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A numerical simulation of the sea ice cover in the northern Greenland Sea

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Abstract. A numerical simulation of the sea ice cover in the northern Greenland Sea (NGS) is presented. The simulation is carried out using the coupled sea ice ocean general circulation model of Oberhuber (1993). The coupled model is forced using monthly climatological atmospheric forcing. The model domain includes both the Arctic Ocean and the North Atlantic. The large-scale characteristics of the observed sea ice cover in the NGS are reasonably well reproduced when compared with the limited observations available. Two notable aspects of the simulation are (1) a trough in the ice compactness across Fram Strait and (2) a polynya along the northeast coast of Greenland. Both of these features are evident in the observations during the spring–summer period. A sensitivity experiment in which the ice internal stress term is removed from the ice model demonstrates that the inclusion of a realistic sea ice rheology is a key factor in simulating the detailed features noted above for the NGS.

1. Introduction

A sea ice model will only produce a reasonable simulation of the ice edge in the northern Greenland Sea (NGS) if it is coupled to an ocean model [*Hibler and Bryan*, 1987]. This is because the horizontal advection and the vertical convection of heat in the ocean are both important in determining the ice edge position. This fact has also been demonstrated by *Holland et al.* [1993] using the same sea ice model as in the present study. Attention in the present study is not focused on the sea ice edge, but rather on the ice characteristics (i.e., compactness, thickness, and velocity) within the pack ice in the NGS. It is there that we propose that a realistic treatment of ice rheology is of fundamental importance for a credible simulation. In contrast to its importance in determining the ice edge, ocean heat transport does not appear to play a dominant role within the pack ice of the NGS.

Observations of the ice compactness within the NGS indicate several consistent features. The particular ones which we note in Figure 1 are (1) land fast ice occurring along the east coast of Greenland; (2) a trough in ice concentration running from Nordostrundingen on the northeast coast of Greenland, southeastward across the pack ice, and terminating at the ice edge in the Greenland Sea; and (3) the appearance of several polynyas along the east coast of Greenland, the most dominant of which occurs just south of Nordostrundingen. It is referred to as the Northeast Water (NEW) Polynya. Features (2) and (3) may also be seen in other observations, as found for instance, in the ice atlas of *Gloersen et al.* [1992, Figure 3.8.2].

The NEW Polynya is characterized by an ice free or partly covered (i.e., 1–4 tenths) ocean surface which one would normally expect to be ice covered owing to the heavy export of ice that occurs from the Arctic Ocean into the NGS. The polynya covers an area of up to 44,000 km^2 [*Wadhams*, 1981]. Polynyas are important in that they are sites of

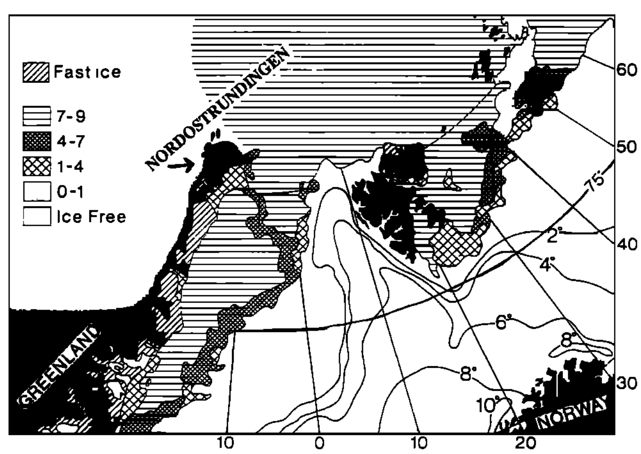

Figure 1. Observed sea ice compactness in June 1983 based on a compilation from various sources as carried out by the *Norsk Meteorologisk Institutt* [1983]. The compactness is in units of tenths, and the legend is given on the left-hand side of the figure. Two features of interest are the trough of ice compactness (i.e., 4–7 tenths) extending from Nordostrundingen in a southeasterly direction toward the open Greenland Sea and the occurrence of a polynya (i.e., 1–4 tenths) just southeast of Nordostrundingen. (Ocean temperature contours are indicated south of the ice edge).

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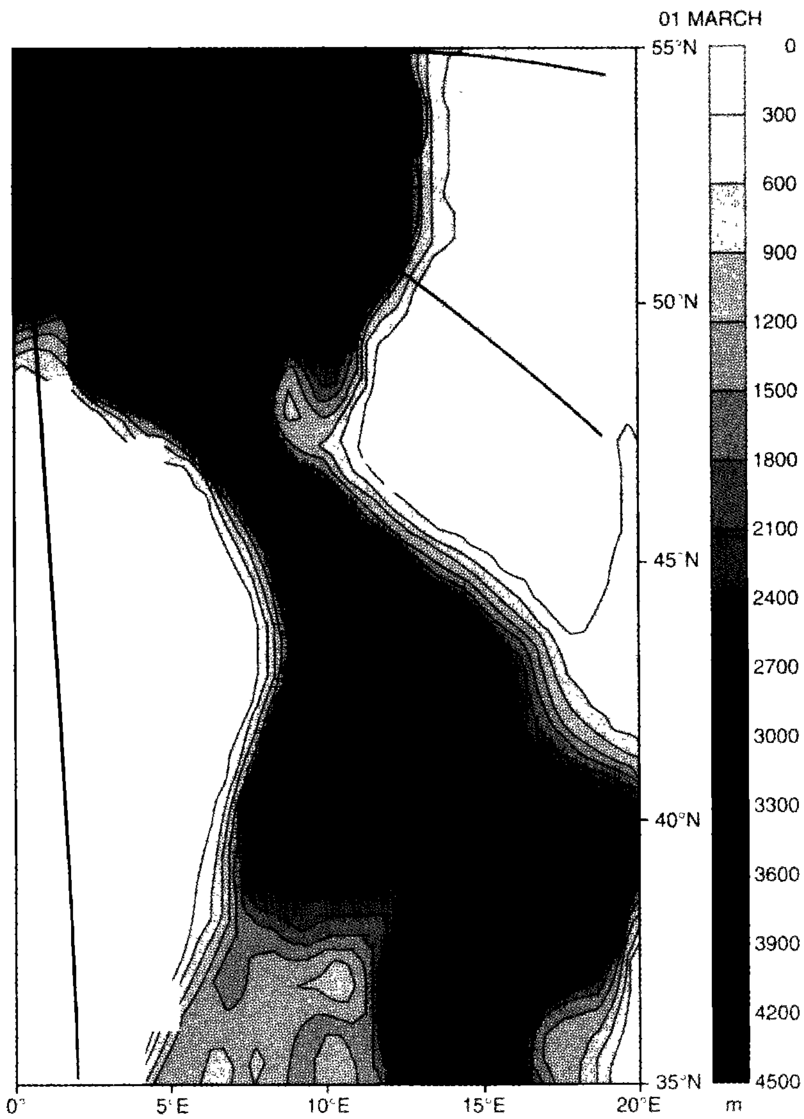

Figure 2. Topography in that part of the model domain which includes the northern Greenland Sea (NGS). The entire Arctic Ocean and North Atlantic Oceans, which are modeled in the simulation, are not shown. The north pole is located precisely at the top left corner. The degrees of latitude and longitude labeled along the axes are in the rotated coordinates of the model and do not correspond to geographic coordinates. As the contour interval is 300 m, the model topography appears much coarser than it is in the actual simulation.

relatively large exchanges of heat and moisture between the atmosphere and ocean. Biologically, they are equally important; because of reduced ice cover and optimal light conditions, they are believed to be regions of significant primary production. They are also important habitats for marine mammals and birds [*Dunbar*, 1981].

Oceanographic studies of the NEW Polynya have been limited by inaccessibility. *Wadhams* [1991] has proposed that the polynya is caused by a combination of strong northwesterly winds, the sheltering effect of Nordostrundingen on the main ice stream coming from the Arctic Ocean via the Greenland offshore zone, and the presence of an eddy or local gyre in this lee. Recent work by the *NEWATER Steering Committee* [1993] has shown the importance of the area for carbon deposition on the local seafloor and also discusses various mechanisms potentially responsible for maintenance of the reduced ice cover in the polynya. They suggest that upwelling of warm water may be important as is the case for the North Water Polynya in northern Baffin Bay [*Mysak and Huang*, 1992]. Hydrographic and current observations by *Schneider and Budéus* [1995] suggest, rather, that a northward coastal current in the polynya interacts with a persistent ice barrier to the south which protects the area from ice advection. As a part of this study, a numerical model is used to investigate an alternative hypothesis whereby the ice internal stress is proposed to be responsible for the ice characteristics in the interior of the pack ice of the NGS, which in turn allows for polynya formation farther south.

This paper is organized as follows. Section 2 briefly describes the layout of the coupled sea ice-mixed layer-isopycnal ocean model. The simulated sea ice characteristics in the NGS are presented in section 3. Section 4 gives a brief discussion on the interpretation of the model results.

2. The Model

The model used for this study is that of *Oberhuber* [1993]; it consists of three coupled submodels. The sea ice is represented by a dynamic thermodynamic model with viscous-plastic rheology [*Hibler*, 1979] and includes a snow model [*Oberhuber*, 1992], the mixed layer by a turbulent kinetic energy model, and the deep ocean by an isopycnal layer model. The models interact via the exchange of momentum, mass, heat, and salt. Forcing occurs via the specification of monthly mean climatological atmospheric fields (see *Oberhuber* [1992] for a discussion of these fields), and realistic topography is employed. The equations describing each model are fully described by *Oberhuber* [1993].

The model domain chosen for this study includes the Arctic Ocean, the Greenland-Iceland-Norwegian Sea, and the North Atlantic Ocean; consequently, there is essentially no influence on the simulation within the NGS from the distant boundaries of the domain. As for the treatment of the distant boundaries themselves, a wall is placed across the equator in the Atlantic, and no exchange through the Bering Strait is allowed (D. M. Holland et al., An investigation of the general circulation of the Artic Ocean using an isopycnal model, submitted to *Dee-Sea Research*, 1994) (hereinafter referred to as submitted manuscript, 1994). Since the focus of this study is the NGS, only a limited portion of the entire model domain is shown (see Figure 2). The model's bathymetry is obtained by interpolating a 5-min of arc resolution topographic data set onto the model's grid of 0.5° (i.e., 30 min of arc) resolution. The main bathymetric features in the vicinity of Fram Strait and the Greenland Sea are preserved (Figure 2).

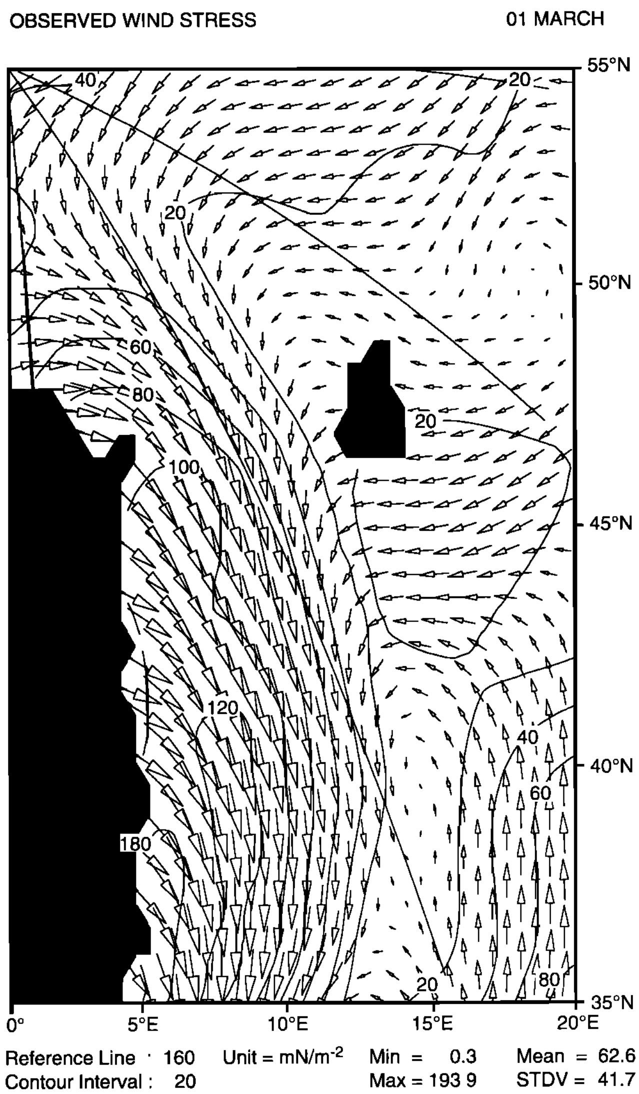

Figure 3a. Observed wind stress for March. The strongest wind stress occurs in March and has a magnitude of about 0. 1 N/m^2.

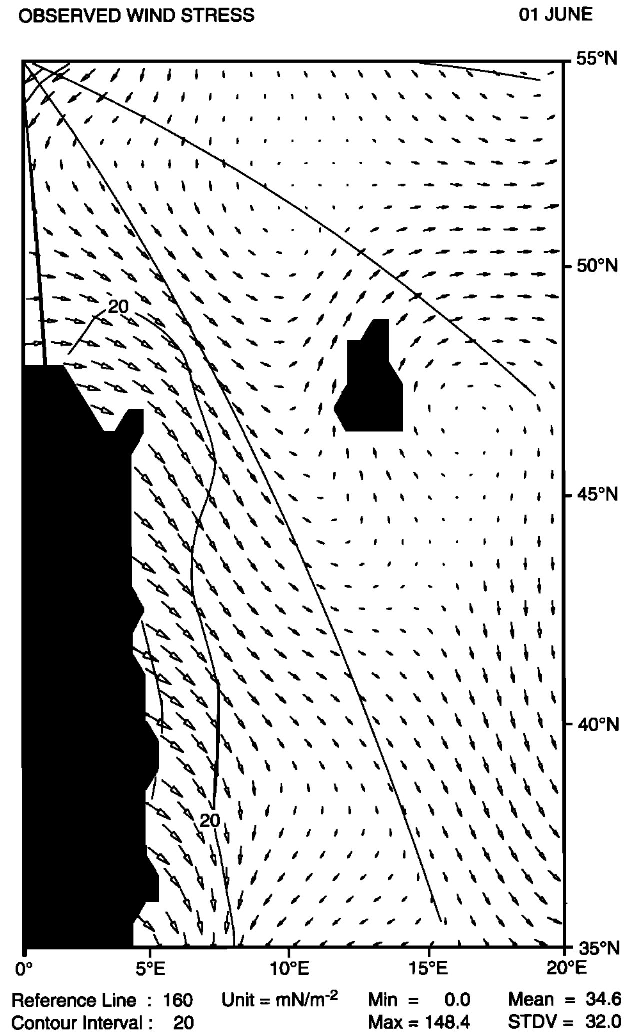

Figure 3b. Observed wind stress for June. The June wind stress is much weaker and even reverses direction in the vicinity of Spitsbergen. The maximum stress is about 0.02 N/m^2.

A common problem with numerical models written in spherical coordinates for the Arctic Ocean is the convergence of meridians of longitude near the north pole. The resulting small east-west grid spacing near the pole leads to inefficient, small time step constraints. This can be overcome by rotating the model coordinates through Eulerian angles such that the model coordinates converge to a point in northern Siberia, which is outside the defined model domain. All figures presented in this paper indicate the rotated latitude and rotated longitude coordinates along their axes.

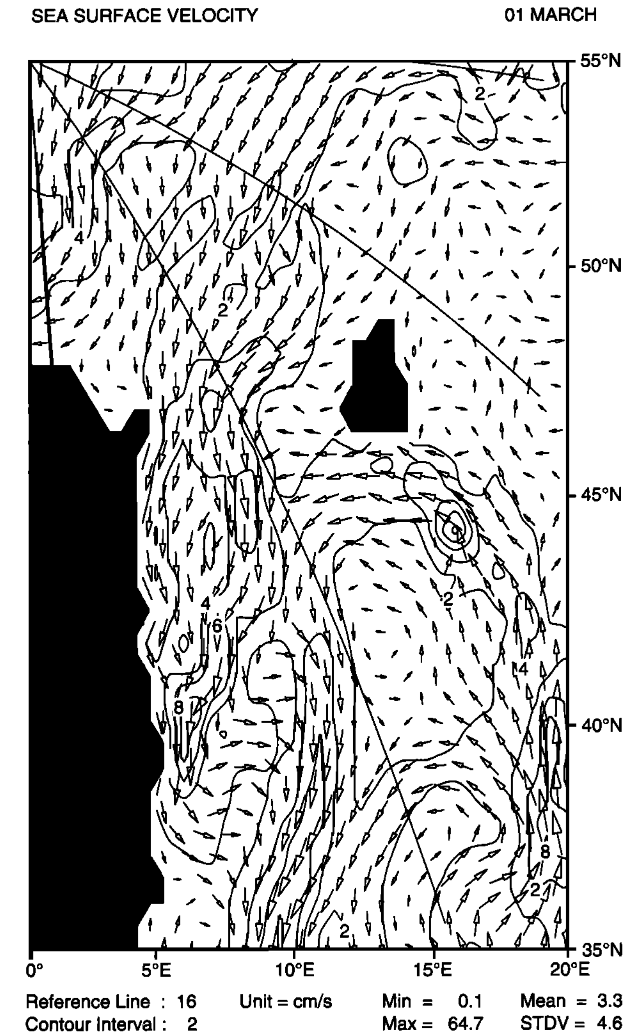

Figure 4a. Modeled ocean surface currents for March. There is little variation in the currents in the NGS from March to June. The magnitude of the current near the trough and the polynya is about 10 cm/s.

The true geographical meridians are superimposed on the figures as thin lines (e.g., Figure 2). The implicit numerical scheme used for solving the sea ice equations has recently been improved such that they may now be solved using a large time step even without rotating the model coordinates away from the geographic coordinates. Previously, this was not possible with this sea ice model. Such a capability is important for global-domain simulations, in which case it is not convenient to rotate the coordinates. In such a situation the model north pole and the geographic north pole will coincide.

The model resolves the water column using nine vertical layers of prescribed potential density. The prescribed initial density and thickness of each layer are obtained via interpolation of the temperature and salinity data of *Levitus* [1982].

The model spin-up is for 50 years with a time step of one-half day. This is an adequate time for the sea ice and mixed-layer models to reach an equilibrium; however, the deep-ocean circulation almost certainly is not in equilibrium after such a short period (Holland et al., submitted manuscript, 1994). One simulated year requires 10 hours of CPU time on a Cray YMP-M90; consequently, integrations for thousands of years are not feasible.

The surface boundary conditions on salinity and temperature are essentially of Newtonian type. The surface temperature is relaxed to an apparent air temperature which is computed as the result of a complete surface energy balance that includes long-wave, short-wave, sensible, and latent heat terms [see *Oberhuber* [1993] for details].

The model is forced using monthly mean climatological fields of wind stress, radiation, air temperature, humidity, rainfall, and cloud cover. The model derives the forcing at a particular time step by interpolating between climatological fields of neighboring months. Owing to the excessive number of monthly figures and because the ice features of interest in this study generally begin to develop in early spring and are most evident in summer (see Figure 1), most figures shown in this paper are only for the months of March and June. The spring-summer variation in wind stress, for example, is shown in Figure 3a for March and Figure 3b for June.

Although this study uses a coupled sea ice ocean model, the focus of the study is the response of the sea ice to forcing from the atmosphere and ocean. In the same manner that the

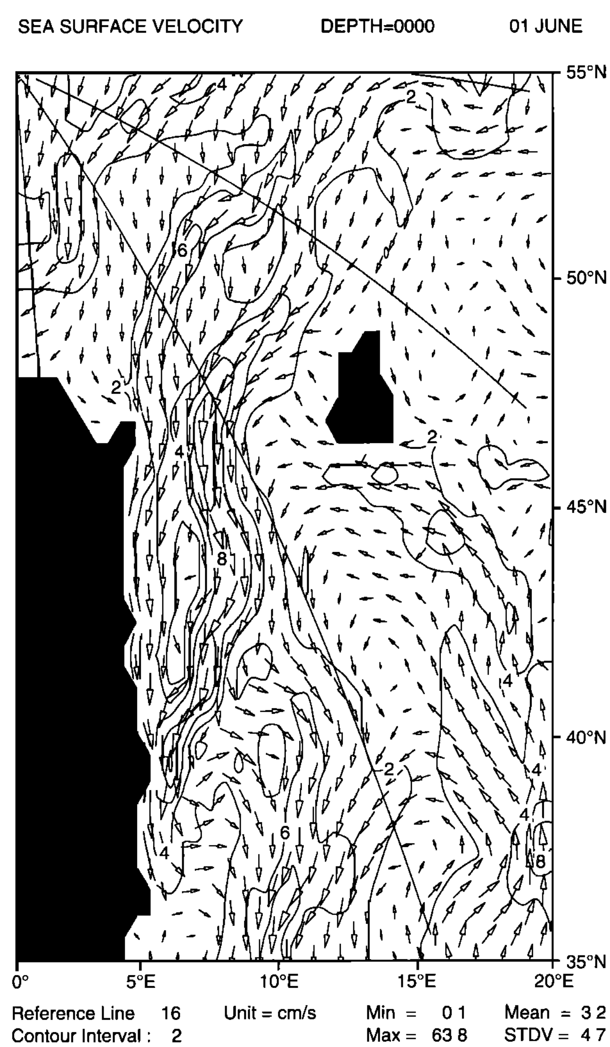

Figure 4b. Modeled ocean surface currents for June. The velocity scale is the same as Figure 4a.

winds (Figures 3a and 3b) provide a stress on the surface of the ice, the surface ocean currents provide a stress to the bottom of the ice. The spring-summer modeled ocean currents are shown in Figures 4a and 4b.

The simulated ocean currents reproduce the East Greenland Current (EGC), the West Spitsbergen Current (WSC), and the cyclonic Greenland Sea gyre. However, the northward flowing Northeast Greenland Coastal Current (NEGCC) is not reproduced. This suggests that the spatial resolution of 0.5° employed here is inadequate for all features in the NGS. A resolution closer to 0.1° may be required to simulate such detailed coastal features as the NEGCC. The reader is referred to *Bourke et al.* [1987] for a discussion of the above mentioned currents.

3. Sea Ice Results

The simulated sea ice motion (Figures 5a and 5b) is, in part, consistent with observations (see Figure 6). The "observations" shown in Figure 6 are derived from an algorithm that tracks ice features from successive satellite images and thereby estimates ice velocities. The most obvious difference between the modeled and the satellite-based velocities occurs along the coastal area of east Greenland. The satellite velocities suggest that the ice is either absent or stagnant in that area, whereas the simulation indicates significant southerly flow of ice in that area. This discrepancy may also be the result of inadequate horizontal resolution in the model.

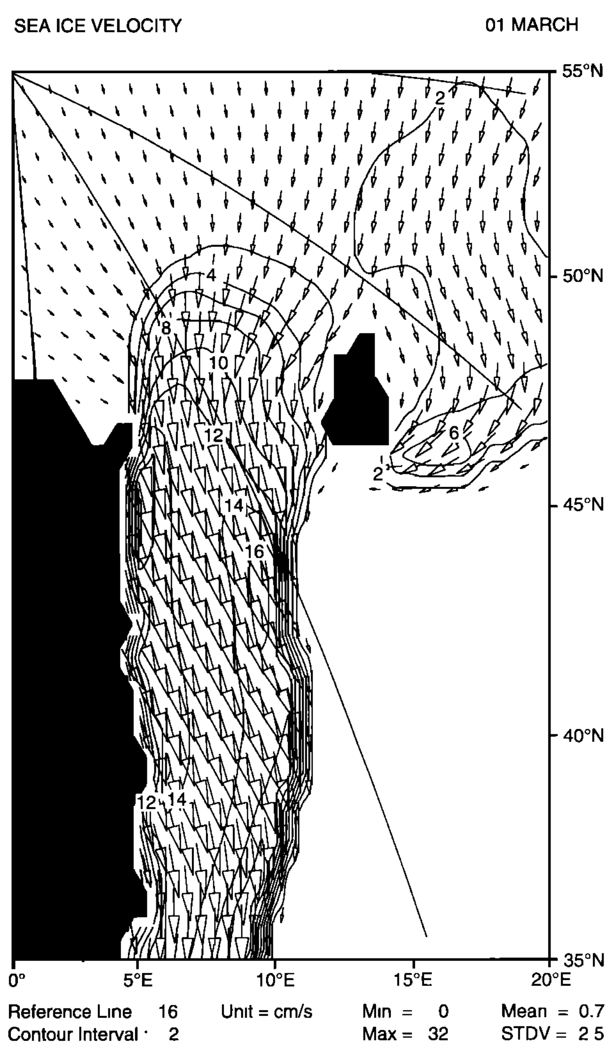

Figure 5a. Modeled sea ice velocity for March. The maximum velocity in March has a magnitude of about 15 cm/s.

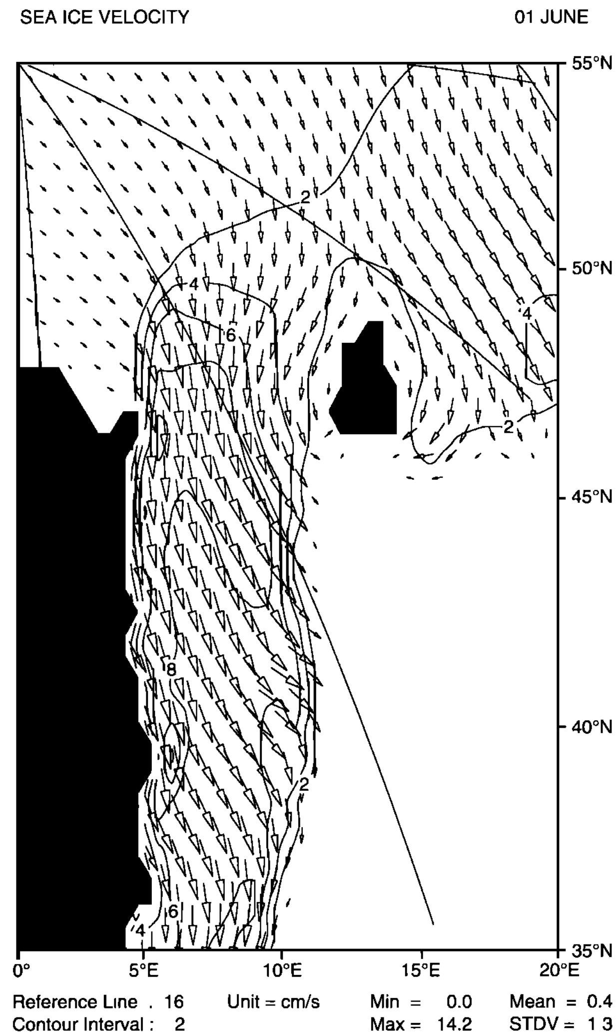

Figure 5b. Modeled sea ice velocity for June. The velocities are somewhat weaker in June than in March. The velocity scale is the same as Figure 5a.

The simulated ice velocity pattern in the vicinity of Fram Strait consists of ice flowing towards the strait and then accelerating southward along the east Greenland coast. The ice undergoes a sudden acceleration just south of the strait because it is driven southward by both the atmospheric winds (Figure 3) and the ocean currents (Figure 4). This divergent forcing of the sea ice may be a contributing factor in controlling the ice characteristics in the NGS.

The simulated sea ice thickness field (Figures 7a and 7b) indicates that ice in the vicinity of the observed NEW Polynya is minimal in thickness; furthermore, a tonguelike feature of thicker ice extends southward from Fram Strait. The actual ice thickness in the polynya region is about 0.75 m.

The simulated sea ice compactness (Plates 1a and 1b) shows a pattern consistent with that of observations (Figure 1). High ice concentration is found both north and south of

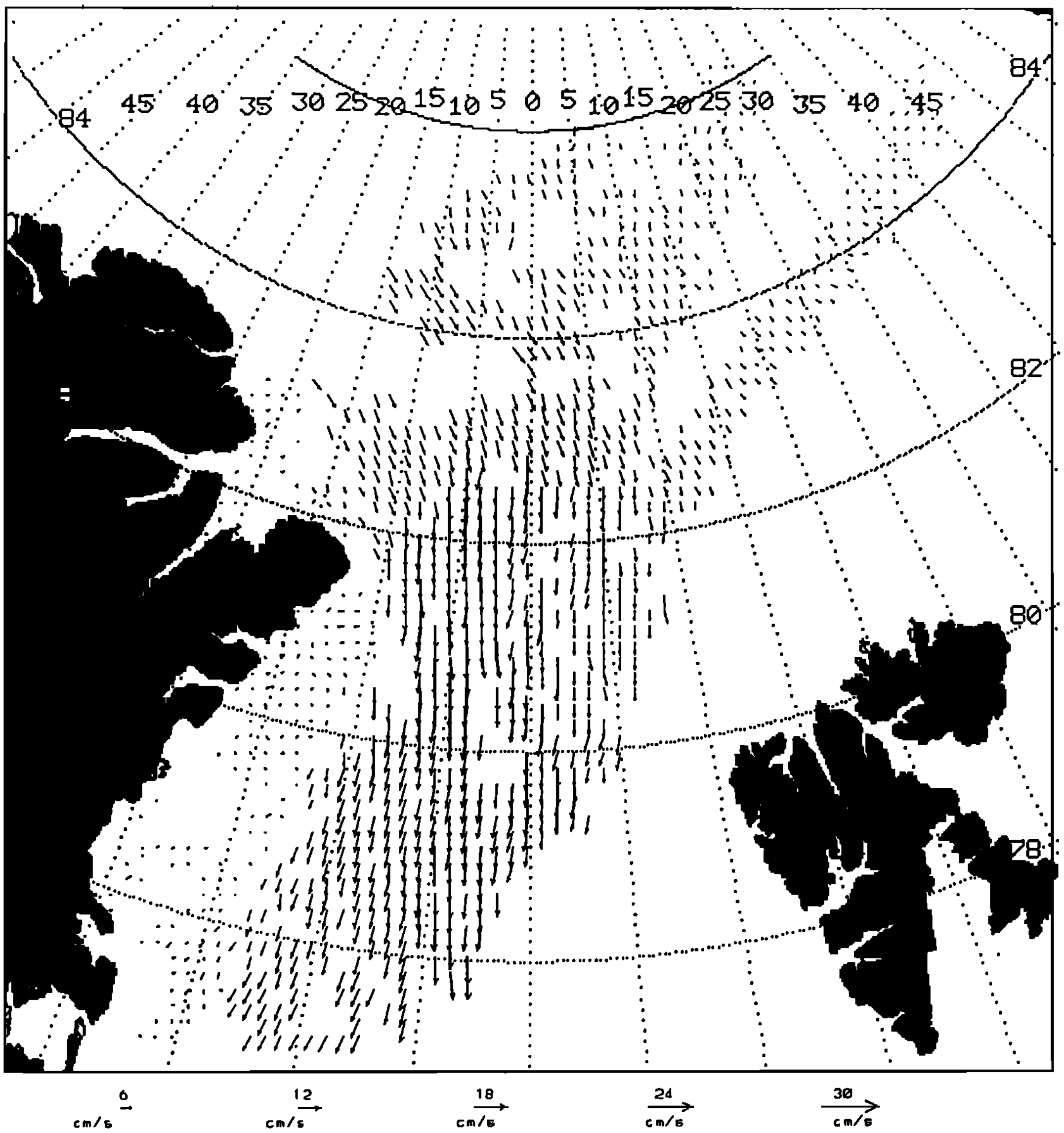

Figure 6. Sea ice velocity inferred from satellite imagery for April (reproduced from *Emery et al.* [1991]).

Fram Strait, with a trough in the concentration extending from the area of the NEW Polynya southeastward to the Greenland Sea. The lowest ice concentration in the interior of the pack ice occurs both in the simulation and in the observations in the vicinity of the NEW Polynya. There are, in reality, several observed polynyas along the east coast of Greenland. The simulation shows that they are all associated with abrupt coastal features.

To test the hypothesis that it is the ice internal stress (i.e., rigidity) which causes the formation and maintenance of the trough and polynya, an experiment is performed in which the ice internal stress is neglected (i.e., the ice is in a so-called "free-drift" mode). In such a case the ice has no internal strength and no longer possess an inherent mechanical strength which would otherwise allow it to form barriers where it meets obstacles (e.g., islands or channels). For this simulation (Plates 2a and 2b) both the trough and polynya disappear. In fact, the area of the observed NEW Polynya shows even higher concentration than neighboring areas in June (Plate 2b). By contrast, the position of the ice edge has not changed significantly between Plates 8 and 9. This is to be expected as the ice edge in the NGS is predominantly controlled by ocean heat transport, as mentioned earlier.

4. Discussion

The study has shown that the *Oberhuber* [1993] coupled sea ice–mixed layer–isopycnal ocean model is capable of producing a reasonable simulation of the ice characteristics in the NGS.

Of particular interest in the simulation was the occurrence of a polynya in the same geographical area as the observed NEW Polynya. The principal mechanism for the formation and maintenance of the polynya is the combination of wind and ocean forcing, the positioning of land masses, coupled with a realistic parameterization for the ice internal stress. The sensitivity experiment in which the ice strength was removed suggests that none of the hypotheses suggested previously by other authors for the formation of the polynya is in itself a complete explanation for the existence of the NEW Polynya.

The mechanism proposed by *Wadhams* [1981], namely, that an abrupt coastal feature (i.e., Nordostrundingen) causes the polynya, is partly in agreement with our hypothesis. However, he did not comment on the role played by the ice stress. For instance, in the sensitivity experiment in which the ice internal stress was set to zero, while the coastal geometry was unchanged, a polynya (or a trough) was not produced. The upwelling of warm water as put forth by the *NEWATER Steering Committee* [1993], while dominant in determining the position of the ice edge facing the open Greenland Sea, does not appear to be a key to the appearance of the polynya. The interaction of the NEGCC with an ice barrier to the south of the NEW Polynya, as suggested by *Schneider and Budéus* [1995], does not seem critical to the occurrence of the polynya, as we obtain a polynya in this study despite not being able to simulate the NEGCC. It must be clearly stated that the present study does not conclusively reject any of the above three hypothesis as none of those hypotheses is explicitly tested in this study. Further numerical experiments would have to be conducted that allow each hypothesis to be selectively tested and judged. Here we are simply presenting our own hypothesis, namely, that because the ice has an inherent mechanical strength, it tends to build up when squeezed through a constricting channel (i.e., Fram Strait) which serves as a large-scale barrier to it freely flowing down along the east coast of Greenland. We argue that on a geophysical scale the ice that is accelerated and then squeezed through Fram Strait experiences sufficient stresses to give rise to the large-scale trough and the polynya that are observed in the NGS. These stresses lead to a mechanical build up of the ice which extends even into the ice which is located to the north of Fram Strait. If the flow of ice through Fram Strait was indeed simply a so-called free-drift flow, then the internal stresses would have no role to play. The simulations in Plates 1 and 2 would have been identical, and a trough and polynya would have occurred in both plates in the same locations.

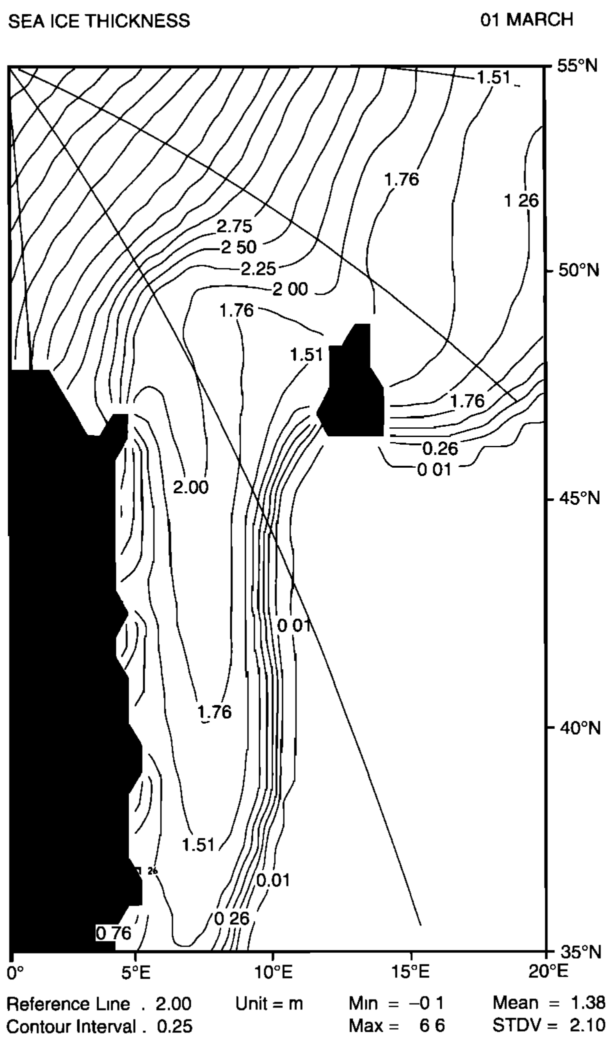

Figure 7a. Modeled sea ice thickness for March. The ice in Fram Strait has a maximum thickness of about 2.00 m in March, while in June it decreases to 1.75 m. The ice thickness pattern for both months depicts a tonguelike pattern emanating from Fram Strait. The thickness in the vicinity of the Northeast Water Polynya is minimal compared with its surroundings. The contour interval is 0.25 m.

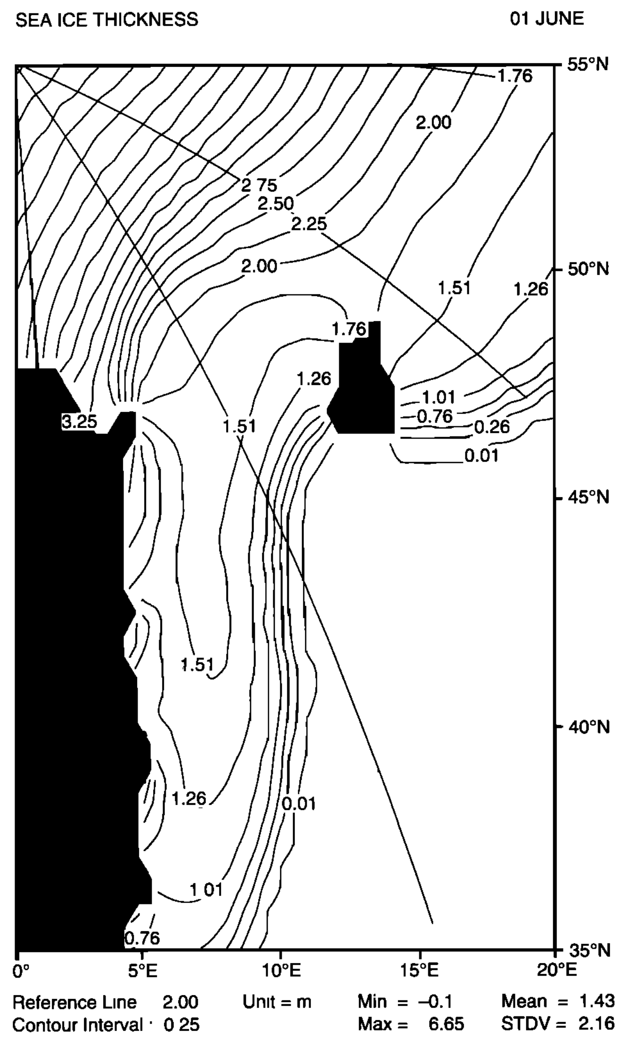

Figure 7b. Modeled sea ice thickness contours for June. The contour interval is 0.25 m.

Quantitatively, there are differences between the observed June (Figure 1) and the modeled sea ice compactness (Plate 1b). However, the emphasis here has been to reproduce the

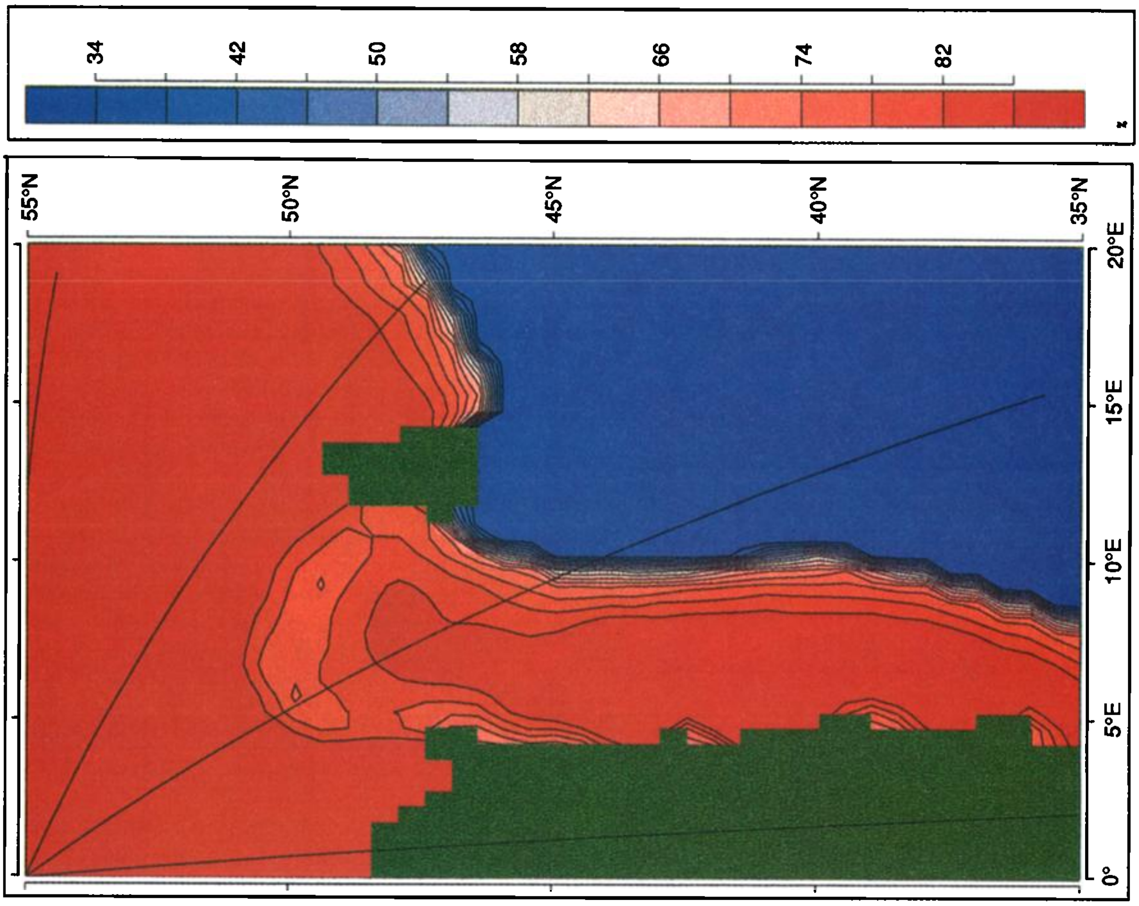

Plate 1a. Modeled sea ice compactness for March. In both March and June there is clear evidence of an archlike feature extending from Nordostrundingen to Spitsbergen. The contours are in percentage.

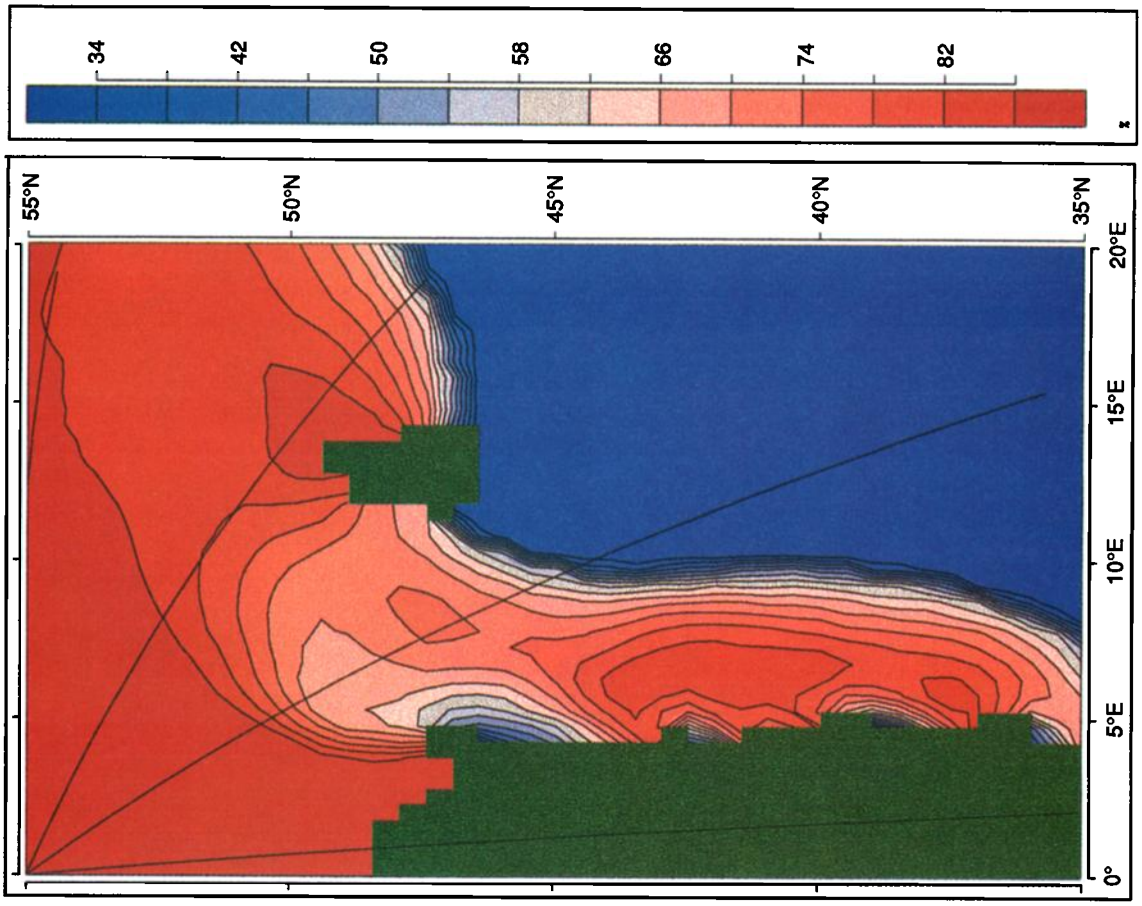

Plate 1b. Modeled sea ice compactness for June. There is a trough in the compactness extending from Nodrostrundingen toward the open Greenland Sea. The lowest compactness in the interior of the pack ice is found in the vicinity of the observed Northeast Water Polynya. The contours are in percentage.

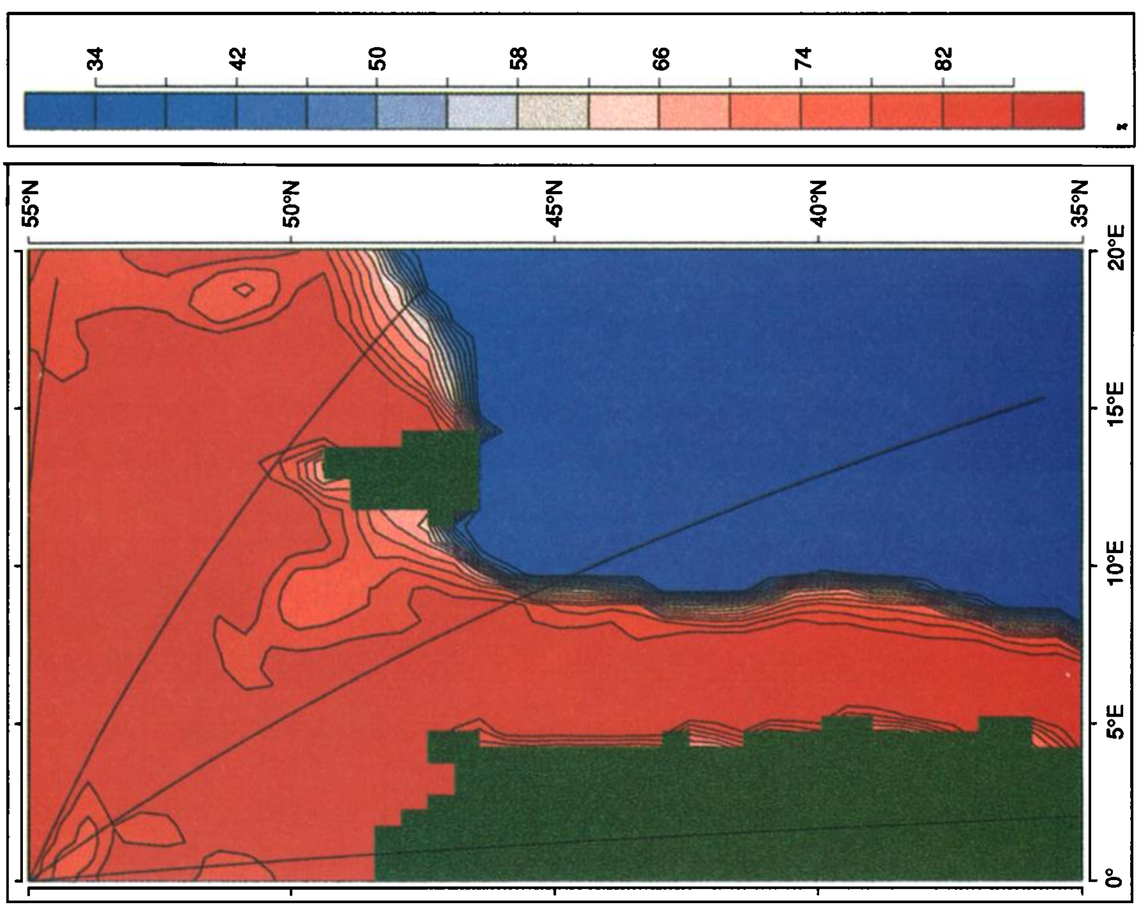

Plate 2a. Modeled sea ice compactness for March for the sensitivity experiment in which the ice internal stress term is omitted from the model. The change in the simulation is drastic. The contours are in percentage.

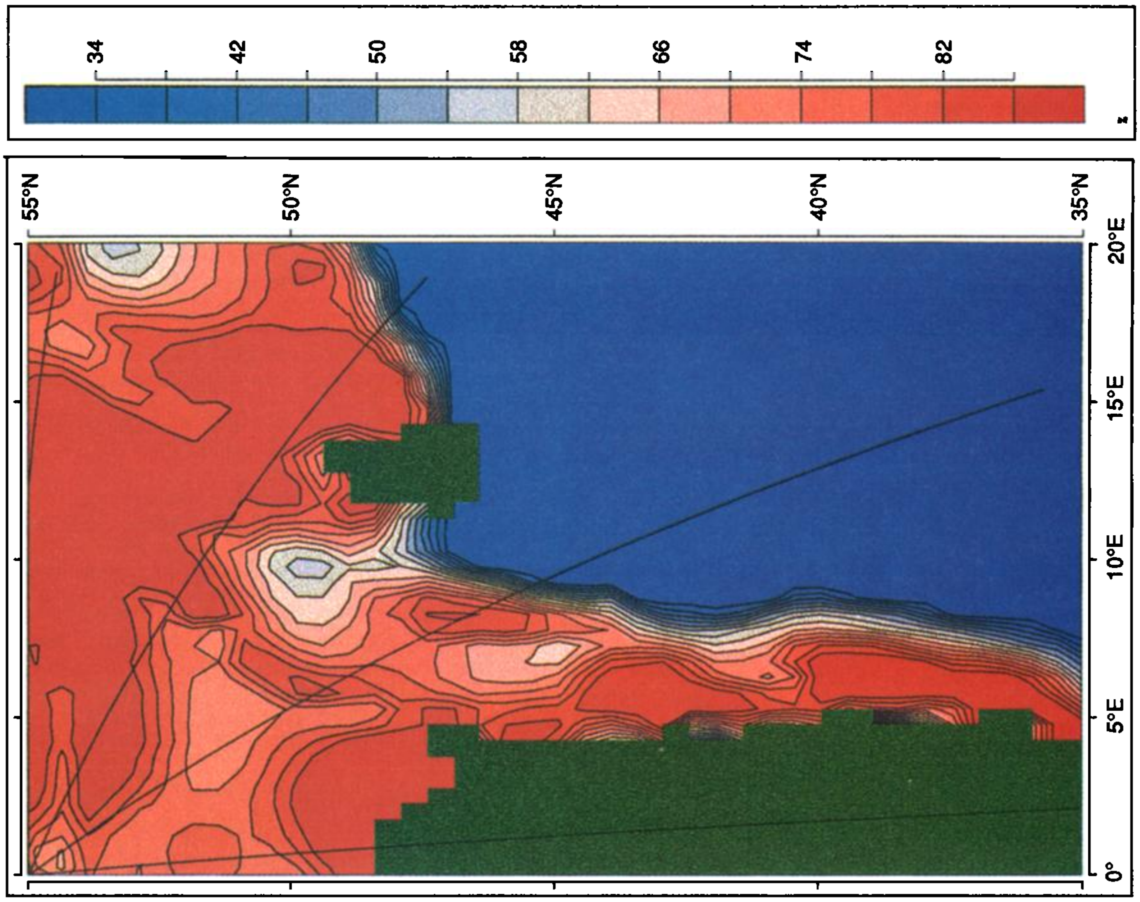

Plate 2b. Modeled sea ice compactness for June for the sensitivity experiment. The contours are in percentage.

main qualitative features of the NGS ice characteristics. Obviously, errors exist in the atmospheric forcing fields, as well as incomplete model physics, which prevent an exact simulation of observed results. In addition, significant interannual variability exists in the size and structure of the NGS ice characteristics which are not represented in this climatological study. The intention here has been to demonstrate that the model used does simulate in a robust manner the main features (i.e., the trough and polynya) which dominate the large-scale ice compactness in the NGS. As the model employed here is also used for global climate studies (albeit, at a lower resolution), it is encouraging that it is capable of simulating naturally occurring local features, such as the trough and polynya. This is achieved without tuning the model parameters from the values used in the global simulations.

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