Deltares

First Steps to Assess How Offshore Wind Farms Affect Waves and Currents

Offshore Wind Energy Shipping Safety Monitoring and Research Programme (MOSWOZ)

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Author(s)
Caroline Gautier
Antonios Emmanouil
Leo Leummens

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Author(s)

	Caroline Gautier Antonios Emmanouil Leo Leummens	

Summary

The North Sea is one of the busiest areas for shipping in the world. The effects of existing offshore wind farms (OWF) and the ambitious plans for additional wind farms and hub islands must be taken into account to ensure shipping safety. Therefore, Rijkswaterstaat has set up the Offshore Wind Energy Shipping Safety Monitoring and Research Programme (MOSWOZ).

One of the MOSWOZ topics is Hydro/Meteo. Within this topic the present study makes a start in assessing the effect of offshore wind farms on North Sea waves, currents and tides. We have started in 2024 and define which parts require further investigation. In a later stage the determined effects will be related to shipping safety.

In WOZEP (Offshore Wind Ecological Programme), the effect of OWF on ecological aspects is studied by means of hydrodynamic simulations considering different scenarios of OWF in the North Sea. The simulations include a hypothetical scenario for 2050, with many OWF at the North Sea, with those in the Dutch waters accounting for a total capacity of 60 GW. The large dataset of the WOZEP simulations (Deltares, 2024a) is analysed in the present study for a preliminary assessment of the effects of large scale OWF on waves and currents in the Dutch EEZ.

The study results show that there is no change in large scale wave patterns expected in the Dutch EEZ due to the presence of OWF, even for the hypothetical scenario for 2050. On average the 2050 OWF scenario will lead to a reduction of the wave heights inside and in the vicinity of the OWF by some 4%. However, for (rare) individual moments the presence of wind farms may enhance as well as decrease the wave heights locally up to 0.5 m. During a longer modelling period than the 2020 year considered in the simulations, larger effects may incidentally occur. The changes in mean absolute wave period and mean wave direction are negligible at the spatial scale of the wind farm. The surface wind and wave height in the direct vicinity of OWF can either decrease or increase due to OWFs. In neutral and stable conditions enhanced mixing by the turbine may lead to an increase of the surface wind speed leeward of the turbines. In unstable conditions the turbines mainly lead to a decrease of the surface wind speed and wave heights.

The average effect of the OWF according to the 2050 scenario on the flow velocities is a typical reduction of some 5-15% within the wind farms and in most cases the effects are almost zero at roughly 30 kilometre distance. For individual moments or other locations the effects can be larger, and also an increase in flow velocity may occur due to the OWF. The average effect on the current directions is about 10-25º within the wind farms, and less outside.

The effect of the OWF according to the 2050 scenario on the water level is small, a reduction of ~1% and spatially quite uniform.

Although much literature has been found on effects of OWF, publications on the effect of OWF on shipping safety is very rare. Most studies deal with the effects of OWF on ecology, coastline morphology and wind yield at hub height.

In the present study, the link with shipping safety has not been made yet. It is suggested to involve nautical experts to discuss which parameters (for instance wave heights, wave periods, wave directions, currents, gradients of those) are relevant for ship safety and which values would be relevant or even critical for shipping safety, differentiating in vessel type. If there is a need for more in-depth knowledge concerning the effects of OWF on ships, a list with possible topics is given in the final chapter.

Contents

1 Introduction

1.1 General

The North Sea is one of the busiest areas for shipping in the world. The effects of existing offshore wind farms (OWF) and the ambitious plans for additional wind farms and hub islands must be taken into account to ensure shipping safety. Therefore, Rijkswaterstaat has set up the Offshore Wind Energy Shipping Safety Monitoring and Research Programme (MOSWOZ). This programme studies the effect of offshore wind farms on shipping safety so that – if needed - measures can be taken to maintain levels of shipping safety.

One of the MOSWOZ topics is Hydro/Meteo. Within this topic the present study makes a start in assessing the effect of offshore wind farms on North Sea waves, currents and water levels. We have started in 2024 with a preliminary assessment of the effects of OWF on waves and hydrodynamics and identification of knowledge gaps. In a later stage the determined effects will be related to shipping safety.

The main goal of the Hydro/Meteo research is to help identifying if risk areas exist for shipping, due to the effects of the OWF of Hydro/Meteo, and whether mitigating measures are necessary. Currently, the wind farms are mainly optimized in terms of energy yield, within certain legislative constrains, mostly related to ecological and spatial planning aspects. Once the OWF effects on shipping safety have been identified, these can also be accounted for. The ultimate goal of the research being thus to contribute to a safer North Sea, helping consequently also with the prevention of environmental disasters due to shipping accidents.

1.2 Scope

The aim of this research is to determine to what extent offshore wind farms in the North Sea have an effect on waves, currents and water levels, and consequently on shipping safety.

1.3 Main message

Offshore wind farms (OWF) do affect wind, waves and currents but it is not clear yet whether the effects are relevant for shipping safety. The main effect is the change in wind, leading to change in waves and currents.

Based on the analysed model simulations, the large scale wave patterns will not change due to the OWF. However, there is an average 4% reduction in wave heights inside and in the vicinity of the OWF. The effects tend to reach over some 10ths of kilometers. Furthermore, for individual moments the presence of wind farms may rarely enhance as well as decrease locally the wave heights by up to 0.5 m. The effects on wave period and direction are negligible at the spatial scale of the wind farm.

Local current reduction within the limits of offshore windfarms reaches 5-15% but diminishes to 1-5% further away depending on wind direction. Considering the current direction, the average effect is some 10º-25º within the OWF, reducing to some 2º at a distance of approximately 20 km and to almost zero at some 30 km.

1.4 Approach

The study started with a literature review, to be aware of the main recent papers and reports on the subject. Next, a preliminary analyses of the effects of OWF on waves and currents, based on existing WOZEP model simulations (Deltares, 2024a) has been carried out. In WOZEP (Offshore Wind Ecological Programme), the effect of OWF on ecological aspects (birds, marine mammals,…) is studied, applying hydrodynamic simulations at the North Sea, focussing on 3D water temperature, salinity, orbital velocities and residual currents. Effects of OWF on these parameters are not considered to affect in a relevant way the shipping navigation. Given that the WOZEP model results also include for MOSWOZ relevant parameters, like momentaneous flow velocities, wave heights, wave directions and water levels which have not been analysed in WOZEP, these are considered in the present study. The effects are shown as the difference between model runs without wind farms and with.

1.5 Set up of the report

After this introduction, the literature overview is given in Chapter 2. Chapter 3 presents the model results of the effects of OWF's on wave conditions. In Chapter 4 the model results related to the effects of OWF on currents are presented. The report ends with conclusions and recommendations in Chapter 5.

2 Literature Study

2.1 Introduction

Although much literature on offshore wind farms has been found, the topic in relation with shipping safety is quite rare. Most studies deal with the effects of OWF on ecology, coastline morphology, wind yield at hub height (wake effects) and not directly on waves and currents in the context of shipping. There is also a wealth of publications on the North Sea wind, wave and hydrodynamic conditions and on the bathymetric characterization.

2.2 Main findings on the effect of OWF on waves

2.2.1 Various WOZEP studies

In various WOZEP studies, three scenarios are hydrodynamically modelled to assess the impact of OWF on tidal flow, stratification and mixing. The impact of OWF is introduced into the hydrodynamic model through two mechanisms: the presence of monopiles in the water column and changes in meteorological conditions. The considered scenarios are:
- reference scenario without any wind farms,
- 2020 scenario with the then present wind farms (approximately 4GW) and
- 2050 theoretical hypothetical future scenario, based on certain national targets for 2050.

The hypothetical 2050 scenario is purely theoretical - and not a proposal for a realistic future scenario - where the Dutch OWF have a capacity of approximately 60GW (at present approximately 5GW, in 2032 21GW is foreseen). Also neighbouring waters are considered. As starting point for the schematization of the wind farms a density of 8MW/km^2 is chosen, using 12MW turbines. This means 0.67 piles/km^2 with a stem diameter of 12 m.

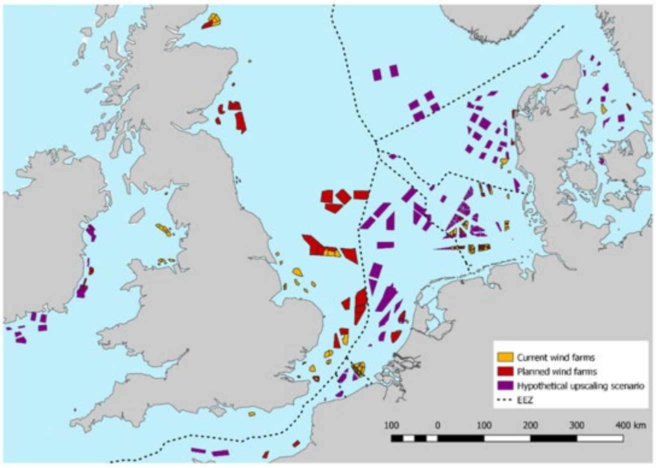

Figure 2.1 Hypothetical future 2050 scenario (source: Zijl et al, 2021).

It is good to realize that the distance between the 12 m wide piles is roughly 1,200 m on the sea surface. Unlike what the plot above shows (with the fully coloured OWF areas), a wind farm is not densely covered with piles. Scaled to 1 cm diameter piles, the next pile is at a distance of 1 m (or each pile is a 2 mm dot on this A4). However, the area covered by the rotor blades is immense, with lengths possibly reaching 200 m.

In Zijl et al., 2021 the 3D DCSM-FM (Zijl et al., 2020) model is used to assess the hydrodynamic effects. Since the piles of the OWF are too small to include within the 900 m grid size of the model, a sub-grid approach is used with a quadratic sink term. The energy extracted from the main flow in this manner is at the same time reintroduced as a source term in the equation for turbulent kinetic energy (k). For the wind, originally a 10% reduction within the wind farm was applied. This ignores the effect of wind wakes which can be felt far away from the wind farms, especially under stably stratified conditions in the meteorological boundary layer. The effect on waves was studied using the SWAN-DCSM (Gautier and Caires, 2015) wave model for the years 2006 to 2017, driven by ERA5 (Hersbach et al., 2020) boundary conditions and wind. Also in that wave study, a 10% reduction of wind speeds is applied uniformly across the areas designated for (possible) future wind farm development (2020 and 2050 scenarios). The effects of the largest wind farms on wave energy are not only limited within the polygons but extend (decreasing) even further according to the local wave propagation direction. Obviously, this is a direct result of the local decrease in wind-induced wave energy generation. Wave heights reduce in the order of roughly 8% as a result of the 10% decrease in wind magnitudes 10 meters above the sea surface. Reduction on peak wave periods is negligible.

In Zijl et al., 2024, advanced meteo input was used for the hydrodynamic computations in which the impact of OWF (pile diameter 8 m and 0.85 piles/km^2) on the atmosphere is included. These scenarios were part of the WINS50 project (Baas, 2024) where the situation of 2019 - 2021 with and without offshore wind farms, as well as a hypothetical 2050 upscaling scenario, was computed. The resulting meteorological data for the latter scenario is used as forcing to the 3D DCSM-FM hydrodynamic model. It was found that a wind speed deficit can reach more than 1 m/s, especially where OWF are clustered, such as in the German Bight. This amounts to around 10-15% of the annual average wind speed in the region. Around the OWF the annual average wind speed is affected by wake effects, with average velocity deficits of more than 0.1 m/s seen up to tens of kilometres away. Using the WINS50 future hypothetical forcing results in a tidal M2 amplitude increase of 2-3 mm in the German Bight. This increase is counteracting the (larger) decrease in M2 amplitude due to the presence of OWF monopiles. Using a localized 10% wind reduction hardly affects the M2 amplitude (Zijl et al., 2024).

The results of the wave computations forced with the WINS50 wind fields have not been published yet, but will be analysed in Chapter 3 of the present report.

In one of the earlier Deltares WOZEP studies (Boon et al., 2018), the effect of OWF's on the surface wind is explained. The plot below is taken from that study. In general, wind turbines will transform stable wind profiles into less stable or neutral wind profiles. Neutral/unstable wind profiles will remain neutral/unstable. In the left panel we see unstable conditions (cold air on warm water) where the air will mix, leading to small vertical gradients in wind speed. Downwind of the rotor, a decrease in wind speed from hub height to the lower part of the rotor can be noticed. The right panel shows the neutral stability situation with less mixing and hence larger vertical gradients in wind velocity. Here the presence of the wind turbine can lead to an increase of the wind at the lower part of the rotor. These changes in wind will also be noticed in the waves.

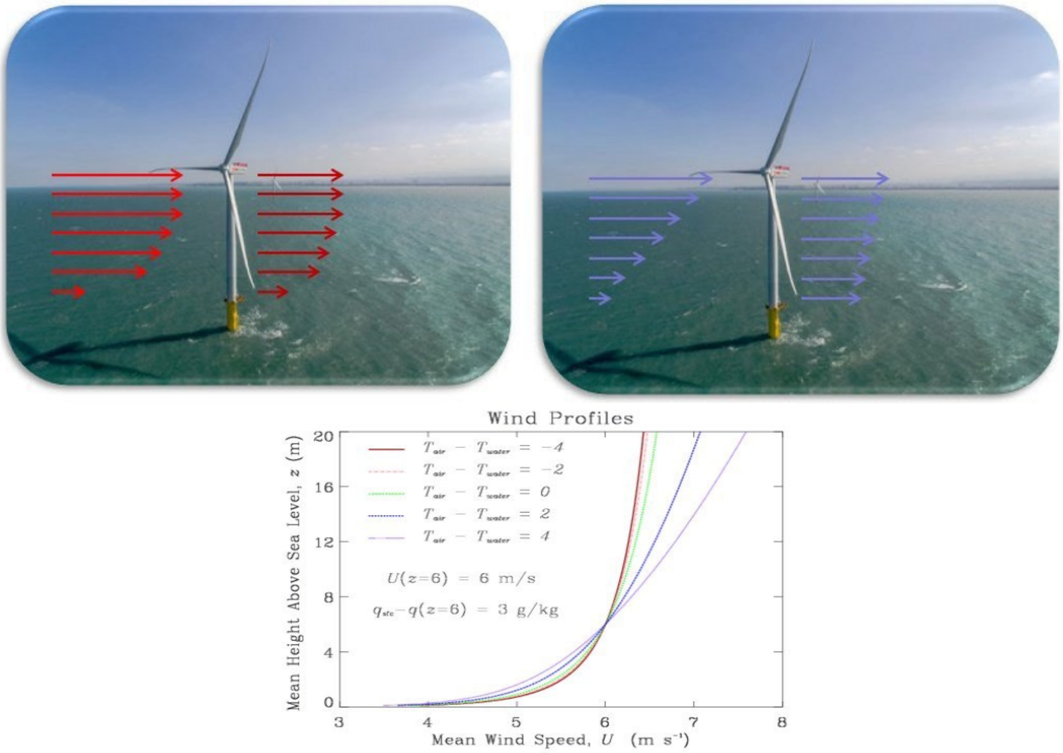

Figure 2.2 Artists impression of the effects of a wind turbine on the wind speed at heights from hub height to the lowest part of the rotor depending on the atmospheric stability. Left: unstable (hence well mixed) situation . Right: neutral stability. The lower panel presents stable (purple; $T_{air} - T_{water} = 4^oC$) and unstable (red; $T_{air} - T_{water} = -4^oC$) wind profiles. Taken from Boon et al. (2018).

2.2.2 Transmission of wave energy through an offshore wind turbine farm (Christensen et al., 2013)

According to Christensen et al. (2013), when studying the effect of OWF’s on waves three processes are to be considered:
A) the dissipation due to monopile drag resistance (less relevant; to be neglected),
B) reflection/diffraction of waves around the structure and
C) changed wind (turbines extract wind energy and act as obstacle).

All three effects will be largest on short waves and smallest for long waves.

Ad A) Low frequency waves are almost unaffected by the piles. As an example for pile diameter D=8 m; water depth h=30 m; wave height H=6 m, wave period T=10 s; ω=2π/T=0.63, we consider the graph for D/h=0.27 and H/h=0.267 and find (for x=0.6) less than 1% dissipation in energy (hence even less reduction in wave height).

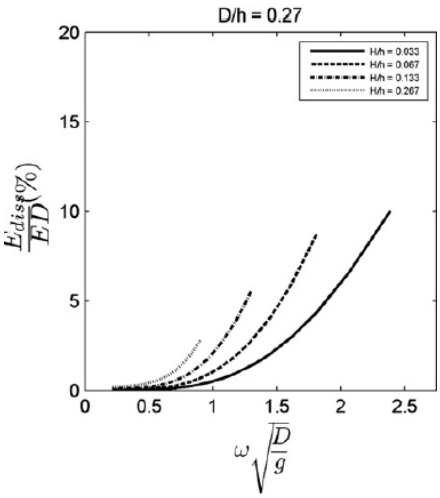

Figure 2.3 Relative wave energy dissipation from a cylinder with diameter D; Source: Fig 2.1 from Christensen et al. (2013).

Ad B) The graph presented in Christensen et al. (2013) states that for D=8 m, short waves may encounter at most 70% energy reflection but for wave periods of T=7 s the reflection is only 10%, for longer waves the percentage is less. For pile diameters less than one tenth of the wave length ($L=1.56T^2$, in deep water), the reflected energy is negligible (Christensen et al., 2013).

Ad C) In Christensen et al (2013), based on satellite SAR observations at the 5 km x 5 km Horns Rev I farm just west of Esjberg (Denmark), the reduction in wind shear stress due to the OWF is assessed with the note that for larger or smaller farms the effects might be different.

Effect A turned out to be negligible and therefore only effects B and C have been included in numerical wave runs with the MIKE21 model and separate and combined effects of the OWF were quantified, leading to the following conclusions:

- The reflection/diffraction of waves by the structures has some effect on the wave height upwind of the wind farm. In the cases analysed here the effect can be up to 2 to 3%.
- For moderate wind speed (U10 = 10 m/s), the local reduction of wave height, i.e. 2 km downwind, comes 1/3 from reflection/diffraction and 2/3 from the reduced wind shear.
- From 15 km downwind (3 times the extent of the OWF) the effect of reduced wind shear controls the major part of the wave height reduction.
- For high wind speeds (U10 = 30 m/s) the most important process is the reduced wind speed inside and on the lee side of the OWF.
- The maximum reduction of wave height downwind the offshore wind farm is in the order of 5%. This means that the reduction in wave energy is reduced up to around 10%.
- 20 km downwind of the wind farm the reduction of wave height is up to around 1%.
- The OWF only had little influence on the wave period. But for large fetches the wave period was increased in the order of 1% downwind of the OWF.

The trend in offshore wind farms is towards larger but fewer wind turbines in the same area. This means that the effect of the reflection/diffraction from structures in general will be smaller while the effect of reduced wind shear will be of the same order of magnitude.

2.2.3 Fit(ch) for shipping Wind farm wake effects at 10 m height (Wijnant, 2023)

Wake effects due to OWF are very relevant for wind energy resource assessments (where the yield is determined from the wind speeds at rotor/hub height), but also for weather forecasting, in particular for shipping forecasts (surface winds and waves) and low cloud/visibility forecasts for helicopter operations at sea. The study of Wijnant (2023) focusses on the effect of wind farms on wind at 10 m height.

Ships may experience a decrease of wind speed in the wind farm wake, but also a speed-up between or at the edge of wind farms. Figure 16 illustrates that the effect may be large: in this particular case ships sailing downwind of the Belgian wind farms experienced a change in wind speed of almost 5 m/s at least twice within 15 km.

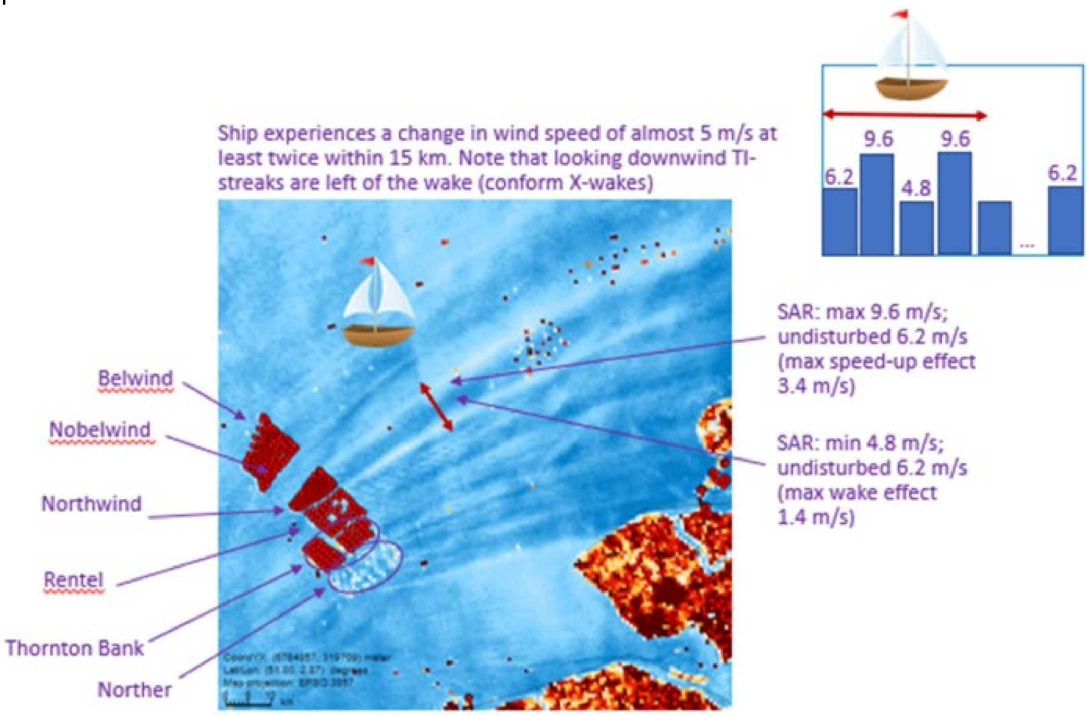

Figure 2.4 SAR-image 22-7-2019 17:33:25 UTC with clear wakes and high wind streaks between and at the edges of the Belgian wind farms (wind farm Borssele was not yet built). Source: Wijnants et al. (2023).

For the 3 year period of this analyses (2019-2021), SAR measurements (at 10m height) show that (1) wakes occur on average about 25% of the days in a year, least in winter and (2) ships may experience a wind speed decrease of up to 4 m/s in the wake downwind from a wind farm as well as a 5 m/s increase as a result of speed-up between and on the edge of wind farms. The Fitch wind farm parameterization (WFP) does not capture these effects at 10 m height. As expected, wakes are strongest and longest for stable or neutral atmosphere and/or wind speeds at hub height of 12-15 m/s. Strong wakes can occur under less favourable atmospheric conditions downwind from wind farms with high capacity densities.

2.2.4 Impacts of accelerating deployment of offshore windfarms on near-surface climate (Akhtar et al., 2022)

Akhtar et al. (2022) computed with a regional climate model COSMO-CLM (Rockel et al., 2008) for 2008–2017, changes in precipitation, temperature, cloud cover, heat flux, etc. due to large-scale clustered OWF. They did not consider waves or currents. They found that the change in the turbulent fluxes is mainly driven by the changes in the near-surface wind speed and turbulent kinetic energy (TKE). The presence of wind farms reduces the 10 m wind speed by approximately 7% and the TKE by approximately 5% for all wind directions (0—360°), mainly inside and outside the wake downwind of the wind farms. However, near-surface wind acceleration is found upstream of the wind farms due to wind channelling effects. The impact of OWFs on sea surface fluxes turns out to be seasonally variable. The near-surface wind acceleration effect is more pronounced during spring and summer when atmospheric conditions are generally stable, see Figure 2.5.

Weak atmospheric mixing during stable atmospheric conditions leads to higher and longer wake effects. The impacts of wakes generated by the large OWF and near-surface wind acceleration were stronger for prevailing south-westerly winds (200—280°) than for the overall mean winds (0—360°).

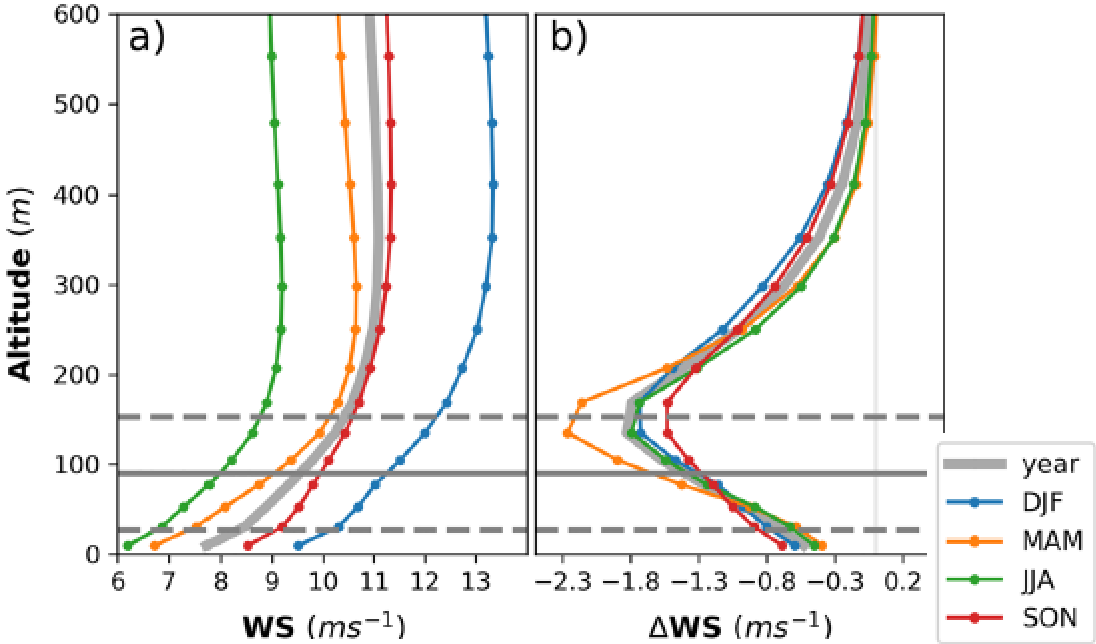

Figure 2.5 Mean vertical profiles of COSMO-CLM simulation without OWF (left) and (right) the difference with COSMO-CLM_WF (with OWF), per season for all wind directions, based on 2008 - 2017. The solid gray line indicates the hub height (90 m) of the turbine, whereas dotted gray lines indicate the lower (27 m) and upper (153 m) tips of the rotor. Source: Fig 2 from Akhtar et al. (2022).

2.2.5 The Impact of Offshore Wind Farms on Sea State Demonstrated by Airborne LiDAR Measurements (Barfuss et al., 2021)

With systematic flights deploying an airborne laser scanner, spectral sea state properties were recorded in the German Bight covering both areas with wind farms and undisturbed areas. The analysis of the spectral energy distribution shows a re-distribution of the wave energy in the downstream area with enhanced energy at smaller wavelengths. The effect is still clearly visible at a distance of 55 km.

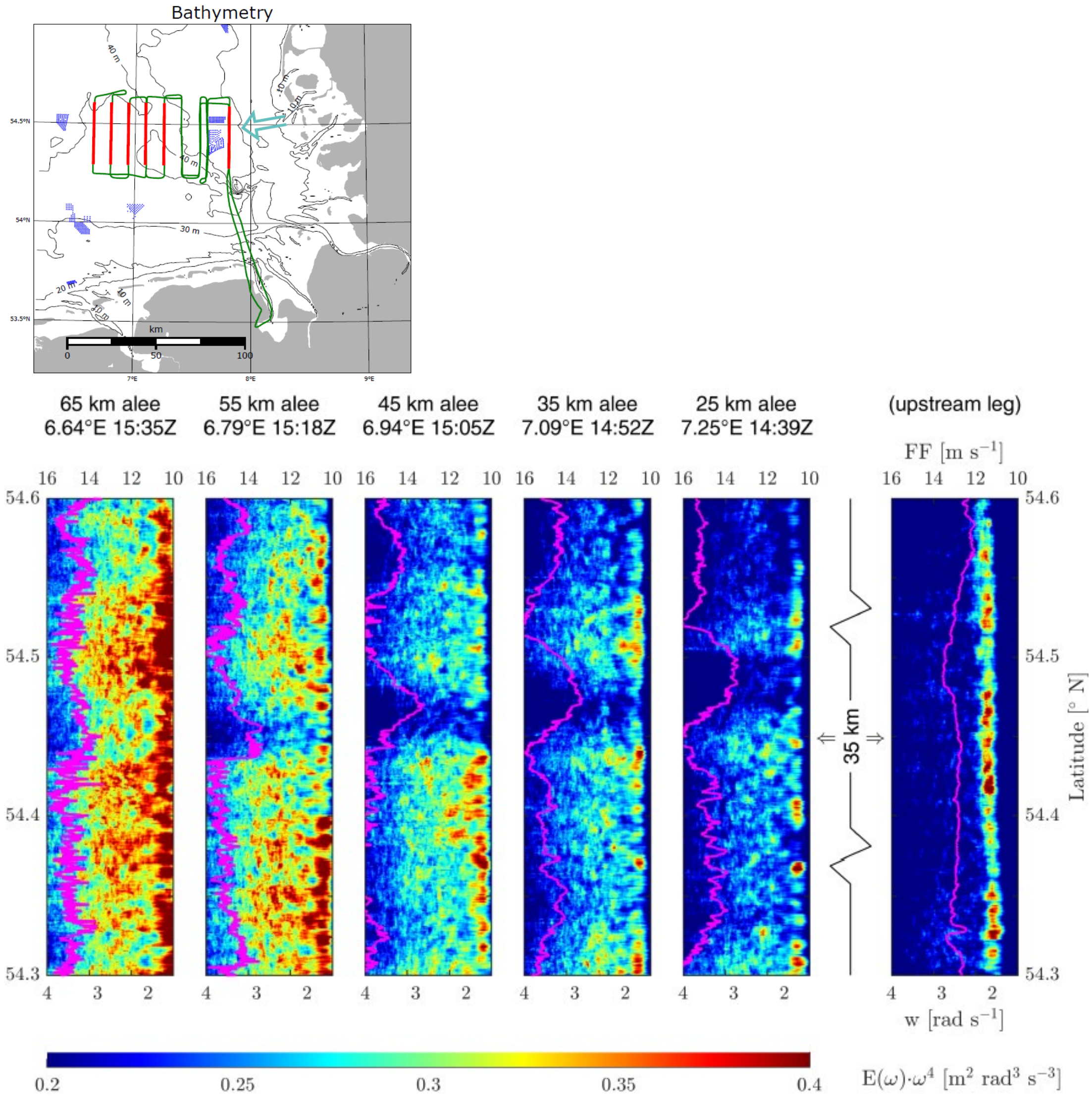

Figure 2.6 Upper panel: The flight pattern is given as a green line, and the horizontal flight legs used in the laser scanner analyses are indicated as red lines. The arrow in light blue indicates the wind direction. Lower panel: Surface energy distribution (variance density multiplied with w4, colour coded) for the flight downstream of the wind park cluster N4 on 8 August 2017 with wind direction from the East. The wind speed measured at hub height is represented as an overlay in magenta. Source: Barfuss et al. (2021).

2.2.6 Less relevant literature

• Simulation of irregular waves in an offshore wind farm with a spectral wave model

In Ponce de León et al. (2011) irregular waves were simulated inside an OWF with a spectral wind wave model but only the effect of diffraction and reflection on the monopiles was considered. Neither the modified wind field nor the wave energy dissipation due to drag resistance was included in the analyses. This makes this study less relevant as they also acknowledge that these effects might have an influence on the waves.

• Current and wave effects around windfarm monopile foundations

Miles et al. (2014) undertook laboratory measurements to investigate wave and (cross) current velocities in the vicinity of a wind turbine monopile foundation. They focus on flow and orbital velocities as environmental aspects. Wind effects are not considered. The experiments suggest that a rule of thumb for engineering purposes is that the downstream effects have a length scale of approximately 8 to 10 D.

• Modelling wind farm effects in HARMONIE–AROME (cycle 43.2.2)– Part 1: Implementation and evaluation.

In Fischereit et al. (2024) explicit wake parameterizations (EWP) have been implemented in the Numeric Weather Prediction (NWP) model HARMONIE–AROME (hereafter HARMONIE) alongside the existing wind farm parameterization (WFP) by Fitch et al. (2012).They evaluated these against research flight measurements. The study focusses more on hub height, rather than on sea surface winds. The results show that the explicit wake parameterization (EWP) and the wind farm parameterization by Fitch et al., (2012) (FITCH) have been correctly implemented in HARMONIE. For the simulated cases, EWP underestimates the WFEs on wind speed and strongly underestimates the effect on turbulent kinetic energy (TKE). FITCH agrees better with the observations, and WFEs on TKE are particularly well captured by HARMONIE–FITCH.

2.2.7 Conclusions

Although much literature has been found on offshore wind farms, the topic in relation with shipping safety is very rare. Most studies deal with the effects of OWF on ecology, coastline morphology and wind yield (at hub height). These are the main conclusions from this review:

- The main cause of OWF effects on waves is the reduced wind. Refraction and diffraction effects are less and the effect of drag resistance on waves is negligible (Christensen et al., 2013).
- It is good to know that are airborne observations of wave spectra near OWF available (Barfuss, 2021).
- In stable conditions (warm air above cold water), the working turbines will enhance mixing, leading to decreased wind speeds at hub height but possibly to increased wind speed near the surface. This could lead to increases of wave heights behind OWF. In unstable conditions the working turbines lead to the reduction of the wind speed throughout the air column (from surface to rotor) behind the OWF and hence smaller wave heights (Boon et al, 2018).
- The effects on wind at hub height can be quite different from the effect near the surface. Akhtar et al. (2022).
- Typical values according to Christensen et al., 2013:
  - The maximum reduction of wave height downwind the offshore wind farm is in the order of 5%. This means that the reduction in wave energy is reduced up to around 10%.
  - 20 km downwind of the wind farm the reduction of wave height is up to around 1%.
  - The OWF only had little influence on the wave period. But for large fetches the wave period was increased in the order of 1% downwind of the OWF.
- According to Zijl et al. (2021) the wind speed deficit can reach more than 1 m/s, especially where OWF are clustered, such as in the German Bight. This amounts to around 10-15% of the annual average wind speed in the region. Around the OWF the annual average wind speed is affected by wake effects, with average velocity deficits of more than 0.1 m/s seen up to tens of kilometres away.

2.3 Main findings on the effect of OWF on hydrodynamics

Wind speed reduction within offshore wind farms is of relevance for the hydrodynamics. However, it is not often included in the modelling, and when it is included, is typically parameterized using a combination of empirical, analytical, and numerical approaches to capture the wake effects generated by wind turbines. These wake effects reduce wind velocity behind turbines, which influences the atmospheric boundary layer and subsequently impacts wave and ocean circulation.

The methods and techniques used to account for OWF effects in hydrodynamic modelling are listed in the following.

2.3.1 Empirical Wake Models

A commonly used method to simulate wind speed reduction due to OWF is through empirical wake models such as the Jensen (Park) model and the Bastankhah Gaussian model (Liu et al., 2023).

Jensen' model assumes that each wind turbine generates a conical wake, where wind speed decreases behind the turbine and gradually recovers as distance from the turbine increases. The model uses a "wake decay constant" to describe how rapidly wind speed recovers downstream. This constant is adjusted based on atmospheric conditions such as turbulence intensity. The Jensen model has been employed in studies examining the large-scale impacts of wind farms on wind velocity fields, particularly when incorporating simplified wind farm parametrizations in hydrodynamic models.

The Bastankhah Gaussian model is an improvement over the Jensen model as it represents the wake as a Gaussian-shaped velocity deficit, which better captures the spatial distribution of reduced wind speeds, especially for modern large offshore wind farms. This model has been applied in studies that couple atmospheric models with ocean models to simulate how wind farms influence coastal hydrodynamics.

In addition, the E10 model by Emeis (2010) is a top-down approach model, meaning that the wind farms are considered as one unit of additional roughness, and describes the wake recovery by an exponential decay function. The E10 model was validated in recent studies, which showed that the exponential approach is able to reproduce airborne measurements of atmospheric wakes appropriately (Cañadillas et al., 2020; Platis et al., 2020).

2.3.2 Coupled Atmosphere-Ocean Models

Modern numerical models, particularly those simulating large-scale ocean processes, often couple atmospheric models (e.g., WRF—Weather Research and Forecasting model) with ocean circulation models like ROMS (Regional Ocean Modeling System) to simulate wind speed reductions and their effects on ocean circulation and stratification.

In such coupled models, wake effects are introduced by modifying the wind stress or wind forcing applied to the ocean surface based on the predicted wind velocity deficits within wind farm areas. The wind speed reduction, in turn, affects the surface wind stress, which directly impacts wave growth, ocean currents, and vertical mixing processes in the upper ocean layers.

For example, studies by Carpenter et al. (2016) explored how wind farms modify wind stress and induce changes in local thermal stratification in the North Sea by enhancing turbulence and altering wind patterns. They highlighted that wind stress reductions within wind farm regions cause a significant reduction in local mixing and vertical energy fluxes.

2.3.3 Wind Farm Parametrization in Ocean Models

Numerical models like Delft3D can be used to integrate wind farm effects by adjusting wind input fields to account for wind velocity reductions within the wind farm arrays.

As mentioned in Section 2.2.1, the initial WOZEP study (Zijl et al., 2021) applied a uniform 10% reduction of wind speeds in the areas designated for (possible) future wind farm development, both for the waves and the Delft3D hydrodynamic computations. A more advanced method is to apply the wind speed reduction not just uniformly within the wind farms but as computed in the WINS50 dataset, counting for wake effects (see also Section 3.2 and 4.2 and Zijl and Leummens, 2024).

Additionally, the drag effects within the water body are introduced in the hydrodynamic modelling, see Section 2.3.4. This has been used in studies focusing on the North Sea but not extensively validated in OWF conditions (Zijl et al., 2023).

2.3.4 Turbulence and Drag Effects

Offshore wind turbines also induce turbulence in the water column, primarily due to the physical presence of the turbine foundations. This turbulence can be parameterized in hydrodynamic models by introducing enhanced drag coefficients or additional turbulence sources within the wind farm areas.

Apart from the Deltares application (Zijl et al., 2023), studies such as those by Wu and Wang (2021) and Carpenter et al. (2016) have shown that turbulence generated by wind farms can significantly enhance vertical mixing in the water column, which influences temperature and salinity gradients. This effect is typically modeled using increased drag coefficients or enhanced turbulence parameterizations within the wind farm regions.

This turbulence-induced mixing may lead to changes in local water column stability and, in some cases, disrupt natural stratification patterns, which are critical for the distribution of nutrients and the overall health of marine ecosystems.

2.3.5 High-Resolution Models

Some models employ high-resolution grids to better capture fine-scale variations in wind speed reductions across wind farm arrays. These high-resolution models such as the one used for the creation of the WINS50 dataset by KNMI allow for more accurate simulation of wake effects but are computationally expensive. To mitigate this, average wind speed reductions are often applied over larger grid cells, balancing accuracy with computational efficiency.

For instance, studies modeling large offshore wind farms in the North Sea use reduced-resolution grids with empirical wind speed reduction factors applied uniformly across the wind farm's area, offering a compromise between detail and processing power.

2.3.6 Conclusions

In summary, modern hydrodynamic models incorporate wind speed reductions within offshore wind farms through a combination of results from empirical wake models, coupled atmosphere-ocean modeling, turbulence parameterizations and high-resolution atmospheric simulations. The coupled models capture the key effects of wind farms on local and regional ocean dynamics, including reduced wind stress, changes in wave heights, and altered ocean mixing. Studies like those by Carpenter et al. (2016) and Wu et al. (2022) provide critical insights into these processes, demonstrating how wind farm-induced changes propagate through the atmosphere and ocean. However, similarly with the waves topic the shipping safety is rarely addressed in the context of OWF effect on ocean dynamics.

Additionally, convenient for this study, the literature review shows that the main efforts on considering the effect of the OWF on hydrodynamics are put to the North Sea region, while other regions contain high potential for future OWF upscaling, such as China or USA coast (Liu et al., 2023).

3 Effect of OWF on Waves

3.1 Introduction

As described earlier, OWF influence waves by changes in wind speed, (thereby directly affecting the wave growth and indirectly the wave propagation, dissipation and interactions), by blockage of wave propagation by the foundations (leading to wave diffraction) and finally by local changes in bathymetry and bed roughness (leading to changes in energy distribution, refraction and dissipation). Such changes may affect both spatial and temporal patterns of waves as well as their magnitudes within navigation routes, thereby potentially posing risks to shipping safety.

Given the relatively slender foundations currently employed in the North Sea (monopiles of a diameter of up to roughly 12 metres), the most significant from the abovementioned influences is the first, i.e. the changes in wave growth associated with changes in wind speed. In fact, this is the only influence modelled in the wave computations performed under the WOZEP research programme. In this section, we analyse recent model results of WOZEP to assess potential impacts on navigation and shipping safety.

3.2 Wave computations from WOZEP

This study employs readily available results from the recent wave numerical modelling performed for WOZEP with the extensively calibrated DCSM-SWAN (Gautier and Caires, 2015) spectral wave model. For more information regarding the set-up of the numerical model, the reader is referred to the Deltares report by Zijl et al. (2021). To assess the effects of OWF on waves in the context of the present study, results from three simulations performed in the latest 2024 WOZEP study (report in preparation) are analysed:

- A “reference” simulation: hindcast of the year 2020, where no effects from OWFs at all are included. The wind is based on ERA5.
- A “basic” wind schematization of the OWF effects: in which the effects of the hypothetical OWF by 2050 are captured through a uniform and constant 10% reduction in ERA5 (Hersbach et al., 2020) wind speeds within the OWF polygons (directions remain unchanged).
- An “advanced” wind schematization of the OWF effects: in which the effects of the hypothetical OWF by 2050 are captured by forcing the models with the WINS50-simulated wind fields. In the WINS50 simulations the effect of the turbines is parametrized, accounting for extraction of momentum, mixing and blockage when the turbines are rotating and just for the presence of the structures above the considered cut out wind speed of 25 m/s, beyond which the turbine will automatically shut down to prevent damage. The model results do not only incorporate the local effects but also the wake effects.

More precisely, the WINS50 dataset was derived using the HARMONIE-AROME (HIRLAM ALADIN Research On Mesoscale Operational NWP in Europe) operational model. In the WINS50 simulations the effect of wind farms is included in HARMONIE using the wind farm parameterization by Fitch et al. (2012), with a cut out wind speed of 25 m/s. In this parameterization, wind turbines act as a sink of momentum leading to a local reduction in the wind speed. The extracted momentum that is not used for power production is released as an increased level of turbulent kinetic energy.

The “basic” and “advanced” simulations were carried out for the reference year of 2020, i.e. using the reference 2020 hindcast model as a basis. This means that all other forcings, numerical settings and boundary conditions are identical to those employed in the reference simulation. Consequently, by comparing the wave model results of the three simulations only the effect of the varied wind input is assessed. This comparison allows for a distinction, in the context of shipping safety, between the relative importance of wind speed reduction inside OWF (e.g. by comparing basic with reference), of wind wakes outside OWFs as well as of mixing induced by the rotating blades, potentially leading to temporal increase of wind speeds near the sea surface (e.g. by comparing advanced with basic).

From a modelling perspective, this comparison also allows us to assess the suitability of the more easily applicable yet crude “basic” wind schematization, in which only a constant and uniform wind speed reduction is applied within the boundaries of the OWF. The advantage of this schematization is that it does not require prior detailed atmospheric modelling (it is noted that the WINS50 wind forcing is only available for a period of one year, 2020) and hence can be applied to model longer periods with readily available wind forcing (e.g. ERA5), thereby leading to larger confidence in the statistical analyses.

3.3 Approach

In this study, we assess the influence of OWF on waves based on relevant and typically widely available integral wave parameters namely significant wave height (Hs), mean absolute wave period (Tm-10) and mean wave direction (MWD). One-year-long timeseries of these parameters were available for all simulations performed with the spectral wave model DCSM-SWAN, at a number of locations corresponding to all the grid points of the wave model (which extends over the entire North Sea). It is noted that other wave parameters and combinations thereof may be important as well for nautical safety but at this phase of the project were not considered. Finally, the reason to consider mean instead of the peak wave period is the less discrete character of that modelled parameter that also better represents the entire wave energy spectrum.

In this study, we first focus on the extended area around the Dutch North Sea for plotting differences in wave fields between the various simulations. We then perform statistical analyses to quantify the percentage change in integral wave parameters for the full modelled period of one year for various cluster of points that are relevant for navigation, exclusively within the Dutch part of the North Sea. To that end, we assess locations within shipping routes, clearways, anchor zones and separation zones, and where relevant also in relation to their proximity to offshore wind farms, using the 2050 OWF scenario in conjunction with the GIS navigation data obtained from Rijkswaterstaat Dataregister WFS[1]. Other relevant clusters of points represent areas within OWFs, at the direct vicinity of OWFs as well as areas that are at the far offshore part of the Dutch EEZ, where navigation can occur without any restrictions.

3.4 Spatial model results

We first focus on changes in the wave fields. The wave conditions and associated differences between the various simulations are presented here for a number of relevant moments within the one-year of simulation, corresponding to highly dynamic conditions and thus relevant for shipping safety. The selected instances correspond to the occurrence of the maximum significant wave height at a reference location in the centre of the Dutch EEZ (with longitude and latitude of 4.15° and 53.9667°, respectively) for each of the four distinct 90° directional sectors (north, east, south and west) in terms of incoming mean wave directions modelled in the hindcast reference simulation (see Table 3.1, Figure 3.1).

[1] geo.rijkswaterstaat.nl/services/ogc/gdr/verkeersscheidingsstelsel_nz/ows?version=2.0.0

Table 3.1 Timings of representative (maximum significant wave height Hs at a reference location in the centre of the Dutch EEZ) wave conditions for each of the four directional sectors defined; for the reference run with ERA5 wind and no OWF effects

Sector	Condition	Timing of $Hs_{max,1}$
North	315° < MWD ≤ 45°	27-Sep-2020 03:00:00
East	45° < MWD ≤ 135°	04-Dec-2020 08:00:00
South	135° < MWD ≤ 225°	09-Feb-2020 14:00:00
West	225° < MWD ≤ 315°	12-Feb-2020 04:00:00

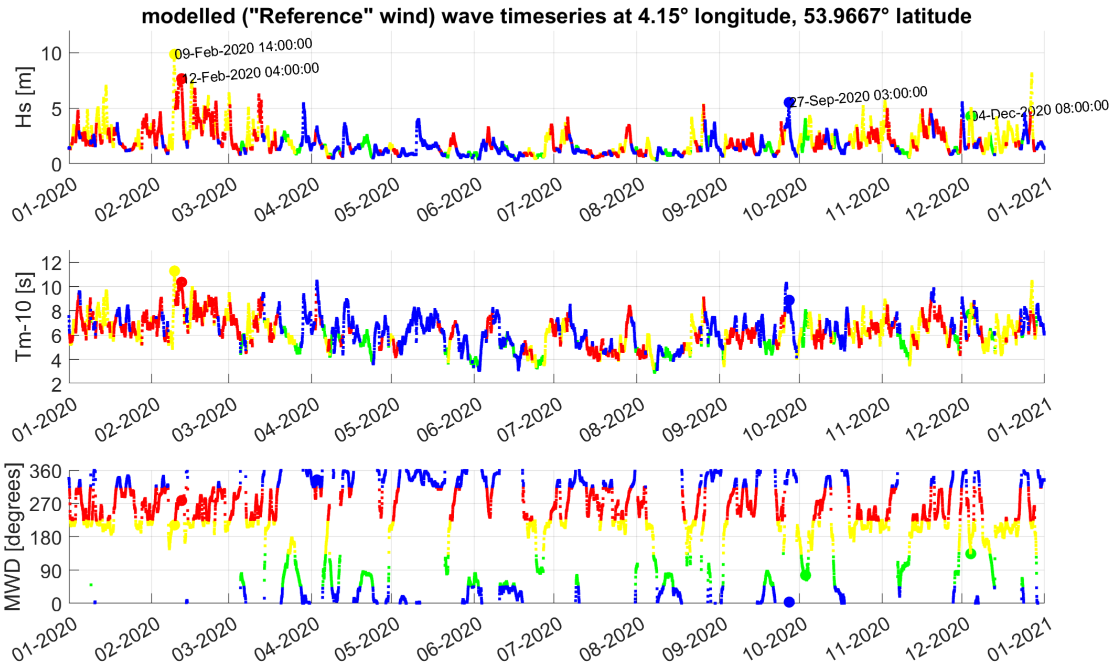

Figure 3.1 Wave timeseries classified by colour to the four directional sectors defined (blue for north, green for east, yellow for south and red for west). The timings of the considered representative maximum significant wave height events are marked.

3.4.1 Example wave fields for North Sector

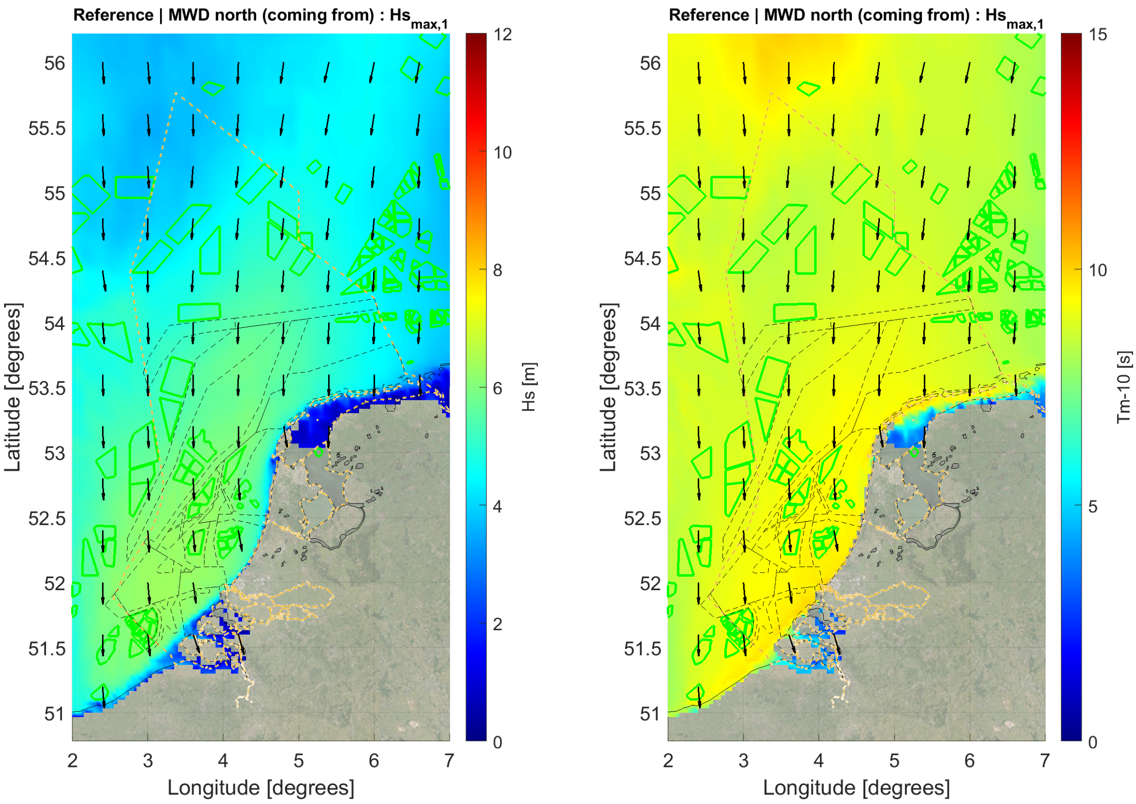

Figure 3.2 Hs (left) and Tm-10 (right) spatial patterns modelled with the Reference wind input at the timing of the north sector Hs_{max} at the reference location with longitude and latitude of 4.15° and 53.9667° respectively.

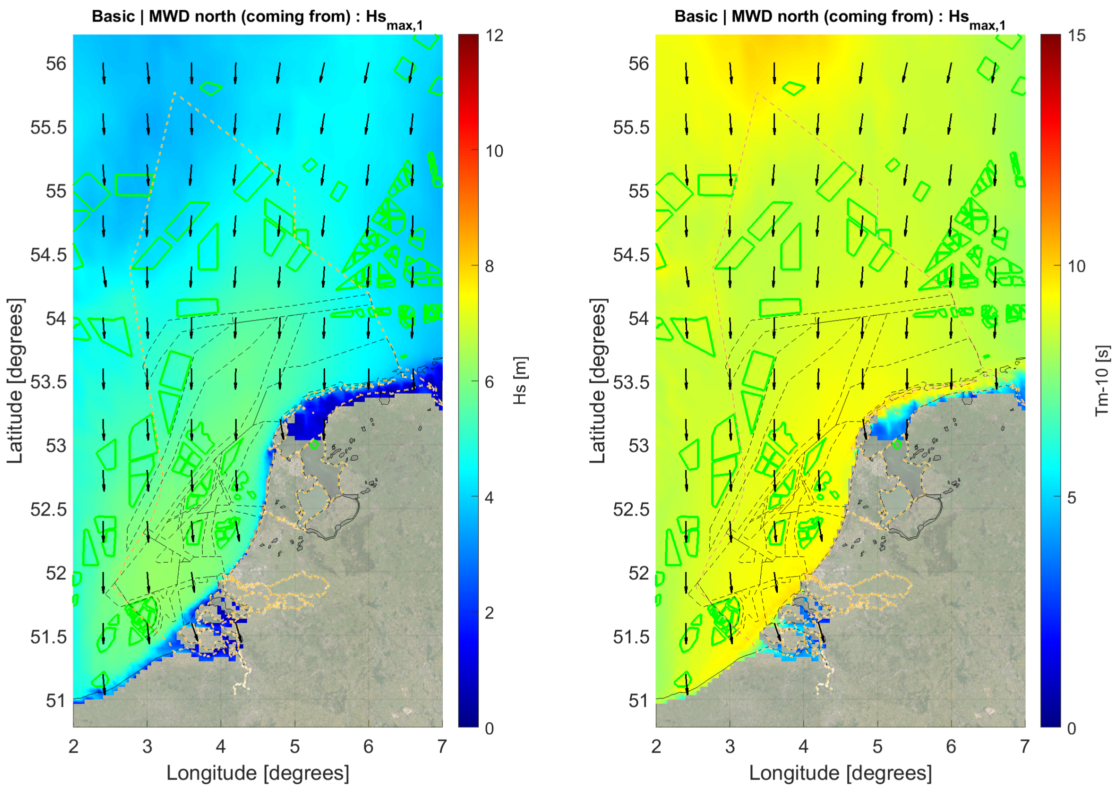

Figure 3.3 Hs (left) and Tm-10 (right) spatial patterns modelled with the Basic wind input at the timing of the north sector Hs_{max} at the reference location.

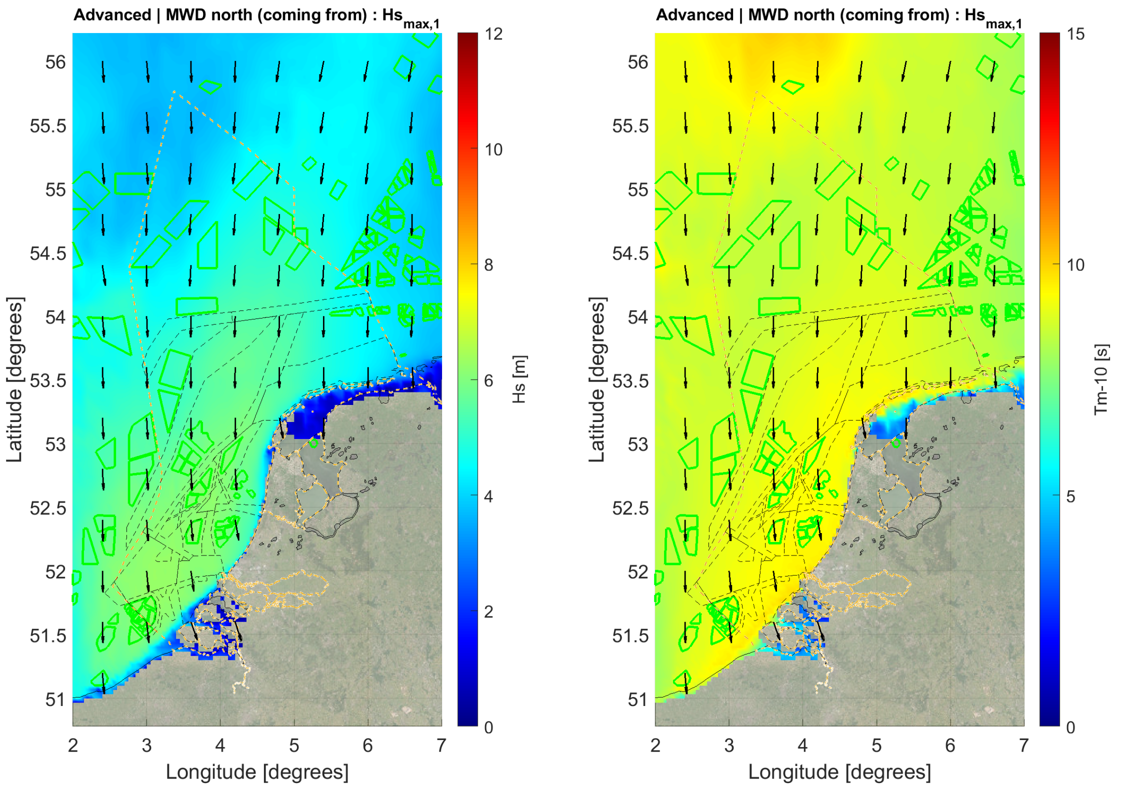

Figure 3.4 *Hs (left) and Tm-10 (right) spatial patterns modelled with the* ***Advanced*** *wind input at the timing of the north sector* Hs_{max} *at the reference location.*

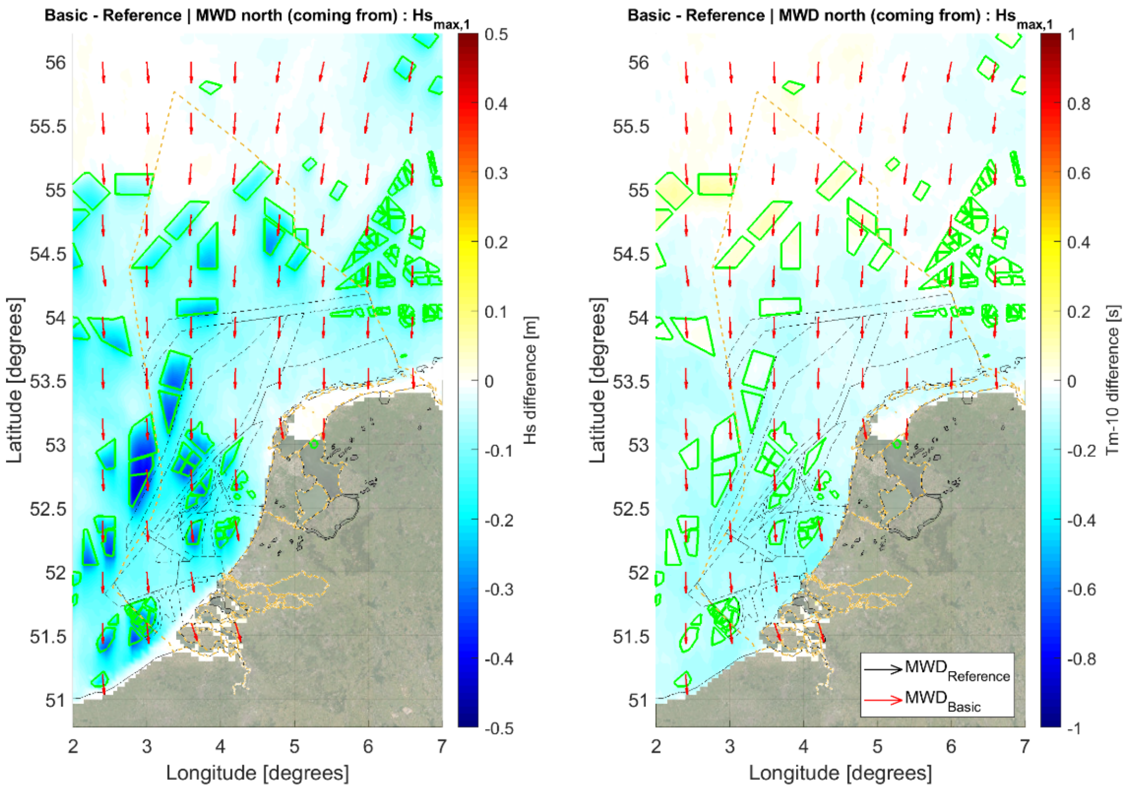

Figure 3.5 *Difference plot ("Basic – Reference" wind input) of Hs (left) and Tm-10 (right) spatial patterns at the timing of the north sector* Hs_{max} *at the reference location.*

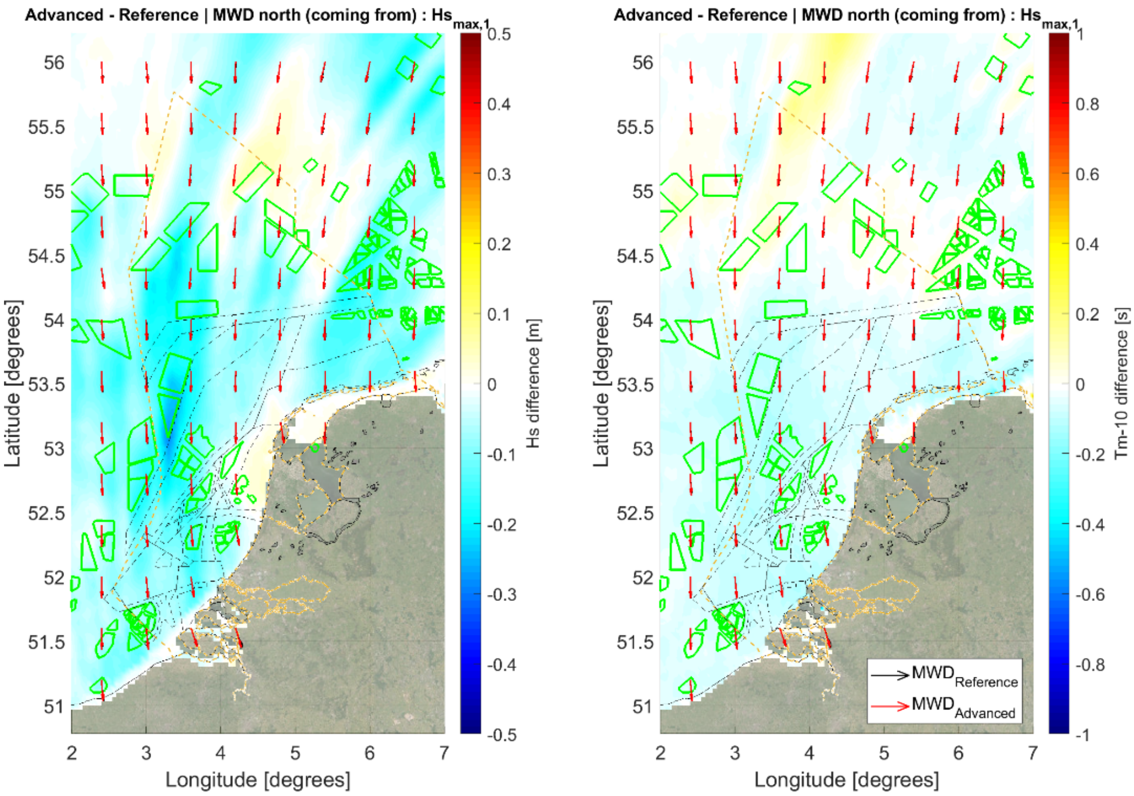

Figure 3.6 Difference plot ("Advanced – Reference" wind input) of Hs (left) and Tm-10 (right) spatial patterns at the timing of the north sector Hs_{max} at the reference location.

A first comparison of the wave fields modelled with the three different wind forcings (see Figure 3.2, Figure 3.3, and Figure 3.4) shows that the overall wave patterns (in terms of spatial distribution of significant wave height, mean absolute period and mean wave directions) remain virtually uninfluenced by the OWFs at the spatial scale of the Dutch North Sea. This finding holds for the entire simulation period and thus is independent from the incoming wave directions or the severity of the wave climate.

Nevertheless, difference plots of the relevant wave parameters between the two simulations involving OWF influence on wind fields compared to the control hindcast simulation (see Figure 3.5 and Figure 3.6) indicate that effects from OWFs on waves are in fact noticeable much further from the boundaries of the OWFs, extending even across the majority of the Dutch North Sea and hence also occur within areas of interest for navigation.

However, the changes in Hs, are most prominent within the OWFs (roughly in the order of 2-5%) and decrease significantly with distance from the OWF boundaries (roughly in the order of 1-2%) outside OWFs. The decrease is larger with downwind distance from the OWF boundary. For this instance corresponding to incoming waves from the north sector, Hs decreases in both Basic and Advanced scenarios, which albeit with some noticeable differences in the spatial pattern is an indication of blockage and extraction of momentum having a predominant effect over mixing from the rotating blades of the wind turbines.

Changes in Tm-10 are even less pronounced (in terms of percentage change) compared to changes in Hs for both modelled conditions and in any case remain for the most part within the model accuracy range (± 0.1 seconds), while changes in mean wave directions are hardly noticeable (by comparing the overlapping directional vectors) even within OWFs. For detailed zoomed in plots of the effects, we refer to Appendix A.

3.4.2 Example wave fields for East Sector

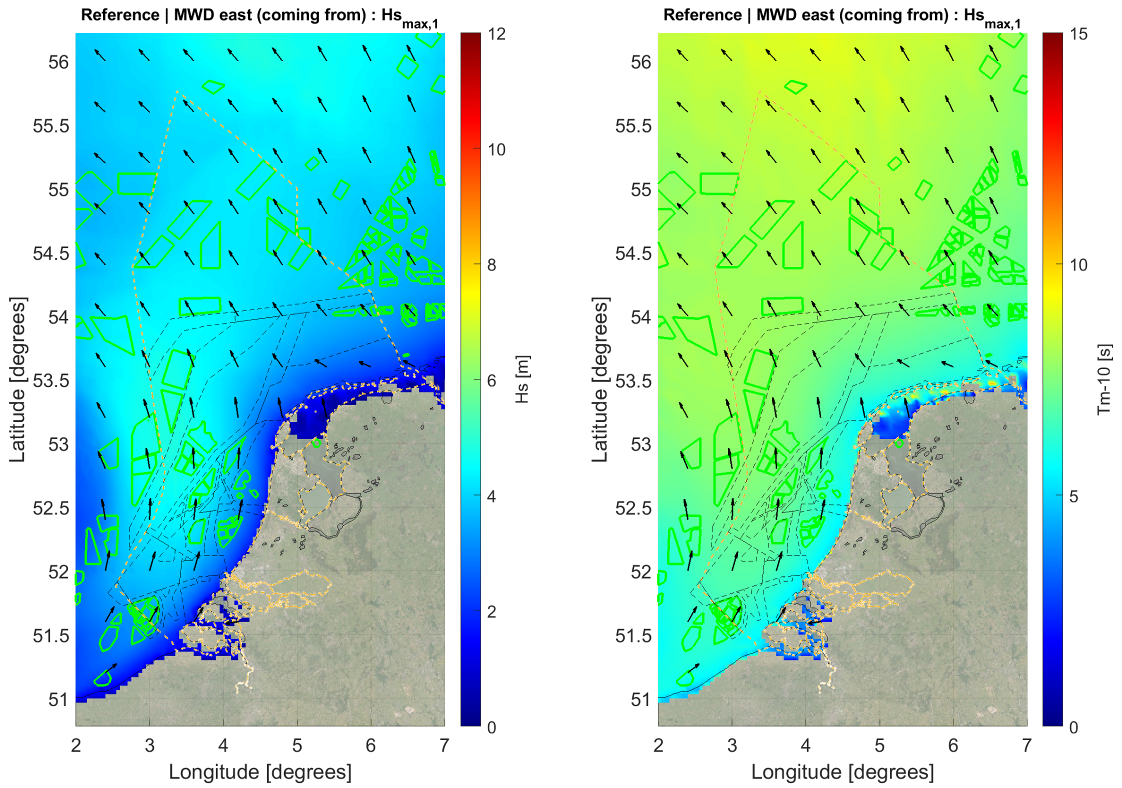

Figure 3.7 *Hs (left) and Tm-10 (right) spatial patterns modelled with the* ***Reference*** *wind input at the timing of the east sector* Hs_{max} *at the reference location.*

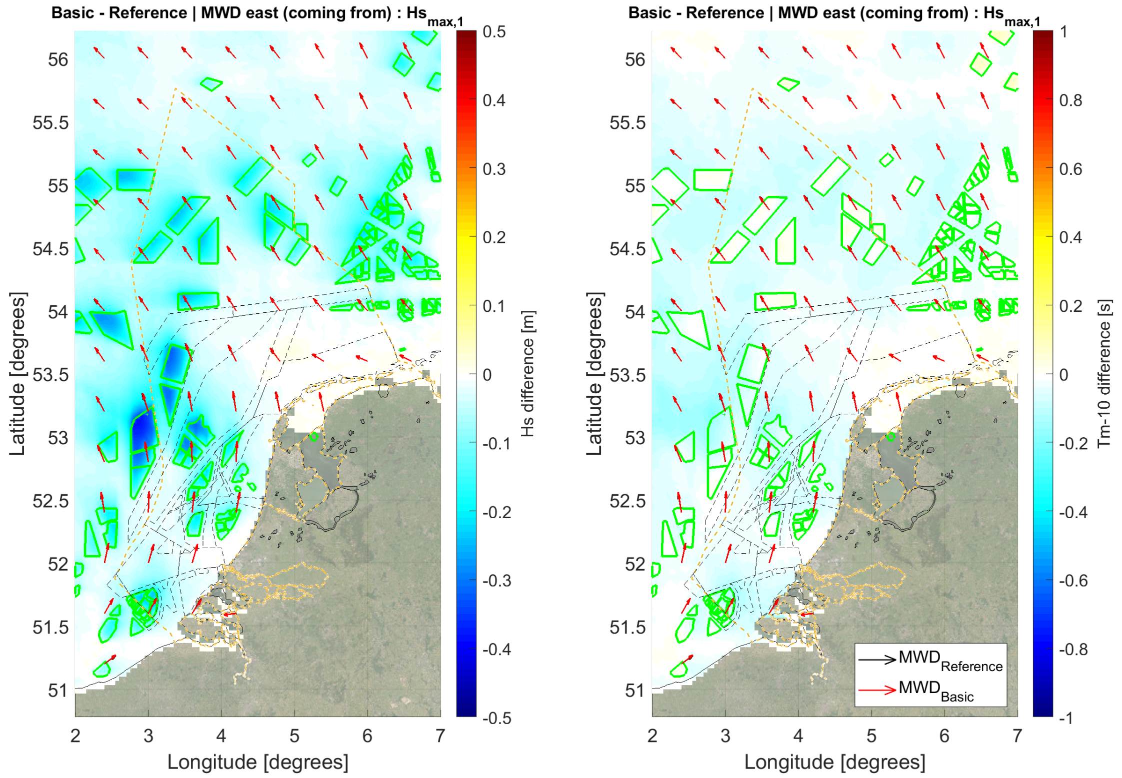

Figure 3.8 *Difference plot ("Basic – Reference" wind input) of Hs (left) and Tm-10 (right) spatial patterns at the timing of the east sector* Hs_{max} *at the reference location.*

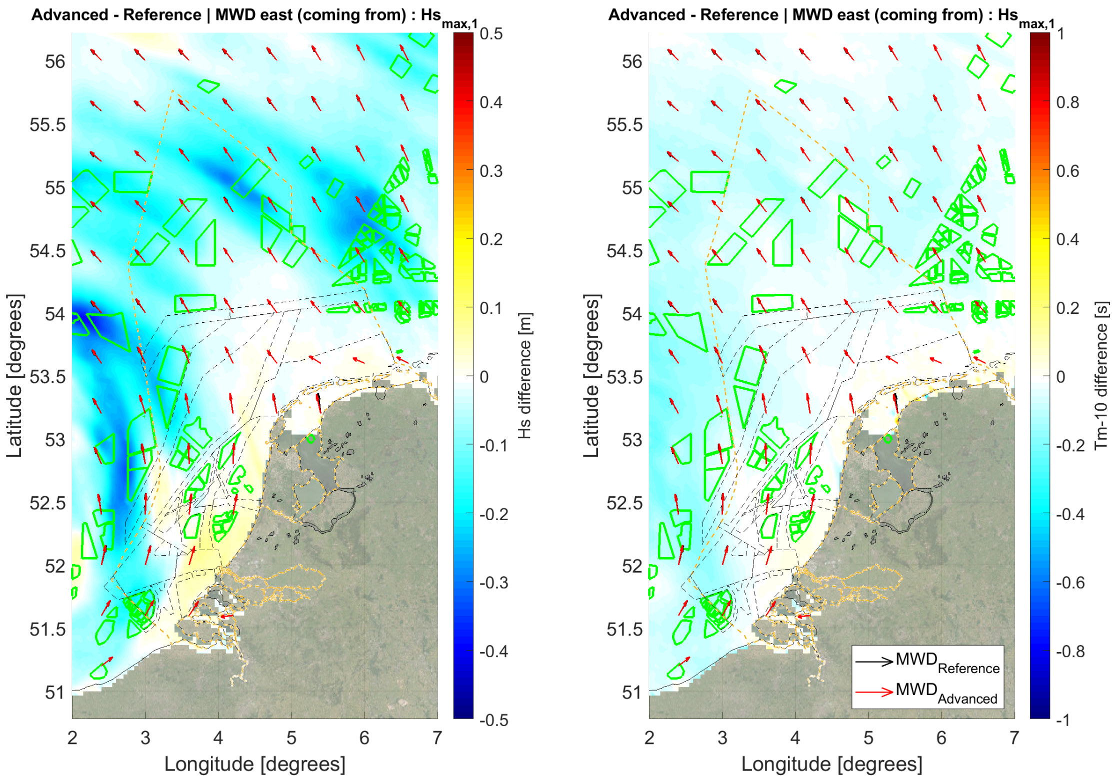

Figure 3.9 Difference plot ("Advanced – Reference" wind input) of Hs (left) and Tm-10 (right) spatial patterns at the timing of the east sector Hs_{max} at the reference location.

In this eastern section, we obviously assess the least energetic wave conditions. Generally speaking, similar influences from OWFs on waves are observed from the spatial results (Figure 3.7) and difference plots (Figure 3.8 and Figure 3.9) as in the northern sector case but the percentage of reduction of Hs is much higher for the eastern sector.

A notable difference for this incoming sector is that a much smaller area of the Dutch North Sea, and in fact of the shipping routes and other areas of navigational interest, is affected for waves approaching roughly from the (south-)east. Obviously, this is due to the orientation of the OWF-induced wakes that extend in an offshore direction. However, it should be noted that these favourable conditions are the least frequent in the Dutch North Sea.

Furthermore, the difference plots reveal that more significant changes of Hs occur mainly within the boundaries of OWFs for the Basic wind schematization, for which the wind speed is reduced uniformly only within OWFs. On the other hand, for the Advanced wind schematization these changes are mostly observed in areas of overlapping wakes, likely a result of the resolved wind wakes outside OWFs. This highlights the importance of resolved wind wakes in the forcing of the wave model, in the context of assessing changes in shipping conditions in the vicinity of the OWFs. For both schematizations, changes in Tm-10 and MWD remain mostly negligible.

3.4.3 Example wave fields for South Sector

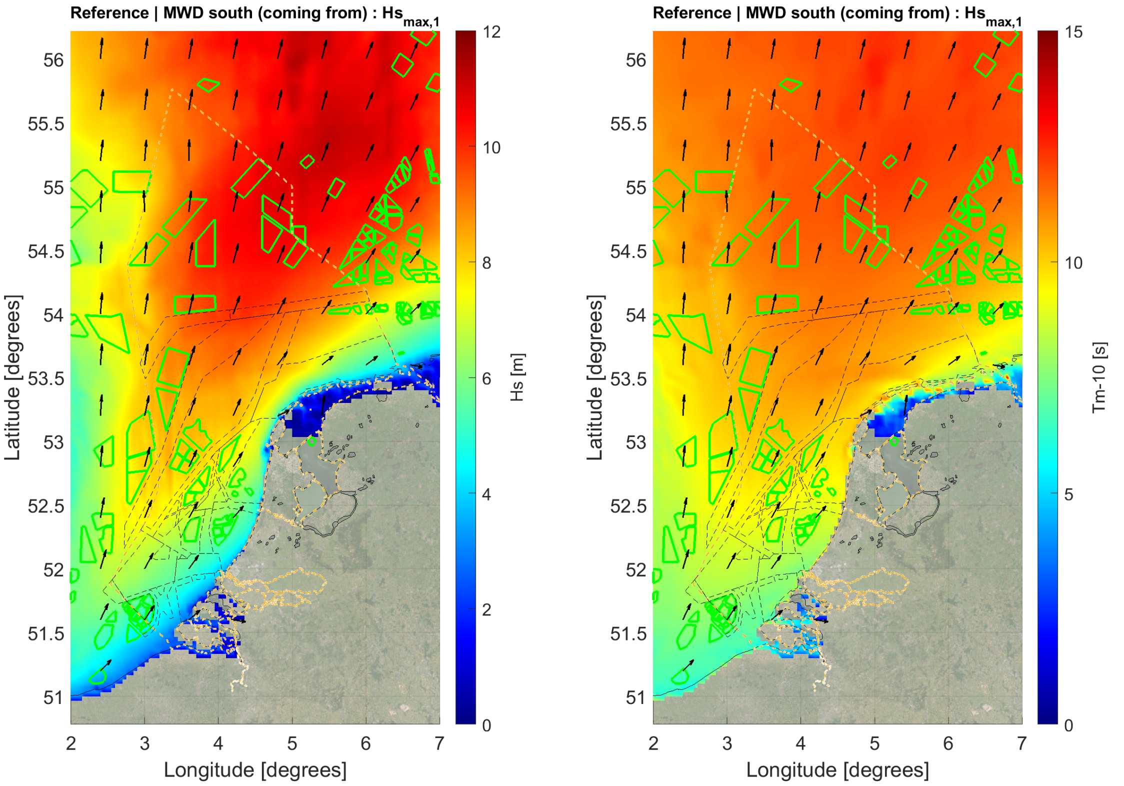

Figure 3.10 Hs (left) and Tm-10 (right) spatial patterns modelled with the *<u>Reference</u>* *wind input at the timing of the south sector* Hs_{max} *at the reference location.*

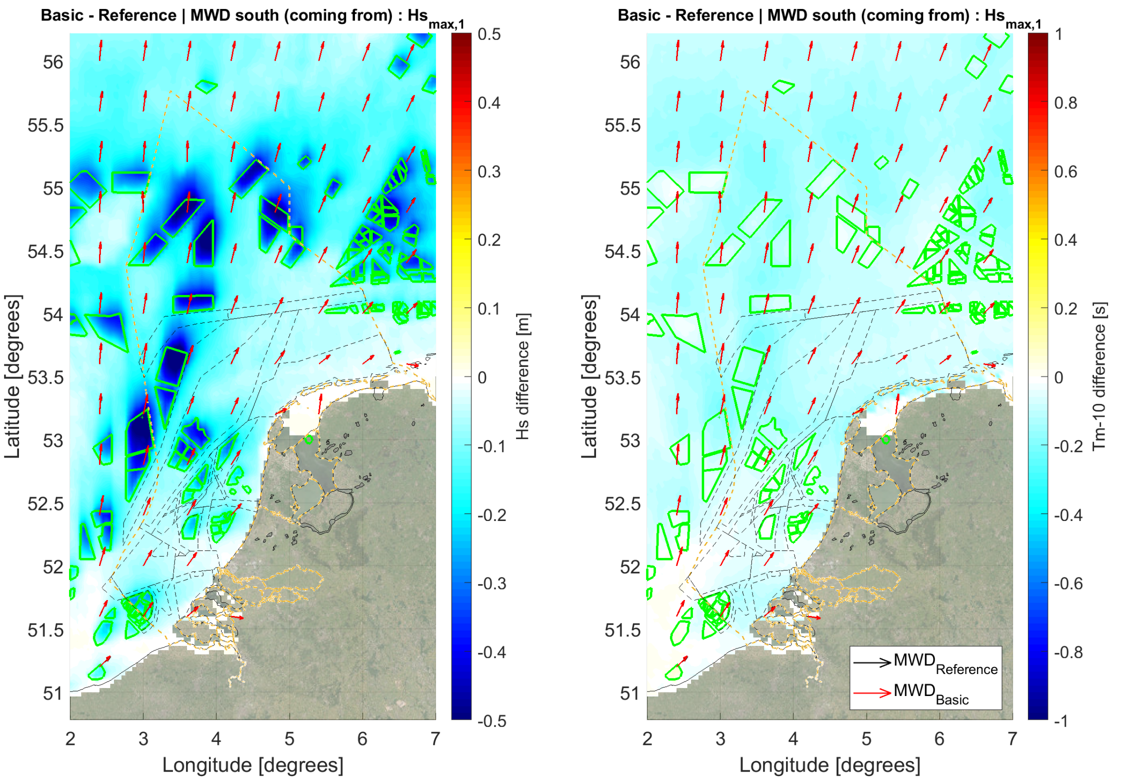

Figure 3.11 Difference plot ("Basic – Reference" wind input) of Hs (left) and Tm-10 (right) spatial patters at the timing of the south sector Hs_{max} *at the reference location.*

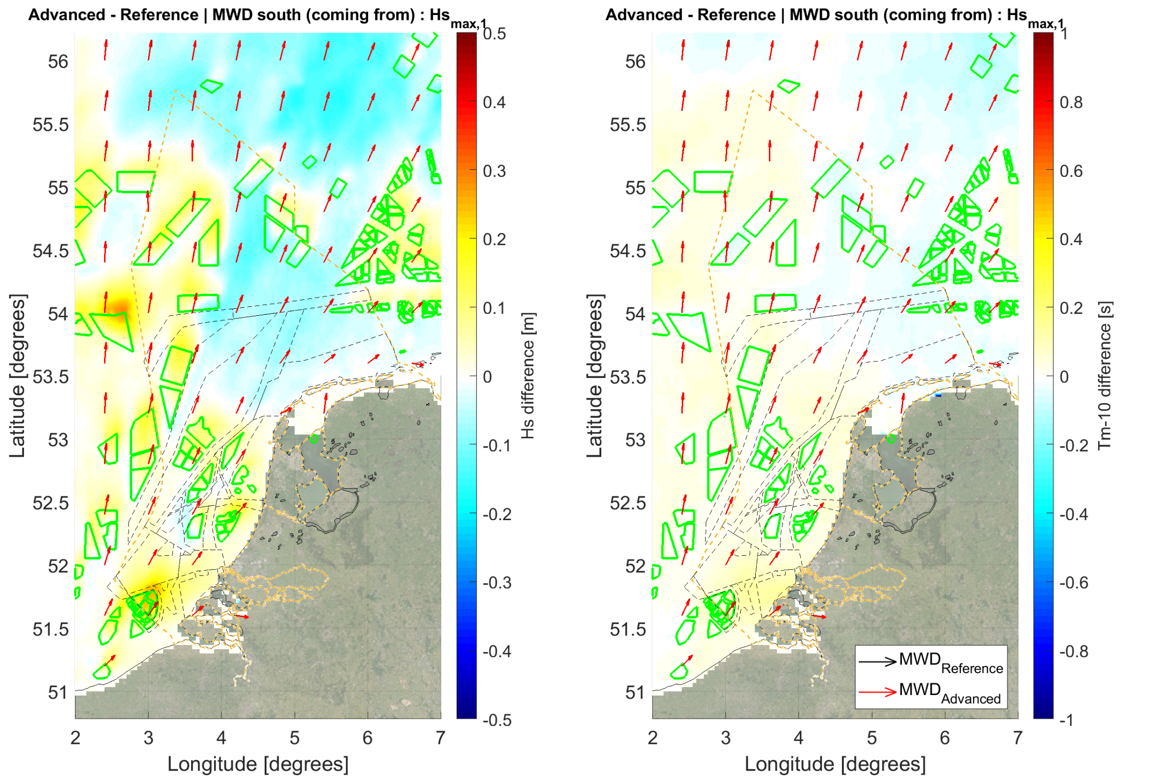

Figure 3.12 Difference plot ("Advanced – Reference" wind input) of Hs (left) and Tm-10 (right) spatial patterns at the timing of the south sector Hs_{max} at the reference location.

In this southern section, the most highly energetic case occurs. Similar to the North case, the effects of the OWF's occur virtually at the entire area of the Dutch North Sea and of the shipping areas.

Most significant change is observed for the Basic wind schematization, where large 8 m high waves nearly uniformly decreases by roughly 0.5 m (appr 6%) within OWFs and roughly 0.2 m (2%)in their vicinity. In the advanced wind schematization however, Hs on the contrary increases(!) inside and in the direct vicinity of OWFs and only decreases with distance from their boundaries. This increase is explained by mixing induced by the wind turbine blades leading (in stable atmospheric conditions) to transport of wind energy from higher up in the atmosphere closer to the sea surface, thereby enhancing wave growth. This is effect is not present in the Basic wind schematization but it is included in the advanced schematization. Note that for unstable (well mixed) conditions, the difference between the basic and advanced wind model will be less. It is kind of coincidence – but not surprisingly - that this maximum plot occurs for stable conditions. Similar to the other wind sectors changes in Tm-10 and MWD are deemed negligible.

3.4.4 Example wave fields for West Sector

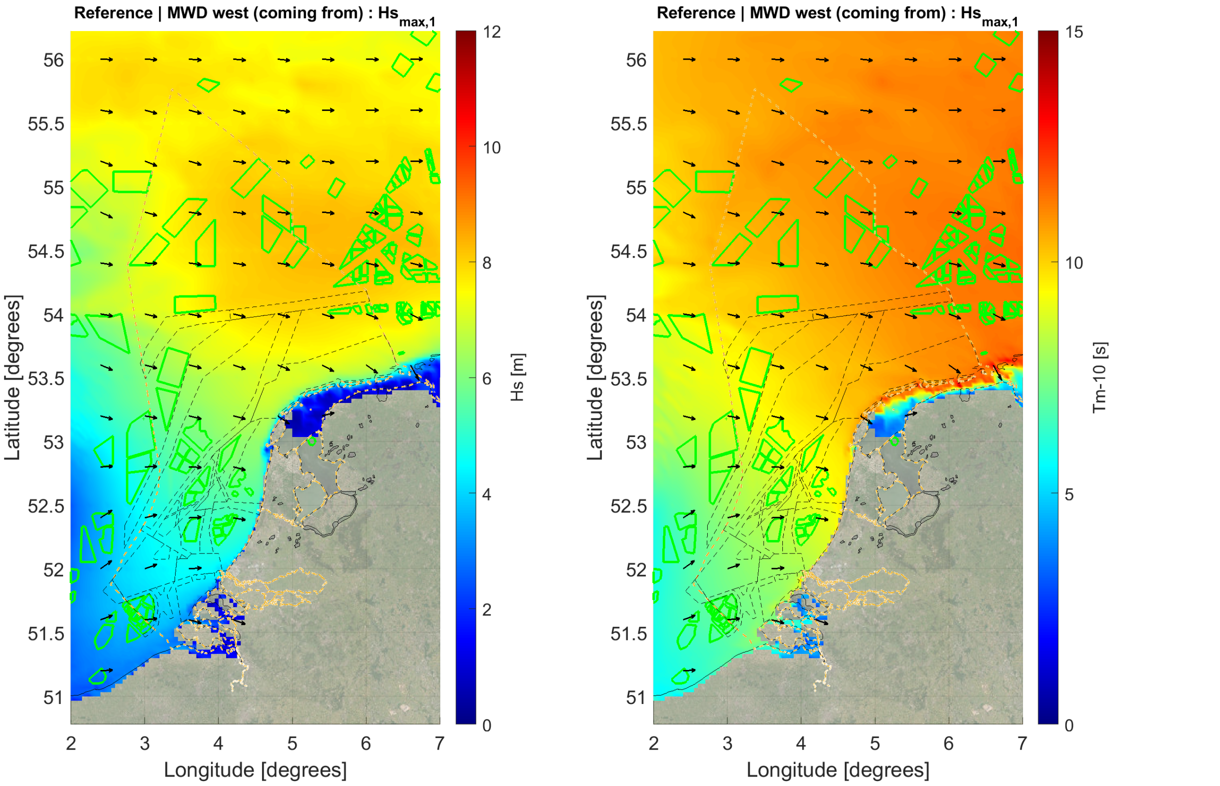

Figure 3.13 Hs (left) and Tm-10 (right) spatial patterns modelled with the *<u>Reference</u>* *wind input at the timing of the west sector* Hs_{max} *at the reference location.*

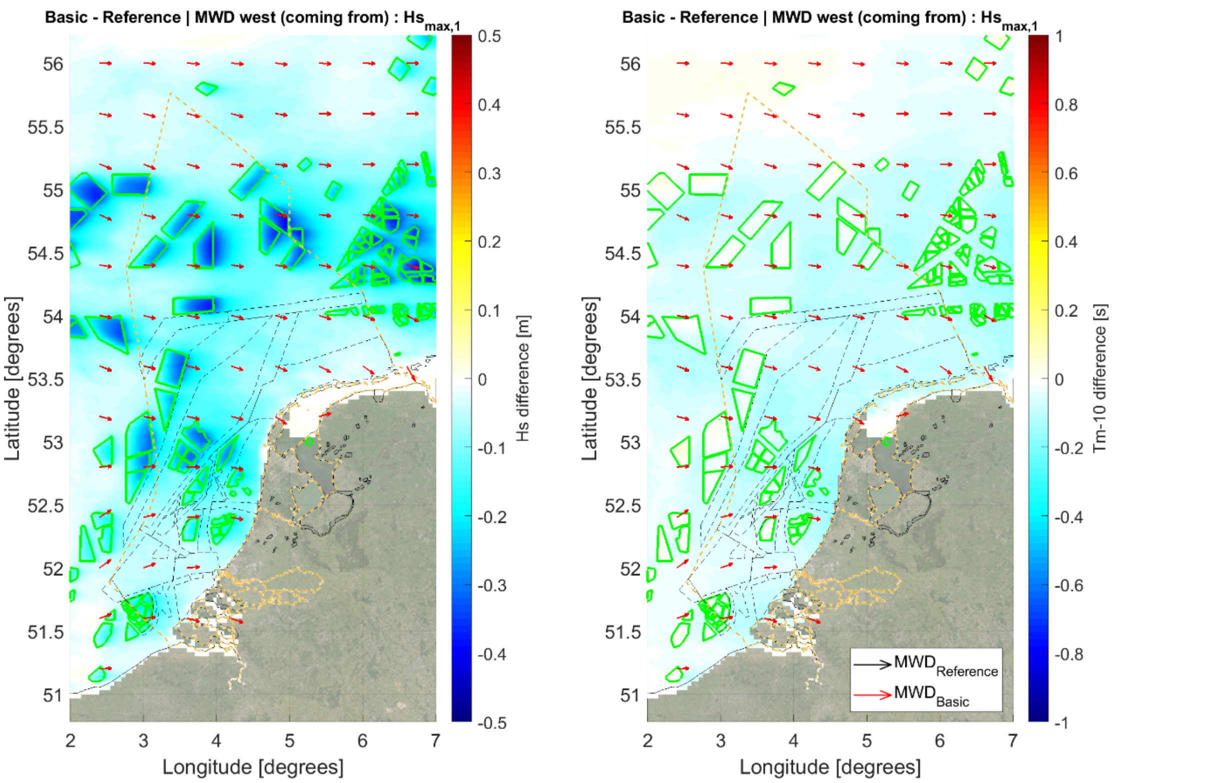

Figure 3.14 Difference plot ("Basic – Reference" wind input) of Hs (left) and Tm-10 (right) spatial patterns at the timing of the west sector Hs_{max} *at the reference location.*

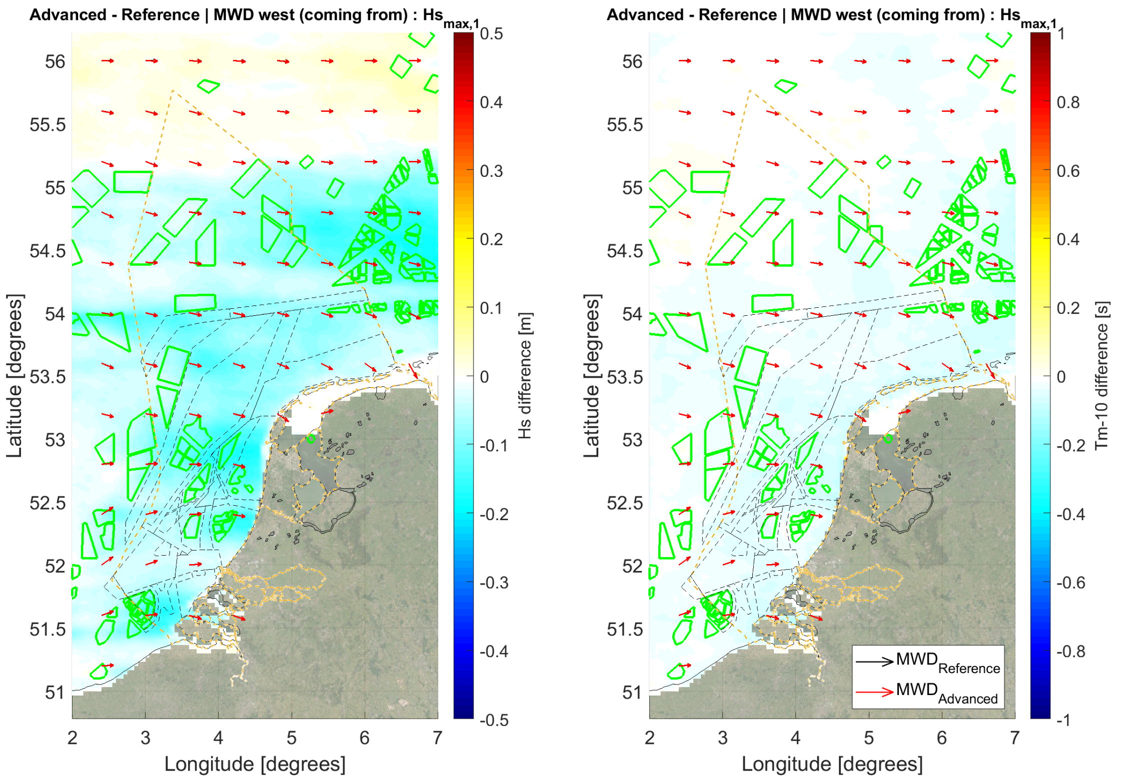

Figure 3.15 Difference plot ("Advanced – Reference" wind input) of Hs (left) and Tm-10 (right) spatial patterns at the timing of the west sector Hs_{max} at the reference location.

The West case presented here is another relatively high energetic wave situation. The overall wave patterns are mostly similar with the south and north sector cases, i.e. the entire Dutch North Sea experiences changes in wave conditions due to OWFs which is especially the case in terms of Hs. Contrary to the south case however, the advanced wind schematization shows a decrease of Hs within the OWFs, an indication of a different condition in atmospheric stability (unstable as opposed to stable atmospheric conditions). The Basic wind schematization shows again largely similar wave conditions further from the OWFs with the Advanced simulations, where shipping routes are positioned but certainly lacks relevant physical phenomena, such as wind mixing or wakes evolving in the direct vicinity of OWFs.

3.5 Statistical analysis

3.5.1 Introduction

In this section, the effects of OWFs on waves and navigation are shown in terms of linear statistical parameters[2]. These are drawn from the comparison of modelled wave parameters between the "Reference" wind and the two wind schematizations (Basic and Advanced) that reflect OWFs influences on wind fields. In this section we will discuss only the Advanced wind schematization which is deemed most representative (see Section 3.4). The statistical parameters for the Basic wind schematization are reported in the Appendix B for completeness. As opposed to the instantaneous comparisons of wave fields in the previous section, the statistical comparisons reflect the entire modelled period of one year in all three simulations. Moreover, the relevant locations are not assessed individually but rather clustered with respect to proximity to OWF (within and surrounding OWF) and to navigational features i.e. (far offshore) shipping areas, anchor zones and (port and inland navigation) approach areas. Regarding the proximity to the

[2] N = sample size, Bias= mean(y)-mean(x), RMSE= root mean square error, std = Standard Deviation of error.

OWF, locations up to a distance of roughly 10 km from the OWF boundaries were considered[3] in line with the wakes reported in Section 3.4. It is noted that only locations within the Dutch EZZ are processed. The most relevant of the clusters analysed are presented in the remainder of this section and summarized in Table 3.2.

Table 3.2 Clusters of offshore locations determined for the statistical analysis of OWFs effects on waves.

Cluster name	Description	# model output points
Dutch OWFs	Offshore locations within the Dutch OWFs (2050 scenario)	716
Surrounding area Dutch OWFs	All offshore locations that fall within roughly 10 km from the boundaries of OWFs	1358
Designated shipping routes	Offshore locations within the designated shipping routes (including separation zones) that fall within roughly 10 km from the boundaries of OWFs	385
Far offshore shipping areas	Far offshore locations within the designated shipping routes that fall within roughly 10 km from the boundaries of OWFs	575
Anchor zones	Offshore locations that fall within designated anchor zones within roughly 10 km from the boundaries of OWFs	20
Approach areas	Offshore locations that fall within designated approach areas within roughly 10 km from the boundaries of OWFs	56

[3] Wakes can extend for more than 10 km from the OWF boundaries, however the effects are low and this is roughly the distance from which the wake effects become insignificant in terms of wave conditions. In addition, based on a sensitivity analysis of the buffer area (on a buffer distance of 5 km) it was observed that there is only a negligible difference in determined statistical parameters in comparison with those presented in the following sections for distances of less than 10 km.

The data are additionally processed for a number of relevant offshore conditions to identify significant aspects of OWFs impacts on waves. To that end, the data are processed for all wave and wind directions (omnidirectional), as well as for the north (315° < MWD, U_{10}DIR ≤ 45°), east (45° < MWD, U_{10}DIR ≤ 135°), south (135° < MWD, U_{10}DIR ≤ 225°) and west (225° < MWD, U_{10}DIR ≤ 315°) incoming sectors of mean wave and 10-meter wind speed directions based on the conditions modelled in the Reference simulation, at each location. Finally, the data are classified in two ranges of local significant wave height (Hs ≤ 5m & Hs > 5m) and two ranges of local mean absolute wave period (Tm-10 ≤ 10s & Tm-10 > 10s). Relevant findings are presented for each cluster in the remainder of this section.

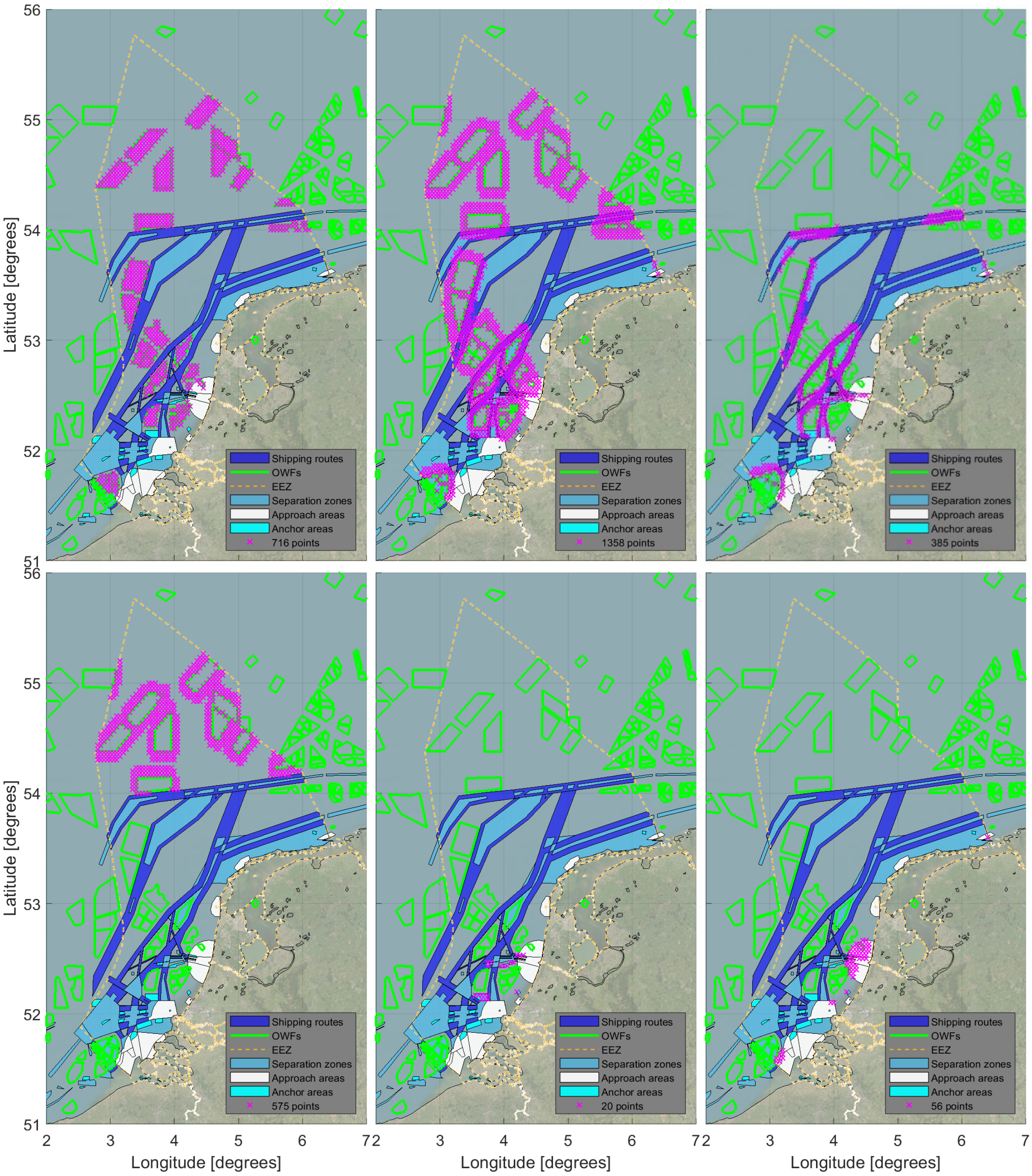

Figure 3.16 Clusters of relevant offshore locations within the Dutch EEZ, indicated by pink markers. Top: Dutch OWF (left), Surrounding area OWF (middle), Designated shipping routes (right), Bottom: Far offshore shipping areas (left), Anchor zones (middle panel), Approach areas (right panel).

A complete overview of the statistical comparisons between a number of wave conditions modelled with the Reference and Advanced wind schematization is only presented for the first reported cluster of locations within “Dutch 2050 OWFs”. For conciseness, only non-negligible changes (observed predominantly for Hs) are discussed for the remaining clusters. The main observations are reported at the end of this section. A complete overview of statistical comparisons is given in the Appendix B for all parameters as well as for the various determined wave condition classifications.

3.5.2 Dutch 2050 OWFs

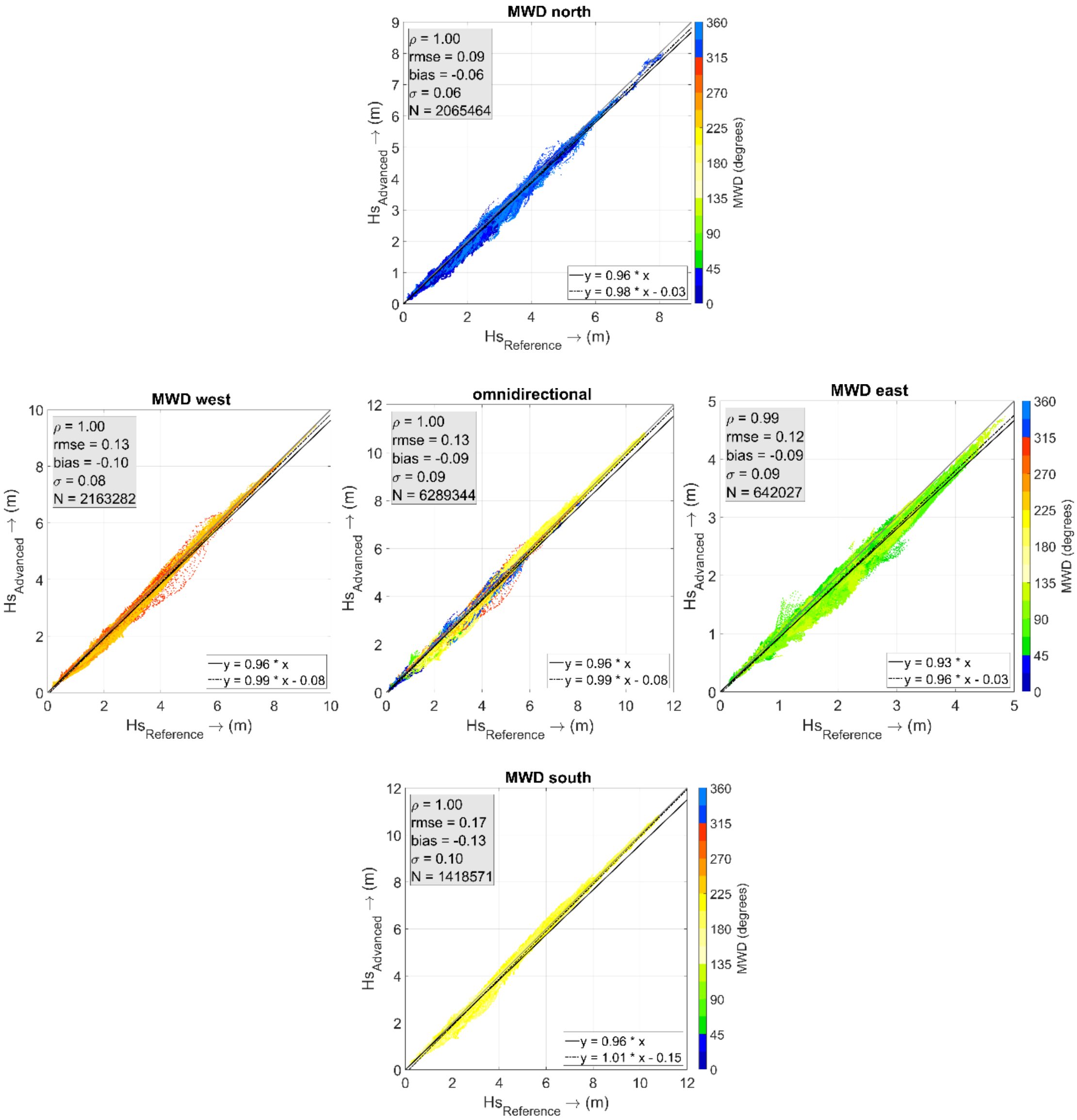

Figure 3.17 Scatter plot comparisons of significant wave height between Reference (x-axis) and Advanced (y-axis) wind schematization model results (simulation period from 01-2020 to 12-2020). The model data are colour-coded and arranged in panels based on MWD, see also Section 3.5.1.

Table 3.3 Linear statistics of significant wave height (Hs) for the "Dutch 2050 OWFs" cluster (Advanced vs Reference) for various offshore conditions based on the full year 2020.

Condition	N [-]	Bias [m]	RMSE [m]	Symmetric Slope: (Adv) = a * (Ref) [-]	(Adv) = b * (Ref) + c	
					b [-]	c [-]
Omnidirectional	6289344	-0.09	0.13	0.96	0.99	-0.08
North MWD	2065464	-0.06	0.09	0.96	0.98	-0.03
Dir. U10 North	1084502	-0.08	0.11	0.96	0.98	-0.04
East MWD	642027	-0.09	0.12	0.93	0.96	-0.03
Dir. U10 East	1015075	-0.07	0.10	0.94	0.96	-0.01
South MWD	1418571	-0.13	0.17	0.96	1.01	-0.15
Dir. U10 South	1980443	-0.11	0.15	0.96	1.00	-0.10
West MWD	2163282	-0.10	0.13	0.96	0.99	-0.08
Dir. U10 West	2210963	-0.09	0.12	0.96	0.99	-0.07
Hs < 5 m	6138148	-0.09	0.13	0.95	0.98	-0.05
Hs > 5 m	151196	-0.05	0.10	0.99	1.02	-0.18
Tm-10 < 10 s	6249867	-0.09	0.13	0.96	0.99	-0.07
Tm-10 > 10 s	39477	-0.03	0.07	1.00	1.00	-0.04

Table 3.4 Linear statistics of mean absolute wave period (Tm-10) for the "Dutch 2050 OWFs" cluster (Advanced vs Reference) for various offshore conditions.

Condition	N [-]	Bias [s]	RMSE [s]	Symmetric Slope: (Adv) = a * (Ref) [-]	(Adv) = b*(Ref) +c	
					b [-]	c [-]
Omnidirectional	6289344	0.01	0.14	1.00	1.00	-0.01
North MWD	2065464	0.07	0.16	1.01	1.01	-0.01
Dir. U10 North	1084502	0.05	0.16	1.01	1.01	0.01
East MWD	642027	0.01	0.15	1.00	1.01	-0.04
Dir. U10 East	1015075	0.03	0.15	1.01	1.02	-0.05
South MWD	1418571	-0.06	0.14	0.99	1.00	-0.04
Dir. U10 South	1980443	-0.02	0.15	1.00	1.00	0.00
West MWD	2163282	0.01	0.13	1.00	1.00	0.03
Dir. U10 West	2210963	0.01	0.13	1.00	1.01	-0.04
Hs < 5 m	6138148	0.01	0.15	1.00	1.01	-0.05
Hs > 5 m	151196	-0.03	0.05	1.00	1.01	-0.15
Tm-10 < 10 s	6249867	0.01	0.14	1.00	1.01	-0.04
Tm-10 > 10 s	39477	0.01	0.08	1.00	0.98	0.27

Table 3.5 Linear statistics of mean wave direction (MWD) for the "Dutch 2050 OWFs" cluster (Advanced vs Reference) for various offshore conditions.

Condition	N [-]	Bias [deg]	RMSE [deg]	std [deg]
Omnidirectional	6289344	-0.17	7.62	4.26
North MWD	2065464	-0.89	4.90	2.83
Dir. U10 North	1084502	-1.15	4.08	2.50
East MWD	642027	-4.35	11.86	4.63
Dir. U10 East	1015075	-2.77	8.37	4.22
South MWD	1418571	0.17	9.58	3.03
Dir. U10 South	1980443	0.99	10.73	3.81
West MWD	2163282	1.52	6.62	3.25
Dir. U10 West	2210963	0.46	4.66	2.76
Hs < 5 m	6138148	-0.18	7.71	4.31
Hs > 5 m	151196	0.09	0.53	0.52
Tm-10 < 10 s	6249867	-0.18	7.64	4.28
Tm-10 > 10 s	39477	0.15	0.69	0.68

3.5.3 Surrounding area Dutch OWFs

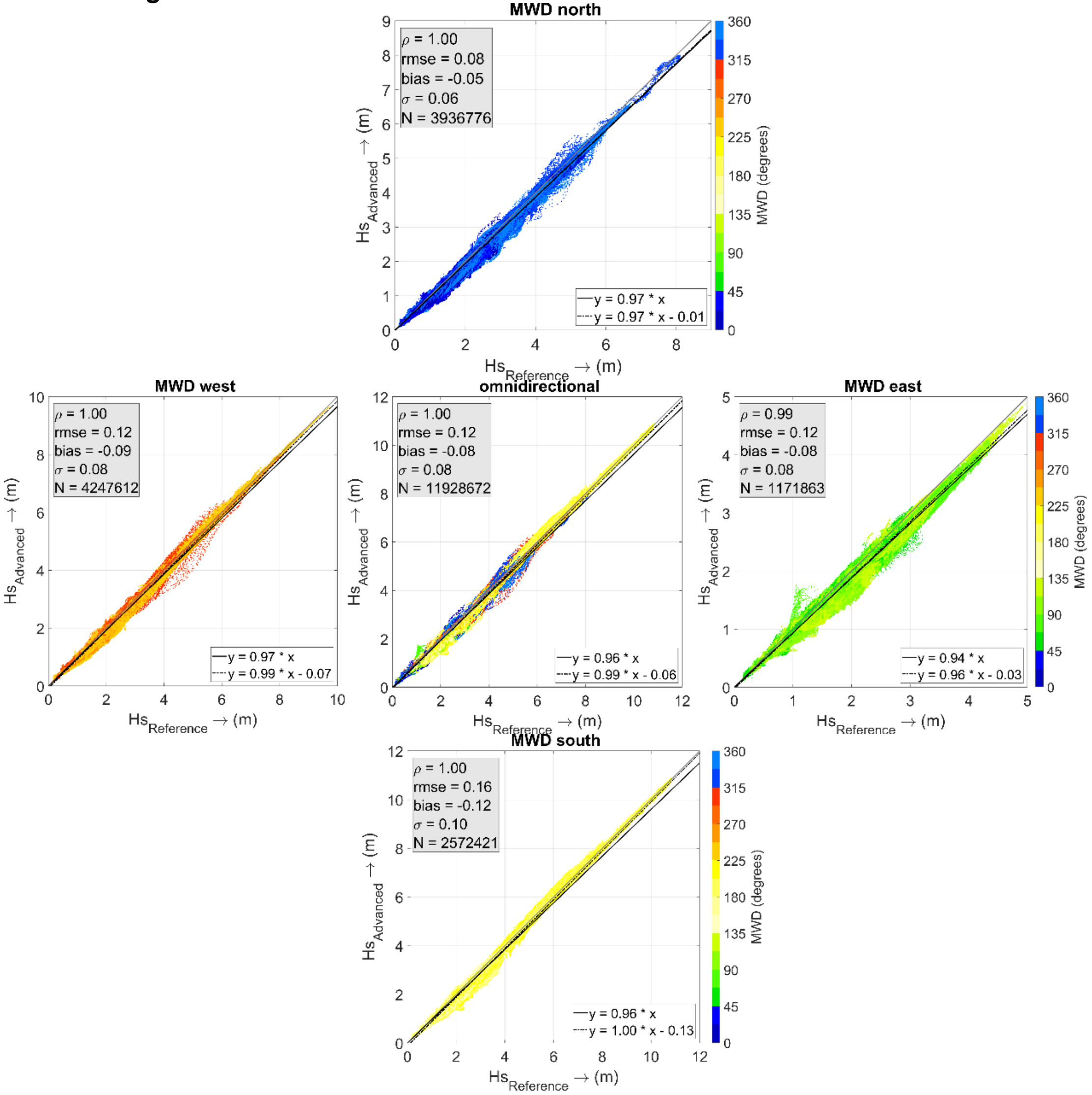

Figure 3.18 Scatter plot comparisons of significant wave height between Reference (x-axis) and Advanced (y-axis) wind schematization model results (simulation period from 01-2020 to 12-2020). The model data are colour-coded and arranged in panels based on MWD, see also Section 3.5.1.

Table 3.6 Comparison statistics of significant wave height (Hs) for the “Surrounding area Dutch OWFs” cluster (Advanced vs Reference) for various offshore conditions.

Condition	N [-]	Bias [m]	RMSE [m]	Symmetric Slope: (Adv) = a * (Ref) [-]	(Adv) = b * (Ref) + c	
					b [-]	c [-]
Omnidirectional	11928672	-0.08	0.12	0.96	0.99	-0.06
North MWD	3936776	-0.05	0.08	0.97	0.97	-0.01
East MWD	1171863	-0.08	0.12	0.94	0.96	-0.03
South MWD	2572421	-0.12	0.16	0.96	1.00	-0.13
West MWD	4247612	-0.09	0.12	0.97	0.99	-0.07
Hs < 5 m	11659624	-0.08	0.12	0.96	0.98	-0.04
Hs > 5 m	269048	-0.05	0.10	0.99	1.02	-0.15
Tm-10 < 10 s	11861929	-0.08	0.12	0.96	0.99	-0.06
Tm-10 > 10 s	66743	-0.03	0.08	1.00	1.00	-0.03

3.5.4 Shipping routes within a buffer of 10km around OWFs

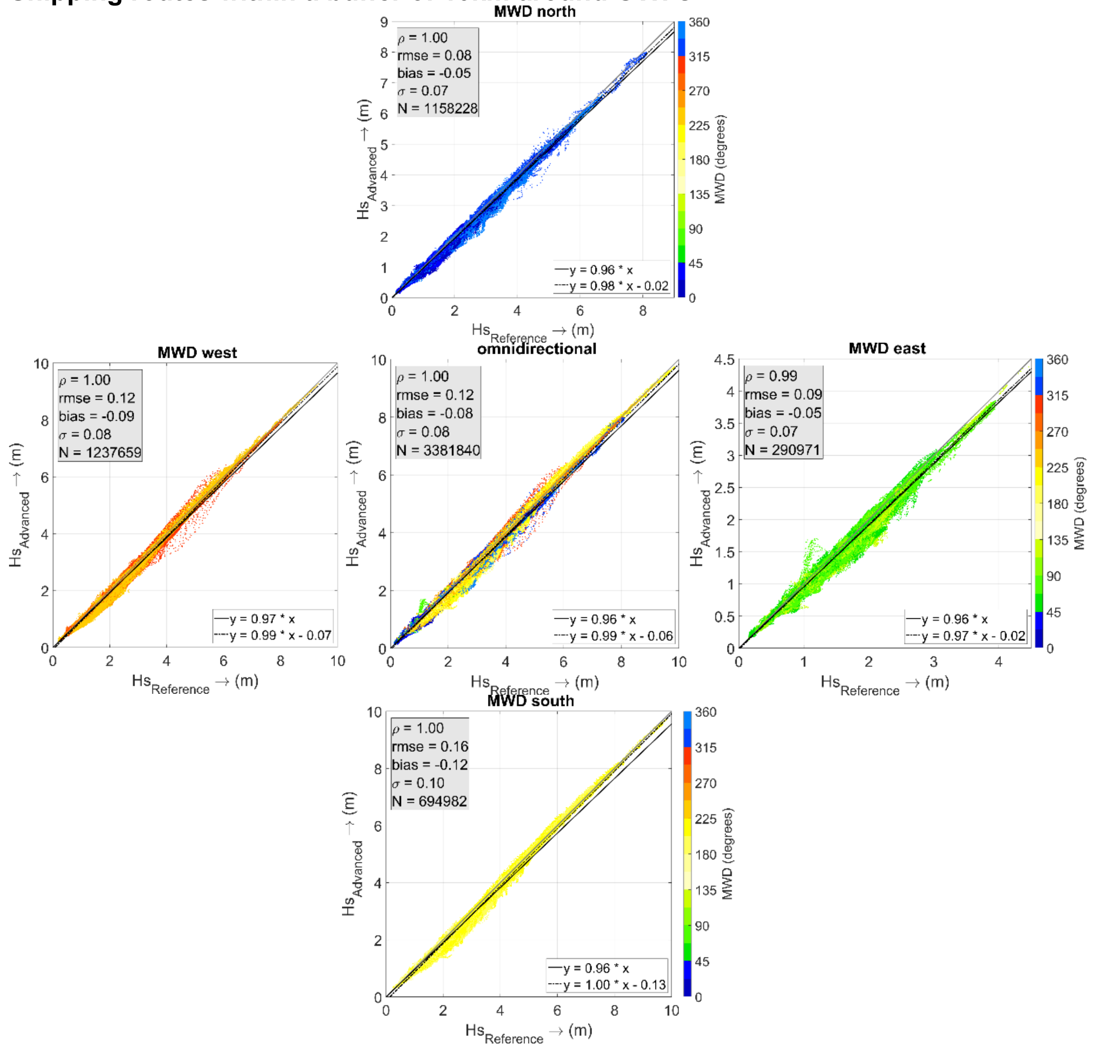

Figure 3.19 Scatter plot comparisons of significant wave height between Reference (x-axis) and Advanced (y-axis) wind schematization model results (simulation period from 01-2020 to 12-2020). The model data are colour-coded and arranged in panels based on MWD, see also Section 3.5.1.

Table 3.7 Linear statistics of significant wave height (Hs) for the "Shipping routes within a buffer of 10km around OWFs" cluster (Advanced vs Reference) for various offshore conditions.

Condition	N [-]	Bias [m]	RMSE [m]	Symmetric Slope: (Adv) = a * (Ref) [-]	(Adv) = b * (Ref) + c	
					b [-]	c [-]
Omnidirectional	3381840	-0.08	0.12	0.96	0.99	-0.06
North MWD	1158228	-0.05	0.08	0.96	0.98	-0.02
East MWD	290971	-0.05	0.09	0.96	0.97	-0.02
South MWD	694982	-0.12	0.16	0.96	1.00	-0.13
West MWD	1237659	-0.09	0.12	0.97	0.99	-0.07
Hs < 5 m	3323201	-0.08	0.12	0.96	0.98	-0.04
Hs > 5 m	58639	-0.04	0.09	0.99	1.01	-0.09
Tm-10 < 10 s	3373975	-0.08	0.12	0.96	0.99	-0.06
Tm-10 > 10 s	7865	-0.02	0.09	1.00	1.00	0.01

3.5.5 Far offshore within a buffer of 10km around OWFs

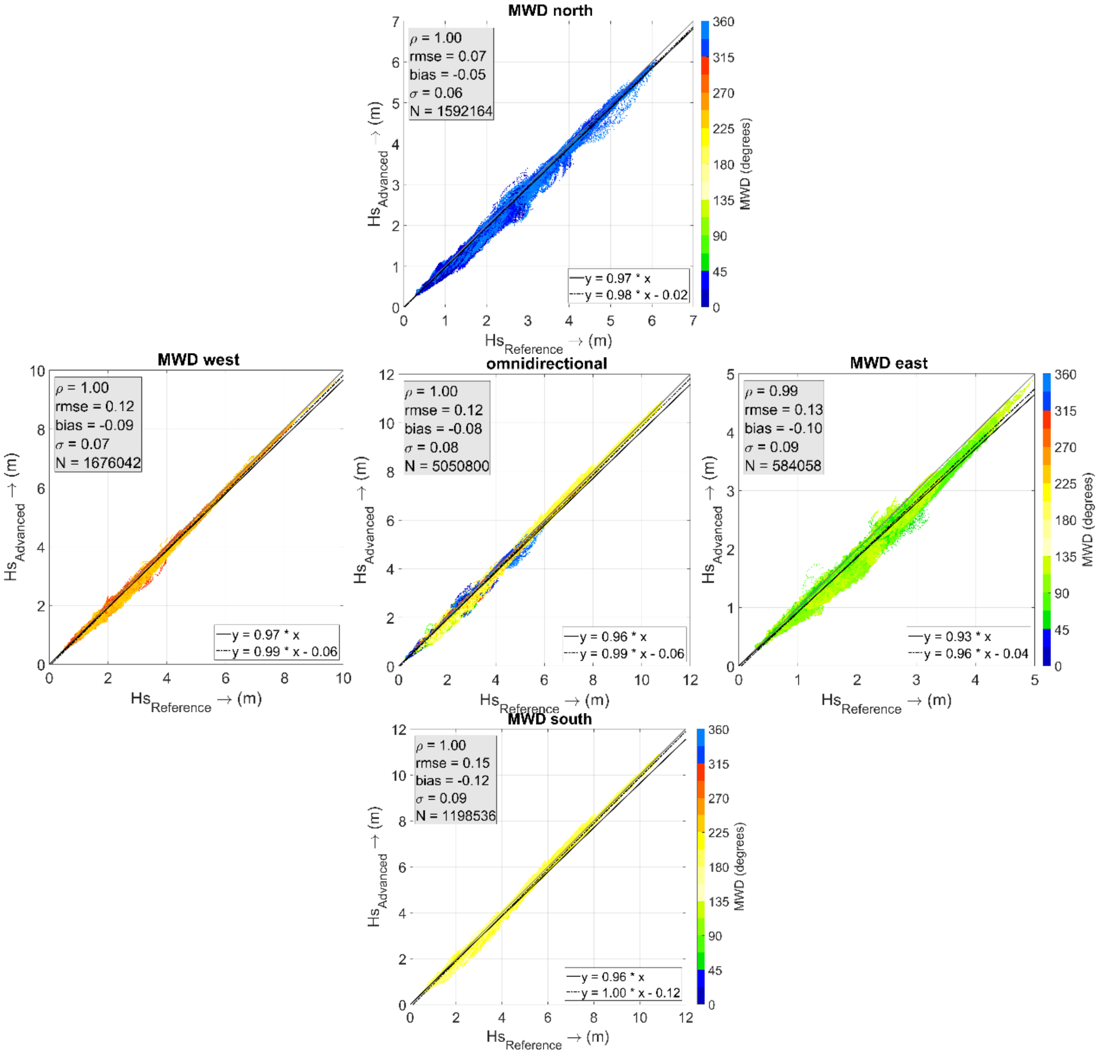

Figure 3.20 Scatter plot comparisons of significant wave height between Reference (x-axis) and Advanced (y-axis) wind schematization model results (simulation period from 01-2020 to 12-2020). The model data are colour-coded and arranged in panels based on MWD, see also Section 3.5.1.

Table 3.8 Linear statistics of significant wave height (Hs) for the “Far offshore within a buffer of 10km around OWFs” cluster (Advanced vs Reference) for various offshore conditions. N = sample size, Bias= mean(y)-mean(x), RMSE= root mean square error.

Condition	N [-]	Bias [m]	RMSE [m]	Symmetric Slope: (Adv) = a * (Ref) [-]	(Adv) = b * (Ref) + c	
					b [-]	c [-]
Omnidirectional	5050800	-0.08	0.12	0.96	0.99	-0.06
North MWD	1592164	-0.05	0.07	0.97	0.98	-0.02
East MWD	584058	-0.10	0.13	0.93	0.96	-0.04
South MWD	1198536	-0.12	0.15	0.96	1.00	-0.12
West MWD	1676042	-0.09	0.12	0.97	0.99	-0.06
Hs < 5 m	4895843	-0.08	0.12	0.96	0.97	-0.03
Hs > 5 m	154957	-0.07	0.10	0.99	1.02	-0.18
Tm-10 < 10 s	4999680	-0.08	0.12	0.96	0.99	-0.06
Tm-10 > 10 s	51120	-0.04	0.07	0.99	1.00	-0.04

3.5.6 Anchor zones

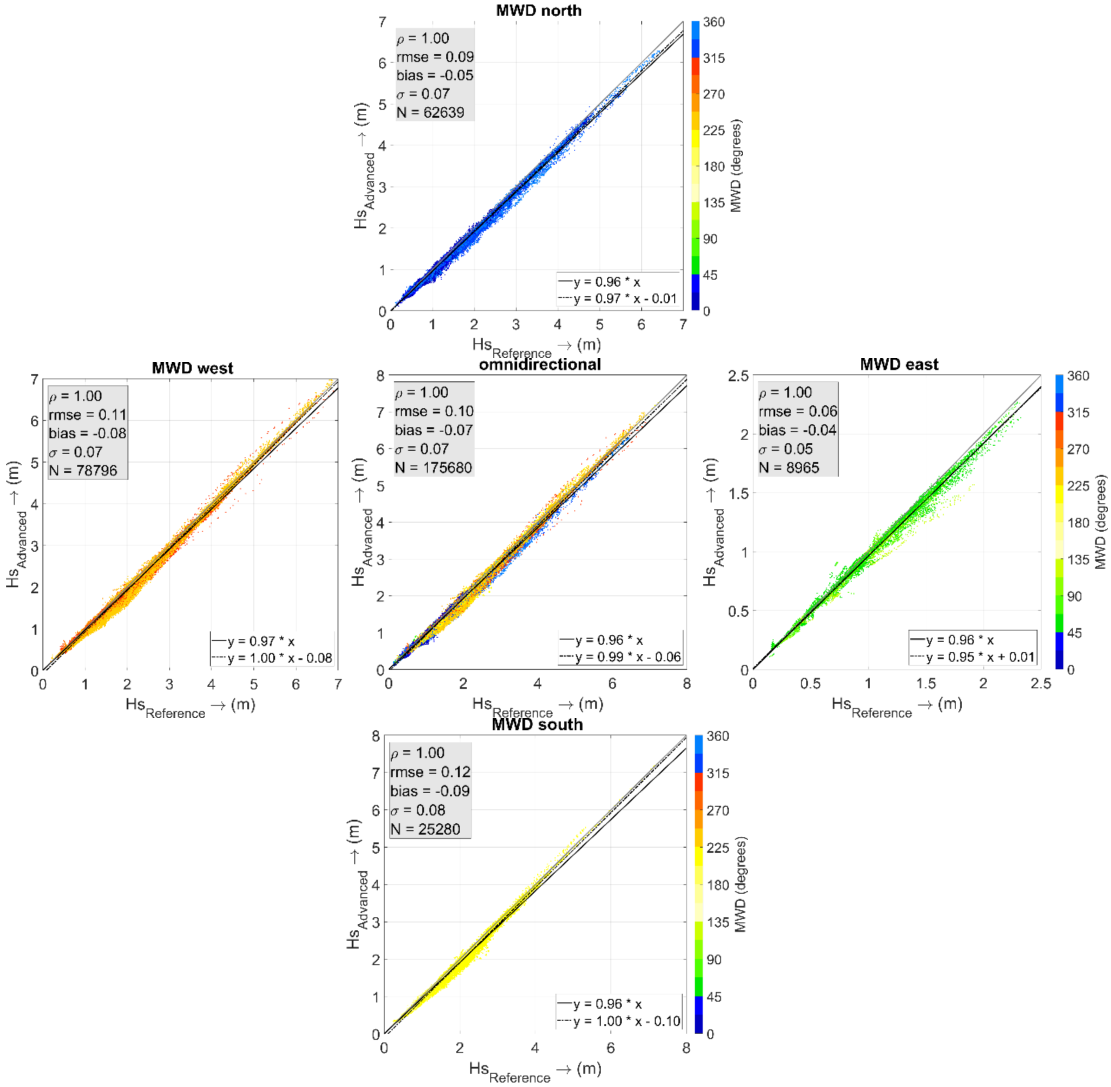

Figure 3.21 Scatter plot comparisons of significant wave height between Reference (x-axis) and Advanced (y-axis) wind schematization model results (simulation period from 01-2020 to 12-2020). The model data are colour-coded and arranged in panels based on MWD, see also Section 3.5.1.

Table 3.9 Linear statistics of significant wave height (Hs) for the "Anchor zones" cluster (Advanced vs Reference) for various offshore conditions. N = sample size, Bias= mean(y)-mean(x), RMSE= root mean square error.

Condition	N [-]	Bias [m]	RMSE [m]	Symmetric Slope: (Adv) = a * (Ref) [-]	(Adv) = b * (Ref) + c	
					b [-]	c [-]
Omnidirectional	175680	-0.07	0.10	0.96	0.99	-0.06
North MWD	62639	-0.05	0.09	0.96	0.97	-0.01
East MWD	8965	-0.04	0.06	0.96	0.95	0.01
South MWD	25280	-0.09	0.12	0.96	1.00	-0.10
West MWD	78796	-0.08	0.11	0.97	1.00	-0.08
Hs < 5 m	173521	-0.07	0.10	0.96	0.98	-0.04
Hs > 5 m	2159	-0.03	0.09	0.99	1.04	-0.26
Tm-10 < 10 s	175600	-0.07	0.10	0.96	0.99	-0.06
Tm-10 > 10 s	0	-	-	-	-	-

3.5.7 Approach areas

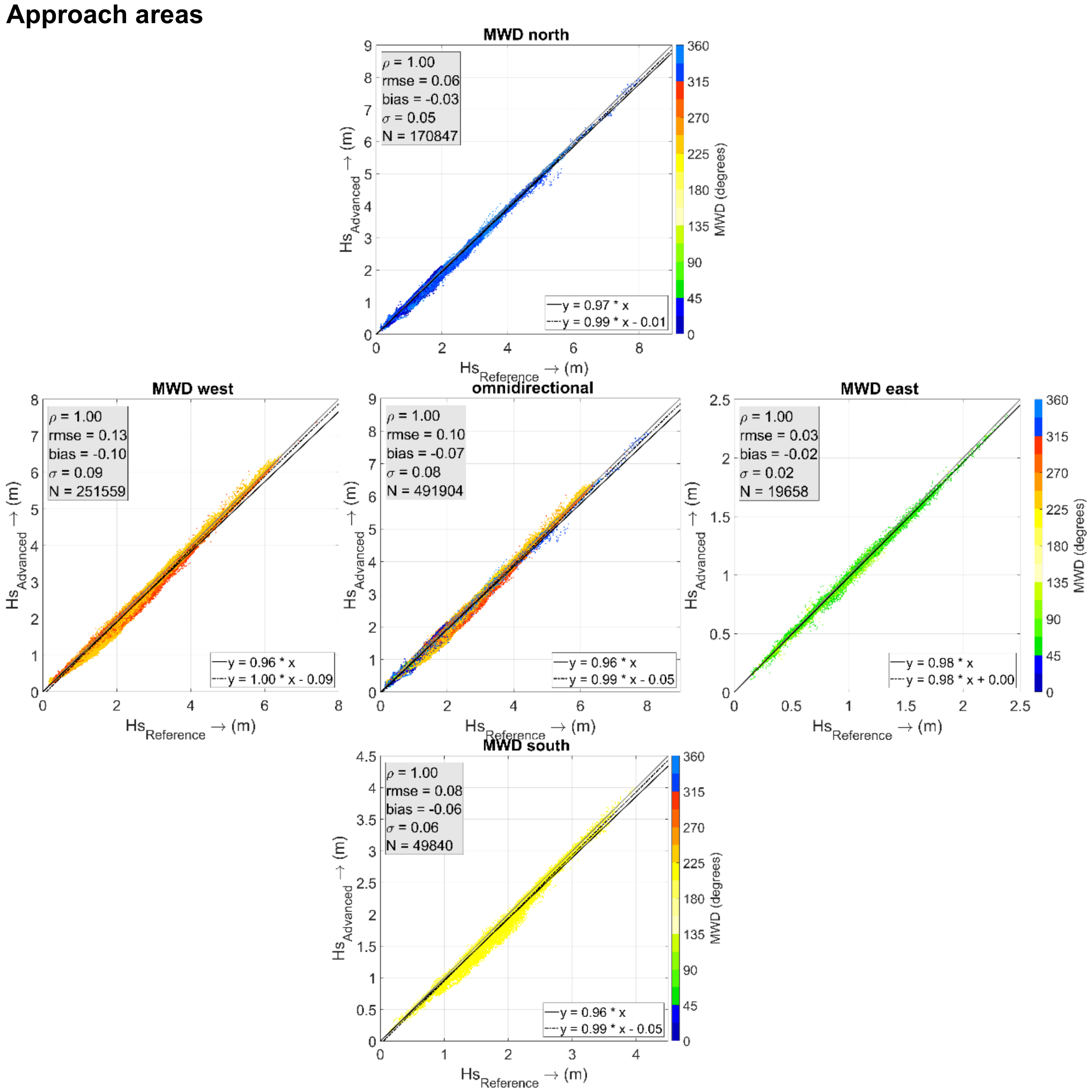

Figure 3.22 Scatter plot comparisons of significant wave height between Reference (x-axis) and Advanced (y-axis) wind schematization model results (simulation period from 01-2020 to 12-2020). The model data are colour-coded and arranged in panels based on MWD, see also Section 3.5.1.

Table 3.10 Linear statistics of significant wave height (Hs) for the "Approach areas" cluster (Advanced vs Reference) for various offshore conditions. N = sample size, Bias= mean(y)-mean(x), RMSE= root mean square error.

Condition	N [-]	Bias [m]	RMSE [m]	Symmetric Slope: (Adv) = a * (Ref) [-]	(Adv) = b * (Ref) + c	
					b [-]	c [-]
Omnidirectional	491904	-0.07	0.10	0.96	0.99	-0.05
North MWD	170847	-0.03	0.06	0.97	0.99	-0.01
East MWD	19658	-0.02	0.03	0.98	0.98	0.00
South MWD	49840	-0.06	0.08	0.96	0.99	-0.05
West MWD	251559	-0.10	0.13	0.96	1.00	-0.09
Hs < 5 m	487281	-0.07	0.10	0.96	0.98	-0.03
Hs > 5 m	4623	-0.03	0.08	0.99	1.01	-0.10
Tm-10 < 10 s	491355	-0.07	0.10	0.96	0.98	-0.04
Tm-10 > 10 s	549	-0.02	0.07	0.99	0.99	0.03

3.5.8 Discussion

The findings are largely similar between the various considered clusters of locations with minimal deviations in the order of 1% when all wave conditions are considered (e.g. see symmetric slope factor in omnidirectional data). The directional scatter plots comparing the annual wave conditions with the modelled Reference and Advanced wind schematization (Figure 3.17 to Figure 3.22), show an average 3-4% reduction in Hs for all clusters (based on the symmetric slope factor) for the north, west and south incoming mean wave sectors and 4% reduction when all data are considered (omnidirectional panel). The average reduction in Hs as a result of OWFs is more significant (e.g., reaches up to 7% within OWFs) for the less frequently occurring eastern wave conditions.

Table 3.3 to Table 3.10 summarize relevant statistics for various wave conditions comparing the annual Hs between the modelled Reference and Advanced wind schematization for the various clusters. As expected, associated wind and wave incoming directions (e.g. northern MWD and northern wind direction) show consistent effects in Hs in terms of percentage change highlighting the strong relation between these two assessed parameters.

Additionally, the more frequent and lower energy wave conditions are associated with an average reduction in Hs (4-5% for the various clusters based on the symmetric slope factor). On the contrary, less frequent high energy states can be associated with an increase(!) in significant wave heights due to the presence of OWF. See for example that the value of ‘b’ exceeds 1 so that for large values (Hs > 9 m) the wave heights from the ‘advanced’ computations are larger those from the reference computations. Navigation within OWF (for example in case of O&M) is nevertheless unlikely during such severe conditions, but similar increase in Hs is also obtained within areas of navigational interest in the vicinity of OWF, e.g. shipping routes, anchor zones and approach channels within a rough distance of 10km from OWF boundaries. This difference likely stems from the relative importance of mixing and extraction of momentum which varies depending the atmospheric conditions. It is noted that in the North Sea for less frequent stable conditions, generally associated with higher wind speeds, mixing from rotating blades may lead to an increase of wind speeds near the sea surface, as visible for example in Figure 3.12.

As expected, a larger average reduction in Hs due to the OWF is seen for lower mean absolute wave periods associated with wind sea state as opposed to higher mean absolute wave periods associated with swell. Finally, Table 3.4 and Table 3.5 show that changes in both mean absolute wave period (in the order of 1% for Tm-10) and mean wave directions (RMSE mostly less than 10 degrees for MWD) are negligible for locations within the OWFs, as already indicated in Section 3.4. This is the case for all analysed clusters of locations.

Table 3.11 to Table 3.14 summarize relevant statistical comparisons of Hs, Tm-1,0 and MWD over the various clusters for a number of relevant conditions.

Table 3.11 Omnidirectional statistics of Hs (Reference versus Advanced wind schematization). Bias defined as Y-X so a positive bias implies increased wave heights due to the OWF.

Cluster	N [-]	Bias [m]	RMSE [m]	SS: (Adv) = a * (Ref) [-]	(Adv) = b * (Ref) + c	
					b [-]	c [-]
Dutch OWFs	6289344	-0.09	0.13	0.96	0.99	-0.08
Surrounding OWFs	11928672	-0.08	0.12	0.96	0.99	-0.06
Shipping routes	3381840	-0.08	0.12	0.96	0.99	-0.06
Far offshore shipping routes	5050800	-0.08	0.12	0.96	0.99	-0.06
Anchor zones	175680	-0.07	0.10	0.96	0.99	-0.06
Approach areas	491904	-0.07	0.10	0.96	0.99	-0.05

Table 3.12 Omnidirectional statistics of Hs (Reference versus Advanced wind schematization) for Hs > 5m.

Cluster	N [-]	Bias [m]	RMSE [m]	SS: (Adv) = a * (Ref) [-]	(Adv) = b * (Ref) + c	
					b [-]	c [-]
Dutch OWFs	151196	-0.05	0.10	0.99	1.02	-0.18
Surrounding OWFs	269048	-0.05	0.10	0.99	1.02	-0.15
Shipping routes	58639	-0.04	0.09	0.99	1.01	-0.09
Far offshore shipping routes	154957	-0.07	0.10	0.99	1.02	-0.18
Anchor zones	2159	-0.03	0.09	0.99	1.04	-0.26
Approach areas	4623	-0.03	0.08	0.99	1.01	-0.10

Table 3.13 Omnidirectional statistics of Tm-10 (Reference versus Advanced wind schematization).

Cluster	N [-]	Bias [s]	RMSE [s]	SS: (Adv) = a * (Ref) [-]	(Adv) = b * (Ref) + c	
					b [-]	c [-]
Dutch OWFs	6289344	0.01	0.14	1.00	1.00	-0.01
Surrounding OWFs	11928672	-0.01	0.14	1.00	1.01	-0.06
Shipping routes	3381840	-0.02	0.13	1.00	1.01	-0.05
Far offshore shipping routes	5050800	-0.01	0.14	1.00	1.01	-0.08
Anchor zones	175680	-0.03	0.13	0.99	1.01	-0.07
Approach areas	491904	-0.03	0.14	0.99	1.00	-0.03

Table 3.14 Omnidirectional statistics of MWD (Reference versus Advanced wind schematization).

Cluster	N [-]	Bias [deg]	RMSE [degg]	Std [deg]
Dutch OWFs	6289344	-0.17	7.62	4.26
Surrounding OWFs	11928672	-0.38	6.92	3.73
Shipping routes	3381840	-0.26	6.92	3.36
Far offshore shipping routes	5050800	-0.54	6.63	4.33
Anchor zones	175680	-0.07	6.33	2.94
Approach areas	491904	-0.03	5.62	2.76

3.6 Conclusions

To assess the effect of OWF on waves we analysed the North Sea wave model results available from the WOZEP project. The simulations cover the conditions of the year 2020, in three variants: One without any OWF (reference) and two with the hypothetical OWF for layout for 2050. Of these two, one is the 'basic' approach in which the wind in the OWF is just locally reduced by 10%, whereas the 'advanced' approach includes the 2020 wind forcing with the effects of an hypothetical OWF layout for 2050. First, we analysed for a few specific moments the spatial effects of the OWF on the waves for more or less the entire Dutch North Sea domain. Next, we considered for just a few locations the waves during the entire period by assessing statistical measures. The statistics were computed for various selections of locations and wave directions. From these model simulations we conclude the following:

- The effect of OWFs - through modelled influences on wind fields (and hence wave growth) – on the overall wave patterns at the spatial scale of Dutch EEZ is very small. They are only found to affect waves and hence eventually navigation conditions in their close vicinity.
- Based on the map-difference plots, the difference between the significant wave height with and without OWFs is mostly small (a reduction <0.1 m). The effects tend to reach over some 10ths of kilometers. However, locally instantaneous differences can reach 0.3 m, both positive and negative (see Figure 3.9 and Figure 3.12). During a longer modelling period more extreme effects may occur. It is unlikely that these effects introduce risks for shipping safety, but it is advised to asses to what extend the exceedance of critical threshold values changes, not only for shipping but also for search-and-rescue helicopter operations.
- The change in mean absolute wave period and mean wave direction is negligible at the scale of the OWF.
- Hs in the vicinity of OWFs can either decrease or increase due to OWFs based on the relative importance of wind field mixing by the rotating blades and extraction of momentum which differs based on the atmospheric stability.
- From a modelling perspective, the Advanced wind schematization appears to be (and with lacking validation data) more appropriate in capturing the actual wind and hence wave fields especially when stable atmospheric conditions (mixing of wind speeds vertically) and wake effects outside OWFs are considered. For this study only one year of wind fields was available. The Basic wind schematization can nevertheless be applied for longer simulations and hence produce longer datasets that increase confidence in statistical parameters describing OWF effects on wave conditions and shipping but requires further parameterization of mixing and developing wakes outside OWFs.

From the statistical analysis, the following conclusions are drawn:

- A reduction of 4% (based on symmetric slope factor) in Hs is observed inside OWFs as well as in areas of navigational interest in the vicinity (within roughly 10km) of OWFs such as shipping routes, anchor zones and approach channels. This suggests a more linear as opposed to a quadratic relation between wind and wave growth in OWFs as modelled here for the Dutch North Sea, given that wind speeds reduction is roughly in the order of 10% in the same areas. Larger reductions are only observed for the less frequently occurring east incoming wave directions.
- The significant wave height is likely to increase in the vicinity of OWFs but only during highly energetic offshore conditions which need to be assessed further because this condition is most relevant for shipping safety in the Dutch North Sea. This is likely correlated to stable atmospheric conditions and associated mixing of wind speeds due to rotating blades.
- For the modelled conditions (the year 2020) the average difference between the significant wave height with and without OWFs is small (just a few percent) but instantaneous differences can easily reach 0.5 m, both positive and negative (see the scatter plots in Figure 3.17 to Figure 3.22). During a longer modelling period more extreme effects may occur. The change in mean absolute wave period is negligible at the scale of the OWF.

4 Effect of OWF on hydrodynamics

4.1 Introduction

The offshore wind farms (OWF) not only affect wind and wave conditions but also the hydrodynamic conditions. Offshore wind farms, as it has been shown by previous research (Chapter 2.3), may have significant effect on the hydrodynamic parameters through several ways. Hydrodynamic conditions, are in its turn, is essential for safe and efficient navigation, as they directly impact vessel maneuvering capabilities, route planning, and general safety. Some of the most relevant hydrodynamic parameters affected include:

1. Current Velocity and Direction

- **Importance:** Strong currents can affect a vessel's trajectory, drift, and fuel efficiency. Understanding current velocity is crucial for maintaining accurate course plotting and for deciding on optimal shipping routes.
- **Relevance:** Coastal navigation, especially near estuaries, where tidal currents can be intense and variable.

2. Sea Level and Surge

- **Importance:** Abnormal sea levels can cause flooding in ports and change navigable depths. Storm surges, in particular, are dangerous during severe weather events.
- **Relevance:** Coastal navigation and port operations, vessel grounding.

3. Salinity and Density Variations

- **Importance:** Changes in salinity and density can affect buoyancy, draft, and ship stability. In extreme cases, such as transitioning between freshwater and saltwater (e.g., river mouths), these variations require careful trim adjustments.
- **Relevance:** Relevant for large vessels and submarines where buoyancy control is crucial.

4. Turbulence and Wake Effects

- **Importance:** Turbulence can disrupt vessel control, especially for small boats in the vicinity of large ships or offshore structures. Wakes can cause unexpected accelerations and impact stability.
- **Relevance:** Navigation near wind farms, bridges, and in busy waterways with significant vessel traffic.

5. Vertical Current Shear

- **Importance:** Vertical current shear can cause significant forces on a ship's hull, affecting steering and stability, particularly for vessels operating in deep channels or during submergence and emergence maneuvers.
- **Relevance:** Important for deep-draft vessels and submarines.

The main point of attention for navigation in relation to the potential effects imposed by OWF operation lies in the spatial or temporal changes of current velocity including both its magnitude and direction. Changes in water level may also affect the shipping safety especially closer to the coast where there is an increased danger of ship grounding.

In this chapter, we analyse model results generated using meteorological forcing that includes elaborate OWF effects on the atmospheric parameters. Those models were created for the WOZEP research programme that focused on ecological impact of OWFs and, therefore, were not optimised for the study related to navigation safety. The aim of this analysis is to assess potential impacts from OWF operation on navigation and shipping safety-based changes in hydrodynamic parameters in the southern North Sea.

4.2 Hydrodynamics computations from WOZEP

This study uses the results from the recent hydrodynamic modelling performed for WOZEP research program with the use of the extensively calibrated 3D Dutch Continental Shelf Model – Flexible Mesh (3D DCSM-FM) model. For more information regarding the set-up of the numerical model, the reader is referred to the Zijl et al. (2023, 2024) reports. Similarly to the wave part of this study, the effects of OWFs on hydrodynamics are assessed based on results from simulations performed in the WOZEP study on wind wakes effects (Zijl and Leummens, 2024), but only considering two of the simulations. In terminology established in Section 3.2, these are:

- A "reference" simulation: hindcast of the 2020 year, where no effects from OWFs are included;
- An "advanced" wind schematization of the OWF effects: in which the effects of the hypothetical OWFs by 2050 are captured by the physically-based simulated wind fields of the year 2020 (involving extraction of momentum, mixing and blockage) from the WINS50 dataset by KNMI, thus additionally including the wake effects of OWFs.

The advanced simulation uses the reference 2020 hindcast model as a basis. This means that all other forcings, numerical settings and boundary conditions are identical to those employed in the reference simulation. Consequently, by comparing the model results of both simulations only the effect of the varied wind input is assessed.

In order to learn more about the WINS50 dataset and the extent to which using physically-based OWF effects in atmospheric forcing affects the hydrodynamic modelling results, the reader is referred to Zijl and Leummens (2024).

Note that OWF not only affect the hydrodynamics due to the wind but also because of the drag of the pile. The OWF piles are represented in the 3D DCSM-FM model as vegetation fields with a certain stem density, diameter and infinite stem height. In this parameterisation, the piles cause a sink of momentum leading to a local reduction in the current. The extracted momentum loss is released as an increased level of turbulent kinetic energy. This method is similar to the parameterization used to include the effect of monopiles in the wind model.

4.3 Approach

We assess the influence of OWFs on water level and current velocity magnitude and direction. Time series at several prescribed locations in the North Sea with 10-minute resolution as well as hourly spatial values on grid points are available for these parameters for both simulations performed with the 3D DCSM-FM model. It should be noted that, while there are other hydrodynamic parameters and combinations thereof that may be important for nautical safety, these were not considered at this phase of the project due to time constrains and restrictions with available modelling data.

First we focus on the spatial effects of the OWF on hydrodynamics (Section 4.4) for a few moments in time.

Next, we perform a statistical analysis to quantify the effects of the OWF for the full modelled period of one year for various locations within the Dutch part of the North Sea. For this we selected locations within and near offshore wind farms, shipping routes, clearways, anchor zones and separation zones. In the statistical analysis we discriminate in wind direction and locations.

4.4 Spatial effects of OWF on surface currents

Spatial model output from the WOZEP research consists of hourly three-dimensional values of hydrodynamic parameters as water level, current velocity, salinity, and temperature. For this study, maps of instantaneous surface current velocity differences between model results with and without OWF effect were created and assessed.

In general, the spatial pattern of differences in current velocity replicates those of the wind itself to a high extent. It is important to note that the WINS50 dataset does not only incorporate the effect of offshore windfarms, but also of windfarms on land including their wakes as well. Consequently, some of the changes in hydrodynamic parameters are caused by the effects of windfarms on shore.

In this chapter we present just a few examples of the spatial differences patterns during the characteristic wind conditions presented in Figure 4.1. Those moments were chosen to cover a representative range of conditions considering wind speed and direction variation. Although tidal currents are included in the model, they are not considered in the selection of moments.

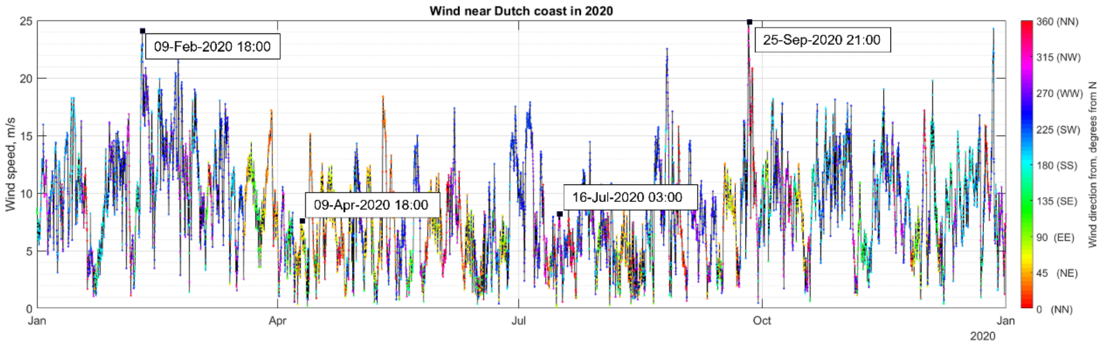

Figure 4.1 Wind conditions near the Dutch coast according to WINS50 control (no OWFs) dataset

The plots of spatial differences (Figure 4.2) show that the type of effects caused by OWF differs depending on atmospheric conditions (atmospheric stability, wind speed, etc.). The absolute values of current speed as well as current direction are highly dependent on the tide as the main driving force in the North Sea. Therefore, patterns presented in spatial difference plots are also a product of a tidal phase and tidal currents in general. It should be noted also that the model uses an additional drag formulation as a method for OWF pile parametrisation. However, as the study aims at assessing surface currents, this effect is small in comparison to the effect of the changes in the wind field.

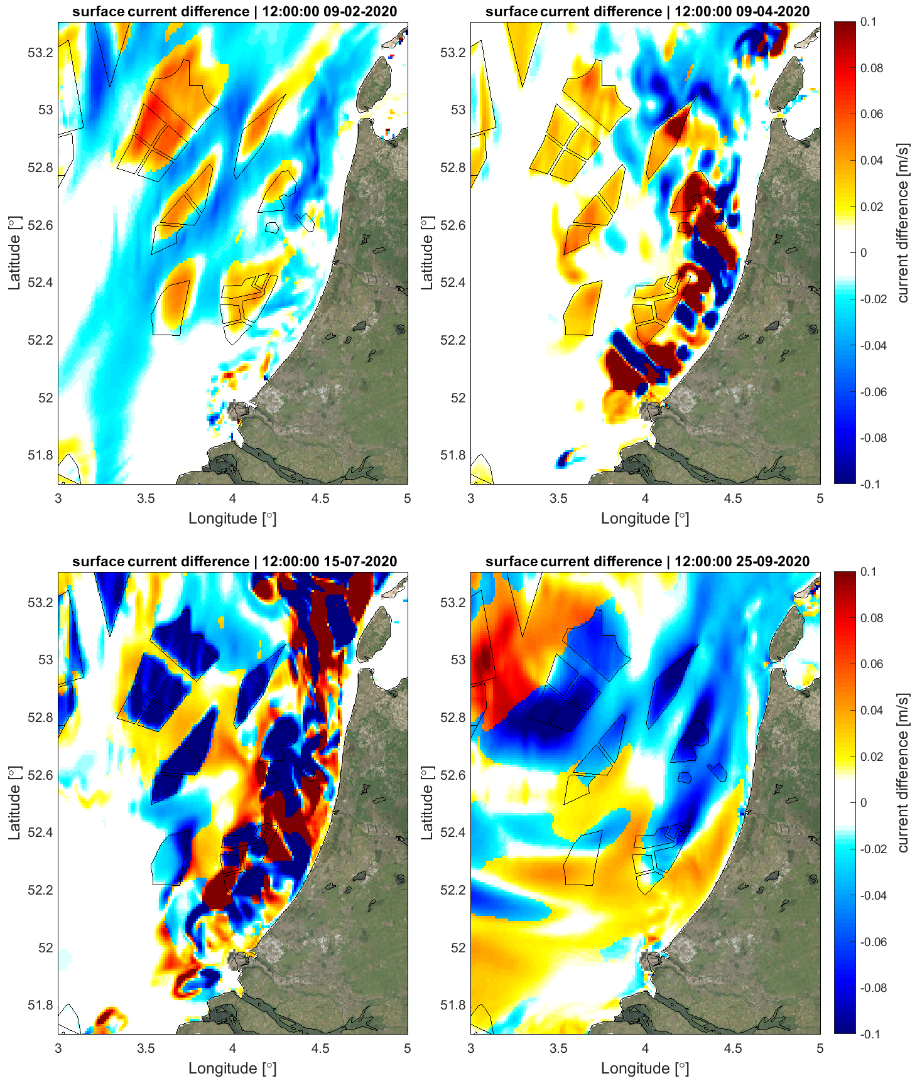

Figure 4.2 Example spatial differences (Adv-Ref) in instantaneous surface current velocity due to OWF effect.

The difference plots unwind one of the misconceptions about the effect of wind turbines on the wind speed (and thus hydrodynamic parameters). It is commonly considered that OWF presence can only reduce the wind speed by absorbing its energy. While this is true in general, there could be some variations in how these effects are constituting themselves in a vertical profile. As such, under stable atmospheric conditions the turbulence due to the turbines leads to an increase in the surface wind speeds. This phenomenon is visible in plots for February 9th and April 9th 2020 where we see an increase in surface current speed (orange colours).

From those plots we also see that the wake effects are stronger during high wind speed periods (February 9th and September 25th 2020), as expected. The wakes at September 25th 2020 are visibly larger, which is most likely related to more unstable atmospheric conditions on the date.

On plots for April 9th and July 15th the larger differences are visible near the coast. That is related to aforementioned effect from the land windfarms and is apparently more profound with lower wind speeds.

4.5 Statistical analysis

4.5.1 Introduction

In this section, the effects of OWFs on the hydrodynamics are analysed in terms of statistical parameters for a few selected locations. Hereto the hydrodynamic model results covering the year 2020 from runs with (the hypothetical 2050 scenario) and without OWF are compared to each other. As opposed to the instantaneous comparisons of hydrodynamic parameters in the previous section, the statistical comparisons reflect the entire modelled one year period.

We selected several output locations of which six on a cross shore ray ('Walcheren ray') passing through the Borssele OWF: Location WALCRN30 is within the OWF, some 30 km offshore and the WALCRN locations with higher numbers are further offshore (WALCRN50 and 70), and with smaller numbers (20, 10, 2) are closer to the coast. This way, we can couple the effects to the distance from the wind farm (see Section 4.5.2).

In order to couple the effects of the OWF to the position relative to the OWF, we defined output locations around location NOORDWK30 in the Hollandse Kust Zuid OWF. These stations (and there position relative to NOORDWK30) are NOORDWK50 (NW), IJGL_MP19 (East), NOORDWK4 (SE), STRAINS_M18 (South), and LICHTELGRE (SW). They are considered as relatively equidistant to the OWF station and located in different direction sectors (Figure 4.3).

Furthermore, we selected locations within shipping routes, clearways, anchor zones and separation zones. For this we used the 2050 OWF scenario in conjunction with the GIS navigation data obtained from Rijkswaterstaat Dataregister WFS[4]. The overview of studied location is presented in Figure 4.3.

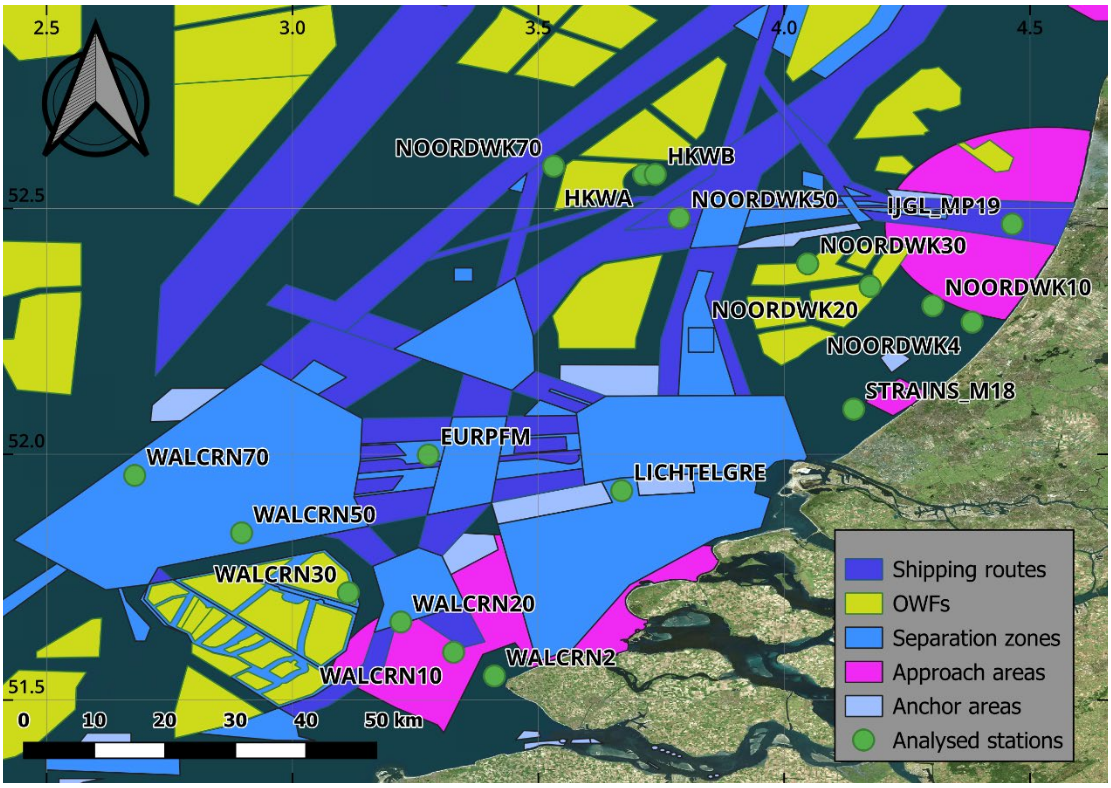

Figure 4.3 Stations analysed for OWF effect on hydrodynamic parameters.

[4] geo.rijkswaterstaat.nl/services/ogc/gdr/verkeersscheidingsstelsel_nz/ows?version=2.0.0

The variation in wind conditions was also considered through segmentation of available data in accordance with predominant wind direction near the Dutch coast. In this study eight sectors representing different wind directions were considered (Table 4.1) as well as the omnidirectional data.

Table 4.1 Definition of 8 directional sectors

Sector	ID	Condition
From North	NN	315° < Wind direction from ≤ 45°
From North-East	NE	0° < Wind direction from ≤ 90°
From East	EE	45° < Wind direction from ≤ 135°
From South-East	SE	90° < Wind direction from ≤ 180°
From South	SS	135° < Wind direction from ≤ 225°
From South-West	SW	180° < Wind direction from ≤ 270°
From West	WW	225° < Wind direction from ≤ 315°
From North-West	NW	270° < Wind direction from ≤ 360°

The statistical parameters for all the stations, parameters and wind conditions are reported in Appendix C.

4.5.2 OWF effects in relation to distance

To assess how the effect of OWFs changes as the distance to the OWF increases, the six output locations at ray Walcheren – with WALCRN30 in the OWF more or less in the middle - are considered. Table 4.2 – Table 4.4 present the statistical correlation metrics between Reference and Advanced scenarios for water level, surface current velocity and direction.

The average reduction in water level caused by the OWF is small (~1%) and spatially uniform, see Table 4.2. This was also reported by the WoZEP study, as the observed annual tidal amplitude changes are rather uniform for the Dutch coast and more prominent in the German Bight and near the English Channel (Zijl and Leummens, 2024), see also Figure A.3 in Appendix A for the effect on the M2 tidal component. Because of the very small effect on water levels, this parameter is not further analysed in this study (see Appendix C for the tables with statistics).

Table 4.2 Omnidirectional-wind statistics of water level (Reference (X) versus Advanced (Y) schematization); bias defined as Y-X so a positive bias implies increased water levels due to the OWF.

Station	Dist. from OWF [km]	Bias [m]	STD [m]	RMSE [m]	(Adv) = a * (Ref)	(Adv) = b * (Ref) + c	
					a [-]	b [-]	c [-]
WALCRN2	38 (SE)	0.00	0.01	0.01	0.99	0.99	0.00
WALCRN10	27 (SE)	0.00	0.01	0.01	0.99	0.99	0.00
WALCRN20	14 (SE)	0.00	0.01	0.01	0.99	0.99	0.00
WALCRN30	-	0.00	0.01	0.01	0.99	0.99	0.00
WALCRN50	27 (NW)	0.00	0.01	0.01	0.99	0.99	0.00
WALCRN70	55 (NW)	0.00	0.01	0.01	0.99	0.99	0.00

Surface current velocities, in their turn, are more susceptible to the effect of OWFs on a local level. In the omnidirectional analysis, we see on average a 4-6% drop in current velocity within windfarms limits (WALCRN30 considering slope a=0.96 and b=0.94). We consider these a and b values since they are relative values, whereas the bias is absolute. Note that these bulk parameters indicate the average effect whereas individual moments or locations can also end up with larger flow velocities due to the OWF. The effects outside of the OWFs are ~1% (a and b being 0.99 and 1.00) and are limited to south-easterly direction from the windfarm in question. This is related to the regional wind climate where westerly winds are predominant over other directions. In order to see this we have separately considered NW and SE wind conditions in the calculation of the OWF effect (Table 4.5, Table 4.6; Table 4.7 and Table 4.8).

Table 4.3 Omnidirectional-wind statistics of current magnitude (Reference (X) versus Advanced (Y) scheme) bias defined as Y-X so a positive bias implies increased flow velocity due to the OWF.

Station	Dist. from OWF [km]	Bias [m/s]	STD [m/s]	RMSE [m/s]	(Adv) = a * (Ref)	(Adv) = b * (Ref) + c	
					a [-]	b [-]	c [-]
WALCRN2	38 (SE)	0.00	0.01	0.01	1.00	1.00	0.00
WALCRN10	27 (SE)	-0.00	0.01	0.01	1.00	0.99	0.00
WALCRN20	14 (SE)	-0.00	0.03	0.03	0.99	0.99	0.00
WALCRN30	-	-0.02	0.04	0.05	0.96	0.94	0.02
WALCRN50	27 (NW)	-0.00	0.01	0.01	1.00	1.00	-0.00
WALCRN70	55 (NW)	-0.00	0.01	0.01	1.00	1.00	-0.00

The effect of the OWF on current directions is rather broad, affecting in either direction (clock wise or anti clockwise), visible in high values of standard deviation and root mean squared error (RMSE), see Table 4.4. On average, the RMSE reaches up to 8°at location WALCRN30 within the OWF and gradually reduces to 2° on a distance of 50 km from the OWF (locations WALCRN2 and WALCRN70). Note that in general the tide causes a temporal and spatial variation in flow direction and therefore it is not surprising that the effect with OWF is also not very homogeneous.

Table 4.4 Omnidirectional-wind statistics of current direction (Reference (X) versus Advanced (Y) scheme)

Station	Dist. from OWF [km]	Bias [deg.]	STD [deg.]	RMSE [deg.]	(Adv) = a * (Ref)
					a [-]
WALCRN2	38 (SE)	0.10	1.47	1.82	1.00
WALCRN10	27 (SE)	0.21	1.67	2.76	1.00
WALCRN20	14 (SE)	-0.03	7.86	6.63	1.00
WALCRN30	-	-1.06	8.14	8.30	1.00
WALCRN50	27 (NW)	0.19	3.23	2.70	1.00
WALCRN70	55 (NW)	0.13	1.57	2.25	1.00

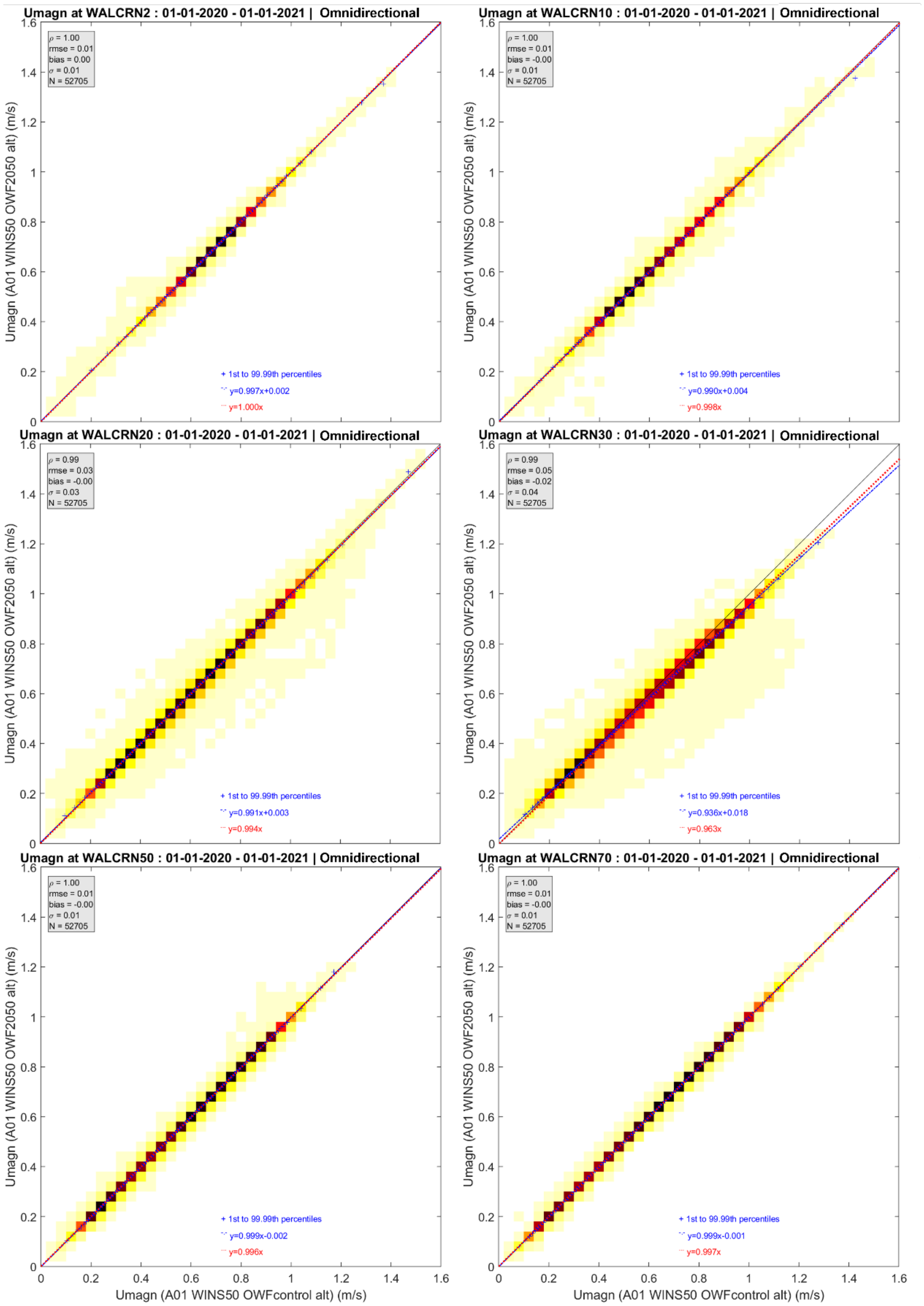

Figure 4.4 Scatter plots of surface current velocity according to Reference (X; WINS50 OWF control) and Advanced (Y; WINS50 OWF2050) scenarios at WALCRN stations with omnidirectional wind.

The scatter plots of surface current velocity with and without OWF show a picture similar to what was presented in Table 4.3. However, from the scatter plots we see that there is quite some spread in the results indicating that the OWF not only cause a reduction in flow velocity but sometimes also an increase for certain locations and conditions. This spread is larger at

WALCRN30 and for the locations closer to the coast (WALCRN2 – 20) than for the offshore WALCRN locations. While considering the average effects as irrelevant for larger vessels, smaller boats could be affected by this new spread of approximately 0.1 - 0.3 m/s as somewhat substantial.

Considering just omnidirectional wind may introduce some sort of averaging of the actual instantaneous changes happening due to OWF. Table 4.5 – Table 4.6 show statistical metrics of differences in surface current between Reference and Advanced scenarios for the wind coming from the North-West.

In case of those particular NW wind conditions the wake effect of the windfarm reaches further down the stream. However, the relative average current velocity reduction still stays on the same value of ~1%. A similar effect is observed for current directions, the wake to the South-East of the studied wind farm is strengthened with an increase of RMSE from 2 to 3°.

Table 4.5 Wind-from-NW-statistics of current magnitude (Reference (X) without OFW versus Advanced OWF (Y)).

Station	Dist. from OWF [km]	Bias [m/s]	STD [m/s]	RMSE [m/s]	(Adv) = a * (Ref)	(Adv) = b * (Ref) + c	
					a [-]	b [-]	c [-]
WALCRN2	38 (SE)	0.00	0.02	0.02	1.00	0.99	0.01
WALCRN10	27 (SE)	-0.00	0.02	0.02	1.00	0.99	0.01
WALCRN20	14 (SE)	-0.00	0.02	0.02	1.00	0.99	0.00
WALCRN30	-	-0.02	0.03	0.03	0.97	0.95	0.01
WALCRN50	27 (NW)	-0.00	0.01	0.01	1.00	1.00	-0.00
WALCRN70	55 (NW)	-0.00	0.01	0.01	1.00	1.00	-0.00

Table 4.6 Wind-from-NW-statistics of current direction (Reference (X) without OFW versus Advanced OWF (Y)).

Station	Dist. from OWF [km]	Bias [deg.]	STD [deg.]	RMSE [deg.]	(Adv) = a * (Ref)
					a [-]
WALCRN2	38 (SE)	-0.07	3.63	3.18	1.00
WALCRN10	27 (SE)	0.19	8.68	3.38	1.00
WALCRN20	14 (SE)	-0.04	11.41	5.37	1.00
WALCRN30	-	-0.97	10.18	7.71	1.00
WALCRN50	27 (NW)	0.21	6.05	1.99	1.00
WALCRN70	55 (NW)	0.15	3.46	2.54	1.00

When considering only these NW winds, the scatter in the current velocity effects is obviously less (Figure 4.5) as the main source of variety here is apparently the wind direction.

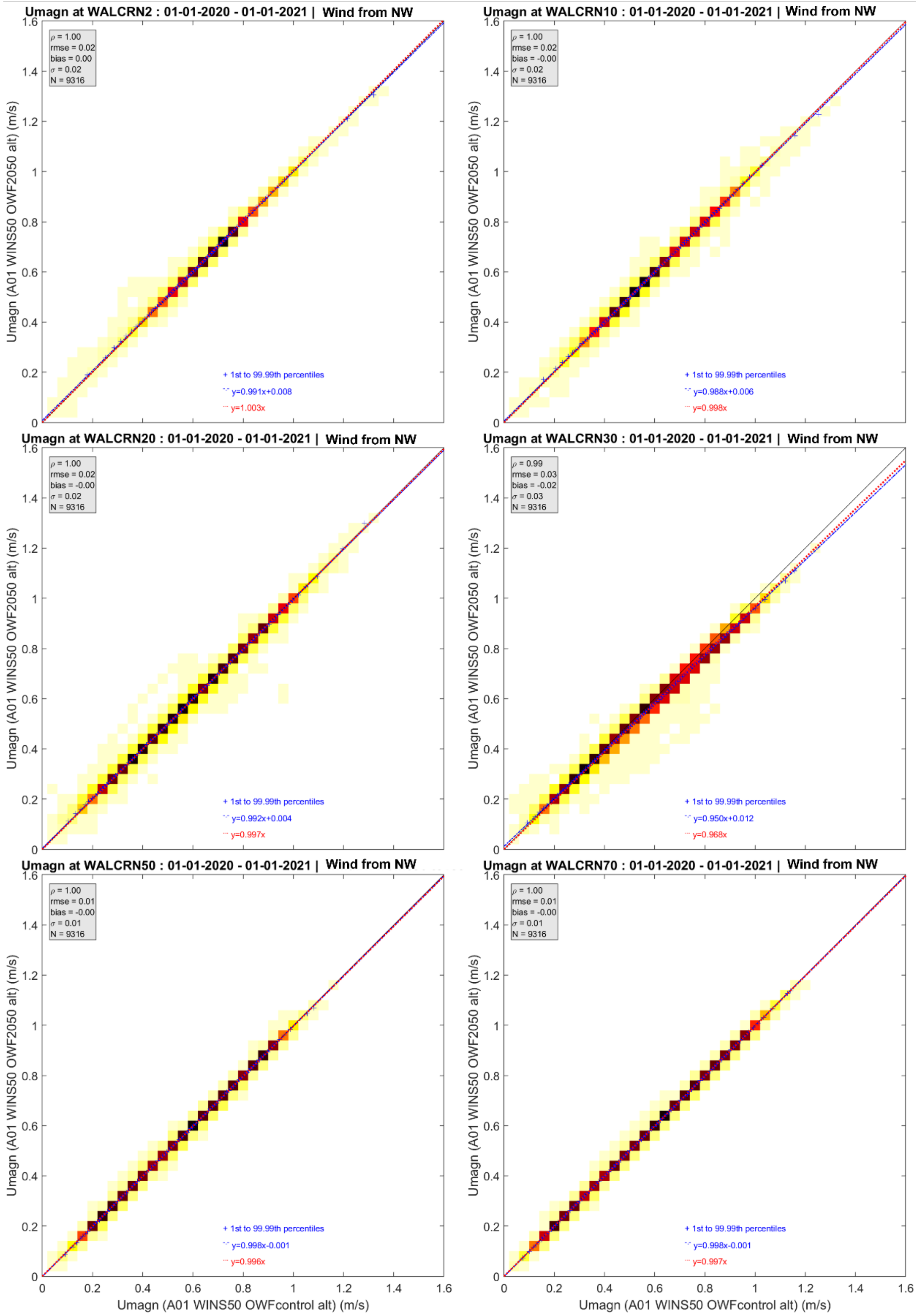

Figure 4.5 Scatter plots of surface current velocity according to Reference (X; WINS50 OWF control) and Advanced (Y; WINS50 OWF2050) scenarios at WALCRN stations with the wind coming from North-West.

Looking at the opposite wind direction (wind coming from South-East), we even see a slight increase of ~1% on average in the upwind side of the OWF (Table 4.7). This is most likely related to the kind of atmospheric conditions that occur in combination with relatively rare south-easterly wind. This includes both relatively lower wind speed for the wind of this direction in the region and possible differences in atmospheric stability.

The effect of the OWF on current direction in those conditions is more widely spread in the near vicinity of the OWF from the upwind side but less uncertain further away (Table 4.8).

Table 4.7 Wind from SE statistics of current magnitude (Reference versus Advanced schematization).

Station	Dist. from OWF [km]	Bias [m/s]	STD [m/s]	RMSE [m/s]	(Adv) = a * (Ref)	(Adv) = b * (Ref) + c	
					a [-]	b [-]	c [-]
WALCRN2	38 (SE)	-0.00	0.01	0.01	1.00	1.01	-0.00
WALCRN10	27 (SE)	-0.00	0.01	0.01	1.00	1.01	-0.01
WALCRN20	14 (SE)	-0.00	0.03	0.03	1.00	1.00	-0.00
WALCRN30	-	-0.02	0.06	0.06	0.96	0.93	0.02
WALCRN50	27 (NW)	-0.00	0.02	0.02	0.99	1.00	-0.00
WALCRN70	55 (NW)	-0.00	0.01	0.01	1.00	1.00	-0.00

Table 4.8 Wind from SE statistics of current direction (Reference versus Advanced schematization).

Station	Dist. from OWF [km]	Bias [deg.]	STD [deg.]	RMSE [deg.]	(Adv) = a * (Ref)
					a [-]
WALCRN2	38 (SE)	0.18	0.76	0.57	1.00
WALCRN10	27 (SE)	0.23	2.21	3.17	1.00
WALCRN20	14 (SE)	0.15	1.99	6.28	1.00
WALCRN30	-	-1.53	2.96	10.05	1.00
WALCRN50	27 (NW)	0.20	18.02	2.54	1.00
WALCRN70	55 (NW)	0.10	2.37	1.93	1.00

Figure 4.6 presents the average effect of the OWF (defined as slope coefficient b) on surface currents as function on the distance from the OWF (being location WALCRN30) for the Walcheren ray. The lower panel is for current direction and instead of the slope, the RMSE is considered.

From these plots we see an average reduction in flow velocities in the Borssele OWF of approximately 5%, due to the presence of the OWF. At further distance from the OWF the effect decreases to more or less zero over a distance of 30 km. However, for wind directions from the south eastern quadrant, there is near the coast a small increase in current velocities noticeable compared to the situation without OWF.

Considering the current direction, Figure 4.6 shows that the average effect on current direction is some 10º within the OWF, reducing to some 2º at a distance of approximately 20 km. There is some variation in the effects for the various wind directions. On the Walcheren ray the effect on the current direction is nowhere zero, possibly because of the effects of other OWF.

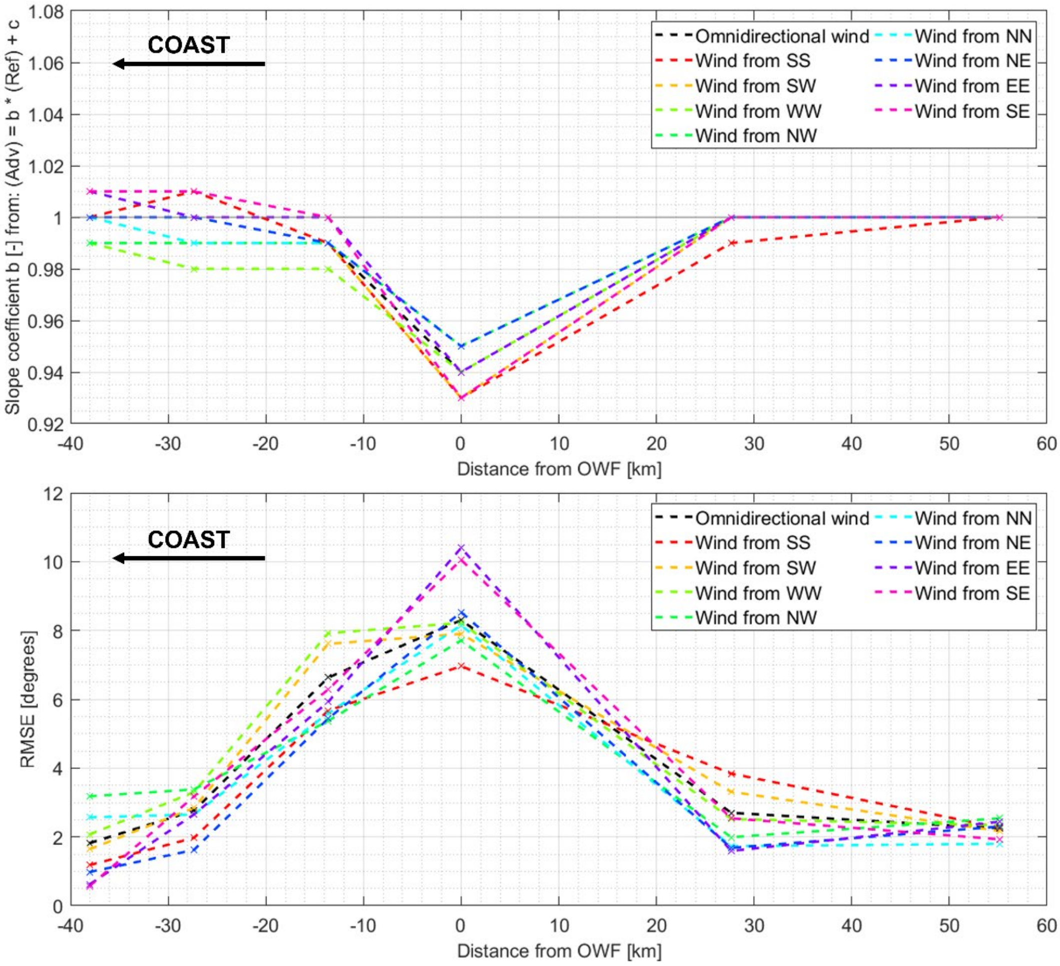

Figure 4.6 Profile of OWF effects on surface current magnitude and direction at WALCRN locations (negative distance is closer to the coast; WALCRN30 is taken as distance 0 km).

To find out whether these findings are general applicable or limited to the Walcheren conditions, a similar analysis has been performed in Figure 4.7 for the Noordwijk ray (NOORDWK4 – NOORDWK70, see Figure 4.3).

As the NOORDWK locations are located in an area more densely packed with OWFs, the effects are larger, reaching approximately 18% respectively 25º at the OWF itself .

Due to positioning in between the two major OWFs, we see bigger variation in profiles for West- and East-bound wind conditions. However, comparable characteristics such as a slight average increase in current velocity near the coast are observed for NOORDWK station as well. Still, note that these qualitative analyses are specific for the considered rays and in this stage of the study not generally applicable for the entire North Sea.

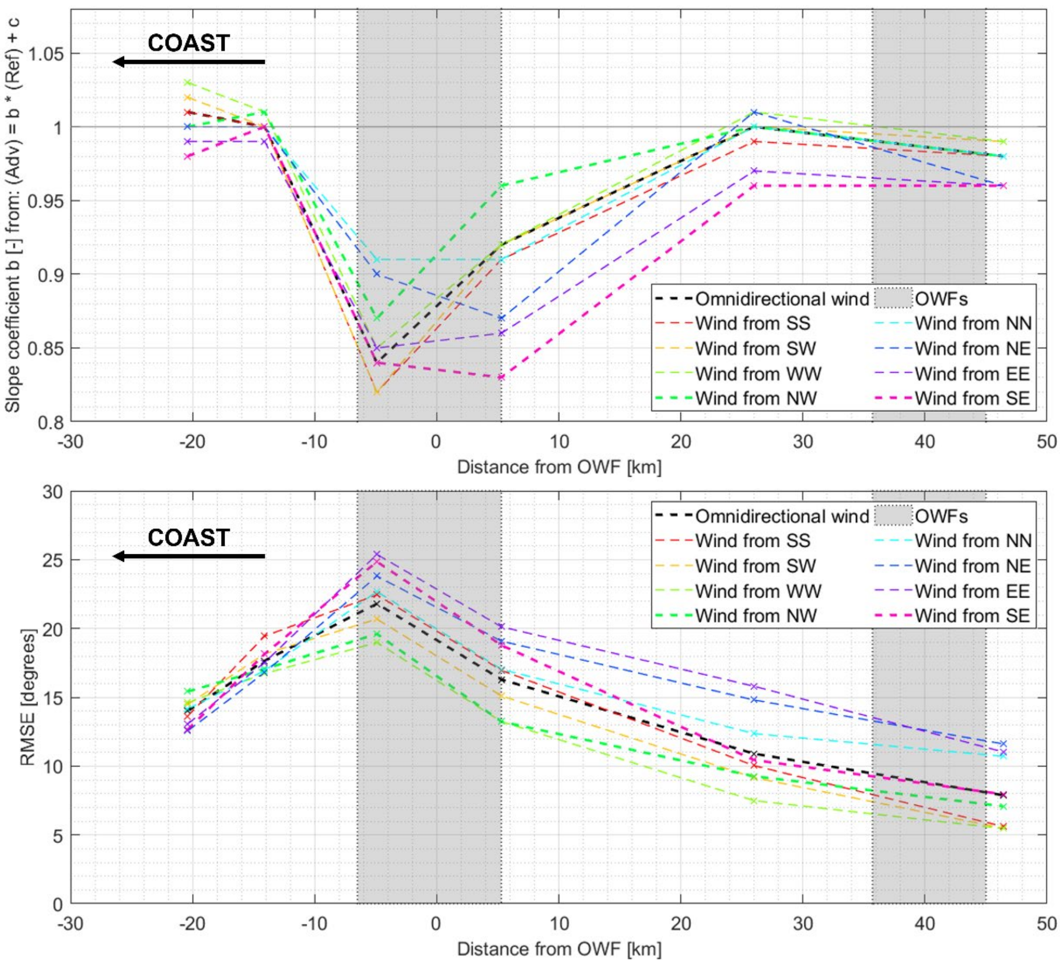

Figure 4.7 Profile of OWF effects on surface current magnitude and direction at NOORDWK locations (negative distance is closer to the coast; NOORDWK20 and NOORDWK30 are within/at the grey OWF band).

4.5.3 OWF effect in relation to positioning

From results presented above it is evident that the effects of OWF on the hydrodynamics are strongly depended on wind direction. In this section an example of variation in OWF effects depending on the primary wind direction is presented for surroundings of NOORDWK-OWF. Locations NOORDWK50 (NW), IJGL_MP19 (EE), NOORDWK4 (SE), STRAINS_M18 (SS), and LICHTELGRE (SW) are considered as relatively equidistant to the OWF location NOORDWK30 and located in different direction sectors (Figure 4.3).

Figure 4.8 presents – geographically positioned – per location the scatter plot of surface currents with OWF (Y) against the currents without OWF (X), only for wind conditions that the wind comes from the OWF (NOORDWK30) towards the analysed location.

From this plot we see that wind coming from the North, North-West, and West is responsible for larger variance in the current velocity magnitude. Apart from the station within the OWF limits (NOORDWK30), only NOORDWK50 station is showing a trend of current velocity underestimation (by ~1%). Other locations as the ones located closer to shore are influenced by the other processes that ensure slight current increase of ~1-2%.

Table 4.9 - Table 4.10, that are showing the statistical metrics of this comparison, are substantiating those conclusions. Table 4.9 also shows that STD, as a measure of variance, is indeed by large extent the single contributor towards Advanced scenario's RMSE.

The RMSE of current direction values is, in its turn, slightly lower on average compared to those of NOORDWK stations, but still significant with spread between 10-15°.

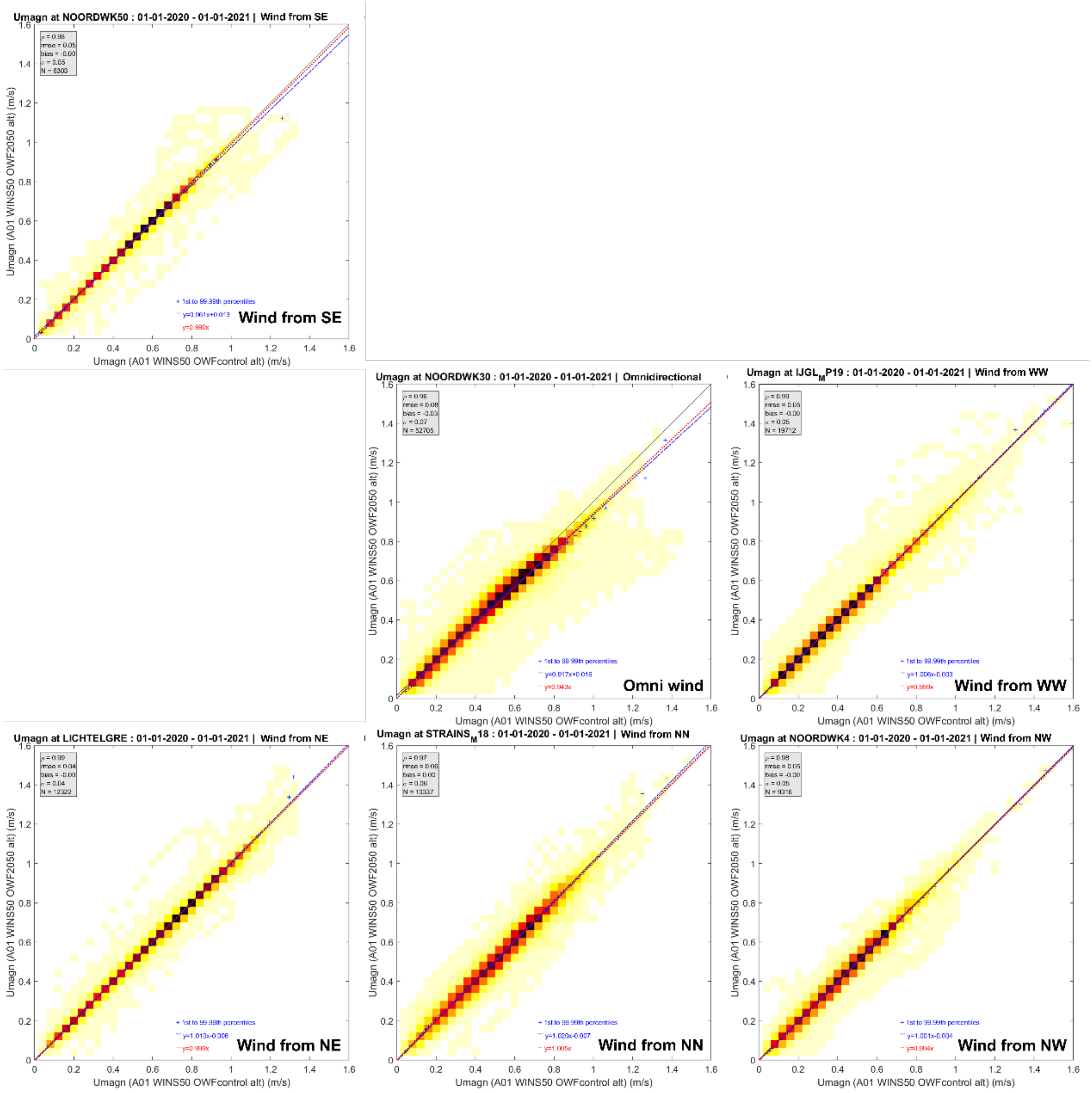

Figure 4.8 Scatter plots per locations of current velocity model results of Reference (x-axis; without OWF) and Advanced (y-axis; with hypothetical 2050 scenario OWF) only for wind conditions that the wind coms from the OWF towards the considered location.

Table 4.9 Statistics of OWF effect on current velocity around NOORDWK30 (Reference vs Advanced) only for wind conditions when the wind direction is from the OWF towards the considered location

Station	Dist. from OWF [km]	Bias [m/s]	STD [m/s]	RMSE [m/s]	(Adv) = a * (Ref)	(Adv) = b * (Ref) + c	
					a [-]	b [-]	c [-]
NOORDWK50	21 (NW)	-0.00	0.05	0.05	0.99	0.96	0.01
NOORDWK30	-	-0.03	0.07	0.08	0.94	0.92	0.02
IJGL_MP19	30 (EE)	-0.00	0.05	0.05	1.00	1.01	-0.00
NOORDWK4	26 (SE)	-0.00	0.05	0.05	0.99	1.00	-0.00
STRAINS_M18	33 (SS)	-0.00	0.06	0.06	1.01	1.02	-0.01
LICHTELGRE	57 (SW)	-0.00	0.04	0.04	1.00	1.01	-0.01

Table 4.10 Statistics of OWF effect on current direction around NOORDWK30 (Reference vs Advanced).

Station	Dist. from OWF [km]	Bias [deg.]	STD [deg.]	RMSE [deg.]	(Adv) = a * (Ref)
					a [-]
NOORDWK50	21 (NW)	-0.27	3.08	10.44	1.00
NOORDWK30	-	0.83	7.06	16.29	1.00
IJGL_MP19	30 (EE)	0.46	5.77	14.64	1.00
NOORDWK4	26 (SE)	-0.06	4.50	15.41	1.00
STRAINS_M18	33 (SS)	-0.52	5.61	13.73	1.00
LICHTELGRE	57 (SW)	-0.06	2.66	8.92	1.00

4.6 Conclusions

Based on hydrodynamic model simulations including the hypothetical OWF 2050 scenario, the effects of OWF on the hydrodynamic conditions have been assessed. Within and near the wind farms the effects are largest, for instance an average reduction in surface current speed by approximately 6% at the Borssele-OWF and 15% near the Hollandse Kust Zuid-OWF. The effects decrease with increasing distance from the OWF and in most cases the effects are almost zero at roughly 30 kilometre away from the OWF. Note that these are average values and for individual moments or other locations the effects can be larger, and also an increase in flow speed may occur due to the OWF.

The effects of OWF on current velocity are due to the effects they have on the wind and due to wake effects of the piles. Current speeds increase with increasing wind speeds and vice versa. The wake effects of the piles are limited to a smaller domain compared to the wind effects.

Also the directions of the currents are affected by the OWF. The average effect near Borssele-OWF is about 10º within the OWF, reducing to about 2º at a distance of approximately 20 km from the OWF. However, at Hollandse Kust Zuid-OWF, which is surrounded by more OWF in the 2050 scenario, the effect on the current direction is rather 25º.

The average reduction in water level caused by the OWF is small (~1%) and spatially rather uniform.

5 Conclusions and Recommendations

5.1 Conclusions

Although much literature has been found on offshore wind farms, the topic in relation with shipping safety is very rare. Most studies deal with the effects of OWF on ecology, coastline morphology, wind yield at hub height.

Simulations from WOZEP simulations have been used to assess the effects of large scale OWF's on waves and currents. Namely, the effects of an hypothetical scenario for 2050, with many OWF at the North Sea, with those in the Dutch waters accounting for a total capacity of 60GW. For that scenario, results are available for two approaches: for modelling the OWF effects on the wind speeds with a simple 10% reduction of the wind speeds within each OWF, and also accounting for wake effects and mixing of the atmosphere as done in the modelling of WINS50 wind fields.

In terms of waves, the results show no change in large scale wave patterns in the Dutch EEZ due to the presence of OWF's, even for the hypothetical 2050 situation. On average the 2050 OWF scenario will lead to a reduction of the wave heights inside and in the vicinity of the OWF by some 4%. The effects tend to reach over some 10ths of kilometers. However, for individual moments the presence of wind farms may rarely enhance as well as decrease the wave heights by up to 0.5 m. During a longer modelling period than the considered year 2020, the effects can be larger. The change in mean absolute wave period and mean wave direction is negligible at the spatial scale of the wind farm.

The wind and wave height in the direct vicinity of OWFs can either decrease or increase due to OWFs. In neutral and stable conditions enhanced mixing by the turbine may increase the surface wind speed behind the OWF. In unstable conditions the effect is mainly decreasing wind and waves. The main cause of OWF effects on waves is the reduced wind. Refraction and diffraction effects are less and the effect of pile drag resistance on waves is negligible (Christensen et al., 2013).

In terms of hydrodynamics, within and near the wind farms the effects of the OWF are the largest, with an average reduction of current speed by approximately 6% at the Borssele-OWF and 15% near the Hollandse Kust Zuid-OWF. The effects decrease with increasing distance from the OWF and in most cases the effects are almost zero at roughly 30 kilometre away from the OWF. Note that these are average values and for individual moments or other locations the effects could be larger, and also an increase in flow speed may occur due to the OWF.

Considering the current direction, the average effect near Borssele-OWF is about 10º within the OWF, reducing to some 2º at a distance of approximately 20 km from the OWF. However, at the Hollandse Kust Zuid-OWF, which is surrounded by more OWF in the 2050 scenario, the effect on current direction is of about 25º.

The average reduction in water level caused by the OWF is small (~1%) and spatially rather uniform. The effects of OWF on current velocity are due to the effects they have on the wind and due to wake effects of the piles. The wake effects of the piles are limited to a smaller domain compared to the wind effects.

5.2 Recommendations

In the present study, the link with shipping safety has not been made yet. It is suggested to involve nautical experts to discuss which parameters (for instance wave heights, wave periods, wave directions, currents, gradients of those) are relevant for ship safety and which values would be relevant or even critical for shipping safety, differentiating in vessel type.

If there is a need for more in-depth knowledge concerning the effects of OWF on ships, possible topics could be:

- Scaling up effects; How much extension or intensifying of the offshore wind parks would lead to unacceptable effects for shipping safety. As a start, the scaling up can be studied based on comparison of the 2020 scenario with the 2050 scenario.
- Effects close to the piles; these were not considered in the present study. If relevant, this could be studied in more detail.
- The presented hydrodynamic effects of the OWF could be analysed in more detail by taking the dependency for atmospheric conditions (stable, unstable atmosphere) into account.
- For waves the focus was fully on effects due to changes in wind. A possible approach for other effects like diffraction / blockage is to study from what pile diameter and pile distance on, these effects are no longer negligible.
- It is suggested to make distinction in the OWF effects within and outside the wind farms, but also for certain conditions. For extreme weather the effects could be different.
- For the WOZEP study there was only one year of advanced wind schematization (including wake effects and the effects on the atmosphere) available and a few years with the basic (10% reduction) schematization. Although the advanced schematization is expected to be more accurate, the longer period of the simplified schematization is interesting for more relevant statistics and extreme events. It would be good to have both combined.

6 Literature

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A Additional plots

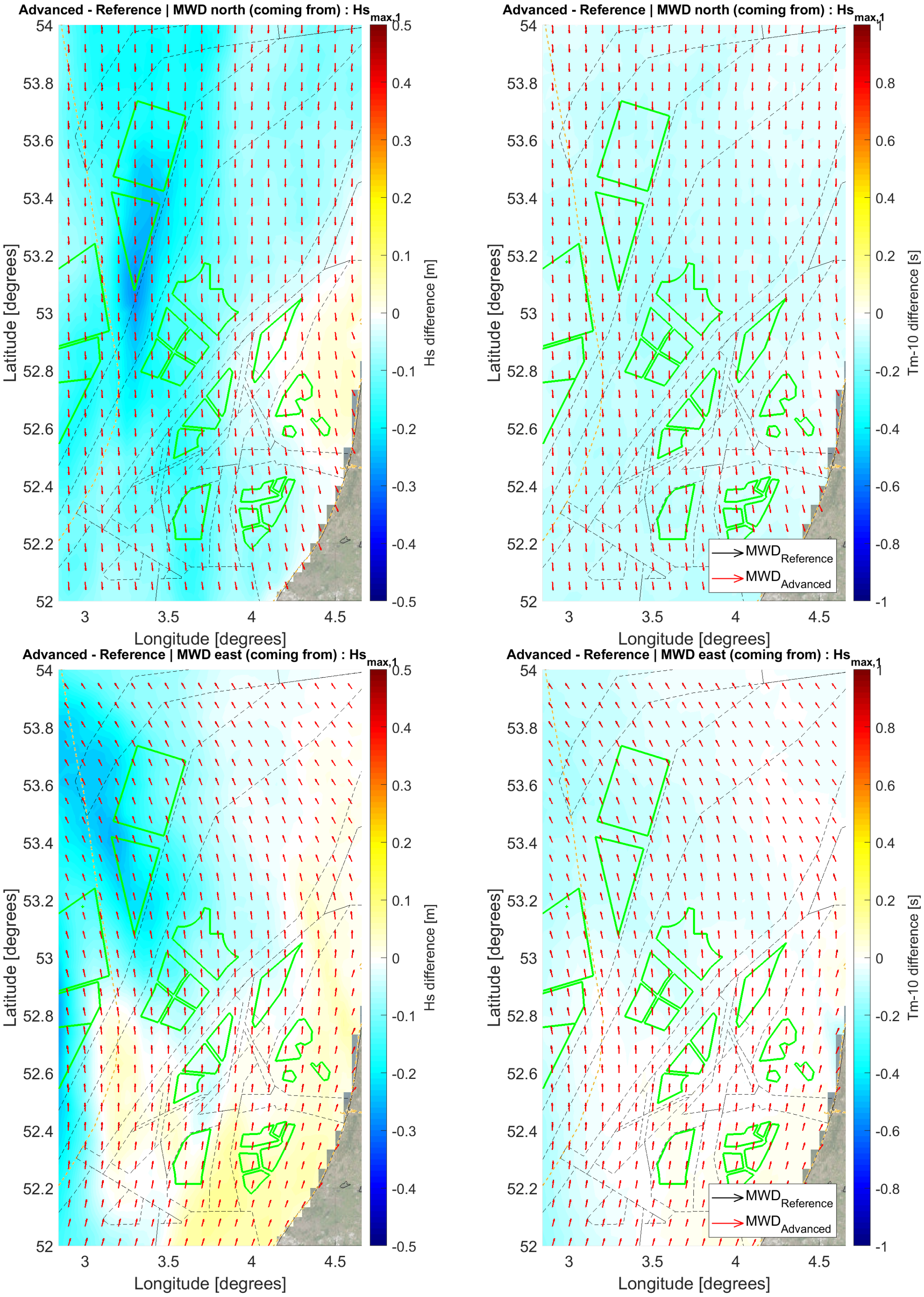

Figure-appendix A.1: Zoom in showing the OWF effects (with – without OWF) on wave height (left) and wave period (right) for mean wave direction North (upper) and East (lower).

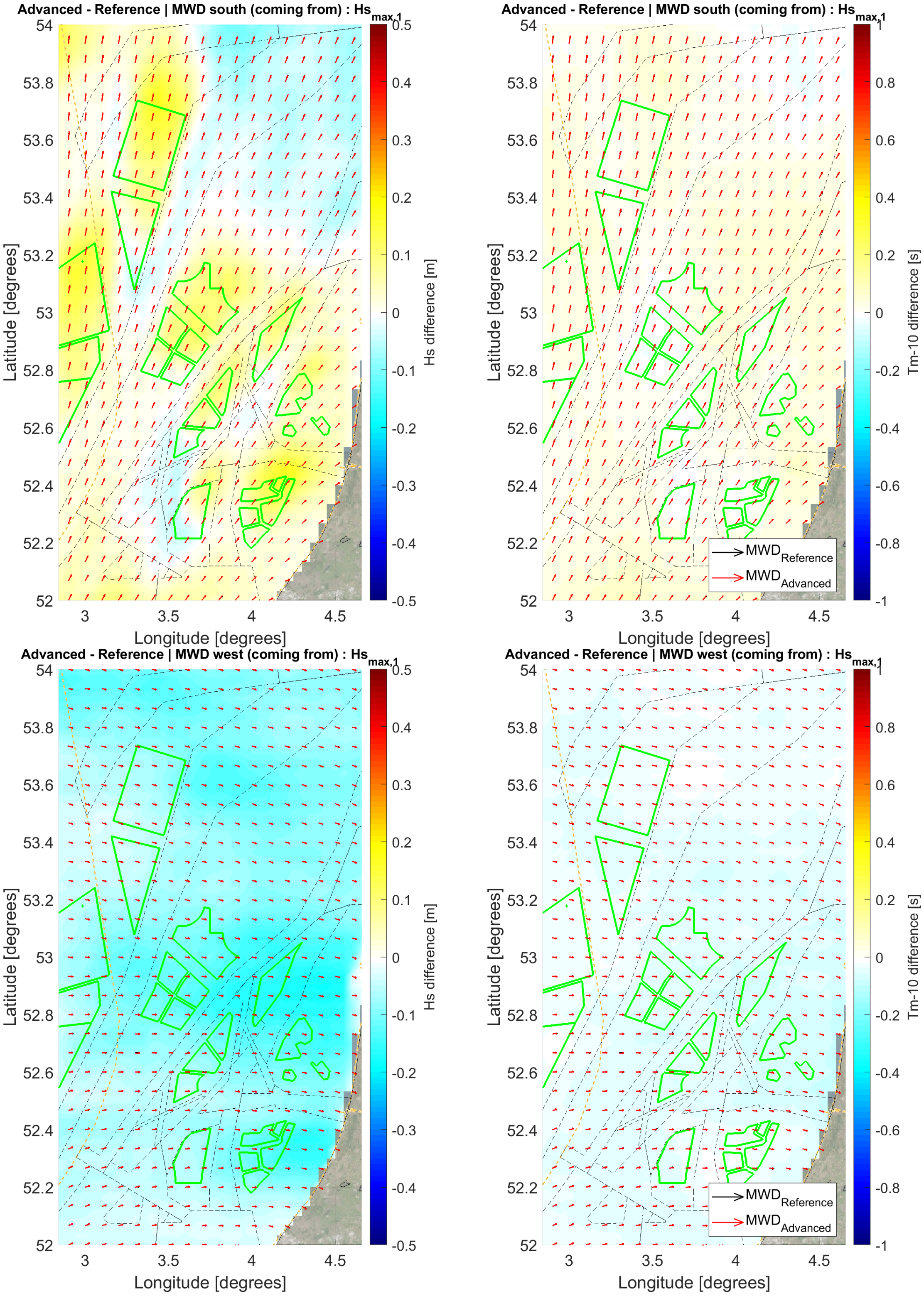

Figure-appendix A.2: Zoom in showing the OWF effects (with – without OWF) on wave height (left) and wave period (right) for mean wave direction South (upper) and West (lower).

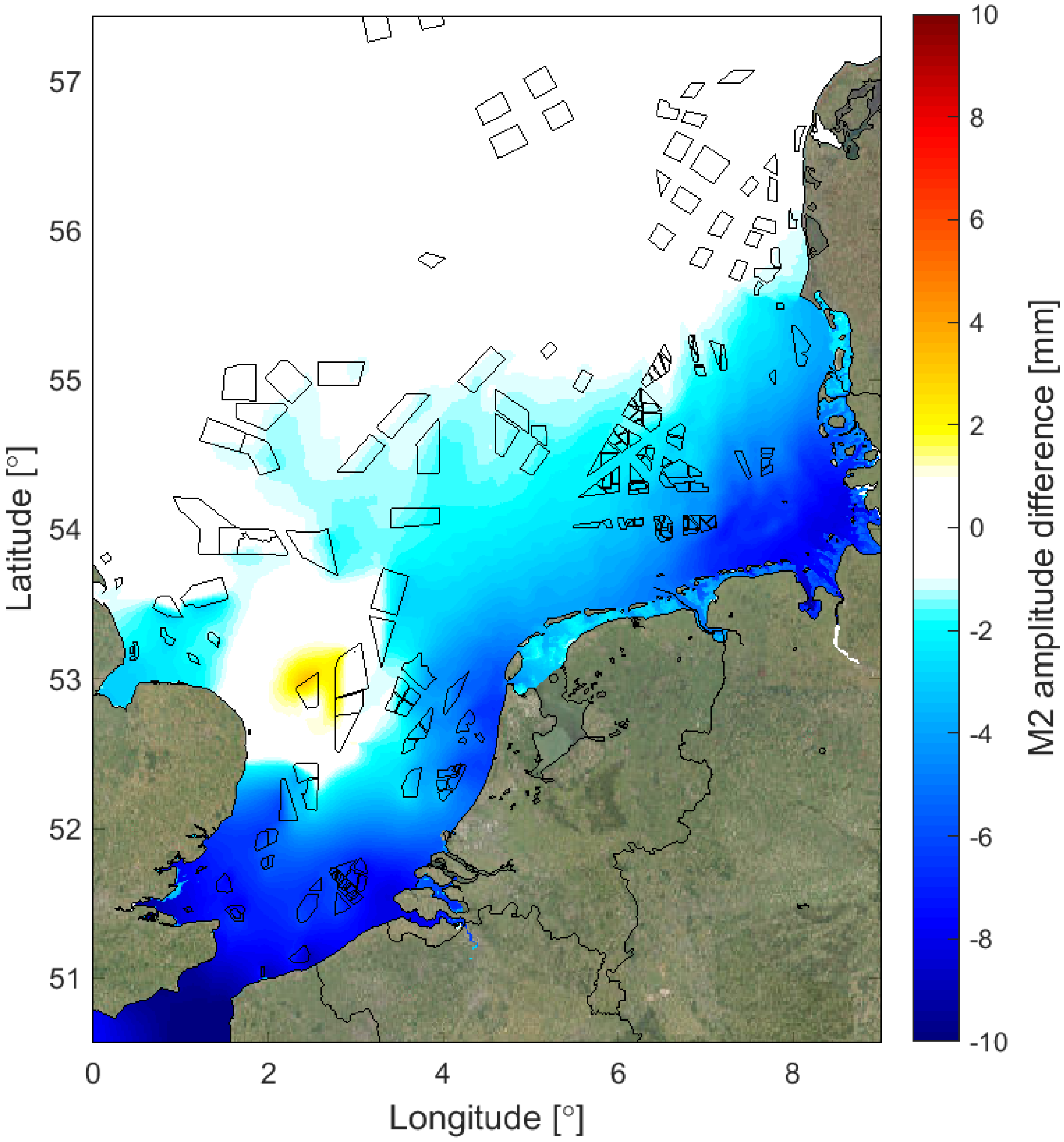

Figure-appendix A.3: Difference in main tidal constituent M2 (advanced with OWF – reference without OWF) based on the year 2020. Source: Zijl and Leummens, 2024.

B Statistical parameters of OWF effects on wave conditions

Locations within “Dutch 2050 OWFs”: Linear statistics of wave conditions modelled with Reference and Advanced conditions.

Condition	**N**	**Hs**					**Tm-10**					**MWD**		
	[-]	Bias [m]	RMSE [m]	Symmetric Slope: (Adv) = a * (Ref) [-]	(Adv) = b * (Ref) + c: b [-]	(Adv) = b * (Ref) + c: c [-]	Bias [s]	RMSE [s]	Symmetric Slope: (Adv) = a * (Ref) [-]	(Adv) = b * (Ref) + c: b [-]	(Adv) = b * (Ref) + c: c [-]	Bias [deg]	RMSE [deg]	std [deg]
Omnidirectional	000006289344	-0.09	0.13	0.96	0.99	-0.08	0.01	0.14	1.00	1.00	-0.01	-0.17	7.62	4.26
North MWD	000002065464	-0.06	0.09	0.96	0.98	-0.03	0.07	0.16	1.01	1.01	-0.01	-0.89	4.90	2.83
Dir. U10 North	000001084502	-0.08	0.11	0.96	0.98	-0.04	0.05	0.16	1.01	1.01	0.01	-1.15	4.08	2.50
East MWD	000000642027	-0.09	0.12	0.93	0.96	-0.03	0.01	0.15	1.00	1.01	-0.04	-4.35	11.86	4.63
Dir. U10 East	000001015075	-0.07	0.10	0.94	0.96	-0.01	0.03	0.15	1.01	1.02	-0.05	-2.77	8.37	4.22
South MWD	000001418571	-0.13	0.17	0.96	1.01	-0.15	-0.06	0.14	0.99	1.00	-0.04	0.17	9.58	3.03
Dir. U10 South	000001980443	-0.11	0.15	0.96	1.00	-0.10	-0.02	0.15	1.00	1.00	0.00	0.99	10.73	3.81
West MWD	000002163282	-0.10	0.13	0.96	0.99	-0.08	0.01	0.13	1.00	1.00	0.03	1.52	6.62	3.25
Dir. U10 West	000002210963	-0.09	0.12	0.96	0.99	-0.07	0.01	0.13	1.00	1.01	-0.04	0.46	4.66	2.76
Hs < 5 m	000006138148	-0.09	0.13	0.95	0.98	-0.05	0.01	0.15	1.00	1.01	-0.05	-0.18	7.71	4.31
Hs > 5 m	000000151196	-0.05	0.10	0.99	1.02	-0.18	-0.03	0.05	1.00	1.01	-0.15	0.09	0.53	0.52
Tm-10 < 10 s	000006249867	-0.09	0.13	0.96	0.99	-0.07	0.01	0.14	1.00	1.01	-0.04	-0.18	7.64	4.28
Tm-10 > 10 s	000000039477	-0.03	0.07	1.00	1.00	-0.04	0.01	0.08	1.00	0.98	0.27	0.15	0.69	0.68

Locations within “Dutch 2050 OWFs”: Linear statistics of wave conditions modelled with Reference and Basic conditions.

Condition	**N**	**Hs**					**Tm-10**					**MWD**		
	[-]	Bias [m]	RMSE [m]	Symmetric Slope: (Bas) = a * (Ref) [-]	(Bas) = b * (Ref) + c: b [-]	(Bas) = b * (Ref) + c: c [-]	Bias [s]	RMSE [s]	Symmetric Slope: (Bas) = a * (Ref) [-]	(Bas) = b * (Ref) + c: b [-]	(Bas) = b * (Ref) + c: c [-]	Bias [deg]	RMSE [deg]	std [deg]
Omnidirectional	000006289344	-0.06	0.08	0.97	0.96	0.02	0.02	0.06	1.00	0.99	0.06	0.21	3.13	2.14
North MWD	000002065464	-0.03	0.05	0.98	0.97	0.01	0.05	0.07	1.01	1.00	0.03	-0.12	1.92	1.40
Dir. U10 North	000001084502	-0.04	0.06	0.97	0.97	0.01	0.04	0.07	1.01	1.00	0.03	-0.17	1.42	1.02
East MWD	000000642027	-0.04	0.05	0.97	0.96	0.01	0.03	0.06	1.01	1.00	0.03	-1.33	4.74	2.14
Dir. U10 East	000001015075	-0.03	0.04	0.97	0.96	0.01	0.04	0.06	1.01	1.00	0.03	-0.82	3.25	1.94
South MWD	000001418571	-0.09	0.12	0.96	0.96	-0.00	-0.01	0.05	1.00	0.98	0.08	0.24	3.88	1.51
Dir. U10 South	000001980443	-0.07	0.10	0.96	0.96	0.01	0.01	0.06	1.00	0.99	0.08	0.67	4.56	2.17
West MWD	000002163282	-0.07	0.09	0.97	0.96	0.01	0.02	0.06	1.00	0.99	0.08	0.97	2.91	1.81
Dir. U10 West	000002210963	-0.06	0.09	0.97	0.96	0.02	0.02	0.06	1.00	1.00	0.05	0.46	1.86	1.38
Hs < 5 m	000006138148	-0.05	0.08	0.97	0.96	0.02	0.02	0.06	1.00	1.00	0.03	0.21	3.17	2.17
Hs > 5 m	000000151196	-0.22	0.24	0.96	0.97	-0.06	-0.06	0.07	0.99	1.00	-0.06	0.05	0.60	0.60
Tm-10 < 10 s	000006249867	-0.06	0.08	0.97	0.96	0.02	0.02	0.06	1.00	1.00	0.04	0.21	3.14	2.16
Tm-10 > 10 s	000000039477	-0.17	0.21	0.97	0.95	0.13	-0.02	0.07	1.00	0.97	0.32	0.16	0.51	0.48

Locations within “10km surrounding OWFs”: Linear statistics of wave conditions modelled with Reference and Advanced conditions.

Condition	N [-]	Hs					Tm-10					MWD		
		Bias [m]	RMSE [m]	Symmetric Slope: (Adv) = a * (Ref) [-]	(Adv) = b * (Ref) + c: b [-]	(Adv) = b * (Ref) + c: c [-]	Bias [s]	RMSE [s]	Symmetric Slope: (Adv) = a * (Ref) [-]	(Adv) = b * (Ref) + c: b [-]	(Adv) = b * (Ref) + c: c [-]	Bias [deg]	RMSE [deg]	std [deg]
Omnidirectional	000011928672	-0.08	0.12	0.96	0.99	-0.06	-0.01	0.14	1.00	1.01	-0.06	-0.38	6.92	3.73
North MWD	000003936776	-0.05	0.08	0.97	0.97	-0.01	0.04	0.15	1.01	1.01	-0.05	-0.84	4.70	2.70
Dir. U10 North	000002070250	-0.07	0.10	0.96	0.98	-0.03	0.02	0.14	1.00	1.01	-0.04	-1.09	3.98	2.46
East MWD	000001171863	-0.08	0.12	0.94	0.96	-0.03	-0.01	0.14	1.00	1.01	-0.05	-3.90	11.32	4.43
Dir. U10 East	000001932634	-0.06	0.09	0.95	0.96	-0.01	0.01	0.14	1.00	1.02	-0.08	-2.46	8.06	4.00
South MWD	000002572421	-0.12	0.16	0.96	1.00	-0.13	-0.08	0.14	0.99	1.00	-0.09	-0.18	8.60	2.94
Dir. U10 South	000003748647	-0.10	0.14	0.96	0.99	-0.08	-0.04	0.14	0.99	1.00	-0.06	0.44	9.46	3.47
West MWD	000004247612	-0.09	0.12	0.97	0.99	-0.07	-0.02	0.12	1.00	1.00	-0.04	0.91	5.82	3.02
Dir. U10 West	000004180254	-0.09	0.11	0.97	0.99	-0.06	-0.01	0.12	1.00	1.01	-0.09	0.20	4.31	2.64
Hs < 5 m	000011659624	-0.08	0.12	0.96	0.98	-0.04	-0.01	0.14	1.00	1.01	-0.09	-0.39	7.00	3.77
Hs > 5 m	000000269048	-0.05	0.10	0.99	1.02	-0.15	-0.03	0.05	1.00	1.01	-0.15	0.05	0.52	0.52
Tm-10 < 10 s	000011861929	-0.08	0.12	0.96	0.99	-0.06	-0.01	0.14	1.00	1.01	-0.09	-0.38	6.94	3.75
Tm-10 > 10 s	000000066743	-0.03	0.08	1.00	1.00	-0.03	0.01	0.07	1.00	0.98	0.18	0.10	0.70	0.70

Locations within “10km surrounding OWFs”: Linear statistics of wave conditions modelled with Reference and Basic conditions.

Condition	N [-]	Hs					Tm-10					MWD		
		Bias [m]	RMSE [m]	Symmetric Slope: (Bas) = a * (Ref) [-]	(Bas) = b * (Ref) + c: b [-]	(Bas) = b * (Ref) + c: c [-]	Bias [s]	RMSE [s]	Symmetric Slope: (Bas) = a * (Ref) [-]	(Bas) = b * (Ref) + c: b [-]	(Bas) = b * (Ref) + c: c [-]	Bias [deg]	RMSE [deg]	std [deg]
Omnidirectional	000011928672	-0.03	0.05	0.98	0.98	0.01	-0.02	0.05	1.00	0.99	0.02	0.06	1.65	1.14
North MWD	000003936776	-0.02	0.03	0.99	0.98	0.01	0.00	0.04	1.00	1.00	-0.02	-0.00	1.14	0.84
Dir. U10 North	000002070250	-0.02	0.04	0.98	0.98	0.01	-0.01	0.04	1.00	1.00	-0.00	-0.01	0.85	0.67
East MWD	000001171863	-0.02	0.03	0.98	0.98	0.01	-0.02	0.03	1.00	1.00	0.00	-0.54	2.57	1.39
Dir. U10 East	000001932634	-0.01	0.02	0.99	0.98	0.01	-0.01	0.03	1.00	1.00	-0.02	-0.28	1.79	1.18
South MWD	000002572421	-0.05	0.07	0.98	0.98	0.00	-0.05	0.07	0.99	0.99	0.04	0.00	2.01	1.01
Dir. U10 South	000003748647	-0.04	0.06	0.98	0.98	0.01	-0.03	0.06	0.99	0.99	0.04	0.17	2.34	1.30
West MWD	000004247612	-0.04	0.05	0.98	0.98	0.01	-0.03	0.05	1.00	0.99	0.03	0.33	1.47	1.06
Dir. U10 West	000004180254	-0.04	0.05	0.98	0.98	0.01	-0.03	0.05	1.00	0.99	0.01	0.16	1.01	0.82
Hs < 5 m	000011659624	-0.03	0.04	0.98	0.98	0.01	-0.02	0.05	1.00	1.00	-0.01	0.07	1.67	1.16
Hs > 5 m	000000269048	-0.13	0.15	0.98	0.98	-0.04	-0.09	0.10	0.99	1.00	-0.06	-0.06	0.57	0.57
Tm-10 < 10 s	000011861929	-0.03	0.05	0.98	0.98	0.01	-0.02	0.05	1.00	1.00	0.00	0.06	1.65	1.15
Tm-10 > 10 s	000000066743	-0.11	0.14	0.98	0.97	0.07	-0.06	0.09	0.99	0.97	0.28	0.05	0.43	0.43

Locations within “Shipping routes”: Linear statistics of wave conditions modelled with Reference and Advanced conditions.

Condition	**N [-]**	**Hs**					**Tm-10**					**MWD**		
		Bias [m]	RMSE [m]	Symmetric Slope: (Adv) = a * (Ref) [-]	(Adv) = b * (Ref) + c: b [-]	c [-]	Bias [s]	RMSE [s]	Symmetric Slope: (Adv) = a * (Ref) [-]	(Adv) = b * (Ref) + c: b [-]	c [-]	Bias [deg]	RMSE [deg]	std [deg]
Omnidirectional	000003381840	-0.08	0.12	0.96	0.99	-0.06	-0.02	0.13	1.00	1.01	-0.05	-0.26	6.92	3.36
North MWD	000001158228	-0.05	0.08	0.96	0.98	-0.02	0.02	0.15	1.00	1.01	-0.07	-0.75	4.82	2.68
Dir. U10 North	000000616111	-0.07	0.11	0.96	0.98	-0.04	0.00	0.14	1.00	1.01	-0.04	-0.98	4.00	2.48
East MWD	000000290971	-0.05	0.09	0.96	0.97	-0.02	-0.00	0.13	1.00	1.01	-0.03	-3.24	11.87	4.08
Dir. U10 East	000000561824	-0.04	0.08	0.96	0.97	-0.01	0.01	0.13	1.00	1.01	-0.06	-1.83	8.06	3.60
South MWD	000000694982	-0.12	0.16	0.96	1.00	-0.13	-0.09	0.15	0.99	1.00	-0.11	0.00	8.64	2.85
Dir. U10 South	000001047015	-0.10	0.14	0.96	0.99	-0.09	-0.05	0.14	0.99	1.00	-0.07	0.55	9.45	3.37
West MWD	000001237659	-0.09	0.12	0.97	0.99	-0.07	-0.03	0.12	1.00	1.00	-0.03	0.74	5.85	3.03
Dir. U10 West	000001157789	-0.08	0.11	0.97	0.99	-0.06	-0.02	0.12	1.00	1.01	-0.08	0.14	4.39	2.64
Hs < 5 m	000003323201	-0.08	0.12	0.96	0.98	-0.04	-0.02	0.14	1.00	1.01	-0.08	-0.27	6.98	3.39
Hs > 5 m	000000058639	-0.04	0.09	0.99	1.01	-0.09	-0.02	0.05	1.00	1.01	-0.08	-0.03	0.48	0.46
Tm-10 < 10 s	000003373975	-0.08	0.12	0.96	0.99	-0.06	-0.02	0.13	1.00	1.01	-0.08	-0.27	6.93	3.37
Tm-10 > 10 s	000000007865	-0.02	0.09	1.00	1.00	0.01	0.01	0.08	1.00	0.99	0.07	0.01	0.79	0.79

Locations within “Shipping routes”: Linear statistics of wave conditions modelled with Reference and Basic conditions.

Condition	**N [-]**	**Hs**					**Tm-10**					**MWD**		
		Bias [m]	RMSE [m]	Symmetric Slope: (Bas) = a * (Ref) [-]	(Bas) = b * (Ref) + c: b [-]	c [-]	Bias [s]	RMSE [s]	Symmetric Slope: (Bas) = a * (Ref) [-]	(Bas) = b * (Ref) + c: b [-]	c [-]	Bias [deg]	RMSE [deg]	std [deg]
Omnidirectional	000003381840	-0.03	0.04	0.98	0.98	0.01	-0.03	0.05	1.00	0.99	0.03	0.03	1.35	0.96
North MWD	000001158228	-0.02	0.03	0.98	0.98	0.01	-0.01	0.04	1.00	1.00	-0.01	0.07	1.03	0.77
Dir. U10 North	000000616111	-0.02	0.04	0.98	0.98	0.01	-0.02	0.05	1.00	0.99	0.02	0.06	0.88	0.65
East MWD	000000290971	-0.01	0.02	0.99	0.99	0.00	-0.01	0.03	1.00	1.00	0.00	-0.46	2.23	1.33
Dir. U10 East	000000561824	-0.01	0.02	0.99	0.99	0.01	-0.01	0.03	1.00	1.00	-0.01	-0.20	1.61	1.09
South MWD	000000694982	-0.04	0.05	0.98	0.98	0.01	-0.05	0.06	0.99	0.98	0.05	-0.07	1.62	0.89
Dir. U10 South	000001047015	-0.03	0.05	0.98	0.98	0.01	-0.03	0.05	0.99	0.99	0.04	0.08	1.80	1.11
West MWD	000001237659	-0.03	0.05	0.98	0.98	0.00	-0.03	0.05	0.99	0.99	0.04	0.16	1.17	0.92
Dir. U10 West	000001157789	-0.03	0.05	0.98	0.98	0.01	-0.03	0.05	0.99	0.99	0.02	0.06	0.86	0.74
Hs < 5 m	000003323201	-0.03	0.04	0.98	0.98	0.01	-0.02	0.05	1.00	1.00	-0.00	0.03	1.36	0.97
Hs > 5 m	000000058639	-0.12	0.13	0.98	0.99	-0.06	-0.10	0.10	0.99	0.99	-0.02	-0.21	0.55	0.51
Tm-10 < 10 s	000003373975	-0.03	0.04	0.98	0.98	0.01	-0.03	0.05	1.00	0.99	0.02	0.03	1.35	0.96
Tm-10 > 10 s	000000007865	-0.09	0.11	0.98	0.98	0.03	-0.07	0.09	0.99	0.99	0.02	-0.12	0.39	0.37

Locations within “Far offshore shipping areas”: Linear statistics of wave conditions modelled with Reference and Advanced conditions.

Condition	N [-]	Hs					Tm-10					MWD		
		Bias [m]	RMSE [m]	Symmetric Slope: (Adv) = a * (Ref) [-]	(Adv) = b * (Ref) + c		Bias [s]	RMSE [s]	Symmetric Slope: (Adv) = a * (Ref) [-]	(Adv) = b * (Ref) + c		Bias [deg]	RMSE [deg]	std [deg]
					b [-]	c [-]				b [-]	c [-]			
Omnidirectional	000005050800	-0.08	0.12	0.96	0.99	-0.06	-0.01	0.14	1.00	1.01	-0.08	-0.54	6.63	4.33
North MWD	000001592164	-0.05	0.07	0.97	0.98	-0.02	0.05	0.14	1.01	1.01	-0.04	-0.91	4.33	2.72
Dir. U10 North	000000834379	-0.06	0.09	0.97	0.98	-0.03	0.03	0.14	1.01	1.01	-0.04	-1.21	3.66	2.36
East MWD	000000584058	-0.10	0.13	0.93	0.96	-0.04	-0.04	0.15	0.99	1.01	-0.10	-4.24	10.49	4.53
Dir. U10 East	000000777983	-0.08	0.12	0.94	0.96	-0.02	-0.00	0.15	1.00	1.02	-0.13	-3.20	7.72	4.40
South MWD	000001198536	-0.12	0.15	0.96	1.00	-0.12	-0.08	0.14	0.99	1.00	-0.09	-0.49	8.03	3.01
Dir. U10 South	000001609580	-0.09	0.13	0.96	0.99	-0.07	-0.04	0.14	0.99	1.00	-0.06	0.22	9.15	3.51
West MWD	000001676042	-0.09	0.12	0.97	0.99	-0.06	-0.00	0.12	1.00	1.00	-0.03	1.07	5.49	2.98
Dir. U10 West	000001830180	-0.09	0.11	0.97	0.99	-0.06	0.00	0.13	1.00	1.01	-0.09	0.23	4.01	2.62
Hs < 5 m	000004895843	-0.08	0.12	0.96	0.97	-0.03	-0.01	0.14	1.00	1.02	-0.12	-0.56	6.73	4.42
Hs > 5 m	000000154957	-0.07	0.10	0.99	1.02	-0.18	-0.04	0.05	1.00	1.02	-0.23	0.12	0.56	0.55
Tm-10 < 10 s	000004999680	-0.08	0.12	0.96	0.99	-0.06	-0.01	0.14	1.00	1.02	-0.11	-0.55	6.66	4.38
Tm-10 > 10 s	000000051120	-0.04	0.07	0.99	1.00	-0.04	0.01	0.07	1.00	0.98	0.19	0.13	0.68	0.67

Locations within “Far offshore shipping areas”: Linear statistics of wave conditions modelled with Reference and Basic conditions.

Condition	N [-]	Hs					Tm-10					MWD		
		Bias [m]	RMSE [m]	Symmetric Slope: (Bas) = a * (Ref) [-]	(Bas) = b * (Ref) + c		Bias [s]	RMSE [s]	Symmetric Slope: (Bas) = a * (Ref) [-]	(Bas) = b * (Ref) + c		Bias [deg]	RMSE [deg]	std [deg]
					b [-]	c [-]				b [-]	c [-]			
Omnidirectional	000005050800	-0.03	0.05	0.98	0.98	0.01	-0.02	0.05	1.00	0.99	0.02	0.11	1.71	1.32
North MWD	000001592164	-0.01	0.03	0.99	0.99	0.01	0.01	0.03	1.00	1.00	-0.02	-0.07	1.08	0.88
Dir. U10 North	000000834379	-0.02	0.03	0.99	0.98	0.01	-0.00	0.03	1.00	1.00	-0.02	-0.07	0.84	0.69
East MWD	000000584058	-0.02	0.03	0.98	0.97	0.01	-0.02	0.04	1.00	1.00	-0.00	-0.56	2.52	1.35
Dir. U10 East	000000777983	-0.02	0.03	0.98	0.98	0.01	-0.01	0.04	1.00	1.00	-0.03	-0.36	1.65	1.23
South MWD	000001198536	-0.05	0.07	0.98	0.98	0.00	-0.05	0.07	0.99	0.99	0.04	0.08	2.02	1.06
Dir. U10 South	000001609580	-0.04	0.06	0.98	0.97	0.01	-0.03	0.06	0.99	0.99	0.04	0.27	2.48	1.41
West MWD	000001676042	-0.04	0.06	0.98	0.98	0.01	-0.02	0.05	1.00	0.99	0.04	0.53	1.59	1.11
Dir. U10 West	000001830180	-0.04	0.06	0.98	0.98	0.02	-0.02	0.05	1.00	0.99	0.02	0.25	1.07	0.84
Hs < 5 m	000004895843	-0.03	0.04	0.98	0.98	0.01	-0.02	0.05	1.00	1.00	-0.02	0.11	1.73	1.35
Hs > 5 m	000000154957	-0.14	0.15	0.98	0.98	-0.03	-0.09	0.09	0.99	1.00	-0.05	0.04	0.56	0.56
Tm-10 < 10 s	000004999680	-0.03	0.05	0.98	0.98	0.02	-0.02	0.05	1.00	1.00	-0.01	0.11	1.71	1.34
Tm-10 > 10 s	000000051120	-0.11	0.14	0.98	0.97	0.08	-0.05	0.09	0.99	0.96	0.34	0.10	0.44	0.43

Locations within “Anchor zones”: Linear statistics of wave conditions modelled with Reference and Advanced conditions.

Condition	**N [-]**	**Hs**					**Tm-10**					**MWD**		
		Bias [m]	RMSE [m]	Symmetric Slope: (Adv) = a * (Ref) [-]	(Adv) = b * (Ref) + c		Bias [s]	RMSE [s]	Symmetric Slope: (Adv) = a * (Ref) [-]	(Adv) = b * (Ref) + c		Bias [deg]	RMSE [deg]	std [deg]
					b [-]	c [-]				b [-]	c [-]			
Omnidirectional	000000175680	-0.07	0.10	0.96	0.99	-0.06	-0.03	0.13	0.99	1.01	-0.07	-0.07	6.33	2.94
North MWD	000000062639	-0.05	0.09	0.96	0.97	-0.01	0.00	0.14	1.00	1.02	-0.11	-0.93	5.61	2.60
Dir. U10 North	000000033585	-0.07	0.11	0.95	0.97	-0.04	-0.01	0.14	1.00	1.01	-0.08	-1.08	4.84	2.62
East MWD	000000008965	-0.04	0.06	0.96	0.95	0.01	-0.01	0.11	1.00	1.02	-0.10	-2.23	12.77	3.51
Dir. U10 East	000000028417	-0.04	0.06	0.96	0.96	0.00	-0.00	0.13	1.00	1.02	-0.08	-1.45	9.00	3.21
South MWD	000000025280	-0.09	0.12	0.96	1.00	-0.10	-0.06	0.13	0.99	0.99	-0.01	0.42	8.32	2.92
Dir. U10 South	000000054591	-0.09	0.12	0.96	1.00	-0.08	-0.04	0.14	0.99	1.00	-0.04	1.09	7.70	3.21
West MWD	000000078796	-0.08	0.11	0.97	1.00	-0.08	-0.05	0.12	0.99	1.01	-0.08	0.70	4.85	2.90
Dir. U10 West	000000059137	-0.07	0.09	0.97	0.99	-0.05	-0.05	0.12	0.99	1.01	-0.12	0.10	3.48	2.50
Hs < 5 m	000000173521	-0.07	0.10	0.96	0.98	-0.04	-0.03	0.13	0.99	1.01	-0.08	-0.07	6.37	2.95
Hs > 5 m	000000002159	-0.03	0.09	0.99	1.04	-0.26	-0.02	0.05	1.00	0.99	0.07	-0.07	0.38	0.37
Tm-10 < 10 s	000000175600	-0.07	0.10	0.96	0.99	-0.06	-0.03	0.13	0.99	1.01	-0.09	-0.07	6.33	2.94
Tm-10 > 10 s	No data	-	-	-	-	-	-	-	-	-	-	-	-	-

Locations within “Anchor zones”: Linear statistics of wave conditions modelled with Reference and Basic conditions.

Condition	**N [-]**	**Hs**					**Tm-10**					**MWD**		
		Bias [m]	RMSE [m]	Symmetric Slope: (Bas) = a * (Ref) [-]	(Bas) = b * (Ref) + c		Bias [s]	RMSE [s]	Symmetric Slope: (Bas) = a * (Ref) [-]	(Bas) = b * (Ref) + c		Bias [deg]	RMSE [deg]	std [deg]
					b [-]	c [-]				b [-]	c [-]			
Omnidirectional	000000175680	-0.02	0.03	0.99	0.98	0.01	-0.02	0.04	1.00	0.99	0.04	0.07	1.05	0.73
North MWD	000000062639	-0.02	0.03	0.98	0.97	0.02	-0.02	0.04	1.00	0.99	0.02	0.13	0.79	0.61
Dir. U10 North	000000033585	-0.02	0.04	0.98	0.97	0.01	-0.03	0.05	0.99	0.99	0.04	0.10	0.63	0.58
East MWD	000000008965	-0.01	0.01	0.99	0.99	0.00	-0.01	0.02	1.00	1.00	-0.00	-0.14	1.64	1.23
Dir. U10 East	000000028417	-0.01	0.01	0.99	0.98	0.01	-0.01	0.03	1.00	1.00	-0.00	0.08	1.15	0.92
South MWD	000000025280	-0.02	0.03	0.99	0.98	0.01	-0.03	0.04	0.99	0.99	0.03	-0.02	1.72	0.75
Dir. U10 South	000000054591	-0.02	0.03	0.99	0.98	0.01	-0.02	0.04	1.00	0.99	0.03	0.15	1.49	0.84
West MWD	000000078796	-0.02	0.03	0.99	0.98	0.01	-0.03	0.04	0.99	0.99	0.04	0.09	0.83	0.72
Dir. U10 West	000000059137	-0.02	0.03	0.99	0.98	0.01	-0.03	0.04	0.99	0.99	0.03	-0.00	0.59	0.55
Hs < 5 m	000000173521	-0.02	0.03	0.99	0.98	0.01	-0.02	0.04	1.00	0.99	0.03	0.08	1.05	0.73
Hs > 5 m	000000002159	-0.09	0.10	0.98	0.98	0.01	-0.08	0.09	0.99	0.96	0.25	-0.04	0.39	0.39
Tm-10 < 10 s	000000175600	-0.02	0.03	0.99	0.98	0.01	-0.02	0.04	1.00	0.99	0.03	0.07	1.05	0.73
Tm-10 > 10 s	No data	-	-	-	-	-	-	-	-	-	-	-	-	-

Locations within “Approach areas”: Linear statistics of wave conditions modelled with Reference and Advanced conditions.

Condition	N [-]	Hs					Tm-10					MWD		
		Bias [m]	RMSE [m]	Symmetric Slope: (Adv) = a * (Ref) [-]	(Adv) = b * (Ref) + c		Bias [s]	RMSE [s]	Symmetric Slope: (Adv) = a * (Ref) [-]	(Adv) = b * (Ref) + c		Bias [deg]	RMSE [deg]	std [deg]
					b [-]	c [-]				b [-]	c [-]			
Omnidirectional	000000491904	-0.07	0.10	0.96	0.99	-0.05	-0.03	0.14	0.99	1.00	-0.03	-0.03	5.62	2.76
North MWD	000000170847	-0.03	0.06	0.97	0.99	-0.01	-0.00	0.14	1.00	1.00	-0.03	-0.32	5.54	2.32
Dir. U10 North	000000101531	-0.04	0.08	0.97	0.99	-0.03	-0.02	0.14	1.00	1.00	-0.03	-0.27	4.47	2.29
East MWD	000000019658	-0.02	0.03	0.98	0.98	0.00	0.01	0.08	1.00	1.00	0.01	-2.16	9.12	3.00
Dir. U10 East	000000078703	-0.01	0.03	0.98	0.97	0.01	0.01	0.13	1.00	1.00	-0.02	-0.97	7.86	2.82
South MWD	000000049840	-0.06	0.08	0.96	0.99	-0.05	-0.06	0.12	0.99	0.99	-0.01	-0.27	6.95	2.45
Dir. U10 South	000000149064	-0.08	0.11	0.96	1.00	-0.07	-0.05	0.14	0.99	1.01	-0.09	0.35	6.14	2.79
West MWD	000000251559	-0.10	0.13	0.96	1.00	-0.09	-0.04	0.14	0.99	1.00	-0.06	0.39	4.97	2.96
Dir. U10 West	000000162730	-0.10	0.13	0.96	0.99	-0.08	-0.03	0.14	0.99	1.00	-0.02	0.24	4.29	2.80
Hs < 5 m	000000487281	-0.07	0.10	0.96	0.98	-0.03	-0.03	0.14	0.99	1.00	-0.05	-0.03	5.64	2.78
Hs > 5 m	000000004623	-0.03	0.08	0.99	1.01	-0.10	-0.02	0.05	1.00	0.99	0.07	-0.07	0.36	0.35
Tm-10 < 10 s	000000491355	-0.07	0.10	0.96	0.98	-0.04	-0.03	0.14	0.99	1.00	-0.05	-0.03	5.62	2.77
Tm-10 > 10 s	000000000549	-0.02	0.07	0.99	0.99	0.03	0.05	0.09	1.00	0.88	1.30	-0.24	0.53	0.47

Locations within “Approach areas”: Linear statistics of wave conditions modelled with Reference and Basic conditions.

Condition	N [-]	Hs					Tm-10					MWD		
		Bias [m]	RMSE [m]	Symmetric Slope: (Bas) = a * (Ref) [-]	(Bas) = b * (Ref) + c		Bias [s]	RMSE [s]	Symmetric Slope: (Bas) = a * (Ref) [-]	(Bas) = b * (Ref) + c		Bias [deg]	RMSE [deg]	std [deg]
					b [-]	c [-]				b [-]	c [-]			
Omnidirectional	000000491904	-0.02	0.04	0.98	0.98	0.01	-0.03	0.05	0.99	0.99	0.04	0.01	1.56	0.76
North MWD	000000170847	-0.01	0.02	0.99	0.97	0.02	-0.01	0.04	1.00	0.99	0.03	0.24	1.74	0.67
Dir. U10 North	000000101531	-0.02	0.03	0.98	0.97	0.02	-0.02	0.05	1.00	0.99	0.04	0.20	0.76	0.60
East MWD	000000019658	-0.00	0.01	1.00	0.99	0.00	-0.00	0.03	1.00	1.00	0.00	-0.03	2.21	1.13
Dir. U10 East	000000078703	-0.00	0.01	0.99	0.98	0.01	-0.00	0.04	1.00	1.00	0.01	0.08	3.23	0.95
South MWD	000000049840	-0.02	0.02	0.99	0.98	0.01	-0.03	0.04	0.99	0.98	0.05	-0.43	1.89	0.93
Dir. U10 South	000000149064	-0.02	0.03	0.98	0.98	0.01	-0.03	0.05	0.99	0.99	0.04	-0.13	1.29	0.87
West MWD	000000251559	-0.03	0.05	0.98	0.98	0.01	-0.04	0.06	0.99	0.98	0.05	-0.06	1.27	0.70
Dir. U10 West	000000162730	-0.03	0.05	0.98	0.97	0.01	-0.04	0.06	0.99	0.98	0.05	-0.02	0.67	0.61
Hs < 5 m	000000487281	-0.02	0.03	0.98	0.98	0.01	-0.03	0.05	0.99	0.99	0.04	0.01	1.57	0.76
Hs > 5 m	000000004623	-0.11	0.12	0.98	0.98	-0.01	-0.11	0.11	0.99	1.00	-0.08	-0.26	0.54	0.48
Tm-10 < 10 s	000000491355	-0.02	0.04	0.98	0.98	0.01	-0.03	0.05	0.99	0.99	0.04	0.01	1.56	0.76
Tm-10 > 10 s	000000000549	-0.07	0.09	0.98	0.98	0.02	-0.09	0.09	0.99	0.99	-0.01	0.07	0.23	0.22

C Statistical parameters of OWF effects on hydro conditions

Wind from North-West: Linear statistics of hydrodynamic conditions modelled with Reference and Advanced conditions.

Condition	N [-]	Waterlevel					Current velocity magnitude					Current direction		
		Bias [m]	RMSE [m]	Symmetric Slope: (Adv) = a * (Ref) [-]	(Adv) = b * (Ref) + c		Bias [m/s]	RMSE [m/s]	Symmetric Slope: (Adv) = a * (Ref) [-]	(Adv) = b * (Ref) + c		Bias [deg]	RMSE [deg]	std [deg]
					b [-]	c [-]				b [-]	c [-]			
WALCRN2	9316	0.01	0.01	0.99	0.99	0.01	0.00	0.02	1.00	0.99	0.01	-0.07	3.18	3.63
WALCRN10	9316	0.01	0.01	0.99	0.99	0.01	0.00	0.02	1.00	0.99	0.01	0.19	3.38	8.68
WALCRN20	9316	0.00	0.01	0.99	0.99	0.00	0.00	0.02	1.00	0.99	0.00	-0.04	5.37	11.41
WALCRN30	9316	0.00	0.01	0.99	0.99	0.00	-0.02	0.03	0.97	0.95	0.01	-0.97	7.71	10.18
WALCRN50	9316	0.01	0.01	0.99	0.99	0.01	0.00	0.01	1.00	1.00	0.00	0.21	1.99	6.05
WALCRN70	9316	0.01	0.01	0.99	0.99	0.01	0.00	0.01	1.00	1.00	0.00	0.15	2.54	3.46
NOORDWK2	9316	0.00	0.01	0.99	0.99	0.00	0.00	0.04	1.00	1.00	0.00	-0.28	11.79	2.97
NOORDWK4	9316	0.00	0.01	0.99	0.99	0.00	0.00	0.05	0.99	1.00	0.00	-0.06	15.41	4.50
NOORDWK10	9316	0.00	0.01	0.99	0.99	0.00	0.00	0.06	1.00	1.01	-0.01	-0.25	17.05	6.78
NOORDWK20	9316	0.00	0.01	0.99	0.99	0.00	-0.03	0.08	0.94	0.87	0.03	-0.06	19.60	7.36
NOORDWK30	9316	0.00	0.01	0.99	0.99	0.00	-0.02	0.05	0.96	0.96	0.00	-1.05	13.23	4.41
NOORDWK50	9316	0.00	0.01	0.99	0.99	0.00	0.00	0.04	0.99	1.00	0.00	-0.52	9.26	4.12
NOORDWK70	9316	0.00	0.01	0.99	0.99	0.00	-0.01	0.03	0.99	0.98	0.00	0.08	7.08	4.04
EURPFM	9316	0.00	0.01	0.99	0.99	0.00	0.00	0.01	1.00	0.99	0.00	-0.14	3.23	5.40
LICHTELGRE	9316	0.00	0.01	0.99	0.99	0.00	0.00	0.03	0.99	0.98	0.01	0.09	9.12	2.20
STRAINS_M18	9316	0.00	0.01	0.99	0.99	0.00	0.00	0.06	1.01	1.03	-0.01	-0.98	15.17	4.72
IJGL_MP19	9316	0.00	0.01	0.99	0.99	0.00	0.00	0.05	1.00	1.00	0.00	-0.55	14.01	4.36
HKWA	9316	0.00	0.01	0.99	0.99	0.00	-0.01	0.04	0.99	1.00	-0.01	-0.35	9.74	4.49
HKWB	9316	0.00	0.01	0.99	0.99	0.00	-0.01	0.04	0.99	1.01	-0.01	-0.38	9.71	4.68

Wind from North: Linear statistics of hydrodynamic conditions modelled with Reference and Advanced conditions.

Condition	N [-]	Waterlevel					Current velocity magnitude					Current direction		
		Bias [m]	RMSE [m]	Symmetric Slope: (Adv) = a * (Ref) [-]	(Adv) = b * (Ref) + c		Bias [m/s]	RMSE [m/s]	Symmetric Slope: (Adv) = a * (Ref) [-]	(Adv) = b * (Ref) + c		Bias [deg]	RMSE [deg]	std [deg]
					b [-]	c [-]				b [-]	c [-]			
WALCRN2	10337	0.01	0.01	0.99	0.99	0.01	0.00	0.01	1.00	1.00	0.00	0.04	2.57	1.80
WALCRN10	10337	0.01	0.01	0.99	0.99	0.01	0.00	0.02	1.00	0.99	0.00	0.09	2.65	1.97
WALCRN20	10337	0.00	0.01	0.99	0.99	0.00	0.00	0.03	1.00	0.99	0.00	-0.10	5.59	5.48
WALCRN30	10337	0.00	0.01	0.99	0.99	0.00	-0.02	0.05	0.97	0.95	0.01	-0.91	8.15	5.86
WALCRN50	10337	0.01	0.01	0.99	0.99	0.01	0.00	0.01	1.00	1.00	0.00	0.30	1.73	11.42
WALCRN70	10337	0.01	0.01	0.99	0.99	0.01	0.00	0.01	1.00	1.00	0.00	0.16	1.80	6.06
NOORDWK2	10337	0.00	0.01	0.99	0.99	0.00	0.00	0.03	1.00	0.99	0.00	0.24	11.18	2.53
NOORDWK4	10337	0.00	0.01	0.99	0.99	0.00	0.00	0.05	0.99	1.00	0.00	-0.03	14.15	7.36
NOORDWK10	10337	0.00	0.01	0.99	0.99	0.00	0.00	0.06	0.99	1.00	0.00	-0.20	16.93	4.57
NOORDWK20	10337	0.00	0.01	0.99	0.99	0.00	-0.04	0.10	0.92	0.91	0.01	1.10	22.68	11.66
NOORDWK30	10337	0.00	0.01	0.99	0.99	0.00	-0.02	0.08	0.95	0.91	0.02	0.90	17.03	14.77
NOORDWK50	10337	0.00	0.01	0.99	0.99	0.00	0.00	0.05	1.00	1.00	0.00	0.11	12.36	11.88
NOORDWK70	10337	0.00	0.01	0.99	0.99	0.00	-0.01	0.05	0.98	0.98	0.00	0.54	10.71	14.60
EURPFM	10337	0.00	0.01	0.99	0.99	0.00	0.00	0.01	0.99	1.00	0.00	0.00	3.18	3.14
LICHTELGRE	10337	0.00	0.01	0.99	0.99	0.00	0.00	0.04	1.00	1.01	0.00	0.24	9.98	4.52
STRAINS_M18	10337	0.00	0.01	0.99	0.99	0.00	0.00	0.06	1.01	1.02	-0.01	-0.52	13.73	5.61
IJGL_MP19	10337	0.00	0.01	0.99	0.99	0.00	0.00	0.05	0.99	1.00	0.00	-0.38	15.81	3.55
HKWA	10337	0.00	0.01	0.99	0.99	0.00	-0.01	0.06	0.98	0.99	0.00	0.42	11.99	17.74
HKWB	10337	0.00	0.01	0.99	0.99	0.00	-0.01	0.05	0.99	1.01	-0.01	-0.07	11.87	17.29

Wind from North-East: Linear statistics of hydrodynamic conditions modelled with Reference and Advanced conditions.

Condition	N [-]	Waterlevel					Current velocity magnitude					Current direction		
		Bias [m]	RMSE [m]	Symmetric Slope: (Adv) = a * (Ref) [-]	(Adv) = b * (Ref) + c		Bias [s]	RMSE [s]	Symmetric Slope: (Adv) = a * (Ref) [-]	(Adv) = b * (Ref) + c		Bias [deg]	RMSE [deg]	std [deg]
					b [-]	c [-]				b [-]	c [-]			
WALCRN2	12322	0.01	0.01	0.99	0.99	0.01	0.00	0.01	1.00	1.00	0.00	0.12	0.98	1.01
WALCRN10	12322	0.01	0.01	0.99	0.99	0.01	0.00	0.01	1.00	1.00	0.00	0.10	1.62	1.40
WALCRN20	12322	0.00	0.01	0.99	0.99	0.00	0.00	0.03	1.00	0.99	0.00	-0.13	5.44	3.14
WALCRN30	12322	0.00	0.01	0.99	0.99	0.00	-0.02	0.06	0.96	0.95	0.01	-1.19	8.53	18.71
WALCRN50	12322	0.01	0.01	0.99	0.99	0.01	0.00	0.01	1.00	1.00	0.00	0.34	1.68	4.71
WALCRN70	12322	0.01	0.01	0.99	0.99	0.01	0.00	0.01	1.00	1.00	0.00	0.13	2.30	1.40
NOORDWK2	12322	0.00	0.01	0.99	0.99	0.00	0.00	0.03	1.00	0.99	0.00	0.23	10.16	2.42
NOORDWK4	12322	0.00	0.01	0.99	0.99	0.00	0.00	0.05	1.00	1.00	0.00	-0.16	12.55	3.76
NOORDWK10	12322	0.00	0.01	0.99	0.99	0.00	-0.01	0.06	0.99	1.00	0.00	-0.11	16.79	6.63
NOORDWK20	12322	0.00	0.01	0.99	0.99	0.00	-0.05	0.11	0.90	0.90	0.00	1.23	23.80	8.57
NOORDWK30	12322	0.00	0.01	0.99	0.99	0.00	-0.03	0.09	0.93	0.87	0.03	1.47	19.08	3.93
NOORDWK50	12322	0.00	0.01	0.99	0.99	0.00	0.00	0.07	1.00	1.01	0.00	0.63	14.80	3.83
NOORDWK70	12322	0.00	0.01	0.99	0.99	0.00	-0.02	0.06	0.97	0.96	0.00	0.32	11.61	5.74
EURPFM	12322	0.00	0.01	0.99	0.99	0.00	0.00	0.01	0.99	1.00	0.00	0.04	3.66	2.88
LICHTELGRE	12322	0.00	0.01	0.99	0.99	0.00	0.00	0.04	1.00	1.01	-0.01	-0.06	8.92	2.66
STRAINS_M18	12322	0.00	0.01	0.99	0.99	0.00	0.00	0.05	1.00	1.01	-0.01	-0.68	12.02	6.84
IJGL_MP19	12322	0.00	0.01	0.99	0.99	0.00	-0.01	0.06	0.99	0.99	0.00	-0.07	15.35	3.84
HKWA	12322	0.00	0.01	0.99	0.99	0.00	-0.01	0.08	0.98	1.00	-0.01	1.28	13.48	3.92
HKWB	12322	0.00	0.01	0.99	0.99	0.00	0.00	0.07	0.99	1.01	-0.01	0.55	12.34	3.41

Wind from East: Linear statistics of hydrodynamic conditions modelled with Reference and Advanced conditions.

Condition	N [-]	Waterlevel					Current velocity magnitude					Current direction		
		Bias [m]	RMSE [m]	Symmetric Slope: (Adv) = a * (Ref) [-]	(Adv) = b * (Ref) + c		Bias [s]	RMSE [s]	Symmetric Slope: (Adv) = a * (Ref) [-]	(Adv) = b * (Ref) + c		Bias [deg]	RMSE [deg]	std [deg]
					b [-]	c [-]				b [-]	c [-]			
WALCRN2	8681	0.01	0.01	0.99	0.99	0.01	0.00	0.01	1.00	1.01	-0.01	0.14	0.62	1.19
WALCRN10	8681	0.01	0.01	0.99	0.99	0.01	0.00	0.01	1.00	1.00	0.00	0.13	2.65	1.15
WALCRN20	8681	0.00	0.01	0.99	0.99	0.00	0.00	0.03	1.00	1.00	0.00	-0.06	5.92	2.56
WALCRN30	8681	0.00	0.01	0.99	0.99	0.00	-0.02	0.07	0.96	0.94	0.01	-1.64	10.40	12.33
WALCRN50	8681	0.01	0.01	0.99	0.99	0.01	0.00	0.01	1.00	1.00	0.00	0.34	1.59	3.62
WALCRN70	8681	0.01	0.01	0.99	0.99	0.01	0.00	0.01	1.00	1.00	0.00	0.11	2.44	2.24
NOORDWK2	8681	0.00	0.01	0.99	0.99	0.00	0.00	0.03	1.00	0.98	0.00	0.31	10.77	2.92
NOORDWK4	8681	0.00	0.01	0.99	0.99	0.00	0.00	0.05	0.99	0.99	0.00	0.41	13.06	3.37
NOORDWK10	8681	0.00	0.01	0.99	0.99	0.00	-0.01	0.06	0.98	0.99	-0.01	0.11	17.52	5.76
NOORDWK20	8681	0.00	0.01	0.99	0.99	0.00	-0.06	0.12	0.89	0.85	0.01	0.70	25.38	6.00
NOORDWK30	8681	0.00	0.01	0.99	0.99	0.00	-0.04	0.10	0.92	0.86	0.03	0.96	20.12	17.05
NOORDWK50	8681	0.00	0.01	0.99	0.99	0.00	0.00	0.08	1.00	0.97	0.01	0.45	15.80	3.53
NOORDWK70	8681	0.00	0.01	0.99	0.99	0.00	-0.01	0.06	0.97	0.96	0.01	0.15	11.03	3.12
EURPFM	8681	0.00	0.01	0.99	0.99	0.00	0.00	0.01	1.00	1.00	0.00	-0.07	3.89	2.25
LICHTELGRE	8681	0.00	0.01	0.99	0.99	0.00	0.00	0.04	1.00	0.99	0.00	-0.23	7.96	2.73
STRAINS_M18	8681	0.00	0.01	0.99	0.99	0.00	0.00	0.05	0.99	1.01	-0.01	-0.70	10.43	10.33
IJGL_MP19	8681	0.00	0.01	0.99	0.99	0.00	-0.01	0.06	0.99	0.99	0.00	0.16	15.41	3.78
HKWA	8681	0.00	0.01	0.99	0.99	0.00	0.00	0.08	0.99	1.03	-0.02	1.22	14.14	9.73
HKWB	8681	0.00	0.01	0.99	0.99	0.00	0.00	0.07	1.00	1.02	-0.01	0.71	12.71	6.33

Wind from South-East: Linear statistics of hydrodynamic conditions modelled with Reference and Advanced conditions.

Condition	**N [-]**	**Waterlevel**					**Current velocity magnitude**					**Current direction**		
		Bias [m]	RMSE [m]	Symmetric Slope: (Adv) = a * (Ref) [-]	(Adv) = b * (Ref) + c b [-]	(Adv) = b * (Ref) + c c [-]	Bias [s]	RMSE [s]	Symmetric Slope: (Adv) = a * (Ref) [-]	(Adv) = b * (Ref) + c b [-]	(Adv) = b * (Ref) + c c [-]	Bias [deg]	RMSE [deg]	std [deg]
WALCRN2	6303	0.01	0.01	0.99	0.99	0.01	0.00	0.01	1.00	1.01	0.00	0.18	0.57	0.76
WALCRN10	6303	0.01	0.01	0.99	0.99	0.01	0.00	0.01	1.00	1.01	-0.01	0.23	3.17	2.21
WALCRN20	6303	0.00	0.01	0.99	0.99	0.00	0.00	0.03	1.00	1.00	0.00	0.15	6.28	1.99
WALCRN30	6303	0.00	0.01	0.99	0.99	0.00	-0.02	0.06	0.96	0.93	0.02	-1.53	10.05	2.96
WALCRN50	6303	0.01	0.01	0.99	0.99	0.01	0.00	0.02	0.99	1.00	0.00	0.20	2.54	18.02
WALCRN70	6303	0.01	0.01	0.99	0.99	0.01	0.00	0.01	1.00	1.00	0.00	0.10	1.93	2.37
NOORDWK2	6303	0.00	0.01	0.99	0.99	0.00	0.00	0.04	1.00	0.99	0.00	0.37	10.70	2.94
NOORDWK4	6303	0.00	0.01	0.99	0.99	0.00	0.00	0.05	0.99	0.98	0.00	0.76	12.65	3.58
NOORDWK10	6303	0.00	0.01	0.99	0.99	0.00	-0.01	0.07	0.99	1.00	0.00	1.14	18.14	3.93
NOORDWK20	6303	0.00	0.01	0.99	0.99	0.00	-0.07	0.12	0.87	0.84	0.02	0.19	24.85	6.06
NOORDWK30	6303	0.00	0.01	0.99	0.99	0.00	-0.03	0.10	0.93	0.83	0.05	0.40	18.78	4.79
NOORDWK50	6303	0.00	0.01	0.99	0.99	0.00	0.00	0.05	0.99	0.96	0.01	-0.27	10.44	3.08
NOORDWK70	6303	0.00	0.01	0.99	0.99	0.00	-0.01	0.04	0.98	0.96	0.01	-0.29	7.95	4.58
EURPFM	6303	0.00	0.01	0.99	0.99	0.00	0.00	0.01	1.00	1.00	0.00	0.02	1.47	2.35
LICHTELGRE	6303	0.00	0.01	0.99	0.99	0.00	0.00	0.03	0.99	0.98	0.01	0.11	5.63	2.60
STRAINS_M18	6303	0.00	0.01	0.99	0.99	0.00	0.00	0.04	1.00	0.99	0.00	-0.41	8.61	5.89
IJGL_MP19	6303	0.00	0.01	0.99	0.99	0.00	-0.01	0.06	0.99	1.00	-0.01	0.92	15.91	3.57
HKWA	6303	0.00	0.01	0.99	0.99	0.00	0.00	0.06	1.00	1.03	-0.01	0.49	9.76	3.25
HKWB	6303	0.00	0.01	0.99	0.99	0.00	0.00	0.04	1.00	1.00	0.00	0.28	9.34	2.99

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