A LOWER TROPHIC ECOSYSTEM MODEL INCLUDING IRON EFFECT IN THE OKHOTSK SEA

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1. INTRODUCTION

The Okhotsk Sea is one of the most biologically productive regions in the world, and it supports high fisheries production (Fig. 1). Several previous reports indicate that the primary productivity of the Okhotsk Sea is very high, especially on the continental shelf.(Sorokin and Sorokin, 1999; Saito et al., 1996) It has been reported that a major fraction of the phytoplankton in this sea are diatoms (e.g., Hanzawa *et al*., 1981), and previous observations revealed maximum diatom cell numbers in spring and minima in autumn (Ohwada, 1957; Hanzawa *et al*., 1981). The Okhotsk Sea is well known as one of the southern most seasonal sea ice zones in the Northern Hemisphere. In winter, sea ice formation begins around Shantarsky Bay at the end of November, and sea ice extension reaches its maximum in late February or March. Most of the sea ice disappears by May. Sea ice in the Okhotsk Sea is generally advected southward by the prevailing northerly or northwesterly winds. In the south western part of the sea, thick "first-year" ice is primarily advected by the East Sakhalin Current (ESC). Some of the ice is advected towards the offshore warm region and melted, making the surface layer water fresher. Some of this water is then frozen again by cooling. This process leads to formation of "new ice" at ice edges (Ohsima *et al*., 2001). Therefore, the seasonal change of sea ice volume depends on climatic conditions, and has large inter-annual variations. The sea ice has been considered to play an important role in the high production at the ice edge in the Okhotsk Sea. A large number of studies paid mention on the spring bloom after the sea ice melting (for example at the Bering Sea; Niebauer and Alexnder, 1985). Matsumoto *et al*. (2004) analyzed the seasonal and interannual variability of Chl-a distributions in the Okhotsk Sea from 1998 to 2001. They concluded that the most important factor required to characterize spatial and temporal variability of spring blooms was the timing of sea ice retreat, while a secondary factor was the adjustment of insolation. Okunishi et al. (2005) showed that the beginning of the spring bloom in Okhotsk Sea depends on the adjustment of light environment, and the presence of sea ice controls light intensity in the surface water and thereby controls the timing of the spring bloom.

In recent years the micronutrient, iron, has been shown to play a key role in limiting phytoplankton growth rates and structuring plankton communities over much of the world ocean, particularly in the high nitrate, low chlorophyll (HNLC) regions (Martin et al., 1989, 1990, 1991; Martin, 1992; Helbling et al., 1991; Price et al., 1994; Takeda and Obata, 1995; de Baar et al., 1995; Coale et al., 1996; Landry et al., 1997; Takeda, 1998; Behrenfeld and Kolber, 1999; Boyd and Harrison, 1999; Moore et al., 2000). Recently study shows that iron is an important factor controlling phytoplankton in the western subarctic Pacific (Tsuda et al., 2003). However, there is little information on iron concentration in the Okhotsk Sea. Tani et al. (2003) showed that Fe(III) solubility in the surface mixed layer was generally high and variable (0.3-0.7nM) in the Southern=Okhotsk Sea during May-June 2000. However, it is not well known whether iron acts as a limiting factor on phytoplankton growth or not, and what is the main source of iron in the Okhotsk Sea. The purposes of this paper are to evaluate the role of iron in biological production, to examine the source of iron in the Okhotsk Sea by using a three dimensional ecosystem - physical coupled model including iron biogeochemistry.

2. Ecological Model Description

Material flow of our ecosystem model is shown in Fig. 2. This model is based on Kawamiya el al. (1995) (referred to as KKYS hereinafter), which is a nitrogen-based model with 6 compartments (phytoplankton; Phy, zooplankton; Zoo, nitrate; NO_3, ammonium; NH_4, particulate organic matter; POM, dissolved organic matter; DOM). Iron compartments which were separated into four according to its source, are added to KKYS as shown in Fig.2 (KKYS-Fe). In order to clarify the iron origin, four iron compartments are taken into consideration. We assumed that the process of iron-supply to the Okhotsk Sea are: 1) atmospheric loadings from Northeastern Asia (FE_{AIR}), 2) riverine input from the Amur River (FE_{RIV}), 3) solution from sediment (FE_{SED}), and 4) feedback by the biological process of zooplankton and bacteria (FE_{BIO}). We assumed that all of the dissolved iron is bioavailable and that particulate iron is not bioavailable (and therefore neglected in the model). We also suppose that the phytoplankton and zooplankton both have same Fe/N ratio 0.044 in [nmol : µmol], assuming carbon/ nitrogen ratio in plankton of 106: 16, based on Gregg (2002) and Gregg et al. (2003). We used the same iron/nitrogen ratio in the other compartments (POM, DOM).

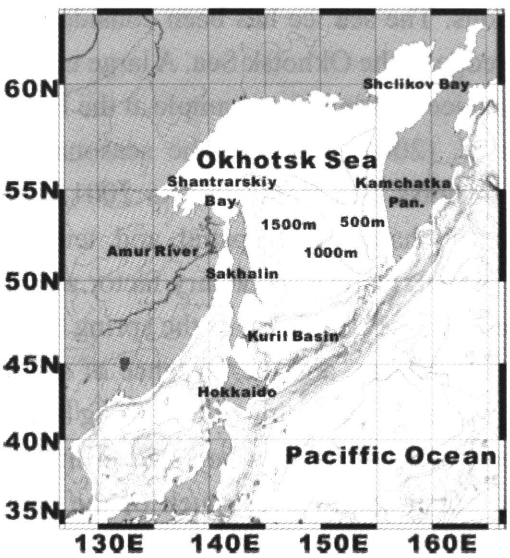

Fig. 1

Study are and bathymetry in the Okhotsk Sea. Contour intervals are 500m.

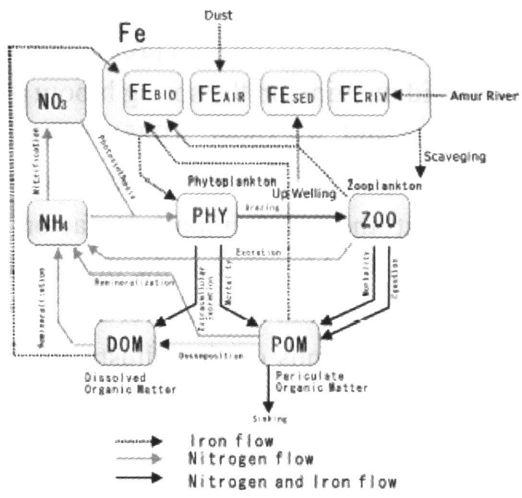

Fig. 2

Schematic of the ecological model (KKYS-FE). Boxes represent nitrogen-based and iron-based standing stocks and arrows represent nitrogen and iron flows in the ecosystem.

3. Physical Model

POM (Blumberg and Mellor, 1987; Galperin and Mellor, 1990) was used for the physical model. This model is a three-dimensional, free surface, ocean model with a second moment turbulence closer scheme (Mellor and Yamada, 1982) to provide vertical mixing coefficients. The model domain extends from 34°N to 63°N and from 127°E to 166°E (Fig. 1). The horizontal grid scale is 1/6°. There are 15 vertical levels with bottom-followed sigma coordinate. The sigma layers were divided to: 0, 0.00313, 0.00625, 0.0125, 0.025, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 1. The surface drag coefficients were used as follows;

$$C_d = 1.6*10\text{-}3 \quad \text{for} \quad W < 7 \text{ m/s} \qquad (1)$$

$$C_d = 2.5*10\text{-}3 \quad \text{for} \quad W > 10 \text{ m/s} \qquad (2)$$

with a smooth transition for wind speeds between 7 and 10 m/s (Csandy, 1982). The time steps for calculating the baroclinic (internal mode) and barotopic (external mode) cycles were taken as 300 and 10 seconds, respectively. At the solid walls of the boundary the normal components of the velocity were set to zero, while at the open boundaries of the computational domain, we specified the conditions of radiation and smoothing of the tangential component. For the sea elevation at these open boundaries, a simple non-gradient condition was assumed. If temperature and salinity were advected into the model domain by inflow velocity at open boundaries, temperature and salinity of the World Ocean Atlas 2001 (WOA 2001) monthly data were used by interpolating into each time step. Under outflow conditions, the radiation condition is adapted at the open boundary. The climatological data from WOA 2001 is also used as initial conditions of temperatures and salinity. The model is run for 250 days in a diagnostic mode (holding the density field unchanged) to obtain velocity and sea surface height field by using climatological wind stress by daSilva *et al.* (1994). After this initial run, the physical fields are used for the initial condition of coupled model.

4. Results and Discussion

Saitoh et al. (1996) showed that the spring bloom was usually formed between April and May in the Okhotsk Sea based on the monthly coastal zone color scanner (CZCS)- chlorophyll (Chl) imagery from 1978 until 1986. Fig 7 shows sea surface nitrate distribution simulated by KKYS and KKYS-FE together with the observed value from WOA in March. In March, before a spring bloom, both results show good agreement with the observation. As is shown in Fig. 7, relatively high nitrate concentration can be found in the northwestern Okhotsk Sea. After a spring boom (July), the sea surface nitrate is depleted in almost all area of the Okhotsk Sea (Fig. 8). Both of KKYS and KKYS-FE' show almost the same feature as WOA data. On the other hand, surface nitrate concentration is high (>5μM) in the Northwestern Pacific. KKYS cannot reproduce this surface nitrate distribution, while KKYS-FE shows a similar distribution there.

The spring bloom in 2001 begins in the southern and northeastern parts of the Okhotsk Sea in May, and moves toward the southern and northeastern parts in June (Fig. 9(a), Fig. 10(a)). Both of KKYS and KKYS-FE can reproduce this characteristic features of spatial distribution of the phytoplankton in spring bloom in the Okhotsk Sea (Fig. 9(b, c), Fig. 10(b, c)).

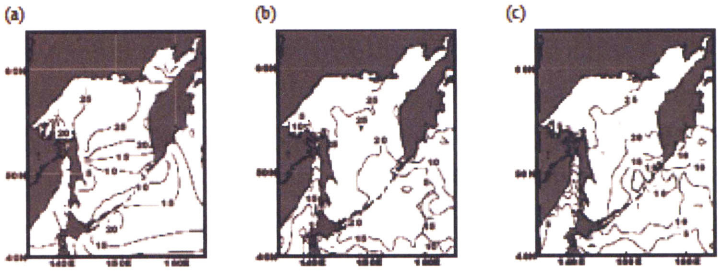

Fig. 8

Monthly mean surface nitrate concentration at March from World Ocean Atlas data (a), KKYS-FE's result (b) and KKYS's result (c). The model results is average of depth from 0m to 10m.

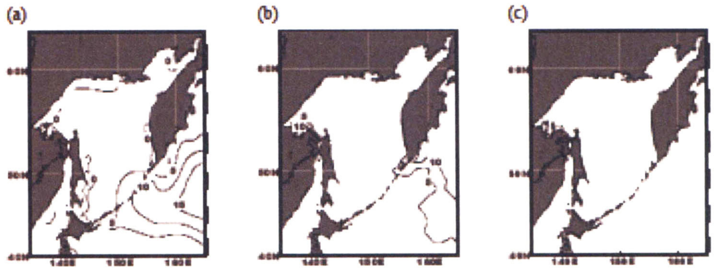

Fig. 9

Monthly mean surface nitrate concentration at July from World Ocean Atlas data (a), KKYS-FE's result (b) and KKYS's result (c). The model results is average of depth from 0m to 10m.

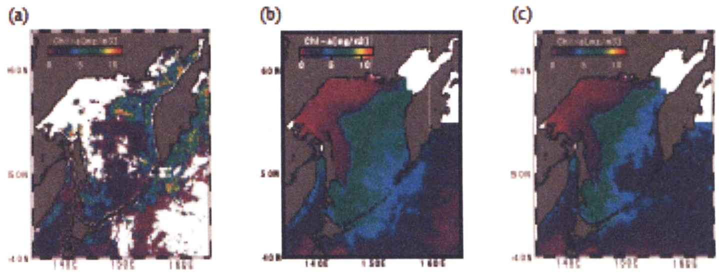

Fig. 10

Monthly mean surface Chl-a concentration at May from seaWiFs-Chl image (a), KKYS-FE's result (b) and KKYS's result (c). The model results is average of depth from 0m to 10m.

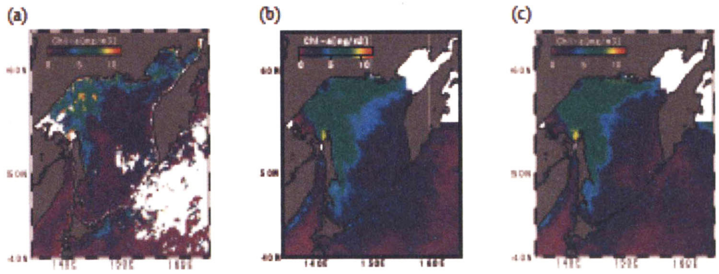

Fig. 11

Monthly mean surface Chl-a concentration at June from seaWiFs-Chl image (a), KKYS-FE's result (b) and KKYS's result (c). The model results is average of depth from 0m to 10m.

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