PRELIMINARY

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Effects of large-scale offshore wind development on trophic transfer pathways in the marine food web

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Client	Rijkswaterstaat Water, Verkeer en Leefomgeving
Contact	Edwin Verduin
Reference	
Keywords	Offshore wind; Ecosystem effects; Wozep; benthos; zooplankton

Document control	
Version	0.3
Date	19-12-2024
Project nr.	11210347-005
Document ID	11210347-005-ZKS-0001
Pages	40
Classification	
Status	preliminary This is a preliminary report, intended for discussion purposes only. No part of this report may be relied upon by either principal or third parties.

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Summary

The large-scale development of offshore wind farms (OWFs) in the North Sea affect the marine environment. OWFs decrease stratification and increase vertical exchange of nutrients and suspended matter (SPM), which subsequently affects primary productivity. This has been shown through multiple studies including the work done for Wozep. To what extent the combined effects of these hydrodynamic processes lead to an increase or decrease of primary productivity depends on the location of the OWFs. The changes in primary production can potentially propagate through the food chain impacting zooplankton and benthic grazers, the primary consumers of phytoplankton. At the same time, OWF pillars provide hard substrate for growth of benthic grazers, such as mussels. This introduces benthic grazers to the upper water parts of the water column, where primary production is highest. This could lead to shifts in competition between benthic grazers (mussels) and pelagic grazers (zooplankton). As carbon transferred via benthic or pelagic pathways end up with different apex predators, such shifts may be relevant for species with specific conservation targets.

To assess the impact of OWFs on the carbon transfer via benthic and pelagic pathways, the modelling of zooplankton and mussels still requires some technical improvements. Thus, this study focusses on the technical improvements of the primary grazers: zooplankton and mussels .

A new set of DEB parameters was implemented to model the growth of *Calanus finmarchicus*, a common zooplankton species in the North Sea. This new set of parameters was tested and validated within a 1D-V column model. Subsequent 3D model runs in DCSM-FM, yielded unexpected effects. Therefore, the potential causes for these results were assessed by comparing the DCSM-FM model with a previous North Sea model in which zooplankton was successfully simulated. It was concluded that the low phytoplankton biomass in winter is the most likely cause of the limited zooplankton growth in DCSM-FM. However, the distribution of zooplankton did seem to follow the spatial patterns of primary productivity. Lastly, the effects of OWF on zooplankton dynamics were assessed qualitatively.

With respect to benthic productivity, the DEB parameter set for mussels was updated. To assess whether mussels only grow in the upper layers of the water column because of better growth conditions in the top layers of due to higher mortality in the deeper layers, an in-situ data analysis of mussel of offshore structures was conducted as well as a column model exercise in which mussels were initialized over the whole water column. The in-situ data analysis showed that mussels do indeed occur mainly in the upper layers of the water column. The modelling exercise showed that mussels can grow over the whole water column. However, their peak biomass does occur in the upper water layers. Thus, it can be tentatively concluded that predation/competition contributes to the depth distribution of mussels.

The ultimate goal is to model zooplankton and mussel dynamics in competition. Although this is technically possible, the reliability of the model results for both zooplankton and mussels are not sufficient at this stage. To address this issue, the following steps for the next year are recommended:

To improve the zooplankton modelling, we recommend to:
1. Validate the modelled phytoplankton biomass in winter to test the hypothesis whether the phytoplankton biomass is currently underestimated in the 3D DCSM model.
2. Induce a diapause in zooplankton when food reaches critically low levels and include a density dependent mortality rate.

3. Simulate zooplankton dynamics in DCSM-FM and validate against in-situ data.

To improve the mussel modelling, we recommend to:
1. Compare in-situ and modelled phytoplankton depth profiles.
2. Should those depth profiles align, then implement depth dependent grazer mortality for mussels within a 1D-V column model.
3. Test the new parameter setting for different offshore locations.

After those steps are completed, a coupled hydrodynamic-water quality model including zooplankton and mussels can be run to investigate the competition effects between mussels and zooplankton within OWFs.

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1 General introduction

1.1 Background

The rapid expansion of offshore wind farms (OWFs) in the North Sea will impact the North Sea seascape and environment. However, the effects of OWFs, and their scale and severity, on marine ecosystems are not yet sufficiently understood (Galparsoro et al., 2022). Wozep (the *Wind Op Zee Ecologisch Programma*) is an integrated research programme to reduce the knowledge gaps regarding the possible negative environmental effects of offshore wind farms on the North Sea.

The current report builds on previous work published on the bottom-up ecosystem effects, investigating the impacts of OWFs on physics and lower trophic levels (Van Duren et al., 2021; Zijl et al., 2023). Within these studies, the 3D DCSM-FM model with fine sediment and water quality and ecology was applied. The studies described that that large-scale development of OWFs will induce mixing and resuspension, which alters stratification regimes and suspended matter (SPM) concentrations. The previous work has highlighted that this affects primary productivity, but the impacts differ in sign and severity per location.

Changes in primary productivity can propagate through the marine food web. Primary productivity can be defined as the biomass growth of primary producers, i.e. benthic and pelagic phytoplankton and aquatic plants. Phytoplankton serves as a food source for both benthic and pelagic grazers, which are subsequently consumed by organisms at higher trophic levels. Grazing may reduce primary production but can also increase it, when part of the nutrients and carbon taken up by grazers are recycled within the marine environment (Tarrant, 2020).

1.2 Impacts on secondary producers

Pelagic grazers (zooplankton) play a crucial role in the transferring energy toward higher trophic levels in the North Sea and other marine ecosystems (Mortelmans et al., 2021; Van Ginderdeuren, 2013). Zooplankton, dependent on phytoplankton as their food source, reacts to changes in timing and amount of phytoplankton. Zooplankton is considered one of the main food sources for fish and their larvae and thereby fulfil a major role in the pelagic transfer of carbon to higher trophic levels. The effects of OWFs on zooplankton have not yet been investigated within the previous Wozep studies.

Benthic grazers benefit from newly introduced hard substrate by turbines and platforms. (Slavik et al., 2019). In their 2021 synthesis publication, Degraer and colleagues (2020) reviewed how offshore wind farms function as artificial reefs. Figure 1.1, taken from their publication (Degraer et al., 2020),visualizes the distribution of biofouling communities over the water column with mussels, macroalgal and barnacles dominating the shallow subtidal zone and filter-feeding arthropods (mainly the suspension feeder *Jassa herdmani*) and anemones the deep subtidal zone. Degraer and colleagues note that there is only one long time study of biofouling on offshore wind farms available in which three distinct succession stages were identified. In the final stage (6+ years), blue mussel (*Mytilus edulis)* and plumose anemones (*Metridium senile*) co-dominate the offshore wind farm pillar (Kerckhof et al., 2019). This corresponds well with biofouling research on oil and gas platform in which mussel and anemones dominate also in deeper areas of water column (15-50 m) (Coolen et al., 2020). Blue mussels have also been found in soft sediment near turbines . In one of the recent Wozep publications Zijl et al., (2023) have shown the potential for mussels (*Mytilus edulis*) to grow within OWFs.

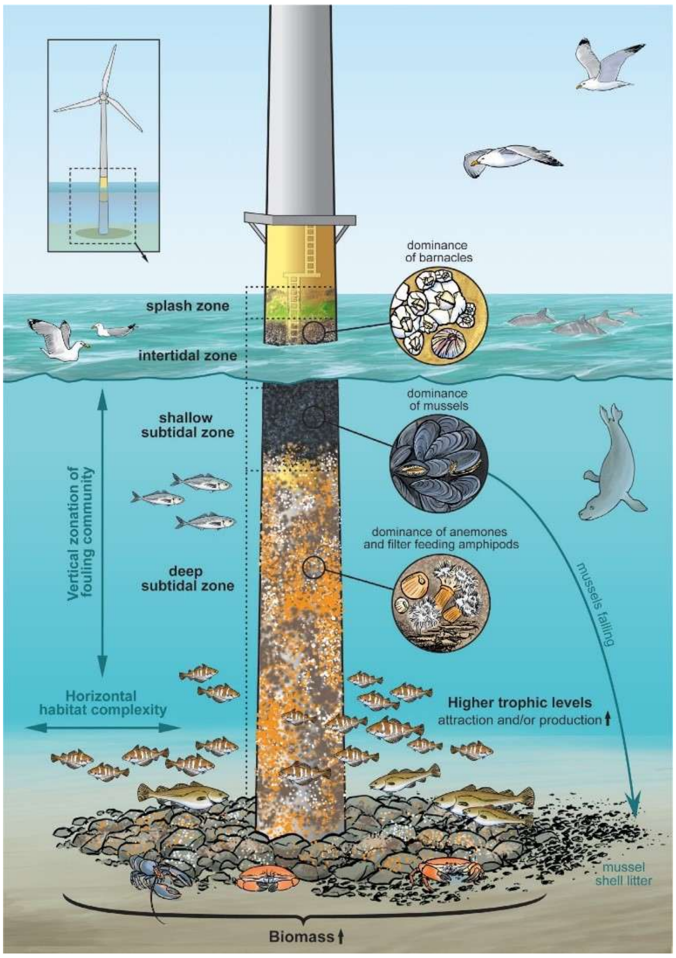

Figure 1.1: Visualization of the depth distribution of biofouling on OWF. From (Degraer et al., 2020).

The introduction of hard substrate by turbines facilitates the colonization of benthic grazer in upper water layers, where the primary productivity is highest. Under natural conditions, the productive upper water layers lack substrates suitable for benthic grazers in the North Sea. Since both benthic and pelagic grazers feed on phytoplankton, the presence of benthic grazers to the upper water layers induces competition for food (Slavik et al., 2019). This competition between pelagic and benthic consumers in upper water layers may therefore alter pelagic and benthic carbon cycles (Duffill Telsnig et al., 2019; Kiljunen et al., 2020). To investigate the competition between the benthic and pelagic components, we include both components in our North Sea model using DEBGRZ, a module based on Dynamic Energy Budget (DEB) theory. DEB provides a suitable modelling framework for modelling grazers as it is based on first principles and metabolic processes, is well known and thoroughly validated and comes with a large database of species-specific parameters.

1.3 Objectives of this study

Building on prior research conducted within Wozep, this study aims to increase understanding of potential alterations in ecosystem dynamics due to large-scale implementation of offshore wind energy by assessing the effects of OWFs on benthic (mussels) and pelagic (zooplankton) grazers. This is done by improving the parametrisation of mussels to better simulate the observed occurrence over the depth gradient, and by incorporating zooplankton in the 3D-DCSM model, thereby further developing a set of tools to assess the competition between benthic and pelagic organisms.

1.4 Lay-out of this report

This report contains a technical description of the progress made in 2024 on the modelling of zooplankton (chapter 2) and mussels (chapter 3) and concludes with summarizing the progress including recommendations for further work for the next year (chapter 4).

2 Zooplankton

2.1 Introduction

Zooplankton is a large and diverse group of aquatic planktonic and heterotrophic organisms. Zooplankton fulfils a crucial role in transfer of carbon towards higher trophic levels within the pelagic marine environment (Lomartire et al., 2021; Tett and Mills, 1991). In terms of biomass, the zooplankton community in the North Sea is dominated by copepods, a group of small (up to several millimetres) crustaceans (Fransz et al., 1991; Williams et al., 1994). The remainder of the zooplankton community is formed by meroplankton (e.g. larvae of fish and echinoderms) and, to a smaller extent species of molluscs (e.g. *Thecasomata*), vertebrates (e.g. *Oikopleura*) and other arthropods (e.g. *Evadne*) (Johns and Reid, 2001). Because of the dominance of copepods within the zooplankton community this group is considered the most suitable group to represent zooplankton.

Given their crucial role within the marine environment, it is essential to evaluate zooplankton within the 3D DCSM modelling framework. The following questions are addressed:

1. To what extent does the model represent observed patterns in spatial and temporal distribution of zooplankton biomass?
2. What are the potential effects of OWFs on zooplankton biomass, and how do these align with patterns of primary productivity?

2.2 Data

At the current stage in the process of modelling zooplankton, the primary objective is to evaluate the magnitude of the modelled zooplankton biomass and its spatial and temporal patterns against observation data. The availability of reliable zooplankton data is limited. The CPR Survey data is useful for this analysis, but it is crucial to be aware of the limitations of that data set.

2.2.1 Observation data

Zooplankton observation data was extracted from the Eurobis search engine (EurOBIS, 2024). Data between 2010 and 2018 was selected, covering a similar area as the DCSM model domain (between 50 and 61 degrees latitude and between -3 and 10 degrees longitude). The majority of data resulting from this search was from the Continuous Plankton Recorder (CPR) Survey). The CPR Survey is distinguished by its extensive temporal span, having been conducted since 1931, and its wide geographical coverage (Vezzulli and Reid, 2003). The CPR is a specialized instrument that is towed behind commercial vessels (ships of opportunity) and features a filter mechanism that allows water to flow through while continuously collecting plankton samples on a fine silk mesh spool (Batten et al., 2019).

The CPR survey data should be interpreted with caution due to a systematic under-representation of plankton abundance (Richardson et al., 2006). This underrepresentation is particularly notable for phytoplankton, as the 270 μm mesh size used in the survey's design is too large to effectively capture this component of the plankton community. Similarly, smaller copepods and their life stages are inadequately sampled. Larger copepods, exceeding this mesh size, can be capable of avoiding or actively escaping the funnel entrance of the CPR device, which also leads to an underrepresentation in the CPR data set. Consequently, it is recommended to use the CPR survey data in a qualitative or semi-quantitative manner (Richardson et al., 2006). Fortunately, Pitois and Fox (2006) developed correction factors for the most common (in terms of biomass) zooplankton species and species groups, by using data from two field stations with more efficient techniques (WP-2 nets). These correction factors enable more accurate estimations of biomass concentration for various copepod groups and the total zooplankton biomass. However, despite the application of these correction factors, the data is still expected to underestimate actual biomass values, given that not all zooplankton species and species groups are corrected for.

Apart from the known underrepresentation caused by the methodology, other commonly expressed concerns regarding CPR data include the bias towards common vessel routes and the inability to measure at depths other than 5-10 meter, where the device is deployed. It is suggested that this could result in the underrepresentation of copepods during certain times of the day or due to seasonal effects, given the vertical migrations typical of most copepod species (Baars and Oosterhuis, 1984; Richardson et al., 2006).

2.2.2 Observed zooplankton distribution

CPR data, corrected based on correction values (Pitois and Fox, 2006) and averaged over the entire North Sea area, show that zooplankton biomass concentrations start to increase in March and peak in May. A second, smaller peak occurs in September or October, after which zooplankton biomass decreases again (Figure 2.1). Average zooplankton biomass is between 0.005 and 0.015 gC/m^3 between April and October. Despite the his is lower than what is commonly reported in literature (e.g. Krause and Martens, 1990). When zooming in on Wozep effect regions (Van Duren et al., 2021), this pattern is the clearest for the Central North Sea, Southern English Coast and the German Bight. In the Rhine ROFI and Unclear Zone CPR zooplankton biomass average is highest in winter. On the Dogger Bank, no spring bloom peak is seen in the monthly zooplankton averages (Figure 2.2).

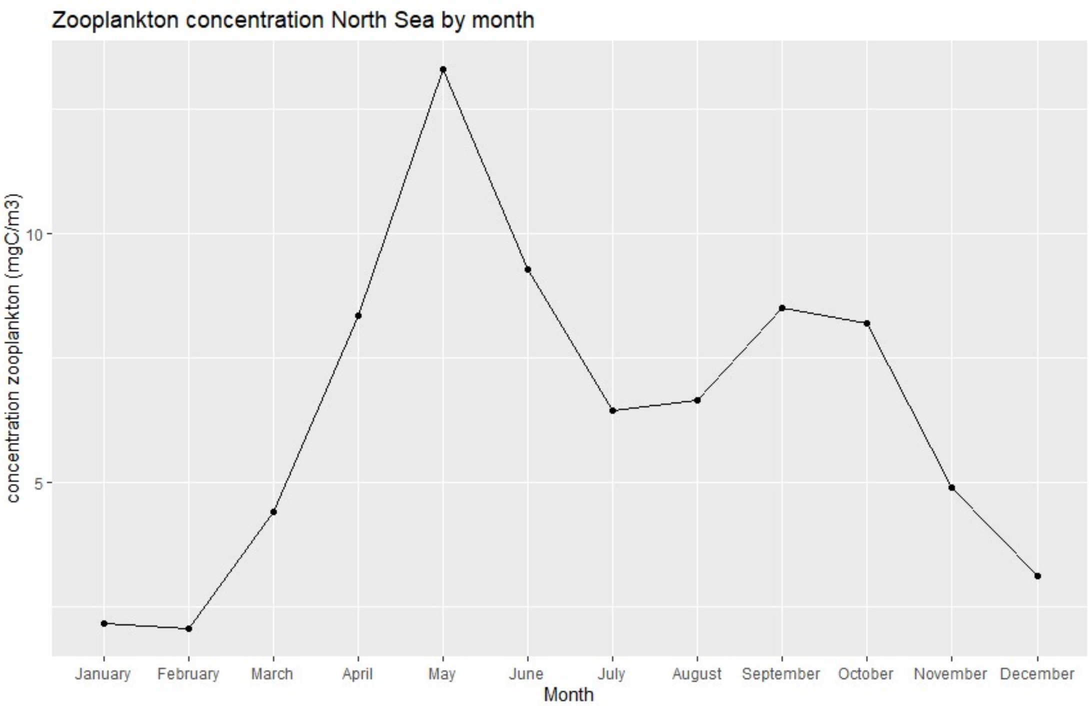

Figure 2.1: Monthly average zooplankton biomass concentration (mgC/m^3) based on CPR Survey data over the DCSM domain between 2010 and 2020.

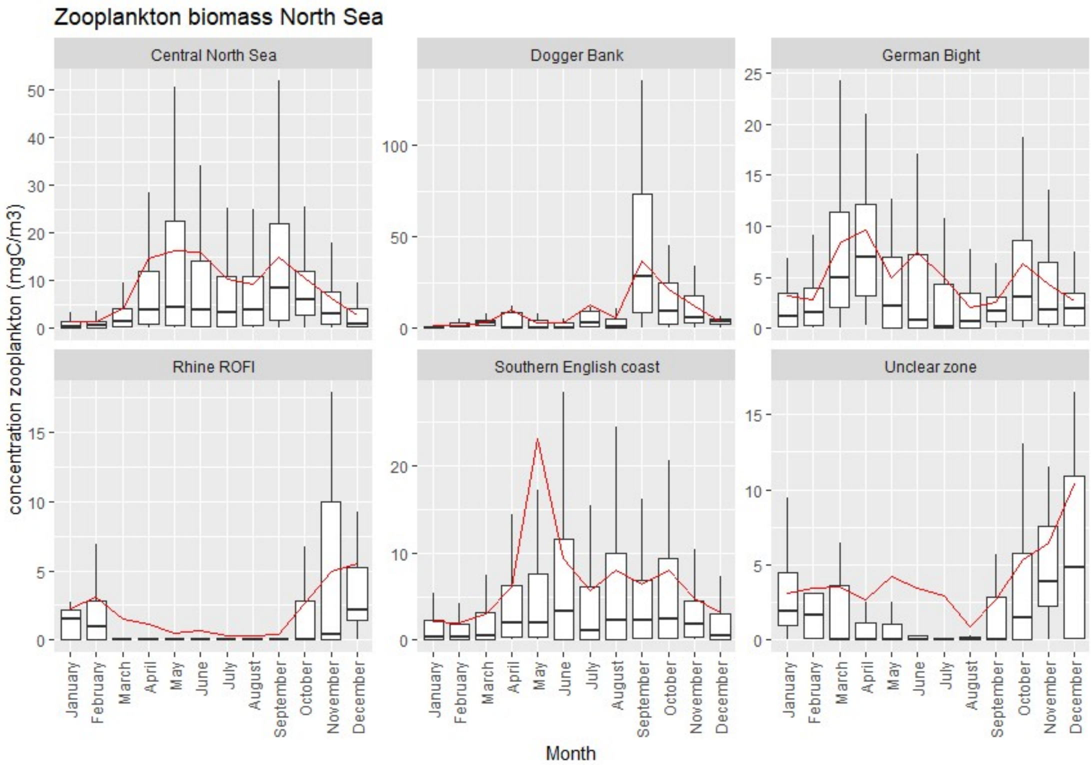

Figure 2.2: Monthly average (red line) zooplankton biomass concentrations based on CPR survey data between 2010 and 2020 for the different assessment areas used within Wozep. Boxplots show the variation in monthly average over the years. Note the difference in scale.

2.3 Modelling

2.3.1 Starting point, initial results and approach taken

Zooplankton biomass has been modelled using the DEBGRZ module in earlier North Sea model versions (GENO, ZUNO), which model configurations were used as a starting point for modelling zooplankton in DCSM. Since then, however, new zooplankton parameter values have become available in the Add-my-Pet DEB database. Hence, we first updated the parameters in the DCSM model accordingly.

Although the earlier zooplankton models did lead to acceptable results regarding zooplankton biomass (e.g. Maar et al., 2018; Troost et al., 2018), the biomass modelled using the 3D DCSM model turned out substantially lower than observed in CPR Survey data (section 2.3.1.2). This difference in biomass model output under comparable conditions and within a similar modelling framework and comparable parameters was a reason for concern. It was therefore decided to continue working along two tracks:

1. Zooming in on the difference between the present and previous modelling exercises to check validity of the current outcomes and model processes, and to identify potential causes of the unexpectedly low zooplankton output (section 2.3.2).
2. Proceeding with calibrating the model, while acknowledging possible shortcomings of the model, to assess relative, rather than absolute, differences in zooplankton biomass under OWF scenarios (section 2.3.3)

2.3.1.1 Update of DEB parameters and model setup

Since our earlier work on zooplankton modelling (Maar et al., 2018), new zooplankton parameter values have become available in the Add-my-Pet DEB database. Hence, we have updated our DEB parameters accordingly. The new set of parameters (Table 2.1) has been derived from parameter values available on the Add-my-Pet DEB data portal for *Calanus sinicus* (Kooijman, 2016). This can be used as a representative for North Sea copepods, as it closely resembles *Calanus helgolandicus*, a common copepod species in the North Sea, particularly in offshore areas. Model results based on this parameter set were calibrated based on CPR data on individual growth using a 1D-vertical column model (Rienstra et al., 2023).

Table 2.1 Key parameters from an updated DEB parameter set for zooplankton

Parameter	Parameter name	Parameter value (unit)
Z_JXm	Ingestion rate	194 (J/d/cm2)
Z_Pm	Maintenance rate	1060 (J/d/cm3)
Z_Em	Reserve capacity	8336 (J/cm3)
Z_Eg	Cost for growth	4497 (J/cm3)
Z_kappa	Energy allocation to soma	0.59 (-)
Z_Ta	Arrhenius temperature	7221 (K)
Z_Xk	Half rate constant for food	0.04 (-)
Z_Vb	Structural volume at birth	2.197E-6 (cm3)
Z_Vp	Structural volume at puberty	5.384E-4 (cm3)
Z_Shape	Shape coefficient	0.37 (-)
Z_rmor	Reference mortality rate	0.1 (-)

One of the recurring challenges during this calibration was the significant decrease of zooplankton population biomass in winter. This resulted in a late and low peak in modelled zooplankton biomass in the next year. It was hypothesized that this discrepancy with observations could be explained by specific behavioural traits allowing them to survive during winter. *Calanus helgolandicus*, for example, is known to undergo diapause, during which various metabolic processes are significantly reduced (Hirche 1983). Overwintering strategies are diverse among North Sea copepod species, but often involve reducing metabolic rates and/or adjusting reproductive timing and methods, such as producing resting eggs during winter (Hansen 2019) (source). These strategies are not a part of our model yet.

To resolve this issue in column models, a minimal amount of zooplankton biomass was continuously introduced into the 1D-vertical model to prevent the biomass from reaching critically low values. For the application of the parameter set in the 3D DCSM model, however, it was assumed that this intervention would not be necessary, since zooplankton would be transported from adjacent areas into the area of interest. Therefore, the revised parameter set was used within the 3D DCSM modelling suite without adding an artificial load.

The initial zooplankton biomass was set at 0.005 gC/m^3 Zoopl_E and Zoopl_V, totalling 0.01 gC/m^3 of zooplankton biomass. These values were based on calibration in column models and although these values are seemingly high in comparison with the CPR Survey data, it was observed that modelled zooplankton biomass decreases significantly in the first weeks and sufficient initial biomass is required to increase chances of representative values in summer.

For the boundary conditions, CPR Survey data was used. Average monthly zooplankton biomass on data points within a degree latitude and longitude of the model domain boundary and taken between 2010 and 2020 were selected. It was assumed that about half of the biomass for zooplankton is structural biomass (Zoopl_V) and the other half can be contributed to energy storage (Zoopl_E), based on column model output.

2.3.1.2 3D DCSM modelling results

Modelled zooplankton biomass remained low throughout the year. Zooplankton biomass remained low throughout the model domain, even during the summer, except for some coastal areas where modelled zooplankton was high compared to CPR Survey data (Figure 2.3).

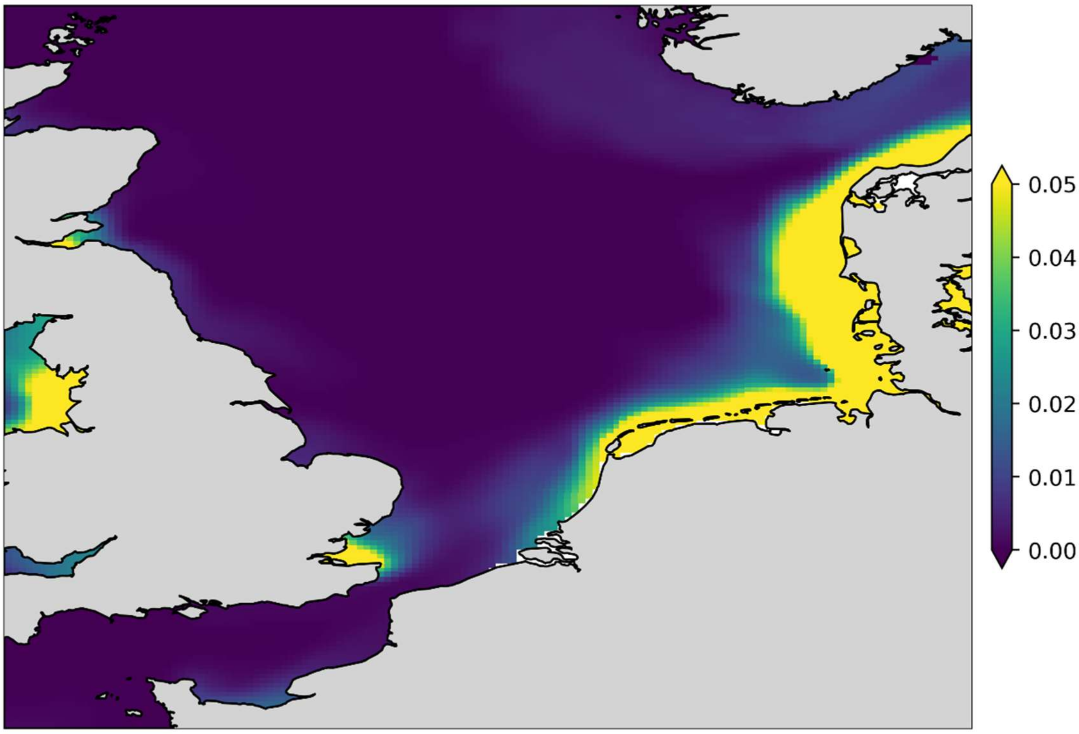

Figure 2.3: Average zooplankton biomass concentration for July 2007. Scale was manually set between 0 and 0.05 gC/m^3.

2.3.2 Comparison with ZUNO model and previous parameter set (Track 1)

Within earlier modelling studies, zooplankton biomass was simulated using the DEBGRZ module within the ZUNO 3D model of the North Sea. Within these studies, zooplankton reached acceptable levels of biomass concentration (Maar et al., 2018; Troost et al., 2018). Total zooplankton biomass concentration at different locations is show in Figure 2.4. Therefore, the 3D DCSM model was set up with the same parameters as used in the ZUNO model (Table 2.2). This resulted in lower zooplankton biomasses that were even lower than in the 1D-vertical model.

Table 2.2: Key parameters from previous DEB parameter set for zooplankton.

Parameter	Parameter name	Parameter value (unit)
Z_JXm	Ingestion rate	58 (J/d/cm2)
Z_Pm	Maintenance rate	1400 (J/d/cm3)
Z_Em	Reserve capacity	3137 (J/cm3)
Z_Eg	Cost for growth	3347 (J/cm3)
Z_kappa	Energy allocation to soma	0.9 (-)
Z_Ta	Arrhenius temperature	8000 (K)

Z_Xk	Half rate constant for food	0.04 (-)
Z_Vp	Structural volume at puberty	4.812E-6 (cm3)
Z_Shape	Shape coefficient	0.37 (-)
Z_rmor	Reference mortality rate	0.1 (-)

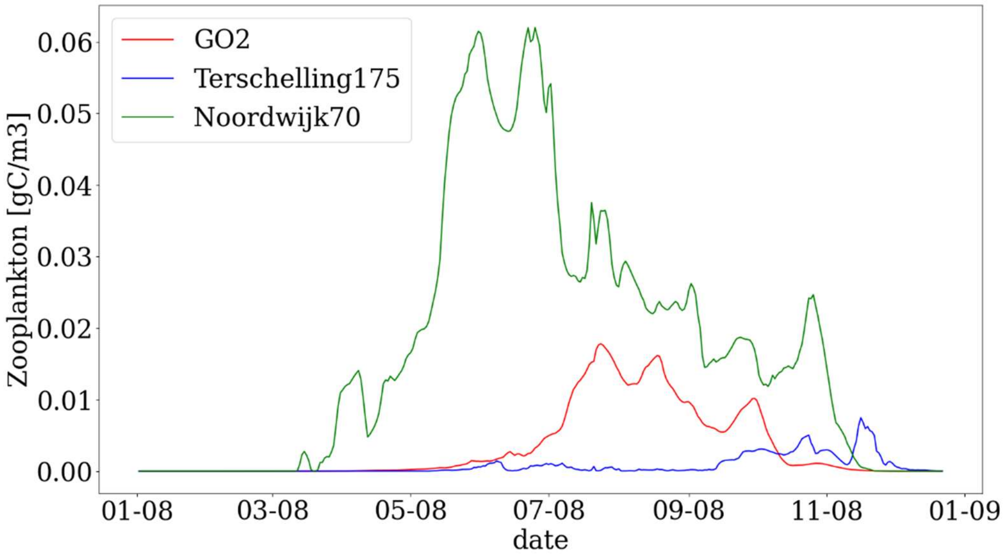

Figure 2.4: Zooplankton biomass in the ZUNO model at different locations

A direct comparison between the ZUNO model and the 3D DCSM model was challenging due to the computational time of the 3D DCSM model and the different way output is created for the different models in terms of data formats, assessment locations and timesteps. Several tests were conducted to identify the cause of the difference in zooplankton biomass response between the ZUNO model and the 3D DCSM model:

1. **DEBGRZ equations and implementation within Delwaq** (Delwaq-executable version). The ZUNO model was executed using the same code version as the 3D DCSM model applied within Wozep. While this resulted in small differences within the ZUNO model, the overall behaviour and survival outcomes remained similar.

2. **Model configuration**: The substances, processes and parameter values that were applied within the models were compared. The parameter values of the zooplankton were fully identical. Although some differences exist regarding some other parameter values and the substances (e.g. differences in particulate and dissolved organic nutrients, inorganic matter, denitrifying processes, vertical diffusion, horizontal flow velocity, mineralization, sedimentation and settling rates algal mortality) no differences were identified that are expected to significantly impact zooplankton negatively in the 3D DCSM model.

3. **Food intake and metabolism.** Mass balances show that the model processes are activated and functioning: algae are being eaten by the zooplankton in both models, and this does lead to zooplankton growth. However, the growth is too small to have the zooplankton survive in the 3D DCSM model.

   Another difference between both models that became evident from the mass balances is that the growth of zooplankton is mostly positive in the ZUNO model, but is below 0 for most of the year in the DCSM model. Negative growth is possible for DEB organisms when the energy intake is below the energy need for somatic maintenance (see eq. 1). Since maintenance is solely dependent on temperature, maintenance rate ($[p_M]$) and size (V) – latter two of which are input parameters and should be identical in both models – the issue is most likely related to temperature and/or the energy (food) uptake.

$$\frac{dV}{dt} = \frac{\kappa\{p_{Am}\}\frac{[E]}{E_m}V^{\frac{2}{3}} - [p_M]V}{\kappa[E] + [E_G]} \qquad \text{eq.1}$$

4. **Food (availability and uptake) and temperature.** The primary productivity and algae biomass simulated by the DCSM model used to be slightly overestimating observed values and recent versions of the model result in lower values of productivity and algal biomass. It was hypothesized that this might cause the difference in zooplankton response. Given the runtime of the 3D DCSM model, a column model on the FINO1 location was set up for a more extensive comparison between the ZUNO model and the newer models. For this exercise, the column model was executed using the same Delwaq executable and the same parameter values. For the analysis, the results of the FINO1 column model were compared with ZUNO output on the GO2 (German Offshore 2) location.

   In terms of primary productivity and phytoplankton biomass, results were comparable between both models, although the spring bloom occurs earlier in the ZUNO model (Figure 2.5, Figure 2.6). Temperature, relevant for the rates of metabolic processes of zooplankton is higher in winter for ZUNO and higher during summer in the column model (Figure 2.7). Under seemingly comparable conditions between the locations, the zooplankton biomass is expected to be similar between both models. However, zooplankton biomass differed strongly; there is a response in zooplankton biomass in the ZUNO model, whereas zooplankton does not grow in the column model (Figure 2.8).

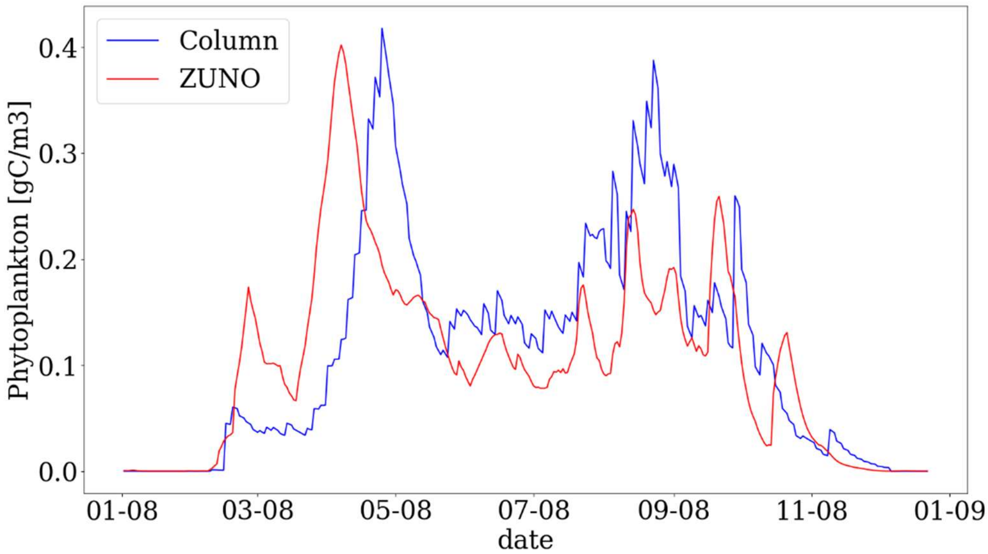

Figure 2.5: Phytoplankton biomass in the FINO1 Column model (red) and the GO2 location of the ZUNO model (blue)

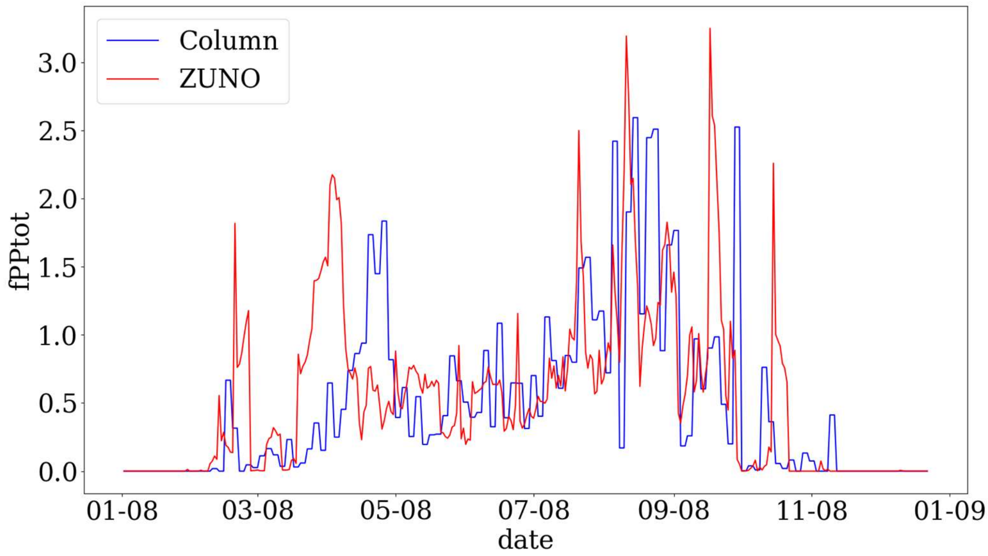

Figure 2.6: Primary production in the FINO1 Column model (blue) and the GO2 location of the ZUNO model (red)

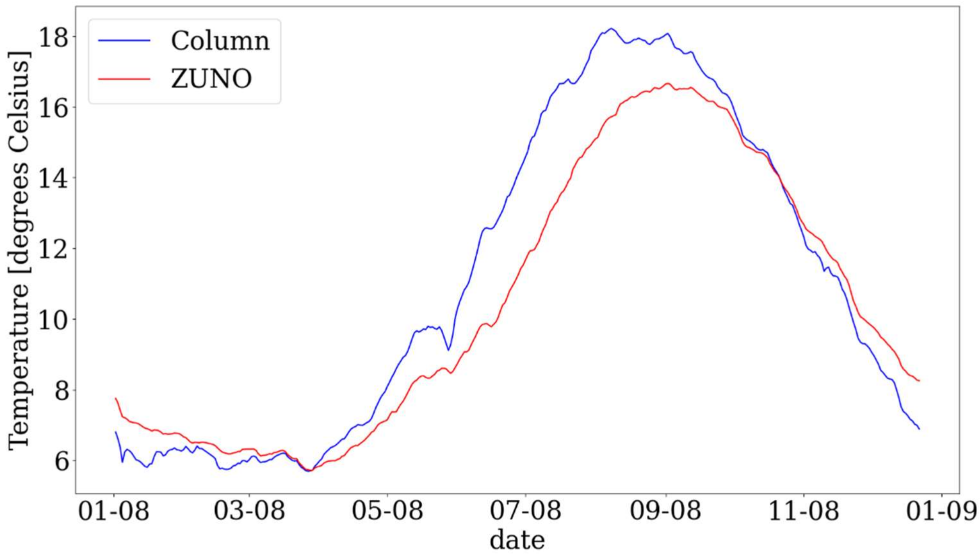

Figure 2.7: Temperature in the FINO1 Column model (blue) and the GO2 location of the ZUNO model (red).

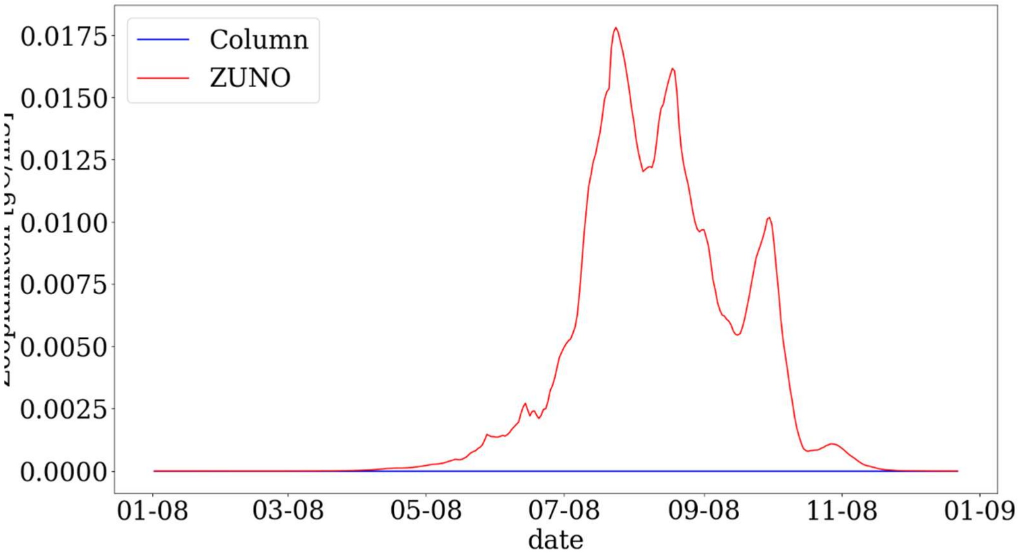

Figure 2.8: Zooplankton biomass in the FINO1 Column model (blue) and the GO2 location of the ZUNO model (red). In the column model, zooplankton drops to levels near zero directly after initiating (not visible on this scale).

To further assess the difference in zooplankton biomass, the energy intake (Ea) and use (for somatic processes and growth; Ec) was investigated. Because of the difference in scale, these results are shown separately for each of the two models (Figure 2.9). The large (absolute difference in (absolute) scale is explained by the fact that these are total mass fluxes for the whole population (which is at a normal size in the ZUNO model but is almost non-existent in the column model). Yet, a comparison of the (relative) patterns in these fluxes shows that the uptake in the ZUNO model starts earlier and takes place over a much longer period during summer (Figure 2.9). Upon closer inspection, however, it became clear that the pattern in energy processes already differed in the first days of simulation: in the ZUNO model energy was taken up and used, whereas in the column model, no energy was being taken up by the zooplankton (Figure 2.10). Most likely, this difference is caused by the difference in available phytoplankton in the first month. Closer inspection of the phytoplankton concentrations (Figure 2.5) shows that there indeed is a big difference in phytoplankton biomass within this first month: Phytoplankton is available in low concentrations form the start in the ZUNO model, whereas phytoplankton is totally absent (<1E-12 gC/m^3) in the column model (Figure 2.11).

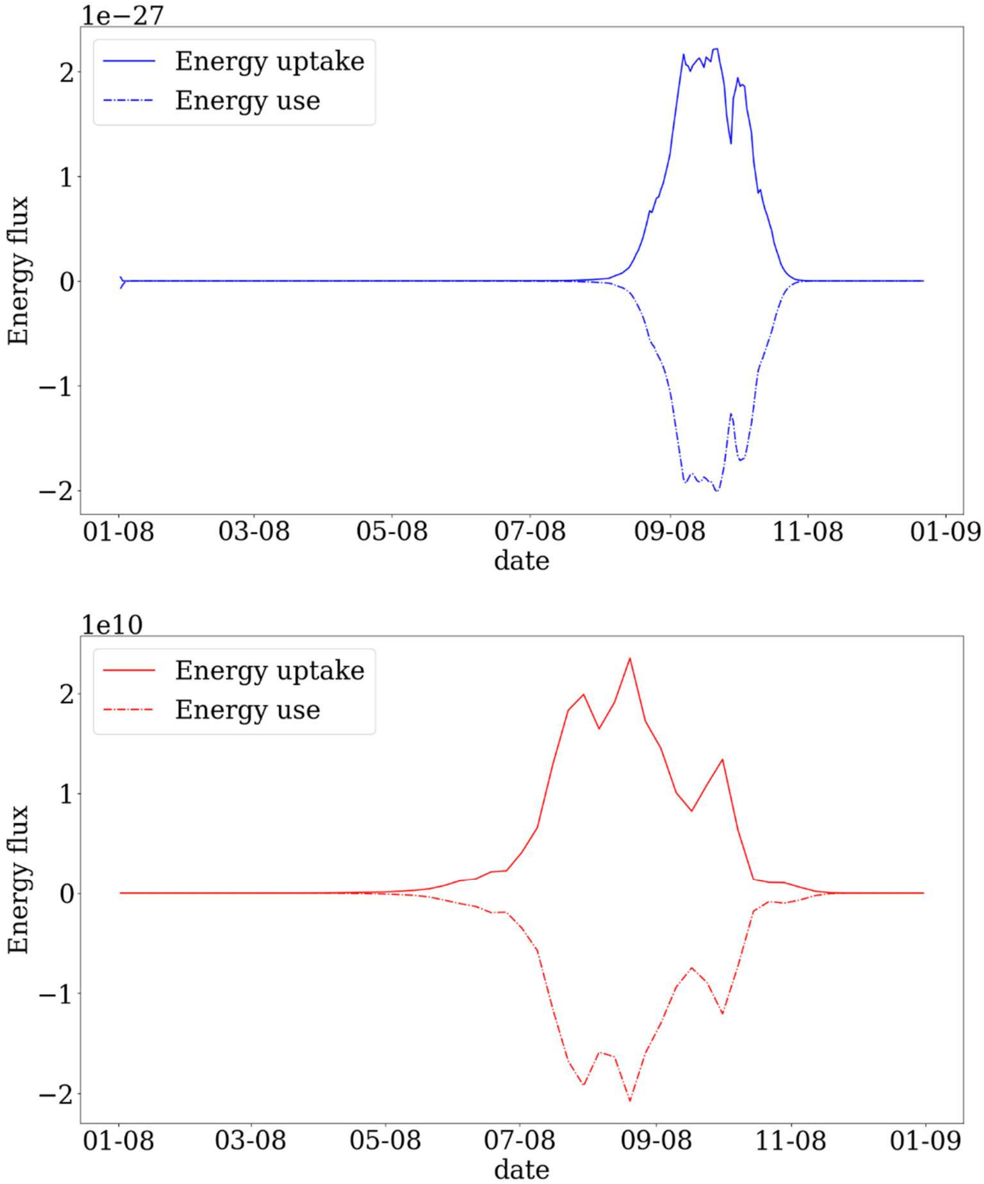

Figure 2.9: Energy fluxes in the FINO1 Column model (blue, top) and the GO2 location of the ZUNO model (red, bottom). Note the difference in scale.

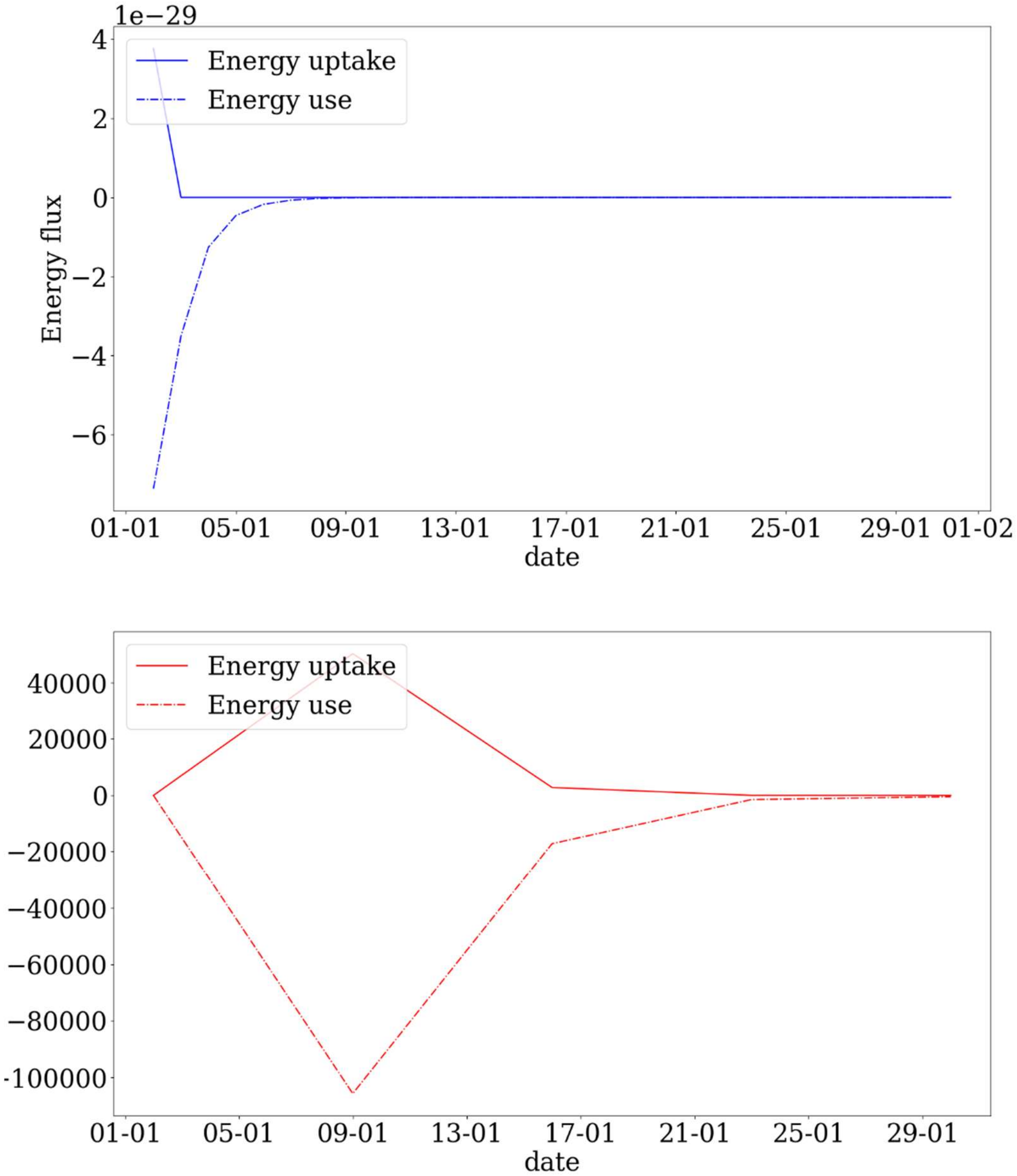

Figure 2.10: Energy fluxes in Januari, for the FINO1 Column model (blue, top) and the GO2 location of the ZUNO model (red, bottom). Note the difference in scale

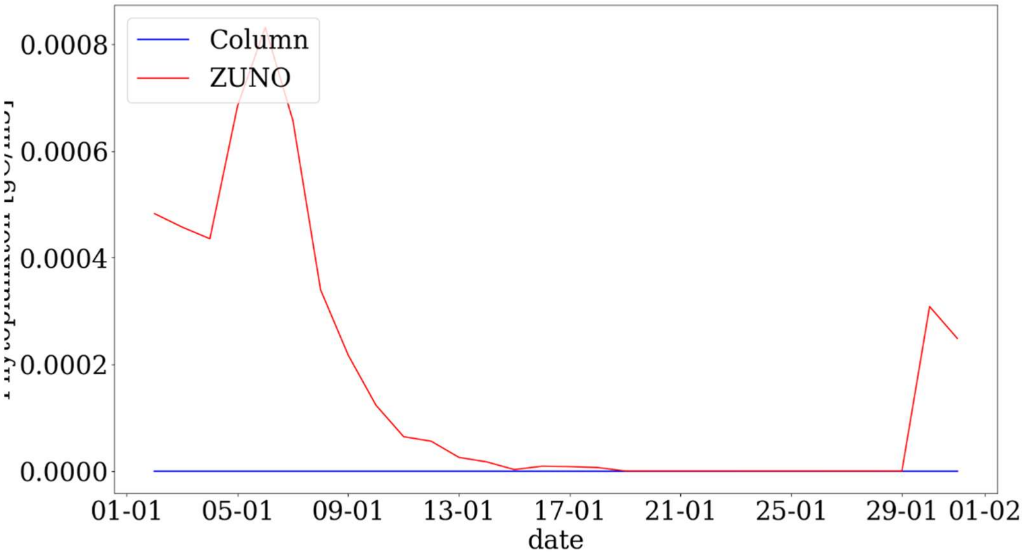

Figure 2.11 :Phytoplankton concentration in Januari, for the FINO1 Column model (blue) and the GO2 location of the ZUNO model (red).

The seemingly different behaviours of the DEBGRZ-zooplankton in the ZUNO and DCSM model can probably be explained by differences in phytoplankton availability and temperature, especially during winter. Other potential factors (such as the use of the DelWAQ-executable, DEBGRZ model code, the model configuration, the numerical integration routine and the timesteps) where investigated, but were all found not to be the cause of the difference in survival.

2.3.3 Preliminary relative effects of OWFs (Track 2)

The previous sections have made clear that simulating DEBGRZ zooplankton within the 3D DCSM model results in unrealistic zooplankton biomass values (2.3.1) and that a potential reason for this is the low amount of modelled phytoplankton during winter (2.3.2). Therefore, the current results cannot be considered reliable estimates of zooplankton biomass concentration in this stage. However, it can still be valuable to qualitatively evaluate the potential effects of offshore wind farms on zooplankton biomass distribution. Zijl and colleagues (2023) reported that the effect of OWFs on primary productivity is spatially varying. In OWFs in the Central North Sea as well as areas directly North of the Wadden Islands and at intermediate distance from the Dutch coast, an increase in primary productivity was expected, whereas for OWFs at intermediate offshore distance from the Wadden Islands and along the coast of The Netherlands and the United Kingdom, a decrease in primary productivity was expected. Zooplankton is expected to show a similar distribution pattern, given their bottom-up dependence on phytoplankton as their main food source.

Zooplankton was simulated with the same parameter set as presented in (Table 2.1), with the single adjustment of reducing the reference length (Lref) to 0.07 centimetre. By decreasing the reference length, a smaller population average length is assumed. In other words, we assume that the average individual within the population is smaller, which results in a higher growth rate and higher modelled biomass concentrations. However, this also results in a strong spatial gradient in zooplankton biomass concentrations: modelled biomass concentrations are very high close to the coast and remain low at offshore locations, which is visualized on the timeseries for a part of the Terschelling transect (Figure 2.12). Although these values and the steepness of the gradient are not realistic, based on CPR survey data (see chapter 2.2), and issues regarding zooplankton growth are not resolved at offshore locations, a response in zooplankton biomass is observed for a large part of the North Sea domain (Figure 2.13). To assess the effects of OWFs on zooplankton, 3D DCSM model comparison was conducted between a scenario without the inclusion of offshore wind farms (Reference) and a scenario including windfarms (Scenario 1; Figure 2.14). This approach was similar to the methodology of (Zijl et al., 2023), with the addition of zooplankton to the model.

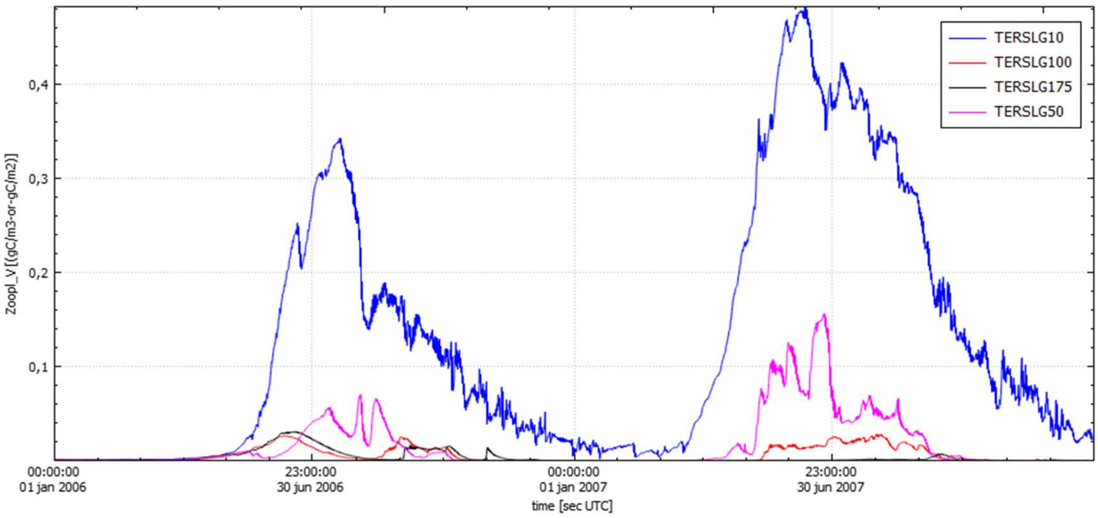

Figure 2.12: Zooplankton structural biomass (Zoopl_V) concentrations (gC/m^3) along the Terschelling transect. Total zooplankton biomass concentations can be estimated by doubling these values.

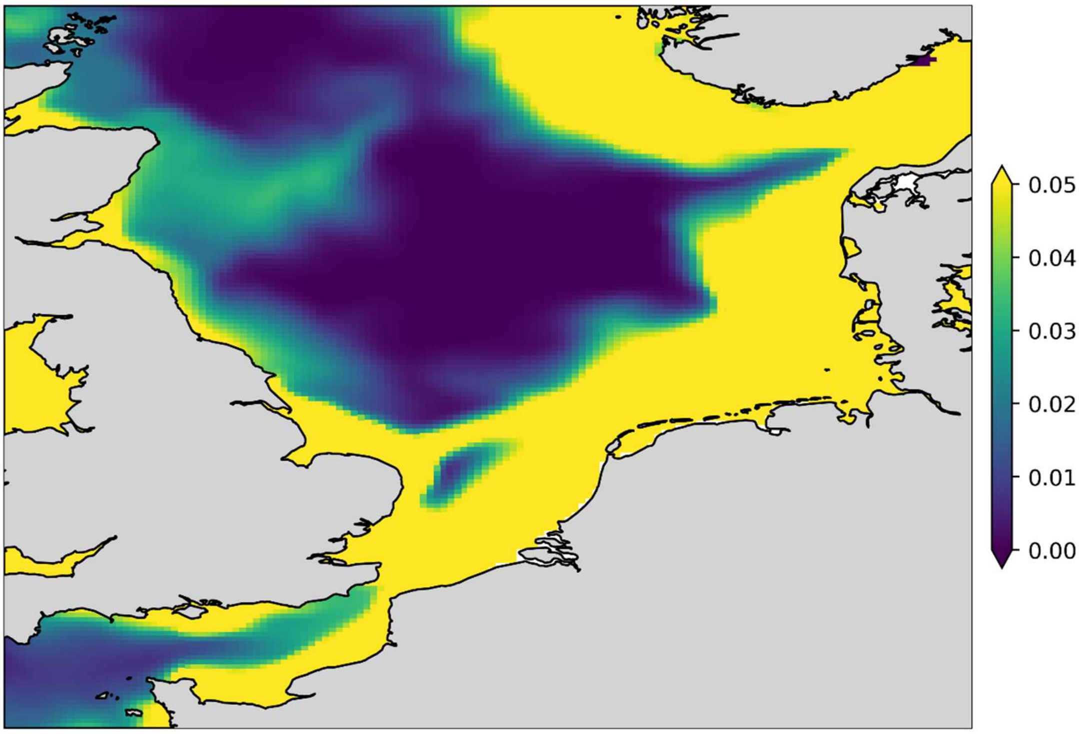

Figure 2.13: Zooplankton biomass concentrations (gC/m^3) for the scenario without wind farm (Reference) in July (monthly average). Colour scale was set between 0 and 0.05 but reached significantly higher levels in certain coastal locations.

Figure 2.14: Map of OWFs under Scenario 1

Difference maps comparing zooplankton biomass for the scenario with (Scenario 1) and without wind farms (Reference) show that the effects of OWFs on zooplankton are spatially variable. Along the Dutch coast and at the southern areas of the Central North Sea, zooplankton biomass estimates are higher for the OWF Scenario 1, whereas zooplankton biomass estimates are lower at intermediate distance from the Dutch coast (Figure 2.15). Relatively, the largest effects are found in certain offshore areas, where a strong increase is simulated locally up to 400% (Figure 2.16). This strong effect can be attributed to the low values for these offshore locations in the reference scenario (as can be deduced from Figure 2.13).

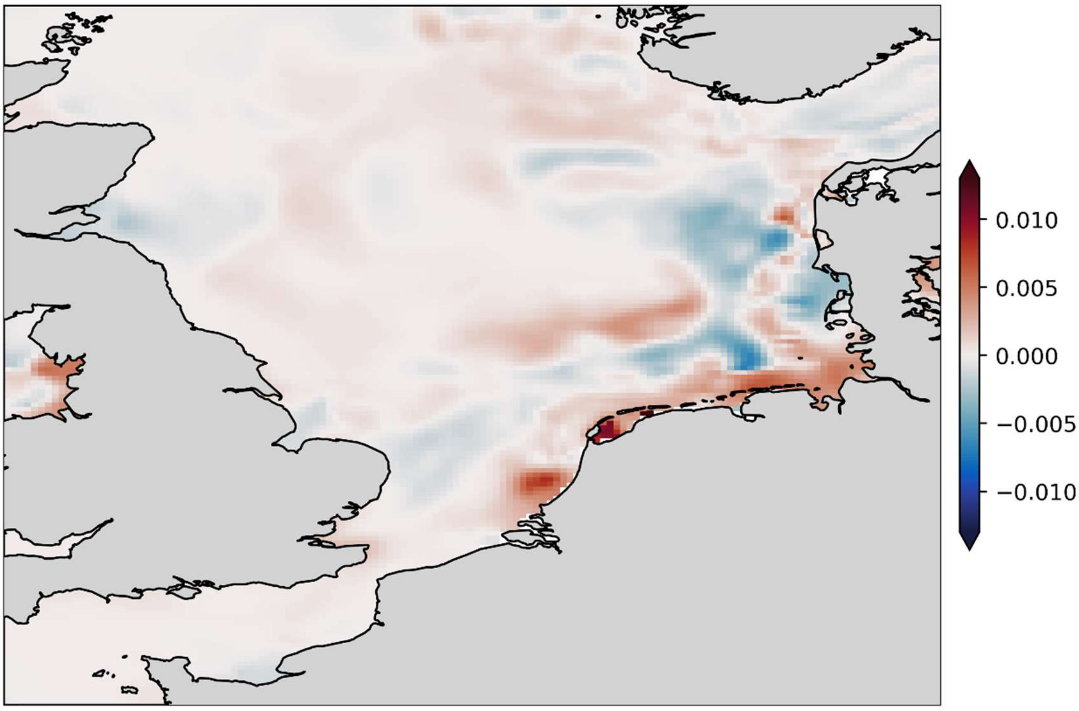

Figure 2.15: Annual mean difference in zooplankton biomass concentrations (gC/m³) between OWF Scenario 1 and Reference.

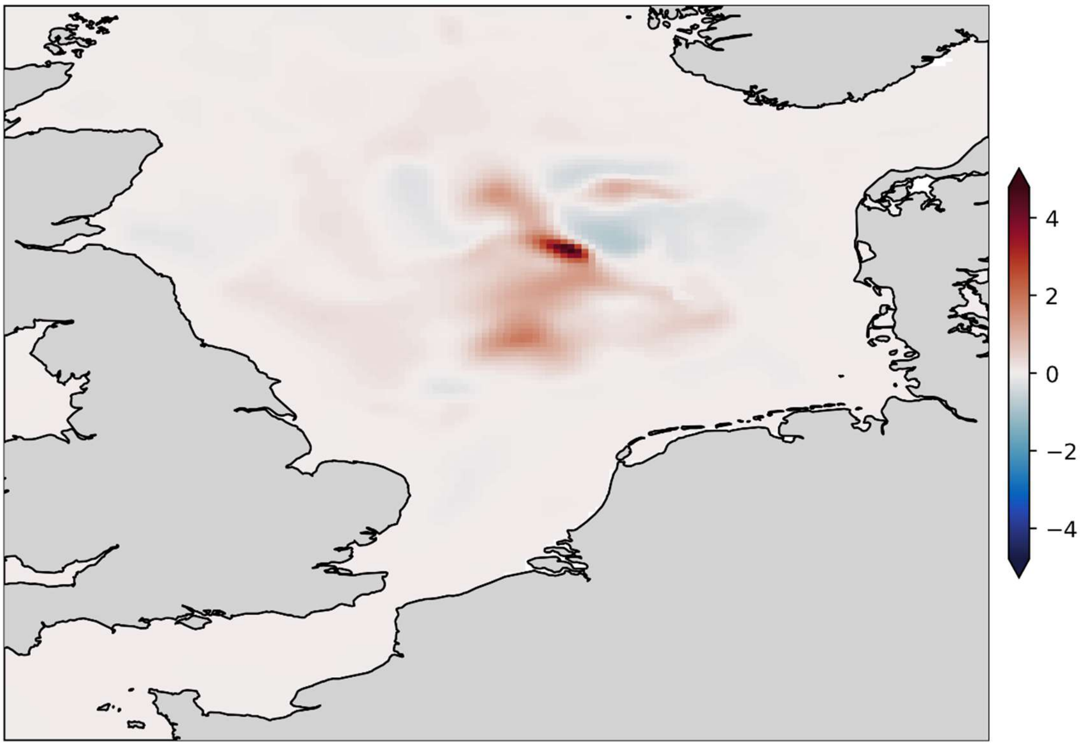

Figure 2.16: Relative (fractional) annual mean difference in zooplankton biomass concentrations (gC/m³) between OWF Scenario 1 and Reference.

The effects of OWFs on zooplankton are comparable to the reported effects of OWFs on primary productivity described by Zijl and colleagues (2023). Both exhibit spatial variability and the spatial patterns correspond relatively well. Primary production is more localized and scattered, whereas zooplankton shows more regional effects to OWFs. This difference could be caused by the slower dynamics of zooplankton compared to phytoplankton. The strong effects of OWFs on zooplankton biomass in offshore locations are likely caused by the models limitations in estimating offshore zooplankton biomass.

These result are promising, as they show that the zooplankton response aligns with those of primary production. This suggests that the model output could lead to understandable results without introducing further complexities, provided that the current limitations in the zooplankton growth at offshore locations, potentially caused by an underestimation of phytoplankton biomass in January, will be resolved.

2.4 Next steps

For next year we recommend to continue focusing on improvement of the modelled response in zooplankton. Based on this year's findings, we recommend to start by preventing the zooplankton biomass to drop during winter. For this, we suggest to explore the following:

1. Validate the DCSM model results of temperature and phytoplankton levels, especially in winter and, depending on the outcomes, improve these model results.
2. Simulate a zooplankton diapause by turning off metabolic processes when food availability reaches critical levels.
3. Apply a more recent DEBGRZ version including density dependent mortality of grazers.

For the model validation and data analysis, we recommend to look beyond the currently used CPR Survey data set and investigate long-term (local) data sets for zooplankton. Once both the DCSM model and the zooplankton module are validated well against data, we recommend to make a comparison similar to the one conducted within this study to investigate the effects of offshore wind farms.

3 Mussels

3.1 Introduction

Offshore platforms such as wind turbines and oil rigs provide new hard substrate for the colonization of sessile species. On these platforms, blue mussels, Anthozoa and the Amphipod *Jassa herdmani* form the dominant species (Borthagaray and Carranza, 2007; Freire and Gonzalez-Gurriaran, 1995; Joschko et al., 2008; Krone et al., 2013; Riis and Dolmer, 2003; Wilhelmsson and Malm, 2008). Other epifauna commonly found on these structures include barnacles, anemones and seaweeds (Krone, 2012; Krone et al., 2013; Lindeboom et al., 2011). The blue mussel is in terms of biomass and in terms of filtration capacity the most dominant colonising species on OWFs and they can be the important drivers of ecological change in these regions (Krone et al., 2013; Maar et al., 2009).

Models are an important tool to research the drivers of ecological change such as the effect of large-scale offshore wind energy production on the carbon transfer through lower trophic levels. Thus, it is important to run the models with the correct processes and conditions for mussel growth to assess the large-scale effects. As a first step, mussels were initialised in the top 5 m of the water column. As a result, they can only grow in that water layer. As mentioned above this is a reasonable first assumption as in the first years of OWF installation they occur mainly in the shallow subtidal zone.

However, it is important to understand whether mussels occur in the shallow subtidal zone because A) the abiotic and biotic conditions are most suited or B) they are outcompeted or grazed on in the deeper zones by other biofouling communities. The two options have different modelling consequences as for option A an initialization over the whole OWF would be needed while for option B a depth dependent grazing function would have to be applied.

To assess whether option A or B would need to be taken, a data analysis and column model exercise was conducted to further assess the situation. The aim was to answer 3 key questions:

1. Can possible differences in the in-situ data be linked to differences in physical and abiotic properties of the water?
2. At which depths do in-situ mussels occur and does their depth distribution vary according to the hydrographic environment?
3. Will modelled mussels growth over the complete water column if initialized to do so?

3.2 Data analysis

3.2.1 Data set description and preprocessing

Mussel occurrence data is extracted from the to-date unpublished BISAR dataset (Dannheim et al., n.d.). This is a compilation of cruise data from Belgium, Denmark, Germany and the Netherlands, in total combining 13 datasets. It includes a range of samples at stations, where the location, depth, time and wet as well as dry biomass of *Mytilus edulis* (among other species and parameters) is recorded per cruise.

The mussel density (kg/m^2) was calculated by dividing the sum of the wet mussel biomass by the sampled area. Those values were used for the analysis of mussel occurrence over the water column in the North Sea. Furthermore, the in-situ locations were grouped according to their corresponding OSPAR assessment area. The OSPAR assessment areas classifies the OSPAR domain in distinct regions based on physical (depth, salinity and stratification), chemical (nutrients) and biological (phytoplankton dynamics) properties (Devlin et al., 2023).

3.2.2 Analysis

Figure 3.1 shows that the locations of the sampling stations fall into two OSPAR assessment areas, Southern North Sea and Coastal Offshore. The Southern North Sea is separated from other surrounding assessment areas by the fact that is mostly less than 35 m deep and permanently mixed. Coastal Offshore is defined as the coastal waters along the coast of DE and DK. The landward boundary is formed by WFD water bodies and the 32 psu salinity level. The outer boundary is formed by the 34 psu salinity level. Coastal Offshore can be seasonally stratified.

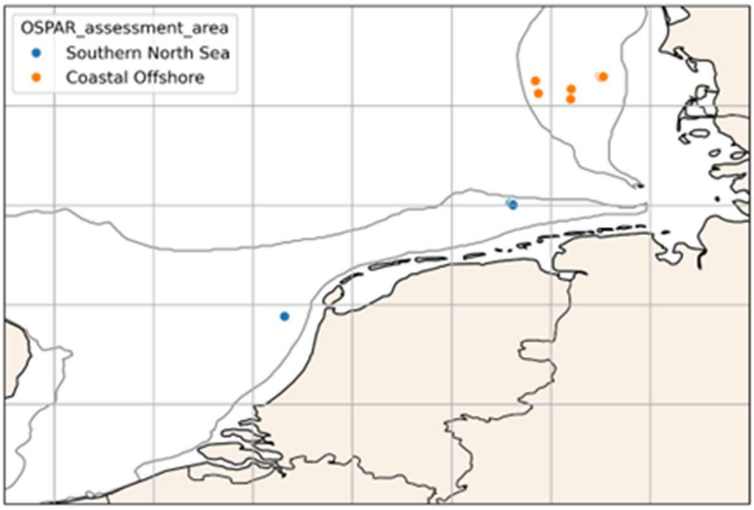

Figure 3.1: The sampling stations are all located within two OSPAR assessment areas.

Figure 3.2 shows the distribution of mussel density over depth for the two assessment areas. Coastal offshore shows higher mussel densities. Both assessment areas show the highest mussel densities in the top 10 m. Very low mussel densities at depth from 15-30 m occur in the Southern North Sea. Figure A 1 in the appendix shows that those occurrences at depth between 15-30 stem from two sampling stations (AV_P11 and Halfweg). A more detailed look per station and sampling date show no temporal or station specific differences in terms of their depth distribution (see figures in appendix A). The highest mussel densities occur in the top 5 m regardless of sampling station and sampling date.

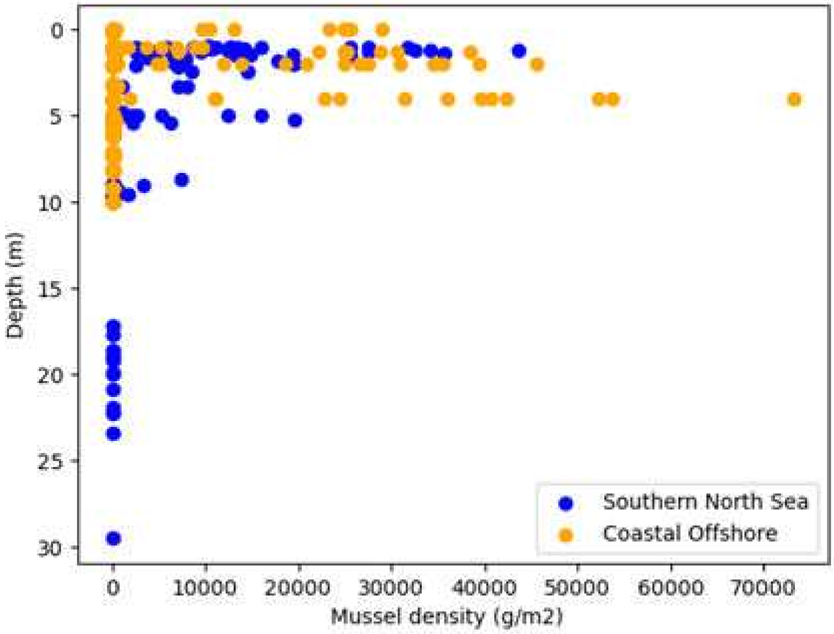

Figure 3.2: Visualization of mussel density across depth grouped per OSPAR assessment area. The highest mussel densities occur within the top 10 m of the water column.

3.3 Column model runs

Here, we performed 1D-vertical modelling tests to analyse if the DEB model is able to represent observed patterns in mussel biomass and vertical distribution on offshore structures. The 1-D vertical model setup here is similar to that described in (Van Kessel et al., 2022). Meteorological parameters, atmospheric deposition, current velocity, vertical dispersion and advective inflows of all simulated water quality variables are forced using the simulated conditions at FINO1 for the years 2006-2008 with the initial ecological model reported in (Zijl et al., 2021), 2006 serving as a spin-up year.

In the previous reports (Van Kessel et al., 2022; Zijl et al., 2023), we assumed that attached mussels could only grow in the top 5m below the water surface, based on observations at the FINO1 OWF from Krone et al. (2013). The DEB mussel parameters were calibrated to simulate a stable yearly average biomass of mussels, varying around the order of magnitude of the density observed by Krone et al. (2013) (assuming this represents the situation, where mussels have settled and reached equilibrium). Here we want to check if the model is able to represent observed vertical gradients in mussel biomass.

3.3.1 Update of DEB parameters

Since the previous parameter set led to underestimation of mussel growth in the offshore cultivation sites, we updated the DEB mussel parameters based on the recent work from Stechele and colleagues (2022), who recently defined an updated DEB parameter set to represent dynamics of blue mussels at offshore suspended cultivation sites. Note that this new parameter set works fine for offshore conditions, but leads to overestimation of mussel growth in food-abundant (i.e. coastal) conditions. The fact that none of the parameter sets is able to function acceptably in both abundant and low food conditions, points to spatial variability in one of the (probably system-specific) parameter values (e.g. mortality rate, half saturation constant).

We then reproduced the calibration steps from van (Van Kessel et al., 2022) to define the reference length parameter of the mussel population:

1) We carried out a test with only one mussel individual, placed near the sea surface, using an iso-morph representation (simulation of the growth curve of individuals). In this version of the column model, the individual was initialized with a structural biomass corresponding to half of the assumed size at reproduction maturity (i.e. 0.00144 gC). Note that the iso-morph doesn't use any reference length parameter, since length is a calculated state variable. This first run therefore allows for assessing the length an individual can reach within the environmental conditions at FINO1. It shows that a mussel individual's length varies between ~1 and 2 cm within the year. We use this as a base to calibrate the reference length of our entire mussel population.

2) The column model was used to simulate the whole mussel population, using a V1-morph representation (assuming a fixed size distribution for the population, represented by a constant reference length , which is used as an input parameter). On the 1st of January 2006, mussels are initialized using a mussel density of 1000 g of mussel wet weight per 0.04 m^2 of pillar, which corresponds to the order of magnitude observed by Krone et al. (2013). Using a wet weight to carbon ratio of 0.0224 gC/gWW for blue mussels, a pillar density of 3.15 /km^2, a stem diameter of 5 m and assuming that the mussels grow over the top 5 meters of the pillars, this translates to an initial structural biomass of 0.1385 gC per m^2 of seabed area. Values of Lref ranging between 1.2 and 1.65 cm (parameter value from Zijl et al., 2023) are tested, with the objective to simulate a stable yearly average biomass of mussels. From these tests, we derive a Lref value of 1.2 cm for the rest of the tests.

The column model was then run with

1. the updated DEB parameters for both Iso- and V1-morph with mussels initialized only in the upper 5 meters of the water column
2. the updated DEB parameters for V1-morph with mussels initialized over the whole water column

3.3.2 Model results

Figure 3.3 shows the modelled reference length for the iso/morph (red dashed line) and the modelled biomass for the V1-morph (black line) modelled in the top 5 m of the water column. The plot shows that both the iso- and V1-morph perform as expected.

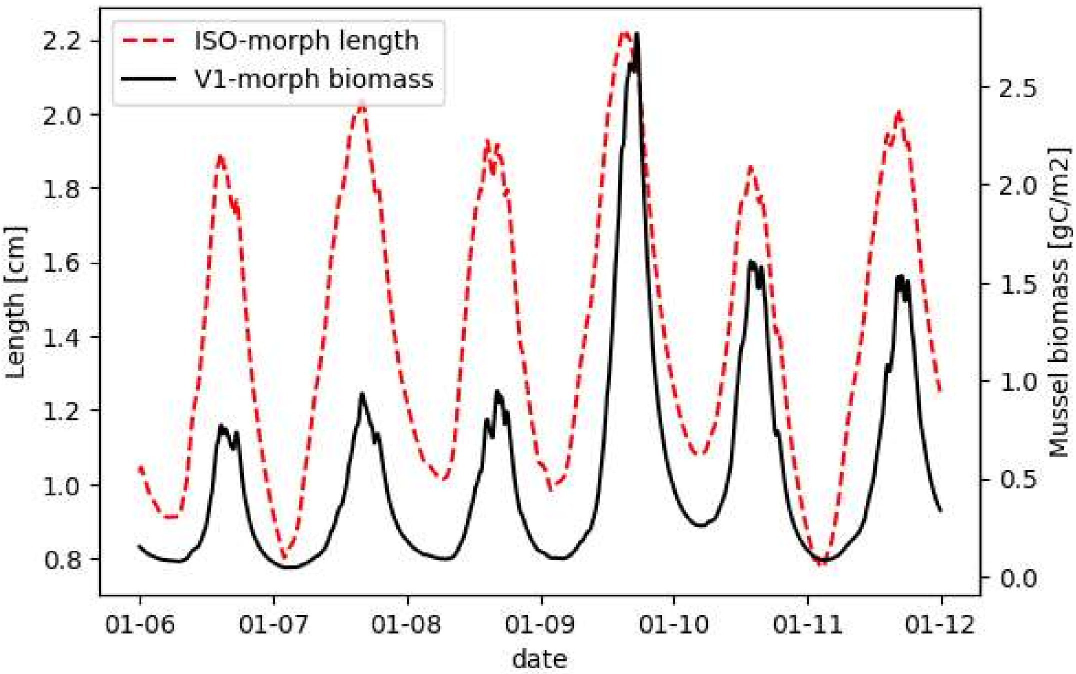

Figure 3.3: Model run simulating an iso-morph and an V1 morph in the upper 5 m of the water column. The red dashed line represents the reference length of the iso-morph and the black line the biomass of the V1-morph.

Figure 3.4 shows the resulting depth profiles for a V1-morph initialzed over the whole water column. Figure 3.4 shows that for all the seasons the mussels occur down to 25 m depth. For each season the highest mussel biomasses occur within the top 5 m of the water column. Summer and fall show the highest biomass which corresponds to the growing period of mussels. Below 5 m depth the mussel biomass declines in every season reaching values between 0.0-0.025 at 25 m depth.

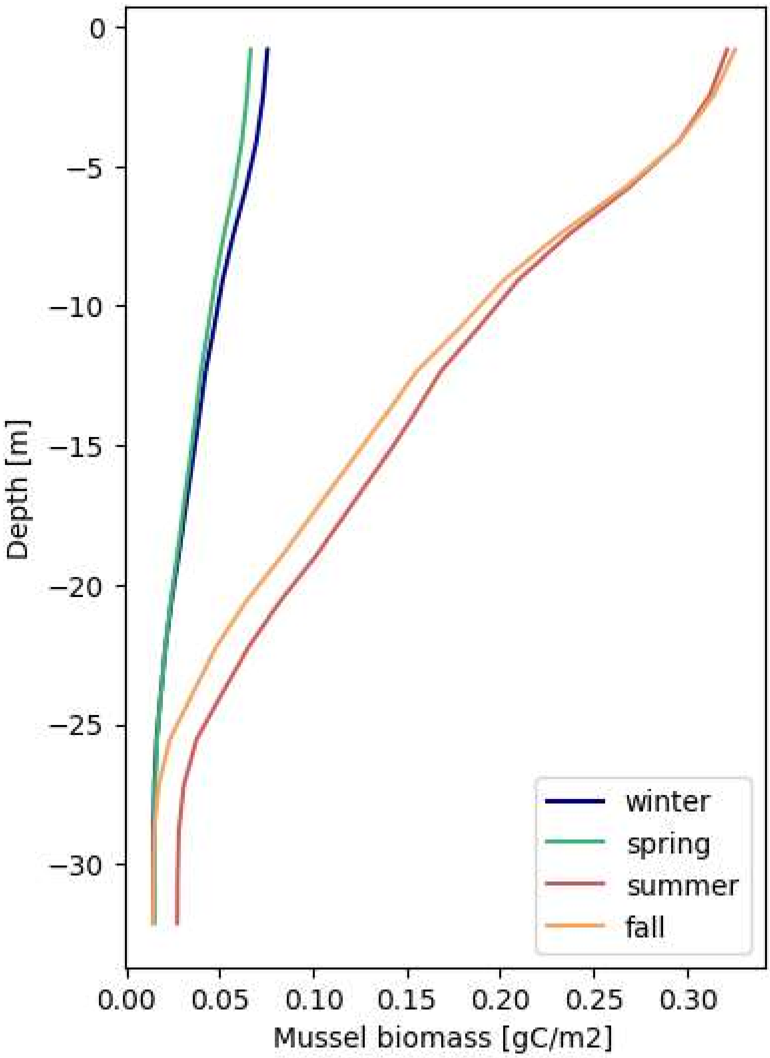

Figure 3.4: Depth profiles per season for V1-moprh initialized over the whole water column.

3.4 Conclusions and next steps

With this data analysis, we can conclude that seeding and initializing mussels in the top 5 m seems to be in line with in-situ data (question 2). However, the assessment areas are too similar regarding their physical (both max 35 m deep), chemical (riverine nutrient supply) and biological (similar phytoplankton dynamics) properties to be able to assess whether different physical, chemical and biological properties would result in different mussel depth distribution (question 1). So using the data analysis, we cannot conclude whether the pelagic conditions or the predation/competition govern the depth distribution of mussels.

At the same time, the model results show that mussels biomass is the highest within the top 5 m of the water column. However, the modelled mussels do occur in deeper areas albeit with lower biomass. Thus, modelled mussels will grow in the deeper areas of the model when initialized to do so (question 3). As we only modelled one location we cannot assess whether different pelagic conditions would lead to different mussel depth profiles. Based on this one model run, one would have to assume that predation/competition governs the depth distribution of mussels.

To test this assumption, we recommend to look at why mussel grow deeper in our model compared to the data. For that in-situ and modelled depth profiles of chlorophyll should be compared. Should those profiles be similar, it might be necessary to implement depth dependent mortality as mussels are grazes on by benthic organisms (such as starfish) that can colonize the deeper sections of a wind pillars. Furthermore, we recommend to analyse whether with the new parameter setting the biomass at offshore location can be modelled with sufficient accuracy. For that the in-situ dataset described in chapter 3.2.1 can be used for comparison.

4 Conclusion and recommendations

4.1 Current state of the model

This study aims to increase understanding of potential alterations in ecosystem dynamics due to large-scale implementation of offshore wind energy by assessing the effects of OWFs on benthic (mussels) and pelagic (zooplankton) grazers. Ultimately, the aim is to examine the competitive interactions between these two types of grazers by modelling zooplankton and mussels simultaneously within the same 3D DCSM model. Although this is technically possible at the current stage, the model results are not sufficiently reliable for zooplankton and lack sufficient validation for mussels. Therefore, a quantitative comparison between the two is not yet feasible. This report contains a technical description of the progress made in 2024 on the modelling of zooplankton and mussels with the objective to improve the parametrization of mussel growth and incorporate the zooplankton within the 3D DCSM-FM modelling framework and contains recommendations for further development.

Zooplankton has been incorporated within the 3D DCSM-FM model, which was not technically feasible in previous years. The current model is not yet capable of producing realistic estimates for absolute zooplankton biomasses, but is able to represent the spatially variable effects of OWFs on zooplankton qualitatively. These qualitative results can be used by Wageningen Marine Research for further analysis of the carbon transfer to higher trophic levels, such as fish and their larvae. To provide realistic quantifications for the spatial and temporal distribution of zooplankton biomass the ecological model requires further improvement. This can be achieved through an iterative process of calibration and validation based on in-situ data. Additional zooplankton data, particularly on species composition and biomass at various times of the year and distances offshore, is highly valuable. However, also the unrealistically low phytoplankton biomass values in winter need to be addressed.

Mussels were already modelled in 3D DCSM-FM in earlier Wozep studies. The current study supports the approach to restrict mussels to the top 5 metres of depth at this stage. The model, incorporating updated DEB parameters for mussels has yet to be run in 3D DCSM-FM and the results require validation. Future improvements on the model should focus on the vertical gradient of mussels, limiting growth at depths below 5 metres.

It is important to recognize the limitations of a comparison based on Dynamic Energy Budget (DEB) theory. DEB theory is useful for evaluating energy allocation within an individual organism or a population and their feedback on lower trophic levels (e.g. on primary production through remineralisation of faeces). However, DEB parameters are species-specific, which introduces challenges when findings are generalized across a diverse range of species. In this study, we encounter this challenge particularly for zooplankton, a very diverse group of organisms. The assumption that a single model species can adequately represent an entire species group is likely over-simplistic. For future research, this limitation can be mitigated by including a second type of zooplankton. However, eliminating species bias within the applied DEB modelling framework is impossible. Additionally, incorporating behavioural characteristics into the DEB model has proven to be challenging. The DEB approach to assess shifts in carbon pathways is very useful, but may not capture all the impacts that offshore wind farms have on the marine ecosystem. E.g. shifts in biodiversity due to changes in habitat requires a different approach. Also, it is likely not feasible to extend the current bottom-up model to trophic levels higher than secondary producers.

4.2 Next steps

To improve the zooplankton modelling, we recommend to:

1. Validate the modelled phytoplankton biomass in winter to test the hypothesis whether the phytoplankton biomass is currently underestimated in the 3D DCSM model.
2. Induce a diapause in zooplankton when food reaches critically low levels and include a density dependent mortality rate.
3. Simulate zooplankton dynamics in DCSM-FM and validate against in-situ data.

To improve the mussel modelling, we recommend to:

1. Compare in-situ and modelled phytoplankton depth profiles.
2. Implement depth dependent grazer mortality for mussels within a 1D-V column model.
3. Test the new parameter setting for different offshore locations.

When the modelling of zooplankton and mussels in is validated after completing these steps, a coupled hydrodynamic-water quality model including zooplankton and mussels can be run to investigate the competition effects between mussels and zooplankton within OWFs. This process should be iterative, continuously integrating additional data and model improvements.

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A Mussel in-situ data analysis

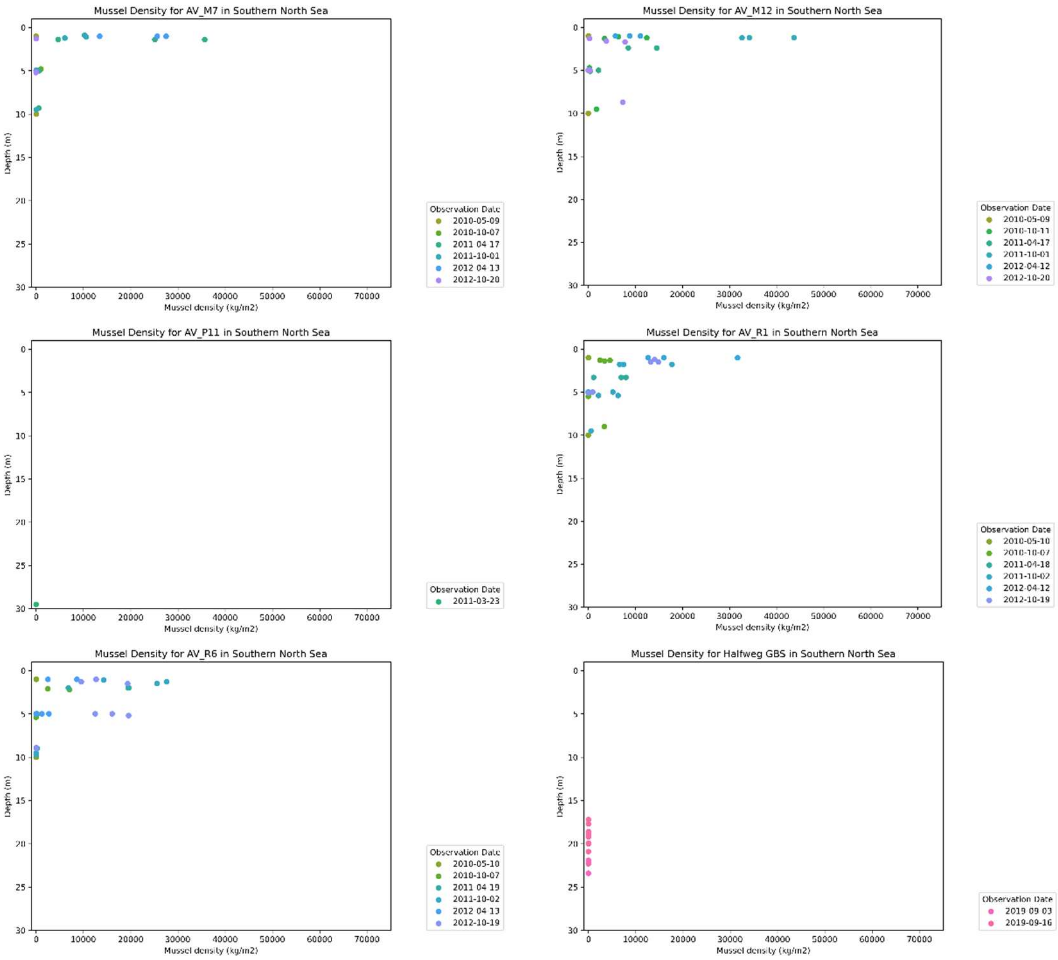

Figure A 1 Mussel densities distribution of depth and color coded according to the sampling date for the different stations located in the assessment area Southern North Sea.

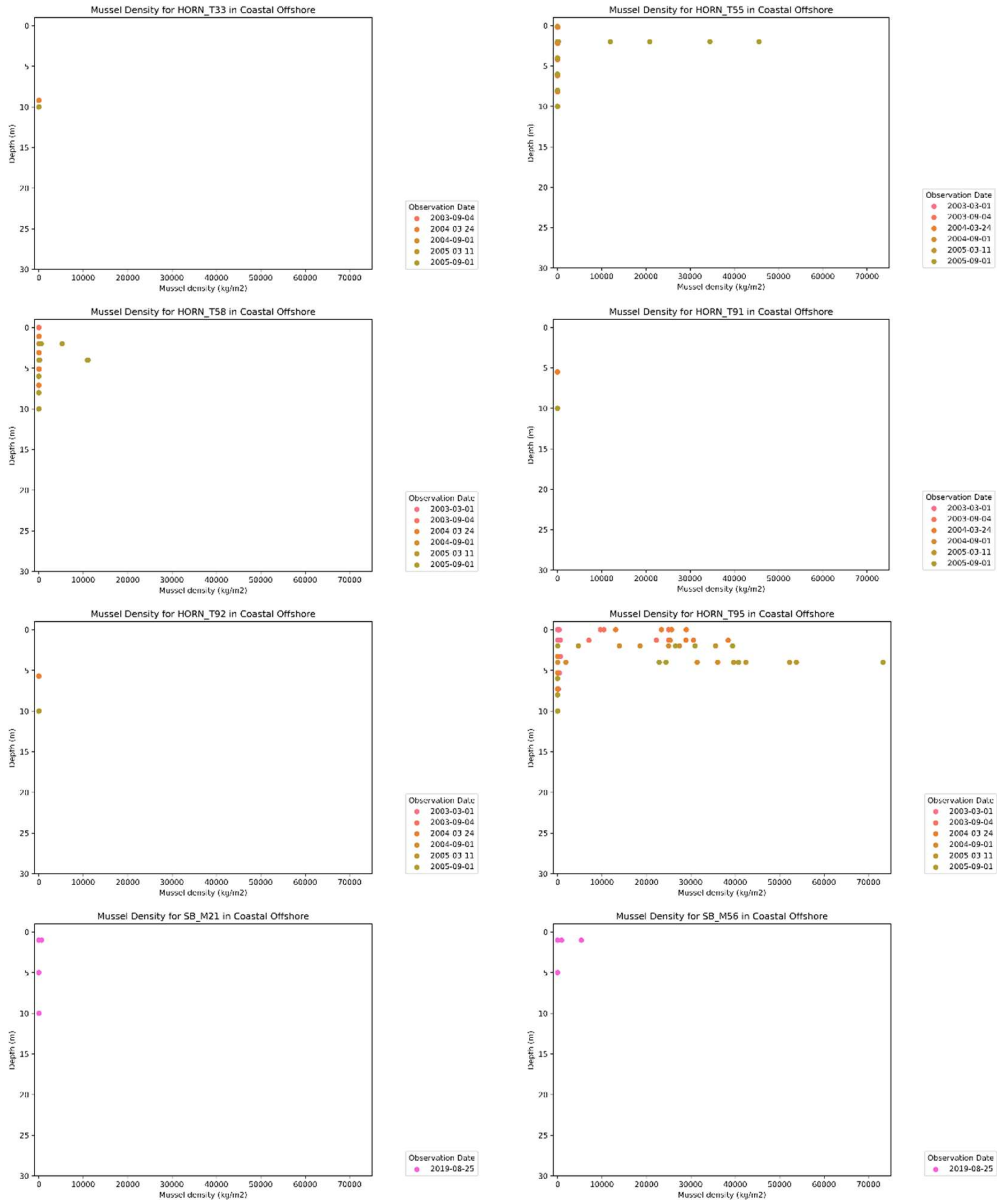

Figure A 2 Mussel densities distribution of depth and color coded according to the sampling date for the different stations located in the assessment area Coastal Offshore

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