Validation and Sensitivity study of a Sigma-coordinate Ocean Model using the Skagex dataset

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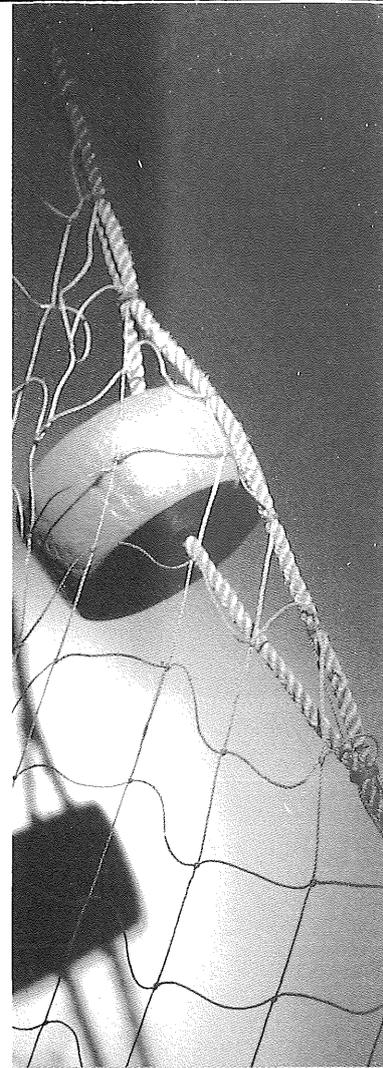Nordnesgaten 50, N-5024 Bergen

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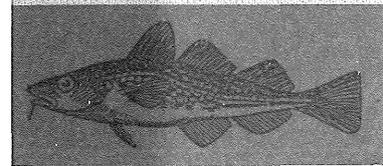Nordnesgaten 50, N-5024 Bergen

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Abstract

Numerical ocean models are now being applied in numerous oceanographic studies. However, standards and procedures for evaluation of these models are far from established. In this paper the use of data from hydrographical transects taken repeatedly over a period for model validation is suggested. In order to illustrate the evaluation technique a 3-dimensional sigma-coordinate model system is set set up for an extended North Sea and run in the period from October 1989 to August 1990. The model system consists of a "large scale" model with 20km horizontal resolution producing the open boundary conditions to a "fine scale" model with 4km horizontal resolution set up for the Skagerrak/Kattegat area. During SKAGEX-90 hydrographical stations were taken every third day along several fixed transects. From these datasets mean values and standard deviations, with respect to time, of salinity and temperature are produced and compared to corresponding measures from model results.

Contents

Chapter 1

Introduction.

A number of numerical ocean circulation models have been under development for the last decades and applied in numerous oceanographical studies. The qualities of the model results are, however, often uncertain and there is a clear need for procedures and standards for model evaluation.

Currents show great variability in space and time. The uncertainties in estimates of average transports based on measured currents will therefore typically be very large and often of the same order of magnitude as the transports themselves. It will therefore be relatively easy to produce model transports that are within the uncertainties of the 'observed' transports, but it will be difficult to quantify the accuracy of individual model results.

The variability in the density field, especially the salinity field, is typically much smaller. Data from hydrographical transects taken repeatedly over a period in time may be used to produce average fields and corresponding standard deviation fields. These fields may be compared to corresponding fields from model results. It will often be a very hard task to produce model fields of salinity and temperature that are within the uncertainties/variability set up by nature. Correct scalar model fields will also be an indication on correct treatment of advective and diffusive processes in the model. Conversely: Correct density gradients are necessary to get the internal pressure and the currents correct. Since the task of getting scalar fields correct is very hard, it is also easier to select the model producing the best fields using this technique.

During SKAGEX-90 (Danielssen *et. al.*, 1991) fixed hydrographical stations along 8 sections were taken every third day in the period from 24 May to 20 June 1990, see Fig.1. From this dataset temporal mean values and standard deviations of salinity and temperature are produced and compared to corresponding statistics produced from model results.

Skagerrak is directly connected to the North Sea through major exchanges of water masses of the order of 1 SVerdrup ($1SV = 10^6 m^3 s^{-1}$). Due to the topographic features with a deep basin down to 700 meters in the center and a trench westward to the North Sea (Fig.1), the general circulation is cyclonic. The high salinity water from the North Sea enters Skagerrak on the Danish side, and after flowing east and north it returns and leaves the area along the Norwegian coast. This relatively simple picture is disturbed by significant amounts of low salinity water originating from the Baltic (with additional riverine inputs). As this surface water reaches the Skagerrak through the Kattegat, it usually has salinities around 20-25. Normally it flows as a typical coastal current along Sweden and Norway with a significant forcing by the density structure. As it leaves the Skagerrak on top of the recirculated North Sea water of Atlantic origin, it typically has a salinity around 30 in the upper layer. The physical oceanography and general circulation of the Skagerrak is in particular described by Svansson (1975) and Rodhe (1987,1989,1991), collated in Rodhe (1992), and a review is given by the North Sea Task Force (1993). Sharp vertical and horizontal density gradients are present between these two water masses, and meanders and eddies of many different scales are often seen in satellite images. Some of the larger meanders are also found to be of a topographic wave type (Djurfeldt, 1984; Shaffer and Djurfeldt,1983), and this indicates that the flow system in Skagerrak is more or less both barotropic and baroclinic instable. Adding into this complex circulation pattern is a third water mass also coming from the North Sea. This is the Jutland Coastal Water originating from the German Bight as a mixture of water from European rivers and the southern North Sea. This water enters the Skagerrak in pulses regulated by local wind and larger scale circulation features of the North Sea (Aure *et al.*, 1990). Due to large variations in mixing with water from the central North Sea as it flows northwards along the Danish west coast, the salinity varies between 31 and 34. This means that when it interacts both with the deeper high salinity water of Atlantic origin and the surface water of Baltic origin, it will be positioned between these water masses and therefore affect the density structure. To study the variability of this complex and highly dynamic system, the Skagerrak Experiment (SKAGEX) was planned and executed (Dybern *et. al.*, 1994). One part of this was a field experiment in May-June 1990 (SKAGEX-90) where up to 17 ships and about 20 institutions in 7 countries were involved. Together with many other observations, most of the transects shown in Fig.1 were hydrographically mapped synoptically every three days from May 24 to June 20. This means that each salinity and temperature section was repeated 10 times, and the averages and standard deviations of these sections are the basis for this work.
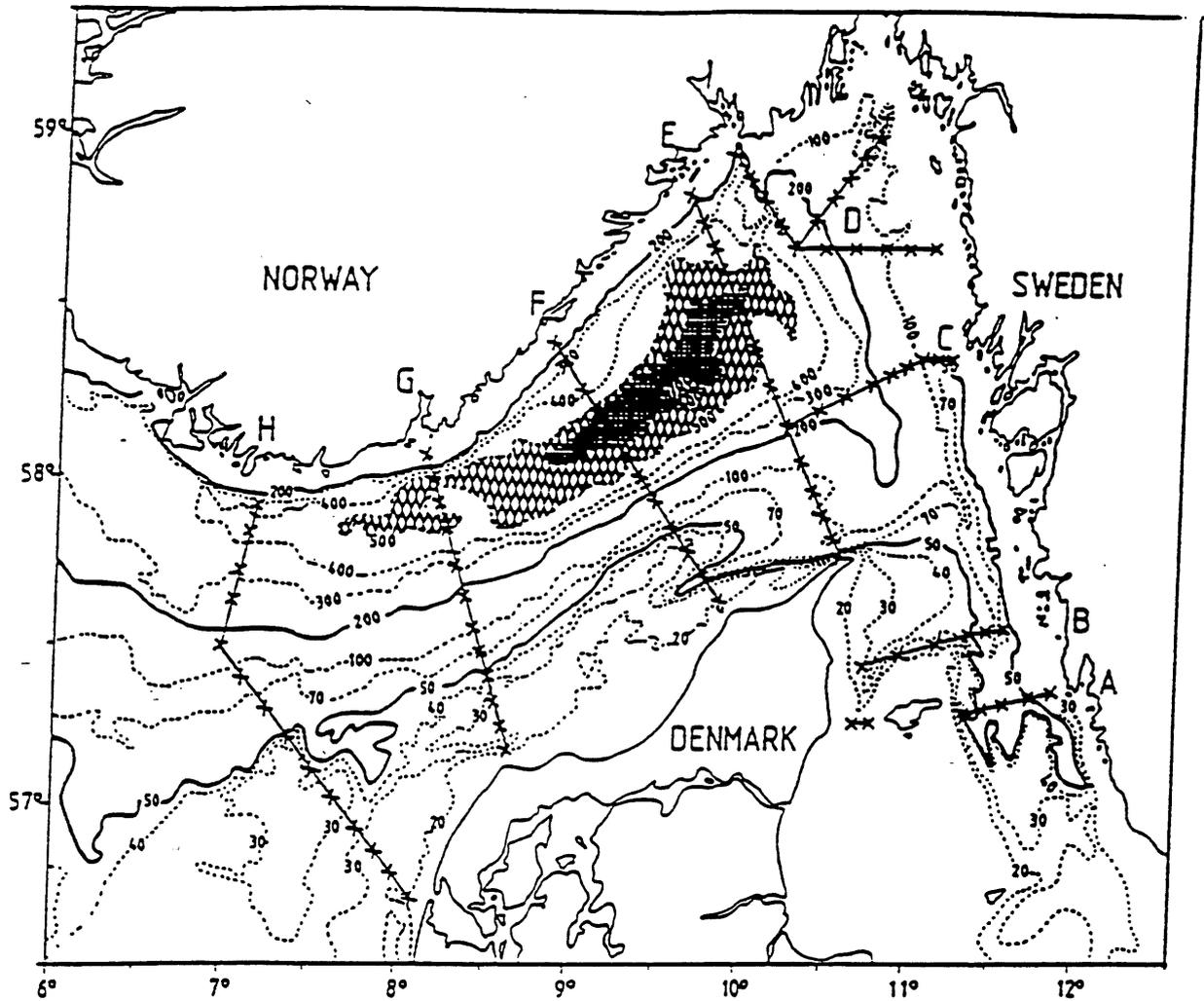
Figure 1. Topography of Skagerrak. A, B, C, D , E, F, G and H show the different sections with the positions of the hydrographica l stations. Areas deeper than 500m are hatched and the 50 and 200m bo ttom contours are enhanced. (From Danielssen *et. al.*, 1995)

Chapter 2

The model design.

The circulation of the North Sea and Skagerrak/Kattegat is approximated by a three-dimensional, primitive equation, time-dependent circulation model due to Blumberg and Mellor (1987). This model performed favorably in a recent model evaluation project (Røed et al., 1989). The prognostic variables of this model are the three components of the velocity field, temperature, salinity, surface elevation and two quantities which characterize the turbulence, the turbulence kinetic energy and the turbulence macroscale. The governing equations of the model are the momentum equations, the continuity equation, conservation equations for temperature and salinity and a turbulence closure model for the turbulence kinetic energy and the turbulence macroscale (Mellor and Yamada , 1982). The governing equations together with their boundary conditions are approximated by finite difference techniques. In the vertical a σ-coordinate representation is used. In this representation the sea surface is mapped to 0 and the sea bottom to -1, thus the depth at each value of σ is proportional to the bottom depth.

The model is implemented for an extended North Sea with a 20km horizontal resolution (Fig. 2) and for Skagerrak/Kattegat with 4km horizontal resolution (Fig. 3). Vertically 11 σ-coordinate layers are used for both models. The layers follow the bottom topography and are chosen to give high resolution near the surface. At 100 m depth the layers are .5 m, .7 m, 1.3 m, 2.5 m, 5 m, 10 m, 20 m, 20 m, 20 m, 15 m and 5 m thick.

2.1 Initial values.

The North Sea model is run from 15/10-89 to 1/8-90 and climatological values of velocity, temperature, salinity and water elevation for October are used as initial values (Martinsen et. al., 1992). Output of these fields from the 20km model at 15/3-90 are interpolated to a 4km grid and used as initial values for the

Skagerrak/Kattegat model which is run to 1/8-90.

2.2 Boundary conditions.

At the lateral open boundaries, except at the boundary to the Baltic, a flow relaxation scheme is implemented (Martinsen and Engedahl, 1987). The FRS-zones for both models are 7 grid-cells wide. For the North Sea model climatological values of velocity, temperature, salinity and water elevation for the respective months are used to specify the lateral boundary conditions, and output from this model of the same state variables is every hour interpolated to the FRS-zone of the 4km model and used as lateral boundary conditions for this model.

The flow to and from the Baltic is implemented after an algorithm due to Stige-brandt (1980). The flow is determined from the difference in modelled water level between the southern Kattegat and the Baltic, taking climatological freshwater input to the Baltic into account. The water entering Kattegat from the Baltic is given a salinity of 8.0. In the 20km model all inflow/outflow is placed at Store-belt. In the 4km model the flow is shared between Storebelt and Øresund.

The models are run with hindcast atmospheric forcing (momentum flux and surface pressure every 6 hour) provided by the Norwegian Meteorological Institute (Reistad and Iden, 1995).

In lack of information on surface heat fluxes, we relax the sea surface temperature towards climatology (Cox and Bryan, 1984). The surface flux of a constituent Θ is specified by

$$K_H \frac{\partial \Theta}{\partial z} = \gamma(\Theta^* - \Theta)$$

where K_H is the vertical diffusivity in the top layer, Θ^* the climatological value of the constituent and γ a time constant selected to be $1.735 * 10^{-5} m s^{-1}$. This means that during weak forcing the constituent in the upper 15m or so of the surface layer return to the climatological value on a time scale of 10 days.

The North Sea model is run with monthly mean river runoff from the Rhine, Meuse, Scheldt, Ems, Weser, Elbe, Humber,Tyne and Tees. Daily river runoff from the 6 largest Swedish rivers between Øresund and Norway is supplied. Fresh water runoff from the coast of Norway, including Glomma, is based on monthly mean fluxes and distributed on 9 outlets along the Norwegian coast. The Sk-agerak/Kattegat model is run with the same fresh water discharge from the Swedish and Norwegian coasts, but because of the finer horizontal resolution

the discharge from the Norwegian coast is distributed on 11 coastal cells.

To represent sub-grid scale processes, the model utilizes the Smagorinsky (1963) diffusion formulation in which the horizontal viscosity,A_M, and diffusivity coefficients, A_H, are modelled by

$$(A_M, A_H) = (C_M, C_H)\Delta x \Delta y((\partial u/\partial x)^2 + (\partial u/\partial y + \partial v/\partial x)^2/2 + (\partial v/\partial y)^2)$$

where Δx and Δx are the horizontal resolution in x and y respectively. The sensitivity of the model results to the parameters C_M and C_H will be studied.

The vertical eddy viscosity, K_M, and vertical eddy diffusivity, K_H, are computed from the turbulent kinetic energy and turbulent macroscale. However, the actual values used in the computations are $K_M + K_{MIN1}$ and $K_H + K_{MIN2}$ respectively and the model results are often very sensitive to the choice of the minimum values K_{MIN1} and K_{MIN2}.
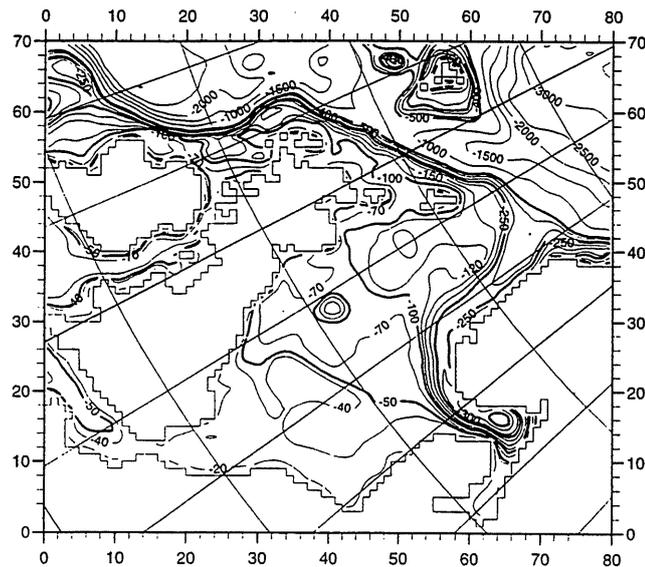

Figure 2. Bottom topography of the North Sea model area.
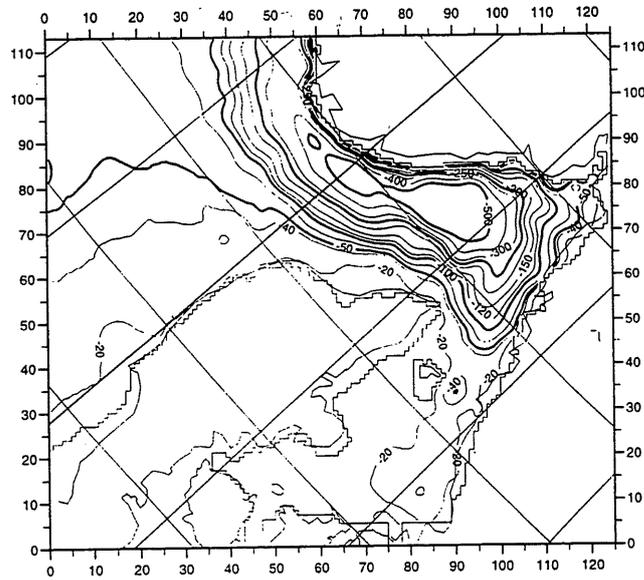
Figure 3. Bottom topography of the Skagerrak/Kattegat model area.

Chapter 3

Comparison of observed and model fields.

3.1 Method

The density field in Skagerrak/Kattegat is mainly determined by the salinity field. Since the sea surface temperature is relaxed towards climatology we believe to have the fresh water fluxes more correct than the surface heat fluxes. We therefore focus on checking the models ability to reproduce the salinity fields. The effects of errors in the salinity and temperature on the velocity fields are of major importance, and we attempt to study these effects by using geostrophic calculations.

During Skagex, most of the CTD sections were taken 10 times with fixed station positions. Mean values and corresponding standard deviations of salinity and temperature are produced from the 10 repeated vertical profiles at each position. These measures are then interpolated spatially to cover the whole transects. Spatial averages along the transects are also computed. We will focus on results for three transects. Section B is at the entrance from Kattegat to Skagerrak. Section F is in the central Skagerrak and is also the section covering the deepest part of Skagerrak. Section H covers the flow between Skagerrak and the North Sea. See figures 1 and 4 to 9. For all section plots the unit along the x-axis is distance from the Danish coast in km and the unit for the y-axis is depth in m.

From the model results pointwise mean values and standard deviations of the fields for the period from 24 May to 20 June are produced along the transects in two ways:

a) From instantaneous model fields taken at the same days as the observations.
b) From instantaneous model fields taken each hour during the experimental pe-

riod.

These measures are interpolated to the same grids as the data.

In order to study the discrepancies between the mean model fields and the corresponding measured fields, we subtract the two interpolated fields. In order to relate the discrepancy to the normal variation of the field variable, we divide the difference by the standard deviation in the data. The discrepancy in model salinity measured in numbers of standard deviations is thus:

$$D_{\overline{S}} = (\overline{S}_{model} - \overline{S}_{data})/S_{SD-data}$$

where $\overline{S}_{model}$ is the average modelled salinity, $\overline{S}_{data}$ the average measured salinity and $S_{SD-data}$ the standard deviation in the salinity data. For each section also area averages of the absolute values of this measure are computed.

In order to study the discrepancies between the variations in model fields and the variations in the measured fields, we subtract the interpolated fields of modelled standard deviation and the measured standard deviation. In order to relate the discrepancy to the normal variation of the field variable, we divide the difference by the minimum of the two standard deviations. The discrepancy in standard deviation of model salinity measured in numbers of standard deviations is thus:

$$D_{S_{SD}} = (S_{SD-model} - S_{SD-data})/min(S_{SD-model}, S_{SD-data})$$

where $S_{SD-model}$ is the standard deviation in the model salinity. For each section also area averages of the absolute values of this measure are computed.

Ocean models are often used in different transport studies and it is therefore of major interest to study how model errors in the density fields may affect the circulation. Based on both the sectional modelled and measured density fields we have used the thermal wind relation

$$-f\frac{\partial v}{\partial z} = \frac{g}{\rho_0}\frac{\partial \rho}{\partial x}$$

to estimate the velocities normal to the sections. f is the Coriolis parameter, g gravity, ρ_0 the reference density, ρ the model result or data density computed from salinity and temperature using the equation of state. We have assumed zero velocity at the bottom. The barotropic current component is not known from data and therefore this will not give the correct picture of the actual flow through the sections, but in this context the differences in model and data geostrophic

currents and transports are of greatest interest. For all three velocity fields total transports in and out of the sections are computed. All transports are measured in Sverdrups ($1\text{Sv} = 10^6 m^3 s^{-1}$).
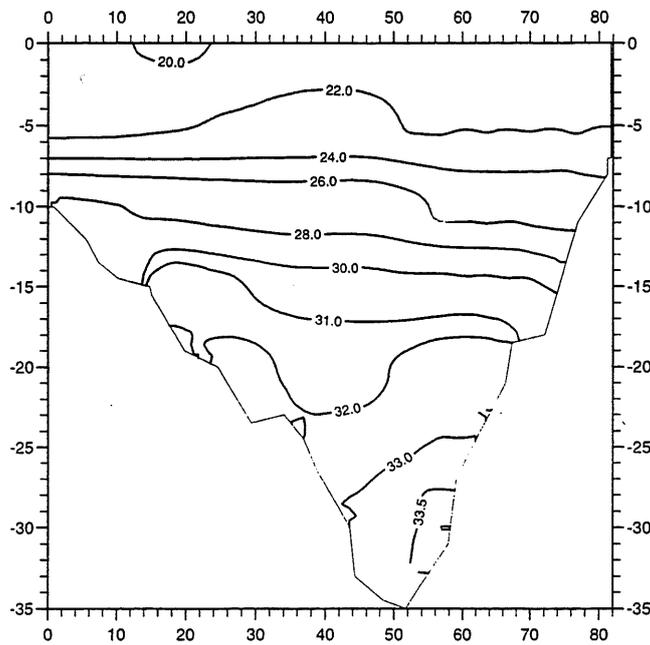

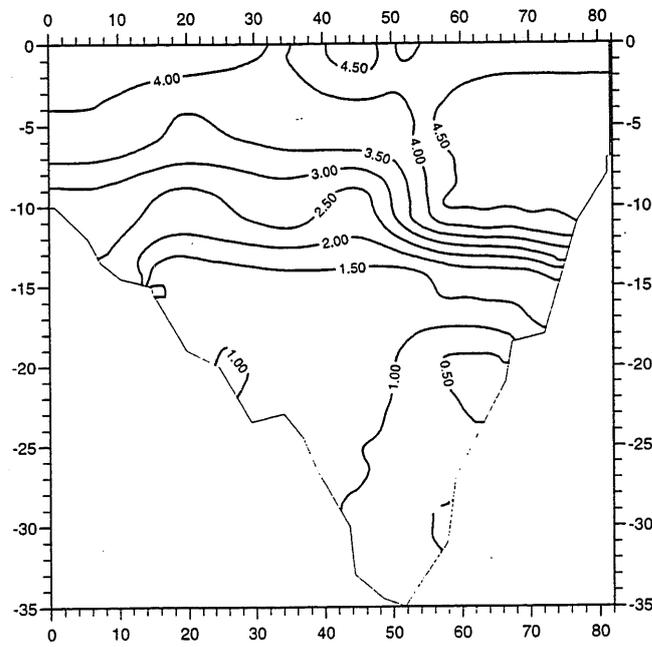**Figure 4.** Mean values of observed salinity for section B.

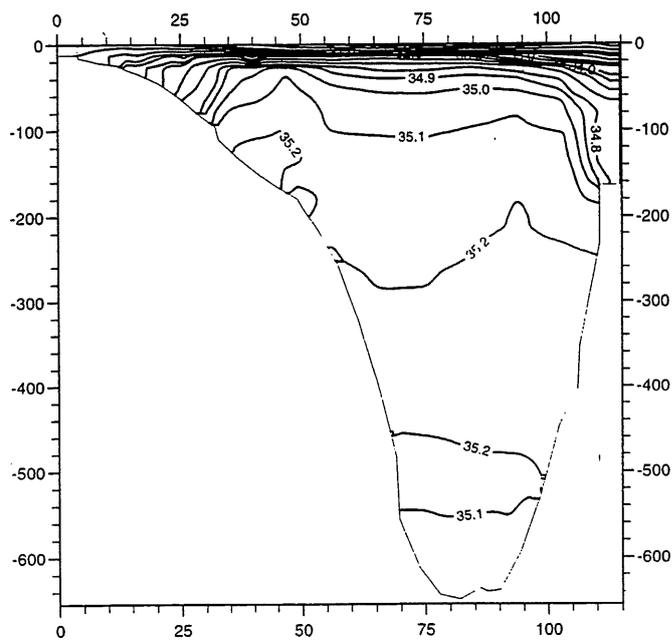**Figure 5.** Standard deviations of observed salinity for section B.
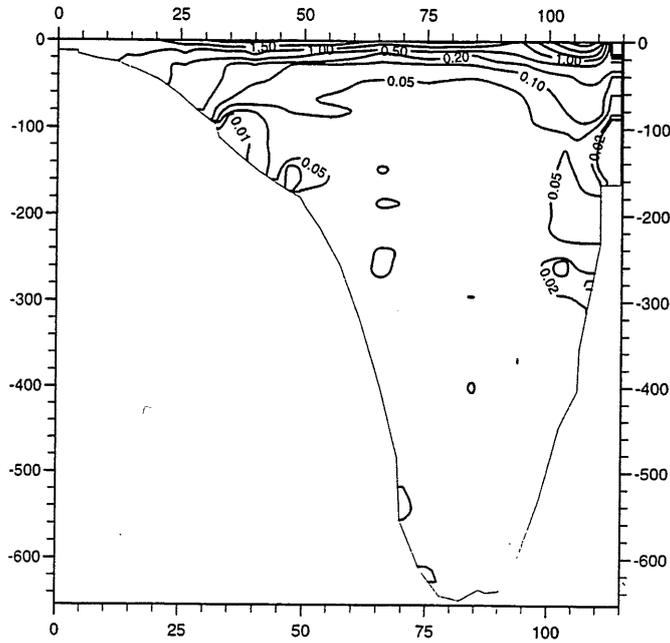

Figure 6. Mean values of observed salinity for section F.

Figure 7. Standard deviations of observed salinity for section F.
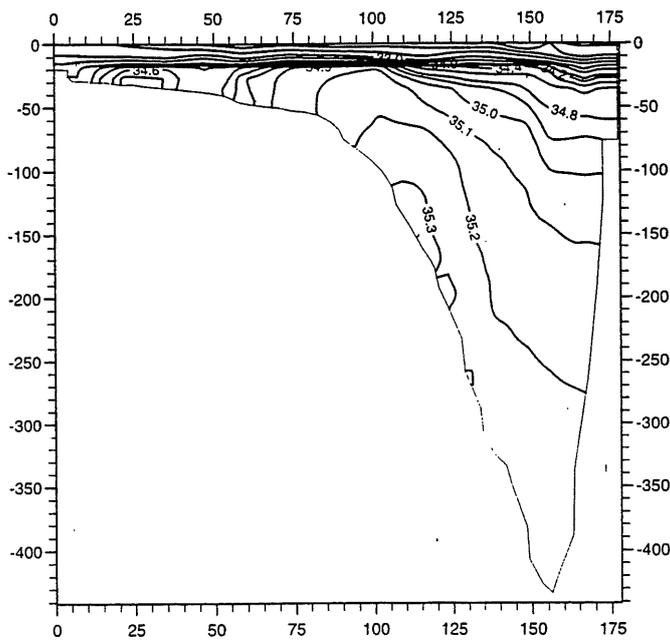

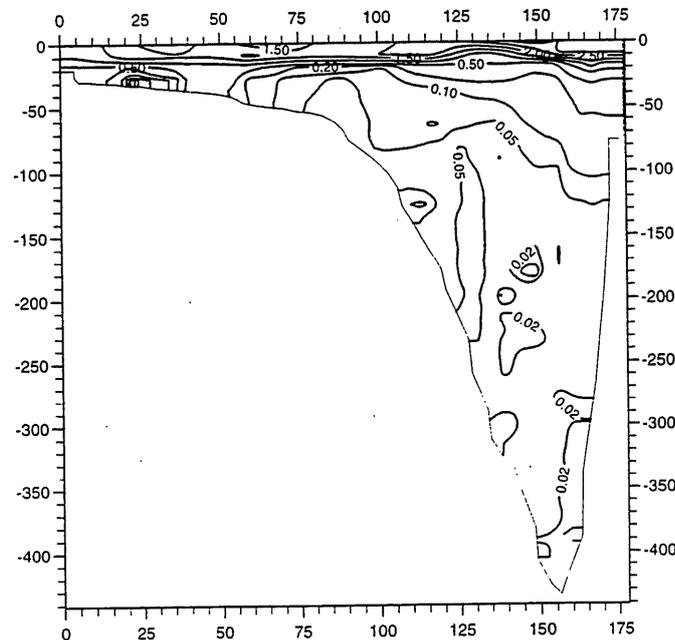**Figure 8.** Mean values of observed salinity for section H.

Figure 9.   Standard deviations of observed salinity for section H.

3.2   Numerical experiments.

In the numerical experiments we focus on the models ability to reproduce the observed fields and its sensitivity to the model parameters C_M, C_H and K_{MIN2} described in section 2.

Table 1 summarizes the parameter values used in different runs. In RUN-1 the parameter settings are as in the public domain version of the Blumberg and Mellor code. Too small values of the vertical eddy diffusivity K_{MIN2} in the upper ocean may cause instabilities. In Skagerrak we have also seen that with small values of K_{MIN2}, heavy water is generated during upwelling, which sinks out and fills up the deeper parts of Skagerrak. We have therefore tried to apply different values of K_{MIN2} in different parts of the water column: one value in the upper 5 meters, one value at the interface to the bottom layer and one value in the remaining water column.

In tables 2, 3 and 4 the area averages for transects B, F and H of mean salinity and standard deviations are presented together with area averages of the discrep-

ancies $D_{\overline{S}}$ and D_{SD}. The model transports into and out of Skagerrak/Kattegat through each transect are computed from time averaged velocity fields based on sampling of model velocities each hour. The remaining measures presented in tables and figures are computed from the average salinity and temperature fields based on sampling of instantaneous model fields at the times of the observations. The average model salinities $\overline{S}$ and the model geostrophic currents and transports are little affected by the sampling strategy.

Parameter	RUN-1	RUN-2	RUN-3
C_M	0.1	0.1	0.05
C_H	0.1	0.1	0.005
K_{MIN1}	2E-5	2E-5	2E-5
K_{MIN2}, $-5m \leq z \leq 0m$	2E-5	1E-3	1E-3
K_{MIN2}, bottom layer interface	2E-5	1E-3	1E-3
K_{MIN2}, remaining water column	2E-5	1E-7	1E-7

Table 1. Values of model parameters.

Measure	Data	RUN-1	RUN-2	RUN-3
$\overline{S}_{aver}$	26.97	31.03	31.49	29.31
$S_{SD-aver}$	2.69	0.84	0.81	2.13
$D_{\overline{S}-aver}$	*	1.58	1.52	0.93
$D_{S_{SD}-aver}$	*	2.86	4.30	0.83
Model transport-out	*	0.034	0.035	0.035
Model transport-in	*	0.021	0.023	0.020
Geostrophic transport-out	0.015	0.065	0.057	0.042
Geostrophic transport-in	0.020	0.001	0.003	0.033

Table 2. Measures transect B.

Measure	Data	RUN-1	RUN-2	RUN-3
$\overline{S}_{aver}$	34.56	35.07	34.71	34.91
$S_{SD-aver}$	0.15	0.19	0.12	0.25
$D_{\overline{S}-aver}$	*	12.90	6.61	10.15
$D_{S_{SD}-aver}$	*	1.12	1.07	1.29
Model transport-out	*	3.072	2.661	2.716
Model transport-in	*	3.031	2.628	2.677
Geostrophic transport-out	0.899	0.882	1.208	1.419
Geostrophic transport-in	0.399	0.734	0.370	0.894

Table 3. Measures transect F.

Measure	Data	RUN-1	RUN-2	RUN-3
$\overline{S}_{aver}$	34.59	34.66	34.62	34.69
$S_{SD-aver}$	0.33	0.24	0.19	0.39
$D_{\overline{S}-aver}$	*	5.74	7.60	4.87
$D_{S_{SD}-aver}$	*	1.51	1.30	2.13
Model transport-out	*	1.779	1.721	2.042
Model transport-in	*	1.750	1.696	2.011
Geostrophic transport-out	0.639	3.238	3.038	2.659
Geostrophic transport-in	0.255	0.087	0.086	0.125

Table 4. Measures transect H.

3.2.1 Results for RUN-1.

The average model salinities for RUN-1 for sections B, F and H are plotted in figures 10 to 12. Comparing these plots with the corresponding plots for observed salinities and by studying tables 2 to 4 we find:

For transect B:
a) The model water is much too saline.
b) The horizontal gradients in model salinity are too large. This explains the large model geostrophic transport out through this section.

For transect F:

a) The salinity of the deep model water is much too high, up to almost 37.0 at the bottom.

b) The model surface water is too saline.

c) The intermediate model water is too fresh. The model 35.0 contour is typically more than 100m too deep.

d) The average model salinity is in average almost 13 standard deviations off the the observed salinity. a) above explains much of this deviation because the standard deviations are small in the bottom water.

The bottom water of section F deserves a comment. From Figure 6 we note that this water is less saline than the intermediate water masses. This bottom water is formed during cold winter conditions. This deep water is not represented in the initial values of the model and the processes generating it are not well represented in the model. Therefore, we can not expect to reproduce this observed feature.

For transect H the comments a), b) and c) for transect F qualitatively apply. The salinity of the model bottom water is almost 36.0. In the model salinity the horizontal gradients are too large, giving an unrealistic strong geostrophic current along the Norwegian coast. On the other hand transports computed from the model average velocities are of the correct order of magnitude (Table 4), and the vertical separation of the inflowing and outflowing water masses (Fig. 13) seems realistic according to Svendsen *et. al.* (1995). The geostrophic currents computed from the measured and modelled density fields are shown in figures 14 and 15 respectively. Due to a large barotropic current component on the Danish side, the velocity distributions are not comparable here. On the Norwegian side the model gives near zero bottom velocities and therefore a direct comparison with the geostrophic calculations is suitable. As expected, the modelled velocities compares well with the geostrophic calculations from the modelled density field (Fig. 13 and 15). However, the geostrophic calculations from the data (Fig. 14) gives at least 10 cm/s weaker velocities over large areas of the outflowing water. In deep water as here, this indicates that the model significantly overestimates the transport out of (and therefore also into) the Skagerrak.

3.2.2   Results for RUN-2.

The numerical model applies the leapfrog scheme for advection both horizontally and vertically, and it is well known that this scheme is non-monotonic. Especially we have seen that during upwelling heavy model water is generated in the bottom cells near the coast. This water sinks out and fills up Skagerrak. Connected to sharp gradients in salinity near the surface stability problems may arise. In RUN-2 we have therefore increased the minimum value of the vertical diffusivity

constant near the bottom and in the upper 5m of the surface layer. The minimum allowed vertical diffusivity is 10^{-7} in the intermediate waters.

These changes had little effect on the shallow northern Kattegat (Fig. 16). However, from figures 17 and 18 we note that the increased minimum vertical diffusivities stops the generation of heavy water efficiently. On the other hand the mixing is too great. Max salinity of bottom water is now slightly above 35.1. Performing this experiment without the reduction of K_{MIN2} to 10^{-7} in intermediate waters had little effect on the average model fields.

3.2.3 Results for RUN-3.

In order to study the effect of varying the horizontal viscosity and diffusivity constants C_M and C_H, experiments with several combinations are performed. Here the results for the minimum values tried are presented. That is $C_M = 0.05$ and $C_H = 0.005$. The reduction of C_M and C_H had a significant effect on the model results. From figures 19 to 21 we note that the vertical stratification has improved significantly. For section B we note a clear reduction of average model salinity towards the average data salinity and 20.0 water is appearing at the Swedish coast. The structure is also becoming more horizontal in accordance with the structure in the data. On the other hand very saline water has appeared near the deepest part of the transect. For section F the vertical stratification has also improved . On the other hand heavy water, up to 36.1 in salinity, has again appeared at the bottom and the error measured in the norm $D_{\overline{S}-aver}$ is therefore larger than in RUN-2. For section H we also note an improvement in vertical structure and heavy water at the bottom. For this section the error measured in $D_{\overline{S}-aver}$ has improved.

Values of C_M and C_H between the selections of RUN-2 and RUN-3 give average fields that are 'between' the fields produced in these runs. We have not tried to locate a selection of parameters that minimize our error measures. The focus is on demonstrating the effects of varying the parameters. A further reduction of C_M and C_H will cause numerical instabilities. To apply $(C_M, C_H) = (0.05, 0.005)$ with the default values $K_{MIN1} = K_{MIN2} = 2 * 10^{-5}$ will also cause numerical instabilities.
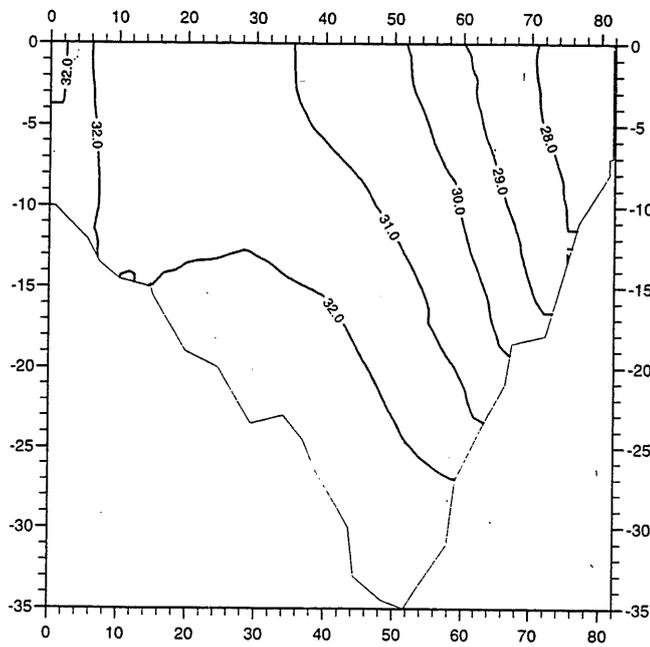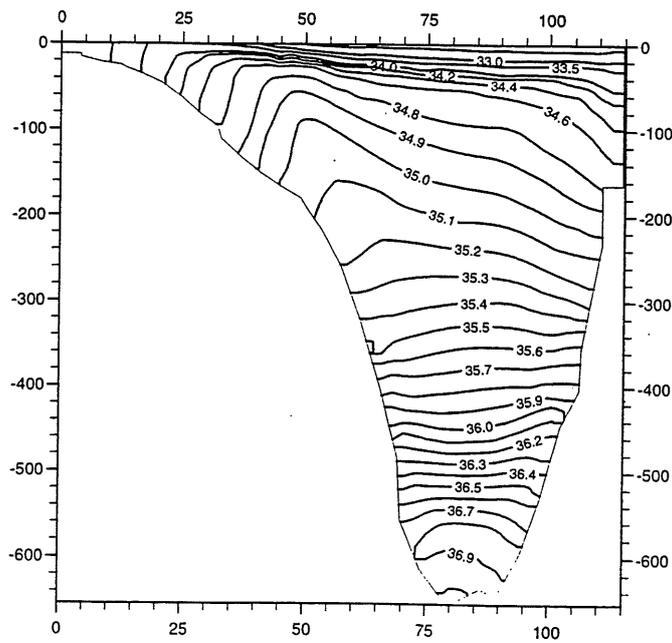
Figure 10. Model salinity for section B (RUN-1).

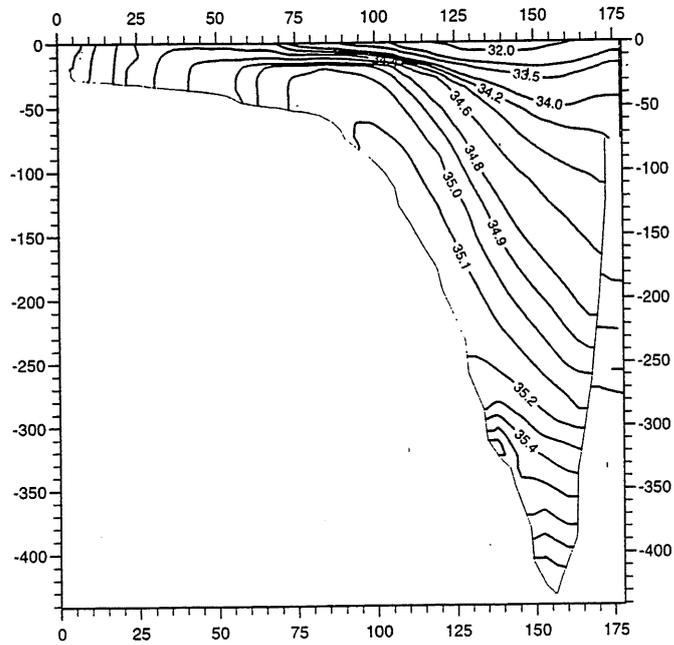

Figure 11. Model salinity for section F (RUN-1).

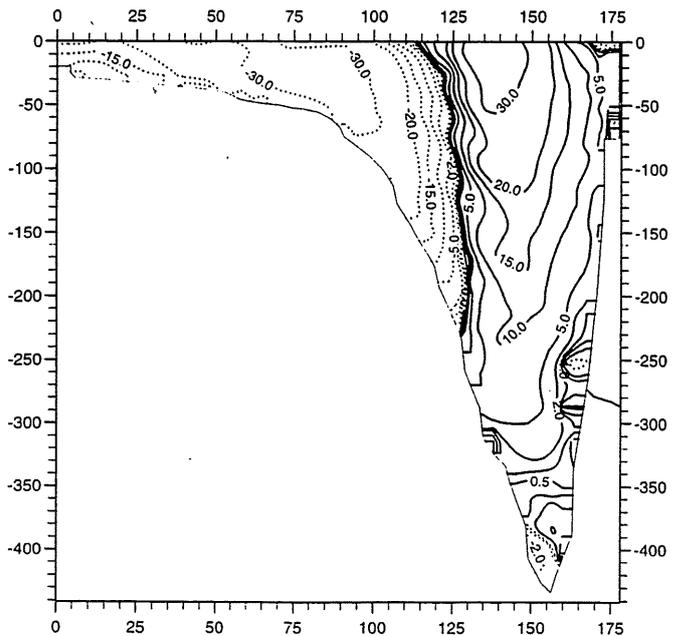**Figure 12.** Model salinity for section H (RUN-1).

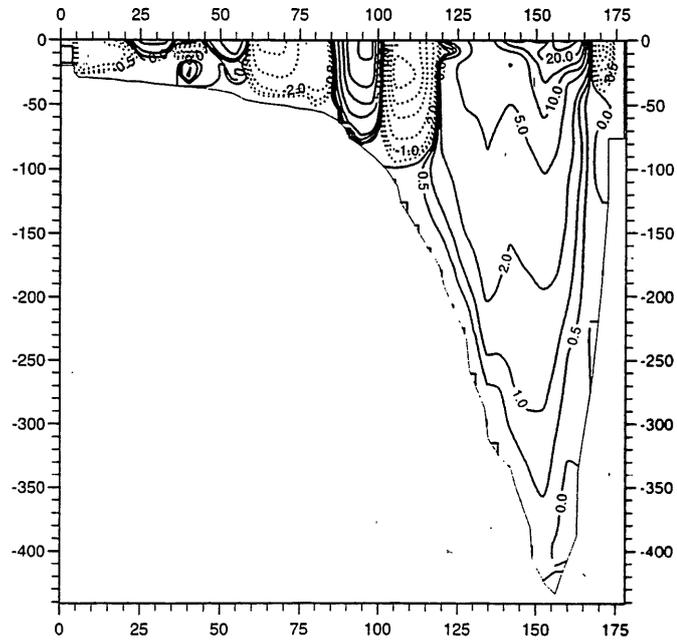**Figure 13.** Model velocities through section H (RUN-1).

Figure 14. Geostrophic currents through section H computed from the observed density field.
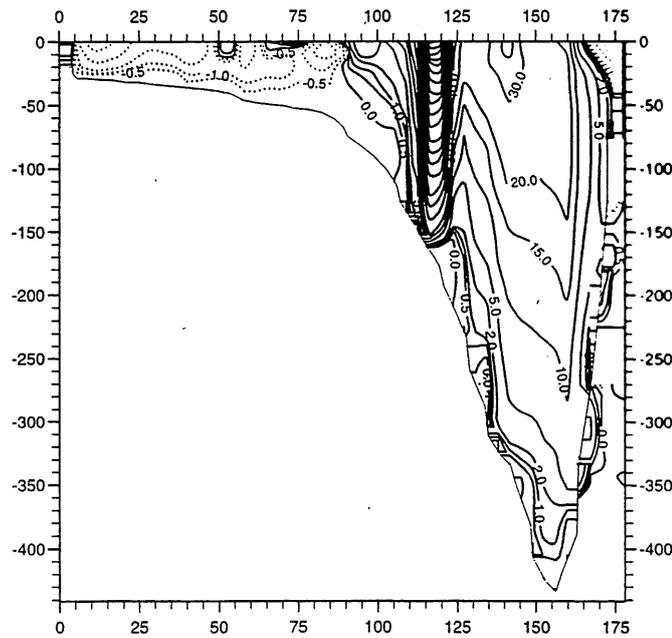
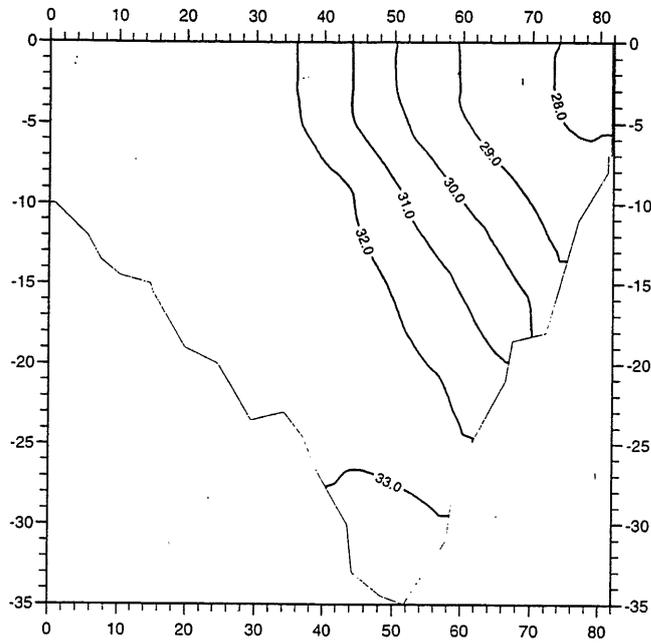**Figure 15.** Geostrophic currents through section H computed from the model density field of RUN-1.

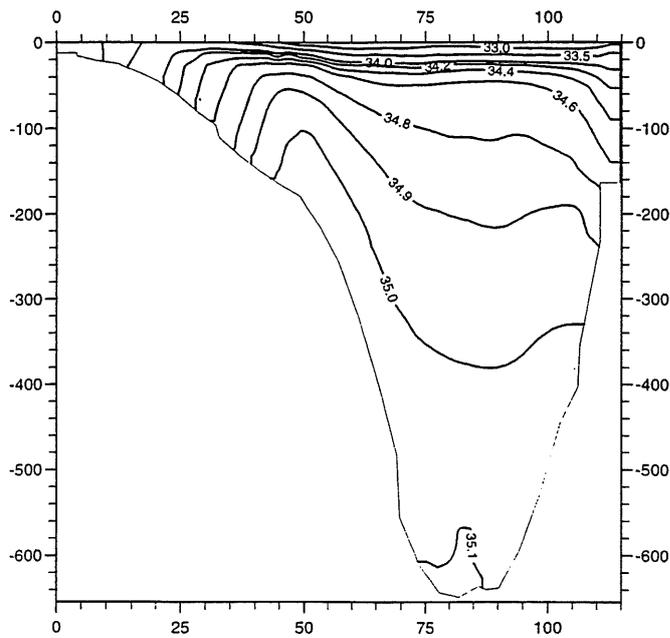**Figure 16.** Model salinity for section B (RUN-2).

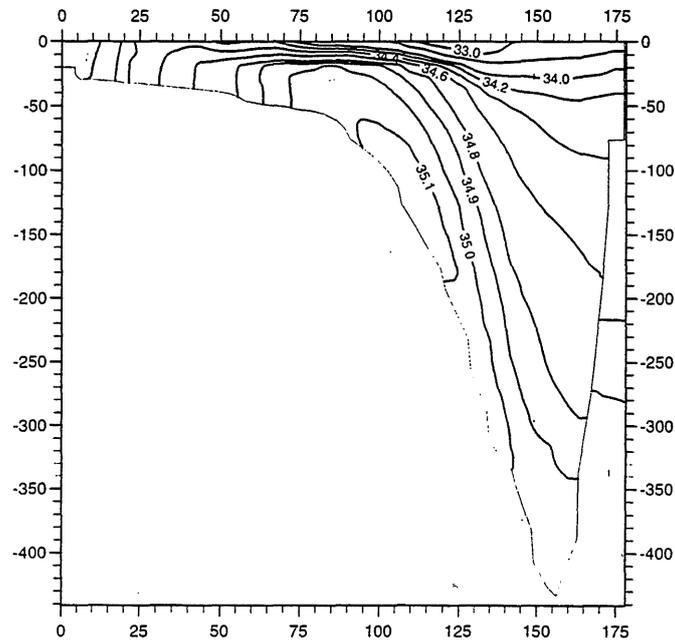**Figure 17.** Model salinity for section F (RUN-2).

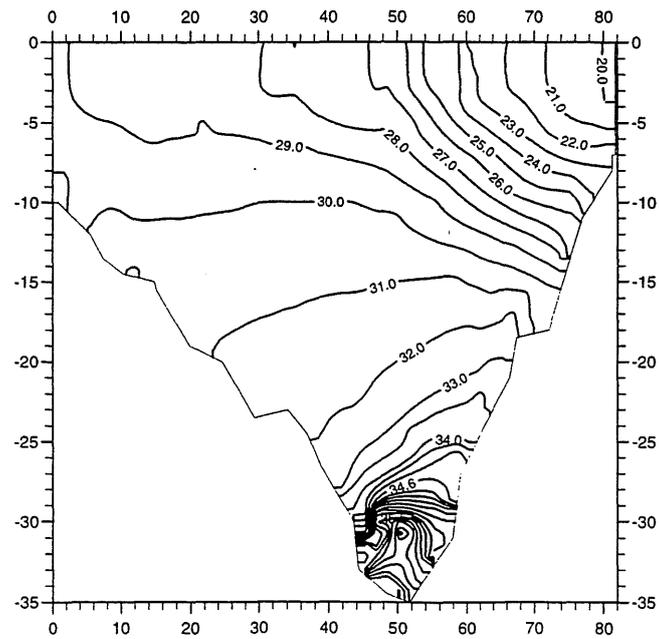**Figure 18.** Model salinity for section H (RUN-2).

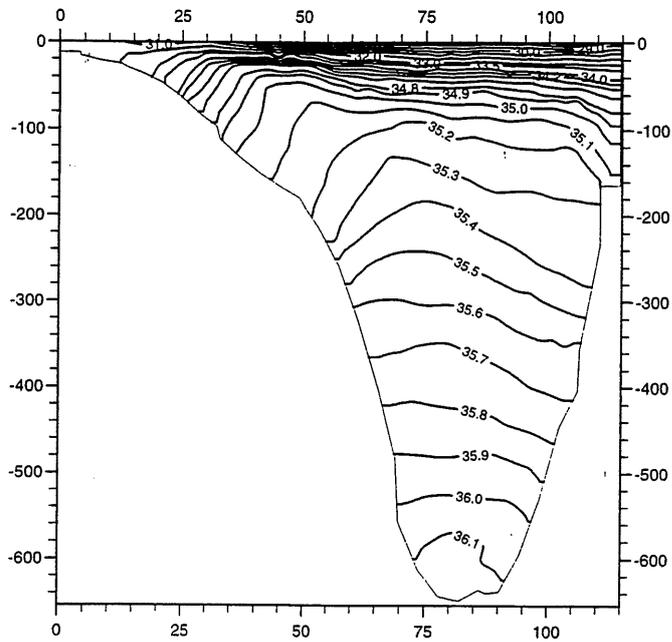**Figure 19.** Model salinity for section B (RUN-3).

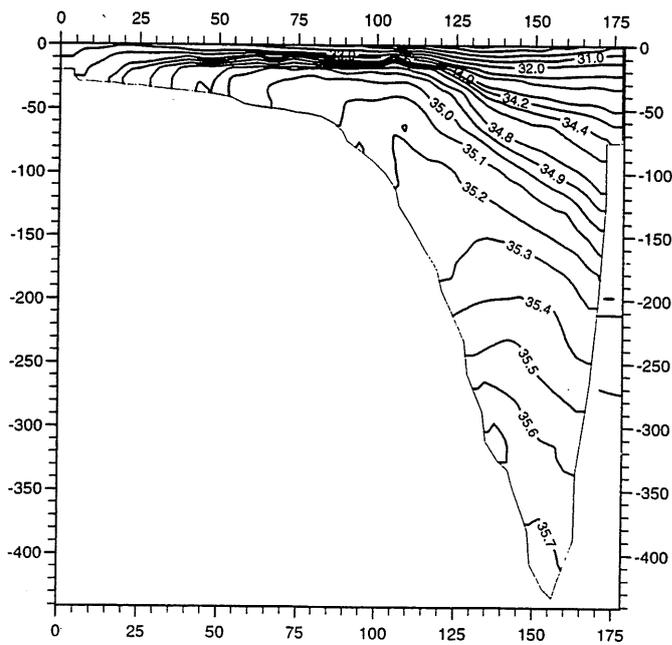**Figure 20.** Model salinity for section F (RUN-3).

Figure 21. Model salinity for section H (RUN-3).

Chapter 4

Conclusions.

Numerical ocean models are now being applied in numerous oceanographic studies. The qualities of the model results are, however, often uncertain and there is a clear need for procedures and standards for model evaluation.

Currents show great variability in space and time. The uncertainties in estimates of average transports based on measured currents will therefore typically be very large (especially in deep waters) and often of the same order of magnitude as the transports themselves. It will therefore be relatively easy to produce model transports that are within the uncertainties of the 'observed' transports, but it will be difficult to quantify the accuracy of individual model results.

The variability in the density field, especially the salinity field, is typically much smaller, and such data are much more available than current measurements. Since it is difficult to produce model fields of salinity and temperature that are within the uncertainties/variability set up by nature, "correct" scalar model fields will be an indication on correct treatment of advective and diffusive processes in the model. Conversely: Correct density gradients are necessary to get the internal pressure and the currents correct. Therefore validation of model fields against temperature and salinity data can be more accurate than validation against uncertain transport estimates.

In this paper we have tried to validate a numerical ocean model using data from hydrographical stations taken repeatedly across Skagerrak in the spring/summer 1990. Average values of the measured fields are compared to corresponding values produced from model results. The qualities of the model results are related to the standard deviations in the observed fields. The integrated effect of errors in the density fields on the currents is studied by computing the geostrophic currents.

We find that the model salinity and density fields are very sensitive to parameters in the model that define the vertical and horizontal viscosity and diffusivity.

Averaged over the area of the transects the model time average salinity deviates from 0.93 (section B) to 12.90 (section F) standard deviations from the observed time averages.

Using large horizontal diffusivities we do not obtain the observed vertical structure of the salinity field at the opening of Kattegat towards Skagerrak (section B). In the model fields the horizontal gradients are much larger causing a density driven geostrophic current component out of Kattegat that is not in accordance with the observations of this period. The area average salinity is also much too high. By reducing the horizontal diffusivity the salinity fields drastically improves in most of the area. On the other hand much too heavy model water is appearing at the deepest part of the transect.

In the central Skagerrak (section F) the model salinity field becomes much too saline in the deeper parts. This heavy water is created in parts of Skagerrak where saline Atlantic water meets fresher water masses. The leapfrog advection scheme being used is not monotonic and the heavy water that is produced near such fronts sinks out and fills up Skagerrak. Using larger vertical diffusivity near the bottom and near the surface the generation of artificial saline water is avoided. However, the price to be paid is too little vertical stratification. Reducing the horizontal diffusivity improves the vertical structure considerably at the cost of introducing more heavy water masses near the bottom.

The fields at the opening of Skagerrak (section H) are least affected by changes in the model parameters. However, for all values tried, the fresh water is too mixed vertically near the coast of Norway causing a very strong geostrophic current out of Skagerrak.

The model average transports through all sections do not vary much with changes in the parameters. Comparisons with drifters and data from current meters (Svendsen *et. al.*, 1995) also indicate that the transports are of correct order of magnitude, but somewhat too high. The too large horizontal gradients in the density field at section H gives a false modelled velocity distribution in the vertical. This seems to give too high velocities especially in the intermediate outflowing watermasses which probably leads to an overestimate of the total transports in and out of the Skagerrak.

The internal Rossby radius in Skagerrak is typically 5-10km. It may therefore be argued that the present resolution (4km horizontally and 11 layers vertically) is not enough to resolve the major processes of the area. However, the model results produced when using small horizontal diffusivities indicate that given a non-oscillatory gradient preserving advection scheme, model fields in much better agreement with observed fields could have been produced.

The ocean model is due to Blumberg and Mellor (1987). The model have been used in numerous oceanographic studies, and a public version is available. The model performed favorably in a recent model intercomparison (Røed *et. al.*, 1989) and has been run operationally by the Norwegian Meteorological Institute. In the present study we have used a technique based on comparisons with time averages of salinity and temperature to reveal the properties of the model and to gain insight in which parts of the model that should be improved. When comparing the model results and the observed fields, it must be kept in mind that Skagerrak is a very complex system with strongly varying topography and sharp gradients in the density field and also an area where a number of water masses are mixed. The model results are also dependent on the initial values, the boundary conditions and the forcing applied. So even if the deviations between the observed fields and results produced by the present model may seem large, it is far from obvious that competing models would have performed better. It is also believed that the horizontal transports are reasonable. To use the model in studies where the vertical processes are more important for instance primary production is more dubious because the vertical mixing is strongly affected be the model parameters. In these cases care must be used when selecting these parameters.

Acknowledgements.

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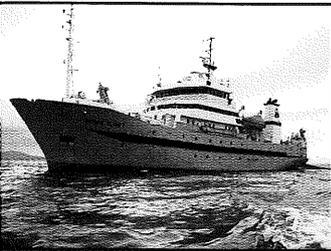
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