SIMULATION OF SEA ICE IN THE BOHAI SEA WITH AN ICE-OCEAN COUPLED MODEL

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ABSTRACT
An ice-ocean coupled model is developed based on the Princeton Ocean Model (POM) and a dynamic-thermodynamic ice model. The coupled model was used to study the variation of ice cover and the heat budget at the interface of sea-ice, air-ice and air-sea in the Bohai Sea during the winter of 1998–1999. In the coupled model, the heat and momentum transfer between the ice and ocean is two-way, and the variation of ice thickness and concentration are governed by the heat fluxes at the surface and bottom of the ice and at the ocean surface. The atmospheric fields are obtained from the results of the T106L19 spectrum model. Air temperature data is corrected by observed data at marine stations. This is the first time that a simulation has been done in the Bohai Sea, for an entire ice season, using an ice-ocean coupled model with real time air forcing. Some important thermodynamic factors are discussed in the paper.

INTRODUCTION
Since the middle of the nineteen eighties notable progress in the research and application of ice-ocean coupled models has been made. In particular, many successful results have been obtained from the studies of thicker ice regions near the poles. Hibler and Bryan (1987) first introduced the results of a three-dimensional ice-ocean coupled model to the research of sea ice in the Arctic and successfully simulated the effect of ocean current on the seasonal variation of sea ice in the Arctic, Greenland Sea and Norway Sea. Recently, the coupling studies in ice margin areas and the surrounding ocean are getting more attention and some studies have already progressed onto seasonal variation of sea ice.

The Bohai Sea is a semi-closed shallow water region including three Bays. It is one of the lowest latitude ocean regions in which there is sea ice formation. Sea ice occurs in Liaodong Bay and Baohai Bay in every winter and Liaozou Bay in some colder winters. Under the joint actions of strong tides, frequently northern wind, and the thermodynamic effects of ice-ocean coupling system, the sea ice condition in the Bohai Sea shows very complex variation.

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The sea ice in the Bohai Sea has been the subject of a number of numerical model studies due to the severe problems it causing. Wang et al. (1984) set up a dynamic-thermodynamic model to simulate the freezing and decay process of sea ice for the normal winter forcing by the monthly averaged meteorological data. Wu (1991) proposed a dynamic-thermodynamic, three-classes, sea ice model according to the features of sea ice and hydrometeorology in the Bohai Sea. Both Wang and Wu’s model is considered the first generation of sea ice numerical model in China. In both of the models, the ocean heat flux and ocean current are constant. Based on the above two models, further progress on thermodynamic studies of sea ice has achieved (Wang and Wu, 1994; Wang et al., 1999; Ji and Yue, 2000).

The studies on ice-ocean coupling in the Bohai Sea still are quite few until now. Zhang and Wu (1994) coupled the sea ice dynamic model with a two-dimensional tidal model and simulated the sea ice movement under the action of M2 tidal component. Li et al. (1998) coupled dynamic sea ice model of the Bohai Sea with Blumberg’s ECOM-si model and simulated the ice movement under the joint action of wind and M2 tidal component during 5 days.

Based on the above studies, a coupled ice-ocean model developed for the Bohai Sea is presented in this paper. This is the first time that the ice freezing and decay process in the Bohai Sea, for an entire winter, are simulated by applying real-time meteorological data. The following will include introduction to the coupling method; the simulated results including ice thickness distribution, time curves of ice thickness and concentration, heat budgets in ice surface, ice bottom, and water surface; and the summary with some discussion.

DESCRIPTION OF THE MODEL
In the present coupled model, the ice model is coupled with the top layer of the ocean model via a two-way transfer of momentum and heat. The salinity changes due to evaporation/precipitation and river runoff are not taken into account, although the advection and vertical mixing of the ocean salinity are calculated.

The ice model (Wu, 1991) used here follows viscous-plastic constitutive law and considers the heat exchanges along both vertical and lateral directions. The ice is thermodynamically divided into three classes, i.e. level ice, ridged ice, and open water. The dynamic part of the model has been applied and tested in the Bohai Sea and Baltic Sea and been continuously revised. The present model has only few improvements on the thermodynamic part.

The POM (1997 edition) is adopted as the ocean model (Blumberg and Mellor, 1987). The stress at the ocean surface is calculated by a weighted average of the wind stress in the open water and the stress at the water-ice interface by means of ice concentration. The boundary condition for the temperature at the surface adds the penetration solar radiation flux term to the one of Liu (2000). The lateral temperature, salinity, as well as velocity boundary conditions of external and internal mode are left as POM provided. The elevation at the boundary is calculated from the observed harmonic constant including four tidal constituents (M2, S2, K1, and O1).
Dynamic Coupling Method
Dynamic coupling is achieved by the stress term between ice and water. The stress not only directly affects ice drift, but also produces the irregularity of ice velocity distribution causing ice deformation. In return, the ice formation and distribution variation changes the stress of the upper boundary of ocean. The stress at the water-ice interface is:

$$\tau_{wi} = \rho_w C_{wi} \left[ \vec{u}_w - \vec{u}_i \right] \left[ \vec{u}_w - \vec{u}_i \right]$$

where $C_{wi}$ is the water-ice drag coefficient. $u_w$ and $u_i$ is the vectors of the first layer water and ice respectively.

Thermodynamic Coupling Method
The thermal evolution of ice thickness is governed by the heat fluxes at the sea-ice, air-ice and air-sea interfaces. The ice thermodynamic growth rate in most coupled models is calculated by a weighted average of the rates in open water and in ice-covered fraction by means of ice concentration. In the present model, the heat flux $F_{wi}$, used in the ice-covered fraction is defined as the heat flux through the interface of ice and water. The heat flux $F_{w}$, used in open water fraction is defined as the upward heat flux towards the interface of water and air.

$$F_{wi} = -\rho_w c_p C_{wi}^h \left[ \vec{u}_w - \vec{u}_i \right] \left[ T_w - T_f \right]$$

$$F_w = 2 \rho_w c_p K_H \frac{\left[ T_w - T_f \right]}{h_{mix}}$$

In these equations, $c_p$ is the specific heat of seawater, $C_{wi}^h$ is the bulk heat transfer coefficient, $T_w$ and $T_f$ is the first layer water temperature and ice freezing point, $K_H$ is turbulent eddy diffusion coefficient, and $h_{mix}$ is mixing layer thickness. In order to keep heat exchange, 0.01 cm s$^{-1}$ is taken as the minimum difference between the velocity of water and ice.

The simulation begins from the condition without ice. When $T_{w1}$ decreases to $T_f$ and the ice thermodynamic growth rate has a positive value, new ice appears and ice concentration becomes greater than zero. Once an area of the grid is labeled as ice covered, $T_{w1}$ remains at freezing point.

EXPERIMENTAL RESULTS
The experimental domain is 117.5–122.5°E, 37–41°N. Real bathymetry was used yielding a minimum depth of 5 m. The grid resolution is 0.1 degrees × 0.1 degrees, and only 6 sigma levels are considered in the vertical. The time step of the ice model is 1 hour, while the ocean model runs 10 steps every hour. POM was run for 14 days with the air forcing field of 2 AM Nov.1 before coupling. However, solar radiation and air temperature was calculated in a daily cycle to get reasonable daily variations in heat flux.

The model is forced by the fluxes of momentum and heat acting at the air-ice, sea-ice, and air-sea interfaces. The atmospheric fields are obtained from the results of the T106L19 spectrum model from National Meteorological Center (NMC) of China. To avoid the excessive error caused by forecasting, we select only the first day’s results. The air forcing fields include air temperature, vapor pressure, air pressure and wind. They are input to the ice model every 6 hours, then interpolated to every hour during simulation. Also, real time observed data from several air stations around the Bohai Sea were used to correct the temperature field every 6 hours. Cloud coverage is a sensitive factor in ice thermodynamic process, but it is the most difficult air factor to predict. So, in this simulation, we simply set it to 0.5, the mean value in winter.
The initial water temperature and salinity fields as well as the open boundary conditions are obtained from the *Ocean Atlas of the Bohai Sea, Yellow Sea, and East China Sea* (1991). To get actual water temperature for the open boundary, surface temperature data from two stations in the north and in the south were used to correct the boundary temperature forcing. The initial ice thickness and concentration fields are set to zero in every grid.

The model is run from Nov. 1, 1998 to Mar. 31, 1999. According to the data analysis, the winter of 1998/1999 is the 13th sequential warm winter and is the warmest winter since the winter of 1986/1987 (Meng and Li, 2000). Fig. 1 shows the daily air temperature in Dalian from Nov. 1998 to Feb. 1999. There are five periods in which air temperature decrease sharply. This occurs in the middle ten days of Nov., the first ten days of Dec., Jan., and Feb., and the middle ten days of Feb respectively. It also shows air temperature remaining higher than the multi-year average (1905–now) value during the whole winter, except the middle ten days of Nov., the first ten days of Dec., and the 7 to 13th, Jan.

![Figure 1: The daily and multi-year average air temperature in Dalian from November 1998 to February 1999 (unit of y axis: 0.1°).](image1)

**Ice extent and ice thickness distribution**

There are four cycles of ice growth and retreat during the winter approximately corresponding to air temperature decreases and increases. According to the observation of marine stations, new ice appeared at the end of Nov. in North Liaodong Bay. The ice freeze-up date in Bayuquan, Huludao, Qinhuangdao and Tanggu stations lagged 6, 7, 9
and 14 days respectively compared to that of the normal year. The ice breakup date at these four stations was 20, 13, 15, and 23 days earlier than in the normal year. The coldest day of this winter occurs on 2, Dec. with the air temperature reaching $-11^\circ$ in Dalian station. The period of greatest ice coverage occurs in the middle ten days of Jan. 1999. According to the satellite images, the ice edge line is 104 km from the north shore of Liaodong Bay on 14, Jan. and the ice extent reached the second furthest on 19, Feb. Fig's 2-a,b show the ice thickness distribution for these two days.

Fig. 3 gives the ice thickness distribution on simulation day 70, 95, 110, and 125. The model’s ice period, on a whole, lags the observed condition. The ice development does however agree with the air temperature changes. The greatest simulated ice extent occurs on the 110 running day, which approximately matches the second greatest extent from observed data. The melting conditions appear correct as the ice along the coast and in the west of Liaodong Bay melt first. Also, the edge of fast ice turns clockwise, while the tongue towards the bottom of Liaodong Bay, along the west coast, was consistent with the tidal residue current direction. Although in simulation, the ice freeze-up date about a month later than observed, once new ice does appear, the ice thickness is rapidly increases and become greater than the real condition.

**Time curves of ice thickness and ice concentration**

To compare the difference between model and the real results, we look at a point on the JZ20-2 oil platform in north Liaodong Bay. From Fig 4 we can see that at this point, both the freeze-up and breakup date lags the observation only several days. The simulation of ice thickness in the first ice process is less than the observed value while it is much larger in the second. The simulation reaches its largest value in the beginning of Feb. with a value of 30 cm while the observed largest value occurs on 11, Feb. with a value of 20 cm.

Figure 3: Simulated ice thickness distribution

Figure 4: Sea ice thickness and concentration.
The ice concentration matches the ice thickness increasing and decreasing process on a whole. It has to be mentioned that ice concentration’s critical value is set to 0.15 in the model. Only when it is larger than or equal to this value, is the point declared ice.

Heat flux contribute to ice growth

In a grid, the ice thermodynamic growth rate consists of two parts: one is for open water while the other is for ice-covered. Fig’s 5-a,b give heat flux terms that are used to calculate these two rates during the relatively steady period of ice development (days 95–105) showing the heat budget on both interfaces. The ice surface absorbs about 50% less solar radiation than the sea surface because of its larger albedo. Since there was no observed cloudiness, solar radiation presents only daily variation and slow seasonal change, i.e. smaller at day 95 and a little large after 10 more days. Long wave radiation of the ice surface is smaller than that in the water surface. Also, long wave radiation and sensible heat flux, and latent heat flux at the ice surface show more obvious daily variation. This is mainly because the ice surface temperature responds more to air conditions than the water surface temperature.

During the winter in the Bohai Sea, the ocean heat flux is considered as the flux from the warm current of the Yellow Sea to the Bohai Sea. According to Atlas of Heat Balance on the Ocean Surface (1977), the magnitude is about 20 ~ 30 W m$^{-2}$ K$^{-1}$. In our simulation, $F_w$ and $F_{wi}$ (Fig. 5-b) is typically less than 50 W m$^{-2}$ except the large values during days 96 and 98. This is reasonable since when ice occurs the difference between water surface temperature and ice freezing point is very small, and the large ocean heat flux (days 96–98) produces the ice thickness and concentration decrease agree with the observation. Sensitivity examinations show that the parameterization of these two variables affects the simulated results greatly.

The lowest subplot of Fig. 5-b gives the total heat flux of open water fraction and ice covered fraction, respectively. They all have a very strong daily variation, and the amplitude of the first is about two times larger. They will contribute to total growth rate by weight of ice concentration.
DISCUSS AND CONCLUSION

One of the purposes of this paper is to check the simulating ability of the coupled model for the ice freezing and decay throughout the whole winter. When calculating ice growth, not only the heat budget across the ice surface and bottom but also the lateral heat budget of the first ocean layer in the open water fraction was considered.

The simulation of the ice process agrees with observation in some aspects, but not so accurately in some more detailed cases. In our model, only when the water temperature of the first layer of ocean reaches to freezing point, does the new ice appear, so whether the ice freeze-up date is good depends on the calculation of the water temperature, and that in turn requires a good initial field and reasonable and matching air forcing fields. It can be understand why the simulated freeze-up date lagged the observation. The marine stations are all located in very shallow water, but the minimum depth is set to 5 m in the ocean model, and the critical ice thickness is set to 2 cm. However, it seems that too much lag was due to the air forcing field’s forecasting error and insufficient ocean model spin up time.

Through the simulation, we found some important factors affect thermodynamic ice processes greatly. They are:

1) Ocean heat flux: the coefficients $C_{wh}$ and $K_H$ are very sensitive factors for this model. We choose $C_{wh}$ as $2.8 \times 10^{-4}$ following the Haapala and Lepparanta (1996) study in the Baltic Sea and $K_H$ as $4 \times 10^{-5}$ to match the Yellow Sea warm water flux into the Bohai Sea. It seems that if we decrease the value of $C_{wh}$ and $K_H$, the simulated freeze-up date will be ahead, however, $T_{w1}$ reached the freezing point even later. Further study will be done about the effect ocean heat flux play.

2) Cloudiness ($c$) and the solar radiation correct factor for cloudiness: In this simulation, cloudiness is set to a constant value, which will cause errors in the result. The solar radiation is calculated according to the Parkinson (1979) formula, except using the solar radiation correct factor for cloudiness from Yue et al. (2000) as: $f(c) = 1 - 0.65c^2$.

3) Ice surface albedo and solar penetration rate: When solar radiation reaches the ice surface, one part is reflected to the air, and one part penetrates through the ice to the sea. The ice only absorbs what is left. Different ice types have different albedos and penetration rate, and these values differ greatly among researchers. Here, we set the ice surface albedo to 0.5, and ice absorbed solar radiation $Q_{sh} = (1 - 0.55 \times 17 \%) \times (1 - 0.5)Q_0$, where $Q_0$ is the solar radiation that reaches the ice surface.

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