Development of Mechanistic Models

Mechanistic Model for the North Sea

Technical documentation on biogeochemical model

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Prepared for Danish EPA (Miljøstyrelsen, Fyn)

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Eelgrass in Kertinge Nor

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1 Executive Summary

The model development presented in this technical note represents the biogeochemical model development for the North Sea. The North Sea model is part of a larger model complex comprising several mechanistic models developed by DHI and a number of statistical models developed by Aarhus University (AU), Bioscience.

The model complex is developed with the overall aim to support the Water Framework Directive (WFD) by introducing mechanistic models in as many Danish water bodies as possible and integrating with Bayesian statistical modelling, and cross-system modelling carried out by AU, Bioscience.

Here we present the overall biogeochemical model set-up covering the North Sea, together with a quality assessment of the model performance. This specific model includes 7 Danish water bodies:

Water Body*)	ID Number
Lister Dyb	107
Juvre Dyb, tidevandsområde	111
Knudedyb, tidevandsområde	120
Grådyb, tidevandsområde	121
Vesterhavet, syd	119
Vesterhavet, nord	133
Skagerrak	221

*) Water bodies defined for the River Basin Management Plans 2015-2021

The North Sea biogeochemical model builds on the developed hydrodynamic model of the North Sea and is developed to describe the biogeochemistry within the model domain with focus on parameters relevant for WFD, including dynamics in nutrients, phytoplankton, primary production, dissolved oxygen, organic matter and benthic vegetation.

The model quality is evaluated from three model performance measures: Percent Bias (P-Bias), Spearman Rank Correlation and Cost Function (CF). According to DHI (2019b), Model Efficiency Factor (MEF) was suggested initially, but during the model development it was concluded that MEF is not suitable to evaluate this kind of biogeochemical models, why Cost Function (CF) is intriduced. The quality measure CF was used in Erichsen and Timmermann (2017) as part of an international evaluation (Hermann et al. 2017). As described in DHI (2019b), the MEF evaluates the Root Mean Square Error (RMSE) to the standard deviation (based on measurements). As model results are compared against measurements at the exact point in time in dynamic estuarine systems with strong gradients the MEF has proven not to be suited (due to it dependency on fully right timing). The CF assesses the fit/misfit between measurements and observations also normalized to the standard deviation (based on measurements) why it is decided to use this measure in the overall assessment of model performance.

Concerning the performance measures, our ambition is to have 75% of all measures (Percent Bias, Spearman Rank Correlation and Cost Function to meet 'excellent', 'very good', or 'good' for all parameters and stations (lumped).

As can be seen from the present technical note, 88% of all data set meet the success criteria when evaluated against the three performance measures, and 84% when assessing both annual performance and summer/winter performance of all data. The average model performance, evaluated at 14 stations within the model domain, for the biogeochemical model of the North Sea is summarized below:

- Model performance measures for dissolved oxygen (DO) are on average 4.2% (P-Bias), 0.7 (Spearman Rank Correlation) and 0.8 (CF). The average model performance for this parameter is categorized to be 'excellent' (P-Bias) and 'very good' (Spearman Rank Correlation and CF).
- Model performance measures for chlorophyll-a (CH) are on average 32.2% (P-Bias), 0.2 (Spearman Rank Correlation) and 0.8 (CF). The average model performance for CH are categorized to be 'very good' (CF), 'good' (P-Bias) and 'poor' (Spearman Rank Correlation).
- Model performance measures for light attenuation coefficient (K_d) are on average 39.4% (P-Bias), 0.2 (Spearman Rank Correlation) and 0.8 (CF). The average model performance for K_d is categorized to be 'very good' (CF), 'good' (P-Bias) and 'poor' (Spearman Rank Correlation).
- Model performance measures for dissolved inorganic nitrogen (DIN) are on average 22.5% (P-Bias), 0.7 (Spearman Rank Correlation) and 0.8 (CF). The average model performance for DIN is categorized to be 'very good' (Spearman Rank Correlation and CF) and 'good' (P-Bias).
- Model performance measures for dissolved inorganic phosphorous (DIP) are on average 16.7% (P-Bias), 0.5 (Spearman Rank Correlation) and 0.8 (CF). The average model performance for this parameter is categorized to be 'very good' (P-Bias, Spearman Rank Correlation and CF)
- Model performance measures for silicate (Si) are on average 31.2% (P-Bias), 0.7 (Spearman Rank Correlation) and 0.9 (CF). The average model performance for Si is categorized to be 'very good' (Spearman Rank Correlation and CF) and 'good' (P-Bias).
- Model performance measures for total nitrogen (TN) are on average 19.7% (P-Bias), 0.64 (Spearman Rank) and 0.6 (CF). The average model performance is categorized to be 'very good' (P-Bias, Spearman Rank and CF).
- Model performance measures for total phosphorous (TP) are on average 38.7% (P-Bias), 0.4 (Spearman Rank) and 0.8 (CF). The average model performance for TP is categorized to be 'very good' (CF) and 'good' (P-Bias and Spearman Rank).

The details behind the above performance are available in Table 5-1, Table 5-2 and Table 5-3. Time-series comparisons are available here: rbmp2021-2027.dhigroup.com (Google Chrome only).

The ambition of meeting 'excellent', 'very good', or 'good' for 75% of all parameters and stations (lumped) has been well reached. The North Sea model will be applied in the Danish waterbodies of the North Sea and contribute with boundary conditions for additional model. In this technical note, we conclude that the North Sea biogeochemical model has been developed successfully for modelling nutrient scenarios in the assessment and maximum allowable inputs (MAI).

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2 Introduction

The model development presented in this technical note represents the biogeochemical model development for the North Sea and builds on top of the North Sea hydrodynamic model (DHI 2019d). Documentation on the model application will be presented in the following reports. The biogeochemical model is part of the mechanistic model complex development, which includes two regional models, three local-domain models, and six estuary specific models. The model complex is developed with the overall aim to support the Water Framework Directive (WFD) by introducing mechanistic models in as many Danish water bodies as possible and integrating with Bayesian statistical modelling and cross-system modelling carried out by AU, Bioscience.

Here we present the overall biogeochemical model set-up covering the North Sea, together with a quality assessment of the model performance. The North Sea model includes the 7 Danish water bodies listed in Table 2-1 below. The location of the Danish water bodies is documented in Erichsen et al (2019).

Table 2-1 Water bodies included in the North Sea model.

Water Body*)	ID Number
Lister Dyb	107
Juvre Dyb, tidevandsområde	111
Knudedyb, tidevandsområde	120
Grådyb, tidevandsområde	121
Vesterhavet, syd	119
Vesterhavet, nord	133
Skagerrak	221

*) Water bodies defined for the River Basin Management Plans 2015-2021

The biogeochemical model computes the development during the modelling period in ecological parameters, including concentrations of nutrients, dissolved oxygen, and organic matter and the Secchi depth, due to, e.g. primary production. The results represent short term changes due to specific weather events, seasonal variations and interannual trends. This project will focus on summer chlorophyll-a and parameters influencing distribution and growth of eelgrass. A detailed description of the specific state variables included in the North Sea biogeochemical model can be found in DHI (2019c).

According to DHI (2019b), the quality measure Model Efficiency Factor (MEF) were suggested as a quality measure initially, but during the biogeochemical model development, it was concluded that MEF is not suitable to evaluate this kind of biogeochemical models. As described in DHI (2019b), the MEF evaluates the RMSE to the standard deviation (based on measurements). As we compare model results to the measurements at the exact point in time in a number of estuary system with strong gradients and variable dynamics, the MEF has proven not to be suited (due to it dependency on fully right timing). For the validation of the biogeochemical models, we have included the quality measure Cost Function (CF) in replacement of MEF (**Error! Reference source not found.**). The CF measure were also used i n Erichsen & Timmermann (2017) and describes how the difference between measured and modelled values is related to the inherent variation in field observations.

3 Modelling Concept

3.1 Mechanistic Modelling

The present technical note represents the biogeochemical part of the model complex covering the North Sea. The North Sea model is one model out of eleven mechanistic models developed to increase the knowledge of pressures and status in Danish marine waters and to provide tools for the Danish EPA as part of the implementation of the WFD. Mechanistic models enable dynamic descriptions of ecosystems and interactions between natural forcing and anthropogenic pressures. Hence, mechanistic models can be applied for predictions of changes in specific components, like chlorophyll-a concentrations, due to changes in e.g. anthropogenic pressures.

The North Sea model is defined as a regional model. The mechanistic model complex development as part of the present projects includes two regional models, three local-domain models, and six estuary specific models:

- The regional models cover both specific Danish water bodies and regional waters, such as the North Sea and a small part of the North Atlantic, which is included in the North Sea-model, and the Baltic Sea, which is covered by the IDW-model (Inner Danish Waters). These models provide model results for specific water bodies but, equally important, give boundaries to local-domain models and estuary specific models.
- Local-domain models are developed to allow for resolving most small and medium-sized water bodies in the north-western Belt Sea, the south-western Belt Sea and the water bodies in and around Smålandsfarvandet.
- Estuary specific models: Six specific estuary (fjord) models are developed to allow for detailed modelling of specific estuaries.

The ecological conditions in marine waters are determined by several different natural factors like water exchange, stratification, water temperature, nutrient availability, sediment characteristics, the structure of the food web etc. On top of that, several anthropogenic factors like nutrient loadings, fishery, etc., also impact the ecosystem and potentially the ecological status.

The model developed in this specific project aims at supporting the Danish EPA's implementation of the WFD. During this project, the models are developed to represent the present period (2002-2016) evaluated against NOVANA measurements. Here we use current data on solar radiation, current nutrient loadings, etc.

After the models are developed, they will be applied for scenario modelling with changed nutrient loading to assess the Maximum Allowable nutrient Inputs (MAIs).

3.2 Model Development

The model development consists of a 3D hydrodynamic model describing the physical system (water levels, current, salinity and water temperatures), and a 3D biogeochemical (ecosystem) model describing the governing biogeochemical pelagic and benthic parameters and processes like phytoplankton, dissolved oxygen, primary production, etc. The model structure is modular, meaning that a hydrodynamic model is developed independently of the biogeochemical model (for further information about the hydrodynamic model see DHI (2019a)). A more detailed description of the biogeochemical model is available in DHI (2019c) and the underlying North Sea hydrodynamic model is described in DHI (2019d).

All mechanistic models have been set up and calibrated/validated for the period 2002-2016 and reported according to the performance measures P-Bias, Spearman Rank Correlation and CF (DHI 2019b). Results from the entire modelling period are furthermore presented as time series in a WEB-tool (rbmp2021-2027.dhigroup.com, Google Chrome only).) with a few examples included in section 5.3. Most data used for calibration and validation originate from the national monitoring programme NOVANA (see http://odaforalle.au.dk for more details). For some models and some parameters, other data are included, and the specific origin of those data will be referenced when used.

3.3 Modelling System

The biogeochemical model is based on the 3D modelling software MIKE 3 HD FM (version 2017) developed by DHI together with the numerical 3D equation solver MIKE ECO Lab to describe the relevant biogeochemical processes in the modelling system. MIKE 3 FM modelling system is based on a flexible mesh approach with horizontal mesh elements of varying size within the modelling domain. The water column is resolved by multiple layers. The modelling system has been developed for applications within oceanographic, coastal and estuarine environments.

The scientific documentation of MIKE 3 HD FM is given in DHI (2019a).

The main components and processes determining the status of the water quality and the response in the ecosystem (e.g. changes in eelgrass biomass) are included in the biogeochemical model. They are based on external factors (meteorology and nutrient supply). The model describes the turnover of organic material and nutrients (dissolved inorganic nitrogen, phosphat and silicate), both in the pelagic (water column) and the benthic phase (seabed or sediment). The pelagic phase includes phytoplankton and nutrients, and the benthic department covers sediment pools of nutrients and the exchange of nutrients between the sediment and water phase. Furthermore, the benthic part of the model describes the biomass and growth of benthic vegetation at the sea bed. The mechanisms behind the biogeochemical model and the ECO Lab templates used are described in DHI (2019c).

4 Model Set-up

The biogeochemical model for the North Sea (UKNS2-HD28-EU) builds on top of the hydrodynamic model (HD) and an integrated transport model (AD). The set-up and calibration/validation of the physical North Sea model (HD and AD) are documented in technical notes (DHI 2019d).

For the present project, the model is set up for the period 2002-2016, which means that all model input data need to cover this period.

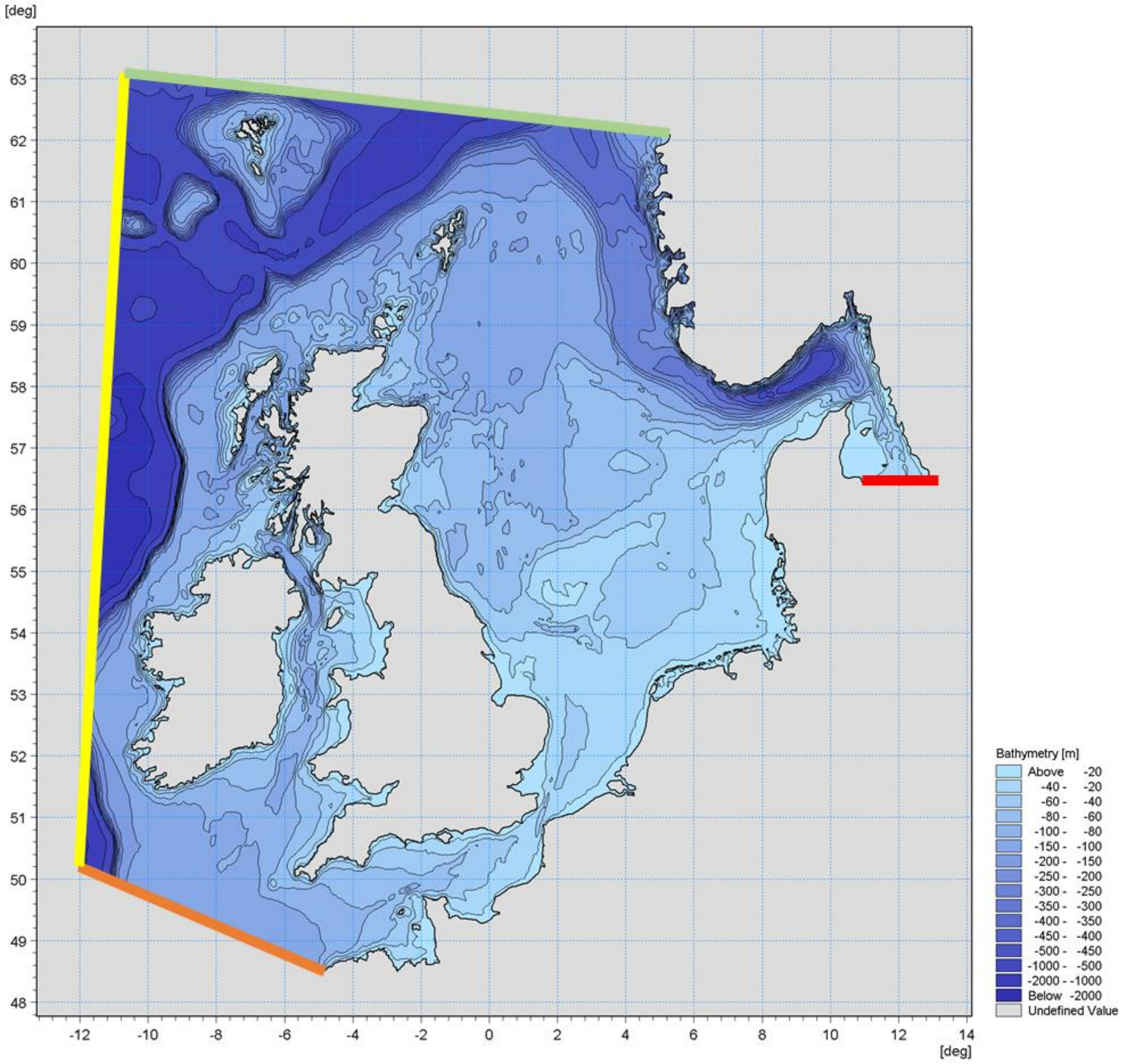

Figure 4-1 Model bathymetry of the North Sea model (UKNS2-HD28). Water depths refer to MSL. The model includes four open boundaries: One in the south-western part of the area (orange line), one west of Ireland (yellow), one just north of the Faroe Islands (green) and one in Kattegat (red).

4.1 Model Domain

The model domain is determined in accordance with the area of interest of the modelling study. Also, considerations of the area of influence, being the surrounding areas that affect the area of interest, and suitable open boundary locations, affect the choice of the model domain.

For the North Sea model being one of DHI's general regional models, the model domain was chosen to include the seas around UK and Ireland as well as the North Sea itself. Skagerrak and part of Kattegat are also included in the model.

The model mesh is the representation of the model domain. More specifically the model mesh defines the model area, the location of the open boundaries, the land-water boundaries, the horizontal and vertical model resolution (discretization), and the water depths (bathymetry) of the area. The bathymetry of the North Sea model is shown in Figure 4-1, whereas Figure 4-2 shows a zoom of the Danish coastal waters in the North Sea. In the vertical mesh the water column is resolved by 13 sigma-layers (same local thickness) from surface to level -61m (or local depth if less than 61m) and up to 33 z-level layers from -61m and below with varying thickness. Further documentation on model mesh and horizontal/vertical resolution of the North Sea HD model can be found in DHI (2019d).

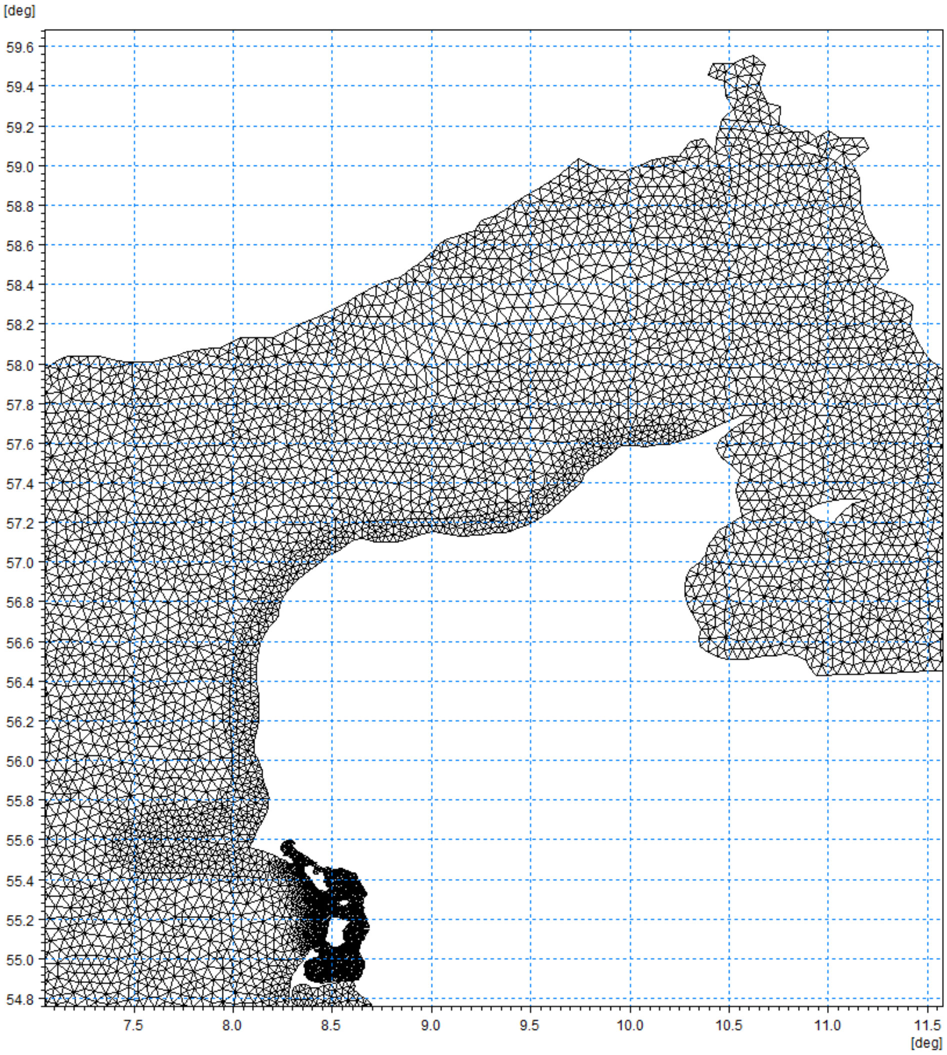

Figure 4-2 Zoom-in showing Danish part of modelling area and resolution of a horizontal model mesh of the North Sea model (UKNS2-HD28).

4.2 Open Boundary Conditions

The North Sea model has four open boundaries: Three boundaries towards the North Atlantic Ocean, and one boundary in southern Kattegat (see Figure 4-1). Biogeochemical boundary data includes data from ICES for the three open boundaries towards the North Atlantic Ocean, and

Swedish[1] observations from Anholt for the Kattegat boundary. Documentation on boundary conditions for the biogeochemical model development is given in DHI (2020).

4.3 Forcings

Data on solar radiation is calculated from clearness percentages and applied as a spatial and temporally varying forcing covering the entire North Sea model domain.

Area distributed atmospheric deposition of nitrogen (N) is provided by AU, Department of Environmental Science, and aligned with HELCOM depositions (see DHI 2020).

To estimate suspended sediment concentrations, a dynamic bottom shear stress information is needed. Wave parameters from a Spectral Wave model are included as model forcing, including significant wave height, wave period and mean wave direction, together with current conditions from the hydrodynamic model results.

Documentation on model forcing is given in DHI (2020).

4.4 Sources

The North Sea model includes sources with land-based nutrient loadings. In Figure 4-3 the location of the sources is illustrated. Freshwater run-off from land is included in the hydrodynamic module. The Baltic Sea inflow (run-off) to the North Sea is included in the model through the Kattegat open boundary.

The model sources are specified as time series with daily loadings of inorganic and organic nutrients, including also total nitrogen (TN) and total phosphorous (TP). The land-based nutrient loadings are based on the following data sources:

- Danish land-based nutrient loadings: DCE/AU, Department of Bioscience
- The Netherlands, Belgium and Germany: Measured data from national monitoring programmes in the individual countries
- United Kingdom, Ireland, France, Sweden and Norway: SMHI model data

More details are included in DHI (2020).

[1] The Swedish data at Anholt are much more frequent than the Danish stations in that area, why these data were applied.

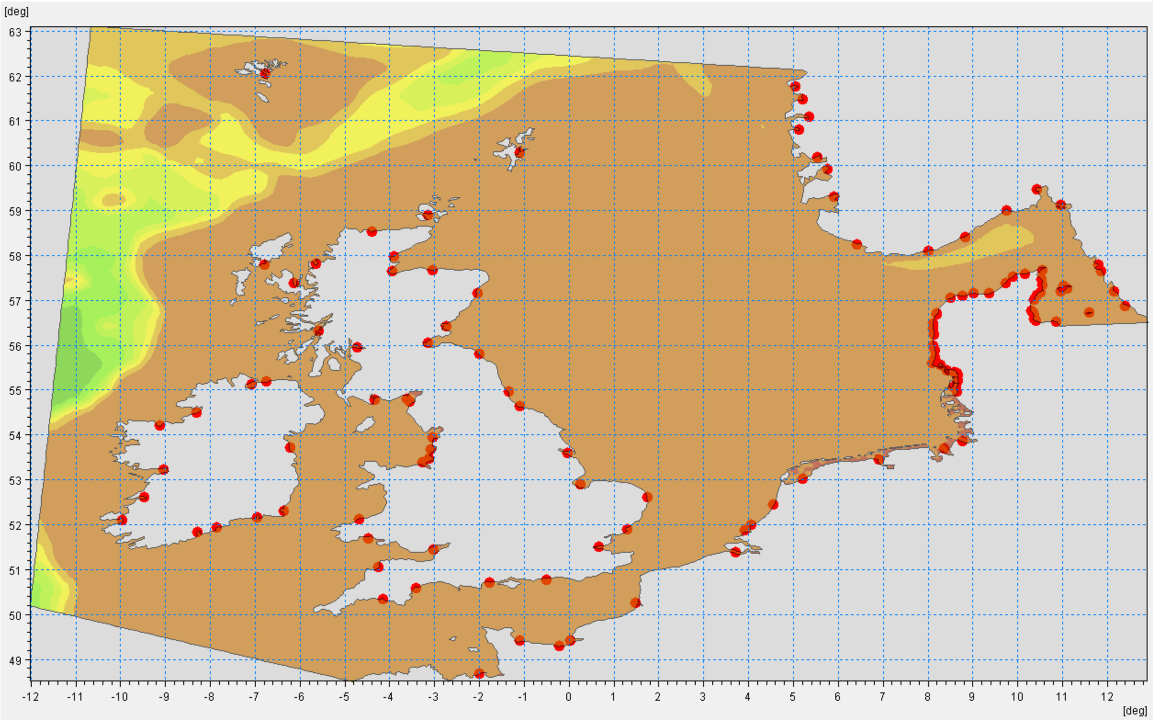

Figure 4-3 Illustration of the location of sources in the North Sea model (UKNS2-HD28). The sources positions represent the main rivers, but loadings are scaled to include all local run-off and point sources from land to sea.

4.5 Initial Conditions

To properly initiate a model simulation, the model requires initial conditions for the various state variables. Initial values in the pelagic phase applied in the North Sea model were estimated based on measurements within the North Sea area. The available measurements from around 2002 were applied as uniform values in the entire model domain, and the model was spun-up by four times run for the year 2002 before being used for calibration/validation.

Initial fields of seabed substrates are based on mud-data from EMODNET (2016). Initial values of benthic vegetation (e.g. eelgrass) were estimated by running a MIKE ECO Lab model with defined initial biomass for the entire model domain for a three-year simulation period.

In DHI (2020) further details on initial model values are given.

5 Model Calibration and Validation

After set-up of the model, calibration and validation of the model are undertaken. The model **calibration** is the process of adjusting model process settings and model constants within the literature range to obtain satisfactory agreement between observations and model results in the local modelling domain. In practice, the model set-up and the model calibration are often performed iteratively, since a good comparison between observations and model results requires a well-proportioned model domain as well as adequate model forcings.

The model **validation** is the process of comparing observations and model results qualitatively and quantitatively for a different period from the calibration period, to demonstrate the suitability of the calibrated model more generally. The qualitative comparison is typically made graphically, and the quantitative comparison is usually made using certain performance (goodness of fit) measures (DHI 2019b; Erichsen & Timmermann 2017). As such, the model validation constitutes the final documentation of the model performance.

The North Sea model was run for the period 2002-2016, and the entire period is used for a combined calibration and validation effort, due to lack of enough observation data for separate calibration and validation tasks. Consequently, model performance measures are presented for this period. The model results compared with observations of the different biogeochemical parameters are presented for the entire period using a WEB-tool (rbmp2021-2027.dhigroup.com, Google Chrome only).

5.1 Model Calibration Procedure

Calibration of the biogeochemical North Sea model is achieved by tuning model constants to optimize model results on calibration parameters compared to measured data. The constants adjusted in the calibration procedure are numerous. They include, e.g. phytoplankton growth rates, grazing rates, mortality rates (phytoplankton and zooplankton), light attenuation constants, sedimentation rates, re-suspension rates, mineralization rates (pelagic and sediment), denitrification rates (pelagic and sediment).

The key parameters to optimize in the calibration procedure include dissolved oxygen, chlorophyll-a, light attenuation, inorganic nutrients, total nitrogen and total phosphorous. After each adjustment of calibration constants, the model is run, and time-series are compared to measured data at selected stations. The procedure is iterated until model results and measured data compare in both time and space.

5.2 Presentation of Key Model Results

During the model calibration procedure, an extensive amount of data on state variables and processes is produced. To allow for a smooth and homogeneous quality assurance, few standard plots and time series are generated automatically and evaluated during the baseline and scenario execution.

Examples of modelled key validation parameters are presented as 2D fields in Figure 5-1 to Figure 5-4, and illustrates the spatial variation of the validation parameters. In the following, a brief assessment of the spatial distribution of key parameters will be given.

Average concentrations of dissolved oxygen in bottom waters during 2016 ranges from a minimum of 6-7 mg/l in the West of Ireland/UK to maximum values of 8-12 mg/l found in the North Sea (Figure 5-1).

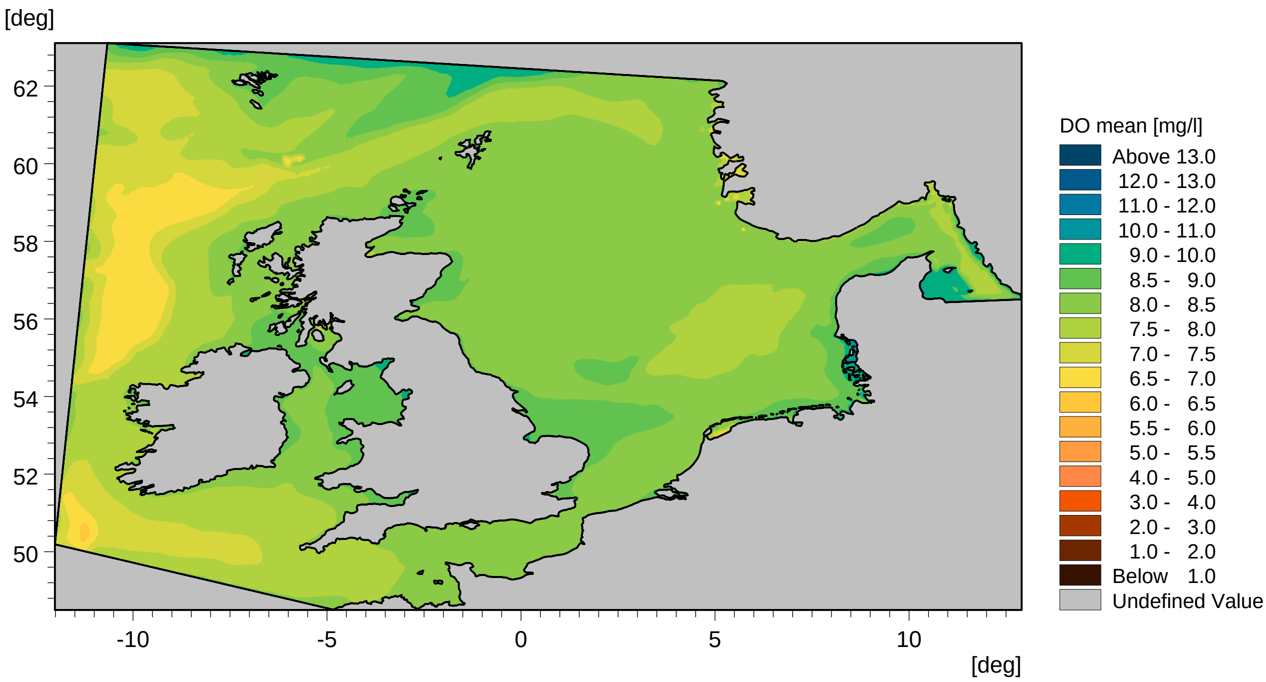

Figure 5-1 Modelled yearly average bottom water concentrations of dissolved oxygen (mg/l) for 2016.

Yearly average concentrations of surface chlorophyll-a during 2016 ranges from less than 1 µg/l near the western and southern boundaries to 1-2 µg/l in the North Sea (Figure 5-2). The highest average concentration of chlorophyll-a in the surface during 2016 is observed in the Danish waters and the German Bight with values ranging from 2 to >3 µg/l.

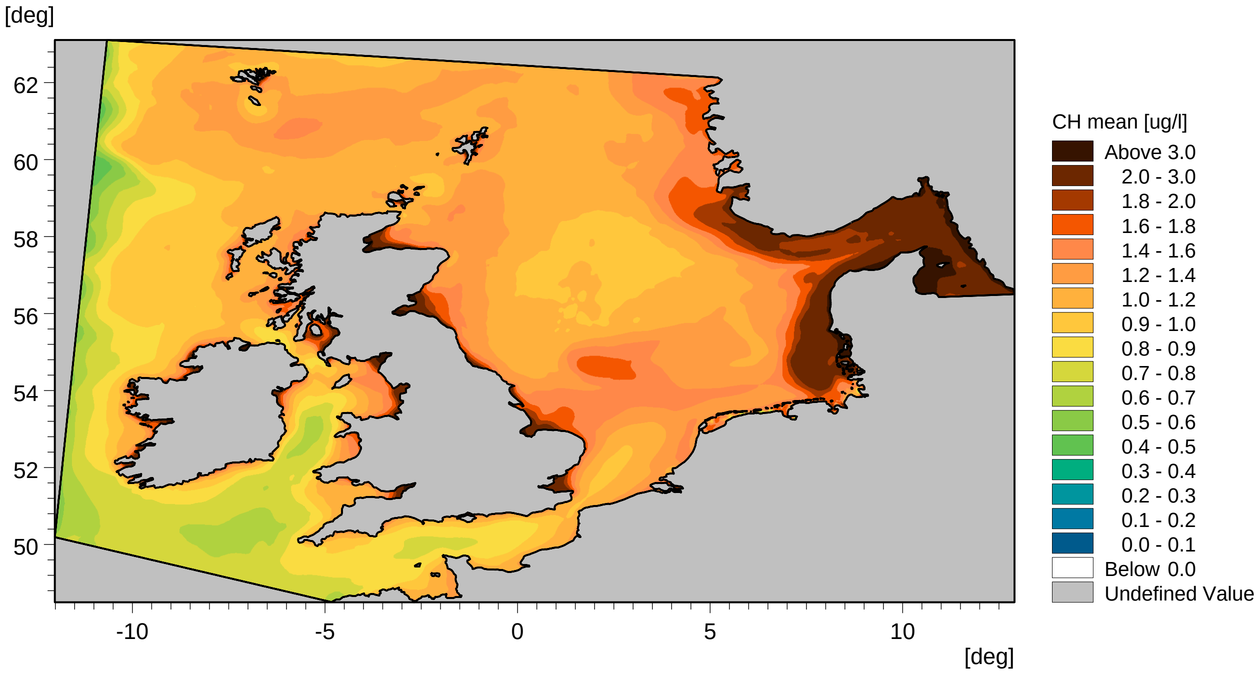

Figure 5-2 Modelled yearly average surface water concentrations of chlorophyll-a (mg/l) for 2016.

Yearly average concentrations of surface total nitrogen during 2016 are highest along the coast near the large river discharges, and especially in the German Bight area, with values ranging between 0.7 - 2 mg/l (Figure 5-3). In the open waters of the model domain, average surface concentrations of total nitrogen range between 0.1 - 0.4 mg/l.

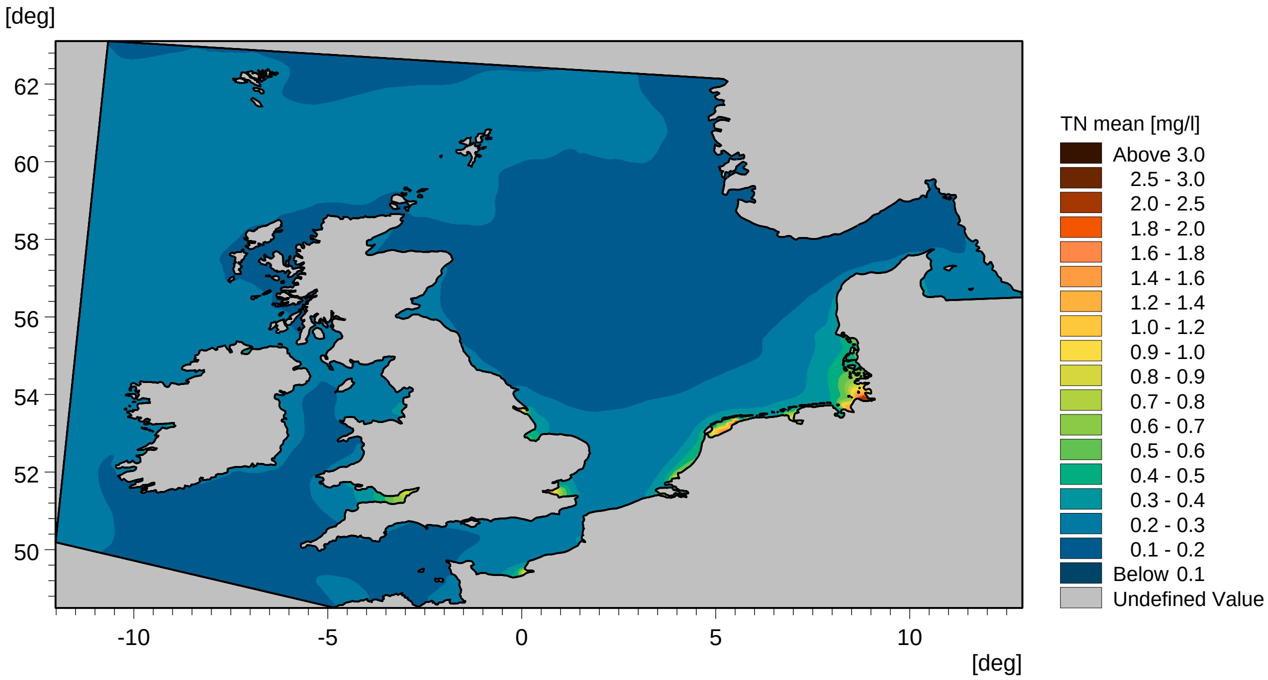

Figure 5-3 Modelled yearly average surface water concentrations of total nitrogen (mg/l) for 2016.

Yearly average concentrations of surface total phosphorous during 2016 are typically between 0.01 mg/l to 0.03 mg/l (Figure 5-4). In some areas close to the larger rivers mean values reach a maximum of 0.1 mg/l.

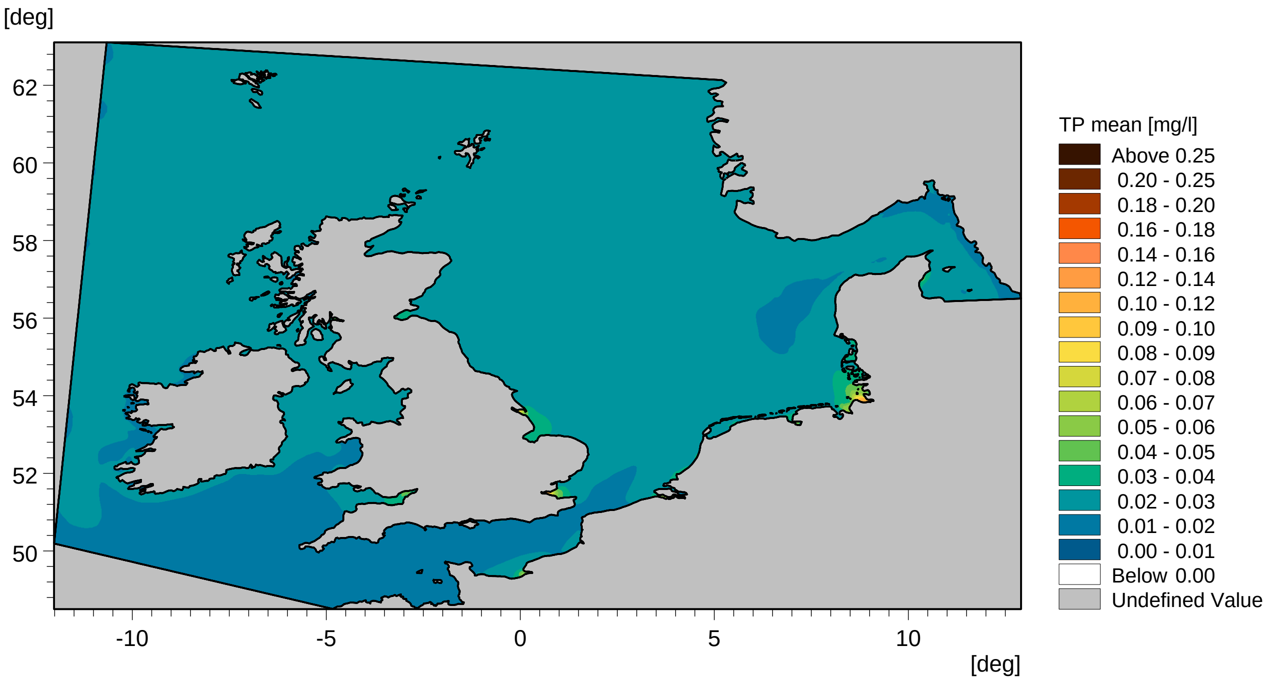

Figure 5-4 Modelled yearly average surface water concentrations of total phosphorous (mg/l) for 2016.

5.3 Model Performance

The North Sea biogeochemical model was calibrated and validated against measured data (observations) on modelled ecosystem parameters at selected stations within the model domain. Figure 5-5 and Figure 5-6 show the location of 19 stations within the model domain. Out of the 19 stations, 14 stations had enough measurement data in the period 2002-2016 to be included in the model calibration and validation (at least one year of weekly or bi-weekly data). The biogeochemical calibration/validation parameters include dissolved oxygen (DO), chlorophyll-a (CH), light attenuation (K_d), silicate (Si), dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorous (DIP), total nitrogen (TN) and total phosphorous (TP). Generally, the North Sea model compares well to the measurements in terms of model parameters (see Figure 5-1 to Figure 5-4 and Figure 5-7 to Figure 5-14), and the overall performance measure (summarized in Table 5-1 to Table 5-3) confirms a statistically good agreement between measurements and model results.

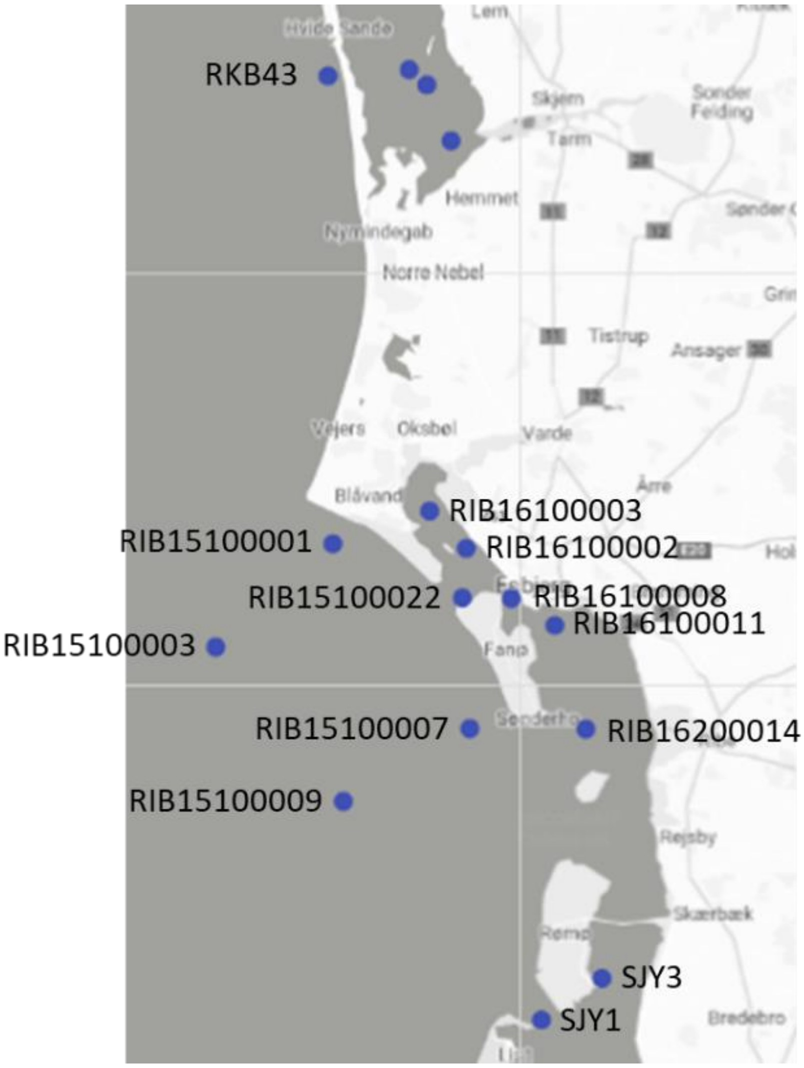

Figure 5-5 Locations used for performance measures in the southern part of the Danish North Sea area (only stations with an ID).

Figure 5-6 Locations of stations within the northern part of the Danish North Sea area. Only station NOR7715 had enough data to be included in the calibration/validation procedure.

5.3.1 Calibration/Validation at Station RKB43

In the following, we present an example on the calibration/validation from the North Sea at station RKB43 and refer to rbmp2021-2027.dhigroup.com (Google Chrome only) for more details on the Danish measurement stations. The location of station RKB43 is shown in Figure 5-5.

The comparison at station RKB43 shows a good agreement between the measurements and the North Sea model for 87.5% of the parameters according to the three performance measure P-Bias, Spearman Rank Correlation and CF (see Table 5-1, Table 5-2 and Table 5-3).

In Figure 5-7 measured and modelled concentrations of dissolved oxygen (DO) at station RKB43 in the surface and at bottom waters (here 10 m) are shown. From the figure, it is seen that for DO the variability and seasonality of the surface and bottom waters are well represented by the model. This is in agreement with the statistical performance measures (see Table 5-1 to Table 5-3), where measured and modelled DO compare 'excellent' (P-Bias) and 'very good' (Spearman Rank Correlation and CF) at station RKB43.

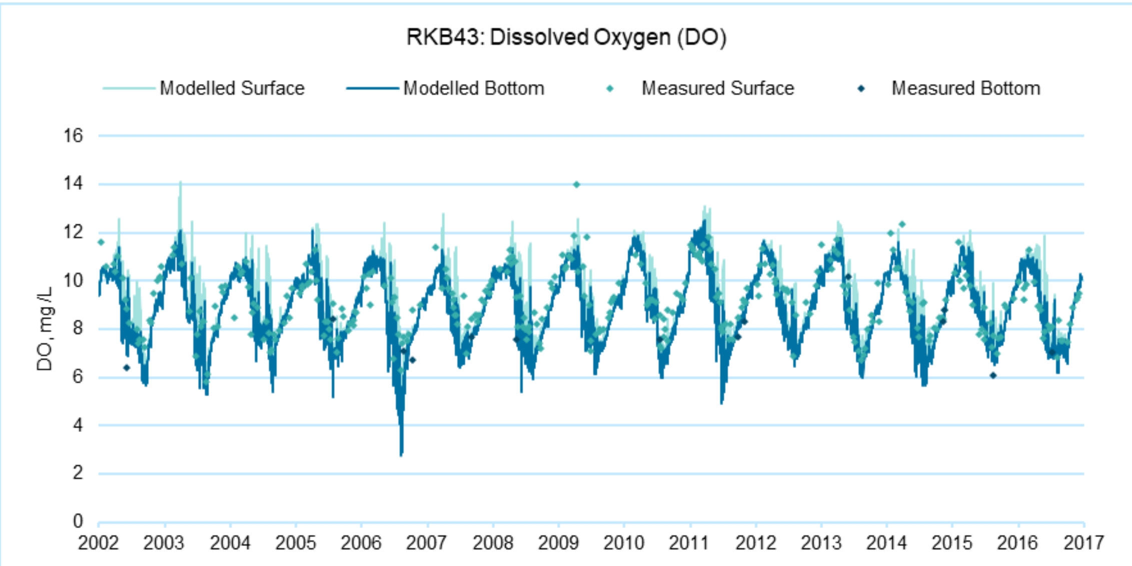

Figure 5-7 Comparison of measured and modelled concentrations of dissolved oxygen (mg/l) at station RKB43 in the surface and bottom (10 m) waters. Dots represent measurements, and the solid line shows modelled data for the entire period.

For chlorophyll-a (CH), the dynamics in seasonality are also well represented by the model (see Figure 5-8). During 2007, however, an extensive bloom was observed in measured bottom CH (up to 300 µg/l, out of plotting range) and this is not detected in the modelled bottom waters. From the statistical performance measures, CH compares ‘very good’ and ‘good’ according to CF and P-Bias, respectively (Table 5-1 and Table 5-3) and ‘poor’ based on Spearman Rank Correlation (Table 5-2).

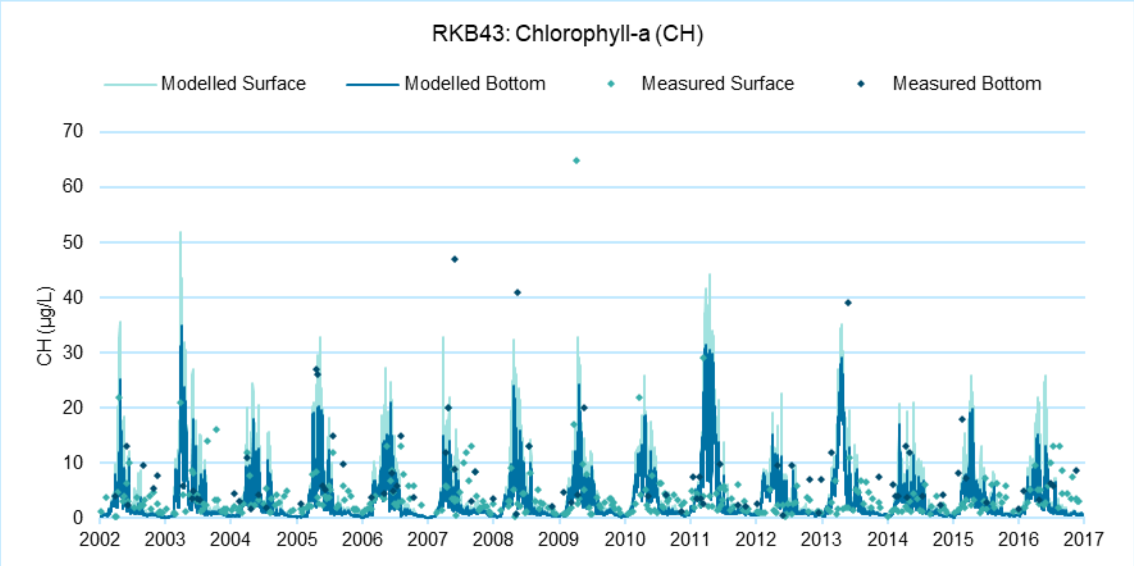

Figure 5-8 Comparison of measured and modelled concentrations of chlorophyll-a (µg/l) at station RKB43 in surface and bottom (10 m) waters. Dots represent measurements, and solid lines show modelled data for the entire period.

The measured light attenuation coefficient (K_d) presented in Figure 5-9 shows a relatively large variability for RKB43. The lower parts of the seasonal dynamics predicted by the model represent the seasonality in measured data. However, especially the high K_d values in the observed data do not compare accordingly. The statistical performance for the annual period measured by P-Bias and Spearman Rank Correlation for this parameter is ‘poor’ (see Table 5-1 and Table 5-2).

When considering the quality measure CF for this parameter (Table 5-3), it is noted that on average the model error is 79% of the standard deviation of the measurements and based on this measure the model meets the ‘very good’ model performance. The model performance for summer (March to September) measurements on K_d evaluated by P-Bias is categorized to be ‘good’, suggesting that the absolute values during summer months are captured by the model prediction. The K_d parameter in the biogeochemical model is developed to account for light attenuation including effects from chlorophyll-a, particulate organic material, coloured dissolved organic matter as well as fine inorganic sediments. Sediment transport at the Danish part of the North Sea coast also entails sediment-fractions not included in the model and with different settling velocities, why the differences between model and measurements are significant during periods. However, light penetration is primarily essential for bottom vegetation and, hence, not that important for the North Sea model since the presence of eelgrass and macroalgae is limited in the Danish part of the North Sea.

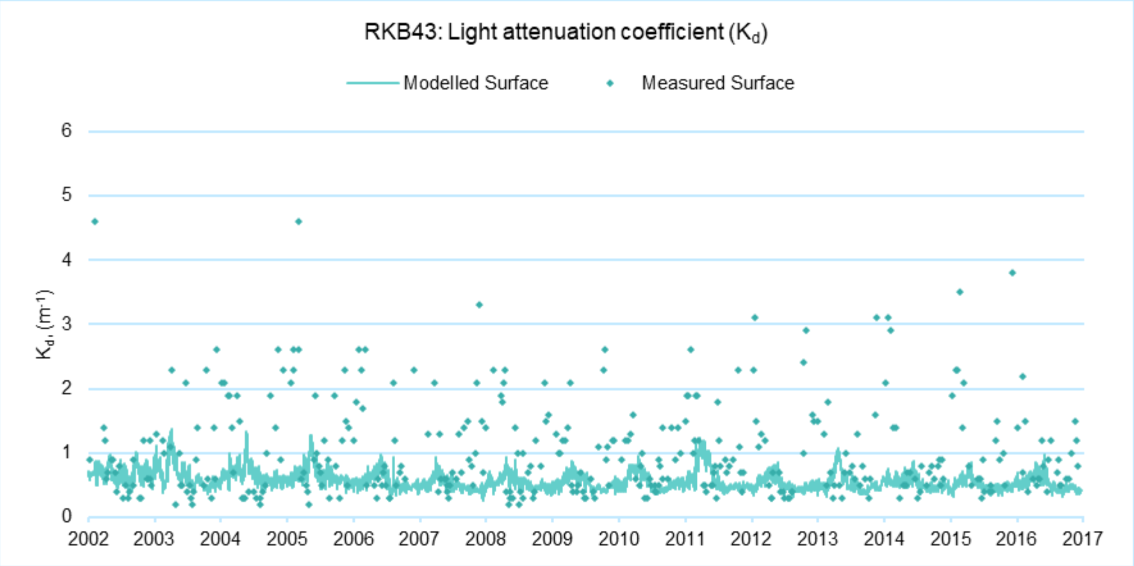

Figure 5-9 Comparison of measured and modelled light attenuation coefficient (K_d) at station RKB43 in the surface waters. Dots represent measurements, and the solid line shows modelled data for the entire period.

For dissolved inorganic nitrogen (DIN), the structure in the seasonality is well represented by the North Sea model (see Figure 5-10), with a tendency to overestimate the summer concentrations. From the statistical performance measures, annual DIN compares 'very good' according to P-Bias and CF (Table 5-1 and Table 5-3) and 'good' based on Spearman Rank (Table 5-2).

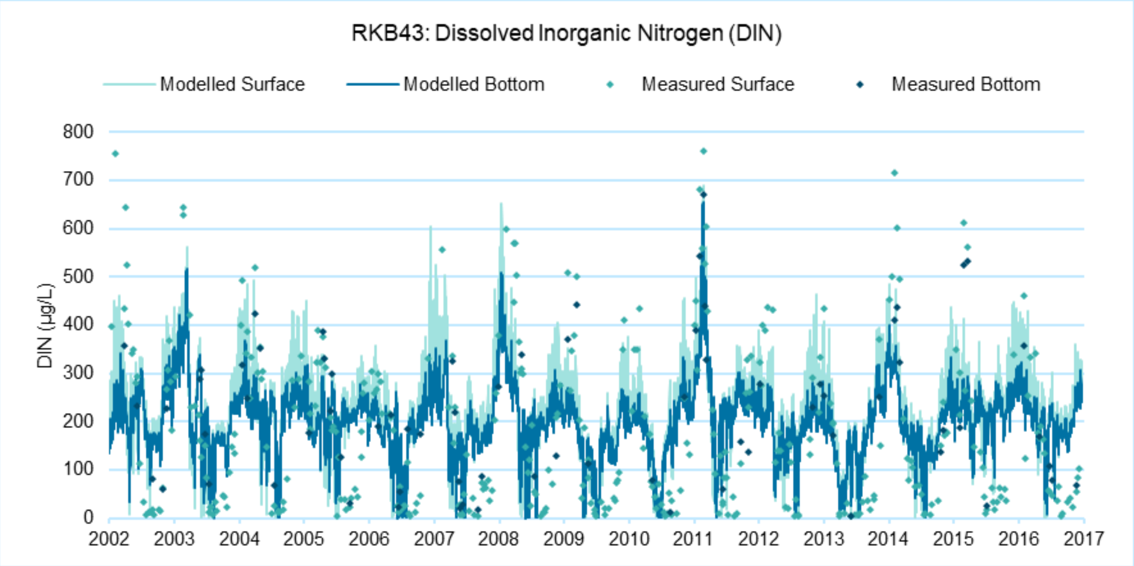

Figure 5-10 Measured and modelled concentrations of dissolved inorganic nitrogen (DIN) at station RKB43 in the surface and bottom (10 m) waters. Dots represent measurements, and solid lines show modelled data for the entire period.

When comparing measured and modelled concentrations of DIP (see Figure 5-11), we see relatively similar winter concentrations and a definite drop in spring. During the summer, the model shows a somehow more dynamic pattern than observed in the measurements. Hence, the overall patterns are well represented by the model, which is further supported by the statistical performance measures, where the model performance for all DIP is 'very good' for all measures at RKB43, and 'excellent' for winter DIP measured from P-Bias (Table 5-1 to Table 5-3).

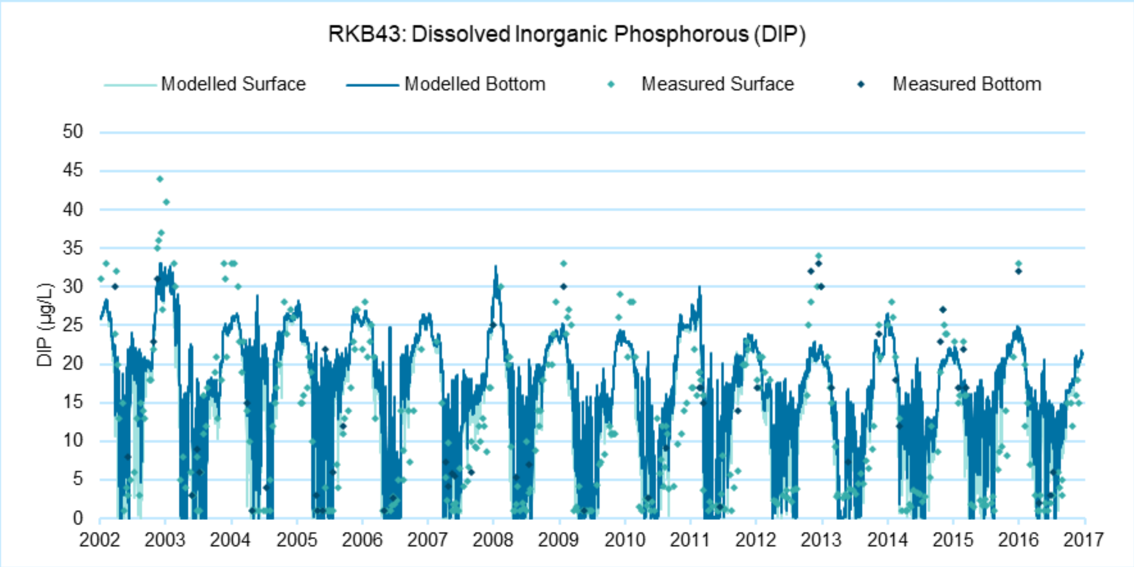

Figure 5-11 Measured and modelled concentrations of dissolved inorganic phosphorous (DIP) at station RKB43 in the surface and bottom (10 m) waters. Dots represent measurements, and solid lines show modelled data for the entire period.

The comparison of the measured and modelled concentration of silicate (Si) presented in Figure 5-12 shows that the North Sea biogeochemical model represents the measured data appropriately in both times and through the water column. The statistical performance measures support this agreement between all measured and modelled Si concentrations and categorizes the model performance at station RKB43 to be 'excellent' (P-Bias), 'very good' (Spearman Rank Correlation and CF).

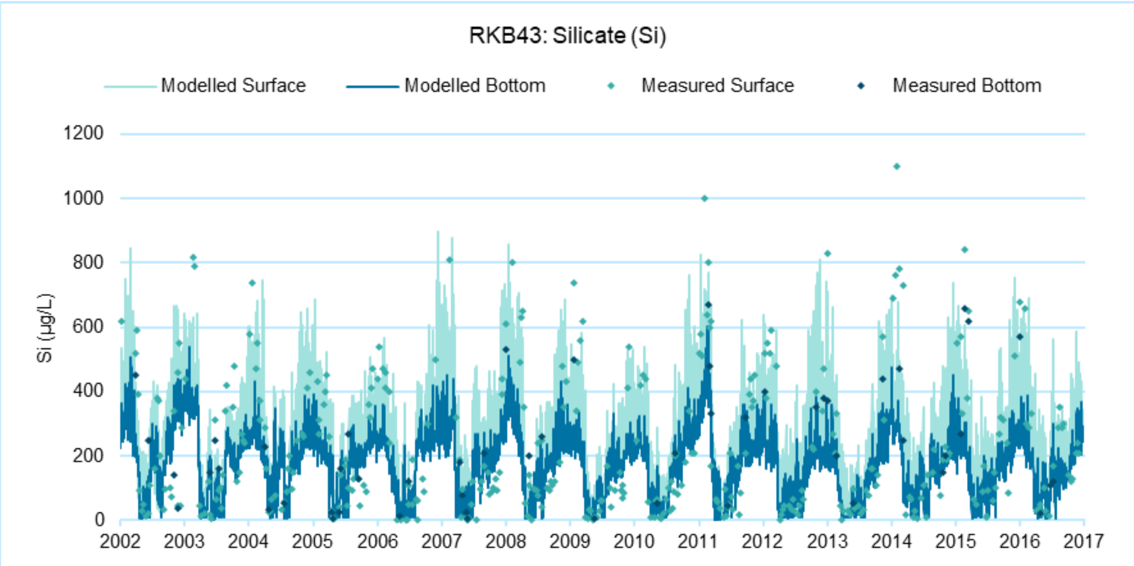

Figure 5-12 Shows measured and modelled concentrations of silicate (Si) at station RKB43 in the surface and bottom (10 m) waters. Dots represent measurements, and solid lines show modelled data for the entire period.

In Figure 5-13 comparisons of measured and modelled total nitrogen (TN) at station RKB43 in surface water and bottom (10 m) water are shown. For TN, the variability in time and through the water column is well represented by the model. This is supported by the statistical performance measures (see Table 5-1 to Table 5-3), where measured and modelled TN compare 'excellent' (P-Bias), 'very good' (CF) and 'good' (Spearman Rank Correlation) at station RKB43.

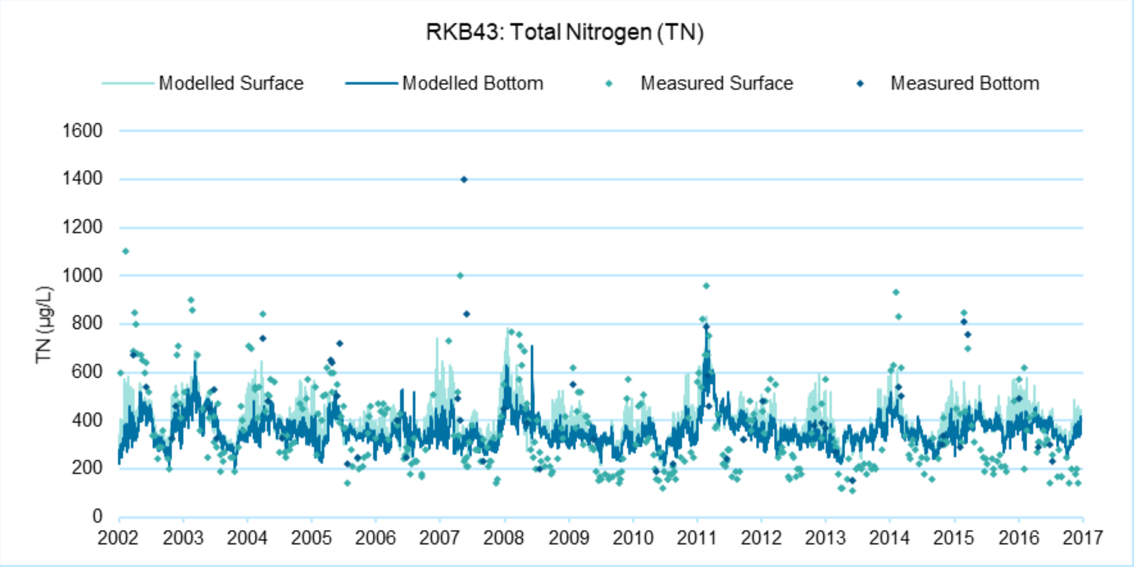

Figure 5-13 Comparison of measured and modelled concentrations of total nitrogen (TN) at station RKB43 in surface and bottom (10 m) waters. Scatter data represent measurements, and solid lines show modelled data for the entire period.

The seasonal dynamics in TP predicted by the model (see Figure 5-14) compare well with measured data on TP. The model tends to predict more accurately for surface water compared to bottom water values. According to P-Bias and Spearman Rank Correlation, the model performance for TP is ‘good’. The statistical performance measure CF evaluates the model performance for TP as ‘very good’ with a CF value of 0.51, indicating that the model error on average is 51% of the standard deviation of the observed TP.

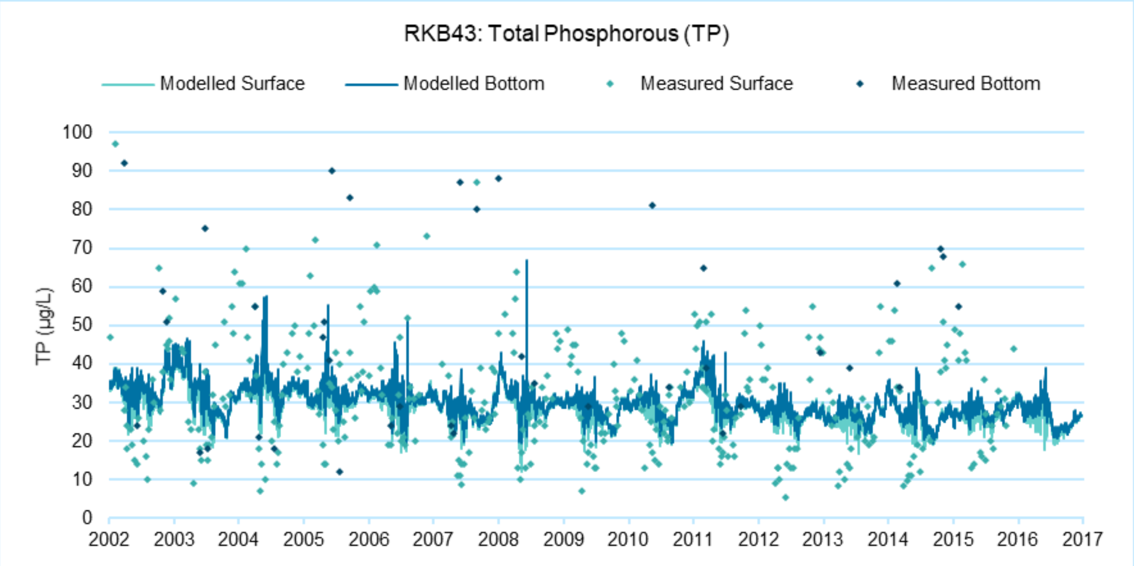

Figure 5-14 Comparison of measured and modelled concentrations of total P (TP) at station RKB43 in surface and bottom (10 m) waters. Scatter data represent measurements, and solid lines show modelled data for the entire period. The y-axis has been cut to better explain the model and measured concentrations, but some bottom measured data reaches levels above 250 µg/l.

5.3.2 General Calibration/Validation for Danish Waters

For the calibration/validation period (2002-2016) 14 out of the 19 stations had a sufficient amount of measurement data (at least one year of weekly or bi-weekly data) to be included in the model performance analysis (stations NOR7715, RIB1510001, RIB1510003, RIB1510007, RIB1510009, RIB1510022, RIB1610002, RIB1610003, RIB1610008, RIB1610011, RIB1620014, RKB43, SJY1, and SJY3). Figure 5-5 and Figure 5-6 show the different Danish locations with measurements on ecosystem parameters (chlorophyll-a (CH), light attenuation (K_d), dissolved oxygen (DO), Silicate (Si), dissolved inorganic phosphorous (DIP), dissolved inorganic nitrogen (DIN), total nitrogen (TN), and total phosphorus (TP)) during the period 2002-2016. Time series data are presented using the WEB-tool (http:// rbmp2021-2027.dhigroup.com).

In Table 5-1 to **Error! Reference source not found.** the model performance are evaluated according to DHI (2019b) based on three performance measures: P-Bias, Spearman Rank Correlation and CF.

In the tables, colour codes are included to highlight the overall model performance as ‘excellent’, ‘very good’, ‘good’ or ‘poor’. For the biogeochemical model covering the North Sea, we aim at ‘excellent’, ‘very good’ or ‘good’ model performance for 75% of the data sets on measures. All model performances (both annual and summer/winter) evaluated against the three different quality measures at 14 stations were found to be ‘excellent’, ‘very good’ or ‘good’ for 84% of the measurements (see Figure 5-15 and Table 5-1 to Table 5-3). The annual model performance was found to be ‘excellent’, ‘very good’ or ‘good’ for 88% of the measurements.

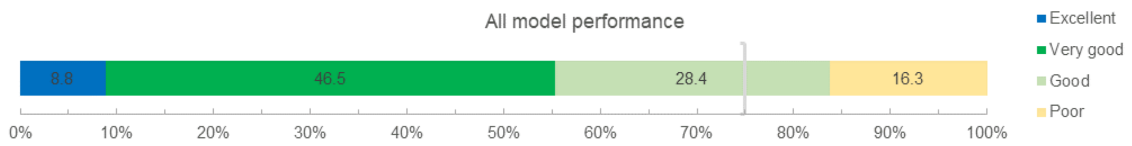

Figure 5-15 Bar chart illustrating all model performance evaluated against three different quality measures and all parameters. Vertical line indicates the aim of 75% being ‘excellent’, ‘very good’ or ‘good’.

According to P-Bias (Table 5-1) the model meets ‘excellent’, ‘very good’ or ‘good’ for 76% of all measurements (including specific winter and summer evaluations) and 79% when evaluating the annual measurements only. A ‘good’ model performance measured by P-Bias for summer and winter measurements indicates that the predicted absolute values of summer chlorophyll a, summer light attenuation, and winter inorganic nutrient concentrations correspond well to the observed values. In general, the P-Bias obtains negative values for most of the parameters, indicating that the model underestimates observed values. On average, P-bias evaluates the model performance for dissolved oxygen to be ‘excellent’; for DIP and TN the model performance is on average ‘very good’ and for CH, DIN, Si and TP the average performance is ‘good’. The model performance for K_d evaluated from P-Bias is on average ‘poor’.

From the quality measure Spearman Rank Correlation (Table 5-2) the model performance meets ‘excellent’, ‘very good’ or ‘good’ in 74% of all measurements (including specific winter and summer evaluations) and 84% in the annual measurements. A good annual correlation obtained from the Spearman Rank measure indicates a good seasonal correlation, where the predicted dynamics correspond well with the observed seasonal variability. On average, the Spearman Rank Correlation evaluates the model performance for dissolved oxygen, DIP, Si and TN to be ‘very good’. For DIN and TP, the average performance is ‘good’. The average model performance for all CH and K_d evaluated from Spearman Rank Correlation is on average ‘poor’. However, when considering the annual performance for CH alone, the model performance is assessed as ‘good’.

According to the performance measure CF (Table 5-3), the model meets ‘excellent’, ‘very good’ or ‘good’ in 100% of all measurements at the 14 stations. On average, the Cost Function evaluates all parameters to be ‘very good’ for all measures and ‘good’ for winter Si.

Table 5-1 Review of model performance at station P-Bias (%) based on measured and modelled data for the validation period 2002-2016. Blue colour indicates an ‘excellent’ model (|x|≤10%), dark green indicates a ‘very good’ model (10<|x|<20%), light green indicates a ‘good’ model (20<|x|<40%) and yellow indicates a ‘poor’ model (|x|>40%).

Station	TN	TP	DIP		DIN		CH		DO	Si		K_d		Number of observations	
	Annual	Annual	Annual	Winter[a]	Annual	Winter[a]	Annual	Summer[b]	Annual	Annual	Winter[a]	Annual	Summer[c]	Annual	Summ/Wint
NOR7715	-8.6	5.9	37.1	18.7	-6.1	-16.5	22.7	17.8	-3.0	-16.4	-29.7	-5.3	12.6	[283-435]	[92-197]
RIB1510001	-25.9	-26.5	4.1	-10.8	0.0	-32.5	-44.0	-45.6	-7.0	-42.6	-48.3	-55.6[d]	-45.9[d]	[96-101]	[14-70]
RIB1510003	-21.0	-4.3	13.9	-5.2	-3.7	-30.2	-6.2	-3.9	-7.7	-39.6	-48.3	-37.7[d]	-21.2[d]	[102-102]	[14-75]
RIB1510007	-10.7	-22.3	9.8	-10.6	8.8	-34.9	-24.7	-28.8	-7.1	-24.5	-47.9	-47.6[d]	-34.3[d]	[284-310]	[52-209]
RIB1510009	-18.0	-11.0	10.8	-18.0	-3.5	-36.3	-9.2	-10.4	-7.6	-38.8	-54.8	-35.8[d]	-21.4[d]	[171-173]	[25-124]
RIB1510022	-29.3	-56.9	-21.2	-0.3	-13.8	-25.4	-49.9	-60.8	-2.6	-11.7	-28.5	-58.9[d]	-56.2[d]	[98-99]	[19-63]
RIB1610002	-5.1	-42.3	-16.3	14.9	-10.3	-15.3	-5.3	-20.6	3.7	15.4	-11.3	-50.2[d]	-44.2[d]	[276-315]	[55-187]
RIB1610003	-38.3	-74.9	-40.7	8.9	-37.1	-32.6	-80.1	-87.7	-7.3	-29.6	-33.9	-76.8[d]	-79.9[d]	[98-99]	[19-63]
RIB1610008	-37.3	-63.5	-35.8	-1.2	-33.5	-39.2	-39.4	-56.8	0.6	-30.8	-40.9	-66.1[d]	-67.5[d]	[106-107]	[22-68]
RIB1610011	-36.1	-65.6	-36.9	1.2	-32.9	-44.7	-54.7	-63.9	-2.6	-33.9	-45.3	-61.7[d]	-62.1[d]	[97-99]	[20-61]
RIB1620014	-4.7	-47.9	2.6	20.4	4.2	-21.3	-16.4	-24.3	-0.8	4.8	-27.5	-47.5[d]	-29.8[d]	[200-224]	[41-136]
RKB43	-1.1	-25.6	19.9	-0.4	15.1	-14.5	-22.8	-34.8	-0.6	-1.0	-24.9	-45.0	-25.9	[370-459]	[85-237]
SJY1	-20.7	-47.3	-28.8	-20.1	-17.7	-42.0	-22.5	-19.3	-5.8	-30.2	-51.4	-14.1	5.5	[115-179]	[27-82]
SJY3	-19.2	-58.9	-52.5	-7.6	-29.3	-28.8	-2.5	-25.2	1.9	-22.2	-38.5	-35.3	-29.5	[261-478]	[70-234]

[a] Jan, Feb, Dec
[b] May-Sep
[c] Mar-Sep
[d] K_d calculated from Secchi Depth (SD)

Table 5-2 Review of model performance at station Spearman Rank Correlation (no unit) based on measured and modelled data for the validation period 2002-2016. Blue colour indicates an ‘excellent’ model (≥0.9), dark green indicates a ‘very good’ model (0.9-0.6), light green indicates a ‘good’ model (0.6-0.3) and yellow indicates a ‘poor’ model (<0.3).

Station	TN	TP	DIP		DIN		CH		DO	Si		K_d		Number of observations	
	Annual	Annual	Annual	Winter[a]	Annual	Winter[a]	Annual	Summer[b]	Annual	Annual	Winter[a]	Annual	Summer[c]	Annual	Summ/Wint
NOR7715	0.56	0.60	0.77	0.37	0.64	0.45	0.36	0.13	0.88	0.77	0.27	0.39	0.28	[283-435]	[92-197]
RIB1510001	0.54	0.41	0.62	0.54	0.58	0.72	0.35	0.03	0.78	0.59	0.63	0.22[d]	0.31[d]	[96-101]	[14-70]
RIB1510003	0.55	0.36	0.72	0.31	0.50	0.67	0.33	-0.11	0.78	0.71	0.78	0.11[d]	0.15[d]	[102-102]	[14-75]
RIB1510007	0.61	0.46	0.71	0.28	0.61	0.55	0.16	-0.14	0.74	0.73	0.57	0.14[d]	0.24[d]	[284-310]	[52-209]
RIB1510009	0.65	0.41	0.75	0.18	0.59	0.68	0.20	-0.20	0.81	0.72	0.73	0.10[d]	0.20[d]	[171-173]	[25-124]
RIB1510022	0.60	0.53	0.60	0.49	0.77	0.79	0.42	0.20	0.58	0.74	0.66	0.25[d]	0.18[d]	[98-99]	[19-63]
RIB1610002	0.76	0.39	0.61	0.36	0.80	0.77	0.37	-0.06	0.46	0.77	0.72	0.14[d]	0.06	[276-315]	[55-187]
RIB1610003	0.80	0.17	0.49	0.35	0.86	0.63	0.48	0.40	0.31	0.73	0.44	0.16[d]	0.07[d]	[98-99]	[19-63]
RIB1610008	0.84	0.46	0.49	0.26	0.83	0.74	0.52	0.15	0.60	0.80	0.67	0.36[d]	0.30[d]	[106-107]	[22-68]
RIB1610011	0.61	0.30	0.42	0.38	0.77	0.75	0.42	0.09	0.65	0.74	0.67	0.27[d]	0.37[d]	[97-99]	[20-61]
RIB1620014	0.64	0.50	0.67	0.34	0.71	0.47	0.21	-0.14	0.78	0.79	0.45	0.16[d]	0.23[d]	[200-224]	[41-136]
RKB43	0.55	0.47	0.80	0.42	0.59	0.59	0.20	-0.19	0.82	0.71	0.42	0.00	0.17	[370-459]	[85-237]
SJY1	0.67	0.35	0.67	-0.18	0.72	0.62	0.33	0.05	0.71	0.75	0.75	0.08	0.14	[115-179]	[27-82]
SJY3	0.61	0.27	0.48	0.27	0.76	0.62	0.35	0.04	0.51	0.69	0.65	0.24	0.34	[261-478]	[70-234]

[a] Jan, Feb, Dec
[b] May-Sep
[c] Mar-Sep
[d] K_d calculated from Secchi Depth (SD)

Table 5-3 Review of model performance at station Cost Function (CF, no unit) based on measured and modelled data for the validation period 2002-2016. Blue colour indicates an 'excellent' model (≤0.4), dark green indicates a 'very good' model (0.4-1), light green indicates a 'good' model (1-2) and yellow indicates a 'poor' model (≥3).

Station	TN	TP	DIP		DIN		CH		DO	Si		K_d		Number of observations	
	Annual	Annual	Annual	Winter[a]	Annual	Winter[a]	Annual	Summer[b]	Annual	Annual	Winter[a]	Annual	Summer[c]	Annual	Summ/Wint
NOR7715	0.58	0.60	0.67	0.92	0.53	0.69	0.75	0.84	0.46	0.43	0.82	0.66	0.75	[283-435]	[92-197]
RIB1510001	0.74	0.70	0.67	0.75	0.67	0.87	0.71	0.94	0.59	0.63	1.52	0.73[d]	0.72[d]	[96-101]	[14-70]
RIB1510003	0.68	0.72	0.60	0.85	0.67	0.68	0.76	1.23	0.56	0.59	1.25	0.59[d]	0.72[d]	[102-102]	[14-75]
RIB1510007	0.66	0.71	0.58	0.92	0.64	1.14	0.75	0.94	0.69	0.52	1.43	0.70[d]	0.62[d]	[284-310]	[52-209]
RIB1510009	0.66	0.71	0.58	1.07	0.67	0.88	0.72	1.03	0.58	0.54	1.62	0.74[d]	0.71[d]	[171-173]	[25-124]
RIB1510022	0.64	1.09	0.66	0.76	0.48	0.90	0.79	0.90	0.84	0.47	1.13	1.07[d]	0.97[d]	[98-99]	[19-63]
RIB1610002	0.47	0.75	0.71	0.89	0.44	0.56	0.91	0.97	1.01	0.50	0.59	0.90[d]	0.88[d]	[276-315]	[55-187]
RIB1610003	0.73	0.85	0.80	0.77	0.57	1.06	0.77	1.06	1.28	0.67	1.24	0.78[d]	0.95[d]	[98-99]	[19-63]
RIB1610008	0.69	1.28	0.88	0.80	0.52	1.40	0.81	0.90	0.88	0.52	1.77	1.14[d]	1.20[d]	[106-107]	[22-68]
RIB1610011	0.76	1.01	0.93	0.87	0.55	1.73	0.80	0.89	0.88	0.57	2.30	0.91[d]	0.94[d]	[97-99]	[20-61]
RIB1620014	0.61	0.62	0.68	0.85	0.51	0.88	0.91	1.01	0.72	0.45	0.97	0.78[d]	0.68[d]	[200-224]	[41-136]
RKB43	0.63	0.51	0.55	0.73	0.66	0.60	0.35	0.34	0.50	0.55	0.86	0.79	0.65	[370-459]	[85-237]
SJY1	0.63	0.63	0.61	1.12	0.55	1.48	0.73	0.97	0.73	0.50	1.41	0.73	0.77	[115-179]	[27-82]
SJY3	0.59	0.77	0.86	0.79	0.46	0.98	1.00	0.85	0.96	0.52	0.85	0.81	0.71	[261-478]	[70-234]

[a] Jan, Feb, Dec
[b] May-Sep
[c] Mar-Sep
[d] K_d calculated from Secchi Depth (SD)

6 Conclusion

This technical note shows that the model performance for the biogeochemical model covering the North Sea meets the performance measure ‘excellent’, ‘very good’ or ‘good’ for 88% of the annual measures and 84% for both yearly and summer/winter measurements evaluated against three quality measures. The ambition is to meet the above criteria in 75% of all measures for all parameters and all stations (lumped).

The parameter light attenuation parameter (K_d) showed the lowest model performance. However, this parameter is of less importance in the North Sea. The North Sea model will be applied in Danish waterbodies and contribute to model boundary conditions.

Hence, we conclude that the biogeochemical model covering the North Sea is well suited for modelling scenarios as part of the overall development of mechanistic models towards the RBMP 2021-2027.

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