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CIRCULATION IN THE NORTHERN JAPAN SEA STUDIED CHIEFLY WITH RADIOCARBON

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ABSTRACT. Radiocarbon concentrations in the northernmost region of the Japan Sea were observed during the summer of 2002. The averaged surface $\Delta^{14}C$ (above 100 m depth) was 52 ± 8‰, which is significantly higher compared with the values of the Pacific Ocean and Okhotsk Sea. The $\Delta^{14}C$ in the deep water decreased with density, and the minimum value was –70‰. By analyzing ^{14}C and other hydrographic data, we found that i) the Tsushima Warm Current Water reaches to the surface layer in the southern Tatarskiy Strait; ii) deep convection did not occur in the northernmost region, at least not after the winter of 2001–2002; and iii) the bottom water that was previously formed in this region may step down southward along the bottom slope and mix with the Japan Sea Bottom Water. Furthermore, a new water mass characterized by high salinity (>34.09 psu) was found in the subsurface layer in the area north of 46°N.

INTRODUCTION

The Japan Sea, with a maximum depth of >3700 m, is a marginal sea in the western North Pacific and is connected to the North Pacific Ocean, East China Sea, and Okhotsk Sea through 4 shallow straits (Figure 1), with these straits forming shallow sills (<150 m). The Tsushima Warm Current flows from the East China Sea through the Tsushima Strait and greatly affects the surface layer of the Japan Sea. The water below the Tsushima Warm Current Water is called the Japan Sea Proper Water (JSPW) and has a large water mass that is colder and richer in dissolved oxygen than the deep water in the North Pacific (e.g. Suda 1932; Nitani 1972). Therefore, the origin of the JSPW must be somewhere within the Japan Sea itself.

Past studies have found that the JSPW consists of 2 waters, the deep water (upper part of JSPW) and the bottom water (lower part of JSPW). The bottom water forms in the northern Japan Sea (e.g. Sudo 1986) and is characterized by extreme homogeneity in the vertical distribution of temperature, dissolved oxygen, and nutrients below 2500 m depth in the deep basin (Gamo and Horibe 1983). In the northern Japan Sea, it has been suggested that the surface water in the winter is dense enough to sink toward the bottom because the water's temperature decreases and the salinity increases due to evaporation or freezing (e.g. Sudo 1986). Ice formation in the Japan Sea occurs in 2 regions: 1) the narrow shelf region adjacent to Vladivostok, Russia; and 2) the much larger area of ice formation in the Tatarskiy Strait (Martin et al. 1992). The bottom water, however, has barely been ventilated since the 1960s or earlier because global warming may have slowed the deep convection in the Japan Sea (e.g. Gamo 1999). On the other hand, in the cold winter of 2000–2001, new bottom water formation was observed in the region off Vladivostok (Senjyu et al. 2002). In the northernmost area, which is another ice formation area, however, hydrographic observations have only been carried out once, in 1995 (Riser et al. 1999). Thus, the bottom water formation and circulation in the northern Japan Sea requires further analysis.

In order to investigate the bottom water formation, circulation, and mixing in the northern Japan Sea, 2 hydrographic sections in the Tatarskiy Strait were surveyed during the 2002 Japanese-

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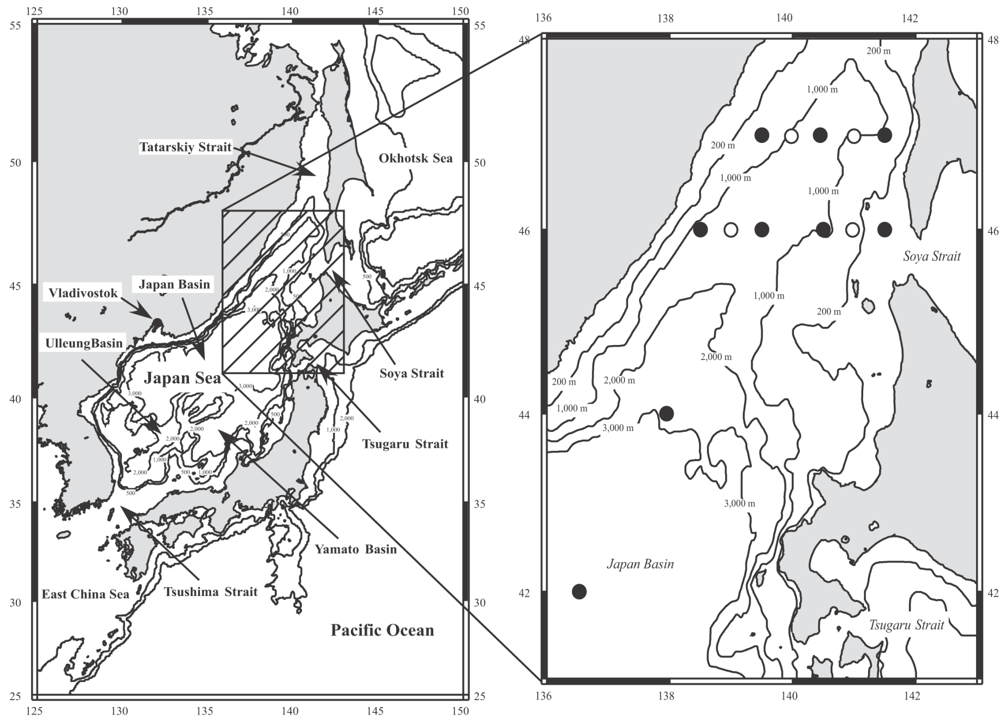

Figure 1 Sampling locations in the northern Japan Sea including 2 stations of the Japan Basin. Solid and open circles show CTD/RMS and CTD observation stations, respectively.

Russian joint expedition (30 June–26 July 2002, R/V *Professor Khromov*) in the Japan Sea. From this expedition, we obtained vertical profiles of radiocarbon, temperature, salinity, and nutrients. In the following section, we will discuss especially the circulation of the northern Japan Sea based chiefly on the ^{14}C results.

OBSERVATION AND METHODS

Observation

During the Japanese-Russian joint expedition in the Japan Sea, CTD (conductivity-temperature-depth profiler with a dissolved oxygen sensor) observations and seawater sample collections with CTD/RMS (CTD with a Rosette multi-bottle sampler) were carried out at 13 stations in the northern Japan Sea (Figure 1). Seawater samples were collected from the surface to the bottom at regular intervals of 25–100 m for measurement of salinity, dissolved oxygen, nutrients (NO_3 + NO_2, PO_4, and SiO_2), and ^{14}C.

^{14}C Analysis

The seawater samples were stored in 500-mL tightly sealed glass bottles after being sterilized with 100 µL of saturated $HgCl_2$ solution onboard the vessel. The dissolved inorganic carbon (DIC) in seawater samples was evolved as CO_2 gas by adding 4 mL of 100% H_3PO_4 and collected cryogenically by purging with pure N_2 gas in a vacuum system (Aramaki et al. 2000). The CO_2-C was reduced to graphite with pure H_2 gas over an iron catalyst at 650 °C. The graphite was then pressed into targets for accelerator mass spectrometry (AMS) ^{14}C measurements.

The $^{14}C/^{12}C$ ratios of the sample graphite were measured by a Tandetron AMS (HVEE, model 4130-AMS) at JAERI-MRL (Aramaki et al. 2000) against a NIST oxalic acid ^{14}C standard (HoxII, SRM-4990C). The $^{14}C/^{12}C$ ratios are expressed by $\Delta^{14}C$ values that were calculated according to Aramaki et al. (2001a). The precision of our AMS measurement was typically less than ±5‰ at 1 σ of the counting statistics. The background level was estimated to be 0.2% of modern carbon. The $\delta^{13}C_{PDB}$ values of samples and the standard were measured for subsamples of the CO_2 gas separated before the graphite production by a triple-collector mass spectrometer, Finnigan DELTA^{plus}, with a precision of ±0.05‰.

Other Chemical Analyses

The salinity of each seawater sample was determined to measure the conductivity of the sample using an "Autosal" salinometer, model 8400B (Guildline Instruments, Ontario, Canada). Dissolved oxygen was determined using the highly precise Winkler titration method (Dickson 1995), and the typical accuracy was <0.3% at 1 σ. Nutrients were measured by the spectrophotometrical method via continuous-flow automated analysis (Knap et al. 1996), and the typical accuracy was <1% at 1 σ.

RESULTS AND DISCUSSION

^{14}C in the Northern Japan Sea and the Japan Basin

The ^{14}C vertical profiles at the 9 stations in the northern Japan Sea and 2 stations in the Japan Basin were compared with those in the Pacific Ocean and the Okhotsk Sea, which were previously observed (Aramaki et al. 2001b) at similar latitude (Figure 2). The averaged surface $\Delta^{14}C$ (above 100 m depth) in the northern Japan Sea is 52 ± 8‰ (1 σ), which is a significantly higher value in comparison with those in the Pacific Ocean and Okhotsk Sea. In the eastern Japan Sea, the surface layer is covered with the Tsushima Warm Current (TWC). After the TWC enters into the Japan Sea from the East China Sea through the Tsushima Strait, the current flows northwards along the Japanese coast and forms outflows to the Pacific Ocean and the Okhotsk Sea through the Tsugaru Strait and the Soya Strait with a timescale of several months (e.g. Suda 1932). Past studies reported that $\Delta^{14}C$ values in Tsushima Warm Current Water (TWCW) were 70–80‰ in 1995 (Kumamoto et al. 1998), and $\Delta^{14}C$ values in the Kuroshio Current Water (KCW) of the Pacific Ocean were close to 100‰ in 1997 (Povinec et al. 2004). Though $\Delta^{14}C$ in TWCW was lower in the late 1990s by 20–30% than that in KCW, it is clear that high surface water $\Delta^{14}C$ in the Japan Sea coincides with that in KCW, which is the major origin of TWCW. Because atmospheric $\Delta^{14}C$ is decreasing exponentially after the late 1960s (Levin et al. 1994), it also suggests that our results are lower by 30% than those in 1995. On the other hand, surface $\Delta^{14}C$ north of 40°N in the western North Pacific is <0‰ (e.g. Key et al. 2002) because this water is well-mixed with the deep water due to deep ventilation in winter and/or upwelling of the Pacific Deep Water (e.g. Stommel 1958), which has a low $\Delta^{14}C$ value of –240‰ in seawater (see Figure 2).

$\Delta^{14}C$ below 2000 m depth in the Japan Basin is homogeneous in vertical distribution; the averaged value is –65 ± 5‰ (1 σ). This water mass is the bottom water reported by Gamo and Horibe (1983). The $\Delta^{14}C$ values in the bottom water are significantly higher than those of the Pacific Deep Water and suggest that the bomb ^{14}C has already ventilated to the bottom. According to an observational study of new bottom water formation, surface water in the northwestern part of the Japan Sea only ventilated the bottom layer during several weeks after the severe winter of 2000–2001 (Senjyu et al. 2002). If the bottom water is formed after every winter, $\Delta^{14}C$ in the bottom water will increase every year. However, the deep convection in the Japan Sea has become less active since the 1960s or earlier, and the bottom water has barely been ventilated due to global warming (e.g. Gamo et al. 1986;

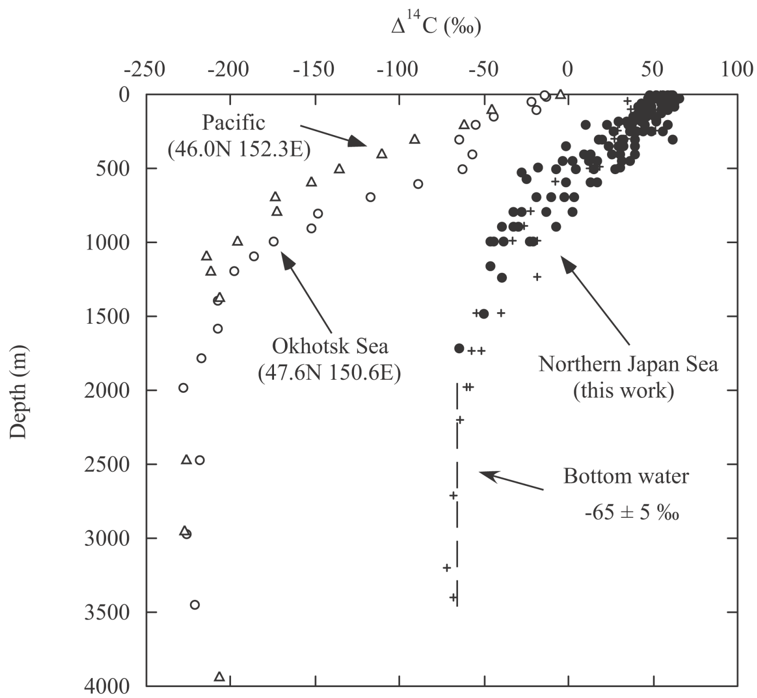

Figure 2 Vertical profiles of $\Delta^{14}C$ in the northern Japan Sea (solid circles), the northwestern North Pacific Ocean (triangles), and the Okhotsk Sea (open circles). Plus signs show $\Delta^{14}C$ in the Japan Basin. The $\Delta^{14}C$ values in the northwestern North Pacific Ocean and the Okhotsk Sea are from summer 1998 (Aramaki et al. 2001b).

Gamo 1999). The $\Delta^{14}C$ in the bottom water is compared with previous studies in Table 1. In the Japan Basin, $\Delta^{14}C$ in the bottom water increased 31‰ during 1977–1995 and then decreased 16‰ during 1995–2002. Because new bottom water formation in the Japan Basin was observed in 2001 (Senjyu et al. 2002), it is implausible that bottom $\Delta^{14}C$ decreased during the last 7 yr. Except for the 1995 data, the ratio of increase of bottom $\Delta^{14}C$ is 0.6‰/yr during 1977–2002, and this agreed with an increase of 0.4‰/yr in the southern basins during 1977–1995. The increasing trend of bottom $\Delta^{14}C$ may mean that small-scale formation events of bottom water intermittently occur for very cold and stormy winters.

Table 1 $\Delta^{14}C$ in the bottom water during late 1970s to 2002. The error bars are differences in (a) counting error by ß counting (only 1 datum) and (b) statistics errors between several data.

Year	Region	$\Delta^{14}C$ (%)	Reference
Northern Basin			
1977	Japan Basin	-80 ± 8^a	Gamo and Horibe (1983)
1995	Japan Basin	-49 ± 4^b	Kumamoto et al. (1998)
2002	Japan Basin	-65 ± 5^b	This work
Southern Basins			
1977	Yamato Basin	-68 ± 8^a	Gamo and Horibe (1983)
1979	Northern Ulleung Basin	-74 ± 6^a	Gamo and Horibe (1983)
1987	Northern Yamato Basin	-66 ± 18^a	Watanabe et al. (1989)
1995	Yamato Basin	-60 ± 7^b	Kumamoto et al. (1998)

Circulation in the Northern Japan Sea

The northernmost region of the Japan Sea is ice covered in winter. Martin et al. (1992) suggested that at least some of the bottom water might originate as a result of winter storms and ice formation in this area. On the other hand, Riser et al. (1999) investigated hydrographic variables in the southern Tatarskiy Strait in the spring of 1995 and suggested that there was no indication of recent deep ventilation in this area, even though the data were collected in May, only 1–2 months after the ice disappeared. In order to examine whether the bottom water originated from the Tatarskiy Strait after the winter of 2001–2002, our hydrographic data including ^{14}C at isobath surfaces of 25 m and 100 m depth are given in Figure 3. The densest water of more than 26.8 σ_ϑ (potential density) exists centering at the northwestern stations according to the isobath surface of 25 m and has the following properties: low temperature, 3.2 °C; low salinity, 33.7 psu; high oxygen, 360 µmol/kg; and low silicate, <3 µmol/kg. Because the surface water in the northern Tatarskiy Strait is greatly influenced by the inflow of fresh water from the Amur River during spring and summer (Martin et al. 1992), it is suggested that the origin of the dense water with low temperature and low salinity is the surface water in the northern Tatarskiy Strait. The potential density of the water, however, is not large enough to sink toward the bottom because the density of the bottom water in the Japan Sea is more than 27.35 σ_ϑ. In the isobath surface of 100 m depth, it is clear that the salinity of the water is much higher than that of water in eastern stations. Thus, although the dense water originated from ice-melt water in the northern Tatarskiy Strait, its properties may be lost in the subsurface (above 100 m depth). We therefore conclude that the bottom water was not formed in northern Tatarskiy Strait, at least not after the winter of 2001–2002.

Two hydrographic sections, along 46°N and 47°N, in the Tatarskiy Strait are shown in Figure 4. High $\Delta^{14}C$ values of more than 50‰ are found in the surface water above 200 m depth. This result indicates that the Tsushima Warm Current Water (TWCW) flows northward as far as north of the Soya Strait. In the 46°N section, the high $\Delta^{14}C$ water along the east coast has a high temperature of more than 6 °C and a low salinity of <34 psu. Furthermore, nutrients such as silicate are negligible (see Figure 3e). The property of the Soya Warm Current Water (SWCW), which originates from TWCW and flows into the Okhotsk Sea through the Soya Strait, is defined by a temperature range of 7–20 °C, a salinity range of 33.6–34.3 psu, and a silicate range of 0–70 µg/L (Takizawa 1982); this agrees with the property of high $\Delta^{14}C$ water found by this work. Though TWCW is generally characterized not only by high temperature and low nutrients but also by high salinity, the salinity of TWCW in the northern Japan Sea may be diluted by mixing with coastal water as it flows northwards along the Japanese coast. On the other hand, in the 47°N section it seems that the TWCW occurred in the central region, and its thickness decreases only to about 100 m. Therefore, it is inferred that a part of TWCW flowing along the Japanese coast is deflected as SWCW at the Soya Strait, and then the remaining part changes the course of flow northwestward in the Tatarskiy Strait. This sequitur is consistent with the distribution of silicate on the isobath surface of 25 m and 100 m depth (see Figure 3e and k).

It is observed that the water with high $\Delta^{14}C$ of more than 50‰ around the central region in the 47°N expands to 300 m in depth. The high $\Delta^{14}C$ water is easily divided into the other water mass with TWCW at the 100 m depth by using the vertical profile of salinity because the other water mass has a high salinity of more than 34.07 psu. The salty water mass is clearly distributed, not only centering on 500 m depth in 100–800 m depth of 47°N but also centering on 350 m depth in 200–700 m depth of 46°N. As the water mass is also characterized by having higher dissolved oxygen than the surrounding water mass (Figure 5), it is deduced that the origin of the water mass is somewhere in the surface water.

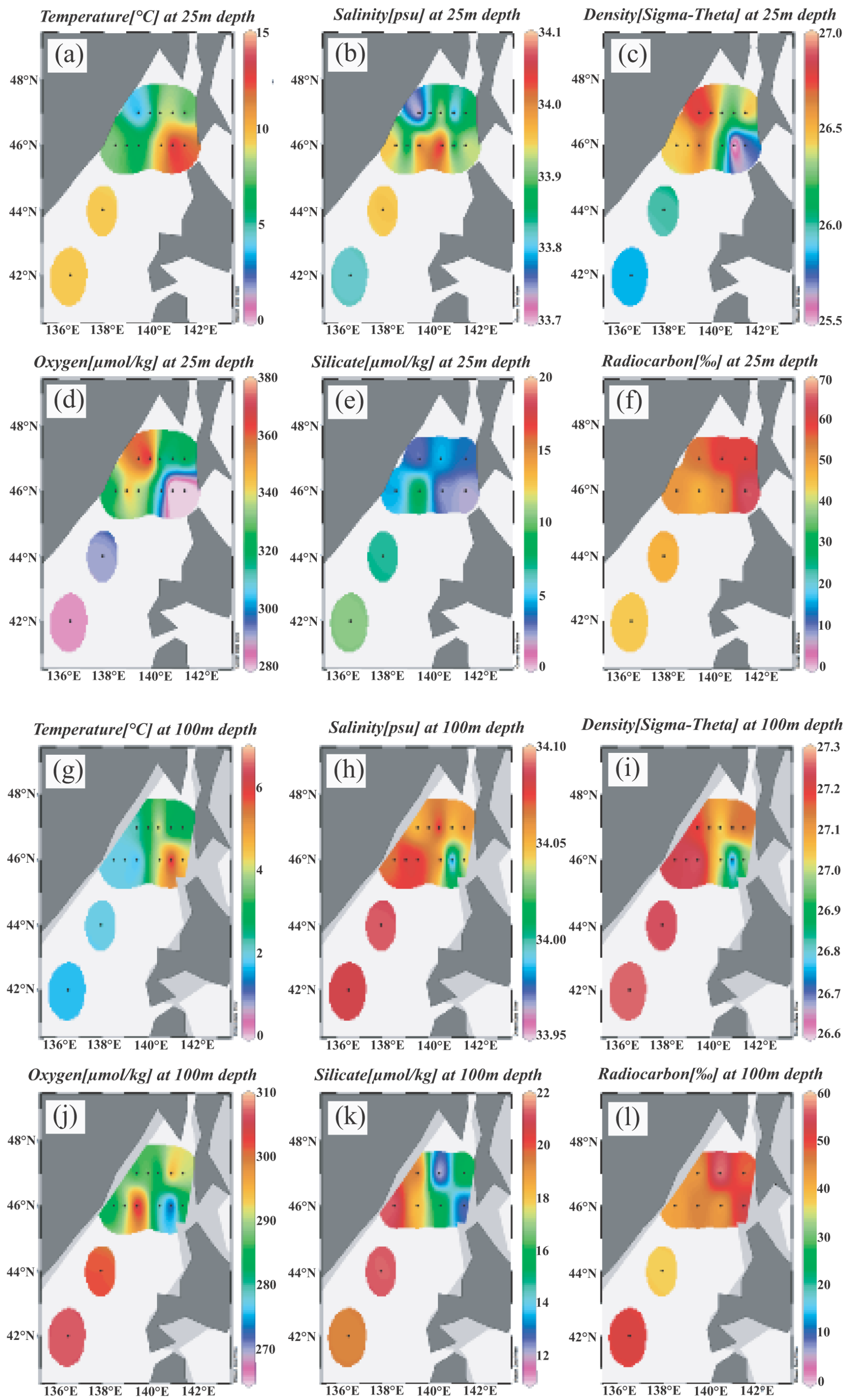

Figure 3 ^{14}C and other hydrographic parameters (potential temperature, salinity, potential density [σ_ϑ], dissolved oxygen, and dissolved silicate) at isobath surfaces of 25 m (a–f) and 100 m depth (g–l).

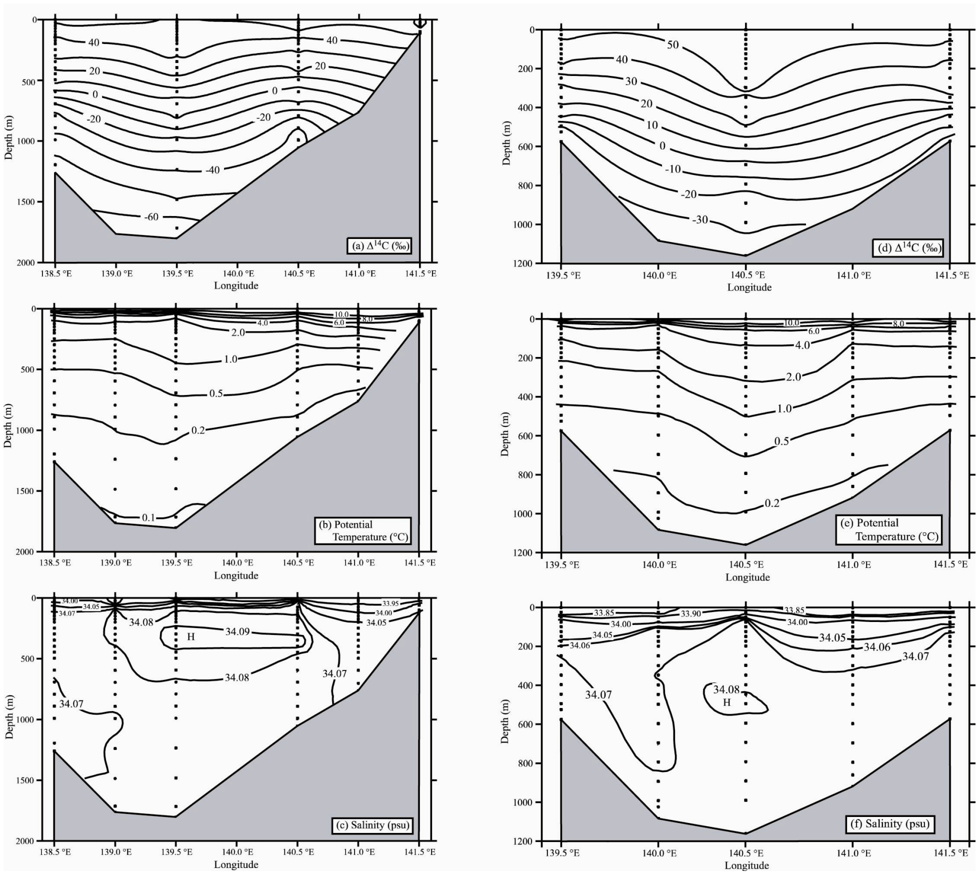

Figure 4 Sections of $\Delta^{14}C$ (a), potential temperature (b), and salinity (c) at 46°N; and $\Delta^{14}C$ (d), potential temperature (e), and salinity (f) at 47°N.

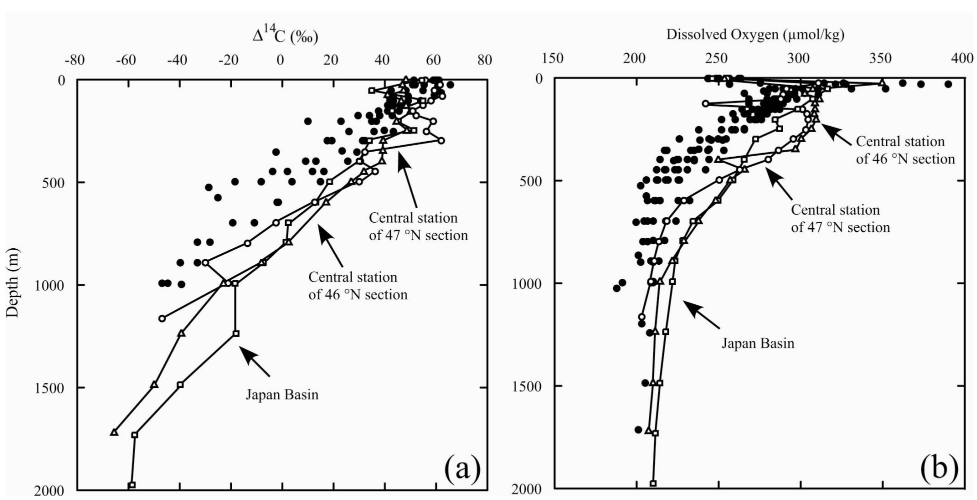

Figure 5 Vertical profiles of $\Delta^{14}C$ (a) and dissolved oxygen (b) above 2000 m depth. Open circles, triangles, and squares show profiles of central station of 47°N, central station of 46°N, and the station in the Japan Basin, respectively.

Interestingly, vertical profiles of $\Delta^{14}C$ and dissolved oxygen are very similar to those in the Japan Basin (see Figure 5). Is this where this salty water mass is formed in the northwestern Japan Sea? However, high salinity (>34.09 psu) is not found in the station of the Japan Basin because even the salinity of bottom water is close to 34.07 psu. Senjyu and Sudo (1993) reported on the basis of hydrographic data that the upper portion of the Japan Sea Proper Water (UJSPW), which is defined as having a potential density of 32.00–32.05 kg/m^3 in the 1000-db range, is formed by winter convection off the Siberian coast between 40°N and 43°N west of 136°E and then advected southward to southwestward. Though it is inferred that $\Delta^{14}C$ and dissolved oxygen of UJSPW agreed with the salty water mass, there is no evidence that UJSPW is advected also northward with increasing salinity. On the other hand, in the northernmost Tatarskiy Strait, a large and transient polynya is created by storms with very strong northerly winds and cold temperatures in winter (Martin et al. 1992). Because the polynya formed in the surface layer and its salinity is increased by evaporation, the property of the water that originated from the polynya may agree with that of the salty water mass. Furthermore, it is suggested that $\Delta^{14}C$ in surface water in the northernmost Tatarskiy Strait is >50‰ because $\Delta^{14}C$ in the dense water (see Figure 3) ranges from 40 to 50‰. However, we do not have direct observational data linking the polynya formed in the winter 2001–2002 with the formation of the salty water and subsequently advected southward and ventilating into the subsurface layer at 100–800 m depth. Though this might be the origin of the water mass of UJSPW, more detailed observations in the northern Japan Sea are necessary to understand the dynamics of the water mass found in this area.

The north-south sections between 42°N and 47°N of $\Delta^{14}C$, including the hydrographic data, are shown in Figure 6. The water below 2500 m depth in the southernmost station is the bottom water in the Japan Sea and characterized by a potential density of 27.35–27.36 σ_ϑ with a temperature of 0–0.2 °C and a salinity of 34.06–34.07 psu (e.g. Gamo and Horibe 1983). According to the potential density contours, it seems that the bottom water is spread along the bottom slope. Similarly, $\Delta^{14}C$ levels in the southern station are lower than those in the northern stations at an isobath surface below 2000 m depth. Comparing the $\Delta^{14}C$ of the isopycnal surface in the bottom water, ^{14}C in the southern station is clearly lower than that in the northern stations (Figure 7). In other words, the northern bottom water is newer than the southern bottom water. These results may suggest that the bottom water in the Tatarskiy Strait steps down southward along the bottom slope and joins with the bottom water in the Japan Basin. Thus, though the bottom water was not formed in the northern Tatarskiy Strait, at least not after the winter 2001–2002, small-scale formation events for bottom water in this area may occur intermittently in very cold and stormy winters, and this bottom water advects southward in the Japan Basin.

SUMMARY

During the Japanese-Russian joint expedition in the Japan Sea, CTD (conductivity-temperature-depth) observations and seawater sample collection were carried out at 13 stations in the northern Japan Sea to study circulation in the study area. Using analysis of ^{14}C and other hydrographic data, we draw the following conclusions:

1. The surface water in the southern Tatarskiy Strait may be occupied by Tsushima Warm Current Water, which flows northward along the Japanese coast, and deep convection does not occur in the northernmost Tatarskiy Strait, at least not after the winter 2001–2002.
2. The water mass characterized by high salinity of more than 34.09 psu is found at the subsurface layer north of 46°N.
3. The bottom water that was previously formed in the northern Tatarskiy Strait may step down southward along the slope bottom and mix with the Japan Sea Bottom Water.

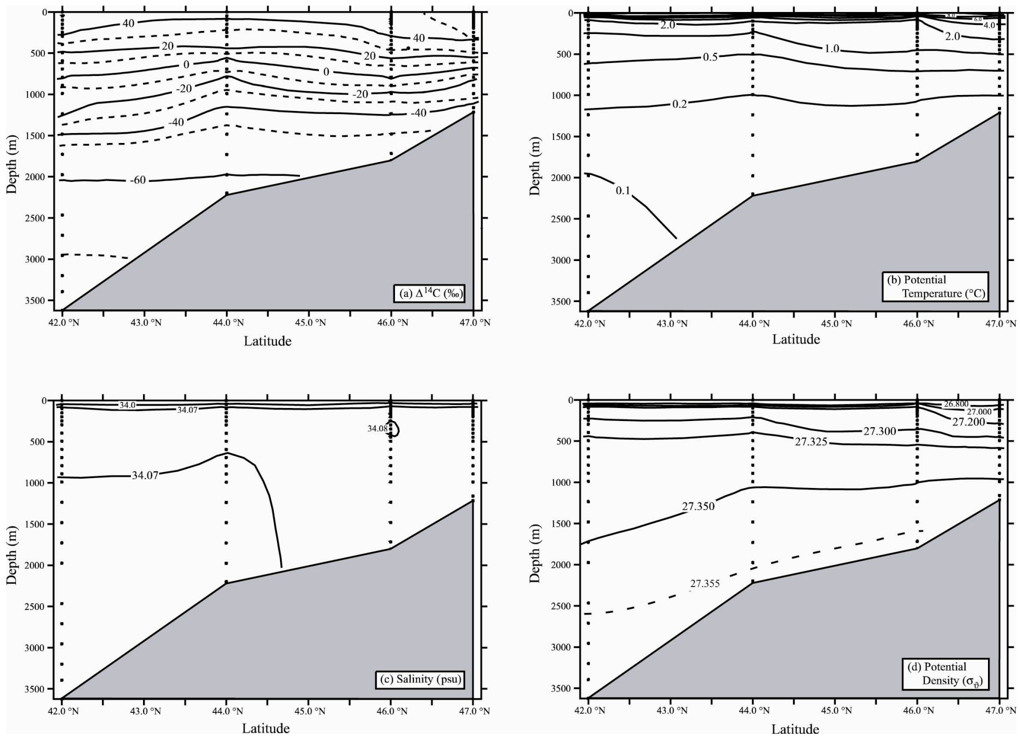

Figure 6 The north-south sections between 42°N and 47°N of $\Delta^{14}C$ (a), potential temperature (b), salinity (c), and potential density (d).

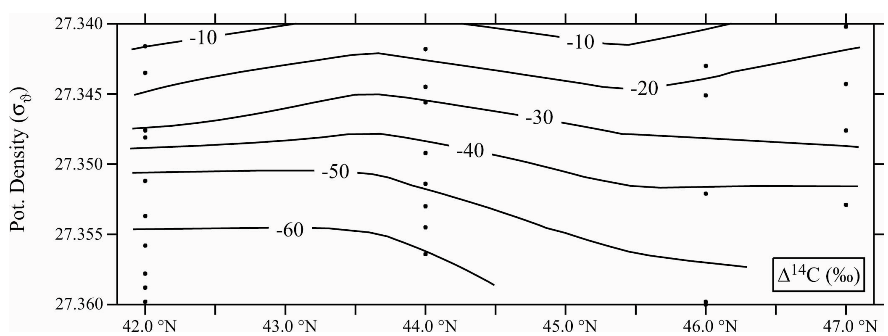

Figure 7 The north-south section between 42°N and 47°N of $\Delta^{14}C$ at the isopycnal surface

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