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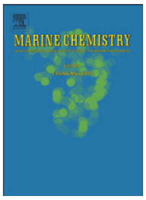

Incorporation of nitrogen compounds into sea ice from atmospheric deposition

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ABSTRACT

Temporal measurements of temperature, salinity, water–oxygen isotopic ratio and nutrient concentrations at Saroma-ko Lagoon, southern Sea of Okhotsk, were made in February–March 2008 to examine the processes by which nitrogen compounds from the atmosphere were incorporated via snowfall into sea ice. Granular ice made up more than half the ice thickness, and the mass fraction of snow in the snow-ice layer on top of the ice ranged from 0.8% to 46.9%. The high concentrations of $NO_3^- + NO_2^-$ and NH_4^+ observed in the snow and snow-ice throughout the study period were likely due to the proximity of the study site, in northern Japan, to the east coast of the Asian continent. Pollutants containing high NO_3^- and NH_4^+ concentrations are transported from East Asia and deposited in snowfall over the sea ice in the southern part of the Sea of Okhotsk. Compared with $NO_3^- + NO_2^-$ and NH_4^+ concentrations, PO_4^{3-} concentrations in the snow and snow-ice were low. The strong correlation between the $NO_3^- + NO_2^-$ and NH_4^+ concentrations in the snow-ice and the mass fraction of snow indicates that the nitrogen compounds on top of the sea ice were controlled mainly by the snow contribution to the sea ice when snow-ice predominated. Our results indicate that chemical cycles in sea ice can be affected by polluted precipitation (snow) originating from a nonpolar sea.

1. Introduction

In sea ice, the ice and brine-channel network system contains abundant microorganisms such as ice algae and bacteria (e.g., Arrigo et al., 2010). Photosynthesis by ice algae causes the low concentrations of nutrients that are observed in sea ice (Dieckmann et al., 1991; McMinn et al., 1999). Nutrients are re-supplied by oxidative remineralization of organic matter by heterotrophic organisms and bacteria (Thomas et al., 1995) and sometimes by replenishment from under-ice seawater (Nomura et al., 2009; Thomas et al., 2010). The atmospheric transfer and deposition of nutrients onto sea ice is an important source of nutrients for potentially nutrient-depleted sea-ice surfaces (Rahm et al., 1995; Kaartokallio, 2001; Granskog et al., 2003; Krell et al., 2003; Granskog and Kaartokallio, 2004; Nomura et al., 2010a). In the Northern Hemisphere, snow on sea ice contains high concentrations of nutrients, which are incorporated into the ice during snow-ice formation. The flooding of sea ice by seawater and the resulting formation of snow-ice are widespread and important ice-thickening processes (Lange et al., 1990; Eicken et al., 1994; Jeffries et al., 2001). When sufficient snow has been deposited on sea ice, the ice surface is depressed below sea level and flooding occurs at the snow–sea ice interface. Subsequent freezing of the snow and water leads to the formation of snow-ice. These processes strongly affect the heat budget, biological productivity and chemical composition of polar oceans. However, the contribution of nutrient loading from the atmosphere has not been studied in detail (Thomas et al., 2010).

In sea ice of the southern Sea of Okhotsk, concentrations of nitrogen compounds, especially NO_3^- and NH_4^+, in snow and snow-ice are high, which implies that these compounds are supplied from the atmosphere by snowfall and are incorporated into the sea ice through snow-ice formation (Nomura et al., 2010a). The high concentrations may be due to the location of the study area, off the east coast of the Asian continent; particulate pollutants from that area contain high NO_3^- and NH_4^+ concentrations (Ooki and Uematsu, 2005). In a previous study (Nomura et al., 2010a), we focused on the spatial distribution of nutrients in sea ice in the southern Sea of Okhotsk, but no information on the temporal variation of nutrient concentrations in the sea ice in this area is available. In particular, there are no data on the incorporation of nitrogen compounds ($NO_3^- + NO_2^-$ and NH_4^+) into the sea ice.

In this study, we investigated the temporal variation of nutrient concentrations in sea ice in Saroma-ko Lagoon to determine the

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incorporation processes, particularly the incorporation of nitrogen compounds during snow-ice formation at the top of the sea ice. We hope that our results will improve our understanding of the role of sea ice in biogeochemical cycling in the southern Sea of Okhotsk and beyond.

2. Materials and methods

2.1. Sampling date and general information of Saroma-ko Lagoon

Sea ice, under-ice water, and snow were sampled at a fixed station on Saroma-ko Lagoon between 25 February and 4 March 2008. The lagoon (surface area, 149 km^2; mean depth, 14.5 m) is located on the northeast coast of Hokkaido, Japan, and is connected to the Sea of Okhotsk by two inlets (Fig. 1). The water mass of the eastern part of the lagoon consists mainly of Okhotsk Sea water with freshwater input from the Saromabetsu River (Shirasawa and Leppäranta, 2003; Nomura et al., 2009; Nomura et al., 2010b). Generally, freezing started at the beginning of January, and the whole surface of the lagoon was covered with sea ice from early February through early April (Shirasawa et al., 2005). The maximum annual thickness of ice was 35–60 cm in the eastern lagoon, and on average, the growth to 34 cm took 1 month, to mid-February, and thereafter the ice grew a further 8 cm (Shirasawa et al., 2005). The average snow thickness on the ice was 11 cm (standard deviation of 10 cm) in mid-February (Shirasawa et al., 2005). Northwesterly winds were dominant in the ice-covered season in this area (Kodama et al., 1999). Because the sea ice grows in a semi-enclosed lagoon, the conditions are stable and thus provide an opportunity to examine the temporal change in the physico-chemical properties of the sea ice at a fixed location (Kudoh et al., 1997; Shirasawa et al., 1997; Nomura et al., 2009).

2.2. Sampling of sea ice, under-ice water, and snow

A subset of sea ice cores per day of the study was collected with a SIPRE (Snow, Ice, and Permafrost Research Establishment) ice corer with an internal diameter of 7.5 cm. Immediately after collecting a core, we measured the ice temperature by inserting a needle-type temperature sensor (Testo 110 NTC, Brandt Instruments, Inc., Prairieville, USA) into holes drilled into the core. To avoid contamination from the temperature sensor, we then collected a new core for nutrient analysis. Then sea ice core was packed it in a polyethylene bag and kept it horizontal in a cooler box with snow as a coolant to avoid the loss of brine from ice core. We did not see any liquid in the plastic bag after storage, supporting low brine drainage. However, it is likely that brine drainage occurred when collecting the sea ice cores from the sea ice, in practice this cannot be avoided, especially for the lowest parts of the ice, as some is lost when a core is retrieved (moved upward). Even though special care was taken and the cores were collected quickly, some brine loss from the sea ice would have occurred. Therefore, these results would have led to a small underestimation of the nutrient concentration in sea ice. However, it is difficult to quantify the nutrient loss during this process.

Thereafter, the ice core was transported to the nearby SRCA (Saroma Research Center of Aquaculture) and stored in a deep freezer at −30 °C for further analysis of ice texture, salinity, nutrients and water–oxygen isotopic ratio (water–δ^{18}O) at Hokkaido University, Sapporo. For measurement of chlorophyll *a* concentrations, a third core was collected on 4 March as described for the second ice core. Immediately upon arrival at the SRCA, this third core was cut into 10–14-cm sections and melted into 200-mL artificial seawater (40 g NaCl in 1 L Milli-Q water) in polyethylene cups to avoid the loss of intracellular organic solute due to cell rupture under osmotic stress (Garrison and Buck, 1988). Melted core samples of known volume

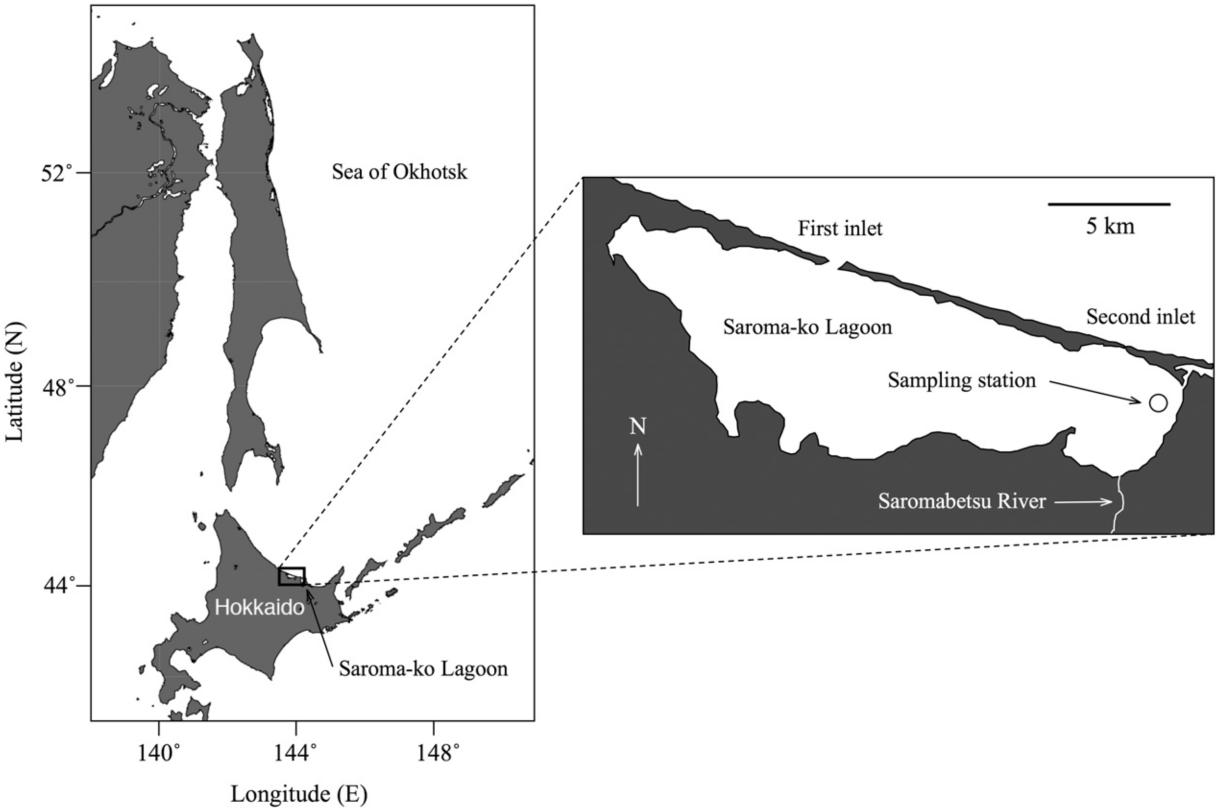

Fig. 1. Location of sampling station in Saroma-ko Lagoon in the southern Sea of Okhotsk.