Interannual variation of material flux under seasonal sea ice in the Okhotsk Sea north of Hokkaido, Japan

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Introduction

The offshore waters along the Okhotsk Sea coast of Hokkaido, Japan are the southernmost area of seasonal sea ice distribution in the Northern Hemisphere. Seasonal sea ice generally drifts ashore along the Okhotsk Sea coast of Hokkaido during January, reaching a maximum extent during February. The ice then moves offshore to the northeast under the influence of southwesterly winds and begins to melt during March, retreating progressively northward during April.

In the Arctic and Antarctic waters, vertical material flux – particularly that of ice algae and the fecal pellets of zooplankton – in regions of sea ice plays an important role in the pelagic–benthic coupling of material cycling and trophic linkages (Hoshiai *et al.*, 1987; Hobson *et al.*, 1995; Schnack-Schiel, 2003). However, a limited number of data on the downward material flux under the seasonal sea ice along the Okhotsk Sea coast of Hokkaido have been reported.

The present study was undertaken to document the spatial and temporal patterns of lithogenic and biogenic fluxes, particularly fluxes of opal and organic material, in relation to sea ice behavior during the pack-ice season at an offshore site in the Okhotsk Sea north of Hokkaido (about 14 km off the Mombetsu coast, water depth of 60 m) from January to March 2005 and 2006.

Materials and Methods

Sea ice coverage in the study area

The first-year ice off the Okhotsk Sea coast of Hokkaido from January to March 2005 behaved in an ordinary pattern; it drifted ashore along the coast late in January, developed to its widest area late in February, and retreated late in March (Hiwatari *et al.*, 2008). On the contrary, the sea ice in 2006 retreated one month earlier than the corresponding period of 2005 (ice data were provided by satellite images 'MODIS' of Japan Aerospace Exploration Agency).

Sediment trap mooring

We measured the material flux under seasonal sea ice using a time-series sediment trap at a site offshore of Mombetsu in the Okhotsk Sea (Fig.1; 44°28.691´N, 143°25.217´E, water depth 60 m). The sediment trap, comprising seven time-series collecting bottles (500 ml each), was situated at 40 m depth (20 m above the sea floor), and the collecting periods were 7 or 14 days in duration for each of the seven collecting bottles over the period from January 13 to March 24, 2005 and 2006 (Table 1).

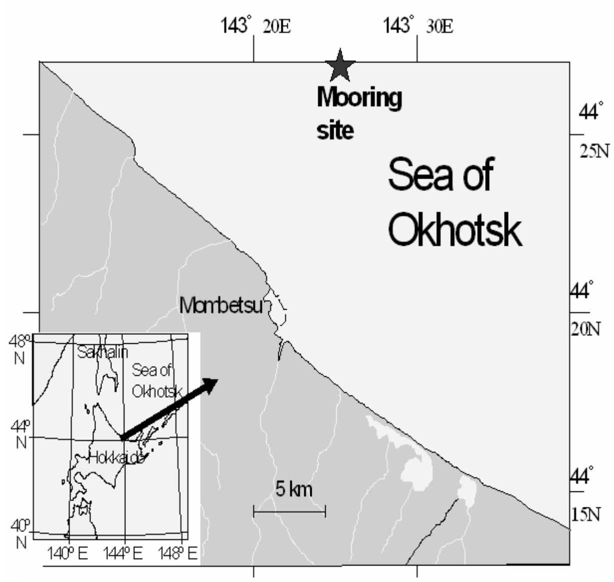

Fig. 1 Map of a portion of the central Okhotsk coast of Hokkaido, showing the location of the sediment trap mooring site.

Table 1 Sampling periods in 2005 and 2006 for the sediment trap.

Sampling bottle	Sampling period	Period (days)
1	January 13–27, 2005 January 13–20, 2006	14 7
2	January 27–February 10, 2005 January 20–27, 2006	14 7
3	February 10–24, 2005 January 27–February 2, 2006	14 7
4	February 24–March 3, 2005 February 3–10, 2006	7 7
5	March 3–10, 2005 February 10–24, 2006	7 14
6	March 10–17, 2005 February 24–March 10, 2006	7 14
7	March 17–24, 2005 March 10–24, 2006	7 14

Chemical analyses

The sediment trap samples were analyzed for the following items: total mass as dry weight, particulate organic carbon (POC), $CaCO_3$, chlorophyll *a* (Chl-*a*), pheopigment, biosilica (BioSi), fecal pellet carbon of zooplankton, and cell identification and enumeration of phytoplankton.

The vertical material flux is expressed as the total mass flux, which consists of the lithogenic and biogenic component fluxes (Fischer and Wefer, 1996; Khim *et al.*, 2007) : total mass flux = lithogenic particle flux + biogenic particle flux, the latter of which is expressed as a total of opal flux, organic matter flux and calcium carbonate ($CaCO_3$) flux. The opal component was calculated by multiplying the BioSi content by 2.4 (Khim *et al.*, 2007). The organic matter was determined by multiplying the POC contents by 1/0.35 (Honda *et al.*, 1997). The lithogenic particle flux was obtained by subtracting the biogenic flux from the total mass flux. The organic matter flux in the study consisted of detritus, fecal pellets, and phytoplankton. In calculating the POC of the phytoplankton in 2005, we used POC = Chl-*a* × 20 (Taguchi *et al.*, 1997). For that of the phytoplankton in 2006, we used POC = cell number × 91.28 × 10–12 g C/cell (Strathmann, 1967). The organic matter fluxes of the phytoplankton and fecal pellets were then calculated by multiplying those POC contents by 1/0.35 (Honda *et al.*, 1997). The detritus flux was obtained by subtracting the organic matter fluxes of phytoplankton and fecal pellets from the total organic matter flux.

Results and Discussion

The total mass fluxes consisting of the lithogenic and biogenic component fluxes in 2005 and 2006 are shown in Figure 2. The total mass fluxes, particularly that of lithogenic particles, were greatest during the early sampling periods in both years. The occurrence of high fluxes of the lithogenic and biogenic (particularly organic material) particle components relative to the total mass recorded during the early sampling periods is consistent with the finding of Noriki and Matsubara (2002).

The particulate materials on early first-year ice were released into the water column as the sea ice melted in seawater temperatures of > 0°C. Oshima *et al.* (2001) observed ice melt around the margins of the sea ice on February 9, 1997, about 140 km northeast of Mombetsu. In this area, first-year ice floes had been advected from the north via the main stream of the southward current.

The organic matter fluxes consisting of detritus, fecal pellets and phytoplankton component fluxes in 2005 and 2006 are shown in Figure 3. The organic matter fluxes, particularly that of detritus in both years, were high during the early sampling periods. The fact that organic matter was found in the early first-year ice offshore from the Okhotsk coast in early February (Granskog, 1999) indicates that decomposition of the organic matter to detritus via the processes of heterotrophic organisms would have occurred in the early first-year ice prior to melting.

During the period from early February to early March 2005, when persistent ice cover was recorded, the fecal pellets of zooplankton were the dominant component of sinking particles. In particular, organic matter comprising fecal pellets contributed more than 70% of the total organic matter flux. We also observed a large number of diatom frustules in the fecal pellets. The present data demonstrate the occurrence of fresh phytoplankton in the form of ice algae beneath the sea ice and the active grazing and egestion of zooplankton during the season of ice cover. On the other hand, fecal pellet flux in 2006 was very little. This suggests that the disappearance of fresh ice algae beneath the sea ice could not induce active grazing and egestion of zooplankton because of the rapid retreat of the sea ice.

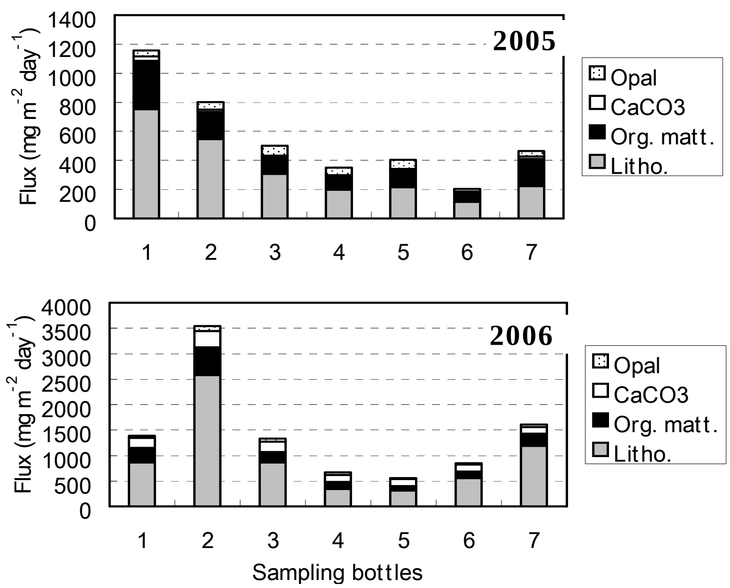

Fig. 2 Temporal variations of lithogenic and biogenic (organic matter, opal, and $CaCO_3$) fluxes consisted of the total mass flux in 2005 and 2006.

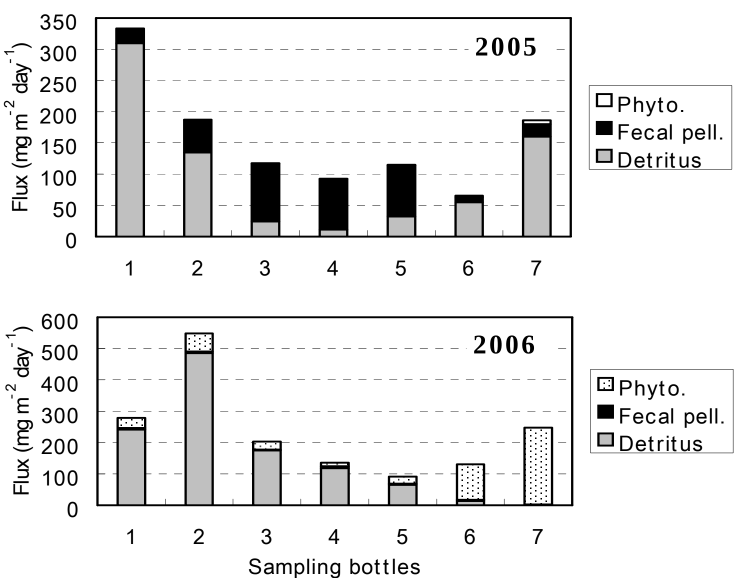

Fig. 3 Temporal variations of organic matter components (detritus, fecal pellets, and phytoplankton) fluxes in 2005 and 2006.

The phytoplankton component flux in 2006 was high during the late sampling periods which indicates that the phytoplankton bloom occurred (not ice algae species) because the sea ice retreated a month earlier than in the corresponding period of 2005.

Conclusions

- The sea ice in 2006 retreated one month earlier than in the corresponding period of 2005.
- Total mass fluxes during January to early February in both years were greater than those in other years. In those periods, lithogenic material occupied more than 60% of the total mass fluxes, much of which would be derived from the sea ice as ice-rafted debris.
- Fecal pellets of zooplankton in 2005 were the dominant components of sinking particles from February to early March, the periods corresponding to a persistent ice cover.

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