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Site selection for macroalgal cultivation in North European waters
Identification of upwelling areas and quantifying nutrient input from nutrient-rich bottom waters using 3-D numerical models

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1 Background

High production rate of seaweed requires sufficient availability to light and nutrients. Such conditions vary significantly within the European Seas.

Inner Danish waters including the Kattegat and the Belt Sea functionally can be considered as a very large estuary where brackish surface water from the Baltic Sea flows (baroclinic) northwards (ca. 850-1.000 km^3/year) to the Skagerrak under mixing with intruding bottom water (ca. 1.000 km^3) with high nutrient and high saline water originating from Skagerrak. In effect, in inner Danish waters the water column is split in large parts of the year (most noticeably during summer) by a pycnocline separating salty and nutrient-rich (originating from the North Sea/Skagerrak) from less salty surface waters (from the Baltic Sea) with a low nutrient content (Pedersen 1993). The depth and the strength of the pycnocline vary between areas and the season. In the Western Kattegat the pycnocline typically is located at 12-14 m depth, while, in Eastern Kattegat the pycnocline is located significantly deeper at 16-17 m. In the water column light intensity decreases with depth due to the presence of microalgae, dissolved organic matter and particles absorbing and scattering the light and, strength and location of pycnocline largely determine if nutrients in the lower layer become available for macroalgae. Based on salt-budgets about 800 km^3 of the nutrient rich and high salinity water from the Skagerrak is mixed with surface water within Kattegat and the Belt Sea while 150-200 km^3 is advected into the Baltic Sea.

In practice, macroalgae may be found down to a depth of 15 to 20 m in Danish waters (Öberg 2006, Helmig and Dahl 2007), but growth rate is low due to limited light availability. At (shallow) depths with sufficient light algal growth is limited by low nutrient concentration during summer. In practice, however, areas with good potential for macroalgae cultivation may be found where:

1) the pycnocline is sufficiently shallow for algae to be exposed to sufficient light intensity and nutrient concentration,

2) bottom water is upwelled carrying nutrients to the surface layer (e.g. Steneck et al. 2002), or

3) where an inclining bottom profile intercepts with the pycnocline, bringing nutrients up near the surface due to turbulence generated by bottom friction. The latter process is found among others in Ålborg Bight.

In this study we attempt to identify areas for cost-efficient macroalgal production in Inner Danish waters based on a combination of hydrodynamic and ecosystem modelling. We have focused on mechanism no. 2 mentioned above, because the potential for additional nutrient input is large, due to the volume of upwelled nutrient-rich waters (≈ 800 km^3 equivalents to 80.000 tons inorganic nitrogen).

2 Optimal sites for macroalgal production

2.1 Scope

In order to map the potential for macro algae production in the Inner Danish Waters (IDW) and the South-Eastern North Sea (SENS) it is necessary to identify areas where the supply of inorganic nutrients is potentially higher than in other areas during the growth season. For this purpose two maps are produced:

- one showing the accumulated upwelling during the growth season
- one showing the average concentration of the in-organic nitrogen

2.2 Methodology

Since concentration levels of in-organic nitrogen in surface water is low during summer stratification, focus will need to be on the water depth at the approximate level of the pycnocline. Here the concentration of inorganic nitrogen is expected to be higher in particular in areas with significant positive vertical water currents, or upwelling. In this analysis and for simplicity data on accumulated upwelling and average concentration of inorganic nitrogen will represent the water volume at the depth of 12 meters, and for more shallow areas data will represent the bottom water layer.

Accumulated upwelling (in “days” and “m3/year”) and the average concentration of inorganic nutrients (mg-N/l) will be extracted from a 3D- hydro-dynamical model and an eutrophication model (~NPZ model) respectively. Extraction will be limited to a 6 month period comprising 1 April to 1 October.

For both the IDW and the NENS the model data available for the analyses include the year 2010. The accumulated upwelling for IDW and SENS respectively is based on two different hydro-dynamic models, - a regional model for the NENS and a more detailed local model for the IDW.

Tthe average inorganic nitrogen concntrations are extracted from the same regional model for both the IDW and the SENS.

The models are described in more detail below.

2.2.1 Hydro-dynamical models

General approach

The applied hydrodynamic models, or current model, described below are based on the MIKE 3 modeling system developed by DHI. The MIKE 3 models are dynamic time-dependent3-D baroclinic model for free surface flows. The mathematical foundation of the models are the Reynolds-averaged Navier-Stoke’s equations in three dimensions, including the effects of turbulence and variable density, together with conservation equations for mass, heat and salt, an equation of state for the density, a turbulence module and a heat exchange module. The equations are solved on either a Cartesian grid by means of the finite difference techniques (MIKE 3) or the equations are solved on an unstructured (flexible) mesh by means of finite volume/finite element techniques (MIKE 3 FM). The hydrodynamic models provide

full 3-D model representation of the water levels, flows, salinity, temperature and density within the modeling domain.
For more information on the MIKE 3 modeling system reference is made to **Error! Reference source not found.** and **Error! Reference source not found.**.

Inner Danish Waters (HD-dkbs)

The hydrodynamic model applied for location of optimal sites for macro algae production in the IDW is based on DHIs Water Forecast services for the Inner Danish Waters and the Baltic Sea. The model named HD-dkbs has been calibration and validated for 2010. The model setup, calibration and validation have been thoroughly documented in a technical note from 2011 **Error! Reference source not found.**. Below is given a summary of the model. For more details, see **Error! Reference source not found.**.

The model mesh applied in the HD-dkbs model is shown in figures Figure 1, and in figure Figure 2 a section of the model mesh and bathymetry covering the inner Danish Waters is shown.

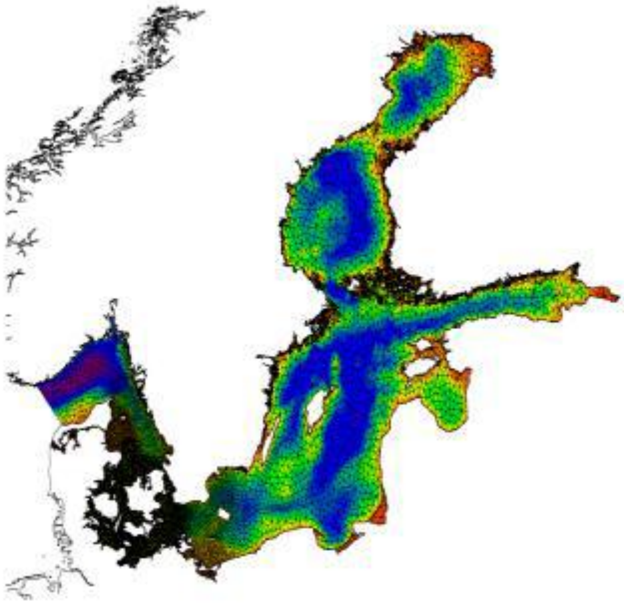

Figure 1. Model mesh of the hydro-dynamic model, HDdkbs, covering the inner Danish Waters and the Baltic Sea **Error! Reference source not found.**. Colours indicate depth intervals, - shallow as red/green and deep as blue.

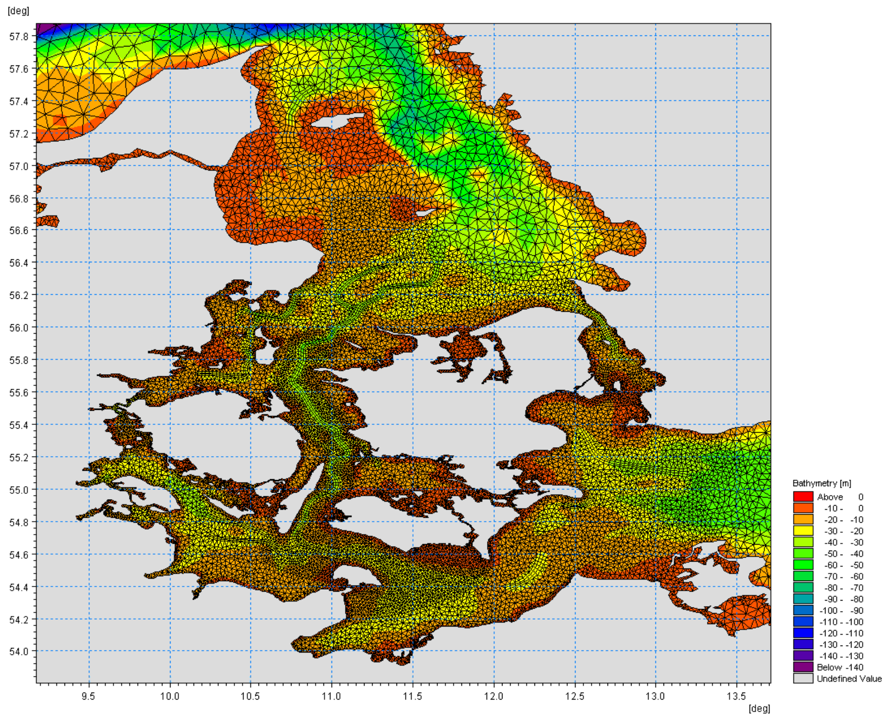

Figure 2. Section of the computational mesh for the hydrodynamic model covering the inner Danish waters. Colors indicate depth intervals in meters.

The mesh has a resolution ranging from 500-1000 m in the Fehmarnbelt area, to 1.0-2.5 km in western Baltic and Belt Sea, to 2-6 km in Kattegat and west of Bornholm, to 5-12 km in Skagerrak, and finally to 5-20 km in Baltic Sea east of Bornholm.

The vertical domain is a combined sigma-z domain with the upper 10 m of the water column represented by 10 sigma-layers and the remaining water column represented by a number of z-layers depending on the local water depth. The adopted vertical resolution allows for the main part of the western Baltic Sea and the Belt Sea including Fehmarnbelt to be resolved entirely by 1 m layers.

Meteorological input data (wind, air temperature, air pressure, clearness and precipitation) is provided by StormGeo (Norway).

Boundary data for the Skagerrak model boundary including water level, current, salinity and temperature are provided by DHIs larger operational forecast models: - water level and current from the Hydrostatic North Sea-Baltic Sea operational model and temperature and salinity are provided by the so-called BANSAI operational model (see section 0).

In order to account for the freshwater runoff within the model domain, the hydrodynamic model includes 82 model sources. These sources represent the total freshwater input to the model domain. Data is based on combination of modeled and climatological data from SMHIs HBV runoff model and from the data sources applied for the Danish NOVANA modeling program.

The model is calibrated by comparing simulated and measured time series of water level, water temperature and salinity at various locations within the model domain. Available monitoring stations used for calibration are shown in Figure 3.

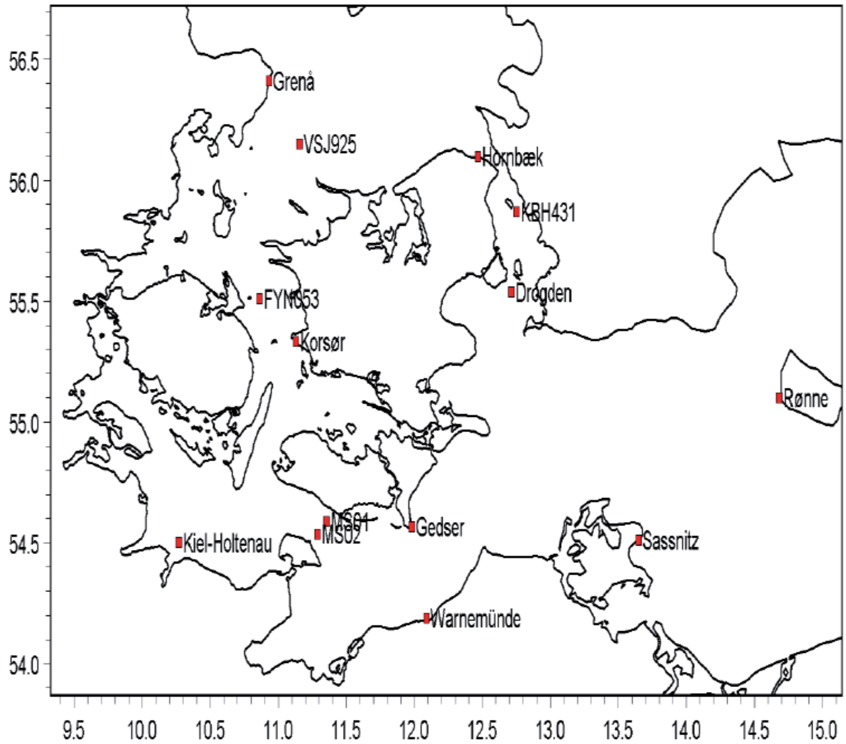

Figure 3 Location of stations available for comparison between measurements and model results of salinity and temperature **Error! Reference source not found.**.

Figures Figure 4 Figure 5 and Figure 13 show the comparison between measured and simulated temperature and salinity for 3 stations, FYN-053, VSJ-925 and MS-02, located Great Belt, Kattegat and Fehmern Belt respectively. The figures show both surface and bottom values in order to illustrate the ability of the model to simulate the stratification of the water column. A 10-month period in 2010 has been selected for the comparisons.

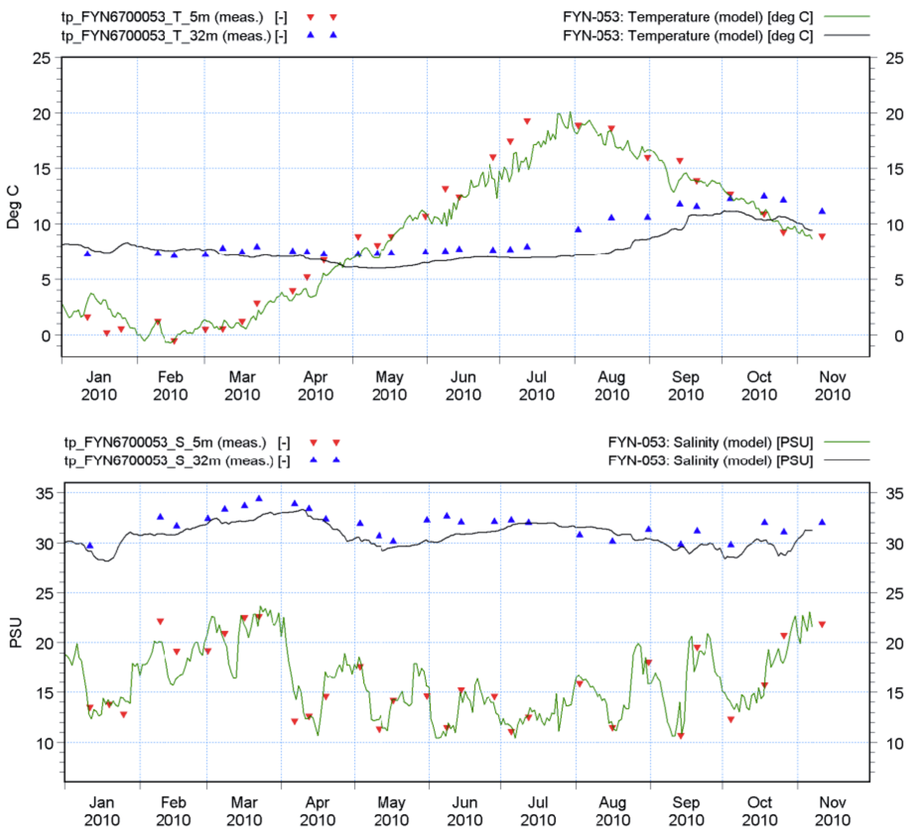

Figure 4. Comparison of measured and modelled temperature and salinity at station FYN053. [1]

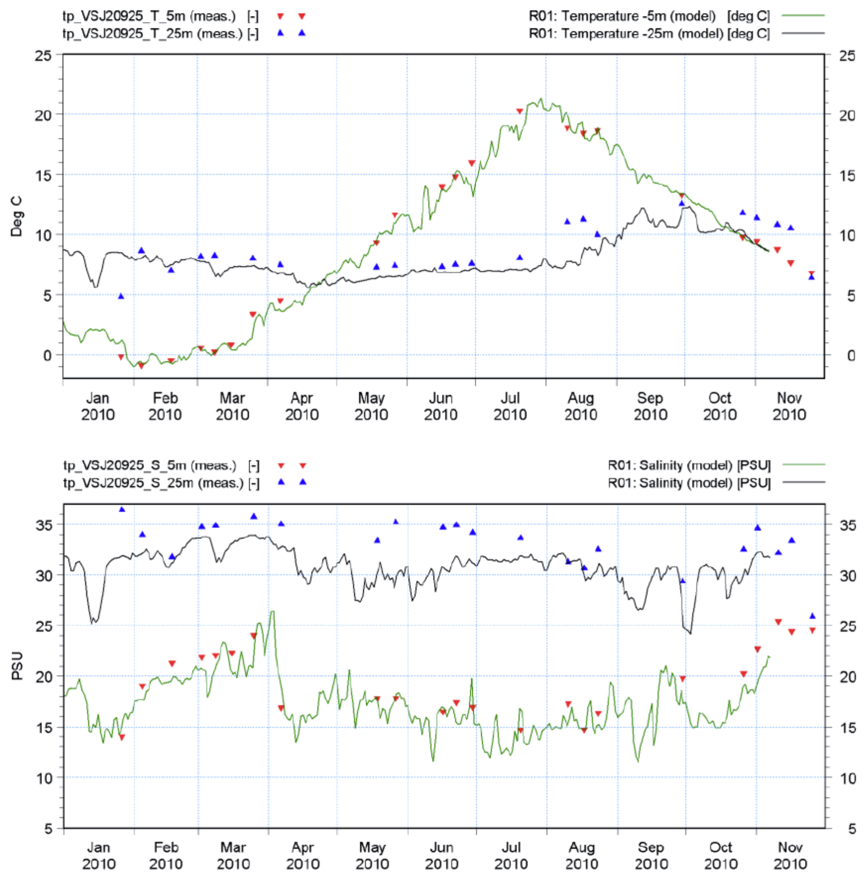

Figure 5. Comparison of measured and modelled temperature and salinity at station VSJ925. **Error! Reference source not found.**

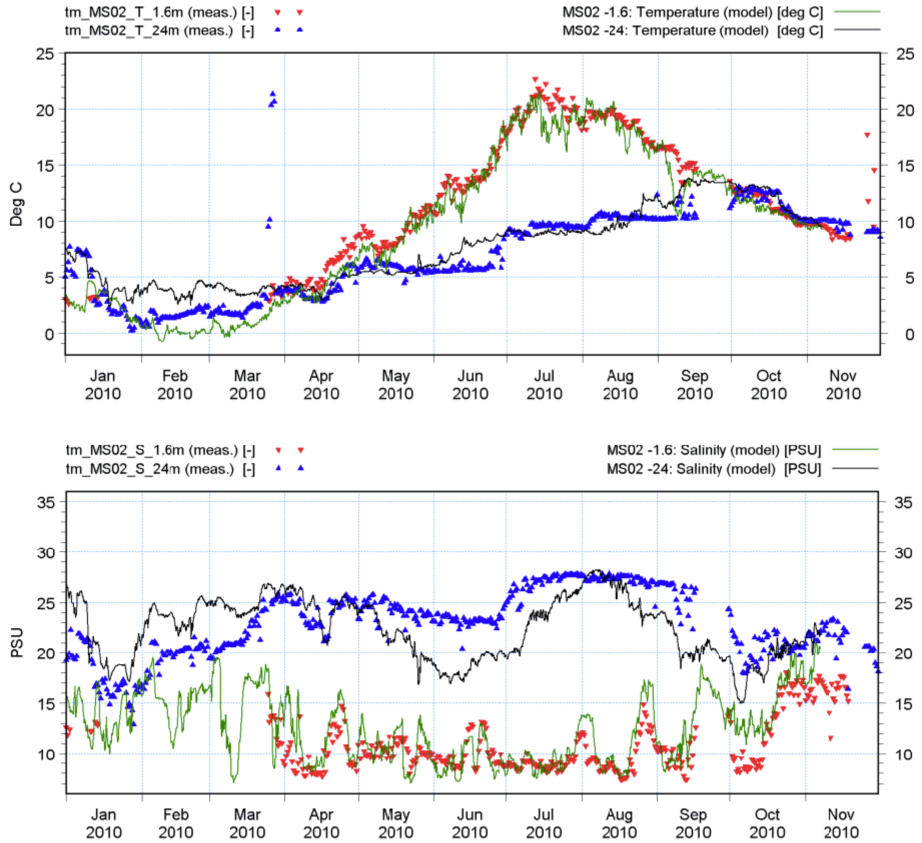

Figure 6 Comparison of measured and modelled temperature and salinity at station MS02. **Error! Reference source not found.**

Figure 7 shows comparison of simulated and measured water level at 3 stations in the inner Danish Waters: Korsør, Grenå and Hornbæk. The comparison shown is for a 1-month period in September-October 2010.

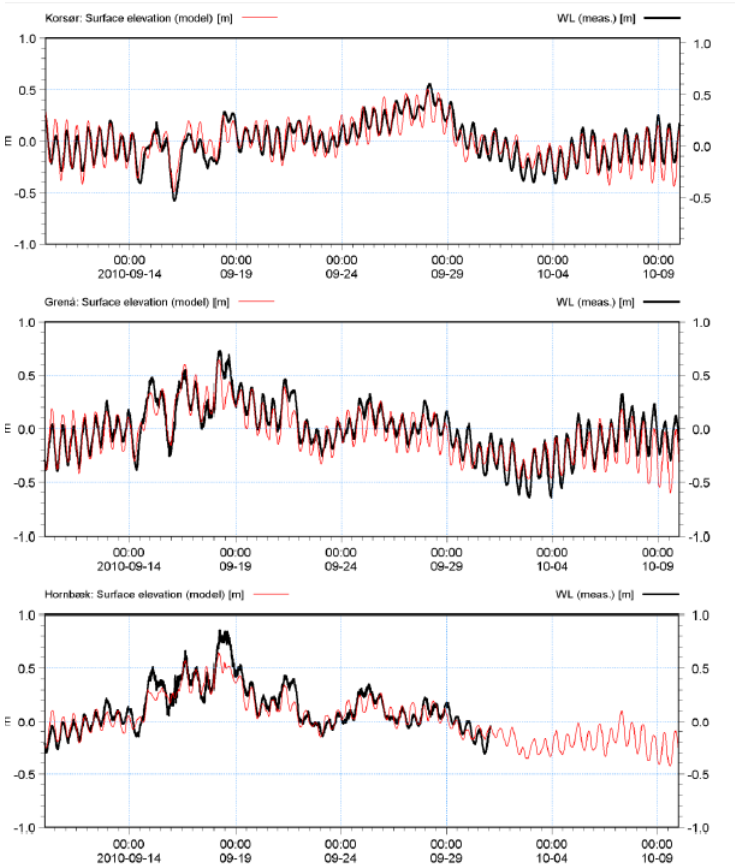

Figure 7. Comparison of measured and modelled water level at stations Korsør, Grenå and Hornbæk **Error! Reference source not found.**

South-Eastern North Sea (BANSAI)

The hydrodynamic model applied for location of optimal sites for macro algae production in the SENS is based on DHIs Regional Water Forecast services for the North Sea, the Inner Danish Waters and the Baltic Sea. The model named BANSAI has been calibration and validated for 2004 with primary focus on the transitional waters between the North Sea and the Baltic Sea. The model setup, calibration and validation have been documented in a technical note from 2006 [4]. The model has been run on an operation forecast model since 2000. Below is given a summary of the model. For more details, see [4].

The model domain includes the major part of the North Sea, the Belt Sea and the Baltic Sea. The model applies a Cartesian grid in UTM-32 projection with a horizontal resolution of 3 nautical miles. In the vertical dimension a 2 m resolution is used, with a maximum of 110 layers depending on the local water depth. However, the surface layer with surface elevation varying with the actual tide has a typical thickness of 5 m. For areas with depths under level -223 m the rest of the water column is included in the lowest layer. The model domain is shown in Figure 8.

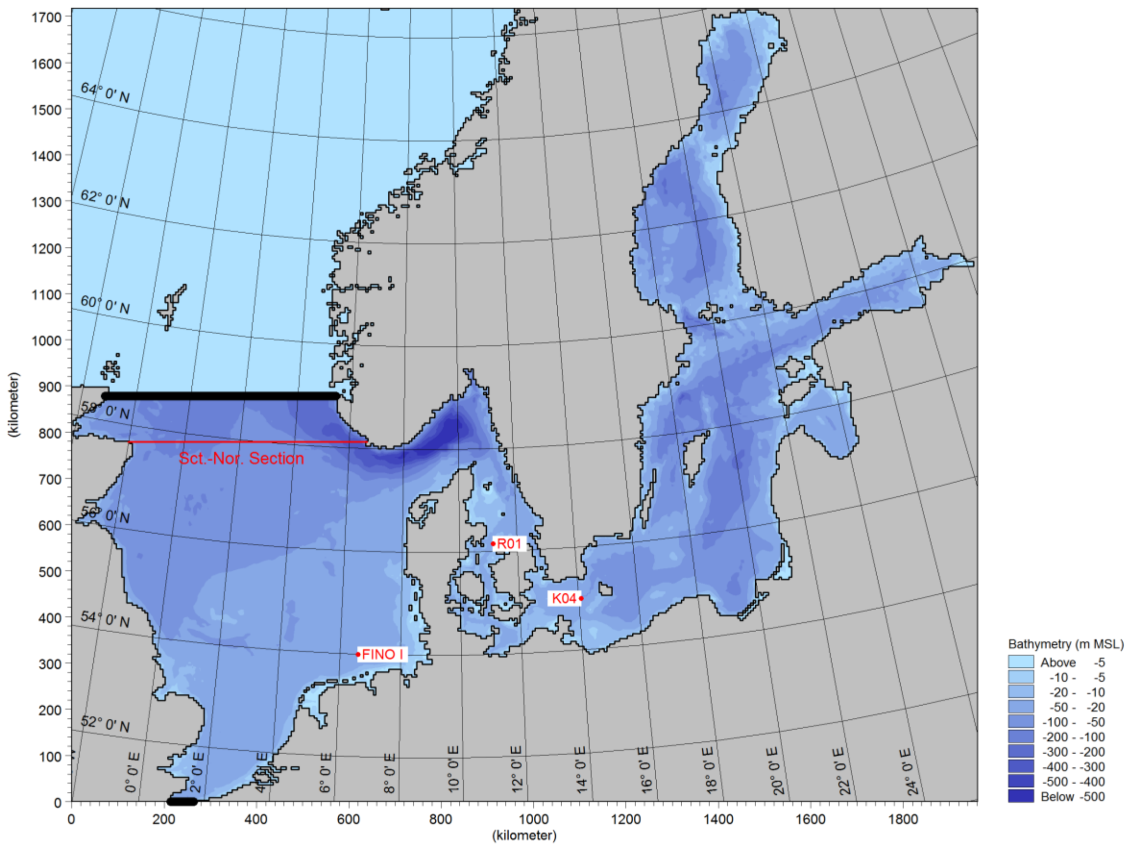

Figure 8 Model domain and location of selected measurement stations. The thick black lines indicate the open boundaries of the model.

The model runs with a hydrodynamic time step of 300 seconds. The model results in terms of 3-D fields of for example current, salinity and temperature are saved every 1 hour.
The forcings on the open boundaries towards the Norwegian Sea and the English Channel include astronomical tide along boundary, salinity distribution in vertical sections (monthly climatologic from ICES) and temperature distribution in vertical sections (monthly climatologic from ICES).

Atmospheric forcing such as wind, air pressure, air temperature, cloudiness and precipitation (actual 2D maps with 1 hour resolution) for 2010 are delivered by the meteorological company StormGeo (Norway).

The runoff in terms of discharges of freshwater from land to the model domain is represented in the model by 85 source points. The runoff is based on data from Swedish Meteorological and Hydrological Institute (SMHI's) operational HBV-model and on data from Global Runoff Data Centre (GRDC).

The present hydrodynamic model setup is an updated version of the model used for the Nordic Council of Ministers project BANSAI, reference [4].

The model is calibrated by comparing simulated and measured time series of water level, water temperature and salinity at various locations within the model domain. Examples of monitoring stations used for calibration are shown in Figure 8.

In Figure 9 and Figure 10 are shown the comparison between measured and simulated temperatures and salinities for 2 stations, R01 in Kattegat (2002-2008) and FIN0 the German Bight (2005). The figures show both surface and bottom values in order to illustrate the ability of the model to simulate the stratification of the water column.

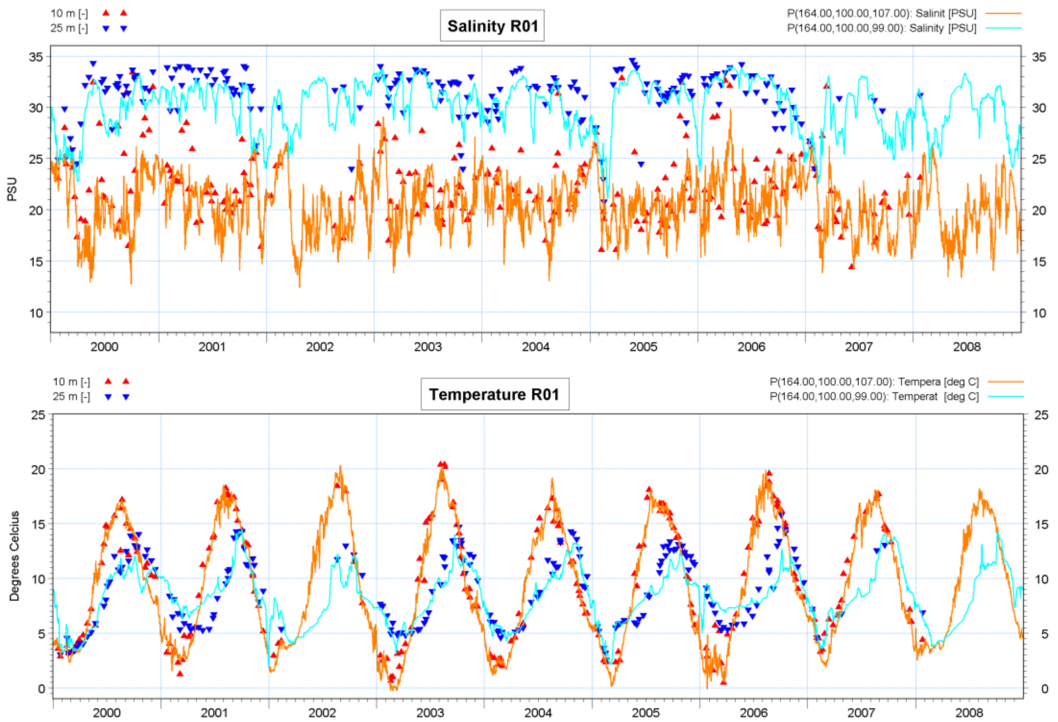

Figure 9 Comparison of measured and modeled salinity (upper) and temperature (lower) in Station R01 in Kattegat. The two depths (10 m and 25 m) represent the surface layer and the bottom layer.

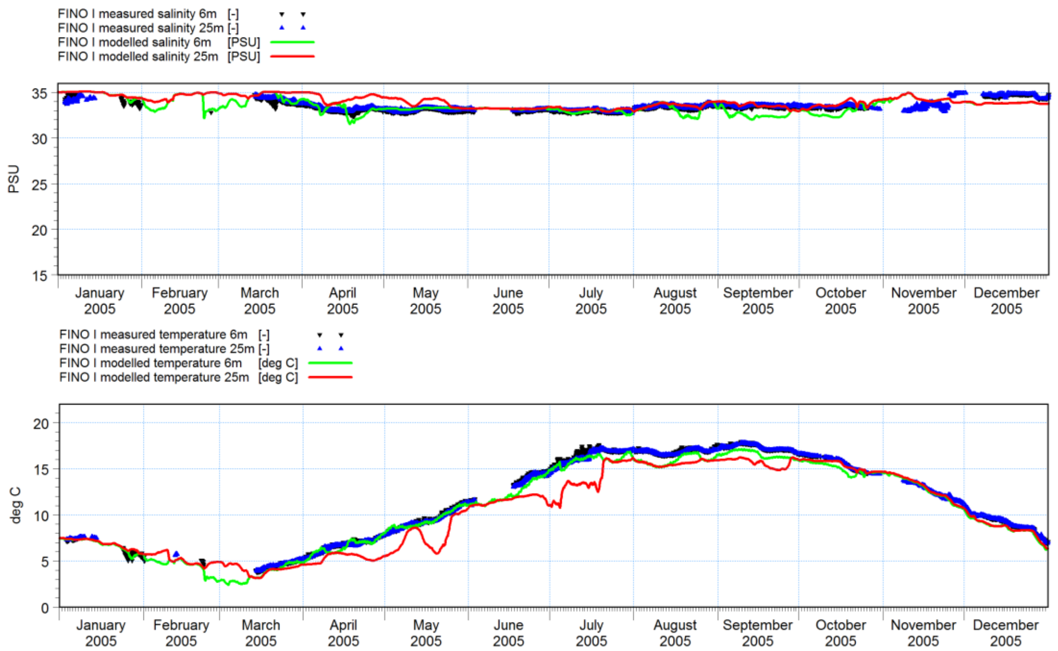

Figure 10 Comparison of measured and modelled salinity (upper) and temperature (lower) in Station FINO I in German Bight. The two depths (6 m and 25 m) represent the surface layer and the bottom layer.

2.2.2 Eutrophication model

General approach

The applied eutrophication model or NPZ model, described below is based on the ECO Lab eutrophication module (EU) available for MIKE 3. The EU module represents the nutrient cycling, the primary production and mineralization, and the associated effect on dissolved oxygen conditions. For further information on the modeling software is referred to **Error! Reference source not found.** and **Error! Reference source not found.**.

The setup and calibration is described in short below, - for details refer to **Error! Reference source not found.**.

Model setup and performance

The boundary conditions for the open water boundaries towards the north Atlantic and the English Channel include climatological values of inorganic and organic nutrients concentrations and DO.

Land loads include actual (established based on measurements) values for Danish sources (monthly) and climatological concentration values for remaining rivers.

Atmospheric deposition is based on actual values (established based on measurements) as monthly values.

Light information is based actual values on photosynthetic active radiation (established based on measurements).

The model is calibrated by comparing simulated and measured time series of chlorophyll a, nitrate, ammonia, total nitrogen, inorganic P, Total P, dissolved oxygen and secchidepth at various locations within the model domain. Locations of some of the monitoring stations used for calibration are shown in Figure 8Figure 3.

In Figure 11 and Figure 12 are shown the comparison between measured and simulated chlorophyll a, nitrate-N (or total N) and ammonia-N for stations, VSJ925 in Kattegat (2004) and FYN053 in the Great Belt (2004). The figures show both surface and bottom values in order to illustrate the ability of the model to simulate concentrations below and above the stratification of the water column.

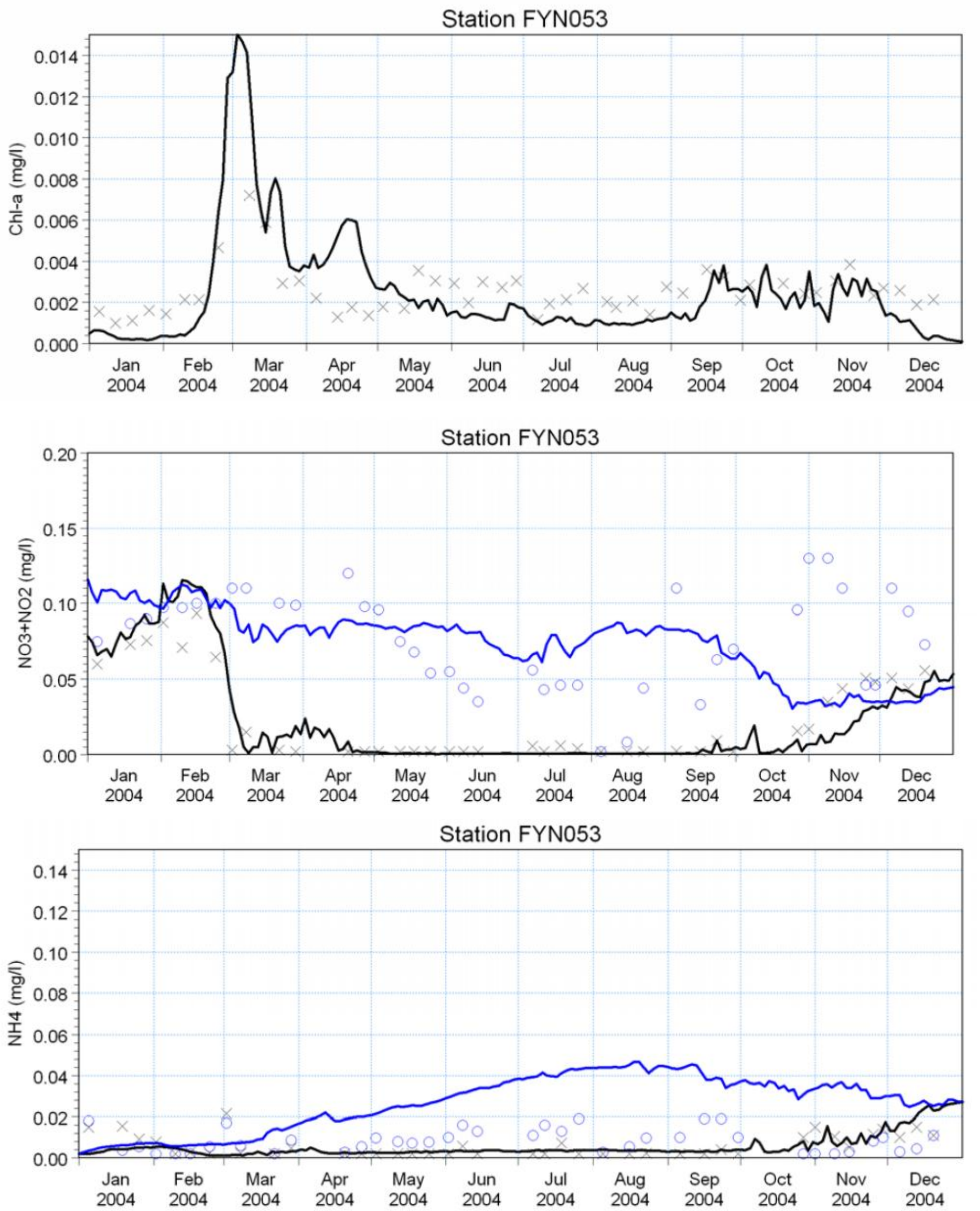

Figure 11 Surface (0-6 meters, black) and bottom (-31 meters, blue) Chlorophyll, Nitrate-N/Nitrite-N and ammonia-N concentrations at the station FYN053 (the Great Belt). Monitoring data (symbols) and modelling results (lines).

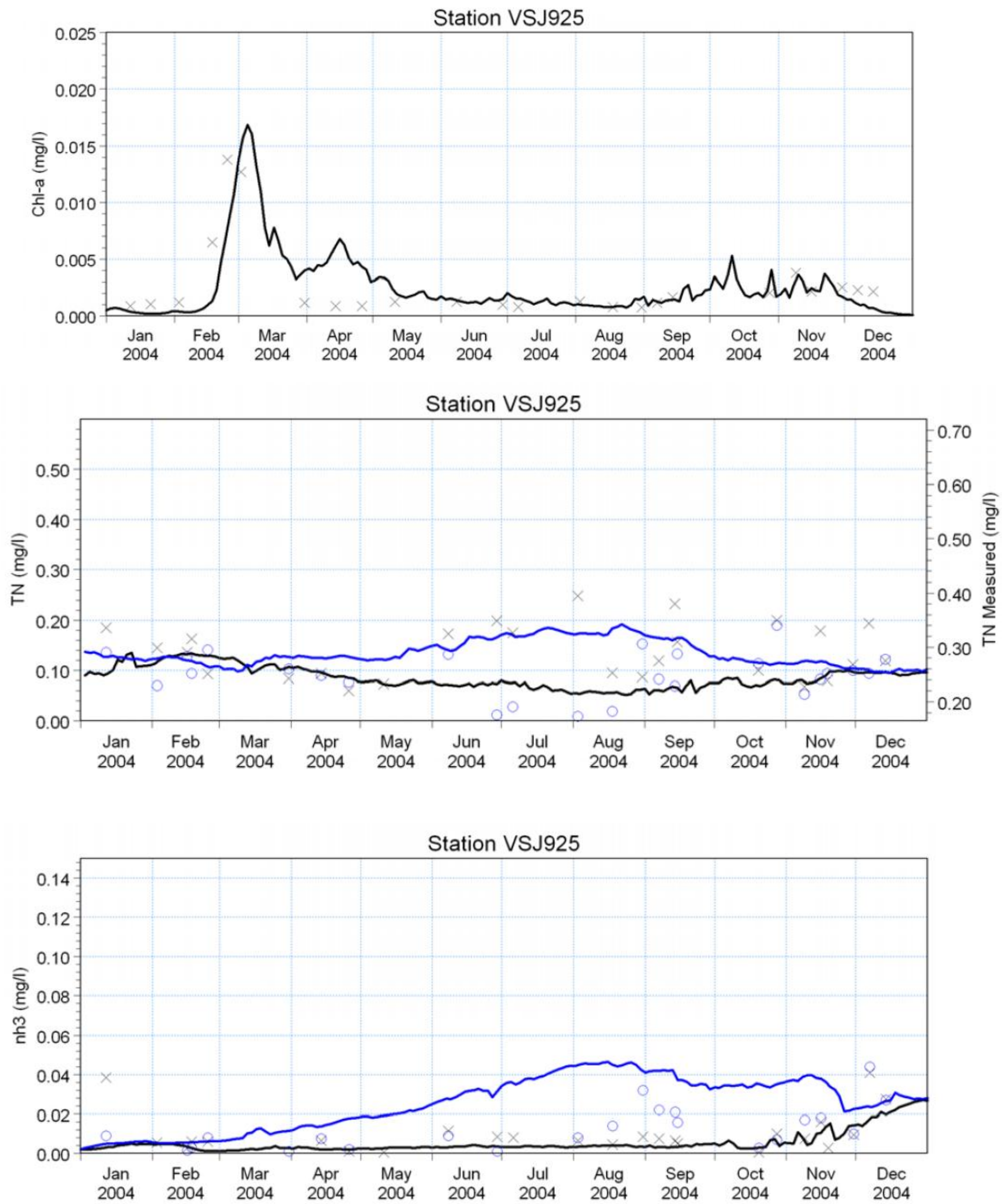

Figure 12 Surface (0-6 meters, black) and bottom (-31 meters, blue) Chlorophyll, Total Nitrogen concentrations (Nitrate-N/Nitrite-N measurements not available) and ammonia-N concentrations at the station VSJ925 (Kattegat). Monitoring data (symbols) and modelling results (lines).

2.3 Results & Discussion

Calculated accumulated (positive) vertical velocity from 1st April through September where nutrient concentrations in surface waters is low and primary production is limited by nitrogen is shown in Fig. 13, and the number of days where upwelling occurs is shown in Fig. 14. Areas with the largest accumulated upwelling (> 1.0 E3.0 m) during the nutrient-poor period occurs Langeland Belt (LB), Great Belt (GB), east of Samsø (SA) and east of Fornæs (FN). In these areas 7-10 m/d of bottom water is introduced into surface water on average.

The consistency of upwelling during the nutrient-poor period is rather scattered but overall consistent with the accumulated upwelling (Fig. 14). In these areas, upwelling occurs at least 66% of the time, and at Fornæs 75% of the time (see Fig. 14).

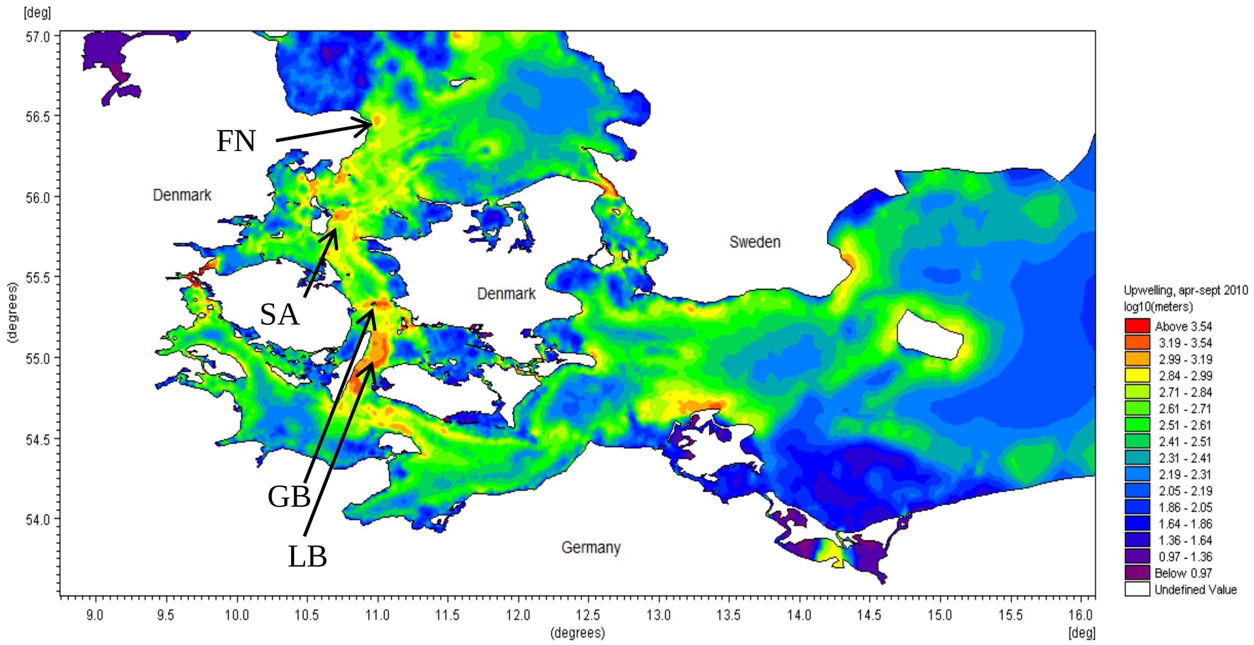

Figure 13 Accumulated positive vertical current velocities in 12 m depth for the period 1-4-2010 to 30-9-2010 for the Inner Danish Waters and the western Baltic Sea. The scale is in log[10.]. For areas with water depth less than 12 meters values represent positive current velocities from the bottom layer to the above layer of the model. Arrows have been inserted where upwelling is most intense (see text).

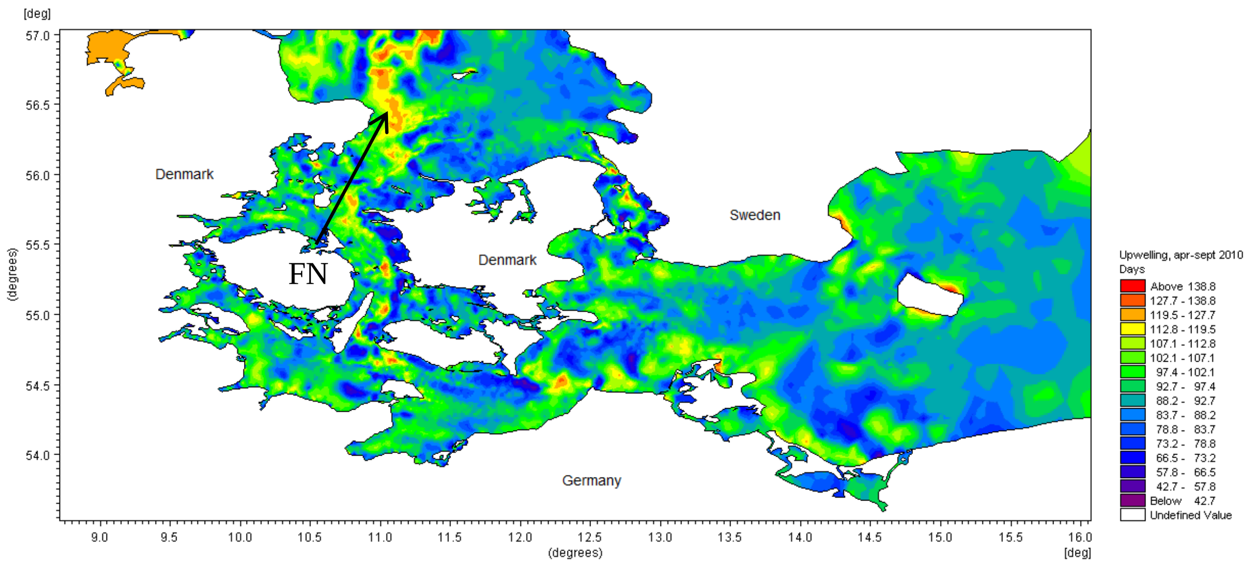

Figure 14 Accumulated time (in days) of positive vertical current velocities in 12 m depth for the period 1-4-2010 to 30-9-2010 for the Inner Danish Waters and the western Baltic Sea. For areas with water depth less than 12 meters accumulated time is calculated for positive current velocities from the bottom layer to the above layer of the model.

Distribution of modelled mean concentration of inorganic nitrogen in upwelling water is shown in Fig.15. Briefly, the highest concentration of inorganic nitrogen (DIN) in bottom water peaked around Fornæs (above 0.03 mg DIN/l) and concentrations gradually decreased through Great Belt and Langeland Belt due increased “down-mixing” of surface water as evidenced by reduction in salinity.

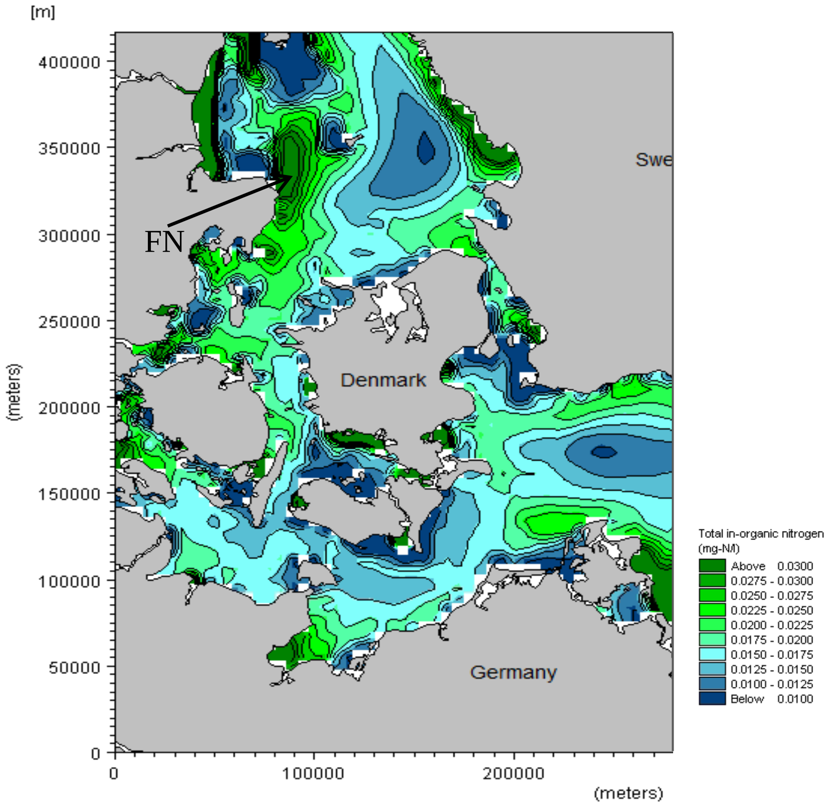

Figure 15. Mean concentration of inorganic nitrogen at 12 meters water depth for the period 1-4-2005 to 31-9-2005 for the Inner Danish Waters and the western Baltic Sea. For areas with a water depth of less than 12 meters values represent concentrations in the bottom layer of the model. Arrow indicate the Fornæs area that must be considered as the most appropriate for macroalgae cultivation in inner Danish waters

To conclude, based on modeled upwelling intensity (Fig. 13), upwelling consistency (Fig. 14) and modeled concentration of inorganic nitrogen in upwelling water (Fig. 15) Fornæs (FN) must be considered as the most appropriate area for macroalgae cultivation. Also, shading from westerly winds is ad additional advantage of the area. If we assume that 50% of the additional nitrogen nutrients introduced to surface layer by upwelling can be incorporated into macroalgae the production theoretically can be increased by 5-600 g dry weight/m^2, i.e. equivalent to 6 tons/ha.

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