Final Report

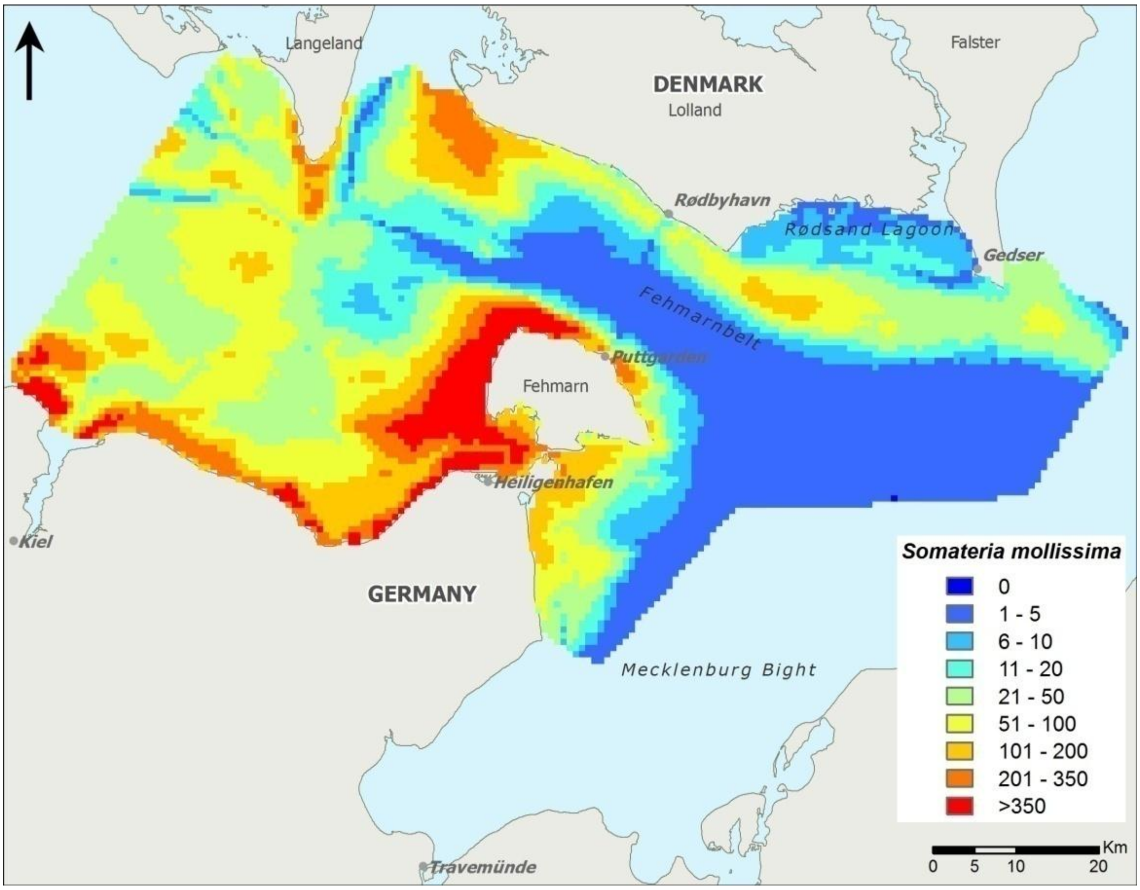
FEHMARNBELT FIXED LINK
BIRD SERVICES (FEBI)

Bird Investigations in Fehmarnbelt - Baseline

Waterbirds in Fehmarnbelt

E3TR0011 Volume II – Appendix I

Description of Oceanographic Variables Applied in the Waterbird Data Analyses



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Note to the reader:
In this report the time for start of construction is artificially set to 1 October 2014 for the tunnel and 1 January 2015 for the bridge alternative. In the Danish EIA (VVM) and the German EIA (UVS/LBP) absolute year references are not used. Instead the time references are relative to start of construction works. In the VVM the same time reference is used for tunnel and bridge, i.e. year 0 corresponds to 2014/start of tunnel construction; year 1 corresponds to 2015/start of bridge construction etc. In the UVS/LBP individual time references are used for tunnel and bridge, i.e. for tunnel construction year 1 is equivalent to 2014 (construction starts 1 October in year 1) and for bridge construction year 1 is equivalent to 2015 (construction starts 1st January).

List of Abbreviations

Abbreviation	Meaning
3D	Three-dimensional
BV	Brunt-Vaisala
CS	Current Speed
FB-WF	Fehmarnbelt Water Forecast
FEHY	Fehmarnbelt Hydrographic Services
FEBI	Fehmarnbelt Bird Studies
HBV	Hydrologiska Byråns Vattenbalansavdelning
MS01	FEHY Main Station 01
MS02	FEHY Main Station 02
NOVANA	National Monitoring and Assessment Programme for the Aquatic and Terrestrial Environments (in Denmark)
PAM	Passive Acoustic Monitoring
PSU	Practical Salinity Unit
RMSE	Root Mean Square Error
SMHI	Sveriges Meteorologiska och Hydrologiska Institut
U	East velocity component
V	North velocity component
W	Vertical velocity component

1. INTRODUCTION

The purpose of the present document is to describe the hydrographic variables applied for the analyses of the field data collected as part of the FEBI baseline studies. The hydrographic variables have been applied for the analyses of aerial and ship-based line transect data of the following, mainly pelagic feeding species of waterbirds:

- Red-throated Diver and Black-throated Diver
- Red-necked Grebe
- Great Crested Grebe
- Little Gull
- Black-headed Gull
- Common Gull
- Herring Gull
- Great Black-backed Gull
- Common Tern
- Arctic Tern
- Razorbill
- Common Guillemot
- Black Guillemot

The hydrographic variables applied include the following variables:

- Horizontal current components in the surface and bottom layers;
- Vertical current velocity as a measure of up- and downwelling in the surface and bottom layers and at 10m depth;
- Current speed (magnitude) in the surface and bottom layers;
- Current gradient as a measure of frontal strength in the surface and bottom layers;
- Vorticity as a measure of eddy potential in the surface and bottom layers;
- Water temperature, salinity and density in the surface and bottom layers;
- Strength and depth of the vertical maximum Brunt-Vaisala frequency as measures of the stratification of the water column;
- The integrated discharge (or flux) of salt across the Puttgarden-Rødbyhavn cross-section as a measure of the flow regime (inflow or outflow from the Baltic).

These variables are all dynamic. Further they are all spatially varying except the discharge of salt across the Puttgarden-Rødbyhavn cross-section, which is an integrated variable. The hydrographic variables are all extracted from the FEHY hydrodynamic models. Some are direct output from the hydrodynamic models and some (denoted derived variables) are the result of a post-processing of the model results.

2. FEHY HYDRODYNAMIC MODELS

2.1. Introduction

The hydrographic variables applied for the FEBI data analyses originate from the FEHY hydrodynamic models. These models are:

- FEHY local hydrodynamic model;
- Fehmarnbelt Water Forecast hydrodynamic model.

These models are very similar and both have a fine spatial resolution in the Fehmarnbelt area. Hydrographic variables from these models in combination have been applied for waterbird spatial distribution modelling within the period of November 2009 – November 2010.

In the following sections a summary of the FEHY models is presented. Further, a justification for combining the two models in order to obtain a full set of hydrographic variables from November 2008 to December 2010 is given.

2.2. FEHY Local Hydrodynamic Model

The FEHY local model covers the area from southern Kattegat to Bornholm. It is a 3D hydrodynamic model based on the MIKE 3 FM modelling system. The model has open boundaries in Kattegat and to the north and south of Bornholm.

In Figure 2.1 the FEHY local model bathymetry is shown. The bathymetry is based on the FEHY 50x50 m bathymetry.

The local model has a horizontal resolution varying from 5-6 km in areas like Arkona Basin to 400 m close to Puttgarden and Rødbyhavn. In the Fehmarnbelt area the resolution is down to about 500 m near the link alignment and 300 m at the landfall areas. A detail of the mesh in the Fehmarnbelt area is shown in Figure 2.2. The vertical resolution of the local model is 1 m in the Fehmarnbelt area (less at water depths below 10 m).

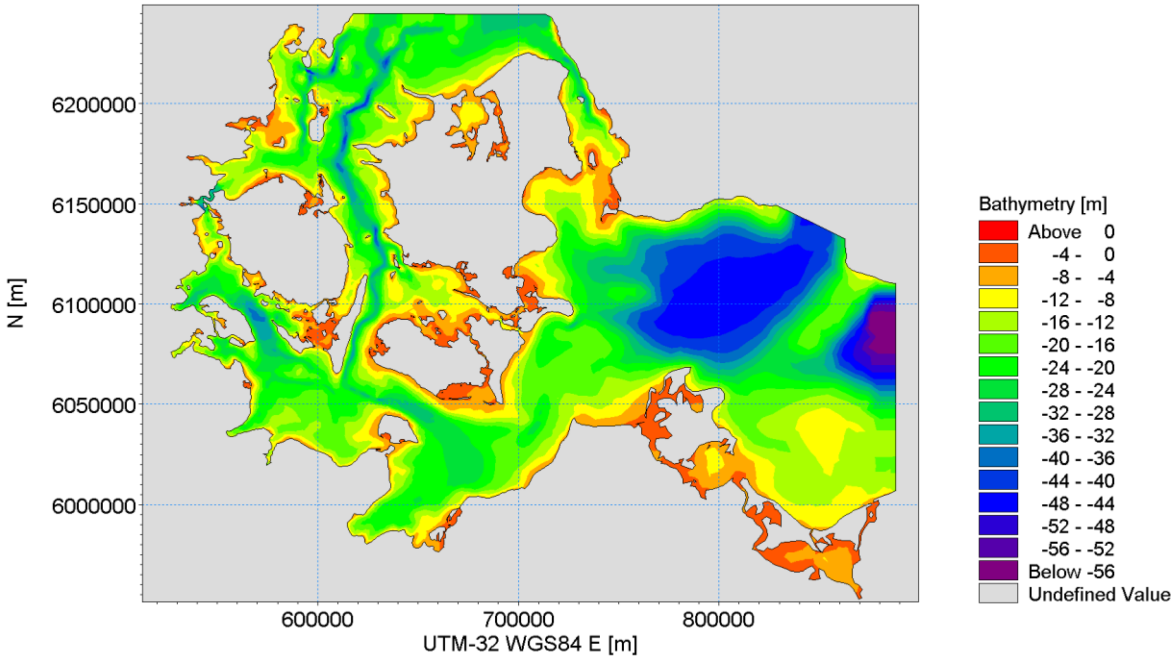

Figure 2.1 FEHY local model bathymetry

The local model is forced by boundary conditions at the open boundaries, by meteorological forcing from a meteorological model and by freshwater runoff from the catchment of the model area. The model is forced by open boundary conditions in the Kattegat (water level and current, salinity, temperature), by meteorological forcing (wind, air pressure, air temperature, cloudiness, precipitation) from a meteorological model and by freshwater runoff from the catchment of the model area.

The model output consists of temporally and spatially varying fields of water level, currents, water temperature, salinity and density. The simulation time step is 300 s and the model output applied for the FEBI analyses is saved every 180 minutes.

The calibration period of the local model is the year 2005 and the validation period is 1 Jan – 1 Oct 2009. Furthermore the model has been run for the period 1 Oct 2009- 1 June 2010. For the purpose of the FEBI analyses model results from Nov 2008 to May 2010 have been applied.

The local model is validated based on FEHY's quantitative acceptance criteria. For water level (7 stations) the acceptance criteria are that the standard deviation of the difference between measurement and model is less than 0.1 m and that the explained variance is larger than 0.8 for minimum 80% of the local gauge stations. For salinity and temperature (15 stations, each 4-34 levels), the acceptance criteria are that the root mean square error (RMSE) between measurement and model is less than 2°C/3PSU and that the bias between measurement and model is less than 1°C/1PSU for 80% or more of all the station levels. For current, the current speed and direction have been compared to continuous measurements at the FEHY main stations. The acceptance criteria for current is that the difference between measured and modelled average current for a certain station in a certain level should be below 0.1 m/s and that the similar difference between average current direction (inflow respectively outflow) should be below 10°. Finally for the general flow, the distribution of mean water discharges through the Little Belt, the Great Belt and the Sound was compared to literature values.

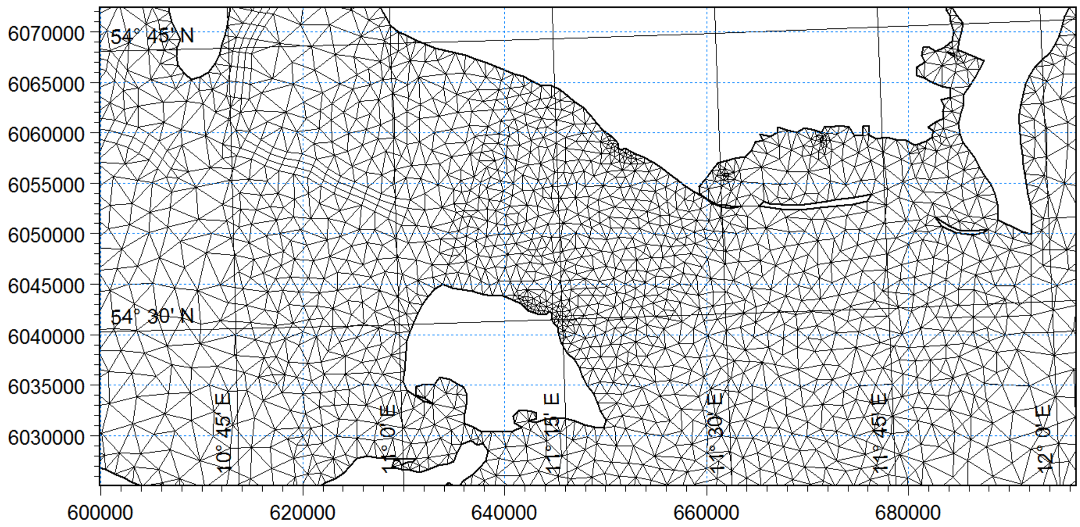

Figure 2.2 Detail of FEHY local model mesh

For the purpose of the FEBI analyses, FEHY local model run No. 9.15 and 11.20 have been applied. The FEHY local model is documented in the MIKE Local Model Calibration and Validation Report (FEHY, 2011b).

2.3. The Fehmarnbelt Water Forecast Hydrodynamic Model

This model is established by FEHY for the purpose of providing Femern A/S with forecasts of water level, current, salinity and water temperature in the Fehmarnbelt area. The model is established as a combination of the FEHY regional and local models, i.e. with the model area and regional resolution of the FEHY regional model, but with the local resolution from Kattegat to Bornholm of the FEHY local model. It is a 3D hydrodynamic model based on the MIKE 3 FM modelling system.

The model bathymetry is shown in Figure 2.3. The bathymetry is based on the same datasets as the FEHY regional and local models. In the Fehmarnbelt area, the model has a horizontal resolution of down to 1km and a vertical resolution of 1m (less at water depths below 10 m).

The model is forced by open boundary conditions in Skagerrak, by meteorological forcing and by freshwater runoff; again the same data sets as used by the FEHY models are used.

Similarly to the two other models, the model output consists of temporally and spatially varying fields of water level, currents, water temperature, salinity and density. The simulation time step is 1800 s and the model output applied for the FEBI analyses is saved every 180 minutes.

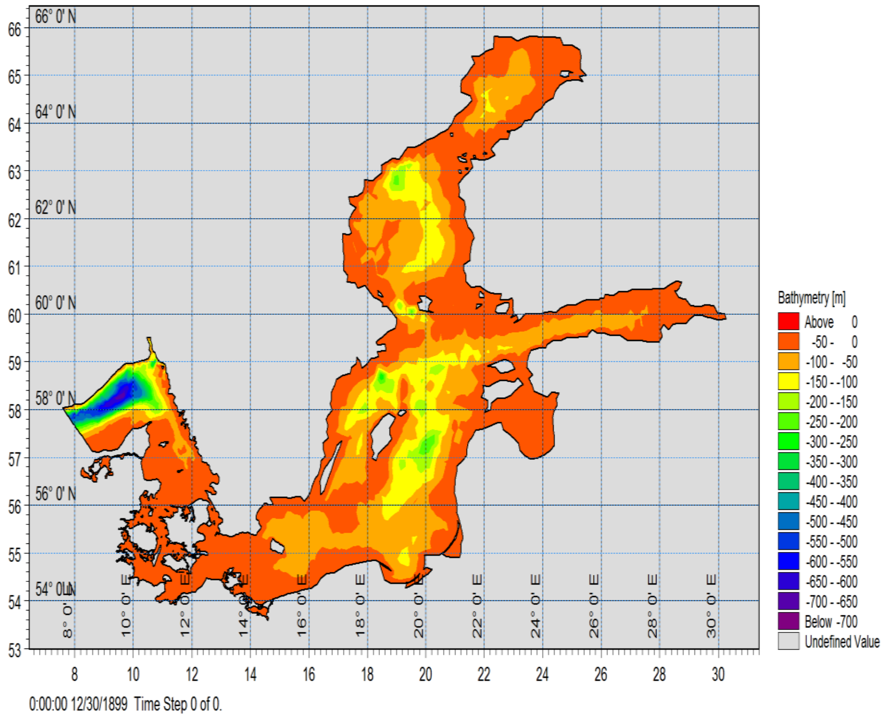

Figure 2.3 Bathymetry of Fehmarnbelt water forecast model

The calibration period of the Fehmarnbelt water forecast model is the year 2005 and the validation period is the period 1 June 2010 – 1 Jan 2011. Furthermore the model has run operationally (in forecast mode) from 1 Nov 2010. For the purpose of the FEBI analyses model results from July – Dec 2010 have been applied.

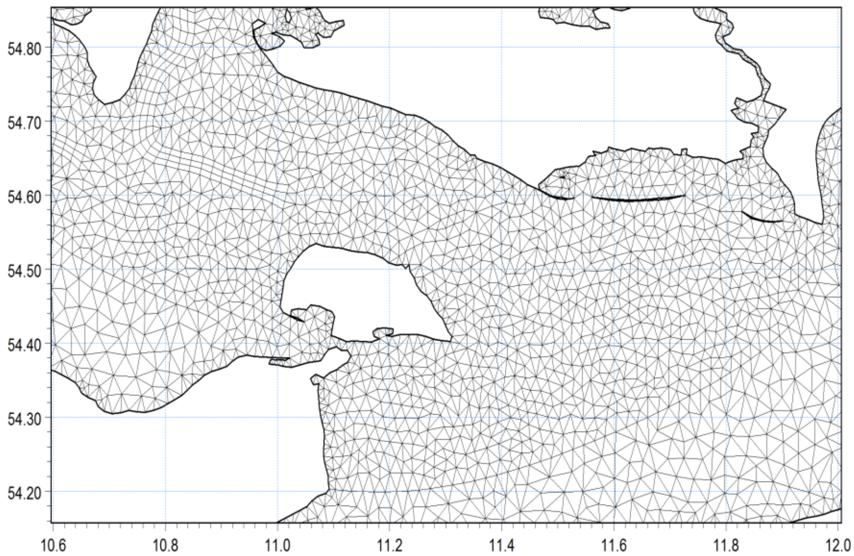

Figure 2.4 Detail of Fehmarnbelt water forecast model mesh

For the purpose of the FEBI analyses, Fehmarnbelt water forecast model run No. 06 and 07 have been applied. The Fehmarnbelt water forecast model is documented in the Water Forecast Service 2010 Performance Report (FEHY, 2010).

2.4. Combining Results from the FEHY Local Model and the Fehmarnbelt Water Forecast Model

2.4.1. Introduction

In order to obtain a set of hydrographic variables covering the period 2009-2010 and having the same spatial resolution, it was decided to combine the results from the FEHY local model and the Fehmarnbelt Water Forecast model. The present section describes the rationale for combining the results of the two models.

2.4.2. Similarities and Differences

The Fehmarnbelt water forecast model has been established to resemble a combination of the FEHY local and regional models. This goes for:

- Modelling system;
- Model coverage;
- Model bathymetry;
- Model resolution;
- Model forcings;
- Model calibration factors.

With respect to modelling system, both models are based on the MIKE 3 FM modelling system. This means that the hydrodynamic model engine in terms of physics, mathematics, numerics, parameterisations, etc., is the same for the two models.

As can be seen in Figure 2.1 and Figure 2.3 the two models cover different areas. How-ever since the FEHY local model receives open boundary conditions from an encompassing regional model, it may be said that the FEHY local model and the Fehmarnbelt water forecast model both include the effect of the same model area, which is the area from Skagerrak to the Baltic Sea. This may be taken even further, since the FEHY regional model and the Fehmarnbelt water forecast model both receive open boundary conditions in the Skagerrak from an even larger encompassing North Sea model, which means that both the FEHY local model and the Fehmarnbelt water forecast model take into account the effect of the North Sea.

The model bathymetry of the two models is based on the same data set, which is prepared by FEHY.

With respect to spatial resolution, the two models are similar but not identical. In Figure 2.2 and Figure 2.4 the two model meshes are shown in the Fehmarnbelt area. It is observed in the figures that the resolution of the two meshes is quite similar both with mesh sizes down to 0.5-1 km, except for a small area at each landfall where the FEHY local model resolution is increased to about 300 m.

Both models have identical vertical resolutions. In the Fehmarnbelt area both models have a resolution (layer thickness) of 1 m from the water surface to the bottom (less at water depths below 10 m).

With respect to model forcings, both models basically apply the same model forcings:

- Meteorological forcing from StormGEO;
- Open boundary conditions (see discussion above);
- Runoff.

(Δ) between average measured and average modelled current speed and direction for a certain period should be below 0.1 m/s and 10°, respectively. The criteria are in the table seen to be met by both the FEHY local model and the Fehmarnbelt WF model for the periods in question.

In Figure 2.9 comparisons of measured and modelled water temperature and salinity at MS01 are shown. Both surface values and bottom values are shown. Notice in the figure that the FEHY local model covers until 1 June 2010 and that the Fehmarnbelt water forecast model (FB-WF model) covers the remaining period. Also this figure shows that the comparison between measured and modelled data is reasonably good, with a correct With respect to runoff the FEHY local model apply data from SMHI's HBV runoff model. The operational Fehmarnbelt water forecast model, on the other hand, has for the period 1 June 2010 – 1 Jan 2011 used climatological monthly runoff data from the NOVANA programme.

Finally with respect to model calibration, the MIKE 3 FM model has the following calibration factors: Bottom roughness, eddy viscosity, wind friction coefficient and dispersion factors for salinity and heat. These factors are the same for the FEHY local/regional models and for the Fehmarnbelt water forecast model.

2.4.3. *Temporal Variability*

Following the above discussion on general similarities of the two models, it may be inferred that the temporal variability of the results of the two models in the area of interest will be similar. This is due in particular to the similar modelling system, similar model forcings and similar model resolution of the two models. In order to illustrate the temporal variability of the model results, and how they compare to measurements, a few examples in terms of time series comparison plots are shown below.

In Figure 2.5, Figure 2.6, Figure 2.7 and Figure 2.8 comparisons of measured and modelled surface current at FEHY Main Station 01 (MS01) are shown. Figure 2.5 shows how the FEHY local model compares to measurements in July 2009 and Figure 2.6 similarly shows how the Fehmarnbelt water forecast model (FB-WF model) compares in July 2010. Figure 2.7 and Figure 2.8 show similar comparisons for Oct 2009 and Oct 2010, respectively. It is observed in the figures that the current comparison is reasonably good both for current speed and current direction and both for the FEHY local model and for the Fehmarnbelt water forecast model. The temporal variability is also observed in the two figures to be similar for the two models. In Table 2.1 the FEHY quantitative measures for the shown surface currents are given. The FEHY compliance criteria state that the difference representation of the annual cycle and also a good representation of the differences between surface and bottom (stratification). It is also noticed that the temporal variability of the two models is similar. In Table 2.2 the FEHY quantitative measures for the shown salinity and temperature are given. The FEHY compliance criteria state that the bias and the root mean square error (RMSE) between measured and modelled salinity and temperature for a certain period should be below 1 PSU/1°C and 3 PSU/2°C, respectively, for 80% of the levels. The criteria for the shown data are in the table seen to be met by the FEHY local model and nearly met by the Fehmarnbelt WF model for the periods in question.

Since the below plots may be regarded as representative with respect to the comparability of the two models, it is concluded that the temporal variability (and comparability to measurements) of the two models is similar. Notice that the above mentioned variables have been chosen as examples since they are direct model output and because they represent well the hydrographic variables used by FEBI.

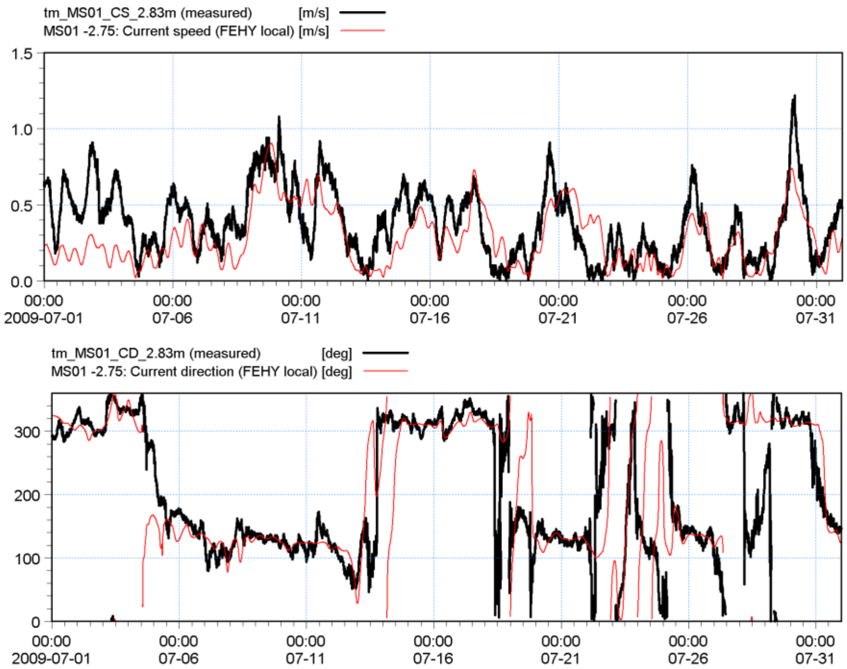

Figure 2.5 Comparison of measured and modelled (FEHY local model) surface current speed (upper) and direction (lower) at MS01 during July 2009

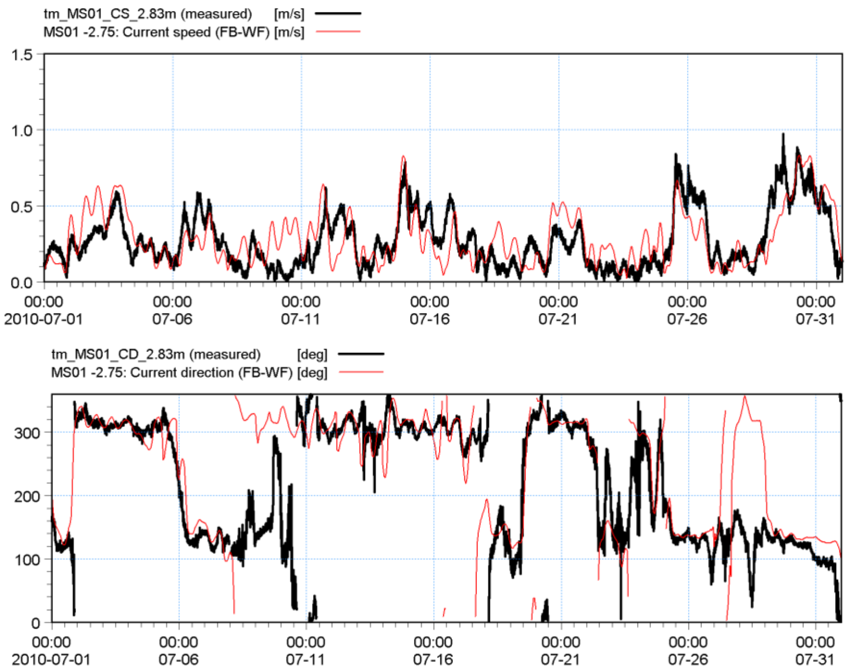

Figure 2.6 Comparison of measured and modelled (Fehmarnbelt WF model) surface current speed (upper) and direction (lower) at MS01 during July 2010.

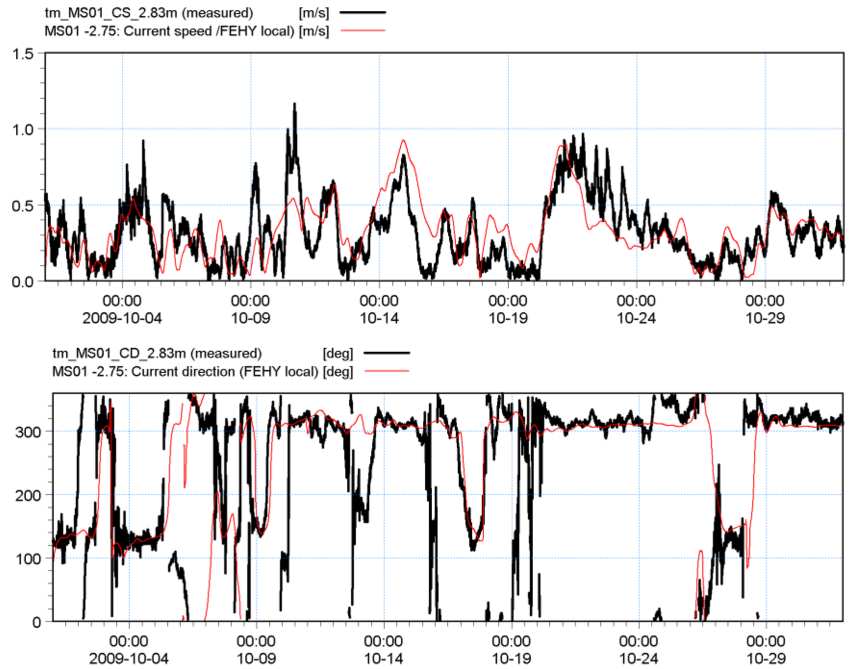

Figure 2.7 Comparison of measured and modelled (FEHY local model) surface current speed (upper) and direction (lower) at MS01 during Oct 2009.

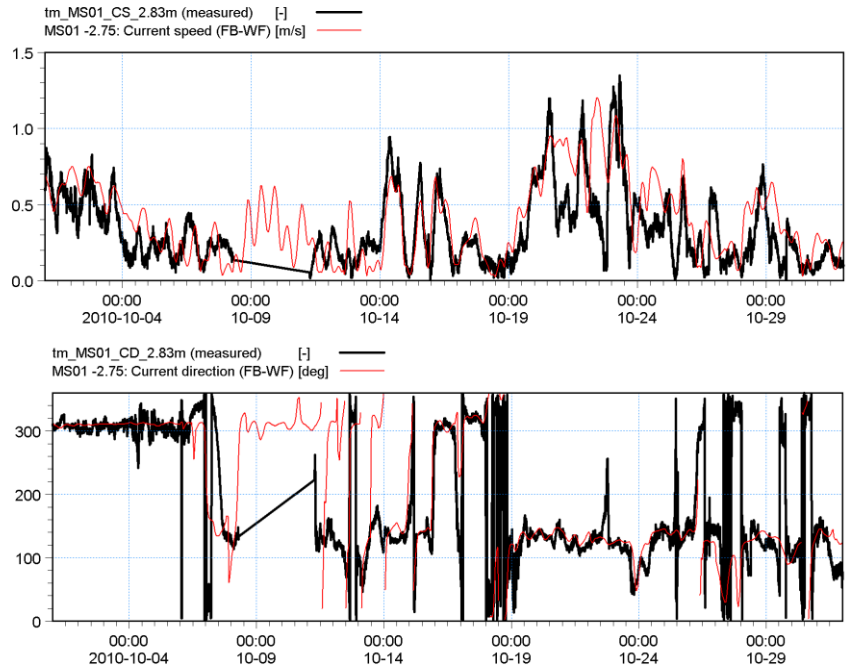

Figure 2.8 Comparison of measured and modelled (Fehmarnbelt WF model) surface current speed (upper) and direction (lower) at MS01 during Oct 2010.

Table 2.1 FEHY quantitative measures for the shown surface current speed (CS) and direction (CD) at MS01.

Model	**Period**	**Diff Avg CS (Δ < 0.1m/s)**	**Diff Avg CD (Δ < 10°)**
FEHY local model	July 2009	-0.02	3.2
	Oct 2009	-0.06	7.6
Fehmarnbelt WF model	July 2010	0.09	8.3
	Oct 2010	-0.01	3.5

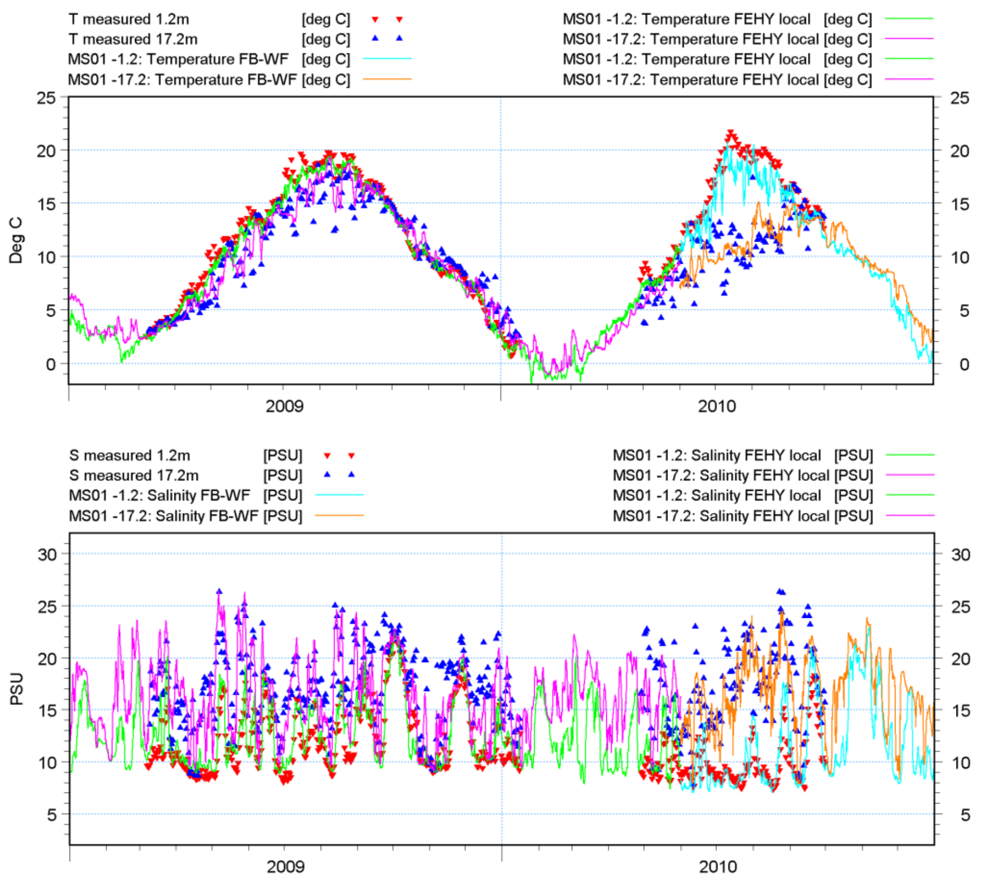

Figure 2.9 Comparison of measured and modelled water temperature (upper) and salinity (lower) at MS01 during the period 2009-2010. Notice that both surface (1.2 m) and bottom (17.2 m) values are included. Notice that some measurements are missing due to gaps (ice problems) in the database of the Fehmarnbelt Data Handling Centre.

Table 2.2 FEHY quantitative measures for the shown surface and bottom salinity and temperature at MS01

Model/period	**Depth of sensor**	**Salinity**		**Temperature**	
	(m)	Bias (<1PSU)	RMSE (<3PSU)	Bias (<1°C)	RMSE (<2°C)
FEHY local model (June-Sep 2009)	1.2 17.2	0.39 -0.96	1.35 2.22	-0.48 0.38	0.71 1.03
Fehmarnbelt WF model (June-Sep 2010)	1.2 17.	0.33 -0.56	1.55 2.60	-1.44 -0.29	1.83 1.79

2.4.4. *Spatial Variability*

Following the above discussion on general similarities of the two models (Section 2.4.2), it may be inferred that also the spatial variability of the results of the two models in the area of interest will be similar. This is due in particular to the similar model resolution of the two models within the Fehmarnbelt area.

In Figure 2.10 and Figure 2.11 examples of instantaneous surface salinity and current from the two models during arbitrary outflow and inflow events, respectively, are shown. Please notice that the instantaneous fields are very variable and that the examples shown are just snapshots and not in any way representative for the total spatial variability. However the figures illustrate well that both models have high spatial variability and that no one model appear to have more variability than the other.

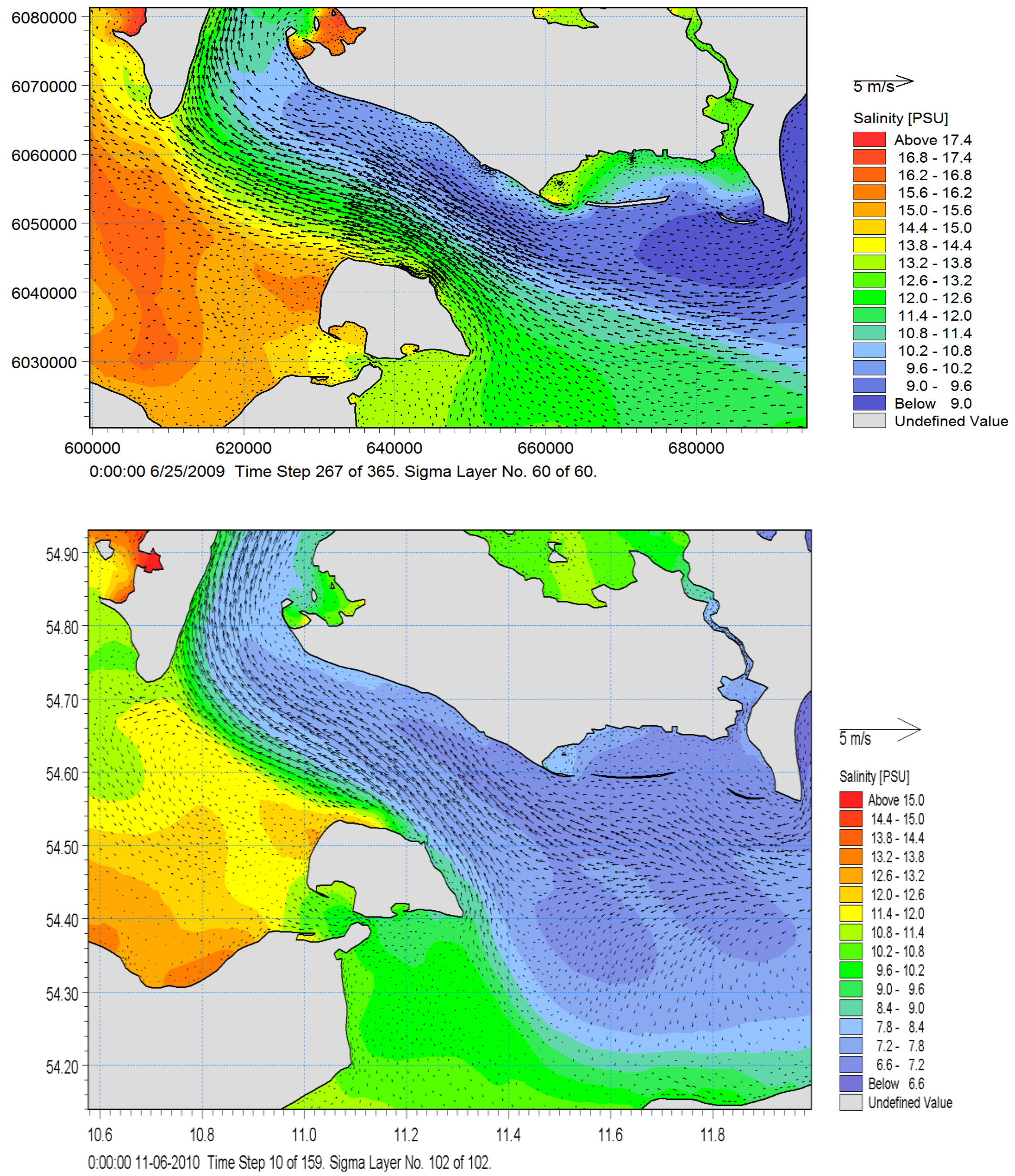

Figure 2.10 *Examples of instantaneous outflow surface salinity (colours) and current (vectors) in the Fehmarnbelt area from the FEHY local model (upper) and the Fehmarnbelt water forecast model (lower).*

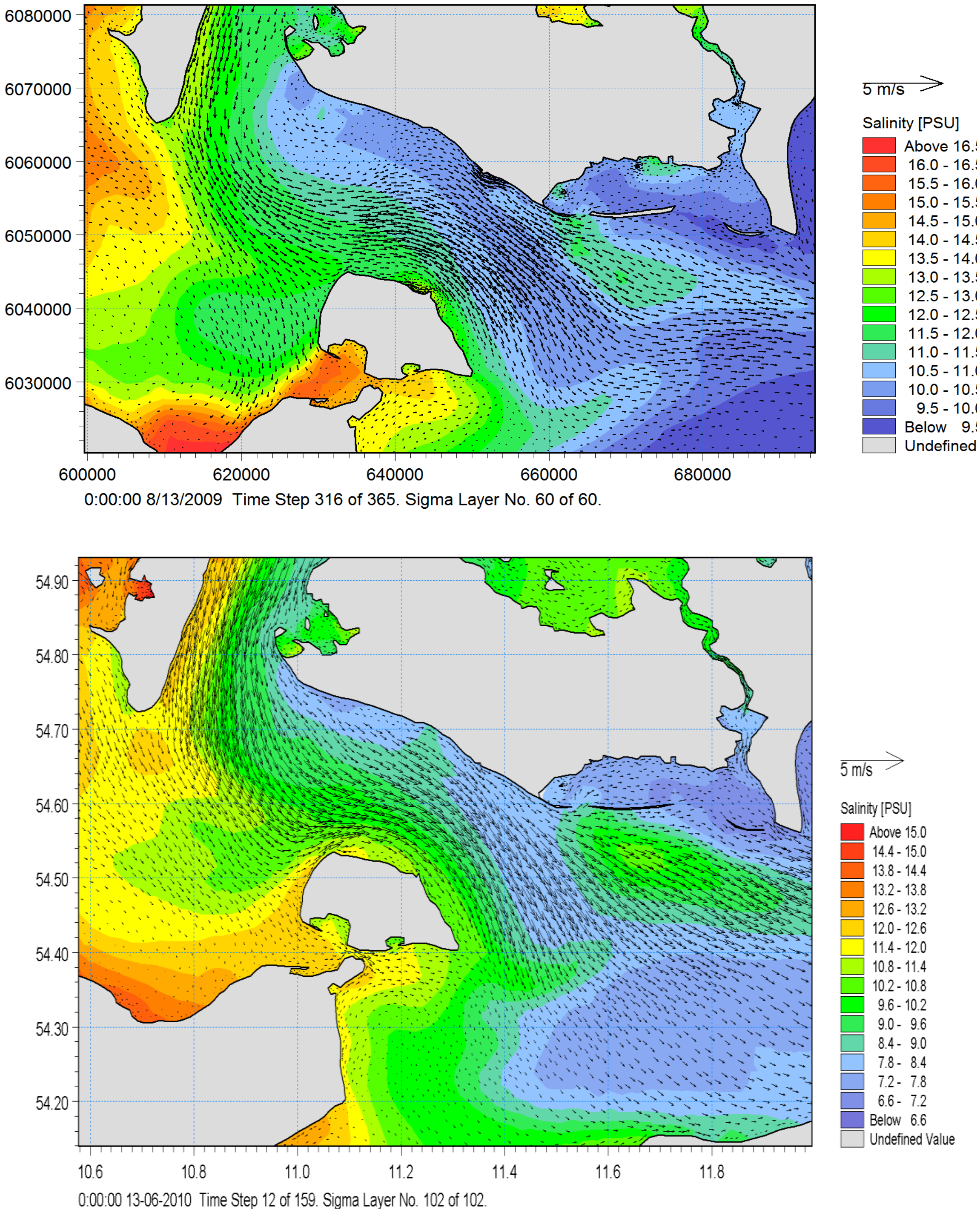

Figure 2.11 Examples of instantaneous inflow surface salinity (colors) and current (vectors) in the area of interest from the FEHY local model (upper) and the Fehmarnbelt water forecast model (lower)

2.4.5. Discussion

Because of the many similarities of the two models including the same hydrodynamic engine, the same bathymetry and resolution and the same (or similar) model forcings, it is concluded that the FEHY local model and the Fehmarnbelt water forecast model are very similar in the Fehmarnbelt area. Resulting from the many similarities, the two models will be able to describe the same hydrodynamic processes and hence demonstrate the same variability in the results.

Based on the above discussion it is therefore concluded that hydrographic data extracted from the Fehmarnbelt water forecast model will be equally suitable for the FEBI analyses as are the data from the FEHY local model. The data from the Fehmarnbelt water forecast model are furthermore very similar in terms of quality and variability to the data from the FEHY local model, such that it will be justified to combine the two data sets for the purpose of covering the whole two-year period 1 Nov 2008 to 1 Dec 2010. This is valid for both the direct model output variables such as current and salinity, but also for the derived (calculated) variables such as current gradient and vorticity.

3. PROCESSING OF HYDROGRAPHIC VARIABLES

3.1. Introduction

For the FEBI data analyses both hydrographic variables, which are direct model output, and hydrographic variables, which are calculated on the basis of model output, have been applied. The variables calculated on the basis of the direct model output are in the following called 'derived' variables.

The hydrographic variables have been extracted for both the surface layer and for the bottom layer. In order to process the variables and calculate the derived variables, the unstructured result files (based on flexible mesh) from the model simulations have been interpolated to a structured 3D Cartesian grid. This grid has a resolution of 500 m horizontally/1 m vertically for the FEHY local model results/Fehmarnbelt WF model results, and 2 km horizontally/1m vertically for the FEHY regional model results. Based on these grids, the variables have been extracted and the derived variables have been calculated and extracted.

Having calculated and extracted the surface and bottom hydographic variables, they have been integrated with the FEBI field data sets, such that every observation (or aggregate observation) has been assigned a value of each of the hydrographic variables corresponding to the position and time of the observation. Having integrated the FEBI field data and the hydrographic variables (and the additional static variables), the datasets have been applied for the subsequent FEBI data analyses.

For some of the FEBI field data sets, so-called prediction grids have been prepared in addition to the integrated datasets. The prediction grids consist of an interpolation to a 750m grid of selected temporally averaged hydrographic variables. The averaging periods depend on the specific analysis.

In the following sections the different hydrographic variables applied and their processing are described.

3.2. Current Velocities

The vector components (U, V and W) in the East, North and vertical direction (positive upwards) have been applied. These are direct output from the hydrodynamic models. Also the current speed or magnitude (CS) is a direct output from the model. The unit for these current-related variables is m/s.

These variables have in common that they are highly variable both in time and space. During an inflow event, the U component may have high positive values in the Fehmarnbelt area, while during outflow it may have equally high negative values. On the other hand, averaging over an inflow and an outflow event may yield a very low average U value.

The current velocities vary with inflow/outflow events, but they also vary on a smaller scale as a result of bathymetry, wind effects, stratification, etc. Generally the current velocities are higher in the surface layer than in the bottom layer.

The vertical velocity W is in this context used as a measure of the local upwelling (positive W) or downwelling (negative W). Similarly to most other hydrographic variables, this variable has been extracted in the surface layer and in the bottom layer, but additionally it has also been extracted in 10m depth. This is due to the fact that the magnitude or trend of the variable sometimes seems to be stronger away from the surface and bottom.

Typical examples of temporal variation of surface current in the FEHY Main Station 01 as calculated by the FEHY local model and by the Fehmarnbelt WF model are shown in Figure 2.5, Figure 2.6, Figure 2.7, Figure 2.8.

Typical examples of surface currents during outflow and inflow as calculated by the FEHY local model and by the Fehmarnbelt WF model are shown in Figure 2.10 and Figure 2.11.

3.3. Vorticity and Current Gradient

The vorticity is a measure of the local rotation of the flow. It is calculated from the horizontal vector components U and V and is thus not a direct output from the model, but is calculated subsequently:

$$Vorticity = \frac{dV}{dx} - \frac{dU}{dy},$$

Where dx and dy are the horizontal grid spacings. The unit of the vorticity is m/s/m and the sign of the vorticity indicates whether the rotation of the flow is clockwise (negative vorticity) or anti-clockwise (positive vorticity). The magnitude of the vorticity indicates the strength of the rotation.

In the present context the vorticity is included as a measure of the eddy (or turbulence) potential in the flow. It is of course important to evaluate the calculated vorticity in relation to the spatial scale applied. For the local model the horizontal grid spacing dx is 500 m, which means that the horizontal scale of the calculated vorticity is in the order of 500-1000 m. For the regional model, the horizontal grid spacing applied is 2 km. It is thus not possible to directly compare the vorticities corresponding to the two quite different model resolutions. Similarly to the current velocities, the vorticity is highly variable in both time and space.

The current gradient is a measure of local gradients in the flow field. It is calculated from the horizontal vector components U and V and is thus not a direct output from the model, but is calculated subsequently:

$$Current\ Gradient = \left|\frac{dU}{dx}\right| + \left|\frac{dV}{dy}\right|,$$

Where dx and dy are the horizontal grid spacings. The unit of the current gradient is m/s/m. The current gradient as applied here may only be positive and the magnitude of the current gradient indicates the strength of the gradient.

In the present context the current gradient is included as a measure of the frontal strength in the flow. Similarly to the vorticity it is important to consider the horizontal scale of the current gradient. Similarly to the current velocities, the current gradient is highly variable in both time and space.

3.4. Water Temperature, Salinity and Density

The variation in time and space of the water temperature, salinity and density is a direct output of the model. Temperature (in °C) and salinity (in PSU), and the derived parameter density (in kg/m^3), represent important properties of the water, which affect both the water flow and the biological activity in the water.

There exists a pronounced salinity gradient from East to West in the Fehmarnbelt area due to the mixing of brackish Baltic Sea water and the saline North Sea water. Furthermore the density differences between brackish and saline water create a stratification of the water column, which is particularly pronounced in summer. Contrary to salinity, temperature follows a distinct seasonal pattern with warmer temperatures and thermal stratification of the water column in summer, and colder, more well-mixed waters in winter.

In Figure 3.1 an example of the summer stratification of the water column in the Puttgarden-Rødbyhavn cross-section as modelled by the FEHY local model is shown.

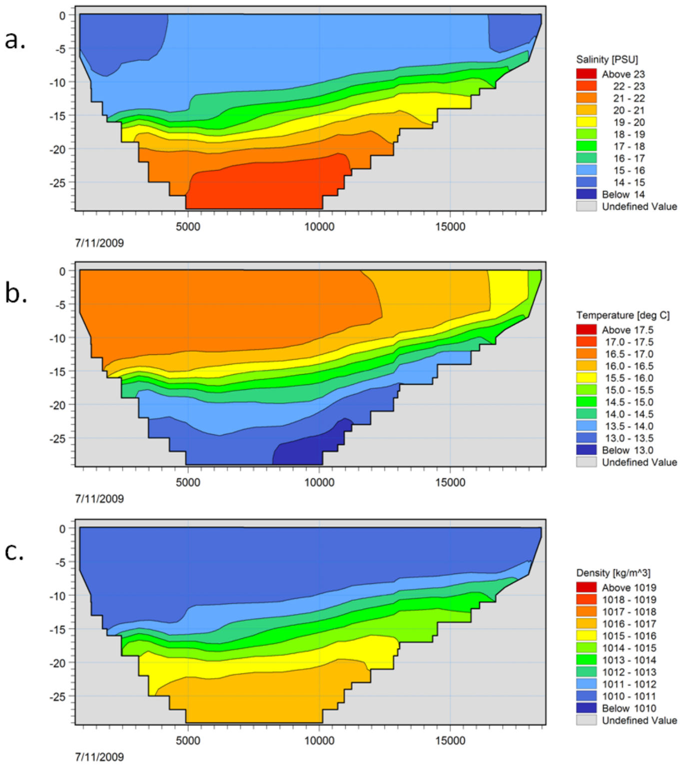

Figure 3.1 Snapshots of modeled (a) salinity, (b) temperature and (c) density in the Puttgarden-Rødbyhavn vertical cross-section.

An illustrative example of the temporal variation of water temperature and salinity in the FEHY main Station 01 as calculated by the FEHY local model and by the Fehmarnbelt WF model are shown in Figure 2.9. This figure shows the temporal variation in the surface and bottom layer during 2009 and 2010. The figure illustrates the annual variation of the water temperature and the stratification of the water column (observed as differences between surface and bottom values), which is more pronounced in summer.

The spatial and temporal variability of the water temperature, salinity and density is lower than for the current velocity and the current velocity derived variables. Figure 2.10 and Figure 2.11 show examples of the instantaneous spatial variability of the surface salinity.

3.5. Stratification of the Water Column

As a measure of the stratification of the water column, the strength and depth of the pycnocline were calculated using Brunt-Vaisala frequencies. At a certain location at a certain time, the magnitude of the maximum Brunt-Vaisala frequency squared, N^2, is calculated as:

$$N^2 = -\frac{g}{\delta_0}\frac{d\delta}{dz},$$

Where g is gravity, δ_0 is a reference water density, δ is local water density and dz (=1m) is the vertical grid spacing. The unit of the maximum Brunt-Vaisala frequency squared is s^{-2}. The Brunt-Vaisala frequency is a measure of the local stability of the water column; the higher the Brunt-Vaisala frequency the stronger the local stratification.

In this context the Brunt-Vaisala frequency is included as a measure of the strength of the stratification. Furthermore, if the maximum strength is above a certain threshold (set at 0.005 s^{-2}), the depth (in m) of the pycnocline is determined as the depth, where the Brunt-Vaisala frequency is highest (maximum Brunt-Vaisala). In this way horizontally as well as temporally varying strengths and depths of the pycnocline has been determined. Figure 3.2 shows an example of the variation of the Brunt-Vaisala frequency over the water column in the Puttgarden-Rødbyhavn cross-section.

In Figure 3.3 the temporal variation of the calculated pycnocline depth and strength at the location of the FEHY Main Station 02 (MS02) are shown. The MS02 station is located in the deeper part of the Fehmarnbelt on the alignment between Puttgarden and Rødbyhavn. It is observed in the figure that the pycnocline generally is stronger in summer and that the depth is missing when the strength is below 0.005 s^{-2}.

It is important to note that the pycnocline variables are more relevant in deeper water larger than say 15 m. This is due to the fact that the pycnocline is typically located in 15-20 m depth. In more shallow water the pycnocline will still reflect the stratification of the water column, but it will typically be a weaker and less frequent stratification.

Similar to the water temperature, salinity and density, the spatial and temporal variability of the stratification variables is lower than for the current velocity, but contrary to the current velocities they have a marked seasonal variation.

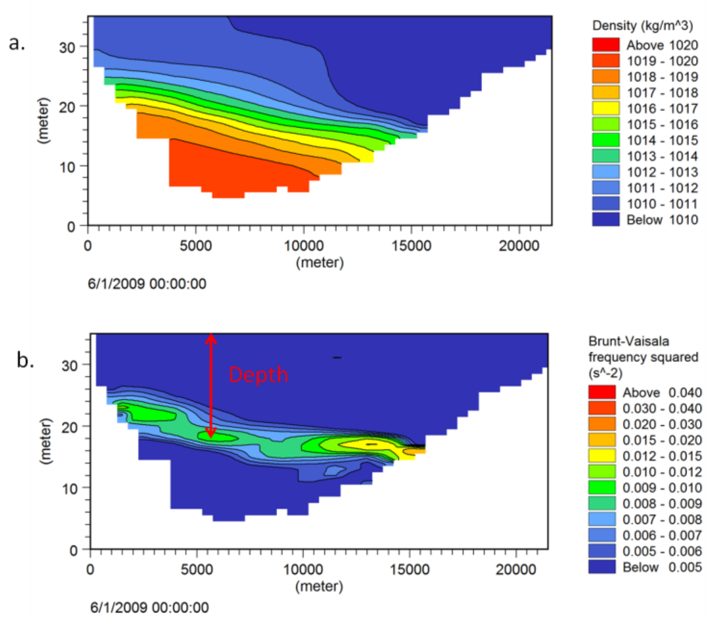

Figure 3.2 Snapshot of (a) modelled density and (b) calculated Brunt-Vaisala frequency in the Puttgarden - Rødbyhavn cross-section. The depth of the pycnocline is indicated in panel b.

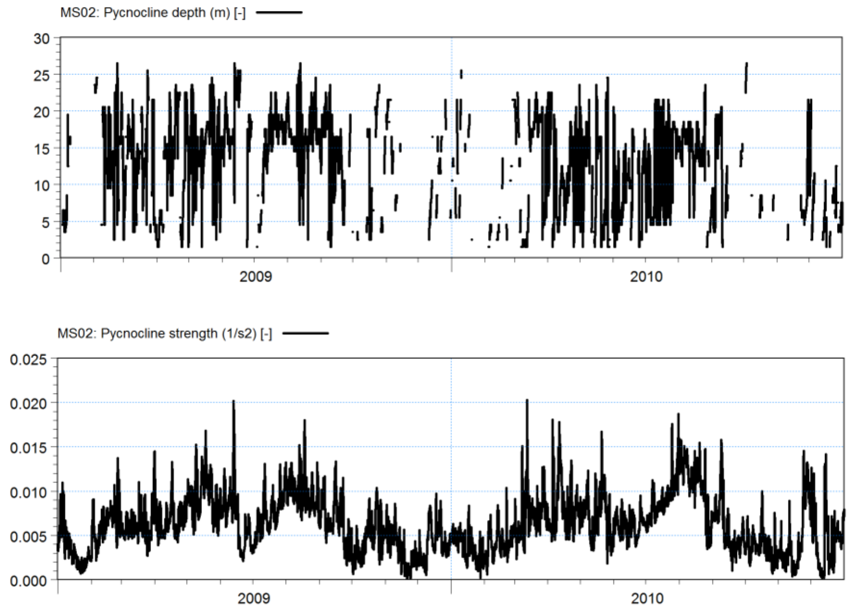

Figure 3.3 Temporal variation of calculated pycnocline depth (upper) and strength (lower) at MS02.

4. REFERENCES

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