論文の内容の要旨

論文題目　Ice-ocean coupled computations for the sea ice prediction to support ice navigation in the Arctic Ocean
（北極海での氷中航行支援のための海氷変動予測を目指した海氷／海洋連成計算）

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INTRODUCTION AND MODEL CONFIGURATIONS

Summer sea ice in the Arctic ocean retreating further away from most Arctic landmasses, opening new shipping routes and extending the navigation season in the Arctic Sea Routes (ASR). The passages through the Arctic Ocean are the shortest sea route from North American and European harbors to Southeast Asian harbors. However to navigate in ASRs, prediction of sea ice condition is crucial, especially in marginal ice zones. Many numerical models have been used to predict the long-term and wide-area sea ice conditions in the Arctic Ocean successfully. However, in general most of the available numerical models have shown high uncertainties in the short-term and narrow-area predictions, especially marginal ice zones like ASRs.

Therefore, in this study we aim to predict the short-term sea ice conditions in Arctic sea routes using meso-scale eddy resolving high-resolution ice-ocean coupled model with explicitly treating the ice floe collision in the marginal ice zones. The following modifications have been made to improve the accuracy of the ice-ocean coupled model predictions. Almost all-existing sea ice forecast models are based on the continuum approach in ice dynamic processes. On scale much larger than floe size, continuum approximation has produced the accurate results in sea ice models. However, since the ASR regions sea ice has both continuum and discrete features, earlier continuum models have certain limitations for accurate predictions in sea ice. Therefore, in this study we have introduced the flow collision rheology of (Sagawa 2007) into the conventional elastic-viscous-plastic rheology of (Hunke 2001) to simulate the both continuum and discrete nature of pack ice. We have also introduced the subgrid-scale ice motion (Lagrangian movements) into the sea ice dynamics to minimize the unrealistic sea ice diffusion along the ice edges.

Ocean part of the ice-ocean coupled model is a parallel, free-surface, sigma-coordinate, primitive equations ocean modeling code based on the Princeton Ocean Model (POM). The level-2.5 turbulence closure scheme (Mellor and Yamada 1982) is used for the vertical eddy viscosity and diffusivity. The horizontal eddy viscosity and diffusivity are calculated using a formula proportional to the horizontal grid size and velocity gradients (Smagorinsky 1963): the proportionality coefficient is chosen to be 0.2. The sea ice part has both dynamics and thermodynamics components. Thermodynamic part is based on (Parkinson & Washington 1979) and adopted the (Semtner 1976) zero-layer model with snow effect taken into account.

There are two main computations were performed which are coarser resolution (about 25km) whole Arctic model (covered area: Arctic Ocean, the Greenland-Iceland-Norwegian (GIN) seas and the North Atlantic Ocean) and high-resolution (about 2.5km) regional models along the northeastern passage of ASRs. The high-resolution northeastern passage is divided into two regions LS region (covered area: Laptev Sea, part of Kara and East Siberian Seas) and CS region (covered area: Chukchi Sea and part of East Siberian Sea) for numerical reasons. The bottom topography is created from 1degree data of ETOPO1 data set and there are 33 vertical sigma layers in every model. To avoid the singularity at the North Pole every models spherical coordinate systems are rotated to the equator.

The atmospheric forcing components are given by the ERA-interim project six hourly databases. The radiation boundary condition is applied at the open lateral boundaries and no-slip boundary condition is used along the coastlines. The river water discharge is not included in the present version of ice-POM model. The Pacific water inflow with seasonal cycle is provided at the Bering Strait based on the hydrographic observation of (Woodgate, Aargaard, & Weingartner, 2005). In the whole Arctic model time integration started from the steady state with a climatological temperature and salinity field provided by Polar science center Hydrographic Climatology (Steele et al. 2001) (PHC3.0). First, model was spun up for 15 years by providing the year 2000 atmospheric data cyclically. Later, entire model domain was reached to the equilibrium after the 15 years spin up. Then the model is integrated from year 2000 to 2012 with ERA-interim realistic atmospheric forcing. On the other hand regional models initaial and boundary conditions are provided by the whole Arctic model results.

First, Numerical difficulties in high-resolution ice-POM model were discussed. We have shown that abrupt changes in the ice strength P (due to the earlier version floe collision rheology) can cause the instability in the high-resolution ice-POM sea ice model. The symptoms of the instability are noisy and unrealistic sea ice thickness, ice concentration, strength, velocity, and strain rates. Unstable flow typically arises near islands and coastlines where convergence and shear are large. The instability is made possible by the large changes in ice stress that occur as the floe collided each other with the maximum compactness. However, the instability is fundamentally numerical, not physical. The model gives realistic behavior with small time steps, becoming unstable only when time step exceeds the timescale for large changes in P. But small time steps are not practical in the sense of computational economy. Modification of floe collision near the maximum compactness (about 90% concentration) and new method of proper damping of elastics waves in EVP rheology successfully resolved the instability issues in the ice-POM model without reduction of time step interval. This modification leads to a stable numerical scheme that further improves the model’s computational efficiency and accuracy.

REPRODUCIBILITY OF WHOLE ARCTIC MODEL RESULTS

Then, coarser resolution (about 25km) whole Arctic model was performed to investigate the reproducibility of basic features in ice-POM model. Figure 1 has shown the September mean model sea ice concentration comparison with corresponding months observational sea ice concentrations obtained from Hadley Centre Sea Ice and Sea Surface Temperature data set (HadISST). The model has reproduced the interannual and seasonal sea ice extents variation in the Arctic Ocean reasonably. The negative trend of September Arctic sea ice extents, year 2007 minimum sea ice concentrations, and year 2005 opening of northeastern passage are well captured with simulated results.

Sea ice thickness distribution is also reasonably reproduced. And except the Canadian Archipelago and northern Greenland the other areas sea ice thickness is quantitatively consistent with available observations. However, the ice-POM model can be used to reproduce the thin first year ice reasonably and can be use to predict the sea ice in Northeastern Passage of Arctic sea routes.

General feature of Arctic circulation patterns, anticyclonic Beaufort gyre and transpolar drift, were reproduced accurately. Salient features of Arctic sea ice circulations were also reproduced reasonably with observational Arctic buoy data sets. On the other hand coarser resolution whole Arctic ice-POM model cannot be used to reproduce the correct fresh water transport and accumulation in the Arctic Ocean. Because as many researchers suggested the Pacific water is transported into the Canada Basin by meso-scale eddy activities, which are hardly resolved in the coarser resolution models.

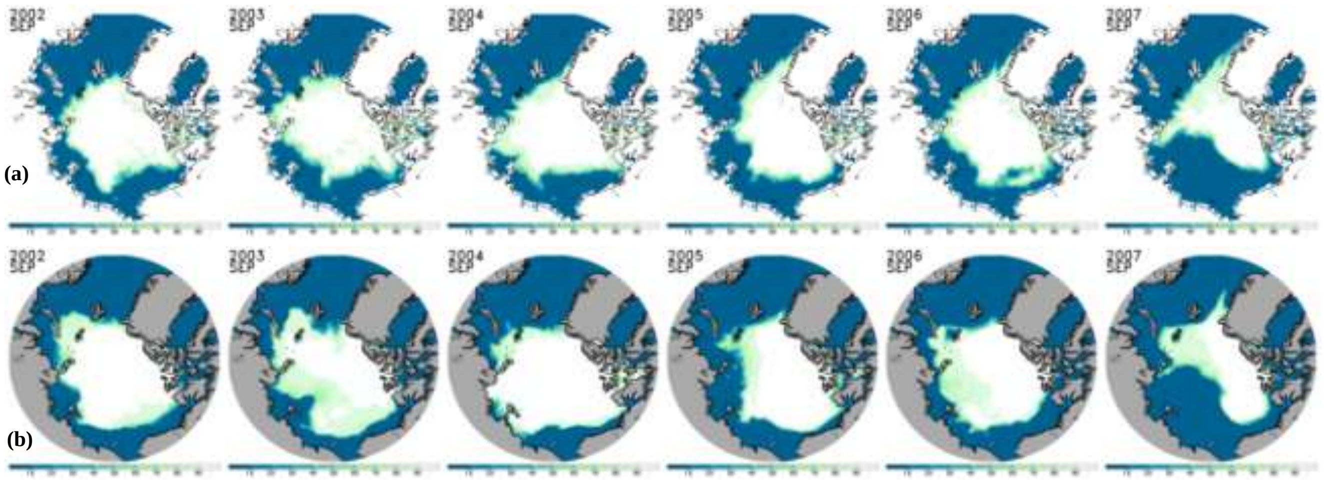

Figure 1 September mean sea ice concentration from year 2002 to 2007. (a) HadISST observational concentration. (b) Numerical model computation.

SHORT-TERM FORECAST FOR THE ARCTIC SEA ROUTE

Next high-resolution ice-ocean coupled system was investigated with a meso-scale eddy resolving model forced by ERA-interim atmospheric data. Numerical codes for the northeast passage of Arctic sea routes have been developed by hindcast computations.

In Figure 2 The Laptev Sea region (LS) sea ice extent variation from 2004 July 20 to 2004 August 17 is compared among coarse grid computation (Whole Arctic model), high-resolution computation (regional model) and satellite observation AMSR-E (Advanced Microwave Scanning Radiometer-Earth Observing System). Please note that for the comparison, grid cells that have concentrations less than 10% are omitted. Throughout the computation period, sea ice extent is almost unchanged in the coarser grid whole Arctic simulation. Even though the whole Arctic model well reproduced the overall trends of long-term changes of the Arctic sea ice, it cannot be used to predict the sea ice in short-terms. On the other hand high-resolution regional model and AMSR-E observations sea ice extent are varied from 1.7 millions of square kilometers to 1.3 millions of square kilometers within the time period due to the thermodynamics and dynamics activities. In first two weeks the computation has shown a similar reduction pattern with observations. In third week, the observational sea ice extents have shown a dramatic reduction but model couldn't capture that exact dramatic reduction behavior, instead it showed a smooth reduction. At the end of third week observed sea ice extent is almost equal with model results and similar behavior is continued in the fourth week. By considering all the qualitative and quantitative comparisons of regional model we have come up with following conclusions. The coarse grid computation cannot reproduce short-term ice reduction in summer seasons accurately. But fine grid computation can predict the sea ice variation accurately with satellite observations.

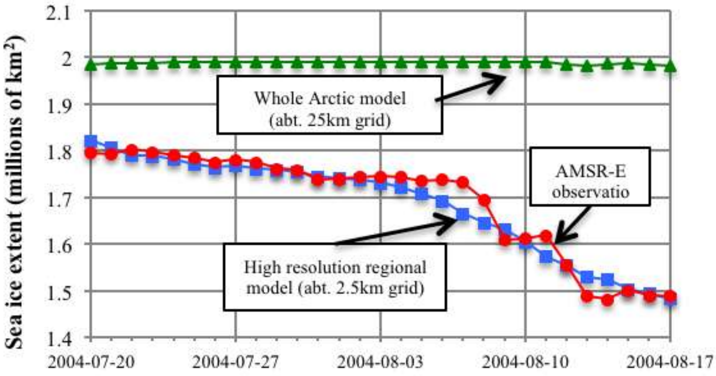

Figure 2. Comparison of sea ice extents between coarse grid computation (Whole Arctic model), fine grid regional computation (LS) and satellite observation (AMSR-E) during 2004-Jul-20 to 2004-Aug-17. Area covered with more than 10% ice concentration is taken into comparison

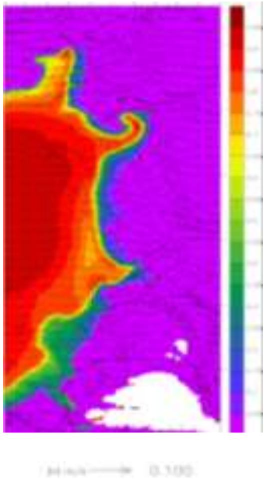

Figure 3. Example of snapshots of ice-eddy interaction: 2005-Oct.-1. Color bar = sea ice concentration; Vectors = surface ocean current; North of Sevelnaya Zemlya Islands

There are several possible reasons for this discrepancy results between coarser and high-resolution grid computations. First, the high-resolution grid computation well expresses the ice-albedo feedback process, which accelerates the ice melting in spring and summer seasons. If the ice is broken up, the areas of open water between floes absorb a great deal of solar energy in warm months. That energy can be transferred both to the sides of the floes and underneath the floes, promoting further melt.

The next one is small-scale sea ice dynamics was correctly captured with high-resolution models compare to the coarser gird models. The wind or ocean on sea ice either push the ice together, resulting in a smaller extent, or spread it out, resulting in larger expanses of sea ice at a lower density. These processes are known as convergence and divergence, respectively. Correctly resolved converging and diverging process of sea ice have improved the sea ice edge locations and extents.

The third reason is ice-ocean interaction. As shown in Figure 3 the high-resolution grid computation reproduces the meso-scale eddies in the ocean. On the other hand coarser resolution whole Arctic computation cannot reproduce the meso-scale eddies. The meso-scale eddies in the ocean draws out the ice from its main body and enhances the melting. On the other hand melted ice supplies the low-salinity cold water into the ocean surface, which activating the eddy production due to baroclinic instability. This positive feedback process increases the ice melting in high-resolution models compare to the coarser grid model. However the detailed investigation of eddy generation mechanism and its influence on sea ice are yet to be done.

As general conclusion, in terms of accurate forecasting sea ice using high-resolution ice-ocean coupled model we have to input the appropriate initial conditions and realistic forcing data. At this point lack of observational sea ice data and coarseness of the reanalysis forcing data are the key bottleneck for making accurate forecasting and validating the model results in Arctic area. However, the present result has shown that our model can be used to predict the short-term sea ice conditions accurately despite those limitations.