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COMPARATIVE STUDY OF OCEANOGRAPHIC CHARACTERISTICS ABOVE/UNDER FIRST-YEAR SEA ICE AT LOW AND HIGH LATITUDES

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Abstract: As part of the joint Japanese and Canadian scientific experiment, the SARES (Saroma–Resolute Studies) project, to study "the biological CO_2 pump under the first-year ice in the Arctic Ocean" and "the biological processes in Arctic polynya areas", meteorological and oceanographic studies were carried out successively at the Saroma Ko lagoon, Hokkaido, Japan from December 1991 to April 1992, and in Resolute Passage, Canadian Arctic from April to June 1992. Seasonal sea ice at its southern limit in the Sea of Okhotsk reaches a maximum thickness of about 40 cm at the Saroma Ko lagoon, while ice reaches a maximum thickness of about 2 m in Resolute Passage. In this paper, meteorological and oceanographic variables obtained from both field experiments of the SARES project are compared.

The presence of sea ice cover leads to major changes in the flow and stratification regime. We observed much weaker currents and the presence of small scale vertical structure in the temperature-salinity regime under complete landfast ice covered areas. It is believed that ice melt and freshwater input from a small river played an important role in generating the observed variability in the lagoon. The presence/absence of sea ice plays a significant role in determining the oceanographic characteristics of the lagoon and its potential for biological productivity. It is believed that the difference in solar irradiance between low and high latitudes in seasonally sea-ice covered waters plays a significant role in biological productivity in the spring regime.

1. Introduction

The Arctic Ocean and its adjacent seas are covered by a thin, uneven sheet of sea ice formed by the freezing of ocean surface water. The area of ocean covered by this ice varies strongly with the season. In spring, the ice extends into the mid-latitudes where its presence impacts on human activities. Minimum coverage occurs in late summer and early fall. Sea ice extent in the Northern Hemisphere is sketched in Fig. 1, where we see that most of the central Arctic Ocean is covered by perennial ice and most of the peripheral seas by seasonal ice. Seasonal sea ice may reach a maximum thickness from a few centimeters to a couple of meters.

Some of the most biologically important sites in the polar oceans are in marginal ice zones. Marginal ice zones are sites of enhanced biomass and growth of

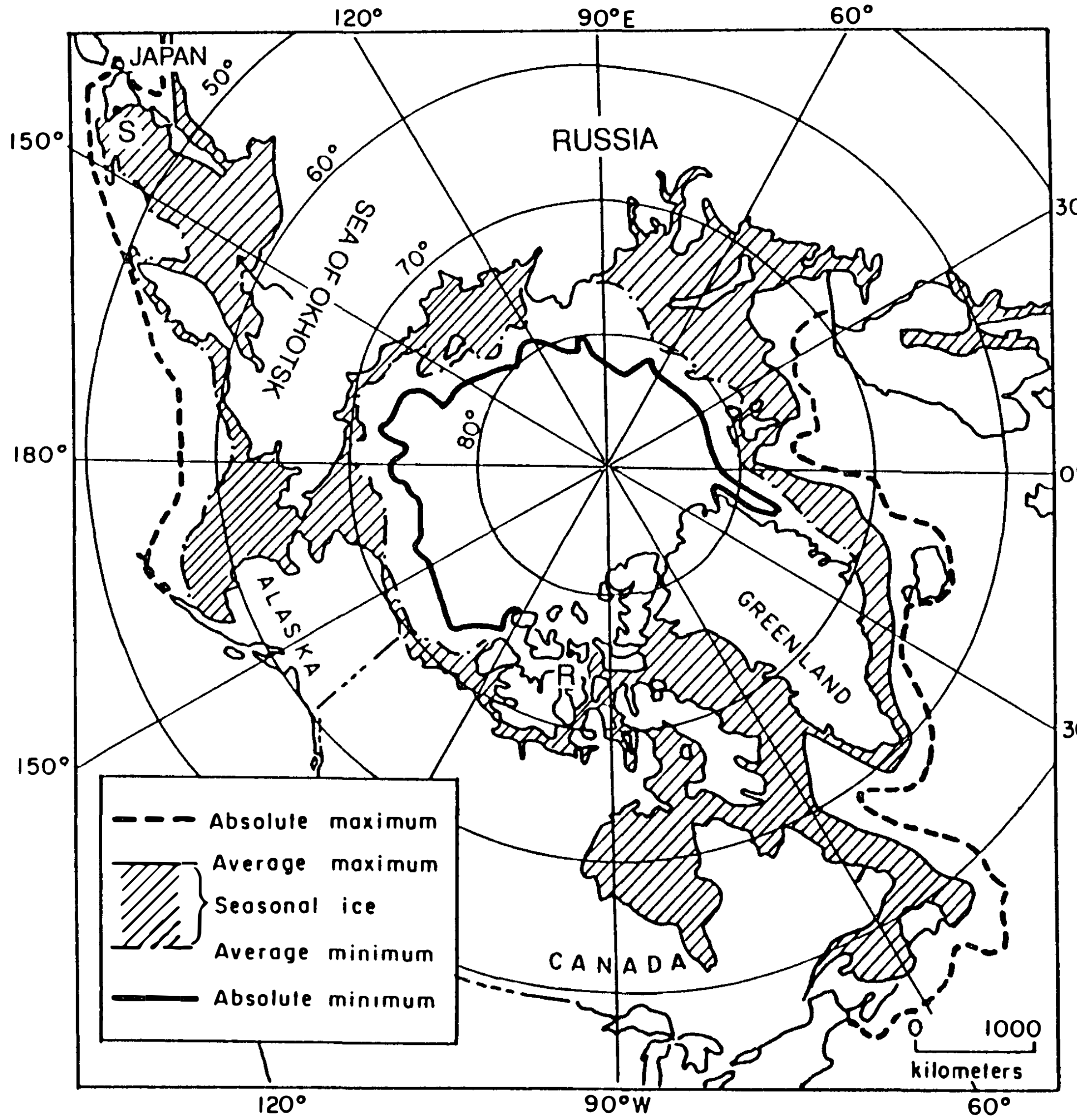

Fig. 1. Sea ice extent in the Northern Hemisphere (reproduced from MAYKUT *(1985)), showing experimental sites of the SARES project, the Saroma Ko lagoon (letter S) and the Resolute Passage (letter R).*

many groups of organisms ranging from microscopic phytoplankton to marine mammals and birds. For example, ice edge phytoplankton blooms have been observed in nearly all polar regions. Marginal ice zones are also physically dynamic regions in which mesoscale phenomena such as upwelling, fronts and eddies are found, and which in turn mediate globally important exchanges of heat and carbon. For example, it has been hypothesized that convective chimneys are dependent on ice edge dynamics, and as a result marginal ice zones potentially mediate the flux of CO_2 from the atmosphere into the ocean (SMITH and NIEBAUER, 1993).

In this study we discuss and compare characteristics of environmental variables at the two sites, where factors such as the period of the ice-covered season and the thickness of sea ice are significantly different. Seasonal sea ice reaches a maximum thickness of about 40 cm at the Saroma Ko lagoon in Hokkaido (at its southern limit) in the Sea of Okhotsk. In contrast, ice reaches a maximum thickness of about 2 m in the ocean waters of the Canadian Arctic Archipelago. The SARES (Saroma–Resolute Studies) project was initiated to conduct projects entitled, "The biological CO_2 pump under the first-year ice in the Arctic Ocean" and "The biological processes in the Arctic polynya areas" within the context of the Canada–Japan Agreement on Cooperation in Science and Technology. The Japanese and Canadian joint field work of the SARES project was conducted during winter and spring of 1992, in Saroma Ko lagoon, Hokkaido, Japan, and in Resolute Passage, Northwest Territories, Canada. Comparison of environmental characteristics at these study sites will be made. The importance of turbulence at or near the ice-water interface will be also discussed.

2. Environmental Variables

Meteorological and oceanographic studies were carried out from landfast sea ice at Saroma Ko lagoon (44°N) in the Sea of Okhotsk from December 1991 to April 1992, and later in Resolute Passage (75°N) in the Canadian Arctic, from April to June 1992. The general atmospheric and oceanographic features obtained from both field experiments are summarized in Table 1. Other atmospheric and oceanographic data obtained from the Saroma Ko experiment in 1992 can be seen in the data report by SHIRASAWA *et al.* (1993). Climatic data were obtained from VOWINCKEL and ORVIG (1970) and KOKURITSU TENMONDAI (1991).

Table 1. A summary of meteorological and oceanographic parameters at Saroma Ko lagoon (SHIRASAWA et al., 1993) and Resolute Passage.

Parameter	Saroma Ko	Resolute Passage
Latitude	44°N	75°N
Sunshine	Jan.–Dec.	Feb.–Oct.
Annual amount (hour)	1845	1465
Air temperature below zero	Mid Nov.–March	Mid Aug.–June
Ice-covered period	Jan.–March	Sep.–June
Period of experiment	21/Feb.–24/March/92	1–12/May/92
Depth (m)	10	200
Ice condition	Fast ice	Fast ice
Ice thickness (m)	0.35	2.2
Water temperature near the interface (°C)	$-0.6\sim-1.45$	$-1.72\sim-1.77$
Salinity of water near the interface (psu)	11.6–32.2	32.2–33.2
Mean current (cm/s)	3.6–5.1†	3–27
Friction velocity, u^* (cm/s)	0.1–0.2†	0.1–1.5
Heat flux, H (W/m^2)	20–90†	10–150
Heat flux coefficient, C_h	0.002–0.007†	0.001–0.01
Drag coefficient, C_l	0.0002–0.002†	0.001–0.008
Vertical eddy viscosity, K_z (cm^2/s)	2–8†	2–33
Roughness Reynolds number, Re^*	Smooth†	Smooth–rough

† Measurements of under-ice turbulent fluxes were made during the period between 26 and 28 February 1992.

2.1. Ice growth

Some of the significant differences in characteristics between Saroma Ko and Resolute Passage are the thickness of ice and the length of the ice-covered season. The ice season in Saroma Ko was from January through April with a maximum ice thickness of 0.35 m, and from September through the following June with a maximum ice of 2.2 m at Resolute Passage (Table 1). Figure 2 shows the growth of ice at Saroma Ko and at Resolute Passage under climatic conditions which are assumed to be uniform from year to year. Note that the net increase in ice thickness slowly decreases as the average thickness becomes larger. Many field studies have shown that the thickness of young sea ice is closely related to the cumulative number of freezing-degree days, which is a time integral of the difference between the freezing point of the water and the air temperature below the freezing point. Near Resolute Passage, the ice cover reached its maximum thickness of 2 m (21 year average) by the middle of April, with year-to-year variations in ice thickness and surface layer characteristics depending on how the freeze-up occurred (PRINSENBERG and BENNETT, 1987). At Saroma Ko, sea ice reaches a maximum thickness of about 40 cm in March, which was estimated from the cumulative number of freezing-degree days (MURAI *et al.*, 1992; SHIRASAWA, 1993).

Monthly mean air temperatures at Saroma Ko and Resolute Passage are shown in Fig. 3. The period with mean air temperature below the freezing point occurs between December and March for Saroma Ko, and between September and the following June in Resolute Passage, which appears to correspond with the pattern of

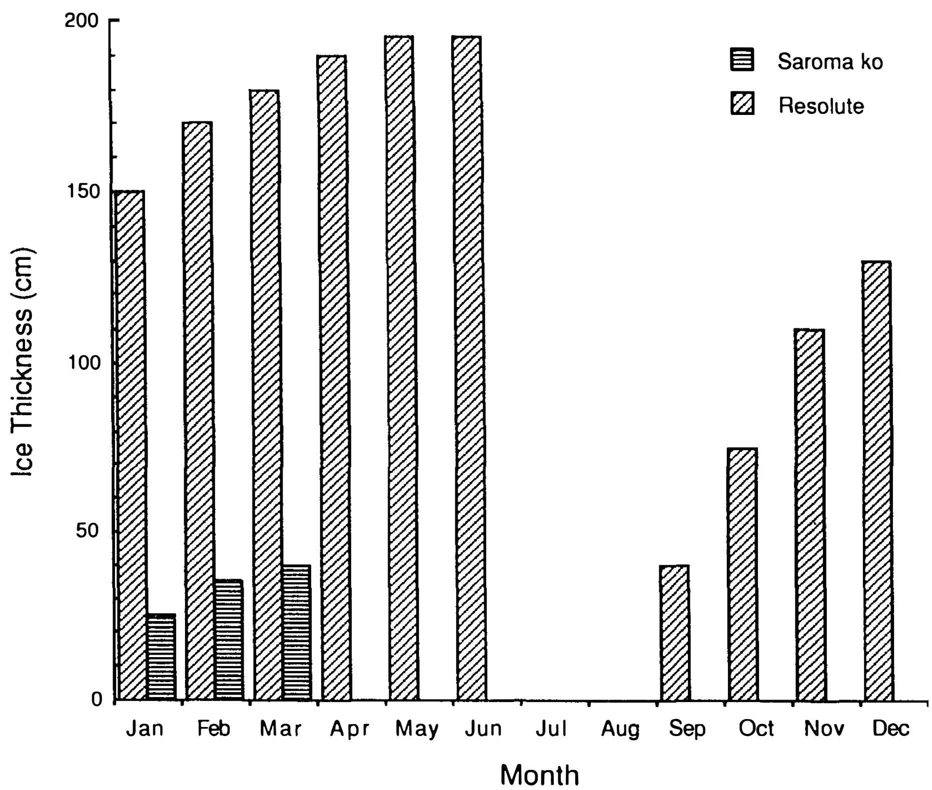

Fig. 2. Ice growth of first-year ice at Saroma Ko and Resolute Passage.

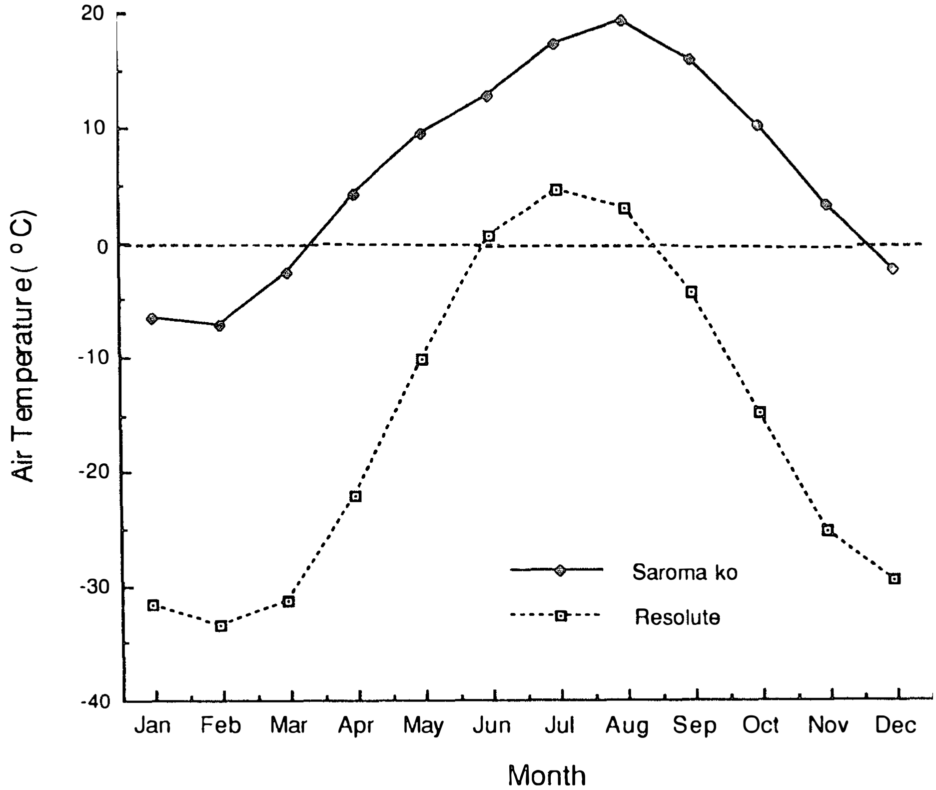

Fig. 3. Monthly mean air temperatures at Saroma Ko and Resolute Passage.

ice growth shown in Fig. 2.

2.2. *Solar irradiance*

Solar irradiance is also significantly different at the two sites. Solar irradiance, on which phytoplankton photosynthesis depends, as does the heating of surface waters and melting of ice, varies greatly with a number of factors in the Arctic region and on a number of time scales (SMITH and NIEBAUER, 1993). Even when the solar angle is positive but small, reflection off the sea surface is large. At Resolute Passage (75°N), the solar angle is smaller, and the sunshine hours are much shorter in the fall and spring and almost absent during the winter, but the midnight sun is found in summer (Fig. 4). In contrast, at Saroma Ko (44°N), the available sunshine does not drastically change. The annual amount of sunshine at Saroma Ko and Resolute Passage is 1845 and 1465 hours, respectively. Also, cloud cover in polar regions is usually greatest where the heat fluxes are greatest, such as at the ice edge and over open water during the spring and summer, while no significant variation occurs through the year in Saroma Ko (Fig. 5).

2.3. *Under-ice oceanic variables*

The presence of sea ice greatly modifies the vertical mixing of the surface layer (LEPAGE and INGRAM, 1991). These mixing events also redistribute chemical and biological properties. Buoyancy effects caused by surface freezing or ice melt are found to play an important role in modifying oceanic turbulent processes under sea

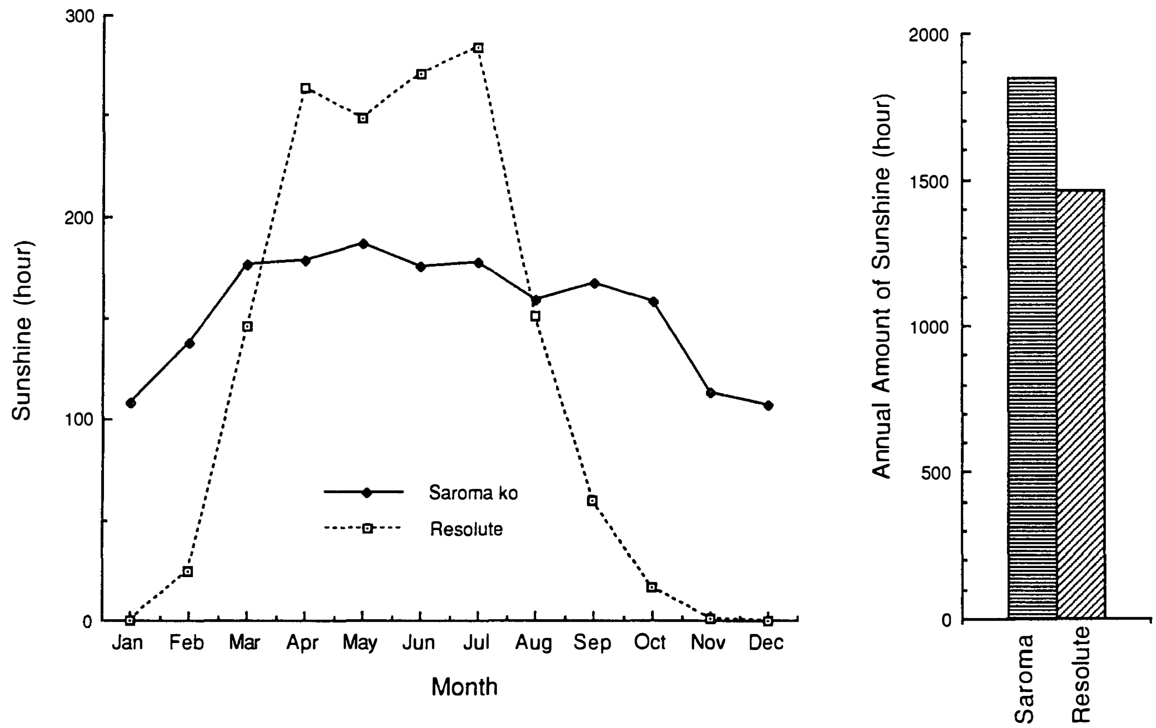

Fig. 4. Duration of sunshine at Saroma Ko and Resolute Passage.

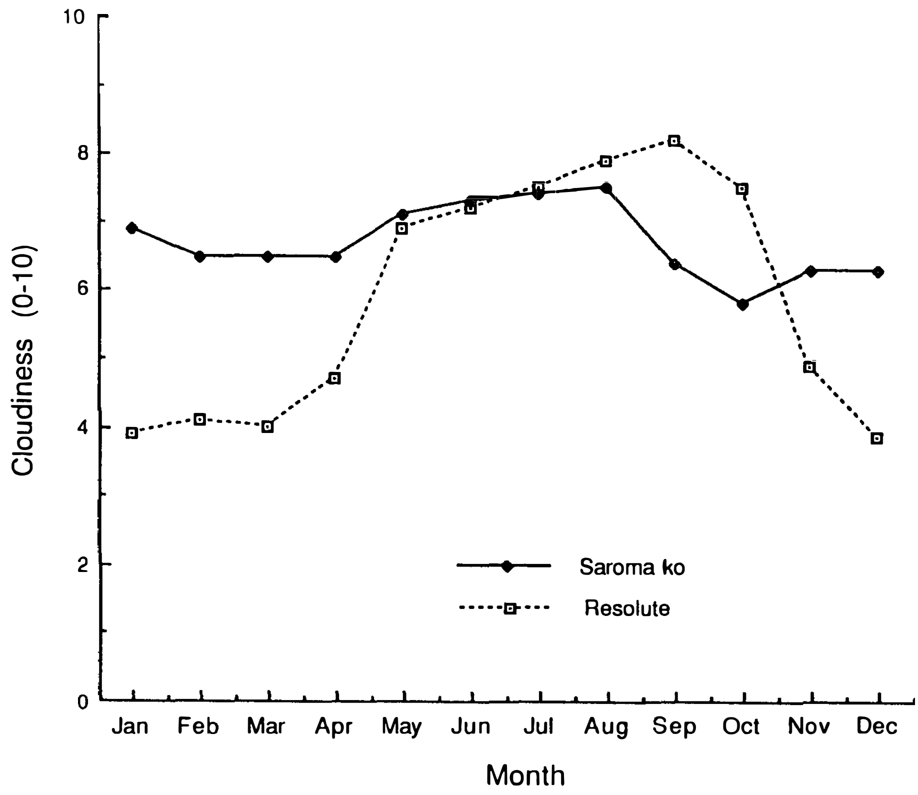

Fig. 5. Cloud coverage at Saroma Ko and Resolute Passage.

ice. As sea ice melts, it introduces fresh or brackish water at the top of the water column, which is buoyant relative to deeper oceanic waters and therefore affects the dynamics of the boundary layer (SHIRASAWA and INGRAM, 1991). The water near the ice-water interface at Saroma Ko had a temperature between -0.6 and $-1.45°C$, and a salinity of 11.6 and 32.2 psu during our sampling period from 21 February to 24 March 1992 (Table 1). It is believed that a combination of ice melt water and freshwater input to the lagoon from a small river caused a reduction of salinity near the ice-water interface. The water temperature at Resolute Passage was between -1.72 and $-1.77°C$, with salinities of 32.2 and 33.2 psu near the ice-water interface over the period from 1 to 12 May 1992 (Table 1). The observed variability may be related to variations of tidal mixing and advection of water masses from adjacent passages. This is suggested by hydrographic and current data from the ice-covered season near Resolute Passage by PRINSENBERG and BENNETT (1987, 1989). They showed that surface water from the western Arctic enters Resolute Passage and joins the northward outflowing water along the eastern shore. The large temporal variability in current is caused by the dominant semidiurnal tidal component, and spatial variability is caused by vertical mixing in the under-ice and bottom boundary layers.

2.4. *Under-ice turbulent fluxes*

Melt processes involve a complex interaction of heat and salt transport, as well as momentum flux at the ice-water interface. The physics of heat and salt transport at the interface are strongly affected by molecular exchange in a thin layer immediately adjacent to the interface. Turbulent processes at the ice-water interface are also important for biological processes both at the interface and in the upper water column (SHIRASAWA and INGRAM, 1991). Much weaker currents of about 4–5 cm/s were observed at Saroma Ko, while stronger flows above 27 cm/s were observed at Resolute Passage (Table 1). The friction velocity, u^*, which is an index of momentum flux at the ice-water interface, varies between 0.1 and 0.2 cm/s under the sea ice at Saroma Ko, while it varies between 0.1 and 1.5 cm/s at Resolute Passage. In addition, the vertical eddy viscosity, K_z, which is also an index of the eddy scale of transport of momentum flux, varies between 2 and 8 cm^2/s during the one-day period at Saroma Ko, while it varied between 2 and 33 cm^2/s during the sampling period from 1 to 12 May 1992 at Resolute Passage. The vertical eddy viscosity is defined here as $\kappa u^* z$, where κ is the von Karman constant, 0.4, and z is the depth in centimeters. It is therefore suggested that the vertical transport of chemical and biological properties near the ice-water interface at Resolute Passage is much more strongly affected by turbulent vertical exchange than that at Saroma Ko.

Underice surface roughness as well as ice melt/freezing and flow strength effects vertical transport of nutrient and biological populations at or near the ice-water interface. The ice-water drag coefficient (referenced to a level of 1 m below the ice), C_1, indicates the degree of underice surface roughness. The drag coefficients obtained at Saroma Ko show that the underice surface was smoother and flatter, while those at Resolute Passage indicate a rougher surface (Table 1). It is thought that the roughness of underice surface affects the flow regime in the frictional boundary layer immediately adjacent to the interface. We usually use the roughness Reynolds number to determine whether the flow regime under sea ice is hydrodynamically rough or smooth. The roughness Reynolds number is defined as, $Re^* = u^* k_s / \upsilon = 30 u^* z_0 / \upsilon$, where k_s is the mean height of roughness elements, z_0 is the roughness length and υ is the kinematic viscosity. The roughness Reynolds number was less than 2 (*i.e.*, the hydrodynamically smooth flow) under the sea ice at Saroma Ko (Table 1). The flows under the sea ice at Resolute Passage varied widely from hydrodynamically smooth to rough (Table 1).

Heat transport is also important in determining turbulent processes at the ice-water interface. The heat flux, H, varied between 20 and 90 W/m^2 at Saroma Ko, while it varied between 10 and 150 W/m^2 at Resolute Passage (Table 1). The heat flux and/or the heat flux coefficient, C_h, the non-dimensional bulk coefficient of heat flux, is related to the under-ice current velocity and the temperature difference between the ice-water interface and the water in a thin layer immediately under the interface. As sea ice melts, it introduces warmer fresh and/or brackish water at the top of the water column, and as a result the heat flux increases as the temperature difference becomes larger. The heat flux values obtained in this study were similar to those obtained under landfast sea ice in southeast Hudson Bay at the beginning of ice-melt season (SHIRASAWA and INGRAM, 1993).

3. Concluding Remarks

Seasonal sea ice reaches a maximum thickness of about 40 cm at Saroma Ko, at the southern limit of the first-year sea ice area, while first-year sea ice reaches a maximum thickness of about 2 m in the Canadian Arctic Archipelago. Factors such as ice thickness and the length of the ice-covered season play an important role in controlling biological processes. For example, solar irradiance at the ice-water interface or near the interface, on which phytoplankton photosynthesis depends, varies greatly with the thickness of ice and snow-cover layer, and the length of ice season. Buoyancy effects caused by surface freezing/melt and freshwater input also play an important role in modifying the turbulent processes under sea ice. Ice melt and freshwater input from a nearby river caused a reduction of salinity in the surface water near the ice-water interface at Saroma Ko. Turbulent processes at the ice-water interface are also important in determining the rate of biological processes both at the interface and in the upper water column. Much weaker currents were observed under the smooth, flat sea ice at Saroma Ko, where the flow regime was hydrodynamically smooth and nearly laminar. At Resolute Passage, the flow regime was hydrodynamically rough, and therefore turbulent exchanges might strongly influence the vertical transport of nutrient and other biologically important properties near the ice-water interface.

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