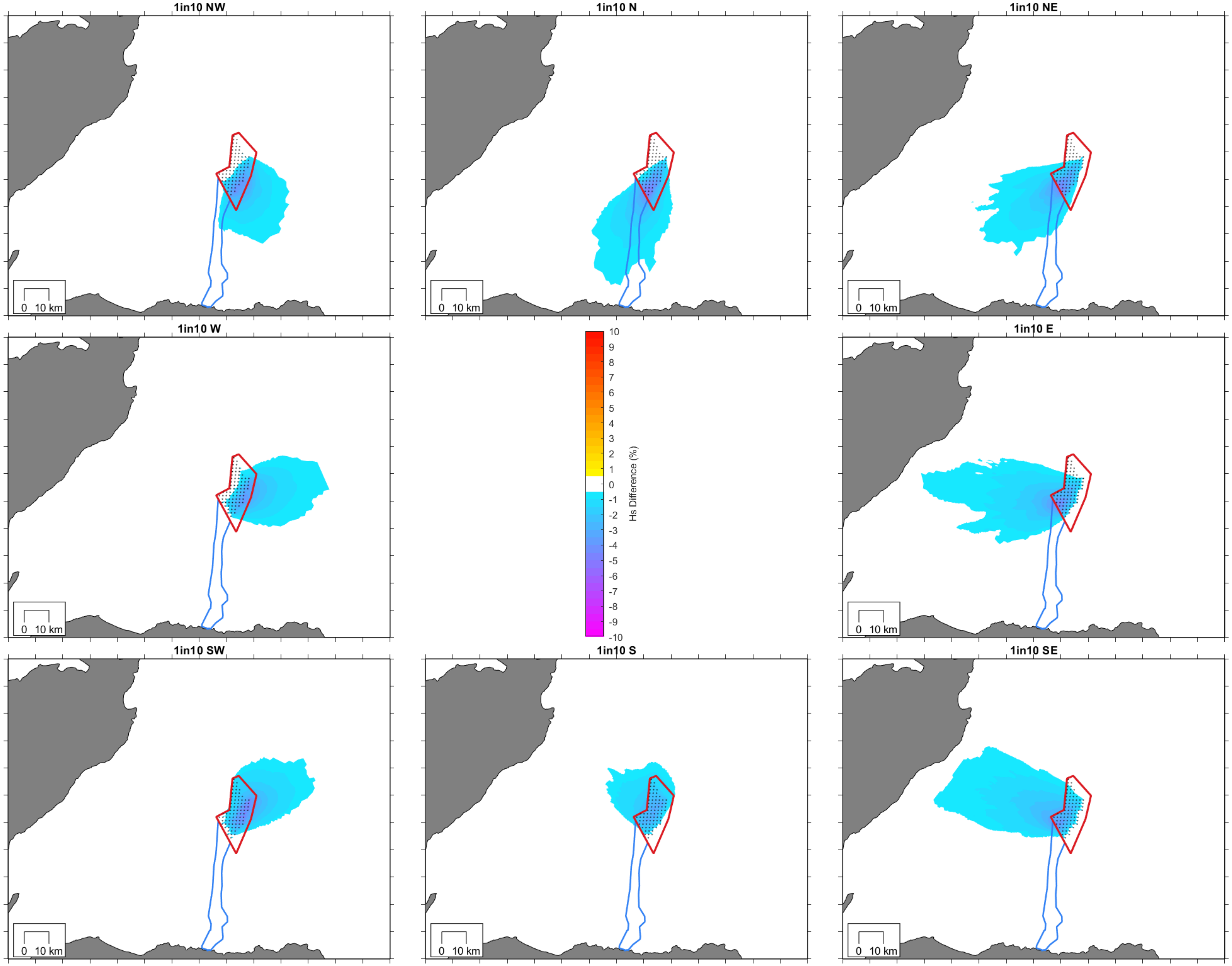

Figure A14. Percentage difference in Hs for the 1 in 10 year ARI events – Caledonia South.

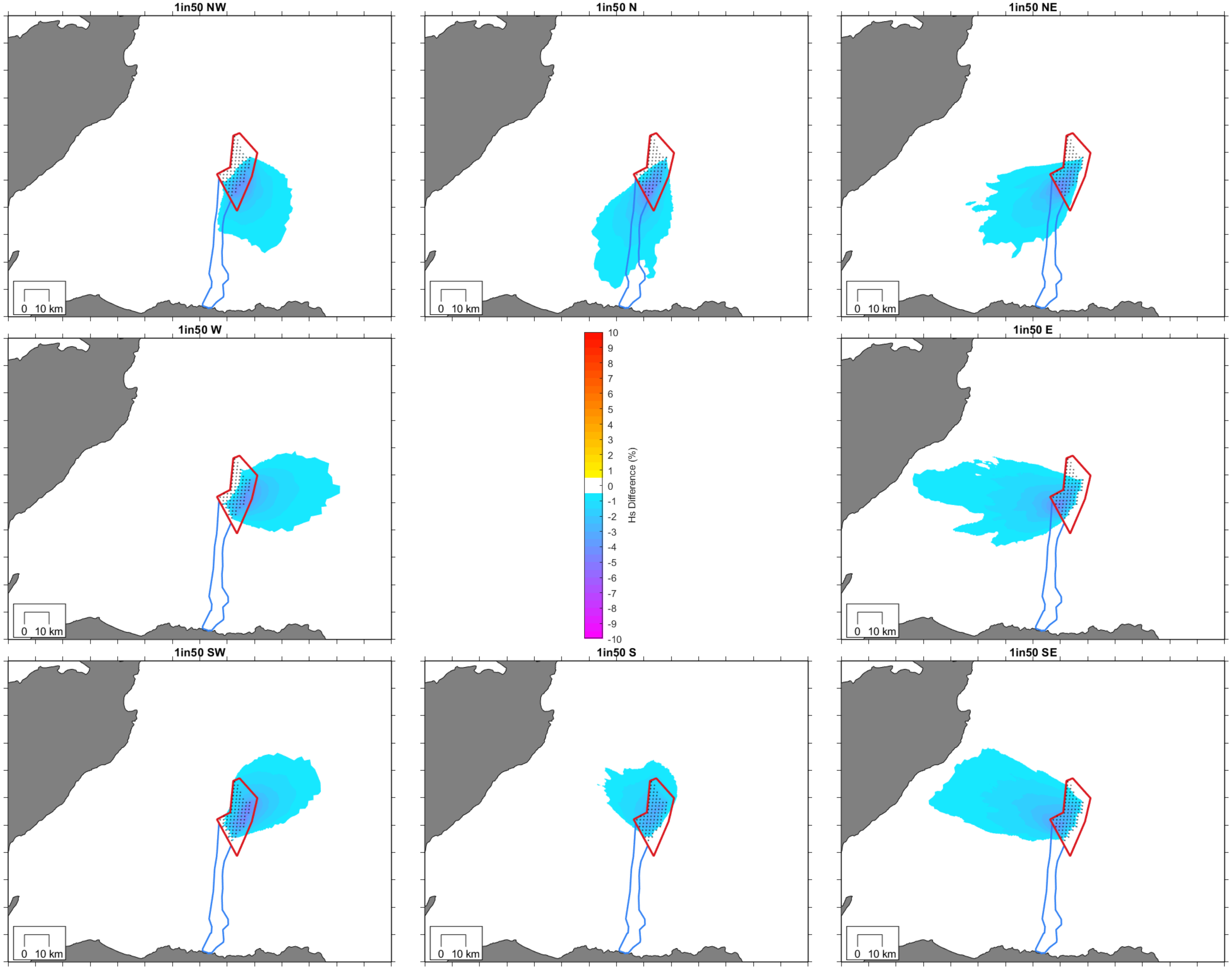

Figure A15. Percentage difference in Hs for the 1 in 50 year ARI events – Caledonia South.

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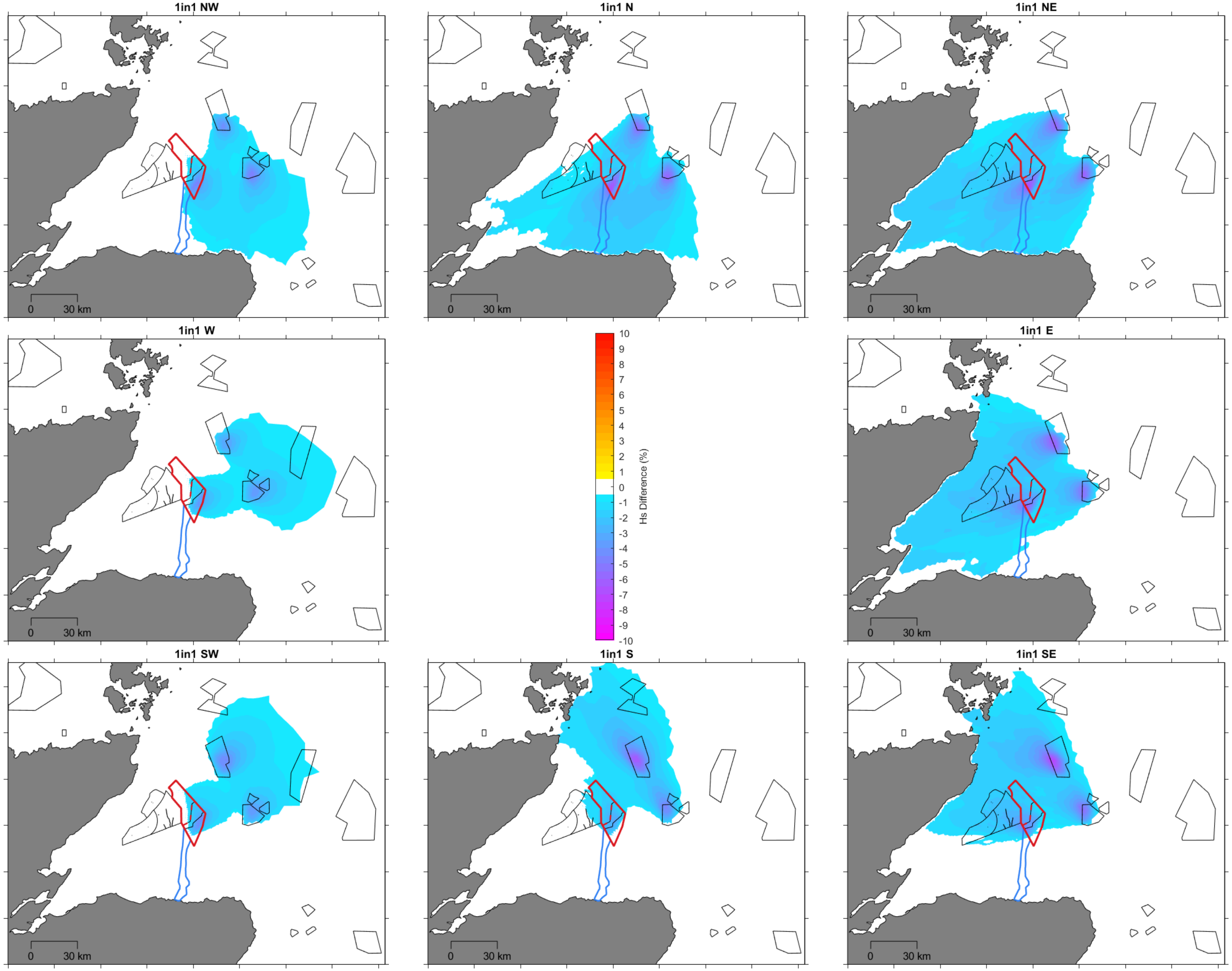

Figure A16. Percentage difference in modelled Hs for the 1 in 1 year ARI events – Caledonia OWF in-combination with other adjacent OWFs.

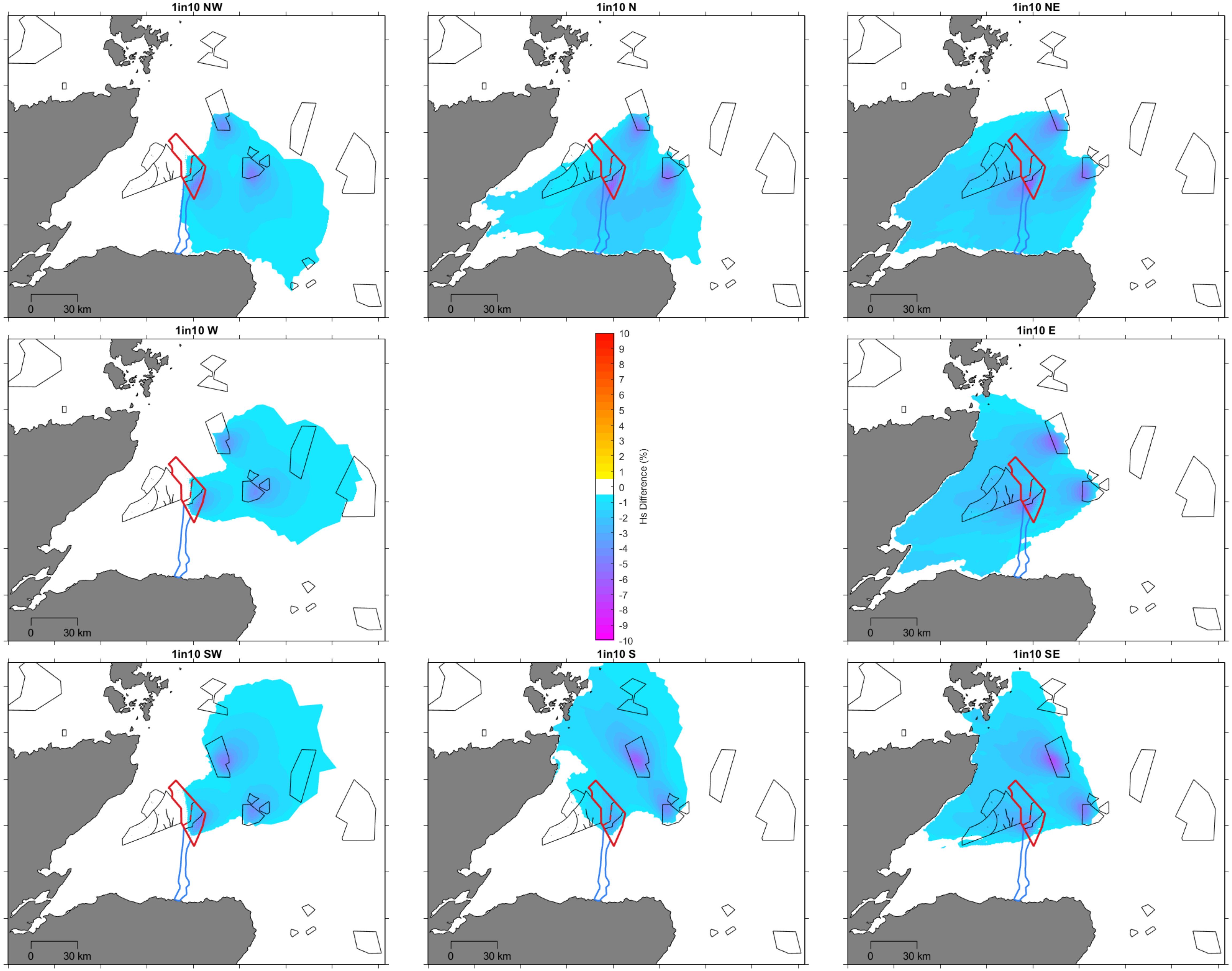

Figure A17. Percentage difference in Hs for the 1 in 10 year ARI events – Caledonia OWF in-combination with other adjacent OWFs.

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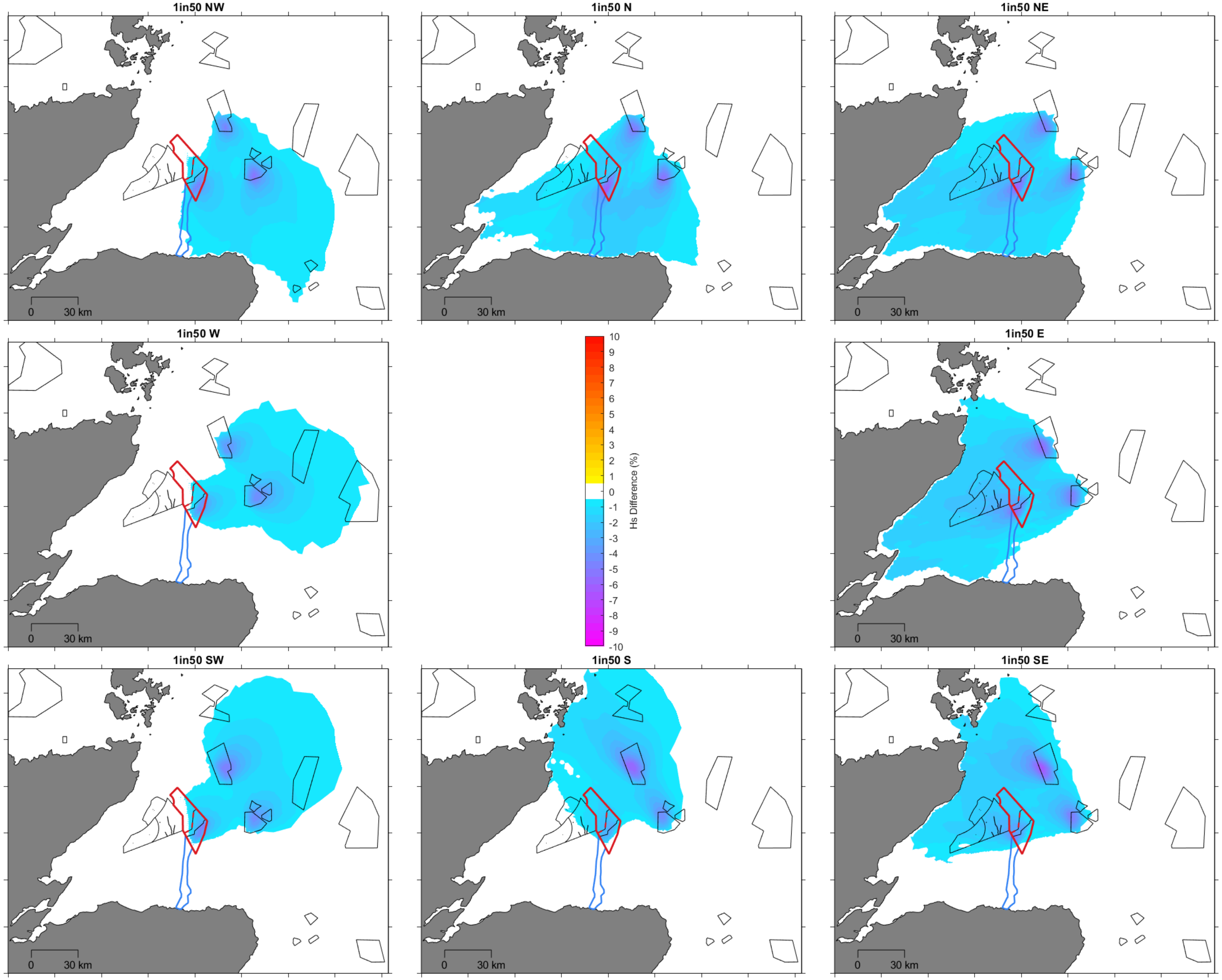

Figure A18. Percentage difference in Hs for the 1 in 50 year ARI events - Caledonia OWF in-combination with other adjacent OWFs

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