DHI

Development of Mechanistic Models

Mechanistic Model for Southern Belt Sea

Hydrodynamic model documentation

Miljø- og Fødevareministeriet
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The expert in **WATER ENVIRONMENTS**

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Mechanistic Model for Southern Belt Sea

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The model development presented in this technical note represents the hydrodynamic model development for Southern Belt Sea. The Southern Belt Sea model (SBS-model) is part of a larger model complex comprising a number of mechanistic models developed by DHI and several statistical models developed by 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 to integrate with Bayesian statistical modelling and cross system modelling carried out by AU, Bioscience.

Here we present the hydrodynamic (HD) model setup covering Southern Belt Sea: The SBS-model. This specific model includes 33 Danish water bodies:

Water Body*)	Number	Water Body	Number
Nakkebølle Fjord	63	Als Fjord	103
Skårupøre Sund	64	Als Sund	104
Thurø Bund	65	Augustenborg Fjord	105
Lindelse Nor	68	Haderslev Fjord	106
Kløven	72	Avnø Vig	108
Nyborg Fjord	73	Hejlsminde Nor	109
Bredningen	74	Nybøl Nor	110
Emtekær Nor	75	Flensborg Fjord, indre	113
Gamborg Fjord	80	Flensborg Fjord, ydre	114
Bågø Nor	81	Kolding Fjord, indre	124
Aborgminde Nor	82	Kolding Fjord, ydre	125
Holckenhavn Fjord	83	Faaborg Fjord	212
Helnæs Bugt	87	Torø Vig og Torø Nor	213
Lunkebugten	89	Det sydfynske Øhav, åbne del	214
Langelandssund	90	Lillebælt, syd	216
Genner Bugt	101	Lillebælt, Bredningen	217
Åbenrå Fjord	102		

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

The SBS hydrodynamic model is developed to describe the physical system (water levels, currents, turbulence, mixing, salinity and water temperature). The model is developed to ensure a quality that will support a robust ecosystem (biogeochemical) model, an ecosystem model that eventually can be used for modelling a number of scenarios in support of the WFD implementation in Denmark.

As can be seen from the present technical note the SBS hydrodynamic model was developed successfully for the entire model period 2002-2016, and from the validation we conclude:

- On average the P-Bias is 2.7% with respect to salinity and -3.9 % with respect to water temperature. Hence, on average the model meets a model performance of 'excellent' for both salinity and temperature. Looking at the individual stations 28 of the stations meet 'excellent' for salinity and three stations meet 'very good', whereas modelled temperature meets 'excellent' for 29 of the stations and two stations meet 'very good'.

- With respect to the Spearman Rank Correlation the average numbers are 0.87 and 0.96 for salinity and water temperature, respectively. This means that on average the model performance at the stations used for validation meets 'very good' and 'excellent' for salinity and water temperature, respectively. This is also the case for the individual temperature stations (28 station out of 31 meets 'excellent' model performance), whereas modelled salinity meets 'excellent' for 11 of the stations and 20 station meet 'very good'.

- The average Modelling Efficient Factor (MEF) for salinity is 0.68 corresponding to a 'very good' model. The MEF at the individual stations varies from 0.26 to 0.88 and covers seven stations meeting the criteria for 'excellent', 21 meeting the 'very good' and three meeting 'good' model performance. With respect to water temperature the average MEF value is 0.90 corresponding to an 'excellent' model. This covers 28 stations evaluated as 'excellent' and three station evaluated as 'very good'.

The details behind the above data are available in Table 6-1 and Table 6-2 and time series comparisons are available here: http://rbmp2021-2027.dhigroup.com (Google Chrome only).

Based on the two tables and the time series (the time series are available at http://rbmp2021-2027.dhigroup.com) we conclude that the model describes the overall physical features in the SBS and that the model is adequate for ecosystem model development.

2 Introduction

The model development presented in this technical note represents the hydrodynamic model development for the Southern Belt Sea. The Southern Belt Sea model (SBS-model) is part of a larger model complex comprising a number of mechanistic models developed by DHI and several statistical models developed by 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 to integrate with Bayesian statistical modelling and cross system modelling carried out by AU, Bioscience.

Here we present the hydrodynamic (HD) model setup covering the Southern Belt Sea. This specific model includes the Danish water bodies listed in Table 2-1.

Table 2-1 Water bodies included in the Southern Belt Sea model

Water Body*)	Number	Water Body	Number
Nakkebølle Fjord	63	Als Fjord	103
Skårupøre Sund	64	Als Sund	104
Thurø Bund	65	Augustenborg Fjord	105
Lindelse Nor	68	Haderslev Fjord	106
Kløven	72	Avnø Vig	108
Nyborg Fjord	73	Hejlsminde Nor	109
Bredningen	74	Nybøl Nor	110
Emtekær Nor	75	Flensborg Fjord, indre	113
Gamborg Fjord	80	Flensborg Fjord, ydre	114
Bågø Nor	81	Kolding Fjord, indre	124
Aborgminde Nor	82	Kolding Fjord, ydre	125
Holckenhavn Fjord	83	Faaborg Fjord	212
Helnæs Bugt	87	Torø Vig og Torø Nor	213
Lunkebugten	89	Det sydfynske Øhav, åbne del	214
Langelandssund	90	Lillebælt, syd	216
Genner Bugt	101	Lillebælt, Bredningen	217
Åbenrå Fjord	102		

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

3 Modelling Concept

3.1 Mechanistic Modelling

The present technical note represents the hydrodynamic part of one model out of eleven mechanistic models. The eleven mechanistic models are 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 forcings and anthropogenic pressures. Hence, mechanistic models can by applied for predictions of changes in specific components, like chlorophyll-a concentrations, due to climatic changes or changes in anthropogenic pressures.

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

The model development in this specific project aims at supporting the Danish EPAs implementation of the WFD. In this first phase of the model development the models are developed to represent the present period (2002-2016) evaluated against NOVANA measurements. Here we use present meteorological data, present nutrient loadings, etc.

After the models are finalized they will be applied for scenario modelling, although the specific scenarios are not yet defined.

3.2 Model development

The model development consists of a 3D hydrodynamic model describing the physical system; water levels, current, salinity and water temperatures. Following the development of the hydrodynamic model is the development of the 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.

The SBS-model is defined as a local-domain model. The mechanistic model complex developed as part of the present project includes two regional models, three local-domain models and six estuary specific models.

- Regional models: 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, provide boundaries to local-domain models and estuary specific models.

- Local-domain models: These models are developed to allow for resolving the majority of small and medium sized water bodies in the North-western Belt Sea (NBS), the South-western Belt Sea (SHS) and the waters bodies in and around the Smålandsfarvandet (SMF).

- Estuary specific models: Six specific estuary (fjord) models are developed to allow for detailed modelling of the particular estuary.

All mechanistic models are setup and calibrated for the period 2002-2011 and validated for the period 2012-2016. In this note the validation will be reported according to specific indices (DHI 2019a), whereas the entire period is included as time series in a WEB-tool (http://rbmp2021-2027.dhigroup.com) with a few examples included in section 6.2.1. The majority of data used for calibration and validation originates 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 hydrodynamic model is based on the modelling software MIKE 3 HD FM (version 2017) developed by DHI. MIKE 3 HD FM is based on a flexible mesh approach and has been developed for applications within oceanographic, coastal and estuarine environments.

The system is based on the numerical solution of the three-dimensional (3D) incompressible Reynolds averaged Navier-Stokes equations invoking the assumptions of Boussinesq and of hydrostatic pressure. Thus, the model consists of continuity, momentum, temperature, salinity and density equations and it is closed by a turbulent closure scheme. The free surface is taken into account using a sigma-coordinate transformation approach. The scientific documentation of MIKE 3 HD FM is given in DHI (2017a).

4 Model Setup

4.1 Introduction

The model setup comprises defining the model domain, establishing the model mesh, preparing the model forcings in terms of open boundary conditions, atmospheric forcing and freshwater inflows, preparing the initial conditions and setting up the model.

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

4.2 Model Domain

4.2.1 Introduction

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

The SBS-model domain includes the Danish waters enclosed by Funen, Jutland and Germany to the South as shown in Figure 4.1.

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 model. In the following sections some details of the horizontal and vertical model mesh are described.

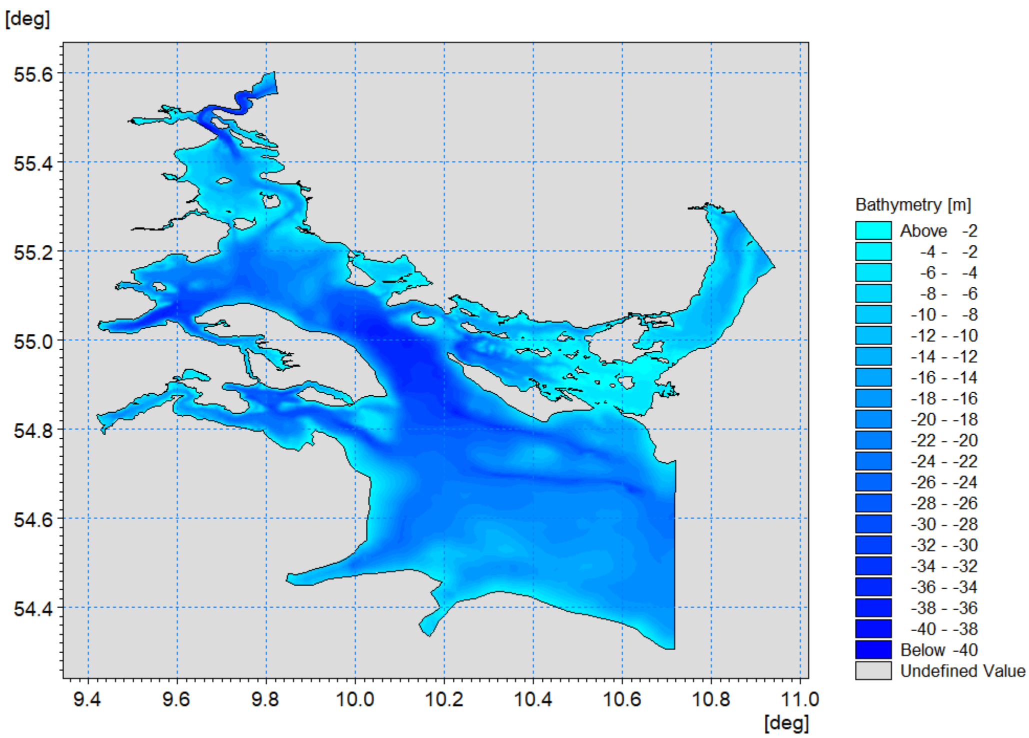


Figure 4.1 Southern Belt Sea model bathymetry. Data originates from Kystdirektorates 50 m bathymetry updated with satellite derived data at shallow waters (DHI 2019b).

4.2.2 Horizontal mesh

The horizontal discretization of the domain applies an unstructured mesh with triangular elements varying in size and quadrangular elements in areas with a predominant flow direction like narrow connections and navigation channels (i.e. Langelandssund).

The different resolutions used are listed in Table 4-1 with the highest resolution in the targeted water bodies within the Southern Belt Sea (levels 2, 3 and 4) and the resolution of the regional model (levels 5 and 6) in the rest of the domain, see Figure 4.2.

The domain representation has been setup using geographical coordinates (longitude/latitude) WGS-84.

Satellite derived data combined with a national 50m bathymetry from Kystdirektoratet were used to generate water depths in the Danish part of the model domain according to (DHI 2019b), while depth data from the IDF regional model has been applied for the rest of the domain. All model elevations are applied relative to DVR90 or MSL.

Table 4-1 Mesh triangulation resolution

Level	Maximum area (deg^2)	Element length (m)	
1	5.0E-07	40-120	Local model resolution
2	2.0E-06	100-200m	
3	8.0E-06	200-300m	
4	2.0E-05	300-500m	
5	0.0001	500-1,200m	Regional model resolution
6	0.00025	1,200-2,000m	

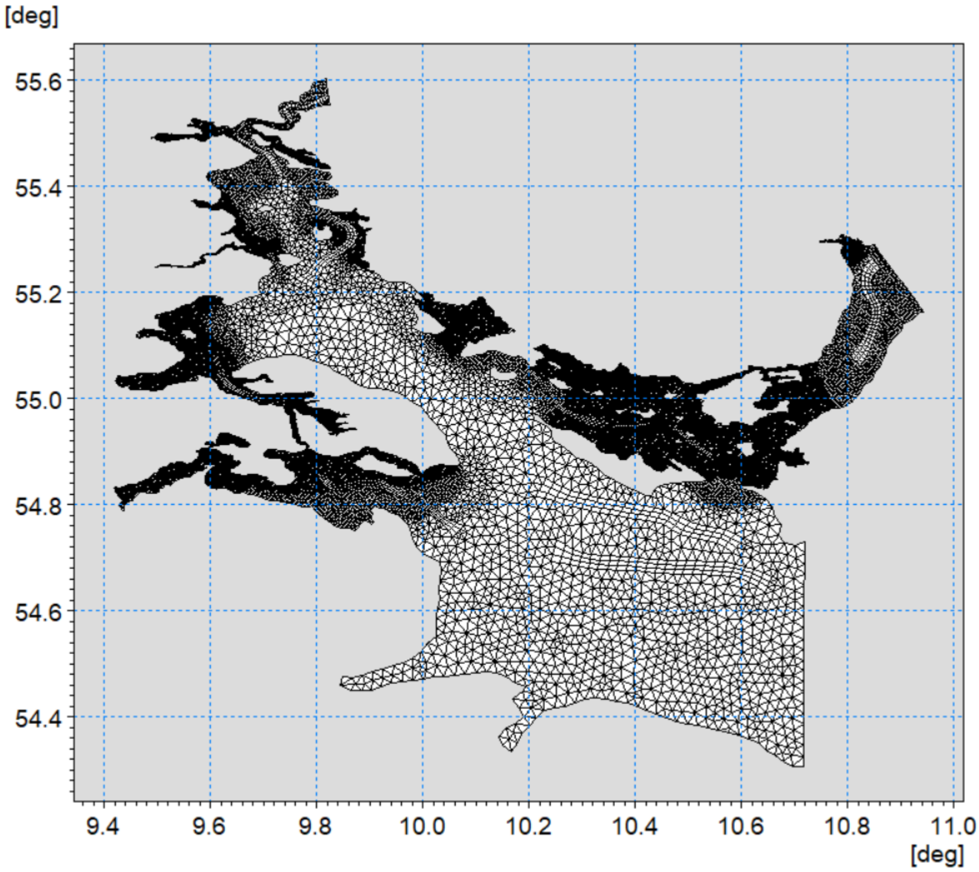


Figure 4.2 SBS-model mesh triangulation including mesh resolution levels from Table 4-1.

4.2.3 Vertical mesh

The vertical mesh is structured and consists of a combination of 10 sigma layers down to -10m and z-layers of 1m thickness for the rest of the water column.

Figure 4.3 show an example of the resulting vertical stratification along one transects from Southern Als to Helnæs Bugt.

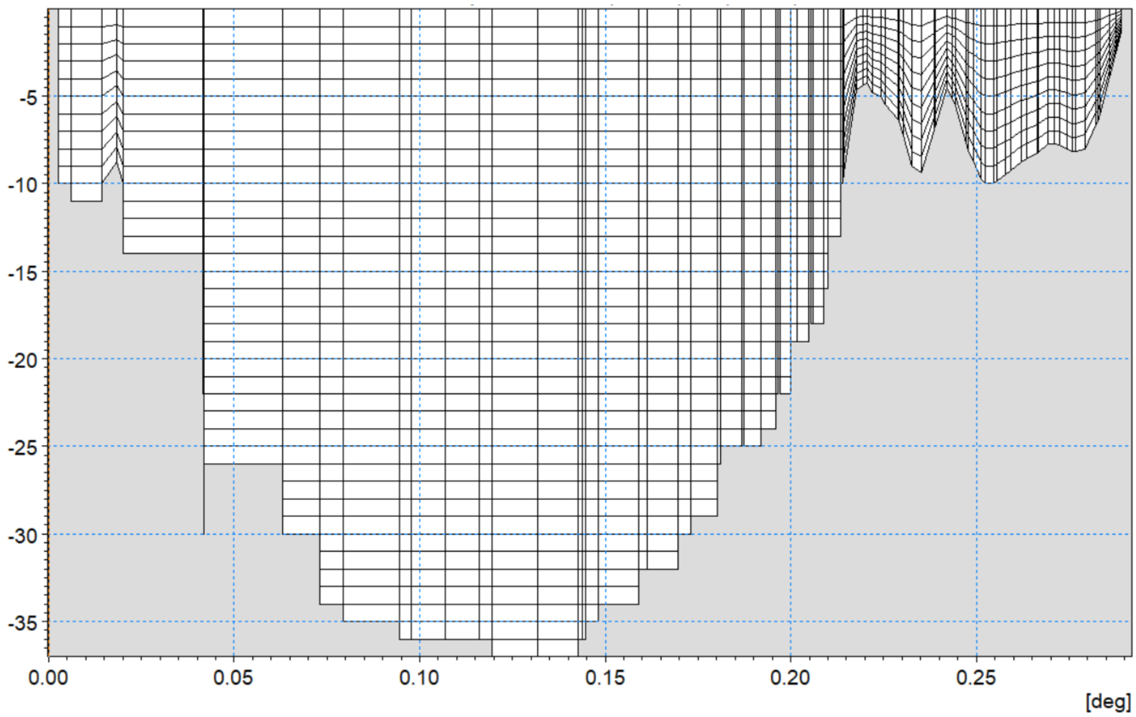


Figure 4.3 Transect along Southern Belt Sea showing the vertical discretization in the column: sigma layers down to -10m and 1m z-layers to the seabed.

4.3 Model Forcings

4.3.1 Open Boundary Conditions

The model domain has three connections to the surrounding Danish waters, Figure 4.4, where water level, currents, salinity and temperature from the IDF regional model are extracted and applied, giving the full dynamic boundary specification for the model

- Kiel Bay/Fehmarn Belt
- Great Belt
- Little Belt

The water level forcing is described by a time varying profile along the boundary, while velocity components, temperature and salinity are defined as 2D vertical maps varying in time along the open boundary.

The forcing of the boundary with water level and currents simultaneously is the so called Flather boundary (Flather, 1976), being one of the most efficient open boundary conditions. It is very efficient in connection with downscaling coarser model simulations to local areas (see Oddo and Pinardi 2007). Instabilities often observed when imposing stratified density at a water level boundary are avoided using Flather conditions.

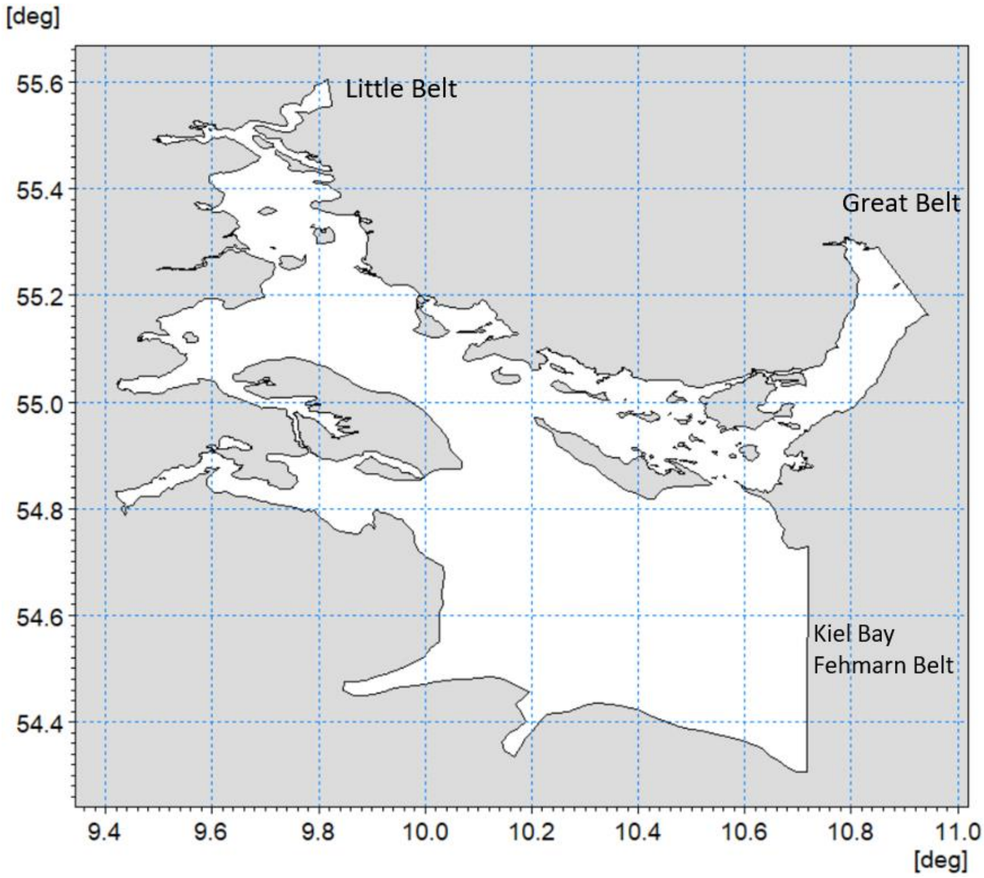


Figure 4.4 Southern Belt Sea model open boundaries

4.3.2 Atmospheric Forcing

The atmospheric forcing of the SBS-model is mainly provided by StormGeo in terms of temporally and spatially varying fields of:

- Wind
- Atmospheric pressure
- Precipitation
- Air temperature
- Cloud cover

The applied atmospheric data is from StormGeo's WRF meteorological model covering the North Atlantic. The data is provided in a resolution of 0.1° x 0.1° in hourly time steps.

The StormGeo data are only available from 2009 and forward. Before 2009 meteorological fields from Vejr2 of Denmark were applied with varying spatial and time resolution (9 nautical miles (2002-2005), 0.15° x 0.15° (2005-2009), 3 hourly (2002-2004) and 1 hourly (2005-2008).

4.3.3 Freshwater Sources

The Southern Belt Sea model includes a number of model sources representing the freshwater run-off from land to sea.

The model sources are specified as daily discharge time series over the modelling period 2002-2016 and are based on data from DCE (Aarhus University).

The run-off sources included in the model are shown in Figure 4.5.

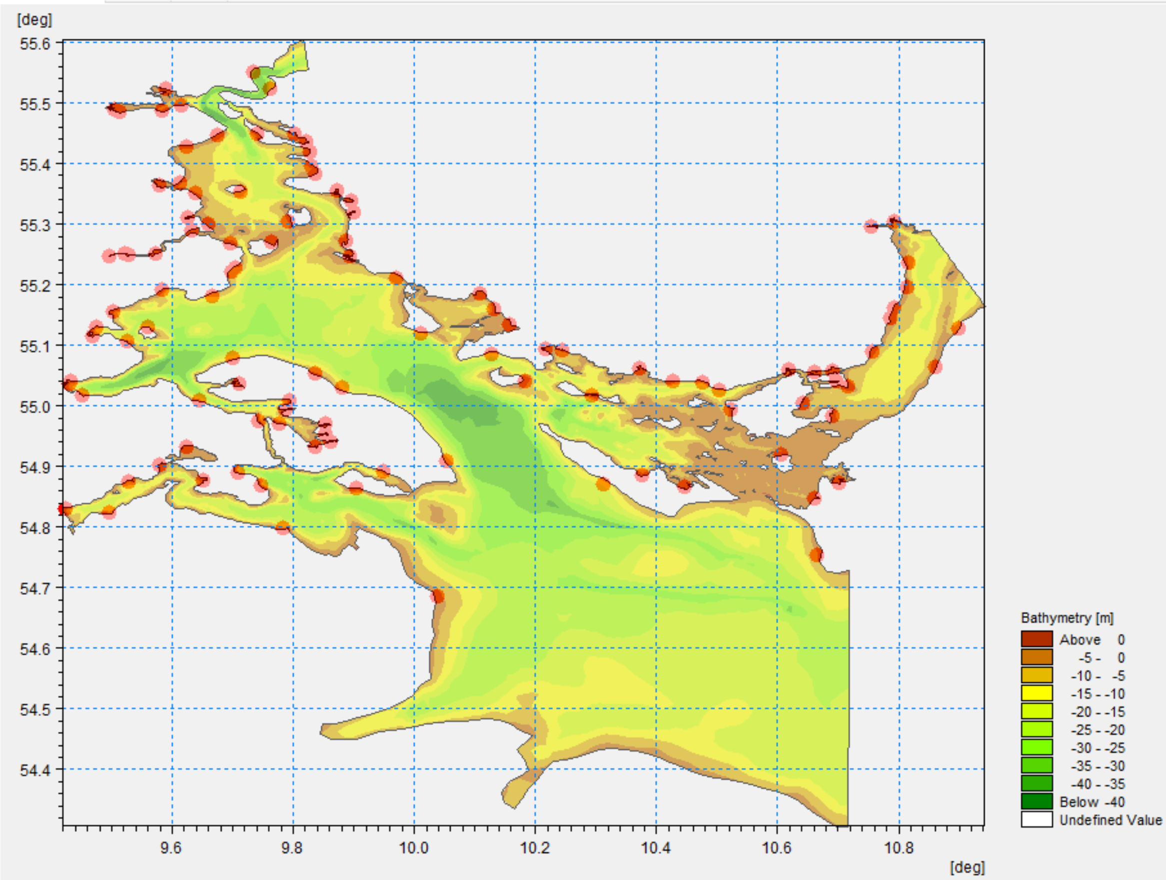


Figure 4.5 Run-off sources included in the Southern Belt Sea model (with dots represents sources located outside the model domain.

These sources represent an input of fresh water to the system that lead to different degrees of stratification of the water column depending of the magnitude and position of the sources.

The total annual runoff discharged into the model domain is summarized in in Figure 4.6.

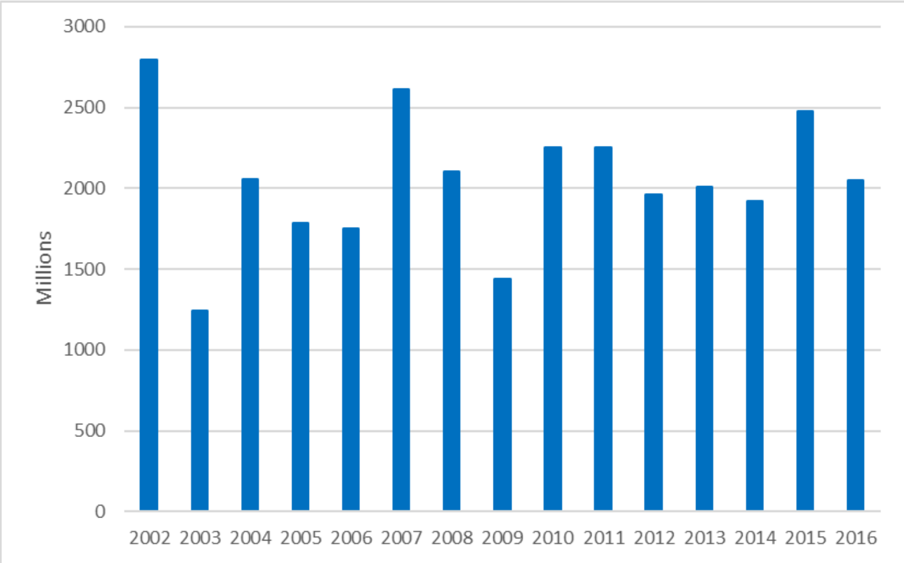


Figure 4.6 Total annual discharge to the SBS-model from the different Danish sources (million m^3 y^{-1}).

4.4 Initial Conditions

4.4.1 Introduction

In order to properly initiate a model simulation, the model requires initial conditions for the various state variables. For the hydrodynamic model the state variables comprise water level, current, salinity and water temperature.

4.4.2 Initial water level and current conditions

The normal procedure for water level and current is to apply a so-called ‘cold start’. This means that the water is stagnant with no currents initially. Immediately after starting the simulation the water begins to move under the influence of the model forcing and after a short time (~1day) the model has ‘warmed up’.

However, to reach stable conditions within a short time, the simulations for Southern Belt Sea was initiated at January 1st, 2002 with a water level distribution from the model results of the Inner Danish Waters (IDW) simulations, Figure 4.7

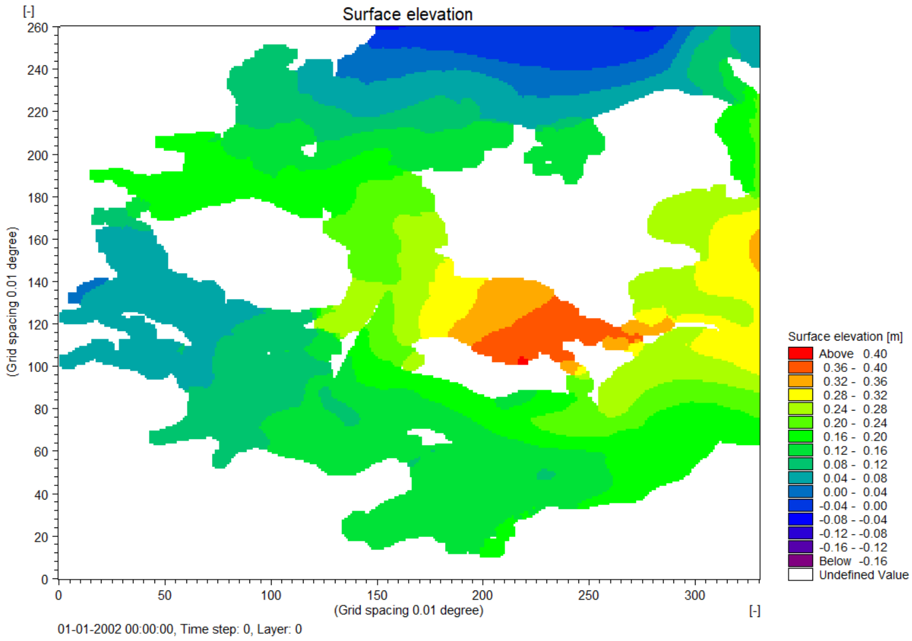


Figure 4.7 Initial 2D map of water level from the IDW-model used for the Southern Belt Sea area

4.4.3 Salinity and Water Temperature

Contrary to water level and current the warm-up time for salinity and water temperature is typically long (months or years), why a 'cold-start' is not feasible. Consequently, 3D fields of salinity and water temperature at the simulation start are prepared and applied as initial conditions for the simulation. These fields are typically established based on results from an encompassing (larger) model or based on local monitoring data.

The SBS-model has applied January 1st, 2002, salinity and water temperature initial fields from the model results of the Inner Danish Waters (IDF) simulations, Figure 4.8.

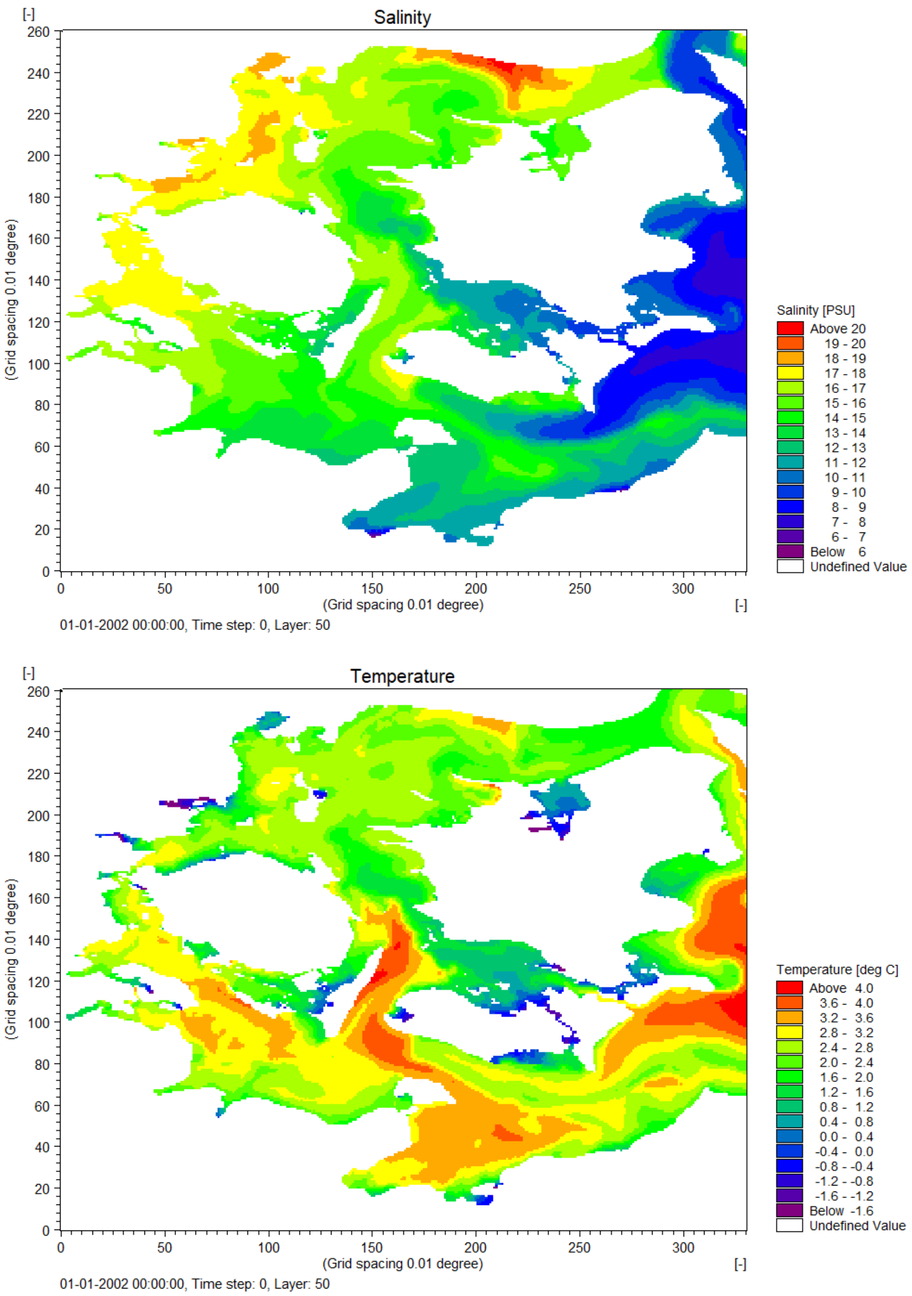


Figure 4.8 Initial surface salinity (top) and water temperature (bottom) from the IDF-model used for the Southern Belt Sea area

5 Model Calibration

5.1 Introduction

Having set up the model, the model calibration is undertaken. The model calibration is the process of adjusting model settings and model constants to obtain satisfactory agreement between observations and model results. In practice the model setup and the model calibration are often performed iteratively, since a good comparison between observations and model results require a well-proportioned model domain as well as adequate model forcings, and this is not always obtained in the first attempt.

5.2 Model Settings

In Table 5-1 a summary of applied model settings and constants is given.

Table 5-1 Summary of applied hydrodynamic model settings and constants in the Southern Belt Sea model.

Feature/Parameter	Setting/Value
Flooding and drying	Included with parameters: 0.005m, 0.05m and 0.1m
Wind friction coefficient	Linearly varying between 0.001255 and 0.002425 for wind speeds between 7 and 25m/s
Bed roughness	Constant 0.005m
Eddy viscosity	Horizontally: Smagorinsky formulation, C_s=0.28 Vertically: k-ε model with standard parameters and no damping
Solution technique	Shallow water equations: Low order Transport equations: Low order
Overall time-step	300s
Heat exchange	Light extinction coefficient 1, otherwise standard parameters
Diffusivity factors (S/T): - Horizontal: Scaled Eddy - Vertical: Scaled Eddy	 1.0 (temperature / salinity.) 1.0 (temperature) / 0 - 1.0 (salinity.)

6 Model Validation

6.1 Introduction

The model validation is the process of comparing observations and model results qualitatively and quantitatively to demonstrate the suitability of the model. The qualitative comparison is typically done graphically, and the quantitative comparison is typically done by means of certain performance (goodness of fit) measures. As such the model validation constitutes the documentation of the model performance.

The SBS-model has been run for the period 2002-2016, but the validation period was defined as the 6-year period 2011-2016. Model comparison plots and performance measures are consequently presented for this period, whereas model results and measurements of salinity and temperature are presented for the entire period using a WEB-tool (http://rbmp2021-2027.dhigroup.com).

Figure 6.1 shows the different stations where salinity and temperature (ST) comparisons are included in the validation period 2011-2016.

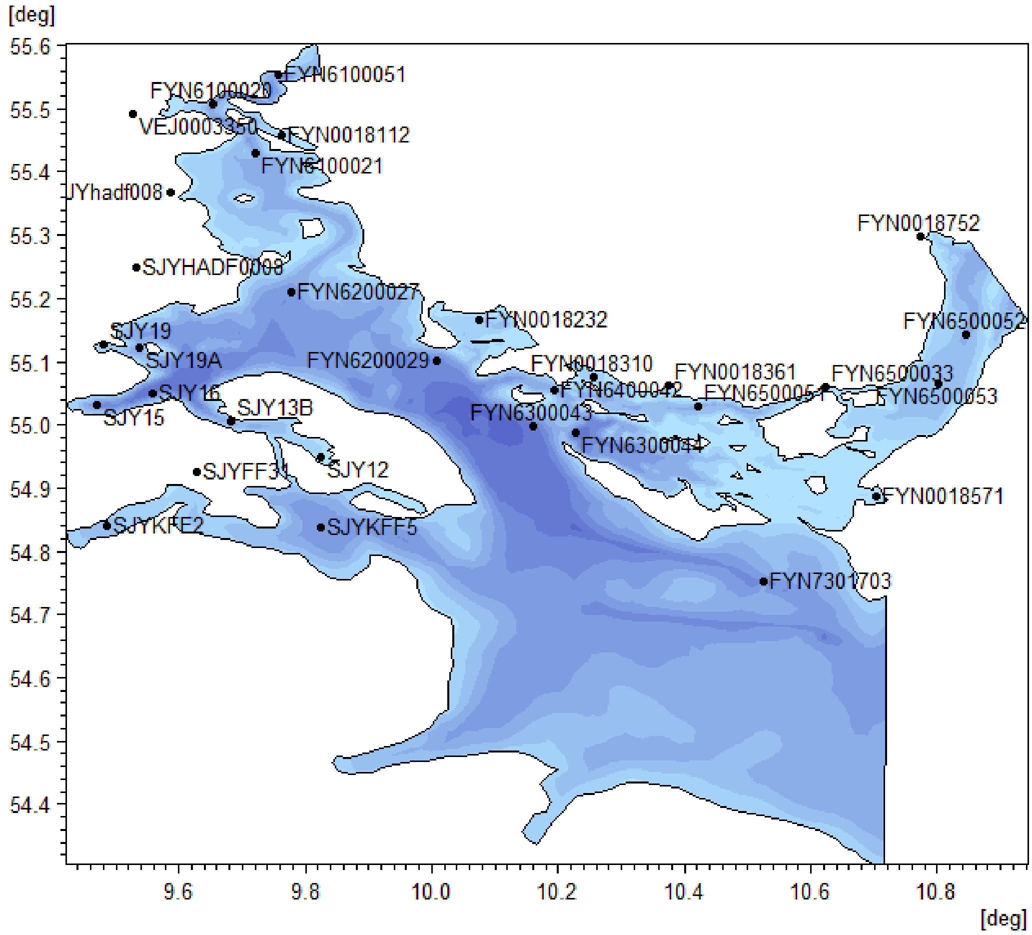
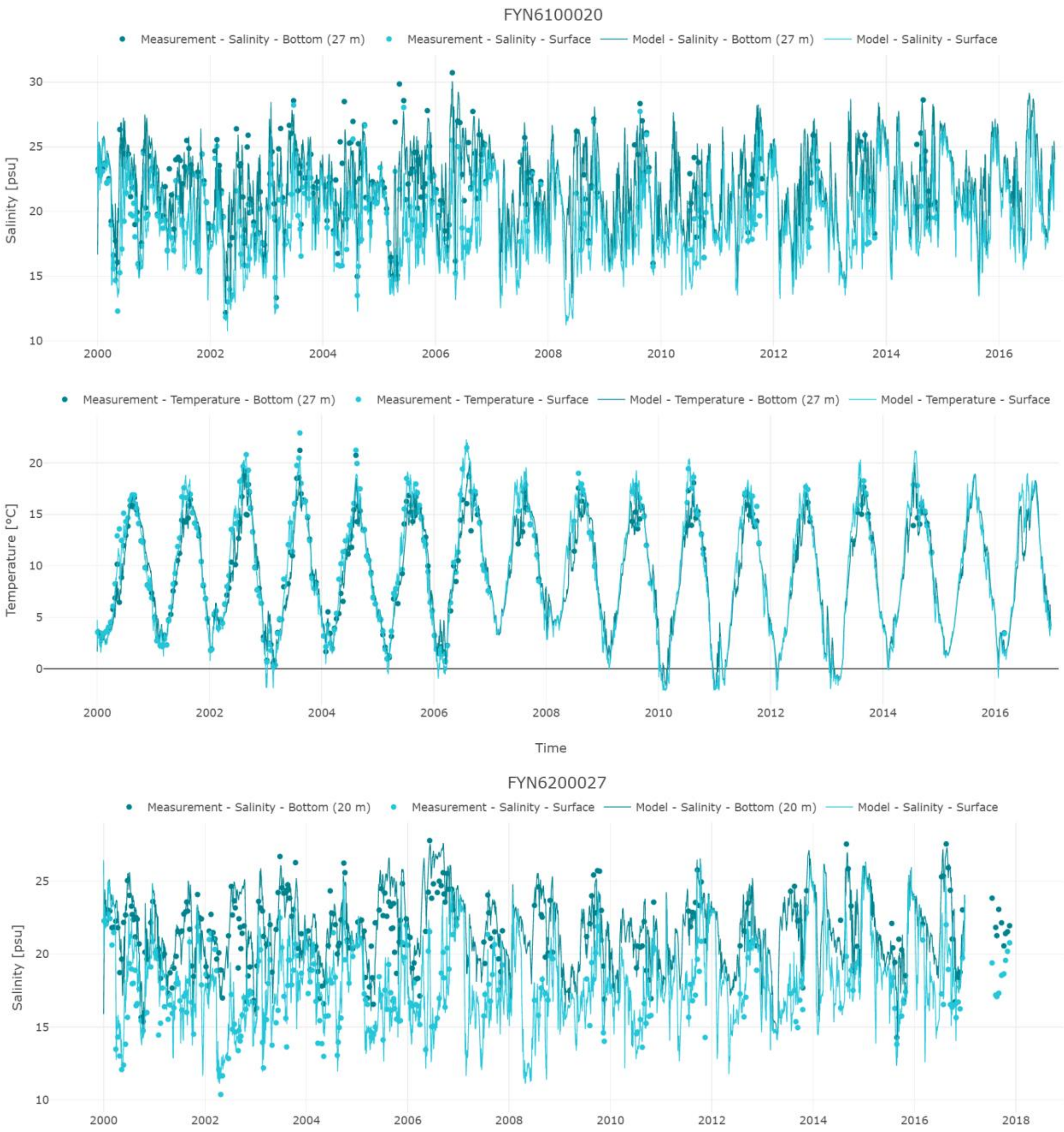


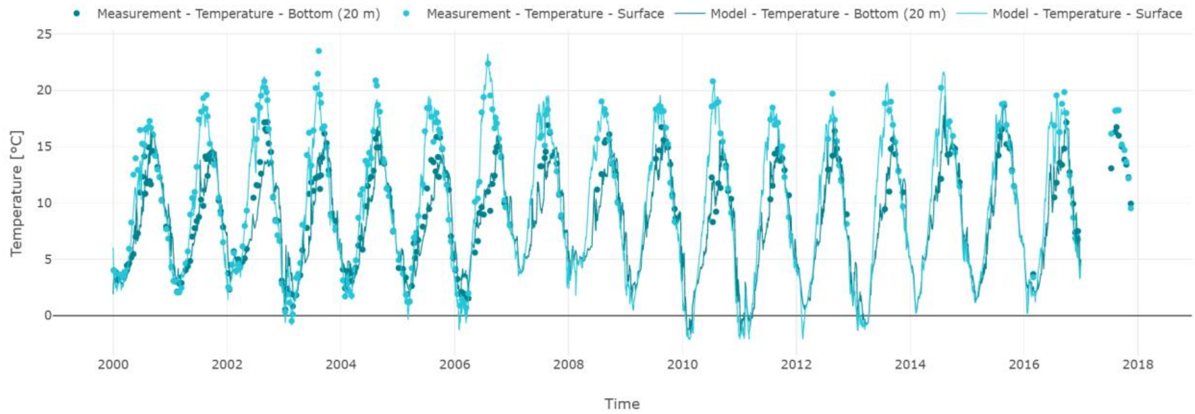
Figure 6.1 Location of the validation stations used for salinity and temperature (ST).

6.2 Model Performance

6.2.1 Salinity and Water Temperature

Figure 6.2 show examples of comparisons of modelled and measured salinity at four different stations. The model reproduces well the seasonal salinity stratification and its variability across the domain. Furthermore, the measured water temperatures are reproduced by the model.





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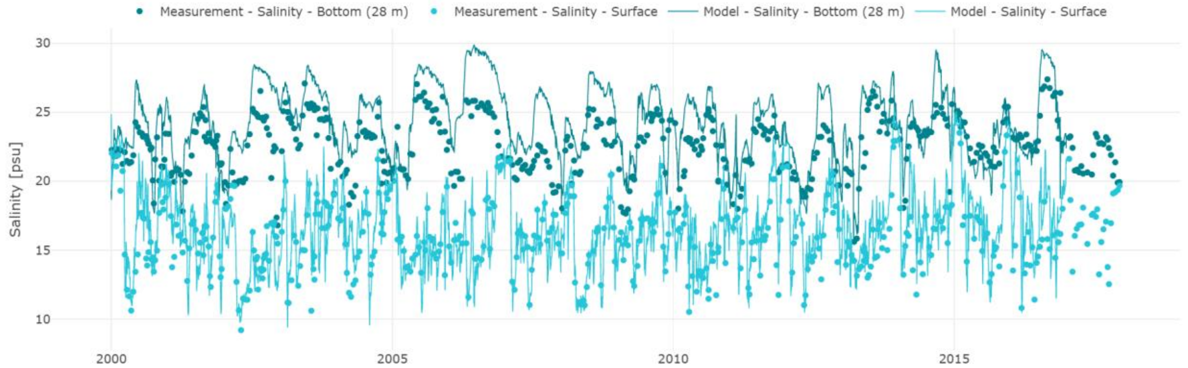

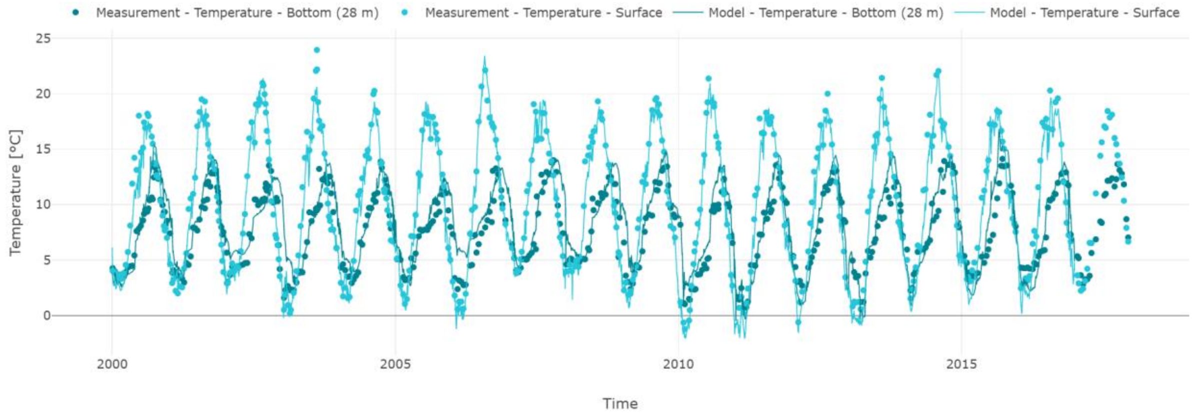

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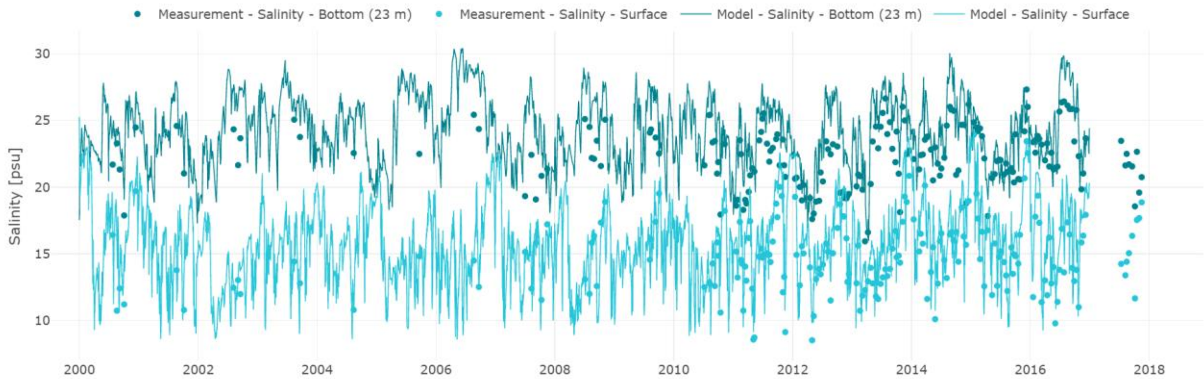

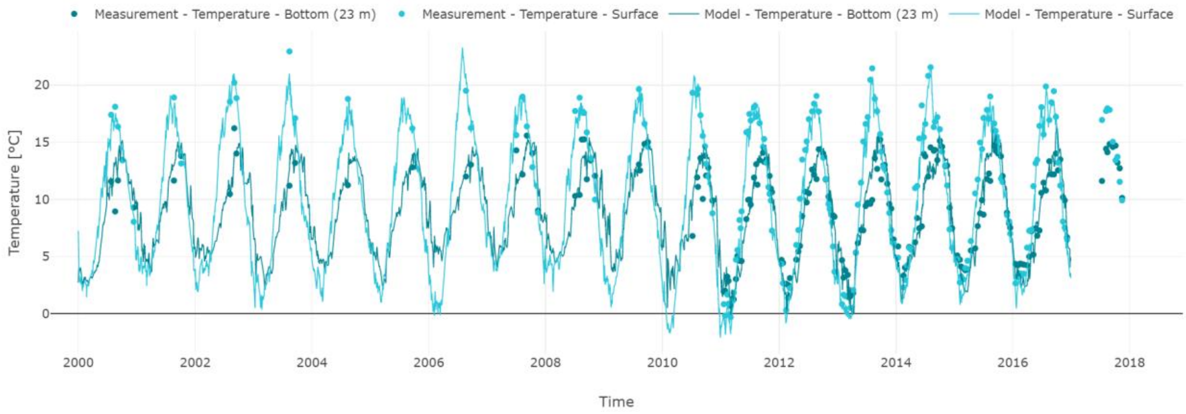

Figure 6.2 Surface and bottom (light blue and grey lines) model salinity at station FYN6100020, FYN6200027, FYN6300043 and FYN7301703 compared to measured surface and bottom (blue and black triangles) values.

In Table 6-1 and Table 6-2 the model performance is evaluated according to DHI (2019a) based on three performance measures: P-Bias, Spearman Rank Correlation and Modelling Efficiency Factor. Representative stations with good coverage available for the period 2011-2016 are included and the entire station network in the SBS-model domain is shown in Figure 6.1. In the tables color codes are included to highlight the overall model performance as 'excellent', 'very good', 'good' or 'poor'.

The model covering Southern Belt Sea includes a relatively large amount of individual water bodies (33 water bodies[1]) with varying tidal and flushing characteristics and varying freshwater influence. Furthermore, parts of the area are stratified whereas other areas and water bodies are well mixed. For the hydrodynamic model covering Southern Belt Sea we aim at 'excellent' or 'very good' model performance at more than 3 out of 4 measurement stations. For salinity the model performance has been evaluated against the three different quality measures at 31 stations, and according to Table 6-1 the model meets 'excellent' or 'very good' in 97% of all measures at all stations. Similarly, the modelled water temperature (see Table 6-2) meets 'excellent' or 'very good' in 100% of all measures at all stations.

Hence, we conclude that the hydrodynamic model covering Southern Belt Sea is well suited for continued biogeochemical model development as part of the overall development of mechanistic models towards the RBMP 2021-2027.

[1] The 33 water bodies refer to the water bodies defined according to RBMP 2015-2021

Table 6-1 Review of model performance based on measured and modelled salinities for the validation period 2011-2016. The performance is evaluated according to DHI (2019a) and blue colour indicates an 'excellent' model, dark green indicates a 'very good' model, light green indicate a 'good' model and yellow indicates a 'poor' model.

Station	P-Bias	Spearman Rank Correlation	Modelling Efficiency Factor	Number of observations
FYN0018112	0.3	0.85	0.76	280
FYN0018232	4.8	0.86	0.56	274
FYN0018310	3.7	0.87	0.68	276
FYN0018361	16.4	0.70	0.26	274
FYN0018571	6.2	0.88	0.62	272
FYN0018752	15.4	0.87	0.69	272
FYN6100020	0.6	0.85	0.68	52
FYN6100021	0.3	0.91	0.84	280
FYN6100051	-4.2	0.86	0.65	53
FYN6200027	-0.3	0.94	0.88	96
FYN6200029	7.2	0.91	0.61	92
FYN6300043	6.4	0.95	0.80	290
FYN6300044	4.6	0.94	0.83	142
FYN6400042	4.4	0.91	0.74	54
FYN6500033	4.3	0.78	0.50	48
FYN6500051	2.2	0.90	0.79	310
FYN6500052	1.9	0.90	0.82	56
FYN6500053	2.2	0.90	0.78	286
FYN7301703	9.4	0.95	0.73	290
SJY12	4.0	0.87	0.68	275
SJY13B	0.1	0.83	0.68	118
SJY15	0.2	0.91	0.83	282
SJY16	-2.6	0.94	0.87	92
SJY19A	1.5	0.75	0.62	50
SJY19	5.0	0.90	0.70	48
SJYFF31	3.5	0.73	0.26	60
SJYHADF0008	-11.7	0.90	0.68	271
SJYKFF2	0.8	0.75	0.54	119
SJYKFF5	6.5	0.93	0.72	284
SJYhadf008	-4.5	0.84	0.64	260
VEJ0003350	-5.1	0.85	0.68	276

Table 6-2 Review of model performance based on measured and modelled water temperatures for the validation period 2011-2016. The performance is evaluated according to DHI (2019a) and blue colour indicates an 'excellent' model, dark green indicates a 'very good' model, light green indicate a 'good' model and yellow indicates a 'poor' model.

Station	P-Bias	Spearman Rank Correlation	Modelling Efficiency Factor	Number of observations
FYN0018112	-5.5	0.99	0.94	280
FYN0018232	-6.3	0.99	0.94	274
FYN0018310	-5.5	0.99	0.95	276
FYN0018361	-12.1	0.98	0.91	274
FYN0018571	-7.5	0.99	0.95	272
FYN0018752	-10.0	0.98	0.92	272
FYN6100020	1.6	0.92	0.90	48
FYN6100021	-3.7	0.99	0.96	280
FYN6100051	4.3	0.89	0.78	53
FYN6200027	-0.9	0.95	0.92	96
FYN6200029	-0.6	0.95	0.89	92
FYN6300043	-3.0	0.98	0.95	290
FYN6300044	4.2	0.94	0.88	142
FYN6400042	0.5	0.94	0.92	54
FYN6500033	-0.6	0.98	0.95	48
FYN6500051	-5.2	0.99	0.95	310
FYN6500052	3.6	0.94	0.87	56
FYN6500053	-3.9	0.98	0.95	286
FYN7301703	-3.0	0.98	0.96	290
SJY12	-7.9	0.98	0.93	274
SJY13B	-2.9	0.95	0.89	118
SJY15	-8.6	0.98	0.91	282
SJY16	-3.0	0.93	0.83	92
SJY19A	-3.4	0.85	0.67	50
SJY19	-5.7	0.97	0.95	48
SJYFF31	-4.6	0.99	0.88	60
SJYHADF0008	-9.5	0.98	0.89	276
SJYKFF2	5.7	0.87	0.69	119
SJYKFF5	-4.2	0.99	0.96	284
SJYhadf008	-16.3	0.99	0.88	272
VEJ0003350	-6.9	0.99	0.92	276

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