

## The effect of wind wakes on hydrodynamic parameters

Coupling 3D DCSM-FM to WINS50 HARMONIE results



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# Summary

The present report deals with the way meteorological impacts of offshore wind farms (OWF's) can be taken into account in hydrodynamic modelling. In the first version of the hydrodynamic model used for Wozep (Zijl et al, 2020), the effect of OWFs on the meteorological forcing was approximated with a uniform neutral wind speed reduction of 10% within offshore wind farm areas, which is a relatively crude assumption. Moreover, 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. In addition, the impact on other meteorological parameters such as radiation, air temperature and dew point temperature, which play a role in the exchange of heat between air and water, is ignored.

In the present study, the impact of these assumptions was investigated by coupling to the HARMONIE meteorological model of KNMI, of which scenario computations exist that include the impact of OWF's. These scenarios are part of the WINS50 project where the situation of 2019 - 2021 with and without offshore wind farms, as well as a future 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.

Before being applied, the annual average impact of OWFs on some of the meteorological parameters used to force the 3D DCSM-FM hydrodynamic model was determined. While wake effects seem smooth in the annual average sense, the instantaneous effects can be more pronounced. Under the right atmospheric conditions, wake effects can be felt hundreds of kilometres downstream from OWFs. Also, the presence of OWFs not only affects wind speed, but also forcing parameters such as air temperature, dew point temperature and radiation. However, the effect of OWFs on these other parameters has only limited impact on the hydrodynamic results.

The impact of OWFs is introduced into the hydrodynamic model through two mechanisms: the presence of monopiles in the water column and changes in meteorological conditions. The impact of using WINS50 future hypothetical 2050 forcing to account for changes in meteorology due to the presence of OWFs is compared to the simplified approach with a 10% wind reduction in OWFs.

- In OWF areas with temperature stratification, there is a decrease in surface temperature and temperature stratification, due to enhanced vertical mixing, with wake effect visible in downstream direction. This is mainly caused by the presence of monopiles, while the changes in meteorology counteract this. The 10% wind reduction underestimates this counteracting effect.
- The presence of OWFs reduces the residual current magnitudes within the OWFs. Both the monopiles and changed meteorological conditions contribute to this. Downstream of the OWFs velocity deficits are also present, while in between OWFs increases in residual current magnitudes can occur. These changes are mainly caused by changing meteorological conditions. While the most significant pattern of impact due to changing meteorology is explained by the simplified 10% reduction approach, the use of WINS50 future hypothetical forcing results in larger areas being affected, especially surrounding OWFs.
- The presence of OWFs reduces the M2 tidal amplitude with more than 10 mm in the English Channel and German Bight, with smaller decreases in Belgian and Dutch coastal waters. The monopiles account for most of this decrease, with the change in meteorological conditions counteracting this in the German Bight. This counteracting effect is absent when using a 10% wind reduction instead.

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# 1 Introduction

## 1.1 Context

In the first version of the hydrodynamic model used for Wozep (Zijl et al, 2020), the effect of offshore wind farms (OWF's) on the meteorological forcing was approximated with a uniform neutral wind speed reduction of 10% within offshore wind farm areas, which is a relatively rough assumption. Moreover, 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. In addition, the impact on other meteorological parameters such as radiation, air temperature and dew point temperature, which play a role in the exchange of heat between air and water, is ignored.

It was proposed to investigate the impact of these assumptions by coupling to the HARMONIE meteorological model of KNMI, of which scenario computations exist that include the impact of OWF's. These scenarios are part of the WINS50 project 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 will be used as forcing of the hydrodynamic model that is part of the Wozep bottom-up model.

## 1.2 Guide to reader

This report includes information about the general approach and the hydrodynamic and meteorological models or data sets used (Chapter 2). In Chapter 3 the impact of OWFs on meteorological parameters is described, whereas Chapter 4 deals with the hydrodynamic results of the various scenario computations. Conclusions and recommendations are presented in Chapter 5.

## 2 Approach

### 2.1 Introduction

The idea for this study is to compute the impact of OWFs using WINS50 meteorological forcing obtained from HARMONIE runs with and without OWF's. The resulting impact can then be compared to the previous approach where the neutral wind speed was reduced by 10% within OWFs. Since the domain of HARMONIE is smaller than our 3D DCSM-FM hydrodynamic model domain, these HARMONIE results are supplemented with ERA5 data. ERA5 also provided the boundary conditions to the WINS50 HARMONIE model setup. In this chapter, the 3D DCSM-FM hydrodynamic model as well as the WINS50 and ERA5 meteorological datasets are presented. Furthermore, validation results from this hydrodynamic-meteorological model combination are presented.

### 2.2 3D DCSM-FM

For the hydrodynamic modelling described in the present report, the 2022 release of the 3D Dutch Continental Shelf Model – Flexible Mesh (3D DCSM-FM) is used. A detailed description of this model can be found in Zijl et al. (2023). Key characteristics are presented below. This study uses an upgraded model version, *dflowfm3d-noordzee\_0\_5nm-j22\_6-v1a*, compared to the one used in the previous study for the Wozep program (Zijl et al., 2021). While the model schematization has changed in many aspects and the accuracy has improved, test computations have shown that the impact of OWF's computed with this improved model version does not differ significantly from the impact computed with the original model version (Zijl et al., 2020).

For the computations presented in this report, use has been made of D-HYDRO weekly release version 2.25.14.78641 (September 23, 2023).

#### 2.2.1 Network and bathymetry

The 3D DCSM-FM has a horizontal grid resolution of 800m to 900m in the southern North Sea and Dutch coastal waters. The grid resolution decreases towards deeper water and the model boundaries.

The vertical discretization consists of 20 sigma layers equidistantly distributed over the vertical at depths of 100m or less. Below a depth of 100m, z-layers are added underneath. The thickness of these z-layers increases exponentially towards the bottom, with a factor 1.19 and starting from a thickness of 5 m. The maximum number of z-layers applied is 30, which only occurs in the deepest part of the model. Together with the 20 sigma layers in the upper part of the water column, this yields a maximum of 50 vertical layers.

The bathymetric and geometric information is obtained from Baseline-NL, which is an ArcGIS database used for hydrodynamic model development at Rijkswaterstaat. For areas outside the Rijkswaterstaat management area, bathymetry has originally been derived from a gridded bathymetric dataset (December 2020 version) from the European Marine Observation and Data Network (EMODnet). The resulting bathymetry and model extent are presented in Figure 2.1.

#### 2.2.2 Calibration

The bottom roughness in 3D DCSM-FM has been used as a calibration parameter to improve tide propagation. A spatially varying Manning roughness coefficient is determined using data-

assimilation techniques by running the model in 2D mode using more than 200 tide gauge stations covering the full model domain.

### 2.2.3 **Open boundary forcing**

The open boundary of the model is located off the Northwest European Shelf at 15°W, 43°N and 64°N. Tidal water levels at this boundary are forced using 39 tidal constituents, based on a blend of three different global sources, namely FES2014 (Lyard et al., 2021), GTSMv4.1 (Muis et al., 2016) and EOT20 (Hart-Davis et al., 2021). Surge water levels at the open boundaries are approximated with a so-called inverse barometer correction, which depends on the local time-varying air pressure. Additional oceanographic forcing at the open boundaries is taken from a global reanalysis<sup>1</sup> by the Copernicus Marine Service (CMEMS). This consists of the hourly sea levels as well as daily profiles of advective velocity, temperature and salinity at each of the 209 boundary forcing locations. In addition, the temperature and salinity profiles are used as initial conditions to reduce the model's spin-up time.

### 2.2.4 **Freshwater discharges**

Freshwater discharges from rivers are included as a climatological monthly mean discharge rate with associated water temperatures from E-HYPE. The main discharges in the Netherlands are replaced with observed discharges.

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<sup>1</sup> Global Ocean Physics Analysis and Forecast (<https://doi.org/10.48670/moi-00016>)

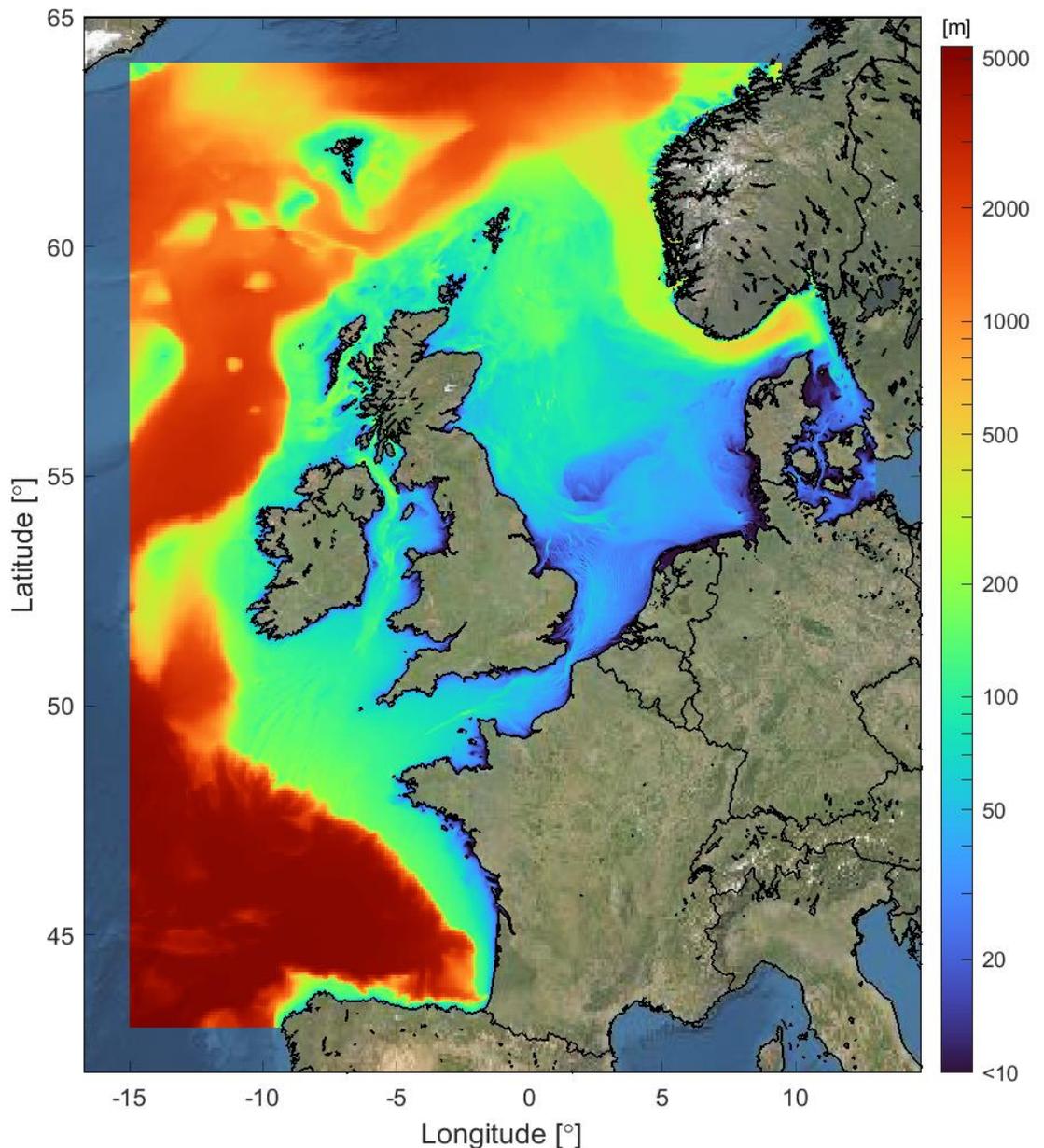


Figure 2.1 \_ Overview of the model bathymetry in 3D DCSM-FM on a logarithmic scale (depth relative to MSL)

## 2.3 Meteorological datasets (WINS50 and ERA5)

### 2.3.1 WINS50

HARMONIE-AROME (HIRLAM ALADIN Research On Mesoscale Operational NWP in Europe) is the operational Numerical Weather Prediction model of KNMI since 2012. It is a limited area model, that was developed by a consortium involving many European countries. A detailed description of the HARMONIE can be found in Bengtsson et al. (2017). A version of this model (cycle 43h2.1) was also used in the WINS50 project to create homogeneous meteorological datasets with and without the effects of a large upscaling of the wind energy capacity in the North Sea. The WINS50 datasets contains hourly data with a spatial resolution of 2.5 by 2.5 km. The full model domain is shown as a yellow box in Figure 2.2. While only the domain in the red box is publicly available through the KNMI Data Portal, the relevant data for the full domain (yellow box) was provided by KNMI for the purpose of this study.

The WINS50 study has resulted in three HARMONIE-based data sets, differing in the presence of OWFs:

- A reference simulation without any OWFs for the years 2019, 2020, and 2021;
- A simulation including the OWFs present at the start of each year, for the years 2019, 2020 and 2021;
- A one-year simulation including the effects of a hypothetical 2050 offshore capacity scenario, using the weather conditions from 2020).

More details on the WINS50 project can be found on the project website (<https://wins50.nl/>).

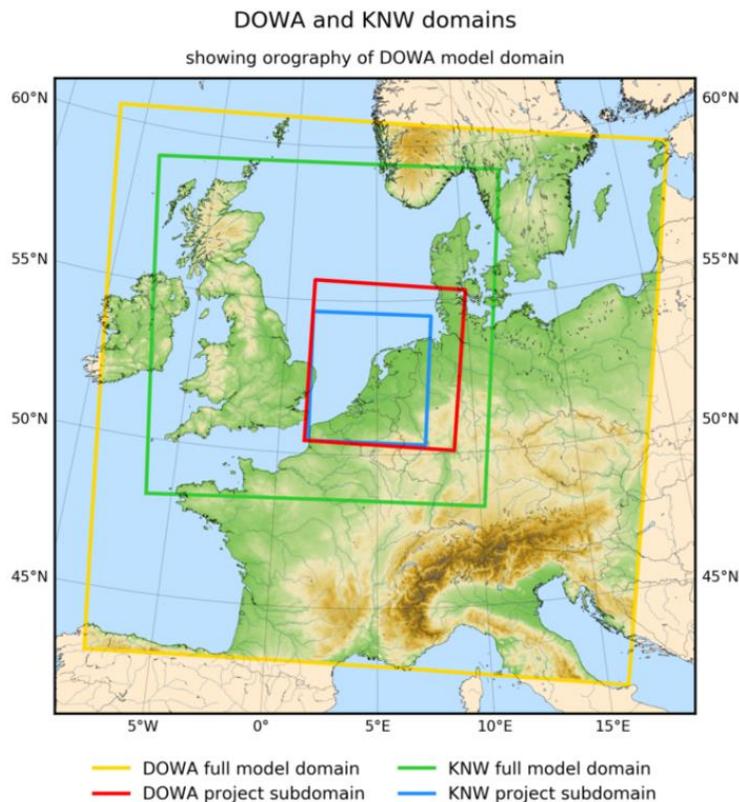


Figure 2.2 \_ Publicly available WINS50 subdomain (red) and full domain of WINS50/HARMONIE (yellow)

#### *WINS50 2050 future hypothetical scenario*

For the present study use has been made of the reference scenario and the 2050 future hypothetical scenario. The latter scenario considers 2020 weather conditions and combines them with a hypothetical projection of installed offshore wind farm capacity that is anticipated for the year 2050. This projection however differs from the Wozep future hypothetical scenario used in Zijl et al. (2021).

Details on operational offshore wind farms and turbine types were obtained by KNMI from various sources. Most of the turbine locations are obtained from OpenStreetMap. For some wind farms, no turbine locations were available at the time of the model simulation. For these wind farms, the boundaries were taken from a wind farm shapefile provided by the European Marine Observation and Data Network (EMODnet), and then the required number of turbines was evenly distributed within the wind farms boundaries. Future hypothetical wind farms were characterized by maximum wind farm size, uniform capacity density, and turbine power varying depending on the time of commission. The location and overall capacity of wind farms were derived using the Wozep 2050 hypothetical upscaling scenario as a starting point. Turbine width was determined based on (expected) turbine type and varied between 6 and 15 MW.

More details on the wind farms parametrization in the HARMONIE model can be found in van Stratum et al. (2022). The effect of wind farms was included in HARMONIE using the wind farm parameterization by Fitch et al. (2012). In this parameterization, wind turbines act as a sink of momentum leading to a local reduction in the wind speed. The extracted momentum not used for power production 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 hydrodynamic model.

### 2.3.2 ERA5

Since the WINS50 HARMONIE dataset covers an area smaller than the 3D DCMS-FM domain, these data were supplemented with data from ERA5, a reanalysis dataset by ECMWF for the global climate and weather for the past 8 decades. An overview of ERA5 datasets is presented by Hersbach et al. (2020). ERA5 provides hourly estimates for atmospheric and ocean-wave quantities with a spatial and temporal resolution of 0.25 degrees and 1 hour, respectively, for the atmospheric quantities. ERA5 data was also used during the development and validation of 3D DCMS-FM and was used to provide lateral boundary conditions for the WINS50 HARMONIE runs.

The full WINS50 model domain does not cover the entire domain of the 3D DCMS-FM model. Therefore, WINS50 data is supplemented by ERA5 in the outer parts of the modelling area. As the boundary condition for HARMONIE model version used to create the WINS50 dataset was forced with ERA5 data, the transition between the two datasets is relatively smooth and does not require any preprocessing. An example of the blended ERA5/WINS50 data is given in Figure 2.3 for wind speed magnitude and 2m air temperature.

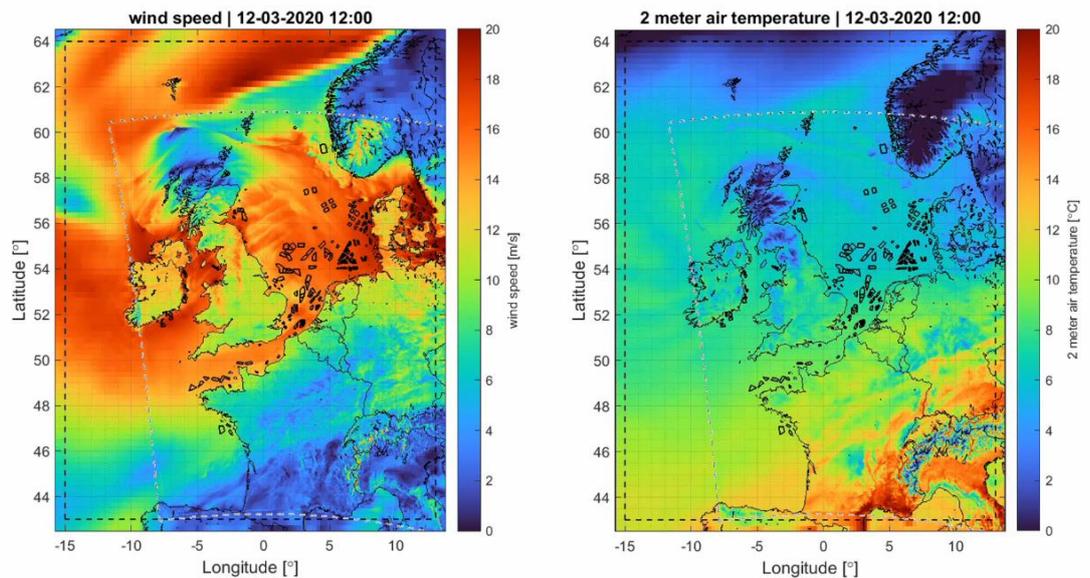


Figure 2.3 \_ Snapshot on 12-03-2020 12:00 of blended ERA5/WIND50 meteorological forcing data for wind speed magnitude (left) and 2m air temperature (right) in DCMS domain (black dashed line: 3D DCMS-FM domain, grey dashed line: WINS50 domain).

### 2.3.3 Meteorological parameters

3D DCMS-FM uses ten different meteorological forcing variables to compute surface fluxes for momentum, heat and mass. Since not all these variables are available from the WINS50 dataset, some had to be converted from other variables. The variables used are listed in Table 2.1 together with the conversion applied.

When 3D DCSM-FM is forced with ERA5 data, the air-sea momentum flux is computed based on the neutral wind speed at 10 m height. For consistency with the Atmospheric Boundary Layer in ERA5, a Charnock formulation with the same temporally and spatially varying Charnock coefficient is used. However, since HARMONIE uses a different approach and the neutral wind speed and Charnock coefficient were not available, two different ways of prescribing the relevant forcing were considered:

1. Applying the 10-meter wind speed, and for the conversion to wind stress (in D-HYDRO) assuming a uniform and constant Charnock coefficient as well as neutral atmospheric conditions. This approach implies that the stress computed by HARMONIE is inconsistent with the stress used by 3D DCSM-FM.
2. Deriving the 10-meter neutral wind speed based on the wind stress, using the same Charnock coefficient and air density as used in D-HYDRO to convert to stress again. In this manner, while wind speed is prescribed, the stress eventually applied is consistent with the wind stress computed by HARMONIE. The disadvantage, however, is that the derived wind speed is inconsistent with HARMONIE and might affect the turbulent heat fluxes.

While not attempted, a third possibility would have been to infer the Charnock coefficient from both the HARMONIE wind speed and stress, and impose this time- and space varying Charnock together with the original wind speed. This would allow for consistency in both wind and stress, although the turbulent heat fluxes might still differ due to the use of different formulations in D-HYDRO compared to HARMONIE.

Validation computations were run for both methods. The results were evaluated with respect to accuracy of water levels (surge and tide) and water temperature. The impact on seasonal temperature stratification in the Central North Seas was also assessed. Eventually, the second method (i.e., using a stress-equivalent wind) was selected since this gave more accurate results in terms of water levels and, more importantly for this application, results in terms of temperature stratification that were more consistent with the calibrated results based on ERA5 (in a different validation period). However, the quality of the computed (surface) water temperature was slightly better with the first method.

Table 2.1 List of meteorological forcing parameters from ERA5 and corresponding parameters from WINS50.

ERA5 variable name	WINS50 parameter (long name)	Comment
Pressure at mean sea level	psl (air_pressure_at_sea_level)	-
U-component of neutral wind velocity at 10m	tauu (accumulated_surface_downward_eastward_stress)	Converted from stress using Charnock value of 0.010 and air density of 1.2265kg/m <sup>3</sup>
V-component of neutral wind velocity at 10m	tauv (accumulated_surface_downward_northward_stress)	Converted from stress using Charnock value of 0.010 and air density of 1.2265kg/m <sup>3</sup>
Charnock parameter	-	Value of 0.010 assumed
Dewpoint temperature at 2m	huss (specific_humidity) psl (air_pressure_at_sea_level)	Converted from specific humidity and pressure
Air temperature at 2m	tas (air_temperature)	-
Surface net solar radiation	rsns (accumulated_surface_net_shortwave_flux_in_air)	-
Surface thermal radiation downwards	rlds (accumulated_surface_downwelling_longwave_flux_in_air)	-

<b>Mean total precipitation rate</b>	prrain (rainfall_amount) prsn (snowfall_amount) prgrpl (graupel_amount)	Sum of rainfall, snowfall and graupel, converted to mm/day assuming a water density of 1000 kg/m <sup>3</sup>
<b>Mean evaporation rate</b>	hfls_eva (accumulated_surface_upward_latent_heat_flux_evaporation) hfls_sbl (accumulated_surface_upward_latent_heat_flux_sublimation)	Converted from latent heat flux (evaporation and sublimation) assuming latent heat of vaporization and sublimation of 2.5008*10 <sup>6</sup> J/kg and 2.8345*10 <sup>6</sup> J/kg, respectively

## 2.4 3D DCSM-FM model validation

The 3D DCSM-FM model has been validated extensively (Zijl et al., 2023, Zijl & Laan, 2022, Groenenboom & Zijl, 2022). Since this was for a different period and with different meteorological forcing (ERA5), some additional validation on water levels and water temperature has been added here, covering the scenario year (2020).

### 2.4.1 Total water levels, tide and surge

The mean model skill in terms of Root Mean Square Error (RMSE) for the tide, surge and total water level for twelve tide gauge stations along the Dutch coast is summarized in Table 2.2. The table shows that using WINS50/ERA5 meteorological forcing (without OWFs) slightly improves the mean surge representation, from 4.6 cm to 4.5 cm, compared to using only ERA5. This also leads to an improvement of the total water level quality, from 6.1 cm to 6.0 cm.

Table 2.2 Mean statistics (RMSE in cm) of the tide, surge and total water level for the year 2020 of twelve tide gauge stations along the Dutch coast.

	RMSE tide (cm)	RMSE surge (cm)	RMSE total water level (cm)
ERA5	3.9	4.6	6.1
WINS50 (+ERA5)	3.9	4.5	6.0

### 2.4.2 Water temperature

In Table 2.3, the quality of the sea surface temperature representation is shown for several stations in the Dutch North Sea. These results show a systematic underestimation of sea surface temperature by on average 0.59 °C and an average RMSE of 0.70 °C, when using WINS50/ERA5 meteorological forcing. This is slightly worse compared to using ERA5 only, where the average bias and RMSE were -0.33 °C and 0.47 °C, respectively. If instead of the WINS50 stress-derived wind speed, the published WINS50 wind speed had been used, the average bias would have been smaller (-0.50 °C), resulting in a smaller RMSE (0.63 °C).

Figure 2.4 shows timeseries and scatterplots of modelled and measured sea surface temperature for station Lichteiland Goeree, using ERA5 forcing as well as WINS50/ERA5 forcing.

Table 2.3 Overview of the sea surface temperature quality (bias, standard deviation and RMSE in °C) for several stations in the Dutch North Sea, for the year 2022.

#	Station	ERA5			WINS50/ERA5		
		bias	std	RMSE	bias	std	RMSE
1	Eierlandse Gat	-0.42	0.32	0.53	-0.66	0.34	0.74
2	Lichteiland Goeree	-0.12	0.36	0.38	-0.37	0.50	0.62
3	Platform K13a	-0.38	0.33	0.51	-0.55	0.28	0.62
4	Q1	-0.24	0.25	0.35	-0.46	0.25	0.52
5	Vlissingen	-0.50	0.28	0.57	-0.93	0.36	1.00
	<b>Average</b>	<b>-0.33</b>	<b>0.31</b>	<b>0.47</b>	<b>-0.59</b>	<b>0.35</b>	<b>0.70</b>

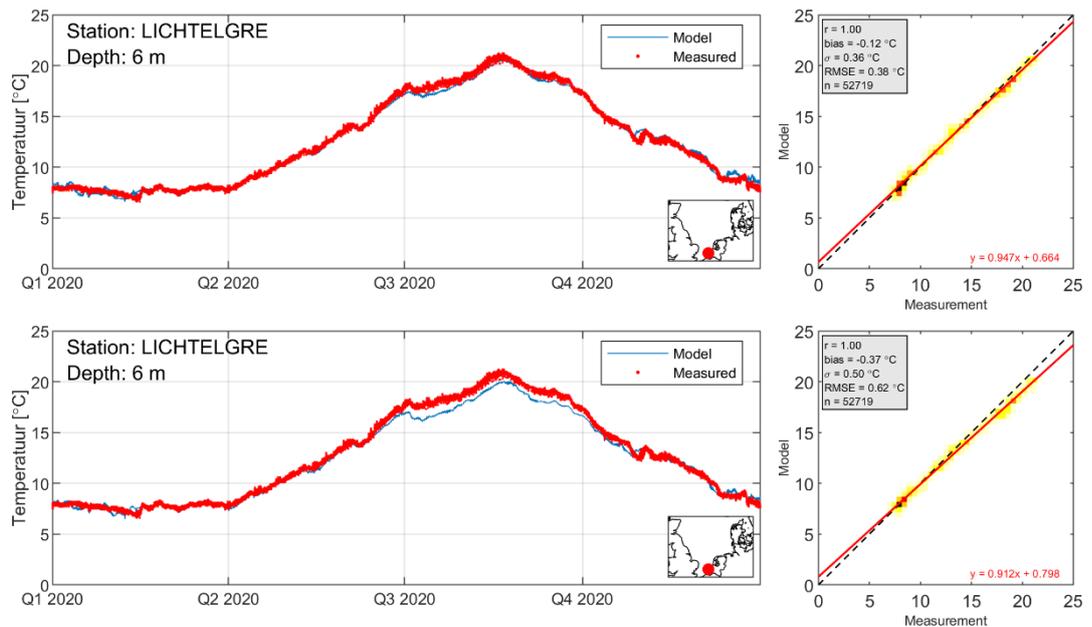


Figure 2.4\_ Timeseries (blue: model, red: measurement) and scatterplot (year: 2020) of the water temperature in station Lichteiland Goeree, using ERA5 (top) and a blend of WINS50/ERA5 (bottom) meteorological forcing.

## 2.5 Implementation of offshore wind farms

### 2.5.1 Parameterization of piles

With a grid size of 900 m or larger, monopiles of offshore windfarms are too small to explicitly include in the model schematization. Therefore, a sub-grid approach is used. This approach, a quadratic sink term, is included in the horizontal momentum equations. In each vertical model layer, the energy extracted from the main flow  $A_{in}$  in this manner is at the same time reintroduced as a source term in the equation for turbulent kinetic energy ( $k$ ). This approach was originally implemented in Delft3D FM for modelling the effect of vegetation (Deltares, 2024).

Locations of offshore windfarms are specified in the model by means of a polygon along its boundaries. In each computational cell within this polygon the appropriate sink and source terms are computed considering the pile density (number of piles per unit of area) and the mean pile diameter. In this study, a pile density of 0.85 piles/km<sup>2</sup> and a pile diameter of 8 m diameter were assumed for all OWF's, independent of the year of construction. This is different

from the assumption in Zijl et al. (2021), where these numbers depend on the construction year.

## 2.5.2 Changes in meteorological conditions

In this study we compare two approaches to include the effect of OWFs in meteorology in our hydrodynamic model. The new method considered here, the use of data from the HARMONIE meteorological model in which OWFs have been included with a sub-grid approach, has been described above. The results from this method are compared to the simplified approach that has been used in Zijl et al. (2021).

### *Simplified approach*

Since the ERA5 meteorological forcing usually applied to force 3D DCMS-FM does not include the impact of the windfarms, this has been included in earlier studies in a simplified manner, through a 10% reduction of the 10-meter wind speeds ( $U_{10}$ ) within the boundaries of the wind farms. Other meteorological forcing parameters, such as long wave and short wave radiation, air temperature and dew point temperature, are left unchanged. Wake effects and directional changes of the wind are not considered.

## 3 Impact on meteorological parameters

### 3.1 Annual average effects

In this section, the annual average impact of OWFs on some of the meteorological parameters used to force the 3D DCSM-FM hydrodynamic model is presented. For this analysis all available hourly WINS50 output within the year 2020 is used. For the average values presented the WINS50 control run (without OWFs) is used. For the differences this field is subtracted from the average values based on the WINS50 2050 future hypothetical scenario.

#### 3.1.1 Wind speed magnitude

The annual average 10m wind speed and the difference therein due to the presence of OWFs in the 2050 future hypothetical scenario are presented in Figure 3.1. These results show that within the OWFs, the wind speed deficit can reach more than 1 m/s, especially where OWFs are clustered, such as in the German Bight. This value amounts to around 10-15% of the annual average value in the region. Around the OWFs the annual average is affected by wake effects, with average velocity deficits of more than 0.1 m/s seen up to tens of kilometres away. These wake effects were not taken into account in previous Wozep model studies, such as Zijl et al. (2021).

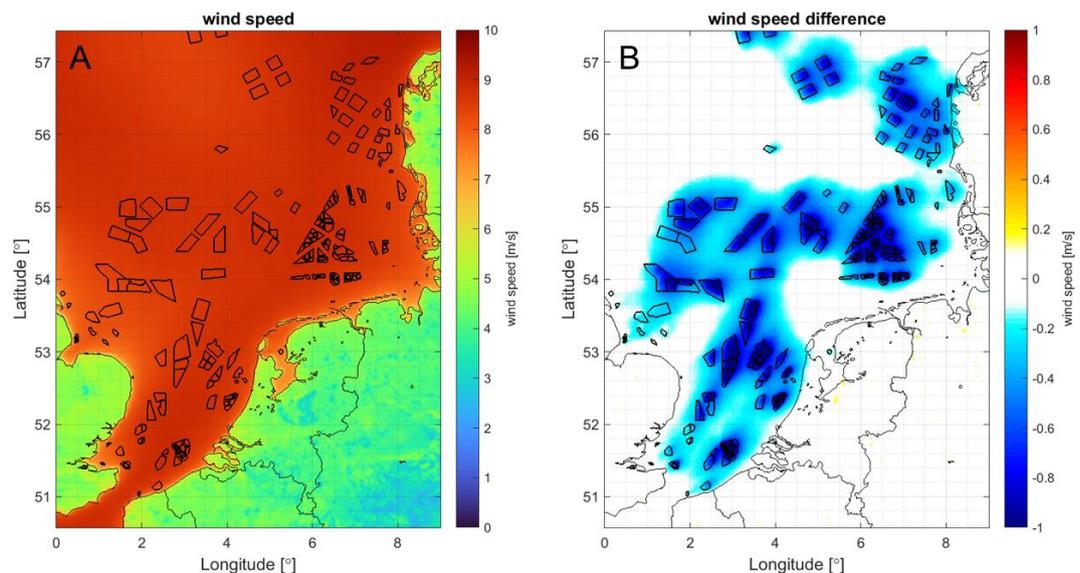


Figure 3.1 – Annual average 10m wind speed (A) and impact on 10m wind speed (B) due to the presence of OWFs in the WINS50 2050 future hypothetical scenario.

#### 3.1.2 Air temperature

The annual average 2m air temperature and the difference therein due to the presence of OWFs in the 2050 future hypothetical scenario are presented in Figure 3.2. These results show that the air temperature within the OWFs increases with around 0.1 – 0.4 °C or up to 3% of the annual average. Outside the OWFs the differences gradually decrease in magnitude. The impact on air temperature was not taken into account in previous Wozep model studies.

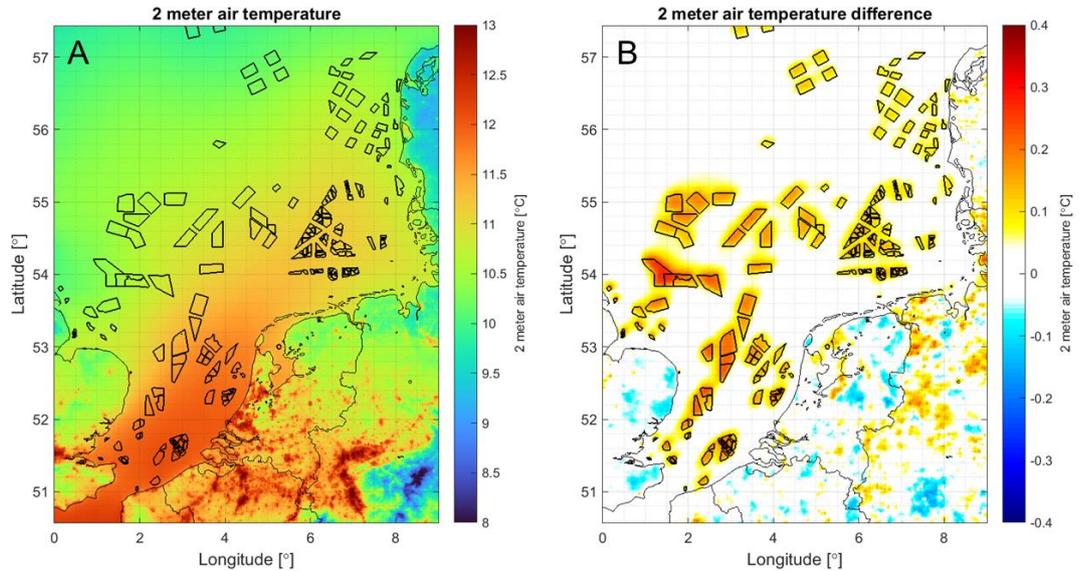


Figure 3.2 – Annual average 2m air temperature (A) and impact on 2m air temperature (B) due to the presence of OWFs in the WINS50 2050 future hypothetical scenario.

### 3.1.3 Dew point temperature

The annual average 2m dew point temperature and the difference therein due to the presence of OWFs in the 2050 future hypothetical scenario are presented in Figure 3.3. These results show that the dew point temperature within the OWFs increases with around 0.1 – 0.4 °C or up to 5% of the annual average. Outside the OWFs the differences gradually decrease in magnitude. Both the decrease in dew point temperature and increase in air temperature contribute to a decrease in relative humidity due to presence of OWFs. The impact on dew point temperature was not taken into account in previous Wozep model studies.

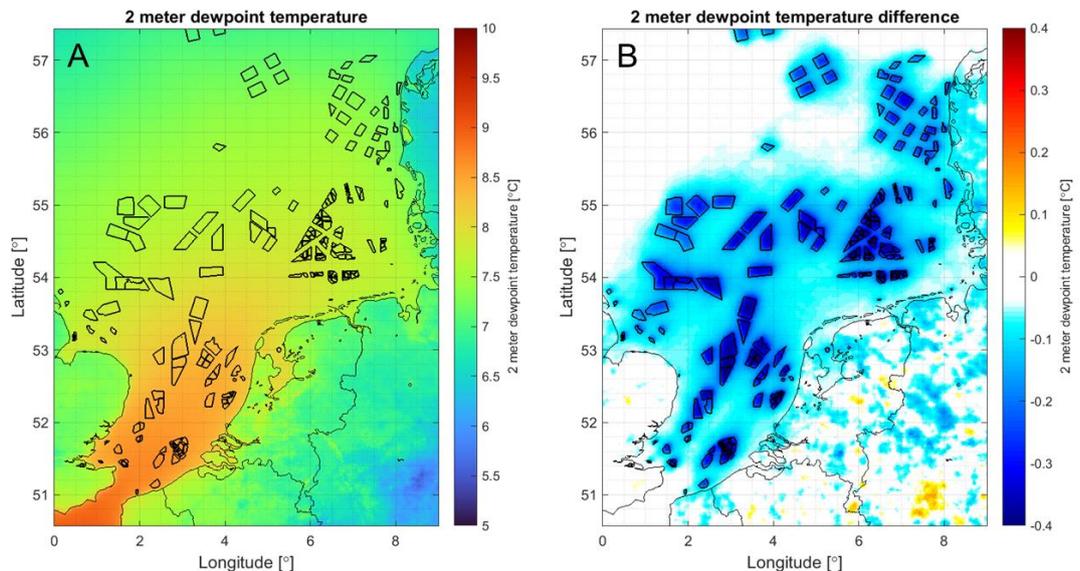


Figure 3.3 – Annual average 2m dewpoint temperature (A) and impact on 2m dewpoint temperature (B) due to the presence of OWFs in the WINS50 2050 future hypothetical scenario.

### 3.1.4 Evaporation rate

The annual average evaporation rate and the difference therein due to the presence of OWFs in the 2050 future hypothetical scenario are presented in Figure 3.4. Note that since negative numbers indicate an upwelling evaporative flux, positive differences indicate a decrease in evaporation. These results show a decrease in evaporation rate of 0.1 – 0.3 mm/day within most OWFs, which amounts to up to 10% of the annual average value without OWFs present. Outside the OWFs the impact on evaporation rate gradually decreases in magnitude. North of the Wadden Sea a slight increase in evaporation rate is visible.

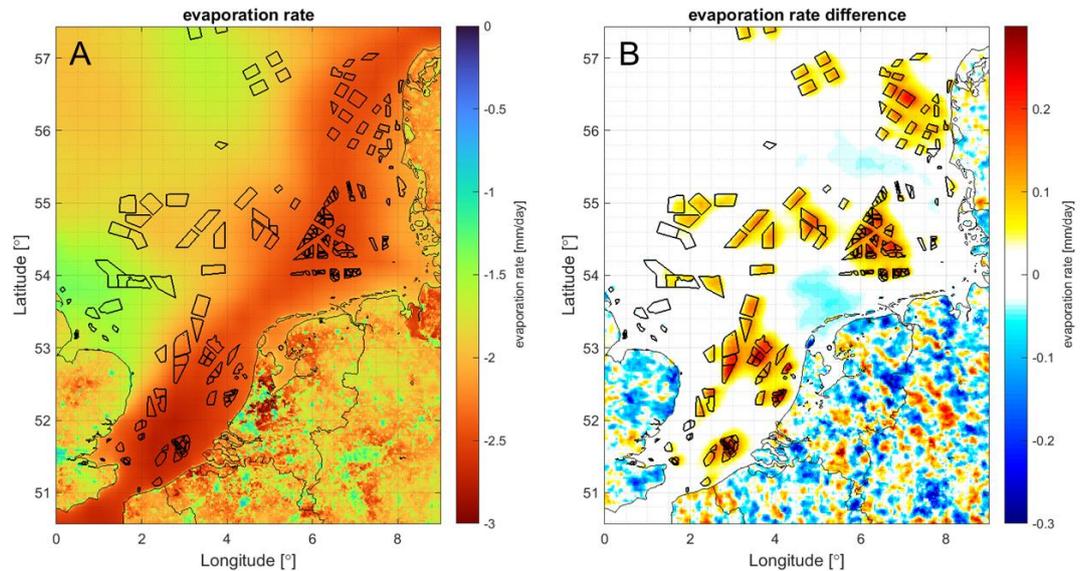


Figure 3.4 – Annual average evaporation rate (A) and impact on evaporation rate (B) due to the presence of OWFs in the WINS50 2050 future hypothetical scenario.

### 3.1.5 Net solar radiation

The annual average net surface short wave (solar) radiation and the difference therein due to the presence of OWFs in the 2050 future hypothetical scenario are presented in Figure 3.5. The net short-wave radiation within the OWFs decreases by up to 4 W/m<sup>2</sup> or approximately 1 to 2% of the annual average value. Outside the OWFs areas the impact is smaller with both increases and decreases in solar radiation visible. The impact on solar radiation is presumably caused by enhanced presence of clouds due to OWF's.

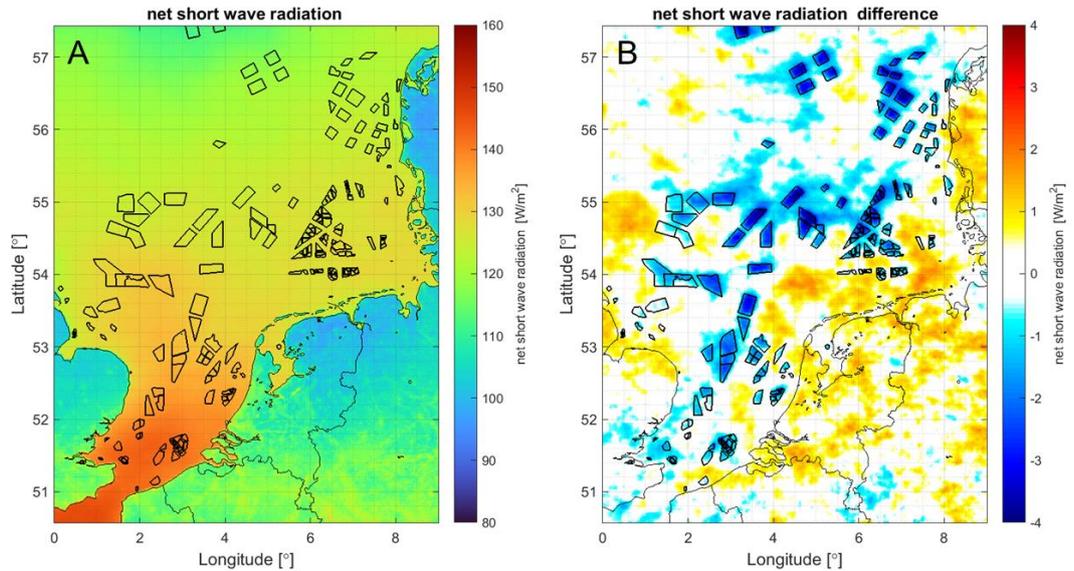


Figure 3.5 – Annual average net surface short wave radiation (A) and impact on net surface short wave radiation (B) due to the presence of OWFs in the WINS50 2050 future hypothetical scenario.

### 3.1.6 Downwelling long wave radiation

The annual average surface downwelling long wave radiation and the difference therein due to the presence of OWFs in the 2050 future hypothetical scenario are presented in Figure 3.6. The increase in downwelling long wave radiation reaches up to 4 W/m<sup>2</sup>, which corresponds to around 1% of the annual average value. Note that the sign of the impact is opposite to the impact on short wave radiation. Outside the OWFs, the long wave radiation generally decreases.

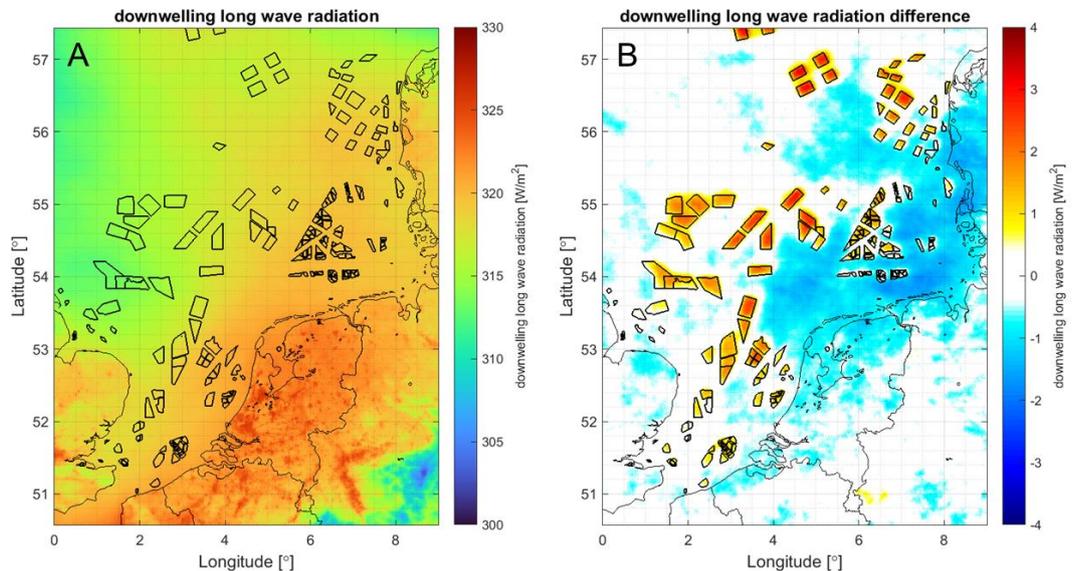


Figure 3.6 – Annual average surface downwelling long wave radiation (A) and impact on surface downwelling long wave radiation (B) due to the presence of OWFs in the WINS50 2050 future hypothetical scenario.

### 3.2 Instantaneous effects

In the previous section, annual average differences were presented. Note however that the spatial patterns of the impact, as well as the sign of the impact can vary over time, depending on for example the season as well as meteorological conditions, such as atmospheric stability. In Figure 3.7 the annual average impact on the 10m wind speed is compared to the impact on an arbitrary moment in time. This shows that while the wake effects seem smooth in the annual average sense, the instantaneous effects can be more pronounced. These results also shown that under the right conditions, wake effects can be felt hundreds of kilometres downstream from OWFs.

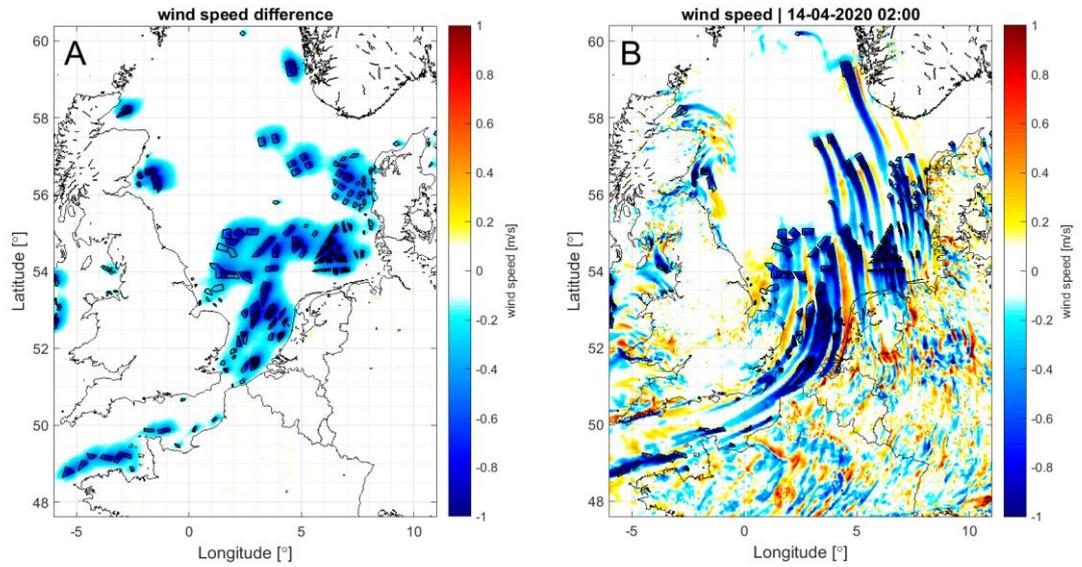


Figure 3.7 - Annual average (A) and instantaneous (B) impact on 10m wind speed due to the presence of OWFs in the WINS50 2050 future hypothetical scenario.

# 4 Results

## 4.1 Scenario computations

Effects of the wind farms and the meteorological forcing used are calculated by taking the difference between a simulation without and a simulation with certain dataset or measure included. The five simulations used for the present study are presented in Table 4.1.

The OWF scenario considered consists of the WINS50 future hypothetical scenario, for which the environmental forcing conditions of the year 2020 have been used. The year 2019 has been used as spin-up, using meteorological forcing from the WINS50 control run (without OWFs).

Table 4.1 Definition of scenario computations, in which 'pol 2050' refers to a polygon specifying the OWF's in the WINS50 2050 hypothetical upscaling scenario.

Computation #	WINS50 version	10% wind red.	OWF piles	year	restart from
1	control	-	-	2019-2020	-
2	WFP2050	-	2050 pol	2020	1
3	control	-	2050 pol	2020	1
4	control	2050 pol	2050 pol	2020	1
5	wind: WFP2050 other: control	-	2050 pol	2020	1

Based on the results of these computations various comparisons are made, which are listed in Table 4.2 List of comparisons made. The numbers refer to the scenario computations listed in Table 4.1. This table includes also shows the section of the current report where the results of the comparison are presented and discussed.

Table 4.2 List of comparisons made. The numbers refer to the scenario computations listed in Table 4.1.

Comparison #		Method 1	Method 2	Section #
1	Reference situation	#1	-	4.3
2	Effect of meteo and piles	#2 minus #1	#4 minus #1	4.4
3	Effect of piles only	#3 minus #1	-	4.5
4	Effect of meteo only	#2 minus #3	#4 minus #3	4.5
5	Effect of wind only	#5 minus #3	#2 minus #3	4.6

## 4.2 Presented parameters

To assess the effects of offshore wind farms on the hydrodynamics, multiple parameters are determined and compared:

- Surface temperature
- Temperature stratification
- Salinity stratification
- Amplitude and phase of the M2 tide
- Residual current magnitude
- Bed shear stress (excluding waves)

Where surface or near-bed values are used, these are taken from the layer highest or lowest in the water column, respectively. This concerns the results for salinity, temperature, and residual currents. Contrary to Zijl et al. (2021), where a model version with a uniform number of sigma-layers was used, the layer number of the bottom layer now varies per computational cell. Salinity and temperature stratification are defined here as the differences between the salinity and temperature values in the top and bottom layers. Water levels (including the M2 tide) and bed shear stress due to currents are two-dimensional quantities, without a vertical component.

For this study, the average values over an entire simulated year (2020) are calculated. To determine the temporal averages over these long periods the 'Fourier' module of D-HYDRO is used. This module calculates the mean values over all simulated timesteps by means of statistical analysis during the model simulation. This allows to store model results in the most accurate and, at the same time, efficient way since it removes the need to write 3D output at a very high temporal interval for post-processing after the simulation.

Furthermore, the 'Fourier' module allows for a simple tidal analysis. Based on the number of cycles within the analysis time frame, as well as prescribed nodal amplification factor and astronomical argument, an approximation of the spatial field of the M2 tidal amplitude and phase is calculated during the computation.

Effects of the wind farms and the meteorological forcing used are calculated by taking the difference between a simulation without and a simulation with certain dataset or measure included.

## 4.3 Reference situation

Visualizations of the spatial patterns of the annual mean of each presented variable and a brief description thereof are available in Zijl et al. (2021). For completeness, these fields have been recomputed with the current model version and added below based on the reference simulation without windfarms. In the reference scenario, the effect of the offshore wind farms is neglected entirely, including that of the already present wind farms. Meteorological forcing is taken from the WINS50 control run, which excludes OWFs.

### 4.3.1 Temperature and salinity

In Figure 4.1 the annual mean bottom and surface salinity are presented for the year 2020 in the reference situation without OWFs, while in Figure 4.2 this is done for the annual mean salinity stratification. Similarly, this is presented for temperature and temperature stratification in Figure 4.3 and Figure 4.4. In these figures the amount of stratification is determined by subtracting the annual mean value in the top model layer from that in the bottom model layer.

The overall pattern of the stratification is in line with the expected spatial variation (Van Leeuwen et al., 2015). A permanently mixed area is present in the most southern part of the North Sea, between the United Kingdom and the Netherlands. The central North Sea shows a large area with temperature stratification. As expected, temperature stratification (and to some extent salinity stratification) is distinctly reduced in the shallower waters of the Dogger Bank, while mean surface temperatures are higher. Along the coast temperature stratification is weaker due to vigorous tidal mixing, but the effect of the ROFIs attaching to the coast is clearly visible in the salinity stratification.

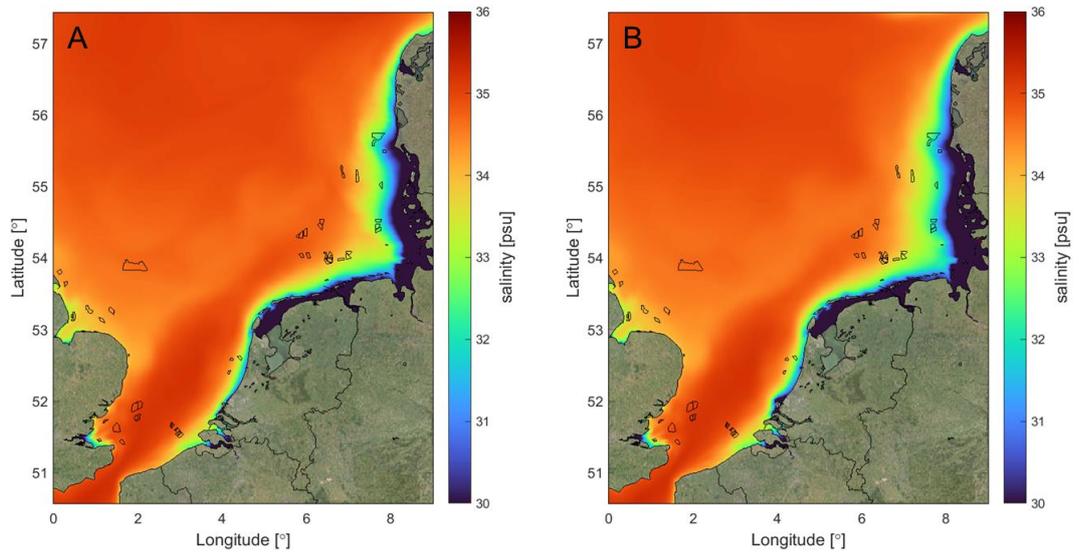


Figure 4.1 – Annual mean bottom salinity (A) and surface salinity (B) in the reference simulation.

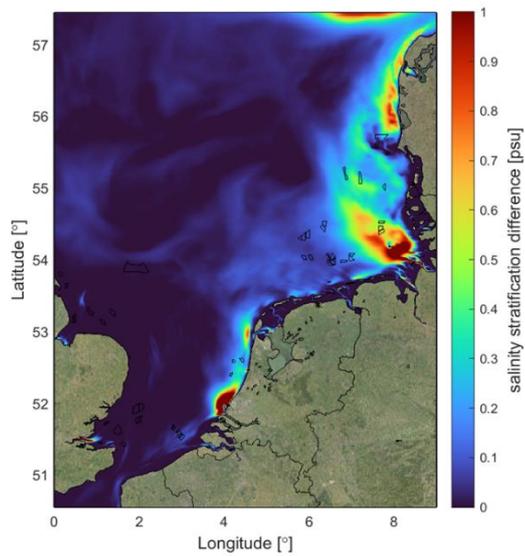


Figure 4.2 – Annual mean salinity stratification in the reference simulation.

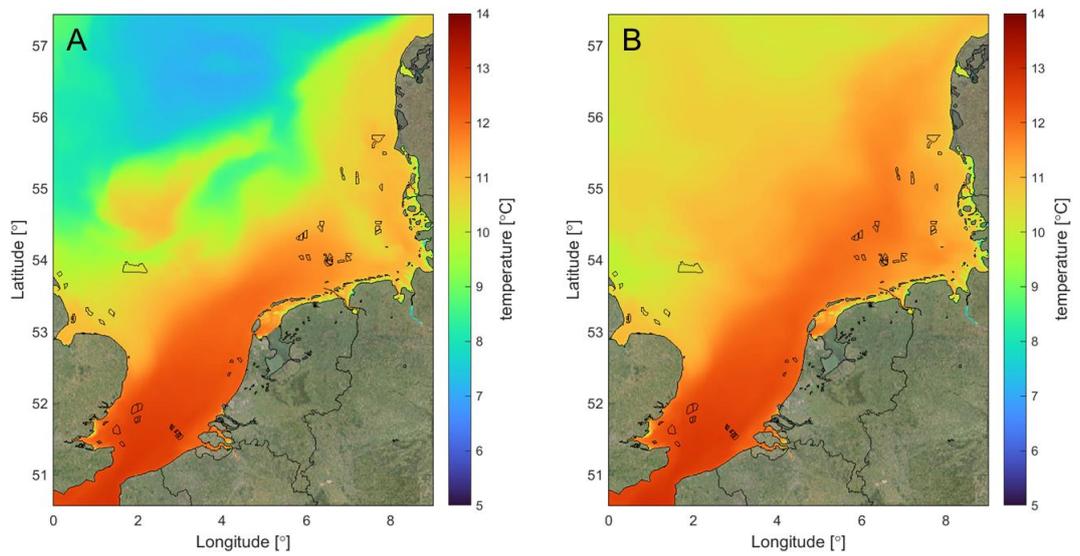


Figure 4.3 – Annual mean bottom temperature (A) and surface temperature (B) in the reference simulation.

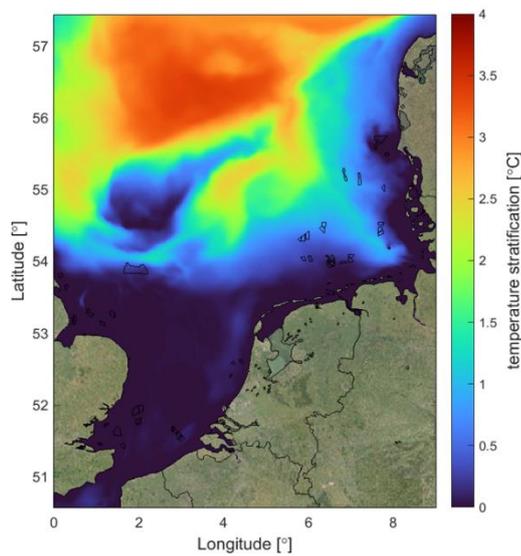


Figure 4.4 – Annual mean temperature stratification in the reference simulation.

### 4.3.2 Residual currents

In Figure 4.5 the magnitude of the annual mean (residual) currents at the surface and near the bottom are presented for the year 2020. These show the residual circulation at the surface roughly following a counter-clockwise pattern, with residual current at the bottom much lower than at the surface. As expected, the residual transport through the English Channel is in the direction of the North Sea.

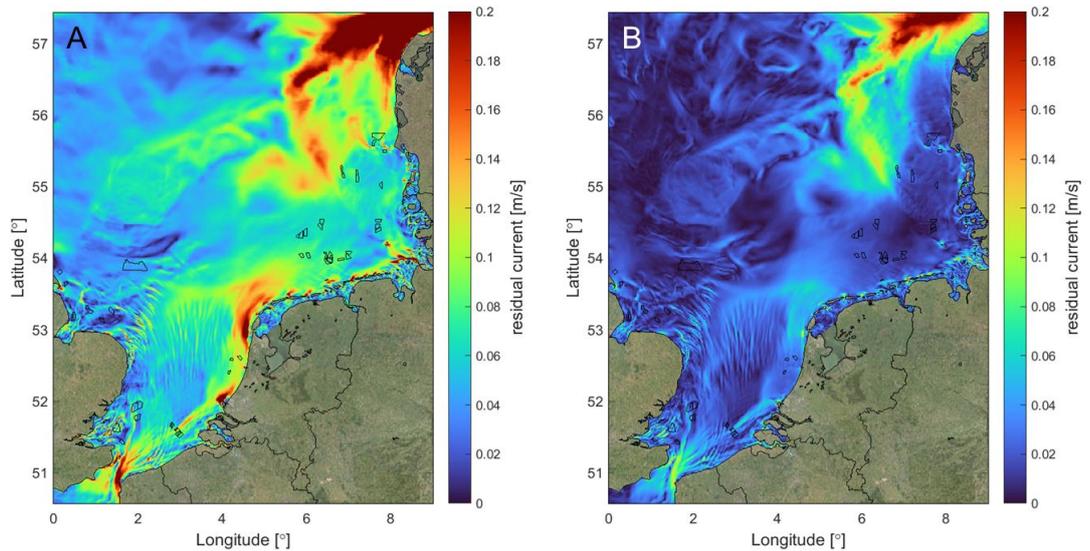


Figure 4.5 – Annual mean velocity magnitude at surface (A) and near bottom (B) in the reference simulation.

### 4.3.3 M2 tide

The semidiurnal lunar M2 tide is the main tidal constituent in most parts of the North Sea. The computed amplitude and phase thereof are presented in Figure 4.6. These figures show the M2 tide behaving as a Kelvin wave, traveling in counter-clockwise direction through the North Sea and with generally higher amplitudes along the coast. Also, clearly visible are the two complete amphidromic systems present in the North Sea, one at a latitude of 52.5° and the other further east near 55-56° latitude. In addition, there is a degenerate amphidromic system near the southern coast of Norway left out of the presented domain.

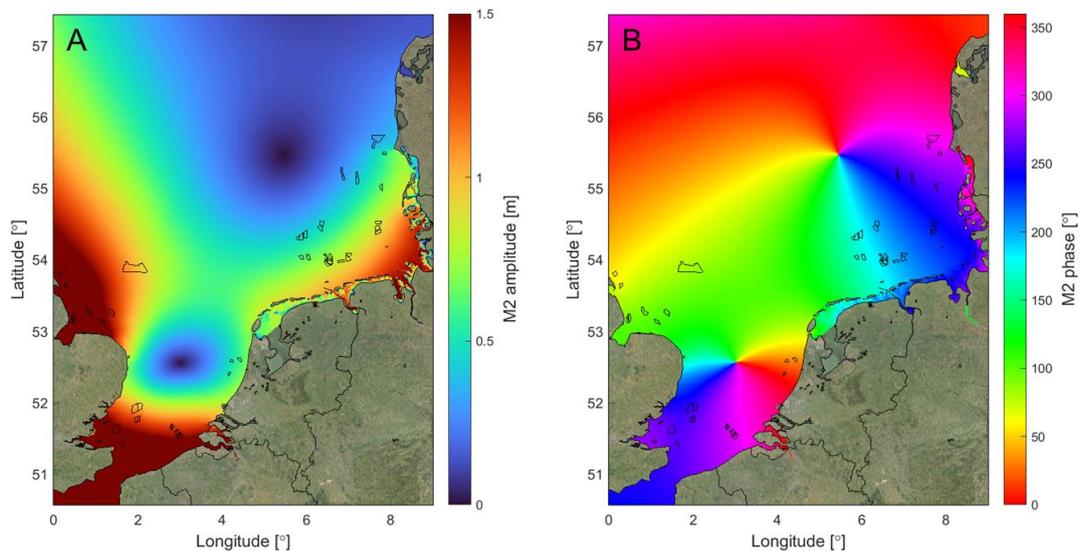


Figure 4.6 – M2 tidal amplitude (A) and phase (B) in the reference simulation.

### 4.3.4 Bed shear stress

The bed shear stress without the effect of waves is presented in Figure 4.7a. This shows lower values in the central North Sea, a bit higher values near the shallow coastal waters and in the

Wadden Sea and the largest values in the southern North Sea near the English coast. Note that the bed shear stress is strongly influenced by the calibrated Manning roughness fields used in 3D DCSM-FM (Figure 4.7b). During this calibration, the Manning bottom roughness in 61 areas was adjusted based on measured water levels at 194 shelf-wide tide gauge locations, using a technique available in the open-source data assimilation toolbox OpenDA (Zijl & Groenenboom, 2022).

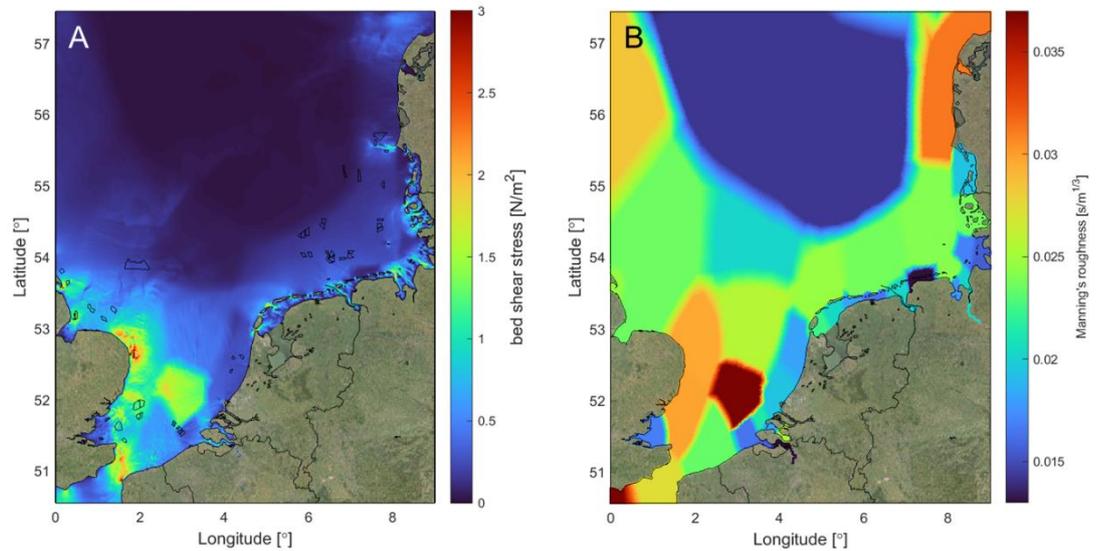


Figure 4.7 – Annual mean bed shear stress in the reference simulation due to currents and prescribed Manning's roughness coefficient.

#### 4.4 Comparison of OWF impacts (piles and meteo combined)

In this section the impact of introducing the effect of the wind farms in the meteorological forcing is compared using two methods: with data from the WINS50 2050 future hypothetical scenario and using the 10% wind reduction approach. The impact is quantified for both cases by comparing to annually-averaged model results without OWFs. In the computations with OWFs both the effect of changed meteorological conditions and the presence of monopiles are taken into account. The comparison presented in this section is labelled as comparison #2 in Table 4.2.

Difference fields of changes for both approaches are calculated by subtracting the outcome of the OWF simulation from that of the reference simulation. Note that salinity stratification is defined as the bottom value minus the surface layer value, whereas temperature stratification is defined as the surface value minus the bottom layer value. In both cases a resulting positive value contributes to stable density stratification.

##### 4.4.1 Salinity

Changes in surface salinity are presented in Figure 4.8. The largest changes in surface salinity are present near the Holland coast and the German Bight, which are areas with salinity stratification. From the comparison of methods, it becomes clear that larger effects are computed using the WINS50 future hypothetical meteorological forcing.

Figure 4.9 shows the change in salinity stratification due to the presence of OWFs. Again, the impact is largest in the vicinity of the OWFs along the Holland coast and the German Bight.

Both methods for taking meteorological changes into account result in a similar impact on salinity stratification.

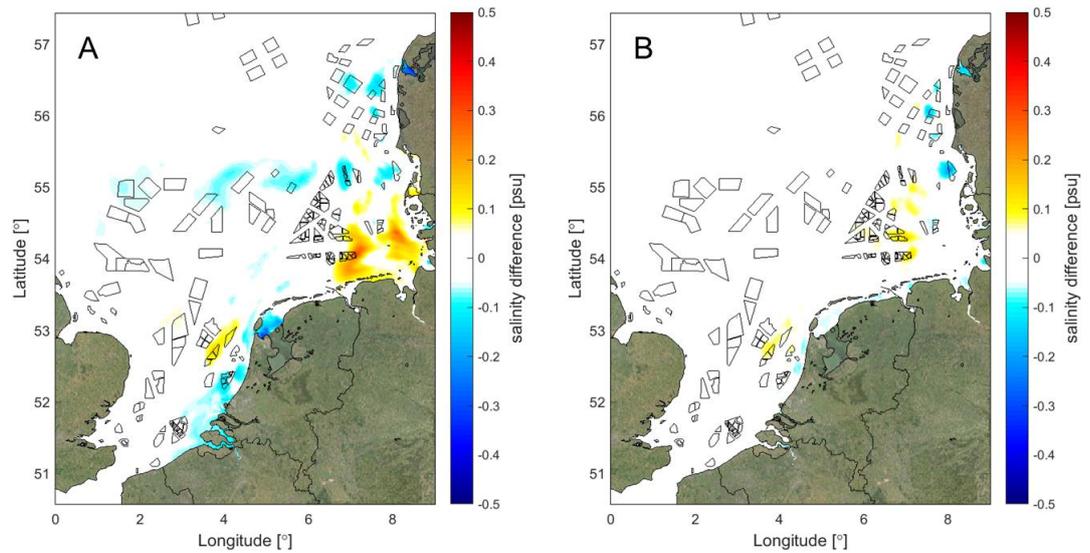


Figure 4.8 – Impact on annual mean surface salinity due to the presence of OWFs (piles and meteo), using WINS50 2050 future hypothetical meteo forcing (A) and wind reduction of 10% applied inside OWFs (B).

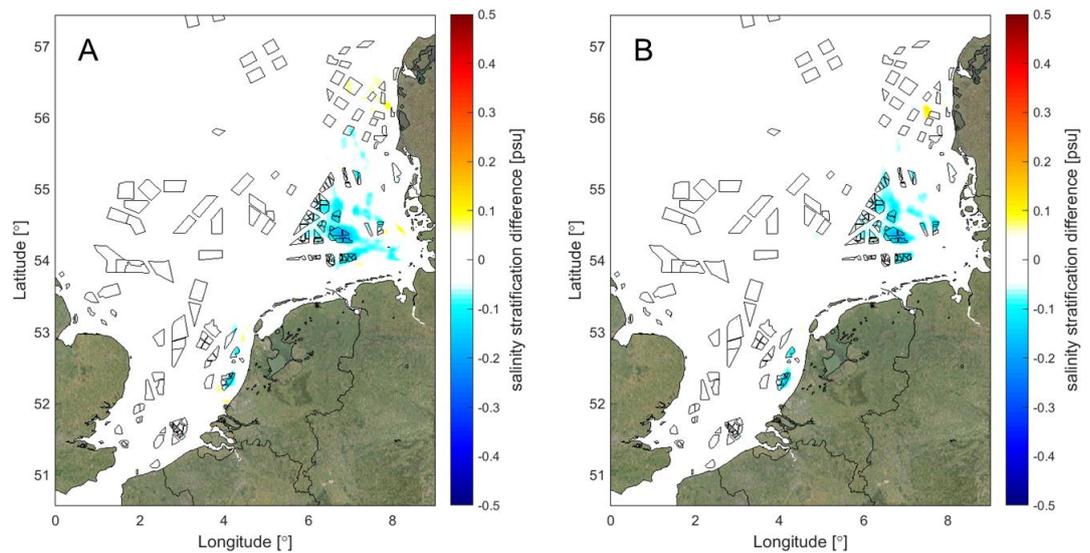


Figure 4.9 – Impact on annual mean salinity stratification due to the presence of OWFs (piles and meteo), using WINS50 2050 future hypothetical meteo forcing (A) and wind reduction of 10% applied inside OWFs (B).

#### 4.4.2 Temperature

Changes in surface temperatures due to the presence of OWFs (piles and meteo) are presented in Figure 4.10. These results show that changes are mostly the same within the OWFs. Using the WINS50 future hypothetical meteorological forcing yields larger areas with increased surface temperatures in the central North Sea, with also an area of decreased surface temperature west of the German OWFs, not present using a 10% wind reduction.

The differences in temperature stratification are given in Figure 4.11. Again, the main patterns are similar. In this case the use of the WINS50 future hypothetical meteorological forcing yields some areas with increased temperature stratification, not present when using a 10% wind reduction.

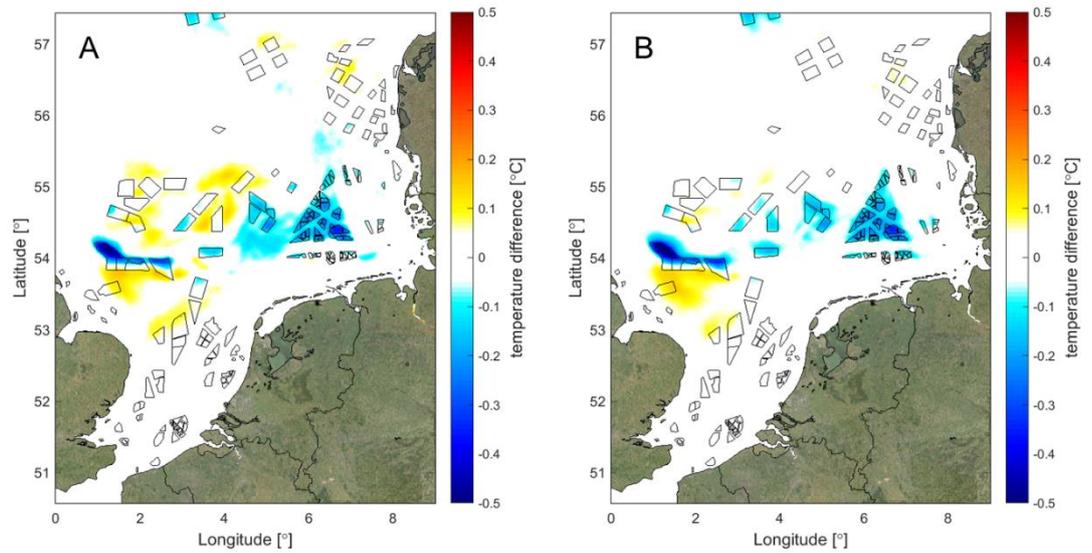


Figure 4.10 – Impact on annual mean surface temperature due to the presence of OWFs (piles and meteo), using WINS50 2050 future hypothetical meteo forcing (A) and wind reduction of 10% applied inside OWFs (B).

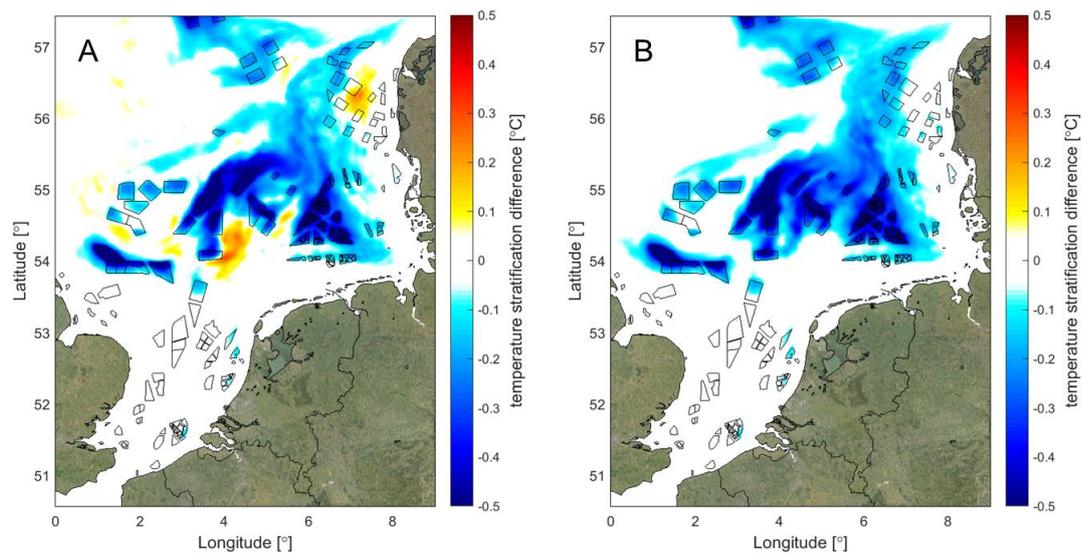


Figure 4.11 – Impact on annual mean temperature stratification due to the presence of OWFs (piles and meteo), using WINS50 2050 future hypothetical meteo forcing (A) and wind reduction of 10% applied inside OWFs (B).

#### 4.4.3 Residual currents

In Figure 4.10, changes in residual surface currents are presented as changes in residual velocity magnitude. The comparison shows that the use of WINS50 2050 future hypothetical meteorological forcing leads to larger impacts on residual currents, primarily outside OWFs.

This larger impact is visible as a more pronounced reduction behind the OWFs, but also as a more pronounced increase in between OWFs.

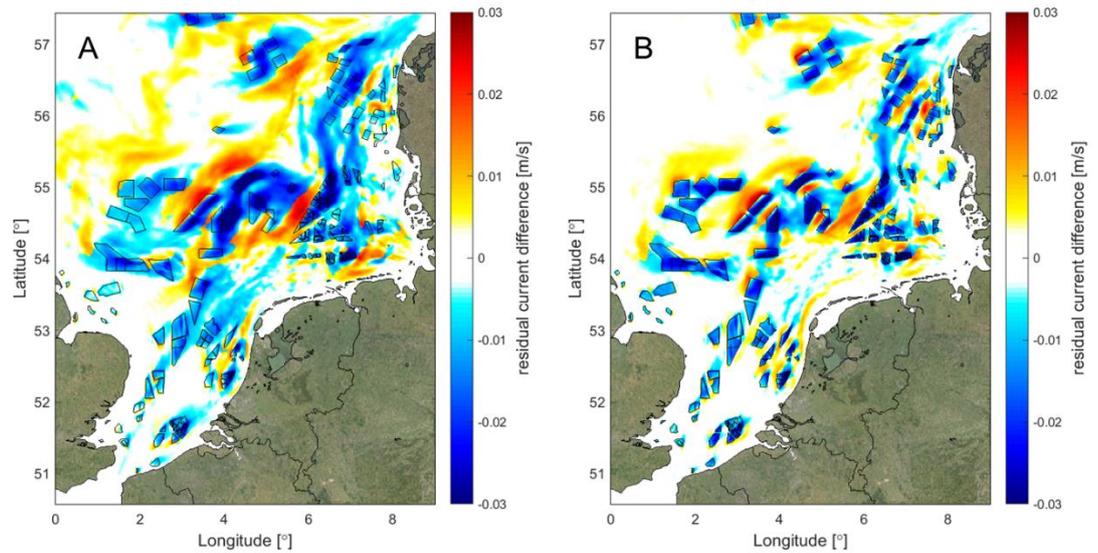


Figure 4.12 – Impact on annual mean residual surface currents due to the presence of OWFs (piles and meteo), using WINS50 2050 future hypothetical meteo forcing (A) and wind reduction of 10% applied inside OWFs (B).

#### 4.4.4 M2 tide

The spatial pattern of changes in the M2 tidal amplitude is presented in Figure 4.13. While the overall pattern of impact on M2 tidal amplitude is very similar for both methods, the use of WINS50 2050 future hypothetical meteorological forcing yields a smaller amplitude reduction in the German Bight.

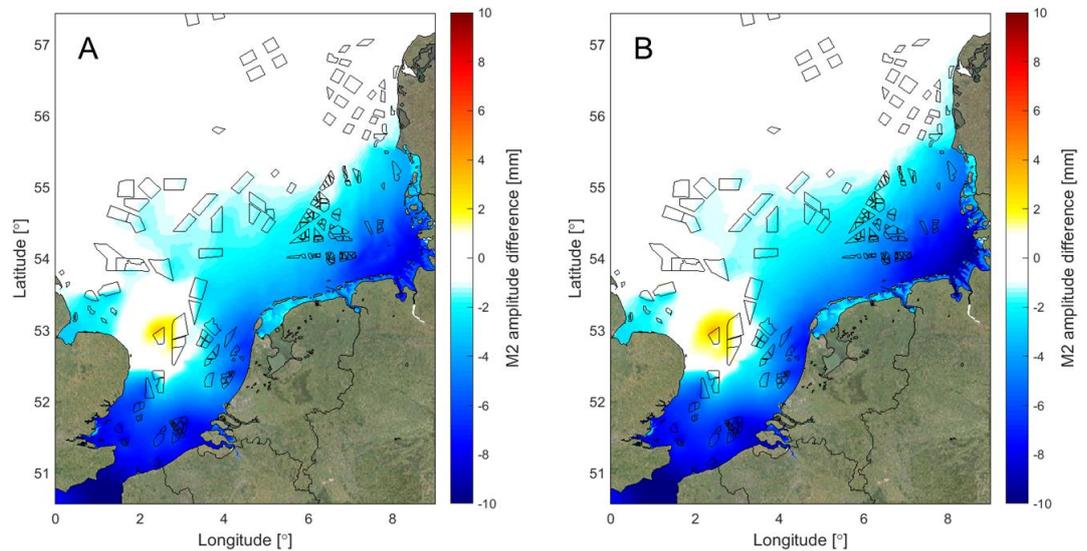


Figure 4.13 – Impact on M2 tide amplitude due to the presence of OWFs (piles and meteo), using WINS50 2050 future hypothetical meteorological forcing (A) and wind reduction of 10% applied inside OWFs (B).

#### 4.4.5 Bed shear stress

The change in bed shear stress is given in Figure 4.14. Note that the bed shear stress only contains the effect of currents and excludes the effect of waves. The impact on bed shear stress looks very similar for both approaches. The only exception is the area off the Northwestern coast of Denmark, where the use of WINS50 future hypothetical meteorological forcing yields a larger reduction.

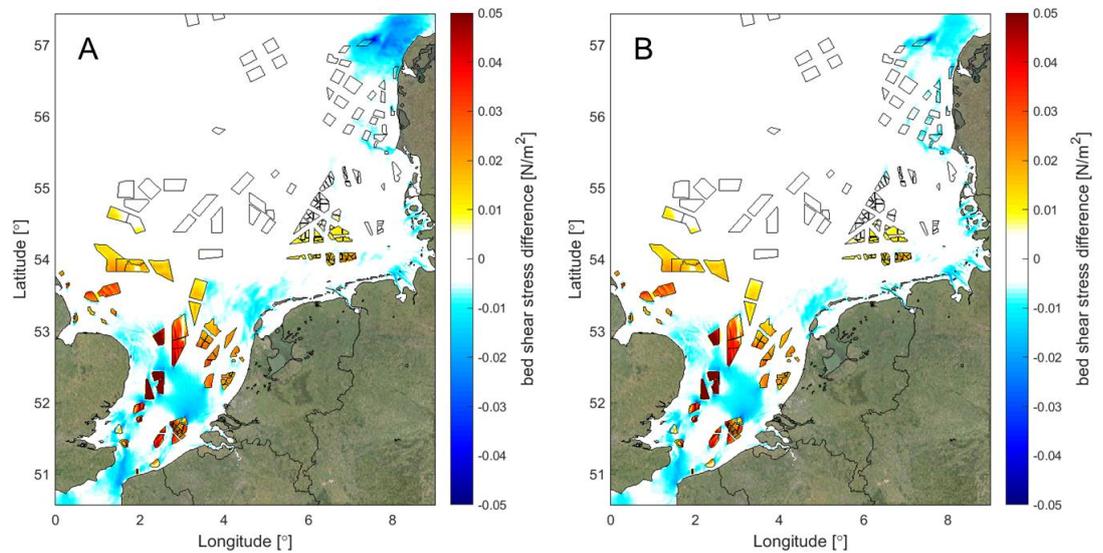


Figure 4.14 – Impact on annual mean bed shear stress due to the presence of OWFs (piles and meteo), using WINS50 2050 future hypothetical meteo forcing (A) and wind reduction of 10% applied inside OWFs (B).

#### 4.5 Comparison of OWF impacts (separation of pile and meteo impacts)

The impact of OWFs is introduced into the hydrodynamic model through two mechanisms: the presence of monopiles in the water column and changes in meteorological conditions. The present study evaluates an alternative method to take the changing meteorological conditions into account. It therefore makes sense to not only look at the changing total impact of the presence of OWFs, but also look at the effect of piles and changing meteorological conditions separately.

In the next paragraph (4.5.1), the impact of the presence of monopiles on hydrodynamic conditions is assessed. This is done by comparing model results with and without monopiles, within both runs including meteorological conditions without the effect of OWFs. This comparison is labelled as comparison #3 in Table 4.2.

Thereafter, in paragraph 4.5.2, the impact of only changing meteorological conditions is assessed by comparing to the situation without the presence of OWFs taken into account in the meteorological conditions, but including the effect of piles. Also here, the impact of changing meteorological conditions due to OWFs is compared using two methods: with data from the WINS50 2050 future hypothetical scenario and using the 10% wind reduction approach. This comparison is labelled as comparison #4 in Table 4.2.

## 4.5.1 Effect of monopiles

### 4.5.1.1 Salinity and temperature

Both surface salinity and salinity stratification change due to the presence of monopiles are shown in Figure 4.15. Salinity stratification in some OWFs along the Holland coast and in the German Bight decreases by around of 0.1 psu, which is similar to the results including both monopiles and changing meteorological conditions (Figure 4.9).

Changes in surface temperature and temperature stratification due to the impact of monopiles are presented in Figure 4.16. In OWF areas with temperature stratification, there is a decrease in surface temperature, due to enhanced vertical mixing. In these areas, temperature stratification decreases by up to 0.5°C or more, with wake effect visible in downstream direction. Comparing to results including both monopiles and changing meteorological conditions (Figure 4.10 and Figure 4.11) shows that the reduced stratification and decreased average surface temperature is primarily caused by enhanced mixing by monopiles.

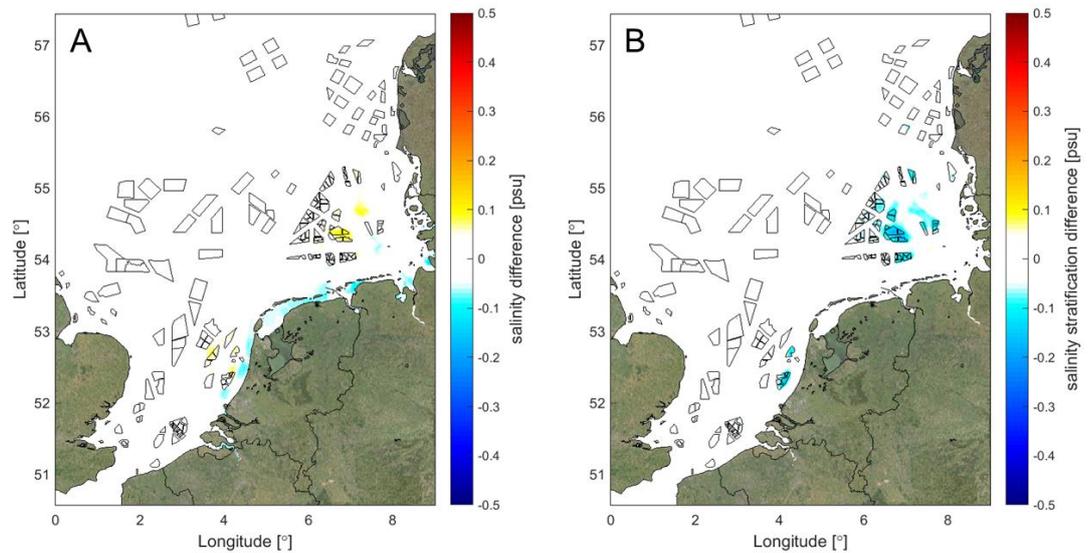


Figure 4.15 – Impact on annual mean surface salinity (A) and salinity stratification (B) due to the presence of OWF monopiles, ignoring changes in meteorological conditions.

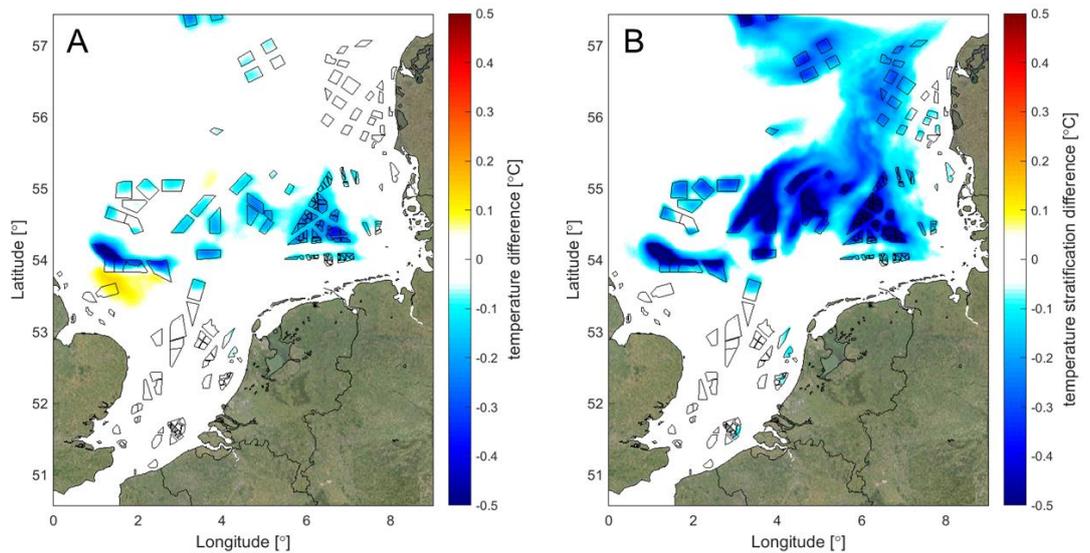


Figure 4.16 – Impact on annual mean surface temperature (A) and temperature stratification (B) due to the presence of OWF monopiles, ignoring changes in meteorological conditions.

#### 4.5.1.2 Residual currents and bed shear stress

In the Figure 4.17 the effect of the monopiles on the residual currents and bed shear stress is shown. Residual current magnitudes are mainly decreased within the OWFs, with a velocity deficit also present in some downstream areas. Between OWFs increases in residual current magnitudes are also present. In general, the effect due to monopiles is substantially smaller compared to the runs also including changes on meteorological parameters (Figure 4.12).

The presence of monopiles increases the bed shear stress within the OWFs in the southern North Sea, by more than  $0.05 \text{ N/m}^2$  at some locations. In between OWFs, a decrease in annual mean bed shear stress is noticeable, in particular in the area north-east of the English Channel. Comparison to the results including both monopiles and changing meteorological conditions (Figure 4.14) shows that the presence of monopiles accounts for most of the change in bed shear stress.

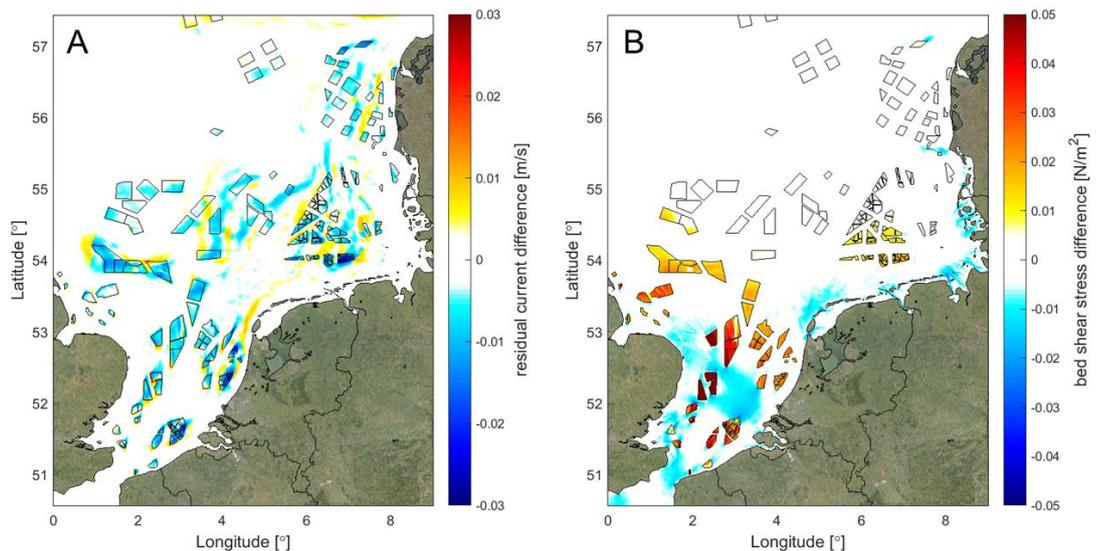


Figure 4.17 – Impact on annual mean residual surface currents (A) and bed shear stress (B) due to the presence of OWF monopiles, ignoring changes in meteorological conditions.

### 4.5.1.3 M2 tide

The changes in the M2 tidal amplitude and phase due to the presence of monopiles are presented in Figure 4.18. A decrease of more than 10 mm in M2 amplitude occurs in the English Channel and German Bight, with smaller decreases in Belgian and Dutch coastal waters. A decrease in amplitude is consistent with the increased dissipations through the drag introduced by the monopiles. Near the amphidromic point in the southern North Sea a slight increase of the amplitude is found. Together with the changes in tidal phase at this location, this reflects a change in the location of the amphidromic point.

Comparison to the results including both monopiles and changing meteorological conditions (Figure 4.13) shows that the presence of monopiles accounts for most of the change in M2 amplitude.

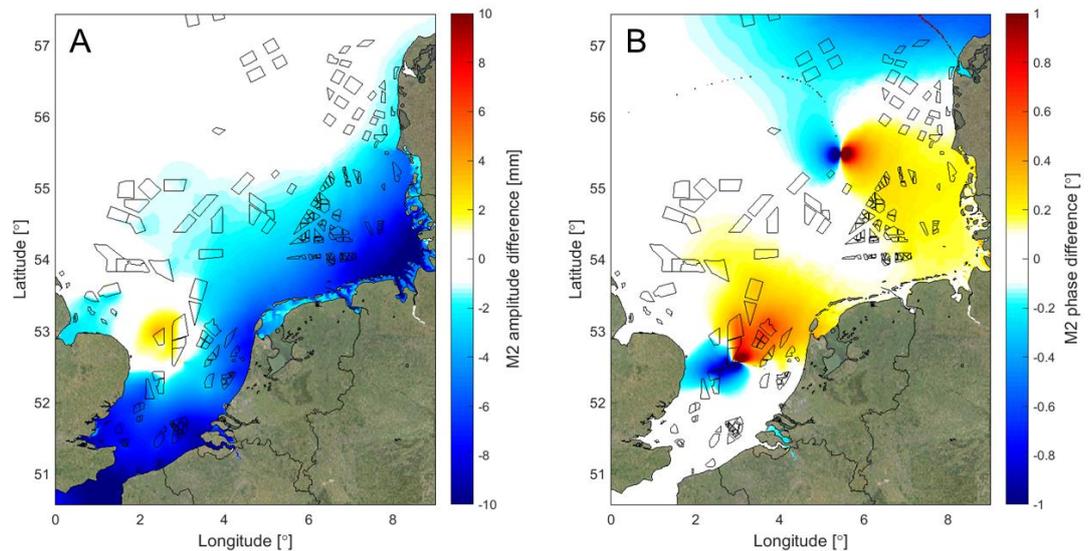


Figure 4.18 – Impact on M2 tide amplitude (A) and phase (B) difference due to the presence of OWF monopiles, ignoring changes in meteorological conditions.

## 4.5.2 Effect of changing meteorological conditions

### 4.5.2.1 Salinity

The impact on surface salinity of the changed meteorological conditions due to the presence of OWFs is presented in Figure 4.19. It shows that using a 10% wind reduction within OWFs hardly influences surface salinity, while using WINS50 future hypothetical forcing shows somewhat larger impacts, primarily as an increase of up to 0.2 psu in the German Bight. The impact of changed meteorological forcing on average salinity stratification (Figure 4.20) is limited (less than 0.1 psu) for both methods.

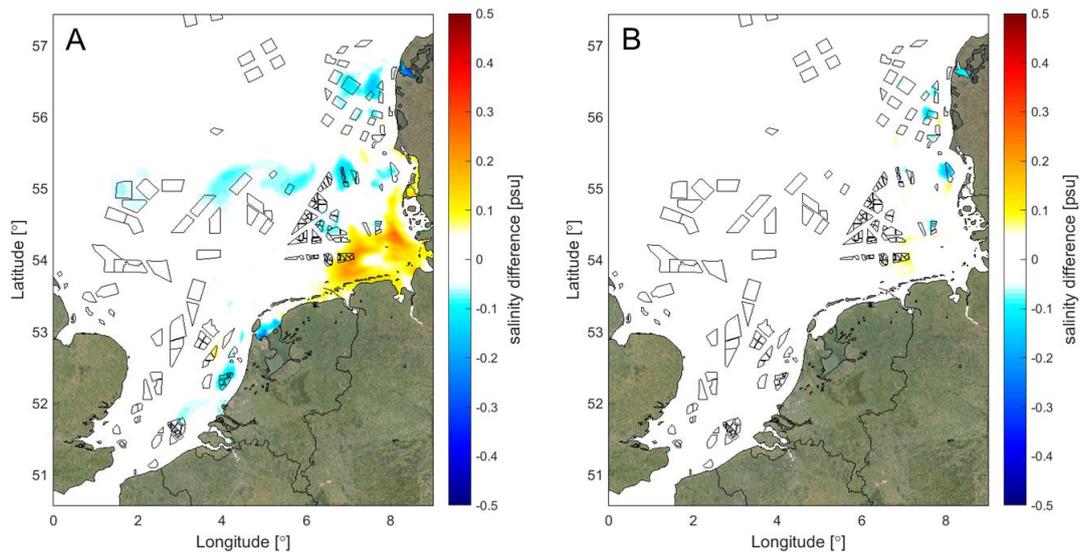


Figure 4.19 – Impact on annual mean surface salinity due to the meteorological effect of OWFs, using WINS50 2050 future hypothetical meteo forcing (A) and wind reduction of 10% applied inside OWFs (B).

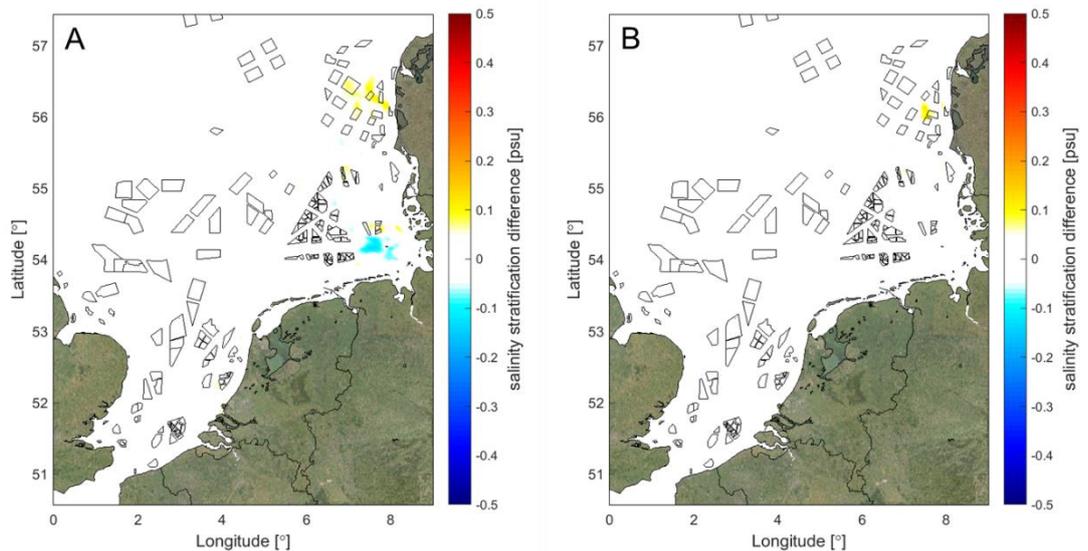


Figure 4.20 – Impact on annual mean salinity stratification due to the meteorological effect of OWFs, using WINS50 2050 future hypothetical meteo forcing (A) and wind reduction of 10% applied inside OWFs (B).

#### 4.5.2.2 Temperature

The impact on surface temperature of the changed meteorological conditions due to the presence of OWFs is presented in Figure 4.21. The same is done for temperature stratification in Figure 4.22. The comparison of methods to take changed meteorological forcing due to OWFs into account shows large differences. The use of WINS50 future hypothetical forcing shows an increase in surface temperature and temperature stratification in and around OWFs in the central North Sea. Note that this counteracts the (larger) effect of the presence of monopiles, which increases vertical mixing and reduces temperature stratification in these areas (Figure 4.16). This counteracting effect is much reduced using a 10% wind reduction in OWFs.

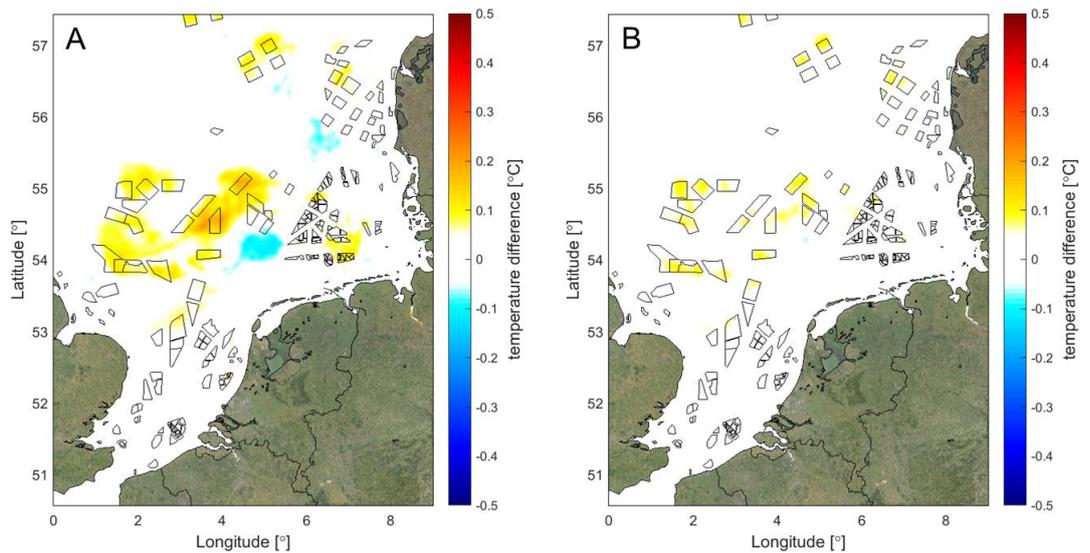


Figure 4.21 – Impact on annual mean surface temperature due to the meteorological effect of OWFs, using WINS50 2050 future hypothetical meteo forcing (A) and wind reduction of 10% applied inside OWFs (B).

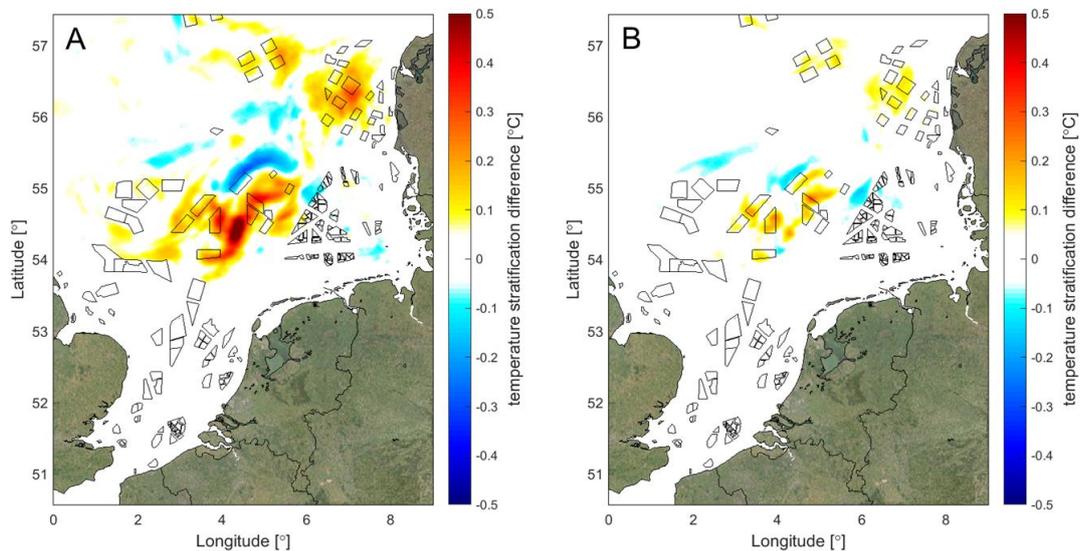


Figure 4.22 – Impact on annual mean temperature stratification due to the meteorological effect of OWFs, using WINS50 2050 future hypothetical meteo forcing (A) and wind reduction of 10% applied inside OWFs (B).

#### 4.5.2.3 Residual currents

The comparison of the OWF meteorological effects on the residual currents is presented in the Figure 4.23. The most significant patterns of changes in residual currents are explained by the simplified 10% reduction approach, especially the decrease of up to 0.03 m/s within the wind farm locations and the compensating increase of around 0.02 m/s in between some of them. However, the use of WINS50 future hypothetical forcing results in larger areas being affected, especially surrounding OWFs.

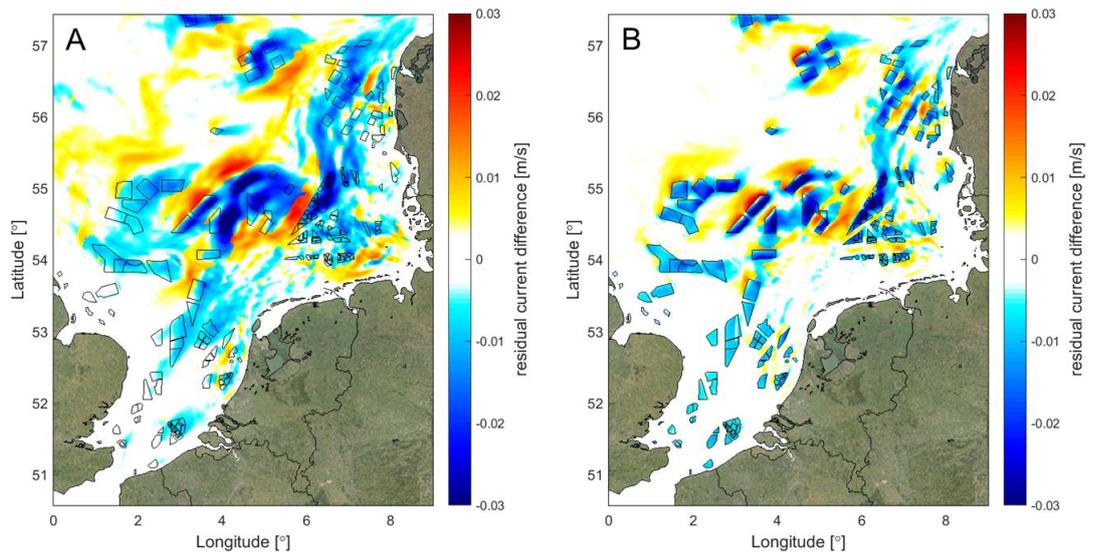


Figure 4.23 – Impact on annual mean residual surface currents difference due to the meteorological effect of OWFs, using WINS50 2050 future hypothetical meteo forcing (A) and wind reduction of 10% applied inside OWFs (B).

#### 4.5.2.4 M2 tide amplitude

The changes in M2 tidal amplitude due to changing meteorological conditions in the presence of OWFs are presented in Figure 4.24. Using the WINS50 future hypothetical forcing results in an 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 (Figure 4.18). Conversely, using a 10% wind reduction hardly affects the M2 amplitude.

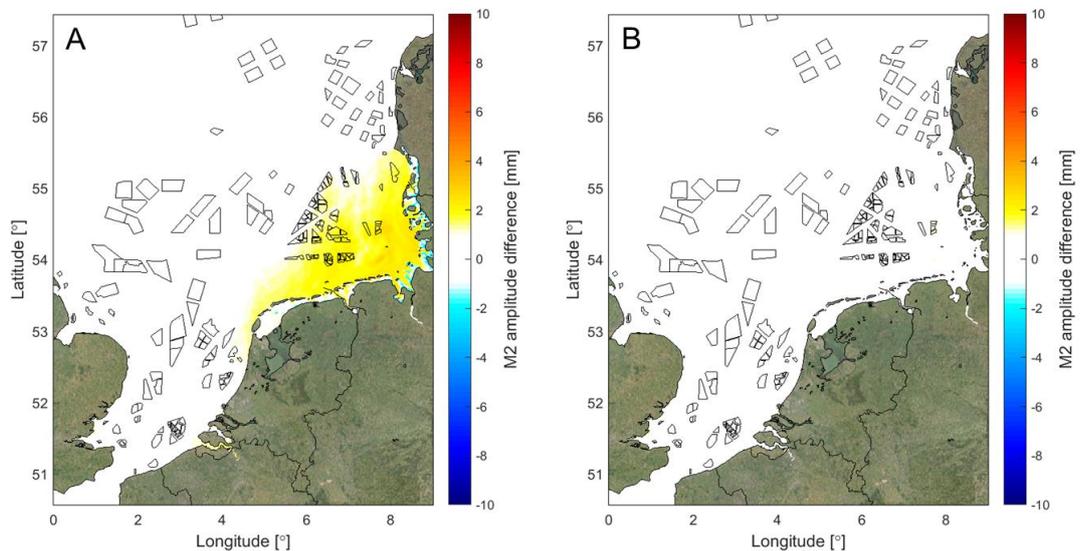


Figure 4.24 – Impact on M2 tidal amplitude due to the meteorological effect of OWFs, using WINS50 2050 future hypothetical meteo forcing (A) and wind reduction of 10% applied inside OWFs (B).

#### 4.5.2.5 Bed shear stress

The impact on bed shear stress due to changing meteorological forcing in the presence of OWFs is presented in Figure 4.25. In both cases the impact is mostly limited ( $<0.005 \text{ N/m}^2$ ). The only exception is an area off the Northwestern coast of Denmark, where the bed shear stress is reduced. This reduction is larger with the use of WINS50 future hypothetical meteorological forcing.

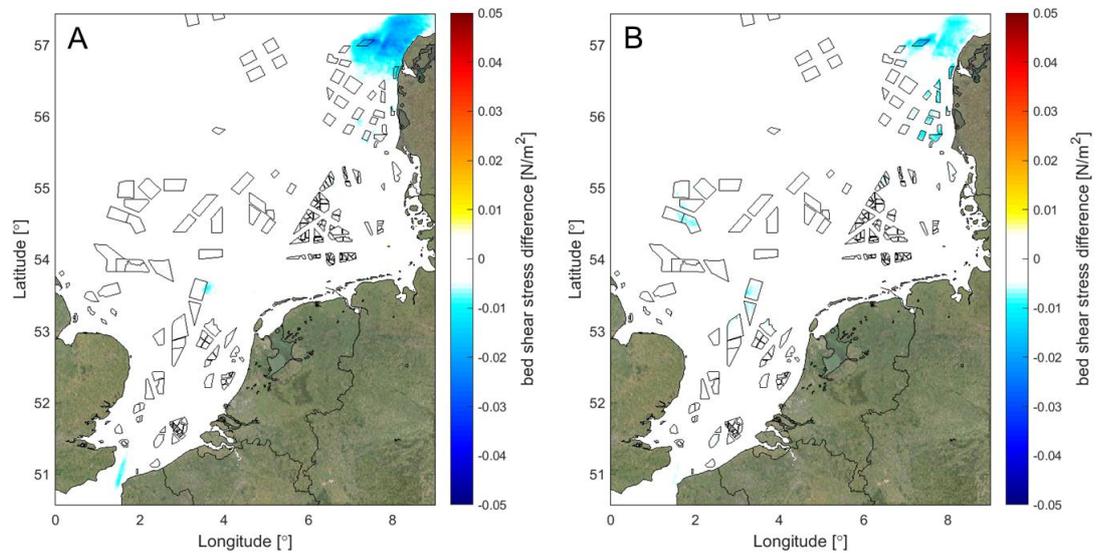


Figure 4.25 – Impact on annual mean bed shear stress due to the meteorological effect of OWFs, using WINS50 2050 future hypothetical meteorological forcing (A) and wind reduction of 10% applied inside OWFs (B).

#### 4.6 Impact (wind only)

With the use of WINS50 future hypothetical forcing, changes in various meteorological forcing parameters are considered, which differs from the approach used up to now, where only the wind speed magnitude is adjusted. We have shown in Chapter 3 that the presence of OWFs has an actual impact on the other forcing parameters. In this section we will investigate to what extent these changes in parameters other than wind speed have an impact on the hydrodynamic results. This is done by comparing impacts using WINS50 future hypothetical forcing for all parameters with using this forcing for only wind. In the latter case the other parameters, such as radiation, air temperature and dew point temperature are obtained from the WINS50 reference scenario without OWFs present. The reference in assessing impacts is a run using the WINS50 reference scenario without OWFs present, but with monopiles included. The comparison is labelled as comparison #5 in Table 4.2.

The results for this comparison can be found in Figure 4.26 to Figure 4.32. Most of the plotted hydrodynamic parameters appear to show a negligible impact of ignoring changes in meteorological parameters other than wind speed. The exception is the surface temperature, which shows a slightly larger increase on an annual scale in and around OWFs when changes in all meteorological parameters are considered.

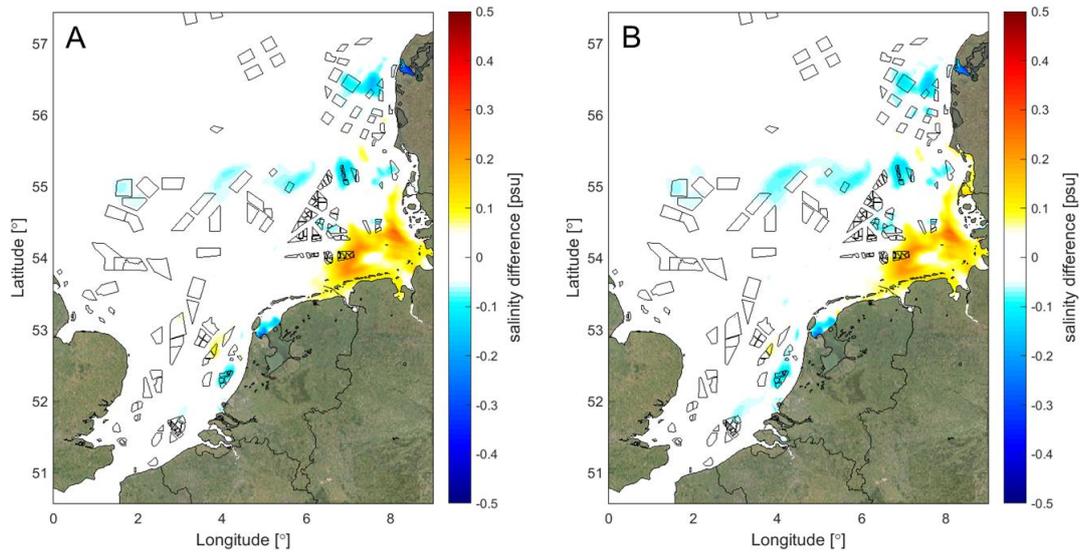


Figure 4.26 – Annually-averaged impact on surface salinity due to the meteorological effect of OWFs, using all WINS50 2050 future hypothetical meteorological forcing parameters (A) and using only the wind forcing thereof (B).

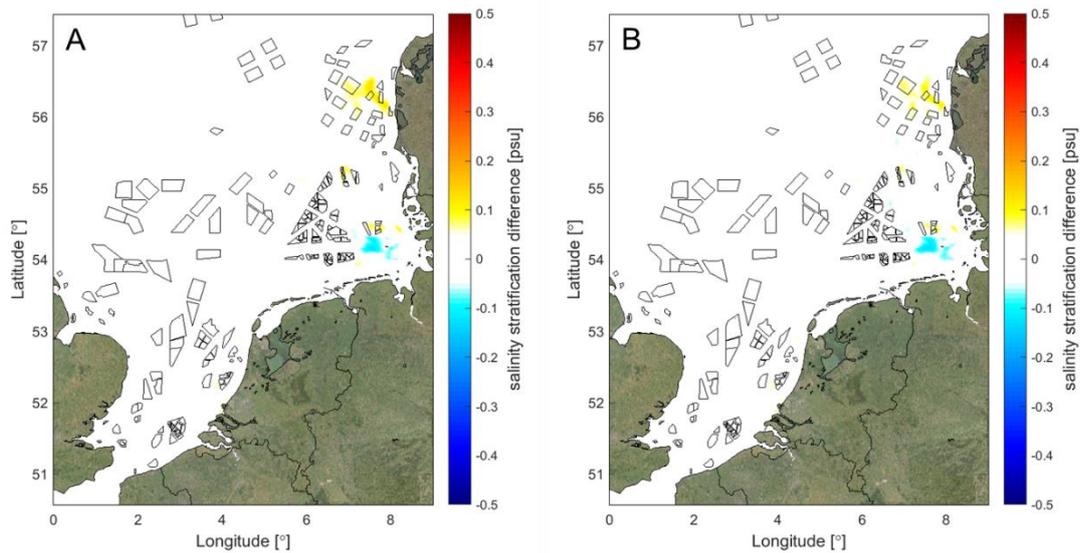


Figure 4.27 – Impact on annual mean salinity stratification due to the meteorological effect of OWFs, using all WINS50 2050 future hypothetical meteorological forcing parameters (A) and using only the wind forcing thereof (B).

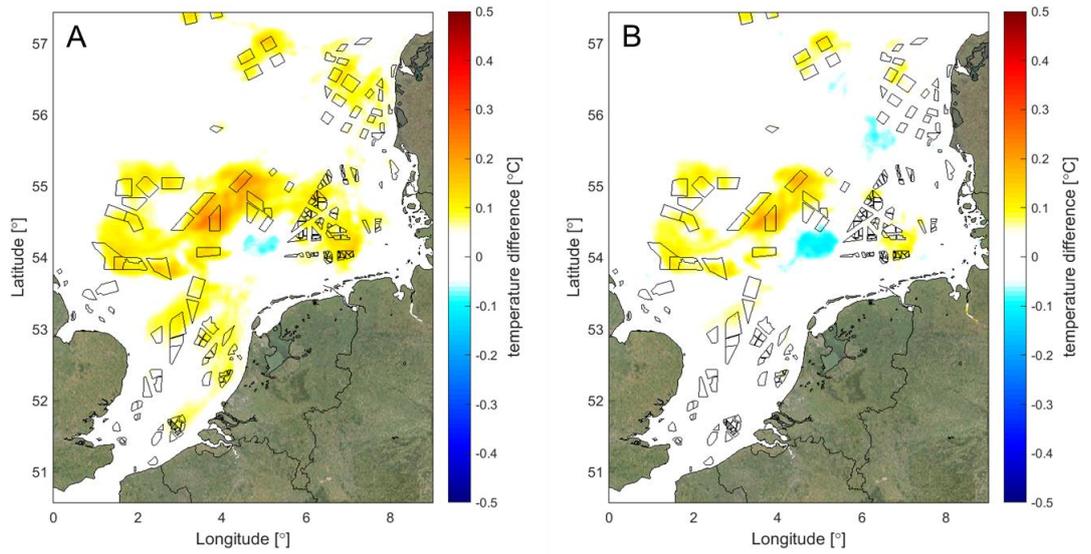


Figure 4.28 – Impact on annual mean surface temperature due to the meteorological effect of OWFs, using all WINS50 2050 future hypothetical meteo forcing parameters (A) and using only the wind forcing thereof (B).

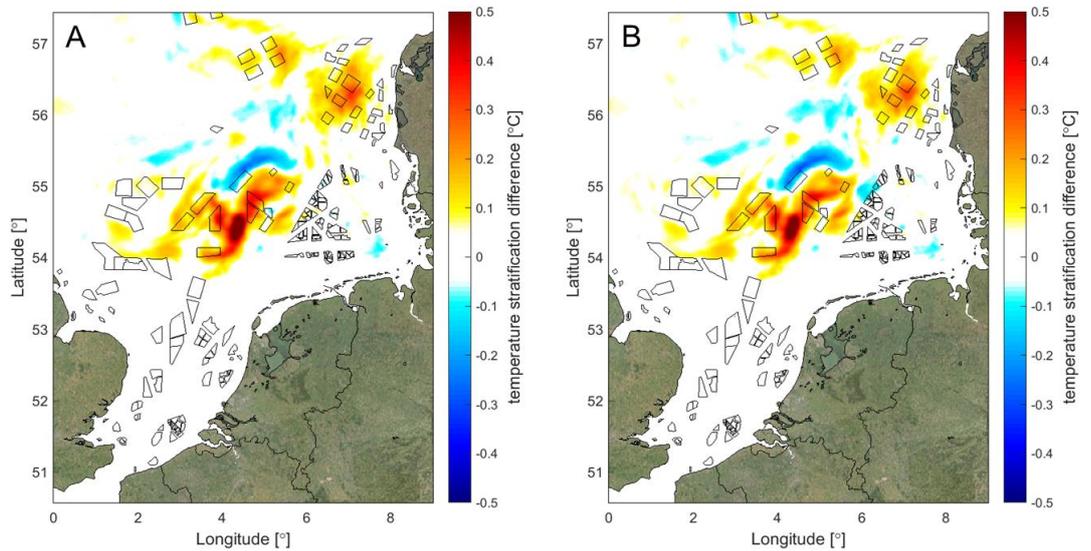


Figure 4.29 – Impact on annual mean temperature stratification due to the meteorological effect of OWFs, using all WINS50 2050 future hypothetical meteo forcing parameters (A) and using only the wind forcing thereof (B).

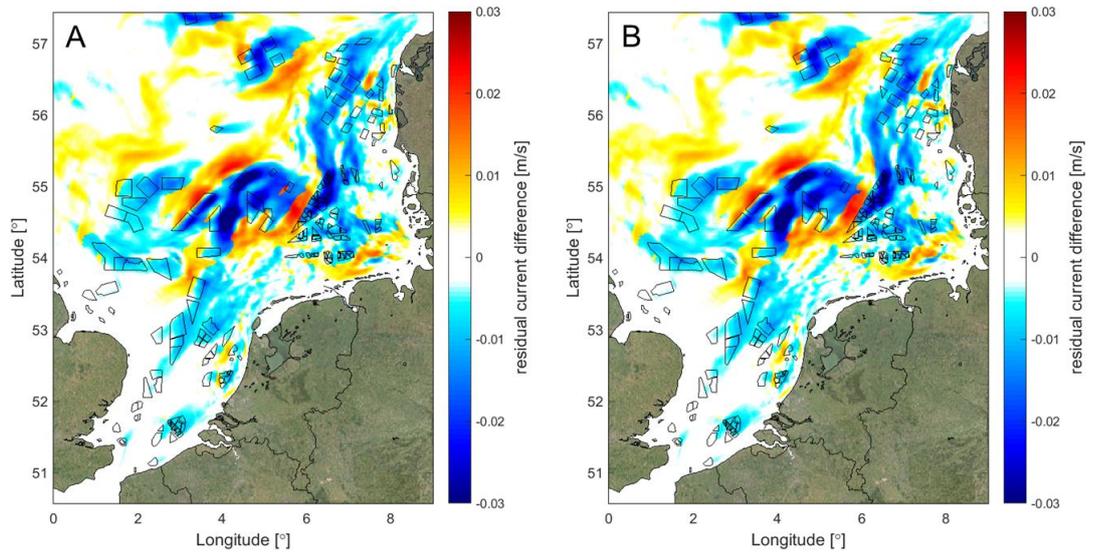


Figure 4.30 – Impact on annual mean residual surface currents due to the meteorological effect of OWFs, using all WINS50 2050 future hypothetical meteo forcing parameters (A) and using only the wind forcing thereof (B).

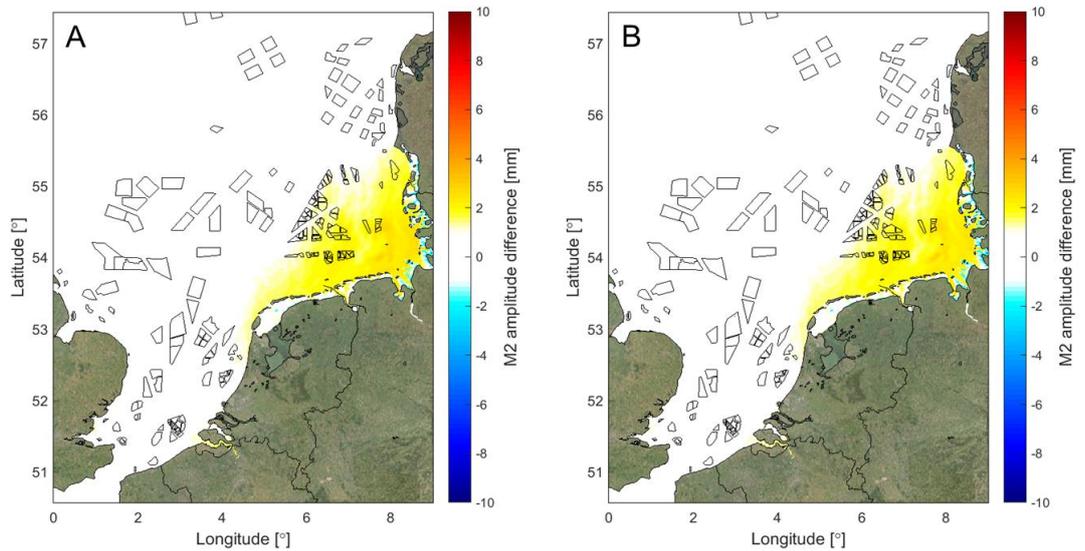


Figure 4.31 – Impact on M2 tidal amplitude due to the meteorological effect of OWFs, using all WINS50 2050 future hypothetical meteo forcing parameters (A) and using only the wind forcing thereof (B).

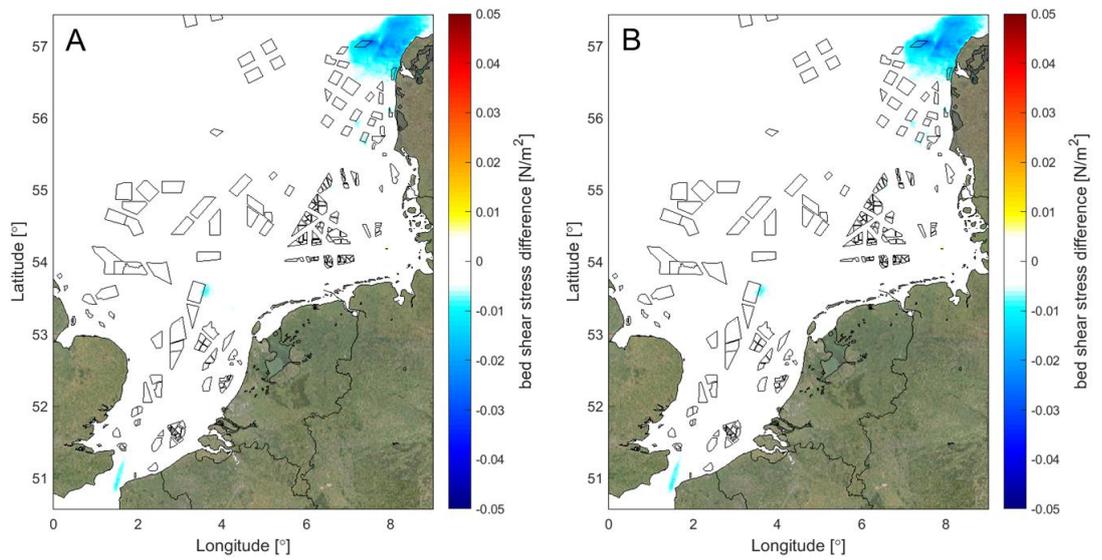


Figure 4.32 – Impact on annual mean bed shear stress due to the meteorological effect of OWFs, using all WINS50 2050 future hypothetical meteo forcing parameters (A) and using only the wind forcing thereof (B).

# 5 Conclusions and recommendations

## 5.1 Conclusions

### 5.1.1 Introduction

In the first version of the hydrodynamic model used for Wozep (Zijl et al, 2020), the effect of offshore wind farms (OWF's) on the meteorological forcing was approximated with a uniform neutral wind speed reduction of 10% within offshore wind farm areas, which is a relatively rough assumption. Moreover, 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. In addition, the impact on other meteorological parameters such as radiation, air temperature and dew point temperature, which play a role in the exchange of heat between air and water, is ignored.

In the present study, the impact of these assumptions was investigated by coupling to the HARMONIE meteorological model of KNMI, of which scenario computations exist that include the impact of OWF's. These scenarios are part of the WINS50 project 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.

### 5.1.2 Validation

The 3D DCSM-FM model has been validated extensively (Zijl et al., 2023, Zijl & Laan, 2022, Groenenboom & Zijl, 2022). Since this was for a different period and with different meteorological forcing (ERA5), some additional validation on water levels and water temperature has been performed, covering the scenario year (2020). Based on this it can be concluded that:

- using WINS50/ERA5 meteorological forcing slightly improves the mean surge representation in stations along the Dutch coast, from 4.6 cm to 4.5 cm, compared to using only ERA5. This also leads to an improvement of the total water level quality, from 6.1 cm to 6.0 cm.
- the average quality of the sea surface temperature representation in Dutch waters reduces somewhat, from an RMSE of 0.47 °C when using ERA5 forcing to 0.70 °C when using WINS50/ERA5 meteorological forcing.

### 5.1.3 Impact on meteorological variables

Before being applied, the annual average impact of OWFs on some of the meteorological parameters used to force the 3D DCSM-FM hydrodynamic model is determined. Based on this it can be concluded that the presence of OWFs in the 2050 future hypothetical scenario causes:

- a wind speed deficit that can reach more than 1 m/s, especially where OWFs 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 OWFs the annual average is affected by wake effects, with average velocity deficits of more than 0.1 m/s seen up to tens of kilometres away.
- changes in annual average air temperature and dew point temperature within OWFs of around 0.1 – 0.4 °C or up to 3-5% of the annual average. Outside the OWFs wake effects are present, with differences gradually decreasing in magnitude.
- changes in surface net short-wave and downwelling long wave radiation within the OWFs of up to 4 W/m<sup>2</sup> or approximately 1 to 2% of the annual average value.

- a decrease in evaporation rate of 0.1 – 0.3 mm/day within most OWFs, which amounts to up to 10% of the annual average value without OWFs present.
- Note that while the wake effects seem smooth in the annual average sense, the instantaneous effects can be more pronounced. Under the right atmospheric conditions, wake effects can be felt hundreds of kilometres downstream from OWFs.

#### 5.1.4 Impact of monopiles versus impact of changed meteorological forcing

The impact of OWFs is introduced into the hydrodynamic model through two mechanisms: the presence of monopiles in the water column and changes in meteorological conditions. With respect to the relative importance of both mechanisms for annual mean impacts, the following can be concluded:

- In OWF areas with temperature stratification, there is a decrease in surface temperature, due to enhanced vertical mixing. Temperature stratification decreases by up to 0.5°C or more, with wake effect visible in downstream direction. This is mainly caused by the presence of monopiles, with the changes in meteorology counteracting this.
- The presence of OWFs reduces the residual current magnitudes within the OWFs. Both the monopiles and changed meteorological conditions contribute to this. Downstream of the OWFs velocity deficits are also present, while in between OWFs increases in residual current magnitudes can occur. These changes are mainly caused by changing meteorological conditions.
- The presence of monopiles increases the bed shear stress within the OWFs in the southern North Sea, with hardly a contribution of the changed meteorological forcing.
- The presence of OWFs causes a decrease of more than 10 mm in M2 amplitude in the English Channel and German Bight, with smaller decreases in Belgian and Dutch coastal waters. The monopiles account for most of the decrease in M2 amplitude, with the change in meteorological conditions counteracting this in the German Bight.

#### 5.1.5 Impact of method to account for OWF-induced meteorological changes

The impact of using WINS50 future hypothetical forcing to account for changes in meteorology due to the presence of OWFs was compared to the simplified approach with a 10% wind reduction in OWFs. Based on this comparison the following can be concluded with respect to annual mean impacts:

- OWF-induced changes in meteorology increase annual mean surface temperature and have a stabilizing effect on temperature stratification in central North Sea, which counteracts the enhanced mixing due to the presence of monopiles. The 10% wind reduction underestimates this stabilizing effect.
- The most significant patterns of changes in annual mean residual currents withing OWFs are explained by the simplified 10% reduction approach. However, the use of WINS50 future hypothetical forcing results in larger areas being affected, especially surrounding OWFs.
- OWF-induced changes in meteorology lead to an increase in M2 tidal amplitude in the German Bight, counteracting a larger decrease caused by the presence of monopiles. The 10% wind reduction does not show a significant effect on M2 amplitudes, thereby taking away this counteracting effect.
- Using the WINS50 future hypothetical forcing results in an 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 10% wind reduction hardly affects the M2 amplitude.

### 5.1.6 Impact of changes in meteorological forcing parameters other than wind speed

With the use of WINS50 future hypothetical forcing, changes in wind speed and other meteorological forcing parameters (such as radiation, air temperature and dew point temperature) are considered. Most of the considered hydrodynamic parameters appear to show a negligible annual mean impact of ignoring changes in meteorological parameters other than wind speed. The exception is the surface temperature, which shows a slightly larger increase in and around OWFs when changes in all meteorological parameters are considered.

## 5.2 Recommendations

- In this study the availability of the WINS50 dataset made it possible to investigate the impact of changed meteorological forcing due to the presence of OWFs. However, the WINS50 dataset is only available for a pre-defined and limited set of years and OWF scenarios. To have more flexibility to run the Wozep suite of models for any scenario and year desired, it is recommended to investigate the possibility to come up with a more advanced parameterization to account for the effect of OWFs compared to the current assumption in a 10% reduction of wind speed in OWFs. This new parameterization should consider both internal and external wake effects, dependent on atmospheric conditions. This new parameterization can possibly be derived using machine learning techniques, for which the WINS50 dataset could form an excellent basis, as this contains various scenarios and a wide range of meteorological conditions.
- In the present study the impact on hydrodynamic parameters of changed meteorological forcing due to the presence of OWFs was investigated. The resulting changes in hydrodynamic conditions might have an impact on subsequent modelling of fine sediment, water quality and ecology. While not studied here, this subsequent modelling might also be affected by impacted wave conditions due to changed meteorological conditions. In addition, changes in radiation forcing might have a more direct impact on the water quality and ecology results. It is therefore recommended to do a coupled scenario simulation with the coupled model framework and assess whether replacing the 10% wind reduction with full WINS50 meteorological model results changes the computed impact of the presence of OWFs.
- Like earlier reports such as Zijl et al. (2021) the present study is based on comparison of annual average values, even though impacts vary throughout the year. Spatially, annual average wake effects seem smooth even though the instantaneous effects can be much more pronounced and felt much further from OWFs. It is therefore recommended to revise the methods for presenting OWF impacts. Besides annual averages, an indication of the temporal variation of impacts might be a useful addition. This could be achieved for example by reporting impacts for each season separately, or quantifying temporal variability. In addition, using aggregated methods for quantifying stratification, such as the Potential Density Anomaly (PEA), could be use useful. PEA takes the entire water column and the effect of both temperature and salinity into account in one quantity. The latter is especially relevant when temperature and salinity stratification work in opposing direction with respect to stability of the water column.
- While the 3D DCMS-FM hydrodynamic model has been validated extensively in a general sense, this does not hold for validation of OWF impacts specifically. It is therefore recommended to validate the stronger impacts directly, by comparing to measurements where the effects are strong.
- There are some aspects in the coupling with WINS50 that can possibly be improved. For example, the meteorological model now assumes stagnant water surface conditions, while in reality tidal currents are quite significant in coastal regions. Furthermore, feed-back loops of OWFs affecting hydrodynamic conditions and feeding

back into meteorology changes are currently not considered. An example is the impact of OWFs on sea surface temperature, which currently does not feed back into the meteorological model, even though a change in turbulent heat fluxes would ensue. Properly accounting for these feed-back loops would require an online-coupled model consisting of a meteorological, hydrodynamic and wave component.

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