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**Prediction of Ice Conditions along the NSR  
Using Satellite Data**

**By Chang Kyu Rheem and Hajime Yamaguchi**

**INSROP International Northern Sea Route Programme**



Central Marine  
Research & Design  
Institute, Russia



The Fridtjof  
Nansen Institute,  
Norway



Ship and Ocean  
Foundation,  
Japan



# International Northern Sea Route Programme (INSROP)

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## INSROP WORKING PAPER NO. 125-1999

Box C RS

Sub-Programme I: Natural Conditions and Ice Navigation

Project I.6.3: Prediction of Ice Condition along the NSR Using Satellite Data

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**Title: Prediction of Ice Conditions along the NSR Using Satellite Data**

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INSROP is a direct result of the normalization of the international situation and the Murmansk initiatives of the former Soviet Union in 1987, when the readiness of the USSR to open the NSR for international shipping was officially declared. The Murmansk Initiatives enabled the continuation, expansion and intensification of traditional collaboration between the states in the Arctic, including safety and efficiency of shipping. Russia, being the successor state to the USSR, supports the Murmansk Initiatives. The initiatives stimulated contact and cooperation between CNIIMF and FNI in 1988 and resulted in a pilot study of the NSR in 1991. In 1992 SOF entered INSRÖP as a third partner on an equal basis with CNIIMF and FNI.

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# PREDICTION OF ICE CONDITION ALONG THE NSR USING SATELLITE DATA: FINAL REPORT INSROP PROJECT I.6.3

by

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## ABSTRACT

A new system for sea ice condition prediction has been developed. The SSM/I satellite ice distribution data is used as an initial data for prediction computation by linking the SSM/I data with the prediction program. The SSM/I data are in digital form and can be obtained almost real time. The prediction computation is made by a dynamic sea ice model, Distributed Mass / Discrete Floe model. The computation time takes only 20 minutes for eight days simulation for the area of 1,000 km, the Sea of Okhotsk. It takes about 4 hours for the whole Arctic Ocean.

The Distributed Mass/Discrete Floe model is a numerical model proposed for the computation of pack ice movement. This model possesses the advantages of both the continuum and the discrete element models: it can express the discrete nature of pack ice which is difficult by using a continuum model, and requires a much shorter computation time than a discrete element model. In the present work, ice concentration dependency of the form drag of an ice floe is newly taken into account. As the result, the over estimation of ice zone has been improved and the prediction has become more similar to observation.

The present system has been applied for the sea ice motion predictions in the Sea of Okhotsk and the Arctic Ocean. The present system is still in developing stage. More improvement of the computation model and scheme is needed, and also more comparison with the observation data is required by acquiring more natural condition data. The present results, however, have showed favorable agreement with the observations, demonstrating the high potential of the present system.

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## 1. INTRODUCTION

The Project Box C-R I.6.3 titled "Prediction of ice condition along the NSR using satellite data" has carried out for two years of 1997 and 1998. The purpose of this project is to develop the prediction system shown in Fig.1, where the satellite ice observation data is directly used for the initial data of the sea ice motion prediction computation. In 1997, the data linkage program was developed and the existing sea ice motion prediction program was improved. Then, the prediction system was applied to the Okhotsk Sea ice as a

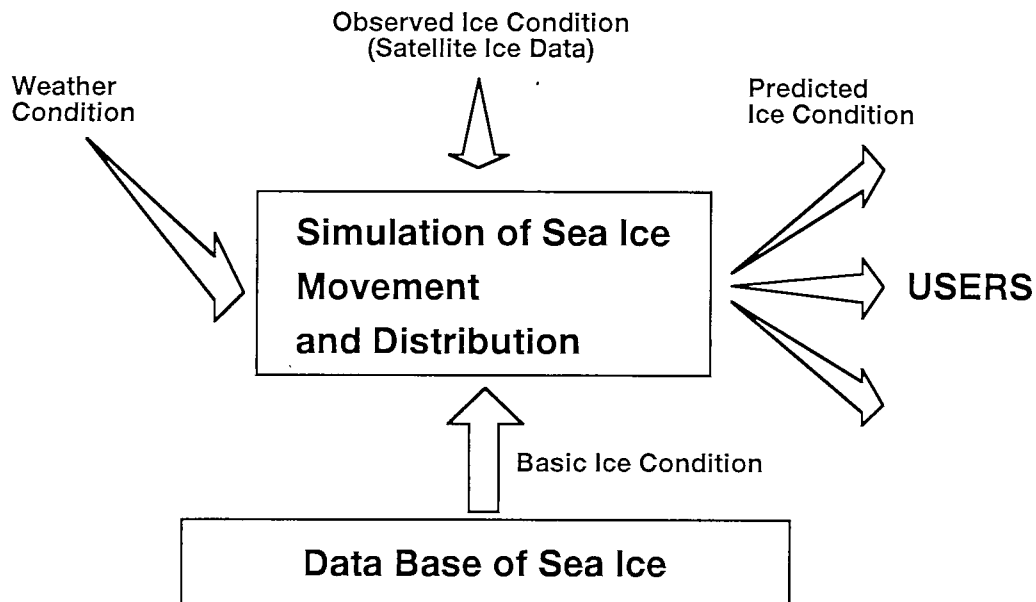


Fig. 1 Concept of ice condition prediction system

test case. Since the system showed favorable performance in the Okhotsk Sea, it was extended to the Arctic Ocean in 1998.

The prediction computation was made by the Distributed Mass / Discrete Floe model, DMDF model, whose basic part was developed in the INSROP Phase I project I.6.2 (Rheem et al., 1997). Several satellite data were investigated during the project, and the SSM/I sea ice data was finally adopted for the initial condition for the computations.

## 2. DISTRIBUTED MASS/DISCRETE FLOE MODEL

Distributed Mass/Discrete Floe (DMDF) model is a dynamic model for numerical simulation of pack ice movement. It has the advantages of both a continuum model and a discrete model. It can express the discrete nature of pack ice, which is difficult to express by a continuum model. It can also treat a larger number of floes in much shorter computation time than a discrete element model. In the present model, ice concentration dependency of the form drag on an ice floe is newly taken into account. The pack ice is divided

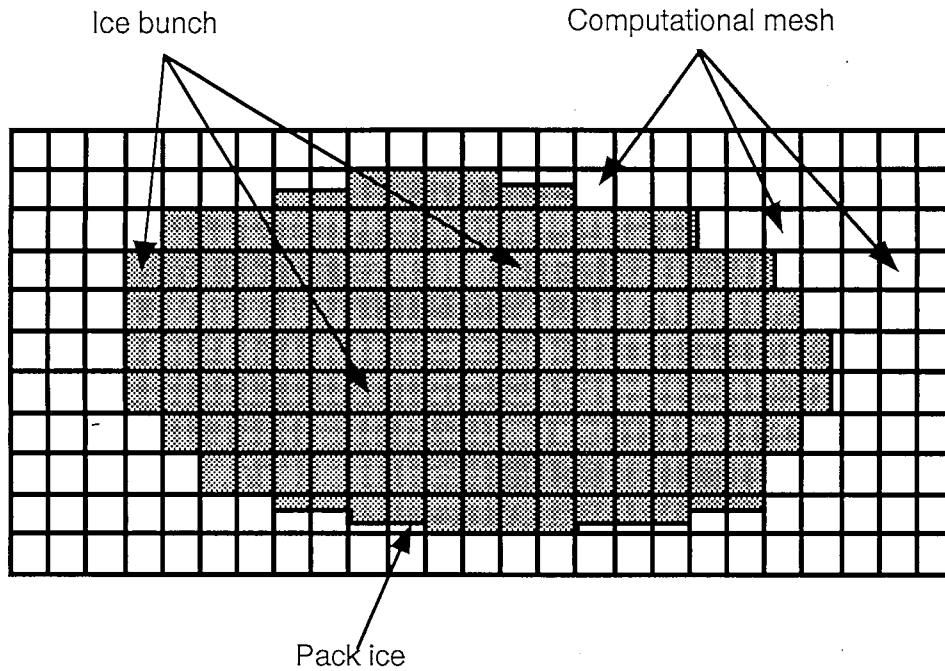


Fig. 2 Pack ice, computational mesh and ice bunch

into rectangular bunches in which the floes, all of equal size, are assumed to be distributed uniformly. The floes are modeled as inelastic disks floating on water. The equations for bunch motion are formulated from the momentum conservation law, taking into account the Coriolis force, the interaction forces between the bunches and the drags due to the wind and current. The ice interaction forces are formulated from the relationship between the impulse on the ice bunch and the variation in the bunch momentum. A semi-Lagrangian ice mass transport procedure is adopted. A multilayer model is used to simulate the flow of sea water simultaneously with the ice floe movement in order to describe

the surface flow more accurately. Finite difference formulations of the sea water flow have been carried out using the MacCormack predictor-corrector scheme.

### 2.1 Ice model

In the present model, in which the orthogonal coordinate system is adopted for computation of pack ice rheology, the pack ice is divided into rectangular ice bunches as shown in Fig. 2. A bunch is characterized by the values of its center position, area and ice concentration as shown in Fig. 3. The ice concentration is a ratio of the ice covered area to the bunch area

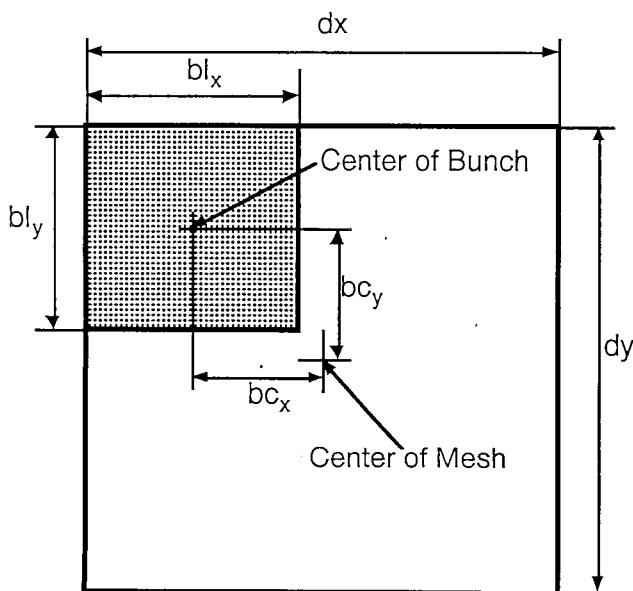


Fig. 3 Bunch and computational mesh

$$C_i = \frac{A_i}{bl_x bl_y} \quad (1)$$

where  $C_i$  denotes the ice concentration of a bunch,  $A_i$  is the total surface area of floes in a bunch and  $bl_x bl_y$  is the bunch area. The floes are modeled as inelastic disks. The floes, all of equal area and thickness, are assumed to be distributed uniformly. The total surface area of floes in a bunch is expressed by

$$A_i = N_{ix} N_{iy} \frac{\pi dl_{ic} dl_{ic}}{4} \quad (2)$$

where  $N_{ix} N_{iy}$  is the number of floes in a bunch,  $dl_{ic}$  is the diameter of a disk floe.

## 2.2 Equations of bunch motion

Ice floe movement on a relatively short time-scale (of the order of several days at most) can be well simulated numerically using a dynamic model in which the Coriolis force, the interaction forces among the ice bunches and the drags due to the wind and water current are taken into account, neglecting ice growth and ablation. The momentum change of the ice bunch in a time interval of  $dt$  can be expressed by

$$M_i(\vec{v}_i^{t+dt} - \vec{v}_i^t) = \int_t^{t+dt} (A_i \vec{\tau}_a + A_i \vec{\tau}_w + \vec{F}_f - M_i \vec{f}_k \times \vec{v}_i^t + \vec{F}_i) \quad (3)$$

where

$$M_i = \rho_i h_i C_i bl_x bl_y \quad (4)$$

$$\vec{\tau}_a = \rho_a C_a |\vec{v}_a - \vec{v}_i| (\vec{v}_a - \vec{v}_i) \quad (5)$$

$$\vec{\tau}_w = \rho_w C_w |\vec{v}_w - \vec{v}_i| (\vec{v}_w - \vec{v}_i) \quad (6)$$

$$\vec{F}_f = C_f \frac{1}{2} \rho_w dl_{ic} h_i N_{ix} N_{iy} |\vec{v}_w - \vec{v}_i| (\vec{v}_w - \vec{v}_i) \quad (7)$$

$M_i$  is the bunch mass, while  $\vec{\tau}_a$  and  $\vec{\tau}_w$  denote the shear stresses acting on the bunch due to the wind and water current, respectively.  $\vec{F}_f$  is the total form drag force on the floes in a bunch.  $-M_i \vec{f}_k \times \vec{v}_i^t$  is the Coriolis force which acts in the clockwise direction perpendicular to the bunch movement in the Northern Hemisphere.  $\vec{F}_i$  denotes the ice internal force, i.e., the interaction force between floes in a bunch and between bunches. This is the force due to the collision and separation of floes.

## 2.3 Form drag coefficient of pack ice

In order to investigate the form drags of pack ice, an experiment was performed in a circulation water channel. Figure 4 shows the principal description of the experiment. Each disk was 10 cm in diameter and 2 cm in draft. The drag force of each floe denoted by gray, was measured under the several floe concentration and current speed. We consider the measured drag force on each floe as form drag force, because the friction force on a floe is very small compared to form drag under this condition. Figure 5 shows the mea-



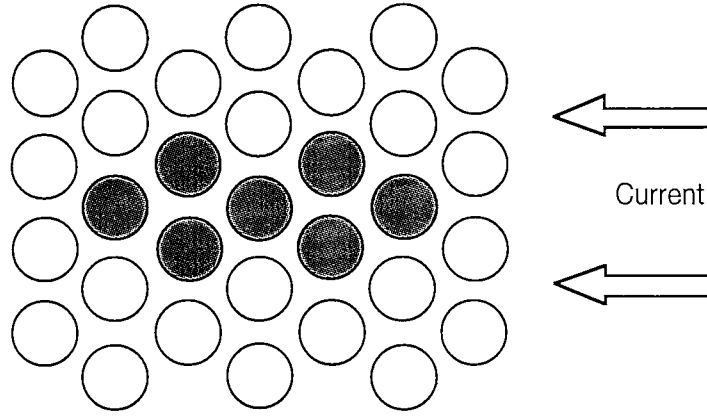


Fig. 4 Principal description of the experiment for measurement of form drag

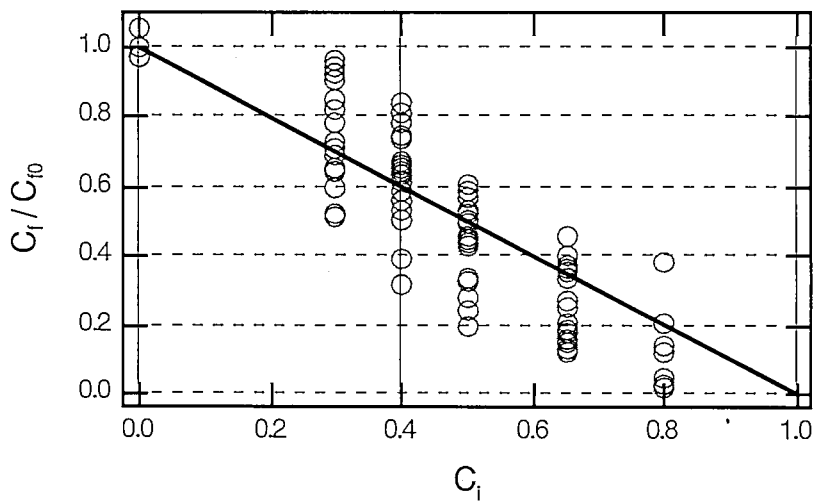


Fig. 5 Form drag coefficient of disk

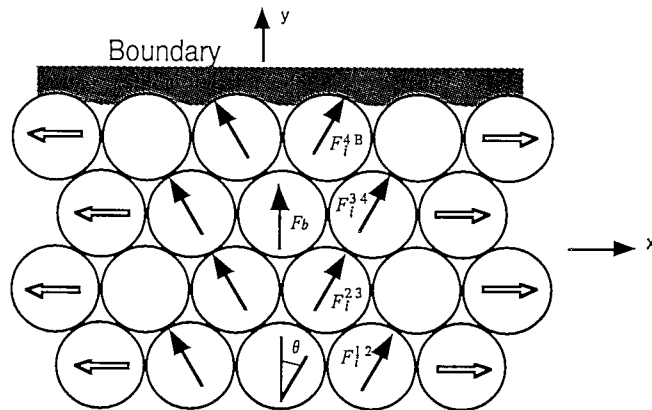


Fig. 6 Lateral expansion of floes

sured form drag coefficient of the floe. The form drag coefficient is defined by

$$C_f = \frac{F_f}{\frac{1}{2} \rho_w d l_{ic} h_i v_w^2} \quad (8)$$

The form drag coefficient decreases as the floe concentration,  $C_v$ , increases. This result is very important to simulate the pack ice movement in the region of low ice concentration and small floe size. In a previous study (Rheem et al., 1997), the effect of ice concentration on the form drag was disregarded. As a result, the extension of the ice zone was over estimated. In the present model, the form drag of pack ice is taken into account as a following relation.

$$C_f = C_{f0}(1 - C_i) \quad (9)$$

where  $C_{f0}$  is the form drag coefficient of an isolated disk.

#### 2.4 Ice interaction force due to floe shape: Lateral expansion of floes

The movement of an ice bunch against a fixed boundary is shown in Fig. 6, where four rows of floes in the bunch collide with the fixed boundary. The floes break away from the group sequentially due to the interaction forces. Half of the ice floes colliding with the boundary moves to the right of the bunch, and half moves to the left. This lateral movement is called "lateral expansion of floe" here. Expressing the number of floe rows that collide with the fixed boundary in the y-direction as  $n_{iy}$ , the total expansion momentum towards the right side becomes

$$F_{ixe}^R dt = \frac{n_{iy} \cdot n_{iy} \cdot F_b (\sin \theta - \mu_i \cos \theta)}{4(\cos \theta + \mu_i \sin \theta)} dt \quad (10)$$

Since the total mass of the floes which move to the right is  $M_i \cdot n_{iy} / N_{iy} / 2$ , their acceleration becomes  $F_{ixe}^R / (M_i \cdot n_{iy} / N_{iy} / 2) = 2 F_{ixe}^R \cdot N_{iy} / (M_i \cdot n_{iy})$ . Thus, the right edge moves to the right for a distance of  $F_{ixe}^R \cdot N_{iy} \cdot dt^2 / (M_i \cdot n_{iy})$  in a time interval  $dt$  by integrating the acceleration. The left edge moves to the left for the same distance. As a result, after a time step  $dt$ , the x-direction length of the bunch becomes

$$bl_x^{t+dt} = bl_x^t + 2 \frac{F_{ixe}^R \cdot N_{iy}}{M_i \cdot n_{iy}} dt^2 \quad (11)$$

#### 2.5 Ice interaction force due to floe collision

The axial interaction forces are formulated from the relationship between the impulse on the bunch and the variation in the bunch momentum, provided the floes being treated as rigid bodies. Two ice bunches are shown in Fig. 7 as an example. The velocity of bunch A relative to bunch B is expressed by

$$v_s = v_i^A - v_i^B \quad (12)$$

In the case where  $v_s dt - dl - (S_x^A + S_x^B) / 2$  is positive ( $dl$  is the spacing between the bunches,

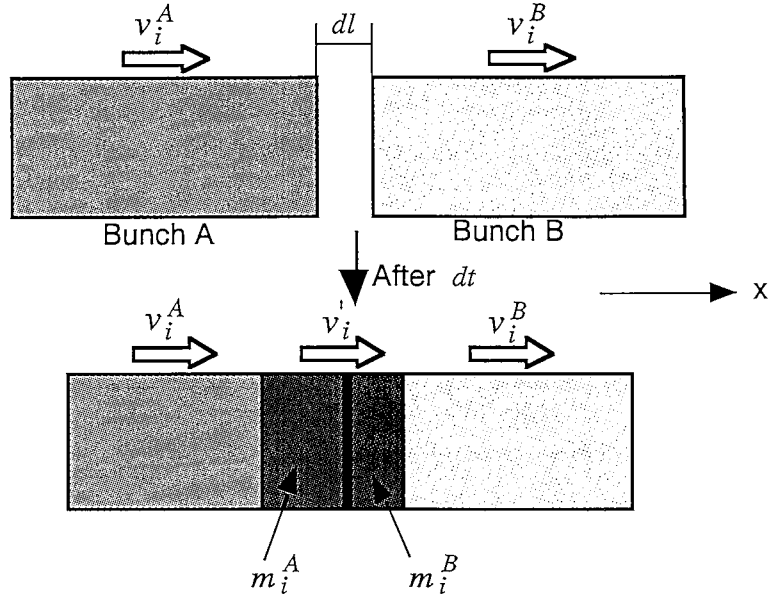


Fig. 7 Axial collision between bunches

$S_x^A$  and  $S_x^B$  denote the distances between the floes in the x-direction in bunches A and B, respectively), bunch A collides with bunch B within one time step  $dt$ . The number of floes in bunch A that take part in the collision with the neighboring bunch is an integer  $n_x^A$ , which satisfies the inequality

$$(n_x^A - 1)S_x^A \leq v_s dt - dl - (S_x^A + S_x^B) / 2 < n_x^A S_x^A \quad (13)$$

$n_x^A = 0$ , if  $n_x^A$  becomes less than 1. In the case  $n_x^A N_{ix}^A$  is the number of floes that collide with neighboring bunch B, the axial momentum change of bunch A due to the collision is expressed by

$$\int_t^{t+dt} F_{ix}^A dt = m_i^A (v_i' - v_i^A) \quad (14)$$

$$v_i' = \frac{m_i^A v_i^A + m_i^B v_i^B}{m_i^A + m_i^B} \quad (15)$$

$$m_i^A = \frac{n_x^A}{N_{ix}^A} M_i^A \quad (16)$$

$$m_i^B = \frac{n_x^B}{N_{ix}^B} M_i^B \quad (17)$$

where  $v_i'$  is the velocity of the floes taking part in the collision. The  $m_i^A$  and  $m_i^B$  are the masses of the floes taking part in the collision in bunches A and B, respectively. In the case where the vertical direction collisions occur simultaneously, the velocity of the floes taking part in the collision becomes

$$v_i' = \frac{m_i^A v_i^A + m_i^B v_i^B + (F_{ixe}^{RA} + F_{ixe}^{LB}) dt}{m_i^A + m_i^B} \quad (18)$$

where  $F_{ixe}^{RA}$  and  $F_{ixe}^{LB}$  are the expansion momenta due to the vertical direction collision, acting on bunches A and B, respectively.

## 2.6 Redivision into bunches at next time step

The bunches move in accordance with the above-mentioned equations and change their shape due to the interaction. As a result, the edges of the bunches do not coincide with the edges of the computation mesh after movement in the time interval  $dt$ . Therefore, the floes are redistributed into one bunch for one mesh, conserving mass and momentum. The characteristic values of the new bunch are given by

$$bl_x^{j,t+dt} = x_{\max}^j - x_{\min}^j \quad (19)$$

$$bl_y^{j,t+dt} = y_{\max}^j - y_{\min}^j \quad (20)$$

$$bc_x^{j,t+dt} = \frac{x_{\max}^j + x_{\min}^j}{2} \quad (21)$$

$$bc_y^{j,t+dt} = \frac{y_{\max}^j + y_{\min}^j}{2} \quad (22)$$

$$C_i^j = \sum_{k=1}^{n_b} C_i^{j,k} \quad (23)$$

$$C_i^j h_i^j = \sum_{k=1}^{n_b} C_i^{j,k} h_i^{j,k} \quad (24)$$

$$C_i^j h_i^j \bar{v}_i^{j,t+dt} = \sum_{k=1}^{n_b} C_i^{j,k} h_i^{j,k} \bar{v}_i^{j,t+dt} \quad (25)$$

where  $n_b$  is the number of bunches redistributed into the computation mesh under consideration (Rheem et al., 1997). Equations (23), (24) and (25) express the conservation of the ice concentration, mass and momentum, respectively.

## 2.7 Ocean flow

For ice movement, it is important to analyze the ocean flow, particularly near the sea surface. In the present computation, the ocean flow is divided into several horizontal layers as shown in Fig. 8. The momentum conservation equations (the Navier-Stokes equations integrated with respect to the layer height) are

$$\frac{\partial q_{wx}}{\partial t} + v_{wx} \frac{\partial q_{wx}}{\partial x} + v_{wy} \frac{\partial q_{wx}}{\partial y} - f q_{wy} = \frac{\tau_{ix} + \tau_{bx}}{\rho_w} + 2 E_{xx} \frac{\partial^2 q_{wx}}{\partial x^2} + E_{yx} \frac{\partial}{\partial y} \left( \frac{\partial q_{wx}}{\partial y} + \frac{\partial q_{wy}}{\partial x} \right) \quad (26)$$

$$\frac{\partial q_{wy}}{\partial t} + v_{wx} \frac{\partial q_{wy}}{\partial x} + v_{wy} \frac{\partial q_{wy}}{\partial y} + f q_{wx} = \frac{\tau_{iy} + \tau_{by}}{\rho_w} + 2 E_{yy} \frac{\partial^2 q_{wy}}{\partial y^2} + E_{xy} \frac{\partial}{\partial x} \left( \frac{\partial q_{wy}}{\partial x} + \frac{\partial q_{wx}}{\partial y} \right) \quad (27)$$

where  $q_{wx} = v_{wx} d z_k$  and  $q_{wy} = v_{wy} d z_k$  are the water fluxes in the x- and y-directions in the k-

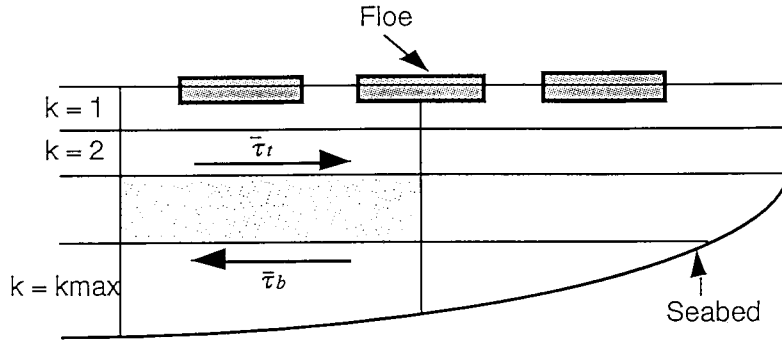


Fig. 8 Modeling of ocean flow

th layer, and  $d_{zk}$  is the height of the  $k$ -th layer.

For  $k=1$  the shear stress on the top layer becomes

$$\bar{\tau}_t = C_i \bar{\tau}_w + (1 - C_i) \bar{\tau}_{aw} + \bar{F}_f / dx dy \quad (28)$$

where

$$\bar{\tau}_{aw} = \rho_a C_d |\bar{V}_a| \bar{V}_a \quad (29)$$

$\bar{\tau}_{aw}$  is the shear stress between the water and air, and  $\bar{\tau}_w$  is the stress between the water and ice given by equation (6). The equation derived by Wu(1982) is used for the friction coefficient due to wind on the water surface.

$$C_d = (0.8 + 0.065 |\bar{V}_a|) \times 10^{-3} \quad (30)$$

For  $k=2$  to  $k_{max}$ ,

$$\bar{\tau}_t^{k-1} = -\bar{\tau}_b^k = \rho_w E_z \frac{\partial \bar{v}_w}{\partial z} \quad (31)$$

with the no-slip condition at the bottom of  $k_{max}$  layer. The eddy viscosity  $E_z$  is obtained by multiplying the grid spacing and the ice concentration parameter with  $E_{zo}$  i.e.,

$$\rho_w E_{zo} = \begin{cases} 0.114 |\bar{V}_a|^3 & |\bar{V}_a| < 4m/sec \\ 5.584 |\bar{V}_a| - 15.04 & 4m/sec \leq |\bar{V}_a| \leq 8m/sec \\ 0.463 |\bar{V}_a|^2 & 8m/sec < |\bar{V}_a| \end{cases} \quad (32)$$

The above equation is a modified form of the equations derived by Ekman and Thorade(1914). Finite difference formulations for the ocean flow are made on the basis of the MacCormack predictor-corrector scheme (Hoffmann, 1989).

### 3. SEA ICE MOTION PREDICTION IN THE SOUTHERN PART OF SEA OF OKHOTSK

The present system is applied to predict the sea ice motion in the Sea of Okhotsk as a test case. The numerical simulation covers the southern part of the Sea of Okhotsk as shown in Fig. 9. The sea ice data which have been obtained from satellite remote sensing



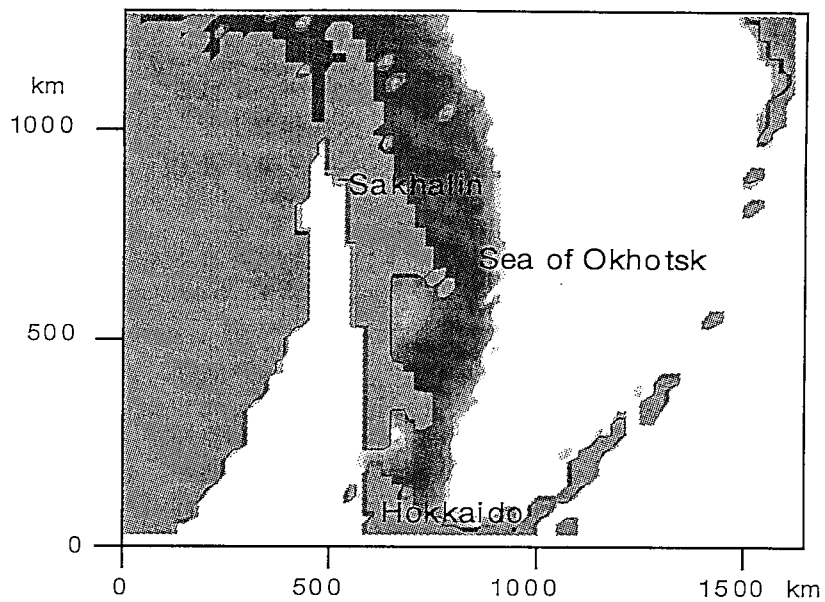


Fig. 9 Sea ice concentration on February 23, 1995

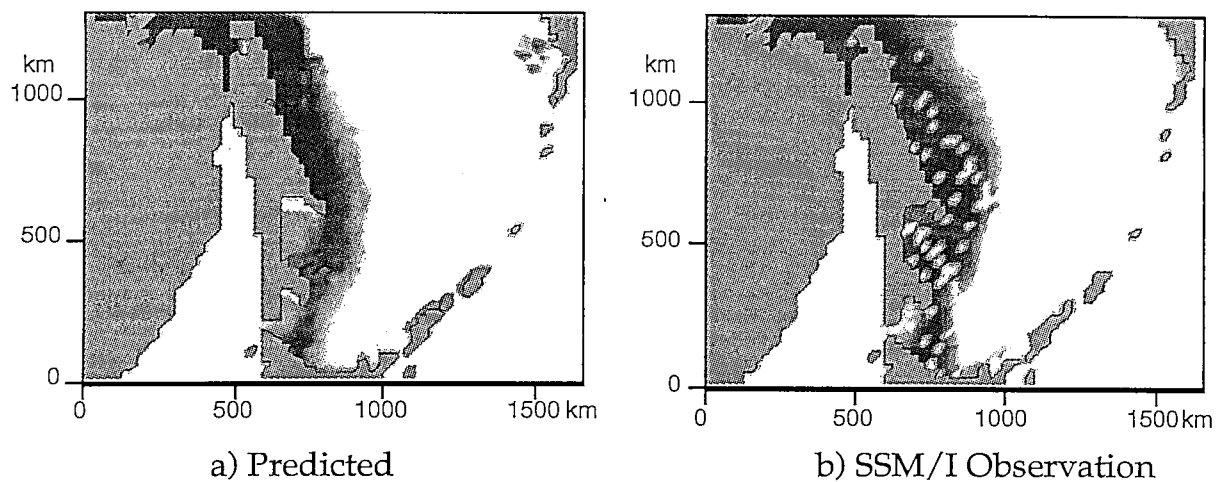


Fig. 10 Ice concentration on February 27, 1995

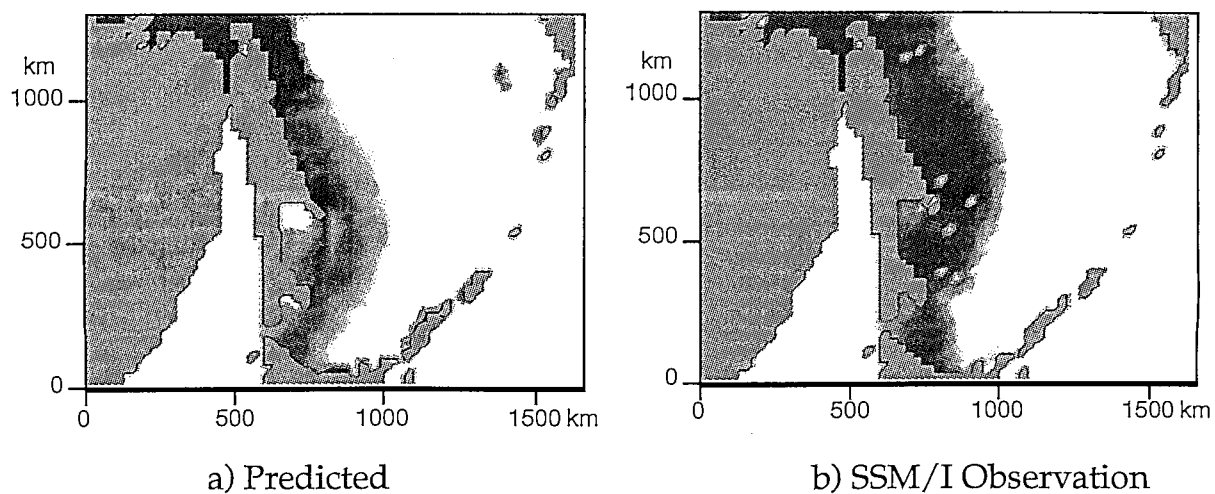


Fig. 11 Ice concentration on March 3, 1995

with passive microwave sensor SSM/I are used for the initial conditions of simulation. The numerical weather prediction data including the wind velocity at 10 m high from sea surface are used. Pack ice is driven by the wind and current. The change of ice condition is simulated during the winter season of that region. The computation domain is divided into 3,432 ( $66 \times 52$ ) square meshes with a size of 25 km which corresponds to the grid size of SSM/I sea ice data. The number of water layers is 4. The thickness of each layer is 5 m, 8m, 13m and 20 m, denoted from the top layer. The friction coefficient between air and ice  $C_a$  is 0.004 and the friction coefficient between water and ice  $C_w$  is 0.001, and the form drag coefficient of the disk  $C_{f0}$  is 1.2. The ice/ice friction coefficient  $\mu_i$  is 0.3. The same value is assumed for the ice/land friction coefficient.

In the present model, the data of ice concentration, ice thickness and floe size are needed for the initial ice condition. However, the SSM/I sea ice data have information of ice concentration only, therefore the ice thickness and floe size are assumed by the following equations,

$$h_i = \{C_{im} h_{im} + (C_i - C_{im}) h_{if}\} / C_i \quad (\text{m}) \quad (33)$$

$$dl_{ic} = 1000 - 950(C_i - 1) \quad (\text{m}) \quad (34)$$

where  $h_{im} = 1.3C_{im} + 0.7$  and  $h_{if} = 0.7(C_i - C_{im}) + 0.3$  denote the ice thicknesses of multi- and first-year ice, respectively.  $C_{im}$  is the concentration of multi-year ice.

The ice conditions are predicted for eight days. The pack ice are driven by the wind and water current. The computation time has taken about 20 minutes for eight days using a Windows NT PC machine with DECchip21164 433 MHz. Figure 9 shows the SSM/I sea ice distribution on February 23, 1995. Figures 10 and 11 show the predicted and SSM/I sea ice distributions on February 27 and March 3, respectively. Although amount of sea ice is less than SSM/I sea ice data, the appearance of predicted sea ice distribution is similar to that.

#### 4. SEA ICE MOTION PREDICTION IN THE ARCTIC OCEAN

The present system is applied to predict the sea ice motion in the Arctic Ocean. Since more time than expected has been needed to look for the data for computations, the prediction work is still preliminary. However, the present results are not too bad. The SSM/I ice concentration data have been downloaded by ftp from the National Snow and Ice Data Center, USA. The wind data has been obtained from the European Centre for Medium-range Weather Forecasts. The sea current data is very limited. Although we will make computations by assuming some current data in near future, the results shown here are those computed with no current assumed. This means that no initial current is assumed and driven by water surface friction due to wind and ice with no velocity set at the bottom of water layer. The depth of water is also assumed constant at 100m. The water depth is divided into 5 layers. The thickness of each layer is 5, 10, 18, 27 and 40m, denoted

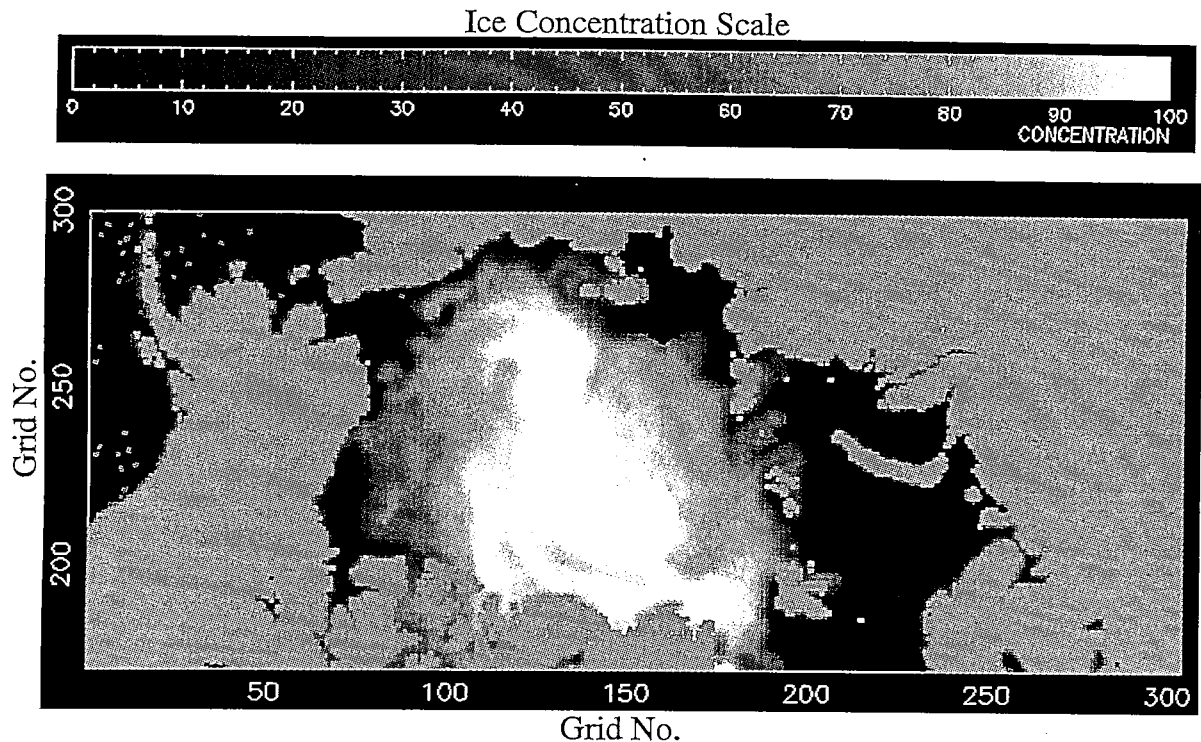


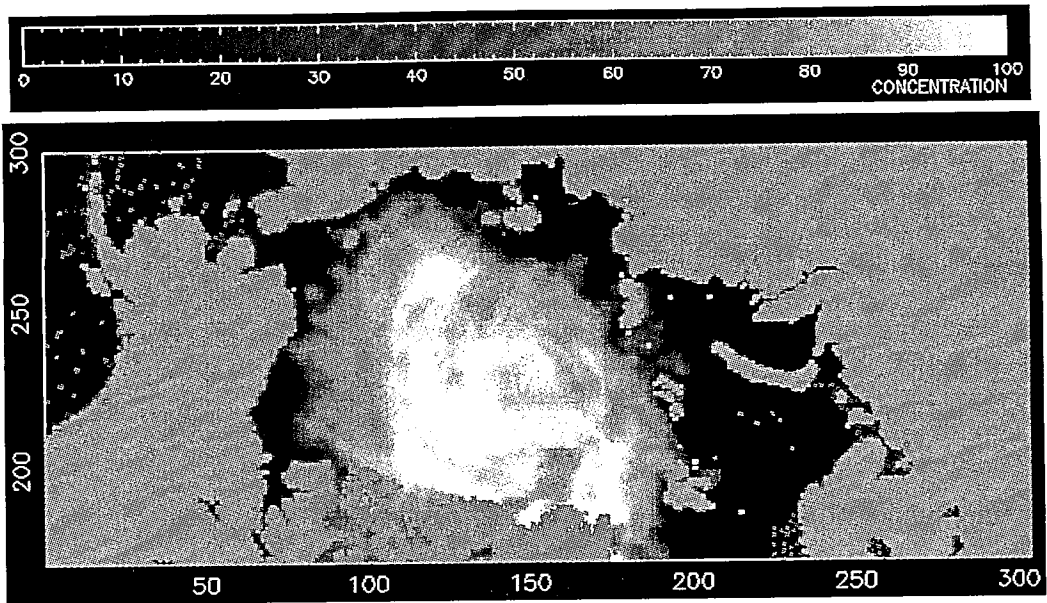
Fig. 12 Ice Concentration map observed by SSM/I on August 5, 1995; Initial value for prediction computation; The whole Arctic Ocean is computed.

from the top layer.

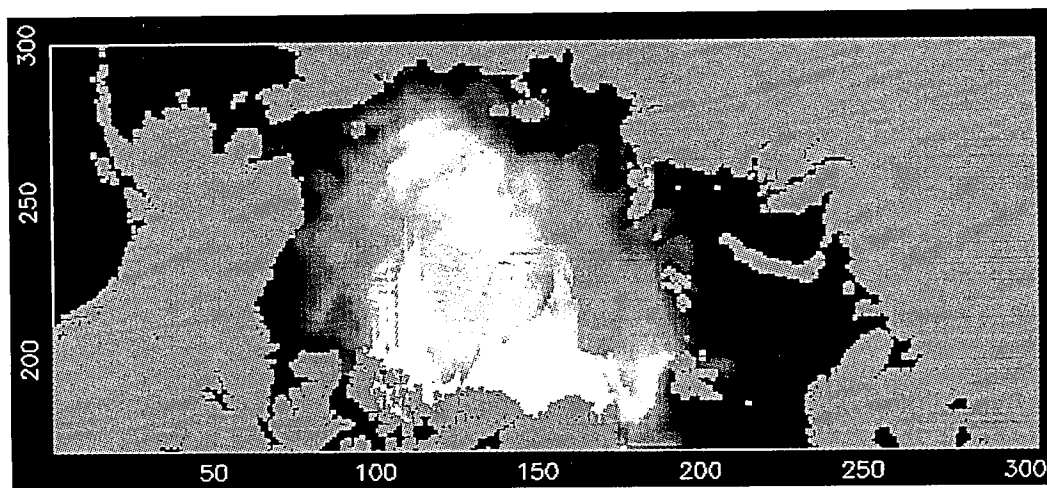
One week prediction computation is made for the whole Arctic Ocean. Figure 12 shows the SSM/I observed ice concentration distribution on August 5, 1995, which is used as the initial value for prediction. The number of computation mesh is  $39,824 = 131 \times 304$  and the one mesh size is 25km. The computation time for one week prediction is about 4 hours. The ice/ice and ice/land friction coefficients are assumed as 0.214 and 0, respectively.

Figure 13 shows the ice concentration distributions of one week later, August 12, as comparison between (a) SSM/I observation and (b) prediction. The figure (c) denotes the discrepancy between the observation and prediction. These figures demonstrate that the present computations have been done properly for the whole Arctic Ocean.

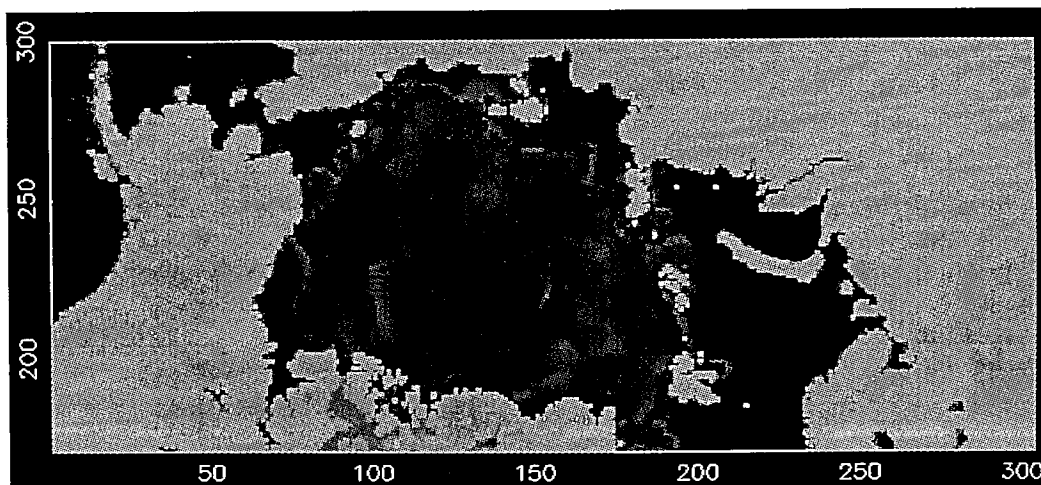
Since the attention should be paid to the Northern Sea Route, the close-ups at the East Siberian, Laptev and Kara Seas are compared, respectively. Figure 14 shows the initial condition at each sea area. Figures 15 and 16 show the comparison at the East Siberian Sea for ice conditions after 3 days and 1 week, respectively. Similar series are shown in Figs. 17-20 for the Laptev and Kara Seas, respectively. Although the present prediction does not take ice melting into account, it properly expresses the retreat of ice due to wind. The coupling with thermodynamic model will be realized in near future to improve the prediction accuracy.



(a) SSM/I Observation, August 12, 1995

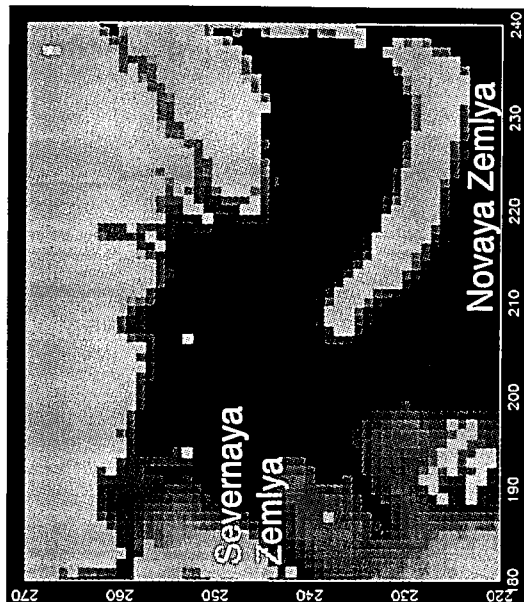
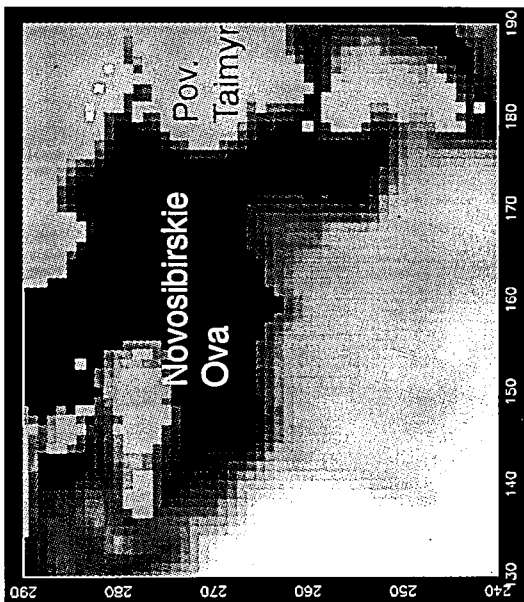
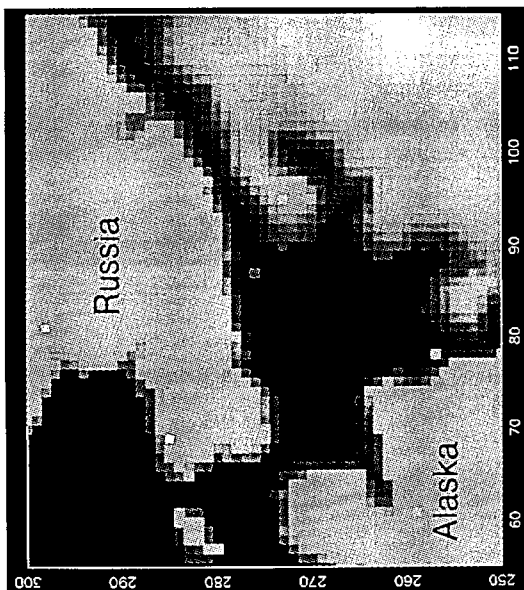
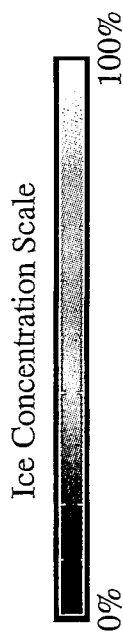


(b) Prediction, August 12, 1995



(c) Difference = |(a)-(b)|, August 12, 1995

Fig. 13 Comparison of ice concentration distribution between SSM/I observation and one-week prediction; The whole Arctic Ocean, August 12, 1995



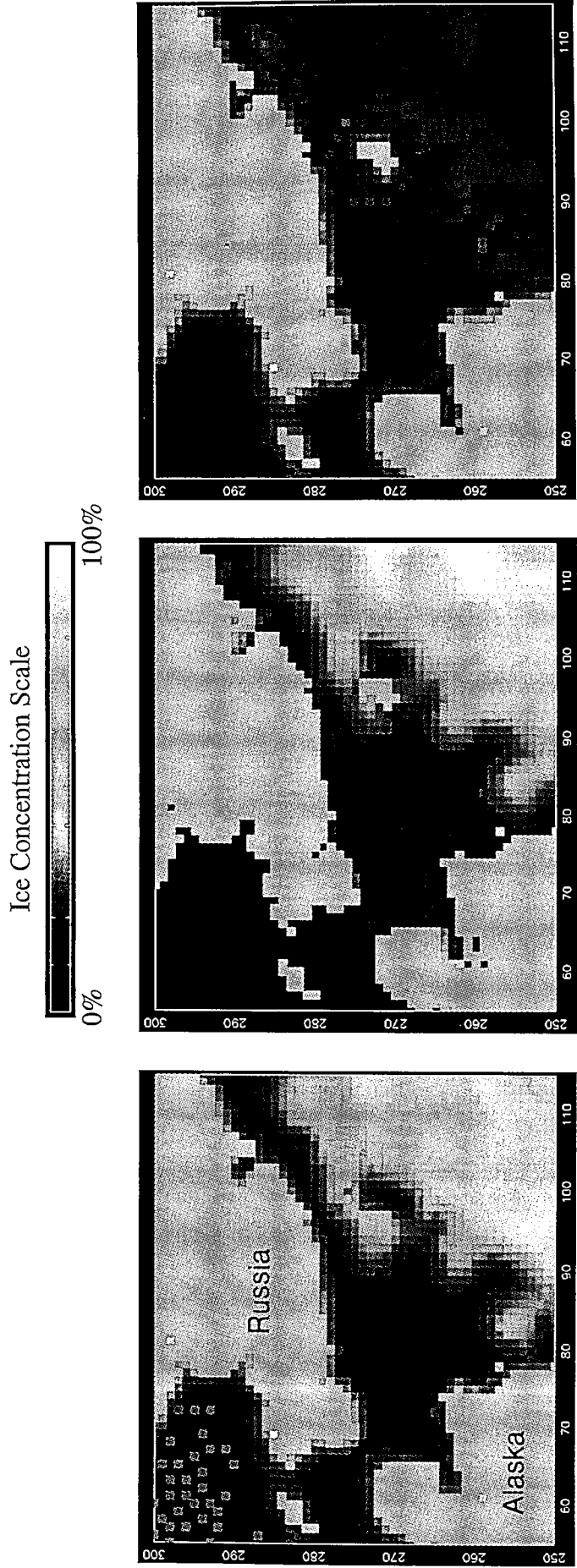
(a) East Siberian Sea, August 5, 1995

(b) Lavtsep Sea, August 5, 1995

(c) Kara Sea, August 5, 1995

Fig. 14 SSM/I observed ice concentration map; Close-ups at 3 sea areas. August 5, 1995. Initial values for computation





(a) SSM/I Observation, August 8, 1995

(b) Prediction, August 8, 1995

(c) Difference = |(a)-(b)|, August 8, 1995

Fig. 15 Comparison of ice concentration distribution between SSM/I observation and 3-day prediction; East Siberian Sea. August 8, 1995.

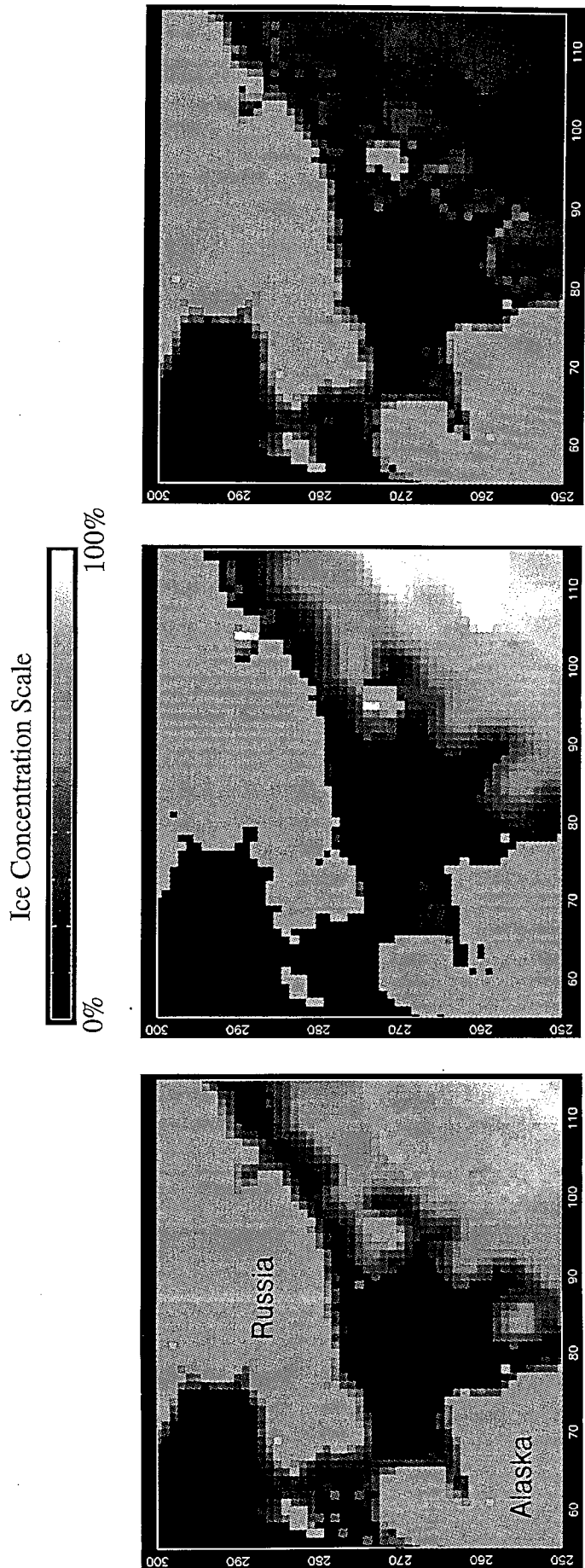
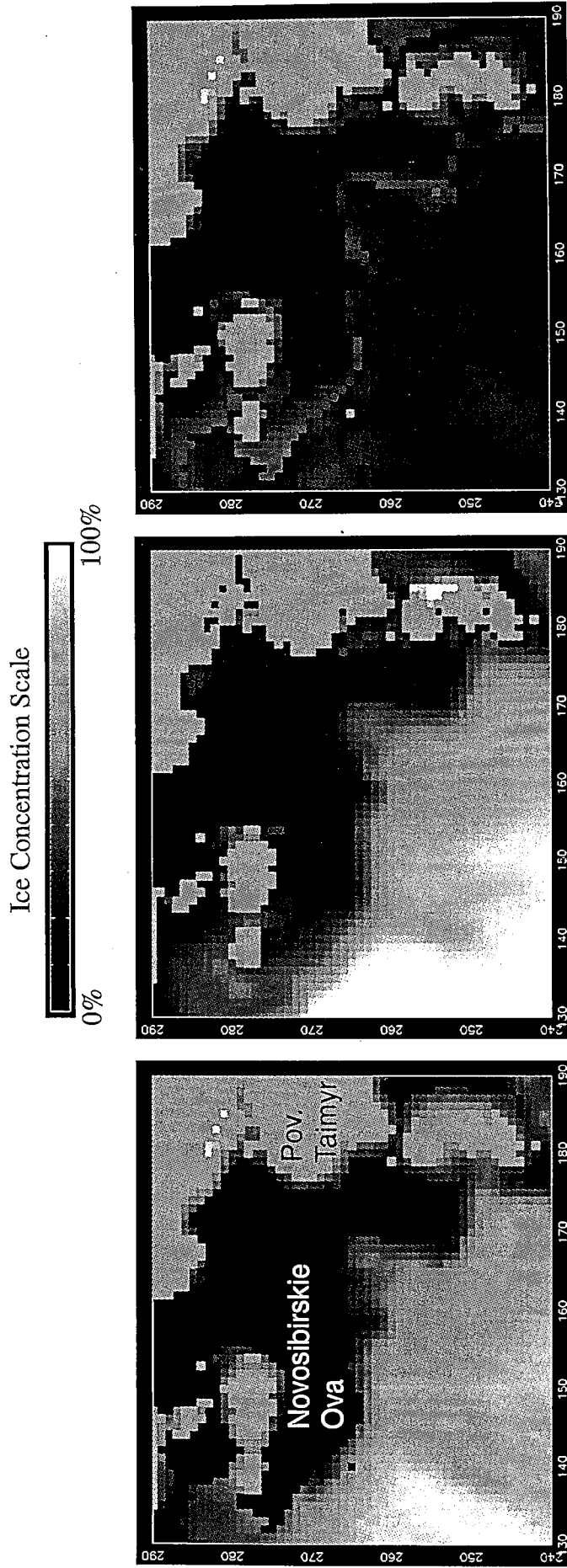


Fig. 16 Comparison of ice concentration distribution between SSM/I observation and one-week prediction; East Siberian Sea. August 12, 1995.



(a) SSM/I Observation, August 8, 1995 (b) Prediction, August 8, 1995 (c) Difference = | (a)-(b) |, August 8, 1995

Fig. 17 Comparison of ice concentration distribution between SSM/I observation and 3-day prediction; Laptev Sea. August 8, 1995.

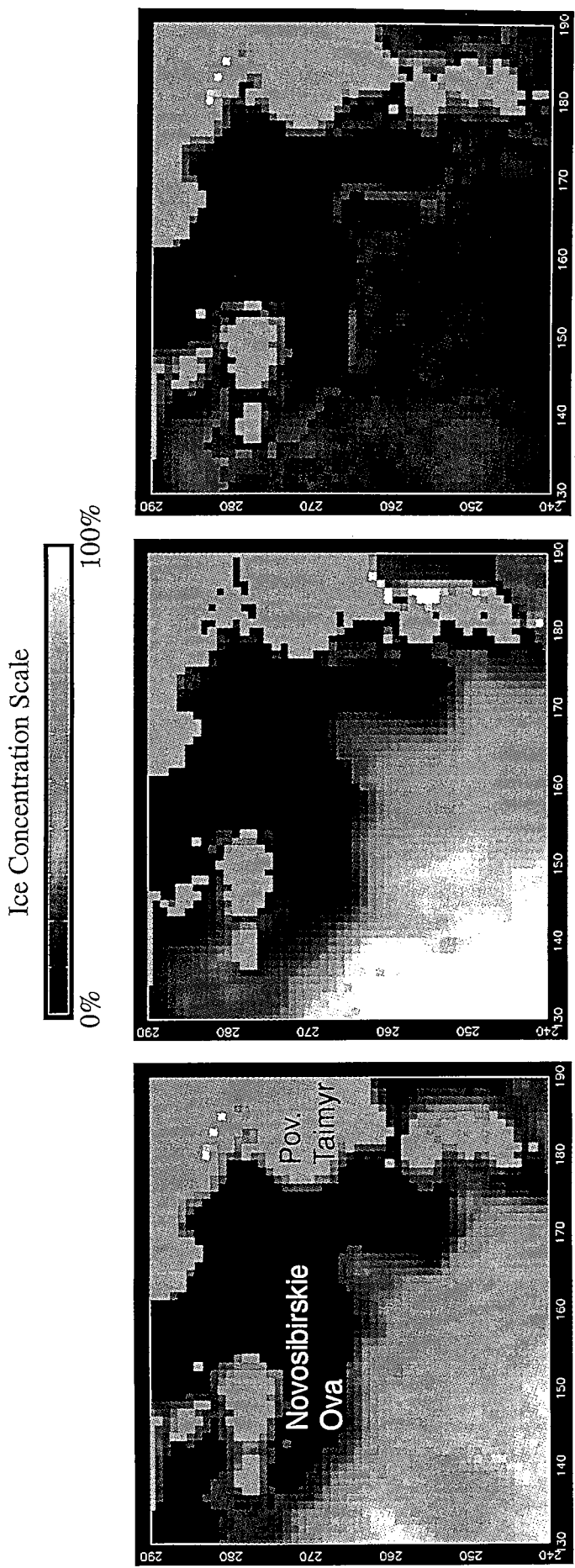
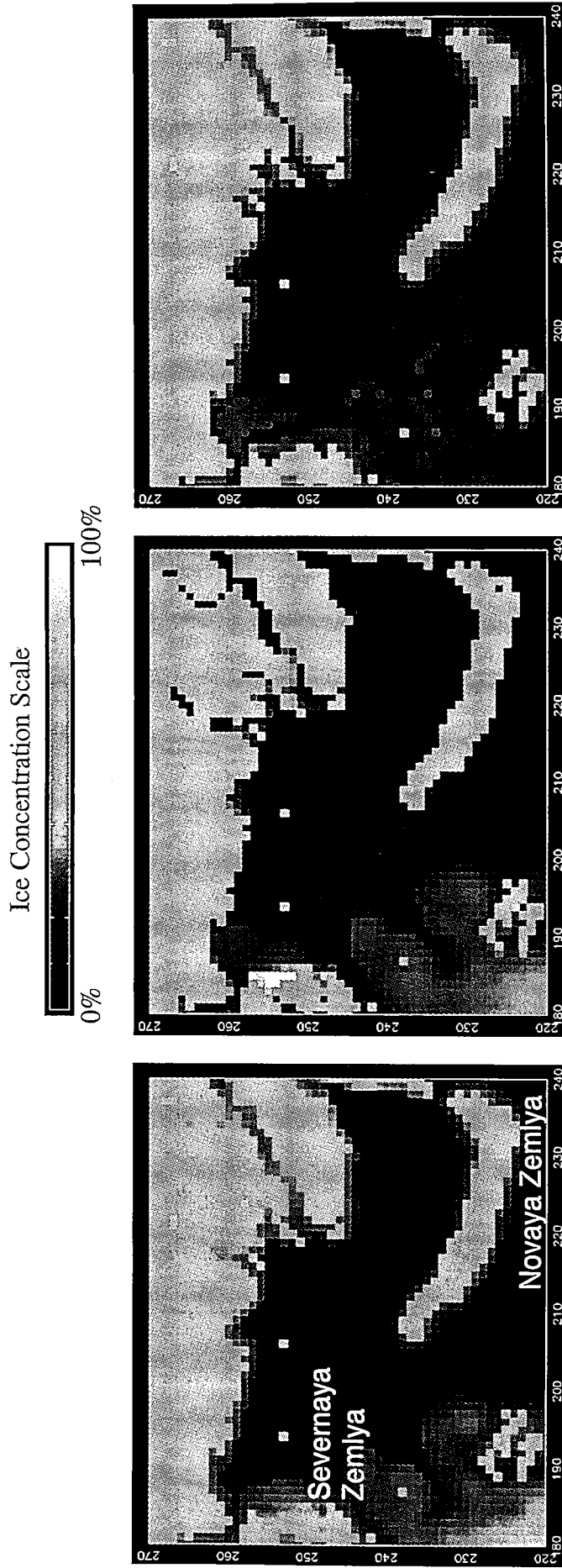


Fig. 18 Comparison of ice concentration distribution between SSM/I observation and one-week prediction; Laptev Sea. August 12, 1995.



(a) SSM/I Observation, August 8, 1995 (b) Prediction, August 8, 1995 (c) Difference = | (a)-(b) |, August 8, 1995

Fig. 19 Comparison of ice concentration distribution between SSM/I observation and 3-day prediction; Kara Sea. August 8, 1995.



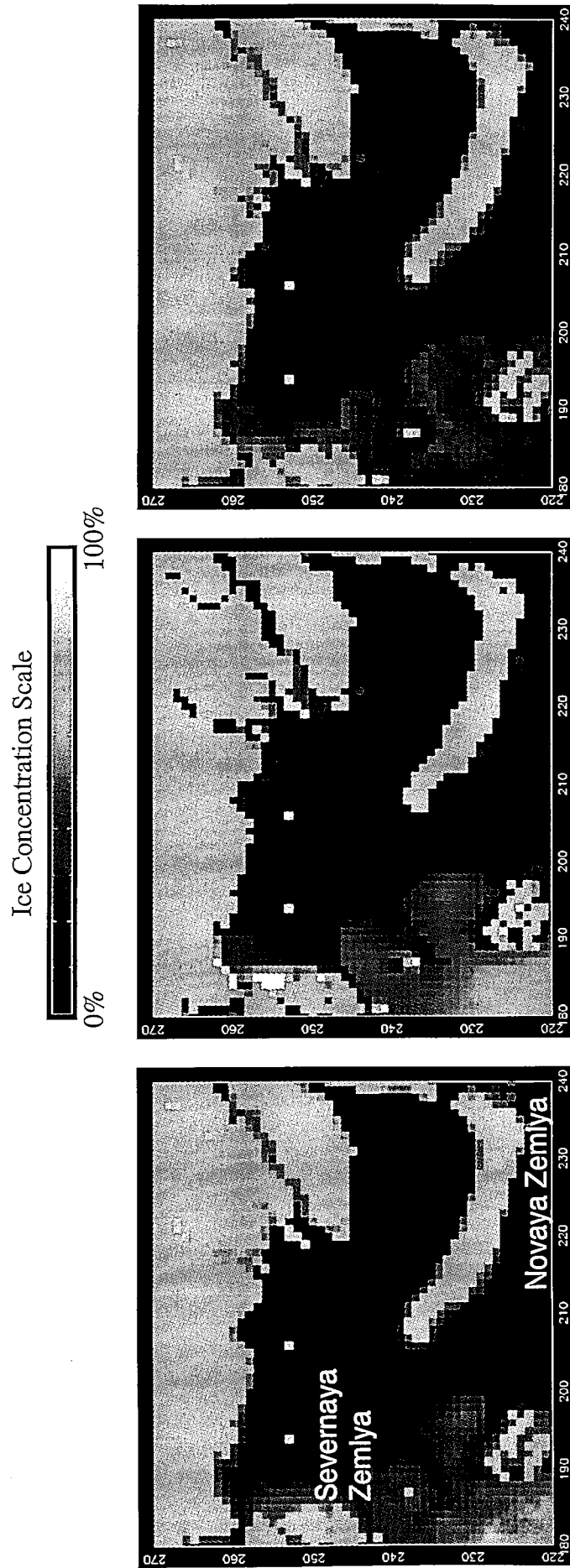


Fig. 20 Comparison of ice concentration distribution between SSM/I observation and one-week prediction; Kara Sea. August 12, 1995.

## 5. CONCLUDING REMARKS

A new system for sea ice condition prediction has been developed. The SSM/I satellite ice distribution data is used as an initial data for prediction computation by linking the SSM/I data with the prediction program. The SSM/I data are in digital form and can be obtained almost real time. The prediction computation is made by a dynamic sea ice model, Distributed Mass / Discrete Floe model. The computation time takes only 20 minutes for eight days simulation for the area of 1,000 km, the Sea of Okhotsk. It takes about 4 hours for the whole Arctic Ocean.

The Distributed Mass/Discrete Floe model is a numerical model proposed for the computation of pack ice movement. This model possesses the advantages of both the continuum and the discrete element models: it can express the discrete nature of pack ice which is difficult by using a continuum model, and requires a much shorter computation time than a discrete element model. In the present work, ice concentration dependency of the form drag of an ice floe is newly taken into account. As the result, the over estimation of ice zone has been improved and the prediction has become more similar to observation.

The present system has been applied for the sea ice motion predictions in the Sea of Okhotsk and the Arctic Ocean. The present system is still in developing stage. More improvement of the computation model and scheme is needed, and also more comparison with the observation data is required by acquiring more natural condition data. The present results, however, have showed favorable agreement with the observations, demonstrating the high potential of the present system.

## ACKNOWLEDGMENTS

The SSM/I sea ice data, DMSP-F11, were obtained from the EOSDIS NSIDC Distributed Active Archive Center (NSIDC DAAC), University of Colorado at Boulder. The numerical weather prediction data used in the Okhotsk Sea Prediction and in the Arctic Ocean Prediction were provided from Japan Weather Association and European Centre for Medium-range Weather Forecasts, respectively. The authors would like to thank the persons concerned.

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# Prediction of Ice Conditions along the NSR using Satellite Data

by

Chang Kyu Rheem and Hajime Yamaguchi

Reviewed by W. M. Sackinger

The authors are to be complemented for their approach in handling the interaction of ice floes, for their treatment of form drag of individual ice floes which are surrounded by other ice floes, and in their formulation of the appropriate interaction equations. It is also very significant that they have reached out to the near-real-time data available on ice coverage, to establish the initial conditions for their calculations, and that they also have included the wind forecasts available on a near-real-time basis for their calculation processes. They also have demonstrated that the calculations can be made on state-of-the-art desktop computers which are now widely available. All of these represent significant advancements in the state of the art of ice forecasting, over the time domain of three to five days. Their neglect of ice growth or ablation due to thermal effects is not serious over such a short time interval.

It appears, however, that their treatment of the boundary of the region of ice movement implies that the boundary is frictionless (there is no mention of an ice/boundary friction coefficient), and also that the boundary is rigid. This approximation is a good one for a bridge pier in a river, for example, or for an offshore structure or rocky island. However, it is not realistic for the ice/land boundaries typical of the Arctic Ocean, which are often beaches with very gradual slopes. In such cases, ice floes moving toward beaches do develop motion parallel to the shoreline because of the water motion component parallel to the shoreline, but the presence of a wind blowing towards the shoreline causes the ice floes to approach the beach and become grounded. The friction between ice and shoreline is then effectively infinite and the floes nearest to the shoreline become integrated into the shoreline, vanishing from the collection of moving floes approximated by the computation. Future improvements of the program should consider this effect.

With respect to the movement of floes in regions far from land boundaries, it is known that open leads form there, and that ice ridges build there, as well. A major reason is the variable draft of the ice floes, which gives a locally-variable form drag coefficient. It would be an improvement in their program if the form drag coefficient were allowed to be different for different floes. This could, for example, be determined from the input data conditions. If the initial conditions at time zero show an open lead, and a wind direction at an angle to the direction of the lead, then an assumption can be made that the form drag coefficient for floes on the upwind side of the open lead is larger than that for floes on the downwind side of the open lead. This local variation in form drag coefficient can be allowed to persist during the computation and will be helpful in explaining details of closure rates of open leads when the wind direction changes.

The authors should be complemented for their advancements, which are very significant.

## Authors' Reply

Thank you very much, Prof. Sackinger, for your kind review. Your suggestions and comments are always invaluable and encouraging. The manuscript you reviewed are revised and some figures are newly added or replaced with the latest ones. I agree that we need further improvement for practical use, although I think the possibility for that is shown in this report. We are now trying to make more computations season by season by collecting the whole year data in order to look at the seasonal characteristics. During this work, we hope to tune-up the parameters and improve the model, including the ice/land friction coefficient you pointed out.

The prediction of open leads is very important for ice navigation. I think the present model on form drag can express the forming of an open lead to some extent since the form drag increases at less ice concentration area. It is needed, however, to make computations with higher spatial resolution than that of present work. It would be necessary to develop a computation scheme which can treat high resolution prediction locally. A nested grid method is one possibility. But as another approach, we are now developing a computer code which couples a discrete element model computation with the DMDF model one to express local but important phenomena.

Thank you again, Prof. Sackinger. The goal is still far away, but we hope to approach it step by step.

With best regards.

Yours sincerely,  
Hajime Yamaguchi, University of Tokyo

18th Dec., 1998



## The three main cooperating institutions of INSROP



### **Ship & Ocean Foundation (SOF), Tokyo, Japan.**

SOF was established in 1975 as a non-profit organization to advance modernization and rationalization of Japan's shipbuilding and related industries, and to give assistance to non-profit organizations associated with these industries. SOF is provided with operation funds by the Sasakawa Foundation, the world's largest foundation operated with revenue from motorboat racing. An integral part of SOF, the Tsukuba Institute, carries out experimental research into ocean environment protection and ocean development.



### **Central Marine Research & Design Institute (CNIIMF), St. Petersburg, Russia.**

CNIIMF was founded in 1929. The institute's research focus is applied and technological with four main goals: the improvement of merchant fleet efficiency; shipping safety; technical development of the merchant fleet; and design support for future fleet development. CNIIMF was a Russian state institution up to 1993, when it was converted into a stock-holding company.



### **The Fridtjof Nansen Institute (FNI), Lysaker, Norway.**

FNI was founded in 1958 and is based at Polhøgda, the home of Fridtjof Nansen, famous Norwegian polar explorer, scientist, humanist and statesman. The institute specializes in applied social science research, with special focus on international resource and environmental management. In addition to INSROP, the research is organized in six integrated programmes. Typical of FNI research is a multi-disciplinary approach, entailing extensive cooperation with *other research institutions* both at home and abroad. The INSROP Secretariat is located at FNI.

