A Hybrid Coordinate Ocean Model for shelf sea simulation

Nina Gjerde Winther [a,*], Geir Evensen [b,a]

[a] *Mohn-Sverdrup Center/Nansen Environmental and Remote Sensing Center, Bergen, Norway*

[b] *Hydro Research Center, Bergen, Norway*

Abstract

The general circulation in the North Sea and Skagerrak is simulated using the Hybrid Coordinate Ocean Model (HYCOM). Although HYCOM was originally developed for simulations of the open ocean, it has a design which should make it applicable also for coastal and shallow shelf seas. Thus, the objective of this study has been to examine the skills of the present version of HYCOM in a coastal shelf application, and to identify the areas where HYCOM needs to be further developed. To demonstrate the capability of the vertical coordinate in HYCOM, three experiments with different configurations of the vertical coordinate were carried out. In general, the results from these experiments compares quite well with *in situ* and satellite data, and the water masses and the general circulation in the North Sea and Skagerrak is reproduced in the simulations. Differences between the three experiments are small compared to other errors, which are related to a combined effect of model setup and properties of the vertical mixing scheme. Hence, it is difficult to quantify which vertical coordinate configuration works best for the coastal region. It is concluded that HYCOM can be used for simulations of coastal and shelf seas, and further suggestions for improving the model results are given. Since HYCOM also works well in open ocean and basin scale simulations, it may allow for a realistic modelling of the transition region between the open ocean and coastal shelf seas.

Key words: HYCOM · hybrid coordinate · shelf sea · North Sea · Skagerrak

* Corresponding author
Email addresses: nina.winther@nersc.no (Nina Gjerde Winther), geir.evensen@hydro.com (Geir Evensen).

1 Introduction

One of the key issues in numerical ocean modelling is the choice of vertical coordinate system and one of three formulations are normally used. These are the z-level coordinate which uses the depth as vertical coordinate, the terrain following sigma coordinate which scales with depth, and the isopycnal coordinate which uses a discretization in potential density referenced to a given pressure.

The z-level models have traditionally been used for basin scale simulations. As discussed by Haidvogel and Beckmann (1998) z-level models must represent irregular topography as a number of steps, and have therefore difficulties of representing strongly varying topography with a limited number of levels. Hence, z-level models are not widely used for coastal applications.

Sigma coordinate models have become a standard for modelling coastal and shallow or unstratified seas. The main advantages of these models are a smooth representation of bottom topography and their ability to retain high vertical resolution near the surface and the sea floor, allowing for a realistic modelling of the surface and bottom boundary layers. The main drawback has been the occurrence of the so-called pressure gradient error (see e.g. Mellor et al., 1998), although the introduction of advanced numerical schemes have significantly reduced the impact of these errors (Shchepetkin and McWilliams, 2003). Further, in stratified regions sigma coordinate models will typically introduce unphysical numerical mixing across isopycnals.

There are many advantages of using isopycnal coordinates, including the proper conservation of deep water masses during very long time integrations where one has total control of the diapycnal mixing. This has motivated the development of isopycnal ocean models, in particular for basin scale and climate simulations. However, these models cannot be used in shelf seas unless there is a significant stratification and they have been limited by the use of a single-layer bulk representation of the mixed layer.

The Hybrid Coordinate Ocean Model (HYCOM) by Bleck (2002) is an outgrowth of the Miami Isopycnal Coordinate Ocean Model (MICOM; Bleck and Smith, 1990). The major improvements in HYCOM relative to MICOM is the introduction of a hybrid vertical coordinate, which allows for the use of coordinate formulations suitable for different ocean regimes. The hybrid coordinate is typically isopycnal in the open, stratified ocean, but there is a smooth transition to z-level coordinates in the mixed layer and a transition to sigma coordinates in shallow coastal regions. This approach allows for high vertical resolution close to the surface and in shallow regions, and has also allowed for implementation of non-slab vertical mixing schemes like the K-Profile Parameterization (KPP; Large et al., 1994).

HYCOM was originally developed as an open ocean model, and has been evaluated in basin scale studies (Chassignet et al., 2003; Halliwell, 2004; Shaji et al., 2005). On the other hand, the objective of this study has been to test the skills of the present version of HYCOM on a coastal application, and to identify areas where HYCOM needs to be further developed. The introduction of the hybrid coordinate gives HYCOM the potential to be extended from the open ocean to coastal and shelf seas, so the question addressed in this study is if HYCOM can be used to realistically model both the open ocean and coastal shelf regions, and in particular, will it provide a realistic simulation of the transition region along the shelf break? These questions are now addressed in an application of HYCOM for the North Sea and Skagerrak which is the first systematic effort to validate HYCOM in a coastal application using an extensive observed data set.

The North Sea is a shelf sea that lies between Norway, the British Isles and the European Continent. The current system in the North Sea is characterized by a southward inflow of Atlantic water and the northward flowing Norwegian coastal current (NCC). The North Sea is a shallow sea, with two thirds of the region having depths shallower than 100 m. The exception is the Norwegian trench, which has depths exceeding 700 m. This special topography controls the circulation to a great extent. The saline Atlantic water enters the North Sea at its northern boundary and also through the English channel. It follows the topography, and is mixed with fresher and colder water from rivers. When it reaches the inner part of Skagerrak, the area between Denmark, Sweden and Norway, it meets brackish water from the Baltic and turns northward. As it reaches Norway, it follows the coast westwards and becomes the Norwegian Coastal Current. The NCC is known as a chaotic current, with high mesoscale activity, but in general it follows the coast northwards. This leads to an overall cyclonic circulation in the North Sea.

The North Sea is a challenging region for any coastal circulation model with it's large range of depths and various water masses and we believe it provides a good test case for HYCOM in this study.

Some important HYCOM features are presented in Section 2. Section 3 describes the model setup, and Section 4 presents the measurements used for model evaluation. In Section 5 model results and measurements are compared and discussed. Finally, Section 6 sums up the work done in this study and gives the conclusions.

2 HYCOM features

For details about the prognostic equations in HYCOM we refer to Bleck (2002), but the important parts that involve the hybrid vertical coordinate and that makes HYCOM different from other numerical codes typically used for shelf sea simulations are summarized in the following. The continuity equation in HYCOM is given by

$$\frac{\partial}{\partial t_s}\left(\frac{\partial p}{\partial s}\right) + \nabla_s \cdot \left(\mathbf{v}\frac{\partial p}{\partial s}\right) + \frac{\partial}{\partial s}\left(\dot{s}\frac{\partial p}{\partial s}\right) = 0, \tag{1}$$

where $\mathbf{v}$ is the horizontal velocity vector, p is the pressure and s is an unspecified vertical coordinate that is held constant during partial differentiation. $\dot{s}\partial p/\partial s$ represents the vertical mass flux across an s surface, and is the term that controls the movement and spacing of layer interfaces in HYCOM. This "grid generator" exploits the fact that all layers have an assigned target density. Whenever the layer thickness tends to zero because this light water does not exist in the water column, this layer is used as a z-level coordinate within the mixed layer. This z-level coordinate is located in depth according to a predefined rule, which uses a minimum z-level thickness, δ_p^{min}, a maximum z-level thickness, δ_p^{max}, and a stretching factor, f_p. These parameters control the z-level spacing and results in a top layer of thickness δ_p^{min} and a minimum allowed thickness, bounded by δ_p^{max}, for each layer given by

$$\delta_n(k) = \min\left(\ \delta_p^{max},\ \delta_p^{min}\ {f_p}^{k-1}\right). \tag{2}$$

In addition, there will be a transition to sigma coordinates in shallow regions, by specifying the number of layers that are to become sigma layers, N_σ, and their minimum allowed thickness, δ_s^{min}. This gives a new expression for the minimum allowed thickness in each layer:

$$\delta_n{}'(k) = \max\left[\ \delta_s^{min}, \min\left(\ \delta_n, \frac{D}{N_\sigma}\right)\right], \tag{3}$$

where D is the water depth. This means that in a given model layer, the transition occurs where the water depth becomes sufficiently shallow to make $D/N_\sigma <\ \delta_n$.

Advection of layer thicknesses in the continuity equation will introduce a vertical movement of the layer interfaces, also among the level coordinates near the surface. Further, horizontal diffusion of temperature and salinity in an isopycnic layer may lead to a deviation from the reference density. Therefore, at every time step, the "grid generator" needs to restore the coordinate surfaces. Among the isopycnal coordinates there is a restoration towards target densities. If the layer is too dense the upper interface is moved upwards, i.e. there is a flux of lighter water across the interface. If the layer is less dense than the target density, the lower interface is moved downward. For the z-level and sigma coordinates there will be a restoration towards their predefined locations at depth. These points comprise the main features of the “grid generator”.

The standard vertical mixing scheme in HYCOM is currently the K-Profile Parameterization (KPP; Large et al., 1994), and was chosen also for this study. HYCOM contains three more sub-models for vertical mixing; Mellor-Yamada level 2.5 (MY; Mellor and Yamada, 1982), Price-Weller-Pinkel dynamical instability (Price et al., 1986) and NASA-GISS level 2 (Canuto et al., 2002).

The KPP scheme provides mixing for the entire water column by matching the parameterization of the surface boundary layer mixing with ocean interior mixing. Viscosity and diffusivities in the surface boundary layer are given by

$$K_x = h_{sbl} w_x(\sigma) G(\sigma), \tag{4}$$

where h_{sbl} is the surface boundary layer depth, w_x is a turbulent velocity scale, G is a non-dimensional shape function and σ is a non-dimensional vertical coordinate ranging from 0 at the surface to 1 at the base of the boundary layer.

For the discussion in this study the diagnosis of h_{sbl} will be an important issue. A bulk Richardson number relative to the surface is given by

$$Ri_b(d) = \frac{(B_r - B(d))\, d}{|V_r - V(d)^2| + V_t^2(d)}, \tag{5}$$

where B is the buoyancy, V is the horizontal velocity and d is the distance from the surface. h_{sbl} is diagnosed as the smallest depth at which a critical bulk Richardson number ($Ri_c = 0.3$) is reached. Subscript r refers to near-surface values. V_t is an estimate of the turbulent velocity contribution to velocity shear.

Below the surface boundary layer there are three processes that contribute to the interior mixing. These are shear-mixing, internal wave-generated mixing and double-diffusive mixing.

The shear-mixing term is parameterized as a function of the gradient Richardson number,

$$Ri_g = \frac{N^2}{(\frac{\partial U}{\partial z})^2 + (\frac{\partial V}{\partial z})^2}, \tag{6}$$

where N is the buoyancy frequency and U and V are horizontal velocity components. Shear-mixing viscosity is estimated as

$$\nu_{sh} = \begin{cases} \nu_0 & Ri_g < 0, \\ \nu_0 \left[1 - (Ri_g/Ri_0)^2\right]^3 & 0 < Ri_g < Ri_0, \\ 0 & Ri_g > Ri_0, \end{cases} \tag{7}$$

where $\nu_0 = 5.0 \times 10^{-3}$ m^2s^{-1} and $Ri_0 = 0.7$.

For internal wave-generated mixing we use the same values that Durski et al. (2004) recommended for highly stratified coastal waters, namely 1.0×10^{-5} m^2s^{-1} for momentum and 1.0×10^{-6} m^2s^{-1} for potential density. For further details about the KPP scheme we refer to Large et al. (1994).

Earlier studies have shown that KPP compares favourably to MY in deep ocean studies (Large et al., 1994; Large and Gent, 1999), but for simulations of the coastal ocean MY has become the standard. Durski et al. (2004) tested the performance of these two vertical mixing parameterizations in idealized continental shelf settings, and stated that the original KPP scheme is inadequate for application on a shallow continental shelf and that a bottom boundary layer parameterization should be appended when used in the coastal ocean. This was not done in this study for two reasons. First of all, within the HYCOM consortium work is already in progress to implement and test an enhanced version of the KPP scheme. Secondly, as the ocean modelling community are moving towards global grids with higher and higher resolution, the models will resolve more of the coastal shelf areas. In this context it is important to quantify how the choice of vertical mixing scheme will influence the results. Hence, we kept the KPP as our vertical mixing sub-model to see how it performs in a realistic shelf sea simulation.

3 Model Setup and Experiments

The overall model system consists of a two-level nested system where a large scale model feeds an intermediate resolution model with boundary conditions. This intermediate model provides boundary conditions needed by the high resolution model covering the North Sea and Skagerrak (Figure 1).

Boundary conditions are treated differently depending on whether the variables are barotropic or baroclinic. For the slowly varying variables, i.e. baroclinic velocities, temperature, salinity and layer interfaces, the boundary conditions are based on the flow relaxation scheme (FRS; Davies, 1983). This means that we use a one way nesting scheme where the boundary conditions of the regional model are relaxed towards the output from the coarser large

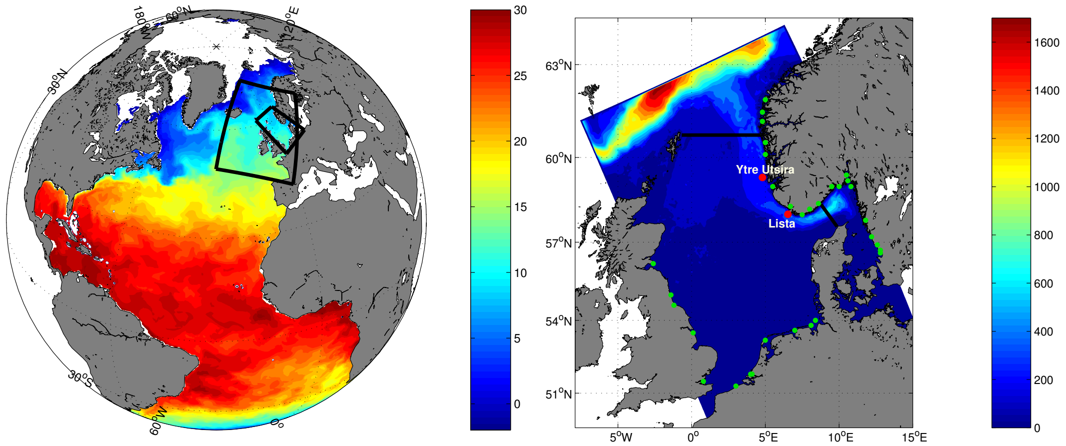

Fig. 1. Left: A two-level nested model system, where the large scale model covers the Atlantic and Arctic ocean. Surface temperature is shown in colours and Arctic sea ice extent in white. Right: Topography of the nested high resolution regional model. The black lines and red dots show the locations where *in situ* data are present. The green dots show the location of river input that are used in this model setup.

scale model. For the barotropic variables the relaxation approach requires careful treatment to avoid reflection of waves at the open model boundaries. In HYCOM the barotropic model is a hyperbolic wave equation for pressure and vertically integrated velocities. Following an approach outlined by Browning and Kreiss (1982, 1986), it is possible to compute the barotropic boundary conditions exactly while taking into consideration both the waves propagating into the regional model from the external solution and the waves propagating out through the boundary from the regional model.

All grids were created with the conformal mapping tools of Bentsen et al. (1999). The large scale model has a variable resolution with approximately 15-20 km grid cells in the Gulf Stream region, and with gradually coarser grid moving into the South Atlantic and the Arctic Ocean. This model ensures that the overall general circulation and water masses in the North Atlantic and its seasonal variability are properly represented. The intermediate model covers all of the North Sea and the Atlantic Margin including the deep waters between Spain, Iceland and Norway. This model has about 7 km resolution, which is sufficient to provide realistic and fairly detailed circulation pattern along the Atlantic Margin. A higher resolution model is needed to ensure good representation of the mesoscale variability and its energetics. Thus, a resolution of 4 km is used for the regional model covering the North Sea and Skagerrak.

Note that 4 km is normally too coarse to properly represent the mesoscale dynamics of the NCC, see e.g. Johannessen et al. (1989); Ikeda et al. (1989); Haugan et al. (1991); Oey and Chen (1992) which indicated that a model of 2 km resolution is needed. However, we have compensated for resolution by implementing a fourth order numerical scheme for the advection terms in the momentum equation which improves the dynamical representation of potential vorticity. In practical applications this leads to similar results with half the resolution compared to the original version of HYCOM as shown by Winther et al. (2005).

The large scale model is coupled to an ice module, which consists of both a dynamic and a thermodynamic ice model. The dynamic ice model uses the Elastic-Viscous-Plastic (EVP) rheology of Hunke and Dukowicz (1999). The thermodynamic ice model is described by Drange and Simonsen (1996).

The topography used was interpolated to the model grid using the General Bathymetry Map of the Oceans (GEBCO), which operates under the auspices of the International Hydrographic Organisation and the United Nations' (UNESCO) Intergovernmental Oceanographic Commission. The resolution is one minute.

The synoptic forcing fields were temperature, wind and humidity (determined from dew-point temperatures) fields from the European Center for Medium-Range Weather Forecasting (ECMWF). Clouds are based on climatologies from the Comprehensive Ocean and Atmosphere Dataset (COADS; Slutz et al., 1985), while precipitation is based on the climatology of Legates and Willmott (1990). All atmospheric fields have a horizontal resolution of 0.5°. River input is modelled as negative salinity flux, and the location of river sources included around the North sea and Skagerrak are shown as green dots in Figure 1. At the surface the ocean model uses a weak temperature and salinity relaxation towards the General Digital Environmental Model (GDEM) oceanic climatology (Teague et al., 1990).

To ensure a proper representation of the Baltic inflow to the North Sea model, a barotropic volume flux is included at the eastern boundary (see Figure 1). Values used to specify the volume flux are monthly climatology data and the Baltic water has been given a salinity of 8 psu.

The regional model includes tides, which are specified as a barotropic forcing at the open boundaries. The data set used originates from the University of Texas and is based on several years of altimeter data collected by the TOPEX satellite. Eight constituents are specified at the boundaries; K_1, O_1, P_1, Q_1, M_2, N_2, S_2 and K_2. These constituents make up a significant portion of the tidal signal, and are considered sufficient in this study.

The vertical discretization uses 22 hybrid layers, with target densities references to σ_0 (i.e., density at atmospheric pressure minus $1000\,\mathrm{kg\,m^{-3}}$) in the range from 21.80 to 28.11. These were chosen to represent water masses and resolve the mixed layer in the Atlantic and Arctic ocean and are therefore not ideal for this coastal application. Note that the lightest layers in this dis-

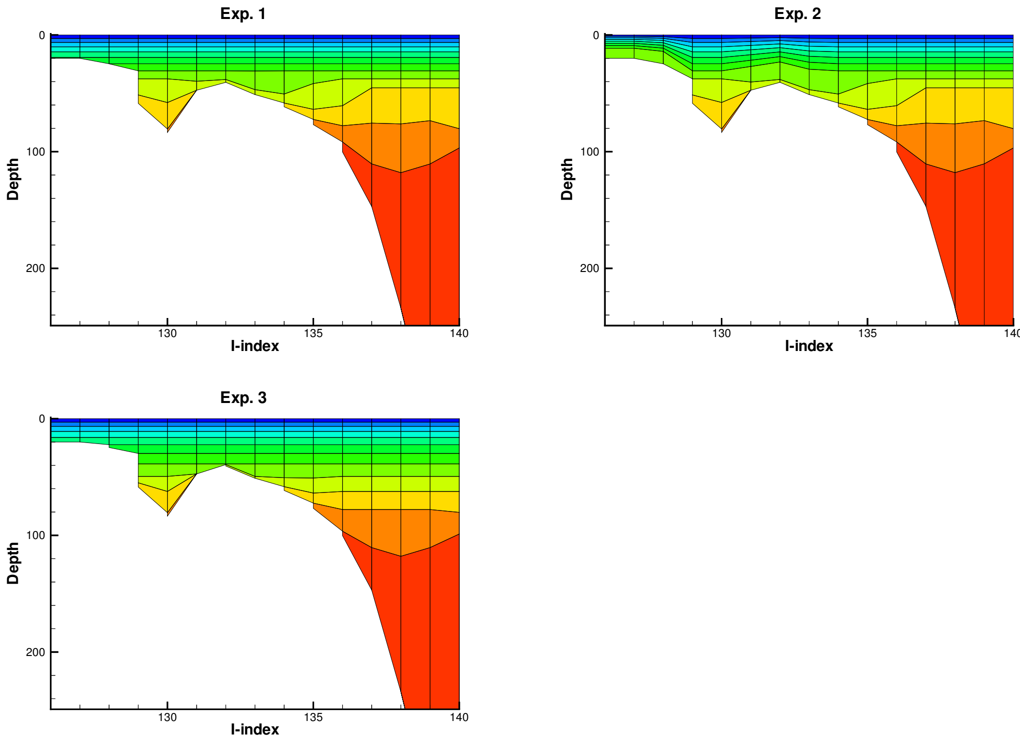

Fig. 2. Illustration of the vertical layer interfaces for the three different experiments. Parameters used to set-up these experiments are given in Table 1.

cretization are primarily used to describe the surface mixed layer, as they are usually too light to describe interior water masses in the ocean. This set-up is valid for the outer models while for the North Sea model the target densities for the top five layers were set to 0.1 to 0.5. This was done to avoid a collapse in the vertical coordinate when including rivers, since river input will cause the water density to get lower than the first target density.

Three different experiments with simulation period starting in January 1997 and ending in July 1998, were carried out. The experiments differ in the way the z- and sigma coordinates are defined and the parameters used are listed in Table 1. The resulting vertical discretizations from the different parameter sets are illustrated in Figure 2.

The three experiments are summarized as follows:

Exp. 1 uses the same vertical coordinate set-up as the outer models, so this was the natural choice for the first simulation. As is seen in Figure 2, z-level coordinates are used both within the mixed layer and on the shelf.

Exp. 2 allows for a transition to sigma coordinates in shallow water regions. The purpose is to examine if sigma coordinates can improve the results compared to using standard z-levels as was done in Exp. 1. In Figure 2 it is seen that there is a transition to sigma coordinates only in very shallow

Exp.	δ_p^{min} (m)	δ_p^{max} (m)	f_p	δ_s^{min} (m)	δ_s^{max} (m)	f_s	N_σ
1	3	12	1.125	-	-	-	0
2	3	12	1.125	1	12	1.125	10
3	3	20	1.2	-	-	-	0

Table 1
Parameters for vertical coordinate setup for the three different experiments. Here δ_p^{min} and δ_s^{min} are minimum z-level thickness in deep and shallow water, δ_p^{max} and δ_s^{max} are maximum z-level thickness in deep and shallow water, f_p and f_s are the stretching factors for the z-levels, and N_σ is the number of sigma levels.

regions where in our case the slopes are gentle.

Exp. 3 uses a different set-up of the z-level coordinates compared to Exp. 1. In particular we choose a larger stretching factor for the z-levels and also allow for a larger maximum z-level thickness. This leads to a hybrid coordinate that retains z-levels for a larger part of the water column, and most importantly across the pycnocline. The purpose is to examine if this set-up can improve the vertical stratification and the placement of the pycnocline. Note that sigma coordinates are not used in this experiment.

4 Measurements used for model evaluation

To evaluate the skills of the numerical ocean model, several types of measurements from the North Sea and Skagerrak have been gathered and used for comparison with HYCOM. The first type of measurements are CTD (Conductivity-Temperature-Depth) data from field cruises carried out by the Norwegian Institute of Marine Research during 1997 and 1998. The first section is located in the northern part of North Sea; from Shetland to Feie at the Norwegian coast, 60.75°N 0.67°W to 60.75°N 4.72°E. This section is repeated three to four times a year. The second section is located in the central Skagerrak; from Torungen at the south tip of Norway to Hirtshals at the Danish coast, 57.57°N 9.87°E to 58.37°N 8.77°E. This section is repeated once a month. For geographical location of the two sections, see black lines in Figure 1. The cruise period for conducting one section takes about one to two days.

The Institute of Marine Research also monitors temperature and salinity at eight stations along the Norwegian coast on a regular basis. Two of these stations, i.e. Ytre Utsira at 59.19°N 4.48°E and Lista at 58.01°N 6.32°E, are located inside the model area, and are used to evaluate the ocean model (see red dots in Figure 1). Measurements are available two to three times per month.

The third type of data used for model evaluation is Sea Surface Temperature (SST) from the NOAA satellite (Vazquez et al., 1998). The product contains data with different spatial and temporal resolutions, but the data used here have a spatial resolution of 9 km and are daily averages.

5 Model results and evaluation

The model's ability to simulate the correct water masses and circulation in the North Sea and Skagerrak was first studied using the measurements from Ytre Utsira described in section 4. Figure 3 and 4 compares measurements of temperature and salinity, respectively, with model results from the three experiments. The figures show temperature and salinity for the upper 200 m from August 1997 to July 1998. (The first half year of 1997 is used as the spin-up period.) Note the black marks at the upper part of first panel. These marks indicate the dates when measurements were collected, and note that model results were extracted for the exact same dates.

The annual cycle of temperature is quite well simulated with HYCOM. Vertical mixing dominates during winter, which results in small temperature differences between surface and bottom. Heating during spring/summer results in a well defined surface layer of about 50 m. Surface layer thickness during summer is well represented in the model, but in late summer 1997 the upper 20 m is about 3°C too cold in all experiments compared to observations. Kara et al. (2005) showed that sea surface temperature is sensitive to both solar attenuation coefficient and misrepresentation of land-sea mask in atmospheric forcing fields. These factors will influence the model results of sea surface temperature also in this study. We use a constant solar attenuation coefficient, and as mentioned previously the ECMWF fields have a resolution of 0.5°, which is very low compared to the ocean model.

The main problem in the model is too smooth stratification between the NCC and the Atlantic water. This is specially evident in the salinity plots, and results in too fresh water from about 50 to 150 m, as seen in Figure 4. The experiments show some differences in temperature and salinity. This is further illustrated in Figure 5, which shows time average profiles of model bias of temperature and salinity at the Ytre Utsira location. Exp. 2 strengthens the thermocline/halocline and lifts the Atlantic water towards shallower depths compared to Exps. 1 and 3. On the other hand Exp. 3 strengthens the gradient in the upper 50 m, and gives the most realistic results of the boundary layer thickness. The exception is the fresh water input in December/January, which produces a fresh surface layer of about 50 m depth, that none of the experiments capture properly.

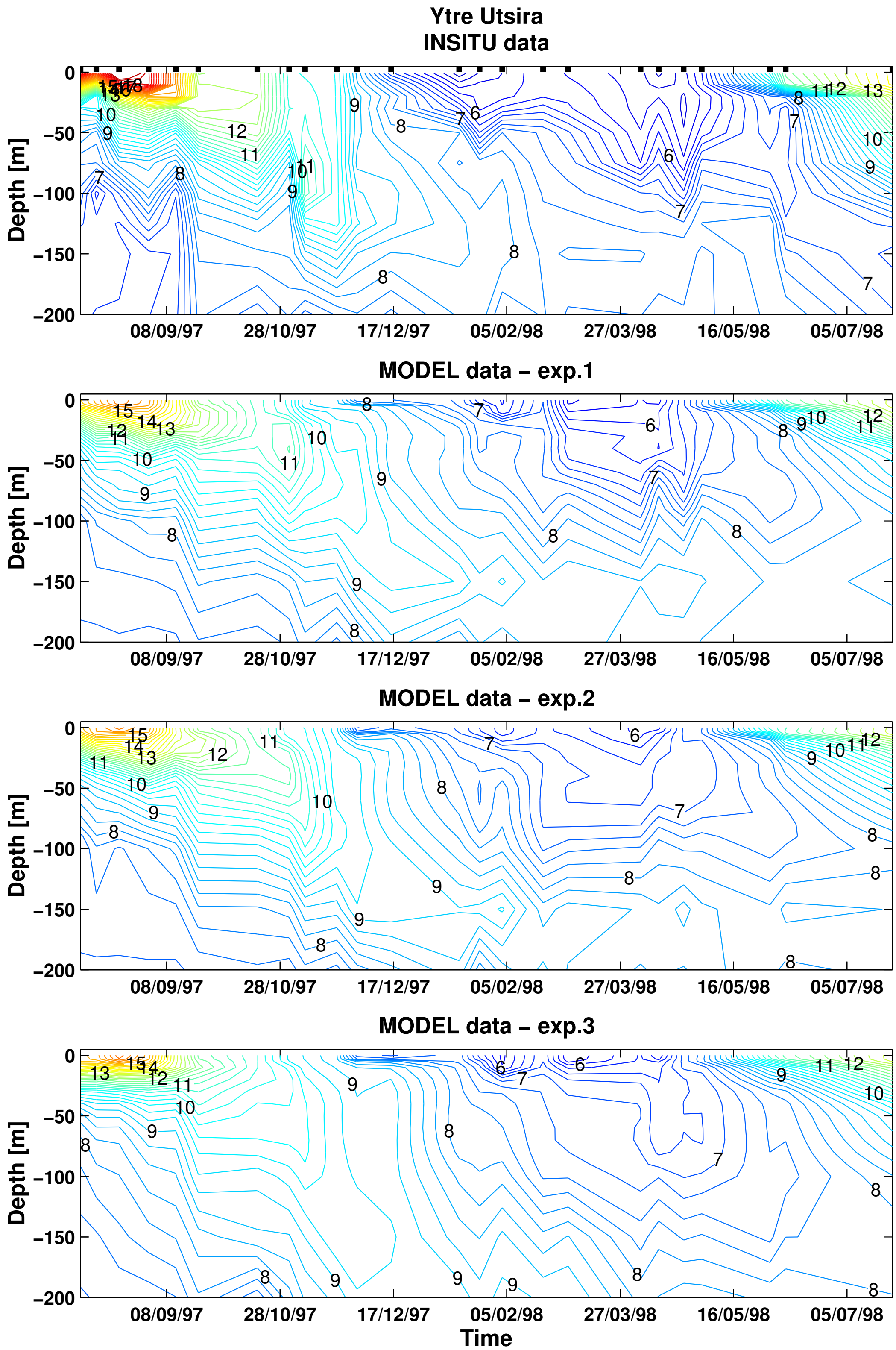

Fig. 3. Annual cycle of temperature at Ytre Utsira; *in situ* observations and model results from three different experiments.

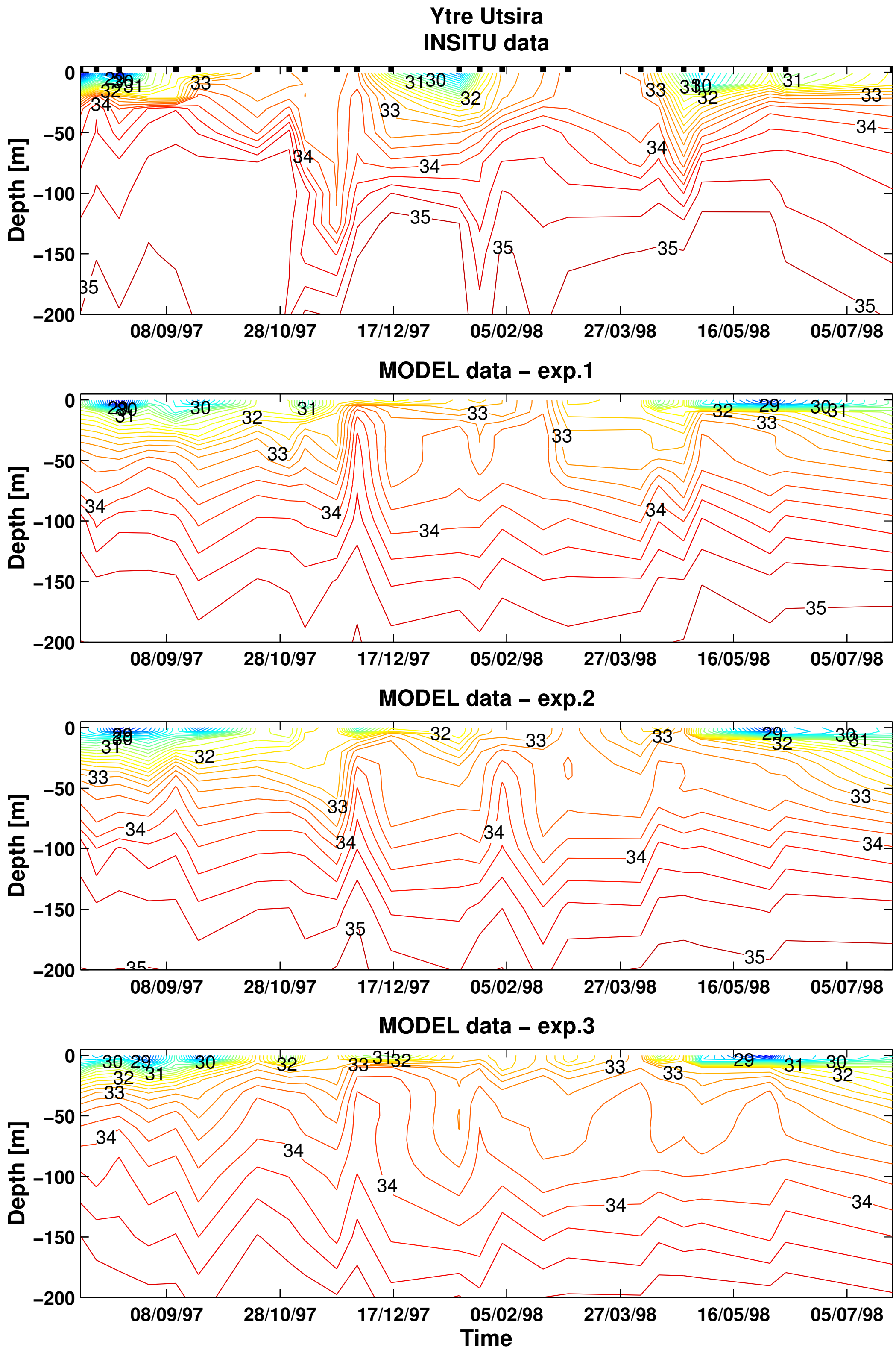

Fig. 4. Annual cycle of salinity at Ytre Utsira; *in situ* observations and model results from three different experiments.

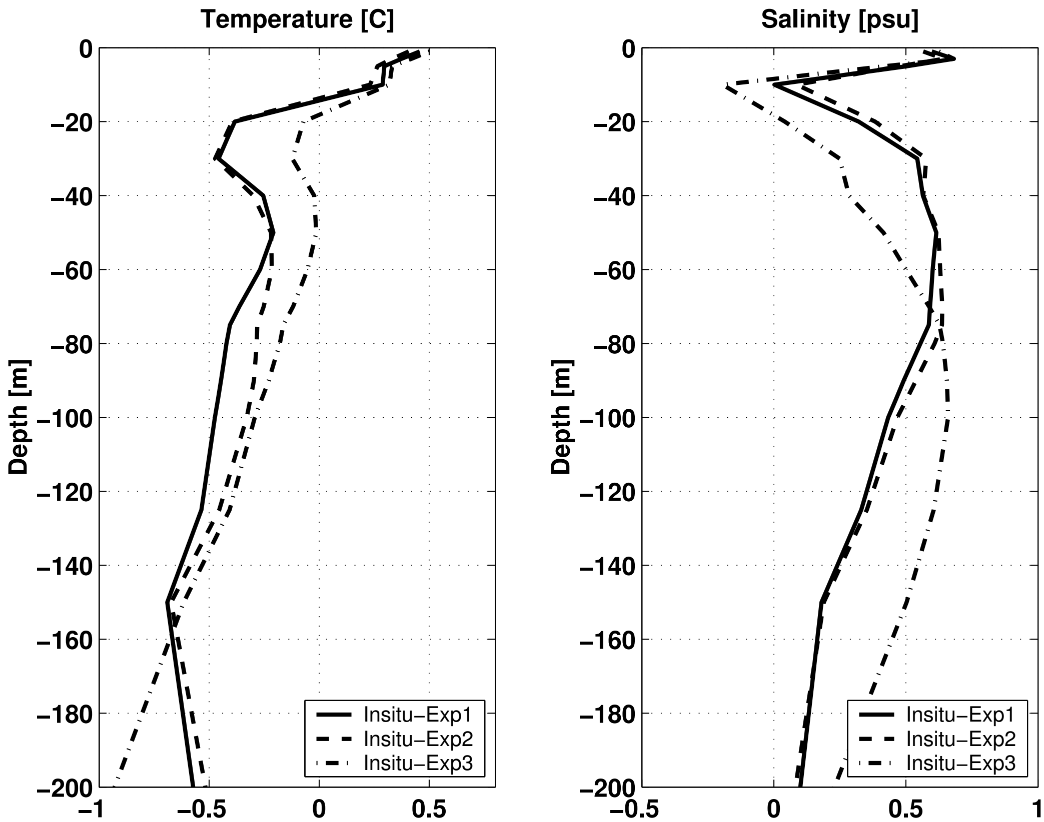

Fig. 5. Time average profiles of model bias for temperature and salinity at Ytre Utsira.

To further examine the vertical structure, model results from a section that crosses the northern North Sea was compared with CTD measurements. Figure 6 shows that the inflow of Atlantic water is well represented in the central North Sea and the deep parts of the Norwegian Trench. The width of the NCC in the model is in good agreement with observations from the Feie – Shetland section in all experiments, but the figures again reveal the very smooth halocline. It is clear that differences between the three experiments are small compared to other errors that are common for all the experiments. But we still think it is useful to discuss some of the differences seen in the experiments. At this location Exp. 2 gives results closest to observations. The shape of the isohalines are more similar, and the horizontal distribution of fresh water away from the coast is better represented.

A special feature of the tracer field in Skagerrak is the domed shape of the isohaline/isotherm surfaces. This feature was examined by using temperature observations from the Torungen – Hirtshals section, and Figure 7 shows that this domed shape is indeed present in the model.

The NCC in Skagerrak can vary from being a very narrow coastal current to extending all the way to Denmark, depending on the dominant wind regime.

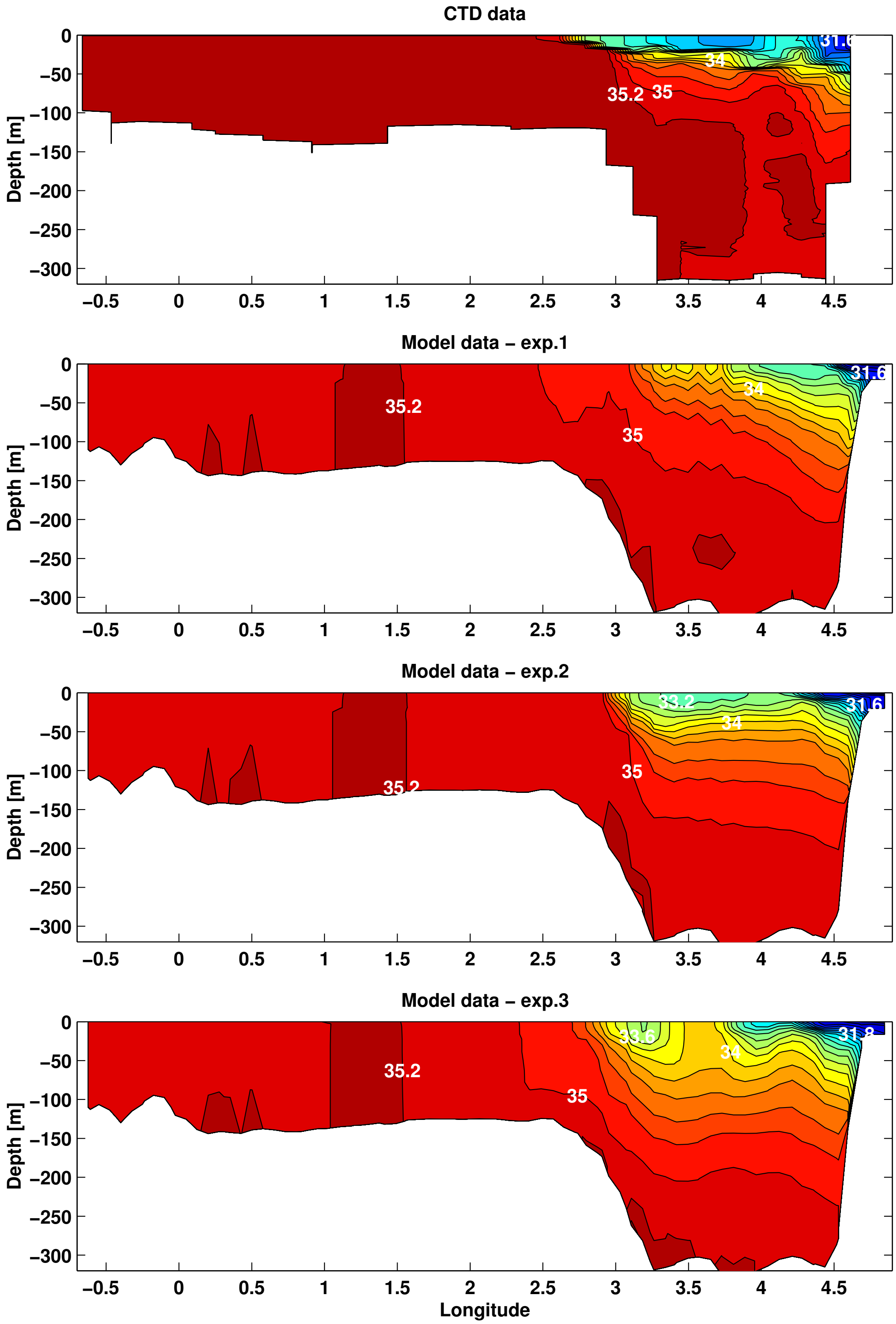

Fig. 6. Vertical section of salinity from Shetland to Feie at the Norwegian Coast. CTD measurements and model results from three experiments for the 23rd of January 1998.

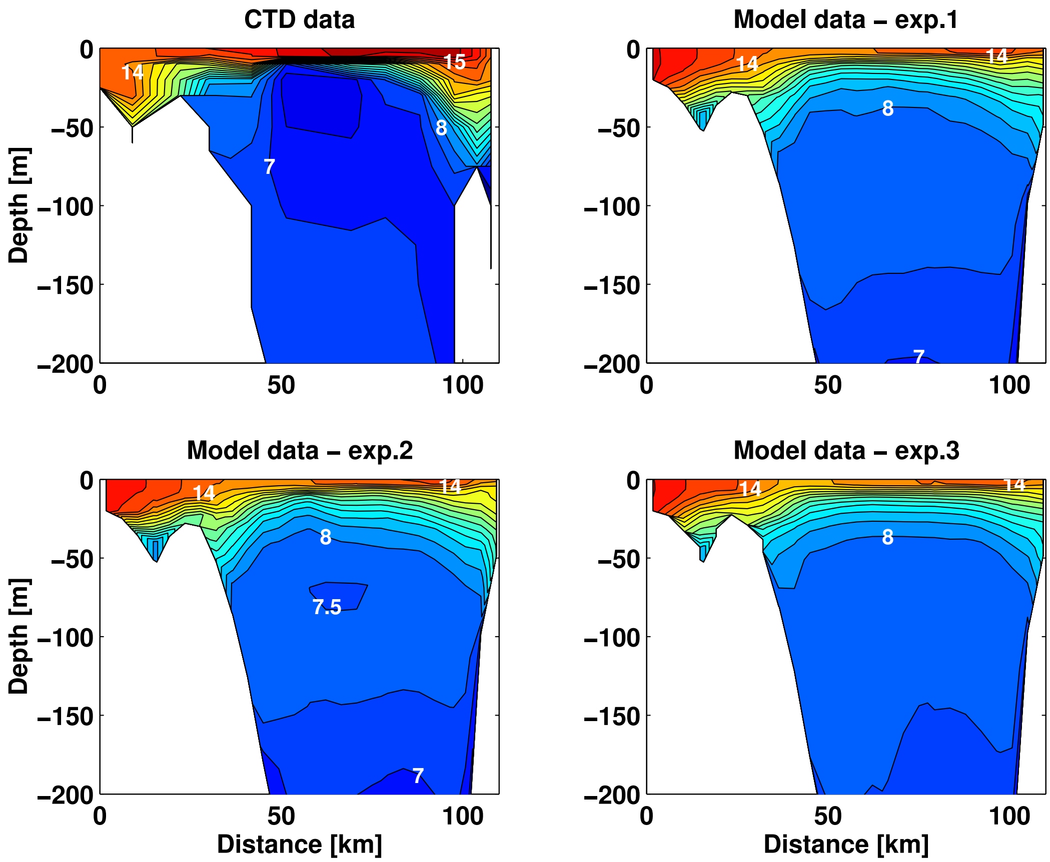

Fig. 7. Vertical section of temperature from Hirtshals, Denmark to Torungen at the southern tip of Norway. CTD measurements and model results from three experiments for the 10th of July 1998.

For this point in time, both observations and the model shows a very broad and shallow NCC with temperature up to 14°C. The core of the Atlantic water is $1 - 1.5$°C warmer than the observations in all experiments, and the thermocline is too smeared out. Again Exp. 2 gives the most realistic results. Using sigma coordinates in shallow regions results in colder water from 50 to 100 m and warmer surface water along the Norwegian coast compared to the other two experiments. Thus, Exp. 2 gives the strongest Atlantic inflow to the Skagerrak.

Different mechanisms can explain the diffuse stratification between the NCC and the Atlantic water seen in the Skagerrak and specially in the northern North Sea. This is now examined further by investigating properties of the vertical mixing scheme in relation to vertical coordinate set-up.

First of all the KPP scheme used in this study does not include a parameterization of the bottom boundary layer. We know from Durski et al. (2004) that this will produce a region of intense mixing in shallow continental shelf areas if there exist a strong velocity shear near the bottom boundary layer. But, other processes within the KPP scheme also contribute to the very diffuse stratification seen in the model results.

Figure 8 shows vertical profiles of temperature diffusivity, K_T (Exp. 1), from the first winter period when the vertical mixing is seen to be very high. Profiles from both the Skagerrak and the northern North Sea section are shown. (Viscosity profiles are not shown here, but are very similar.) Both locations have large values of K_T in the surface boundary layer, but there is a big difference in boundary layer depth, h_{sbl}. KPP gives a h_{sbl} of about 20 m at the deepest point along the Torungen - Hirsthals section, while along the Feie - Shetland section h_{sbl} is around 50 m. This means that the model predicts high mixing across the area where we expect to find the boundary layer base.

As described in Section 2, h_{sbl} is diagnosed as the shallowest depth at which a critical bulk Richardson number, Ri_c, is reached, which again is calculated by using buoyancy and horizontal velocities. Outside Feie KPP diagnose values of Ri_b below Ri_c for a large portion of the water column, while at the Skagerrak location $Ri_b < Ri_c$ for only the top two layers. This is because the density gradient is weaker and horizontal velocities are stronger along the Feie - Shetland section than in Skagerrak. This means that for this particular study, the dependence on the Ri_b leads to an overestimation of h_{sbl}. In addition shear-mixing from the interior, will contribute strongly below the boundary layer for certain periods, when there is a strong velocity shear created by the northward flowing NCC and the southward flowing Atlantic water. The shear-mixing is dependent on the gradient Richardson number, Ri_g, and is initiated when $Ri_g < Ri_0$ (see Eq. 7). Together these processes give excessive vertical mixing across the thermocline/halocline.

These results can also be related to the work of Durski et al. (2004). They showed that differences in response between KPP and MY are mainly related to their different dependence on the gradient Richardson number, and that KPP has much stronger response to incidents of enhanced shear at the base of the boundary layer (at least compared with MY).

It is important to notice that the diffusivity profiles in Figure 8 are from the first winter period, when the vertical mixing was seen to be particularly large, and that these profiles vary a lot during the simulation period.

Since buoyancy forcing is important for the vertical mixing parameterization, model results will be sensitive to e.g. fresh water input. Here it is important to remember that the model uses climatological monthly mean values both for river input and to specify the volume flux of brackish water from the Baltic. This means that errors in fresh water input will influence the capabilities of the mixing scheme.

The spacing between vertical grid lines are illustrated as horizontal lines in

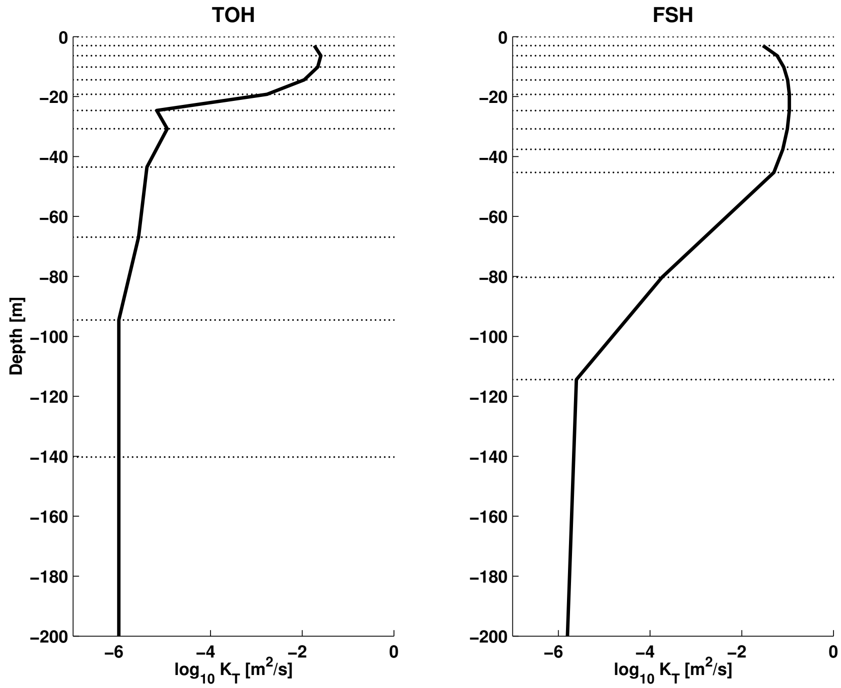

Fig. 8. Winter profiles of temperature diffusivity from Exp. 1 at two locations in the Norwegian Trench; the deepest point along the Torungen - Hirtshals section (left) and the deepest point along the Feie - Shetland section (right). Top 200 m of the water column are shown. Horizontal lines show the location of the vertical grid layers.

Figure 8. The transition from z-levels to isopycnal coordinates takes place at the boundary between Atlantic water and the coastal current, and the Atlantic water is represented by just a couple of isopycnal layers. This illustrates that the choice of target densities in this model configuration is not the ideal choice for the North Sea and Skagerrak. Together with the properties of the KPP scheme and the approximation of Baltic inflow, this can explain the very diffuse thermocline/halocline seen in the model results.

Exp. 2 gives results closest to the observations, with increased inflow of Atlantic water and better representation of the NCC. The reason for this is better resolution of surface waters in the shallow regions, and this has a significant effect in Kattegat; the area where Atlantic water meets the brackish water from the Baltic. Model results from this area (figures not shown) show that using sigma coordinates results in increased transport of Baltic water to the Skagerrak. Fresher water in surface layers will change the Ri_b, which again changes the profiles of K_T. Therefore we see a slightly less diffuse halocline in Exp. 2, although the results still show a too diffuse stratification. The opposite happens in Exp. 3, where the distance between each z-level layer has increased. The exception is across the thermocline/halocline. At this location Exp. 3 uses z-level coordinates throughout a larger part of the water column, while the other experiments have a transition to isopycnal coordinates. Hence,

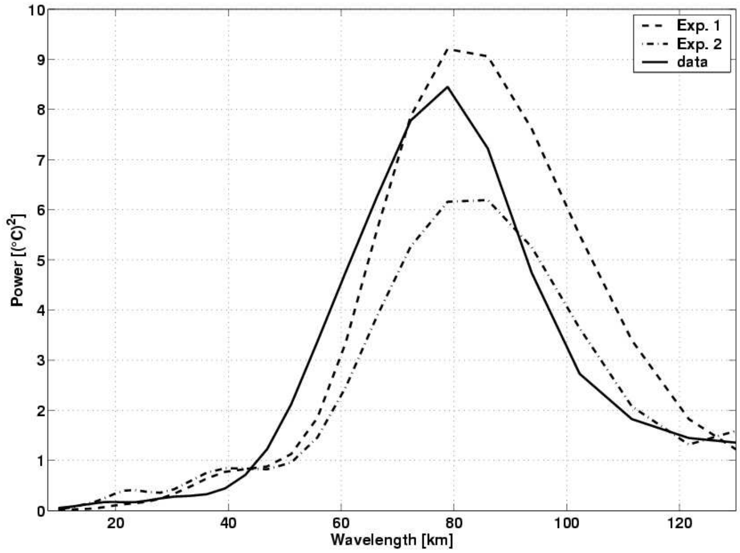

Fig. 9. Global wavelet power spectra of HYCOM SST, Exps. 1 and 2, and AVHRR SST from the 14th of May 1998.

Exp. 3 has a higher vertical resolution here, and a slight improvement is seen.

To evaluate the mesoscale structure in the NCC, wavelet analysis of SST was performed for both satellite data and model results (Figure 9). SST from 14th of May 1998 was chosen, since this was one of the few days of cloud free conditions that coincides with the simulation period. Data was extracted along 4°E and from 59.3°N to 62°N, which gives a section trough the mesoscale structure in the NCC. Wavelet analysis was performed using the Matlab package by Torrence and Compo (1998). Both observations and model results show global wavelet energy spectra with similar shape and energy focused on a wavelength interval around 50 to 120 km. Unfortunately data from Exp. 3 was lost for this particular date.

All examples above give an evaluation of the model either at a specific point in space (Ytre Utsira) or at a specific point in time (vertical sections and wavelet analysis). Therefore, transports were computed from the model results to evaluate the mean flows in the model. Rodhe (1996) reviews the large-scale hydrography of Skagerrak, and states that the inflow from the west is somewhere between 0.5 and 1.0 Sv. Danielssen et al. (1997) estimated the transport in the upper 100 m to be about 1 (±0.5) Sv. In Exps. 1, 2 and 3 we predicted transport values of 1.12, 1.16 and 1.04 Sv, respectively, for the inflow to the Skagerrak. Thus, all three values correspond well with observations.

6 Conclusions

In this study we have used HYCOM to simulate the circulation in the North Sea and Skagerrak. In general, HYCOM gave good results in comparison with different types of observations. It was seen that different water masses are well represented in the simulations, and that the general circulation is well reproduced. In addition we found that the dynamics of the chaotic NCC is well simulated in the model. Three experiments with different configurations of the vertical coordinate were carried out. Differences between the three experiments are small compared to other errors, and weaknesses related to properties of the vertical mixing scheme in combination with the model setup are quantified. It is concluded that HYCOM can be used for simulations of coastal and shelf seas, but in different areas the model should be further developed.

To use HYCOM for the coastal ocean an enhanced version of the KPP (see Durski et al., 2004) should be included to reduced erroneous mixing at the shallow continental shelf. A valuable study would also be to run the same set-up with alternative vertical mixing schemes. Another natural improvement would be to extend the code and include capabilities that can use horizontally varying target densities. This would allow for tuning the target densities for specific areas, and most likely improve the results. Both these issues are already worked on within the HYCOM consortium. Also a better representation of fresh water input to the model would improve the results, specially more realistic boundary conditions towards Baltic.

One of the questions we asked in the introduction was if HYCOM could handle the transition from open ocean to coastal shelf regions. In this study we have not evaluated how the different shelf break processes are represented in HYCOM, but as the previous chapter shows the correct water masses are entering the North Sea. Indirectly this implies that the main dynamics along the shelf break are well represented in HYCOM, at least for the area studied in this paper.

Acknowledgements

This work is part of the Norwegian Research Council project *Monitoring the Norwegian Coastal Zone Environment* (MONCOZE) with contract no. 143559/431. This work has also been supported by the Norwegian Research Council (Program for Supercomputing) trough a grant of computing time. We would like to thank the Norwegian Institute of Marine Research for providing *in situ* data. This study has also benefited greatly from discussions with colleague K.A. Lisæter.

References

Bentsen, M., Evensen, G., Drange, H., Jenkins, A. D., 1999. Coordinate transformation on a sphere using conformal mapping. Mon. Weather Rev. 127, 2733–2740.

Bleck, R., 2002. An oceanic general circulation model framed in hybrid isopycnic-cartesian coordinates. Ocean. Mod. 4, 55–88.

Bleck, R., Smith, L. T., 1990. A wind-driven isopycnic coordinate model of the north and equatorial atlantic ocean. 1. model development and supporting experiments. J. Geophys. Res. 95, 3273–3285.

Browning, G. L., Kreiss, H.-O., 1982. Initialization of the shallow water equations with open boundaries by the bounded derivative method. Tellus 34, 334–351.

Browning, G. L., Kreiss, H.-O., 1986. Scaling and computation of smooth atmospheric motions. Tellus, Ser. A 38, 295–313.

Canuto, V. M., Howard, A., Cheng, Y., Dubovikov, M. S., 2002. Ocean turbulence. Part II: Vertical diffusivities of momentum, heat, salt, mass and passive scalars. J. Phys. Oceanogr. 32, 240–264.

Chassignet, E., Smith, L., Halliwell, G., Bleck, R., 2003. North Atlantic simulation with the HYbrid Coordinate Ocean Model (HYCOM): Impact of the vertical coordinate choice, reference density, and thermobaricity. J. Phys. Oceanogr. 33, 2504–2526.

Danielssen, D. S., Edler, L., Fonselius, S., Hernroth, L., Ostrowski, M., Svendsen, E., Talpsepp, L., 1997. Oceanographic variability in the Skagerrak and Northern Kattegat, May-June, 1990. J. Marine Science 54, 753–773.

Davies, H. C., 1983. Limitations of some common lateral boundary schemes used in regional NWP models. Mon. Weather Rev. 111, 1002–1012.

Drange, H., Simonsen, K., 1996. Formulation of air-sea fluxes in the ESOP2 version of MICOM. Tech. Rep. 125, Nansen Environmental and Remote Sensing Center, Bergen, Norway.

Durski, S. M., Glenn, S. M., Haidvogel, D. B., 2004. Vertical mixing schemes in the coastal ocean: Comparison of the level 2.5 Mellor-Yamada scheme with an enhanced version of the K profile parameterization. J. Geophys. Res. 109, C01015, doi:10.1029/2002JC001702.

Haidvogel, D. B., Beckmann, A., 1998. Numerical models of the coastal ocean. In: Brink, K. H., Robinson, A. R. (Eds.), The Sea. Vol. 10. John Wiley & Sons, Inc., pp. 457–482.

Halliwell, G., 2004. Evaluation of vertical coordinate and vertical mixing algorithms in the HYbrid Coordinate Ocean Model (HYCOM). Ocean. Mod. 7, 285–322.

Haugan, P. M., Evensen, G., Johannessen, J. A., Johannessen, O. M., Pettersson, L., 1991. Modeled and observed mesoscale circulation and wave-current refraction during the 1988 Norwegian continental shelf experiment. J. Geophys. Res. 96 (C6), 10,487–10,506.

Hunke, E. C., Dukowicz, J. K., 1999. An elastic-viscous-plastic model for sea-ice dynamics. J. Phys. Oceanogr. 27, 1849–1867.

Ikeda, M., Johannessen, J. A., Lygre, K., Sandven, S., 1989. A process study of mesoscale meanders and eddies in the Norwegian coastal current. J. Phys. Oceanogr. 19, 20–35.

Johannessen, J. A., Svendsen, E., Sandven, S., Johannessen, O. M., Lygre, K., 1989. Three-dimensional structure of mesoscale eddies in the Norwegian Coastal Current. J. Phys. Oceanogr. 19, 3–19.

Kara, A. B., Wallcraft, A. J., Hurlburt, H. E., 2005. Sea surface temperature sensitivity to water turbidity from simulations of the turbid Black Sea using HYCOM. J. Phys. Oceanogr. 35, 33–54.

Large, W. G., Gent, P. R., 1999. Validation of vertical mixing in an equatorial ocean model using large eddy simulations with observations. J. Phys. Oceanogr. 29, 449–464.

Large, W. G., McWilliams, J. C., Doney, S. C., 1994. Oceanic vertical mixing: A review and a model with a nonlocal boundary layer parameterization. Rev. of Geophys. 32, 363–403.

Legates, D., Willmott, C., 1990. Mean seasonal and spatial variability in gauge-corrected global precipitation. Int J. Climatol 10, 110–127.

Mellor, G. L., Oey, L.-Y., Ezer, T., 1998. Sigma coordinate pressure gradient errors and the seamount problem. J.Atmos. Ocean Tech. 15, 1122–1131.

Mellor, G. L., Yamada, T., 1982. Development of a turbulence closure model for geophysical fluid problems. Rev. Geophys. Space Phys. 20, 851–875.

Oey, L.-Y., Chen, P., 1992. A nested grid model: With application to the simulation of meanders and eddies in the Norwegian Coastal Current. J. Geophys. Res. 97 (12), 20,063–20,086.

Price, J. F., Weller, R. A., Pinkel, R., 1986. Diurnal cycling; observations and models of the upper-ocean response to diurnal heating, cooling, and wind mixing. J. Geophys. Res. 91, 8411–8427.

Rodhe, J., 1996. On the dynamics of the large-scale circulation of the Skagerrak. J. Sea Research 35 (1-3), 9–21.

Shaji, C., Wang, C., G.R. Halliwell, J., Wallcraft, A., 2005. Simulation of tropical Pacific and Atlantic Oceans using a hybrid coordinate ocean model. Ocean. Mod. 9, 253–282.

Shchepetkin, A., McWilliams, J., 2003. A method for computing horizontal pressure-gradient force in an oceanic model with a non-aligned vertical coordinate. J. Geophys. Res. 108 (C3), doi:10.1029/2001JC001047.

Slutz, R., Hiscox, S. L. J., Woodruff, S., Jenne, R., Joseph, D., Steurer, P., Elms, J., 1985. Comprehensive ocean-atmosphere dataset; release 1. Tech. Rep. NTIS PB86-105723, NOAA Environmental Research Laboratories, Climate Research Program, Boulder, CO.

Teague, W. J., Carron, M. J., Hogan, P. J., 1990. A comparison between the Generalized Digital Environmental Model and Levitus climatologies. J. Geophys. Res. 95 C5, 7167–7183.

Torrence, C., Compo, G. P., 1998. A practical guide to wavelet analysis. Bulletin of the American Meteorological Society 79 (1), 61–78.

Vazquez, J., Perry, K., Kilpatrick, K., 1998. NOAA/NASA AVHRR Oceans Pathfinder Sea Surface Temperature Data Set User's Reference Manual Version 4.0. JPL Publication D-14070.

Winther, N. G., Morel, Y., Evensen, G., 2005. Efficiency of high order numerical schemes for momentum advection, To be submitted.