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Water Mass Formation Variability in the Intermediate Layer of the East Sea

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Abstract – Long-term variability in the intermediate layer of the eastern Japan Basin has been investigated to understand the variability of water mass formation in the East Sea. The simultaneous decrease of temperature at shallower depths and oxygen increasing at deeper depths in the intermediate layer took place in the late 1960's and the mid-1980's. Records of winter sea surface temperatures and air temperatures showed that there were cold winters that persisted for several years during those periods. Therefore, it was assumed that a large amount of newly-formed water was supplied to the intermediate layer during those cold winters. Close analysis suggests that the formation of the Upper Portion of Proper Water occurred in the late 1960's and the Central Water in the mid-1980's.

Key words – long-term variability, East Sea, water mass formation, intermediate water mass, water property

1. Introduction

Most of the East Sea is filled with cold water with temperatures less than 1°C except in the upper layer in the southern region where the Tsushima Warm Current (TWC) supplies warm water. Since the water that flows into the East Sea is generally warmer than 10°C, it is natural to assume that cold water forms in the northern East Sea during the winter.

Since the overall cold water mass below the thermocline was named as the Proper Water (PW) by Uda (1934), there have been several efforts to divide the PW into more specific waters. Sudo (1986) divided the PW into two water masses, the Upper Portion of the Proper Water (UPPW) and the deep water, at a depth of potential temperature 0.1°C (about 800-1000 m). He pointed out that the oxygen concentration of the UPPW was higher than 6.0 ml/l (about 268 μmol/l) and a discontinuity was present at the bottom of the UPPW. Later, the definition of the UPPW was modified by Senjyu and Sudo (1993) in terms of σ_1 (potential density referred to the 1000 dbar) in the range of 32.00-32.05 kg m^{-3}, corresponding to the σ_θ range of 27.31-27.34 kg m^{-3}. The UPPW is believed to be formed by winter convection in the region north of 41°N between 132°E and 134°E (Sudo 1986), or if expanded, west of 136°E between 40°N and 43°N (Senjyu and Sudo 1993).

In the 1990's, with the aid of precision instruments, the salinity minimum was observed at a depth of approximately 1500 m. Oxygen concentration in water above the salinity minimum was higher than the water below. Kim *et al.* (1996) named the water above the salinity minimum, the Central Water (CW). On the other hand, water having a salinity maximum with high oxygen content (> 250 μmol/l) was found in the eastern Japan Basin between surface water and the CW. Kim and Kim (1999) named this water, the High Salinity Intermediate Water (HSIW).

The CW and the HSIW definitions based on 1990's observations overlap the UPPW regarding the water properties (Fig. 1). Despite this overlapping, there are differences between these water masses. The CW is colder than the UPPW and its oxygen content is lower than that of the UPPW. Although the HSIW has a high oxygen content similar to the UPPW, the HSIW is warmer and more saline than the UPPW and its depth is shallower than the UPPW (Kim and Kim 1999; Watanabe *et al.* 2001). It is plausible that the CW and the HSIW were new water masses replacing the UPPW. Indeed, the characteristics of

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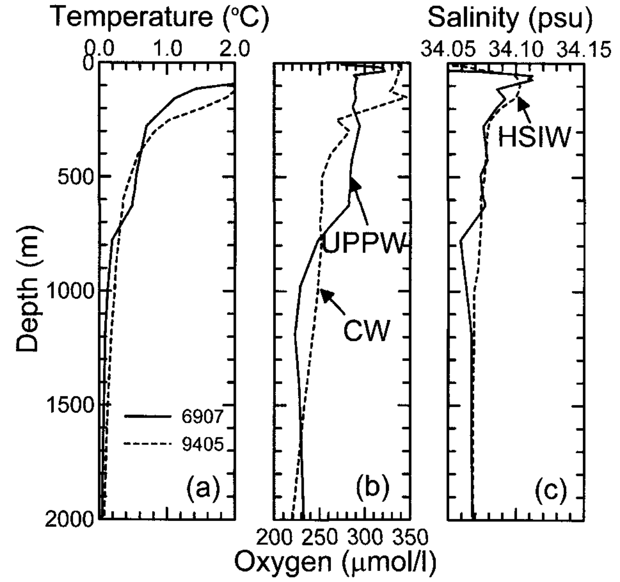

Fig. 1. Vertical profiles of (a) temperature, (b) oxygen, and (c) salinity in July 1969 (solid) and May 1994 (dashed) in the eastern Japan Basin, taken at two representative stations.

the UPPW that Sudo (1986) and Senjyu and Sudo (1993) defined with the hydrographic data obtained in the late 1960's and the early 1970's were not observed in the 1990's.

To comprehend the change in characteristics of the intermediate waters (the UPPW, the CW, and the HSIW), long-term variabilities of water properties in the intermediate layer in the northern region of the East Sea as well as winter conditions related to the formation of the intermediate waters were investigated.

2. Data and Method

Taking into account the scarcity of data in the western Japan Basin since the 1970's, a rectangular domain of 40.5°-44°N and 136°-139°E in the eastern Japan Basin was determined as the study area (Fig. 2). Cyclonic circulation in the Japan Basin was reported in several studies (Isobe and Isoda 1997; Park 2001) and rotation of the cyclonic gyre in the eastern Japan Basin was estimated to be approximately 15 months at 800 m using profiling floats (Park 2001). This implies that it takes less than a year for intermediate waters such as the UPPW formed in winter west of 136°E to be present in the study area. Therefore, it is reasonable to consider that this area might be the best candidate for studying temporal variations in the water properties in the intermediate layer in the northern region of the East Sea.

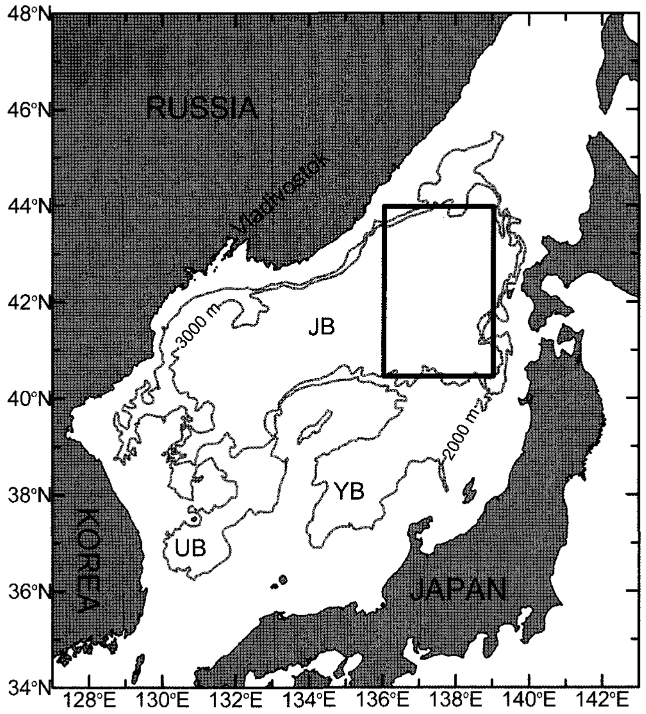

Fig. 2. Geographic map of the East Sea and location of hydrographic data used in this study. JB, UB, and YB represent the Japan Basin, the Ulleung Basin, and the Yamato Basin, respectively.

Among the historical data included in the World Ocean Database 2005, only profiles of temperature and oxygen with salinity were employed. The Tsushima Warm Water (TWW) plays a critical role in hydrographic conditions in the southern region rather than the northern region, but some profiles in the study area are thought to be influenced by the TWW. These profiles have been characterized by the gradually decreasing temperature with depth, whereas the typical structure in the northern East Sea is the shallow and sharp thermocline. Since profiles showing salinity higher than 34.1 psu at temperatures above 5°C were different from the typical ones, those were regarded as having been affected by the TWW and thus disregarded in order to exclude the influence of the TWW. Furthermore, hydrographic data from January to March were also discarded because vertical structures during that period were significantly different from others due to surface cooling. Although this study employed salinity to discriminate which profiles rather than salinity were under the influence of the TWW, temperature and oxygen data were mainly investigated because the accuracy of the salinity observed before the mid-1960's was considered to be no better than 0.01 psu (Senjyu and Sudo 1993).

3. Results

Vertical distribution of temperature and oxygen in the 1960's

Fig. 3 illustrates the mean vertical profiles of temperature and oxygen in the early 1960's (hereafter E60) and the late 1960's (hereafter L60), in which vertical distribution of temperature and oxygen in the study area changed noticeably during the 1960's. The most prominent change occurred in the intermediate layer during this period. Temperatures above 400 m in L60 were lower than that of E60, whereas temperatures below 400 m implied the opposite trend. Below the thermocline, temperatures during L60 decreased with depth more smoothly than in E60. For example, gradient in L60 at a depth range of 150-500 m was half of the gradient present in E60.

Remarkable differences between L60 and E60 were also present in the vertical distribution of oxygen (Fig. 3b). A relatively homogeneous layer between 150 m and 500 m appeared in L60, which contrasted from the steep gradient in E60. When oxygen was higher than 270 μmol/l in the homogeneous layer, oxygen in L60 was much higher (> 20 μmol/l) than that in E60 at a depth range of 300-600 m. This homogenous layer with oxycline at its bottom corresponded exactly to the characteristics of the mode water as pointed out by Sudo (1986), which was the UPPW. Together with the homogeneity of both temperature and oxygen, higher oxygen in L60 than E60 implied that a new homogeneous layer was formed in L60.

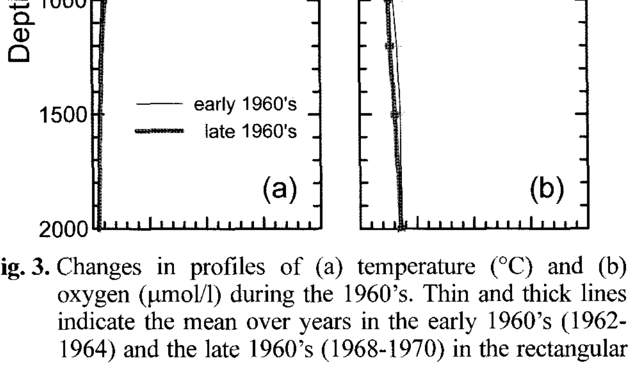

Fig. 3. Changes in profiles of (a) temperature (°C) and (b) oxygen (μmol/l) during the 1960's. Thin and thick lines indicate the mean over years in the early 1960's (1962-1964) and the late 1960's (1968-1970) in the rectangular domain in Fig. 1, respectively. One standard deviations are denoted with horizontal bars.

Temporal variabilities of temperature and oxygen

As shown in Fig. 3, while the newly formed homogeneous layer caused an overall increase of oxygen at intermediate depths, it caused different changes in temperature depending on depth, such as a decrease at shallower depths but an increase at deeper depths. The range of change in oxygen was large at approximately 500 m. However, temperature changes were larger at shallower depths than deeper depths. Therefore, a shallow depth for temperature but deeper depth for oxygen were suitable depths to trace the temporal variability of changes due to newly formed water. Therefore, temporal variabilities at 250 m and 500 m were examined for temperature and oxygen, respectively.

Together with an overall warming trend, there is evidence of significant decadal variability (Fig. 4a). It was worth noting that temperatures increased almost monotonically more than 0.4°C per decade until the mid-1960's and from the late-1980's through the 1990's. Between the two warming periods, there was considerable fluctuation such as a noticeable decrease in temperature in L60 and the mid-1980's (hereafter M80) and a less obvious increase present from the mid-1970's through the early 1980's.

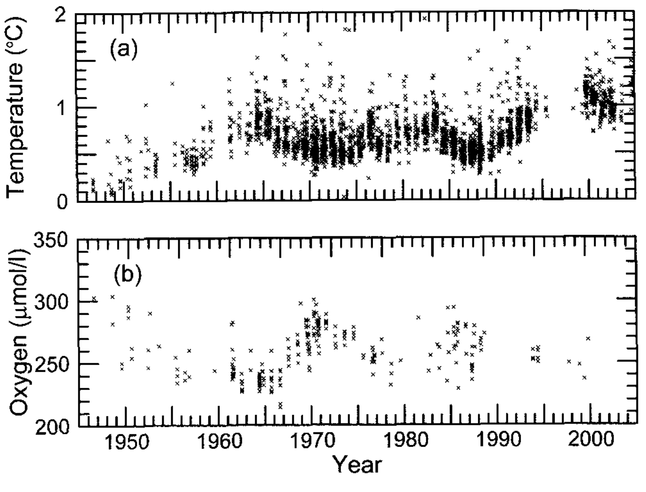

Fig. 4. Temporal variation of (a) temperature (°C) at 250 m and (b) oxygen (μmol/l) at 500 m. Profiles with salinity higher than 34.1 psu at temperatures above 5°C were excluded in order to discard data under the influence of the TWW.

Although the scarcity of observed data made it difficult to examine temporal variability, a remarkable increase in oxygen was recorded in L60 and a decrease in the 1970's (Fig. 4b). Without a supply of oxygenated surface water into this depth, oxygen decreased because oxygen was consumed due to biological utilization. Therefore, the increase in L60 implied that an increase in supply exceeded consumption while the decrease in the 1970's intimated an insufficient supply of oxygen-rich water. The decreasing rate of oxygen in the 1970's (about 5 μmol/l per year) was equivalent to the consumption rate of the UPPW estimated by Chen *et al.* (1996). Despite the variability in the 1980's is ambiguous because of dispersed values, oxygen levels appear to be higher in the late 1980's than in the late 1970's and the 1990's.

Variabilities under winter conditions

When formed in winter, intermediate water mass characteristics are related to atmospheric forcing and sea surface conditions. Fig. 5a shows the temporal variability of sea surface temperatures (SST) in February in the formation region of 132°-134°E north of 41°N where the heat flux center is located (Kawamura and Wu 1998). It was worth noting that SST was low in L60 and M80 and considerable warming took place from the late 1980's to the early 1990's. Low SST in M80 but high SST in the 1990's was consistent with the first EOF mode of SST distribution reported by Chu *et al.* (1998), showing colder SST in the cold season (November-April) of 1984-1987 but warmer SST between 1989-1993.

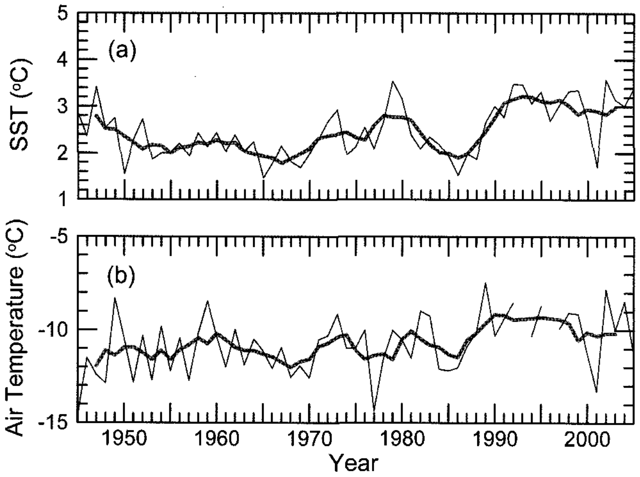

Fig. 5. Temporal variation of (a) sea surface temperature (SST) in February averaged over the region of 132°-134°E and 41°-43°N and (b) air temperature at Vladivostok averaged during the winter season (December-February). Thick lines denote five-year moving averages. SST from the Japan Meteorological Agency (JMA) was used.

Air temperature in winter (December-February) at Vladivostok exhibited consistent variability with the SST not only interannually but also decadally (Fig. 5b). Particularly, low air temperatures in L60 and M80 corresponded with the low SST during those periods. On the other hand, SST as well as air temperatures were extremely low in 2001 when a renewal of bottom water was reported (Kim *et al.* 2002; Senjyu *et al.* 2002; Talley *et al.* 2003), while SST in 1977 was higher than anticipated caused by exceedingly low air temperatures.

Many studies have confirmed that the supply of oxygen-rich water into the deep layer has reduced over the last 50-60 years while the supply into the intermediate layer has increased (Gamo 1999; Gamo *et al.* 2001; Kim and Kim 1996; Kim *et al.* 1999; Kim *et al.* 2001). It was proposed that the mode change from deep water formation to intermediate water formation started sometime during the 1950's (Kim *et al.* 2001). However, noticeable warming during the 1950's was not present, which implied that the mode change was triggered indirectly through the changes in oceanographic conditions rather than directly by atmospheric forcing in the 1950's.

Following the mode change, the occurrence of severe winters was considered favorable in order to supply oxygen-rich water into the intermediate layer even if small amounts continued to be supplied to the deep layer. Judging from the coincidence of a temperature decrease at 250 m and oxygen increase at 500 m, large amounts of newly-formed water appear to have been supplied to the intermediate layer in L60 and M80 when severe winters persisted for several years.

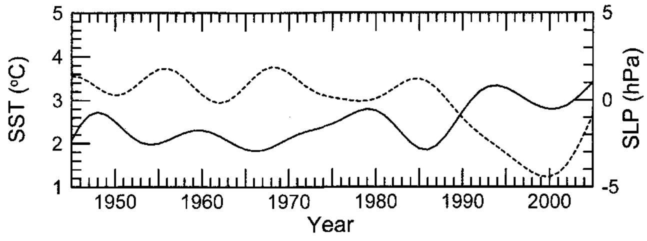

Fig. 6. Time series of SST (solid line) in Fig. 5a and intensity of the Siberian High (dashed line). Sea level pressure averaged during the winter season (December-February) over the region of 80°-120°E and 40°-60°N was used for the intensity of the Siberian High. Both variables are ten-year low-pass filtered.

The change in water formation may be related to changes in the atmospheric system. Fig. 6 shows decadal variabilities of SST and sea level pressure (SLP) of the Siberian High (SH) in winter. Cold SST in L60 and M80 and warming during the late 1980's to the early 1990's were consistent with high SLP and SLP decrease of the SH. This coincided well with the suggestion by Minobe *et al.* (2004) that the decadal variability of the northern East Sea is dominated by the decadal oscillation of the northern half of the SH, which is related to Arctic Oscillation.

Senjyu and Sudo (1996) suggested that the increase in oxygen content in the UPPW occurred after cold and/or windy winters using air temperatures at Vladivostok and air pressure differences between Vladivostok and Otaru that were regarded as wind speed indices. SLP differences (Vladivostok minus Otaru) in winter showed some consistent variability such as a decrease in the late 1980's (not shown), which may be related to increases in SST at that time. However, no significant contrast was evident between E60 and L60, which may imply that the increase in northerly wind speed was not the main cause for the striking increase in intermediate water formation occurring in L60.

4. Concluding Remarks

The UPPW with a high concentration of oxygen 6.0 ml/l appears to have been formed in L60 according to the temporal variability of oxygen at 500 m showing an increase in L60 and then higher values in successive years. Temperature variability at 250 m showed a decrease in M80 followed by an increase. Oxygen variability at 500 m showed a higher concentration in M80 followed by a decrease. This implies that the CW was formed in M80. Lower concentrations of oxygen in the CW in the 1990's compared to the UPPW in L60 may be due to consumption beginning when the CW was formed.

Salinity at the intermediate depth increased from the late 1970's through the early 1980's (not shown). Salinity in the formation region could be determined by fresh water supplied from the Amur River and saline water from the TWC, which are advected southwestward along the Russian coast (Yoon and Kawamura 2002). Although the reason for an increase in salinity is not known, changes in the current system as well as atmospheric forcing may be responsible. Kwon *et al.* (2004) explained the structural differences in water properties between observations in 1969 and 1995 by means of a simple diagnostic inverse model. They suggested that the changes in the intermediate layer were primarily due to a change in salinity at the surface outcrop. Therefore, it was inferred that the increase of salinity from the late 1970's through the early 1980's gave rise to the difference in water characteristics between the UPPW and the CW.

The remarkable warming of SST from the late 1980's to the early 1990's may be related to the change in water characteristics. Although a more in-depth examination is needed, there is a possibility that the characteristics of the HSIW observed in the 1990's, which is warmer and more saline than the UPPW and the CW, were a result of warming as well as an increase in salinity as mentioned above.

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