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MILJØ - RESSURS - HAVBRUK

Nordnesparken 2 Postboks 1870 5024 Bergen
Tlf.: 55 23 85 00 Faks: 55 23 85 31

Forskningsstasjonen	Austevoll	Matre
Flødevigen	Havbruksstasjon	Havbruksstasjon
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DESCRIPTION AND VALIDATION OF A THREE-DIMENSIONAL NUMERICAL MODEL OF THE NORDIC AND BARENTS SEAS

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Lars Asplin, Randi Ingvaldsen,
Harald Loeng og Bjørn Ådlandsvik

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As a part of the VEINS project, IMR carries out both a numerical model study of the seasonal and interannual variability of the flow through the Barents Sea and an observational programme at the Bear Island-Fugløya section. A numerical simulation with realistic wind forcing covering the period November 1996 to April 1998 has been performed, and the results of this simulation are compared to observations.
The numerical ocean model results are generally in reasonable agreement with the observations, and the simulated transports across the Bear Island-Fugløya section are in accordance with previous knowledge. A weakness of the present version of the model is the lack of ice modelling, and the model performance in areas of ice formation and strong thermodynamical forcing is unsatisfying. However, after a scheduled inclusion of an ice model, the model performance is expected to improve significantly in the Barents Sea.

Emneord - norsk:
1. Barentshavet
2. Transport
3. Numeriske simuleringer

Emneord - engelsk:
1. Barents Sea
2. Transport
3. Numerical simulations

Harald Loeng
....
Prosjektleder

Einar Svendsen
....
Seksjonsleder

1. Introduction

The VEINS-project (MAS3-CT96-0070) is funded by the Commission of the European Union under the MAST III Programme. It started in February 1997 and will last until July 2000. The field work, modelling activities and analysis are carried out by 18 institutions from nine European countries The overall objective of VEINS is to measure and to model the variability of the fluxes between the Arctic Ocean and the Atlantic Ocean with a view on implementing a long term system of critical measurements needed to understand the high-latitude oceans steering role in decadal climate variability.

The Institute of Marine Research (IMR) is participating in the VEINS program with responsibilities in the Workpackage 1.2; North-Eastern Boundaries. This includes field measurements of hydrography at the sections Svinøy-NW, Gimsøy-NW and between Norway and Spitsbergen. In the Bear Island-Fugløya section, also currents are measured. In addition to the field programme, IMR is responsible for a regional numerical modelling component. The seasonal and interannual variability of the flow through the Barents Sea, including the effects of local wind forcing and sea ice (and brine drainage), will be the objective of the modelling component. The Barents Sea is of special climate relevance because a large amount of heat is lost from the inflowing Atlantic water to the atmosphere. This, as well as the brine drainage due to net freezing, determine the hydrographic properties of an important inflow into the Arctic Ocean. The volume of Atlantic water entering the Arctic Ocean through the Barents Sea is estimated to be approximately 2 Sv (Blindheim, 1989; Loeng *et al.*, 1997). This amount of Atlantic water inflow to the Arctic Ocean through the Barents Sea is comparable to the inflow west of Spitsbergen (Rudels, 1987), a fact emphasizing the importance of the Barents Sea. Another important outflow from the Barents Sea is the flow of Barents Sea bottom water through the Bear Island Channel into the Norwegian Sea giving a substantial contribution to the intermediate water there (Blindheim, 1989).

The present report is the first contribution from the numerical component of Workpackage 1.2. The report mainly represents a description of the numerical model tool to be used and how it is planned to be validated against observations. A brief comparison of numerical model results and observations at the Bear Island-Fugløya section is included. Finally, the report contains some concluding remarks on the future work and planned improvements of the model.

2. Materials and methods

2.1. Observations

IMR performs routinely hydrographic mapping of several standard sections in The Nordic Seas and the Barents Sea. The Bear Island-Fugløya section (Figure 1) is frequently occupied with 6 samplings per year since 1977. The hydrographic data to be presented from this section were collected at two cruises, in August 1997 and March 1998.

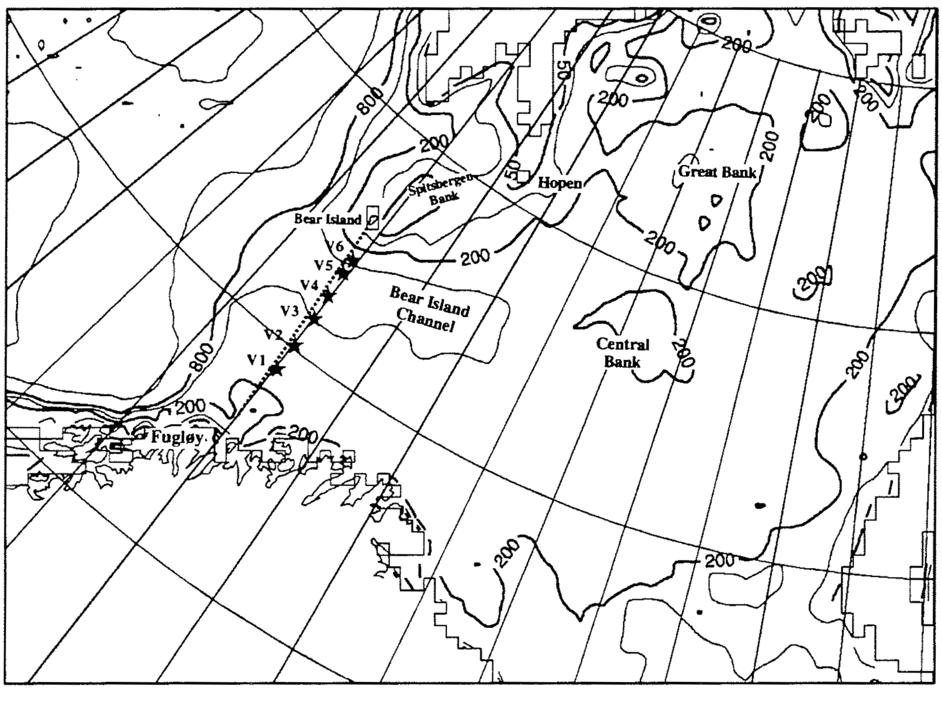


Figure 1. Map of the Barents Sea, including the positions of the current meter moorings VEINS1 to VEINS6 and the Bear Island-Fugløya section (dashed line).

As part of the VEINS programme, IMR deployed 6 current meter moorings (VEINS1 - VEINS6) in the Bear Island-Fugløya section in August-September 1997 (Figure 1). This was the initiation of the long-term current observation programme of VEINS in the Barents Sea, a programme IMR will continue to August 1999. The data available for comparison with the numerical model results, were collected in the period August 1997 to March 1998. Three or four current meters (Aanderaa RCM7) were deployed at each mooring. The three uppermost current meters at the moorings were deployed at the depths of approximately 50 m, 125 m and 225 m, while the lower meters were deployed 15 m above the bottom.

2.2. The numerical model

The numerical model used is the Princeton Ocean Model (POM) developed by Blumberg and Mellor (1987) with modifications done at The Norwegian Meteorological Institute (DNMI) and IMR. POM is a three-dimensional baroclinic ocean model, with the surface elevation, three components of velocity, salinity, and temperature as the main model variables. In addition to the initial and boundary conditions of the model variables, the model forcing may include wind stress, air pressure gradients, atmospheric heat exchange, tidal forcing, and river runoff.

The model solves the primitive equations numerically using finite differences techniques. In the vertical, bottom following σ-coordinates are used. The model uses mode splitting between the external gravity wave mode and the internal baroclinic modes. The leapfrog technique is used to step forward in time. For vertical mixing a level 2.5 Mellor-Yamada turbulence closure scheme is used (Mellor and Yamada, 1982).

At the open boundaries, a 7 grid cell wide zone using a Flow Relaxation Scheme (FRS) (Martinsen and Engedahl, 1987) is applied. Each prognostic variable, ϕ, in the FRS-zone is simply updated by the translation $\phi = (1-\beta)\phi_{int} + \beta\phi_{ext}$, where ϕ_{int} contains the time integrated, unrelaxed values calculated from the model equations, and ϕ_{ext} is the specified external solution in the zone (i.e. the open boundary values). ϕ is the new value and β a relaxation parameter which varies from 0 at the end of the zone facing the interior model domain to 1 at the outer end of the zone (at the open boundary).

In cooperation between IMR and the Department of Fisheries and Marine Biology (IFM) at the University of Bergen, a model for nutrients and primary production has been developed and coupled to POM. This ecological model is called NORWECOM and is documented in Skogen (1993). For the present simulation experiments, this extension is not used.

2.3. The model setup

The model domain is shown in Figure 2, and covers the Nordic Seas, the Barents Sea, the North Sea, and parts of the Arctic and the North Atlantic Seas. The horizontal grid resolution is 20 km and the number of grid cells is 208 x 120. This grid size is too large to resolve mesoscale dynamics in the Barents Sea (where the internal radius of deformation is 5-10 km), thus some natural variability is lost in the numerical results. The bottom topography is compiled at DNMI from various sources. In the vertical 15 σ-levels are used with σ-coordinates: 0, -0.00025, -0.00075, -0.002, -0.005, -0.012, -0.025, -0.05, -0.1, -0.2, -0.4, -0.6, -0.8, -0.95, -1.

The initial description of sea surface elevation, currents, salinity, and temperature is taken from the DNMI-IMR diagnostic climatology (Engedahl *et al.*, 1998). At the open boundaries this is complemented by the four tidal constituents K_1, M_2, N_2, and S_2. The tidal data are compiled at DNMI on the basis of the model results from Flather (1981), Gjevik and Straume (1989) and Gjevik *et al.* (1990).

The meteorological forcing is taken from the hindcast archive of DNMI (Eide *et al.*, 1985). This consist of analysed sea-surface air pressure on a 75 km grid covering the Nordic Seas. The time resolution of the archive is six hours. The surface wind stress is derived from the air pressure by the assumption of geostrophy.

In the lack of data on heat exchange between the ocean and atmosphere, a simple approach of Cox and Bryan (1994) is used. Based on the difference between the sea surface temperature computed by the model and the climatological temperature, a heat flux is prescribed forcing the model towards the climatology on a two week time scale. This procedure gives a reasonable seasonal temperature cycle. On the other hand, it makes the surface temperature not a purely prognostic variable.

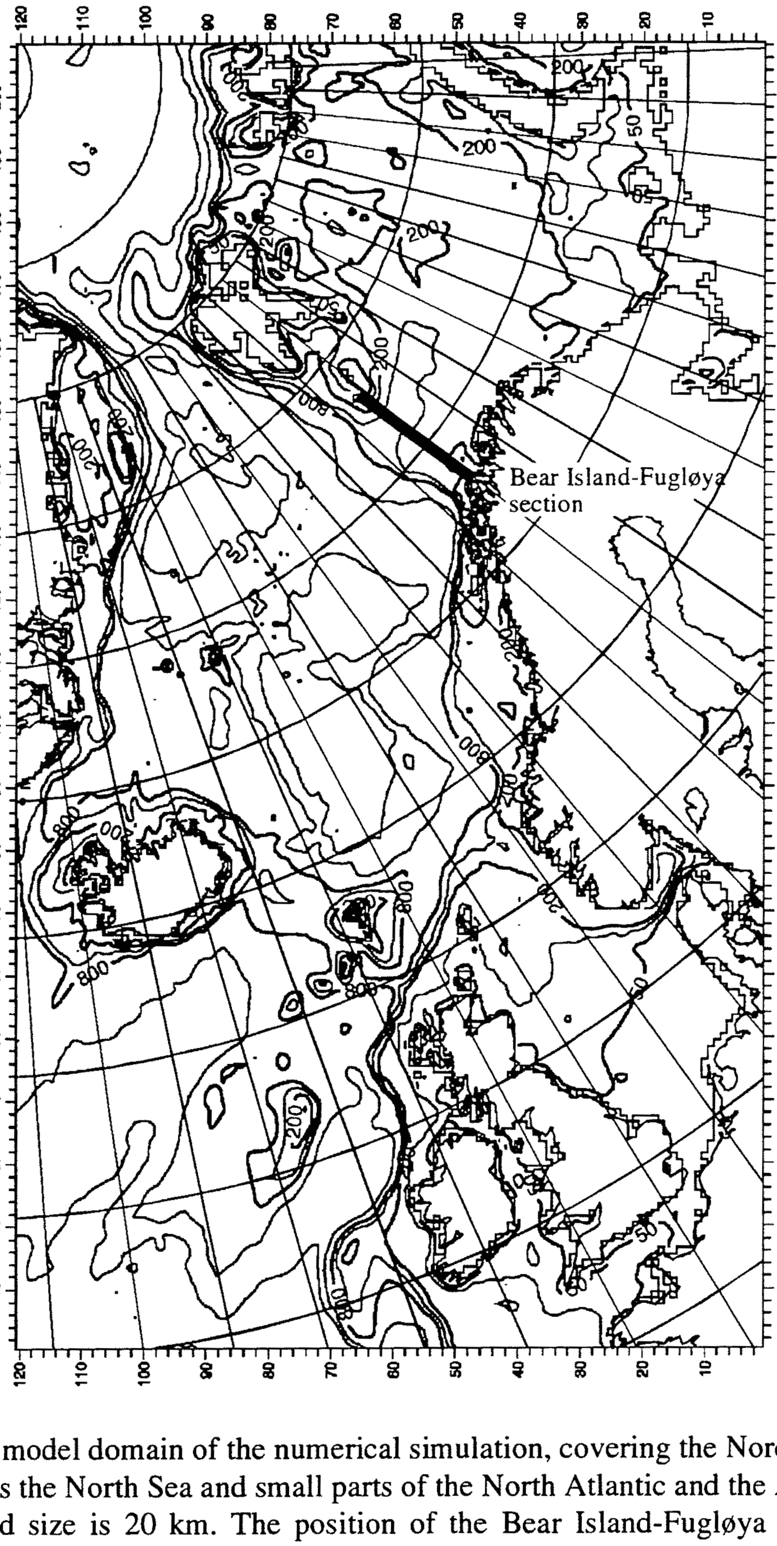


Figure 2. The model domain of the numerical simulation, covering the Nordic and Barents Seas as well as the North Sea and small parts of the North Atlantic and the Arctic Sea. The horizontal grid size is 20 km. The position of the Bear Island-Fugløya hydrographical section is indicated by the thick line.

The precipitation minus evaporation is set to zero. Rivers are included as sources for freshwater and volume. Altogether 27 Norwegian and 20 foreign rivers are included. The river discharge data are compiled on a monthly basis with a realistic seasonal cycle. For some rivers actual data for each simulation year are available, for others a climatology or a specific year has been used.

The in/outflow from the Baltic is calculated (using the algorithm of Stigebrandt, 1980) from the modelled water elevation in Kattegat and the climatological monthly mean freshwater runoff to the Baltic. The water entering Kattegat from the Baltic has throughout the year a salinity close to 8 psu.

With a grid size of 20 km and a maximum bottom depth of 4700 m, the CFL-criterion for numerical stability requires an external mode time step less than 32.8 s. Thus, the simulation uses an external mode time step of 30 s and an internal mode time step of 900 s.

October 16 1996 is the starting date of the simulation, and it lasts through April 1998. Due to the spinup of the model, the results of the first 1-2 months are uncertain. The results of the simulation includes three-dimensional fields of the currents, salinity and temperature, stored as monthly mean values. In addition, 25 hours mean values of the variables are stored once a day along several standard cross-sections, including the Bear Island-Fugløya section.

2.4. Numerical model validation

The presented numerical ocean model (POM) is a complex tool designed to predict certain aspects of the behaviour of the simulated natural system (here: the Nordic and Barents Seas) through the calculations of mathematical equations expressing appropriate physical laws. The quality of these predictions is of course of greatest interest to establish, however, this is presently a non-trivial task. There are many reasons for this, one of them is the fact that it is no general agreement on how the framework and standard procedures for such model validation should be.

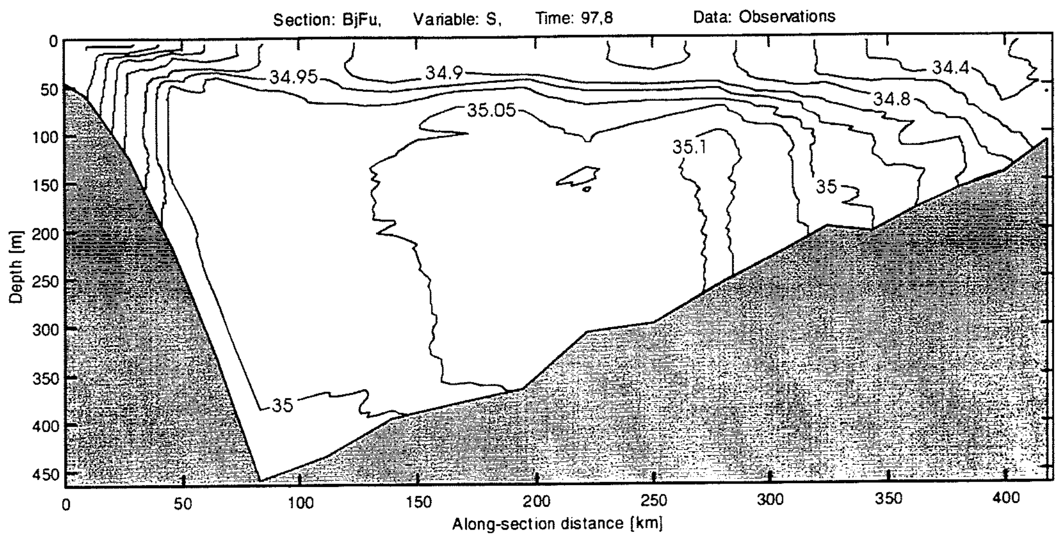
Dee (1995) describes a pragmatic approach to model validation. He propose the following definition: "Validation of a computational model is the process of formulating and substantiating explicit claims about the applicability and accuracy of computational results, with reference to the intended purpose of the model as well as to the natural system it represents". Thus, a validated model is not necessarily "correct", but it has been subject to a variety of validation activities that have produced arguments and evidence that justify the use of the model in a particular situation, and well-founded information about the expected accuracy of model predictions is provided. As to generic numerical ocean models, the model validation will be an endless ongoing process.

POM is used in many applications world wide. Thus, the validation of the model (following the approach of Dee, 1995, although without the described rigorous validation documentation) is ever-increasing. POM is widely used in the Nordic, North and Barents Seas, with large modelling communities at IMR and DNMI (e.g. Engedahl *et al.*, 1998; Skogen *et al.*, 1995, Skogen *et al.*, 1998). As to model validation, Berntsen *et al.* (1996) attempted to formulate objective criterions for the quality of the numerical results of POM. They focus on the models ability to reproduce the salinity fields, as it is generally more difficult for a model to produce salinity and temperature fields within the uncertainties and variability of the simulated natural system than current fields. The method of Berntsen *et al.* (1996) relies upon repeatedly hydrographical observations, and 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.

3. Results

3.1. Observations

The hydrographical observations at the Bear Island-Fulgøya section to be presented are taken from cruises in August 1997 and March 1998. Vertical sections of salinity and temperature from these observations are presented in Figures 3 and 4.



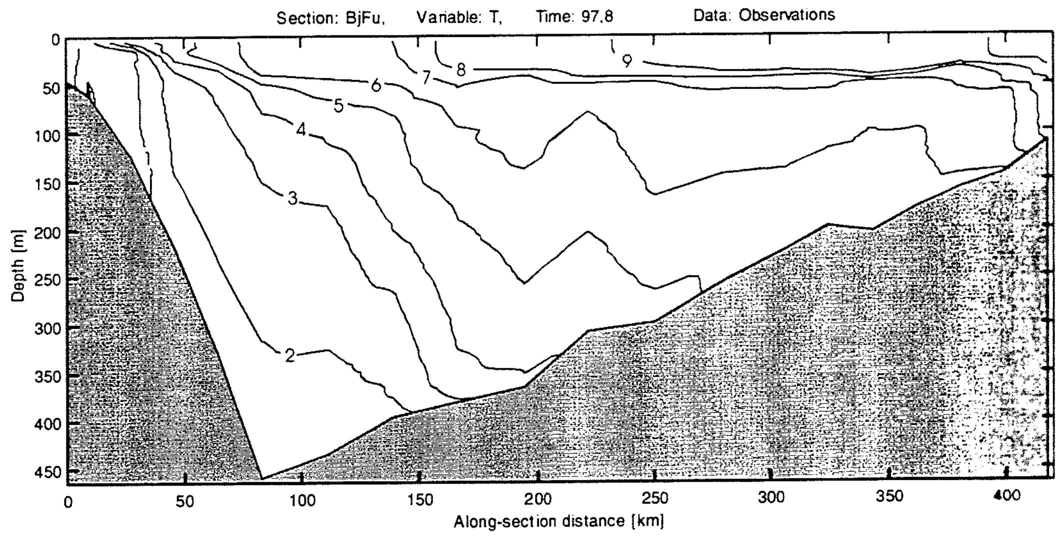


Figure 3. Vertical sections of salinity (psu, upper panel) and temperature (°C) at the Bear Island-Fugløya section as observed in the period August 21-22 1997.

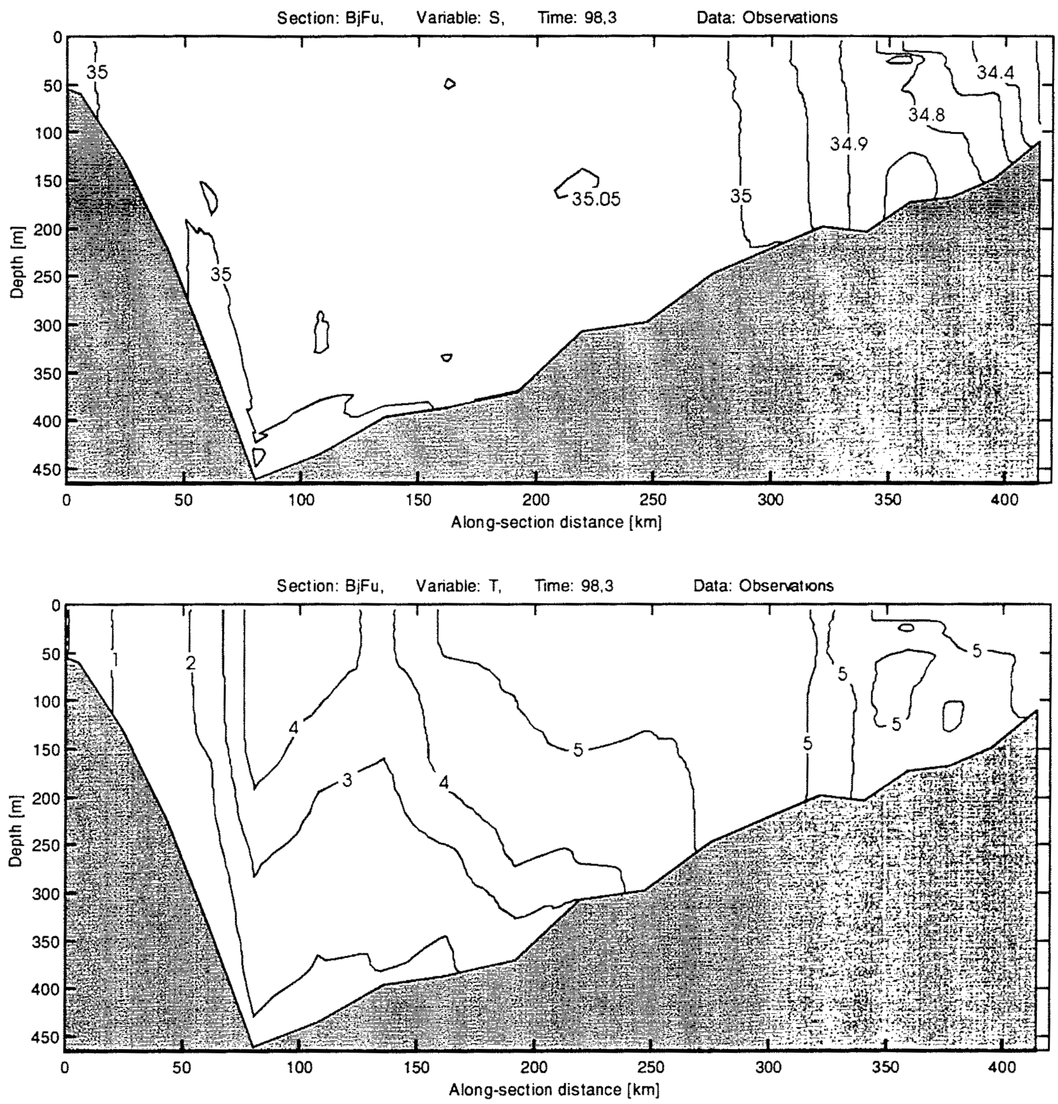


Figure 4. Vertical sections of salinity (psu, upper panel) and temperature (^{o}C) at the Bear Island-Fugløya section as observed in the period March 4-5 1998.

The current observations from mooring VEINS3 are presented in Figure 5 as vector diagrams of 30 days lowpass-filtered time series in the period August 1997 to March 1998. The observations from the other current meter moorings are presented as selected statistical values only. Table 1 shows the mean values and the range of the E-W component of the currents for the moorings VEINS1-5.

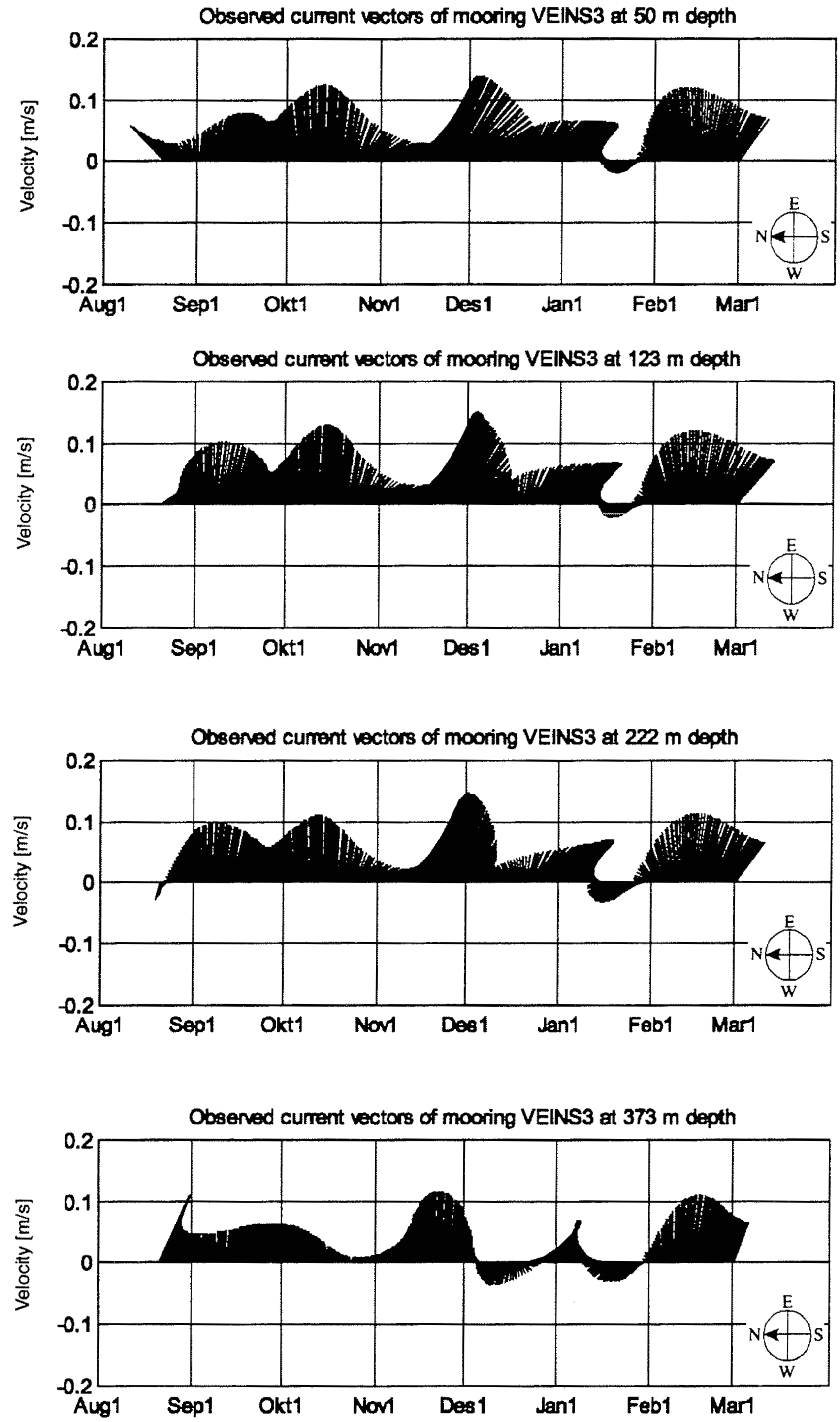


Figure 5. Time series of 30 days lowpass filtered current vectors as observed at the VEINS3 current meter mooring in the period August 1997 to March 1998.

Table 1: Statistical values of the observed velocity component (m s^{-1}) normal to the Bear Island-Fugløya section from current meter moorings at VEINS1-VEINS5.

	Max	Mean	Min	Std. dev.
VEINS1	0.263	0.026	-0.215	0.069
VEINS2	0.346	0.031	-0.187	0.079
VEINS3	0.362	0.058	-0.250	0.095
VEINS4	0.380	0.011	-0.356	0.123
VEINS5	0.363	-0.039	-0.342	0.083

Based on the current measurements, estimates of the transport (m^3 s^{-1}) through the Bear Island-Fugløy section were made. As the recordings of the VEINS6 mooring end in November, the transport estimates are made without these measurements. Thus, calculations are valid for the Bear Island-Fugløya section between 71.00° N and 73.37° N. The results should give a good estimate of the influx of Atlantic water, but the transports due to the Norwegian Coastal Current and the Bear Island current are underestimated. The values of calculated net transport, transport into the Barents Sea (positive values) and transport out of the Barents sea (negative values) are presented in Table 2.

Table 2: Calculated transport (Sverdrup) through the major part of the Bear Island-Fugløy section based on the current observations

	Sep97	Oct97	Nov97	Dec97	Jan98	Feb98	Mar98
In-flux	4.7	2.3	2.9	2.0	3.3	4.4	3.0
Out-flux	-1.1	-1.0	-0.8	-2.6	-0.6	-1.0	-1.4
Net flux	3.6	1.3	2.1	-0.6	2.7	3.4	1.6

3.2. Numerical simulation

The results of the numerical model are too extensive to be fully presented. Thus, mostly results comparable to the observations described in the previous section will be presented. However, an illustration of the large-scale situation is given in Figures 8-13. These figures show monthly mean horizontal fields for the total model domain at 10 m depth of current vectors (at every second grid node), isohalines and isoterms for August 1997 and February 1998.

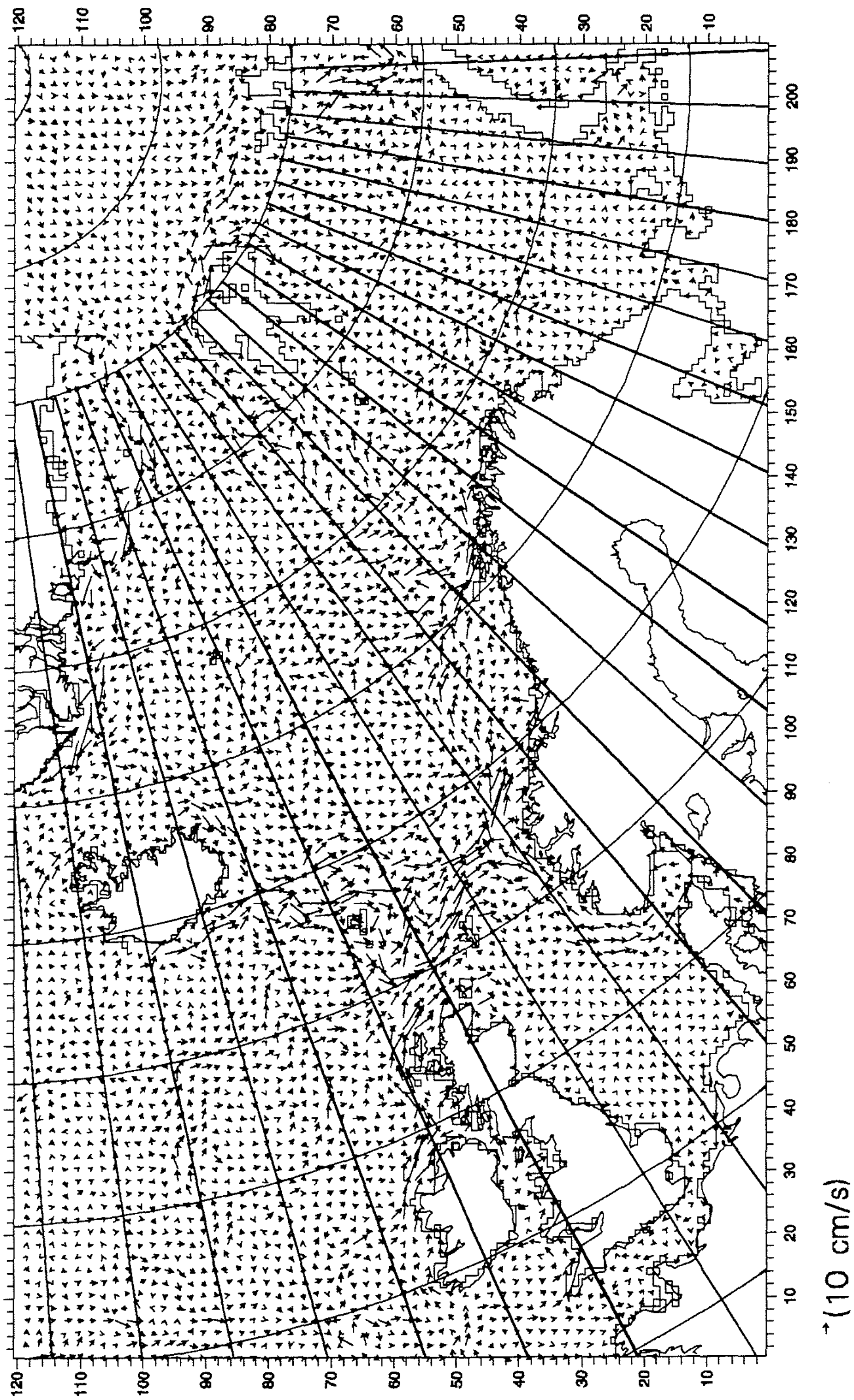


Figure 8. Current vectors showing the simulated monthly mean velocity field at 10 m depth for August 1997.

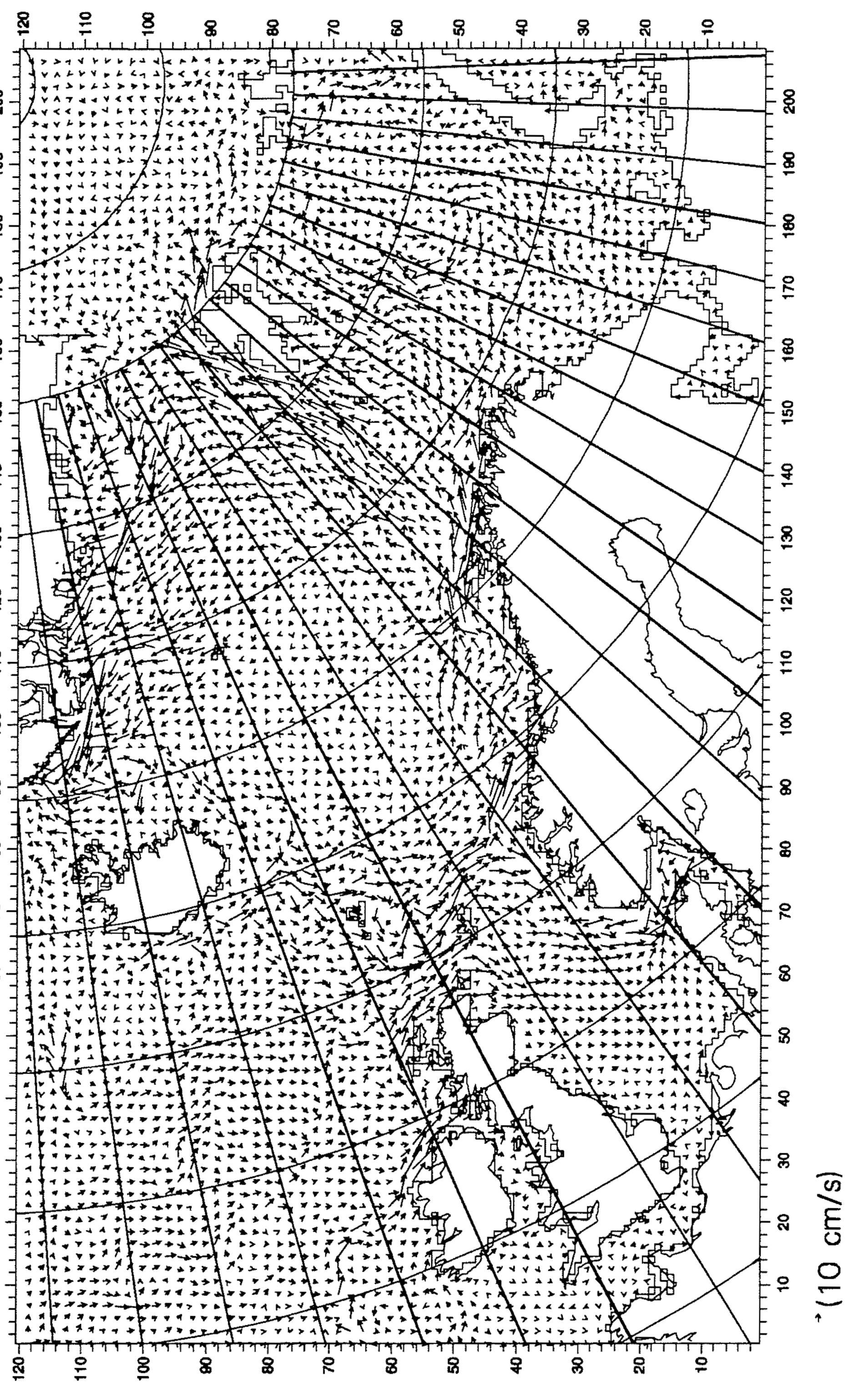


Figure 9. Current vectors showing the simulated monthly mean velocity field at 10 m depth for February 1998.

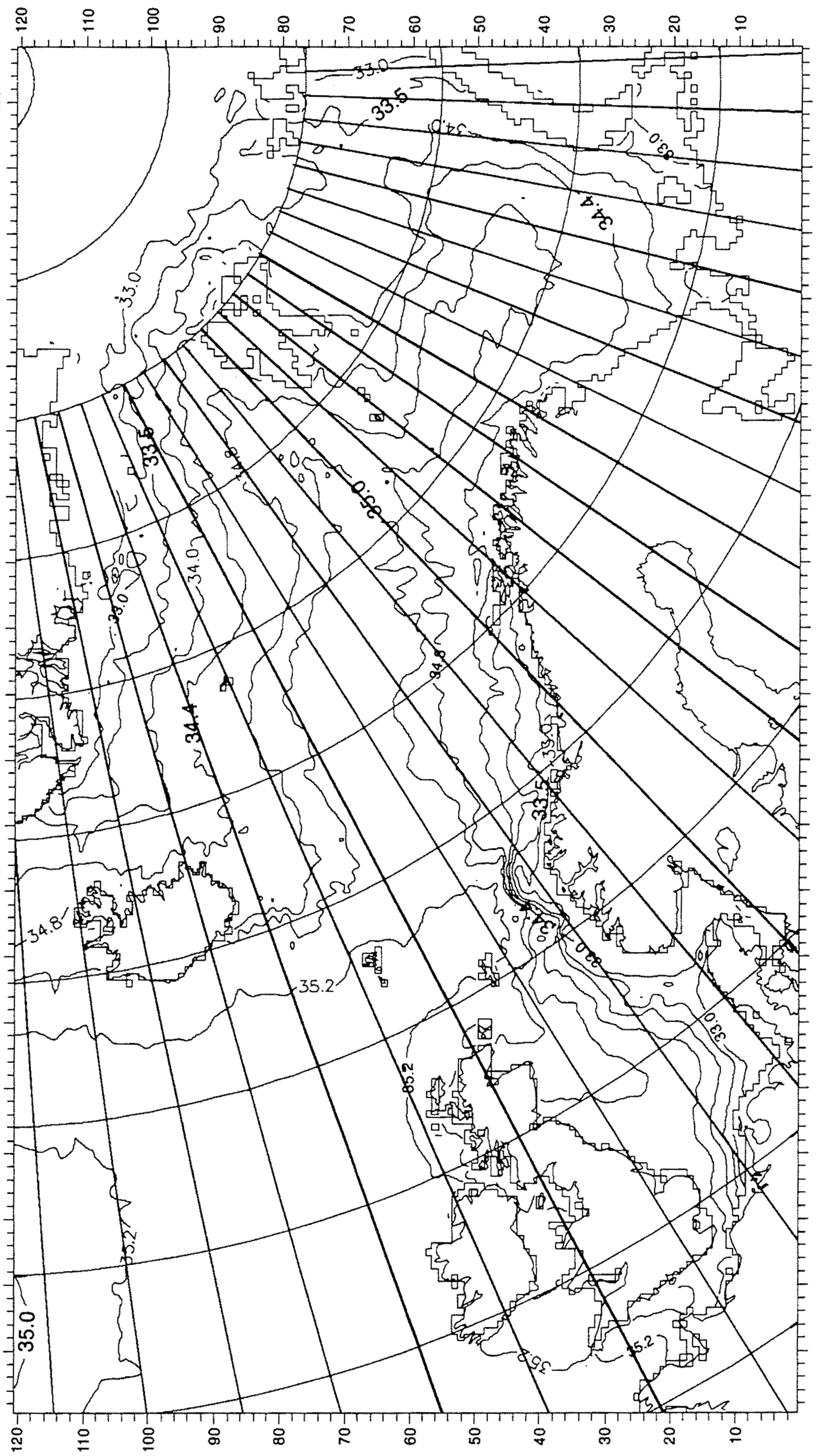


Figure 10. Isohalines showing the simulated monthly mean salinity field (psu) at 10 m depth for August 1997.

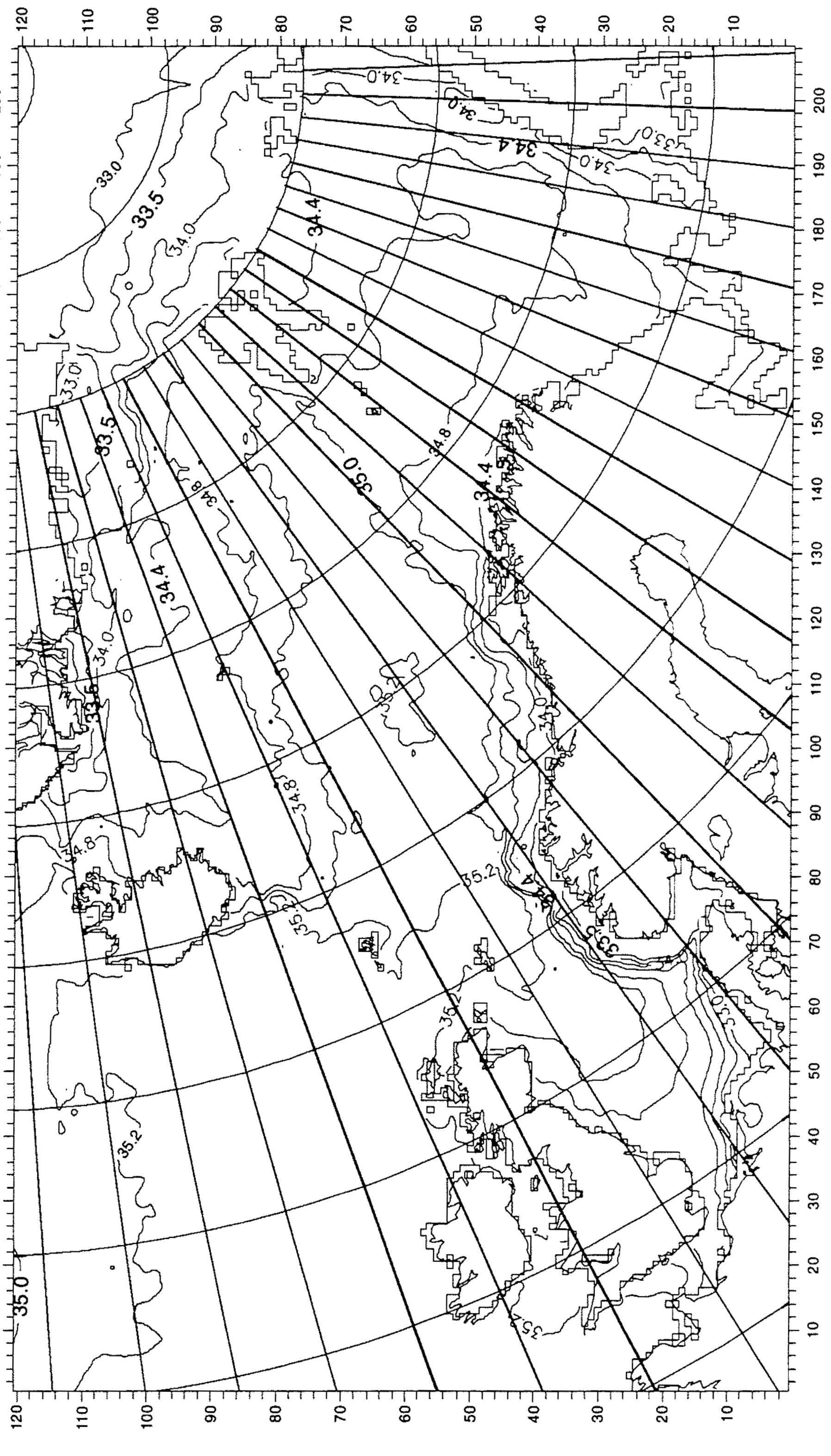


Figure 11. Isohalines showing the simulated monthly mean salinity field (psu) at 10 m depth for February 1998.

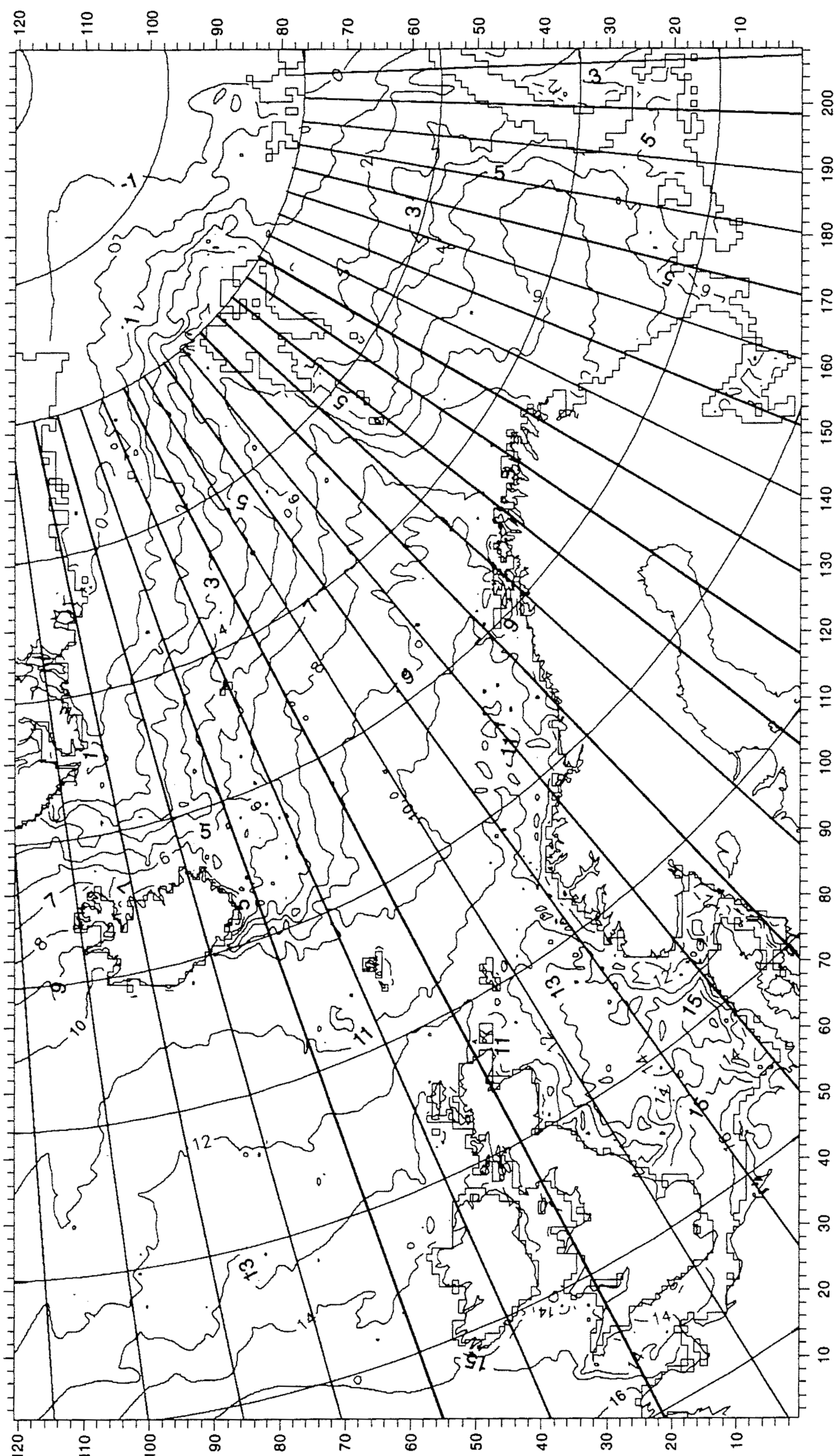


Figure 12. Isotherms showing the simulated monthly mean temperature field (°C) at 10 m depth for August 1997.

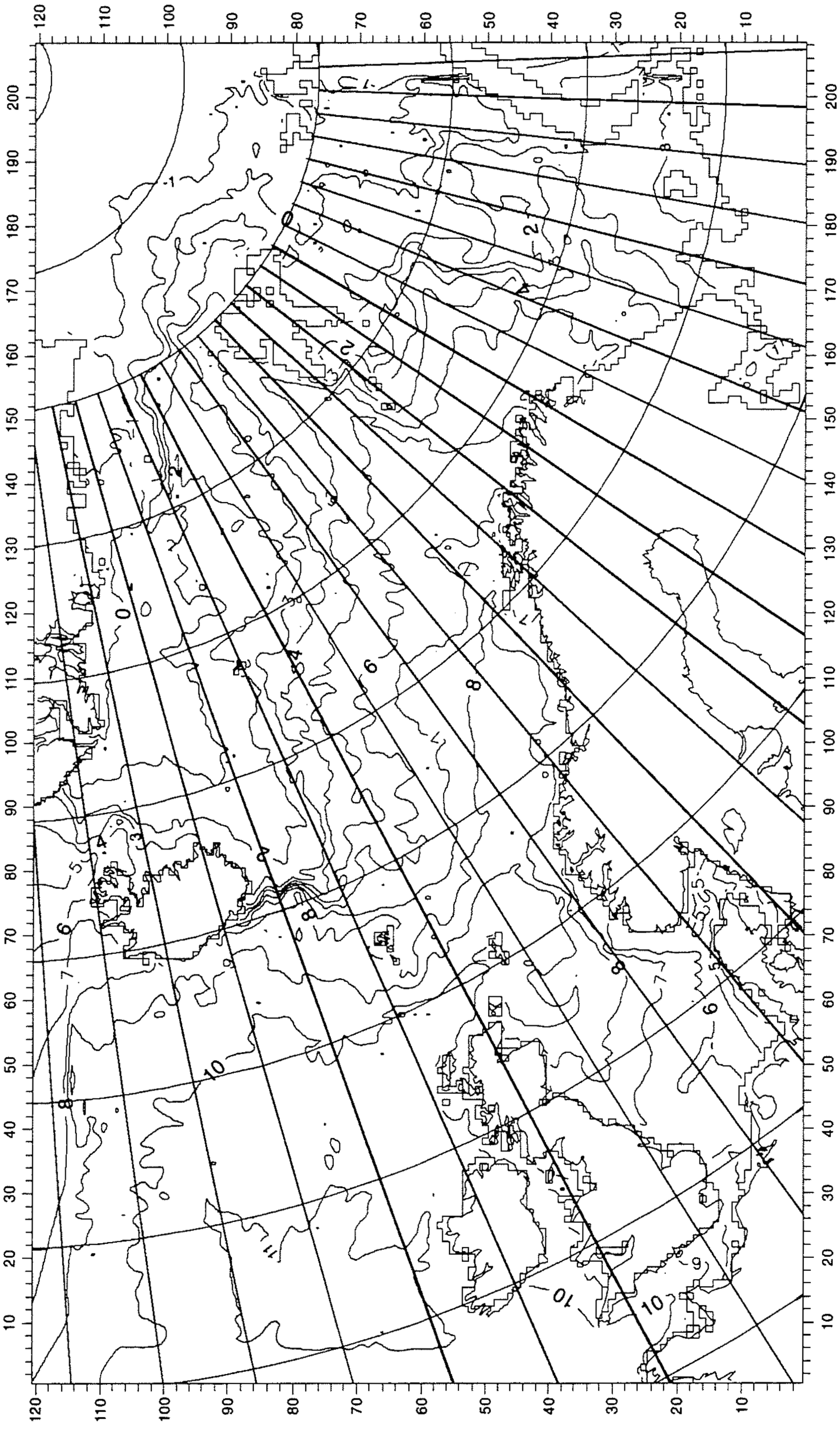


Figure 13. Isotherms showing the simulated monthly mean temperature field (°C) at 10 m depth for February 1997.

For comparison with the observed hydrography of the Bear Island-Fugløya section, vertical sections of simulated 25 hour mean values of salinity and temperature for the same periods and positions are constructed and presented in Figures 14 and 15. Similarly, time series of 25 hour mean currents were collected from the positions in the numerical model grid approximately at the locations of the current meters of the mooring VEINS3. These time-series are lowpass-filtered with a cut-off period of 30 days and presented in Figure 16 as vector diagrams.

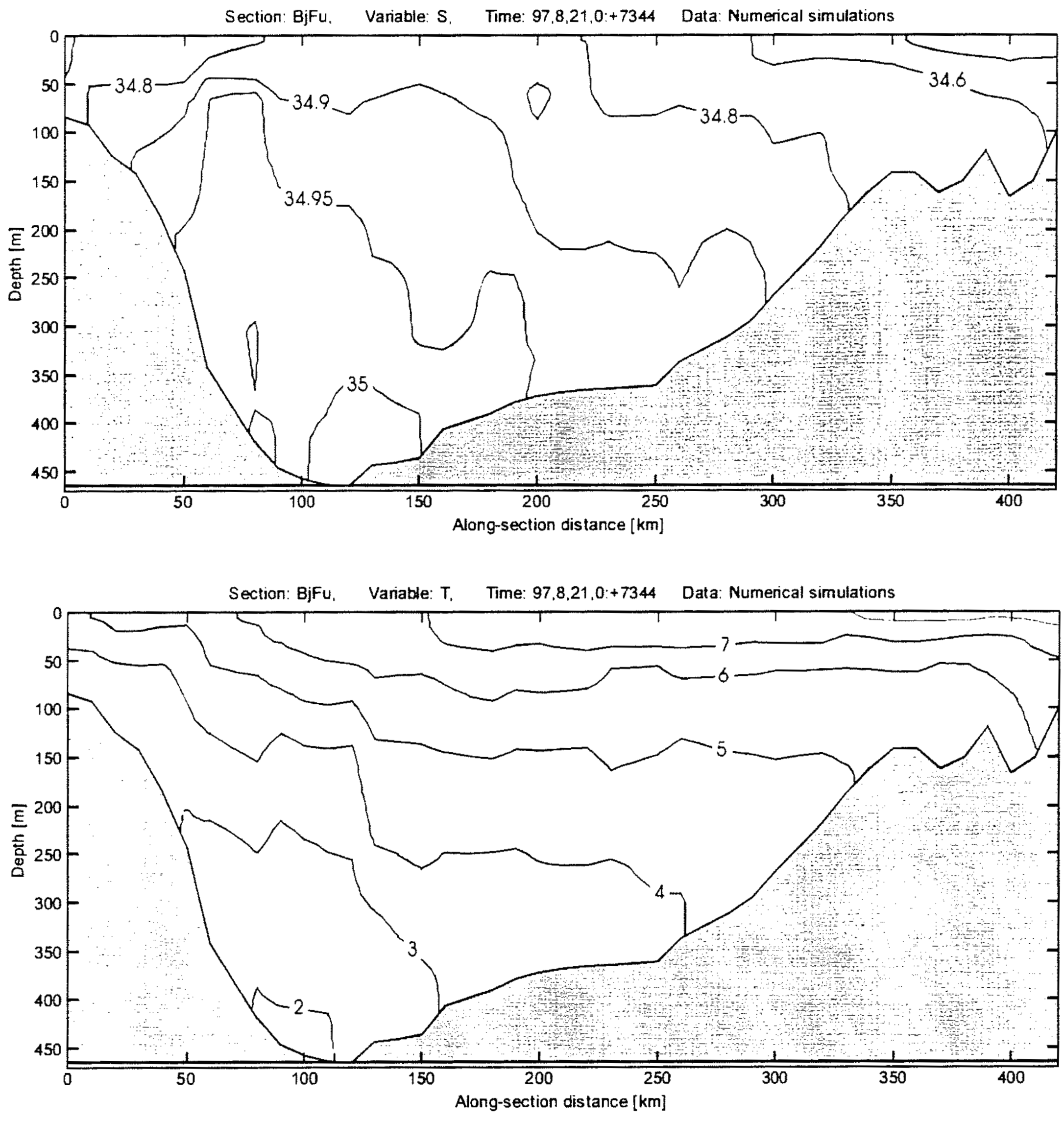


Figure 14. Vertical sections of simulated salinity (psu, upper panel) and temperature (^{o}C) at the Bear Island-Fugløya section as 25 hours mean values of August 21 1997.

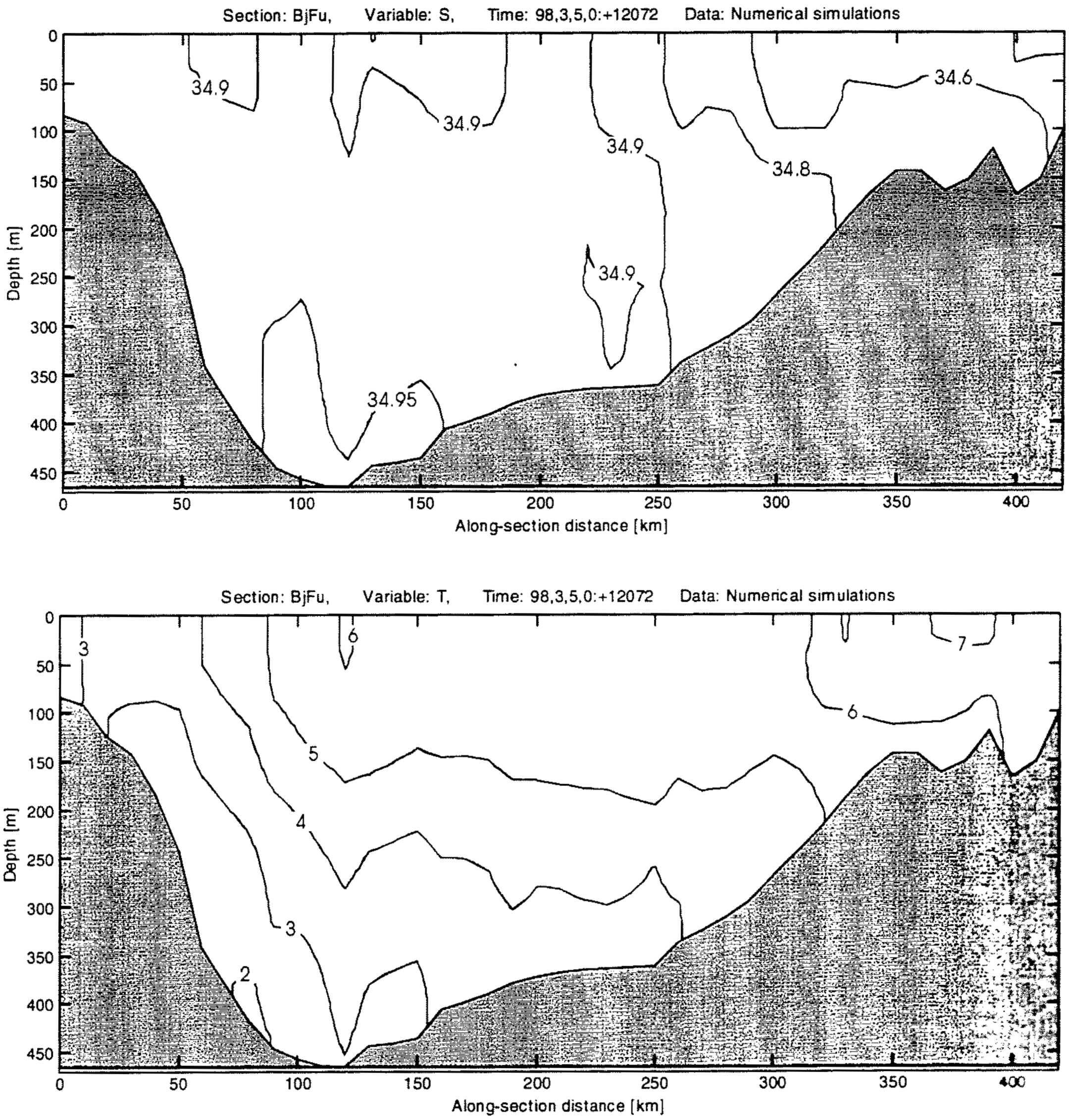


Figure 15. Vertical sections of simulated salinity (psu, upper panel) and temperature (°C) at the Bear Island-Fugløya section as 25 hours mean values of March 5 1998.

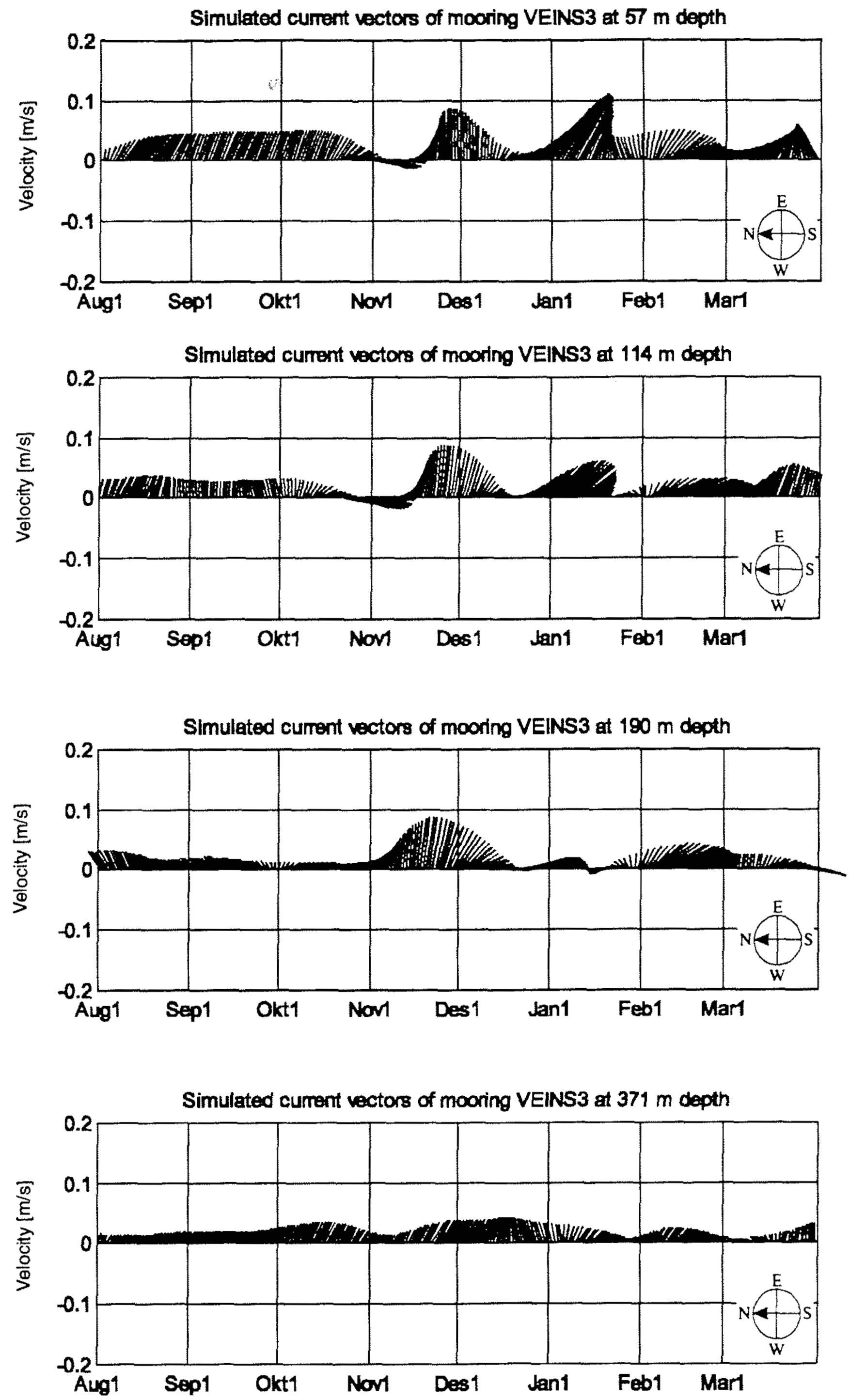


Figure 16. Time series of 30 days lowpass filtered current vectors from the numerical results at the VEINS3 current meter mooring in the period August 1997 to March 1998.

4. Discussion

4.1. General situation

The general current system in the Nordic Seas and the Barents Sea is indicated in Figure 17. In the Nordic Seas, the main currents are the Norwegian Atlantic current and the East Greenland current. The Norwegian Atlantic current with warm water is roughly following the continental shelf edge in a direction to the north along the western coast of Norway. Approximately equal amounts of Atlantic water enters the Arctic Ocean through the Barents Sea and west of Spitsbergen (Rudels, 1987; Loeng *et al.*, 1997). The East Greenland current carry cold and less saline water from the Arctic Ocean south along Greenland and into the Atlantic Ocean between Greenland and Iceland. Both these currents also branches off into the interior of the Nordic Seas.

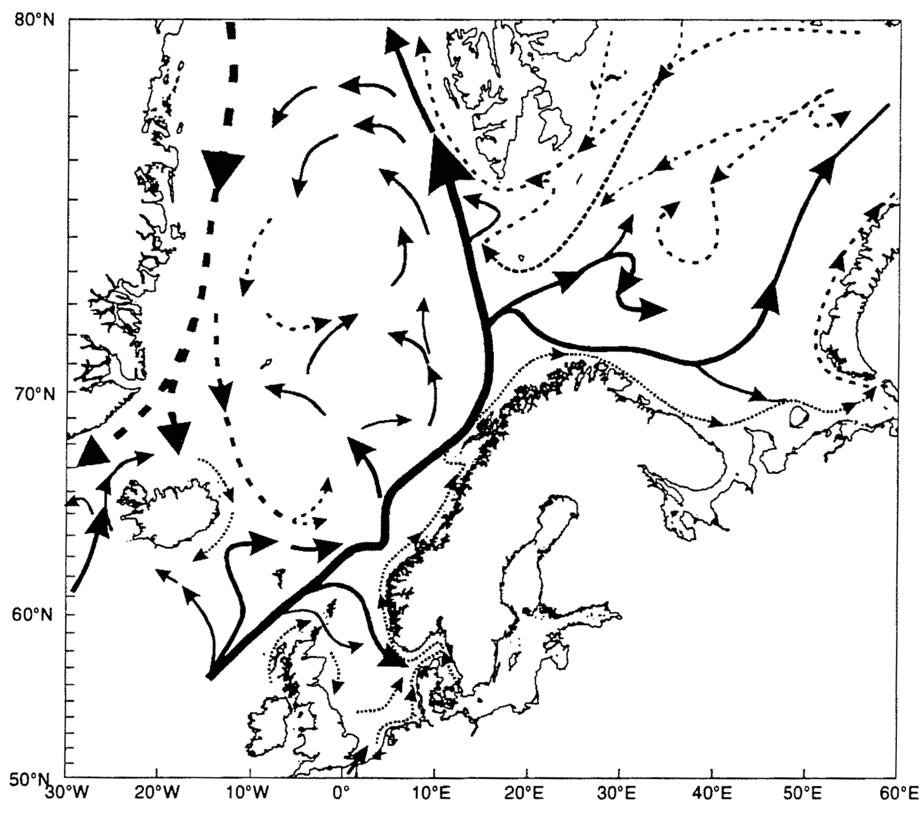


Figure 17. The mean current system of the Nordic and Barents Seas. The main components are the branch of the North Atlantic Current towards the north (thick solid line) and the East Greenland Current (thick dashed line).

The Barents Sea (Figure 1) is a relatively shallow continental shelf sea where the topography strongly influences the currents. The Norwegian Atlantic current flows into the Barents Sea along the Bear Island channel, and divides into two main branches (Figure 17). The southern branch continues eastward parallel to the coast. The other main branch turns north along the Hopen trench and divides into smaller branches (Loeng, 1991). Two of these branches continue as intermediate currents as they submerge below the lighter Arctic water on their way north between Hopen and the Great Bank, and eastwards between the Great bank and Central Bank. This is one of the few areas in the Barents Sea where the surface and the deeper currents oppose; for most of the Barents Sea the current direction indicated in Figure 17 are valid for the whole water column.

The influx of Arctic water to the Barents Sea take place along two main routes: between Spitsbergen and Franz Josef Land, and through the opening between Franz Josef Land and Novaja Zemlja (Dickson *et al.*, 1970). The main part of the inflow between Spitsbergen and Franz Josef Land flows as the East Spitsbergen Current southward along the coast of Spitsbergen. The inflow south of Franz Josef Land flows in a direction to the southwest, and splits north of the Central bank with the main part going southwestward along the eastern slope of the Spitsbergen bank as the Bear Island current, playing an important role regarding the physical conditions in this area.

The physical oceanographic conditions in the Barents Sea depend mainly on the variability in the Atlantic and Arctic inflows (Loeng *et al.*,1997). The transport out of the Barents Sea consists of transformed Atlantic water to the Arctic ocean and also partly to the Norwegian Sea (Blindheim, 1989). To describe the water balance, good estimates of the volume transports between the different seas are needed. In a study of the water fluxes through the Barents Sea, Loeng *et al.* (1997) found a clear seasonal variation with maximum flow during wintertime, as well as a clear inter-annual variability. According to them, both the seasonal and inter-annual variability was linked to the atmospheric pressure in the central and western parts of the Barents Sea, with the highest inflow when the pressure is low. A balance budget for the Barents Sea throughflow indicated an average ingoing and outgoing transport of approximately 4 Sv, of which the throughflow of Atlantic water contributed to the half.

4.2. Observations

The observed salinity and temperature from the Bear Island-Fugløya section in the fall of 1997 and in the winter of 1998 (Figures 3-4) show a seasonal cycle with a 50-75 m deep fresher and warmer surface layer in the autumn, which diminishes to vertical homogeneity during winter. The Atlantic water (salinity > 35 psu) occupies almost the entire deeper parts of the section during the whole period. Another interesting feature is the changing characteristics of the Polar Front. In August 1997 the front area is wide but distinct, while in March 1998 isoterms show a significant doming upwards in the frontal area, probably due to a return flow (i.e. out of the Barents Sea).

The most obvious characteristic of the observed currents (Figure 5) is the barotropic structure, there are only minor changes of the velocity with depth. The 3 moorings in the south (VEINS1-3) are, as expected, located in the inflowing Atlantic water (Table 1), while the 2 northernmost moorings (VEINS5 and 6) sample in the Bear Island current, dominated by the outflowing modified Arctic water. The VEINS4 mooring seems to have the most variable flow pattern. This is probably due to its location in the shear zone where the current is unstable and turbulent with frequently occurring eddies (Blindheim, 1989).

4.3. Numercical results

Figures 8 and 9 show the horizontal distribution of the currents at 10 m depth for the whole model domain as monthly mean fields for August 1997 and February 1998. Compared to Figure 17 the main features are included in the numerical results, with the Norwegian Atlantic current going northwards along the Norwegian shelf edge and the East Greenland current southward on the other side of the basin. The numerical results show an annual variability, with stronger currents during winter, as expected (Blindheim, 1993; Loeng *et al.*, 1997). The inter-annual variability and details that appear in these and comparable numerical results, are mainly produced by winds, as the boundary conditions and thermodynamic relaxation have a fixed annual variability. In the Barents Sea, the branches of the Norwegian Atlantic current seems to be captured. However, the details of the simulated currents in the eastern and northern parts are more questionable, most likely due to the vicinity of the open boundary and to the lack of ice in the model. The horizontal distributions of salinity at 10 m depth (Figures 10 and 11) are realistic, but with the frontal areas being smoothed (mostly due to the grid resolution of 20 km). The salinity of the Atlantic water entering into the Barents Sea is slightly less than 35 psu. As to the temperature distribution (Figures 12 and 13) these are expected to have less variability than nature, since the numerical model is forced without realistic heat energy transfer with the atmosphere. DNMI produces every fortnight an ice-chart for the area with observations of ice-cover and surface water temperature. Comparing the charts of September 2 1997 and March 3 1998 (Figures 18 and 19) with the simulated temperature distribution of August 1997 and February 1998 (Figures 12 and 13), the agreement is found to be reasonable except in areas of ice-formation and in the vicinity of land.

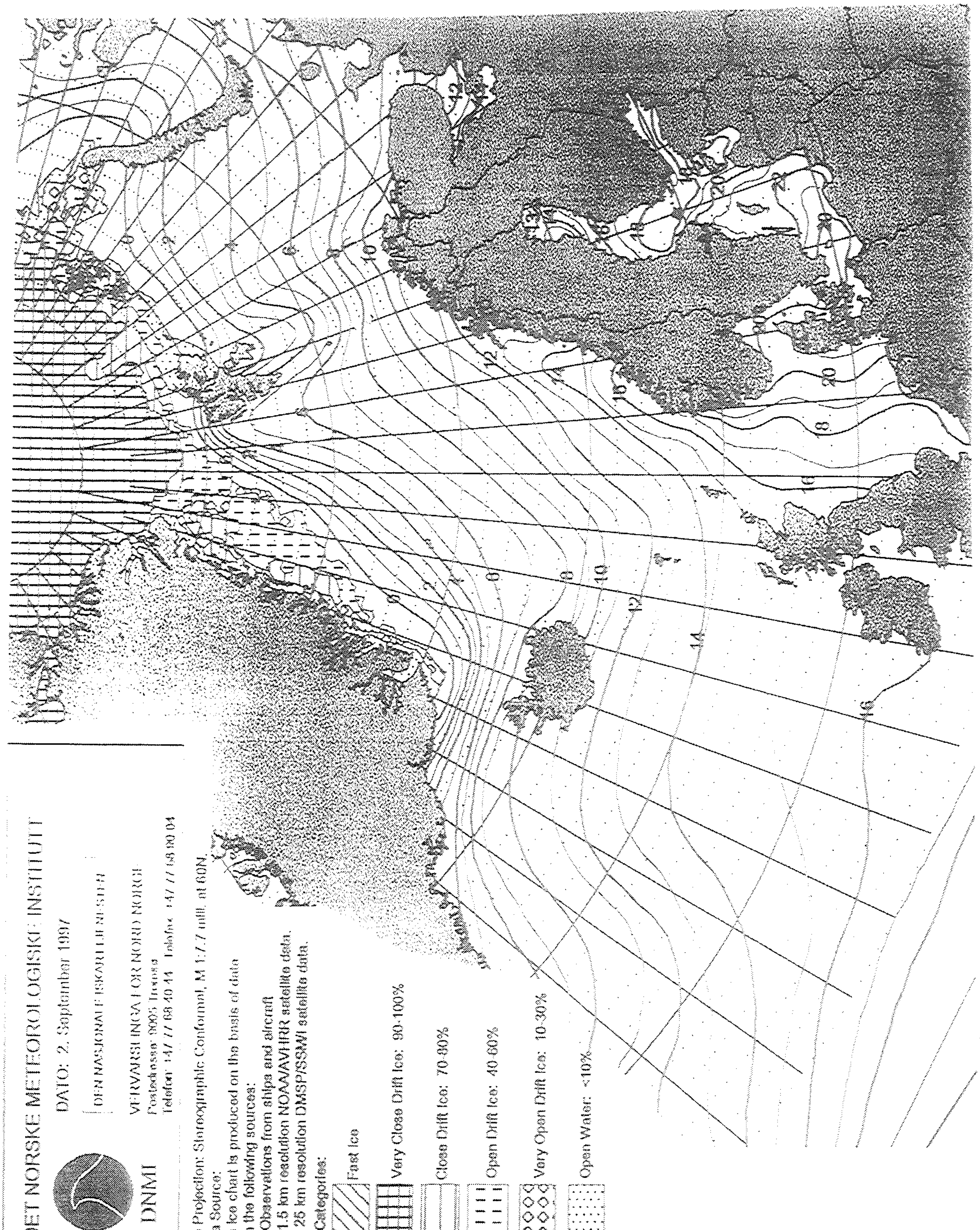


Figure 18. Ice chart from the Norwegian Meteorological Institute of September 2 1997 showing isoterms at the surface of the Nordic and Barents Seas.

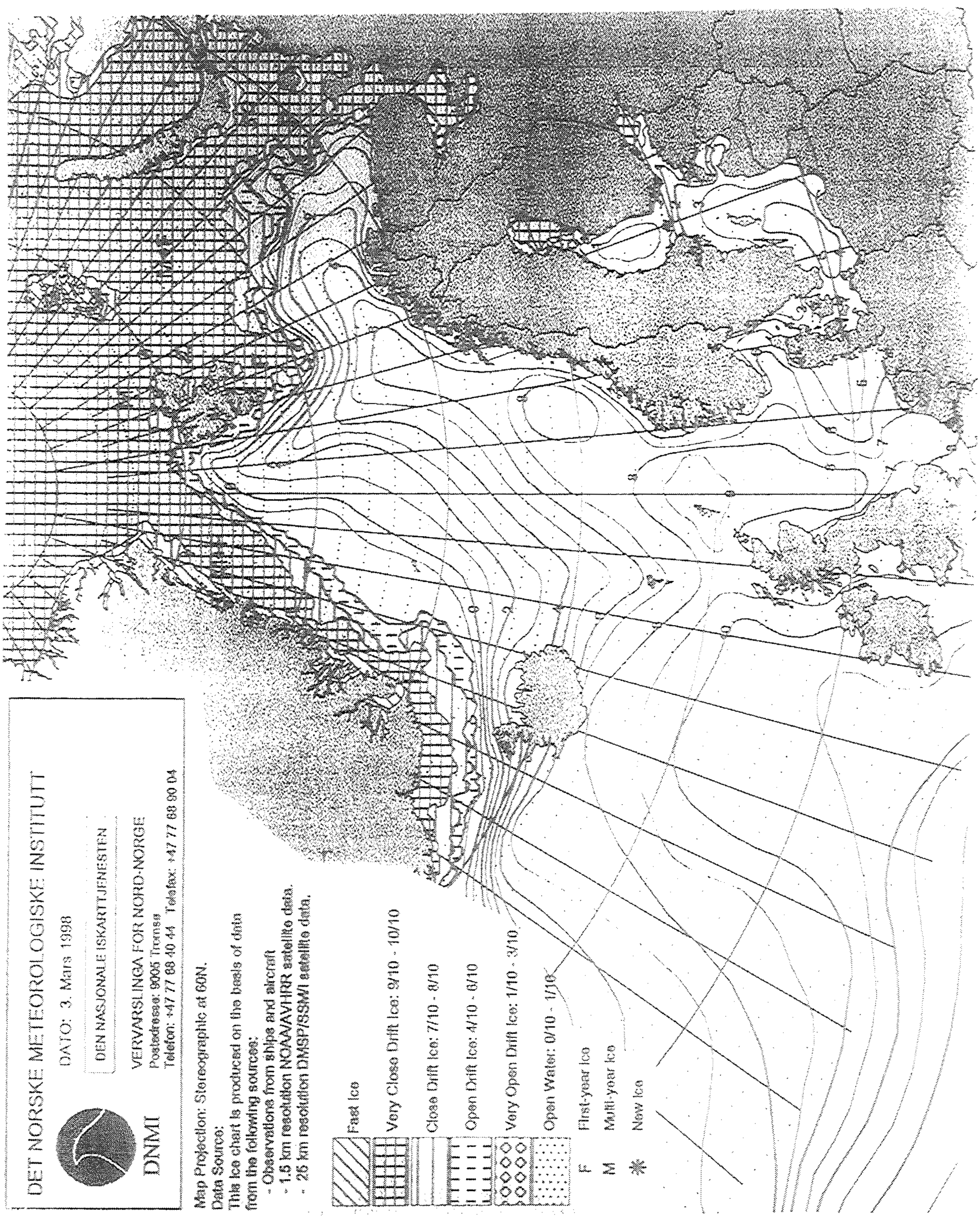


Figure 19. Ice chart from the Norwegian Meteorological Institute of March 3 1998 showing isoterms at the surface of the Nordic and Barents Seas.

The numerical model's inability to reproduce natural high variability of temperature, is manifested further when examining the results of the Bear Island-Fugløya section (Figures 14 and 15). Compared to the observations (Figures 3 and 4) the differences in temperature are several degrees in the northern part of the section (i.e. to the left on the figures) where the Bear Island current carry cold modified Arctic water. Also in the areas in the vicinity of the Norwegian coast, the model fails to reproduce the summer warming of the upper layer (although this was exceptionally high in 1997 due to sunny weather conditions in July and August). In the middle and deeper parts of the section, the differences between the observed and modelled temperature is less than a degree. As to the salinity, the same tendency with largest deviations between simulated results and observations in the north and in the south persists. The difference between simulated and observed salinity in the middle of the section is less than 0.2 psu, while up to 1 psu in the Bear Island current. These differences are assumed mainly to be connected to the lack of ice-modelling, although the numerical results are generally sensitive to the settings of the different mixing parameters of the model (Berntsen *et al.*, 1996). Especially the low salinity of the Atlantic water entering the Barents Sea might be a result of a slightly erroneous setting of the mixing levels.

In a direct comparison of the observed and simulated current vectors of mooring VEINS3 (Figures 5 and 16), it is obvious that the currents of the numerical model are less energetic than the natural current. This is due to the natural high variability of currents, caused by small scale phenomena not included in the model. Nevertheless, subjectively the currents compare quite well. To make a more objective comparison, similar statistical values of the E-W flow component from each mooring as presented from the observations (Table 1) were extracted from the numerical results, and these are gathered in Table 3. Once again, the simulated flow components are much smoother than the observed flow components. The differences between the observed and simulated mean values are 2-3 cm s^{-1}, but with a quite large relative difference (50%). However, these differences are less than the standard deviations of the simulated flow components and much less than the standard deviation of the observed flow. Furthermore, the simulated mean flow component has the same sign (i.e. direction) as the observed mean flow component.

Table 3: Statistical values of the velocity component (m s^{-1}) normal to the Bear Island-Fugløya section from current meter moorings at VEINS1-VEINS5 extracted from observations and the results of the numerical simulation.

		Max	Mean	Min	Std. dev.
VEINS1	Obs	0.263	0.026	-0.215	0.069
	Sim	0.141	0.026	-0.055	0.030
VEINS2	Obs	0.346	0.031	-0.187	0.079
	Sim	0.144	0.046	-0.011	0.027
VEINS3	Obs	0.362	0.058	-0.250	0.095
	Sim	0.133	0.030	-0.048	0.030
VEINS4	Obs	0.380	0.011	-0.356	0.123
	Sim	0.182	0.035	-0.056	0.042
VEINS5	Obs	0.363	-0.039	-0.342	0.083
	Sim	0.157	-0.015	-0.173	0.050

From the simulated currents at the Bear Island-Fugløya section, the volume flux can be calculated. Figure 20 shows a time series from August 1997 to April 1998 of the net volume flux across this section (positive values indicate flux into the Barents Sea), with large fluctuations and a mean volume flux into the Barents Sea of approximately 3 Sv. For comparison, the dotted line shows the net volume flux calculated by a barotropic wind-driven numerical model by Ådlandsvik (1989) (Ådlandsvik and Loeng, 1991). The mean volume flux of POM is 2-3 Sv greater as the barotroopic model mean flux, as expected since the barotropic model lacks the density driven portion of the volume flux across the section (i.e. mainly an inflow of Atlantic water). The agreement between the variability of the two models is good. Both estimates have a standard deviation of 2.6 Sv, indicating that the density driven part of the flux is stable.

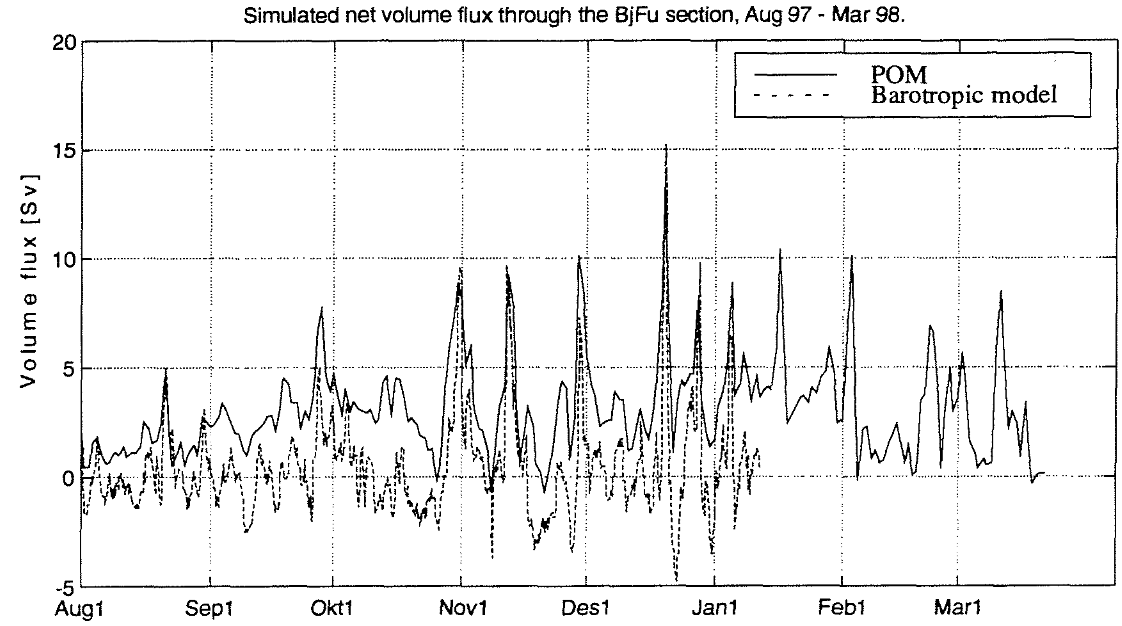


Figure 20. Time series of calculated volume flux through the Bear Island-Fugløya section between August 1997 and April 1998. Positive values are flux into the Barents Sea. The solid line represents the results of POM, and the dashed line the comparable results of a barotropic model.

Estimates of monthly mean volume fluxes through the Bear Island-Fugløya section based on the current observations at VEINS1-VEINS5 were presented in Table 2. Similar transport estimates are constructed based on the numerical results, and a comparison is presented in Figure 21. The agreement is fair except for December 1997 when the observations indicate a net outflow of the Barents Sea. Based on only a few points of observation (with about 50 km horizontal spacing between the moorings), the uncertainty of the transport estimates from the current observations is expected to be large. Thus it is non-trivial to determine which of the transport estimates are closest to the natural transport through this part of the Bear Island-Fugløya section.

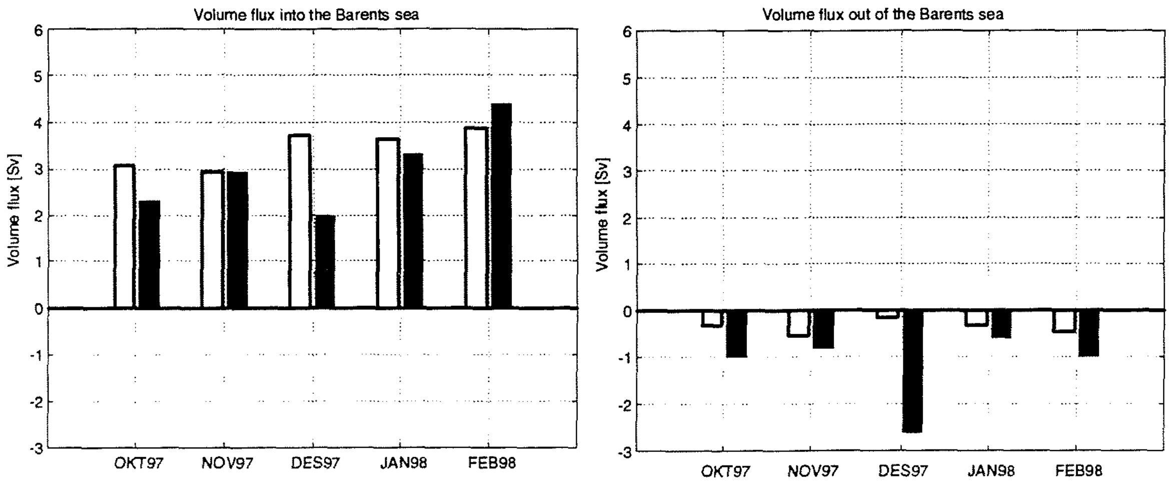


Figure 21. Monthly mean values of volume flux through the Bear Island-Fugløya section as calculated by the numerical model (white bars) and estimated from the current observations (black bars). The left panel shows transport into the Barents Sea and the right panel shows transport out of the Barents Sea.

5. Concluding remarks

The validation of the numerical results is difficult (Dee, 1995). There exists no general agreement on how numerical model results should be validated, and validation using objective methods is not common. In this report, mainly subjective methods for validation are used. Objective methods requires statistical estimates from a large number of observations. With an extensive archive of observations, IMR has started a process of establishing objective methods for validation of our numerical simulations of the North, Nordic and Barents Seas (Berntsen *et al.*, 1996).

The purpose of this numerical modelling component of Workpackage 1.2 in VEINS is to study the seasonal and interannual variability of flow through the Barents Sea. In general, the results of the numerical model (Figures 11 and 12) capture the main flow patterns and the annual variability of the Nordic Sea (Blindheim, 1993; Loeng *et al.*, 1997), but the overall performance is not acceptable for all of the Barents Sea. The reason for this is the lack of realistic thermodynamical forcing (including ice modelling). The calculated mean transport across the Bear Island-Fugløya section, however, appears to be in agreement with the expected natural transport of 2 Sv (Blindheim, 1989; Loeng *et al.*, 1997). Most of the variability due to the wind also seems to be captured by the model.The agreement between the transport across the Bear Island-Fugløya section as estimated from the observed currents and that from the numerical results is reasonable, except for one event in December 1997 when the observations indicated a net transport out of the Barents Sea and the numerical results gives a net in-flux. The reasons for this discrepancy are yet unknown, and it is also uncertain which of the two estimates being closest to the natural transport.

With its relative coarse resolution (20 km horizontally) and smooth forcing fields (e.g. winds of 75 km resolution), the results of the numerical model are as expected much smoother than the observations. From the statistical values of the E-W flow component for each mooring (Table 3) it is found that the range of the simulated currents are much narrower than the observed currents, with the standard deviations of the simulated flow components being less than 50% of the standard deviations of the observed flow components. The mean values of the simulated and observed flow components, however, are deviating by maximum 2.8 cm s^{-1} (the mean standard deviation for the observed flow component is 9.0 cm s^{-1} and 3.6 cm s^{-1} for the simulated flow component). Whether the observed high variability of the natural flow is important to the mean transports through the Barents Sea is uncertain. However, it is well known that the day-to-day weather is unimportant to the atmospheric climate, a fact that supports the hypothesis that the natural variability on a short time scale (day) is unimportant to simulate correctly the mean flow in the Barents Sea in order to study the variability on larger time scales (year).

The first scheduled model improvement is to incorporate realistic thermodynamics and a sea ice model. This will be a major extension of the numerical model, and it is assumed that the model performance in the Barents Sea will improve significantly. Furthermore, some testing of the open boundary condition to the Arctic Ocean will be made, and possibly the model domain should be extended further east. It will be looked into whether better resolution of the model domain (to capture more of the natural variability and baroclinicity of the Barents Sea) is necessary. Finally, the settings of mixing parameters of the model will be considered, since the model results will be sensitive to mixing as shown by Berntsen *et al.* (1996).

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