A modeling study of the North Atlantic with emphasis on the Greenland-Iceland-Norwegian Sea

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This essay presents the results of a modeling study that addresses the circulation and convection of ocean currents. A possible change in the global climate due to human-induced increase of atmospheric CO_2 and other greenhouse gases is one of the major environmental challenges in our time. In order to get more insight into this problem, one needs to better understand the various components of the climate system and how they interact. Due to the large heat capacity of the global ocean, the magnitude, delay, and regional distribution of a potential global warming are to a large extent determined by exchanges of heat between the upper ocean and the world's deep ocean. An important process in this regard is deep water formation due to convection. The North Atlantic and the Greenland-Iceland-Norwegian Sea are particularly important regions for this process. Major parts of the circulation in this area are simulated by a coupled ice-ocean model that also includes the entire Arctic Ocean.

Since the beginning of the industrial era, the atmospheric concentration of the greenhouse gas carbon dioxide (CO_2) has increased from about 280 parts per million to about 350 parts per million today. In addition, there is also a strong increase of other greenhouse gases such as methane and chlorofluorocarbons. The greenhouse gases influence the long wavelength radiation budget, which, in turn, affects the earth's temperature. An accumulation of these gases in the atmosphere might result in a temperature increase. The anthropogenic increase of greenhouse gases has resulted in a debate on the possibility of a global warming. The question is how the increase of greenhouse gases will affect the climate during the next century.

Predictions based on models indicate global warming ranging from 1.5 to 4 degrees Celsius in response to a doubling of greenhouse gases. However, at present there are large uncertainties in the predictions with regard to magnitude, delay, and regional effects. The Intergovernmental Panel on Climate Change (IPCC) has pointed out that in order to improve our predictive capability, it is necessary to better understand the various climate-related processes, particularly those associated with clouds, the ocean, and possibly the carbon cycle.[1]

In the project "Climate of the 21st Century," which is part of the European Program on Climate and Natural Hazards (EPOCH) initiated by the Commission of the European Communities, there is participation from about 20 European research institutes. In this project, scientists from the Nansen Environmental and Remote Sensing Center and IBM Bergen Environmental Sciences & Solutions Centre in Norway are participating in a joint subproject, focusing on the role of the North Atlantic and the Arctic Ocean in the global climate system. This involves regional modeling and sensitivity studies of the ice-ocean system in the Iceland-Greenland-Norwegian Sea and the Arctic Ocean, including studies of convection and deep water formation.

Deep water formation due to convection determines the heat exchange between the atmosphere and the deep ocean, and causes the renewal of the water masses in the world's deep oceans. Deep water formation, which is localized in high-latitude regions, involves complicated processes that are only partially understood.[2] Global models do not resolve length scales typical for convection, and results from large-scale climate models are sensitive to the way these processes are included. In order to predict future climate, it is important to have a good representation of deep water formation in climate models.

In this essay, a modeling study of the North Atlantic, the Greenland-Iceland-Norwegian Sea, and the Arctic Ocean is presented. The work addresses circulation and convection in the Greenland-Iceland-Norwegian Sea and the exchanges with adjacent basins, particularly the flow across the ridge between Greenland and Scotland.

For the model study, the coupled ice-ocean model by Oberhuber,[3] which is described later, is used. The Greenland-Iceland-Norwegian Sea is a complicated region due to the fine-scale topography and the deep and narrow channels that connect the North Atlantic and the Greenland-Iceland-Norwegian Sea. In order to resolve circulation and convection in the region better than is possible with global models, the model used has a higher resolution in the Greenland-Iceland-Norwegian Sea.

Today, a number of computer models are used in climate studies. The most advanced models include many of those processes of importance for the earth climate. The interaction between these processes is often so complicated that it can only be studied and understood by use of large mainframes and supercomputers. At the IBM Bergen Environmental Sciences & Solutions Centre, the research on ocean climate is performed on an IBM 3090*/600S with vector facilities.

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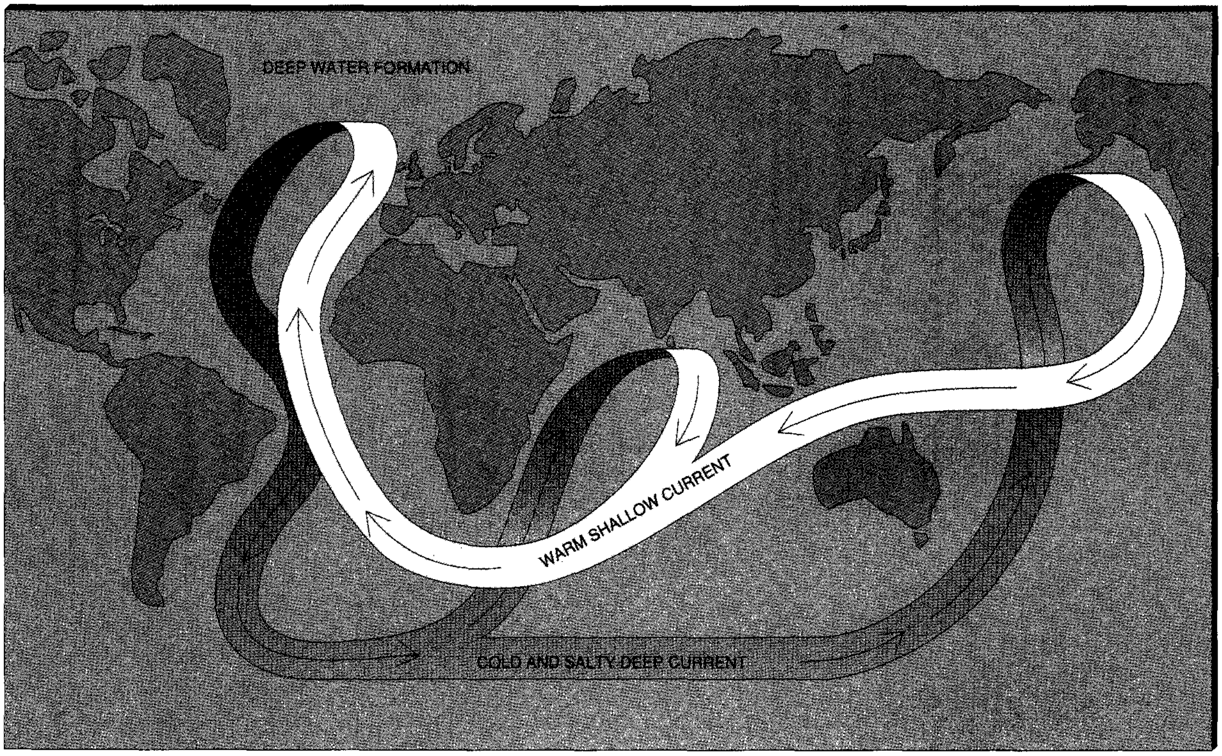
Complex computations such as ocean and atmosphere simulations produce large data sets of multiple three-dimensional scalar and vector fields that have to be analyzed and interpreted. In such cases, effective tools are required to visualize results in two and three dimensions, in order to fully utilize the output of large-scale computation studies. Imaging of scalar and vector data is often done on workstations or special-purpose graphic machines. The two-dimensional and three-dimensional figures presented in this paper were mostly produced on IBM Personal System/2* (PS/2*) machines and IBM RISC System/6000* workstations.

Climate change and the ocean

Due to the special geographic structures that allow atmospheric moisture transport from the Atlantic to the Pacific but block moisture-bearing winds into the Atlantic basin, the Atlantic Ocean is under present climate conditions more saline than the Pacific and the Indian Ocean. The northward flowing arm of the warm and saline North Atlantic surface water penetrates into high latitudes, where the warm surface water and the cold atmosphere in the winter time support large oceanic heat loss. When the saline surface water is cooled it can become dense enough to sink. It is estimated that about 15–20 megatons per second of surface waters cool and sink to lower levels in some very limited area in the subpolar North At-

Figure 1 Diagram of the Atlantic thermohaline circulation conveyor belt

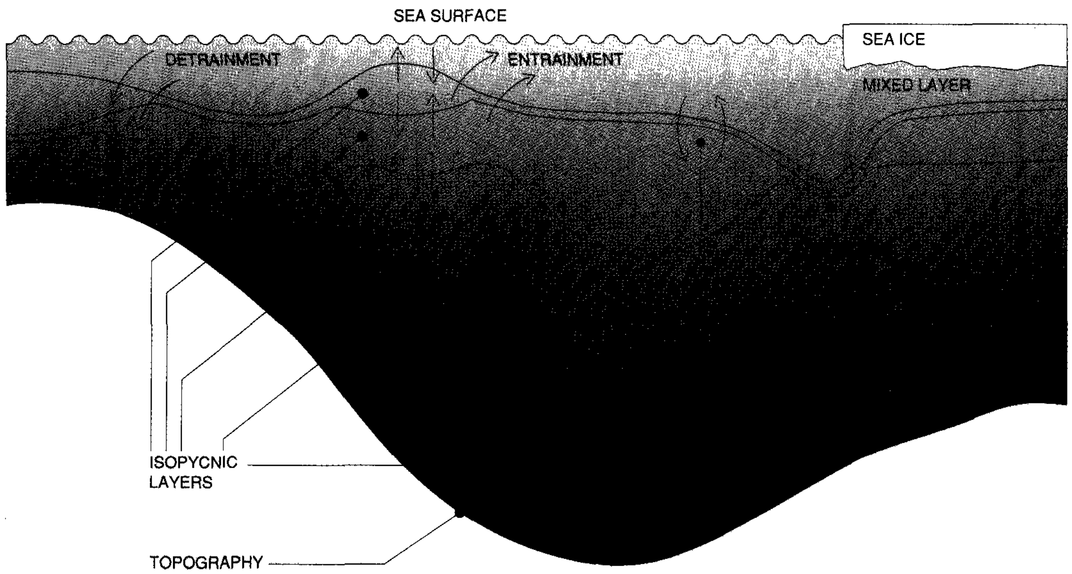


lantic, including the Greenland-Iceland-Norwegian Seas. Deep and heavy water produced in these regions is thought to account for a major fraction of the renewal of all the abyssal water of the world ocean. This sets up a *conveyor belt*, which in a sense is self-supporting; as the upper water sinks, more surface water from the south flows in to take its place. Figure 1 is a schematic diagram of the Atlantic thermohaline circulation conveyor belt that illustrates present ideas of parts of the overturning circulation of the world ocean.[4] The deep water flows southward in the Atlantic at deep and intermediate depths, and goes into the Indian and the Pacific Ocean where it rises to the surface about 1000 years later.

The exchanges of heat between the atmosphere and the deep ocean need not operate with the same magnitudes as they do today. For example, low salinity in the surface layer can shut down or reduce deep water formation and the Atlantic conveyor belt.[4,5] A global warming might also result in reduced deep water formation or formation of less cold deep and intermediate water, which gradually could change the heat storage of the deep ocean and change the heat transport of the ocean currents.[6]

Thus, in order to make realistic predictions of magnitude, delay, and regional effects of a possible climate change, it is important to be able to model the large-scale heat transport in the ocean. The first climate models contained representations of the ocean but did not account for changes in oceanic heat storage and circulation. Today, coupled ocean-atmosphere circulation models are used to study the response of increased concentration of greenhouse gases. In these models, increased temperature in the deep ocean is concentrated in convection regions such as in the North Atlantic and the Antarctic.[6–9] The present study was initiated in order to investigate the role of the Greenland-Iceland-Norwegian Sea for cli-

Figure 2 Vertical cross section of the layer thickness distribution



mate fluctuations in more detail than is possible in global models.

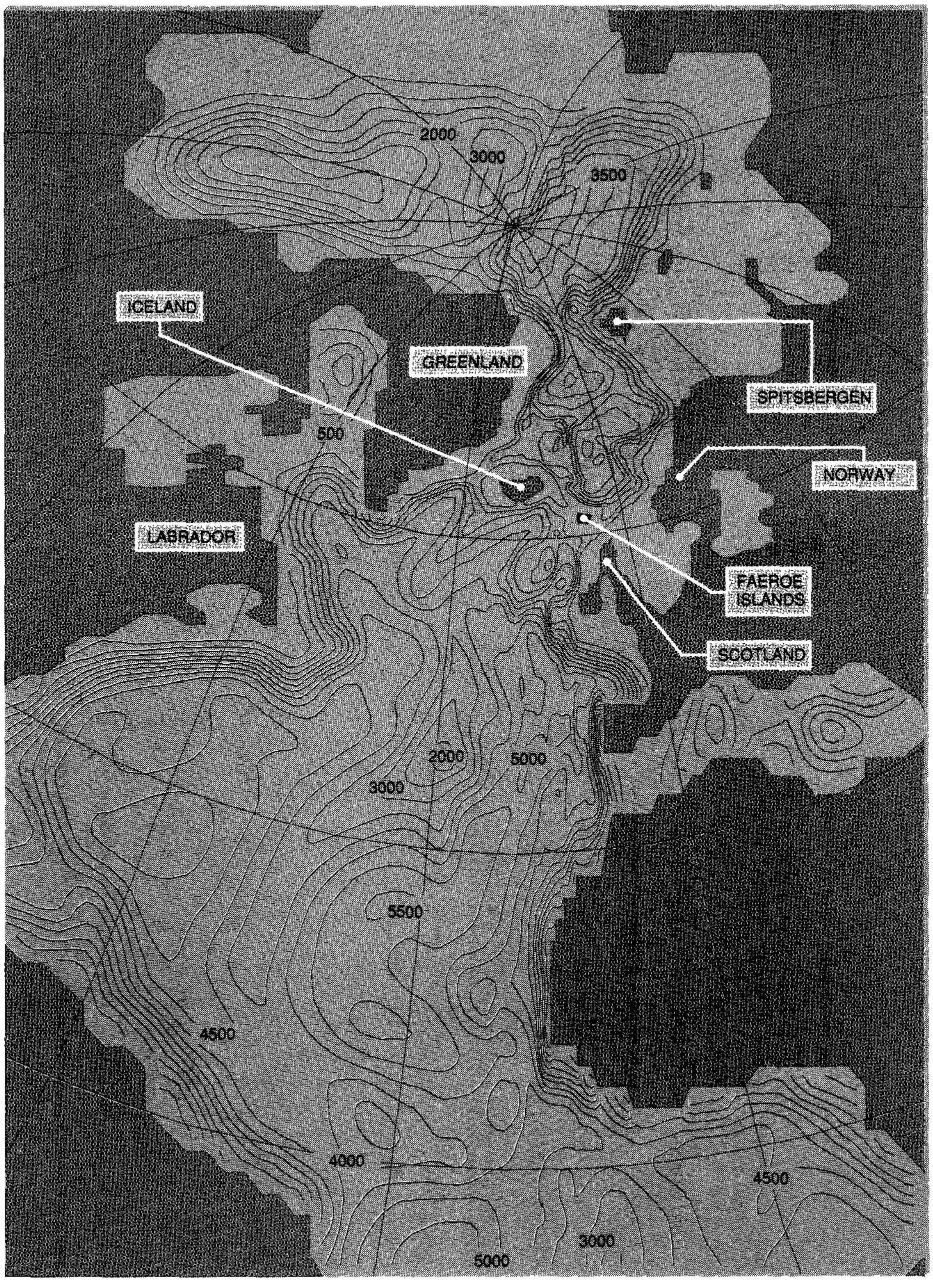
The simulation model

The model used in this work is the coupled sea-ice mixed-layer isopycnal ocean model by Oberhuber (see Reference 3). Isopycnal models, such as the models by Bleck[10,11] and Oberhuber,[3] use Lagrangian coordinates in the vertical. The ocean is divided into layers of constant potential density with varying thickness as shown in Figure 2. Figure 2 shows the vertical cross section of the layer thickness distribution. The uppermost layer is the mixed layer, and lower layers are isopycnic layers. Arrows indicate mass transfer rates due to various mixing parameterizations. The potential density is the density a water mass would have if it was brought to a reference pressure, for example the sea surface pressure. Transport in the ocean tends to follow isopycnal surfaces, i.e., surfaces of constant potential density. Isopycnal models are generally expected to handle flow along and across isopycnic surfaces in a more natural way than level models, such as the Bryan-Cox type[12,13] and the Large-Scale Geostrophic model by Maier-Reimer and Hasselmann[14,15] in which the grid points are at fixed levels in the vertical.

The ocean model by Oberhuber is based on primitive equations in flux form in order to conserve mass, mass flux, heat, and salt, and has a realistic equation of state. In the uppermost layer, the mixed layer, the density is allowed to change in the horizontal. The mixed layer density and depth are determined prognostically from the surface forcing and the interaction with lower layers. The mixed layer is coupled to a sea-ice model that has prognostic equations for ice mass, areal coverage, and movement, and where the ice-floe interaction is treated by using the viscous-plastic rheology introduced by Hibler.[16] The time integration scheme consists of a predictor-corrector technique combined with a semi-implicit scheme.

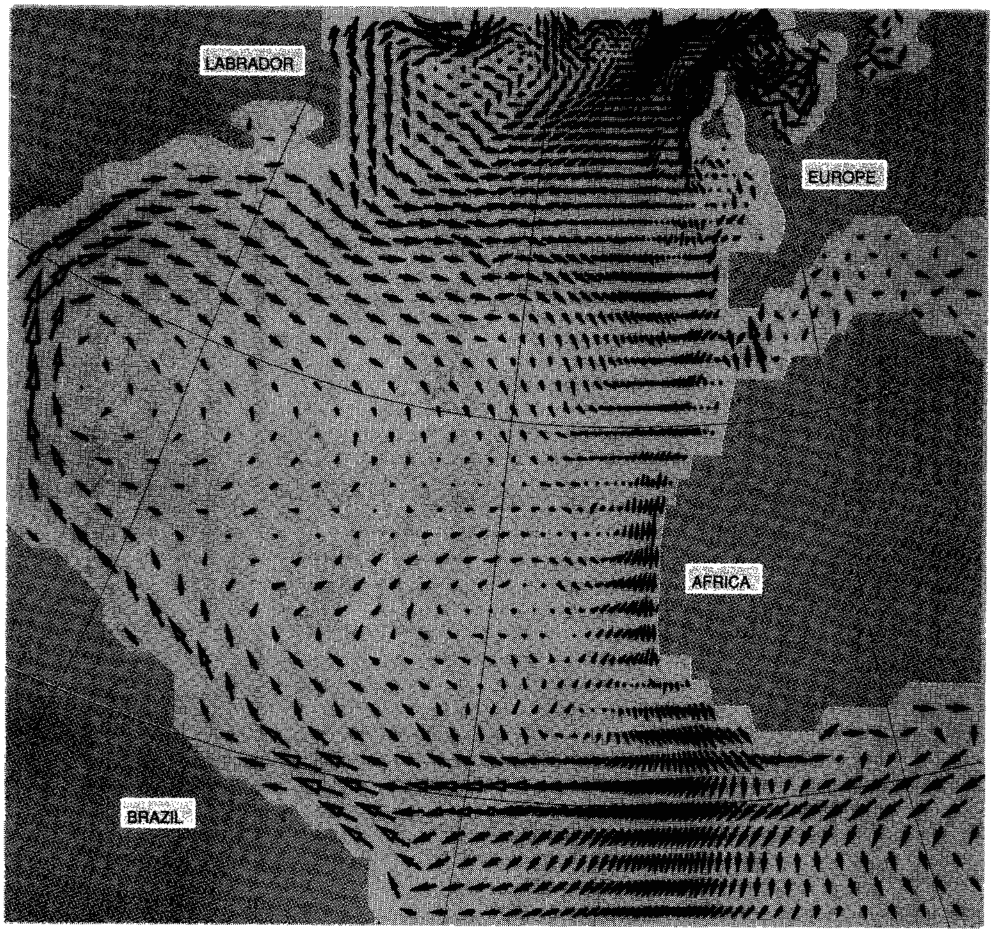
Thermal forcing, wind stress, and surface input of turbulent kinetic energy are determined from at-

Figure 3 Bottom topography used in the model



mospheric quantities. Monthly mean average fields for wind stress and air surface temperature have been determined from a five-year data set (1985–1990) from the European Centre for Medium Range Weather Forecasts (ECMWF). Salinity and temperature data by Levitus[17] have been used to initialize the model. The surface salinity is relaxed toward observed surface salinity by estimating the fresh water fluxes required to maintain this salinity. In experiments where the cli-

Figure 4 Simulated surface flow in March for the North Atlantic

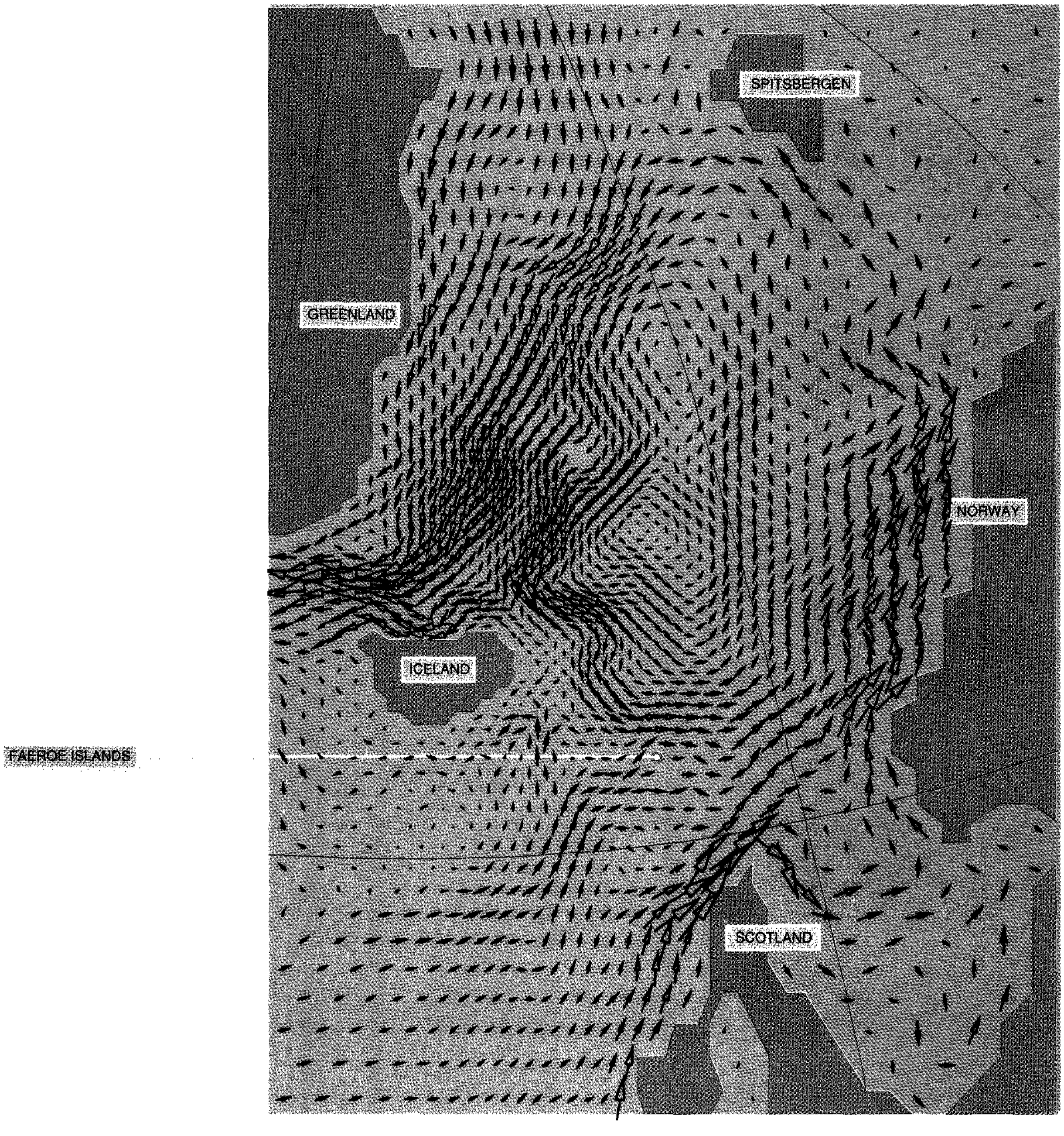


mate is allowed to drift, similar methods are used to estimate surface fluxes required to maintain the present climate. Anomalous forcing will then result in a climate drift. This technique is widely used in uncoupled models[18] and global atmosphere-ocean models.[19]

The model domain represents the Atlantic Ocean bounded meridionally at 10 degrees south, the Greenland-Iceland-Norwegian Sea and the whole Arctic Ocean. The topography of the model, which is shown in Figure 3, is based on a five-minute (or 9 km) resolution global topography data set from the National Oceanic and Atmospheric Administration (NOAA). The major topographic features of the region of interest include the ridge between Greenland and Scotland, the continental slopes along the coasts of Norway and Greenland, and the strait between Greenland and Spitsbergen. The deepest connection between the Greenland-Iceland-Norwegian Sea and the North Atlantic is about 800 meters in the channel between the Faeroe Islands and Scotland, while the strait between Greenland and Iceland has a depth of about 600 meters.

In order to obtain a sufficient resolution of the current system in the Greenland-Iceland-Norwegian Sea, the model has a variable horizontal resolution increasing from about 2 × 2 degrees near the equator and in the western Arctic, to less than 30 × 30 kilometers in the Greenland-Iceland-

Figure 5 Simulated surface flow in January for the Greenland-Iceland-Norwegian Sea



Norwegian Sea. The number of grid points in the horizontal is 107 × 122 and the number of layers used is nine. In order to resolve the weak stratification of the deep water at high latitudes, a fine resolution in the prescribed potential density for the lowest layers is used.

Previous model studies of the Arctic Ocean and the Greenland-Iceland-Norwegian Sea have been done with regional models using prescribed boundary conditions.[20] The present model domain represents the first attempt on a fine resolution coupling of the North Atlantic and the Arctic, and is suitable for the study of the interaction between the North Atlantic, the Greenland-Iceland-Norwegian Sea, and the Arctic Ocean.

The model has first been run for about 20 years with a coarse resolution everywhere. The results have then been interpolated onto the model version with the fine resolution in the Greenland-Iceland-Norwegian Sea and continued for approximately 10 years. The coarse resolution model version was run with a time step of one day, while for the fine resolution model version a time step of six hours was used. About 90 percent of the code is vectorized. The fine resolution model version requires about 150 megabytes of machine memory and uses about one week of CPU time on one processor of the IBM 3090/600S to perform a one-year integration that produces 150 megabytes of single-precision data.

Results from model simulations

The circulation in the North Atlantic is mainly wind-driven. A westerly equatorial current transports water masses toward the Gulf of Mexico. From there the Gulf Stream flows northward and separates from the east coast of the United States. As it comes into the North Atlantic it splits into a southward recirculation and a northward branch, called the North Atlantic Current, which continues toward the Norwegian Sea. South of Iceland and in the Labrador Sea, there is a counterclockwise circulation consisting of water masses from the north and from the Gulf Stream. Figure 4, which shows the simulated surface circulation in the North Atlantic, demonstrates that the model reproduces the main features of this circulation. The figure shows simulated surface flow field for March in the North Atlantic. Typical velocities are about 20 centimeters per second in the equatorial current and in the Gulf Stream. Only each second vector is plotted.

Figure 5 presents the simulated surface circulation in the Greenland-Iceland-Norwegian Sea. In January, the typical velocities are 20–30 centimeters per second in the inflow of North Atlantic water into the Norwegian Sea. Only each second vector is plotted. The figure shows that as the continuation of the North Atlantic current flows northward, some of it flows west of the Faeroe Islands, while the main current enters the Norwegian Sea between the Faeroe Islands and Scotland. Some of this inflow extends into the North Sea, before it continues northward and joins the main current again along the Norwegian coast and the shelf slope. At the northern part of Norway a small branch enters the Barents Sea and continues into the Arctic, while the main current continues toward Spitsbergen.

As the Atlantic water comes up toward the strait between Spitsbergen and Greenland, some of it continues into the Arctic Ocean below the less saline and lighter polar surface water, while most of it recirculates in the Greenland-Iceland-Norwegian Sea. In each of the major basins there are gyres with counterclockwise circulation that are strongly governed by the topography.[20]

From the Arctic Ocean there is a strong southward flux of polar water that follows the coast of Greenland, called the East Greenland Current. This current is relatively fresh and cold and transports large amounts of ice along the coast of Greenland. Most of the East Greenland Current continues southward between Greenland and Iceland into the Labrador Sea, while some recirculates in the Greenland-Iceland-Norwegian Sea.

The main regions for deep penetrative convection in the model are in the Greenland-Norwegian Sea and south of Iceland and Greenland where maximum convection depth is of the order 1000 meters. The most dense water is produced in the Greenland Sea, but there it does not extend deeper than about 700 meters due to the dense water masses that are present at this depth north of the sill between Greenland and Scotland.

Figure 6 shows simulation of vertical convection as part of a three-dimensional visualization of particle trajectories.[21] In the figure, land is removed except for the surface and the reference layer at 500 meters. As the flow paths enter a convection region the particles are distributed randomly down to the convection depth. The figure illustrates two cases. A cluster of particles enters a convection region south of Spitsbergen, and the particles are redistributed vertically. Some of them recirculate in the Greenland-Iceland-Norwegian Sea, and escape the region at the surface and at intermediate depths between Greenland and Iceland. Other particles flow into the Arctic at an intermediate depth. As a second flow path enters a convection region south of Iceland, the particles

Figure 6 Velocity trajectories with convection

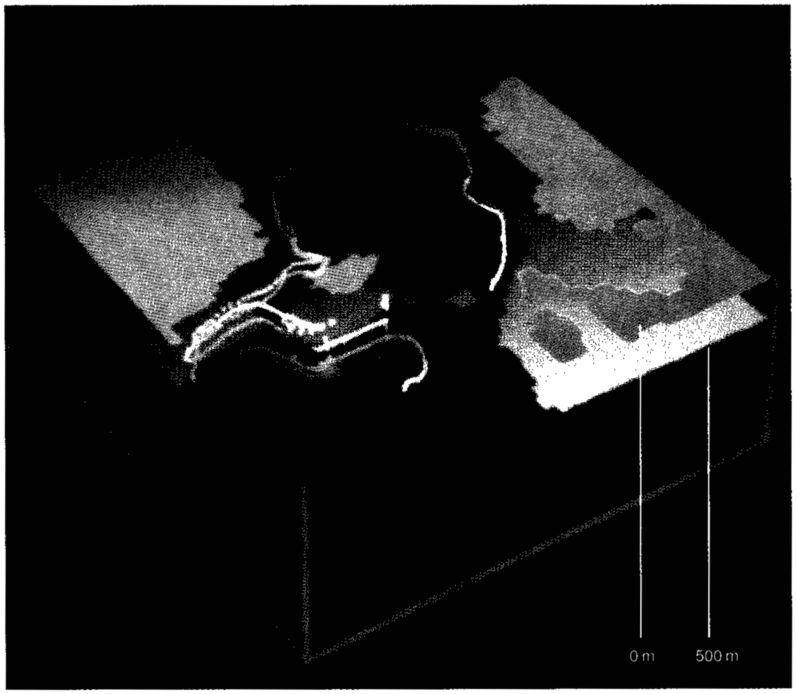
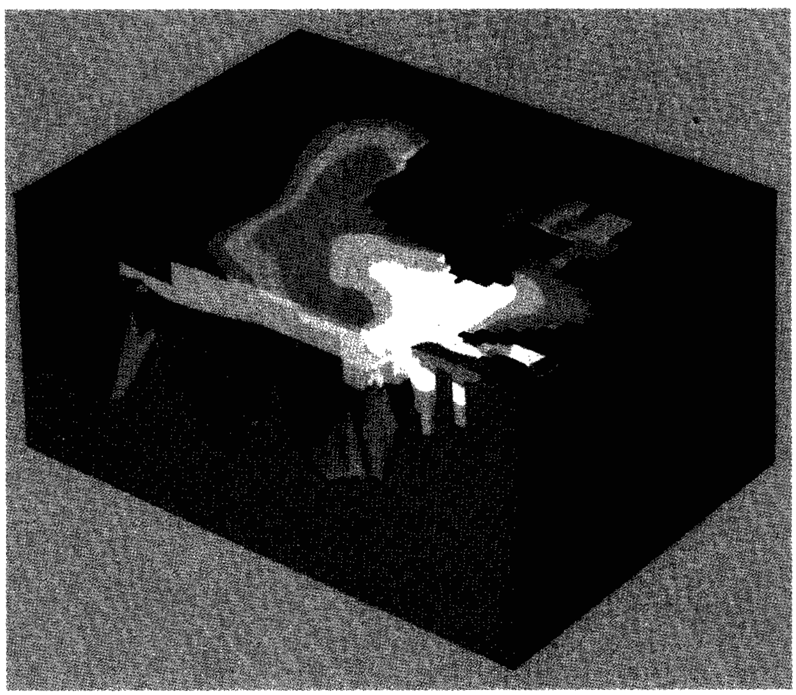


Figure 7 Simulated temperature in winter for the Greenland, Norwegian, and Barents Sea



are redistributed vertically and continue toward Greenland and the Labrador Sea.

Figure 7 shows the simulated temperature in the Greenland, Norwegian, and Barents Sea in the winter time. The temperature range is from −2 to +12 degrees Celsius. The vertical cross section is west of Spitsbergen and Ireland. The temperature drop shows how the Atlantic water releases heat to the atmosphere on its way northward. In the vertical cross section it is seen how the warmer and more saline Atlantic water flows under the cold and fresh polar surface water west of Spitsbergen.

This study of the Greenland-Iceland-Norwegian Sea is relevant for the study of climate change and variability.

The fluxes across the sill between Greenland and Scotland have large year-to-year variability and are not known in great detail. Estimates based on observed data, and water and salt balance calculations show large discrepancies (see Reference 22 and references therein). Estimates for the inflow of Atlantic water into the Norwegian Sea range from about 3 to 8.3 Sverdrups (Sv) with the strongest flow occurring between the Faeroe Islands and Scotland. (1 Sverdrup $[Sv] = 10^6 m^3/s$ and is approximately 1 megaton per second.) The outflow through the strait between Greenland and Iceland consists of the East Greenland Current above more dense and saline intermediate and deep water masses. Estimates of the outflow are of the order 2.8 to $3.5Sv$ for the upper water masses, and about $3Sv$ for the deep and intermediate water masses. In addition, there are some dense water masses spilling over the sill between Iceland and the Faeroe Islands. In particular, there is an outflow near the bottom of the channel between the Faeroe Islands and Scotland of about $1.3Sv$ of the most dense water masses entering the North Atlantic.

In the model, the inflow of warm and saline water from the North Atlantic into the Norwegian Sea is of the order 3 to $6Sv$. The flows between the Faeroe Islands and Scotland, and between Iceland and the Faeroe Islands, are of the order $4 \pm 1Sv$ and $0.5 \pm 0.5Sv$, respectively, with the maximum in the winter time. The outflow to the North Atlantic takes place through the strait between Greenland and Iceland. Most of this, about $3.5 \pm 1.5Sv$, is captured in the East Greenland Current. Below these water masses there is an outflow of the order $1.0Sv$ of more dense and saline intermediate water masses.

There are some observed features which are not present in the model simulations. A narrow clockwise circulation that occasionally transports Atlantic water west of Iceland into the Iceland-Norwegian Sea is not resolved in the model. The outflow of intermediate water across the sill between Iceland and the Faeroe Islands, and the outflow through the deep and narrow channel between the Faeroe Islands and Scotland, are also missing.

Concluding remarks

The model reproduces the major features of the ocean circulation in the North Atlantic and the Greenland-Iceland-Norwegian Sea. The inflow of Atlantic water into the Norwegian Sea, and the outflow of upper water masses between Greenland and Iceland, are consistent with previous estimates.[22] The model underestimates the outflow of intermediate and deep water masses between Greenland and Scotland. However, the real topography between Greenland and Iceland, and particularly between the Faeroe Islands and Scotland, have deep and very narrow channels that are important for the deep outflow. In order to model these fluxes in a more realistic manner, one might have to employ much finer resolution than is used in this work.

The model gives weaker and more shallow convection in the Greenland-Norwegian Sea than obtained in estimates from a few decades ago. However, the atmospheric temperature data that are used in the simulations are monthly means of the ECMWF data from 1985 to 1990, which are warmer than previous temperature climatologies. Reduced convection in the Greenland Sea in the last decade has also been found in tracer studies.[23] Processes that might be of importance for deep water formation, which are not included in the model,[2] could also be a reason for weaker convection in the model.

The motivation for this study of the Greenland-Iceland-Norwegian Sea is its relevance for climate change and variability. In this work we have focused on the circulation in the Greenland-Iceland-Norwegian Sea, deep water formation due to convection, and exchanges with adjacent basins. The work presented is the first attempt at a fine resolution coupling of the North Atlantic and the Arctic via the Greenland-Iceland-Norwegian Sea.

Exchanges with the North Atlantic and the Arctic Ocean are found to be crucial for the circulation in the Greenland-Iceland-Norwegian Sea. The circulation in the region is strongly constrained by the bottom topography. In order to get realistic fluxes across the ridge between Greenland and Scotland the coupling between the North Atlantic, the Greenland-Iceland-Norwegian Sea, and the Arctic is essential. This is due to the outflow of cold, relative fresh upper water from the Arctic that follows the coast of Greenland, and convection and deep water formation in the Greenland-Norwegian Sea that contributes to the outflow of the dense water masses across the ridge between Greenland and Scotland.

In addition to its relevance to climate studies, this model can also be used to study other environmental problems. The fluxes of warm and saline water in the North Atlantic and the Greenland-Iceland-Norwegian Sea are crucial for biological production, fish population, and ecosystem dynamics in this region. The North Atlantic and the Greenland-Iceland-Norwegian Sea are also thought to be important for the oceanic uptake of atmospheric CO_2. This is a motivation to also use the present model in studies of the oceanic carbon cycle.

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The model simulations were performed on an IBM 3090/600S with vector facilities at the IBM Bergen Environmental Sciences & Solutions Centre in Bergen, Norway. The three-dimensional temperature profile in Figure 7 was produced by use of the Bergen Scientific Centre Advanced Data Visualization software on an IBM RISC System/6000 workstation.

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