North Sea Monitoring of chlorophyll

Environmental monitoring and assessment based on satellite data, mechanistic modelling and *in situ* sampling – performance and perspectives

Monitoring related to the Marine Strategy Framework Directive

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Report

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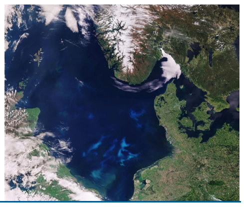

Satellite image of the North Sea on a clear day

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CONTENTS

FIGURES

1 Background

Environmental monitoring of the North Sea is expensive due to significant sailing times. Today's Danish monitoring is therefore limited to only two pelagic campaigns annually (mainly occurring in February to April and August/September), covering about 20 stations within the Danish part of the North Sea and one benthic campaign. However, two campaigns are insufficient to provide a robust data set for evaluating the environmental status concerning pelagic parameters like chlorophyll, oxygen and nutrients. This is so because parameters such as phytoplankton blooms, which change the dynamics of other vital parameters such as oxygen and nutrients, may appear, flourish and decay quite rapidly and thus remain unobserved with only two campaigns during the growth season. Moreover, phytoplankton abundance can be very spatial and temporally heterogeneous, so that conventional ship-based *in situ* sampling could easily overlook such events /1/. In addition, two campaigns do not provide sufficient data to validate other data sources like ferry box data, satellite observation or mechanistic modelling results. Neither are two campaigns enough to fulfil the requirements in Marine Strategy Framework Directive (MSFD). In the inner Danish waters (from Skagen and southwards), most pelagic monitoring stations are visited about 24 times a year, which is considered sufficient for evaluating environmental status or as input when evaluating other data sources.

As traditional monitoring from ships does not provide a reliable source of data for model validation and is not very cost-effective in the open part of the North Sea, new sources of monitoring data are needed to cover data in both time and space. Hence, the Danish EPA is considering integrating 3D-hydrodynamic-ecological models with satellite data and a ship-based sampling programme to validate vital water quality parameters such as chlorophyll in future.

To investigate the possibilities and assess the uncertainties in the proposed approach, the Danish EPA has collected data from 12 ship-based campaigns within the Danish part of the North Sea and initiated the current project. Here, Aarhus University and DHI have analysed satellite data (both Sentinel-3 (S3) and old satellite sensors) and model data for three years (2017-19) and compared with the 2018 measurement campaign. Hence, the current project is a first analysis of whether the traditional measurement from two existing campaigns, supplemented with model results and/or satellite data, can serve as a feasible monitoring strategy in the future of, e.g. chlorophyll in the Danish part of the North Sea. In addition, as the *in situ* data were too limited for the Danish part of the North Sea to make a detailed comparison with S3, we have also analysed a data set of *in situ* observations of chlorophyll covering a large part of the North Sea from 1998 to 2016. This data set is analysed and compared with older satellite observations to show how the satellite, in general, performs in the North Sea. These data were made available through the participation in the project 'Joint monitoring programme of the eutrophication of the North Sea with satellite data' by Aarhus University.

Therefore, the current project has a limited scope and budget and is not a comprehensive analysis of the problem.

2 Introduction

According to the European Marine Strategy Framework Directive, Denmark is obliged to contribute with knowledge of the environmental status in all Danish marine waters. However, as monitoring in the North Sea is costly (depending on the weather, it takes up to 5 days per campaign), it is not realistic to perform frequent traditional monitoring based on ship measurements, as is the case in the inner Danish waters from Skagen and southwards.

Therefore, alternatives to traditional ship-based monitoring are needed to obtain a satisfying level of documentation to assess water quality status. Here we examine the use of biogeochemical modelling and the use of satellite data. For the present project, we used *in situ* chlorophyll data collected by MST during 10 campaigns (8 campaigns in 2018 and 2 in 2019) in the North Sea to analyze if and how modelled data and satellite data can supplement the two standard annual monitoring campaigns within the Danish part of the North Sea.

The project is divided into four tasks:

1) Collecting and processing chlorophyll-based satellite and *in situ* data for 2018

During 2018 and 2019, Aarhus University (AU) participated in an EU-funded (JMP-EUNOSAT) project (with co-financing from the Danish EPA), where satellite data was used to evaluate the usefulness of satellites as part of the future environmental monitoring in the Danish waters.

As part of the JMP-EUNOSAT project, chlorophyll-based satellite data covering the Danish and broader part of the North Sea was used in this project. The data from the old satellite sensors (including names of sensors – MERIS etc.) was available for the years 1998-2016. The data from new Sentinel satellites (S3) was only available from 2018. Therefore, the comparison between S3 and the *in situ* dataset for the Danish part of the North Sea only covers 2018.

2) Analyzing the satellite data and comparing it with *in situ* data

The data sets prepared under task 1 are compared and analyzed for trends and possible spatial effects. The comparisons were made between the growing season average (GSA) estimated through old satellite sensors and *in situ* for the broader part of the North Sea for the years 1998-2016. For S3, the comparisons were made between GSA estimated through S3 and *in situ* for the Danish part of the North Sea for the year 2018. Furthermore, time-series were compared between S3 estimated and the *in situ* chlorophyll values as collected during MST campaign in the year 2018.

3) Modelling the years 2017 and 2018 with the mechanistic model covering the North Sea

As part of the project "Novana Modelling 2019 - Modelling to supplement the assessment of the environmental status and hydrographic interpretation of physical and biogeochemical parameters presented in the marine NOVANA report" the hydrodynamic model (salinity, temperatures etc.) for the North Sea has already been completed for 2017 and 2018. However, when assessing chlorophyll modelling in the North Sea, two additional models need to be completed: The wave model and the biogeochemical model.

Hence, within this task, those two models are set up and executed, and model results are extracted and presented in the present technical note focusing on the new in-situ data from the Danish part of the North Sea.

4) Assessment of possibilities and uncertainties when using model and/or satellite data for monitoring in the North Sea

Finally, the results of the three previous tasks are evaluated to discuss possibilities and uncertainties of utilizing model results and/or satellite data as part of the overall monitoring programme of the Danish part of the North Sea.

3 Project data

3.1 Chlorophyll based satellite data

For this task, two sets of satellite data were used. One is based on the 'old' satellite sensors for the years 1998-2016; and another, S3, from year 2018, to be compared with in situ chlorophyll values. The old satellite sensor data was compared with *in situ* observations from stations over the entire North Sea, whereas the analyses based on S3 only focused on the Danish part of the North Sea.

The satellite data from 1998-2016 is referred to as 'old' sensor data hereafter and is in the resolution of 20*20 km. S3 data used in this study is in the resolution of 1*1km.

S3 data for this project was obtained from the Royal Belgian Institute of Natural Sciences, where the S3 data was downloaded using the Sentinel hub Creodias platform, resampled using the average bucket approach into the area of interest, from where daily estimates of S3 chlorophyll were extracted and validated against the *in situ* data. The neural network (NN, Schröeder et al. 2007algorithm applied chlorophyll products were used in this study to be compared with *in situ* observations. The NN algorithm is specially designed for complex water bodies, like Danish waters, and considers impacts of coloured dissolved organic matter (CDOM) and total suspended matter (TSM) concentrations.

3.2 Analyzing the satellite data and comparing with *in situ* data

We analyzed the long-term time-series data available for the North Sea with the old satellite sensors from the years 1998-2016 and validated them with the *in situ* measurements (

Figure 3-1). *In situ* data for hydrographic stations was provided by ICES. This raw data was first processed using the geopy distance function in the Jupyter Notebook, where each hydrographic station was assigned into the unique monitoring station (centroid of the 20*20 km grid) within the 20km distance based on the shortest distance to the centroid. From this, we chose the stations having at least 40 data points in a 20-year period, which means a minimum of 2 data sets each year for further analyses. The growing season was chosen as the period from 1 March to 30 September (OSPAR commission), and the average growing season (GSA) was estimated for both *in situ* and satellite data by averaging the chlorophyll values during the period. For the larger part of the North Sea, a 20*20 km grid cell size was chosen for satellite observations from old satellite sensors. Any satellite scene with fewer pixels than 180 out of 361, e.g. due to cloud cover, was discarded in the data quality control process. Only stations with 10 years of GSA data within a 20-year period were selected for further analysis for both satellite and *in situ* methods.

In situ chlorophyll concentration (µg L^{-1}) data for the years 2017-2019 was extracted from the Danish NOVANA programme (https://oda.dk) from the standard depth of 1 m, where water samples were filtered, and chlorophyll was extracted from the filter using ethanol and measured spectro-photometrically in the laboratory according to the Danish standard methods. Similar to satellite, GSA was estimated for *in situ* by averaging the chlorophyll values during the growing season defined as the period from 1 March to 30 September.

3.2.1 Results

Figure 3-1 shows the locations of 35 stations over the broader part of the North Sea where GSA was estimated from *in situ* and old satellite chlorophyll values, and Figure 3-2 shows the GSA over the years (1998-2016) for those stations. Out of 35 stations, 29 stations had GSA values from both *in situ* and old satellites. Overall, our visual inspection gave eight stations with a good match over time, 12 stations with a poor match and nine stations with some resemblance over the period. It is important to remember that a poor resemblance can be due to weakness in both methods. The uncertainty is mainly due to the limited number of observations, both in terms of time and space for the *in situ* observations. For the satellite values, there is an inherent uncertainty of the observation itself.

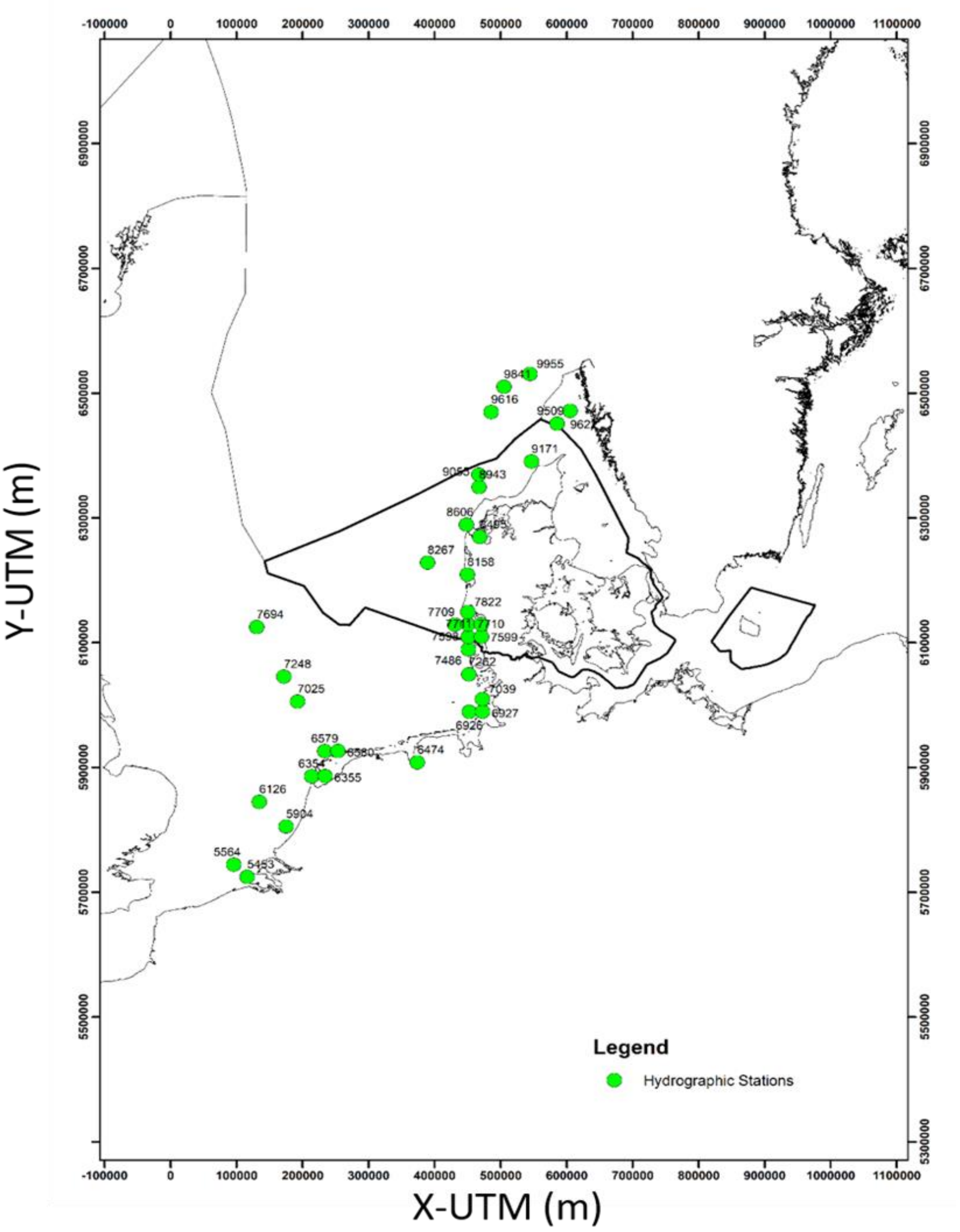

Figure 3-1 Location of hydrographic stations in the North Sea.

Figure 3-2 Average growing season (GSA) values estimated with satellite ('old' sensors, 20km grid cells) compared with in situ (20*20 km grid cells) observation for stations in the North Sea for the years 1998-2017. Station names refer to hydrographic ICES stations shown in

Figure 3-1.

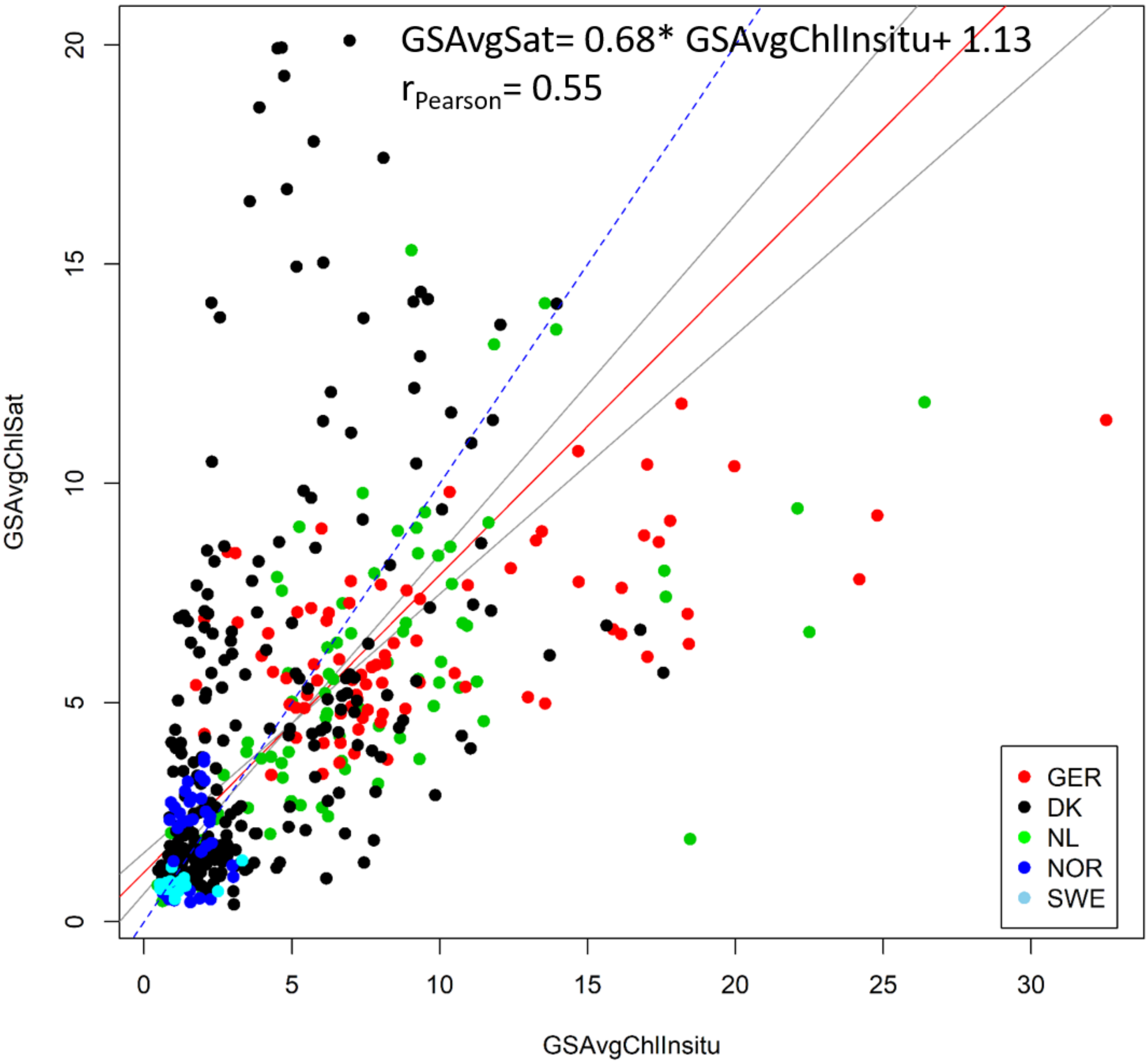

Figure 3-3 Relationship between satellite observations with ‘old’ sensors (20km) and *in situ* observations (20*20 km) based on growing season average in the North Sea. Each point represents a specific year for the specific country. The dashed line represents the 1:1 line. The red is the model 2 regression line, and the grey is the 95%CL.

The two methods were also compared in an x-y plot with values for GSA for each station and year (Figure 3-3). Overall, there was a positive relationship between GSA estimated from *in situ* and old satellite sensors. Notably, there was a clear tendency for a larger spread of data with increasing concentrations. Part of this variation was related to differences in chlorophyll level in the different national areas with low values for Norwegian and Swedish territorial water and high values for German and Dutch waters. The 1:1 line is also displayed in Figure 3-3, and it is clear that overall, the slope is below one (0.68), suggesting that these ‘old’ satellite observations underestimate the chlorophyll concentration at high values, especially for the Danish waters. A fraction of the points from Danish waters is considerably above both the 1:1 line and the general slope and forms a separate cluster where the satellite observations are higher than the *in situ* values.

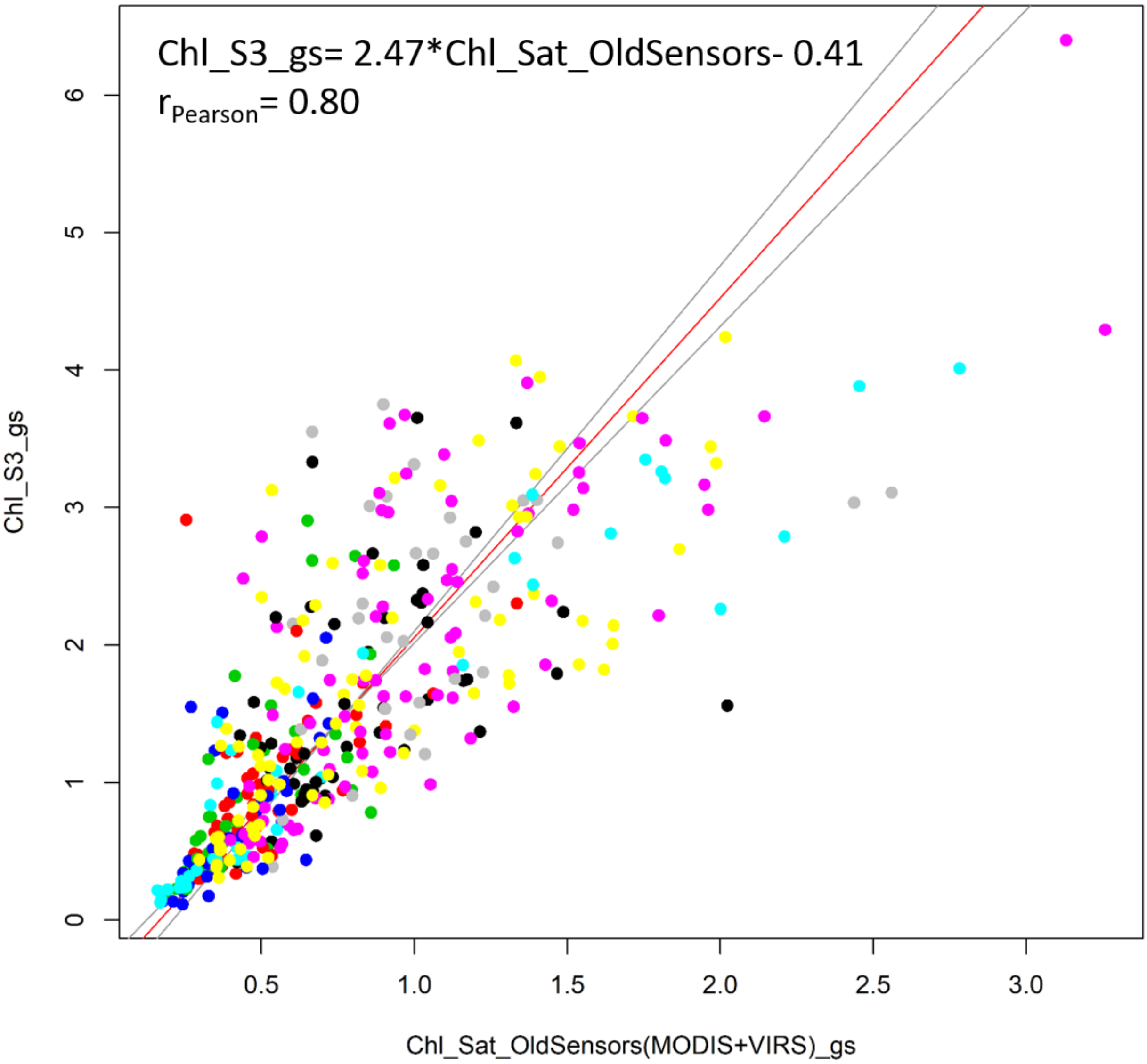

Figure 3-4 Relationship between 'old' satellite observations (20x20 km) and S3 observations (20x20 km) sensors in the year 2017 for Danish monitoring stations. Each colour represents a grid-cell (station).

The relationship between the 'old' satellite observations and corresponding S3 observations is shown in Figure 3-4. There is a significant positive relationship, but with a significant slope of 2.5, indicating that the new S3 satellite estimates are significantly higher than estimates based on the 'old' satellites. With the expectation that S3 has improved sensors, this analysis is particularly interesting as it can explain the observation from Figure 3-3 where the 'old' satellite estimates are generally lower than the *in situ* observations. However, a caveat to this interpretation is that the level and range of values in Figure 3-4 are much lower (less than about 3 µg l^{-1}) than about 20 µg l^{-1} in Figure 3-3.

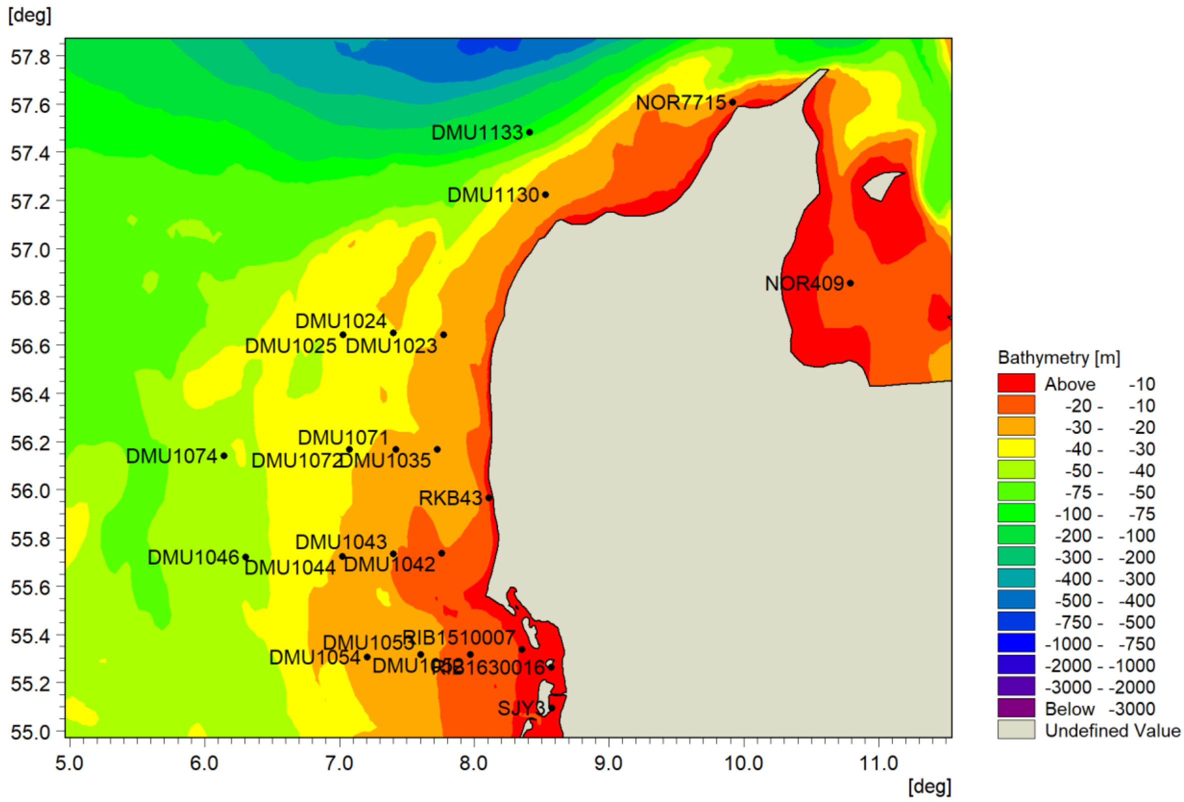

Figure 3-5 Location of Danish monitoring stations in the North Sea.

S3 chlorophyll values during the growing season were compared with the *in situ* measurements for the year 2018 at the Danish monitoring stations (see Figure 3-5). The variability captured by S3 is shown in the boxplot in Figure 3-6, which shows the GSA estimated through both methods. Overall, S3 captured the variability in the chlorophyll concentration as observed through *in situ* sampling. Figure 3-7A shows the GSA estimated with S3 (1*1 km grid cell size) and the *in situ* method. Overall, there is a significant positive relationship with a correlation close to 1:1 at concentrations below about 2 µg Chl l^{-1}. However, it is also clear that S3 estimates are lower at a higher concentration than *in situ* values. Figure 3-7 displays the average salinity for the same stations from day 100 to 279, i.e. the same time the satellite observations are available. The figure shows a decreasing trend in salinity with increasing chlorophyll concentration. The explanation is most likely that stations with low salinity are more influenced by freshwater run-off from the German rivers the Elbe and the Rhine, which also come with high nutrient concentrations giving higher chlorophyll concentrations than at stations further offshore. The hydrography of the area is dominated by the Jutland coastal current flowing northwards along the coast, often with a sharp separation to the more saline open North Sea water. Based on this observation, we have developed a model for the relationship between S3 values and *in situ* chlorophyll concentrations and salinity.

$Chl_{sen3} = c_1 * Chl$ *in situ* $+ c_2 *(\text{salinity} – \text{threshold})$. Eq. 1

The following parameters are estimated: c1 = 0.279 ± 0.055, c2 = -0,402 ± 0.084 with threshold = 36.5 ± 0.5. All parameters are highly significant, with a *p*-value for the model below 0.0001. The intercept in the model is found in the product of c_2 and threshold. The relationship between *in situ* chlorophyll concentration and the values predicted from the model is shown in Figure 3-8.

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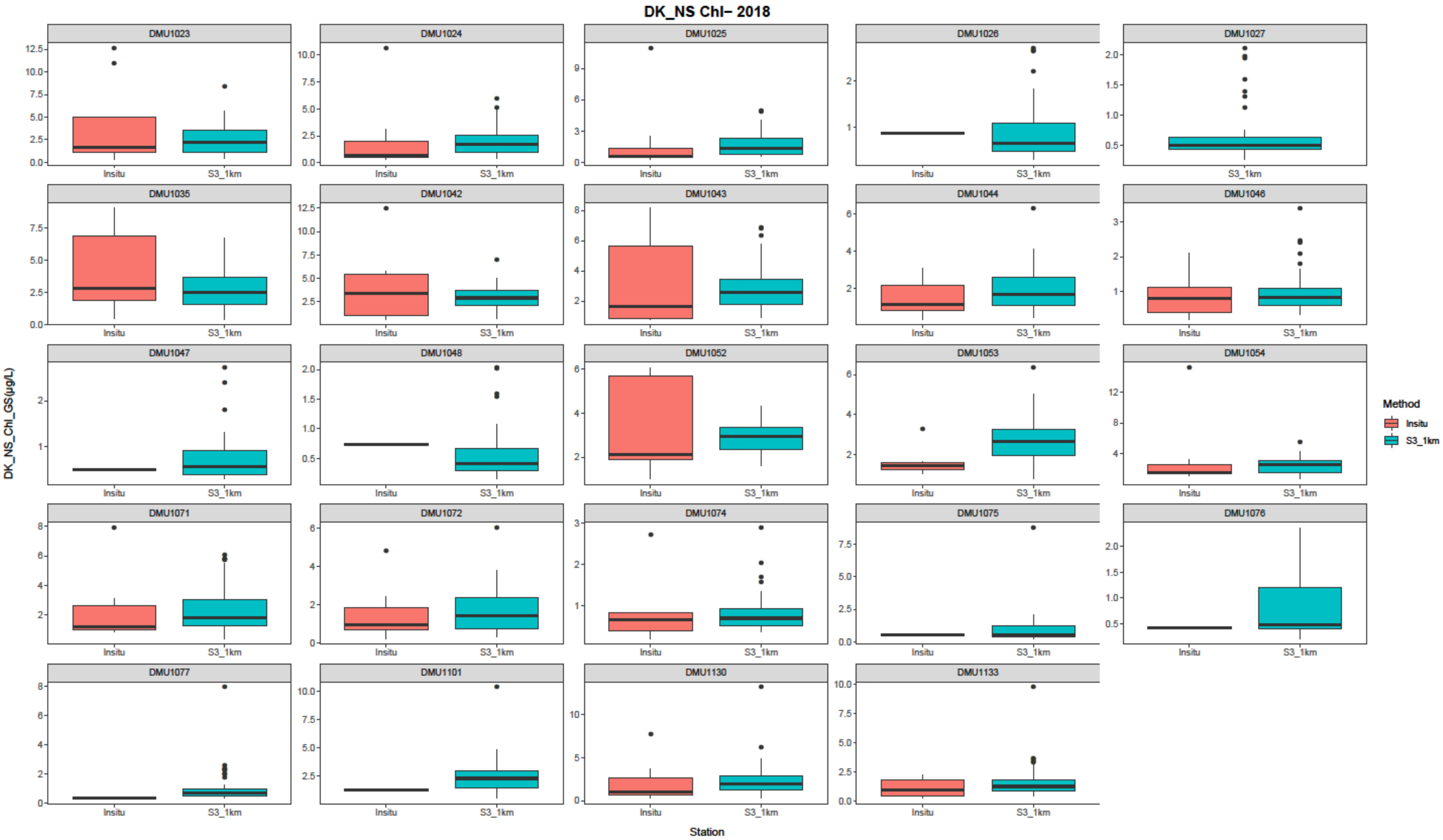

Figure 3-6 Boxplot showing the GSA estimated through S3 (1*1 km grid cells) compared to in situ for Danish monitoring stations for the year 2018.

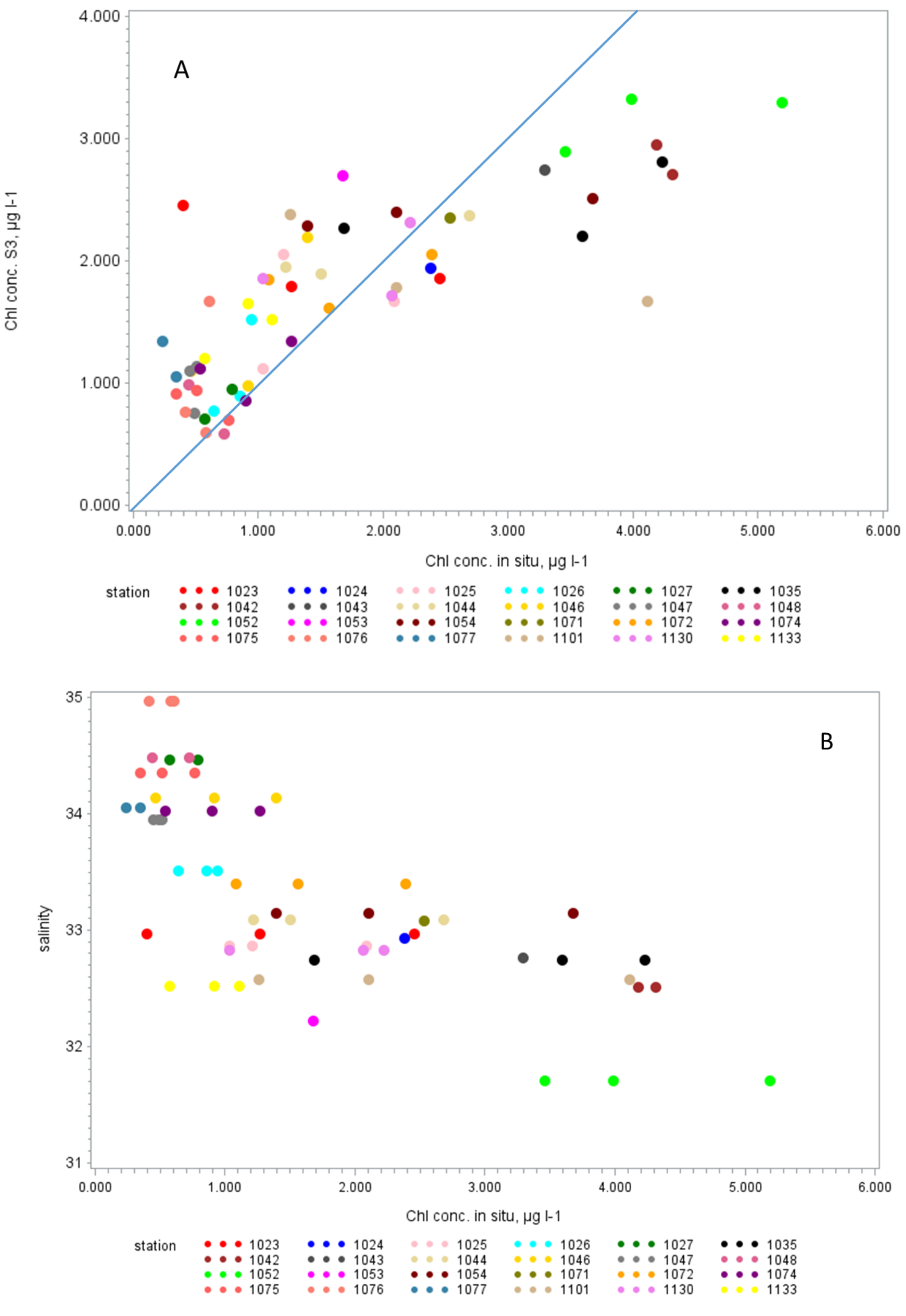

Figure 3-7 A) GSA from S3 compared with *in situ* observations for Danish monitoring stations for three years (2017, 2018 and 2019) 1:1 line shown. Colours represents different monitoring stations. B) Salinity for the same stations from day 100 to 279 based on all observations from 1982 to the present.

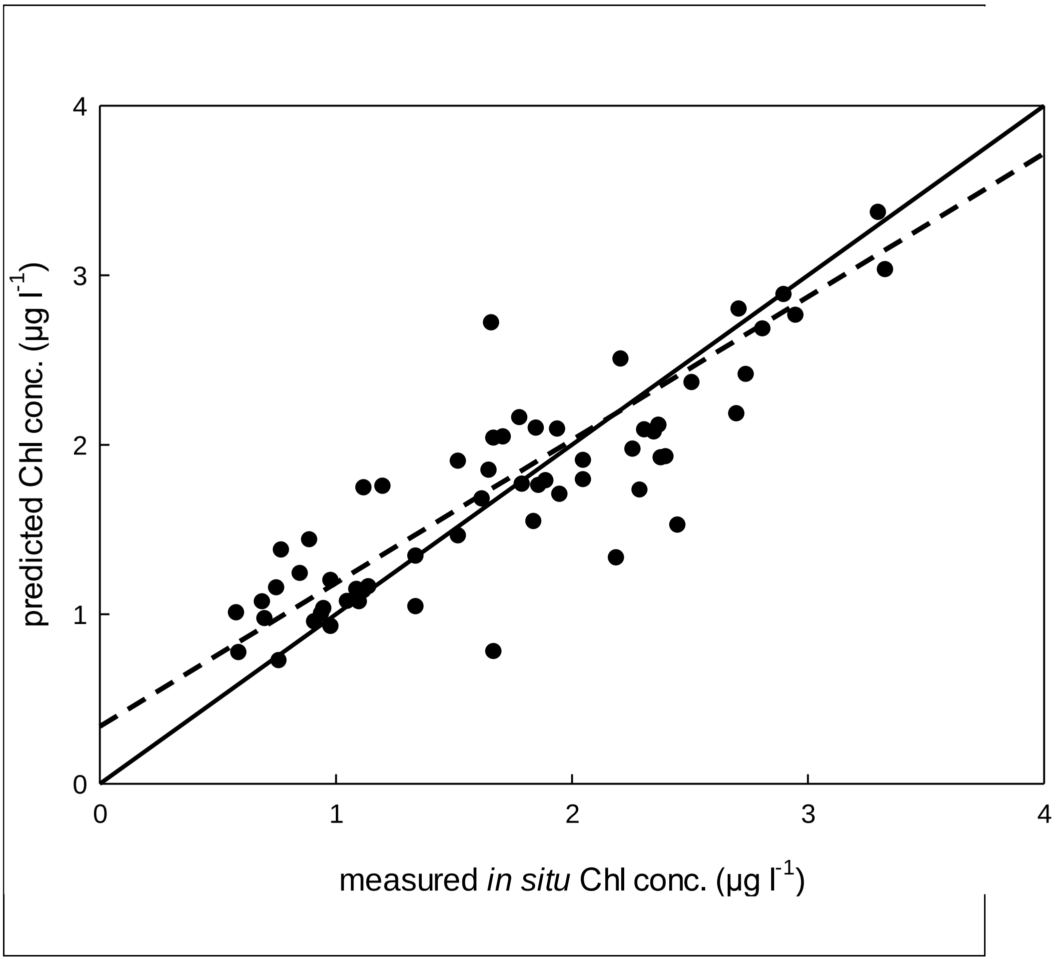

Figure 3-8 Predicted versus measured GSA chlorophyll values. The linear relationship (geometric mean regression) is shown (dashed line, 0.34 + 0.85* *in situ* Chl) together with the 1:1 line.

The correction for salinity produces new estimates for chlorophyll concentration based on S3 values with a much better match to *in situ* values, although there is still a significant positive intercept, and the slope is significantly lower than 1. The corrected estimate is free of a systematic relationship to salinity.

The correction for salinity is negative and significant. We do not expect that this relationship is directly related to salinity but more likely because low salinity is associated with the influence of freshwater and hence higher concentrations of CDOM and higher nutrient concentrations. Most likely, there is also higher concentrations of TSM at stations with lower salinity due to the proximity to the coast. A third possibility is that the algorithms for S3 data do not fully account for the self-shading effect that occurs in the water column at higher concentrations of chlorophyll. Based on the analyses in this project, we cannot identify which of the three suggested explanations (CDOM, TSM or self-shading at high chlorophyll concentration) cause the lower estimates at high salinity. This aspect is essential, as the latter reason can pose a problem from a management perspective. If the bias is related to the chlorophyll concentration, it will change with a change in chlorophyll concentration and hence the environmental status of the area. This means that a status assessment based on satellite observation will systematically underestimate the true change in chlorophyll concentration and hence the ecological status of the particular area.

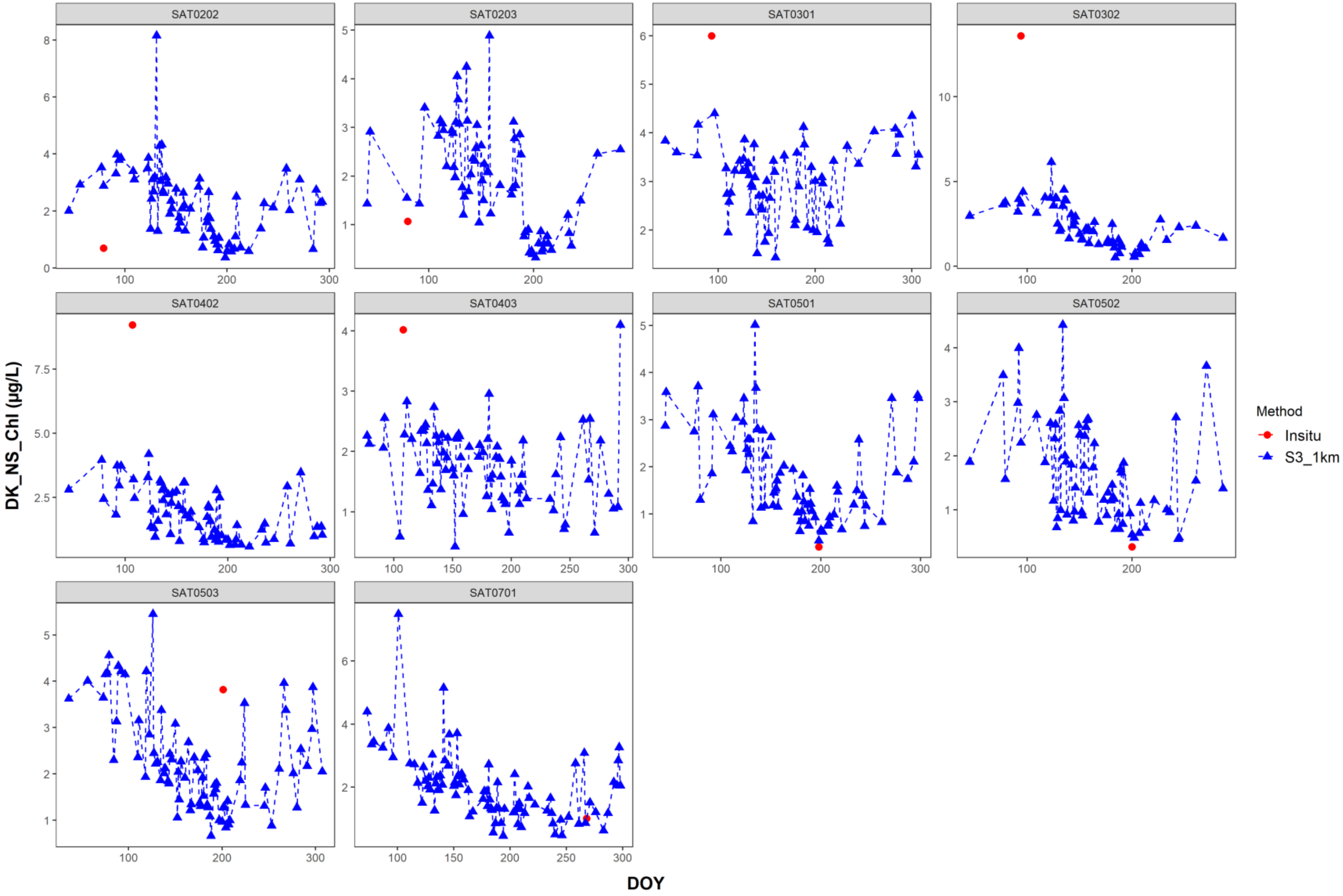

Figure 3-9 Time series of chlorophyll estimated by S3 (blue, 1'1 km grid cells) and *in situ* (red) for the year 2018. MST undertook *in situ* sampling during satellite overpass.

As shown in Figure 3-9*, in situ* chlorophyll samples were taken by MST in the North Sea in the year 2018 during the satellite overpass (locations shown in Figure 3-5). Comparing the time series of S3 and the *in-situ* measurements made during the satellite overpass does not show a good relationship, except for stations SAT0501, SAT0502, and SAT0701. For all other stations, S3 either over- or underestimate the chlorophyll concentration.

In conclusion, we find that S3 data for GSA values provides reliable estimates of chlorophyll after a correction for salinity. This correction is area-specific since it is not a mechanistic effect of salinity but more likely an indirect effect where salinity is a proxy for an influence of freshwater impact on the satellite estimate in the Danish part of the North Sea. However, it is possible to use S3 data operationally with an appropriate validation from *in situ* observation. Such validation requires *in situ* observations and is preferably measured several times during the growing season period. We, therefore, recommend continuing the work on developing corrections of estimates from the standard satellite algorithm for the Danish part of the North Sea.

3.3 Mechanistic modelling

3.3.1 North Sea Model

As part of the Danish preparation for the River Basin Management Plans (RBMP) 2021-2027, a number of mechanistic biogeochemical models have been developed. One of these models include the North Sea; see Figure 3-10 for details on the extent of the model.

The model development covers three specific models:

- The hydrodynamic model: This model describes the overall current, water transport, mixing, densities (based on salinity and water temperature) etc. and is used as the driver of the biogeochemical model.
- The wave model: This model is included in the model complex as waves are an essential driver for, e.g. re-suspension, which affects water transparency and allows inorganic and organic material to be transported along the Danish west coast.
- The biogeochemical model: This model is forced with the results from the hydrodynamic and wave models and describes the different biogeochemical state variables such as chlorophyll, inorganic nutrients etc. and biogeochemical processes as primary production.

The different models are described in more detail in Erichsen & Birkeland (2019a; /2/ and 2019b; /3/), and Nielsen et al. (2020; /4/).

The model development has focused on the period 2002-2016, but as part of the present project the models have been setup and executed for the years 2017 and 2018 with the aim of evaluating the model results against the specific 2018 monitoring campaign.

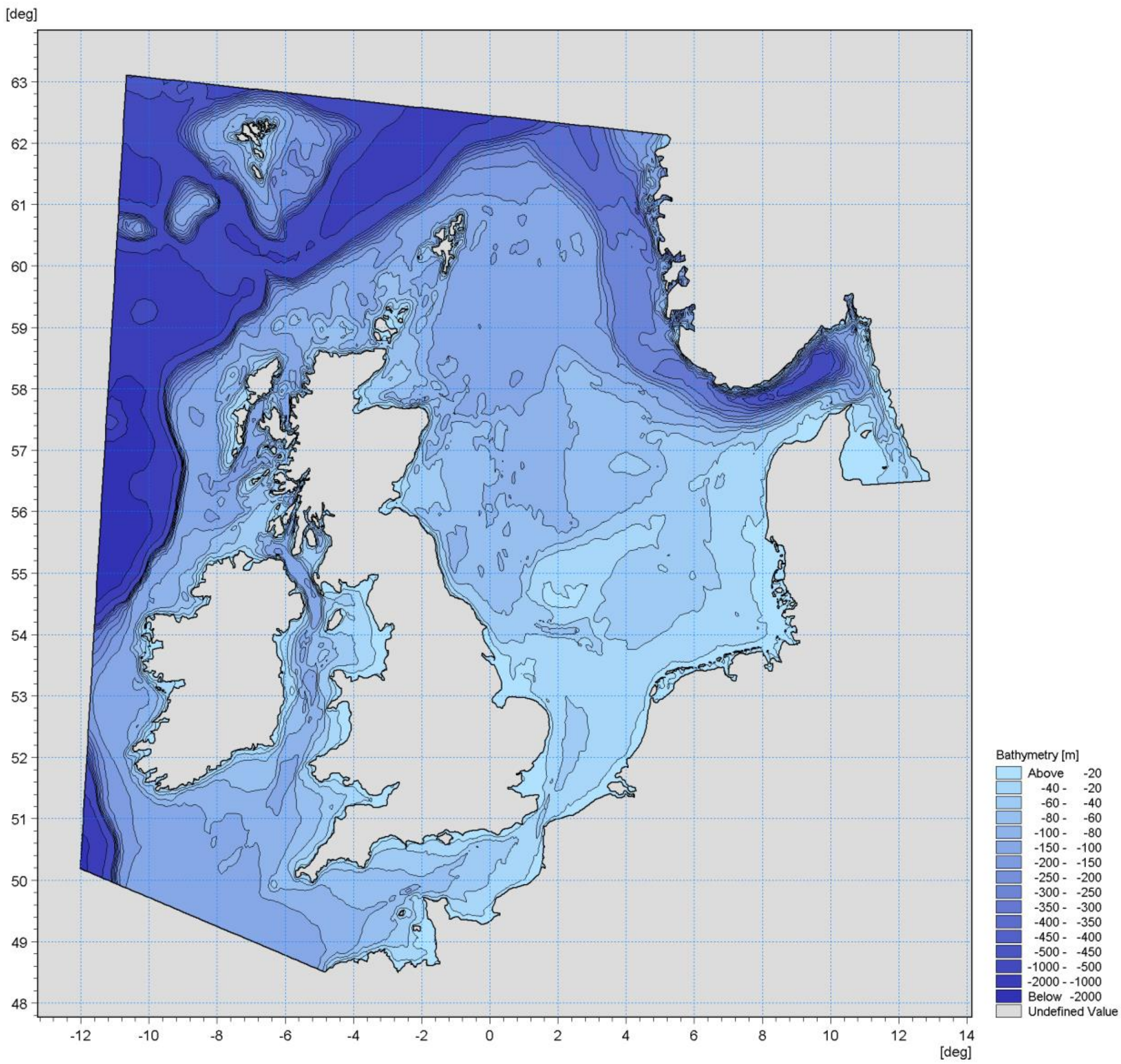

Figure 3-10 Model bathymetry of the North Sea model (UKNS2-HD28). Water depths refer to mean sea level (MSL).

3.3.2 Model setup

The data requirements and data sources applied for the biogeochemical model development are described in more detail in Erichsen & Birkeland (2020; /5/). This data covers meteorological data (e.g. wind, air temperature and solar radiation), boundaries (North Atlantic and Kattegat boundary data), atmospheric deposition as well as freshwater loadings:

- **Meteorological data:** This data is provided by STORM Geo in an hourly resolution. The North Sea model-complex has previously been calibrated with STORM Geo data, why we expect similar performance as reported in Erichsen & Birkeland 2019a; /2/.

- **Boundary-data:** The North Sea model has three open boundaries in the North Atlantic, where boundary conditions are estimated based on ICES data. The conditions for the open boundary in the Kattegat are estimated based on NOVANA data. For the boundaries in the open North Atlantic waters, the boundaries remain unchanged compared to the previous modelling, i.e. same conditions as in previous years, whereas the Kattegat boundary has been updated based on 2017-2018 NOVANA data.

- **Atmospheric data:** Aarhus University usually provides the atmospheric nitrogen depositions as part of these modelling projects. Here, however, the project did not allow for updated depositions as we have used the 2016 deposition as a proxy for the monthly depositions in 2017 and 2018.

- **Danish loadings:** Important model input is freshwater and nutrient loadings to the model. Aarhus University has provided 2017 and 2018 data on a 4th order water body scale for the Danish sources, which is similar to previous model developments.

- **North Sea loadings:** Similarly, essential data to the North Sea model is freshwater and nutrient loadings from other countries than Denmark, especially the countries in the German Bight. This data initially contained a combination of model data (E-HYPE) and measured data (see Erichsen & Birkeland (2020; /5/) for details). For the present study, we did not have access to updated freshwater and nutrient loadings from the countries surrounding the North Sea and have applied climatological data[1].

We have updated external forcing data to cover 2017 and 2018, except for the German Bight loadings, where this has not been possible. This has an impact on the model results, which will be discussed in the following sections.

3.3.3 Chlorophyll model results

As described above, the model development for 2017 and 2018 builds on the previous model development reported in Erichsen & Birkeland (2019a; /2/). In Erichsen & Birkeland (2019a; /2/) the model results (2002-2016) are compared to measurement within the Danish coastal waters, and the calibration is available online: http://rbmp2021-2027.dhigroup.com/model-performance (Google Chrome only).

For the present study, the model has been extended to cover the years 2017 and 2018. Only a few measurements are available in 2017, which is why we focus on the 2018 measurement campaign. The different locations of the measurement stations included in the 2018 measurement campaign are visualised in Figure 3-5. Additional to the 2018 measurement stations, we have included the coastal stations covering the Danish part of the Waddenzee, the west coast, and one station in Skagerrak. These stations are part of the national NOVANA programme.

In the following, we have included a few examples (see Figure 3-11 to Figure 3-14). For the two stations (DMU1130 and DMU1024) located in the more central part of the Jutland current, the modelled concentration of chlorophyll increases steadily from March and peaks in May during 2018. In late June, a minor peak is also modelled, and from July and the rest of the year, the modelled concentrations are low. The modelled concentrations in 2017 are similar, but with an earlier peak (March/April) and a decline in concentration during May.

The model represents the measured chlorophyll concentrations well. However, no measurement exists during the period with the highest modelled chlorophyll concentrations (May and June). This means that we cannot verify if the magnitude or duration of the peak bloom is modelled correctly, and there is a risk that the model overpredicts.

[1] Monthly freshwater and nutrient loadings based on 10-year data

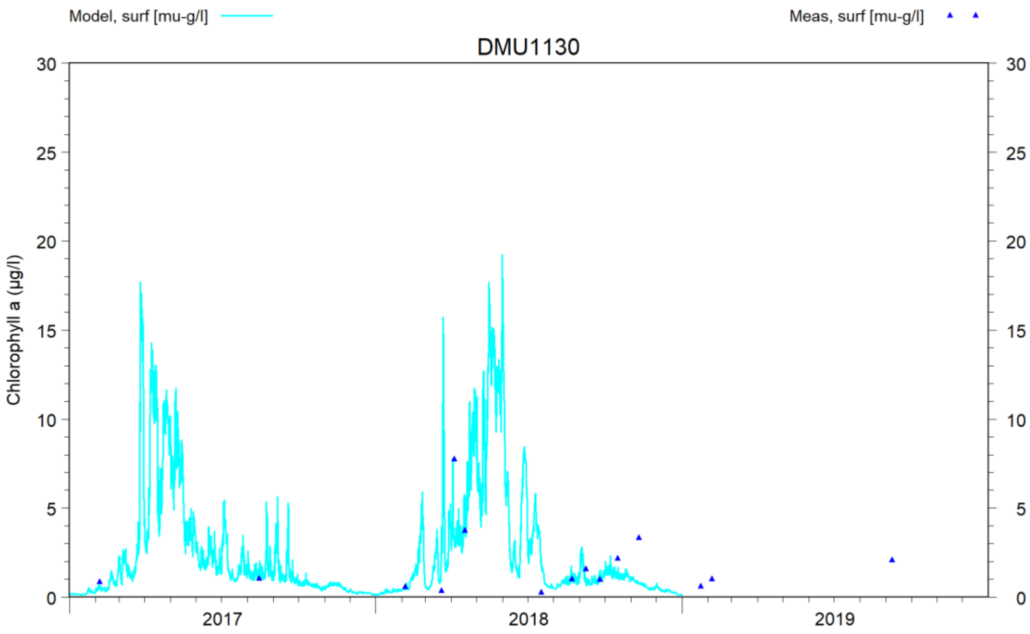

Figure 3-11 Time series of measured surface chlorophyll (triangles) and modelled surface chlorophyll (blue line) during 2017-2019 at measurement station DMU1130 (see Figure 3-5 for location).

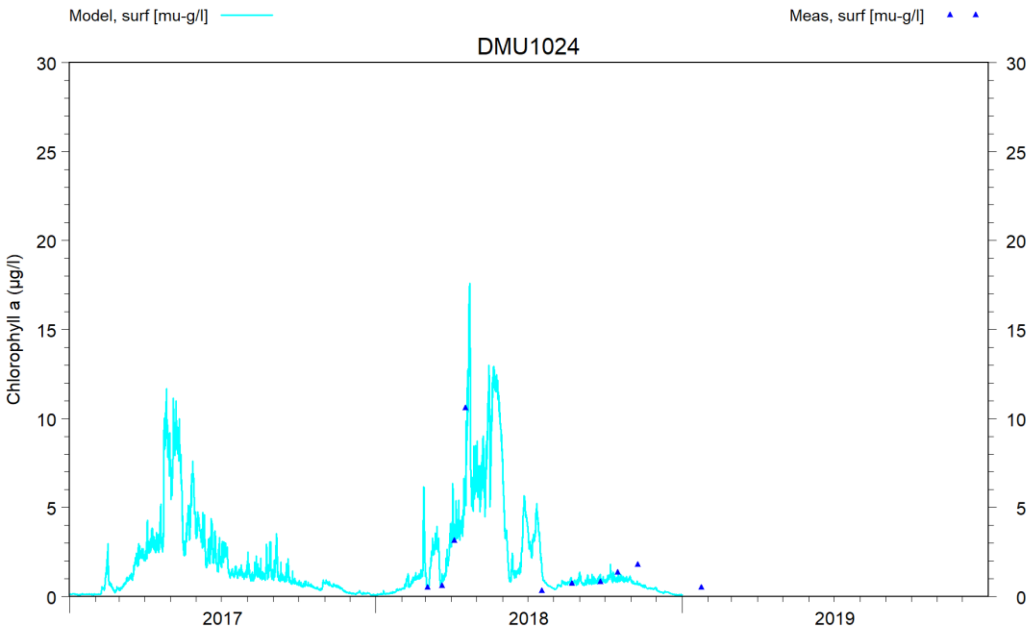

Figure 3-12 Time series of measured surface chlorophyll (triangles) and modelled surface chlorophyll (blue line) during 2017-2019 at measurement station DMU1024 (see Figure 3-5 for location).

At the more open water station (DMU1074), the modelled concentrations of chlorophyll follow the same pattern as the two coastal stations, with the modelled peak in late April and less pronounced chlorophyll concentrations. As with the two other stations, there is no measured data to verify the modelled concentrations during May and June, except for one value in April, which the model does not capture.

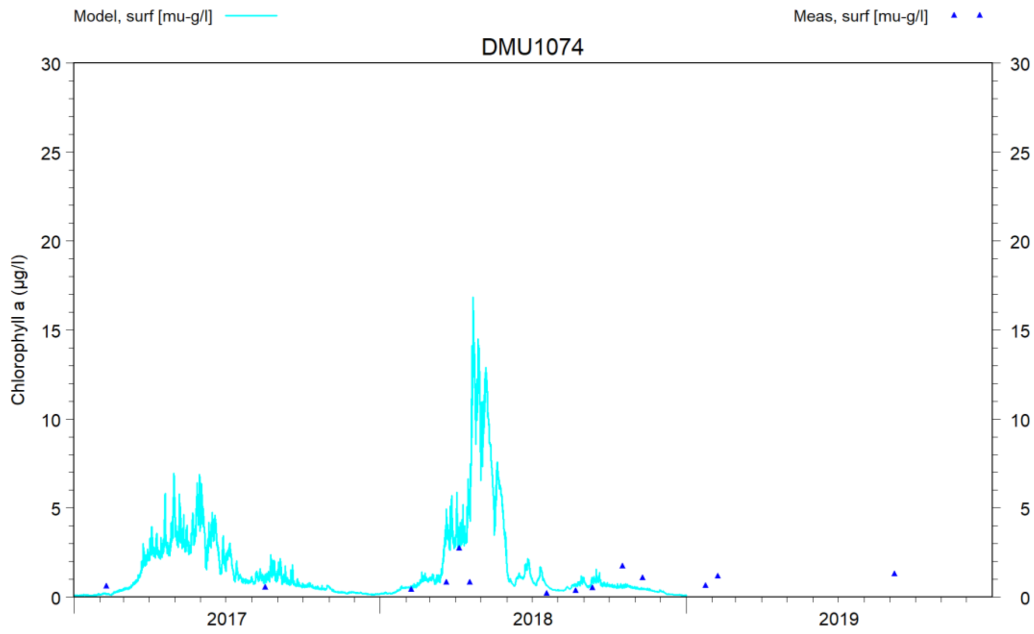

Figure 3-13 Time series of measured surface chlorophyll (triangles) and modelled surface chlorophyll (blue line) during 2017-2019 at measurement station DMU1074 (see Figure 3-5 for location).

In the Waddenzee (see Figure 3-14), the modelled concentrations are much higher than in the more open waters, with a distinct spring bloom peak in April and elevated concentrations during the summer. The model does reproduce the measurements but has a tendency to overestimate during 2018 and underestimate during 2017.

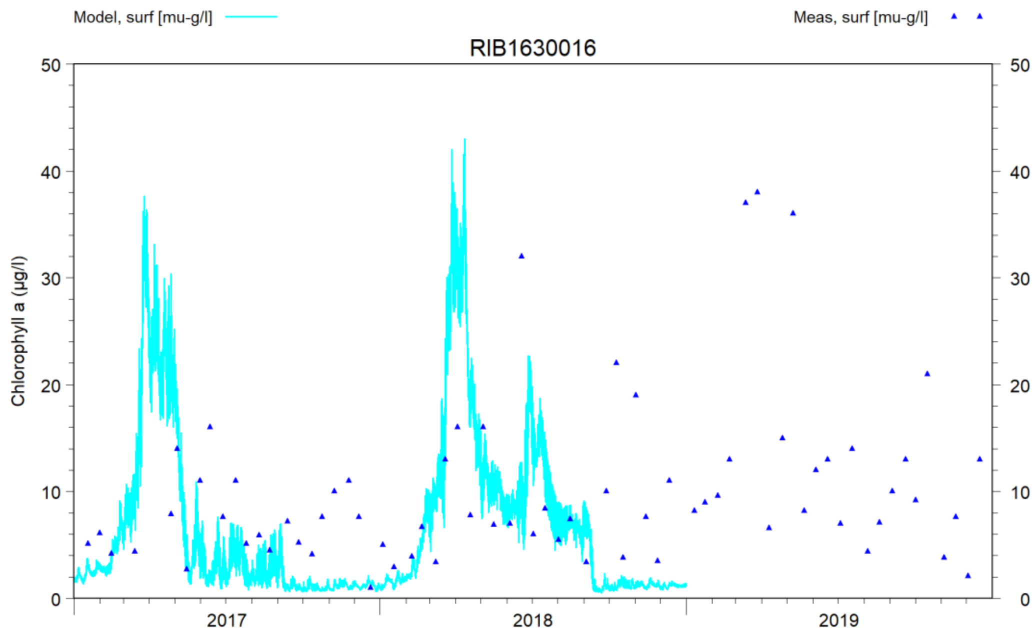

Figure 3-14 Time series of measured surface chlorophyll (triangles) and modelled surface chlorophyll (blue line) during 2017-2019 at measurement station RIB1630016 (see Figure 3-5 for location).

3.3.4 Growth Season average

In the previous section, we have only included a few samples of the model results. In Figure 3-15, GSA averages and medians from all measurement stations in 2018 have been compared. There is a clear correlation between measured and modelled concentrations of average and median summer chlorophyll with a tendency for the model to over-estimate, which is caused by the modelled chlorophyll peaks in May-June with no corresponding measurements during that period.

Looking at earlier measurements (see Figure 3-2), we see average summer concentrations of higher values. Measurements from station 8267-DK, located somewhat similar to DMU1074, indicate GSA concentrations between 5-10 µg/l in the first part of the period and lower values later on. The later part of the period only includes the February and August measurements, whereas the first part of the earlier years also includes measurements from April. A review of older measurements from www.odaforalle.au.dk also revealed frequent measurements of more than 5 µg/l in April, similar to the data from the 2018 measurement campaign.

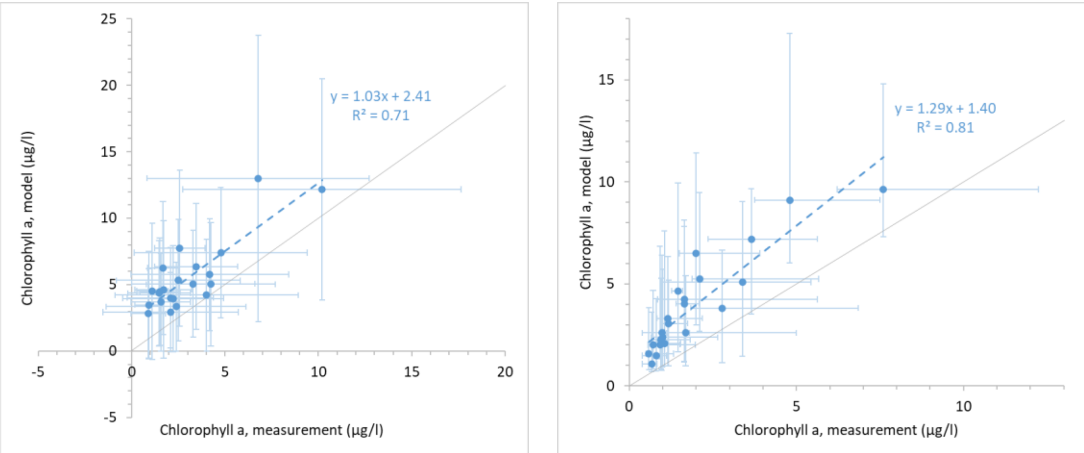

Figure 3-15 XY scatter plots of measured (x-axis) and modelled (y-axis) GSA chlorophyll concentrations (March to September). The left figure is based on averages ± 1 × standard deviation, whereas the right figure is based on medians ± 25% percentiles.

3.3.5 Supplementary model results (nutrient and oxygen)

As a supplement to the modelled chlorophyll data, the model also provides results for dissolved oxygen, inorganic nutrients (dissolved inorganic nitrogen (DIN), phosphorus (DIP) and silicates (Si)) as well as total nitrogen (TN) and total phosphorus (TP). For example, we have included modelled and measured data at one measurement station: DMU1130, in the following figures (Figure 3-16 to Figure 3-21).

The model has been run for 15 years prior to 2017 and 2018 without any adjustment (data assimilation or equal) to any kind of measurements. This section briefly discusses the model results; however, it is essential to consider the issues with the fresh water and nutrient loadings input from other countries than Denmark. Especially the winter of 2017/2018 was very wet, whereas the 2018 summer was very dry. Hence, while applying climatological loadings, we under-estimate during winter 2017/2018 and over-estimate during summer 2018, which will also be somehow visible in the following figures.

In Figure 3-16, the modelled and measured concentrations of dissolved oxygen are included. The saturation level mainly governs concentrations in surface and bottom waters following the same pattern. The water column shows minor signs of stratification at the specific station, which is also expected. During the warm 2018 summer period, the bottom layer of oxygen declines compared to the surface concentrations, but without showing signs of critical levels. Here, we only include one measurement station as an example, but in some of the other stations in the central part of the Jutland current, the combination of warm water and large nutrient loads results in short periods of critical oxygen concentrations during August. The lower oxygen levels are also somewhat visible in the measured data, but the model over-estimates the drop, most likely due to the over-estimated loads during the 2018 summer period.

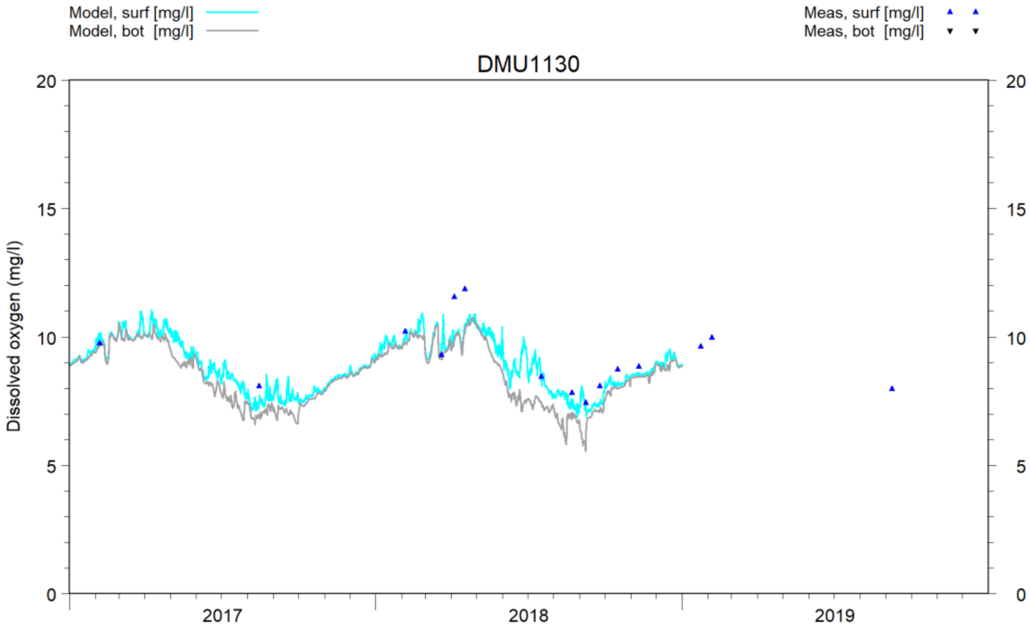

Figure 3-16 Time-series of measured oxygen concentrations (triangles) and modelled oxygen concentrations (surface data (blue line) and bottom data (grey line)) during 2017-2019 at measurement station DMU1130 (see Figure 3-5 for location).

Inorganic nutrients (DIN, DIP and Si) are shown in Figure 3-17, Figure 3-18 and Figure 3-19. Almost no measurements existed in 2017, but the three inorganic nutrients have the right level at the beginning of the year, showing a clear drop during the period when chlorophyll increases and then recover to the same level in December as at the beginning of the year.

The measurements follow a similar drop as the model results in the surface waters but end at much lower levels, which we assume is due to the lower run-off and loadings during the 2018 summer (which is not accounted for in the model). Also, we see a stratification in nutrients which is not evident in the measurements but could be due to a more significant drop in oxygen levels in the central part of the Jutland current.

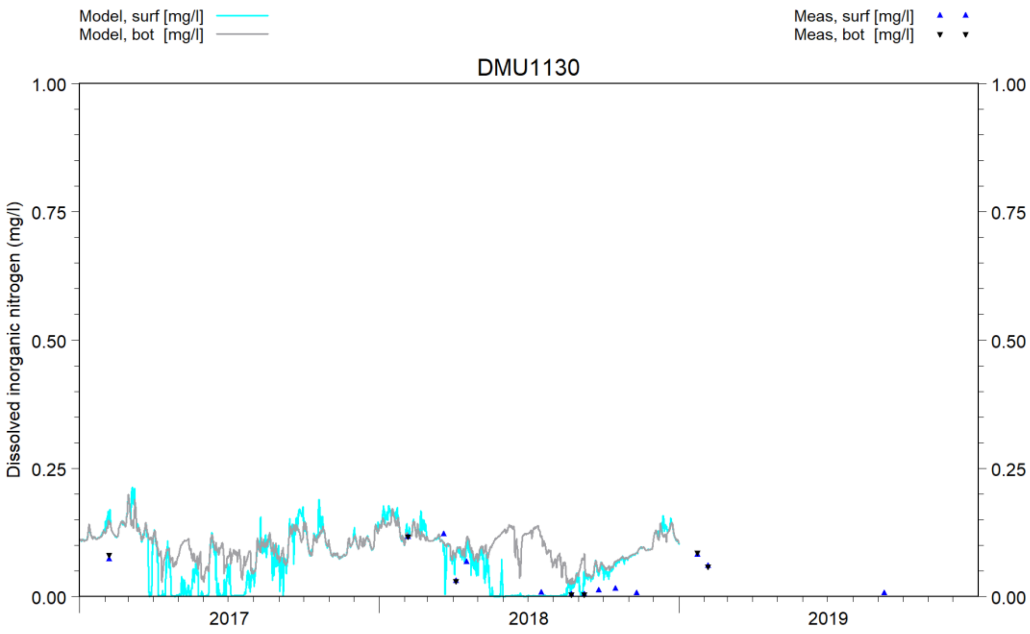

Figure 3-17 Time-series of measured DIN concentrations (surface data (blue triangles) and bottom data (black triangles)) and modelled DIN concentrations (surface data (blue line) and bottom data (grey line)) during 2017-2019 at measurement station DMU1130 (see **Error! Reference source not found.** for location).

Figure 3-18 Time series of measured DIP concentrations (surface data (blue triangles) and bottom data (black triangles)) and modelled DIP concentrations (surface data (blue line) and bottom data (grey line)) during 2017-2019 at measurement station DMU1130 (see Figure 3-5 for location).

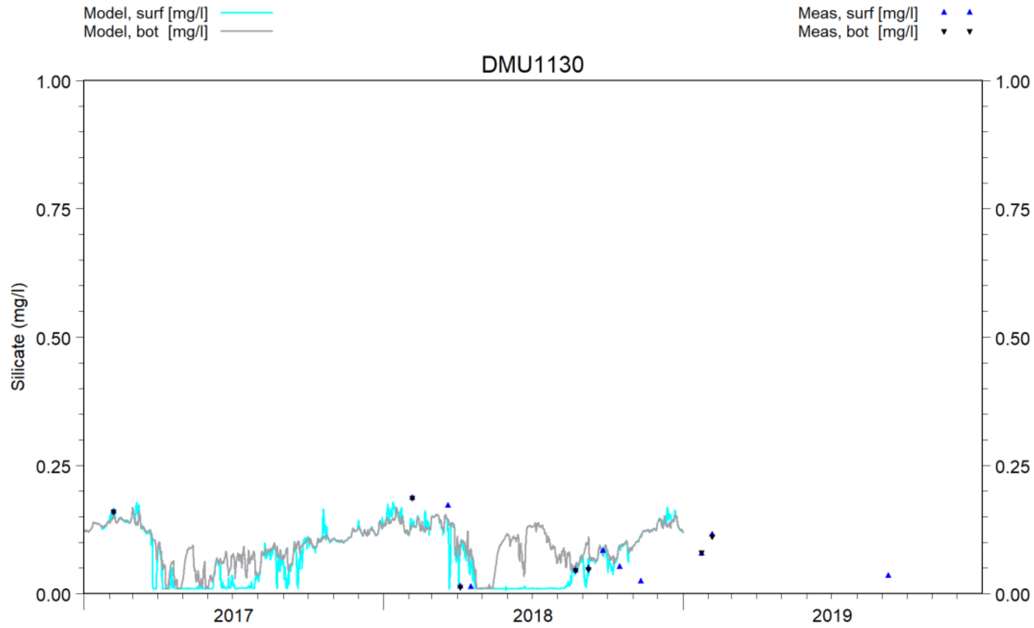

Figure 3-19 Time-series of measured Si concentrations (surface data (blue triangles) and bottom data (black triangles)) and modelled Si concentrations (surface data (blue line) and bottom data (grey line)) during 2017-2019 at measurement station DMU1130 (see Figure 3-5 for location).

For TN and TP (Figure 3-20 and Figure 3-21), we see a similar pattern as for the inorganic nutrients. At the beginning of the year, the levels are identical between measurements and model results, modelled surface concentrations follow the measurements (the same pattern for TP, but the model overestimate the levels), and at the end of the year, the model returns to the same levels as at the beginning of the year, whereas the measurements are lower. Also, we see a result of nutrients being released in the bottom waters due to the larger oxygen drop as described earlier.

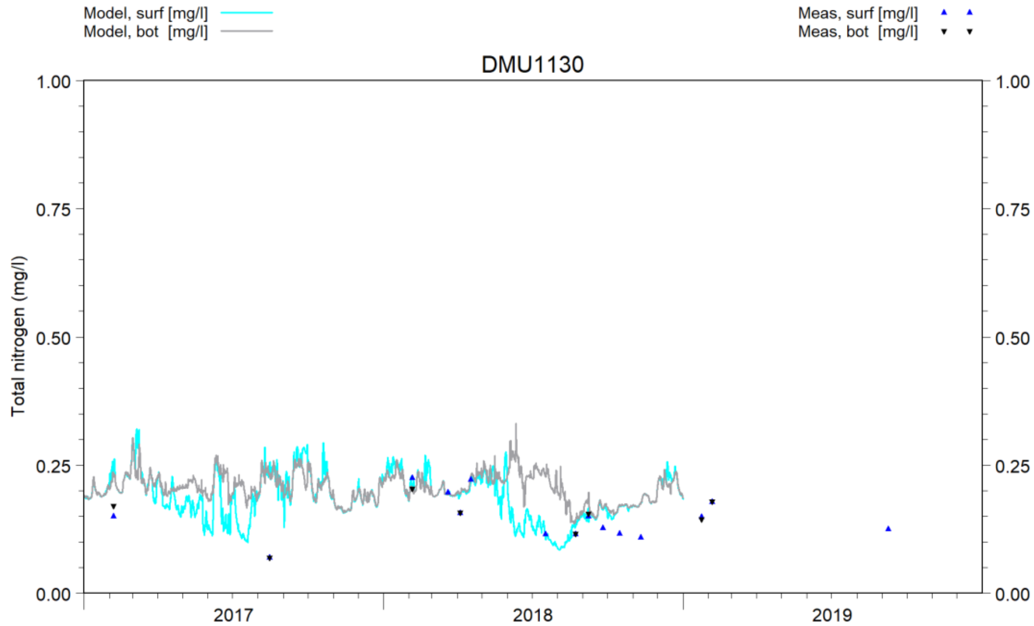

Figure 3-20 Time-series of measured TN concentrations (surface data (blue dots) and bottom data (black dots)) and modelled TN concentrations (surface data (blue line) and bottom data (grey line)) during 2017-2019 at measurement station DMU1130 (see 1 for location).

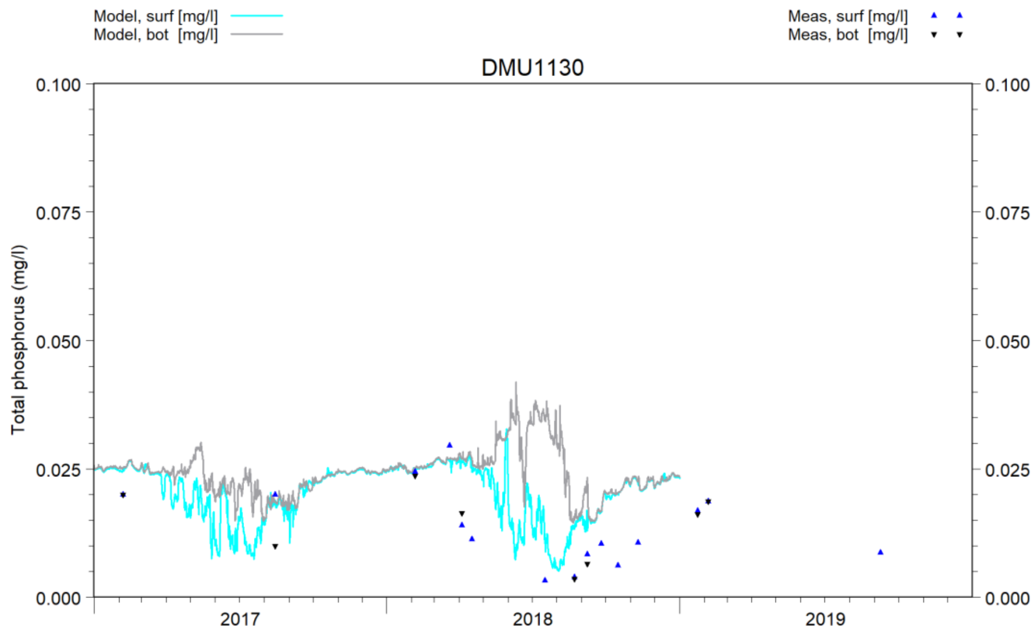

Figure 3-21 Time series of measured TP concentrations (surface data (blue dots) and bottom data (black dots)) and modelled TP concentrations (surface data (blue line) and bottom data (grey line)) during 2017-2019 at measurement station DMU1130 (see Figure 3-5 for location).

4 Discussion and recommendations

4.1 Satellite *versus* ship based *in situ* sampling

- The launch of the Sentinel programme has made satellite observations of chlorophyll even more reliable and accessible for monitoring of the marine environment. In optically complex waters such as the Danish part of the North Sea region, it remains challenging to transform satellite reflectance into accurate values of chlorophyll concentrations in the surface layer by a single algorithm. The solution presented in the recent JMP UNOSAT project,/6/, /10/; has therefore been to combine different algorithms, which handle the variable contributions from CDOM and TSM on the S3 reflectance signal. This report documents that S3 derived estimates of Chl concentrations for the Danish waters is more accurate and less variable than estimates derived from older satellite sensors. The methods behind the use of several algorithms and the associated selection procedure are still being developed and will most likely continue to improve the accuracy of chlorophyll estimates. A likely scenario is a continuous process where the overall method (satellite sensors, number of satellites, atmospheric correction, absorption to chlorophyll algorithms and techniques for selecting the best algorithms for each area) become better and better over time. Thus, the reality will be better and better but still incomplete satellite products for chlorophyll. In this report, we propose the use of a 'post processing tool' that compares the result of the satellite products with *in situ* data and systematically analyze the consequences of using the current 'state of the art' satellite products for time-series and assessment of the environmental status. The present report and others are attempts to develop such a post-processing tool (/7/, /8/, /10/) that is regarded as a necessary component in the future use of satellite products. In the present report, the 'post-processing tool' is a correction for salinity. In others the 'post processing tool' make a correction for systematic deviations over time between satellite estimates and *in situ* observation or related to proximity to the coast (Upadhyay et al. submitted).

- In addition to assessing chlorophyll concentrations, the satellites can also estimate water clarity, turbidity and CDOM concentrations. These parameters are less developed than the estimation of chlorophyll but will be developed over the coming years. An important aspect is that they can support chlorophyll assessment as they allow the quantification of factors that affect the estimation of chlorophyll.

- This report has identified a systematic underestimation of the chlorophyll concentrations with S3 with increasing concentrations. This is obviously a problem for using satellites observations in monitoring as it might affect time series. We propose four reasons for this phenomenon; 1) The cell size and hence internal self-shade increase with increasing nutrient status of the cells. 2) Self-shading by chlorophyll in the water column when chlorophyll concentrations increase. 3) That areas with high chlorophyll concentration co-vary with high turbidity as both nutrient and suspended particles increase with re-suspension of sediment. 4) That areas with high chlorophyll concentration co-vary with high CDOM-concentrations as both nutrient and CDOM co-vary with freshwater input. Currently, this effect must be accounted for in a post-processing step when satellite products are used for monitoring.

4.2 Modelling versus ship based *in situ* sampling

- Authorities and academia around the North Sea have been working with mechanistic models for several years, and models have been adopted in some North Sea regions as an essential tool for managing the environmental status of the North Sea. This is a somewhat new method for Danish waters. With the model developments behind the River Basin Management Plans 2021-2027, Denmark has now obtained similar modelling tools and will be able to contribute to OSPAR working groups focusing on the use of models as managing tools and as part of a future monitoring strategy. However, models require a number of data sets to be included regularly, like updated meteorological data and updated river run-off and nutrient loadings. In the present study, the meteorological data was updated, whereas the river run-off was estimated using historical data sets.
- Another issue is the validation of model results. The model data presented in this report compares favourably to the measured data, but in the period May-July, no data exists, and here the model predicts relatively high concentrations of chlorophyll values, and at station 9933 probably also too high values. However, we have no possibility for validating those values. Hence, moving forward, the introduction of more measurements will be necessary.
- As for satellite data, the potential introduction of mechanistic models as part of the overall monitoring strategy will also allow for some model developments. This could (but is not limited to) include a more detailed zooplankton model to improve the summer chlorophyll-a and/or the introduction of dinoflagellates as a fourth functional phytoplankton group. These developments should focus on the summer chlorophyll concentrations (May-July), and data should be incorporated from other regions to validate the overall performance in that specific period as well.

4.3 A strategy - national and international needs

The potential for the use of satellite observations and mechanistic modelling calls for a national strategy. Currently, Denmark participates and financially supports satellite observations for monitoring in the North Sea through OSPAR, and therefore gets access to the data generated by RBIN in Belgium. We regard this as a very useful approach that should continue. However, as described above, the condition varies spatially in the North Sea, and the Danish areas are complicated with high turbidity and CDOM inputs from both the large rivers, The Elbe and The Rhine and high CDOM concentrations in the outflow of the Baltic Sea. Thus, there is a need for a national effort for developing and selecting the best-suited algorithms for Danish conditions. In addition, we recommend that a ‘post-processing tool' of S3 Chl data is applied, which compares satellite observations with ship-based *in situ* observations to improve the accuracy of S3 Chl estimates. Such a comparison must rely on *in situ* observations, which are expensive in open seas like the North Sea. However, all contracting parties in OSPAR around the North Sea perform ship-based monitoring, and there is an urgent need for Danish participation in this collaboration, which will give access to much more *in situ* data and at a much lower cost than if Denmark does this on their own.

In addition to the possibilities in a joint monitoring programme with the other partners around the North Sea, there are unexploited possibilities in combining monitoring of fish stock and environmental monitoring. Fish stock monitoring visits all grid cells in the North Sea (10 *10 nautical miles) several times per year. Although the timing is not ideal for environmental monitoring, it is worth exploring the possibilities combined with satellite observations and models, as such data could serve as validation /8/.

At the same time, modelling has been an integrated part of the OSPAR work for years. However, Denmark has not been part of this, which over time could be valuable if mechanistic modelling will become part of the overall monitoring strategy in Denmark.

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