Progress in Oceanography xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Progress in Oceanography

journal homepage: www.elsevier.com/locate/pocean

A new perspective on origin of the East Sea Intermediate Water: Observations of Argo floats

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ARTICLE INFO

Keywords:
Argo float
East/Japan Sea
East Sea Intermediate Water
Water mass origin
Low salinity water

ABSTRACT

The East Sea Intermediate Water (ESIW), defined as the salinity minimum in the East Sea (hereafter ES) (Sea of Japan), is examined with respect to its overall characteristics and its low salinity origin using historical Argo float data from 1999 to 2015. Our findings suggest that the ESIW is formed in the western Japan Basin (40–42°N, 130–133°E), especially west of the North Korean front in North Korean waters, where strong negative surface wind stress curl resides in wintertime. The core ESIW near the formation site has temperatures of 3–4 °C and less than 33.98 psu salinity, warmer and fresher than that in the southern part of the ES. In order to trace the origin of the warmer and fresher water at the sea surface in winter, we analyzed the data in three different ways: (1) spatial distribution of surface water properties using monthly climatology from the Argo float data, (2) seasonal variation of heat and salt contents at the formation site, and (3) backtracking of surface drifter trajectories. Based on these analyses, it is likely that the warmer and fresher surface water properties found in the ESIW formation site are attributed to the low-salinity surface water advected from the southern part of the ES in autumn.

1. Introduction

The East Sea (a.k.a., the Sea of Japan, hereafter ES) is a semi-enclosed marginal sea surrounded by Japan, Korea, and Russia, connected to the North Pacific with four shallow straits (sill depth of around 100 m): the Korea/Tsushima Strait (KTS), the Tsugaru Strait, the Soya Strait and the Tatarsky Strait (Fig. 1a). Warm waters known as Tsushima Warm Water flow into the ES through the KTS and mainly flow out to the Pacific through the Tsugaru and Soya Straits. More than 90% of the ES is occupied by waters colder than 5 °C (Yasui et al., 1967), even though the inflow waters through the KTS are always warmer than 10 °C. Thus, it is reasonable to think that such cold waters must be formed inside of the ES in winter time, filling up in the intermediate and deep layers. Uda (1934) considered waters colder than 1 °C as a single water mass called "Japan Sea Proper Water". However, nowadays it seems widely accepted that the Proper Water consists of two or more water masses (c.f. Nitani, 1972; Gamo and Horibe, 1983; Sudo, 1986; Kim et al., 2004).

Conversely, there is a distinctive water mass at the intermediate depth in the ES which is usually warmer than the "Proper Water". The intermediate water was first noticed by Japanese scientists (Kajiura et al., 1958; Moriyasu, 1972), who found a layer with high oxygen concentration and low salinity below the thermocline. Later Kim and Chung (1984) also found a water mass with similar properties in the Ulleung Basin (UB), officially naming it as "East Sea Intermediate Water" (ESIW) based on oxygen concentration profiles. They suggested that the water mass should be ventilated from the sea surface in the northern part of the ES. Kim and Kim (1999) described the spatial distribution of ESIW properties using high resolution CTD and oxygen data in 1994, 1995, and 1996. The spatio-temporal variation of ESIW enabled the researchers to infer that the intermediate water might be formed in the western part of the Japan Basin (WJB) and that the water mass must be formed every year (Kim et al., 1999; Kim and Kim, 1999). Likewise, using the 1969 observation data, Senjyu (1999) and Watanabe et al. (2001) (who called it as the Japan Sea Intermediate Water) illustrated a similar distribution of the salinity minimum layer as Kim and Kim (1999), suggesting that the intermediate water would have been subducted in the western area of 132 °E. Since those two waters can be considered as the same water mass, we call the intermediate water as the ESIW following the one named by Kim and Chung (1984).

The quantitative definition of the ESIW has been provided by Kim and Kim (1999): the potential density (σ_θ) ranges from 26.9 to 27.3 kg m^{-3}, the corresponding water temperature varies between 0.6 °C and 5 °C, and with a lower salinity of 34.06 psu or below (Fig. 1b). The ESIW is characterized by a high oxygen content of over 250 μmol kg^{-1} as well as a salinity minimum layer. The high oxygen concentration indicates that the

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http://dx.doi.org/10.1016/j.pocean.2017.10.015
Received 12 January 2016; Received in revised form 22 October 2017; Accepted 23 October 2017

Please cite this article as: Park, J.J., Progress in Oceanography (2017), http://dx.doi.org/10.1016/j.pocean.2017.10.015

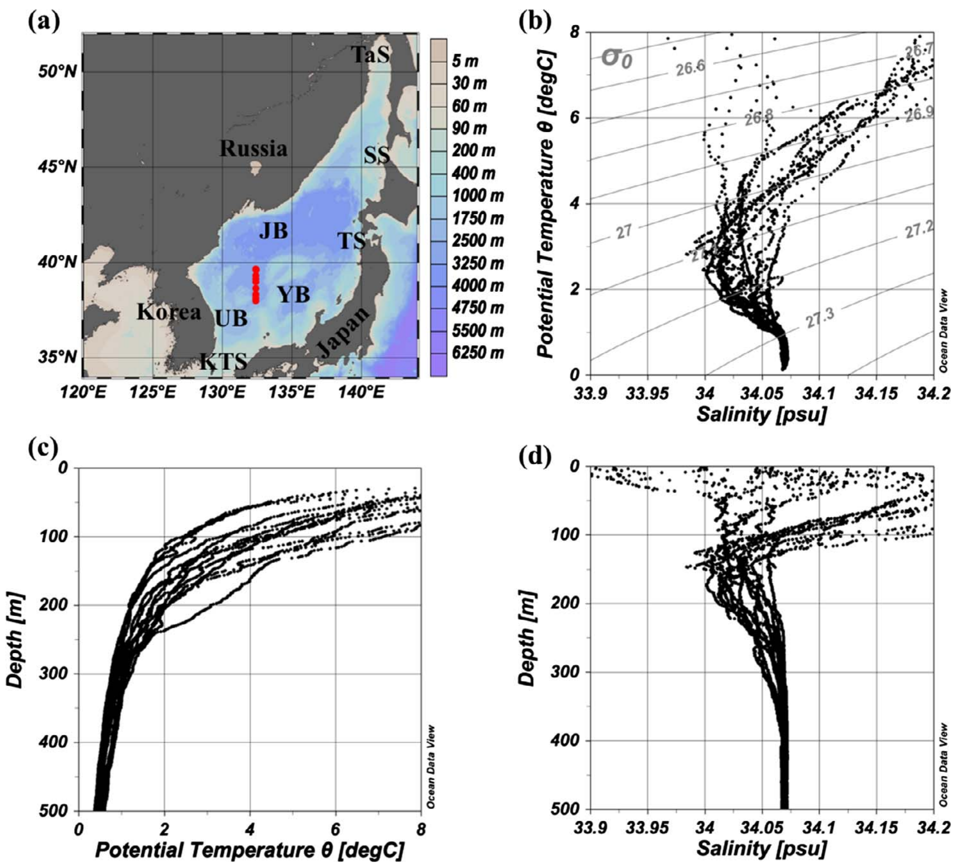

Fig. 1. (a) Station map of shipboard CTD data along the meridional line of 132.3°E obtained from the CREAMS program in 1994–2004 in summer (June to August). Ulleung Basin (UB); Yamato Basin (YB); Japan Basin (JB); Korea/Tsushima Strait (KTS); Tsugaru Strait (TS); Soya Strait (SS); Tatarsky Strait (TaS) Background color indicates bottom topography (b) θ-S diagrams (c) Potential temperature (θ) profiles (d) Salinity profiles corresponding to the stations in (a).

intermediate water was subducted below the permanent thermocline from the sea surface, where abundant oxygen is supplied by the winter atmosphere. The intermediate water is widely spread over the western and the southern parts of the ES. The ESIW is clearly different from the other intermediate water, named as High Salinity Intermediate Water (HSIW). The HSIW is mostly found inside of a cyclonic gyre in the eastern part of the Japan Basin, with similar temperature ranges and dissolved oxygen concentrations as the ESIW, yet higher potential density ranges of 27.00–27.32 kg m^{-3} and salinity higher than 34.07 psu (Kim and Kim, 1999; Watanabe et al., 2001; Kim et al., 2004; Min and Kim, 2006).

Some of the ESIW flows zonally along the subpolar front near 40°N, establishing a tongue-shaped structure, and is adjacent to the HSIW in the Eastern Japan Basin (Kim and Kim, 1999; Senjyu, 1999), as well as penetrating below the front, extending to the Ulleung Basin, the southwestern part of the ES. The other part of the ESIW advances southwards along the eastern coast of Korean Peninsula, the western boundary of the ES, and forms a major water mass in the North Korea Cold Current (Kim and Kim, 1983; Kim and Min, 2008). The salinity of the ESIW in the western boundary is lower than that in the interior of the ES by about 0.01–0.03 psu (Kim et al., 1999). The ESIW finally reaches the bottom layer of the Korean Strait (Cho and Kim, 1994; Cho and Kim, 1998; Yun et al., 2004; Min and Kim, 2006; Kim et al., 2006) and may be mixed away with the Tsushima Warm Water above it. Also, some amount of the ESIW may flow out to the North Pacific through the Tsugaru Strait as suggested by Park et al. (2008), but the major destruction mechanism of the ESIW remains undetermined (Park et al., 2016).

Fig. 1c and 1d show vertical structures of the water temperature and salinity obtained from the Circulation Research of the East Asian Marginal Seas (CREAMS) experiments in the northern part of the UB from 1994 to 2004 in summer time (June through August). As portrayed, water layers with salinity lower than 34.06 psu in Fig. 1d are found under the strong thermocline, where the intermediate water resides. Above the ESIW, there are two different kinds of water masses flowing through the KTS: low salinity Tsushima Warm Water (LSTWW) near the sea surface and high salinity Tsushima Warm Water (HSTWW) below the LSTWW. The LSTWW is found only in summer while the HSTWW persists throughout the whole year. The ESIW supposedly affects the surface water temperature via upwelling or vertical mixing that occur in the coastal areas, and it may exert influence over weather conditions and climate changes, manifested for example as temperature drops and sea fogs in the east coast of Korean Peninsula.

As compared to water masses in open oceans, water masses in semi-open marginal seas are susceptible to change in their properties during formation periods in winter, not only by atmospheric forcing but also by water advected from other regions. If distinct water masses flowing into the ES significantly affect the properties and formation of water masses in the interior of the sea, it should be known which exterior water mass is responsible for controlling the water mass formation; this knowledge would enable an understanding of the long-term variability of interior water masses in a rapidly-varying climate system. Prior researches regarding the origin and formation process of the ESIW have been mainly conducted numerical simulation. Kim and Yoon (1999) demonstrated that the ESIW was formed north of the subpolar front before flowing southward and streaming into the UB by a recirculation gyre connected with the East Korea Warm Current. The simulated distribution of the intermediate water in the model was similar to that based on the existing observation data (Kim and Kim, 1999; Senjyu, 1999). Applying a similar model to study origins of the ESIW, Yoon and Kawamura (2002) argued that origin of the low-salinity intermediate water shown in the model was near the Russian coast, especially the freshwater flowing from the Amur River around the Tatarsky Strait. Yoshikawa et al. (1999) also attempted to simulate the formation of ESIW by a numerical model. However, the simulated formation area of ESIW significantly differs from the results of the numerical model (Yoon and Kawamura, 2002) and from the previous observations. The formation area simulated in the model was located close to the southern coast of Vladivostok, between 131°E and 135°E, far east from the one estimated based on observed data. Besides, Yoshikawa et al. (1999)