An extremely turbid intermediate water in the Sea of Okhotsk: Implication for the transport of particulate organic matter in a seasonally ice-bound sea

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[1] We found a water mass characterized with enormous turbidity and very low temperature in the intermediate layer of the Sea of Okhotsk in September 1999. In June 2000 and September 1999, the cold and turbid water mass was also located in bottom boundary layer on the northwestern shelf region, where sea ice had rejected large amounts of brine waters in winter. Cold brine waters settled on the bottom of shelf must have entrained sedimentary particles, including newly produced organic matter, due to strong tidal mixing, and finally flowed out into Okhotsk Sea Intermediate Water (OSIW) by a western boundary current intensified in autumn. Sediment traps moored in the deep basin recorded the outburst of particles in autumn. This mechanism is likely to export the particulate organic matter produced on the shelf efficiently to pelagic intermediate waters. INDEX TERMS: 3022 Marine Geology and Geophysics: Marine sediments—processes and transport; 4806 Oceanography: Biological and Chemical: Carbon cycling; 4219 Oceanography: General: Continental shelf processes; 4805 Oceanography: Biological and Chemical: Biogeochemical cycles (1615); 4850 Oceanography: Biological and Chemical: Organic marine chemistry

1. Introduction

[2] Since Walsh et al. [1981] pointed out a potential role of the particle export from shelves to slopes as a significant sink for missing CO2 from atmosphere, several research projects have been carried out in the world to clarify the material transport through shelf edge processes [Monaco et al., 1990; Biscaye et al., 1994; McCave et al., 2001]. However, one of the main conclusions from those projects was that most of biogenic particle produced on the shelf is recycled and oxidized there and only a small proportion (of order ≈5% [Biscaye et al., 1994]) is exported to the adjacent slope, due to a temperature-salinity front between the shelf and slope area. While the majority of the investigated shelf areas were located in middle latitudes, continental shelves in high latitudes may have a different significance for the particle export to deep oceans because there are often characteristic dense water masses, originating from sea-ice brines, which directly spreads into the deep and/or intermediate layers on adjacent slopes [Schauer, 1995; Honjo et al., 1988].

[3] The Sea of Okhotsk is a marginal sea on the northwestern edge of Pacific Ocean and known as a seasonal sea ice area at the lowest latitude in the world [Alfultis and Martin, 1987; Kimura and Wakatsuchi, 2000]. A fresh water discharge from Amur River (Figure 1) promotes the formation of sea ice by making a strong halocline, and a large volume of cold brine water is rejected and settled down on the bottom of the northwestern continental shelf along Siberian coast to form Dense Shelf Water (DSW) [Martin et al., 1998; Gladyshev et al., 2000]. Because the density of DSW generally does not exceed 27.0 σ0 reflecting the low salinity of the surface water, it spreads into the intermediate depths (200–500 m) to mix with OSIW [Kitani, 1973; Wong et al., 1998; Itoh, 2000]. In spite of the temporal sea-ice cover, the primary productivity of the Sea of Okhotsk is very high, especially on the continental shelf [Sorokin and Sorokin, 1999; Saitoh et al., 1996], due to the relatively high insolation and the nutrient input from Amur River and Pacific Ocean. Therefore DSW flowing into OSIW may export large amounts of organic matter from the continental shelf to the adjacent slope.

2. Observations and Analytical Methods

[4] In order to clarify the potential role of the DSW outflow for the particle export, CTD observations and water samplings were carried out at more than 50 stations on the northwestern continental shelf and the slope area off east Sakhalin in September 1999 and June 2000 (Figure 1). During the CTD/water sampling, a laser fore-scattering type of turbidity meter (ALEC Denshi, ATU6-8M) was attached on the frame of water sampler. This instrument directly presents turbidity data in a unit of ppm, according to a conversion factor determined with kaolinite suspensions in factory. For comparison with the turbidity, 4 liters of water samples were filtered on Whatman GF/F at a station on the continental shelf in June 2000 and the weight of suspended particles was measured (Figure 2a). The relationship was linear in the deeper layer (Figure 2c), indicating its ability to monitor the particle distribution below the euphotic zone, and a factor (0.75) will be multiplied for the measured turbidity to calculate particle concentrations in Figure 3. In June 2000, water samples were also filtered for measurements of Chl.a and particulate organic carbon (POC) at all stations. However, they were collected only for Chl.a in September 1999 due to the shortage of sample volume. Chl.a...
was analyzed using a Turner fluorescent spectrophotometer, and POC was measured by an elemental analyzer (Fisons NA-1500) after removal of carbonate by acidification.

Four time-series sediment traps (PARFLUX McLane Mark 78G-21) were applied at two sites M4 and M6 (Figure 1) from August 1998 to August 1999 to detect the possible outflow of particles from the continental shelf. Each sampling cup was filled with a buffered 5% formaldehyde solution in filtered seawater to prevent in-situ biological degradation of sample. After removal of swimmers using 1mm-mesh, total dry weights of samples were measured.

3. Results and Discussion

In September 1999, an intermediate water mass (300–450 m depths) containing more than 1 mg/l of suspended particles was found at a station on the slope close to the continental shelf (Figure 3a). Particle concentration of this water mass was more than 10 times as high as those observed ordinarily at intermediate layers on other continental slope areas [Richardson, 1987; McCave et al., 2001]. This turbid intermediate water was very cold (lower than −1°C) and had a density of 26.8–27.0 σ0 that is characteristic of OSIW [Watanabe and Wakatsuchi, 1998; Wong et al., 1998; Itoh, 2000]. The highly turbid and cold intermediate waters were also found at several other stations on the slope area along the northeastern Sakhalin (Figures 3b and 3c) in September 1999. However in June 2000, profiles of turbidity and temperature off Sakhalin Island did not show such large excursions at intermediate layers.

Extremely cold and turbid water masses (σ0 > 26.8) were also located on the bottom of the continental shelf north of Sakhalin in both September 1999 and June 2000 (Figures 3d–3f). The bottom boundary layer on the shelf was very thick, indicating the existence of strong tidal currents on the bottom [Kowalik and Polyakov, 1998]. The tidal currents must have promoted the resuspension of sedimentary particles and also reduced the density of original brine water to that of DSW (σ0 = 26.8–27.0) by mixing with surrounding waters. The density of the cold and turbid intermediate water layer increased southward with distance from the northwestern shelf edge (Figures 3a–3c), probably reflecting the seasonal decrease in the density of DSW. The negative correlation between turbidity and temperature in the intermediate water clearly demonstrates that the cold brine water, which has settled down and entrained large amounts of suspended particles on the bottom of shelf, flows out into the intermediate layer of deep basin and mixes with relatively warm and clear pelagic waters.
At M4 site that is close to the shelf region (Figure 1), an extraordinary high flux of sinking particles was observed at the lower trap from September to November (Figure 4). While, at the upper trap, seasonal difference in the flux was not clear, indicating that an outburst of particles into the intermediate layer from the shelf occurred in autumn. At M6 site that is far distant from the northwestern shelf edge, both seasonal variation and vertical difference in sinking particle flux were relatively small. Hence, most of particles discharged from the northwestern shelf are likely removed by sedimentation within the central basin (Deryugin Basin) in the Sea of Okhotsk.

The timing of particle export observed at the M4 site that is close to the shelf region (Figure 1), an extraordinary high flux of sinking particles was observed at the lower trap from September to November (Figure 4). While, at the upper trap, seasonal difference in the flux was not clear, indicating that an outburst of particles into the intermediate layer from the shelf occurred in autumn. At M6 site that is far distant from the northwestern shelf edge, both seasonal variation and vertical difference in sinking particle flux were relatively small. Hence, most of particles discharged from the northwestern shelf are likely removed by sedimentation within the central basin (Deryugin Basin) in the Sea of Okhotsk.

The distribution of the highly turbid intermediate waters along the northeast Sakhalin in September 1999 (Figure 1) indicates that DSW is exported from the shelf by a gravity current along the slope modified by Coriolis force and/or a western boundary current. The reason why DSW is discharged in autumn is likely explained by the western boundary current, which is usually intensified in autumn by the onset of winter monsoon [Ohshima et al., 2002]. However, the gravity current may play an important role for the discharge of DSW in autumn too [Mizuta et al., 2001].

Based on the assumption that DSW stays on the shelf during spring and summer and is discharged throughout in autumn, we can estimate the efficiency of DSW to export POC from the shelf to OSIW. We firstly calculate the POC stock in DSW at the beginning of autumn and then compare it with the primary production on the shelf. In September 1999 when DSW had just begun to flow out, the average thickness of DSW (characterized by the high turbidity and low temperature) was about 50 m (Figures 3d and 3e). Unfortunately, we did not analyze the POC in September 1999. Therefore, we estimated the averaged amount of POC in DSW at that time as 48 μgC/l and 2.4 gC/m², by multiplying the observed POC concentration in DSW at St. 81 (Figure 2b) in June 2000 (73 μgC/l) by the ratio of the averaged concentrations of “chloroplast pigment equivalent” (CPE) in DSW in September 1999 to that observed at

![Figure 3](image-url)

**Figure 3.** Profiles of particle concentration (solid line), water temperature (dashed line), concentration of chloroplast pigment equivalent (Chl.a + Phaeopigment) (open circle) at stations 78 (a), 40 (b), 34 (c), 61 (d), 63 (e) in Sept. 1999, and 81 (f) in Jun. 2000. Shaded zones correspond to the layers of density between 26.8 and 27.0 σt. Thick solid bars show the position of water bottom.

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The timing of particle export observed at the M4 site is consistent not only with the occurrence of highly turbid intermediate waters on the slope in September 1999 (Figures 3a, 3b, and 3c), but also with the seasonal changes in the distributions of DSW on the northwestern shelf reported by Gladyshev et al. [2000] and Itoh [2000]. They compiled hydrographic data from different sources and found that DSW is usually deposited on the shelf in spring and summer but disappears during autumn, as illustrated by the retreat of DSW (>26.8σt) from Siberian coast in September 1999 (Figure 1). These facts suggest that DSW produced by brine rejection in winter stays on the shelf during spring and summer, and accumulates large amount of sedimentary particles effectively, including newly produced phyodetritus (Figures 3e and 3f) and organic matter (Figure 2b), before being discharged into OSIW in autumn. Low C/N ratios of particulate organic matter in DSW also indicate their less degraded nature (Figure 2b).

![Figure 4](image-url)

**Figure 4.** Seasonal variations in the total mass flux of sinking particles collected by sediment traps at M4 (a) and M6 (b) from Aug. 7, 1998 to Aug. 7, 1999. Open and solid symbols indicate those observed at upper and lower trap depths, respectively. Sites and depths of the sediment traps were as follows (M4: 53°00’N, 145°29’E, water depth 1754 m, upper trap 300 m, lower trap 1550 m; M6: 49°31’N, 146°30’E, water depth 812 m, upper trap 300 m, lower trap 700 m).
profiles obtained in September 1999, utilizing nitrate in the surface layer before September. This indicates a very low degradation rate of the organic matter in DSW observed in June are existing in September must be discharged into the ocean interior.

4. Perspective

The outflow of DSW in the Sea of Okhotsk has three potential advantages for the exportation of particles, especially particulate organic matter, from the shelf to the adjacent slope. 1) DSW may flow out of the shelf by itself as a gravity current. 2) Even if DSW is discharged by surface currents but consists of only flux by the DSW efficiently, because this estimate does not include the flux of suspended particulate matter in the North Atlantic, Deep Sea Res., 34, 1301–1329, 1987.


Watanabe, T., and M. Wakatsuchi, Formation of the OKTW in following season, is equivalent to 4% of the new production and there remain many uncertainties in the process of flux estimation, we can at least conclude that the Sea of Okhotsk exports POC from the shelf to deep sea very efficiently, because this estimate does not include the flux by surface currents but consists of only flux by the DSW outflow in autumn.

4. Perspective

The outflow of DSW in the Sea of Okhotsk has three potential advantages for the exportation of particles, especially particulate organic matter, from the shelf to the adjacent slope. 1) DSW may flow out of the shelf by itself as a gravity current. 2) Even if DSW is discharged by another mechanism such as a western boundary current, contained particles may be easily settled down on the slope without being consumed by pelagic organisms, because DSW does not spread onto surface or suburface layers but penetrates into intermediate layers. 3) The very low temperature in DSW must reduce decomposition rate of organic matter by microorganisms. Because part of these mechanisms must function at all high latitudinal continental shelves other than the Sea of Okhotsk too, the particle exports through the shelf edge in the high latitudinal oceans may play an important role in global organic carbon transports into the ocean interior.

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References


