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Impact of offshore wind farms on the North Sea ecosystem

Scenario study for the partial revision of the Dutch offshore wind planning

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Summary

Offshore wind can have a substantial impact on the marine ecosystem, through bottom-up processes. These have previously been researched in Wozep and a modelling suite has been developed to investigate future offshore wind scenarios with respect to changes in hydrodynamics, suspended particulate matter (SPM) dynamics and ecological processes such as primary production.

Scenarios
This modelling suite has now been applied to a highly likely wind energy scenario for 2031, which will be used in the following evaluation round for assessing cumulative impacts of offshore wind in 2031 also known as “Kader Ecologie en Cumulatie, versie 5.0” (KEC 5.0). Since this scenario has a high probability of realisation, this is called the *base scenario*. This scenario (in this report named: the base scenario) was assessed against the *reference* scenario without any wind farms in the North Sea.

Furthermore the modelling suite has been applied to four (theoretical) scenarios for the Partial Revision of the North Sea Programme 2022 – 2027, which aims to ensure the continuity of offshore wind energy, by designating offshore wind farm zones to be developed after 2031. The areas under consideration are search area 6/7, part of the Doordewind and Doordewind (west) areas, and Lagelander. Search area 6/7 is so large that zoning arrangements (which sub-areas will be suitable for offshore wind farms and which sub-areas will remain open) are being investigated. The four investigated scenarios look at the impact of all mentioned areas combined, with different options for the lay-out of area 6/7. Note: these scenarios are hypothetical and the model results are intended to investigate the extreme options. Three scenarios were run with the whole area being filled with a uniform distribution of different sizes and densities of turbines and one scenario was run with a broad, open space in the central part of the area. These scenarios were primarily assessed against the base scenario for 2031 (used for KEC 5.0). Some comparisons were also made with the reference scenario.

All scenarios (i.e. base scenario and the four scenarios for the partial revision) contained a lay-out for offshore wind farms in North Sea countries other than the Netherlands, based on the best available information to date. All scenarios were run with the same input for meteorological data, impacts of potential climate change were not assessed in this study.

Results
The general pattern of impacts was in line with the difference found between sub regions in previous studies. In the base scenario (KEC 5.0) most wind farms see a decrease in primary production due to elevated SPM concentrations in the top layer. The most pronounced effects are found in the German Bight, where local decreases are strongest and also most interaction occurs between wind farms. Particularly the areas “TNW” and the Gemini farms in the base scenario indicated clear negative effects on primary production. In these areas primary productivity was reduced by about 0.3 gC/m^2/day, which is a reduction of about 60%. In the larger “Doordewind” area primary production was reduced with about 25%, from around 0.4 gC/m^2/day to around 0.3 gC/m^2/day. In the directly adjacent German farms reductions are larger due to interference and accumulation of effects. Despite the reduction in primary production, annual average chlorophyll concentration was elevated in Doordewind, locally by about 0.4 µg/l (60%). However, this appeared to be due to an increase in proportion of algae with a higher chlorophyll content (i.e. species adapted to low light levels).

Phytoplankton biomass concentrations showed a patchy response, with a 10% reduction in the downstream part, adjacent to the German sites.

For Doordewind primary production was reduced for a further 30% in the Partial Revision scenarios where the size of the area as well as the density of turbines was higher. The Lagelander wind farm area is located in an area with very limited stratification and showed some (up to 0.07gC/m^2/day, i.e. 20%) reductions on primary production due to elevated fine sediment in the top of the water column (causing light limitation). This lead to decreases of >2.5%, in chlorophyll in over half of the wind farm; but this was much less than impacts in the German Bight.

The Search Area 6/7in all Partial Revision scenarios sees a boost in primary production and phytoplankton biomass, due to the fact that the summer temperature stratification, which limits productivity in that area, is reduced, more nutrients are available in the top layer for primary production. Stratification does not disappear completely, which confines any extra resuspended SPM to the layers below the pycnocline in the summer season, which means that it does not reduce light availability in the growing season of phytoplankton, as is the case for most other wind farm areas.

The magnitude of the effects is influenced by the energy density of the wind farm. However, increasing turbine size has much less effect than adding extra turbines. The density of turbines (number per km^2) has more effect than their size.

Scenario 4 involved a large open space in the centre of the wind farm, and this scenario seemed to have the lowest impact on stratification and on annual average increases of SPM in the top water layer. However, in terms of primary production the difference between this scenario and scenario 1 (with similar sized turbines and a similar total capacity of 24 GW) was relatively minor. Effects were patchy, and at most 10% in the southern part of the open space (about 0.05 µg/m^2/year), averaged out over the whole of the farm differences were less than 1%. Note that the density of the turbines in scenario 4 is higher than in scenario 1 (0.49/km^2 *versus* 0.31/k m^2). This means that both the effects of a large open space and a higher density of the turbines are compared between the scenarios 1 and 4.

Contents

1 Introduction

1.1 Offshore wind and the marine environment

Wozep (the *Wind Op Zee Ecologisch Programma*) is an integrated research programme to reduce the knowledge gaps regarding the possible environmental effects of offshore wind farms (OWFs) on the North Sea.

Previous studies have indicated that ecosystem effects of large-scale offshore wind can be profound. These effects are due to interactions of the wind turbines with the ambient flow, resulting in changes in currents spatio-temporal patterns, stratification, changes in fine sediment dynamics and consequently changes in primary production. In a first study (Van Duren et al. 2021) we demonstrated the applicability of the new Dutch Continental Shelf model- flexible mesh (DCSM-FM) model to quantify such processes. In this first modelling study (Van Duren et al. 2021) a more or less hypothetical scenario layout was used to assess potential effects, as at that time the available plans for future offshore wind were limited to a few wind farms. A subsequent study (Zijl et al. 2023b), already used a different, more likely set of scenarios, and an improved version of the model, in order to test very extreme upscaling. These scenarios were on the one side based on realistic options for future offshore wind developments and hypothetical potential scale up locations on the other side. These scenarios were therefore still fundamentally aimed at research into potential effects. These studies identified regions in the North Sea that, due to their different physical properties, showed different responses to the implementation of large-scale offshore wind energy. Appendix B shows the different regions and the impacts we see in the model runs.

The current model is still not finished in terms of model development and validation, but the current version is now deemed fit for use in more applied project to assess potential effects of different configurations of wind farm lay-out, and to assess pros and cons of different options in marine spatial planning.

1.2 Framework for Assessing Ecological and Cumulative Effects (KEC)

In order to assess whether impacts of offshore wind developments are within acceptable limits, the Dutch government is developing a framework for the assessment of Ecological cumulative effects (or Kader Ecologie en Cumulatie; KEC). There have been several iteration of this framework and KEC 5.0 looks cumulatively at the effects of national and international wind farms that will be built up to 2032. The effects on marine mammals, birds, bats, marine Strategy Framework (MSFD) indicators and ecosystems are examined. The underlying report describes the ecosystem effects. The scenario for KEC 5.0 (i.e. the expected lay-out of wind farms operational in 2031) is also used as a baseline for the Partial Revision scenarios (see section 1.3).
With the offshore wind target being increased from 11 GW to 21 GW by 2031, more areas for offshore wind farm development are needed. On the 18th of March 2022 the Dutch government approved the North Sea Programme 2022-2027, which among other things designates offshore wind farm zones that provide space for the development of wind farms up to and including 2030/31. The new designated areas included Nederwiek, Lagelander and Doordewind, while IJmuiden Ver (Noord) was reconfirmed, as was the southern part of Hollandse Kust West (Figure 1.1). At the same time it was agreed that no more than 10,7 GW will be realised in these wind farm zones until 2031, and that the remaining parts are to be reconsidered in a Partial Revision (section1.3).

Two of the older wind farms, close to the coast (Offshore Windpark Egmond aan Zee and Prinses Amalia Wind Park) are not taken up in the base scenario, as they may possibly be decommissioned prior to 2030.

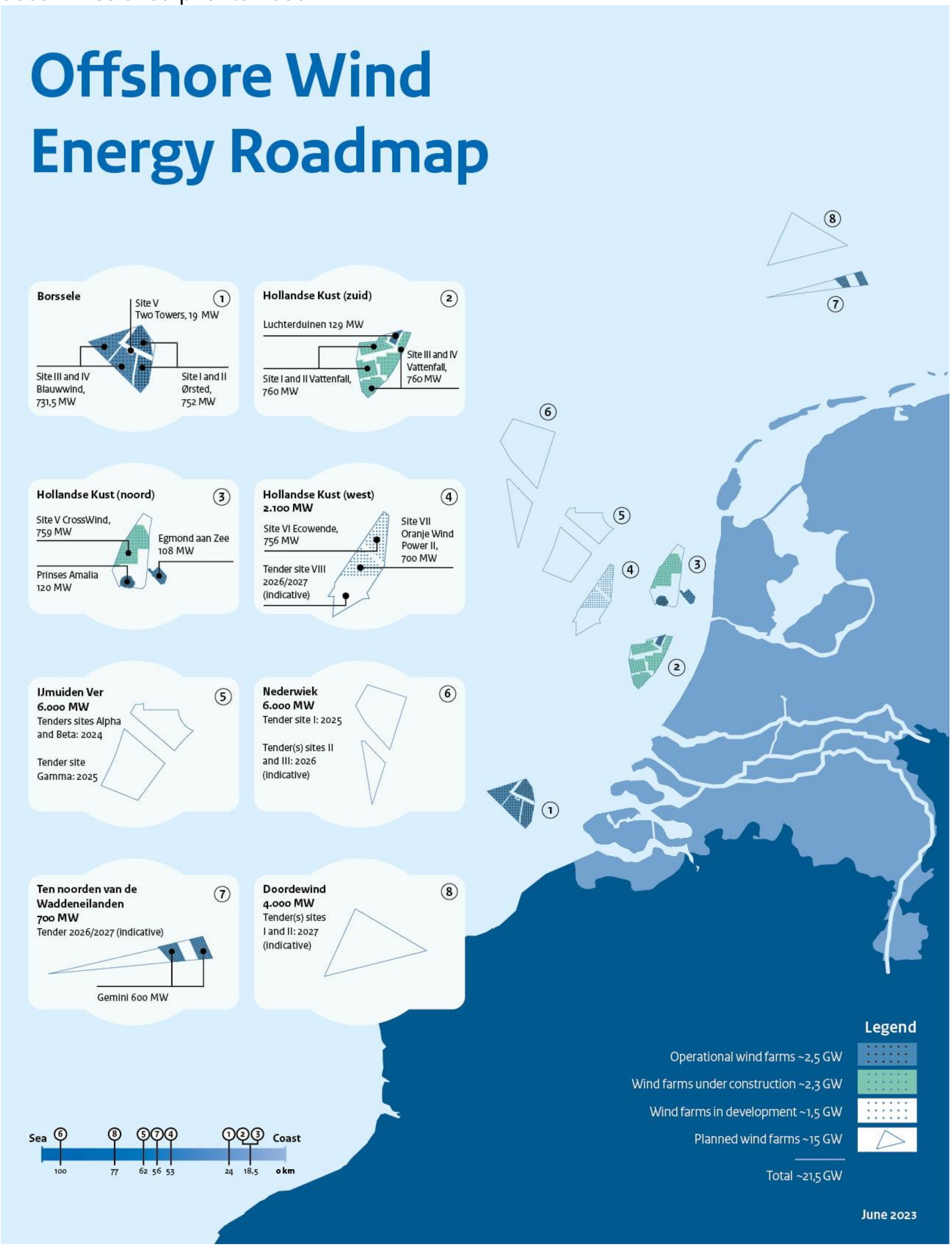

Figure 1.1 Currently designated areas for offshore wind energy development (figure from RVO website: https://english.rvo.nl/topics/offshore-wind-energy/plans-2030-2050).

1.3 Beyond 2030: Partial Revision (PR)

The North Sea Programme 2022-2027 also announces an interim change, the Partial Revision (PR), with the aim of creating wind energy areas for the period after 2031 and thereby determine the spatial location of surrounding shipping routes. A partial revision is necessary to ensure the continuity of the realization of offshore wind farms. Designating wind energy areas is a necessary first step for this. Further background information regarding the Partial Revision and the links with other North Sea related policies can be found in the Concept Note Scope and Level of Detail[1]. In the PR search areas are investigated as well as (parts of) already designated areas that remain unused when implementing the Supplementary Roadmap 2030. In the North Sea Programme 2022-2027 it was agreed that the (parts of) the wind energy areas designated therein remain unused after the realization of a total of 21 GW until approximately 2030, as detailed in the afore-mentioned Concept Note[1.]..
The following areas are considered for specifying at least 23-26 GW in the PR:

- Search area 6/7
- Search area Doordewind (west)
- Doordewind: already designated but unused part of this area
- Lagelander: already designated but completely unused

Figure 1.2 shows a map showing the location of these areas.

[1] https://www.platformparticipatie.nl/programmanoordzee/concept-nrd-participatieplan-programmanoordzee/handlerdownloadfiles.ashx?idnv=2609791

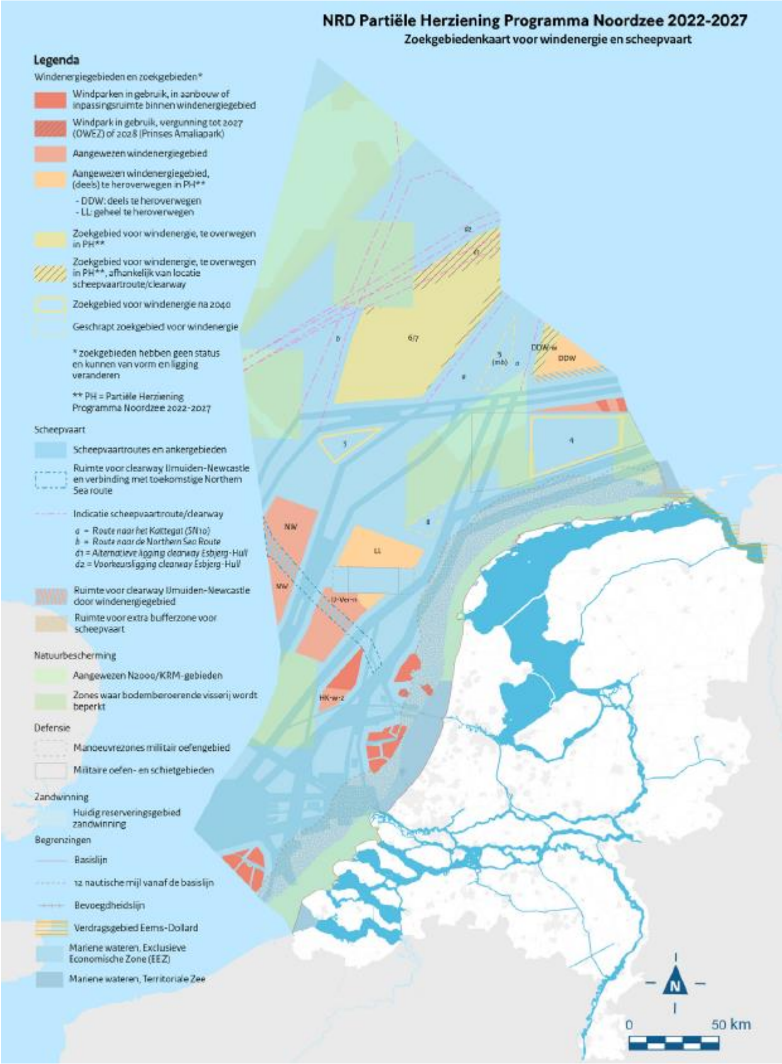

Figure 1.2 Map of wind search areas and shipping (from the Concept Note on the Partial Revision[1].

Meanwhile there are also more details available regarding the plans for offshore wind in neighbouring countries.

The previous studies indicated that the effect of several wind farms together can be different from the sum of the component parts. Hence, wind farms in other North Sea countries have an impact on the effects in and around Dutch wind farms. The German bight was in the previous Wozep studies already identified as an area that appeared to be especially sensitive (Van Duren et al 2021; Zijl et al 2023, and Appendix B), and particularly there the plans for offshore wind have substantially increased.

1.3.1 Search area 6/7

Of the areas under consideration in the Partial Revision, the largest one is an area with an energy capacity that is currently under investigation. For this search area 4 different scenarios were run. In most scenarios the capacity was assumed to 24 GW, . It is located in the northern part of the Dutch EEZ. It consists of the former search areas 6 and 7 that were combined into one large search area (Search area 6/7). This area is located in a deeper part of the Dutch part of the North Sea and borders the marine protected area the Central Oyster Grounds. This area is characterised by a strong summer stratification. Earlier studies indicated that in this area the presence of monopiles may cause a reduction, but not elimination of stratification, and a later onset of stratification (van Duren 2023, Zijl et al. 2023b).

In comparison to most other parts of the Dutch North Sea the area has a fairly large mud content in the seabed and the bed is stable, without large mobile bed forms. Further details about the characteristics of this area can be found in Van Duren (2023). The increased nutrient availability in the top layer is likely to cause an increase in primary production, but the later onset of stratification also is likely to cause a delay in the spring bloom. Impacts in this area are therefore potentially large. This area is relatively large. Therefore it is possible that not the whole area will be covered with wind turbines, or that lower densities will be applied. In this study the ecosystem effects are investigated in case that the whole area will be uniformly covered in wind turbines applying different densities and wind turbine sizes, and in case that the area is split in two sections with a broad open space in between.

1.4 Aim of this study

The aim of this study is to apply the Wozep modelling suite to a set of scenarios that should give insight in the potential “bottom-up” impacts on the marine ecosystem of several design options. The base scenario is the situation around 2031 (as indicated in Figure 1.1), used for the KEC 5.0 assessment. In additional scenarios are the scenario’s with the area’s Lagelander and Doordewind and a number of extremes for the layout of search area 6/7, focussing on the size and spacing of turbines and on the impact of a broad open space in the central part of the area, which is relatively rich in fine sediment in the seabed. Note that the current scenarios are likely still extreme scenarios. The scenarios are designed to gain insight in certain design aspects. Options for lay-out choices will be developed later on in the process of the Partial Revision.

The assessments for the KEC 5.0 analyses will be done with the effects relative to the reference scenario (no wind farms present). The 2031 KEC 5.0 scenario will be termed the “Base scenario” throughout the report. The analyses for the Partial Revision will primarily be done with respect to the base scenario, with occasional comparisons to the reference scenario.

Note: all scenarios were run with the same meteorological input (actual meteorological data from the year 2007, similar to previous studies). Hence impacts of e.g. climate change, or expected changes in nutrient run-off from land, are not assessed.

1.5 Terminology of scenarios.

The term “reference scenario” for the situation without wind farms is in keeping with the previous Wozep reports on ecosystem effects (Van Duren et al. 2021, Zijl et al. 2021, Van Kessel et al. 2022, Zijl and Laan 2022, Zijl et al. 2023b). Note that in the policy documents relating to the Partial Revision the term “*Reference scenario*” is used for the expected situation in 2031, which is the *Base scenario* in this study. The *Base scenario* is the relevant scenario for KEC 5.0.

1.6 Layout of this report

Chapter 2 describes the different scenarios that were assessed. Chapter 3 describes the Impact of the scenarios on the North Sea hydrodynamics (current speeds, residual currents, impacts on stratification etc.). Chapter 4 describes the expected impact of the scenarios on the wave field. Chapter 5 describes the impact of the scenarios on the fine sediment dynamics (using input from the hydrodynamics models from chapter 3 and the wave modelling from chapter 4). Chapter 6 reports the modelled impacts on water quality and ecology. In chapter 7 the overall impacts of the different farm lay-outs on ecosystem functioning are discussed. Chapter 8 discusses the knowledge gaps and uncertainties.

2 Scenario choice

2.1 Reference scenario

The reference scenario is the North Sea area without the presence of wind farms, similar to the earlier reports on ecosystem effects (Van Duren et al. 2021, Zijl et al. 2023b). For a map with all the Dutch wind farm areas and search areas with names see Appendix A.

2.2 Base scenario

The base scenario is the current scenario for wind farms operational in 2031. This includes the wind farms that are currently operational, the ones that are currently licenced (most are under construction, some in the early stages), the ones that are currently designated areas (either currently tendered or in the near future). The scenario does not include the two older wind farms OWEZ and Prinses Amalia (PAWP), as they possibly are going to be decommissioned before 2031. It also includes the locations of the wind farms outside the Netherlands that are likely to be in operation by 2031. Figure 2.1 shows this scenario. OWEZ and PAWP are indicated in the figure in orange but are not part of the scenario calculations.

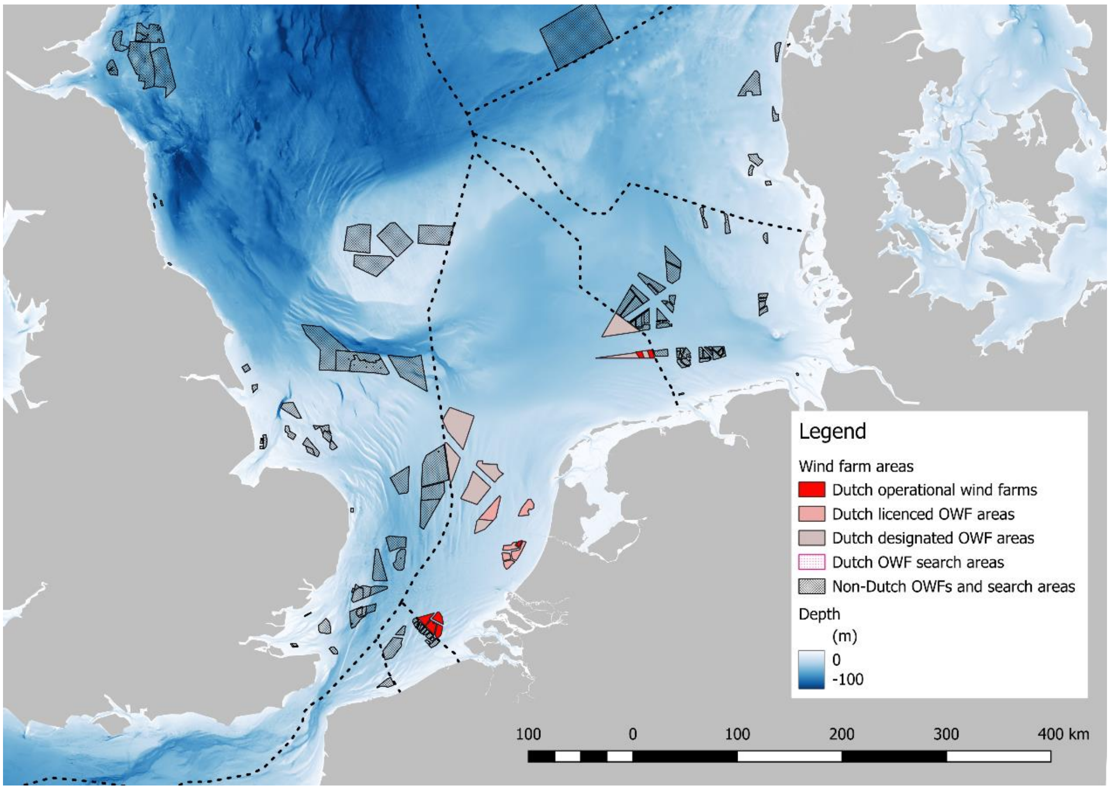

Figure 2.1 Lay-out of the base scenario. The status of wind farms and search areas outside the Netherlands is not differentiated.

This scenario is used in the KEC 5.0 assessment. This is the framework for cumulative ecological impacts used by the Dutch government to assess whether ecological impacts of offshore wind remain within acceptable levels (https://www.noordzeeloket.nl/en/functions-and-use/offshore-wind-energy/ecology/accumulation-ecological-effects/framework-assessing-ecological-cumulative-effects/). Note: the assessment area for the KEC runs further north, but that area is outside of the area affected by ecosystem effects by Dutch wind farms.

2.3 Partial revision scenarios

The Base scenario (used for KEC 5.0) has a total capacity of 2.3 GW in the Doordewind area, generated by 115 20 MW turbines. In scenarios 1, 2, 3 and 4, the size of the site is extended with an area called Doordewind West, forming one larger wind farm. In these scenarios this farm yields 6 GW and contains 300 turbines of 20 MW. Hence not only is the surface area of the site larger in the Partial Revision scenarios, also the density of turbines is substantially higher. The Base scenario has an average density of about 0.3 turbines per km^2, while the density in the Partial Revision scenarios vary in number of turbines per km^2 for area 6/7.

Also in all four scenarios there is a wind farm "Lagelander Noord" with a 2 GW capacity and 100 turbines of 20 MW each. The differences between scenarios 1, 2, 3 and 4 are in the configuration of the large Search area 6/7.

2.3.1 Scenario 1, 2 and 3

These are 3 scenarios in which the Search Area 6/7 is divided into 4 sections with a narrow separation. The whole area is nearly fully covered in wind farms, but with differences in the size and spacing of turbines (Figure 2.2).

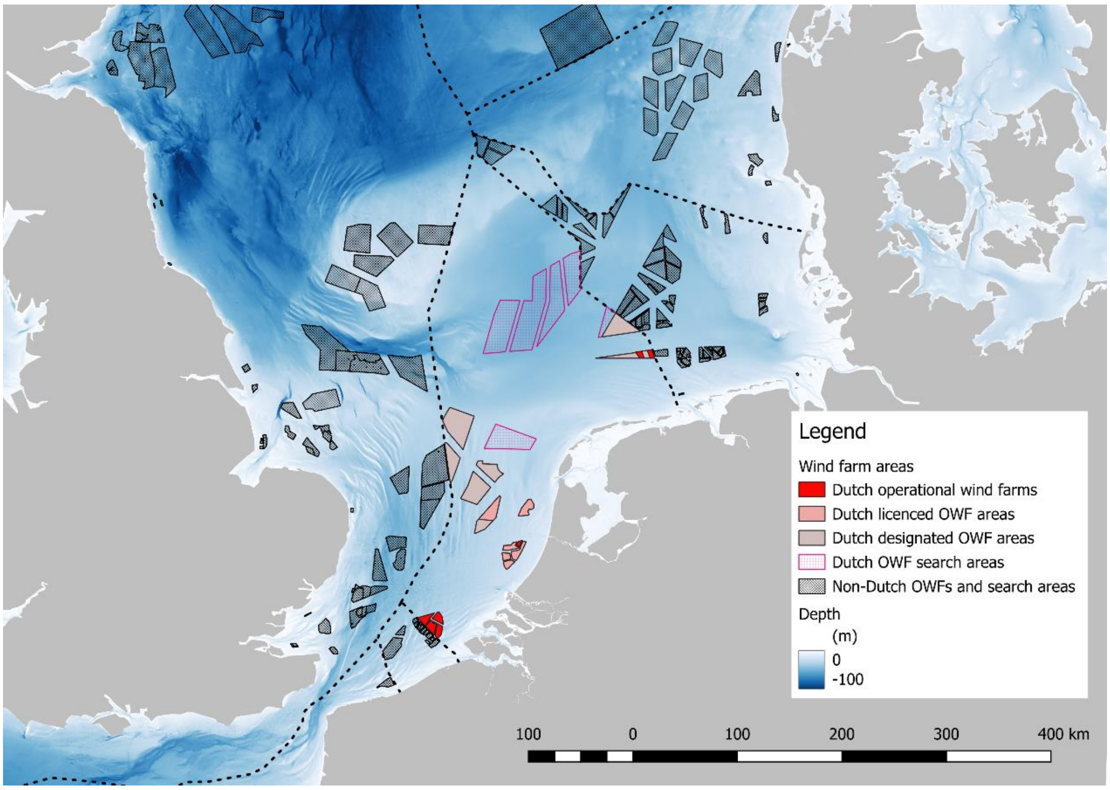

Figure 2.2 the spatial lay-out for scenarios 1, 2 and 3.

- In scenario 1 the total capacity of the farm is 24 GW and it contains 1200 turbines each of 20 MW with a diameter of 11.3 m. Turbine density 0.31 turbines /km^2.
- In scenario 2 the total capacity of the farm is 24 GW and it contains 960 turbines of 25 MW, with a diameter of 13 m. Turbine density 0.25 turbines /km^2.
- In scenario 3 the total capacity of the wind farm is 37.4 GW and it contains 2492 turbines of 15 MW and a diameter of 9.9 m. Turbine density 0.65 turbines /km^2.

2.3.2 Scenario 4

In the 4th scenario, the central part of Search Area 6/7 is left open. The gap between the 2nd and 3rd section measures between 20 and 45 km. This area coincides with the most muddy part of this search area. The mud content of this section ranges between 10 and 25%, which is high for the Dutch part of the North Sea (Figure 2.3).

In this scenario the total capacity of the wind farm is 25.4 GW and the four sections contain in total 1272 turbines of 20 MW each, with a diameter of 11.3 m. Turbine density 0.49 turbines /km^2.

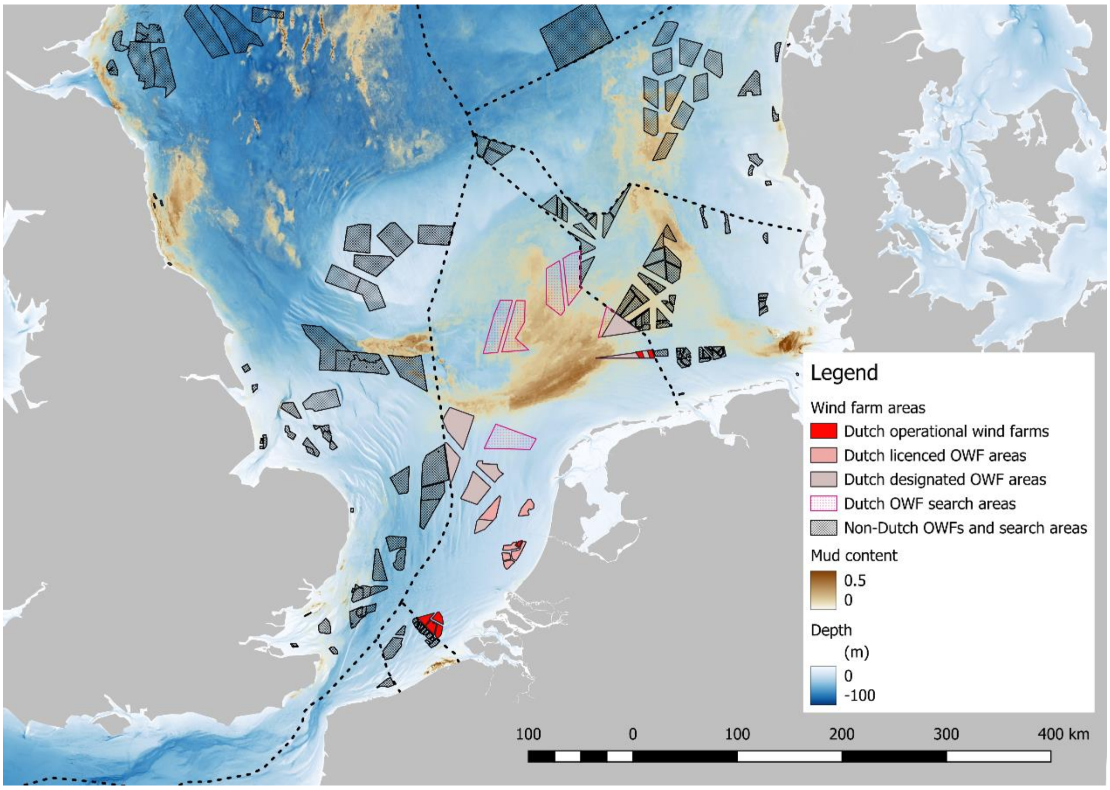

Figure 2.3 Spatial lay-out of scenario 4, with a model prediction of the mud content. The data for the mud content are based on detailed random forest models using bathymetry and bed shear stress (Stephens 2015). The lay-out of wind farms outside of this view are the same as in Scenarios 1, 2 and 3.

2.4 Non-Dutch OWFs

The offshore wind farms outside the Dutch EEZ were kept the same in scenario’s 1-4. For the farms already operational or under construction the known number and size of turbines were used. For the search areas to be developed in the future, turbines of 20 MW were assumed with a monopile diameter of 11.3 m.

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3 Impact on hydrodynamics

3.1 Model setup

3.1.1 Introduction 3D DCSM-FM

For the hydrodynamic modelling, the 3D Dutch Continental Shelf Model – Flexible Mesh (3D DCSM-FM) is used, which was developed in recent years as part of Deltares' strategic research. The main purpose of 3D DCSM-FM is to have a versatile model that can be used for all manner of studies and research on the Northwest European Continental Shelf, including the North Sea and adjacent shallow seas, such as the Wadden Sea. It aims to combine state-of-the-art capabilities with respect to modelling of water levels (tide and surge) as well as (residual) transport phenomena. The latter is crucial for application in water quality and ecological modelling. By combining this, the model is ideally suited for this study.

This model is the successor of the 3D southern North Sea model ZUNO-DD. 3D DCSM-FM is based on 2D DCSM-FM 0.5nm, which has been developed for the Dutch Ministry of Infrastructure and Water Management (Zijl and Groenenboom, 2020) and is used for operational forecasting of water levels. The model includes 20 equidistant layers of the water column. Although, upgraded model version has been developed for 3D DCSM-FM in 2022, this study uses the same version as in the previous study for the WOZEP program (Zijl et al., 2021) to ensure continuity in modelling results.

3.1.2 Computational grid, bathymetry and bottom roughness

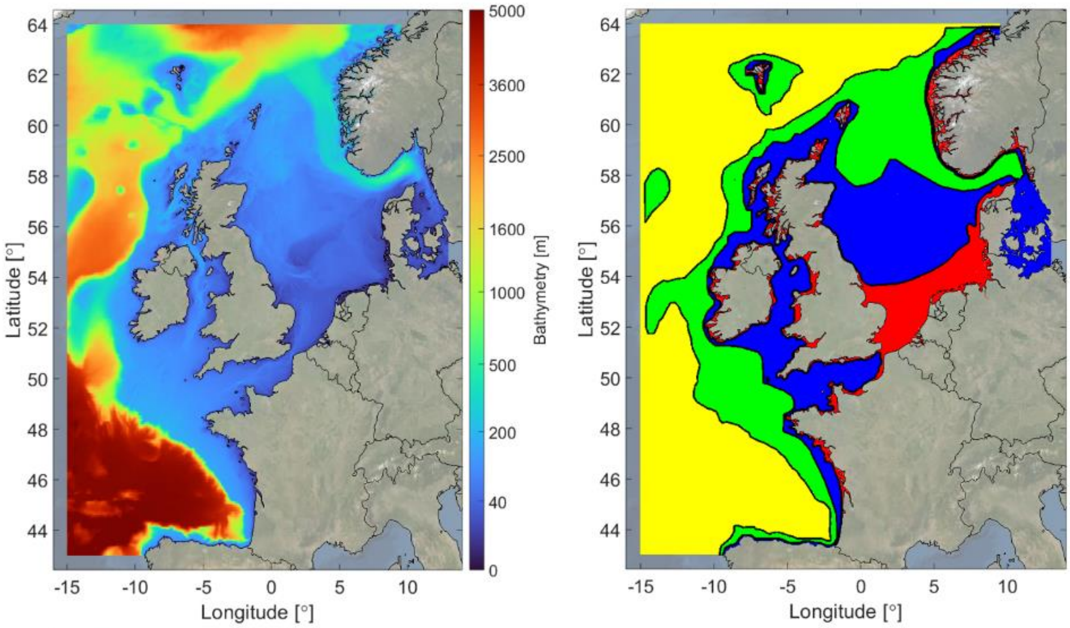
3D DCSM-FM covers the Northwest European Continental Shelf, specifically the area between 15°W to 13°E and 43°N to 64°N. The network consists of approximately 630,000 grid cells. Compared to a structured grid approach, the new flexible mesh has coarser grid cells near the open boundaries and in deep waters, whereas the resolution increases toward the shallower waters. This gives a better match with the spatial scales of the locally relevant physical processes. Cells in deep oceanic waters have a resolution of 1/10° in longitudinal direction and 1/15° in latitudinal direction, which corresponds to approximately 4 by 4 nautical miles (nm). Along all coasts and in the southern North Sea cell sizes decrease to 0.5 by 0.5 nm, which corresponds to approximately 900 m.

The area of interest in this study, namely Search Area 6/7, lies primarily within the area with 1 by 1 nm resolution having few cells within the 0.5 nm area. Given the stability of the model and extensive calibration and validation performed on the model, this does not present any adverse effect on the quality of the results obtained within this project.

A sigma-layer approach is used for the vertical schematization of the model. This implies that a fixed number of layers, with a thickness dependent on local water depth, is present. This results in a high vertical resolution in shallow areas. A total of 20 layers with a uniform thickness of 5% of the water column is applied.

The model bathymetry is based on the gridded dataset by the European Marine Observation and Data Network (EMODnet), a consortium of organizations collecting and distributing European marine data from different sources. For large parts of the Dutch waters, bathymetric information from the detailed baseline database by the Dutch government is used.

For the bed friction, a spatially varying Manning roughness coefficient is used. During the model calibration, using OpenDA-DUD, these values were adjusted to obtain an optimal water level representation. For the calibration of the bed roughness the model was run in 2D mode for the entire year of 2017, using more than 200 tide gauge stations shelf-wide.



Yellow:	1/10° x 1/15°	~ 4.0 nm x 4.0 nm	
Green:	1/20° x 1/30°	~ 2.0 nm x 2.0 nm	→800m isobath
Blue:	1/40° x 1/60°	~ 1.0 nm x 1.0 nm	→200m isobath
Red:	0.75’ x 0.5’	~ 0.5 nm x 0.5 nm	→ 50m isobath

Figure 3.1 Bathymetry and grid cell sizes in 3D DCSM-FM.

3.1.3 Open boundaries

Water levels

At the northern, western and southern open boundaries of 3D DCSM-FM, water level boundaries are applied. At these locations, astronomical water levels are imposed, derived from a harmonic expansion of the amplitudes and phase lags of 31 tidal constituents. These constituents are retrieved from the global tide model FES2012. The surge at the open boundaries is approximated by addition of an inverse barometer correction (IBC) to the astronomical water levels. This correction is a time- and space-dependent function of the local atmospheric pressure. To account for steric effects, the daily mean water levels from CMEMS are used.

Salinity and temperature

At the lateral open boundaries, temperature and salinity are derived from CMEMS. These daily values at 50 non-uniformly spaced vertical levels are interpolated by Delft3D Flexible Mesh to the right horizontal location and model layers. The spatially varying salinity and temperature in the model are initialized by nudging 3D DCSM-FM with the data from the same source.

3.1.4 Meteorological forcing

For this study 3D DCSM-FM has been coupled to ECMWF's ERA5 reanalysis dataset. The forcing parameters used are described below.

Momentum flux

To account for the air-sea momentum flux time- and space-varying wind speeds (at 10 m height) and atmospheric pressure (at mean sea level (MSL)) are applied. With respect to air-sea momentum exchange, the aim is to be consistent with the Atmospheric Boundary Layer (ABL) model that is used in the meteorological model applied. For coupling to ERA5 this implies using a Charnock formulation and specifying a time-and space-varying Charnock coefficient.

In computing the wind shear stress, which represents the momentum exchange between air and water, the wind speed relative to the flow velocity at the water surface is used. While this implies less consistency with the ABL approximation in the meteorological model, this was proven to be beneficial to the quality with which water levels are represented (Zijl, 2016).

Heat flux

Horizontal and vertical spatial differences in water temperature affect the transport of water through their impact on the water density. Heating of surface water and shallow waters cause temperature gradients that can generate horizontal flow. It can also lead to temperature stratification with accompanying damping of turbulence and hence a reduction in vertical mixing. To include these effects, the transport of temperature is modelled. For its main driver, exchange of heat with the atmosphere, a heat flux model is used. The temporally and spatially varying turbulent exchange of heat through the air-water interface is computed based on air temperatures (at 2 m), cloud cover, dew point temperature and wind speed from the ERA5 meteorological reanalysis. To account for the radiative heat fluxes the surface net solar (short-wave) radiation and the surface downwelling long wave radiation have been imposed, while the surface upwelling long-wave radiation is computed based on the modelled sea surface temperature. The incoming solar radiation is distributed over the water column, depending on the water transparency prescribed with a Secchi depth. In the hydrodynamic model a constant, uniform value of 4 m has been applied, except at the Wadden Sea, where this value is set to 1 m. This was based on a calibration for sea water temperature which has shown a good performance using the mentioned values (Zijl and Laan, 2022b). Although it is clear that in reality the Secchi depth varies in time and space, such approximation is sufficient for the needs of the model due to low sensitivity to Secchi depth parameter in many regions. This is, however, something that might be addressed in the future model upgrades.

3.1.5 Mass flux

To account for the mass-flux through the air-sea interface time- and space varying fields of evaporation and precipitation have been applied.

3.1.6 Freshwater discharges

Freshwater discharges in the 3D DCSM-FM domain are prescribed as depth-averaged, climatological monthly means based on data from E-HYPE (the E-HYPE model calculates water balance, dynamics of hydrological variables and daily discharge for the continental Europe). These discharges include varying water temperatures. The seven most important discharges in the Netherlands and three most important German rivers are replaced by gauged discharges with an hourly or daily interval.

3.1.7 Computational performance

After starting from an external solution (CMEMS) with respect to temperature and salinity, a spin-up period of one year, forced by realistic meteorological and river discharge values, is applied to reach a dynamic equilibrium.

Computations were performed on Deltares' h6 Linux-cluster using 5 nodes with 4 cores each. With a maximum timestep of 100 s, this results in a computation time of approximately 15 minutes per simulation-day (3.5 days per simulation-year). These computational times are for the hydrodynamics-only model. Together with the D-WAQ module for water quality, computational times are a factor 3-4 longer.

3.1.8 Parameterization of wind farms

With a grid size of at least 900m, the individual piles of the OWFs are too small to explicitly include in the model schematization. Therefore, a sub-grid trachytope approach from the D-Flow FM vegetation module is used. In this approach, each OWF area is viewed as a vegetation field with specific density and width of the piles. There a quadratic sink term is included in the horizontal momentum equations which is represented by changed bed roughness within this field. The effect of OWF piles on roughness is computed based on their density and width, water depth, and drag coefficient. 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). More detailed information on this technique as well as specific formulations used there could be found in D-Flow FM User Manual (Chapter 15).

The locations of the offshore wind farms are specified in the hydrodynamic 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 mean pile diameter. Various values for turbine density and pile diameter are used for areas that are operational in 2031 scenario or are part of Scenarios 1-4.

Since the surface forcing applied does not yet include the impact of OWFs on the meteorological conditions, this has been included in a simplified manner through a 10% reduction of the 10 metre wind speeds (U_{10}) based on literature (Rosencrans, 2024). Other meteorological forcing parameters, such as air temperature and relative humidity, are left unchanged. Wake effects and directional changes of the wind are not considered. Other work within the Wozep project has identified that the wind wakes do have an impact, particularly if instantaneous effects are considered, but that annual average effects of wind wakes are relatively minor in comparison to the hydrodynamic wake effects (Zijl and Leummens 2023).

The impact of the OWFs is assessed through the comparison of a multi-year scenario computation with a baseline computation. For the modelled period the environmental forcing conditions of years 2007 and 2008 have been selected, with 2006 used for spinning up the model to the initial conditions of January 1st, 2007. The selection of the period was based on several considerations including data availability, the inter-annual variability in temperature stratification in the central North Sea and residual transport through the English Channel. Details on model validation can be found in Appendix D.

3.2 Results

3.2.1 General

The hydrodynamic impact of the OWFs will be assessed and presented in the following sections with respect to impact on:

- Sea surface temperature
- Temperature stratification
- Salinity stratification
- Residual currents
- M2 tidal amplitude and phase

The impact of each OWF configuration within Search Area 6/7 will be presented in comparison to the base 2031 OWF scenario in order to look more closely on effects caused by changes in this particular area. Due to the scale of the model and wind farms of interest, spatial patterns within each OWF are not considered in the input and methodology, as well as during the analysis of the results.

3.2.2 Reference (no OWFs)

In the reference scenario, the effect of offshore wind farms is neglected entirely, including that of the already present wind farms. The results of this scenario give an overview of the occurring spatial patterns in the North Sea. The simulations for the reference scenario have been done during the previous study for the WOZEP program and were described in detail in the corresponding report (Zijl et al., 2021).

3.2.3 Base scenario (OWFs in 2031)

In this section, the results of the Base Scenario are presented both as absolute values of studied parameters and as effect of wind farms operation in comparison with reference scenario.

Temperature and salinity

Below, the 2031 OWF scenario situation in terms of the mean annual sea surface temperature and salinity as well as stratification thereof is presented along with its comparison to reference. 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 (temperature) or other way around (salinity).

The overall pattern of the stratification is resembling the one determined in the previous WOZEP study, thus staying in line with the expected spatial variation (Van Leeuwen et al., 2015). A permanently mixed area is present in the part of the North Sea between the United Kingdom and the Netherlands with salinity stratification being high near the Dutch coast due to the effect of the ROFIs attaching to the coast.

Differences of the 2031 scenario with the reference show changes in surface temperature and temperature stratification around ±0.2°C and ±0.4°C, respectively, with primary changes occurring within OWF limits. The relative changes of the temperature stratification reach almost 60% within OWFs with pronounced larger relative effect of the temperature decline. However, the general spatial distribution of relative difference follows the absolute values.

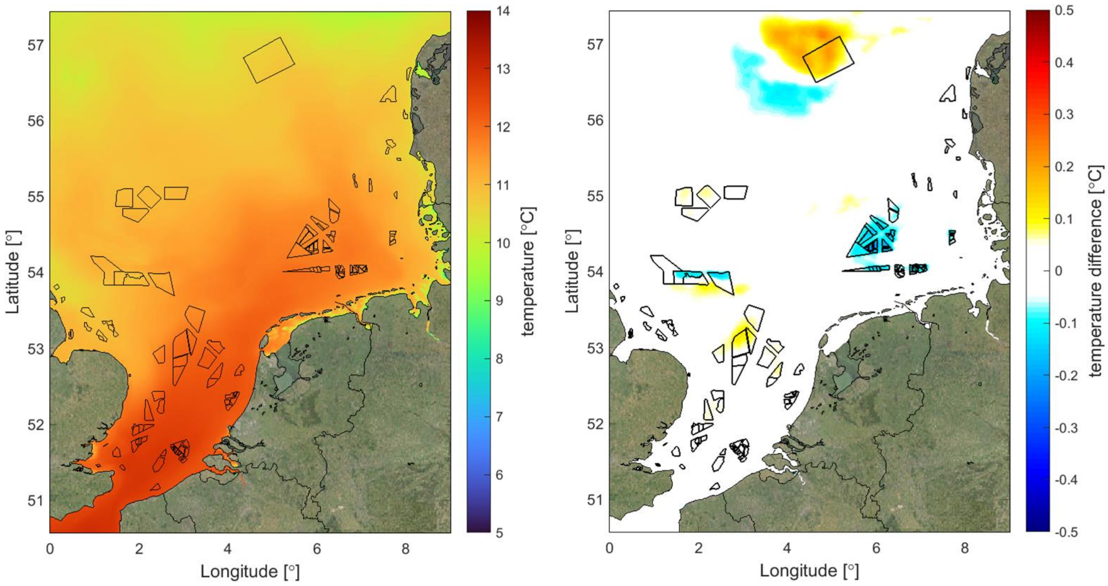
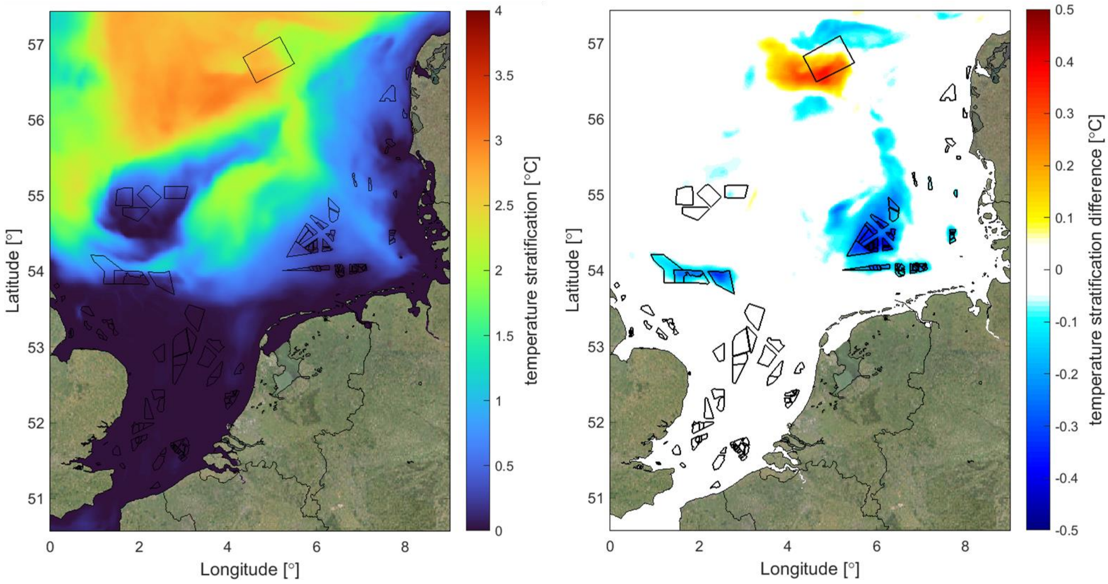


Figure 3.2 Annual mean of sea surface temperature according to Base 2031 scenario (left) and its difference with Reference scenario (right).



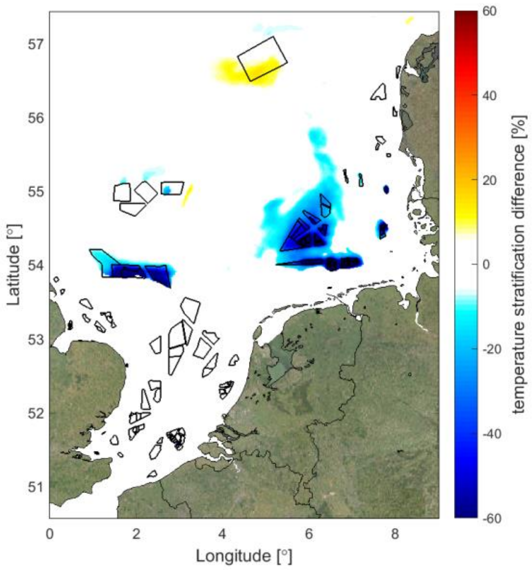


Figure 3.3 Annual mean of temperature stratification according to Base 2031 scenario (top left) and its absolute (top right) and relative (lower left) difference with Reference scenario.

Largest changes in salinity or salinity stratification are smaller on relative scale compared to those of temperature values. The most effect imposed by OWFs operation on salinity is observed in areas of higher stratification, such as near the Dutch coast. There salinity stratification reduction reaches up to 0.4 PSU on account of approximately 0.3 PSU surface salinity increase. Most significant relative salinity stratification differences, contrary to the absolute changes, are extremely localized to a selection of OWF areas where the difference may reach up to +20% or -60%. The values outside of OWFs are more stable in a relative sense (absolute difference of under 0.05 PSU was ignored). It must be noted that such high relative changes are manifested due to the small values of stratification. This leads to small absolute difference between scenarios to be considered as substantial in a relative sense.

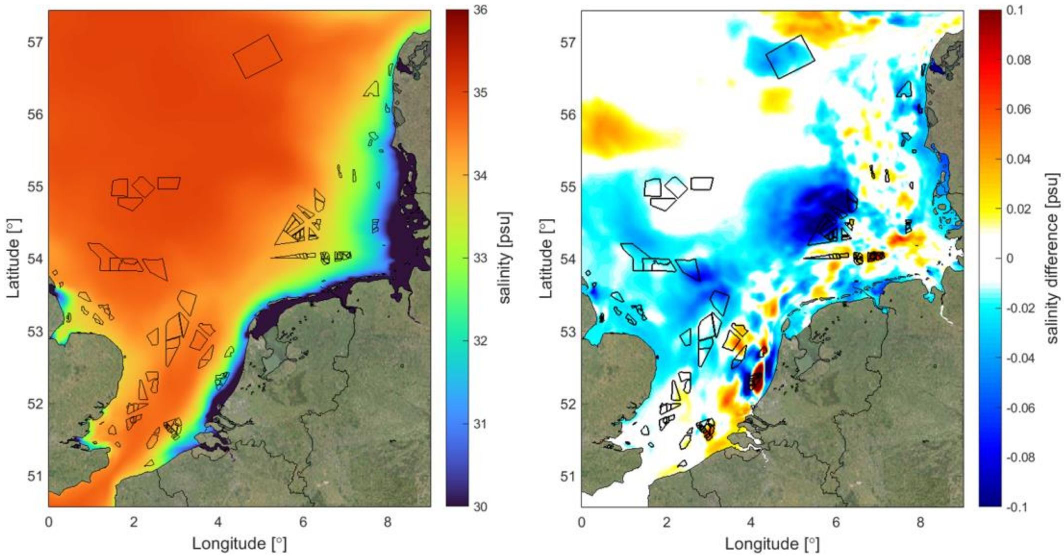


Figure 3.4 Annual mean of sea surface salinity according to Base 2031 scenario (left) and its difference with Reference scenario (right).

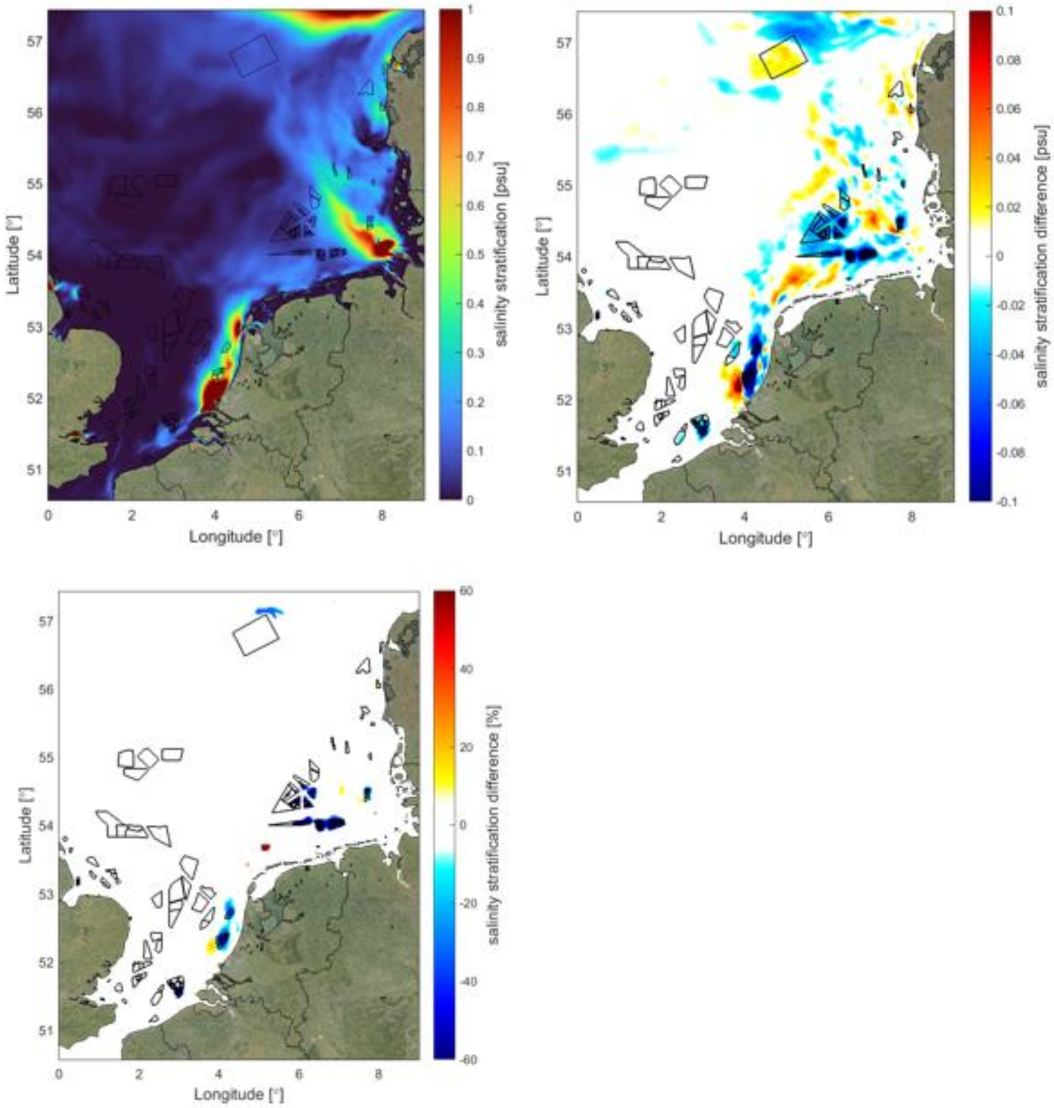


Figure 3.5 Annual mean of salinity stratification according to Base 2031 scenario (top left) and its absolute (top right) and relative (lower left) difference with Reference scenario.

Residual currents
In Figure 3.6 the magnitude of the annual mean (residual) currents at the sea surface is presented. The overall pattern of the same compared to the reference scenario with around 0.03 m/s reduction in residual velocity magnitude within the wind farms and slight compensating increased outside of them.

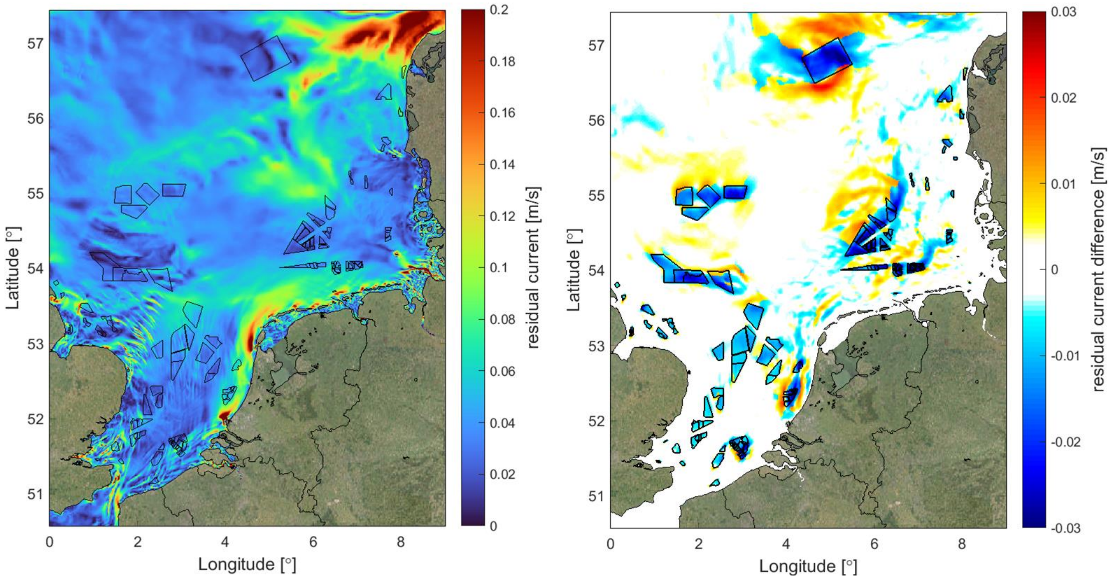
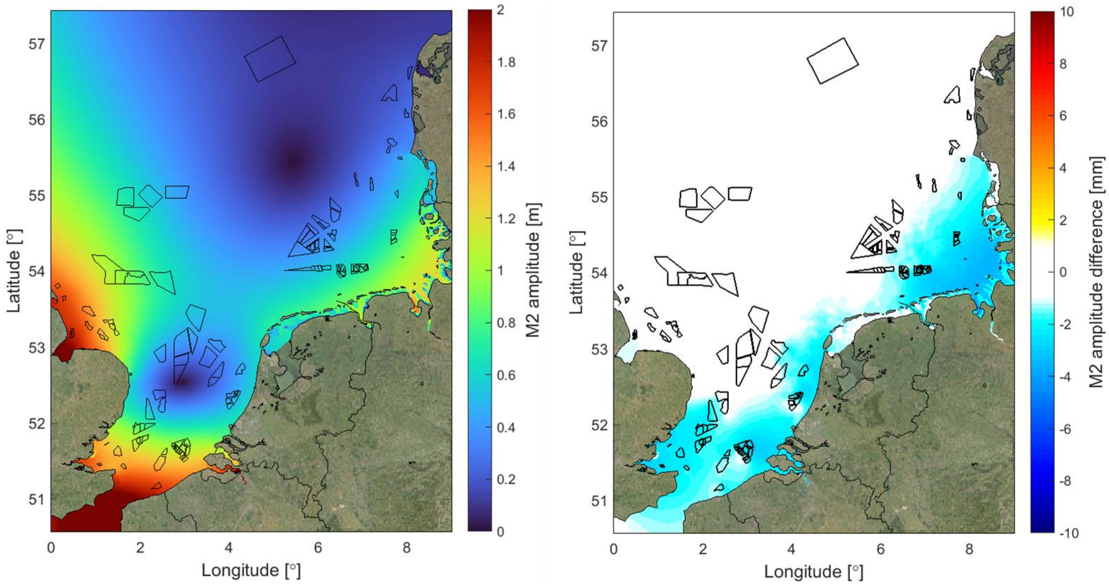


Figure 3.6 Annual mean velocity magnitude according to Base 2031 scenario (left) and its difference with Reference scenario (right).

M2 tide
The semidiurnal lunar M2 tide is the main tidal constituent in most parts of the North Sea. There 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. The presence of two complete amphidromic systems in the North Sea is evident, one at a latitude of 52.5° and the other further east near 55-56° latitude. This is in line with the results of the previous WOZEP study and expectation. The changes in M2 parameters are limited to a slight shift of the amphidromic points and a decrease of amplitude up to 3-5 mm near German coast. The relative difference of the water levels in its turn can be considered as negligible.



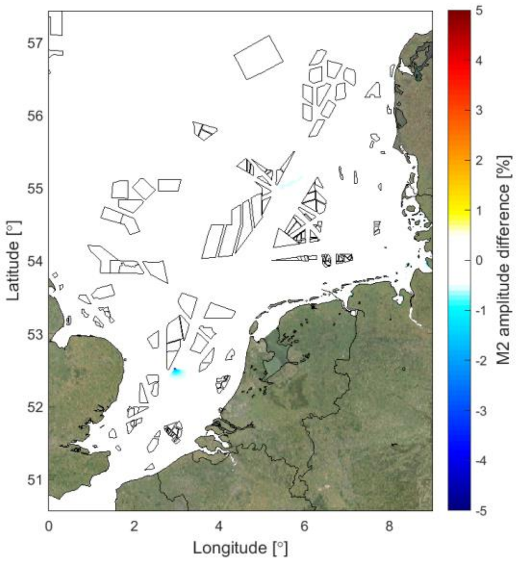


Figure 3.7 Annual mean M2 amplitude according to Base 2031 scenario (top left) and its absolute (top right) and relative (lower left) difference with Reference scenario.

3.2.4 Partial revision scenarios

In this chapter, the effects of different Search Area 6/7 OWF implementations are considered in comparison with Base scenario. Thus, only the effects caused by wind farms added after 2031 are studied, allowing for better comparison of differences between scenarios.

Temperature

In Figure 3.8 Annual mean sea surface temperature difference caused by implementation of Scenarios 1-4,Figure 3.8 the change in the annual mean sea surface temperature is presented for Scenarios 1-4, relative to the base scenario. From it, the differences between Scenarios 1 and 2, Scenario 3 and Scenario 4 are evident. The intensity of sea surface temperature reduction within the Search Area 6/7 wind farms changes with the number of piles and their density in OWF (or with the total energy production estimate). For a larger number of turbines in studied area (considering the same OWF surface area), the temperatures are diminishing more intensely. Though the overall reduction is still limited within a range of ±0.2°C.

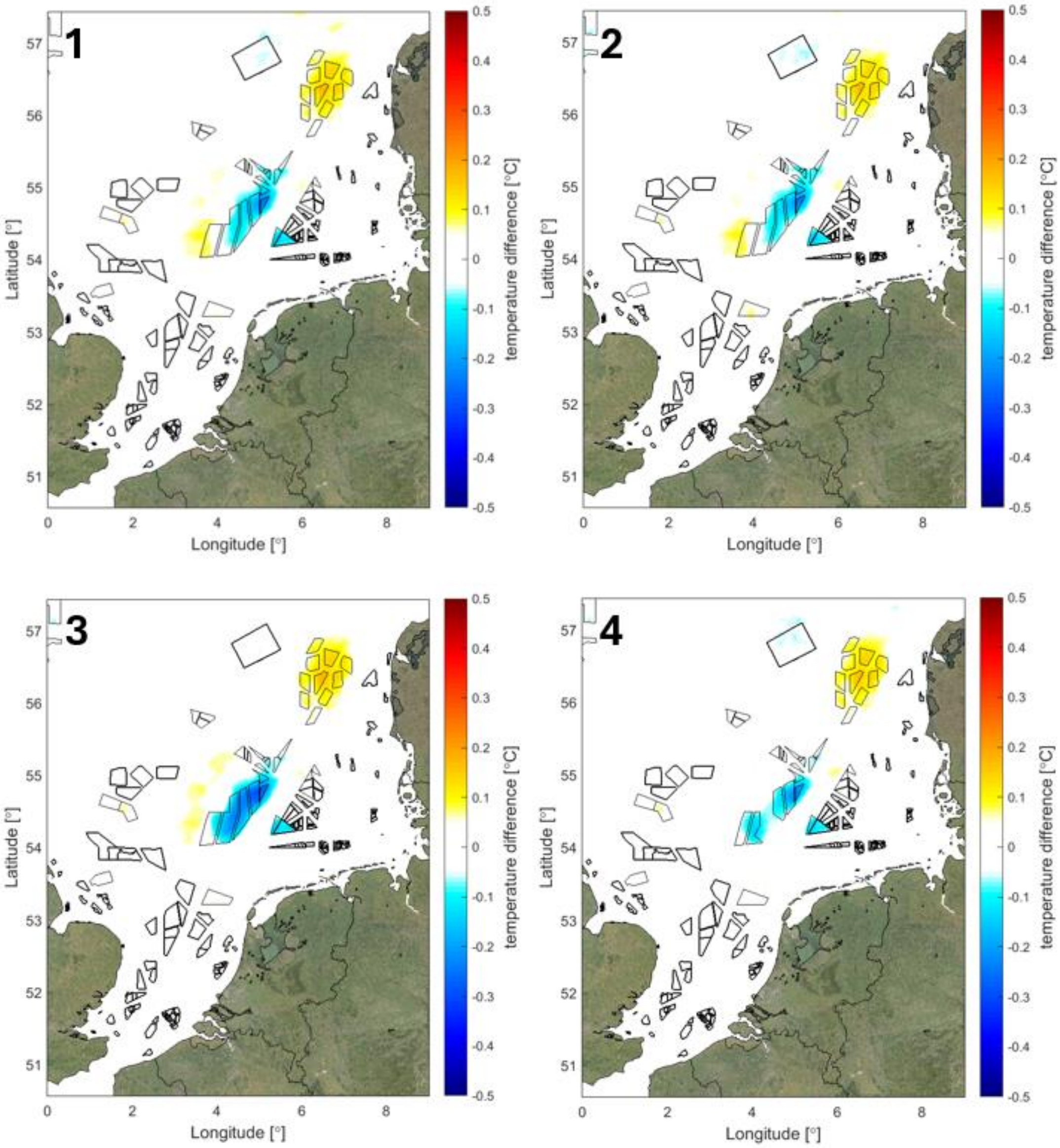
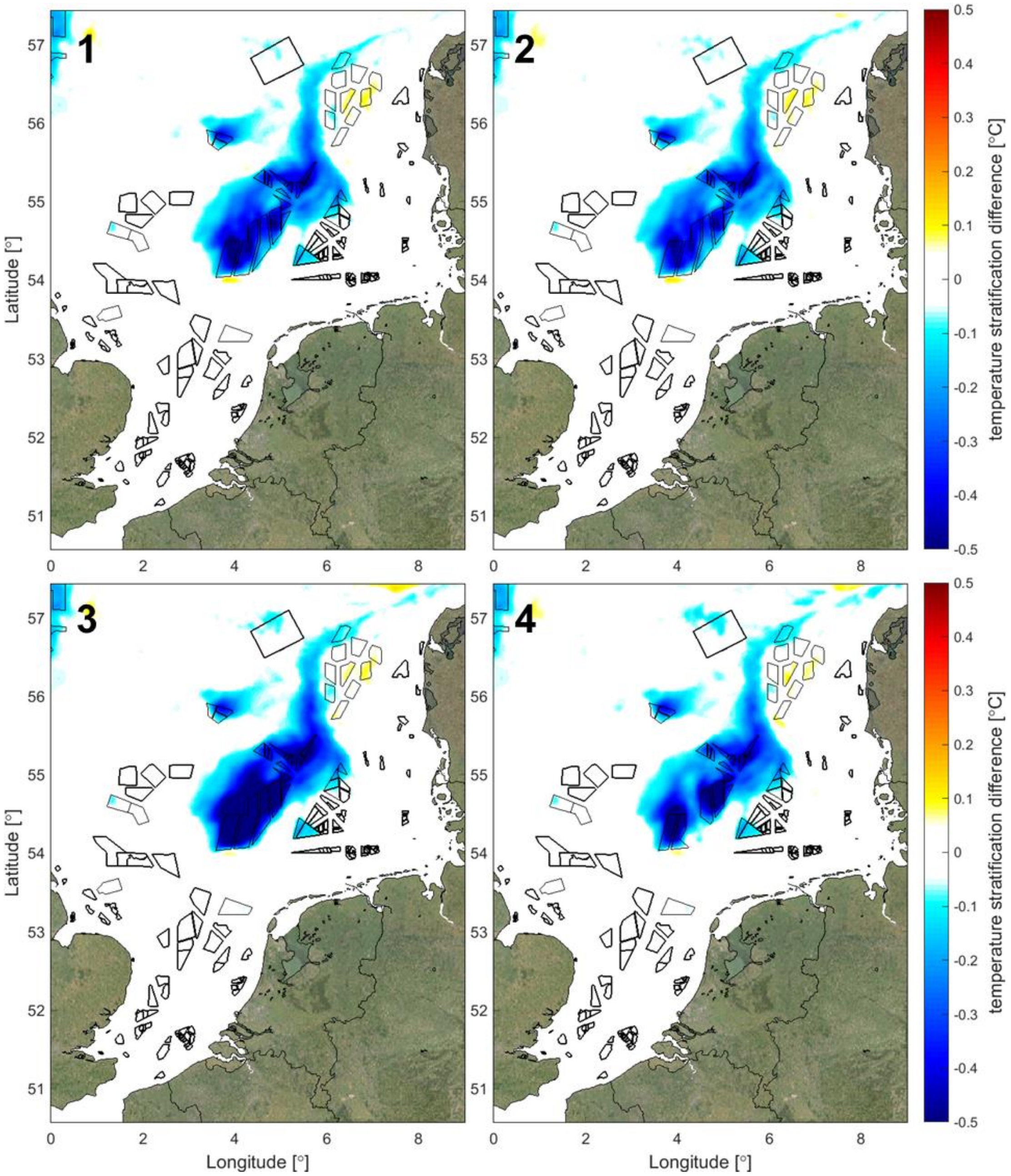


Figure 3.8 Annual mean sea surface temperature difference caused by implementation of Scenarios 1-4, relative to the base scenario.

The temperature stratification changes are more one-sided as could be seen in Figure 3.9. The difference between surface and near-bottom temperature is decreasing by over 0.5°C in case of Scenarios 3-4 indicating less mixing in the area of interest. While being less drastic, the reduction of temperature stratification in Scenarios 1-2 is still evident and reaches up to 0.3-0.4°C. Similarly to the changes in surface values, the intensity of stratification changes due to OWF effect is increasing with higher number and density of turbines in the wind parks.


1
2
3
4
Latitude [°]
Longitude [°]
temperature stratification difference [°C]

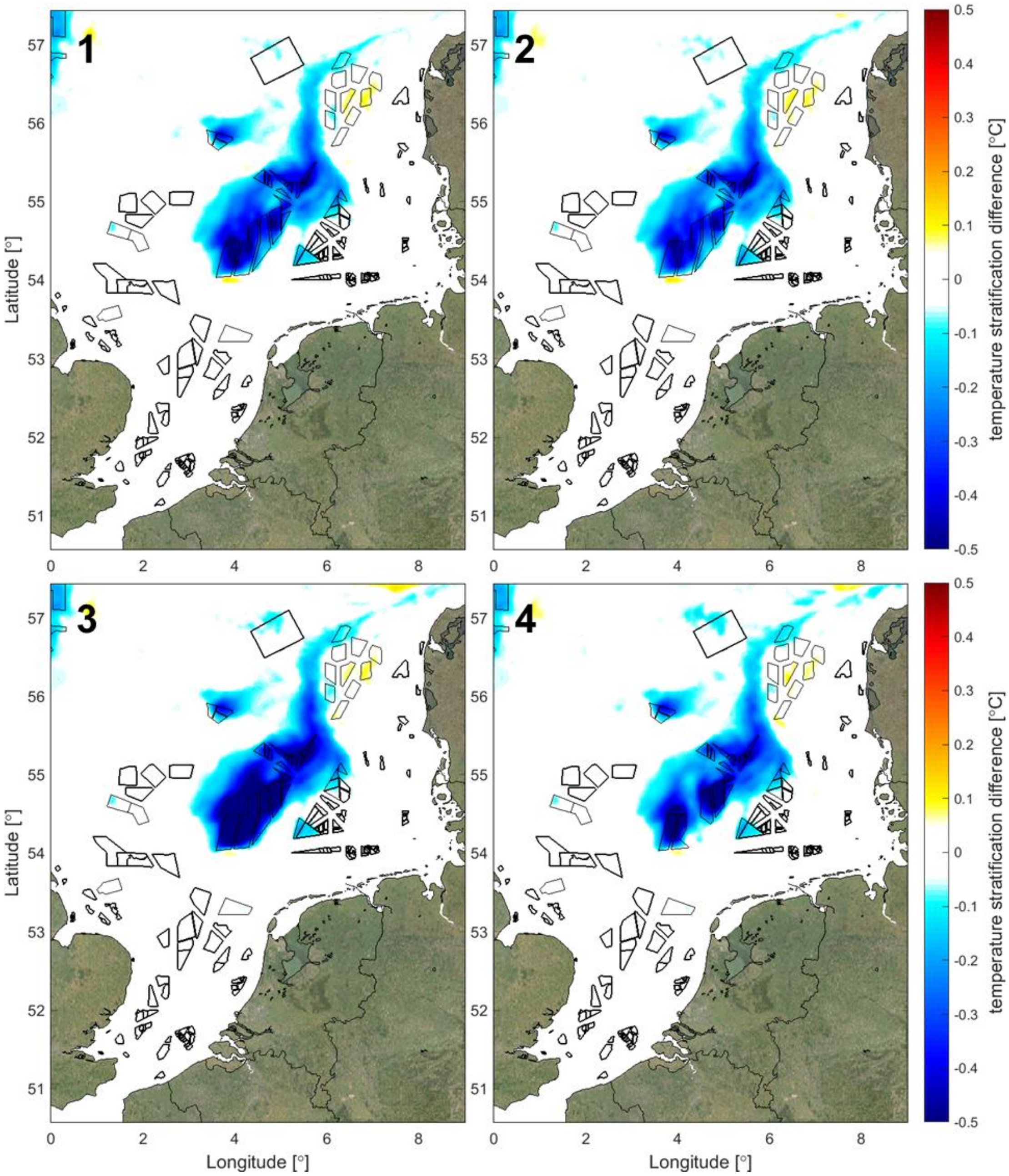


Figure 3.9 Annual mean temperature stratification difference caused by implementation of Scenarios 1-4 relative to the base scenario, without wind farms.

Salinity

In Figure 3.10 the change in annual mean sea surface salinity is presented for Scenarios 1-4. The salinity at surface in the southern part of the North Sea increases by up to 0.05 PSU near the coast and decreases by more than 0.1 PSU further offshore. Although the changes themselves are significant, the differences between effects of Scenarios 1-3 are small. In case of salinity value, it seems that the leading role in determining the effect of the OWF composition is played by the extent and configuration of its area.

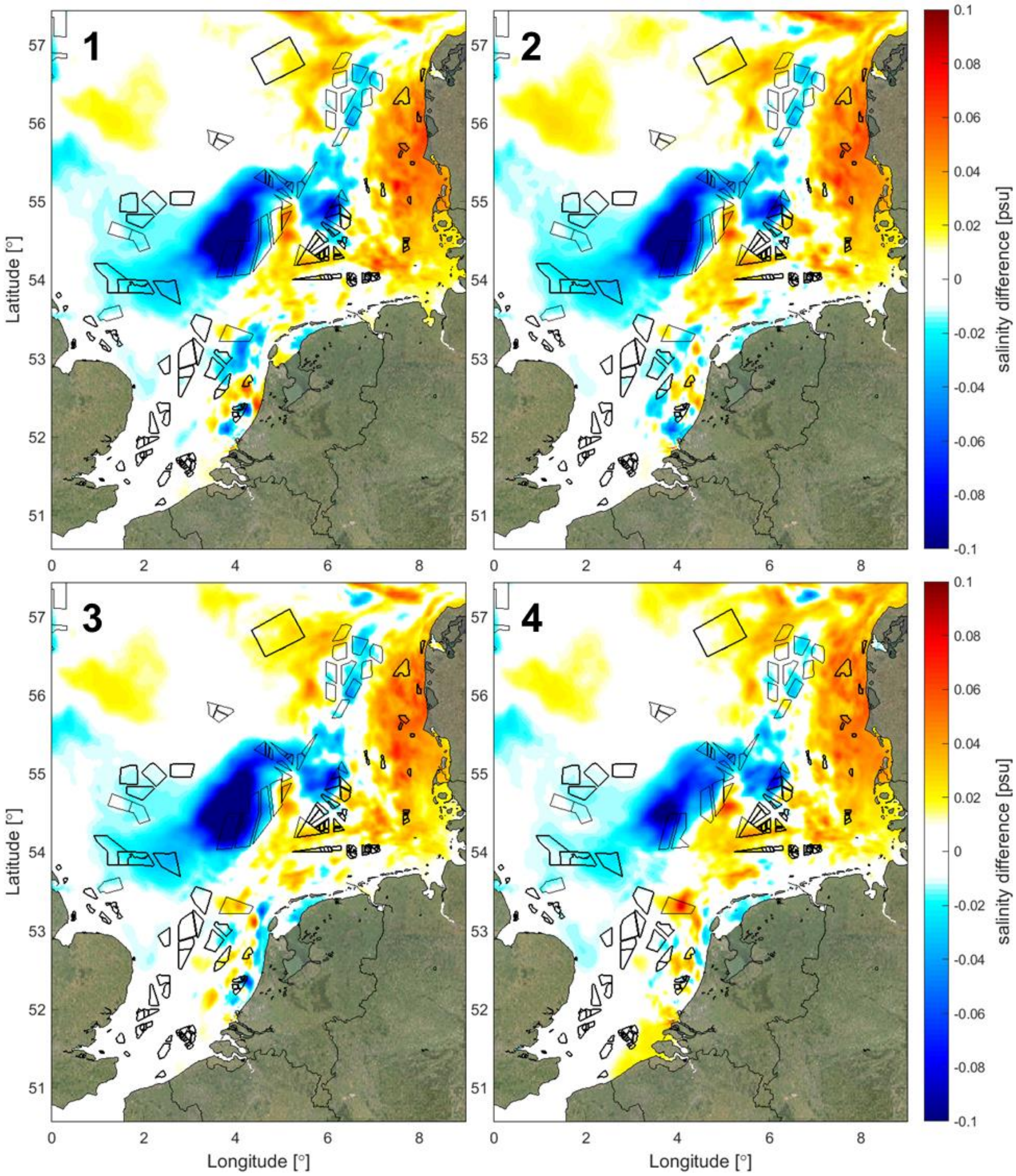


Figure 3.10 Annual mean sea surface salinity difference caused by implementation of Scenarios 1-4.

The same applies to salinity stratification which is presented in Figure 3.11. Though contrary to the salinity values at surface, the overall changes from 2031 scenario are even smaller. Stratification parameter in the studied area varies between ±0.02 PSU. The differences between scenarios of Search Area 6/7 OWF composition are therefore considered negligible.

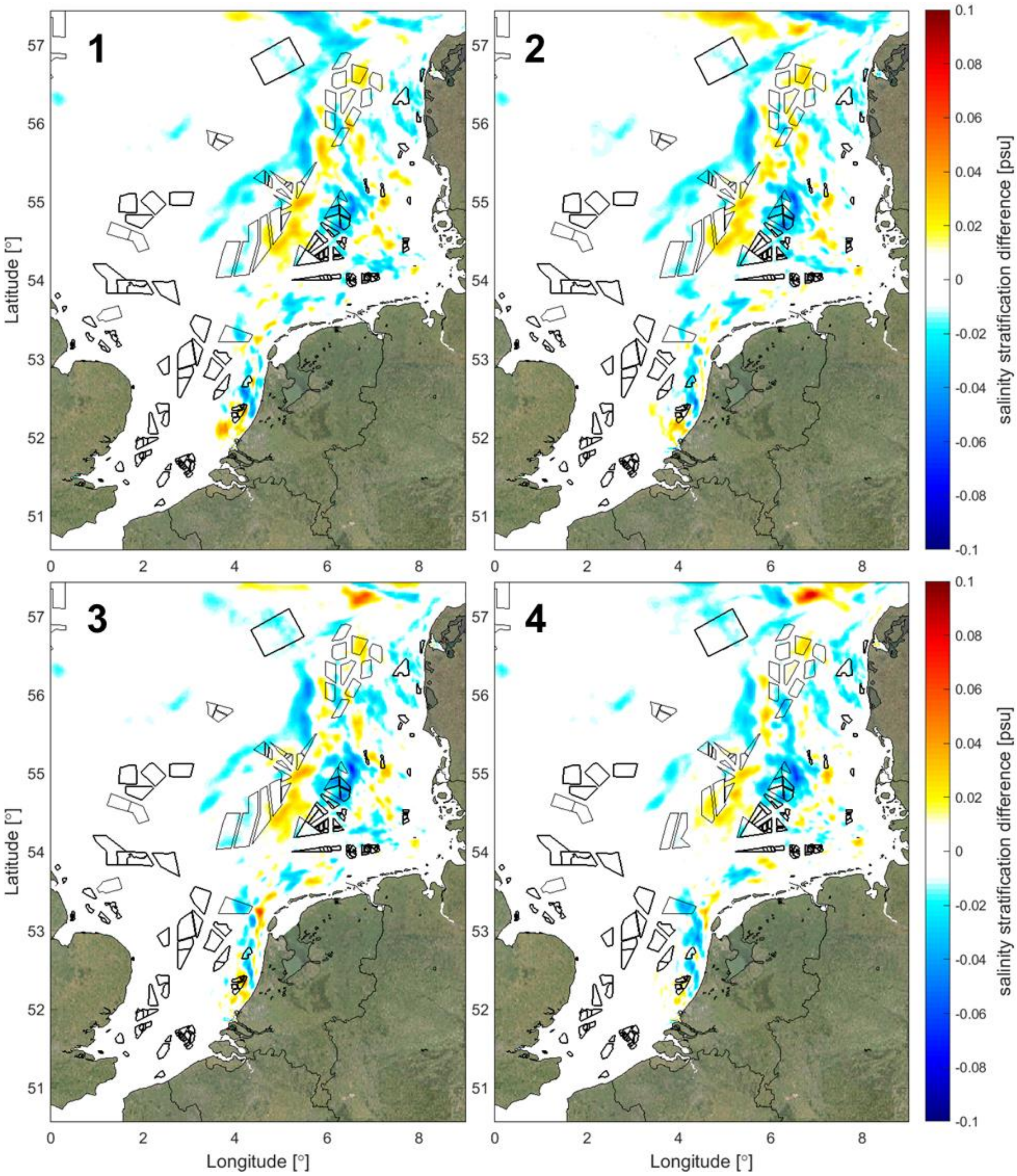


Figure 3.11 Annual mean salinity stratification difference caused by implementation of Scenarios 1-4, relative to the base scenario.

Currents

In Figure 3.12 the change of the annual mean (residual) currents at the surface is presented. The reduction of residual currents of up to 0.03 m/s at the surface primarily happens inside the OWFs. Outside of the OWFs, both growth (mostly) and reduction of up to 0.01-0.02 m/s in magnitude occurs. The differences between the Scenarios 1-3 could be considered negligible. Scenario 4 shows that residual current magnitude is more susceptible to the spatial composition of the wind park than to the turbine parameters. It should be noted that the OWF meteorological effect in 3D DCSM-FM model (10% wind velocity reduction within OWF) does not take the latter aspects into account. Therefore, parameters highly dependent on wind velocity, such as current velocity at surface, could be affect by this simplification.

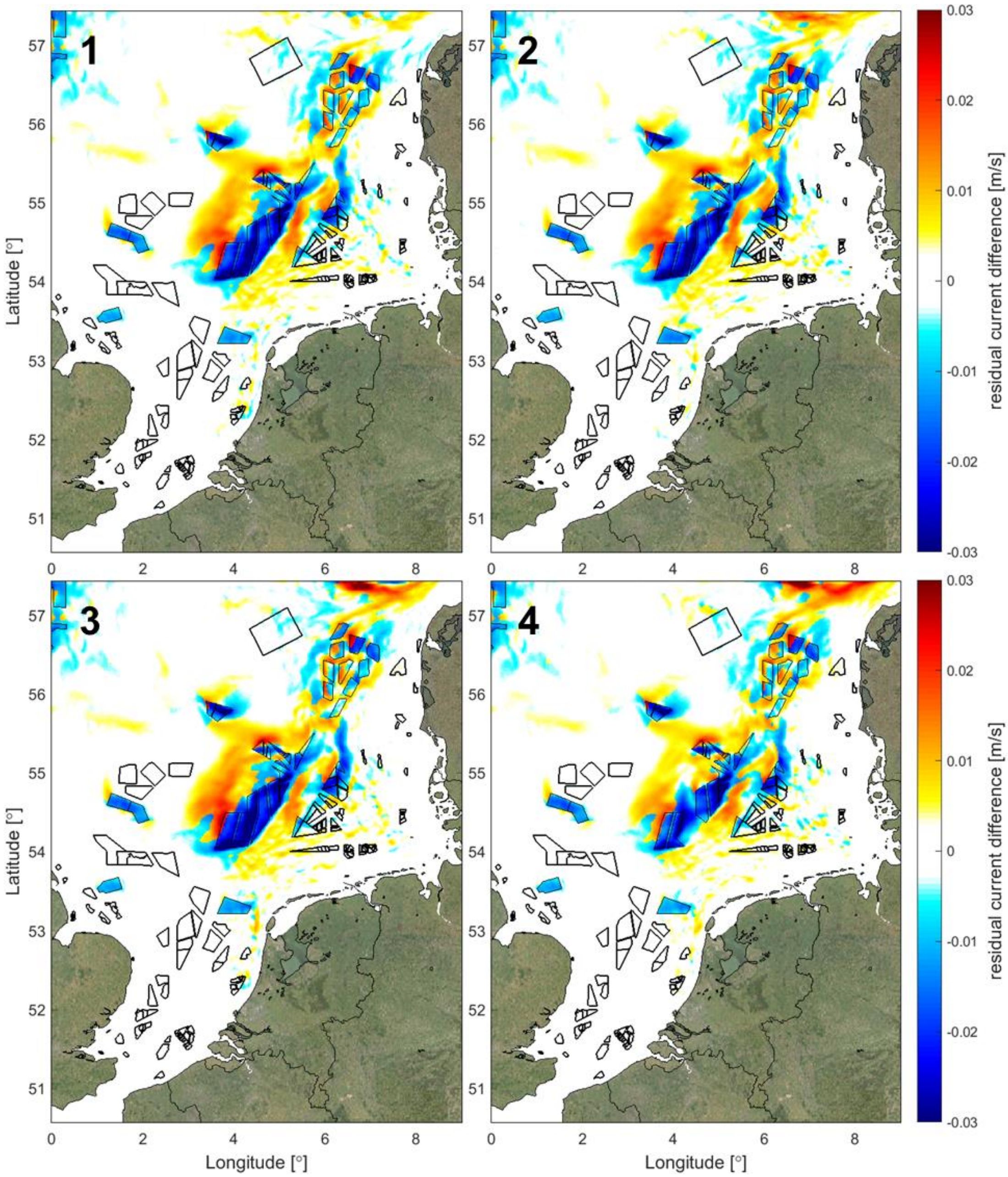


Figure 3.12 Annual mean residual current magnitude difference caused by implementation of Scenarios 1-4, relative to the base scenario.

M2 tide

The changes in M2 amplitude and phase between the considered scenarios and base scenario were found to be minimal. This is due to the limited number of the OWFs introduced in the Scenarios 1-4 (compared to Base), which was not enough to affect such large system as the North Sea.

Bed shear stress

In Figure 3.13 changes in bed shear stress due to interaction of flow with the seabed are presented. The absolute value of change due to any of the scenarios is limited to approximately ±0.005 N/m^2. Because of connection to current velocity value, the spatial distribution of differences resembles one of velocity magnitude. Although the composition of the OWF probably has larger effect on the specific scenario effect compared to the number of turbines or their density, the latter also has some influence as seen by Scenario 3 comparison with Scenarios 1-2 (0.002 N/m^2 growth → 0.004 N/m^2 growth).

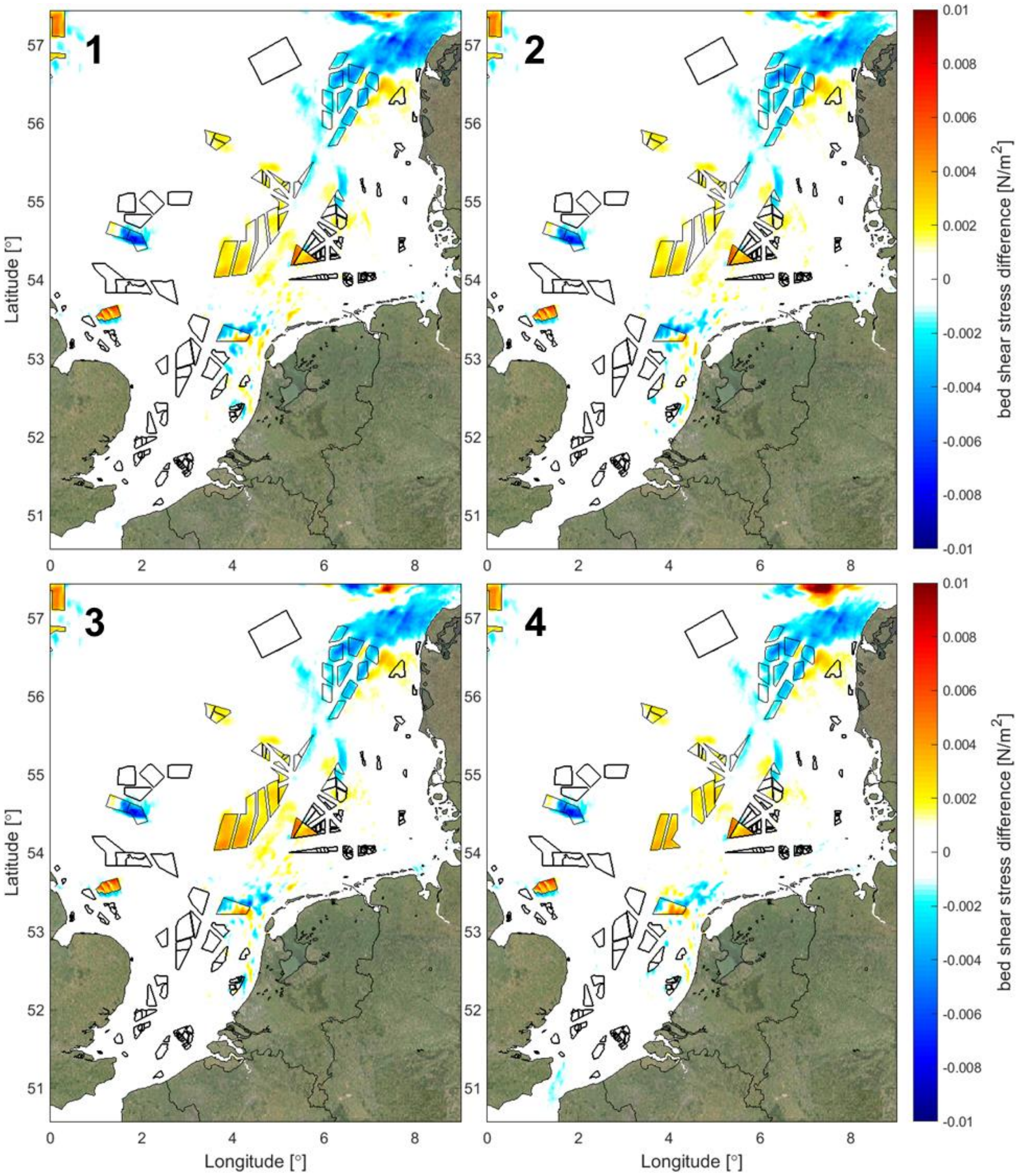


Figure 3.13 Annual mean bed shear stress difference caused by implementation of Scenarios 1-4.

3.3 Discussion

3.3.1 Conclusions regarding the hydrodynamic model

From previous validation studies and extensive use in projects, it was concluded that 3D DCSM-FM serves as a good representation of levels, temperatures, salinity, and stratification in the North Sea, including their seasonal and interannual variations.

A Base scenario, which represents a realistic situation with operational offshore windfarms in 2031, shows the expected patterns for all physical parameters considered in this study both in terms of absolute values and differences caused by introduction of the wind farms into the North Sea.

With respect to the impact of the Search Area 6/7 OWF composition scenarios, the following can be concluded:

- All four scenarios show expected level of change in the studied parameters. The spatial distribution of differences imposed by OWF operation is also in line with the previous studies.
- With larger total energy production in Search Area 6/7 and the same OWF surface area, the temperature stratification reduction becomes more profound, as well as slightly lower temperatures and salinity values are observed. Residual currents magnitude is not affected by changes in turbine composition, it is by larger extent dependent on spatial composition of the offshore wind park itself. The balance between the two is the most visible for bed shear stress, where the increase in parameter's value is almost doubled (from 0.02 to 0.04) both when increasing total energy production (Scenario 1 → 3) and when increasing density of produced energy by decreasing the OWF area (Scenario 1 → 4).
- Not all hydrodynamic parameters are equally sensitive to changes in the OWF-designs. While effects on temperature (stratification) substantially vary, effects on residual currents are more similar for Scenarios 1-3. This could be explained by variability in leading sources of changes due to OWF operation. For some parameters such as temperature, pile parametrization below the surface plays more important role in determining the outcome of the measure, while other parameters such as residual currents at sea surface are mainly dependent on wind difference and hence its parametrisation in the model. Since the OWF effect on wind is not explicitly introduced in the meteorological forcing, a standard 10% reduction is applied to all wind farm without any distinction based on energy production, turbine count, or their density.
- Changes in hydrodynamic parameters between scenarios are relatively small compared to those caused by the presence of OWFs itself. The applicability of each scenario should not be decided based on the changes it causes to hydrodynamic parameters. Therefore, the final decision should be made based on the effects on other environmental parameters and local aquatic communities.

3.3.2 Recommendations

Although the approach to parametrisation of the offshore wind farms influence on the hydrodynamic parameters has been used throughout several studies in Deltares, including those done as a part of WOZEP project, it has not yet been fully validated for the effects imposed by OWFs. A priority, therefore, would be the validation of the parameterization of OWFs in the present application of this model. This is less straightforward than validating against measurements near OWFs, especially since the impact in the existing situation is limited compared to natural variability. Specific measurements just upstream, inside and downstream of OWFs would be useful. If these are not readily available, a dedicated measurement campaign might be required.

Additionally, meteorological changes due to the presence of OWFs in the present approach are limited to the OWF area itself while wake effects are ignored altogether. This affects how well the changes inflicted by OWFs to hydrodynamic parameters that are highly dependent on meteorology (especially those in near-surface layers) could be predicted by the model. For example, the parameterisation of the impact on U_{10} (wind speed at 10 metres above the water surface) is very rough (-10%) and does not account for the composition parameters (number of turbines, their size and density) of specific wind parks. Impacts of OWFs on meteorological parameters influencing the exchange of heat with the atmosphere are also neglected (except for U_{10}), although there is evidence that this might be important. A recent study within the WOZEP project has coupled the hydrodynamic model directly to a meteorological model that includes the effects of OWFs on the relevant meteorology parameters. One of conclusions states that it would be recommended to look at other means to account for the OWFs effect on meteorology that will allow to introduce it to the commonly used products (e.g. ERA5, HARMONIE) by including both averaged and instantaneous aspects of such influence. This could be done with help of statistical analysis, machine learning, or other data analysis techniques.

4 Impacts on wave dynamics

The wave modelling approach taken in this study is identical to the approach used in the previous phase of the scenario study (Zijl et al. 2023b) and is based on the wave model setup used in the 2021 WOZEP modelling study (Zijl et al. 2021). We refer to these reports for further details on the wave model and modelling approach.
The new scenarios of offshore wind development as well as the base scenario for 2031 were used as input to the wave modelling, where a separate model run was set up for the different scenarios. The effect of wind farm presence was again schematized by adjusting wind speeds within the wind farm contours by 10%. This reduction factor is assumed to be the same regardless of wind farm parameters (size of turbines and placement density), which means that the obtained wave fields are identical for the scenarios where the wind farm contours are identical. This means that Scenarios 1, 2 and 3 for the Partial Revision Are identical, while scenario 4, with a different outline is different. No wave breaking or dissipation is included. In reality, the larger density of smaller turbines in scenario 3, which will also have a lower hub height than the turbines in e.g. scenario 1 are likely to give a larger reduction of wind at sea surface level. Such differences are not taken into account. Based on earlier expertise we expect this to have limited effect on the ultimate results of sediment dynamics and primary productivity.

4.1 Results of the Base scenario

The base scenario with offshore wind development projected for 2031, already has some influence on the wave dynamics due to the reduced wind speeds and therefore reduced wave generation. Figure below illustrates the change in significant wave height for one instance in the dynamic wave modelling simulation (the timestep was selected to illustrate the change in wave heights during a moment with relatively high waves in the northern part of the Netherlands).

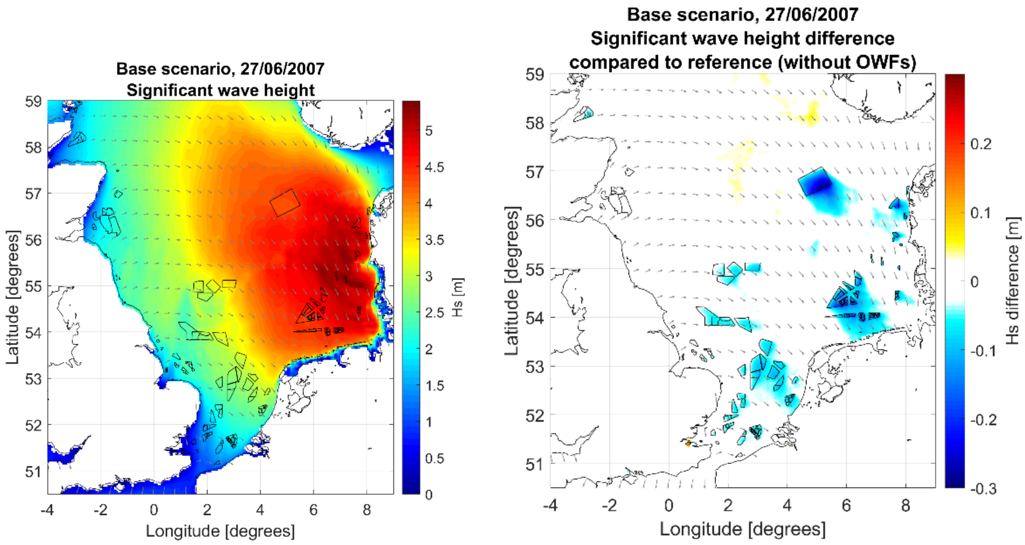


Figure 4.1 Effect of changes in the wind forcing within wind farm contours on the wave field at a given time moment within the wave simulation in the reference scenario (OWFs in 2031) compared to the baseline (without wind farms).

4.2 Results of the Partial Revision scenarios

Reduced wind speeds cause a reduction in wind-driven wave generation, which results in local decrease of wave heights and altering of wave directions. When wind farms are located close to each other in a dense arrangement (as in Scenario 1 in the vicinity of the Dutch coast), this effect of reduced wave heights can extend further away from the wind farm locations in the wake of the wind farms.

Figure 4.2 shows the impact of the reduced wind speeds on the wave heights at a specific time moment in the wave simulations. Please note that the wave simulations were done in non-stationary mode and therefore the reductions in wave heights that are shown here are not equilibrium values, but rather represent a realistic snapshot of changing weather conditions in time. The snapshot of wind and wave conditions shown in Figure 4.2 depicts conditions with relatively high wind speeds and waves in the Eastern part of the basin, which is reflected also in the relatively high reduction in wave height in Scenarios 1, 2 and 3. In the Scenario 4, where the wind farms contours are different (less dense clusters at the northwest of the Dutch coast), the wave heights are altered to a lesser extent in the wake of those wind farms.

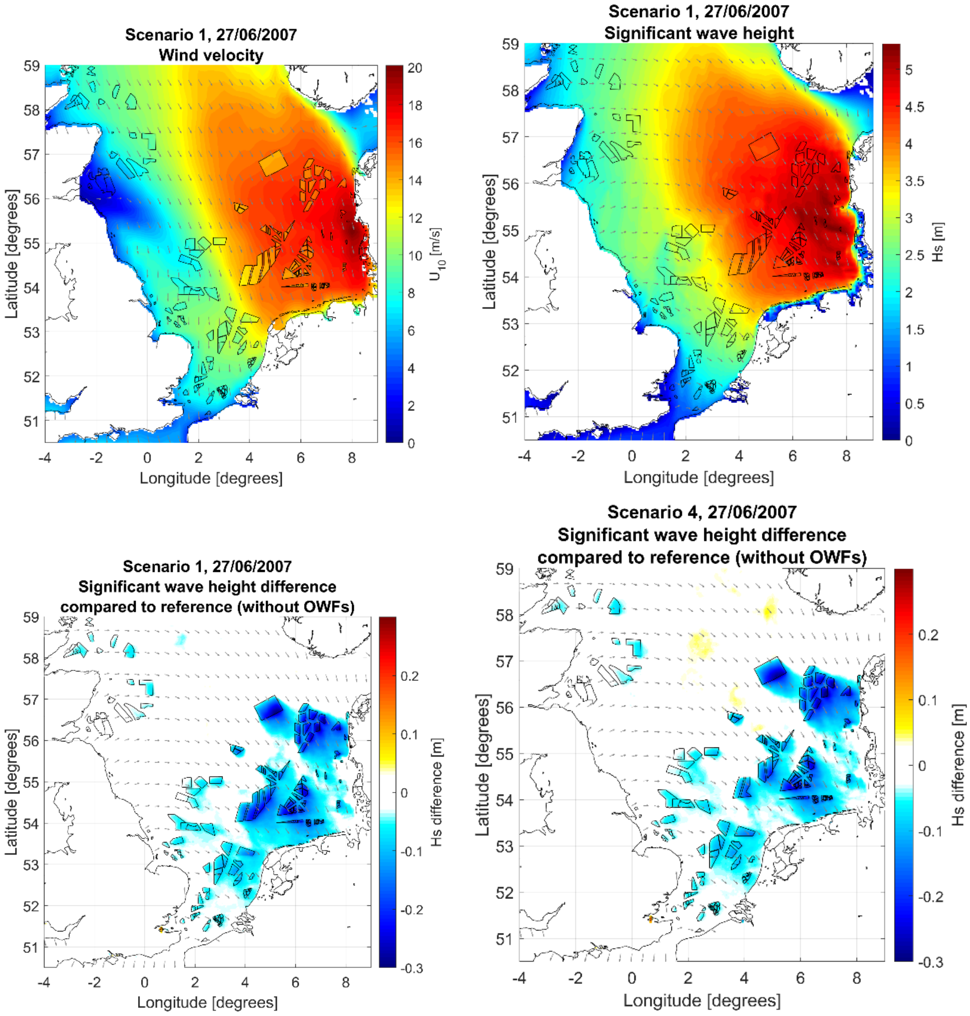


Figure 4.2 Effect of changes in the wind forcing within wind farm contours on the wave field at a given time moment within the wave simulation. Top left: wind forcing with reduced wind speeds within the wind farm contours in Scenario 1, 2 and 3; top right: significant wave height in Scenario 1; bottom left: difference in wave height in Scenario 1 compared to the reference scenario without wind farms; bottom right: difference in wave height in Scenario 4 compared to the reference scenario.

It should be noted that the assumed reduction in wind speeds by a constant percentage is a simplified schematization. Further improvements in the schematization where the wind speed reduction can be varied based on the local wind speed, wind turbine placement and wind turbine power curve would improve the accuracy of modelling impacts of wind farms of wave conditions. It would also lead to different model results for Scenarios 1, 2 and 3. For the purposes of the present study this schematization is deemed sufficient when the wave model results are used as input for further modelling of fine sediment transport as described in the following sections.

5 Impact on fine sediment dynamics (SPM)

This chapter discusses the effects of the offshore wind farm (OWF) scenarios presented in Chapter 2 on the fine sediment dynamics. Section 5.1 shows that the validation reported in Zijl et al. (2023) still holds when using the coupled water quality model instead of the standalone fine sediment model used in previous reports. The effects of wind farms in the (2031) Base Scenario are presented in Section 5.2. The results of the Partial revision scenarios are presented in Sections 5.3, 5.4 and 5.5. Finally, the findings are summarised and discussed in the context of their validity in Section 5.6.

5.1 Validation of fine sediment results using the coupled water quality model

The fine sediment results produced with the coupled water quality model are validated. First, they are compared to the results derived from the standalone fine sediment model used in previous reports to show that the calibration still holds (Section 5.1.1). Secondly, a comparison is made to measurement data (Section 5.1.2). Finally, Section 5.1.3 examines if the previously reported effects of wind farms on the fine sediment concentrations remain consistent.

5.1.1 Comparison to the previous uncoupled fine sediment model

It is found that the modelled year-averaged Total *Inorganic* Matter (TIM) does not strongly change (<10%) in the areas of interest for the construction of OWFs, when the coupled water quality model is used instead of the standalone fine sediment model. This is shown in Figure 5.1 and Figure 5.2 for the surface and near-bed concentrations, respectively. Note that the scales for the absolute figures are different because near-bed concentrations are higher than near-surface concentrations. Only in nutrient-rich areas such as the Dutch and German estuaries, the effects on TIM are locally higher, yielding increases and decreases up to 50%. This difference may be caused by the presence of organic matter in the bed in the coupled model, which may modify the erosion flux of inorganic matter. Although this hypothesis should still be verified, this could help explain why the change in TIM near the bed (Figure 5.2) is stronger than near the water surface (Figure 5.3). This is visible most clearly in the Norwegian trench.

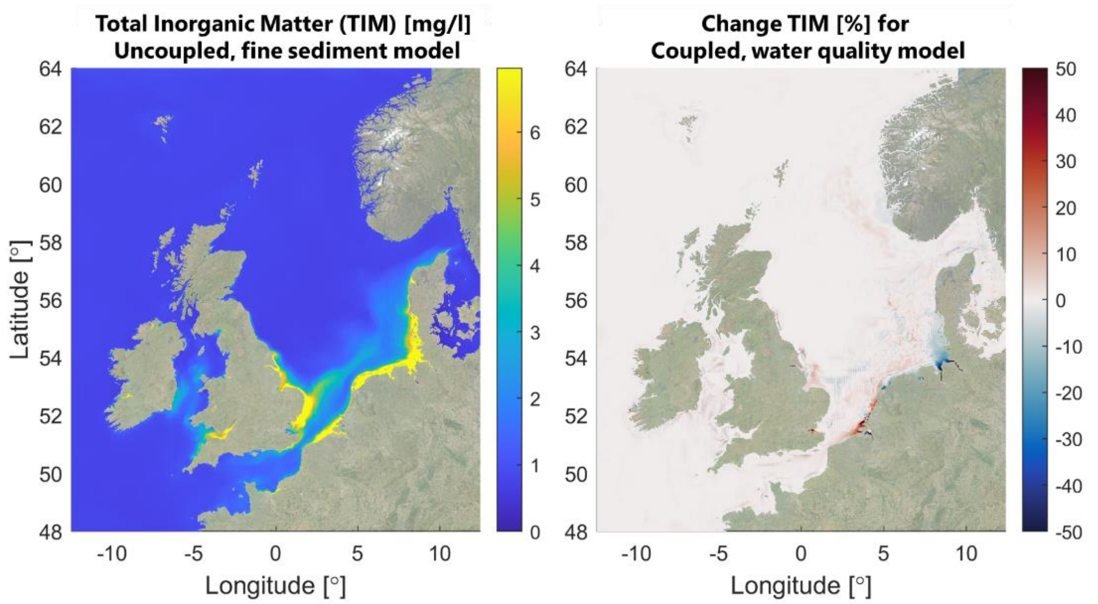


Figure 5.1 Change in year-averaged Total Inorganic Matter (TIM) <u>near the water surface</u> when using the coupled water quality model instead of the uncoupled, fine sediment model. Left: Year-averaged TIM based on the uncoupled, fine sediment model [mg/l]. Right: Percentual change in TIM when using the coupled water quality model.

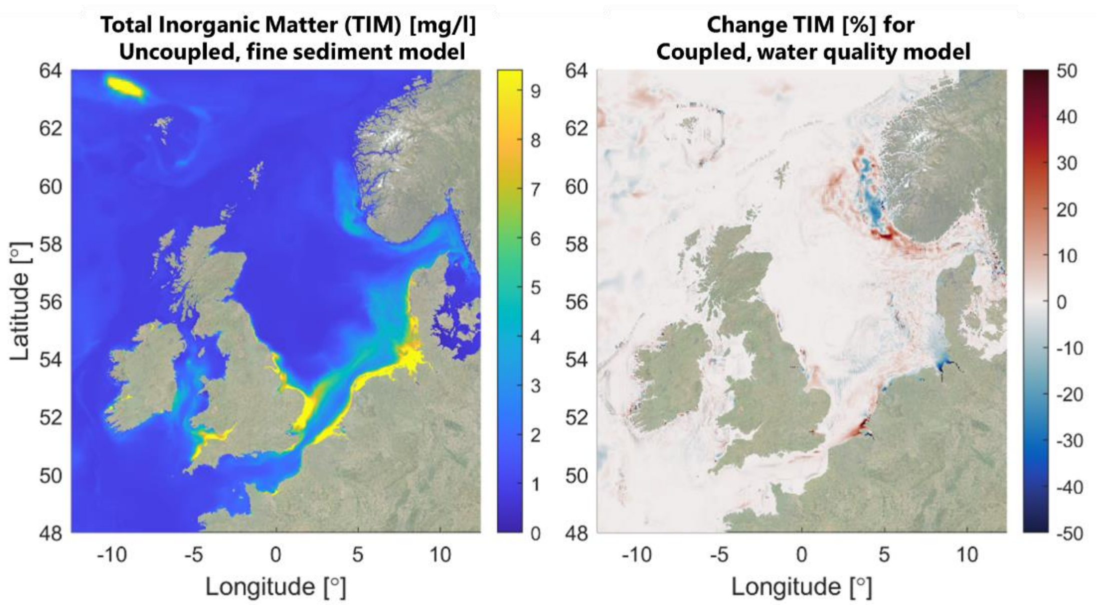


Figure 5.2 Change in year-averaged Total Inorganic Matter (TIM) <u>near the bed</u> when using the coupled water quality model instead of the uncoupled, fine sediment model. Left: Year-averaged TIM based on the uncoupled, fine sediment model [mg/l]. Right: Percentual change in TIM when using the coupled water quality model.

5.1.2 Comparison to measurement data

It is found that the fit of the modelled Total Inorganic Matter (TIM) with Earth Observation (EO) data does not notably change when the coupled water quality model is used instead of the standalone (uncoupled) fine sediment model. This is shown based on a comparison of the measured Suspended Particle Matter (SPM) from CEFAS EO and the modelled year-average TIM (Figure 5.3), and the average of a summer (Figure 5.4) and winter month (Figure 5.5). In these figures only surface layers are shown. Near-bed layers have been inspected and support the conclusions.

Note that the modelled TIM is expected to be lower than the SPM from CEFAS EO, as it does not account for the organic fraction. A minor deterioration of the results can be seen in the German estuaries where a decrease in TIM further enhances the underestimation of TIM compared to EO data. The variation of TIM in time is not strongly influenced either (< 0.5 mg/l) and still compares well to the MWTL measurement time series of SPM when the coupled water quality model is used instead of the uncoupled fine sediment model (Figure 5.6).

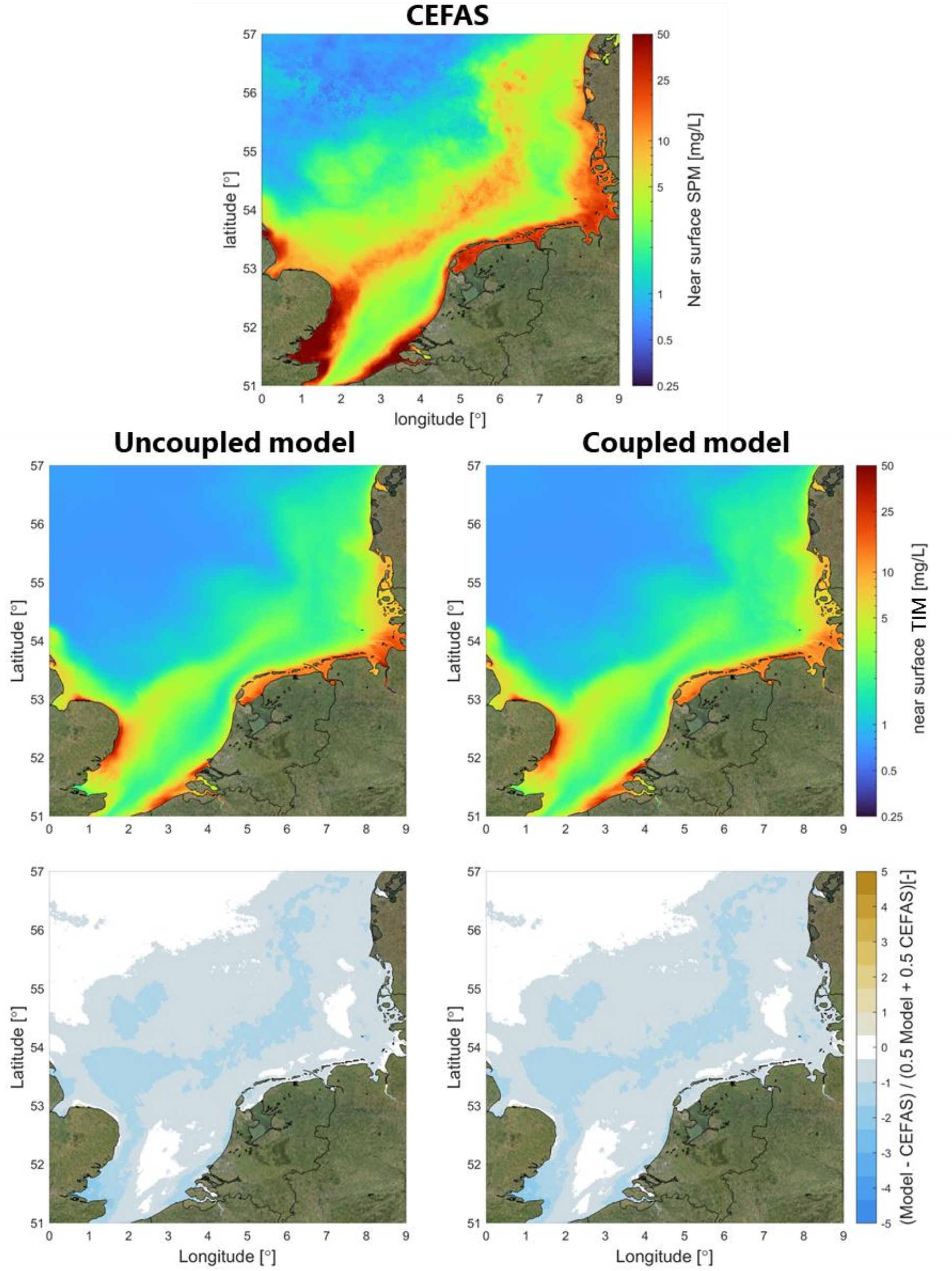


Figure 5.3 <u>Year-averaged</u> Total Inorganic Matter (TIM) at the water surface in the uncoupled fine-sediment model (left) and coupled water-quality model (right) compared to CEFAS EO measurements of Suspended Particle Matter (SPM) (top panel). The lower two panels show the relative difference between the CEFAS measurements and the respective models.

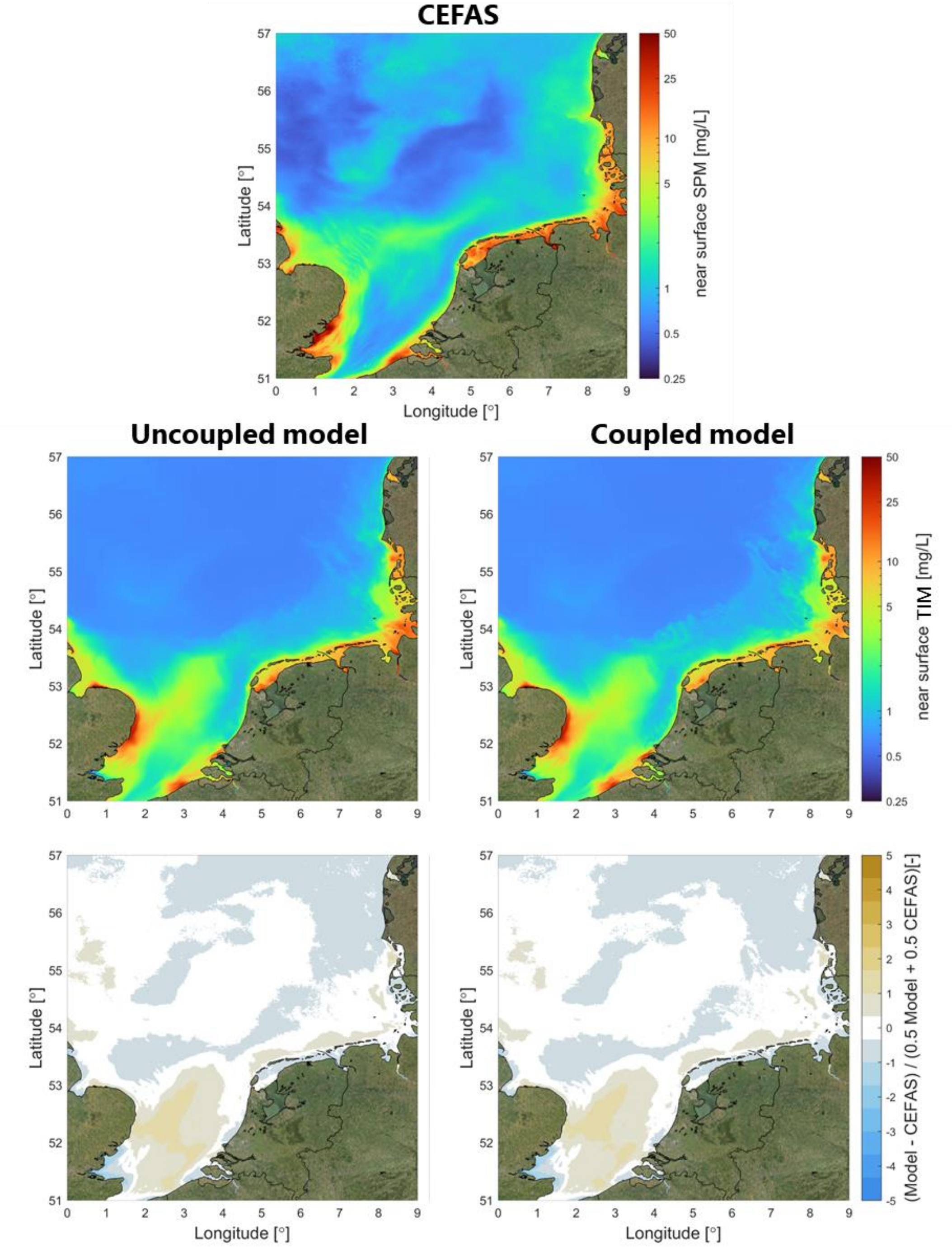


Figure 5.4 June-average Total Inorganic Matter (TIM) at the water surface in the uncoupled fine-sediment model (left) and coupled water-quality model (right) compared to CEFAS EO measurements of Suspended Particle Matter (SPM) (top panel). The lower two panels show the relative difference between the CEFAS measurements and the respective models.

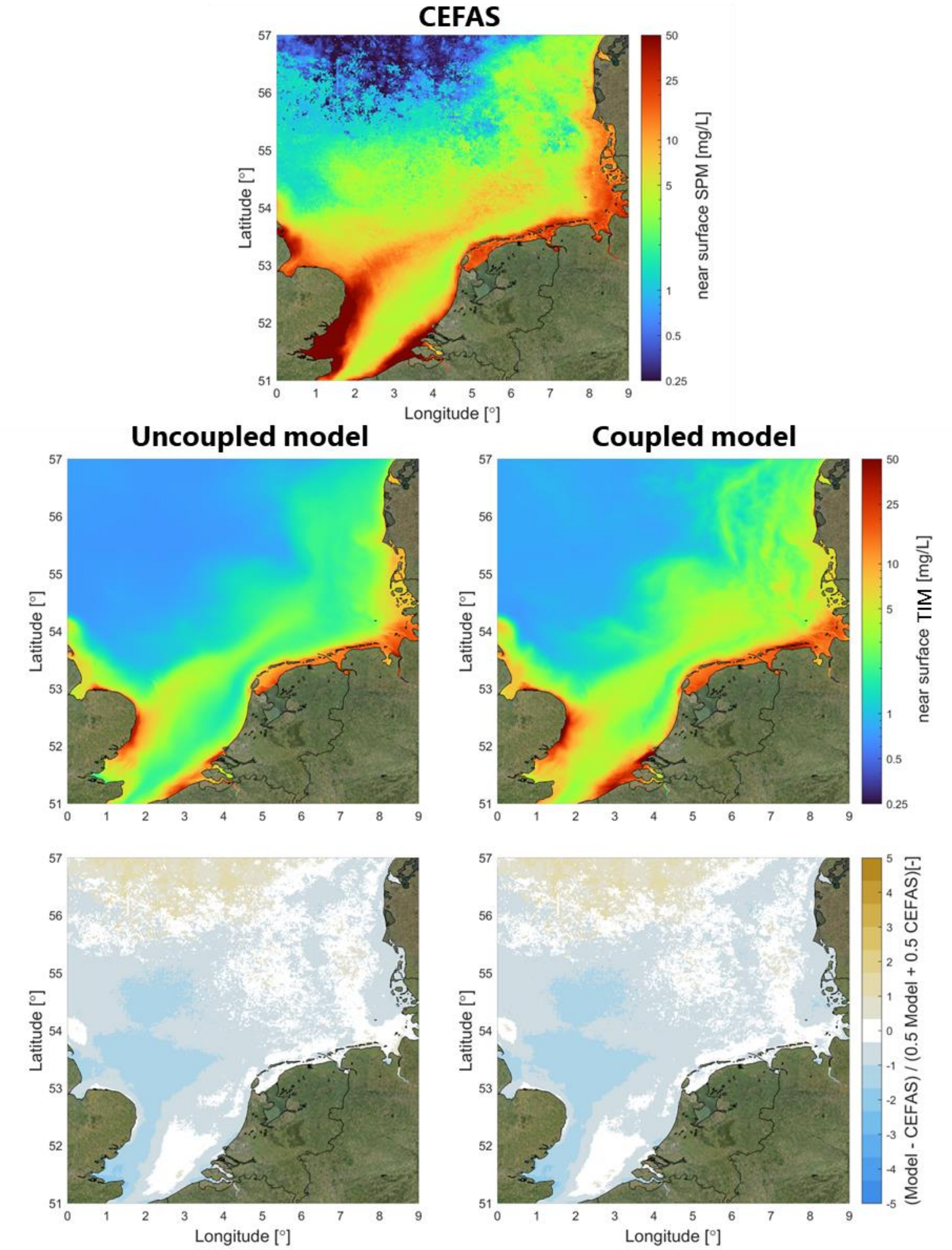


Figure 5.5 December-average Total Inorganic Matter (TIM) at the water surface in the uncoupled fine-sediment model (left) and coupled water-quality model (right) compared to CEFAS EO measurements of Suspended Particle Matter (SPM) (top panel). The lower two panels show the relative difference between the CEFAS measurements and the respective models.

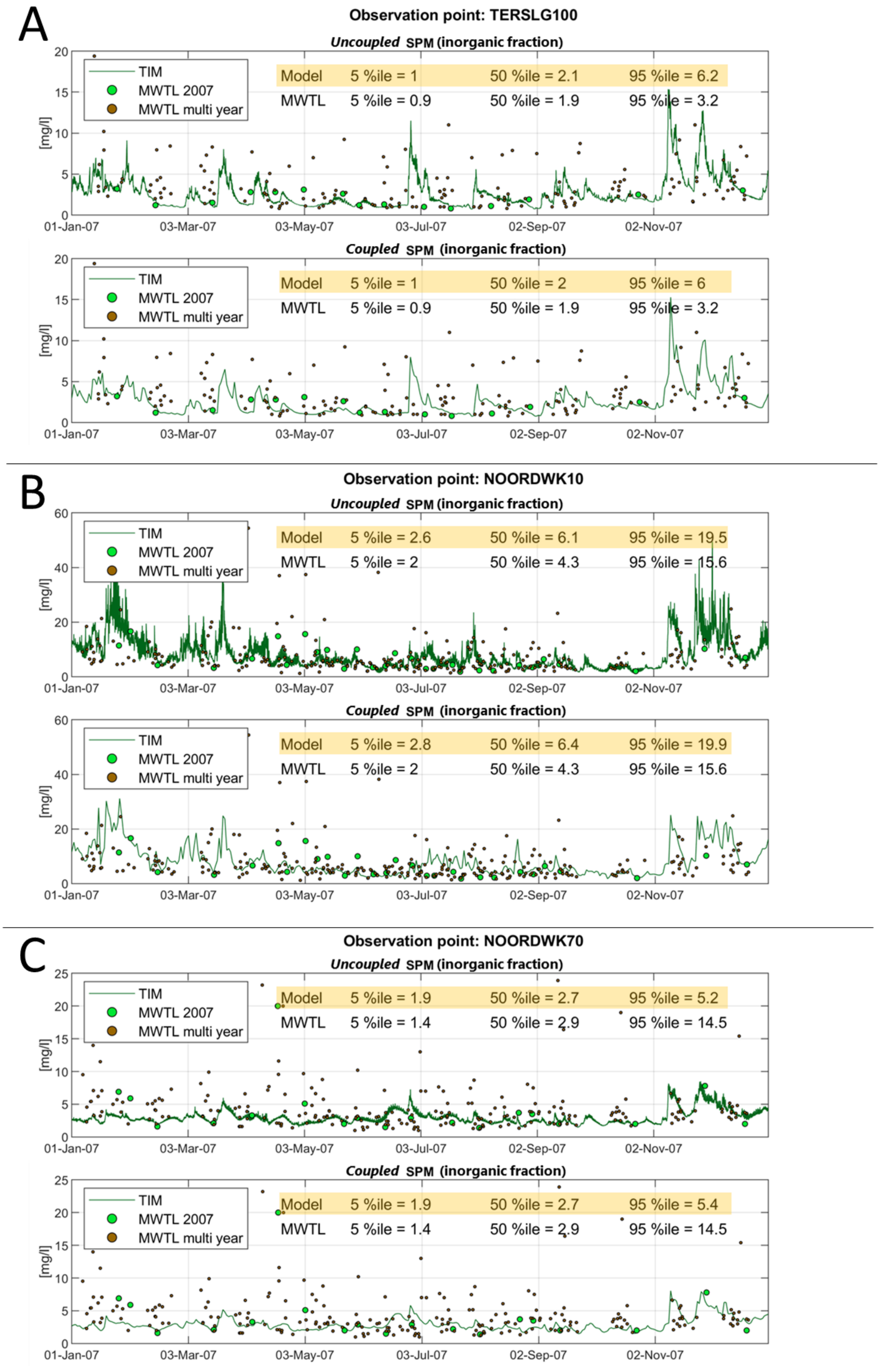


Figure 5.6 MWTL measurements (dots) of Total Inorganic Matter (TIM) at stations Terschelling100 (A), Noordwijk10 (B) and Noordwijk70 (C) compared to modelled TIM time series based on the uncoupled fine-sediment model (top panels, at an hourly-minute interval) and the coupled water quality model (bottom panels, at a daily interval).

5.1.3 Influence on relative wind farm effects

Finally, we verified if the simulated relative wind farm effects are influenced by using the coupled water quality model. An OWF Scenario from Zijl et al. (2023a) is taken as an example. It is found that the simulated effects of wind farms on Total Inorganic Matter (TIM) are practically the same when a coupled water quality model is used instead of a stand-alone fine sediment model. This is shown in Figure 5.7, Figure 5.8 and Figure 5.9 by visualizing the year-average, summer-averaged, and winter-averaged percentual change in TIM as a result of the presence of OWF, respectively.

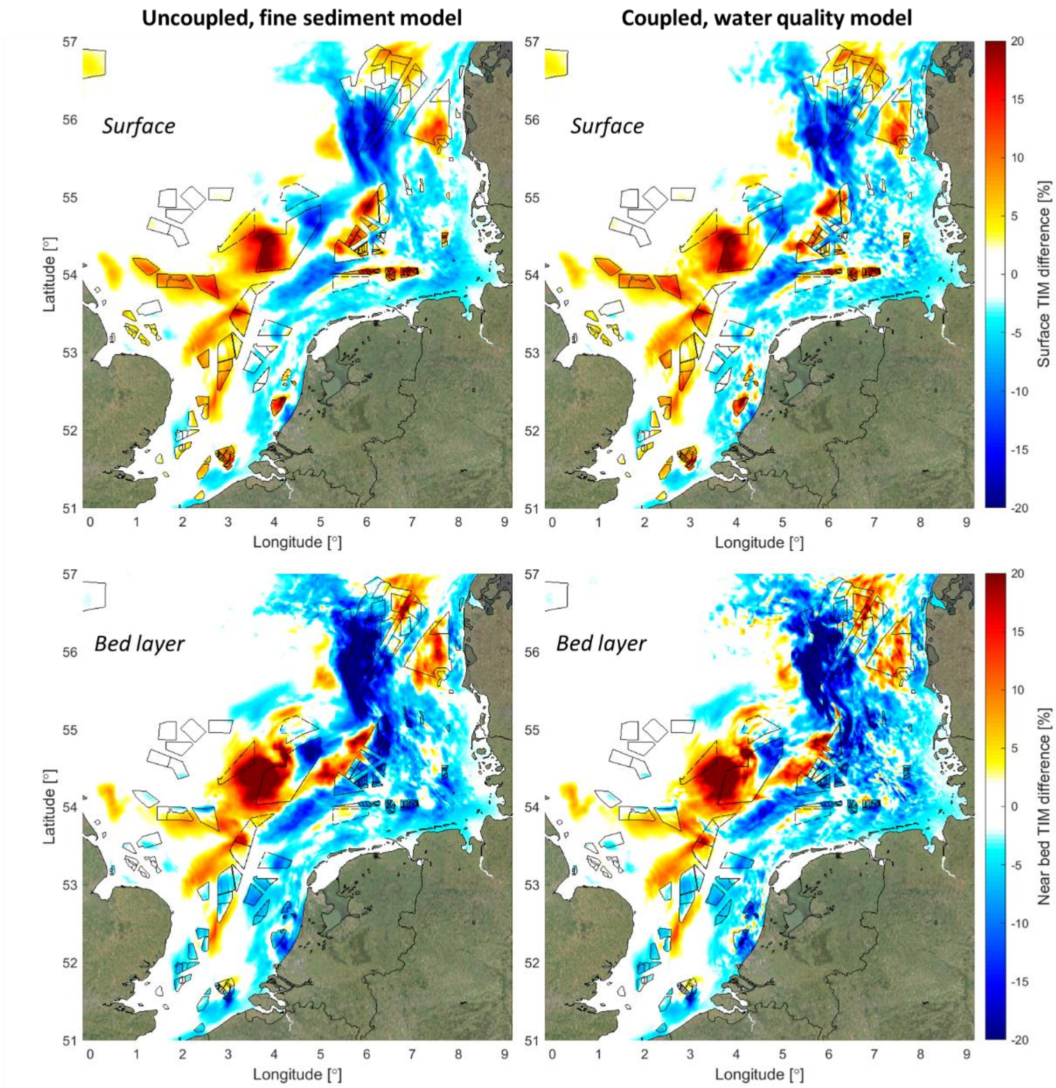


Figure 5.7 Relative [%] year-averaged effect of wind farms (with respect to the reference scenario) on Total Inorganic Matter (TIM) based on the uncoupled, fine-sediment model (left column) and the coupled water quality model (right column). Top and bottom panels show the difference near the water surface and bed, respectively.

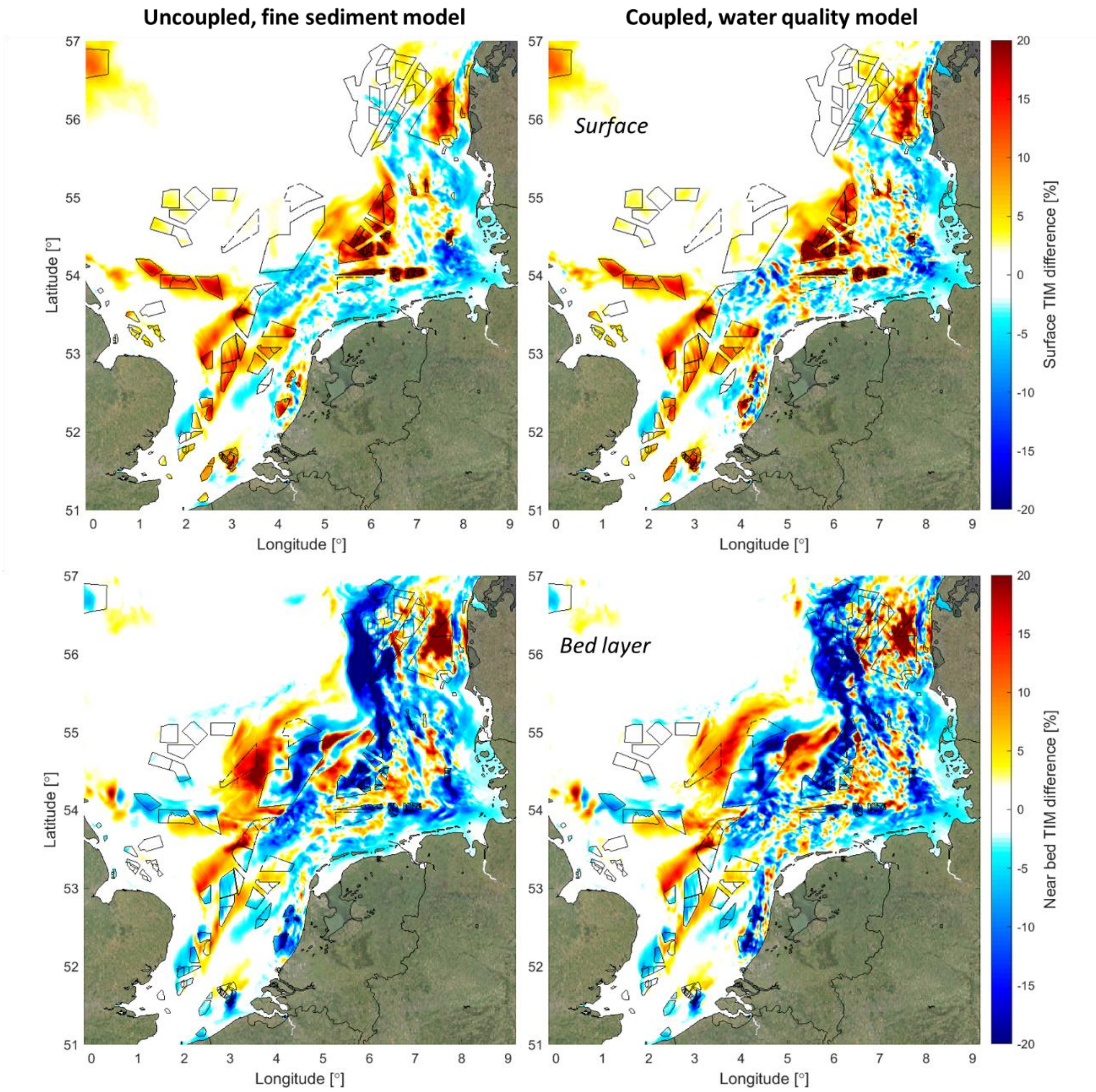


Figure 5.8 Relative [%] effect of wind farms on Total Inorganic Matter (TIM) in summer (June-August 2007) based on the uncoupled, fine-sediment model (left column) and the coupled water quality model (right column). Top and bottom panels show the difference near the water surface and bed, respectively. The effect of wind farms relative to the reference scenario is shown.

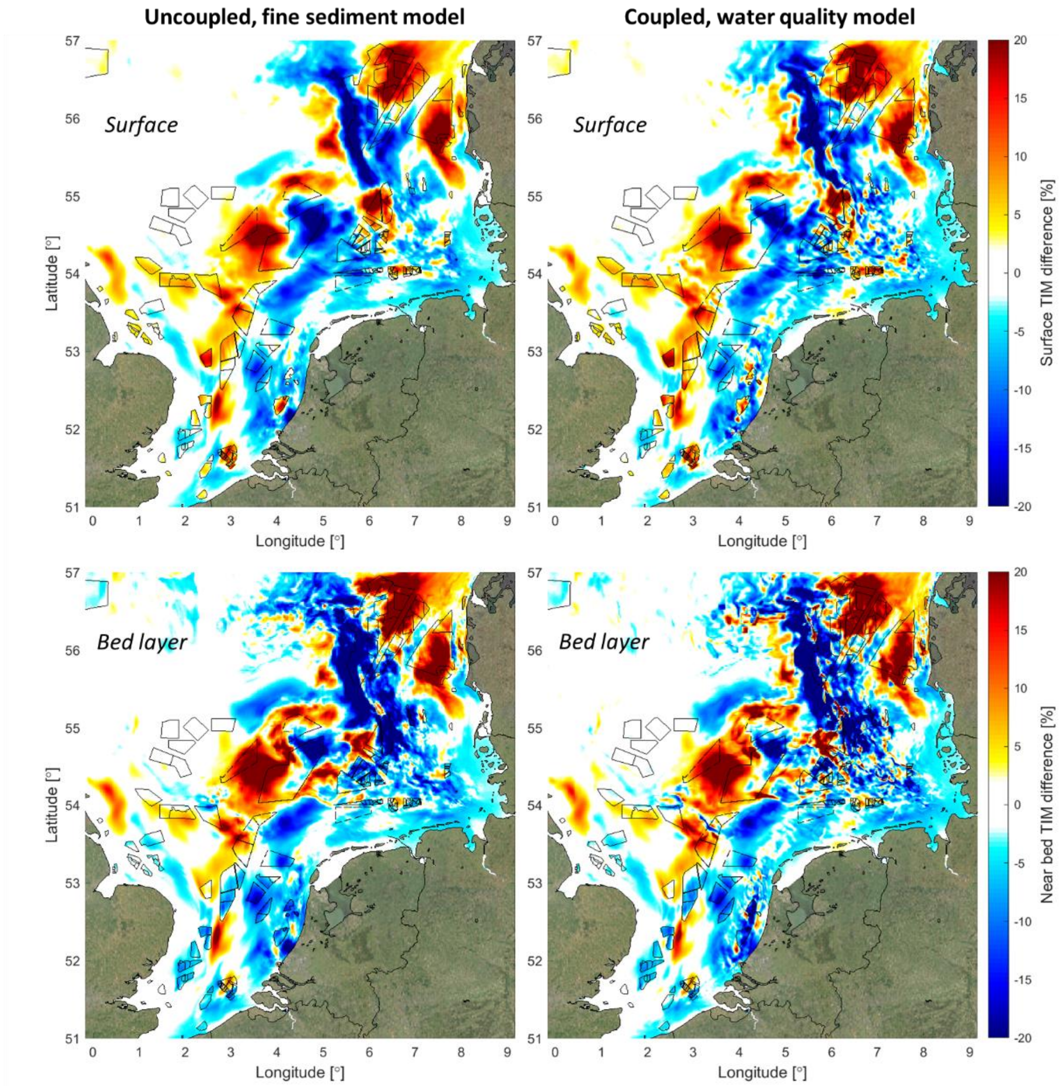


Figure 5.9 Relative [%] effect of wind farms on Total Inorganic Matter (TIM) in winter (September-December 2007) based on the uncoupled, fine-sediment model (left column) and the coupled water quality model (right column). Top and bottom panels show the difference near the water surface and bed, respectively.

5.2 Effect of the Base scenario (OWFs 2031)

The overall effects of the North Sea wind farms on the fine sediment dynamics are studied by comparing the model results of the 2031 Base scenario to the Reference simulation without any wind farms.

First, in Section 5.2.1, the effects of wind farms on bed shear stress are studied. This is relevant for the resuspension of sediment. In Section 5.2.2 the year-average effects on the fine sediment concentrations are studied. Finally, Section 5.2.3 examines how strongly the effects vary throughout the year. The presented results closely align with those reported in Zijl et al. (2023a), where readers can find more detailed information.

In this section, and following ones on scenario analysis, yearly-average maps are calculated based on simulated 3D map outputs from the coupled hydrodynamics-sediment-water quality and ecology model, available at a 2.5-day resolution.

5.2.1 Stirring of sediment: changes in bed shear stress

The total bed shear stress is computed to decrease across the southern North Sea and along the Dutch, German, and Danish coast, with a few exceptions within certain wind farm areas where the bed shear stress is enhanced (Figure 5.10). The decrease in bed shear stress is thought to be caused by a decrease in M2 amplitudes (see hydrodynamic results, Chapter 3) and a general decrease in wave-induced bed shear stress (Figure 5.11).

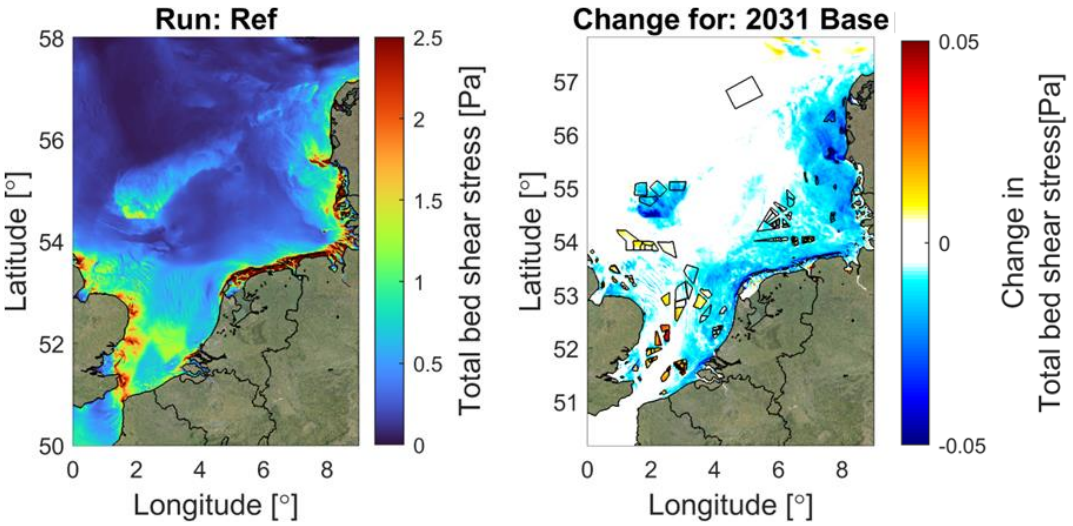


Figure 5.10 Change in year-averaged <u>total bed shear stress</u> [Pa] for the 2031 Base scenario (right panel) compared to the Reference run without any wind farms (left panel). The presented “total” bed shear stress amounts to the linear sum of the flow and wave induced bed shear stress values. Black contours indicate the location of the wind farms.

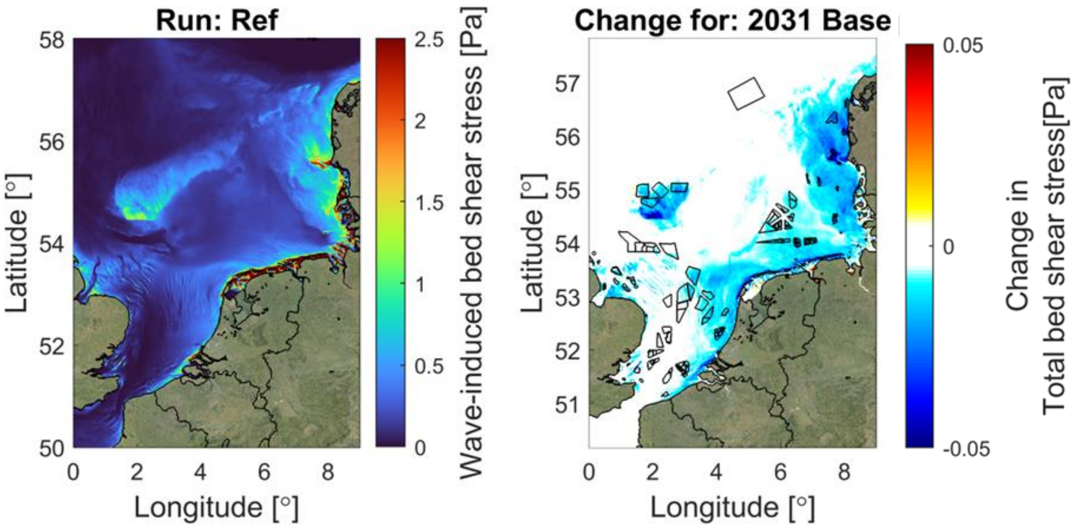


Figure 5.11 Change in year-averaged, <u>wave induced bed shear stress</u> [Pa] for the 2031 Base scenario (right panel) compared to the Reference run without any wind farms (left panel). Black contours indicate the location of the wind farms.

5.2.2 Year-average effects on Total (suspended) Inorganic Matter

The Total Inorganic Matter (TIM) values are found to decrease near the shores of the Netherlands, Germany and Denmark, but increase farther offshore towards the UK. This is computed both near the bed (Figure 5.12) and near the surface (Figure 5.13), although inside wind farms the surface TIM increases in many (but not all) OWFs due to additional mixing.

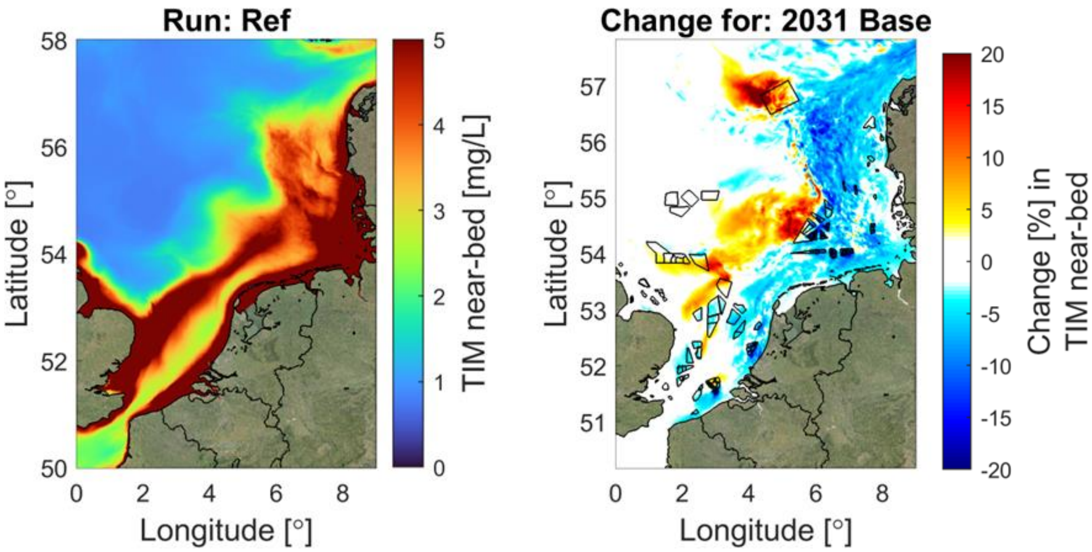


Figure 5.12 Effect of North Sea wind farms on the year-averaged total inorganic matter (TIM) near the bed. The panels show the TIM [mg/l] in the Reference simulation without wind farms (left), and the relative change [%] for the Base scenario (right panel) . In the right panel, red indicates an increase in turbidity compared to the Reference simulation without wind farms. Black contours indicate the location of the wind farms for each scenario.

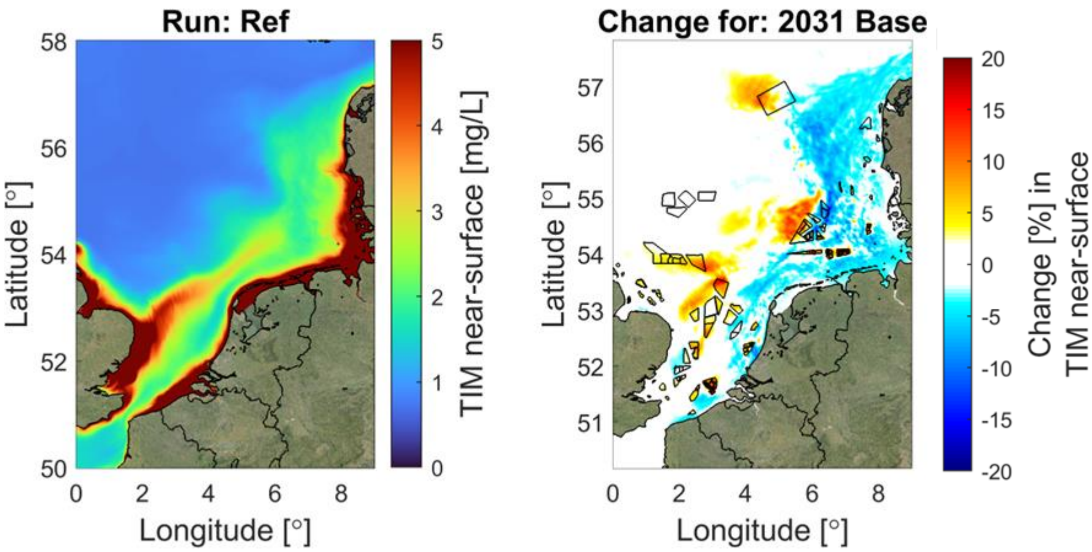


Figure 5.13 Effect of North Sea wind farms on the year-averaged total inorganic matter (TIM) near the water surface. The panels show the TIM [mg/l] in the Reference simulation without wind farms (left), and the relative change [%] for the Base scenario (right panel) . In the right panel, red indicates an increase in turbidity compared to the Reference simulation without wind farms. Black contours indicate the location of the wind farms for each scenario.

5.2.3 Seasonal variation

The near-surface response in Total Inorganic Matter (TIM) to the presence of wind farms is more pronounced in the winter compared to the summer (Figure 5.14).

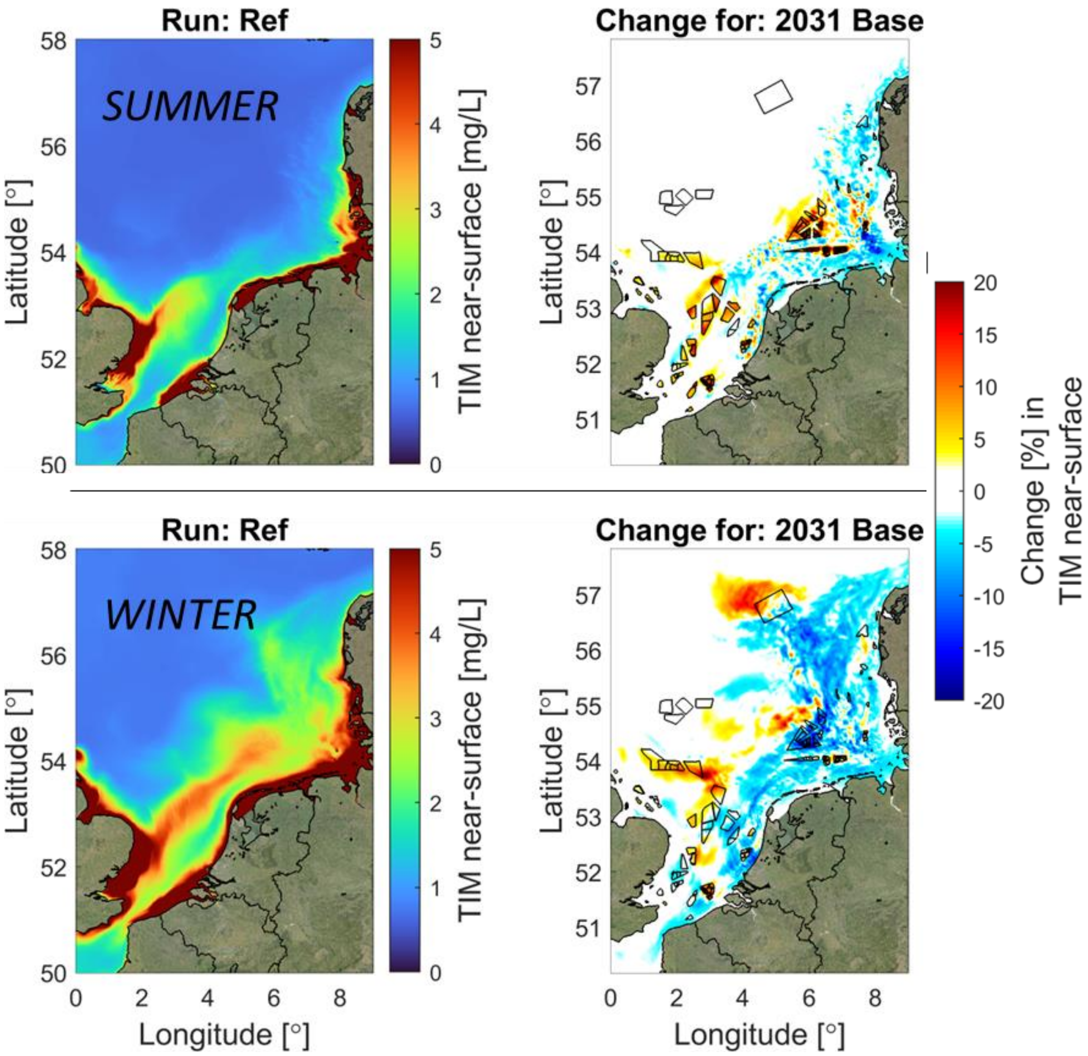


Figure 5.14 Seasonal variation of wind farm effects on the year-averaged total inorganic matter (TIM) near the surface. Same as Figure 5.13, but now the top row shows the average effects in the summer (June-August 2007) and the bottom row shows the average effects in the winter (September-December 2007).

5.3 Results Partial revision scenarios

In this section, we discuss the effects of adding wind farms off the Danish coast and in Search Area 6/7 and Lagelander, as well as extending wind farm area Doordewind. To this purpose, Scenario 1 is compared to the 2031 Base scenario. The year-average and seasonal effects are studied in Sections 5.3.1 and 5.3.2, respectively. Appendix C discusses the verification of the elevated mud content in the bed in Search Area 6/7, which is an important feature of this zone and which has been taken into account for the scenario definition.

5.3.1 Year-average effects on Total (suspended) Inorganic Matter

The construction of wind farms in Search Area 6/7 is computed to decrease the turbidity in the tip of the East Anglia plume, east of these wind farms, while simultaneously increasing the turbidity in what are normally relatively clear waters west of these wind farms. This can be seen in Figure 5.15, where both an increase and decrease in Total Inorganic Matter (TIM) up to 0.4 mg/l is computed in the surface waters.

Lateral mixing at the interface of the turbid waters of the East Anglia plume and the less turbid surrounding waters, caused by wind farms in Search Area 6/7, most likely contributes to this phenomenon. A similar effect is computed off the Danish coast, where the new additional wind farms redistribute the fine sediment concentrations from more to less turbid areas.

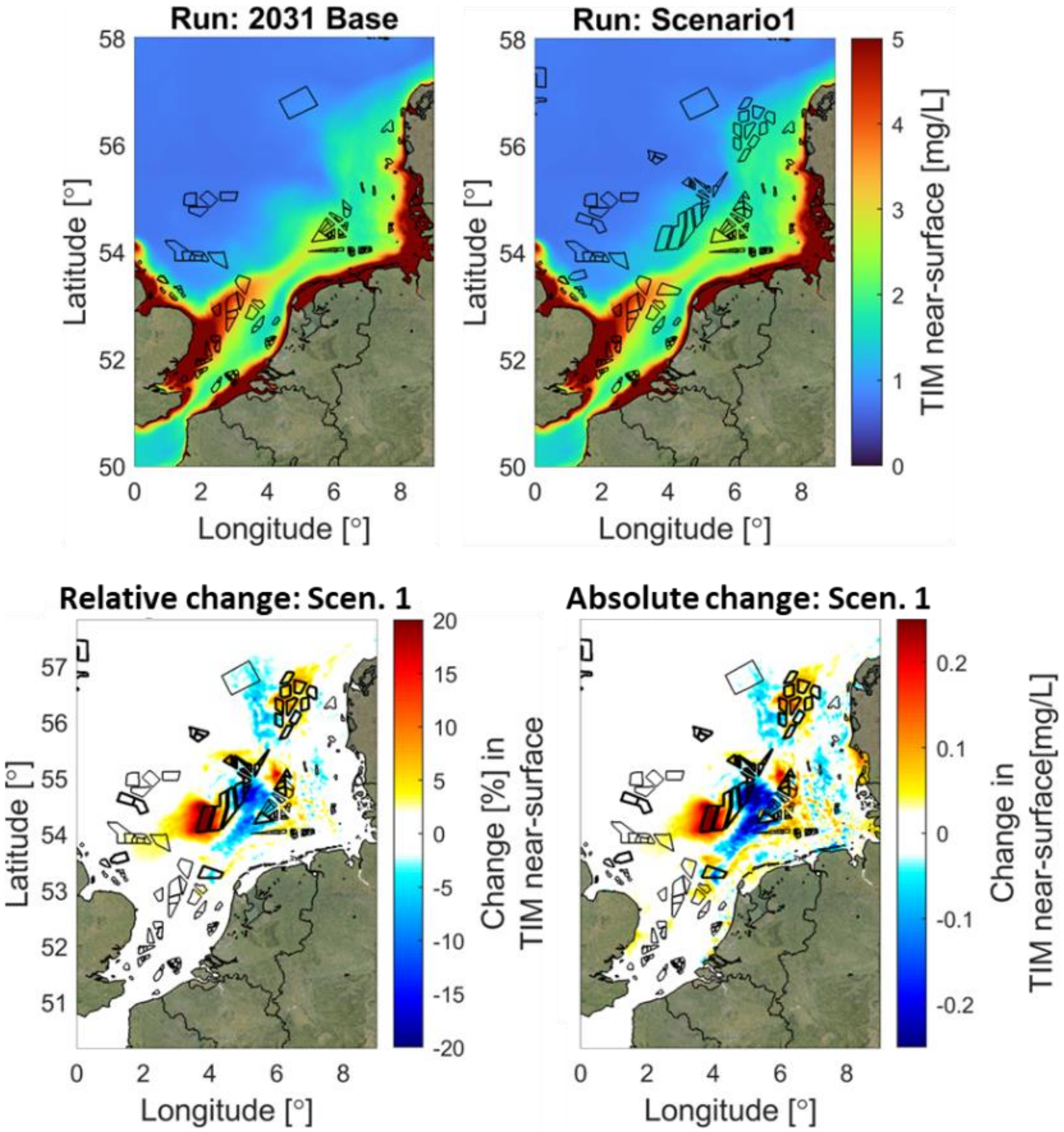


Figure 5.15 Effect of the additional wind farms in Scenario 1 compared to the Base scenario on the year-averaged total inorganic matter (TIM) near the water surface. The top panels show the TIM [mg/l] in the Base simulation (left) and Scenario 1 (right). The bottom panels show the relative change [%] (left) and absolute change [mg/l] (right) in TIM in Scenario 1 compared to the Base scenario. The thick black contours in the bottom panels show the additional wind farms in Scenario 1 compared to the Base scenario.

5.3.2 Seasonal variation

The effect of wind farms in Search Area 6/7 on near-surface turbidity is most prominent during the winter months when the East Anglia plume extends to this region, aided by the weak temperature stratification. This is shown in the bottom panels of Figure 5.16, where a similar yet even stronger effect on the TIM is computed during winter compared to the year average effect (Figure 5.15). In the summer months, when the turbid waters of the East Anglia plume do not extend to Search Area 6/7, lateral mixing does not result in prominent changes in surface TIM (top panels of Figure 5.16).

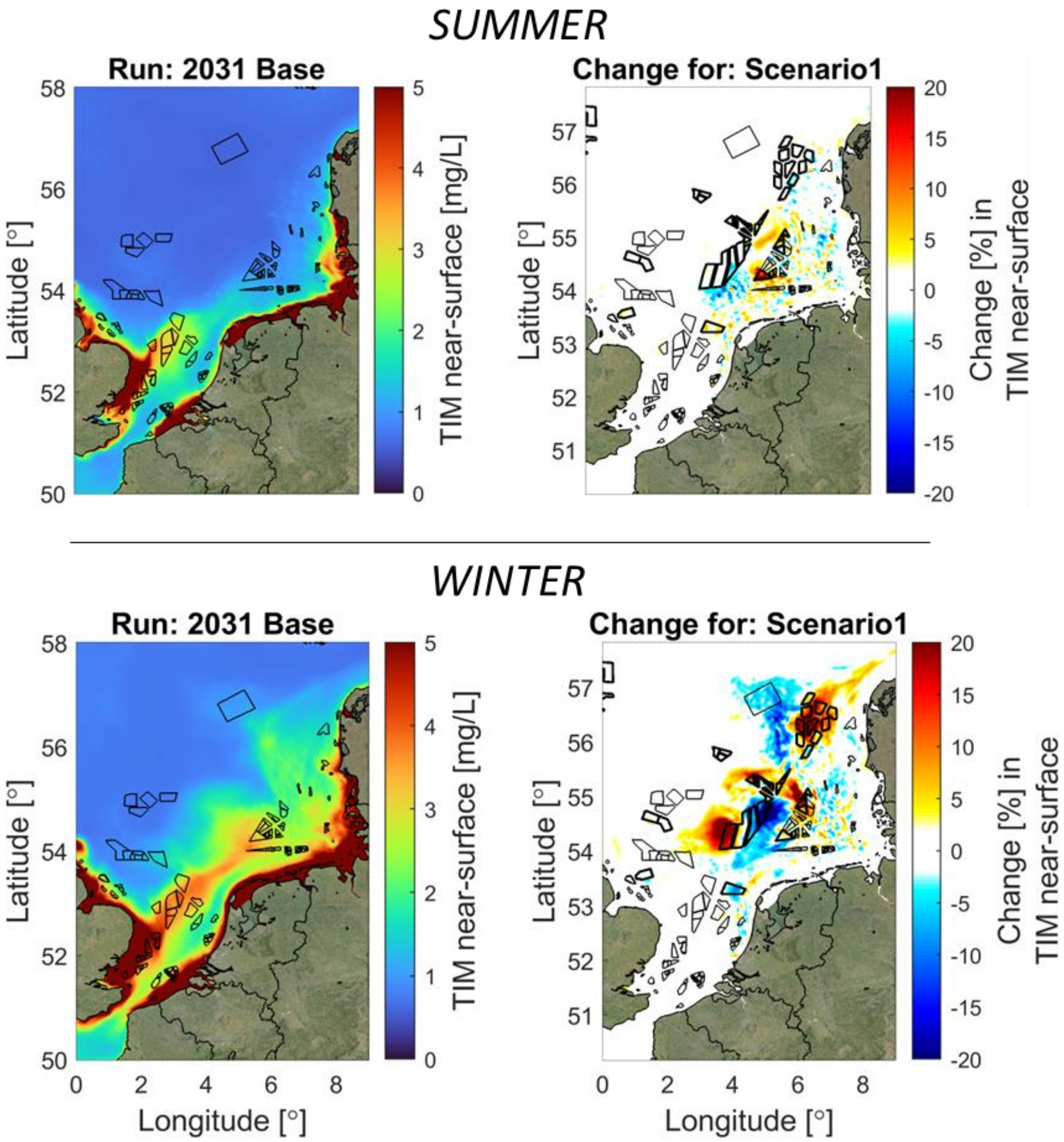


Figure 5.16 The additional wind farms in Scenario 1 compared to the Base scenario have a more pronounced effect on the near-surface total inorganic matter (TIM) in the winter compared to the summer. Top row shows the average effects in the summer (June-August 2007) and the bottom row shows the average effects in the winter (September-December 2007). The panels show the TIM [mg/l] in the Base scenario (left), and the relative change [%] for Scenario 1 (right panel).

5.4 Effect of the size and number of pillars

The size and number of pillars in Search Area 6/7 is varied in Scenarios 1-3 to assess if the turbidity footprint can be optimized while maintaining the same surface area in wind farms. Scenario 1 has an energy production of 24GW based on 1200 pillars of 11.3m diameter in

Search Area 6/7. Scenario 2 has an identical energy production as Scenario 1 but with fewer yet larger pillars (960 pillars of 13m diameter). Scenario 3 has a larger energy production compared to Scenario 1 based and has more yet thinner pillars (2492 pillars of 9.9m diameter).

5.4.1 Year-average effects on Total (suspended) Inorganic matter

Figure 5.17 shows the absolute differences between the three scenarios and the base scenario. All three have similar effects. The main changes (relative to the base scenario are in and around Search area 6/7, where in the most part of the area SPM concentrations increase by more than 0.2 mg/l, which amounts to more than 20% (Figure 5.18).

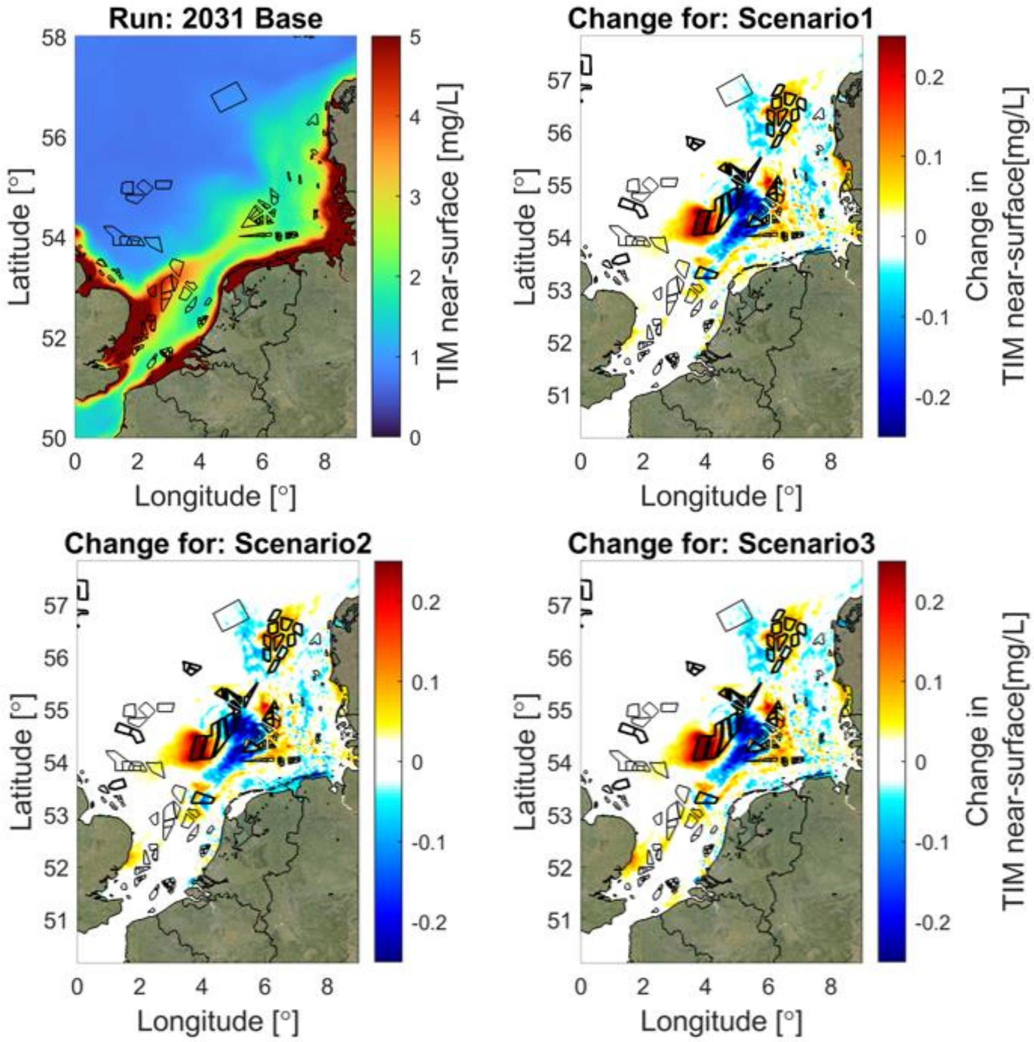


Figure 5.17 The absolute effects on the near-surface year-average total inorganic matter (TIM) for scenarios with different pillar quantities and sizes in Search Area 6/7 compared to the Base scenario. The top left panel shows the TIM [mg/l] in the Base scenario without wind farms in Search Area 6/7. The other three panels show the absolute change in TIM [mg/l] for Scenario 1 (upper right), Scenario 2 [lower left), and Scenario 3 (lower right). Thick black lines indicate the wind farms that are new in scenarios 1-3 compared to the base Scenario.

In the areas downstream from Search area 6/7 there is a decrease in comparison to the Base scenario.

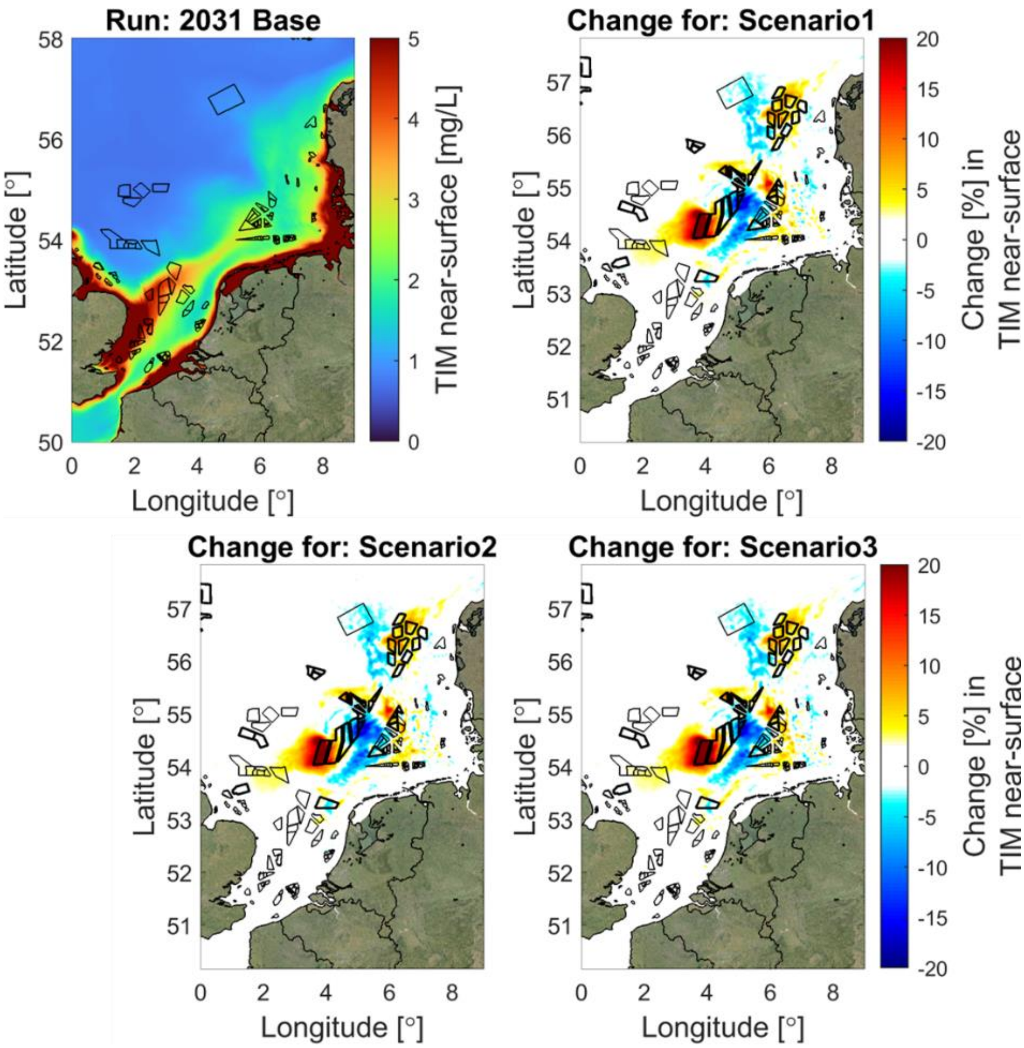


Figure 5.18 As figure 5.18, but with relative differences to the base scenario.

In comparison to the base scenario (the wind farm scenario for 2031) there appears to be relatively little impact in the southern part of the North Sea. When the cumulative effect of all wind farms in scenario 1, 2 and 3, compared to the reference scenario without wind farms, indicates that in the southern part of the North Sea also substantial increases take place (in some cases, e.g. for Nederwiek North more than 0.25 mg/l, i.e. a 20-25% increase). Note that the bulk of the effects, relative to the base scenario, take place in areas that are seasonally stratified. As indicated in section 5.2.3, this is mainly due to increases in winter. The impact in summer is minor in these areas.

In comparison to the base scenario the impact in the Lagelander wind farm appears to be a small (<5 mg/l, 2-3%) reduction in fine sediment concentration in the top layers.

Comparing the three scenarios to the reference situation (without wind farms) we see that this occurs over a larger area. These wind farms are not seasonally stratified, hence these differences also visible in the summer season.

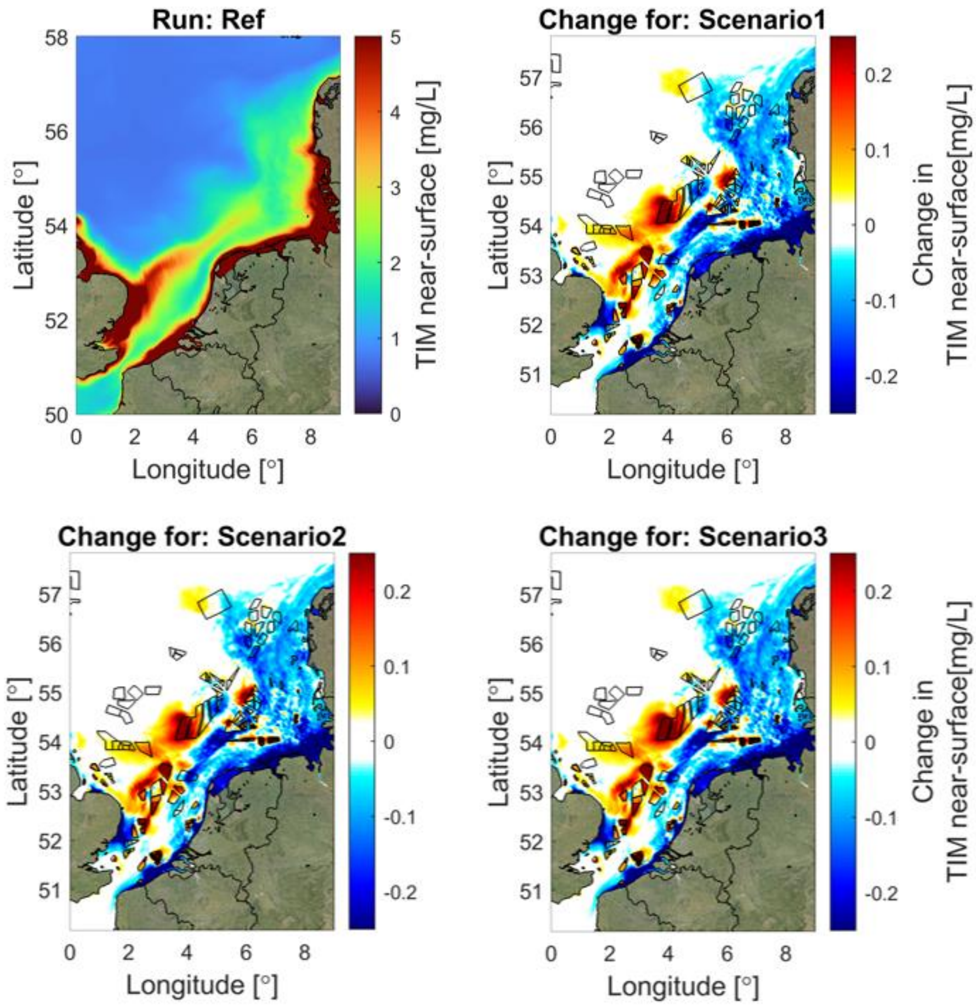


Figure 5.19 Absolute changes in total inorganic matter in Scenario 1. 2 and 3 in comparison to the reference scenario (no wind farms).

5.4.2 Impact of pillar density and size

As the overall effects of scenarios 1, 2 and 3 appear very similar, the best way to assess the differences, is to compare them relative to each other. We found that both an increase in pillar size and an increase in pillar density, enhance the OWF footprint. However, for a constant total energy production, changes in pillar size do not affect the modelled turbidity. This can be seen in Figure 5.20 and Figure 5.21 where the effect of Scenario 1 and 2 on the near-surface Total Inorganic Matter (TIM) is identical. In these scenarios the total energy production is the same, but scenario 2 has fewer, but larger turbines. However, there is a clear difference between scenario 1 and 3. Scenario 3 has a higher production capacity and more, but smaller turbines. Figure 5.21 shows the modelled surface TIM in Search Area 6/7 is 5% higher compared in Scenario 3 - with a 37.4 GW energy production - compared to Scenario 1 – with a 24 GW energy production.

These are annual averaged differences. As Search Area 6/7 is seasonally stratified, these differences are only caused by the winter concentrations, when the system is mixed. Once stratification sets in the differences with the base scenario and the reference scenario, is in all three cases virtually 0.

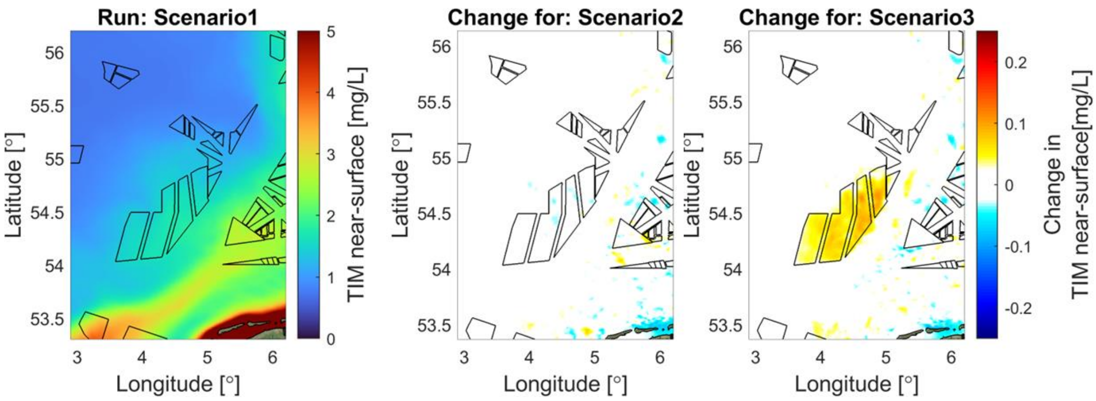


Figure 5.20 Absolute differences in the near-surface Total Inorganic Matter (TIM) between Scenario 1 and Scenario 2 (middle) and the difference between scenario 1 and scenario 3 (right).

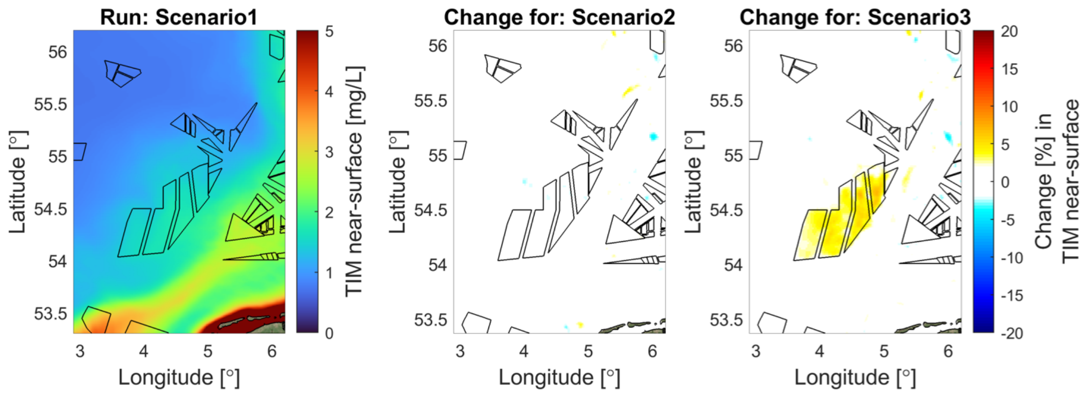


Figure 5.21 Relative differences in the near surface Total Inorganic Matter (TIM) between Scenario 1 and Scenario 2 (middle) and the difference between scenario 1 and scenario 3 (right).

5.5 Effect of an open space

Scenario 1 and scenario 4 have both the same total energy production, the same number of turbines and the same size of turbine. In Scenario 4 an open space is created, which means that in the adjacent areas where there are turbines, the density is larger than in scenario 1.

5.5.1 Year-average effects on Total (suspended) Inorganic Matter

The effect of the wind farms in Search Area 6/7 on the near-surface Total Inorganic Matter (TIM) is less pronounced when a space is left open as is the case in Scenario 4 (Figure 5.22 and Figure 5.23).

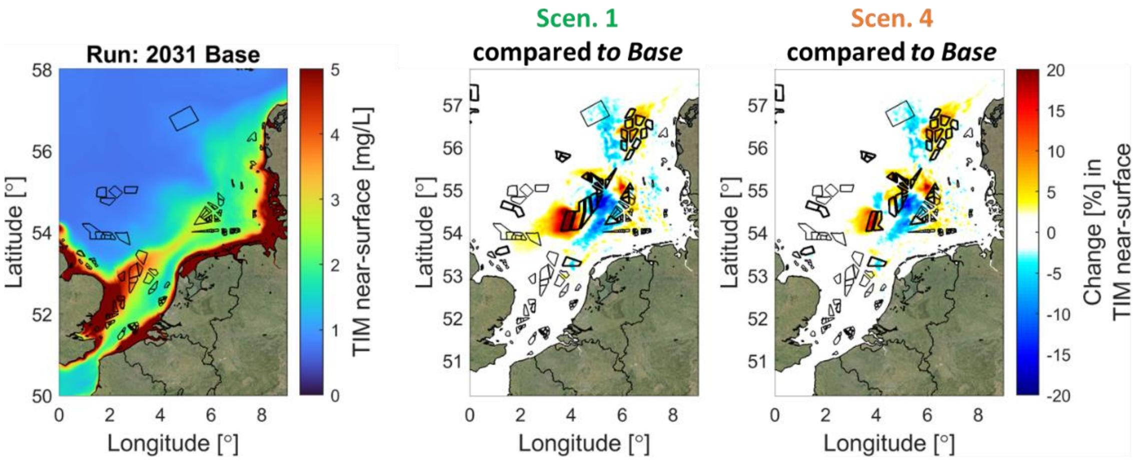


Figure 5.22 The effects on the near-surface total inorganic matter (TIM) for scenarios with a different distribution and density of pillars in Search Area 6/7 compared to the Base scenario. The left panel shows the TIM [mg/l] in the Base scenario without wind farms in Search Area 6/7. The other panels show the relative change in TIM [%] for Scenarios 1 (middle panel) and 4 (right panel) Thick black lines indicate the wind farms that are new in scenarios 1 and 4 compared to the base Scenario; Scenario 4 has an open space in Search Area 6/7.

In comparison to the reference scenario (with no wind farms) the relative difference between scenario 1 and scenario 4 is of course the same. Outside of the vicinity of Search area 6/7 the impacts between the scenarios are identical Figure 5.23.

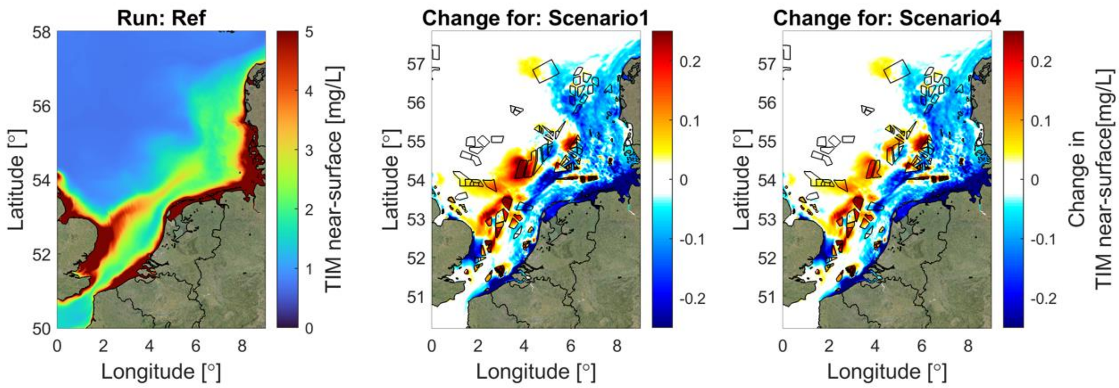


Figure 5.23 As in Figure 5.22, but relative to the situation without wind farms.

The open space in Search Area 6/7 applied in Scenario 4, partly mitigates the effect of wind farm induced lateral mixing at the tip of the East Anglia plume. This can be seen in Figure 5.24, where it is shown the increase (decrease) in turbidity west (east) of Search Area 6/7 is mitigated compared to Scenario 1. The open space has a more pronounced mitigating effect in winter (not shown) when the strongest effects of having wind farms in Search Area 6/7 are computed (Figure 5.16).

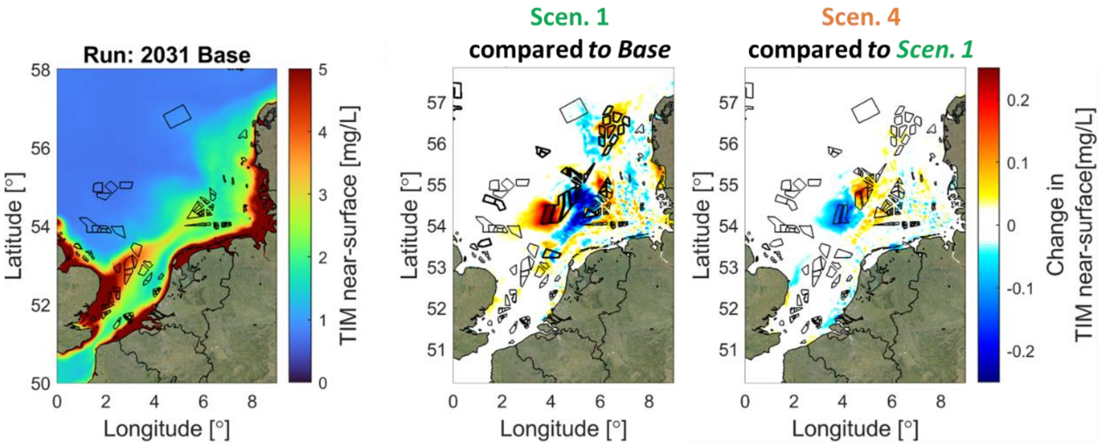


Figure 5.24 An open space in Search Area 6/7 partly mitigates the redistribution of Total Inorganic Matter (TIM) caused by the construction of wind farms in Search Area 6/7. The first (left) panel shows the TIM [mg/l] in the Base scenario without wind farms in Search Area 6/7. The second (middle) panel shows the absolute change in TIM [mg/l] for Scenario 1.

5.6 Summary and conclusions

OWF configurations that enhance the energy production, such as an increase in pillar size or pillar density result in a larger OWF footprint. It cannot be concluded which parameter yields a stronger footprint, as the effects of OWFs on mixing and turbidity have not yet been validated. The results do suggest that keeping certain areas open can mitigate effect. For a constant total energy production, the turbidity is not strongly influenced by pillar size and the turbidity effects are smaller for a smaller OWF surface area. However, these optimizations result in minor changes compared to the major overall effect of having many OWFs in the North Sea.

The model is not yet validated on the impact of OWFs on turbidity and bed composition. For this comparison with field data inside and around OWFs in required, which is still work in progress. Notably, results on local details such as pile density and open spaces are indicative. The effects of changes in pile diameter and density on mixing and turbidity have not yet been validated. Wave effects are modelled through a local reduction in wind speed. No wave breaking or dissipation is included.

6 Impact on water quality and ecology

In this section, results from the water quality component of the model are presented. These results were produced with the fully coupled hydrodynamic-sediment-water quality version of 3D DCSM-FM, using the same set-up as reported in Zijl et al. (2023). All runs analyzed here use atmospheric, offshore and river forcings from the year 2007, and were spun-up for one year, using conditions from 2006.

Effects of OWFs are investigated looking at difference maps of variables relevant to ecosystem functioning, more specifically: yearly average phytoplankton primary production, integrated over the entire water column, near-surface chlorophyll a concentrations, and depth-averaged chlorophyll a concentrations. Phytoplankton primary production is calculated as the net autotrophic organic carbon production by phytoplankton, based on temperature conditions, nutrient and light availability at a specific location. Chlorophyll a concentrations (proxy for phytoplankton biomass) are the resultant of transport, phytoplankton primary production and phytoplankton mortality.

All yearly-average maps are calculated based on simulated 3D map outputs from the coupled hydrodynamics-sediment-water quality and ecology model, available at a 2.5-day resolution (using all output dates in the year). Net depth-integrated primary production outputs are expressed in $gC/m^2/day$.

Three additional observation locations were defined in the model within different parts of Search Area 6/7 to further investigate effects on vertical gradients and temporal dynamics (Figure 6.1).

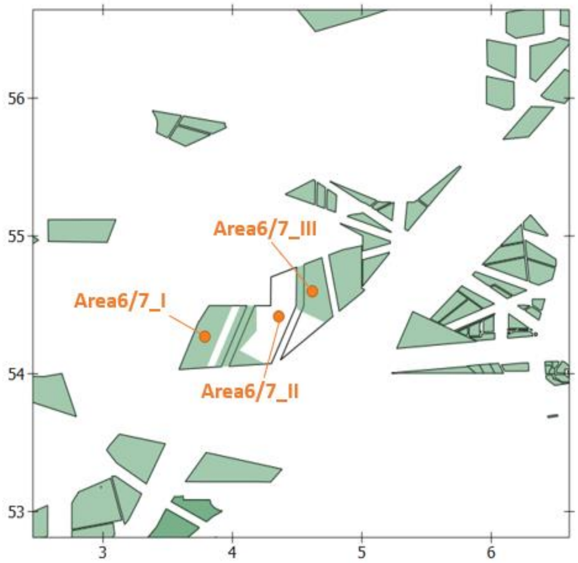


Figure 6.1 Model observation locations in Search Area 6/7 to investigate vertical gradients and time-series. The polygons outlined in black represent OWFs in Scenarios 1-3; the green shaded polygons are the OWFs in Scenario 4.

6.1 Reference situation: 2007 conditions without OWFs

For reference, results from the simulation without OWFs are presented here.
Simulated phytoplankton primary production is highest in areas closer to the shore, receiving nutrient inputs from river plumes, and where light availability isn't limiting (Figure 6.2), reaching yearly-average values of ~1 gC/m^2/day. Offshore primary production is lower (~0.2-0.3 gC/m^2/day), with slightly higher values in the more shallow and better mixed area of the Dogger Bank. Near-surface and depth-averaged chlorophyll a concentrations show sharp spatial gradients from near-shore, nutrient rich areas to offshore (Figure 6.3). While there is little difference in near-surface and depth-averaged concentrations in more shallow and well mixed near-shore areas, depth-averaged chlorophyll a concentrations are significantly lower offshore. More offshore, maximum chlorophyll a concentrations are simulated in the Dogger Bank area.

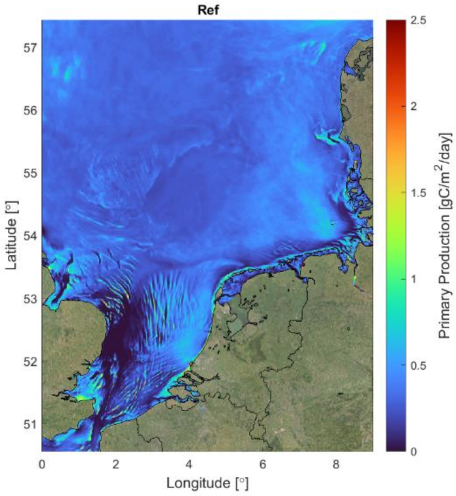


Figure 6.2 Yearly average, depth-integrated phytoplankton primary production.

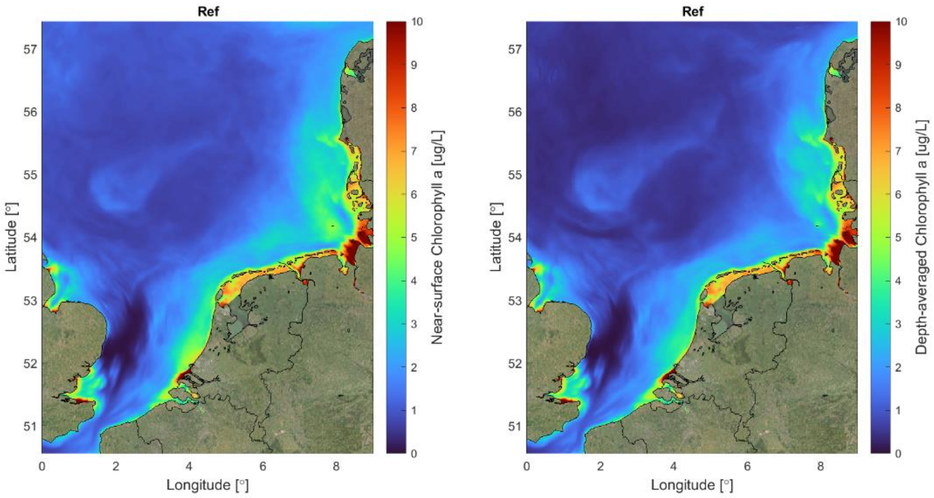


Figure 6.3 Yearly average chlorophyll a concentrations. Left: Near-surface; Right: Depth-averaged.

6.2 Effects of the base scenario (OWFs 2031)

6.2.1 Yearly average effects on primary production

Compared to the situation without wind farms we see in the 2031 scenario a decrease of primary production in the wind farms in the Holland coast and particularly in the German Bight. The local decrease in primary productivity is largest in the Ten Noorden van de

Wadden (TNW) and GEMINI farms (number 7 location in Figure 1.1). Also the Doordewind windfarm shows a clear decrease, but this less than in the TNW and GEMINI locations and also less than in some of the adjacent German wind farms (Figure 6.4). In these areas decreases in primary production can be up to 60%, while in the Doordewind farm the decrease is around 20% Particularly in the German Bight wind farms there appear to be increases in the areas surrounding the farms, indicating some compensatory effects. Figure 5.14 shows that in the summer season the fine sediment (SPM) levels inside the wind farms in the surface layers are higher, but outside the farms not. It appears that nutrients that cannot be utilised in the wind farm areas, due to increased light limitation, are boosting primary production levels in the surrounding areas of the wind farms. More detailed mass balance analyses on large (regional) scales need to be carried out to see to what extent these compensatory effects alleviate the impacts within the farms. For this, relevant assessment areas for changes in ecosystem functioning should be defined. These compensatory effects should be in areas with similar conditions/habitats to alleviate shifts in the food chain. As a starting point, OSPAR assessment areas, based on abiotic conditions, or Wozep areas defined in the first bottom-up report (Zijl et al., 2021) could be used.

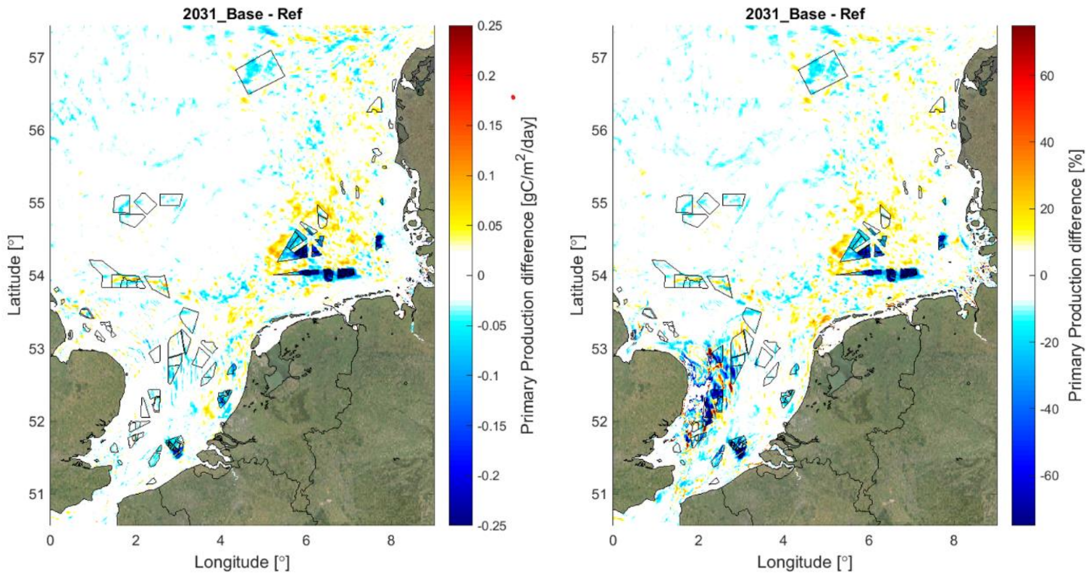


Figure 6.4 Left – Absolute difference in yearly-average depth-integrated primary production between the base scenario and the reference scenario; Right – relative difference in yearly-average depth-integrated primary production between base and reference scenario.

The impacts are visible in both the absolute changes as well as in the relative changes. It is useful to consider both absolute and relative effects. In Figure 6.4 in the righthand panel large relative changes are visible in the English coast. However, as primary production in this area is very low due to the high SPM concentration originating from the Thames, in this area even a tiny change is a large relative effect.

6.2.2 Yearly average effects on Chlorophyll a

The chlorophyll concentration is an indication of the available algal biomass. This is the result of primary production minus algal mortality. In most areas the trends in chlorophyll follow the trend in primary production, but not everywhere (Figure 6.5 and Figure 6.6). The Doordewind wind farm and the German wind farms most distant from the coast seem to show an increase in chlorophyll, instead of a decrease.

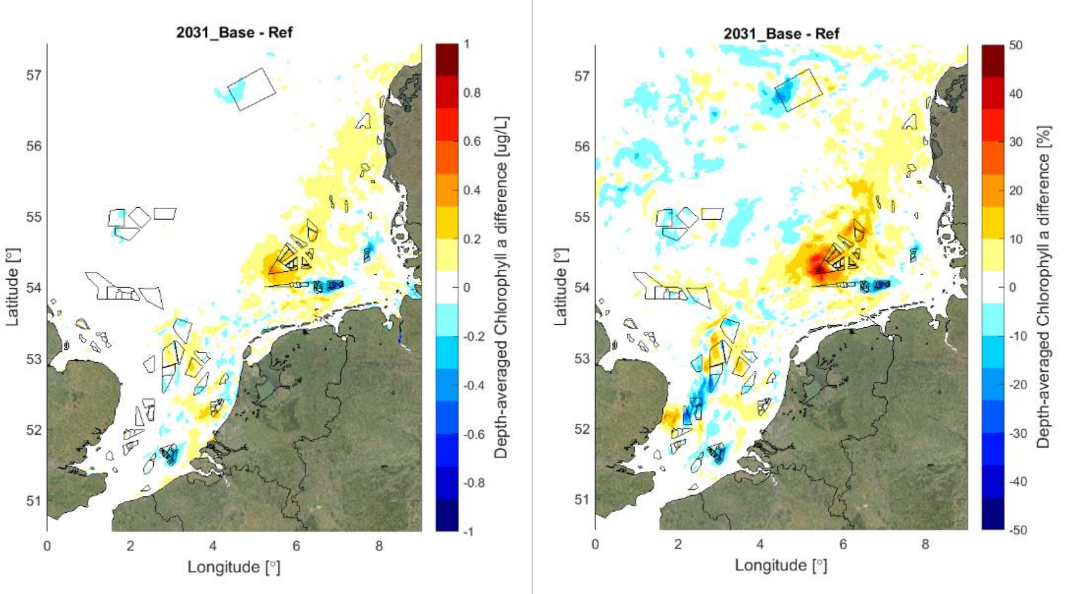


Figure 6.5 Left – absolute depth-averaged chlorophyll concentration difference between the base scenario and the reference scenario. Right - relative depth-averaged chlorophyll concentration difference between the base scenario and the reference scenario.

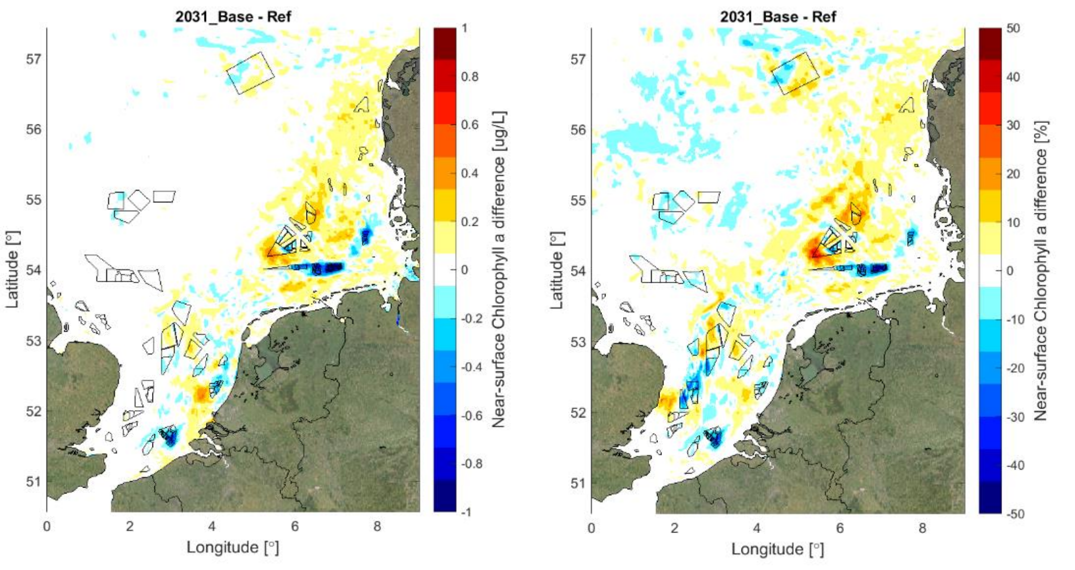


Figure 6.6 Left – absolute chlorophyll concentration difference between the base scenario and the reference scenario in the upper layer. Right - relative chlorophyll concentration difference between the base scenario and the reference scenario in the upper water layer.

The cause for this is not immediately clear. There are two options. The first is that the chlorophyll is not produced locally, but transported there from other areas. The other option is a process we have seen in previous studies for the environmental impact assessment on sand mining (Van Duren et al. 2017). The area Doordewind has lower primary productivity due to the increased presence of SPM in the top layer. In this area light limitation is increased while nutrient limitation is reduced (due to the mixing of more nutrients into the top layer during stratified periods. In the model there is less phytoplankton biomass, but these microalgae have a high proportion of phytoplankton, adapted to low light conditions. This results in lower algal biomass but higher chlorophyll levels.

6.2.3 Yearly average effects on phytoplankton biomass

If we explore the results further and we express the changes in phytoplankton biomass in terms of milligrams carbon/L, the picture looks different (Figure 6.7). Here we see that inside windfarm Doordewind phytoplankton biomass (based on carbon) is reduced. Outside the windfarm we see indeed increases; likely compensatory effects of nutrients that cannot be used inside the farm due to light limitation, being used outside the farm, where nutrient limitation is more important.
This illustrates that for this area chlorophyll is not the best proxy for algal biomass.

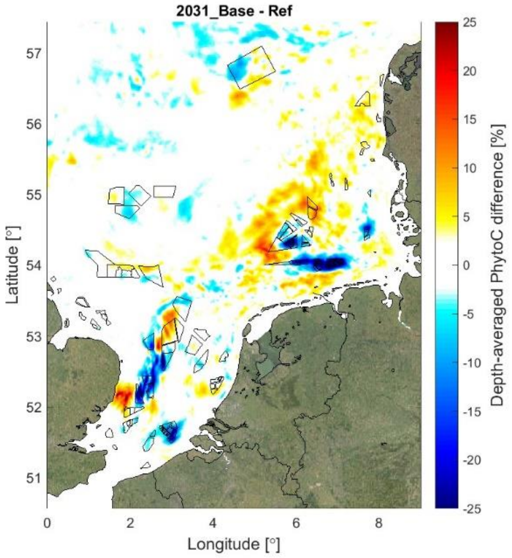


Figure 6.7 relative change in depth-averaged phytoplankton biomass.

6.3 Results on yearly average effects Partial Revision scenarios

6.3.1 Comparison to the 2031 situation (Base run)

Compared to the Base situation, Scenarios 1-4 lead to similar overall changes in terms of primary production over the Southern North Sea, with, as expected, slight differences around Search Area 6/7 (Figure 6.8). Therefore, only results for Scenario 1 are shown in the rest of this section. More local differences, linked to the different set-ups in Search Area 6/7 are discussed more in detail in subsections 6.3.2 and 6.3.3.

When comparing Scenario 1 results to the 2031 Base situation, the spatial patterns are comparable to those discussed above. Simulated depth-integrated phytoplankton primary production decreases in the Doordewind OWF by up to ~50% with respect to the 2031 Base situation (Figure 6.8). This is due to a decrease in light availability due to increased re-suspension of fine sediments. On the contrary, primary production increases within and Search Area 6/7 east from it (downstream in the direction of residual currents), with differences of ~10-20% inside the Search Area 6/7 and up to ~50% directly downstream (Figure 6.9). These increases can be explained by reduced stratification and thus higher nutrient availability closer to the water surface, while the additional re-suspended fine sediments do not reach the upper layers of the water column in the phytoplankton growing season. Even though results are a bit patchy, primary production slightly decreases in Lagelander Noord, UK's Dogger Bank South OWFs and the Danish OWFs from Scenario 1, built after the 2031 Base situation. As observed in the previous report (Zijl et al., 2023), simulated decreases in primary production due to reduced light are generally more local, directly within OWFs, while increases due to mixing of the water column can still be visible far downstream from the OWFs. This is consistent with the simulated extents of effects of OWFs on surface inorganic sediment concentrations and stratification.

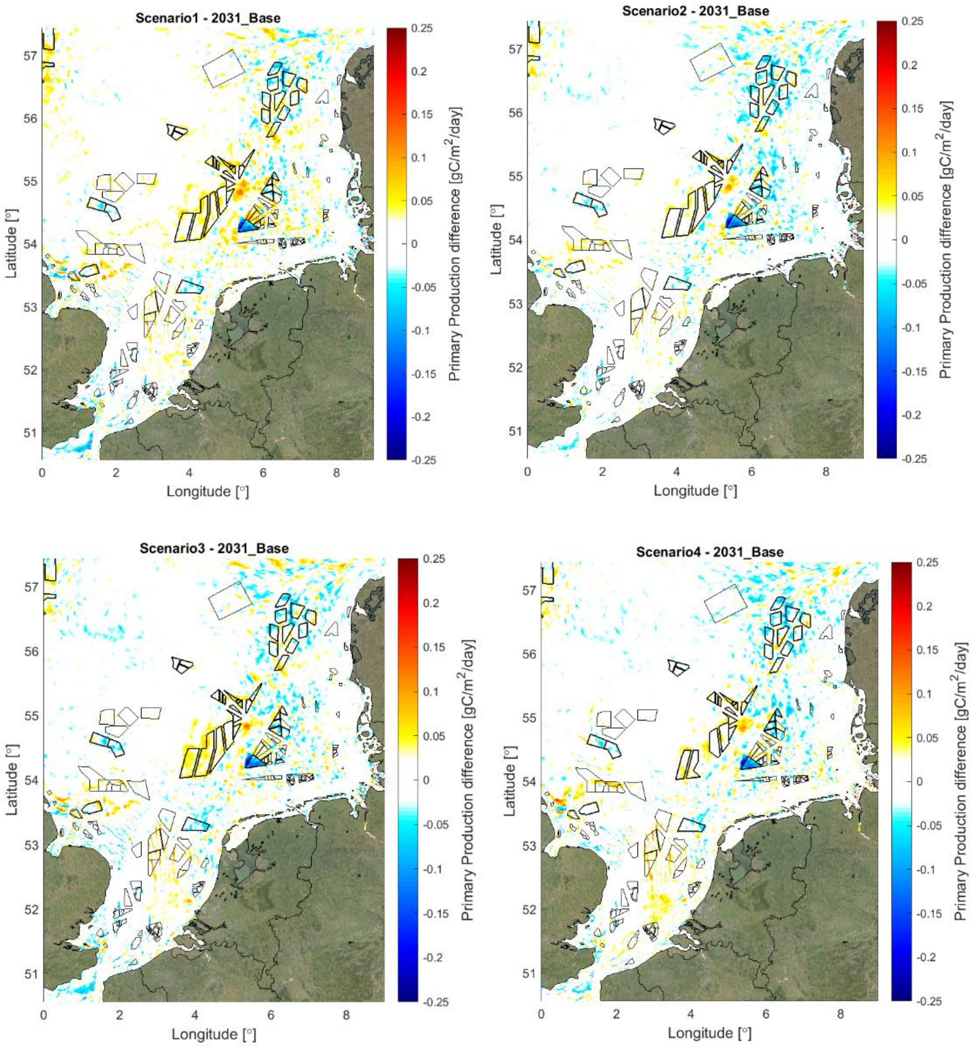


Figure 6.8 Absolute difference in yearly average depth-integrated phytoplankton primary production between Scenarios 1-4 and the Base situation.

Simulated differences in chlorophyll a concentrations between Scenario 1 and the 2031 Base situation show similar spatial patterns (Figure 6.10). Near-surface chlorophyll a concentrations in the Doordewind OWF decrease locally by ~20-30% with respect the 2031 Base situation; depth-averaged concentrations decrease by ~10-20% (Figure 6.11). In the vicinity of Search Area 6/7, the new OWFs lead to increases in near-surface concentrations by ~10% and up to ~20-30% locally downstream. In that area, depth-averaged concentrations increase by ~20% and locally by more than 30%. Chlorophyll a concentrations also decrease locally within Lagelander and within the Danish OWFs from Scenario 1, built after the 2031 Base situation.

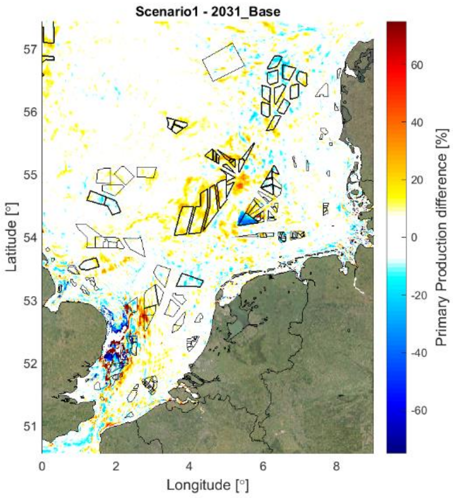


Figure 6.9 Relative difference in yearly average depth-integrated phytoplankton primary production between Scenario 1 and the 2031 Base situation. Bold polygons represent OWFs that, within Scenario 1, are constructed after 2031.

In Search Area 6/7 and further east, increases in chlorophyll a concentrations are sharper when looking at depth-averaged concentrations than at near-surface concentrations (Figure 6.10 compared to Figure 6.11). This is due to the fact that: 1) the maximum chlorophyll a concentrations do not occur directly near the surface but in the subsurface (~10-15 m depth) and 2) due to the increased mixing, the additional produced biomass is vertically transported deeper in the water column (Figure 6.12).

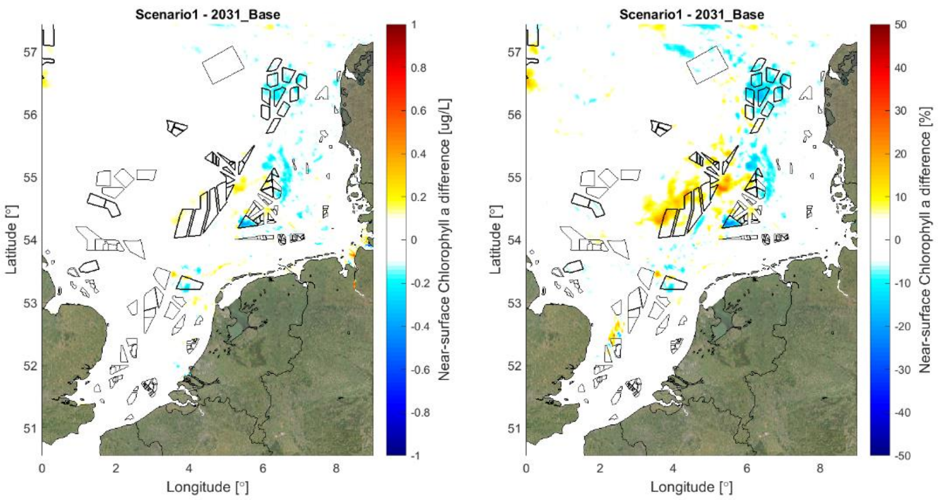


Figure 6.10 Difference in yearly average near-surface chlorophyll a concentrations between Scenario 1 and the 2031 Base situation. Left: Absolute difference; Right: Relative difference. Bold polygons represent OWFs that, within Scenario 1, are constructed after 2031.

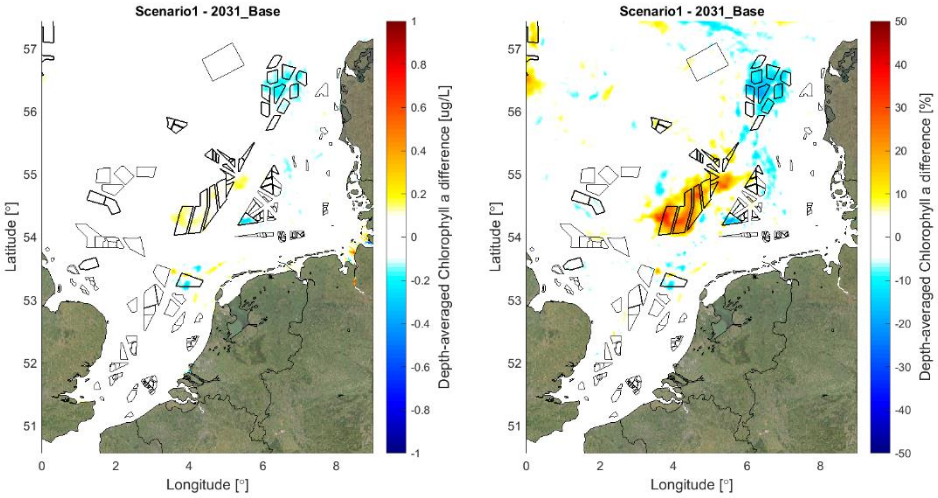


Figure 6.11 Difference in yearly average depth-averaged chlorophyll a concentrations between Scenario 1 and the 2031 Base situation. Left: Absolute difference; Right: Relative difference. Bold polygons represent OWFs that, within Scenario 1, are constructed after 2031.

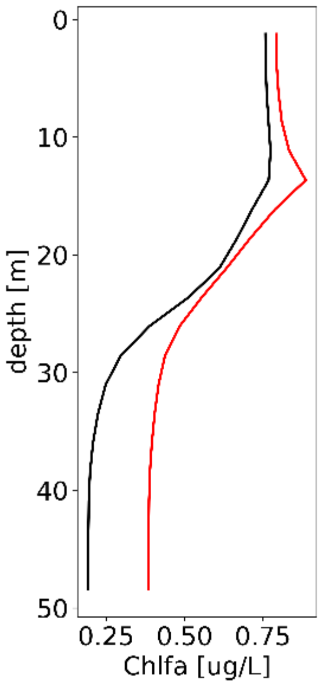


Figure 6.12 vertical profile of yearly-average chlorophyll a concentrations at location Area6/7_II (see map in Figure 2.1). Black line: Base run; Red line: Scenario 1.

6.3.2 Effect of the size of pillars

To look more specifically at the effect of size and proximity of the turbine pillars Scenarios 2-3 are compared to Scenario 1. All three scenarios have the same OWF delineations. In Scenario 2, Search Area 6/7 contains less turbines of larger diameter; in Scenario 3, Search Area 6/7 contains more turbines of smaller diameter. Scenario 3 also has a higher total energy production with Search Area 6/7. For comparability, colour scales are kept the same as in previous sections.

Simulation results show that, compared to the effects of the presence of OWFs themselves (Appendix E), the difference in effects on primary production and chlorophyll a concentrations

between Scenario 1 and Scenario 2 are small (Figure 6.13, Figure 6.14, Figure 6.15, Figure 6.16 left panels). However, locally within Search Area 6/7, phytoplankton primary production is up to ~10% lower in Scenario 2 than in Scenario 1. This shows that a set-up with fewer, but larger turbines in Search Area 6/7 might lead to slightly lower impact (i.e. less of an increase in primary production) within the windfarm and downstream.
The effects of both having a higher energy production and higher density of smaller turbines are more pronounced (see right panels of Figure 6.13, Figure 6.14, Figure 6.15 and Figure 6.16). In sections I and II of Search Area 6/7 (most Western sections), yearly average phytoplankton primary production increases further locally by 15-20% compared to Scenario 1. Similarly, near-surface chlorophyll a concentrations increase further by ~15% and depth-averaged chlorophyll a concentrations by up to ~25%. Effects downstream are more patchy, and directly downstream Search Area 6/7, primary production is locally up to 15-20% lower in Scenario 3 than in Scenario 1, and chlorophyll a concentrations ~10% lower.

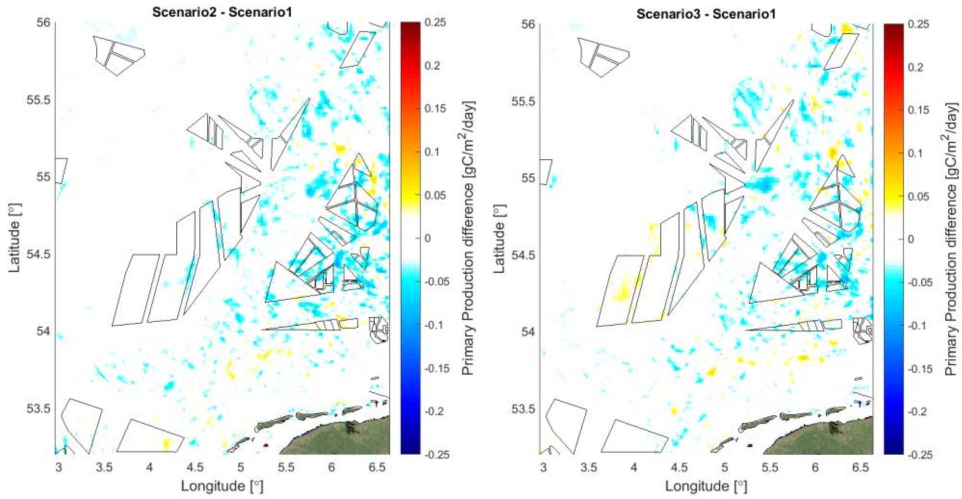


Figure 6.13 Absolute difference in yearly average depth-integrated phytoplankton primary production between Scenarios 2-3 and Scenario 1. Left: Scenario2 – Scenario1; Right: Scenario3 – Scenario1.

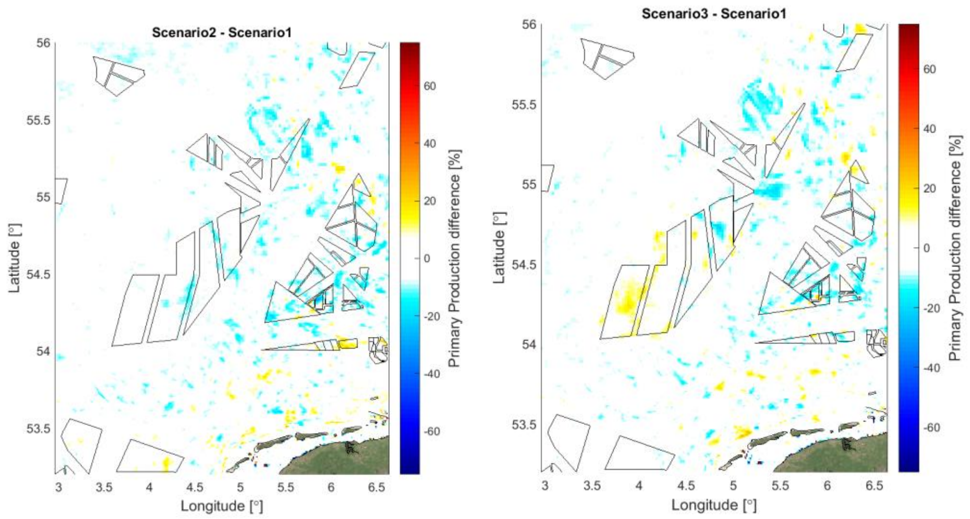


Figure 6.14 Relative difference in yearly average depth-integrated phytoplankton primary production between Scenarios 2-3 and Scenario 1. Left: Scenario2 – Scenario1; Right: Scenario3 – Scenario1.

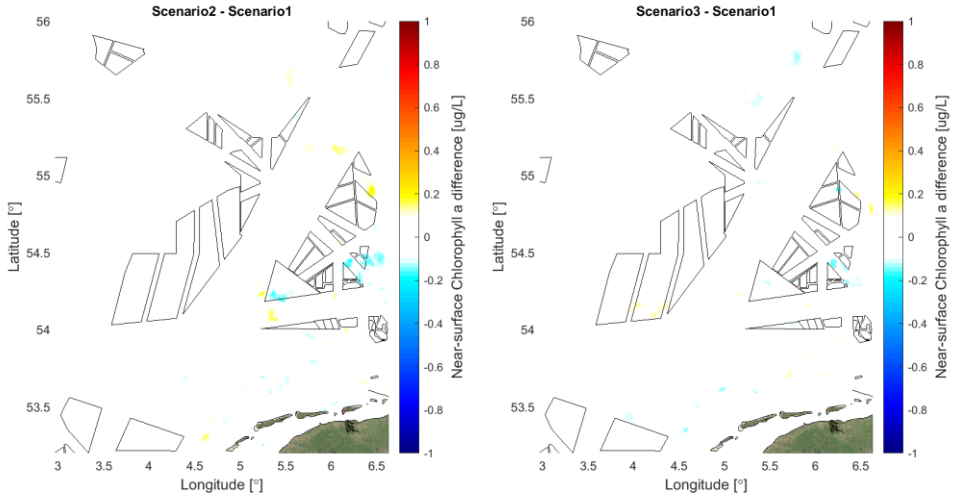


Figure 6.15 Absolute difference in yearly average near-surface chlorophyll a concentrations between Scenarios 2-3 and Scenario 1. Left: Scenario2 – Scenario1; Right: Scenario3 – Scenario1.

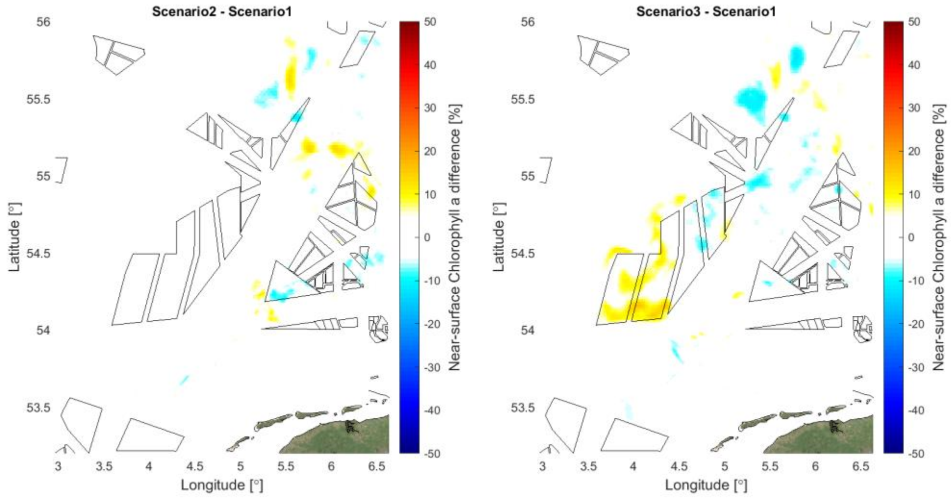


Figure 6.16 Relative difference in yearly average near-surface chlorophyll a concentrations between Scenarios 2-3 and Scenario 1. Left: Scenario2 – Scenario1; Right: Scenario3 – Scenario1.

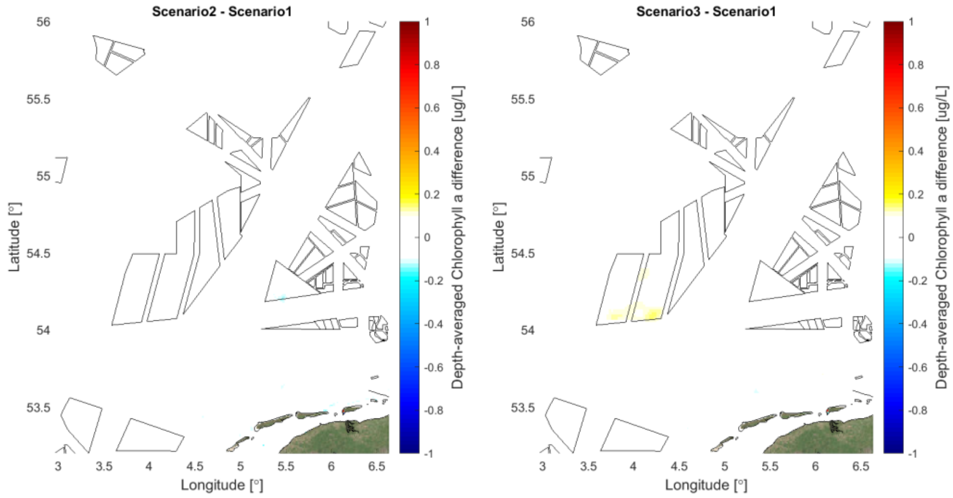


Figure 6.17 Absolute difference in yearly average depth-averaged chlorophyll a concentrations between Scenarios 2-3 and Scenario 1. Left: Scenario2 – Scenario1; Right: Scenario3 – Scenario1.

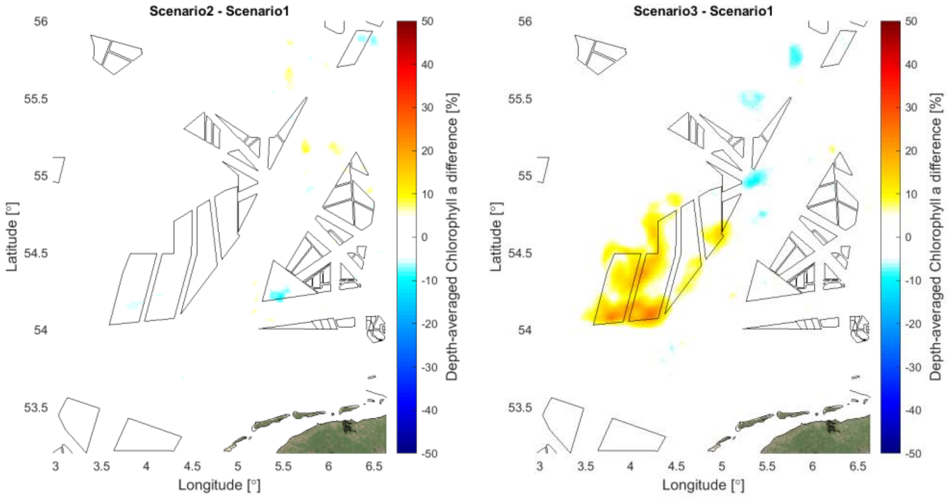


Figure 6.18 Relative difference in yearly average depth-averaged chlorophyll a concentrations between Scenarios 2-3 and Scenario 1. Left: Scenario2 – Scenario1; Right: Scenario3 – Scenario1.

6.3.3 Effect of an open space in Search Area 6/7

To look more specifically at the effect of leaving space for an open space in the centre of Search Area 6/7, Scenario 4 is compared to Scenario 1.
Such an open space seems to have a reducing effect with respect to local increases in primary production and chlorophyll a, compared to Scenario 1. Within the open space, phytoplankton primary production is locally decreased by ~15-20% in Scenario 4 compared to Scenario 1 (Figure 6.19). Primary production and Chlorophyll concentrations are still elevated in and around the search area 6/7, (Figure 6.22), but less so than in Scenario 1. Phytoplankton primary production increases locally at the most Eastern edge of the open space, in comparison to Scenario 1. This is most likely the result of reduced mud re-suspension within the open area. Chlorophyll a concentrations follow similar patterns (Figure 6.21 and Figure 6.23). Depth-averaged chlorophyll a concentrations decrease by ~5-20% within most of the open area with respect to Scenario 1, while these increase by 10-15% at its Eastern edge.

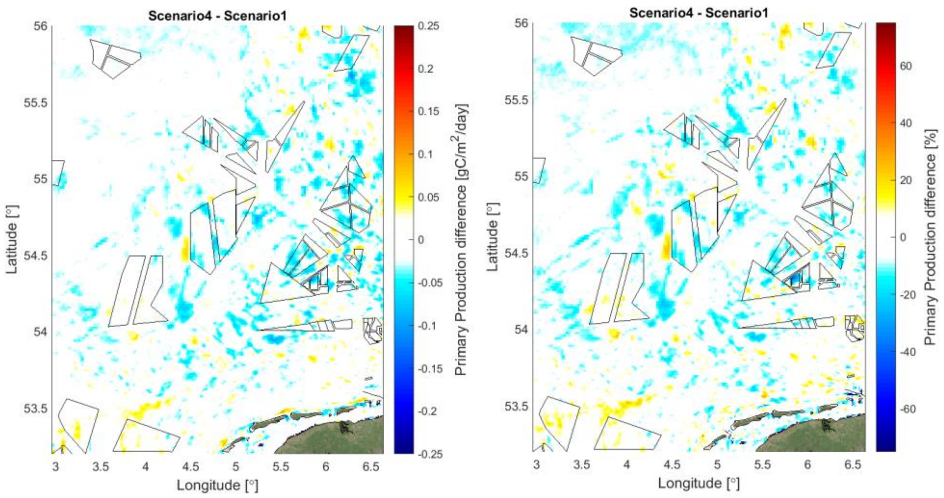


Figure 6.19 Difference in yearly average depth-integrated phytoplankton primary production between Scenario 4 and Scenario 1. Left: Absolute difference; Right: Relative difference.

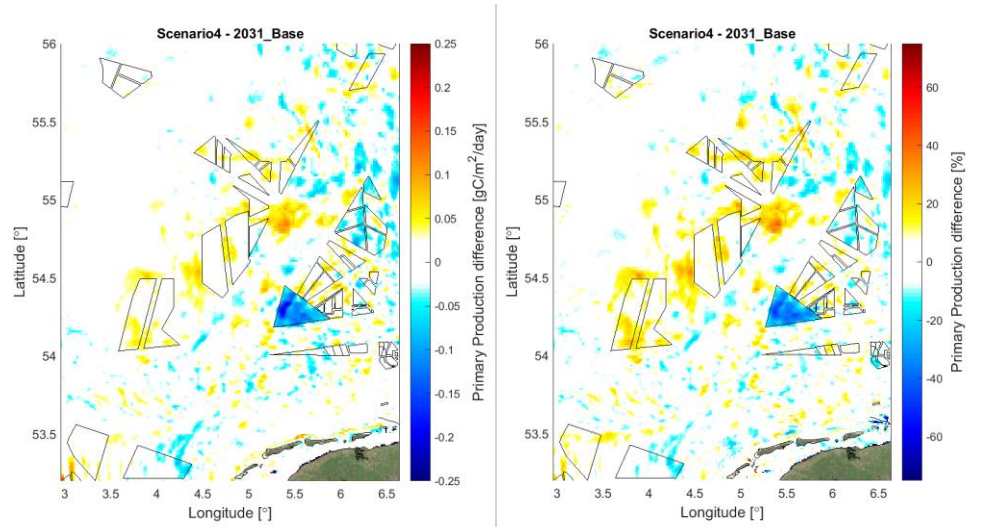


Figure 6.20 Difference in yearly average depth-integrated phytoplankton primary production between Scenario 4 and the Base situation (for reference). Left: Absolute difference; Right: Relative difference.

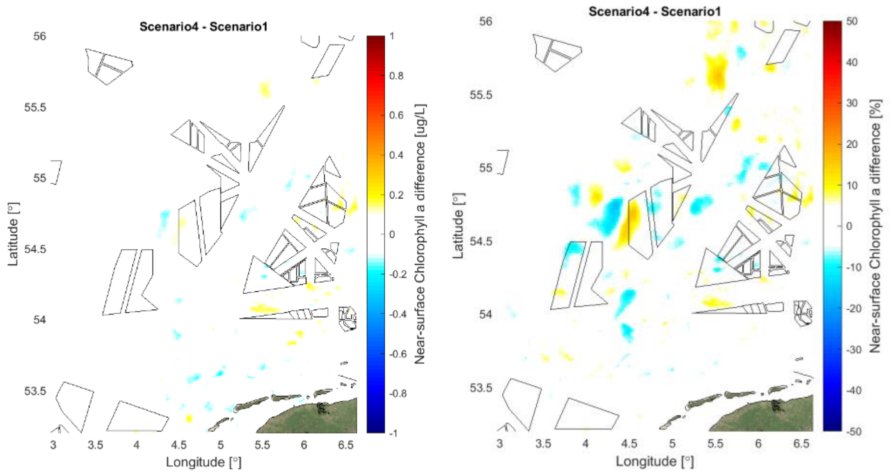


Figure 6.21 Difference in yearly average near-surface chlorophyll a concentrations between Scenario 4 and Scenario 1. Left: Absolute difference; Right: Relative difference.

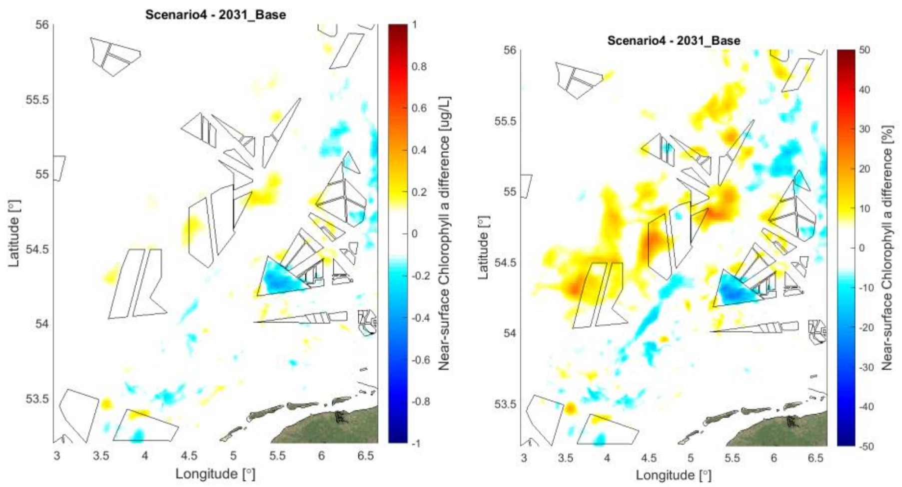


Figure 6.22 Difference in yearly average near-surface chlorophyll a concentrations between Scenario 4 and the Base situation (for reference). Left: Absolute difference; Right: Relative difference.

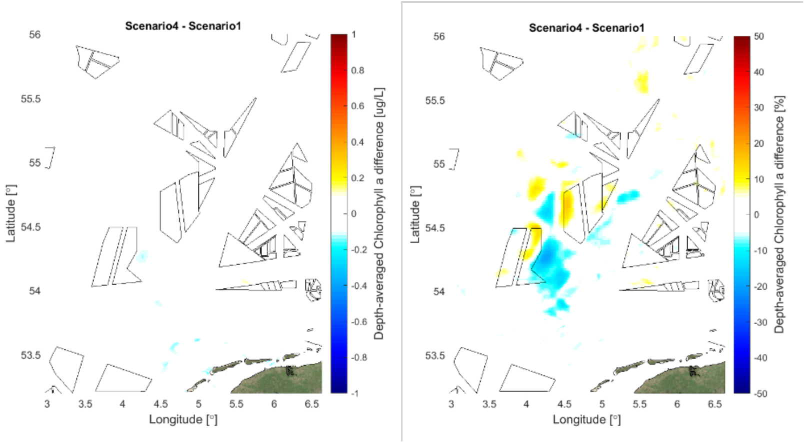


Figure 6.23 Difference in yearly average depth-averaged chlorophyll a concentrations between Scenario 4 and Scenario 1. Left: Absolute difference; Right: Relative difference.

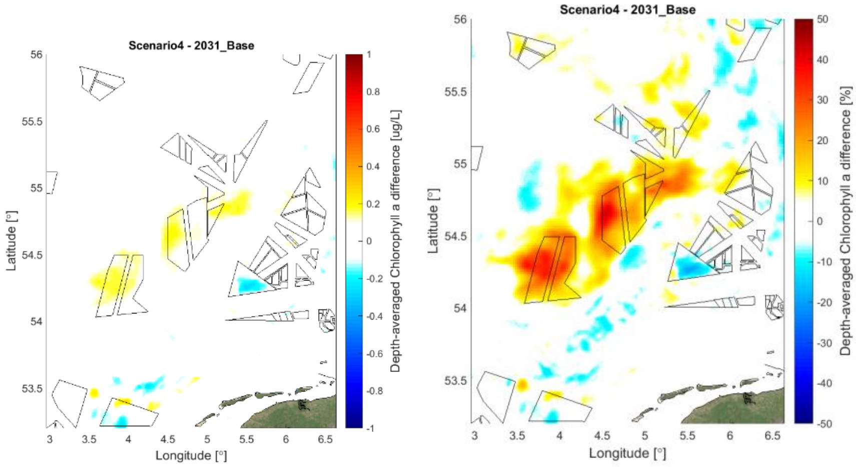


Figure 6.24 Difference in yearly average depth-averaged chlorophyll a concentrations between Scenario 4 and the base situation (for reference). Left: Absolute difference; Right: Relative difference.

6.4 Results on temporal dynamics

Scenarios 1-4 also have different effects on temporal dynamics of phytoplankton. Simulated time-series of near-surface chlorophyll a concentrations in different sections of Search Area 6/7 shows that the presence of OWFs in this area leads to a delay of the spring bloom compared to a situation without OWFs (Figure 6.25). This delay occurs in all scenarios. It is however clearly larger in Scenario 3, where the spring blooms occurs around half a month later than in a scenario without OWFs. This is probably due to a combination of drivers: the increased mixing of the water column leads to lower near-surface temperature in the early spring and lower light availability, delaying the occurrence of optimal conditions for phytoplankton growth. On the contrary, the presence of an open space in the centre of the Search Area 6/7 seems to reduce that effect. Simulated time-series are closer to the situation without OWFs compared to Scenarios 1-3.

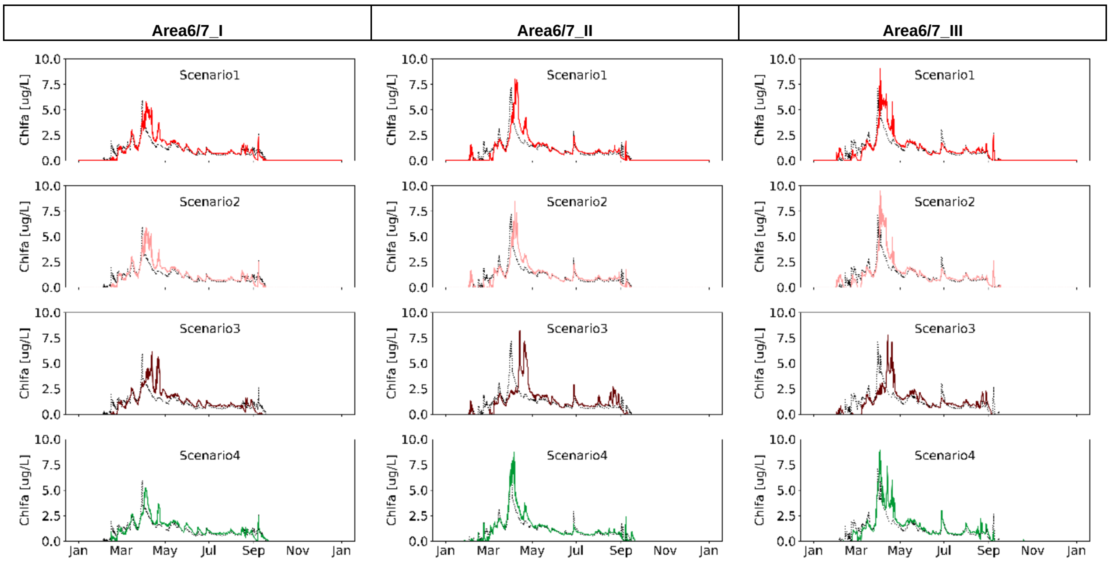


Figure 6.25 Simulated near-surface chlorophyll a concentrations in different sections of Search Area 6/7 for Scenarios 1-4 (full coloured lines). Black dotted lines represent results from the scenario without OWFs, for comparison.

6.5 Discussion and conclusions on water quality and primary production impacts

6.5.1 Base scenario (for KEC 2031)

Model results show that the presence of OWFs leads to a decrease in phytoplankton primary production in Borssele, Hollandse Kust Zuid and Doordewind, as well as in OWFs in the German Bight. Mostly, the effects of OWFs on chlorophyll a concentrations follow similar patterns. In some areas however, such as Doordewind, the presence of OWFs leads to an increase of chlorophyll a, while primary production decreases locally. Particularly in the base scenario, we observed increased chlorophyll concentrations, while primary production was reduced. The additional chlorophyll concentration appears to be consequence of the increase in phytoplankton types adapted to low light intensity and with a higher Chlorophyll a to carbon ratio. The presence of OWFs can also lead to changes in vertical gradients of chlorophyll a and temporal dynamics (timing of the spring bloom).

As we already saw in previous work, the increases in primary production due to changes in mixing can occur not only directly within the OWFs, but also downstream, where differences in stratification still occur. On the other hand, increases in suspended sediment concentrations/decreases in light availability are more limited to the OWFs themselves, which also translates into more localized effects on primary production.

6.5.2 Scenarios for partial revision

The reduced primary production, observed in the base scenario (reduction from roughly 0.4 gC/m^2/day to about 0.3gC/m^2/day), is for wind farm Doordewind reduced by a further 0.1-0.2 gC/m^2/day in the scenarios for the partial revision. This is due to the extension of the site and the increase in energy density. In this scenario we also see negative effects on primary production in the added Lagelander area but impacts there are less than in Doordewind. In Lagelander, the average decrease is about 0.03 gC/m^2/day. As can be seen in Appendix D, Lagelander contains very little mud in the seabed. This means that in that area there is little fine sediment available to be resuspended and reduce light availability. Additionally, Doordewind is situated in an area with a high number of neighbouring wind farms (German and Dutch) in very close vicinity. The combination of a larger mud content of the seabed and the interaction with other wind farms makes this area especially vulnerable to negative impacts on primary production.

On the contrary, simulated primary production increases in more offshore areas, the central / Southern North Sea, such as in Search area 6/7. In scenario 1 the increase varies within the wind farm, but is is more than 0.1 $gC/m^2/day$ over the most part of the farm (i.e. about a 20% increase, t.o.v. the base scenario. Model results show that the effects of changes in pillar sizes and density are smaller than those due to the presence of OWFs themselves. A higher energy production capacity within Search Area 6/7 with a higher density of pillars (Scenario 3) would, however, leads to a higher increase on primary production (about 0.01 $gC/m^2/day$ more than scenario 1, in the western part of the wind farm) and chlorophyll a concentrations (about 0.06 µg/l more than scenario 1) in the model. According to the model results, this higher density in turbines would also lead in that area to larger delays in the timing of the spring bloom than in other scenarios.
However, the presence of an open space in the centre of Search Area 6/7 would have mitigating effects. It would lead to smaller effects on primary production (and chlorophyll a concentrations within the open space and would reduce the differences in the timing of the spring bloom. In the open space, primary production is still increased, in comparison to the base scenario (by about 0.03 $gC/m^2/day$), but less than in scenario 1, where in the section where there is a gap in scenario 4 the increase is about 0.05 – 0.06 $gC/m^2/day$.

6.5.3 General discussion points

The water quality and ecology runs in this report do not include the effects of grazers growing on pillars (e.g. mussels). These grazers would most likely have little effects on primary production: even though grazers feed on primary producer biomass, they lead to additional re-mineralization, subsequently promoting extra growth of primary producers. The presence of grazers on pillars could however have local effects on chlorophyll a concentrations. According to preliminary results from Zijl et al. (2023), these effects are most likely smaller than those induced by changes in hydrodynamics and sediment dynamics simulated here.

7 General discussion and conclusions

7.1 Regional patterns in environmental effects of offshore wind farms

The current set of scenarios broadly give the same type of environmental effects due to the presence of offshore wind farms in the different regions as were identified in the previous studies (Van Duren et al. 2021, Van Kessel et al. 2022, Zijl et al. 2023b). These can be summarized as follows:

- Central North Sea: this area is deep, relatively far from shore and hence relatively low in nutrients. In this area summer stratification is slightly diminished to allow more nutrients in the upper layer increasing production, but not sufficiently diminished to allow SPM to penetrate in the top layer. Hence the net effect of OWFs in this area is an increase in primary productivity. The extra mixing by the wind turbines does delay the onset of stratification and hence the onset of the spring bloom. In this area the extra mixing also leads to lower temperatures in the upper water layers and lower temperatures in the bottom layer.
- German Bight: this area is characterised by intermittent temperature and salinity stratification. It is not deep and there is a substantial amount of fine sediment in the bed. Stratification is relatively easily diminished by storms. In this area the net effect of OWFs on primary production tends to be a decrease, due to the increase of SPM in the top of the water layer, reducing light availability. In this area German and Dutch wind farms are planned in close proximity and tend to influence each other strongly, as the wakes interact. In other areas where farms are not in close proximity impacts on e.g. SPM and primary production are more confined to the wind farm and immediate surroundings. In the German Bight we see impacts in a large part of the area, also beyond the wind farms.
- English coast and Wadden coast: these areas tend to be either fully mixed, or very limited in stratification. Most of these areas are very dynamic, which also means that the seabed is relatively poor in fine sediment content. The net effect on primary production a decrease, but less so than in the German Bight. This is due to increased SPM in the top layers, but due to the fact that the seabed is relatively low in fine sediment, this is less prominent than e.g. in the German Bight.
- Rhine region of freshwater influence: this area is permanently salinity stratified. As this area has high nutrient concentrations, originating from the Rhine, which are in the top layer, the extra mixing from the turbines in this area does not lead to higher productivity (if anything, it will reduce primary production, as high nutrient water is mixed down). The increase in fine sediment in the top layers leads to a decrease in primary productivity within the wind farms. Effects in this area tend to be confined to the immediate vicinity of the wind farms.
- Dogger bank: this area has limited and very intermittent stratification. It is shallow, so any stratification is quickly broken up by wind and waves. However, due to the fact that the sediment tends to be coarse, with little mud content in the seabed, any extra mixing from wind farms does not lead to more SPM in the top layer. In this area bottom-up ecosystem effects are limited.

7.2 Base scenario (for KEC 5.0)

7.2.1 Wind farms in the Holland Coast

The scenario for wind farms expected to be operational in 2031 shows relatively minor impacts in the Dutch EEZ with respect to temperature stratification. This is not surprising, since the majority of the wind farms are in areas that either are not stratified, or have limited, intermittent stratification. The wind farms in the Holland coast tend to be further apart, particularly in the main direction of the flow, than those in e.g. the German Bight. These areas have limited temperature stratification, and only some (mainly HKZ) have salinity stratification. Most of the Holland Coast area has a relatively low concentration of fine sediment in the seabed. Hence, although any extra sediment that is resuspended, will immediately impact the top layers, the concentration increases are not large here. Hence in the Holland Coast the direct impacts on primary production limited, particularly in search areas IJmuiden Ver, IJmuiden Ver Noord and the Nederwiek farms.

Earlier work (Van Kessel et al. 2022) indicated that the combined presence of all windfarms in the Southern part of the North Sea, does have some impact on the behaviour of the Rhine region of freshwater influence (ROFI), which does have an impact on the along shore transport of fine sediment. This was not the result of one single farm. So, there are still some far field effects, even in this region where the direct impacts on primary production are more isolated. To understand these processes fully, this would require more targeted research.

7.2.2 Wind farms in the German Bight

The scenario for wind farms expected to be operational in 2031 shows impacts on and effects of stratification changes in the OWFs in (or near) the German Bight (Gemini, TNW and Doordewind). Combined with the effect of the German wind farms that are planned before 2031 these ones have a marked effect on temperature stratification, on SPM in the top layer and on primary productivity. The impact in the German Bight is fairly widespread, while in the Holland coast, effects on SPM and on primary production are more confined to the wind farm locations.

It appears the decreases in primary production in the German Bight differ per wind farm. Some of these differences may be due to the fact that certain farms are older and turbines are closer together than assumed in the scenarios for future farms, but it also appears to be the case that the wind farms nearer the shore (i.e. in shallower parts) have larger effects. E.g. the Doordewind location appears to give markedly lower impacts on increased SPM in the top layer than the neighbouring German farms Deutsche Bucht, Veja Mate and BARD. These German farms are already operational and have 6 MW turbines, while the scenario for Doordewind has been run with 15 MW turbines.

However, it is also clear that the wind farms in the southern part of the German Bight (TNW, the GEMINI farms and the German ones, such as Borkum Riffgrund and the ones further to the east, have very pronounced effect, with reductions of over 60% in primary production. The older GEMINI farms have indeed smaller turbines and hence a much higher density of turbines, but the adjacent Borkum Riffgrund has 11 MW turbines and sees similar effects. This area is around 30 meters deep, while the more Northerly farms, such as Doordewind are about 40 meters deep. The smaller depth means that SPM from near-bed layers is easily mixed up to the top, where it reduced light penetration.

Finally the Wind farms in the German Bight appear to be in each other’s zone of influence with respect to impact on temperature stratification (e.g. see Figure 3.3) as well as sediment plumes in the growing season (Figure 5.14, top section).

7.3 Partial revision scenarios (in comparison to the base scenario)

7.3.1 Lagelander North area

Comparing scenarios 1-4 to the base scenario, the additional impact of the 2GW farm Lagelander Noord area is minor, considering the modelled parameters.

The area is not stratified (temperature or salinity), the sea bed contains in most of the area relatively little mud. In comparison to the base scenario, the primary production does not change in most parts of this area or at most shows very slight (<5%) decrease.

7.3.2 Doordewind area

In the four Partial Revision scenarios there is a clear impact of the additional 3.7 GW in Doordewind + Doordewind West on the SPM concentration in the upper layers and on primary production. The Doordewind West part has a slightly higher mud content in the seabed than the main Doordewind area. The combination of extending the area and increasing the density of turbines leads to an additional 50% decrease in primary production in this area in comparison to the base scenario. The reduction is from 0.4 gC/m^2 in the reference scenario to 0.3 gC/m^2 in the base scenario and then a further 30% (0.1 gC/m^2 reduction) in the Partial Revision scenarios. The Doordewind area is directly adjacent to German wind farms (some already operational, but many planned to be operational before 2045). In order to assess what impact can specifically be attributed to the Dutch farms and which are the combined effects might need some extra scenario runs to tease the effects apart. However, the physics of the area combined with the high density of German and Dutch wind farms mean that the German Bight part of the North Sea appears to be susceptible to substantial decreases of primary production. Particularly in this area, we see in the results some compensatory effects in primary production. Nutrients not being used inside areas with elevated SPM levels can boost productivity outside these areas, but this does not appear to be sufficient to compensate the reduction in primary productivity completely. Mass balance analyses on regional and subregional scales can give better insight in this.

7.3.3 Search area 6/7 variants

In general, in this area on primary production is increased. In this area there is clear summer stratification, which when reduced, is mixing more nutrients to the higher water levels, but due to the fact that stratification is not removed altogether, SPM is still confined to the lower water levels in summer, even though in winter SPM levels are clearly elevated in all scenarios. However, due to the fact that phytoplankton growth takes place in the summer half year, the net effect is in all scenarios an increase in productivity. Not only is production higher, but also the distribution of chlorophyll throughout the water column is more even, so availability of food for grazers near the bed is disproportionally higher. Near-bed layers increase from 0.2 µ/l in the base scenario to about 0.37 µ/l in scenario 1, while in the top layer both scenarios show concentrations around 0.75 µ/l (Scenario 1 only a few µ higher than the Base scenario.
In this area the spring bloom appears to be delayed, due to the fact that the onset of stratification is later and temperature in the upper layer is lower. The impact is most marked in scenario 3, with the highest density of turbines and the highest energy density.

Higher productivity is difficult to value in terms of positive or negative impact. More food near the seabed will offer more opportunities and higher growth rates for benthic species. However, all large impacts must be seen as risky. The size of the turbines (inversely relating to the density) appears to have some effect on mixing, stratification and hence on fine sediment. However, the differences between scenarios 1 and 2 (both with a similar total production capacity of 24 GW, only differing in turbine size (20 or 25 MW turbines) was relatively small, while the impacts in scenario 3 (smaller turbines, but a much higher total capacity of the wind farm) was much more pronounced. This appeared to be consistent with impacts on stratification, SPM and primary production. Search area 6/7 also directly borders German wind farms and within this area there are differences between impacts in the western part and the eastern part, that are likely associated with the fact that the area to the west is free from other wind farms.

The scenario that does appear to have less impact on SPM and particularly on stratification is the one with the open zone, scenario 4. Primary production is still increased in this area, but less so, than in Scenarios 1, 2 and 3. There is a slight reduction on both primary production and chlorophyll *a* levels in the central part of the wind farm at the location of the open space, in comparison to scenario 1. In the open space in scenario 4, primary production is still increased, in comparison to the base scenario (by about 0.03 gC/m^2), but less than in scenario 1, where in the section where there is a gap in scenario 4 the increase is about 0.05 – 0.06 gC/m^2. However, the effect is patchy and proportionally less than the impacts on stratification, which is likely the main driving force to boost productivity. In scenario 4 the delay in spring bloom is clearly less in the centra area, so that is also a mitigating impact of the open zone. Also, for this scenario mass balance analyses on a regional and subregional scale can give more insight in the importance of the different impacts.

8 Knowledge gaps and uncertainties

The ecosystem effects investigated in the Wozep project and assessed for a number of policy-relevant scenario in this report are assessed with numerical models. Such models are basically the only tool available to get an idea about effects of situations that currently do not exist and can therefore not yet be measured. However, numerical models are associated with uncertainties. The most important ones are highlighted below.

8.1 Validation data

The reference scenario is well validated with respect to patterns of stratification, patterns of SPM concentrations in the top layers and primary production. However, we still lack substantial validation of the modelled impacts of offshore wind on these parameters. Qualitatively the results match with observations in Germany (Floeter et al. 2017) and in the project “Effects of windfarms on the marine ecosystem, and implications for governance” (Hendriks et al. 2024). However, we lack validation data for areas that are seasonally stratified, since there are currently no wind farms present there.
Gradually there are more data becoming available. In follow-up projects (either Wozep or the recently submitted NWA proposal No-Regrets) it will be important to substantiate various aspects of the model much better. For the physical impacts of the monopiles on the water movement there are some measurements and also CFD models that can be used. At present we particularly lack data on primary production.

8.2 Wind

In the current model we include a reduction of 10% of wind speeds inside the wind farms, but depending on atmospheric stability the wakes behind wind farms can reach many tens of kilometres (Hasager et al. 2015, Boon et al. 2018), which can affect the wave field and hence resuspension. In a Wozep study we analysed the relative importance of these wind wakes relative to the impacts of tidal current interaction with turbine monopiles. That study indicated that instantaneous effects can be large, but annual averaged effects are moderate in comparison to the enhanced mixing from tidal current interaction (Zijl and Leummens 2023). However, the subsequent impact on primary production still has to be assessed. Particularly in areas with interactive effects between wind farms (such as in the German Bight), this may be important. We are also aware that within wind farms lower turbines and a higher density will also impact the wind speed within a wind farm. The 10% reduction currently taken for all wind farms should also be evaluated and possibly be made dependent on turbine design and lay-out.

8.3 Grazers

In the modelling suite used in this study there is mortality of phytoplankton, which is determined by calibrating the reference scenario model, based on observations. In reality there will be feedback processes from pelagic and benthic grazers (zooplankton and zoobenthos) on phytoplankton. The first modelling results in Wozep from a suite including observed biomasses of mussels on the wind farm turbines (Van Kessel et al. 2022, Zijl et al. 2023b) indicate that this predominantly has effects on the biomass of phytoplankton (i.e. on the chlorophyll concentration). Impacts on primary production were relatively low. Grazers reduce the standing stock of phytoplankton (for which chlorophyll concentrations are a good proxy). In areas with high grazer concentrations, there can also be feedback impacts on productivity due to the faster remineralisation of faecal material (Troost et al. 2010, Troost 2011). The same was true for the first modelling efforts on including dynamic grazing pressure of zooplankton (Rienstra 2023). However, the latter study only considered 1D column models (where environmental conditions from the 3D Wozep model we used as boundary conditions) and this was done with Dynamic Energy Budget model parameters from a copepod species that is not typical for the North Sea. Future Wozep work on the impacts on grazers as well as the grazer impacts on primary production and on chlorophyll concentrations should shed more light on these impacts.

8.4 Impacts on higher trophic levels

This study only assesses the impacts on primary production. The framework for cumulative ecological impacts, predominantly assesses whether impacts are within acceptable limits based on the impact on species with targets under Natura 2000. These are all apex predators such as birds, marine mammals and some iconic fish species such as sharks and rays. On a large scale there are obviously links between e.g. primary production and fish (Chassot et al. 2010, Capuzzo et al. 2018), but with the current level of knowledge and the currently available models it is not yet possible to translate any impacts at the base of the food web on target species such as harbour porpoises, kittiwakes or gannets. Internationally there are programmes running such as PELaGIO (https://ecowind.uk/projects/pelagio/) where changes in physical forcing and food web structure and their consequences for higher trophic levels are researched. However, all this work is still very much in its infancy.

8.5 Interaction with other human impacts.

In this study only the impacts of offshore wind on the ecosystem are studied. The presence of offshore wind will also impact other human activities, such as the location of high fishing intensities (Dunkley and Solandt 2022). The modelling suite is calibrated on a situation with limited presence of wind farms. So lack of bottom trawling within the wind farms, or increased fishing in certain areas outside wind farms, is not taken into account. For most areas this is probably a limited impact, as the Holland coast area is relatively sandy and bottom trawling frequencies in most areas are limited to once or twice a year. This might still impact the composition of benthic biota but will have limited impact on e.g. fine sediment concentrations in the water column. For changes (reductions or concentrations) in bed disturbance in and around Search area 6/7 the net impact may be larger, due to the fact that this area has little natural bed mobility and has in certain areas an elevated amount of fine sediment in the seabed.

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A Wind farms and search areas

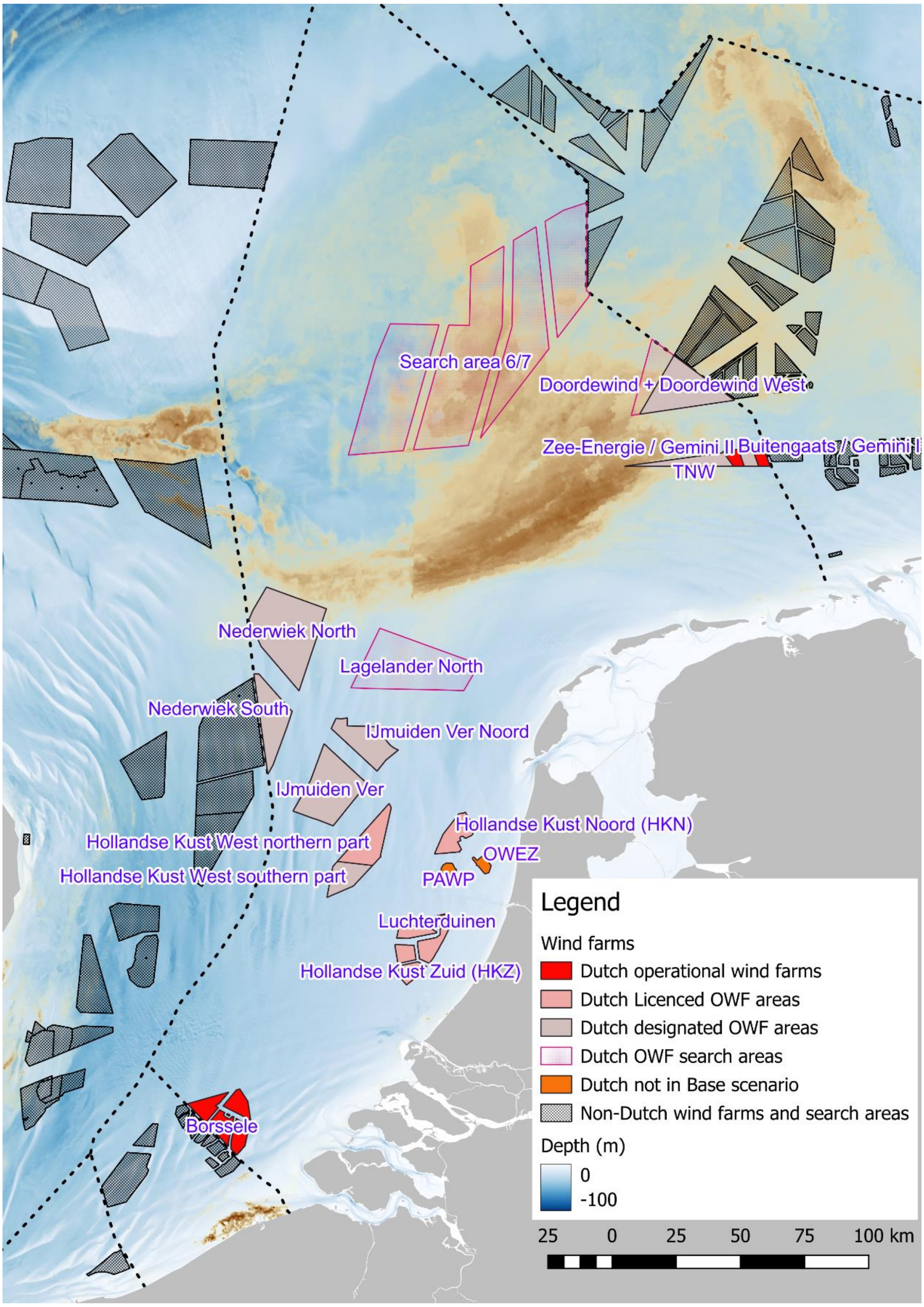

Figure 9.1 Wind farms and search areas with names.

B Regional differences in the North Sea in impact of offshore wind.

Earlier work (Van Duren et al. 2021), identified a number of different impact regions in the North Sea, where the effect of offshore wind on primary production differed
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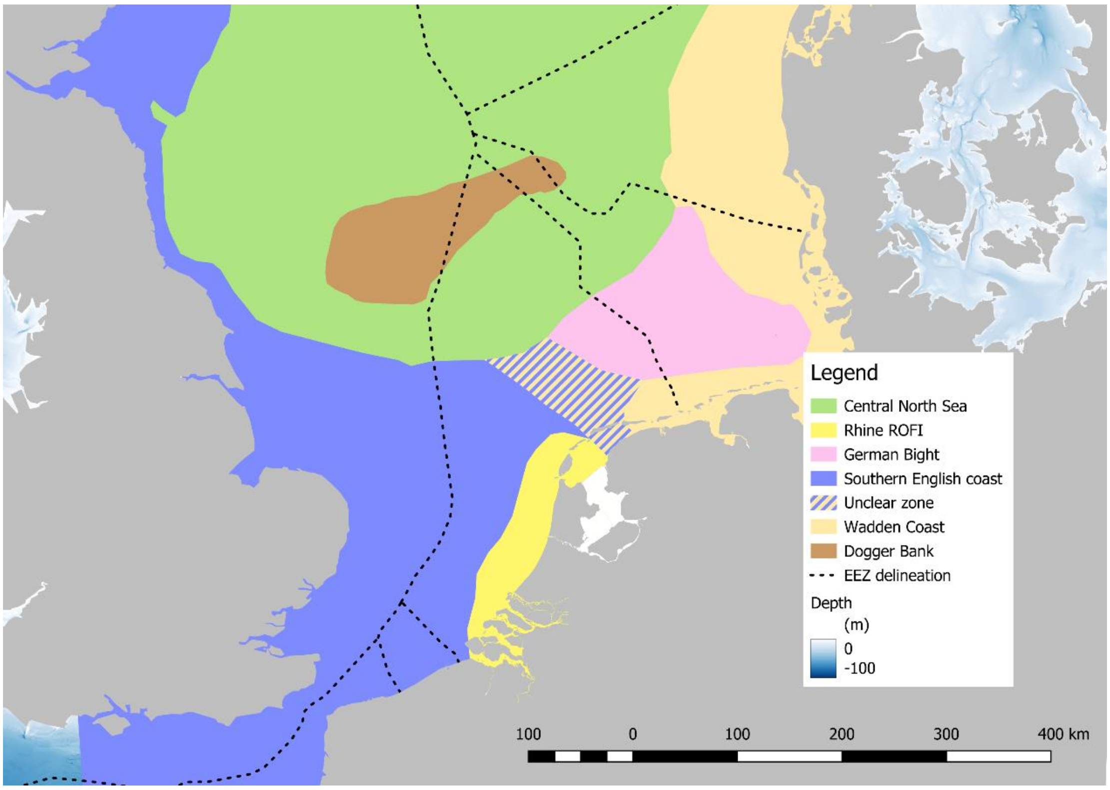

Figure 9.2 the effect areas identified in earlier Wozep studies.

B.1 Central North Sea

This area is intermittently to seasonally stratified due to temperature. Enhanced mixing in the wind farms has the effect to weaken stratification and enhance vertical exchange of heat, SPM and nutrients. SPM concentrations in the upper layer are elevated in winter, but when stratification sets in, SPM is confined to near-bed layers. This area tends to see an increase in primary production and a delay in the onset of the spring bloom.

B.2 Rhine ROFI

This is an area with high nutrient availability and without temperature stratification, but some salinity stratification. It is a highly dynamic area with strong tidal currents. In this area primary production is more light-limited than nutrient-limited. Nutrient availability in upper layers is high due to riverine input. The net effect is that higher fine sediment concentrations in the upper layers decrease primary production, but increased mixing does not enhance productivity. The changes in mixing in this area (in horizontal and vertical direction) are likely to have some effect on the transport of fine sediment along the Dutch coast and towards the Wadden Sea.

B.3 German Bight

This area is characterised by frequent but not very strong stratification. Temperature stratification is dominant, but also salinity plays a role here. The model runs (Zijl et al. 2023) suggest that SPM effects tend to be dominant in this area. Leading on average to a suppression of primary production in and around wind farms. Due to the high density of planned wind farms in the German and Dutch part, effects of wind farms tend to interact and effects on primary production can extend well beyond wind farm perimeters.

B.4 Southern English coast and western part of the Dutch Continental Shelf and the German and Danish Wadden coast

These are the areas that are fully mixed or nearly always fully missed. Changes in stratification do not occur here, depending on the amount of fine sediment in the seabed. The main effect of windfarms is the increase in turbidity in the top layers of the water column. In some parts, e.g. close to the Thames estuary, the system without wind farms is extremely turbid and hence very low in productivity. In absolute terms, any increase in SPM in the top layers does not decrease productivity much further, although in relative terms the decrease may be large. In all other areas, increased turbidity due to wind farms reduces production. In Van Duren et al (2021) an unclear are was identified between the western part of the DCP and the Wadden Coast. As mixing regimes and depth are similar to the two former areas we assume this area would respond in the same way. As we have not had any wind farms in that area, that has not been tested.

B.5 Dogger Bank

This is an isolated shallow area surrounded by deep seasonally stratified waters. It has a unique composition of ecological communities. The Dogger Bank is has some areas that occasionally have some intermittent (not very strong) temperature stratification, other parts are nearly always fully mixed. The bed consists predominantly of medium sand and coarse-grained material, so even though waves easily reach the bed, resuspension of fine sediment from the bed is limited. The resulting effects of offshore wind farms on the Dogger Bank on primary production are limited.

C Model validation, hydrodynamics

C.1 Water levels

The quality of the water level representation in the year 2014 has been determined in terms of the root-mean-square error (RMSE) and presented in Table 9.1. For these Dutch coastal stations, the average total water level RMSE is 6.9 cm. This result is significantly better than that of the previous generation 3D ZUNO-DD model of the southern North Sea (25.6 cm) and due to improvements in both tide and surge.

Table 9.1 Comparison of water level representation (RMSE, determined for 08-01-2014 to 01-01-2015) between ZUNO-DD and 3D DCSM-FM (0.5 nm), for tide, surge and total water level signal.

Station	RMSE tide (cm)			RMSE surge (cm)			RMSE water level (cm)		
	ZUNO-DD	0.5nm	%	ZUNO-DD	0.5nm	%	ZUNO-DD	0.5nm	%
Cadzand	30.5	5.0	-84%	13.1	4.2	-68%	33.2	6.6	-80%
Westkapelle	27.0	5.8	-79%	12.7	4.1	-68%	29.9	7.1	-76%
Haringvliet 10	21.1	4.5	-79%	11.9	4.5	-62%	24.3	6.3	-74%
Hoek van Holland	17.1	5.4	-68%	11.8	4.9	-58%	20.7	7.3	-65%
Scheveningen	19.5	4.9	-75%	12.0	4.6	-62%	22.9	6.7	-71%
IJmuiden Buitenhaven	18.7	5.7	-70%	12.2	5.0	-59%	22.4	7.6	-66%
Average	22.3	5.2	-77%	12.3	4.6	-63%	25.6	6.9	-73%

C.2 Temperature (stratification)

A comparison of the observed and modelled sea surface temperature shows an average RMSE of around 0.4 – 0.5 °C in the southern North Sea. The results for offshore measurement location Europlatform are shown in Figure 9.3. Crucially, the model shows a good representation of inter-annual variation in seasonal temperature stratification (cf. Figure 9.4). This variation is of importance to correctly predict oxygen profiles in subsequent water quality simulations.

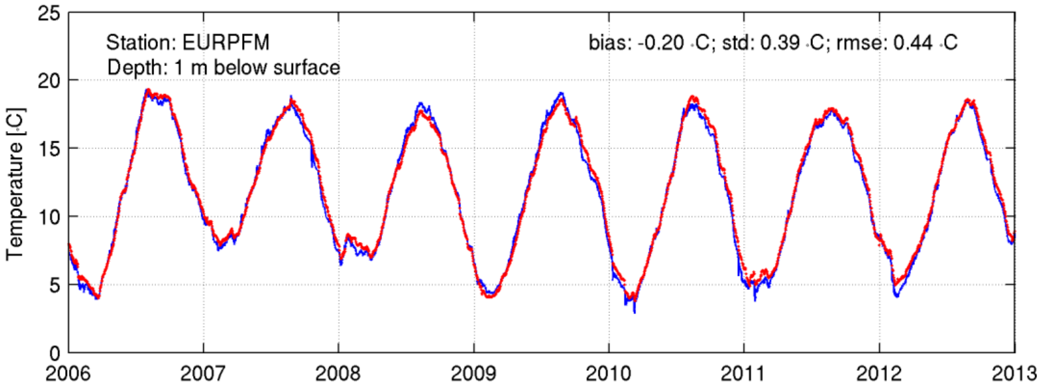

Figure 9.3 Time series of measured (red) and modelled (blue) surface temperature at offshore measurement location Europlatform.

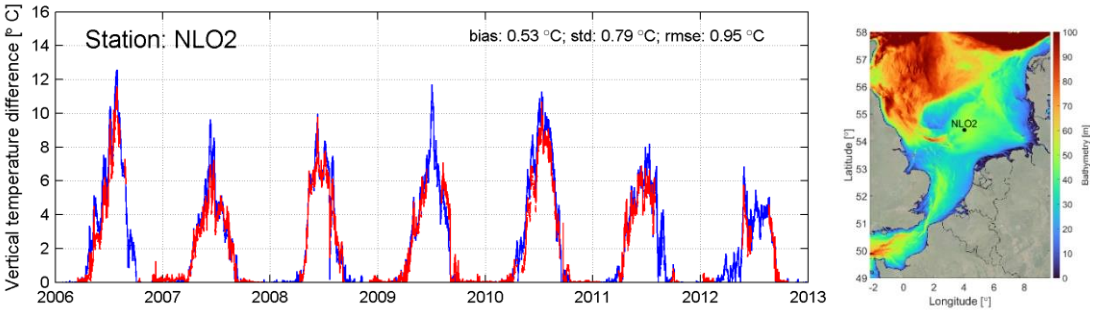

Figure 9.4 Time series of measured (red) and modelled (blue) vertical stratification at station NL02.

C.3 Residual transport through the English Channel

In the previous generation 3D ZUNO-DD model, tilting of the southern boundary was needed to achieve a correct representation of residual transport through the English Channel. 3D DCSM-FM has a much larger model domain and thus there is no open boundary in the English Channel. This results in a good representation of this residual transport without the need to artificially adjust the open boundaries, due to a better representation of mainly barotropic phenomena. Model results show a considerable inter-annual variation in residual transport (cf. Figure 9.5).

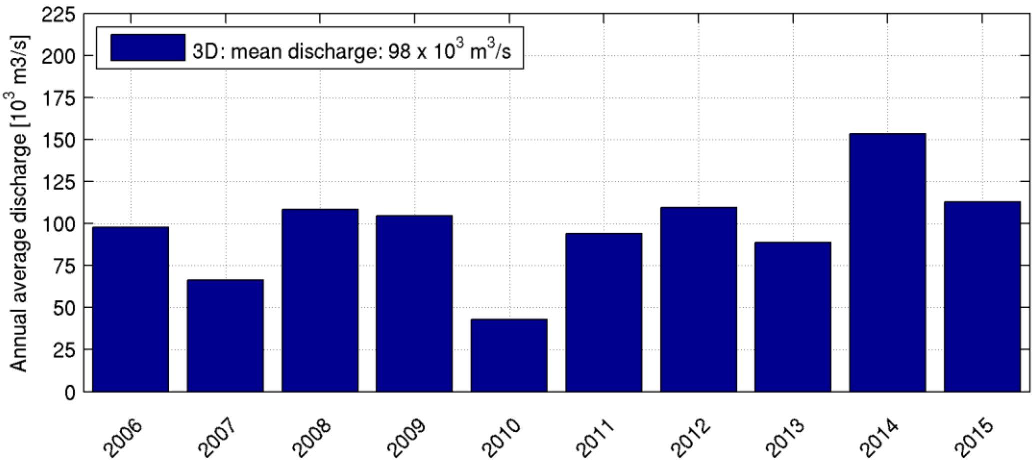

Figure 9.5 Annual average discharge through the English Channel computed with 3D DCSM-FM.

D Verification of mud content in Search Area 6/7

The model has been verified to capture the strong variation in mud content in the bed near the Oyster grounds in Search Area 6/7. This is an important precondition to assess the effects of the different OWF scenarios that have different layouts in this search area, particularly the impact of the open space in the centre of this area (in Scenario 4). This open space coincides with the muddiest part of Search Area 6/7.

It is found that the model captures the strong variation in mud content in the bed near the Oyster grounds in Search Area 6/7. This is shown in Figure 5.9 where two different OWF layouts are projected on the modelled mud content in the reference scenario (without wind farms). In agreement with Stephens (2015), the Oyster grounds (i.e. the open corridor in Scenario 4) hold a higher mud content compared to the surrounding area. This sets the way to assess the effects of different wind farm layouts in Search Area 6/7 on the mud content and turbidity.

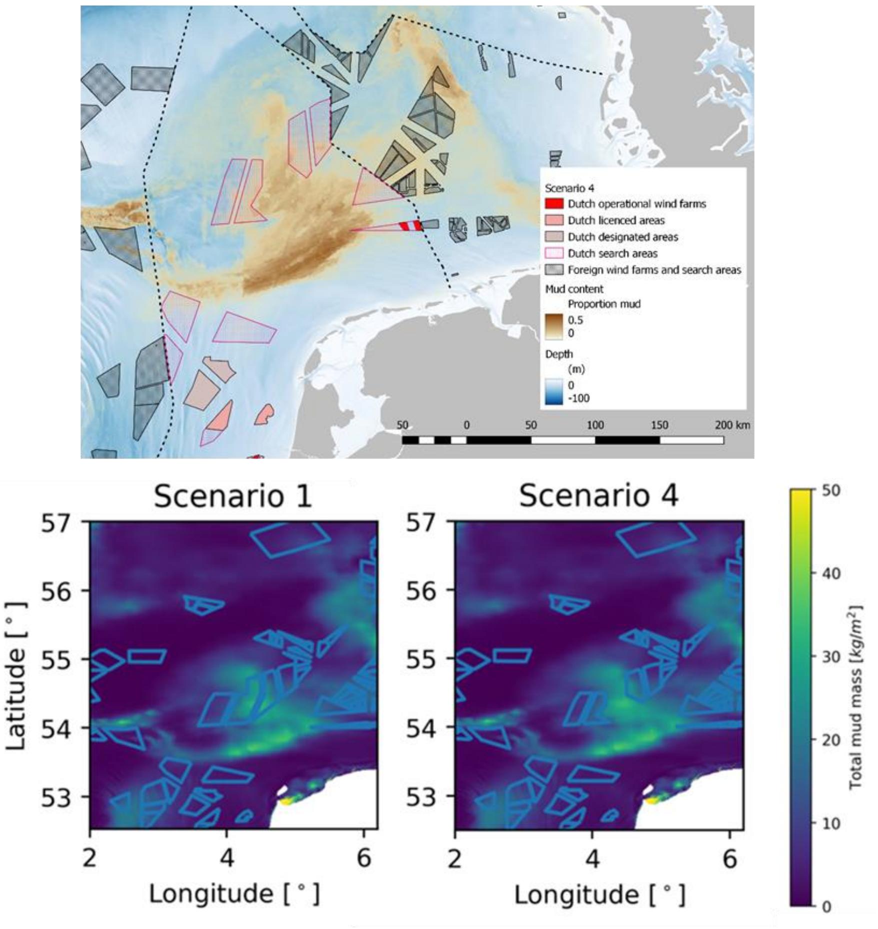

Figure 9.6 Mud distribution in the seabed based Stephens (2015) (top panel) and model results (bottom row). In agreement with field observations, the modelled reference scenario contains a high mud content in the potentially open space in Search Area 6/7 designated for ecological or fishing purposes. Background colour in the bottom panels indicates the modelled mud mass in the bed [kg/m^2] without the effect of wind farms accounted for. Yellow shades indicate muddy areas. The left panel shows that in Scenario 1, wind farms would be constructed in this muddy area known as the Oyster grounds. The right panel shows that this muddy area would largely be left open in Scenario 4.

E Impact on base of the food web of Scenarios 1-4 to in comparison to the reference situation (without OWFs)

Compared to the situation without OWFs, Scenarios 1-4 lead to similar overall changes in terms of primary production over the Southern North Sea, with, as expected, slight differences around Search Area 6/7 (Figure 9.7). Therefore, only results for Scenario 1 are shown in the rest of this section and section 6.3.1. More local differences, linked to the different set-ups in Search Area 6/7 are discussed more in detail in subsections 6.3.2 and 6.3.3.

The presence of OWFs leads to a decrease in yearly average phytoplankton primary production directly within the most nearshore OWFs along the Southern Dutch coast (e.g. Borssele and Hollandse Kust Zuid), with relative differences up to more than 60% within Borssele and 20% in Hollandse Kust Zuid (Figure 9.7 and Figure 9.8). In these areas, the water column is well-mixed and the presence of OWFs leads to a decrease in light availability. Sharp decreases in phytoplankton primary production, up to more than 60%, are also simulated in the German Bight, where light availability is reduced due to increased re-suspension of fine sediments. Phytoplankton primary production increases within and especially east from Search Area 6/7 and west from Doordewind and German OWFs (downstream from Search Area 6/7 in the direction of the residual currents). These increases, due to reduced stratification and thus higher nutrient availability closer to the water surface, reach up to 40-50% east from Search Area 6/7 compared to the scenario without OWFs.

Effects of OWFs on chlorophyll a concentrations overall show similar patterns as those for phytoplankton primary production, except in Doordewind and the most offshore German OWFs (Figure 9.9 and Figure 9.10). While chlorophyll *a* concentrations decrease due to the presence of OWFs in the most nearshore parks in the German Bight (by up to ~40% near the surface and ~25% for depth-averaged concentrations), it clearly increases in Search Area 6/7 and more east, in all most offshore German OWFs (up to ~40%). It is possible that again we are dealing with the same phenomenon as described in section 6.2.2. The reduced light availability leads to more chlorophyll per unit biomass. So, although chlorophyll has increased, this does not mean that biomass has increased.

As observed in 6.3.1, in Search Area 6/7 and more east, increases in chlorophyll a concentrations are sharper when looking at depth-averaged concentrations than at near-surface concentrations since the maximum chlorophyll a concentrations occur in the subsurface (~10-15 m depth) and the additional produced biomass is vertically transported deeper in the water column.

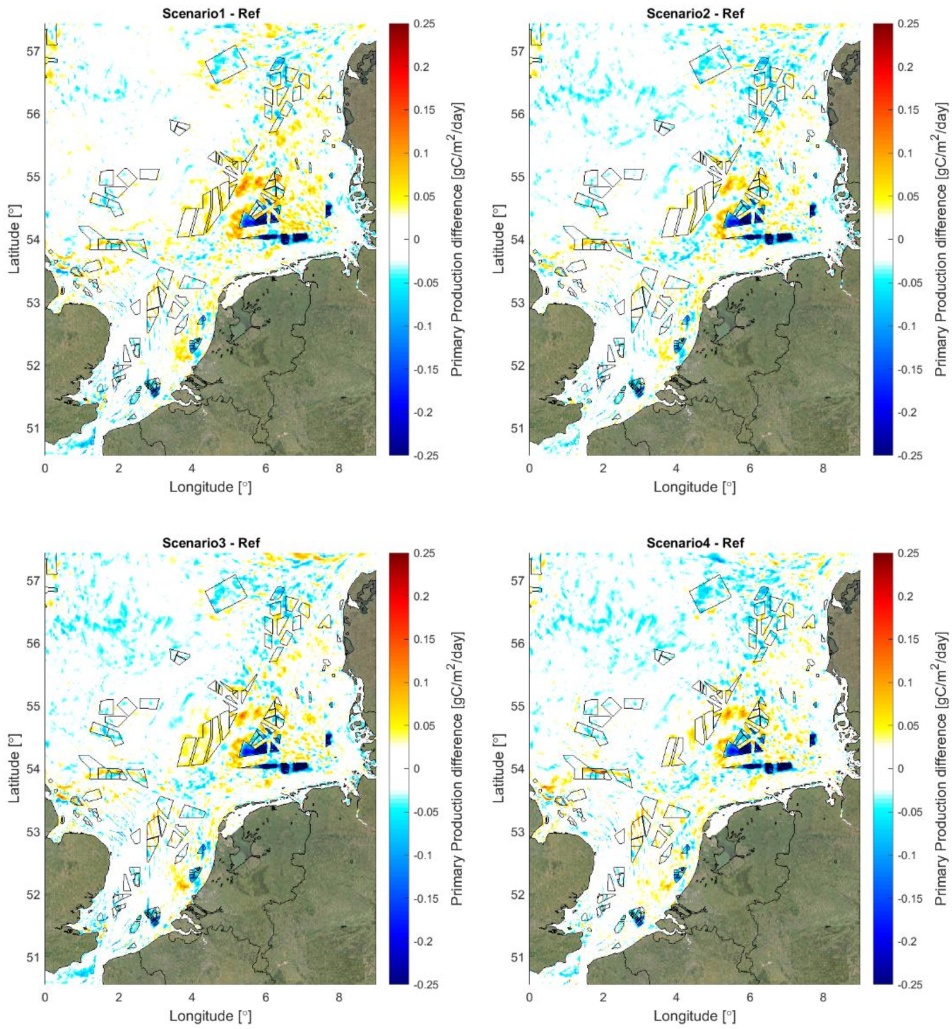

Figure 9.7 Absolute difference in yearly average depth-integrated phytoplankton primary production between Scenarios 1-4 and the reference scenario (without OWFs).

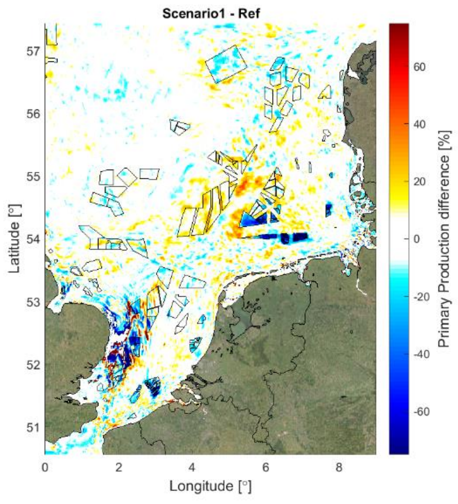

Figure 9.8 Relative difference in yearly average depth-integrated phytoplankton primary production between Scenario 1 and the reference scenario (without OWFs).

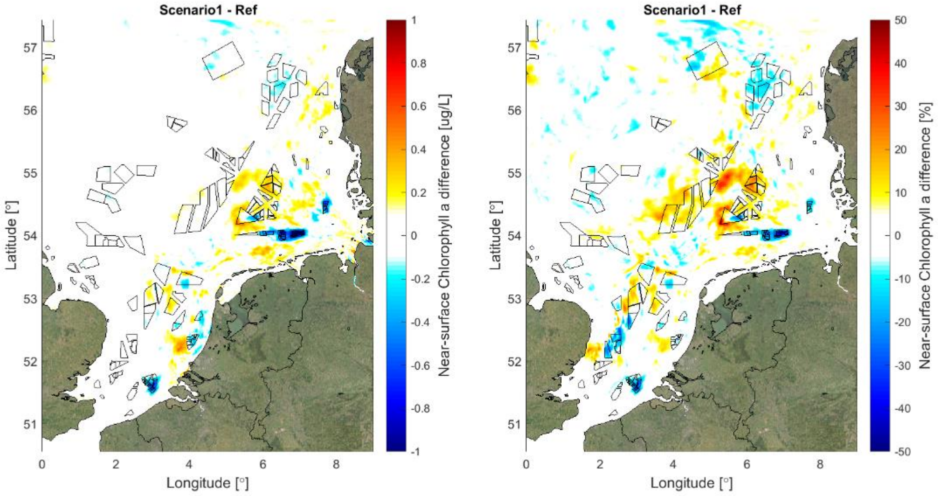

Figure 9.9 Difference in yearly average near-surface chlorophyll a concentrations between Scenario 1 and the reference scenario (without OWFs). Left: Absolute difference; Right: Relative difference.

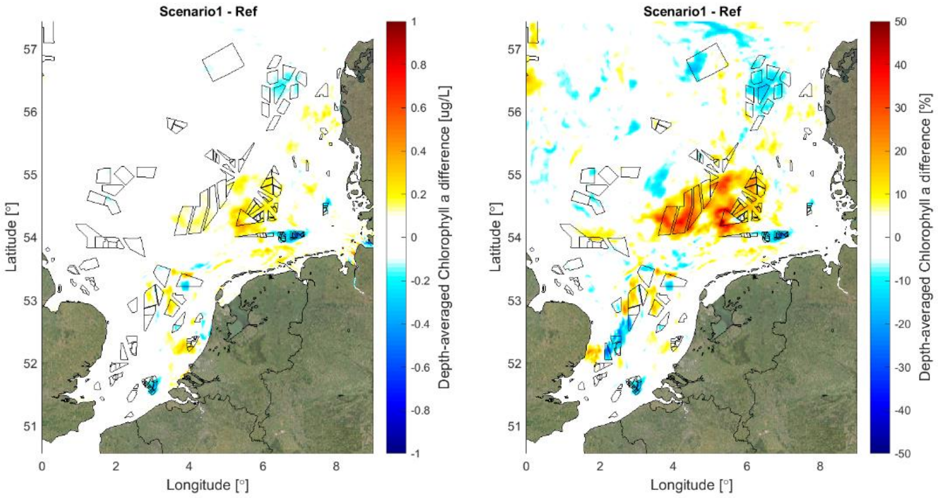

Figure 9.10 Difference in yearly average depth-averaged chlorophyll a concentrations between Scenario 1 and the reference scenario (without OWFs). Left: Absolute difference; Right: Relative difference.

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